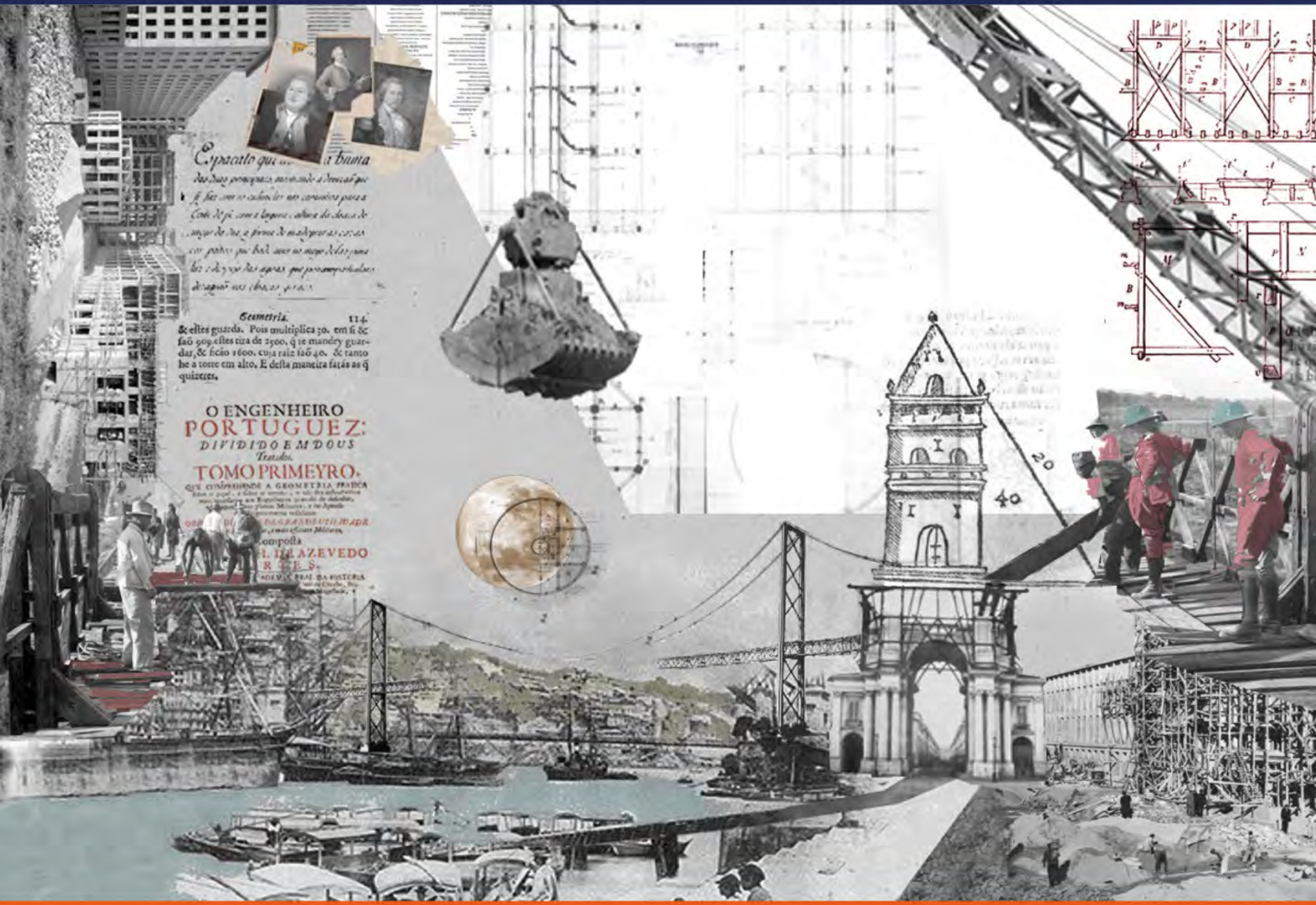
HISTORY OF CONSTRUCTION CULTURES

VOLUME 2



edited by
João Mascarenhas-Mateus
and **Ana Paula Pires**

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HISTORY OF CONSTRUCTION CULTURES

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History of Construction Cultures

Editors

João Mascarenhas-Mateus
Universidade de Lisboa, Portugal

Ana Paula Pires
Universidade dos Açores, Portugal

Co-editors

Manuel Marques Caiado & Ivo Veiga
Universidade de Lisboa, Portugal

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Introduction: *History of Construction Cultures*

We are what we build and how we build; thus, the study of Construction History is now more than ever at the centre of current debates as to the shape of a sustainable future for humankind. Embracing that statement, the present work takes the title *History of Construction Cultures* and aims to celebrate and expand our understanding of the ways in which everyday building activities have been perceived and experienced in different cultures, times and places.

This two-volume publication brings together the communications that were presented at the 7ICCH – Seventh International Congress on Construction History, broadcast live from Lisbon, Portugal on 12–16 July 2021. The 7ICCH was organized by the Sociedade Portuguesa de Estudos de História da Construção (Portuguese Society for Construction History Studies – SPEHC); the Lisbon School of Architecture, University of Lisbon; its Research Centre (CIAUD); and the College of Social and Human Sciences of the NOVA University of Lisbon (NOVA FCSH).

This is the first time the International Congresses on Construction History (ICCH) Proceedings will be available in open access format in addition to the traditional printed and digital formats, embracing open science principles and increasing the societal impact of research. The work embodies and reflects the research done in different contexts worldwide in the sphere of Construction History with a view to advancing on the path opened by earlier International ICCH editions. The first edition of ICCH took place in Madrid in 2003. Since then, it has been a regular event organized at three-year intervals: Cambridge (2006), Cottbus (2009), Paris (2012), Chicago (2015) and Brussels (2018).

7ICCH focused on the many problems involved in the millennia-old human activity of building practiced in the most diverse cultures of the world, stimulating the cross-over with other disciplines. The response to this broad invitation materialized in 357 paper proposals. A thorough evaluation and selection process involving the International Scientific Committee resulted in the 206 papers of this work, authored by researchers from 37 countries: Australia, Austria, Belgium, Brazil, Bulgaria, Canada, China, Dominican Republic, Ecuador, Egypt, Estonia, France, Germany, India, Iran, Ireland, Italy, Japan, Mexico, Netherlands, New Zealand, Norway, Peru, Poland, Portugal, Puerto Rico, Russia, Serbia, Spain, South Africa, Sweden, Switzerland, Thailand, United Arab Emirates, United Kingdom, United States of America, and Venezuela.

The study of construction cultures entails the analysis of the transformation of a community's knowledge capital expressed in the activity of construction. As such, Construction History is a broad field of knowledge that encompasses all of the actors involved in that activity, whether collective (contractors, materials producers and suppliers, schools, associations, and institutions) or individual (engineers, architects, entrepreneurs, craftsmen). In each given location and historical period, these actors have engaged in building using particular technologies, tools, machines and materials. They have followed specific rules and laws, and transferred knowledge on construction in specific ways. Their activity has had an economic value and belonged to a particular political context, and it has been organized following a set of social and cultural models.

This broad range of issues was debated during the Congress in general open sessions, as well as in special thematic sessions. Open sessions covered a wide variety of aspects related to Construction History. Thematic sessions were selected by the Scientific Committee after a call for proposals: they highlight themes of recent debate, approaches and directions, fostering transnational and interdisciplinary collaboration on promising and propitious subjects. The open sessions topics were:

- Cultural translation of construction cultures: Colonial building processes and autochthonous cultures; hybridization of construction cultures, local interpretation of imported cultures of building; adaptation of building processes to different material conditions;
- The discipline of Construction History: Epistemological issues, methodology; teaching; historiography; sources on Construction History;
- Building actors: Contractors, architects, engineers; master builders, craftspeople, trade unions and guilds; institutions and organizations;
- Building materials: Their history, extraction, transformation and manipulation (timber; earth, brick and tiles; iron and steel; binders; concrete and reinforced concrete; plaster and mortar; glass and glazing; composite materials);

- Building machines, tools and equipment: Simple machines, steam operated-machines, hand tools, pneumatic tools, scaffolding;
- Construction processes: Design, execution and protective operations related to durability and maintenance; organization of the construction site; prefabrication and industrialization; craftsmanship and workshops; foundations, superstructures, roofs, coatings, paint;
- Building services and techniques: Lighting; heating; ventilation; health and comfort;
- Structural theory and analysis: Stereotomy; modelling and simulation; structural theory and structural forms; applied sciences; relation between theory and practice;
- Political, social and economic aspects: Economics of construction; law and juridical aspects; politics and policies; hierarchy of actors; public works and territory management, marketing and propaganda;
- Knowledge transfer: Technical literature, rules and standards; building regulations; training and education; drawings; patents; scientific dissemination, innovations, experiments and events.

The thematic sessions selected were:

- Form with no formwork (vault construction with reduced formwork);
- Understanding the culture of building expertise in situations of uncertainty (Middle Ages-Modern times);
- Historical timber constructions between regional tradition and supra-regional influences;
- Historicizing material properties: Between technological and cultural history;
- South-South cooperation and non-alignment in the construction world 1950s–1980s;
- Construction cultures of the recent past: Building materials and building techniques 1950–2000;
- Hypar concrete shells: A structural, geometric and constructive revolution in the mid-20th century;
- Can engineering culture be improved by construction history?

Volume 1 begins with the open session “Cultural translation of construction cultures” and continues with all the thematic sessions. The volume ends with the first part of the papers presented at the open sessions, organized chronologically and the introductory texts by the chairs for each thematic session. Volume 2 is dedicated to the remaining topics within the general themes, also in chronological order.

Four keynote speakers were chosen to present their most recent research results on different historical periods: Marco Fabbri on “Building in Ancient Rome: The fortifications of Pompeii”; Stefan Holzer “The role of temporary works on the medieval and early modern construction site”; Vitale Zanchettin “Raphael’s architecture: Buildings and materials” and Beatriz Mugayar Kühl “Railways in São Paulo (Brazil): Impacts on the construction culture and on the transformation of the territory”.

The editors and the organizers wish to express their immense gratitude to all members of the International Scientific Committee, who, despite the difficult context of the pandemic, worked intensively every time they were called on to give their rigorous evaluation of the different papers.

The 7ICCH was the first congress convened under the aegis of the International Federation of Construction History, founded in July 2018 in Brussels. Therefore, we are also very grateful to all the members of the Federation, composed of the presidents of the British, Spanish, Francophone, German, U.S. and Portuguese Societies and its Belgian co-opted member. A special thanks is due for all the expertise and experience that was passed on by our colleagues who have been organizing this unique and world significant event since 2003, and in particular to our predecessors from all the Belgian universities who organized 6ICCH.

The editors wish to extend their sincerest thanks to authors and co-authors for their support, patience, and efforts. This two-volume work would not exist but for the time, knowledge, and generosity they invested in the initiative.

Our sincere thanks also go out to Kate Major Patience, Terry Lee Little, Kevin Rose and Anne Samson for proofreading every paper included here, and to the team at Taylor & Francis (Netherlands), in particular Germaine Seijger and Leon Bijnsdorp.

Finally, we are grateful to all members of the Local Committee and to the institutions that have supported both the 7ICCH event and the publication of these proceedings.

The Editors
João Mascarenhas-Mateus and Ana Paula Pires

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Early Greek temple design and roof construction

A. Pierattini
University of Notre Dame, Notre Dame, USA

ABSTRACT: Beginning in the 8th century BC, large temples appeared across the Greek world. In continental regions, this large size was achieved through length, resulting in narrow, elongated ground plans. In most of the Aegean islands, the temples had a more compact aspect ratio, with broader interiors. Several scholars have associated this difference to limitations in the span of thatched roofs, which were common in continental Greece. However, the nature of these limitations has not been investigated. Using modern structural theory and wind engineering studies, this paper examines how the aspect ratio of temple ground plans related to roof construction. It concludes that excessive width made steep thatched roofs susceptible to buckling and damage due to wind force, while width did not affect the stability of the flat roofs prevalent in the Aegean islands.

1 INTRODUCTION

This paper addresses the design of the first monumental Greek temples in relation to their construction. Specifically, it examines how the aspect ratio of temple ground plans related to roof construction. Beginning in the late 8th century BC, large temples appeared across the Greek world. In continental regions, an increase in the length of temples resulted in an elongated aspect ratio. The largest temples reached over 30 m long (or c. 100 ft., hence the archeological term *hekatompedon*) (Figure 1a–d), while their width rarely exceeded 7 m. Temples in most of the Aegean islands typically had ground plans with a more compact aspect ratio. Particularly in the Cyclades, they were remarkably broad in relation to their length. For example, the second and third temples at Yria on Naxos (c. 730 and 680 BC) were about 11 m wide by 16.50 long (Figure 1e, f), and the so-called Pre-oikos of the Naxians on Delos (first half of the 7th century BC) was about 10 m wide by 24 m long (Figure 1g). The broad interiors of these temples raise the question as to why Cycladic builders chose to emphasize the temple's width.

Vassilis Lambrinoudakis (1991, 185) has suggested that, unlike other areas of the Greek world, Cycladic builders were concerned with the spatial quality of the interior rather than the exterior. Such an explanation is plausible but unprovable. It is also possible that the width of island temples served a functional purpose. Animal remains and pottery found in several of these temples show that their interiors served as communal dining halls. Yet, in continental Greece, a number of elongated temples served a similar purpose. In both regions, participants are assumed to have dined on benches along the perimeter. We do not know how the central space might have been used differently, therefore the functional reasons remain hypothetical. Turning the question on its head, some scholars have asked what may have *limited* the span of continental temples. A connection between their narrow ground plans and the spanning limitations of the sloped roofs of thatch common to continental Greece is generally accepted (Snodgrass 1980, 58). What exactly may have limited the span of these roofs has not been thoroughly investigated, but this question can be answered on technical grounds.

This paper examines the different aspect ratios of continental and insular Greek temples in relation to roof construction by using modern structural theory and wind engineering studies. It begins by examining the evidence for the connection between the aspect ratio of temple ground plans and roof construction. It then explores the technical features of roofs in continental and insular Greece based on the archaeological evidence and ethnographic accounts of traditional roofing in those areas. Next, it discusses the frame that supported the roof and how an increase in width would have affected structural behavior depending on the regional roof technologies. As the conclusion will show, excessive width made steep thatch roofs prone to instability due to buckling and wind force, while width did not affect the stability of the flat roofs prevalent in the Aegean islands.

2 PLAN ASPECT RATIO AND ROOF CONSTRUCTION. GEOGRAPHICAL DISTRIBUTION

Before the adoption of terracotta roof tiles in the mid-seventh century BC, the roofs of Greek temples

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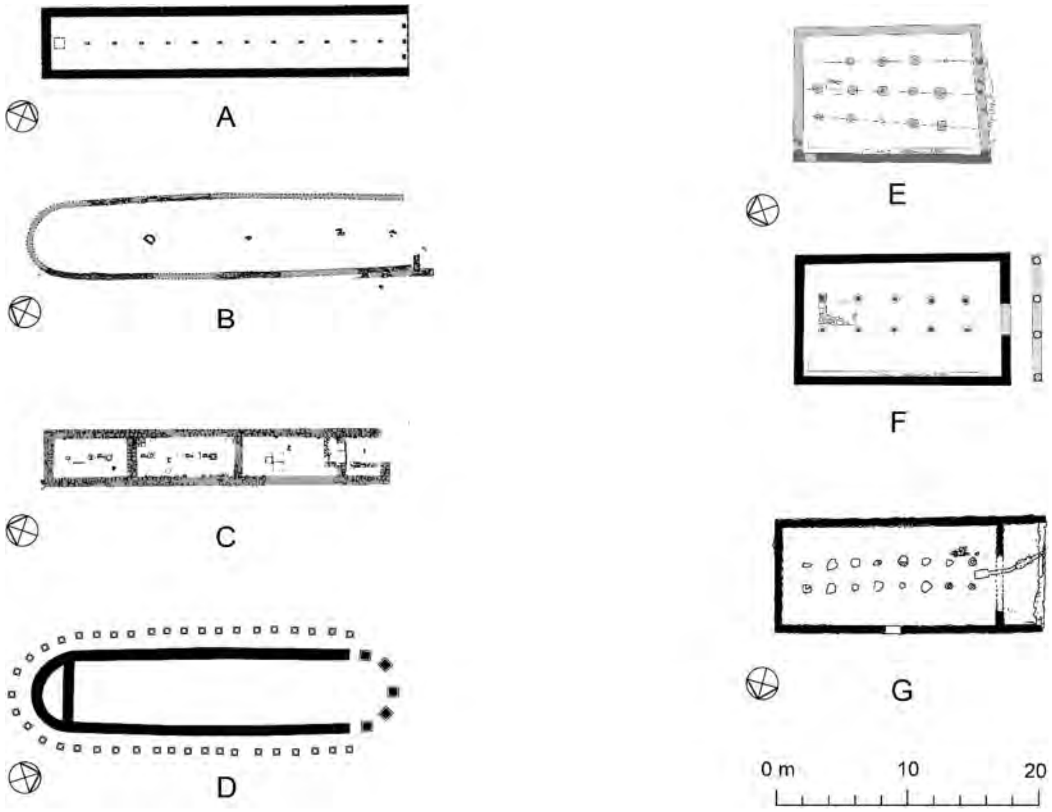

Figure 1. Some of the largest Greek temples built in the late 8th and early 7th centuries BC. A: first Hekatompedon in the sanctuary of Hera on Samos; B: Building Ed2 (Hekatompedon) in the sanctuary of Apollo Daphnephoros at Eretria; C: temple of Apollo at Halieis; D: Temple of Artemis Aontia at Ano Mazaraki; E–F: second and third temples at Iria on Naxos; G: pre-Oikos of the Naxians in the sanctuary of Apollo on Delos.

(like the roofs of houses) were either steep and thatched or flat and covered with clay. According to Vitruvius (2.1.5) and other ancient authors, roofs of thatch or clay could still be seen in first-century Rome and Athens. The thatch-covered hut of Romulus on the Palatine Hill, preserved as a relic, was repeatedly and faithfully reconstructed, while the Athenians preserved the venerable, clay-roofed building on the Areopagos.

The geographical distribution of the two roof types in the ancient Greek world suggests a connection between the plan aspect ratio and roof technology. Built mostly of perishable materials, the roofs themselves have not survived. Contemporary or slightly later terracotta and stone votive models of buildings, which have been found at sanctuaries across the Greek world, are the principal sources of information on Greek roofs of the eighth and early seventh centuries BC. The roofs and find places of these architectural models give a fairly clear idea of the geographical distribution of pitched vs. flat roofs. Models from continental Greece, such as those from the sanctuaries of Hera at Argos and Perachora, or Poseidon at Nikoleika (Figure 2), feature steeply pitched roofs. By contrast, models from Crete and the Cyclades have flat roofs. Excavations at the sanctuary of Hera on the island of Samos, in East Greece, have produced models with both flat and pitched roofs (Figure 3). Here, the first two temples of Hera (Hekatompedon 1 and 2) had elongated plans and probably pitched roofs, while the small shrines (*naiskoi*) found around the altar presumably had flat roofs.

The distribution of the models suggests that pitched roofs were mostly, although not exclusively, concentrated in continental regions while flat ones were dominant on the Aegean islands. Climate is a main factor influencing roof technology. Pitched roofs, which allow rain water to run off quickly, are necessary in areas where rainfall is intense. Flat clay roofs, structurally simpler and requiring fewer timbers, are more resistant against the powerful Aegean winds. While flat–covered structures also existed in some coastal areas of the mainland, for example at Thorikos in Attica (Coulton 1988, 62), the flat roof has been the dominant type in the dry, windy climate of Crete and the Cyclades from antiquity to the present day.

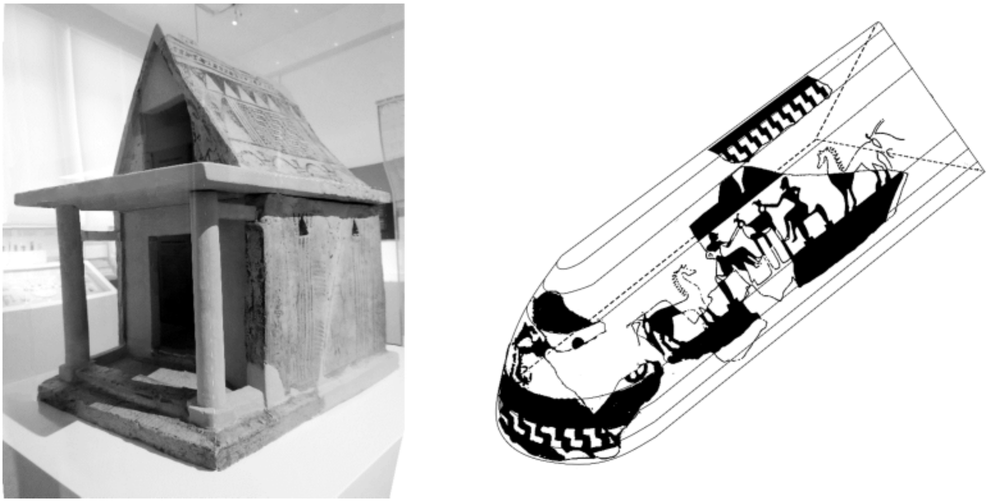

Figure 2. Left: house model from the sanctuary of Hera at Argos (first quarter of the seventh century). Photo by the author. Right: temple model from the sanctuary of Poseidon at Nikoleika (ancient Helike) (late eighth century). Drawing by the author after Gadolou and Paschalidis 2020, fig. 4.9.4b.

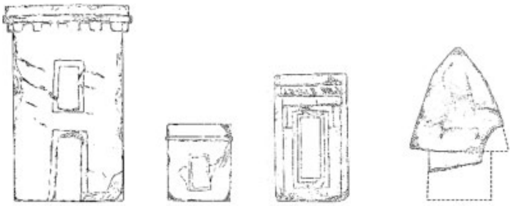

Figure 3. Architectural models from the sanctuary of Hera at Samos (seventh and sixth centuries BC). Drawing by the author after Schattner 1990, figs 26, 28, 20, 17.

3 TECHNICAL FEATURES OF FLAT AND PITCHED ROOFS

In addition to flat-roofed architectural models, there is direct evidence at several Aegean sites that roofs were flat and covered with clay. Layers of clayey earth found above the floors of many late eighth to early 7th century buildings at Emporio on the island of Chios, near the coast of Eastern Greece, are probably the remains of collapsed clay roofs (Boardman 1967, 36). The excavations at Iria on the Cycladic island of Naxos have produced a marble waterspout (Lambrinoudakis 1996, 55) that belonged to the third temple (c. 680 BC). The excavators restored it on top of a flat clay roof bordered by a low stone wall. Several contemporary flat-roofed architectural models from Samos have a similar border (Schattner 1990, 177–80, and 168 fig. 46; Walter et al. 2019, ch. 10 and pls 37–41). Ethnographic accounts of traditional clay roofing in modern times explain that this border prevents rain from quickly washing the clayey layer away (Minke 2000, 133 fig. 14.6-3). Moreover, the border allows water to be collected and potentially conveyed into storage containers. Considering the scarcity of water on many Aegean islands, particularly Delos in the Cyclades, this was an important factor (Mays et al. 2013, 1921). Ethnography can also help us reconstruct the technical features of the roof coat. Whether horizontal or moderately sloped, clay roofs consist of a thick layer of clay (up to or over 40–50 cm) that rests on planks, reeds, twigs, or flat stone slabs laid on the roof's joists (Schattner 1990, 177–8; Rapoport 69, 106). Such a coat is remarkably heavy. With clay density being around 1.75 T/m^3, a coat 40 cm thick weighs around 700 kg/m2, and even more once it has absorbed rainwater.

Both literary and archeological evidence support the idea that pitched roofs in pre-Archaic continental Greece were thatched. The Iliad provides the first reference to thatch roofing (24.451). The Myrmidons make a shelter for their king, Achilles, with thatch from the meadows. Here, the Greek word for thatch is *orophos*, which in Homer, as in later Greek texts, is also a word generally used for roof. Direct archaeological evidence is admittedly scant, consisting of a few finds of carbonized reeds such as those from South Temple 5 at Kalapodi (9th century BC), in Phokis (Niemeier 2017, 327). The steep pitch of the model roofs (up to c. 65°) is telling, as it is characteristic of thatching (Schattner 1990, 182). Other than this evidence provided by the slope, Greek votive models are poor in construction details. Among the few exceptions are two models from Perachora and one from Tegea (Nordquist 2014; Schattner 1990, 33–4, 37). A twisted rooftop, a feature still found on modern thatched roofs, appears on one of the Perachora models and that from Tegea (Figure 4). The eaves of the second Perachora model gently curve upwards, a feature also sometimes used today to prevent thatch from slipping.

Ancient Greek thatching methods probably varied in quality and durability within the range of traditional methods still used today. Traditional thatching employs reeds or straw, ideally from cereal grasses.

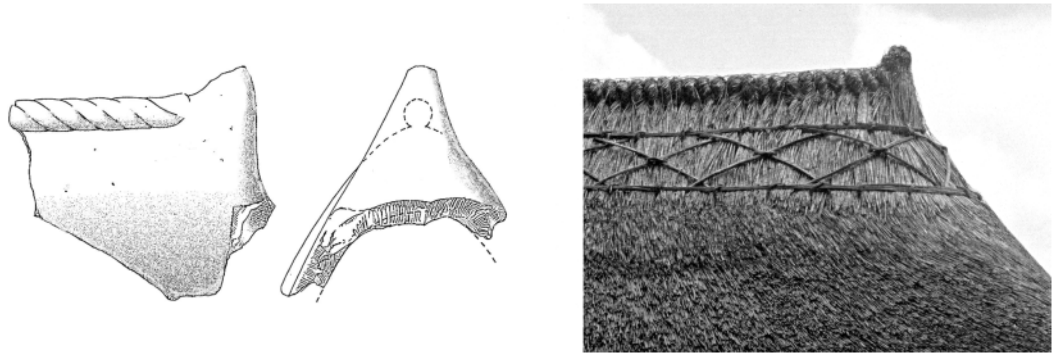

Figure 4. Left: Fragment of an eighth-century house model from the sanctuary of Hera at Perachora, showing a twisted rooftop. Drawing by the author after Payne 1940, pl. 9. Right: the same motif on a modern thatch roof from England. Courtesy of Graham Cook @ thatchinginfo.com.

Figure 5. Layers of thatch bundles in a modern thatch roof (England). Courtesy of Graham Cook @ thatchinginfo.com.

Historically, straw was always favored wherever cereals were cultivated. The use of reeds was mostly confined to marshy areas. The most durable thatch roofs are made by laying reeds or bundles of straw on horizontal battens, which in turn are laid upon the roof's rafters. Successive layers cover the lower ones to form a thick coat (20–40 cm) so only the lower ends of the stems (the butts) are exposed (Figure 5). Because of this overlap, and because the butts are thicker than the tops, each reed or strand of thatch lies closer to the horizontal than the roof pitch. Yet the runoff of rainwater requires the strands to be laid at an adequate slope (at least 20°), which demands a dramatically steep roof pitch (minimum 45°). According to modern thatching manuals, a coat of straw thatch, together with the battens it is laid on, weighs around 30 kg/m^2 (Macey 1904, 160, 396). A reed coat can be as much as twice as heavy, which is still over ten times lighter than a coat of clay.

4 STRUCTURAL FRAME AND WIDTH INCREASE

The interior wooden posts that supported the roofs of pre-Archaic Greek buildings are not preserved. However, post bases or post holes found at many sites, combined with the remains of mud brick or rubble walls, allow us to reconstruct the buildings' structural frames. On the Aegean islands, most buildings that were presumably flat-roofed had relatively narrow interior aisles, including the largest temples with their broad overall spans. On Delos, Artemision E and the Pre-Oikos of the Naxians had three interior aisles that spanned about 3 or less meters each. At Iria on Naxos, each aisle spanned less than 2.50 m in the first and second temples and c. 3.30 m in the third. At Emporio on Chios, most of the eighth century buildings had interior aisles with spans shorter than 2.50 m.

In terms of the use of roofing materials and structural behavior, expanding the width of a building with a flat roof took no more effort than increasing its length. Broadening each aisle's span would have much increased the load on the roof's cross beams and required massive timbers, for the weight of the clay coat was considerable. As discussed above, Cycladic builders obviated the problem by increasing the number of aisles, thus keeping the span within manageable limits. At Iria, the Naxians expanded the temple's width from 5 m to 11 m by doubling the number of aisles from two to four. Multiple narrow aisles could be covered with short beams, which were easier to source than larger beams. In the Cyclades and on other Aegean islands, supply considerations were critically important since wood was never plentiful. With local

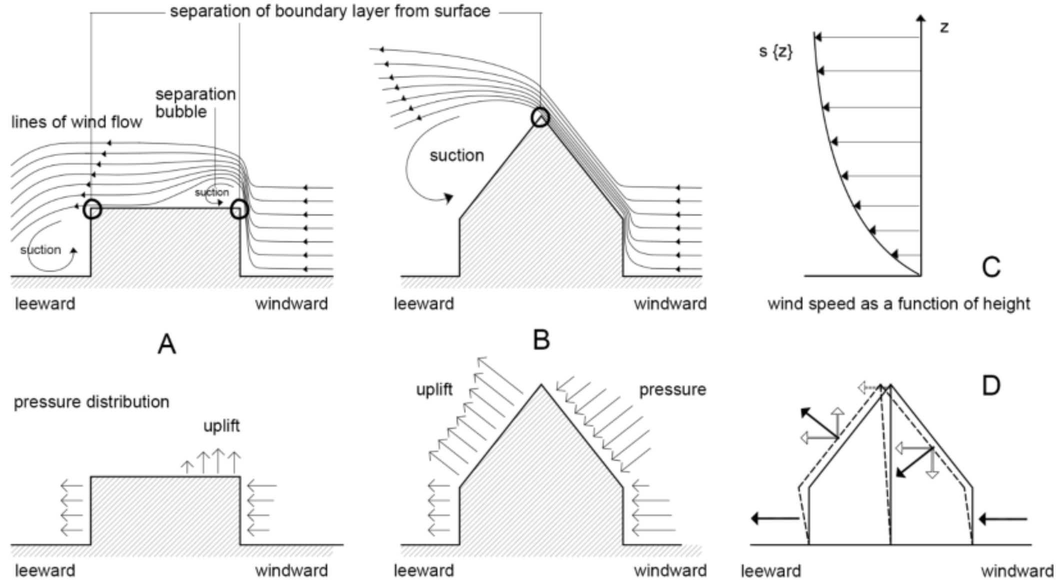

Figure 6. Effects of wind on flat and high-pitch roofs. Drawings by the author.

economies based on trade and fishing, wood of the best quality would have been reserved for ship construction. Delos had no timber besides palm and fig trees, both very poor building materials (Meiggs 1982, 442).

On the Aegean islands, the strong local winds had to be taken into special consideration—especially close to the coast, where topography was less likely to mitigate their force. Exposed to the wind, a structure acquires a layer of air flow around it (laminar boundary layer). At the windward edge of a flat or low-pitched roof, this layer detaches from the roof, which creates a region of intense low pressure (separation bubble) (Figure 6a) (Cigada et al. 2006). This results in an uplift suction of the portion of the roof exposed to the flow separation. This uplift reaches a peak at the windward edge—another reason for capping the edge of flat roofs with stones. If the building is long enough (length is intended as the dimension in the wind's direction), the flow on the roof becomes laminar again, and the separation bubble does not significantly grow beyond a certain length. As a result, increasing the length or width of a flat-roofed building does not aggravate the wind's effects. At any rate, the upward suction caused by the wind was no concern for heavy, flat roofs of clay.

Pre-Archaic Greek buildings with elongated ground plans, presumably covered with steep thatched roofs, were usually divided in two longitudinal aisles. An axial row of posts supported a ridge beam, which in turn held the roof's rafters. With the same aisle spans, a thatched roof required longer beams than a flat clay roof. A two-aisled building 7 m wide required rafters and axial posts about 5 m long. Nonetheless, the interior aisles of pitched-roofed buildings could span longer than flat roofed ones, reaching 3.5 or more meters. Thatch is much lighter than clay and continental areas were better provided with timber. Fir in particular was available in most of continental Greece (*Abies alba* in Macedonia and *Abies cephalonica* in central and southern Greece) (Meiggs 1982, 43). Providing long, straight timbers, it was the wood the Greeks used most both for ship building and general construction.

Increasing width in a highly sloped, thatched roof produces a notable increase in height, with the ratio of roof height to width usually varying between ½ (with a 45° slope) to 1 (at c. 63°) or more. This raises problems of stability. Structurally, even a small increase in a post's height significantly increases the risk of buckling (sudden sideways bending), since the force necessary for buckling an axially loaded post diminishes with the square of the post's height. According to Euler's theory, the critical value of the load above which a post will buckle is $P_{cr} = \pi^2 EI / KL^2$, where $E =$ material's modulus of elasticity; $I =$ moment of inertia of the post's cross-section; $K =$ the column's effective length factor, which depends on the column's end conditions; and $L =$ column's height.

In addition to increasing the risk of buckling, height amplifies the wind's destabilizing effects on a pitched roof. With a high pitch, the laminar boundary layer detaches from the peak of the roof. Thus, while the windward side of the roof incurs positive pressure, a separation bubble produces suction on the leeward side (Figure 6b). These positive and negative pressures result in upward and downward forces as well as sideways thrusts (pressure drag). Pressure drag increases with the relative angle between wind direction and the surface (angle of attack), so the steeper the roof the more prone to dragging.

Besides increasing the roof surface exposed to the wind (and therefore the resultant wind forces), an increase in height further aggravates the problem because wind pressure increases with the square of its speed, which in turn rises with height (Figure 6c) (Garratt 1994; Kaimal & Finnigan 1994). In addition, the higher the roof, the less it benefits from the shelter of topographical features such as rocks and trees, which reduce wind near the ground (Belcher et al. 2003). The effect of a sideways thrust applied on top of the roof becomes more destabilizing the higher the axial post (Figure 6d). Indeed, the effect of a force is proportional to its arm (perpendicular distance from the axis of rotation to the line of action of the force), which in this case corresponds to the post’s height.

From early times, sailors in the ancient Mediterranean and Near East may have intuited the relationship between height and the effects of wind pressure by observing how the height of the mast and the position of the yard along the mast affected the speed of a sailing vessel. Such concerns seem to have guided the Egyptians in designing their river boats, whose tall sails were probably made to catch the upper breezes when the Nile flowed between high-rising cliffs (Casson 1994, 21). The greater effect of wind on a sail placed high on the mast is discussed in the third century BC in the pseudo-Aristotelian *Mechanics* (851b): “Why when the yardarm is higher does the boat sail faster, with the same sail and the same wind?” (transl. Winter 2007). The text, however, incorrectly explains the phenomenon in terms of the lever principle, an error that Vitruvius (10.3.5-6) repeats some three centuries later (see Fleury 1993, 80-2). We cannot expect eighth-century Greek roof builders to have understood wind dynamics and mechanics, yet experience would have taught them that taller roofs were more prone to wind damage.

5 CONCLUSIONS

By examining the first monumental Greek temples of the 8th and early 7th centuries BC through the lens of modern structural theory and wind engineering, the connection between the aspect-ratio of their ground plans and their roof construction is demystified. The narrow, elongated aspect ratio of the largest temples of mainland and East Greece was most probably due to concerns about the stability of their steeply pitched, thatched roofs. Unlike the flat clay roofs that covered the broadest temples of the Aegean islands, the increased width of a steep thatched roof resulted in a considerable increase in height. The laws of mechanics and wind-dynamics show that height quadratically increased risks of collapse due to buckling or wind pressure. Classical builders did not know these laws but were surely familiar with their effects. The technical arguments above do not preclude that other reasons may have influenced the aspect ratio of Greek temples. Ritual use of the interior may have conformed to spaces whose proportions were dictated by technique, or ritual may have dictated its own rules with which technique had to come to terms. Both likely interacted to shape the space of the temple.

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Precursors of aseismic design: The case of Achaemenid monumental architecture

M. Motamedmanesh
Tarbiat Modares University, Tehran, Iran

ABSTRACT: This interdisciplinary study investigates technical strategies that enabled the Achaemenids to create monumental architecture. Their success in building tall, spacious halls on the seismogenic Iranian Plateau relied on special techniques employed by master builders to improve the behaviour of colossal monuments against earthquake forces. This paper focuses on the arrangement of major load-bearing elements and on foundation systems, notably an embryonic form of the seismic isolation system. The objective evolution of architectural forms in Achaemenid court culture illustrates the attention paid by royal architects to the geological characteristics of building sites and the physical properties of materials. This analysis examines the principles of mechanics employed in Achaemenid monumental architecture, drawing upon detailed observation of archaeological remains as well as written sources documenting the craft of construction in Antiquity. The theoretical framework presented here traces the origins of the Achaemenids' aseismic building knowledge.

1 INTRODUCTION

The Achaemenids were one of the greatest powers of Antiquity. Their vast empire extended from Northeast Africa and the European shores of the Black Sea through all of Asia Minor, the habitable lands of the Middle East, the plains and highlands of Central Asia, and the lowlands of the Indus Valley. For about two centuries (550–330 BC), this early "world empire" ruled over territories encompassing almost innumerable ethnicities, languages, and beliefs (Kuhrt 2001, 93). Though the Achaemenids relied on a provincial administration system to control conquered nations, their ruler was the autocratic "King of Kings" who reigned over the empire from his gigantic palaces in the Persian heartland (Pasargadae, Persepolis, Susa and Ecbatana), as well as the Mesopotamian Babylon (Meadows 2005, 181–4). These majestic residences symbolised Achaemenid political authority and spectacularly advertised its power and glory; this required court architects to incorporate highly decorative elements and innovative construction solutions to create an architecture of imposing size and beauty. The monumental architecture that resulted from these efforts has been described as representing "the culminating phase of the architecture of the Ancient East" (Pope 1977, 309). Certainly, it provides lasting evidence of some of the most advanced achievements of Antiquity.

To construct the colossal palaces, Achaemenid architects drew inspiration from contemporaneous civilizations, adopting a variety of decorative and architectonic forms from other cultures (Genito 1998, 534). For many years, this way of building caused scholars to label Achaemenid architecture as "eclectic," frequently downplaying the role this dynasty played in the advancement of Antiquity's architecture. In the past half century, however, several art historians have shed light on the creative and innovative merits of Achaemenid architecture. In particular, leading figures, such as Margaret Root and Heleen Sancisi-Weerdenburg, strove to analyse Achaemenid material culture on its own terms rather than simply identifying visual parallels with other traditions. They placed great emphasis on stylistic progress, iconography and symbolism, but the Achaemenids' technical strategies received less attention. This is unsurprising; historical accounts, generally speaking, have ignored the capacity of load-bearing structure for determining the building form, even for monumental projects (Mark 1990, 30). Nevertheless, a handful of publications in recent decades focused on filling this knowledge gap (e.g. Farshād 1996, Motamedmanesh 2018). This paper aims to build upon these projects to promote a better understanding of Achaemenid building culture, concentrating on the aseismic technologies that enabled Achaemenid master builders to construct monumental palaces on the notoriously earthquake-prone Iranian Plateau.

2 MONUMENTALITY IN ANTIQUITY AND NATURAL DISASTERS

Monumentality was an important theme in Antiquity's architecture; in the eyes of ancient peoples and rulers, monumental architecture fulfilled a transcendent purpose, embodying the glory and majesty of peoples' heritage for future generations (Thomas 2007). The major qualities of this architecture included: 1) unity of conception and overall mass, 2) proper direction

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of labour, 3) grand scale, and 4) refinement and elegance of details (Reilly 1912). In other words, monumental architecture manifested its patrons' enduring sovereignty over materials, crafts, and mass labour (Trigger 1990). Within this framework, defeating Mother Nature was a fundamental requirement.

References to natural disasters across a wide range of classical genres, such as poetry, history, meteorology and epistolography, attest to early civilizations' experiences with these phenomena. However, ancient peoples lacked knowledge about the nature of these catastrophic events, often associating them with deities and proposing superstitious interpretations. For instance, in Greek mythology, Zeus was known to be responsible for droughts, and Poseidon, the god of the sea, was the creator of earthquakes (Grant & Hazel 2002, 441–43). In spite of these incorrect assumptions, ancient civilizations gradually developed solutions to decrease the devastating effects of environmental crises on their life. Early bridges, dams, and defensive walls are various examples of these endeavours. Aseismic construction techniques were also introduced, adopted, examined and developed in Antiquity (Stiros 1995, 1996, 139).

3 ACHAEMENID COURT ARCHITECTURE AND EARTHQUAKE READINESS

The Iranian Plateau is one of the most tectonically active zones on earth. The collision between the Eurasian and the Arabian tectonic plates gave birth to the Iranian mountain belts, but their convergence forces also produce disastrous earthquakes (Berberian 2014, 183). The archaeological record indicates the long-term seismicity of this region, influencing ancient peoples' lives and settlement patterns. The effect of abrupt seismogenic disturbance can be seen in localised damage data (e.g. differential settlement, structural damage, and deformation) in many ancient sites (Berberian 2014, 177) including the Achaemenid structures in Fārs province. Seismological studies indicate that this province, located in the south-western region of the Plateau and in the heartland of the Achaemenid Empire, experiences earthquakes 2.5 to 6.9 in magnitude – although 70% of earthquakes are at magnitudes of below 4.5 on the Richter scale (Shāyān & Zāre 2014). Since Antiquity, the various fault zones that shaped this region, particularly, the Kāzerun and Zāgros active faults have posed a continuous life-threatening danger for monuments and civilizations (Berberian et al. 2014), prompting indigenous peoples to devise strategies to enhance the coherency and elasticity of rigid masonry monuments to enable them to resist ground motions (Berberian et al. 2017).

The ancient Indo-Iranians thought that air movement caused earthquakes (Berberian 2014, 94). Iranian epic literature also reflects a Zoroastrian belief that assigned supernatural powers to sacred cypress trees capable of protecting cities from earthquakes (Ibid, 44–5). These historical notions, however, did not prevent Achaemenid royal architects from devising techniques to improve the behaviour of their majestic palaces during tremors (Berberian et al. 2014, 28). This cautious approach was consistent with their efforts in other areas: for instance, adverse environmental conditions in Persia also forced them to incorporate complex water systems in all construction projects at Marvdasht, Pasargadae, and Susa (Ladiray 2013, 139–75; Stronach 1978, 161; Tilia 1972, 63). Indeed, canals, conduits, and dams were used to allow surface water to drain off, preventing structural damage. While the Achaemenids' hydraulic engineering received scholarly attention from the time of the earliest excavations, the seismic stability of their buildings has not attracted the same interest.

Seismic waves impose two major types of forces that act mostly in lateral and vertical directions. The waves vary in amplitude and constantly alternate their direction, tending to momentarily deform or oscillate all the structures they encounter. From a structural engineering standpoint, increasing a building's strength, stiffness and ductility – characteristics determined by many factors including construction methods, the dynamic properties of the building's materials/structure, and its overall shape – can decrease the devastating effect of bending moments and shear stresses caused by tremors (Charleson 2008, 25). To dissipate energy, conventional earthquake readiness systems concentrate on such capacity factors. The dynamic response of the rigid-body ancient monuments differed significantly from those of modern structures, relying primarily on the sliding and rocking of component elements (Konstantinidis & Makris 2005). In the late 20th century, engineers coupled these mechanical principles with higher-performance engineering materials to produce safer and more economic strategies. Commonly called a "base isolation system," this contemporary approach principally relies on advanced foundation systems that mitigate the transmission of horizontal acceleration into the superstructure (Kelly 1982, 17). However, primitive methods that perform similarly to this passive earthquake protection technique existed in Antiquity.

Overturning and sliding are among the most common causes of earthquake damage to buildings, making the foundation system a vital part of any seismic-resistant concept (Charleson 2008, 25). The remains of various types of foundation systems in Achaemenid palaces illustrate the master masons' awareness of the role of these hidden substructures in the structural behaviour of superstructures. In Pasargadae (i.e. Palace P and Palace S, 559–530 BC), one can distinguish a special foundation system composed of two superposed layers of stone that extend under the entire area of each palace (Figure 1). The slabs in the lower layer – itself laid on top of a short course of mortar and a pebbly subsoil (Stronach 1978, 63) – are held together with an adhesive mortar, whereas the large stones of the top layer – the slabs of Palace S are 1–3 m long and about 50 cm thick – are arranged tightly side by side (Ibid, Pl. 84–85). Masons roughly polished the contacting surfaces of both foundation slabs. If struck by horizontal loads, the bottom course and the ground surface around it move simultaneously, while the upper layer slides over the polished surface that lies underneath. The brick perimeter walls of the palaces were built on the second tier—routinely called "pavement" by excavators. However, stone elements (e.g. column bases, anta and socle) which had a separate foundation, stood on the lowest level of slabs and benefitted individually from the sliding interfaces. This is an embryonic form of a base-isolated system that protected Achaemenid palaces against earthquakes. It is interesting to note that the arrangement of stone blocks and their joints in the lower course does not align with the joints in the upper tier (see Stronach 1978, fig. 40). This distributed the weight of the gigantic palaces, particularly the concentrated loads of their large intercolumniations, over a greater area, thereby inhibiting differential settlements and structural deformations. The polygonal stonework of this foundation shows similarity with that of the mat foundation of various temples (Temples of Zeus, Bassae and Aphaia) built in the Greeks' territories in the 6th and 5th centuries BC (cf. Cooper 2008, 231–34).

Figure 1. Archaeological remains at Palace P, Pasargadae.

Typologies of the decoupling of superstructure and foundation are also observable in the Achaemenids' memorial architecture. The Zendān-e Soleymān in Naqsh-e Rostam (540–520 BC), Kabe-ye Zartosht (Figure 2a) in Pasargadae (520–500 BC), the unfinished Takht-e Gohar (530 BC), and Gur-e Dokhtar (Figure 2b) in the Bozpar Valley (6th–5th centuries BC) all stand on large, rectangular stepped plinths composed of independent limestone course. For instance, in the Kabe, the three interfacing slabs are respectively 14.81 × 14.82 m, 11.66 × 11.65 m, and 9.01 × 9.02 m in area (Schmidt 1970, 28). These plinths were laid on a separate foundation level. Although archaeological excavations have not yielded much information on the finer construction details, the excavator of the Kabe hypothesised that cramps may have been used to attach the blocks of the lowest course to the foundation slabs (Ibid, 35), thereby creating a solid base. This was a wise precaution, since the uneven settling of weak foundations in a soil bed overstresses the structure and plays a key role in structural failures.

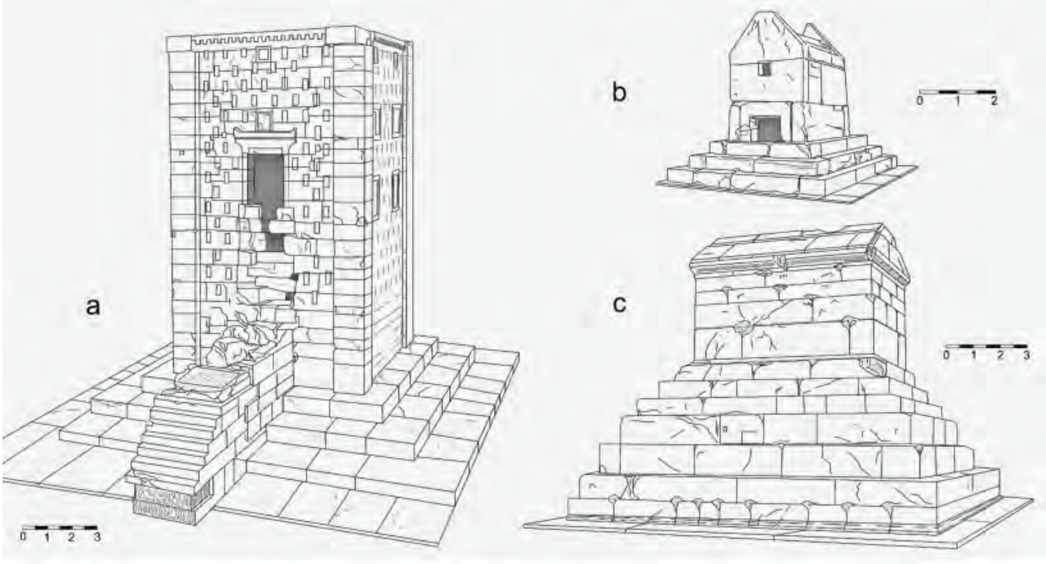

Figure 2. Achaemenid buildings standing on stepped slabs.

The ziggurat shape of Cyrus's tomb (Figure 2c) represents the exposed version of sliding slabs. This technique was executed on an imposing scale: a 7.12 m high plinth composed of six receding courses, of which the largest is 13.35 × 12.3 m. Scholars label the mausoleum as the world's oldest structure to employ seismic isolation principles to uncouple the structure from ground motions (Saiful Islam et al. 2011). Interestingly, the architects of the mausoleum used the principle of symmetry in arranging architectural elements—a factor known to be highly important in resisting building torsion caused by horizontal forces (Charleson 2008, 27). They also reduced the weight of the monument by carving out unnecessary bulk (e.g. the hollow compartment in the ceiling of the chamber). It is known that weight reduction improves the dynamic behaviour of structures.

In the Bardak-e Siyāh Palace (559–530 or 522–486 BC) near Borāzjān, not far from the Persian Gulf, another typology of aseismic design can be distinguished. Here, the foundation course, a condensed tier of clay, is underlaid with a layer of ash/charcoal and sand (Yaghmāyi 2004/2005). According to Diogenes Laërtius (*Book II*, 103) and Pliny (*Natural History* 36, 95–7), in his construction of the temple of Artemis at Ephesus, Theodorus of Samos used layers of ash and sheepskin as a sub-foundation (Cooper 2008, 231). Nineteenth-century excavations revealed the use of packed charcoal under the foundation of this temple (Ibid). These descriptions and archaeological findings show similarity with the ancient remains unearthed in south Iran. Modern-day structural analysis has shown that granulated coal-ash improves the seismic stability of structures by means of particle crushing that results in a higher cumulative dissipated energy (Yoshimoto et al. 2014). Moreover, the sand-gravel padding placed in between the ground bedding and foundation course not only uniformly distributes the weight of the building, but also dampens the imposed seismic forces (Kirikov 1992, 33, 48). This method was first used by ancient Egyptian masons (e.g. in the tomb of Ramses IV in the 12th century BC), and it eventually became a common practice in later Antiquity (Ibid). Achaemenid architects even employed the seismic isolation concept in monumental projects outside the Persian heartland of the empire. For instance, according to the Book of Ezra (the Old Testament), in Cyrus' reconstruction of the temple in Jerusalem (i.e. House of the Lord), three layers of huge stone slabs, as well as one layer of timber were used to build the foundation (Ezra 6, 3–5).

The earthquake readiness of Achaemenid court architecture is a wise precautionary approach observable not only in the foundation systems, but in many architectural details. The seismic behaviour of the free-standing, soaring columns of Achaemenid Palace is an interesting, but complicated, phenomenon. These are multi-drum columns; in Palace S (Pasargadae), four drums of diminishing height make up the length of the unfluted shafts (12.10 m tall). Each of the very tall (more than 19 m) hybrid columns of the Persepolis Apadāna (520–465 BC) is composed of three drums of diminishing size—the largest of which is about 8 m tall—that together shape the 15.65 m shaft (Motamedmanesh 2018, fig. 3; Krefter 1971, 35; Stronach 1978, 59). Modern structural analyses (i.e. empirical and numerical models) of classical structures prove that multi-drum columns rely on the relative sliding—usually only a few millimetres—of stone elements to withstand ground shakings with magnitudes Mw = 6.0 to 7.4 (Konstantinidis & Makris 2005, 115). Indeed, the rocking response of the undowelled drums/capitals makes the effect of micro dislocations/deformations beneficial in short-period harmonic excitations (Ibid, 124, Sinopoli 1991, 248). Achaemenid architects also drew upon this mechanical principle.

The Greek architects of Archaic and Classical eras also inserted a wooden cylindrical pole (pin) and two wooden empolia (plugs) in the cavities carved in adjacent drums. These wooden elements, however, only allowed the rotation of the drums during the construction phase and did not create a shear link between the jointing surfaces (Konstantinidis & Makris 2005, 119). Cuttings similar to those of classical columns are also observable in some Achaemenid columns. In many cases, however, no hole can be found on the interfacing drums. Thus, restorers of Achaemenid sites argue that column blocks were simply stacked on top of one another (Tilia 1968, 85). According to Hasan Rāhsāz, who since the 1970s has actively participated in the restoration of Achaemenid palaces in Fārs province, the only wooden pole found was discovered in Palace S in Pasargadae (pers. comm., cf. Stronach 1978, Plate. 54b). Modern-day, shear strength experiments prove that ancient wooden poles would not withstand the sliding of drums (Papadopoulos & Vintzileou 2013, 761). Thus, in recent restorations of the Greeks' structures, restorers favoured a tiny difference between the

Figure 3. Earliest techniques used for hollowing the inside of column shafts/torus in Palace P, Pasargadae.

maximum size of the new pole and the minimum diameter of the new empolia mortises inserted into ancient emplacements; this small margin of space guarantees the proper response of the drums when hit by a dynamic load (Ibid, 762). The marginal role of wooden links in the stability of segmented columns explains the functionality of the Achaemenids' easier method of centring which relied on a sheet of dry lead between the interfacing elements (Krefter 1971, 35). This enabled the free rotation of the pieces, and even more importantly, the lead compressed under the huge weight of the dressed drums created an almost invisible joint (Ibid). Although the restorers' reports do not provide much information about the drums in which cavities were cut out, the given dimensions – notches observable on the Persepolis columns are 12 cm wide and 8 cm deep (Tilia 1968, 73) – indicate cavities slightly larger than the Greeks' mortises (cf. Konstantinidis & Makris 2005, 115; Papadopoulos & Vintzileou 2013, 760–61). Thus, we can reasonably assume that the few reported cavities belonged to the largest drums. Given the huge weight of these pieces, as well as the logistical difficulties from mines to building sites, it is likely that Achaemenid masons used wheeled transport systems in which the block itself acted as an axle (cf. Right 2005, fig. 76). Thus, the cavities in question may have been used for inserting the wheels from the ends. As far as the observations of restorers at Persepolis are concerned, a square-shape iron dowel sunk in lead provided the link between the torus and column base (Rāhsāz, pers. comm., Tilia 1968, fig. 93). Also, in some cases, the presence of a red dye between the interfacing surfaces of the torus and the base led the restorers to hypothesise the use of a special mastic with adhesive characteristics (Ibid, 73). In any event, Achaemenid architects intentionally inhibited the relative displacement of the column base and the torus. As mentioned above, the reliance on enabling the base of columns to rock/slide with the foundation course guaranteed the functionality of the Achaemenids' choice.

Recent analyses show that imperfections such as the loss of contacting surfaces due to edge damage has a negative impact on the sliding principle, making columns vulnerable to tremors (Psycharis et al. 2000). The objective evolution of Achaemenid columns demonstrates builders' efforts to counteract this shortcoming. In Pasargadae, dating back to the initial phase of Achaemenid large-scale building projects (559–530 BC), the inner section of the lowest segment of some columns (in Palace P) is hewn out, causing an extruded circumferential band to appear (Figure 3). Given the great influence of Ionian masons in the architecture of Pasargadae (Nylander 1970), the use of this style, which was also in practice in Samos, Ephesus and other eastern regions of the Hellenic world, is hardly surprising. This technique not only prevents the use of entire column sections for the transfer of loads but also reduces the surface area of interfacing elements, thus attenuates the dry friction resistance. Subsequently, this disrupts the rocking effect. As discussed above, the situation could become even worse in the case of physical damage to the lowest drum or torus. Achaemenid architects abandoned this carving technique in all their future projects in Persepolis and Susa, where the interfacing components were evenly smoothed—with the exception of a relatively small area at the centre part of each drum that showcased the Anathyrosis technique (see Tilia 1968, figs. 9–10).

The horizontal loads of earthquakes were not the only ones that could topple the Achaemenids' columns; given the devastating buckling impact of any eccentricity imposed on a compressive system (Macdonald 1998, 251–2), even low-intensity shaking or small displacements of the drums could threaten the palaces. The principles of statical mechanics prove that this was an inevitable scenario: after each shock and the subsequent oscillation, column shafts would have eventually collided with the rigid ground or base underneath them, resulting in horizontal sliding (Sinopoli 1991). In this regard, the role of large zoomorphic imposts that crowned all pillars is noteworthy. The recessed back of protomes that gripped the beam running across the capitals of an entire row of columns created a joint, partially holding the columns and beams together and preventing off-centre loading (Motamedmanesh 2018, 965). To put it in engineering terms, the zoomorphic imposts augmented the fixity of the columns at the top, thereby increasing the buckling capacity of the columns (Ibid). As discussed above, the interaction between buildings and the ground underneath can aggravate or moderate the impact of an earthquake. Generally, the non-uniform settlement of a weak foundation on a weak soil bed causes buildings to fail. This was one of the many reasons that ancient master builders, including Achaemenid architects, chose to erect their projects on gigantic terraces. Such multipurpose platforms are also thought to have been a provision against seismic waves: they offered means of smoothing out the wave, so that the superimposed building would be hit only by moderate ground shaking (Kirikov 1992, 28–29).

Thus, the construction of levelled platforms was a common practice in Antiquity, particularly in areas with weak soil (Ibid), such as the Achaemenid Pasargadae and Susa.

The high level of attention Achaemenid builders devoted to the ground bedding is reflected in royal inscriptions dating back to the era of Darius I (re. 522–486 BC). A foundation tablet from Susa (known as DSf) explains how the builders dug until they reached stone bedrock, then used gravel to fill one trench that was 40 cubits deep, and a trench 20 cubits deep on the other side. The palace was eventually placed on these gravel fills (Lecoq 1997, 235). The Franco-Iranian excavations at Susa confirmed the accuracy of Achaemenid inscriptions: they unearthed the deep trenches dug for each wall and column and filled with gravel to allow the load-bearing elements be placed securely on hard ground (Ladiray 2013, 140–41). Another royal inscription from Persepolis (called DPf)

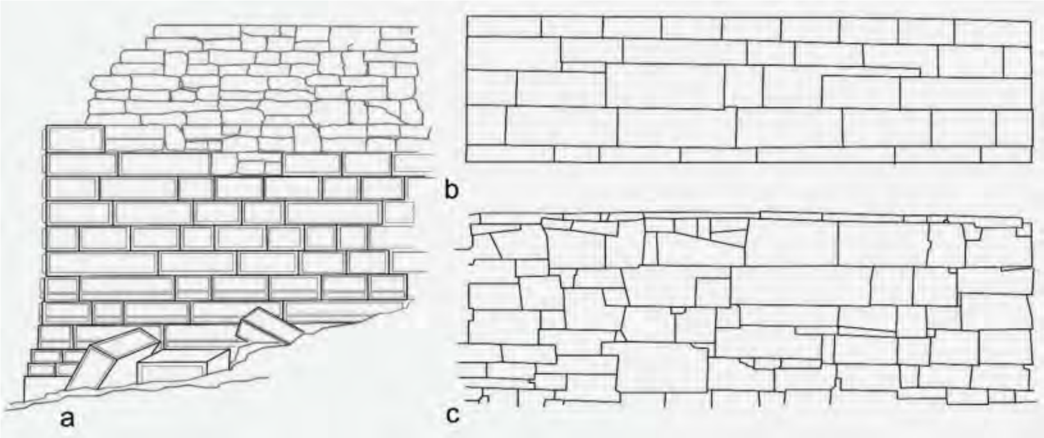

Figure 4. Schematic drawing of the various types of ashlar work in the Achaemenid era (not-to-scale).

stresses that the King ordered the construction of an excellent and sturdy palace in a site where no other structure was previously built (Lecoq 1997, 229). IsMEO's restoration activities in Persepolis in the 1970s showed how the bedding of this gigantic terrace – covering an area about 125,000 square metres – was levelled and cut away from the mountainside below, then crevices and depressions were filled with small stones to create a solid base (Tilia 1978, 3–4). The Urartians (9th–7th BC) employed similar techniques in their fortifications built in the seismogenic highlands of northwest Iran and the Caucasus (cf. Kleiss 1991).

The Tal-e Takht in Pasargadae exemplifies the use of an earlier type of terrace (Figure 4a). Here, the platform is composed of a soft core of soil surrounded by piled, roughly-cut blocks; an outer layer of rectangular blocks joined tightly by metal clamps secures the inner filling materials by compressing them horizontally (Stronach 1978, 155). In the pre-Achaemenid era, masonry platforms were constructed by Mesopotamian civilizations who also relied on a soft core's capacity to absorb earthquake shocks (Kirikov 1992, 27–30).

The retaining walls of these enigmatic platforms also illustrate the gradually developing understanding of earthquake-resistant construction under the Achaemenid rule. At the Tal-e Takht, regular isodomic blocks represent the Achaemenids' earliest methods of wall construction. This technique was later abandoned, as attested by the arrangement of blocks in the Persepolis terrace. The cutting of the enormous stone slabs used in these platforms even evolved during the timeframe of construction itself (i.e. 522–465 BC): irregular jigsaw-puzzle blocks (Figure 4c) took the place of the relatively regular polygonal and trapezoidal blocks used in earlier decades (Figure 4b), such as those used to build the south side of the terrace (Tilia 1978, 8–27). These stones are laid on top of each other, secured only by their own weight and are vulnerable to seismic shocks – blocks of the topmost level are the only exception to this as they are attached with dowels. The technique of interlocking blocks that was adopted later offered a way to improve the seismic response of the walls by increasing the frictional resistance between interfacing surfaces. This structural benefit can justify the additional effort of cutting and arranging adjacent blocks precisely enough to interlock them. Therefore, this method was employed in various geographic regions from the time of the Mycenaean civilizations (1600–1100 BC). Achaemenid masons even employed this technique in Kabe (Figure 2a), causing its construction details to be quite different from those of the Zendān—despite a high degree of formal similarity between these monuments.

As can be seen from the cavities cut out of ancient remains, Achaemenid ashlar masonry relied on the lead-sealed clamps and dowels made of metal. Clamps were invented in Egypt in the second half of the third millennium BC (Nylander 1966, 132). There is sparse evidence of their usage by ancient civilizations in the region ranging from the Aegean and Mediterranean seas all the way to Mesopotamia, yet the Achaemenids and Archaic Greeks used them in abundance (Ibid). This helped their buildings withstand the displacements caused by earthquake loads. A detailed study of Achaemenid metal joints – for which Carl Nylander's pioneering work is a helpful reference – is beyond the scope of this article, but it is worth examining one constructional feature of these clamps that has received little attention. The chemical properties of lead have commonly been regarded as the reason for its use in Antiquity's architecture: opting for lead protects the stone blocks from the corrosion occurring in metal links, and from their expansion/shrinking with temperature fluctuations. However, lead's mechanical properties play a paramount role in the dynamic behaviour of structures: encasing the metal dowels in lead provides a degree of plasticity and ductility that enables the less-malleable elements to deform and absorb seismic energy, instead of transmitting it to the stone blocks and causing failure (Stiros 1995, 732).

It should be emphasised that an earthquake is a complicated phenomenon/sequence. The seismic response of any structure will be influenced by a matrix of geological and seismogenic factors, as well as construction-related parameters, including the amplitude, velocity, the intensity and duration of the earthquake waves, the orientation of building blocks relative to ground motion, the structural and geometrical characteristics of the monument, and the geological features of the construction site, to name only a few. This complicates the task of predicting the buildings' behaviour, requiring scientific research, reasonable assumptions, and precise analysis. The techniques discussed here represent only the earliest endeavours for minimizing the risks to human life and structures in hazardous areas.

4 FTHE ORIGINS OF THE ACHAEMENIDS' ASEISMIC CONSTRUCTION

Construction historians generally consider that analytical calculations began to be used to assess the stability of structures in the 18th century (Mainstone 2001, 321). Yet the existence of advanced building knowledge in Antiquity, particularly embryonic forms of aseismic design, is not surprising when one investigates archaeological remains and witnesses the ancient architects' success in devising effective building systems and geotechnical verifications across different regions with varying characteristics. Thus, current scholarly debate on this matter only reflects our present-day fragmentary knowledge about ancient peoples, their building style, and its development (Stiros 1995, 726).

The Oxford Handbook of Engineering and Technology in the Classical World regards the engineering feats observable in archaeological remains as representative of the empirically-based practices and principles considered worth preserving, and handed down throughout the generations by means of written and oral traditions (Cooper 2008, 226). It also refers to evidence in Classical texts for a body of scientific theory and engineering practice providing a basis for employing technology in construction. Achaemenid inscriptions known as the "Foundation Charters" from the era of Darius I provide valuable information in this regard. They describe how the Achaemenids relied on materials and skilled craftsmen gathered from all over their vast empire to construct the palaces at Susa – and presumably other royal residences. According to these documents, Babylonians were responsible for digging the foundation, the production of sun-dried clay and baking the bricks, whereas Lydians and Greeks took care of stonework. Assyrians, Greeks and Carians collaborated to bring cedar timber from the Lebanon mountains, enabling Lydians and Egyptians to work with this material in Susa. The gold mined in Anatolia and Central Asia was wrought in Susa by Median and Egyptian goldsmiths. Other precious materials, such as silver, ebony, ivory and lapis lazuli came from remote areas of the empire in Northeast Africa, the Indian subcontinent and Central Asia (Lecoq 1997, 235–37). The scale and complexity of this blend of work is so considerable that it is difficult to grasp without first locating all of these places on a map, and imagining the amount of knowledge and expertise required for each of these building tasks. It then becomes clear that these royal inscriptions describe an unparalleled process of knowledge exchange and synthesis, on the scale of a region encompassing almost the entire world known to the Achaemenids at the time. This melting-pot of skills produced the insight and broad-mindedness required for distilling and combining the most effective traditions of various regions, and provided a source of innovation for construction in Antiquity.

On the other hand, given the pivotal role of trial and error in the advancement of earthquake-resistant architecture in historical times, the intervals between earthquakes constitute an important parameter that may shed light on the other roots of aseismic design. Indeed, frequent tremors not only prevented a region's inhabitants from forgetting the catastrophe or ignoring seismic hazards (Stiros 1995, 733), but also enabled masons to put their theories/ideas into practice and observe the outcome. This provided opportunities to choose or reject specific construction techniques. Thus, seismically active regions that were hit by strong tremors every few years – such as Thessaly, the Corinth area, and the Ionian Islands in Greece (Kirikov 1992, 31; Stiros 1996, 133) – played a leading role in developing this knowledge by creating a so-called "seismic culture", focusing on the perception of the disaster, recovery in its aftermath, and earthquake-resistant construction (Stiros 1995, 726).

5 CONCLUSION

This study highlights the pivotal role of load-bearing structures in the formation of monumental architecture in Antiquity. In reviewing the aseismic techniques employed by the Achaemenids, this paper retraces the transformation and accumulation of historic aseismic building knowledge. This investigation provides insight into the innovative methods ancient peoples devised to minimise the seismic vulnerability of their buildings, using the tools, techniques and knowledge available to them. The introduction of flexibility at the base of structure to reduce transmission of earth tremors, and reliance on gravity, frictional resistance and mechanical properties of materials to improve the dynamic behaviour of superimposed, vertical elements are among these early efforts.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Incomplete: The discontinued building project of a Greek temple of the Classical period

H. Bücherl
Brandenburgische Technische Universität Cottbus-Senftenberg, Cottbus, Germany

ABSTRACT: Temple O and its neighbour, Temple A, seem to have been intended to form an ensemble of two ostensibly identical temples, which were to embellish the long-established city-sanctuary on the acropolis of the Greek colony of Selinous (Selinunte, Sicily, Italy) around the middle of the 5th century BC. The exposed remains of the so-called Temple O, in particular, offer a snapshot of the building site of a Classical temple, because the foundations had not even been finished when the construction project was abandoned. This exceptionally advantageous situation is ideal for studying the initial construction process of a large-scale Greek building project and is further enhanced by the fortunate fact that the neighbouring Temple A, very similar in size and floor plan, had been completed just before Temple O was abandoned and is therefore – alongside other temples of Magna Graecia – an excellent reference point for architectural analysis.

1 INTRODUCTION

Selinous' main sanctuary is located in the south of the city, perched on top of the cliffs where the terrain drops off steeply (Figure 1). When the construction of the so-called Temples A and O began, it consisted of the Archaic *peripteroi* C and D as well as the *megaroi* R and P and their respective altars and outbuildings. For the upcoming construction project, an area south of Temple C and Megaron R and north-west of Megaron P was cleared of any existing, possibly residential constructions (Helas 2011, 77 Figs. 3, 47; Mertens 2003, 249, 2006, 400).

While the northern one of the two new buildings, Temple A, was completed, the foundations of Temple O were never finished. This abandonment in the construction project's early stages is often associated with the invasion of the Carthaginians, who conquered and destroyed Selinous within only a few days in 409 BC. The city was then repopulated with culturally, clearly distinct, Punic inhabitants, who were probably not interested in continuing the construction of a Greek temple, especially since Selinous already possessed numerous sanctuaries. These were (re-)used by the Punic residents, although often for different purposes.

The fact that the building project was stopped shortly after the start of construction offers researchers insights into the early building process, since the foundations were never covered with a superstructure. Also, some elements that would normally have been removed after the building's completion have thus been preserved; they can provide additional information about the building process.

Due to their excellent state of preservation, the late-Archaic Temple of Aphaia on Aegina (Bankel 1993), the so-called Old Temple of Hera at Paestum (Mertens 1993) and the Great Temple of Segesta (Mertens 1984) are used as primary references. Especially the latter, also a Doric *peripteros* dating to the Classical period, is suitable for comparison purposes, since the Elymian settlement of Segesta is not far from Selinous and this temple, too, remained unfinished.

Figure 1. Aerial view of the urban sanctuary of Selinous, looking south-east (Photo: M. Jakobi, 2019. Magdeburg-Stendal University of Applied Sciences).

2 OBJECT OF INVESTIGATION

The foundations of Temple O (approximately 43.25 × 21 m) are oriented east-west and are almost completely exposed. Nevertheless, not all sections are visible, since remains of a medieval fort – seemingly built mainly from structural elements taken from neighbouring Temple A – overlay the temple foundations (Mertens 1989). The north-west corner and the east side of the temple are most affected by this,

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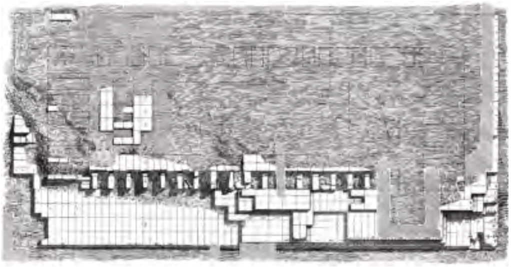

Figure 2. Plan of Temple, O by Robert Koldewey (Koldewey & Puchstein 1899, Pl. 14).

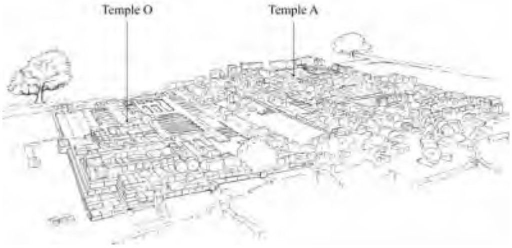

Figure 3. Perspective sketch of Temple A and Temple O, looking west.

Figure 4. The Cave di Cusa quarries.

while the south-east part of the foundations, where the largest part of the fort's extant interior structures have been preserved. Furthermore, isolated structural elements of the ruined Temple A can be found all over the area. Particularly in the south-west sector and the south-east corner of the structure, foundation blocks have been removed. At least four complete foundation courses were extracted, most likely in order to be used as building material elsewhere.

The load-bearing elements, such as columns and walls, were meant to rest on massive, strip-like foundations of perfectly-fitted blocks. The remaining areas correspond to the sections that were to be covered with floor slabs. Here, the foundations consist of individual, parallel rows of stone blocks laid on end at roughly the same distance, always bridging the shortest distance (Figure 2). In combination with the strip-like foundations, these rows form a grid pattern. This type of foundation is typical for the Greek temples of Sicily (e.g. the so-called Temples F and E in Selinous, or the temple in S. Biagio and the so-called Temple of Herakles at Agrigento). According to M. Klinkott (2017, 304, 306), this is to be attributed to the grid foundations' particular resistance to damage caused by earthquakes. This may also account for the rather loose integration of the individual rows into the massive strip-like foundations, which can hardly be the result of different parts of the foundations settling in different ways, since the foundations were probably laid directly on the bedrock.

The strip-like foundations mirror the design of the original floor plan: the structure was to consist of a *peripteros* with *pronaos*, *naos*, *adyton* and *opisthodom*. Both in regards to dimensions and proportions, the foundations show considerable similarities with those of the adjacent Temple A. Even the foundations of the wall dividing *pronaos* and *naos* is much wider than the others, which suggests that here, too, a pair of staircases was meant to be constructed, as can be seen in Temple A. It is clear that Temple O was meant to be very similar to Temple A, not only in size but also in regards to the structure of the floor plan.

The extremely wide south stereobate is striking, however. At about 5.35 m, it is almost twice as wide as the north stereobate (about 3 m wide). Since the terrain slopes from north to south, a stepped stone terrace was built on the southern side of the temple to respond to the difference in level (Figure 3). The three lowest courses are still partly preserved. Their fronts are in alignment and possess drafted margins along the lower edge. The parts of the blocks facing east, west and north are still mostly in their unworked state, since they were not meant to be visible. According to R. Koldewey, a total of 12 steps would have led to the temple's stylobate from the south (Koldewey & Puchstein 1899, 112, Fig. 88).

3 FROM QUARRY TO CONSTRUCTION SITE

3.1 *Extraction sites*

The local rock – a type of arenite – was used as building material. There were quarries in the immediate vicinity, such as on the west slope of the acropolis plateau near the agora and, as well as in the city environs. The most famous quarry is at Cave di Cusa (Figure 4), south of present-day Campobello di Mazara and located about 12 km north-west of Selinous. The exact composition of the local rock varies from quarry to quarry, which means that the Selinuntine building material can often be assigned to a specific location (Peschlow-Bindokat 1990, 9). It is therefore likely that at least some components of Temple A probably originated in Cave di Barone, a quarry about 5.5 km north of Selinous (Peschlow-Bindokat 1990, 11). Additional

Figure 5. Substructures of the south *pteron* and the south *cella* wall with markings carved into the foundation blocks, in red.

quarries nearby may well have contributed other elements, however, since the quality of the mined stones was not uniform, thus restraining their application to specific uses or particular sectors of the structure (Peschlow-Bindokat 1990, 12).

3.2 *Markings*

Roughly-hewn marks can be found on the faces of some blocks (Figure 6). Most of them are located at the edges of the strip-like foundations. This is due to the fact that these surfaces were not meant to connect to other ashlars and thus still possess their bosses. Some of these markings have already been noted by previous scholars (Patricolo & Salinas 1888). After comparison with the letterform used in the Selinuntine *lex sacra* (Dimartino 2015, 159), these marks seem to depict the Greek letters omicron (O), xi (Ξ) or epsilon (E) and possibly a combination of kappa (K) and chi (X), the latter of which appear mainly on the southern faces of the foundation blocks of the southern *cella* wall (Figure 5). Furthermore, a combination of omicron and eta (OH/HO), which can be found on some blocks of the eastern foundations, a combination of nu and eta (NH/HN) on the front of a block of the north stereobate and possibly a pi on the front of a block of the west stereobate can be added to the already published signs. Were most of the outer faces of the foundation blocks not covered with soil or otherwise inaccessible, even more marks could certainly be added to this list. The frequent appearances of the letter omicron (O) on the blocks of the south-west corner of the *cella* as well the combination of omicron and eta (OH/HO) on the east side of the temple is, however, clearly noticeable.

3.3 *Possible interpretation of the marks*

While the number of these markings is not sufficient for a systematic investigation, a preliminary interpretation shall be attempted. The first possibility is that the letters were applied at the quarry as a banker mark by a person directly involved in the extraction process, in order to identify the stones as having been prepared by a specific mason and to facilitate payment. This would also explain the rough execution of the marks. The abbreviations may have referred to specific individuals, work teams or different organisations. In this way, the six known signs would mean that at least six masons or work teams were involved in quarrying the foundation blocks. This type of mark, meant exclusively for accounting purposes, would have had no bearing on the blocks' use at the construction site, since the workers responsible for the stones' extraction would most likely already have been paid at the production site. This interpretation is supported by the fact that no consideration was given to legibility when the blocks were laid: the combination of eta and nu (HN/NH) was installed right-side up, while that of omicron and eta appears both as OH and as HO. In all probability, these two are the same mark, which in this case can be read both right-side up and upside-down.

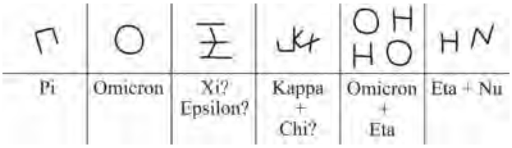

Figure 6. Markings and their possible ambivalent Greek letters.

Another possible interpretation is that as numerals, which might have represented the total number of blocks delivered from a quarry to the construction site. According to the acrophonic system, eta (H) means *hekaton* and stands for the number 100, while pi means *pente* and represents the number 5. These two interpretations are not necessarily mutually exclusive, as eta (H) in particular has so far only appeared in combination with other symbols (OH and NH). It is therefore possible that the numbers were combined with a letter denominating a specific mason or work team. The interpretation of the symbols as typical mason's marks, i.e. as markings assisting in the assembly or distribution of construction elements, seems unlikely, since the letters are very large as well as rather roughly designed and carved.

Based on the assumption that the marks held no further significance for the construction process, it can be assumed that the unfinished blocks were delivered to the construction site in groups, each furnished with their own letters. These were then frequently used in the same sector, thus explaining the clusters of specific marks in particular spots, e.g. of OH and O in different areas of the temple foundations.

4 CONSTRUCTION PROCESS

4.1 *Preparations*

When the strip foundations – consisting of at least eight layers of ashlars placed on top of each other – were being constructed, the blocks of each layer must have

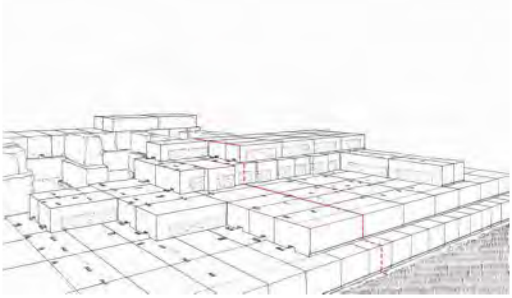

Figure 7. Perspective sketch of the foundation structure of Temple O with the centre axis marked in red for the start of the workflow.

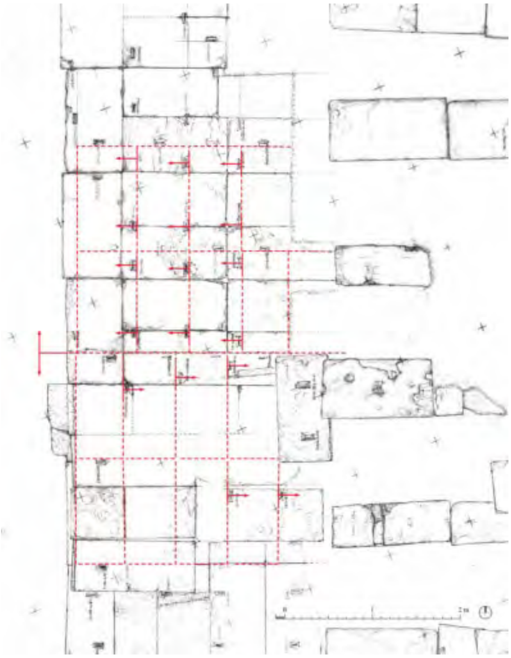

Figure 8. Excerpt of the documentation plan, west stereobate with marking of the workflow in red.

been laid according to a plan or grid. Special care was taken to ensure that each layer was made up of blocks of roughly equal format and size. In order to prevent an undesired alignment of the joints of an upper and lower layer, the principle of cross-bracing (a layer of binders was followed by a layer of runners) was observed, particularly in extensive areas such as the south stereobate (Figure 7) (Koldewey & Puchstein 1899, Pl. 14). Each new layer thus followed its own grid system. This is particularly noticeable in the south stereobate, where each step-like rising layer is set back further towards the north, resulting in a progressive narrowing of the foundation. Here, one can still see grid system of the upper layers, which takes the form of fine lines that have been scratched into the upper surface of the lower ones (Figure 9).

Figure 9. A mortise parallel to the scratched line and accurate joint closure in detail.

4.2 *Workflow directions*

Each layer of the massive foundations of Temple O was always laid from the centre out. In the case of the south stereobate, the first block was laid exactly at the centre of the foundation's length, or directly next to it if the previous layer featured a joint at this point (Figure 7). The west stereobate seems to possess a starting point located somewhat off-centre, but it must be stressed that due to the state of conservation, only the seventh foundation layer can be surveyed (Figure 8).

The same workflow from the centre towards the corners could also be observed by D. Mertens for the construction of the *krepis* at the Temple of Segesta, who suggests that, in theory, eight work teams would have been able to work side by side simultaneously during the construction of the *peristasis'* foundations (Mertens 1984, 32). This theory may in fact be corroborated by findings concerning the construction of the west stereobate of Tempel O: while the seventh layer of the foundations was being constructed, the north part of the rows of blocks was being laid from east to west, beginning at the central starting point. In the south half, however, the rows were laid down from west to east (Figure 8).

In most areas, the workflow can be traced by means of the mortises and scoring lines cut into the top surfaces of the foundation layers. In some places, the corresponding blocks of the upper layer are also preserved (Figure 9). In addition to that, the connecting surfaces differ in their design depending on whether they belong to a block to be added or a block already in position: surfaces against which another block was to be placed possess a completely smooth surface finish. In contrast, surfaces that were meant to rest against an already-laid ashlar were only partly smoothed and thus feature an *anathyrosis*. For this method of dressing the joints of abutting surfaces – done in order to limit the time and effort needed to create exactly fitting joints – only a narrow margin on the top and sides of a block was smoothed while the interior was worked into a somewhat rougher recess. Also, a part of the contact surfaces was not worked vertically but rather slightly sloped. At the *krepis* of the Temple of Segesta, an identical surface design can be found, but in reverse.

Here, the outer surfaces of the blocks already in position show the *anathyrosis*, whereas the ashlars placed against them possess smoothed connecting surfaces (Mertens 1984, 33).

On the south side of Temple A, which has been much affected by stone robbery, it is possible to gain insights into the structure of the uppermost foundation layer leading up to the *krepis*. It is striking to see that the workflow is completely different compared to the adjacent Temple O and the Temple of Segesta: the blocks were first laid in the corners, with the work spreading towards the centre of the foundations. This workflow direction avoids the issues described by E. Hansen (1991, 72-3) which arise when working from the centre, i.e. the problem of moving corner blocks into place despite a lack of lateral supports for inserting the levers into the ashlars. In this way, the tread of the step of the *krepis* can theoretically be used as support for the levers necessary to move the blocks into place. This, however, leaves clearly visible traces on the steps, which had to be avoided. A solution for the problem of placing the last foundation blocks in the corners of a structure had evidently been found when Temple O was built. Here, mortices appear only on the top surface of a layer whose edges are irregular, and were never uniformly dressed and which is therefore to be interpreted as the building's *euthynteria*. However, no mortises were found on the treads of the first step. This suggests that, whereas levers were used to move the final blocks of the first step into place while using the *euthynteria* as support, a solution had been found for laying the corner stones without leaving mortices on the surface of the lower steps, despite working from the centre. Unfortunately, the badly-damaged corners of the temple foundations make an investigation of the exact methods used almost impossible.

Possible reference points are the Temple of Aphaia in Aegina and the Temple of Poseidon in Paestum. In both structures, the floor slabs of the *pteron* are trapezoidal, thus making it possible to slide them into position from the sides. This is particularly useful in enclosed areas where lateral working space is limited, i.e. in this case by the toichobate and stylobate (Bankel 1993, 5, 2010, 18-9; Koldewey & Puchstein 1899, 27, Pl. 4).

4.3 *Lifting techniques*

When the overall grid to be used for the next foundation layer had been determined, the blocks had to be moved to their place of use. For this purpose, the blocks were raised using so-called lifting bosses (Figure 10) (projections located on opposite outer faces). Ropes were looped around these bosses in order to lift them into their designated position. These bosses were then usually eliminated, since bossed surfaces could not be fitted against each other with any degree of precision. For reasons of economy, only connecting surfaces were treated in this way; lifting bosses can thus still be found on some foundation blocks, especially along the edges of the strip foundations.

Figure 10. Assembly of the foundation structure of Temple O with some examples of vertical and horizontal transport of the blocks.

Before lifting the blocks into position, they had to be moved across the building site. This was generally accomplished by using rollers: iron ones were, for example, used during the construction of the Parthenon in Athens (Korres & Ohnesorg 2017, 26–27). While there is not yet any clear evidence of their use during the construction of Temple O, it seems most likely that wooden rollers were used instead of metal, which thus left no further traces (Figure 10).

Once close to their final position, the foundation blocks had to be dressed in preparation of being joined to the ashlars already in place. For this, the connecting surfaces were given an *anathyrosis*, and, in some cases, the abutting surfaces were worked off at a slight angle in order to join them accurately, as already explained above. Fine level differences on the tops of the individual layers indicate that the bedding for each individual block was prepared just before final positioning (cf. Mertens 1984, 33).

Finally, the blocks were pushed into position using levers inserted into mortices cut on top of the upper faces of the layer already in place (Figure 10). On some blocks still *in situ*, roughly-worked recesses were found on the face of one of the long sides, located at about the centre of the lower edge and slightly offset from the corresponding mortice hole. Some mortises occur in combination with groove-like cuts along the bottom edges of the blocks to be moved. This made it possible to lift the block briefly in addition to moving it sideways. On this occasion, for example, the transport rollers under the block might have been removed.

As D. Mertens has rightly remarked (Mertens 1989, 394, 2003, 249, 2006, 400), the building process came to a stop shortly after the uppermost preserved course of the foundations had been laid and was never continued. How else could the lack of markings and mortices in this top layer, which are absolutely necessary for laying further blocks, be explained? This is even more noticeable due to the large number of such marks and grooves cut into the blocks of the lower courses.

4.4 *Metal elements*

Unlike in mainland Greece or Asia Minor, building elements were not typically joined with each other

Figure 11. Clamp connection (right) and mortise (left) in detail.

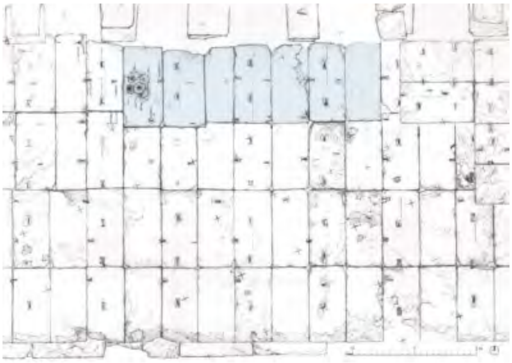

Figure 12. Excerpt of the documentation plan. Possible repair site highlighted.

using pins or clamps in the cities of Magna Graecia. Such metal connecting components were used only very sparingly, and mostly for corner elements (Fastje 1984, 37; Koldewey & Puchstein 1899, 226; Mertens 1993, 75). This is confirmed by findings from both Temple A and Temple O. In the case of the latter, a number of T-shaped grooves can be found in the blocks of the south-east corner (Figure 11), some of them still containing corroded metal. The corner blocks of Temple A possess similar grooves, which also appear in some of the architectural elements of the front sides of the antae. Evidence for the use of pins has so far only been found on both top and bottom surfaces of column drums as well on the bottom of capitals.

5 REPAIR AND SACRIFICE?

While the blocks were being dressed and fitted, small points of indentation and misalignment were created, especially at the joints. These usually range in the millimetres or centimetres. An exception is a series of seven binders placed next to each other in vicinity of the *adyton*, in the fourth row of the lowest step of the south stereobate. They recede slightly towards the south (Figure 12).

This row forms the north boundary of the south stereobate and the transition to the linear structures of the south *pteron*. The little shift of the blocks to the south creates a detachment of the south stereobate from the south *pteron*. It seems unlikely that this was done deliberately, for reasons of connection alone, since the south running joint now corresponds with the joint of the layer above due to the offset and this was hardly intended. On the basis of the mortises, it becomes clear that in the layer above, no consideration was given to the resulting joint concordance, probably to prevent this exception from being transported into each layer above. It is possible that these seven blocks had to be swapped out even while the construction process was still ongoing.

A peculiar cluster of five depressions in the westernmost block of the row may be connected to such a procedure (Figure 13). The top surface of the blocks is badly weathered, however, thus masking any possible tool marks or other clues that might explain the origins of the indentations. However, the central depression is the deepest and may also be the remains of a now-eroded fossilised maritime inclusion in the rock, as quite often occur in this type of stone quarried in the area. This hole could then have purposely been supplemented by four additional indentations, perhaps in order to serve as the receptacle for a foundation sacrifice as was discovered in the foundation trenches of the Hestiaterion on Selinous' *agora* (Dehl-von Kaenel in prep.; Helas in prep.). In this case, the sacrificial site was located directly in the foundations themselves and, after the rites had been completed, was covered by the next course of foundation blocks (Bücherl in prep.). As a working theory, it is conceivable that an incident (accident, defective building material, planning error etc.) occurred which required that a number of blocks had to be replaced. In order to guarantee more architectural success in the future or simply to beg for good luck for the building project, the spot was then chosen as a place of sacrifice.

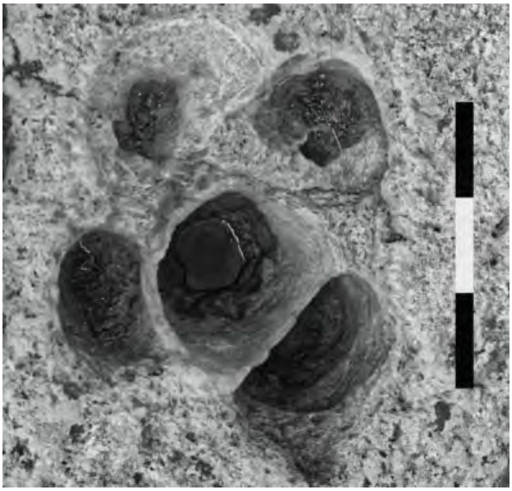

Figure 13. A cluster of five indentations.

6 CONCLUSION

The foundations of the unfinished Temple O in Selinous are a typical example of the building tradition of the temples of Magna Graecia, which usually have grid foundations. Because the building project was abandoned and the foundations thus remain uniquely accessible, they give evidence on many aspects of the building process. For instance, a series of marks (Greek letters) has been discovered that can be interpreted in relation to logistic and organisational issues of the construction. The evidence also gives reasonable insight into the single stages of the construction process. It becomes obvious that even the substructures of the temple were subject to detailed and refined planning, and that the specifications were followed carefully and with great efficiency. In relation with the neighbouring Temple A, as well as to the Great Temple in Segesta, a specific development regarding the working procedure seems to emerge that will be verified more clearly in future investigations.

ACKNOWLEDGEMENTS

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Within the framework of this project, a detailed building survey of the existing structures will be compiled. Finally, I would particularly like to thank Philip Brize, Sophie Helas, Claudia Mächler, Dieter Mertens, Klaus Rheidt, Thekla Schulz-Brize, Eva Träder and David Wendland for their numerous suggestions and ideas.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

On-site design decisions at the Basilica of Maxentius in Rome

L. Albrecht
Technische Universität Berlin, Berlin, Germany

M. Döring-Williams
Technische Universität Wien, Vienna, Austria

ABSTRACT: The design provides a decisive component and basis for all subsequent building processes, the substance of communication between planning and realisation. This applies not least to the imperial projects of Roman antiquity. But we still have limited knowledge of the Roman design processes, which since Wilson Jones' "Principles of Roman Architecture" (2000) must at least be considered fluid. Using the late antique Basilica of Maxentius in Rome as a case study, the moments when design decisions were made can be determined very precisely at several points. The assumption that the design work was already completed when construction began can be clearly refuted here. Numerous proven deviations from the regular design scheme at various levels show that the final detailed design must first have been developed 1:1 on the construction site.

1 DESIGN ANALYSIS

1.1 *Applying design analysis studies: Methodical approach*

Design analyses are typically based on the detailed documentation and analysis of all available (built) dimensions. The aim is – in the sense of a master plan – to decipher the basic design concept. Depending on the interpretive approach, this involves conducting metrical and proportional studies (see Wilson Jones 2000, 1–14 as a compilation of historical facts), defining regularities and recognising deviations as such. The design process needs to be reconstructed in reverse order – starting from the last state of construction to the establishment of the construction site.

In our case, the measurement unit is the Roman foot (which will be abbreviated as RF in the following descriptions) with large, square-shaped Roman bricks, called *bipedales,* as a kind of base module. It is well known that the dimensional accuracy can vary quite considerably, especially in buildings constructed using Roman concrete – *opus caementicium* (e.g. Hecht 1979, 118). It can be assumed that the accuracy varies by more than 0.5% on average for longer lengths (Wilson Jones 2000, 72). In addition, permanent deformations, e.g. due to settlement or seismic disturbances, must also be taken into account. The "Roman foot" as a measurement unit was usually multiplied by 10, 12 and sometimes 16 (Wilson Jones 2000, 77–79). There is only occasional evidence of other numbers being used as the base, e.g. 99 instead of 100 (see e.g. Birnbaum 2006, 87–90. 109; Svenshon 2010). Given all these dimensional uncertainties, the search for key parameters for the original design scheme can easily lead to circular reasoning.

However, this inevitably raises an even more crucial problem: the "re-designing" process is based on the final results, on a completed building that is generally now in a ruinous state after having been damaged over the centuries.

When reconstructing design processes from the perspective of a modern architect, one would assume that this process would have been largely completed before starting construction. The fact that this is unlikely to have been the case with antique construction sites has already been noticed by Wilson Jones (2000, 63). He identifies four design stages – the inception, preliminary scheme, interim scheme and, last but not least, use combined with beauty. His interpretation is derived from 1:1 architectural drawings, Roman temple models and corresponding text passages from Vitruvius' "De architectura libri decem" (p. 58–63). However, although he proves the four phases with examples of several buildings, his argumentation concentrates on the situation before the start of construction (with the exception of the Principia in Palmyra, p. 62).

In general, the design process can be described as an accumulation of many individual design decisions regarding the dimensions and proportions chosen as well as suitable logistical (construction site) procedures, and which subsequently involve determining and prioritising all the different parameters related to the construction process as well as considering or negating all further influencing factors. Even the postponement of design decisions is structurally noticeable when, for example, structural changes or corrections are made in reaction to it. Precisely these corrections

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could help to answer the question as to when these decisions were made. Following a general introduction to the Basilica of Maxentius, this paper first of all examines these corrections and presumed omissions.

2 CASE STUDY: THE BASILICA OF MAXENTIUS

2.1 *Introduction*

Methodically the basilica provides an excellent building for studying the interrelation between the design process and construction progress: this building, whose main structure was built in the early 4th century, was constructed using regular masonry in *opus testaceum* with an extremely stringent system of levelling layers using *bipedales* (square-shaped Roman bricks measuring 2 RF along each side) with putlog holes in the layer above (Albrecht, Döring-Williams 2018; Döring-Williams, Albrecht 2020, 369). In a similar way to a palimpsest, disruptions, irregularities and deviations in the regular masonry make the timeline of the construction progress readable, from the treatment of the previous buildings on the site to the alterations – both improvements and corrections – during the ongoing construction work. The inaccuracies in the setting out and the as-built geometry are in fact remarkable: for example, the north wall, which has a nominal thickness of 7 RF throughout, varies by a total of 9 cm with values between 2.05 m and 2.14 m. These inaccuracies mean that often only approximate values can be given below for the length measurements using the RF unit. On the other hand, the wall thicknesses, which were consistently dimensioned as whole-number multiples in RF, provide the best evidence that arithmetic methods were used on the construction site to set out the walls. Deviations of this magnitude over short lengths also show, however, that it is effectively impossible to reconstruct an “ideal plan” for the Maxentian basilica.

2.2 *Project history*

The restoration of the Basilica of Maxentius during the Great Jubilee in 2000 (1998–2003), headed by the *Soprintendenza alle Antichità di Roma* (CisteC 2003, Giavarini 2005), was used as an opportunity to launch a comprehensive collaborative project. The authors were involved in the joint project on conducting building-archaeology investigations, which was organized by the Technische Universität Berlin and was funded by the Fritz Thyssen Foundation, Cologne. The work package headed by J. Cramer (TU Berlin) and M. Döring-Williams (TU Berlin/TU Wien) included the first detailed geodetic survey of the building, together with manual documentation and complex analysis.

2.3 *Topography and urban development*

The late antique basilica can be considered to be an exceptional building in several respects: it was one of the largest monuments in Rome, and it was constructed in the middle of an extremely densely built-up urban area in the northern vicinity of Palatine Hill, directly in the heart of the city along the Via Sacra. To understand the design challenges, we must first look at the topography and find out what the site looked like before construction began. Most of the area occupied by the basilica covers the former site of the Horrea Piperataria, which was probably a lively shopping centre for luxury goods. According to Barosso (1940, 59) it consisted of up to 150 small rooms distributed around at least two courtyards. It occupied an entire city block that was organised on different ground-floor levels. The antique Via Sacra, running more than 100 metres first alongside the Horrea, and later alongside the basilica, is quite steeply inclined. Summing up, the basilica was laid out in an area that was already fully built-up and situated on a slope that varied in height by about 14 metres (Albrecht 2019, 173).

3 EVIDENCE OF MODIFIED DESIGN DECISIONS OR THOSE REQUIRING FURTHER ELABORATION

3.1 *A Selection of findings*

3.1.1 *The foundations (Figure 1, A)*

Unlike the usual strip foundations, a slab foundation occupied the entire area of the north-western corner that was in the northern direction more than 8 m longer than needed (Albrecht 2019, 178–179, see Figure 4). It is obvious that the decision as to where exactly to position the north-western corner was only made after the completion of this foundation section. A *bipedales* layer covering the top of this foundation can also be traced throughout a tunnel, the so-called Arco di Ladrone, and along the western outer wall. At the beginning of construction, the two walls of the *Aula Forma Urbis* and the *Aula di Culto* apparently formed the lateral boundary for the new foundations being laid. In an easterly direction, this foundation section probably extended to the predecessor buildings, the tabernae, which led along the Via ad Carinas street up to the street junction. The foundation area in the north-west corner was therefore approximately 40 m^2 larger than directly required for the walls on top. Similar findings can be found in the area of the western apse and along the southern terrace, a substructure along the Via Sacra (Albrecht 2019, 178–179, 185). It is noteworthy that no reference values are discernible between the levels of the upper edges of the foundations and that of the intended flooring. Such rigid regulations were obviously neither desired nor necessary and indicate here, too, a certain scope for decision-making during the realisation phase.

3.1.2 *Modification of the passage width in the southern side aisle (B)*

In the southern section of the eastern wall, the reveal of the passage between the narthex and the eastern bay

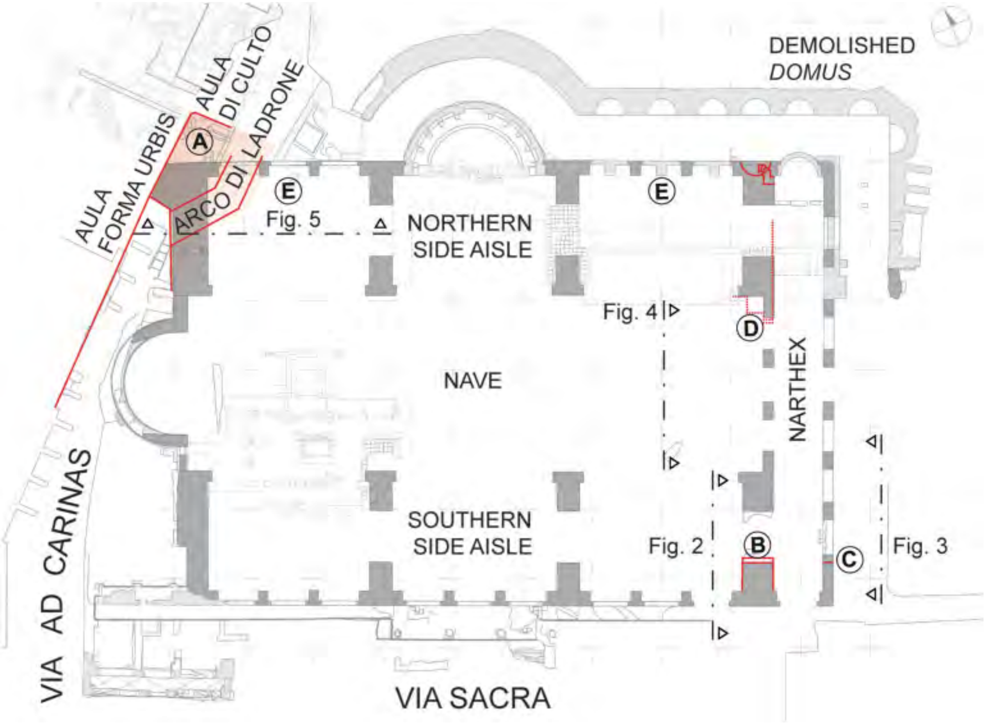

Figure 1. Basilica of Maxentius, Rome. Schematic ground plan. Drawing: TU Berlin. Graphic revision: L. Albrecht, including references to figures.

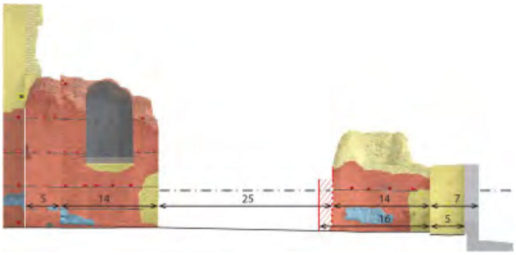

Figure 2. Rome, Basilica of Maxentius. Southern side aisle, eastern bay. The red hatching marks the original wall shell of pier (B), that has been hacked-off subsequently. Digital rectification: Fokus, Leipzig; TU Berlin. Graphic revision: L. Albrecht.

of the south aisle was initially conceived at a position 2 RF further north (Figure 2).

A continuous joint at floor level indicates the original *opus testaceum* facing. The northern wall of the pier, on the other hand, has no *opus testaceum* facing up to a height of about 2 m above floor level, but instead shows hacked-off *opus caementicium* belonging to the masonry core (see Amici 2005b, Fig. 5.33). Because of the rough surface, the mortar for the marble cladding applied later adheres particularly well here, so that a large part of the surface is covered. This finding was already described by Amici (2005b, 146), but misinterpreted, as here the two wall surfaces of this and the following finding described under (C) are not – as claimed by her – aligned.

3.1.3 *Joints*

The following feature makes it necessary to refer to the joints. Most of them run vertically, but in several cases two sections were interlocked by ending every second layer with a slight protrusion, like a zip.

Some joints are diagonally stepped and thus show the construction sequence even more clearly. With all vertically running joints, the later added area was docked to the existing wall with mortar, so that the construction sequence can be identified by closely observing the joints. These observations are important in order to distinguish ordinary construction joints from corrections. In the case of corrections, the desired interlocking was usually not achieved or, in some cases, it was even necessary to demolish a wall section. Two such distinctive corrections are presented below.

3.1.4 *Addition of a wall section in the narthex façade (C)*

In the narthex façade there is a modification in the southern area: here a wall section was added. Initially, starting from the south-eastern perimeter corner, a 21 RF wall section (6.27 m) had been erected and a door reveal with a vertical *opus testaceum* face was constructed (misinterpreted by Amici 2005b, 146 as a window reveal in the first stage).

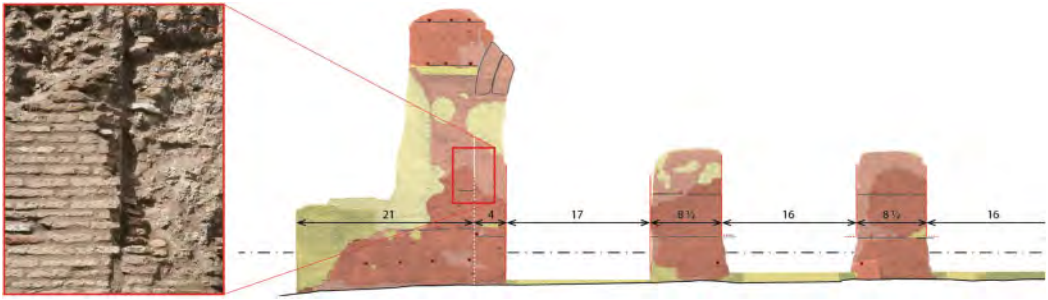

Figure 3a and 3b. Rome, Basilica of Maxentius. Narthex façade, southern part. View from the east. 3a: Added wall section (C). Photo: L. Albrecht. 3b: Digital rectification, white dashed line: joint run of the added wall section (C). Digital rectification: Fokus, Leipzig; TU Berlin. Graphic revision: L. Albrecht.

The height of this reveal area can no longer be clearly determined due to subsequent alterations, but it extended to a height of at least 5.60 m above floor level, probably even close to 7 m. A wall section of about 4 RF (1.14 m) in width was then added, so that the southernmost reveal is located at a distance of 25 RF (7.41 m). On both sides of the wall, it can be clearly seen that a smooth reveal surface was left in the wall core (Fig. 3a), but on the wall face the corner was knocked off on every second layer to achieve minimal interlocking. The façade design now shows regularities: the two entrances from the east are each on the central axis – in line with the nave and the central axis of the south aisle – and have a clear width of 17 RF, while the windows (whose reveals clearly show that they were later altered to form passages) are 1 RF narrower. The wall sections between the openings have been designed with the same width of 8.5 RF.

3.1.5 *A similar phenomenon at a position two window rows higher (D)*

A majority of the east wall of the central nave has been lost. In 1958, a portion of the wall with several round-arched windows was reconstructed. When the windows were reconstructed, they were designed and measured by plumbing the lower reveals – a procedure that, as shown below, was not carried out anywhere in the original structure.

A third window level with a preserved reveal over a height of 3.30 m still begins *in situ* at the truncated northern edge at a height of about 27 m above floor level. The upper shape is usually indicated in reconstruction proposals as a thermal (Diocletian) window (e.g. Amici 2005a, Fig. 2.20). This is another case where the reveal area was only fixed in its final position following modifications. Parallel to this surface, a vertical joint can be traced on both sides of the wall over a height of 2.80 m, which was initially the reveal surface at a distance of 1.5 RF to the north (Figure 4).

3.2 *An interim summary of the modifications made*

In particular, the three examples (B), (C), and (D) clearly show that, at the beginning of the respective wall section, the planning had not yet been completed and modifications were necessary which were primarily decisive for the elevational treatment of the respective walls.

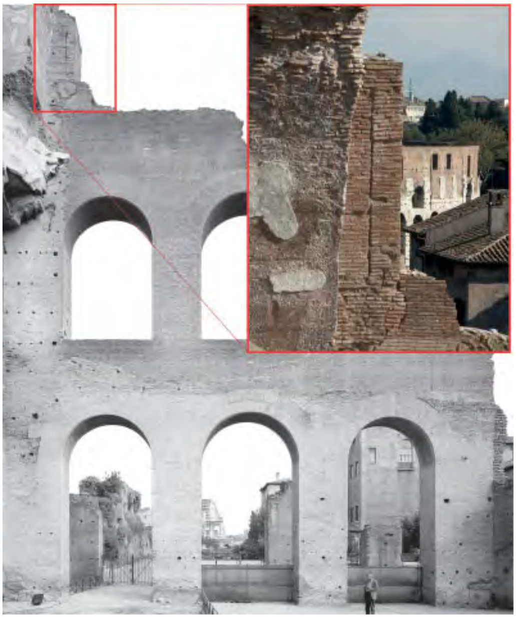

Figure 4a and 4b. Rome, Basilica of Maxentius. Central nave, east wall. View from the west. Added wall section (D). 4a: Photo: Fokus, Leipzig. 4b: Photo: L. Albrecht.

In example (D), however, it is also clear that this modification was only made when the building progress reached the height of almost 30 m above floor level. Presumably, this was the precise moment when decisions about the shape, size or arrangement of the windows in the top row were made.

This clearly demonstrates that the elevation was not entirely planned prior to or at the very beginning of the construction process. Instead, at each level the concept was either adapted, or even initially designed, and the corresponding instructions communicated to the construction site. In the case of the Basilica of Maxentius, it cannot be assumed that any consistent designs for the floor plans, elevations (and sections) existed prior to the construction work, as is generally the case nowadays before starting building.

4 THE DESIGN “ERROR” OF THE NORTHERN FAÇADE

4.1 *The windows in the top row (E) – the vault window conflict*

Compromises, changes in approach and imperfect execution have always been – and always will be – a normal part of the construction process (Wilson Jones 2000, 11). However, particularly the study of atypical or puzzling features, of errors that have occurred, can make a significant contribution to understanding the design principles applied. Such an example is presented in more detail below.

The investigation primarily concerns the two completely preserved sections along the northern perimeter façade in the northern side aisle in the eastern and western bays. In the middle bay, a large part of the wall was demolished in order to erect the northern apse at a later time (Döring-Williams, Albrecht 2020). However, even here there are the similarly strange findings, which are described below.

The zones of the barrel vaults adjoining the northern perimeter wall are remarkably irregularly shaped, especially in the windows area, where some vault portions even tend to overlap the window. Instead of a semicircle as a guideline, the shape tends to have five corners, i.e. to be part of an octagon with rounded corners (Figure 5). Lancaster 2005, 34 interpreted this phenomenon as the result of formwork deformation due to preloading of the centering. Albuerne, Williams 2011 revised that interpretation (repeating: Albuerne, Williams, DeLaine 2012, 301; Albuerne 2016, 39; Albuerne, Williams 2017, 906 with adjustments of the terminology: “distortion” instead of the erroneous term “deformation”). They noticed that the northern wall was constructed prior to the vaults (based on Albrecht 2009 and personal communication), concluding that thus an “error must have been made in the construction process, locating the windows in the top row either too high up or too far apart from each other. As a result, the geometry of the vault had to be altered, deviating from the ideal semicircle, in order not to obstruct the windows.” (Figure 5) Since this so-called “error” is based on design decisions, it is necessary to subject the built version to a detailed design analysis. The key question here is once again whether the design decisions can be assigned to a respective moment in time.

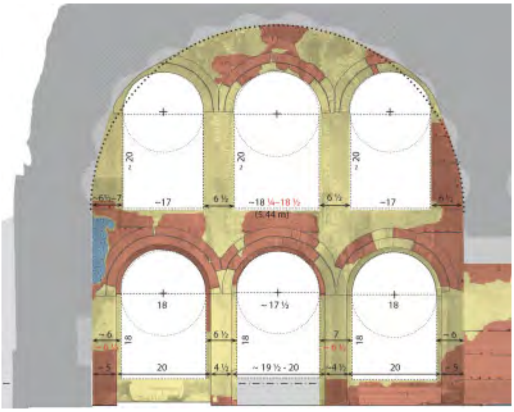

Figure 5. Rome, Basilica of Maxentius. Northern side aisle, west bay, view from the south: vault/window conflict (E). Digital rectification: Fokus, Leipzig; TU Berlin. Graphic revision: L. Albrecht.

Each bay originally had six large windows, three at the bottom and three at the top. All windows feature a semi-circular arch. A striking aspect is the difference in both the wall thickness and the general window type between the bottom and top rows. Due to the exterior cornice and the setback of 1 RF above it, the wall thickness at the upper part is reduced to 6 RF. The lower row of windows has wall niches with masonry jambs, while the upper row of windows does not.

4.1.1 *Design scheme and layout of the lower windows in the plan view*

The walls, which are 7 RF-thick in the lower row of windows, are divided into 5 RF-deep window recesses and 2 RF-deep wall openings. The clear width of each opening is 2 RF narrower than that of the window recesses, so the openings feature a 1 RF-wide surrounding masonry window jamb. In the western bay, there were several modern modifications affecting the two western openings. The clear width of the window recesses in the west and east bays on the northern side aisle is relatively uniform at ~ 20 RF (between 5.86 m and 5.90 m). The dimensions of the windows in the central bay in the northern side aisle are unknown due to the demolition of the corresponding wall sections.

Since the bays in the side aisles differ slightly in size, it is necessary to analyse not only the opening dimensions, but also the arrangement of the windows within the façade. The east and middle bays (in the northern side aisle) are each about 79-80 RF wide, while the west bay is only 78-79 RF. Considering a possibly idealised basic size of 80 RF for the east bay, there were 5 RF-wide wall sections alternating with 20 RF-wide window niches in the floor plan scheme, in accordance with the sequence: 5 / 20 / 5 / 20 / 5 / 20 / 5. In the case of the west bay, which is about 1 RF shorter, a somewhat indecisive approach to reducing the dimensions can be observed: on the one hand, it is apparent that the wall sections between the windows were made smaller (tending to be 4.5 RF) and, on the other hand, the opening in the middle appears to have been somewhat reduced as well, in accordance with the following sequence: 5 / 20 / 4.5 / 19.5-20 / 4.5-5 / 20 / 5 (Figure 5).

Priority was probably given to ensuring that the opening niches and openings had uniform dimensions. Consequently, the wall sections with dimensions of either 4.5 RF or 5 RF were adjusted to the respective overall dimensions. Within a single bay, the wall sections between the openings tended to have similar size. The difference in design between the various bays was certainly not noticeable to the naked eye.

4.1.2 *Design scheme and layout of the lower windows in the elevational view*

A continuous *bipedales* layer forms the lower window sill level in the northern aisle, which varies in the east-west direction by about 20 cm at a height of 1.60 m to 1.80 m above floor level. The elevation design is simply based on a 1:1 ratio between the clear width and the springline of the semicircular arches (Figure 5). The 18 RF-wide openings therefore result in a springline that is 18 RF higher than the window sill level. However, with the extremely stringent system of *bipedales* and putlog holes regularly placed every 5 RF, an 18 RF level is not going to match this system. Yet a similar height was also used for the vault springers for the passages between the bays, which also resulted in a 1:1 ratio between the width and the height of the springline.

4.1.3 *Design scheme and layout of the upper windows in the plan view*

The main difference in the layout between the upper and lower row of windows is that the opening width is not more or less the same, but instead is divided into a larger central window and two smaller side windows, e.g. in the western bay more than 18 RF, as opposed to approximately 17 RF (Figure 5). Accordingly, there is absolutely no vertical alignment with the lower windows. The wall sections, on the other hand, measure pretty much the same width (6.5 RF), both between the windows and the section to the corner. The reveal lines were clearly newly marked out here. This was done on a continuous *bipedales* layer running along the entire side aisle. In the transverse walls, the boundary line between the wall surface and the barrel vault is set at exactly the same height.

4.1.4 *Design scheme and layout of the upper windows in the elevational view*

In the elevational view, too, the design principle for the upper row differs from that of the lower row: rather than a 1:1 ratio, there are taller window openings here and the springline for the semicircular arches starts exactly four *bipedales* positions higher. This height should normally equate to 20 RF, but in fact the measured height is probably closer to 21 RF (6.10 m and 6.21 m in the middle bay, measured in the only areas that have not been restored). Due to its larger radius, the apex of the middle window would normally be located at a higher point than the other windows if all the arches had their centre at the same height. However, they evidently wanted to prevent this: the centre point is shifted slightly downwards in the eastern bay, and so clearly in the western bay that the apexes are positioned at about the same level (Figure 5).

4.2 *The window design as "error"?*

To check the claim made by Albuerne and Williams that an "error must have been made in the construction process", it is helpful to look at alternatives: two proposals that would have prevented the so-called error – either locating the windows in the top row so that they did not extend so far upwards, or so that they were positioned closer together – could theoretically have been realised without any great difficulty.

The simplest solution to prevent the semicircular barrel vault from colliding with the window openings would have been to position the window reveals exactly as they were built, but to reduce the opening heights. A 1:1 ratio, as with the lower windows, would not have led to any conflicts along the northern façade.

However, the built version was the option that was chosen. The design of the upper level was either completely conceived on site (after being precisely measured), or at least specified. This was done after the entire northern side aisle had been completed up to the springline and covered with a *bipedales* layer for measuring and marking out.

As shown in Albrecht 2009, Figure 7, the general construction process for the barrel vaults in the side aisles was divided into two main stages: in the first stage the vault flanking walls were built using the stringent and regular system of putlogs placed upon *bipedales* layers. This stage included the openings with its semicircular arches. When completing these walls the inner scaffolding was removed in order to make space for the centering. During the second stage, the vault *caementicium* was laid in layers on the formwork (upon the centering). However, the leading curvature line was already determined in the first stage and structurally established with a recess. This practice can best be traced in the vaulting of the Quadriporticus of the Maxentius Mausoleum at the Via Appia, which was stopped in the middle of the construction work (Albrecht 2009, 24; Rasch 1984, pl. 16–24).

Precisely this determinant guide line with a presumably 1 RF-deep recess also existed at the basilica north wall. The curvature of the vault was therefore not created later in a second stage, but at the same time as the north wall was erected. It therefore becomes apparent that not only the setting out of the window reveals and the barrel vaults in the ground plan proceeded in parallel, but also that the guiding line for the vault in the elevation grew from the very beginning. If a recess was set exactly along a semicircle, but the geometry deviated outwards when the vault *caementicium* was laid (for instance due to the shape of too large windows), a joint would be visible in the space between. Such joints can occasionally be observed, for example in the Caracalla Baths (Figure 6). Since no joints have yet been observed in the outer northern wall sections,

Figure 6. Rome, Baths of Caracalla. Joint at the boundary between the recess line and the masoned vault portion. Photo: L. Albrecht.

it seems reasonable to assume that the idiosyncratic curvatures were planned from the very beginning.

Therefore, the built version is fully intended and can by no means be called an "error". Avoiding the vault/window conflict would have been easy and possible during the construction process by reducing the height of the upper windows. This example excellently shows the importance of linking a design analysis with the study of construction processes. Otherwise, as with the provisional assessment in Albuerne and Williams, one would not realise that all atypical findings in this particular area are the result of contemporaneous decisions. It is precisely here that design decisions stand out. These trade-offs, which are manifested quasi structurally, took place when the upper level was set out, and were made in favour of the windows. Here, the higher windows in the upper row were clearly prioritised – whereby the visual effect created by the taller, elongated form was probably the important aspect.

It seems that only from today's perspective does the realised version look odd. Spatially, the side aisle rooms were not only unusual but probably the first to be built using this hybrid design and to this consistency: using barrel-vaulted rooms that were clearly oriented towards the central nave in combination with a uniform row of large-format windows. Thus the idiosyncratic curvature solution actually reflects the conflicts in balancing the architectural parameters for a newly created building type.

5 CONCLUSIONS

These selected examples show a whole spectrum of supposed construction "errors", modifications and corrections that were evidently made during the ongoing construction process. In attempting to categorise these changes, to understand their triggers and consequences, not only does the moment of intervention become tangible, it also reveals an insight into the design methodology used in late Roman antiquity. However, the supposed sequence of four design stages – based on Vitruvius' elaborations – seem to be only partially transferable and applicable to the Basilica of Maxentius.

For instance, it turns out that example (A) – the oversized foundations – were not trying to compensate for a measurement error on the construction site, but were one of the precautionary measures taken when installing the foundations. One would expect that some sort of rough floor plan would have already existed at this point. Nevertheless, in several places, as in example (A), the foundations were built "oversized", since presumably the exact positioning of the structure on the site and the possible outline dimensions had not yet been conclusively defined, especially in the north western part of the complex. Some leeway was obviously necessary here.

Planning uncertainties also become tangible in examples (B) (partially dismantled pier in the south aisle), (C) and (D) (complemented wall sections in the narthex and eastern façade). The changes and corrections seem to emanate from the floor plan, but were probably triggered by the elevation situation. Obviously, the aforementioned structural elements only take on their final form and size in the building during the construction work. In this context, the action and reaction between the floor plan and elevation should not be underestimated, as they directly affect the dependencies between the span and rise of an arch or crown, and thus also the proportions. Moreover, these architectural elements in the building should not be regarded as isolated cases. Rather, the aforementioned pier and wall sections in the narthex façade are, in a sense, prototypes for the seven other side aisle piers and for the subsequent arcades in the narthex. The modifications shown are the result of a concretisation process on the construction site.

In general, it is noticeable at the Basilica of Maxentius that all levels where decisions had to be made on the dimensions or shape of sections being subsequently built on top of them feature a continuous *bipedales* layer. Examples include the covering layers on the foundations, the niche floors, the window sills and the vault springers. Indeed, based on the different dimensional systems for the window rows and modifications, it can be seen that it was precisely these *bipedales* layers that were used to carry out the detailed design layout directly on site, with the dimensions measured in-situ forming the basis. Presumably, short lines defining the wall alignments were carved directly on site into the *bipedales* – as suggested by findings at, for example, the Maxentius Mausoleum (Rasch 1984, 40).

One last observation might inspire further investigation. In the Basilica of Maxentius, two aspects stand in stark contrast to one another: on the one hand, the extremely stringent, almost modular system of regularly installed *bipedales* and putlog layers in all walls; on the other hand, a planning methodology, which begins only with a kind of conceptual design.

The concretisation, the response to particular situations, apparently took place during the construction itself. A correlation between these two aspects is quite feasible.

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Investigating forms and formwork in the nave aisles at Tewkesbury Abbey

J. Hillson, A. Buchanan & N. Webb
University of Liverpool, Liverpool, UK

ABSTRACT: Recent study of medieval vaults using digital scanning methods has tended to focus on the design and construction of the ribs, with less scholarly attention being directed towards the webs in between. The study of webbing has been impeded by the limitations of both the raw data and the range of research methods which are available to architectural historians. This paper focuses on a series of vaults which were added to the 11th-century nave aisles of Tewkesbury as part of an extensive 14th-century remodelling scheme. It considers whether or not formwork was used in erecting the webbing at Tewkesbury, using a variety of digital methods including contour analysis, course tracing and normal vector mapping to investigate the structure and three-dimensional curvature of the masonry.

1 INTRODUCTION

Our research project, "Tracing the Past" (www.tracingthepast.org.uk), uses experimental digital methods to investigate the design and construction of English vaults between the 11th and 16th centuries. The innovations which took place during this period were fundamental to the ongoing development of European architecture, with the emergence of ribbed vaults, tiercerons, liernes and fan vaulting dramatically increasing the range of possibilities available to medieval designers. Yet whilst many studies of medieval vaults have attempted to understand them by analysing the geometry of their ribs, relatively few have focused on the masonry between them. These webs are seldom visible in English buildings, as they are usually covered by layers of plaster or whitewash. However, in the few cases where the masonry of the webbing is exposed, its form and structure raise many questions regarding its design and construction process.

The consensus among architectural historians is that a vault's ribs were erected with the aid of some kind of formwork or centering. The designs for each rib would be worked out at a 1:1 scale, probably using lines and arcs incised into a plaster or stone surface conventionally called a tracing floor (Pacey 2007). The resulting arcs would then be converted into a set of stone components through a process of projection, facilitated by a set of templates giving the profile, curvature and angle of the joints between each block. Once the walls had been raised and *tas-de-charge* blocks inserted, a wooden framework would then be assembled spanning the vault bay, probably taking the form of a series of wooden arches corresponding to the curvatures of the ribs above. Bosses would be placed at the apexes of these arches and voussoirs would then be laid to meet them from the *tas-de-charge* upwards, eventually forming a self-supporting framework of stone arches defining the outer bounds of the webs. Yet though it is practically certain that formwork was essential for erecting the ribs, this is not necessarily the case for the webbing. At some sites the three-dimensional curvatures of the webs and the cambered courses of stones raise the possibility that some of these surfaces may have been self-supporting, requiring no formwork beyond the ribs themselves.

This paper reopens the question of whether or not formwork was necessarily used in the construction of webbing by focusing on a single targeted case study: the 14th-century nave aisle vaults at Tewkesbury Abbey (Figure 1). Despite the apparent simplicity of their plan, the geometry of the ribs in these bays is remarkably complex, an observation equally reflected in the structure of the webs. The exposed surfaces of their masonry reveal a complex pattern of interlacing courses, with a unique arrangement appearing in every bay.

As we have demonstrated previously in our studies of vault ribs (Buchanan & Webb 2017a, 2017b, 2018, 2019), digital technologies present a range of new techniques for analysing the masonry patterns and three-dimensional forms of these webs. This paper describes these analytical tools and demonstrates how they can be applied to studying the form and structure of the vaults at Tewkesbury, with a particular emphasis on how they were constructed and whether or not formwork could have been involved.

2 FORM AND STRUCTURE

The community that became Tewkesbury Abbey was originally a Benedictine religious house founded at

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Figure 1. Tewkesbury Abbey, north nave aisle, bay N8, mesh model, perspective view facing northeast.

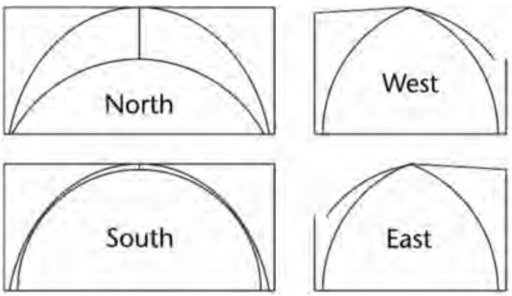

Figure 2. Tewkesbury Abbey, bay N8, design hypothesis.

Cranborne (Dorset) in c. 715. During the late 11th century, the Earl of Gloucester Robert Fitzhamon (d. 1107) decided to move the abbey it to its present site at Tewkesbury, starting construction of a new church on a far larger scale. Begun after 1087, the first phase of works was probably largely completed during the 1090s, with the monks moving into their new buildings in 1102. By this stage the architectural choir, transept and first two bays of the nave at least were presumably complete, including both the high altar and liturgical choir in the nave. The church was apparently consecrated in 1121 (Thurlby 2003), at which date the first iteration of the nave would almost certainly have been finished. With the exception of repairs conducted after the fire of 1178, there were no major works on the nave until the mid-14th century (Morris & Thurlby 2003). From ca.1280 onwards a series of ambitious new revaulting projects were initiated, starting with the choir. By ca.1350 the vaulting in the central vessels of the choir, transept crossing and nave had all been replaced by lierne vaults of remarkable complexity.

Whereas the majority of scholars have focused exclusively on the high vaults at Tewkesbury, comparatively little attention has been given to the adjoining aisles. Though the exact date of the nave aisle vaults is not known, it was probably somewhere in the region of ca.1335–49 – the date range ascribed to the main vault above (Morris 2003). The unusual form and structure of these vaults was the product in part of its relationship with the existing fabric. The 11th-century walls, piers, responds and arcade arches were all retained, with the springing levels of the ribs on the window side of the bays being slightly lower than those on the arcade side – a common feature in 11th-century aisle construction. The semi-circular form of the arcade arches is repeated in the curvature of the adjoining ribs, but the wall ribs on the window side are significantly lower, taking the form of a depressed segmental arch. The apexes of these wall ribs are connected to the crown of the vault by an unusual ridge rib constructed as a segmental half-arch. Such a design might have been intended to reflect the form and structure of the previous iteration of the aisles (Figure 3), which may have been covered by a half barrel vault (Thurlby 2003). Evidence for this is provided by both the masonry breaks visible in the outer walls and the half arches marking the transition between the transept and nave aisles. The apexes of the pointed arches of the transverse ribs on the east and west sides of the 14th-century vaults are positioned along the curvature defined by these half arches. This provides the level for the crown of the vault and its corresponding horizontal ridge rib, which is slightly higher than the level of the arcade wall ribs. The diagonal ribs were constructed as segmental arches, with slight irregularities resulting from the different springing levels that they span.

Figure 3. Tewkesbury Abbey, south nave aisle, bay S12, tentative reconstruction of 11th-century vault.

The unusual form of the ribs is further exacerbated by their corresponding webs. Those immediately flanking the longitudinal ridge rib represent an approximately horizontal tunnel from east to west.

Their masonry is mostly fairly conventional, consisting of courses laid roughly parallel to the ridge, but the stones used are highly irregular in shape and size and in some bays the direction of the coursing switches towards the ridge, their stones lying perpendicular to the lower courses (Figure 8). A similar approach can also be seen in the webs directly abutting the arcade, where the tunnel and ridge rib have a slight upwards incline towards the crown of the vault. However, the webbing on the window side is unusual, with few parallels in English vaulting. Whereas on the other sides the webs each correspond to two distinct rib curvatures, on the window side they each correspond to three: a wall rib, a diagonal and a curved ridge rib. The result is a bulging surface produced by a highly irregular and improvised pattern of stonelaying, with every web being constructed using a unique and ad hoc set of courses.

3 QUANTIFICATION AND ANALYSIS

The principal problem which our project encountered in the aisles at Tewkesbury was how to quantify such curvatures and the stonelaying practices which produced them. Before this point, the digital techniques which we had developed were exclusively focused on analysing rib geometries, following the principle established by the 19th-century scholar Robert Willis (1842) that ribs were the defining elements of a vault's three-dimensional form. Surveys were conducted using digital laser scans taken at strategic points in each of our case study sites, creating detailed point cloud models made up from hundreds of thousands of individual measurements. These were then converted into mesh models which could be imported into Rhinoceros, an advanced 3D modelling program. The software was then used to trace the intrados lines of each rib in three-dimensions, producing a wire-frame model of best fit curves. These lines enabled us to quantify the vault's design by extracting data which could be analysed geometrically, including distances, proportions, positions of centres and radii. Such data allowed us to investigate the geometrical methods which could have been used to lay out each rib, enabling us to produce informed hypotheses regarding the design processes of the vaults themselves. However, the techniques which we developed for ribs were not applicable to the webbing. Rather than being conceived using two-dimensional curvatures arranged in three-dimensional space, webs present a fully three-dimensional curvature created by patterns of stonelaying, with the orientations and positions of each block gradually giving shape to the structure as a whole. Consequently, it was necessary to develop a new set of techniques to quantify and analyse the masonry surface.

The first method which we attempted involved using contours (Figure 4). Derived from topographical mapping, this technique quantifies the gradient of a slope in terms of the change in height, visualized from a single two-dimensional plane. In Rhinoceros we used the "contour" command to take horizontal sections of the mesh models at regular vertical intervals, defining the starting plane as well as the direction and distance between the sections. Viewed from a direction perpendicular to the starting plane, the result is a pattern of two-dimensional lines which describe the three-dimensional structure of the vault, with the changing gradient of its surface being given by the distances between the contours.

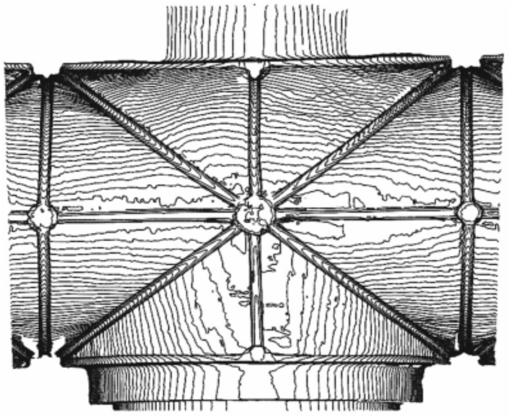

Figure 4. Tewkesbury Abbey, bay N8, contours.

The starting plane can be aligned in any orientation, allowing several different types of contour to be generated. The most versatile and straightforward of these is produced by aligning the direction of contours perpendicular to the base of the model. Viewed from the top down, these produce a plan of the vault analogous to a topographical map (Figure 4). Alternatively, the contours can be aligned perpendicular to the longitudinal or transverse axis of the model (Figure 5). Rather than displaying changes in gradient, these contours show changes in curvature, allowing us to assess whether or not the webs are horizontal tunnels or other, more rounded forms. Yet whilst contours can give an impression of the overall three-dimensional form of the webbing, they do not show how that shape was constructed, nor do the resulting lines give any indication of how the individual stones were laid.

The latter point can be demonstrated through a process which we have called course tracing. This is conceptually similar to the tracing methods we have adopted for rib intrados lines, using the tools available in Rhinoceros to record the lines of the courses on a stone-by-stone basis. Lines were drawn over the mesh model from a viewpoint perpendicular to the transverse axis of the vault. Though initially we attempted to trace the lines of the mortar joints, we soon discovered that these were extremely difficult to identify owing to the limited fidelity of the mesh model and its surface texture.

Instead, we found that the centreline of the courses was a more reliable alternative, following the midlines of the exposed faces of the individual stones. Once these lines were in place, the "project" command was used, an operation which automatically extrudes the polyline in a direction perpendicular to the selected viewport and plots its points of intersection with the mesh surface. Excess lines were removed using the "delete" and "trim" commands and the results tested against the model, with the original set of lines being adjusted and the projection repeated where required to

Figure 5. Tewkesbury Abbey, bay N8, contours (parallel to transverse axis) superimposed on mesh model.

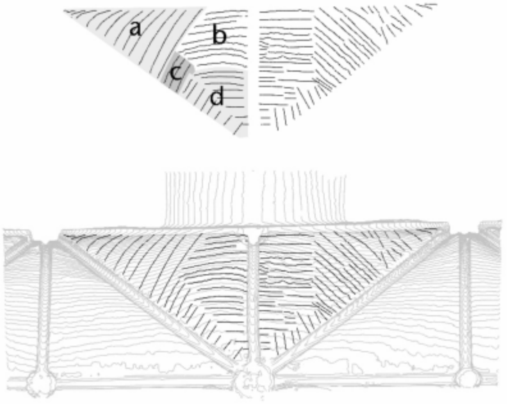

Figure 6. Tewkesbury Abbey, bay N8, course tracing (black) superimposed on contours (grey).

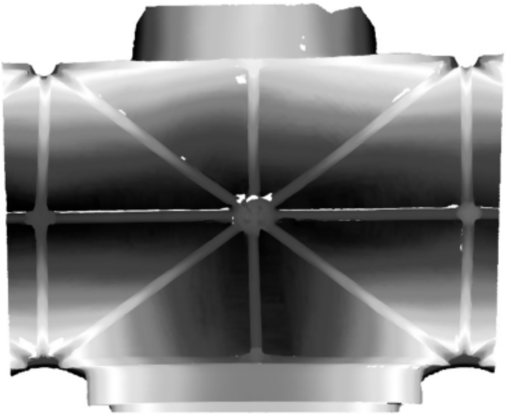

Figure 7. Tewkesbury Abbey, bay N8, height map.

improve accuracy. For the upper parts of the webs it was necessary to switch to a top-down viewpoint, as it was otherwise difficult to record the courses with any degree of precision.

The resulting course tracings could then be overlaid directly onto the contours, allowing the two methods to be compared directly (Figure 6). In the nave aisles at Tewkesbury, there is a significant difference between the lines of the coursing and of the contours, especially webs adjoining the window side. Consequently, it follows that contours are not particularly useful for analysing the vault's construction, as they relate more closely to the results of the stonelaying process than its underlying methods. Yet while course tracing can circumvent this to a degree, its limited accuracy is potentially problematic. Not all courses can be identified or differentiated easily, even with the aid of photographs, surface textures or orthographic representations. Sometimes the gaps between courses are only visible when the digital model is viewed at oblique angles, making it difficult to locate the centreline precisely for tracing purposes. Furthermore, unlike our rib tracings, the resulting wireframes are not the product of quantitative data, but rather a qualitative process of interpretation based on careful observation and intuitive draughtsmanship.

The result is closer to a visual record of an investigative process than a means of extracting precise analytical data, providing a structured means of visual analysis that encourages close observation of the vaults and their masonry.

An alternative method which we attempted was height mapping. This is a method of indicating the differences in height across the surface of the vault using a graduated change in colour. This was accomplished using a script written using Grasshopper, a plug-in for Rhinoceros which uses an advanced visual programming language as a parametric design tool. Mesh models are a polygonal surface consisting of tens of thousands of triangular facets, forming a mesh of lines connecting individual points or vertices. Our script deconstructed the mesh into these vertices and extracted the z component of their coordinates within Rhinoceros, giving a numerical value for the height of each vertex. Each point was then mapped automatically onto a colour gradient extending from black (top) to white (bottom), producing a new texture which was then overlaid onto the surface of the model (Figure 7).

The resulting height maps were effectively a means of displaying an infinite series of contours on the same image, with the rate of change in colour being proportionate to the gradient of the slope beneath. However, whilst it does provide a greater density of information than contours, it is ultimately subject to the same limitations. The structure of the masonry could not be revealed by a measurement of height alone. Instead what was required was a vector quantity rather than a simple magnitude, indicating not the position of each point on the model, but its orientation within three-dimensional space.

In order to achieve such an analysis, we developed a method which we have called normal vector mapping. Within Rhinoceros, the orientation of each of the faces on the mesh model is expressed in terms of a vector with a total magnitude of one arbitrary unit, its direction perpendicular (or “normal”) to its respective surface. These “normal vectors” are the numerical equivalent of an angle in three-dimensional space, defined in terms of three components: x, y and z. The relative magnitude of these components is determined trigonometrically by the formula $x^2 + y^2 + z^2 = 1$, with the values of each ranging between -1 and 1. Through extracting theses normal vectors from the model, we were able to produce a set of locally determined values for the orientation of its faces which are entirely independent from their respective heights. Isolating a single component of these vectors allowed us to measure the flatness of the mesh faces with respect to a specific cardinal direction (north, south, east or west). Within a room modelled as a simple cube, the flat ceiling (facing downwards) would possess an (x, y, z) value of $(0, 0, -1)$. The level floor (facing upwards) would possess a value of (0, 0, 1) and the walls (facing inwards) a z component of 0, with the north wall represented by $(0, -1, 0)$, the south wall (0, 1, 0), the west wall (1, 0, 0) and east wall $(-1, 0, 0)$. Alternatively, if the room had a ceiling sloping upwards from east to west at an angle of 45°, then its surface would possess a y component of 0, an x component of $-\sqrt{0.5}$ and a z component of $-\sqrt{0.5}$, resulting in a value of $(-0.707, 0.000, -0.707)$ to three significant figures.

As in the case of height mapping, we were able to use a Grasshopper script to extract the individual components of the normal vectors automatically and position them on a colour gradient that could be overlaid directly onto the mesh model (Figure 8). If the z component is isolated, the resulting texture relates the changing slope of the vault surface from block to block, the shade assigned to each face indicating how close its gradient is to that of a flat ceiling (-1, black), wall (0, grey) or floor (1, white). As the stones used in webbing are usually straight oblongs, the majority of the faces on each surface will share a similar orientation and therefore colour, giving a clear indication of how the orientations of stones change both from course to course and within the courses themselves. This illustrates how the curvature of the webbing was shaped on a stone-by-stone basis, allowing the three-dimensional form of its masonry to be analysed in an unprecedented level of detail.

At Tewkesbury, the results of these methods can be seen by focusing on a specific example, in this case the third bay from the transept in the north aisle (henceforth N8). Using a Z component map, it is possible to see that there is a fairly uniform gradient in the longitudinal tunnel (Figure 8).

Though the angles of the courses approach being parallel to the ridge as they rise, at the base they are bent slightly inwards, a phenomenon called ploughsharing which is caused by the difference in curvature between the diagonal and transverse ribs. However, the webs abutting the wall on the window side are quite different. Rather than being uniform, the shades of several of the courses gradate from stone to stone, indicating that the coursing itself is cambered.

Figure 8. Tewkesbury Abbey, bay N8, normal vector map, Z component.

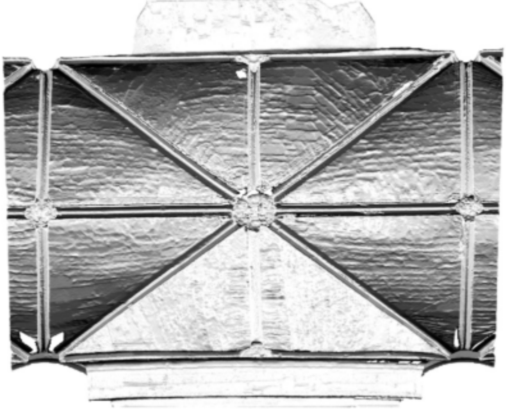

Figure 9. Tewkesbury Abbey, bay N8, normal vector map, Y component.

This can be further illustrated through course tracing, which shows many of the courses of stones being laid on a distinctly curved path. Considered as a whole, the effect of this approach is similar to that of the horizontal tunnel in gradient, but with a subtle difference that is revealed by isolating the other components of the normal vector. A Y component map shows that the gradient respective to the central ridge is slightly offset from those in the longitudinal tunnels, flattening more rapidly towards the apex in a circular rather than linear pattern (Figure 9). This is further illustrated by the X component map, which indicates a slight bowing outwards in the longitudinal direction towards the lower half of the web (Figure 10). The net result of these observations is a slight bulging of the vault as it rises, the three-dimensional curvature corresponding to the cambering of its component courses. This can also be seen in contours taken from a plan view, which show an increasingly curved profile as they rise towards the vault’s crown.

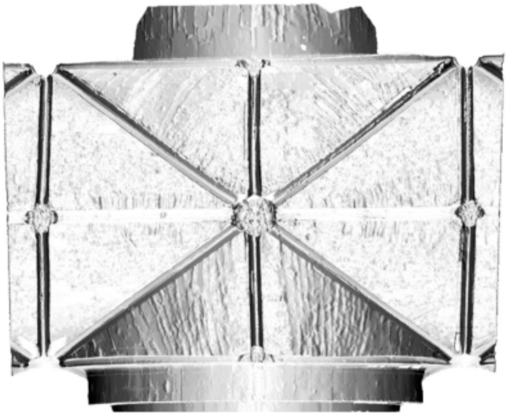

Figure 10. Tewkesbury Abbey, bay N8, normal vector map, X component.

4 CONSTRUCTION

It has traditionally been assumed that some kind of formwork was used for setting out the webbing of the nave aisle vaults at Tewkesbury. The first possibility is an arrangement similar to that which survives in the octagonal 14th-century bell tower of the church at Lärbro on Gotland, which features a set of wooden flats stretching between the framework for the ribs. This could have been further augmented by a layer of mason's earth above acting as a bedding surface for the stones, a method which was employed for the vaults at Troyes Cathedral during the 15th century (Murray 1987).

However, there is no known example of this technique being used in England. It is possible that mortar was used in a similar way instead, as the marks left behind by centering of this type can still be seen in several buildings, though this could also have been caused by seepage from the rubble and mortar infilling above. While these marks tend to be found in earlier examples of English vaulting, it is possible that this practice was more widespread than can be accounted for, as in most cases such evidence would have been concealed by later layers of plaster. An alternative method has been proposed by Malcolm Thurlby, who suggested that flexible wattle surfaces might have been used to give shape to the webbing, a method evidenced both by mortar markings and remaining fragments in several other English sites (Thurlby 2004).

The key question, however, is whether such formwork would actually have been necessary at Tewkesbury. Robert Willis (1842) and Eugène-Emmanuel Viollet-le-Duc (1854–68) both argued that the cambered surfaces would be sufficient to be self-supporting, citing the theory developed by the architect Johann Claudius von Lassaulx (1830-31). This idea has been further developed by David Wendland (2007), who has demonstrated it using a combination of geometrical analysis and physical modelling. Could something similar have taken place in the vaults at Tewkesbury? If so, was this the reason why the coursing was so complex?

On the window side webs of bay N8 at Tewkesbury, the lower set of courses are laid diagonally, following a curved path extending from wall rib to diagonal (Figure 6). In the northwest cell of webbing, this continues for 14 layers (see (a) on Figure 6), after which a new set of horizontal courses is laid with a slight curvature (b). The first six extend from the curved ridge rib to the edge of section below, but the subsequent three layers are raked back, producing a stepped masonry break. The gap between these coursings and the diagonal rib are filled by a further three courses, laid at a slanting angle and resting on the exposed faces of the horizontal courses below (c). The horizontal courses then resume and the pattern repeats, the masons having alternated between horizontal and diagonal courses until the remaining space between the ribs was knitted together (d). This approach was used for almost all of the nave aisle vault at Tewkesbury, with minor variations from bay to bay. In some bays, the uppermost sets of diagonal courses were omitted, the top set of horizontal layers instead resting directly on the vault's diagonal ribs. Similarly, in bay S12 the beginning of the horizontal courses is much closer to the springing point than in the other bays, creating a haggled edge to the masonry where it abuts the wall ribs. Rather than adopting a uniform method of construction, the builders of these vaults adopted a shared body of principles that could be variously mixed, matched, omitted or repurposed to suit the peculiar demands presented by each bay.

The reason for the changing directions in the coursing may have been a combination between mediating the shape of the web's three-dimensional curvature whilst ensuring that the masonry remained self-supporting. Initially, the gap between diagonal and wall rib was small enough for the courses to be supported, with the switch to horizontal courses occurring at the point where the masons feared their overbalancing. This mode of coursing was then continued for a few layers before a new set of diagonal courses was used to lock them into place, the alternating pattern being essential to maintain the vault's stability during construction. The differences from bay to bay can be ascribed both to the variability of the sizes of the available stone blocks and the level of confidence of the stonelayers, with the decision to switch courses being made individually on an ad hoc basis. Some evidence for this can be found in the window side webs of bay S7, which features a unique masonry pattern in which only diagonal courses were used. For whatever reason, the masons in this case were confident of the stability of the courses throughout the erection process.

5 CONCLUSIONS

On the basis of the stonework alone, it seems possible that at least some of the webs in the nave aisles at Tewkesbury could have been constructed without supporting formwork. The cambered surface of the courses and the pattern of their changing directions suggest not random placement, but a careful, if improvisational, attempt to ensure stability during the construction process by following a set of shared principles. However, it is not absolutely certain that no formwork was used, and further testing would be required before any definite conclusions can be drawn.

The next phase for our research will be to use the data gathered during our modelling process for structural analysis. Dimensions, positions and orientations of the stones will be used for piece-by-piece numerical simulation of the construction process, enabling us to analyse whether or not the webbing could support itself as each course was laid. Estimates for the shape and structure of the stones beneath the surface of the webbing will be provided by comparative study of ruined or partially deconstructed vaults at other sites, as well as reference data relating the material properties of the stone and mortar. This numerical model will then be validated using small scale construction experiments of parts of the vault, allowing us to test whether our theoretical modelling could work in practice.

Even if such a modelling process is ultimately inconclusive, the form of the masonry at Tewkesbury has far wider implications for the study of medieval design and construction processes. The cambered surfaces of the webbing indicate that their form was not solely defined by the geometry of the surrounding ribs. Instead, the stonelaying process itself was integral to the conception of the vault's three-dimensional form, constituting as much a process of active design as passive realization. The coursing produced by the masons at Tewkesbury does not give the impression of meticulous planning, but instead an intuitive grasp of masonry mechanics which could be adapted to any vaulting surface. While the form of the window side webs has few if any parallels in English vaulting, it is possible that the same ad hoc approach was more widespread. With the webbing of the overwhelming majority of comparable vaults being concealed by plaster or whitewash, there is no way of knowing how many other sites made use of multidirectional coursing to achieve their three-dimensional forms. Whether it was constructed using formwork or not, the form of the nave aisle vaults at Tewkesbury offer a challenge to our conception of medieval vaulting techniques, both within England and beyond.

ACKNOWLEDGEMENTS

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Three hybrid church roofs from 1150–1200 in Western Sweden

R. Gullbrandsson
Göteborgs Universitet, Gothenburg, Sweden

M. Hallgren
Traditionsbärarna, Stockholm, Sweden

ABSTRACT: This paper is the result of three case studies connected to a survey of preserved Romanesque church roofs in the western Swedish province of Västergötland. The roofs in question are rare examples of medieval hybrid roofs, trussed constructions with an integrated ridge purlin. From the perspectives of the archaeologist and the craft researcher, the authors interpret the original constructions and their systems, which differ from other Romanesque church roofs in the province. Based on the results, the connection between these roof types and traditional rural post and plank barns is discussed.

1 INTRODUCTION

1.1 *Background*

The preserved medieval church roofs of Sweden have in recent years been surveyed in projects run by several Swedish dioceses. The western Swedish province of Västergötland has 28 Romanesque churches with original roof structures (Gullbrandsson 2015). During 2020–21, the authors investigated seven of these roofs in depth, three of them are the focus of this paper. The central part of Västergötland was one of the key areas in Sweden for the establishment of a centralized church in the 11th century, with the diocese of Skara, and the subsequent formation of an integrated Swedish kingdom (Dahlberg 1998).

1.2 *Single and double framed roofs*

Historically in Sweden, and other parts of Europe, there have been two dominating roof types. One is the purlin roof with purlins going from one gable to the other, typical of log-timbered Nordic buildings, or supported by posts as in many excavated prehistoric buildings (Rosberg 2009; Sjömar 1988; Werne 1993). The purlin roof can be with or without rafters. The other type is the roof with independent trusses resting on the long sides of the house. In Sweden, the purlin roof has been a tradition in rural log-timbered houses whereas the oldest preserved examples of trussed roofs are in Romanesque churches. The trussed roof with a tie beam in each truss was common in Romanesque churches of continental Europe (Courtenay & Alcock 2015) and in many Swedish churches applied throughout the Middle Ages and even later. The advent of Gothic architecture in northern France during the 12th century led to a hierarchy of trusses, where only the primary ones have a tie beam (also known from Norwegian stave churches). Double-framed roofs developed, which have primary trusses with crown posts, joined with a longitudinal frame, which allowed for bigger roof structures on lighter walls (Binding 1991; Épaud 2007; Hoffsummer 2011; Storsletten 2002). The first known example in Sweden of a Gothic double-framed roof is from the early 15th century in the Bridgettine monastery church of Vadstena, thus applied very late (Menander & Hallgren 2017).

A small group of Romanesque churches in Sweden has preserved trussed roofs from the 12th century with a ridge purlin, in effect a different type of double framing than the Gothic construction, more related to purlin-and-rafter-roofs (Figure 1). Three of these of the total 11 known church roofs are situated in Västergötland and will be discussed in this paper.

1.3 *Approach and objectives*

The authors have an approach rooted in buildings archaeology and craft research. The collaborative work between the archaeologist and the craft researcher has broadened the interpretation of the roofs. The traceological, experience-based understanding of tool traces and processes is essential (Bláha 2013). Much knowledge has been gained in Sweden from the experimental project of reconstructing the burnt medieval timber church of Södra Råda (Almevik & Melin 2015). Dendrochronology was also part of the investigations.

How do these hybrid roofs differ from the common Romanesque tie beam roofs? The paper starts with an analytical description of the roofs. This leads to conclusions on the original system and an interpretation of the “chaîne opératoire” based on the traces found. Finally, the authors try to contextualize these roofs and propose an explanation to their origins.

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Figure 1. Swedish medieval church roofs of hybrid type with ridge purlin. Drawing. R. Gullbrandsson.

2 THREE HYBRID CHURCH ROOFS

2.1 *The nave roof of Edåsa church*

The church of Edåsa is situated east of the cambro-silurian plateau of central Västergötland. The original chancel with a rectangular plan was replaced in 1765, but the nave (10.7 × 7 m) has remained (Figure 2). It is built of crude fieldstones, and the corners of sandstone ashlars. Apart from the southern portal in carved sandstone, the masonry has no decorative elements. The interior has traces of mural paintings, stylistically dated to around 1200 (Hernfjäll 1993). The interior has never been vaulted and still has a flat wooden ceiling. The baptismal font is undecorated.

The pines for the roof structure were felled in 1177–79, probably in the region (Linderson 2020a). The timber was left to dry one or two years before construction. Most parts in the roof are whole timbers, block hewn in the Scandinavian technique of "sprätthuggning", which means hewing with a felling axe in the direction of the wood fibres. This technique is characteristic for timber structures before the mid-14th century in Scandinavia (Sjömar 1988; Storsletten 2002). All timbers have been given sharp edges, but seldom in a straight angle. Embedded in the masonry top is a high wall plate with a shelf for the board covering the eaves. Placed in recesses, stand 16 original trusses, each with a heavy tie beam in its base. The cc-measure from beam to beam is ca 56 cm. The beams are higher than broad and the height increases above the middle of the nave, which is a common trait of Romanesque tie beams as well as the angled outer ends. Centred in the longitudinal axis of the nave is a profiled steering plate, locking the tie beams from above (Figure 3), a kind of reversed wall plate noted in several Romanesque church roofs in Sweden (Lundberg 1940, 1971; Sjömar 1995).

The bottoms of the rafters have a lap joint, connected to the tie beam without recess and fixed with a dowel. The rafters are fixed to the west respective east side of the tie beam. The tops of the rafters do not meet in a joint. Instead, they were tenoned into mortises in a now absent ridge purlin. Each rafter is supported by two struts. These intersect and form a rhomboid lattice typical for many Romanesque roof trusses in the province (Gullbrandsson 2015). The struts stand in recesses on top of the tie beam, each pair a bit set off from the centre. The tops of the struts have a lap joint nailed to the east or west side of the rafter without recess. The joints are placed in an even line along the imprint of a blackened cord on the rafters.

The middle truss of the roof differs from the rest. The timbers are thicker, the rafters are connected on top with a half lap joint, the tie beam joints have a recess. The struts equally have lap joints with a recess.

This truss thus corresponds to a large part of the preserved Romanesque trusses in the province (Gullbrandsson 2015). This "primary" truss has supported the middle of the disappeared ridge purlin, thus dividing the roof in two bays. But what did the purlin end rest on? Today the west gable is a masonry one. The east gable was torn down in 1749. The tie beams of the first and the last truss have joints for an original brace, which once supported king posts on the gable walls. Originally the gable crests ought to have had wooden boards. Preserved details give more information on the appearance of the crests. The wall plates earlier protruded a bit outside the gable walls, which can be seen in older photos. The former, built-in, east gable still has one of the outer plank-shaped rafters in place, which corresponds to the overarching of the wall plate, thus providing good protection for the original wooden gable. In the northeast, three tie beams have recesses interpreted as mountings for two liturgical bells, indicating that the roof trusses were originally not hidden by a ceiling. Lime plaster on the west gable also supports this assumption together with observations in several other roofs (Gullbrandsson 2015; Sjömar 1995). Only later was a flat wooden ceiling nailed to the bottoms of the tie beams.

2.2 *The nave roof of Valtorp church*

The church of Valtorp is situated some ten kilometres southwest of Edåsa, on the cambro-silurian plateau. The chancel and apse were replaced in 1722. The nave (9 × 7.2 m) is built of crude local sandstone and

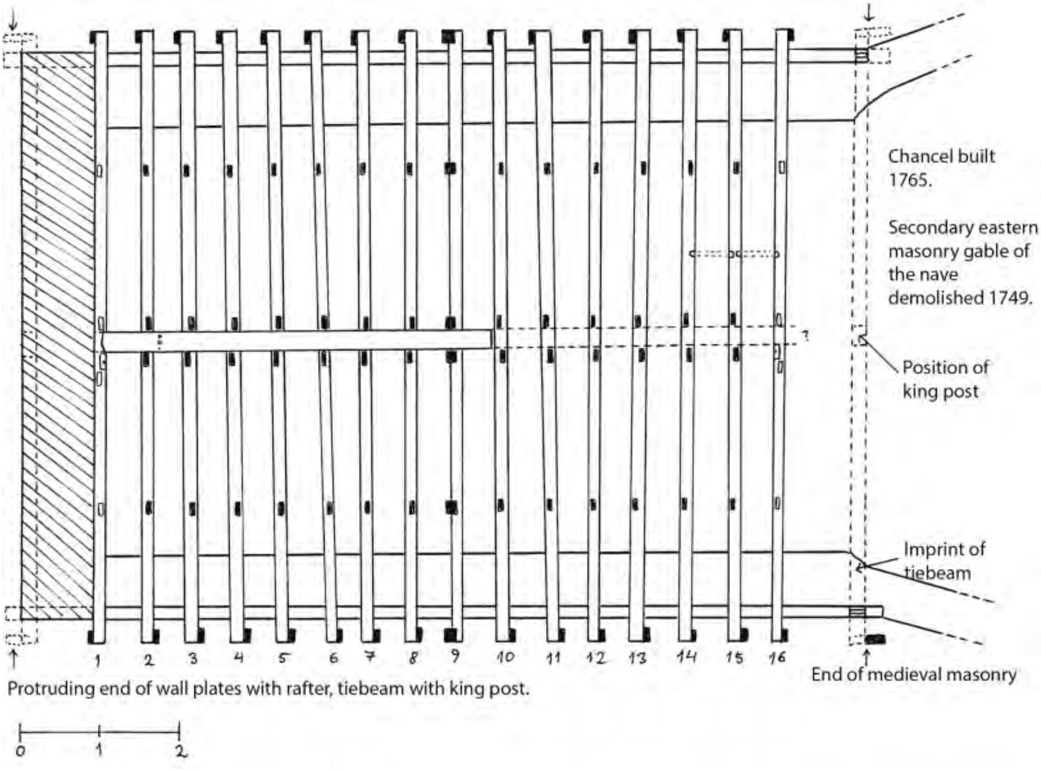

Figure 2. Plan of the nave roof in Edåsa church. Drawing. R. Gullbrandsson.

Figure 3. Detail of the intersection of tie beams and steering plate in the west end of the nave roof in Edåsa church. The first tie beam by the gable has an empty joint for a brace to an earlier king post. Photo. M. Hallgren.

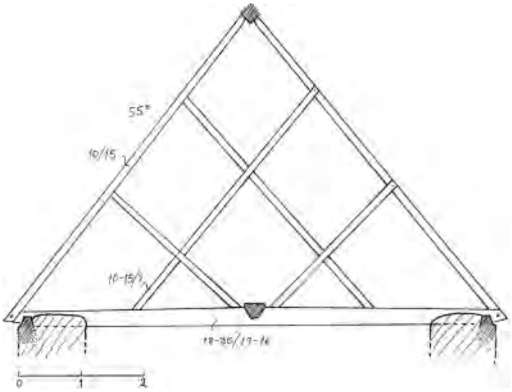

Figure 4. Section of a truss in the nave roof of Valtorp Church. Drawing. R. Gullbrandsson.

limestone. The corners are made of sandstone ashlars, as in Edåsa. The southern portal is very plain, but the rest of the northern one is framed with ashlars. A reused small Romanesque window frame of sandstone has figurative carvings. Apart from this, the church has no original decorative building elements. The interior has a flat ceiling and an undecorated font.

The pines for the roof were felled on at least two occasions, in the summer of 1188 and in 1200-4 (Linderson 2020b). The authors connect the later span to the actual construction work (with due time for seasoning the wood) and the earlier felling as use of an older timber stock or the indication of a break in the building process. The timbers are hewn as in Edåsa. The roof structure corresponds to that of Edåsa, but is better preserved, with the ridge purlin still in position (Figure 4). Wall plates carry 13 trusses with tie beams, standing with a cc-measure of 50–60 cm, the beams locked in the middle axis by a steering plate. The trusses are made as in Edåsa, as is the fixing of the

Figure 5. Detail of the ridge purlin in the roof of Valtorp Church. Note the “sprätthuggning” on the rafters. Photo. M. Hallgren.

struts along a snap of blackened cord onto the rafters. Halfway stands the supporting “primary” truss for the purlin. As a proper truss it has nicely made half-lap joints for rafters and struts. The finish of this truss is better than in Edåsa and the carpenters have strived to get an even upper face where the joints are placed, which is common in other Romanesque trusses. An identical supporting “primary” truss is placed at the east end of the roof. The continuing wall plates indicate that the east gable originally was in masonry (taken down in 1722). A recess with dowel in the west end of the steering plate indicates the brace for a disappeared king post on the west gable wall, the present masonry is secondary. The ridge purlin has a rhomboid section, the mortises are marked with vertical scribing (Figure 5).

2.3 *Roofs of nave and chancel in Eriksberg church*

The third church with trusses and ridge purlin in the province is Eriksberg, situated southwest of the cambro-silurian plateau, some 30 kilometres from Valtorp. The barrel-vaulted chancel (4.5 × 5 m) with apse and the nave (9 × 7.5 m) retains their medieval shape. The nave was already enlarged to the west and given a flat wooden ceiling in medieval times. The masonry is of crude fieldstones with ashlars of sandstone in the corners. The interior has fragments of high-quality mural paintings, dated stylistically to the 1170s and possibly connected with the royal house of Erik (Hernfjäll 1993). Strengthening the status of the church is a gilt, 12th-century reliquary.

The oaks for the intact roofs of the chancel and the original part of the nave were felled in 1153, probably locally (Bråthen 1990; Seim et al. 2015). The timbers are, apart from the tie beams, cleaved and hewn with “sprätthuggning”, with differing dimensions. The 12 trusses of the original nave ride on heavy wall plates and are placed with a cc-measure of 65 cm. The sides of the tie beams have received a final finish with a broadaxe to get an even surface, indicating a visible roof. The rafters are connected to the tie beams with half-lap joints and dowel. In the top they have tenons inserted in the mortises of a ridge purlin, which is hewn like the tie beams. Unlike in Edåsa and Valtorp, the north and south mortises are placed in line. Vertical scribe marks, apart from those made for the mortises, correspond to the distance between the tie beams. The original west truss has a king post (replaced in 1723 according to an inscription) to support the purlin, probably by the side of a later torn down masonry gable crest. Middle or east primary trusses do not exist. Either the east end of the purlin rested on the present medieval masonry gable crest or on a now disappeared king post. Obviously, the carpenters did not see any need for a support of the purlin in the middle. Each rafter is, like in the other roofs, supported by a pair of thin struts, but here they are connected to the tie beam with nailed lap joints and to the rafters with tenon and mortise. The mortises are positioned by snapping a blackened cord.

The six trusses of the chancel correspond to the ones of the nave, only the struts have a different joint with the tie beams, set into small recesses from the side and fixed with a nail or dowel. The ridge purlin has been replaced. A brace embedded in the masonry of the east gable corresponds to a joint in one of the tie beams and bears witness to an older wooden gable crest with a king post supporting the purlin (Figure 6).

3 THE “CHAÎNE OPÉRATOIRE”

3.1 *The materials*

All the roofs have been built from dried timbers, which is common for Nordic church roofs of the time, thus differing from the use of green wood in, for example, Germany and France (Épaud 2007; Fischer-Kohnert 1999). Whereas the carpenters of Eriksberg had access to large and straight old oaks, the colleagues of Valtorp some 50 years later had to use fast grown, young pine, which must have grown in an open environment, maybe a clearance. This indicates a local lack of the type of pine and oak wood we see in older Romanesque roofs, maybe a result of the intense building of stone churches in the province during the 12th century.

3.2 *The hewing*

The hewing technique is typical of Romanesque timber structures in Scandinavia. For Edåsa and Valtorp the carpenters have used one log per element and hewn away just as much as was necessary to obtain sharp edges. In all three roofs, the dimensions were a natural result of the size of the timbers. What mattered were the sharp edges. In Eriksberg though, they used large oak logs that were first cleaved. The hewing of the tie

Figure 6. Remaining brace of a king post in the masonry gable crest of the chancel in Eriksberg church. Photo. R. Gullbrandsson.

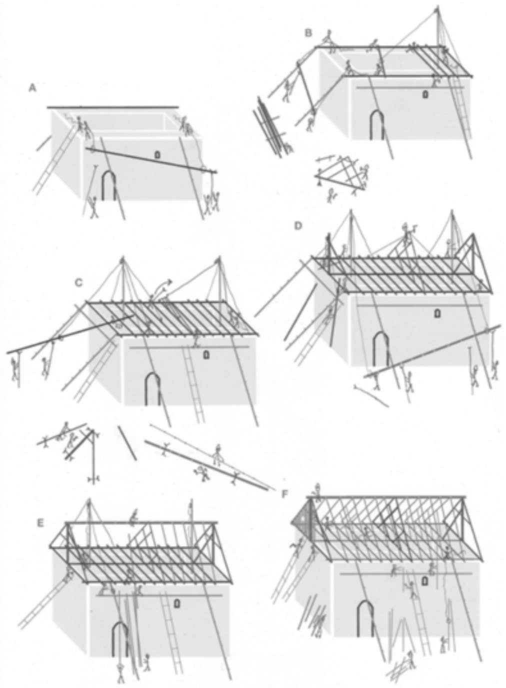

Figure 7. Interpretation of the “chaîne opératoire” in erecting the Edåsa nave roof. A. Placing the wall plates. B. Placing the tie beams and assembling the mid-truss. C. Raising the mid-truss and placing the steering plate. D. Placing the king posts and raising the ridge purlin. E. Placing the rafters. F. Placing the struts. Drawing. M. Hallgren.

beams is more elaborate here with a final finish with broadaxe, a procedure noted in several church roofs interpreted as originally visible. Edåsa and Valtorp thus give a rougher impression.

3.3 *The process of construction*

In both Edåsa and Valtorp, the height of the roof corresponds to the height of the masonry walls, which thus gave the pitch. As a first step, the wall plates and tie beams were positioned, later on they were fixed by complementary masonry work, making them partly embedded (Figure 7). The steering plate was placed on the tie beams (none in Eriksberg). On the gable walls of Edåsa and the west wall in Valtorp, as well as the east chancel gable in Eriksberg, a king post with brace was erected. In Valtorp – and maybe Eriksberg – there was an original masonry gable crest between the nave and chancel, in Valtorp with a “primary” truss beside it. In the middle of the roofs of Edåsa and Valtorp, a “primary” truss was erected. The ridge purlin was prepared on the ground with a wall plate as template for making the mortises, which was the procedure at least in Eriksberg according to the scribing. The purlin was then lifted onto the king posts/“primary” trusses/masonry crest. The next step was to put the rafters in place, placing the top tenon in the mortise of the purlin and adapting the bottom joint with the tie beam. In both Edåsa and Valtorp the adjoining surfaces of the tie beam have been adjusted by axe to make the rafter fit. The lack of recess in these tie beams facilitated the procedure. The hole for the dowel was drilled from outside the wall, which explains its diagonal direction. Finally came the insertion of the struts. In Edåsa and Valtorp their position was determined by snapping a blackened cord onto the already fixed rafters (straightened from the west to the east end in Edåsa and resulting in double and triple lines on the middle rafters). In Eriksberg, the snapping was made on the ground since it would have been a strenuous work making the mortises later. The struts in Edåsa and Valtorp were first put into the recesses on top of the tie beams, then nailed to the rafters on the marked spot. In Eriksberg it was the other way around. Why was an exact positioning of the struts important? With other Romanesque roofs this did not seem to matter and the position of the joints are seldom identical from one truss to another, mirroring a different way of assembly and erection. The authors propose that the timbers in the hybrid roofs were made in advance to a certain length. After the insertion of rafters and struts, the trusses worked together with the purlin in transmitting the loads to the masonry.

Table 1. Churches with ridge purlin.

Church, province	Part of building	Felling year
Bredestad, Småland	Apse	–
Edåsa, Västergötland	Nave	1177–79
Eriksberg, Västergötland	Nave/Chancel	1152–53
Furingstad, Östergötland	Chancel	1166/1167
Hagebyhöga, Östergötland	Nave	–
Hammarlunda, Scania	Chancel	–
Härad, Södermanland	Nave	1166–1183
Ravlunda, Scania	Chancel	1242–1247
Skepperstad, Småland	Nave	ca 1160
Valtorp, Västergötland	Nave	1200–1204
Övraby, Scania	Nave	1126–1137

4 THE EARLY “DOUBLE-FRAMED” CHURCH ROOFS OF SWEDEN – FORGOTTEN HYBRIDS

The preserved Romanesque church roofs in Sweden have individually-made trusses, often with identical shape but seldom with any use of templates, beside the outer sides of the roof triangle. The three roofs presented have shown a different way of construction and assembly, a well-thought-out line of assembling ready-made parts. The presence of “primary” trusses shows, however, that the carpenters must have known how to build a common roof truss. Having a post from the ground interfering in the church room was probably undesirable.

4.1 *Other hybrid church roofs of the 12th and early 13th century in Sweden*

Eleven intact or fragmentally preserved hybrid church roofs have been documented: in Scania (in the Middle Ages part of the Danish kingdom), Västergötland, Östergötland, Småland and Södermanland (Table 1). The earliest dating is of an ornate ridge purlin from Övraby, Scania, 1126–37. The youngest is in the chancel of Hammarlunda, Scania, dated to 1242–47. The others belong to the span 1153–1204: the three roofs in Västergötland, the nave of Skepperstad in Småland, the chancel of Furingstad in Östergötland and the nave of Härad in Södermanland. The apse roof of Bredestad in Småland and the rebuilt nave roof in Hagebyhöga, Östergötland, have not been dated, the original phase of the latter belongs to 1119–20, but does not concern the actual ridge purlin.

All of these roofs show similar traits but also variations in the number of struts, their positioning and joinery as well as the presence of a steering plate on the tie beams. The common thing is the ridge purlin with mortises for the rafters, sometimes with decorations. The original gable support for the purlin is still unclear for some of the roofs. Skepperstad has an intact, east king post: an elaborate and long brace to a lost king post remains in the west, placing support on the steering plate. The gable crests were probably wooden. Härad has three preserved “primary” trusses, on each original gable and in the middle. The mixing of purlin and truss roofs in churches has also been found in other parts of Europe, like southwestern Germany in the 13th century, proposed as relics of a once more common use of purlin roofs (Lohrum 2004). Apart from Övraby and Ravlunda, the roofs have been erected in a span of ca 50 years, mainly from the 1160s up until around 1200. These churches do not therefore belong to the first wave of stone churches in these provinces, rather a second or third. None of the examples from Västergötland show any elaborate stone architecture like the ashlar masonry found in several 12th-century churches of the province. Only Eriksberg is a bit exceptional with its murals and reliquary. The roofs of Edåsa and Valtorp give the impression of being the products of local craftspeople rather than carpenters taking assignments in a wider region.

Figure 8. Decorated ridge purlin in the nave roof of Härad church. To the left, the mid-truss. Photo. R. Gullbrandsson.

4.2 *Similarities with wood-building traditions*

The purlin roof with or without rafters was a common building practice in traditional Swedish wooden houses (Sjömar 1988; Werne 1993). As stated, the building of roofs with posts supporting purlins has been archaeologically documented from prehistory to the Middle Ages and has been used in early modern times on rural farm buildings in different parts of Europe. In Västergötland and other – mainly western Swedish – provinces, the tradition of barns in post and plank technique with ridge purlins was maintained until the beginning of the 19th century (Erixon 1947; Henriksson 1996; Roland 1906; Västgötagårdar 1932; Werne 1993). The ridge purlin is supported in the gables by posts and in longer buildings by posts each 5–6 metres, these are joined with a tie beam connected to the wall plates. The thin rafters are placed on top of the purlin and fixed to the wall plates. This building technique is called “mesula”, meaning mid-post. Early researchers such as Sigurd Erixon saw these barn types as rooted in prehistoric building techniques (Erixon 1947). The art historians Gerda Boëthius (1931) and Erik Lundberg (1940) argued that the prehistoric building technique with purlins on posts was “transferred” onto the top of a masonry with the first stone churches, but they did not know about this group of hybrid church roofs. Several elements of the church roofs presented show similarities with the roofs of post and plank barns. The ridge purlin on king posts, a mid-truss shaping two bays and protruding wall plates in the gables are examples of this. With the original wooden cover of the gable crest the similarity is even more apparent. Many other churches show signs of later "petrified" gables. The neighbouring church of Eriksberg, Mjäldrunga, still has a wooden west gable crest and a masonry east gable.

The authors propose that the actual roofs show significant influence from wood buildings with purlin-and-rafter-roofs. Ola Storsletten has pointed at relicts of ridge purlin on king posts in a pair of Norwegian stave churches, the former church in Nes with a mid-post and steering plate supporting rafter struts and braces to king posts on the gables, and the Reinli church with steering plate supporting gable braces (Storsletten 2002). A contemporary historic source to church roofs with ridge purlin is the "Church section" of the Old Law of Västergötland, written down in the first half of the 13th century. It states that a church has its full "sanctity" as long as, among other things, "lies ridge purlin (*kamber*) intact" (Äldre Västgötalagen 2011). The church type concerned by the law is a wooden one, built by peasants. But, by then, a large number of the churches in the province were actually built of stone, often with a high-ranking patron (Claesson 1989; Dahlberg 1998; Västergötland – landskapets kyrkor 2004), their roofs trussed, without ridge purlin. The trussed roof was possibly applied already in stave churches, according to fragments from Herrestad in Östergötland and Hemse on Gotland (Eckhoff 1914–16; Eriksson 2006). The law reflects a church building tradition, by then no longer general, and it stresses the importance of the "kamber", a central element in the hybrid roofs. The lack of decorations and finish in Edåsa and Valtorp fits the image of more or less local carpenters applying a system they knew well, adapted for the purpose of a stone church. This hybrid was obviously an option for church roof construction in Scandinavia at least from the first half of the 12th century until the mid-13th century. Size and roof pitch in the three churches do not differ much from other churches with normal trusses and was not per se a reason for this early, double-framed system.

With the system of "primary" trusses and "bays" in Edåsa and Valtorp there would have been no need for tie beams in the secondary "trusses", the rafters could as well have been fastened to the wall plates. Still, the tie beams fulfil a function since purlin and trusses work together. But maybe the visual aspect in the church room was as important. Kristina Linscott has proposed that the carpenters knew about constructing with primary and secondary trusses, with regard to vernacular buildings, but that the use of tie beams in each truss was a "rule" in the Romanesque church roofs of the province (Linscott 2017). This rule is clear with these hybrid roofs as they represent a system in itself, but placed within the continental "Common-Tiebeam Tradition" of Romanesque church architecture (Courtenay & Alcock 2015). From the church room, the roof structure more or less looked like the ordinary Romanesque church roofs of the province, with tightly spaced tie beams and a lattice of struts. It must have been important to adapt to a widespread, easily recognisable church room ideal. The wholly visible ridge was not desired and the roof and the room were two distinct zones, eventually separated by a ceiling.

4.3 *Early tendencies to longitudinal framing in Swedish church roofs*

Normally the Romanesque church roofs of Sweden have no other longitudinal framing of the trusses than the outer boards fixed to the rafters. An exception is the aforementioned steering plate, positioned on the tie beams and/or ridge, even on collar beams. The only known counterparts outside Sweden are in the aforementioned Norwegian stave churches in Nes and Reinli. The ridge-steering-plate is visually similar to the ridge purlin, but is placed on top of the rafter joint, stabilising the trusses, similar to the wall plates in the base. Meanwhile, the ridge-steering-plate, as well as other steering plates, fulfilled a decorative function. We find the same arch with a centred bulb on several steering plates, as well as on the ridge purlins of Furingstad, Hammarlunda, Härad and Övraby (Figure 8). The oldest, ornate ridge-steering-plate is a reused one in Herrestad, Östergötland, (post-966), probably from a preceding trussed stave church roof. The youngest example is from the early-15th century in Halland, seemingly an anomaly. The visible ridge purlin with inserted rafters was a common feature of many log-timbered, rural, dwelling houses in Västergötland until the mid-19th century (Erixon 1947; Västgötagårdar 1932).

The ridge purlin must have been an important interior detail long before the stone churches in question were built, justifying the use of decorated ridge purlins and ridge-steering-plates even in the shadows of trussed church roofs with tightly spaced tie beams. These elements contribute to the diversity of the Swedish, 12th-century, church roofs and could be regarded as relicts of earlier, more open, purlin roofs.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The construction of the medieval domes of the Basilica of St Anthony in Padua

M. Diaz, L. Vandenabeele & S.M. Holzer
Eidgenössische Technische Hochschule Zürich, Zurich, Switzerland

ABSTRACT: The Basilica of St Anthony in Padua, Italy, is one of the major pilgrimage landmarks of the 13th and 14th centuries. Its silhouette is dominated by no less than eight imposing domes composed of inner masonry shells surmounted by timber structures. In the scope of an ongoing research project, it has been established that the domes formed an integral part of the building plan from the very beginning. This paper aims at understanding the successive configurations of the timber structures and at providing a set of hypotheses about the original construction process. As archival material on the early building periods has been lost, the study is mainly based on onsite analyses, including dendrochronological dating.

1 INTRODUCTION

1.1 *Research scope*

The present study on the timber domes of the Basilica of St Anthony in Padua is part of a four-year research project on the Franciscan church, directed by professor Stefan M. Holzer (IDB, ETH Zurich) and funded by the Swiss National Science Foundation (SNSF). Historical sources date the beginning of the construction shortly after the death of St Anthony in 1231, but no documentation directly related to the 13th-century construction yard is preserved. Regarding the domes, the most ancient chronicle describing them was written by the Paduan author Giovanni da Nono in the first decades of the 14th century. The author describes seven domes from the inside (but ambiguously, only six from the outside): two on the nave, a conical “dome” on the crossing, two on the transept arms, one on the presbytery and one on the choir (Fabris 1977). The presence of these domes in the first half of the 14th century is also reflected by stone reliefs on two medieval tombs from 1329 and 1345. Furthermore, the ongoing analysis of the lower brick structures tends to confirm that the domes were included in the original project. This early planning of the domes makes their analysis and dating of primary importance to determine the erection sequence of the entire Basilica.

The closest model for St Anthony was likely the Basilica of St Mark in Venice, the five domes of which were topped by higher timber structures somewhere between the second quarter of the 13th century and the 1270s (Piana 2019). However, the medieval timber domes of St Mark’s cannot be used for comparison since they were lost during a fire at the beginning of the 15th century (Piana 2019). As further discussed, the Basilica of St Anthony in Padua might thus exhibit the oldest preserved timber domes in Europe.

1.2 *State of the art*

In previous research, Lorenzoni (1981), Bresciani Alvarez (1981) and Salvatori (1981) hypothesized different timelines for the medieval worksite based on general observations and historic events. In later publications, the domes are imprecisely dated to a period spanning the second half of the 13th century and up to ca.1310, the year of a *magna et immensa mutatio* noted by archival sources and probably marking an enlargement of the Basilica (Ruzza 2016). Recently, Heinemann (2012) and Valenzano (2012) have highlighted that the domes were likely included in the original plan. However, the timber structures of St Anthony’s have only been superficially described in literature (Briseghella 2012; Salvatori 1988, 1989). Their constructive features, original aspect and state of preservation have never been analysed in detail.

1.3 *Goals and methodology*

This study approaches its subject from different angles, such as the absolute dating of the domes, the identification of original elements still in place, the reconstruction of the original configuration and assumptions regarding their erection process. The methodology relies on a building archaeology approach, combining laser scanning and manual measurements. These onsite investigations have provided a precise survey of the structures (joints, repairs, transport marks, tool marks, etc.). Moreover, preliminary dendrochronological analyses have yielded the identification of original elements and later interventions.

This contribution aims at positioning the domes of St Anthony’s in the panorama of medieval carpentry, hereby contributing to enhancing the limited base of knowledge about ancient timber domes. After a discussion about the current state of the domes following

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Table 1. Main dimensions of the domes

	Ø brick dome[1] [m]	H brick dome[2] [m]	H timber dome[3] [m]
d01	14.4	10.96	16.37
d02	14.46	11.09	16.09
d03	14.48	10.78	15.45
d04	14.3	10.92	34.96
d05	14.43	10.72	16.89
d06	13.95	10.36	19.01
d07	13.62	11.29	19.52
d08	14.3	6.47	11.84
min	13.62	6.47	11.84
max	14.48	11.29	34.96

[1] Internal diameter measured at the base of the brick dome.
[2] Height from the base to the upper side of the brick dome.
[3] Height from the base of the dome to the top of the roof.

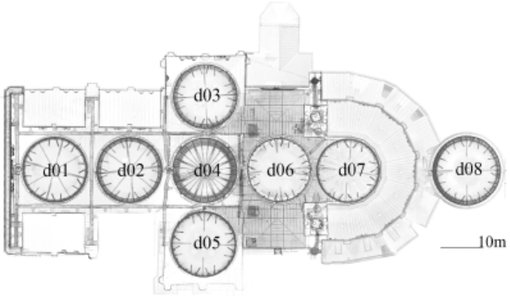

Figure 1. Plan of the domes: façade dome (d01), intermediate dome (d02), *arca* dome (d03), angel dome (d04), Chapel of St Jacob dome (d05), presbytery dome (d06), choir dome (d07), Chapel of the Relics dome (d08). D01, d02, d03 are supposed original. d04, d05, d06 and d07 suffered fire damage in 1749.

Figure 2. d02. Interior of the attic with the masonry vault and the wooden superstructure (photo: author).

important interventions between the 16th and 19th centuries, this paper sheds light on their original configuration and a probable construction strategy. The results presented here pave the way for a finer understanding of these exceptional structures, which turn out to be unique in Europe.

2 THE DOMES OF THE BASILICA

2.1 *General description*

The imposing domes of the Basilica have dominated the skyline of Padua for centuries. On the western side, the nave is topped by two twin domes of very similar dimensions. Behind those, a truncated cone crowned by a 4-metre-high angel covers the crossing. This cone is flanked by two domes above the arms of the transept sheltering the Chapels of St Anthony and St Jacob. On the eastern part of the church, three additional domes were erected during later building phases. The dome of the presbytery was likely erected in the 14th century, while that of the choir dates back to the early 15th century and the last one was built in the 18th century over the Chapel of the Relics. Four of the eight domes were rebuilt after a fire in 1749, largely reproducing the previous layout. Consequently, only the façade dome, the intermediate dome and the *arca* dome above the Chapel of St Anthony still include 13th-century structural elements (Figure 1).

Each dome is composed of an internal masonry shell (32–43 cm) surmounted by a relatively lightweight timber structure covered by lead sheets. The main dimensions of these domes are presented in Table 1. These measurements highlight the similarities of the domes in the western part of the church (d01–d05).

Leaving aside the truncated cone of the angel dome (d04), each three-dimensional structure can be streamlined as two perpendicular frames, each composed of two diagonal struts, a short king-post and one or two collar-beams (Figure 2). In the original domes (d01, d02, d03), lower collar-beams rest on top of the masonry vault, whereas this layer is absent in later structures. Intermediate struts placed at the base of the parapet support additional collar-beams, on top of which rest circular rings. These concentric rings are located on top of the parapet, at the levels of the collar-beams and close to the king-post. The slender ribs supporting the outer cover lie directly on these rings and run from the parapet to the king-post. All struts rest on short horizontal wooden supports at the level of the floor, separated from the lower masonry by a stone. The structural integrity of the timber domes mostly lies in the use of lap joints fastened by iron nails.

3 HISTORY OF REPAIRS

There is still no definitive explanation for the complete lack of original documentation related to the early building phases (Heinemann 2012; Ruzza 2016). The oldest available documents mentioning renovation works on the domes date back to the late 15th century and mostly report on their general state of conservation. Archival sources mention the supply of wood and lead for various roofing works and, in rare cases, the name of the domes concerned. Unfortunately, precise descriptions of the structures and of repair activities are missing for that period. Nevertheless, the study of archival documents related to repair campaigns permits the identification of three intense restoration periods: a first one in the mid-16th century, a second one following the fire in 1749, and a last one in the 1860s.

Mid-16th century reports attest to the decay of all seven domes (the eighth dome was only built 200 years later). Some documents reveal the presence of supervisors, carpenters and blacksmiths with Venetian background, sometimes also involved in works on the timber domes of the Abbey of Santa Giustina in Padua and St Mark's in Venice (Negri 1988; Sartori 1983). Lists of building materials include larch and lead bought on the Venetian market. A text even documents the remaking of the cover of the façade dome, including the wooden ribs and the rings. Despite the lack of any other clear descriptions, preliminary dendrochronological analyses carried out in the scope of this project have already confirmed that the secondary struts in the intermediate dome were replaced at that time.

From the beginning of the 18th century, various documents report on the poor condition of some superstructures. After the dreadful fire in 1749, reparations included the complete reconstruction of the burnt structures: the angel dome (d04), the dome of St Jacob (d05) and the domes above the presbytery and the choir (d06, d07) (Figure 3).

In the second half of the 19th century, under the Austrian government, interventions occurred in the domes above the nave (d01, d02), in the dome above the Chapel of St Anthony (d03), in the St Jacob dome (d05) and in the presbytery dome (d06). The reports mention the following tasks:

- replacement of the king-posts (d01, d02 d03, d05);
- partial renewal of the main structure (d03, d05);
- renewal of the first wooden ring (d01, d02, d03, d05, d06);
- partial replacement of ribs (d01, d02, d05);
- renewal of the external wooden boards and lead plates (in d01, d02, d03, d06);
- intervention on the masonry drums (d02, d03, d05, d06).

Carefully executed drawings show the interventions on d01, d02 and d06 (Figure 4). Moreover, the texts provide precise descriptions of the scaffoldings installed for the renovation campaign (Figure 5). The hosting of materials relied on a 30-metre-high lifting tower flanking the building. A system of pathways and platforms guaranteed the carriage and storage of materials on top of the pitched roofs. Cantilevered galleries installed in the existing putlog holes surrounded the drums, vaguely indicating what the medieval scaffoldings might have looked like.

These scattered sources leave many questions unanswered, but nevertheless provide crucial indications about the parts in which medieval timber could still be found.

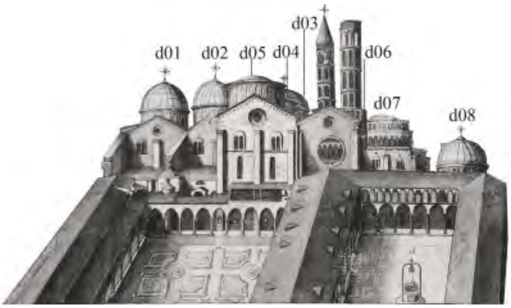

Figure 3. Depiction of the southern façade of the Basilica after the fire in 1749 with the loss of the wooden superstructures in d04, d05, d06 and d07. Based on an engraving by Cerato F. & Fossati G., 18th century (Civic Library of Padua RIP XXX/2603).

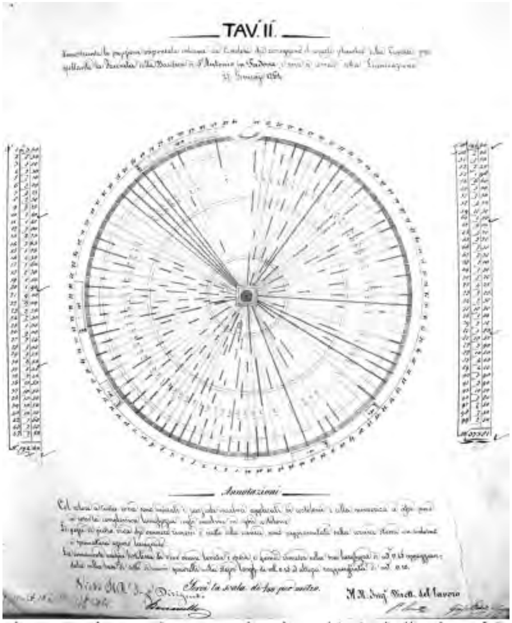

Figure 4. Nineteenth-century drawing with the indication of the ribs and king-post replacements in d01. (In the Archivio della Veneranda Arca di Sant' Antonio (ArA), fasc. 24.2068, all. 4: coloured plan G. Modaz 1864 gen. 27).

4 DATING AND HYPOTHETICAL ORIGINAL CONFIGURATION

4.1 *Preliminary dendrochronological results*

Ongoing dendrochronological analyses aim at dating the elements through three successive sampling campaigns, in collaboration with the Laboratory Dendrodata in Verona. The dating focusses primarily on the earliest domes spared by the 1749 fire (d01, d02, d03),

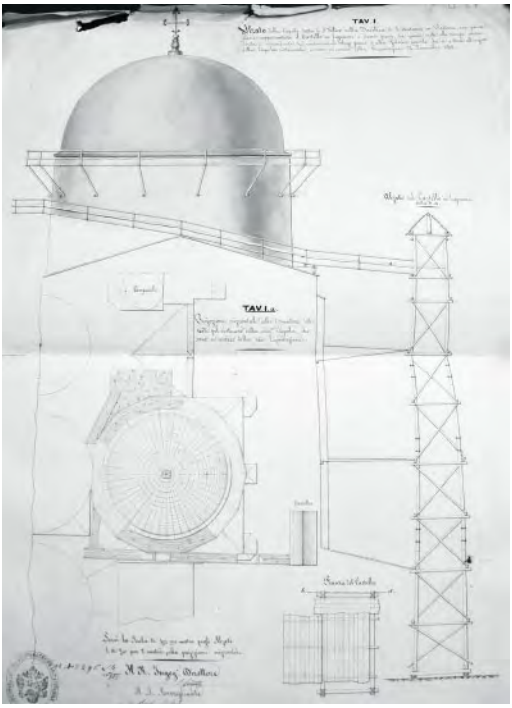

Figure 5. Nineteenth-century drawings of the lifting tower and pathways arrangement during the renovation in d05. (In ArA, fasc. 24.2069, all. 1: coloured plan G. Modaz 1864 Jan. 27).

prioritizing elements which do not show clear traces of later repairs (e.g. 18th-century shipping marks).

At this stage, the results from the first campaigns confirm the existence of beams dated back to the last quarter of the 13th century in the three considered to be the oldest domes. Due to the rare presence of bark on the elements, only two absolute datings have been obtained so far: 1282 in the dome over the Chapel of Saint Anthony (*arca* dome) (d03), and 1551 in the intermediate dome (d02). A *terminus ante quem non* has been identified for 11 other elements. As some 13th-century curves fit closely with each other, several timbers of the first construction phase could already be identified in the three surviving domes (d01, d02, d03). Two other results have confirmed the replacement of entire domes around 1750 (Pignatelli 2020). These dates thus match with the first building phase in the 13th century, with 16th-century interventions mentioned in archival documents and with the reconstruction after the fire of 1749 (Figure 6).

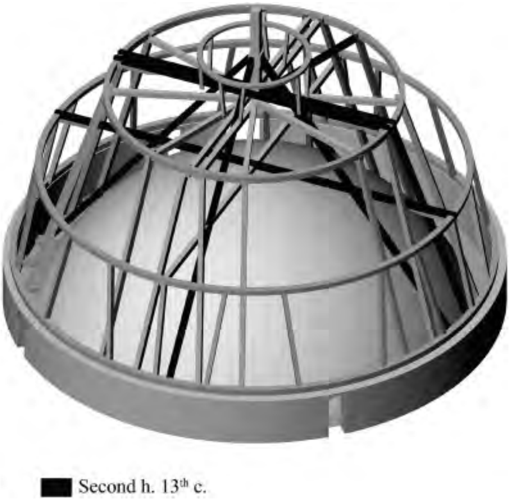

Figure 6. 3D model. Schematic identification of the dated elements during the dendro-analyses campaigns in d03. The black elements are original (3D model: author).

Figure 7. d02: notch visible on the bottom side of a collar-beam (photo: author).

4.2 *Hypothetical original configuration*

In the most ancient domes (d01, d02, d03), notches are visible on the lower extremities of some collar-beams, at both levels (Figure 7). Since such notches are missing in the domes reconstructed later, their presence seems to identify original elements. In some occasions, these notches cover the whole width of the beam, whereas in other places they are positioned only on one side. In a few instances, holes from iron nails are visible on these beams in the immediate proximity of the notches. The presence of these empty joints could fit with a previous brace tightening the connection between struts and collar-beams (Figure 8b). The lack of traces on the outer struts tends to indicate their replacement in the 16th century, which is also confirmed by preliminary dendrochronological results as discussed in the previous paragraph. This kind of arrangement would align with typical solutions recurring in medieval timber frames, the stiffness of which was often insured by such short braces between inclined struts and collar-beams. However, the main struts running to the king-post are likely untouched as they are inserted between two original collars with lap joints.

In the domes above the nave (d01, d02), the upper collar-beams present an empty mortise on their upper

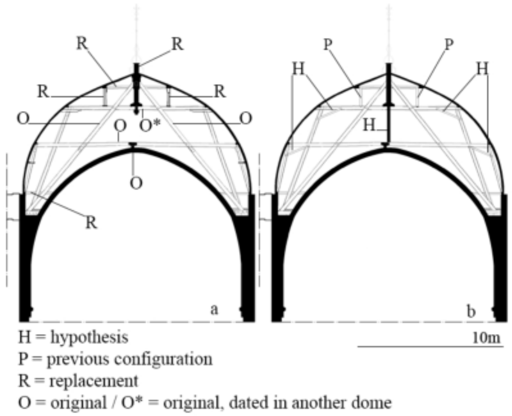

Figure 8. d02. Cross section: a) current state, b) hypothesis on the original layout (drawing: author).

Figure 9. d02: topside of the upper collar-beam with the empty joint for the previous brace position (photo: author).

Figure 10. d01, wooden base of a strut placed between the masonry vault and the drum (photo: author).

Figure 11. d01: lower collar-beam leaning on the vault's extrados (photo: author).

face (Figure 9). This provides evidence of the installation of previous – likely vertical – posts supporting the highest ring, another hint about the early appearance of the roofs.

Eventually, 19th-century replacements mentioned in archives are clearly discernible on site. For instance, single ribs were partly replaced with double-layer elements in the façade dome. The replaced wooden boards of the cover are recognizable by similar shipping marks. The newer king-posts stop at the level of the upper collars and are encased by thick wooden boards (d01, d02, d03, d05). Cross sections of the Basilica published by Gonzati (1852) seem to suggest that the original king-posts were significantly longer. The scale of the drawing is too small to determine whether they rested directly on the beams or not. However, no clear traces of a previous connection with a post have been recorded on the collar-beams, suggesting that if the king-post was indeed longer, it simply rested on top of these beams.

At this stage, a hypothetical original configuration can thus be proposed. Collar-beams featuring notches have been confirmed as belonging to the earliest period, as well as the four main struts which were connected to a previously longer king-post. Moreover, it is likely that the outer struts supporting the end of the collars, later replaced in the 16th century, share the same position as their predecessors.

4.3 *Preliminary masonry work*

Based on onsite observations, it is possible to assume that the masonry dome was already in place when the timber structures were erected.

Firstly, the bases of the timber struts rest above the start of the dome, showing that the vaulting was at least started when the carpenters set to work. Furthermore, the timber is never embedded in the masonry but completely independent, although it is likely that the short bases are not original but have been substituted due to decay, probably in the 16th century when some struts were replaced (Figure 10).

Secondly, the lower collar-beams of the oldest domes rest directly on the vault and do not show any deflection at the centre, which tends to indicate that the vault was there before. Also, the masonry is perfectly smooth at this point. If the timber was there before, it would have been difficult to make a regular finishing at the top of the vault (Figure 11).

Eventually, considering the network of galleries connecting all the attics, it is discernible that those were part of a unitary project from the very beginning.

Hence, the dating of the wooden frames determines a *terminus ante quem* for the masonry domes in the last quarter of the 13th century.

5 MEDIEVAL CONSTRUCTION PROCESS

5.1 *Hypothetical construction sequence*

As the time span between the construction of the brick dome and timber structure is still unclear, one cannot exclude that provisional coverings protected the extradoses until the completion of the roofs. The successive construction steps might have followed this logical sequence (Figure 12):

1. erection of the principal bearing system composed of four main struts attached to the king-post;
2. triangulation with horizontal collar-beams supported by secondary struts and posts (likely from the bottom up);
3. outer skeleton and roof cover.

The first stage would have consisted in the establishment of the four main struts and the king-post, forming a stable base on which to develop the whole frame. These struts, inclined at an angle of 50 degrees, could have been temporarily maintained in position by means of gin poles until they were connected with the king-post. At that time, the king-post might have been longer. Wooden steps nailed on the main struts might have facilitated the access to higher altitudes to nail the joints, as demonstrated by those still in place (although they were likely replaced) (Figure 12b–c).

The next step would have consisted in the establishment of a first level of collar-beams just above the brick dome. These two orthogonal collar-beams placed on top of each other and attached to the struts with lap joints contributed to strengthening the two main frames (Figure 12d–f).

In the above-mentioned historical cross section dated to the mid-18th century, the length of the king-post reaches this level of lower collars in d01 (Gonzati 1852). One can suppose that it rested on the vault until the positioning of the first horizontal beam. Then it would have been shortened to place the transversal beam.

The secondary spokes are connected with nails to the main collar-beams at the centre of the dome. They exhibit a hole at this end, which indicates that they were lifted or dragged with ropes. At this stage, the minor struts were installed on the first ring above the parapet. Furthermore, all joints between struts and collars would have been reinforced by short braces, which would match with the observed empty notches. This first level could have enabled the installation of temporary working floors facilitating the construction of the upper levels (Figure 12g–i).

The stabilization of the two triangles would then have been further improved with the upper level of doubled collar-beams. These beams are attached on both sides of the king-post and the struts with lap joints and nails (Figure 13).

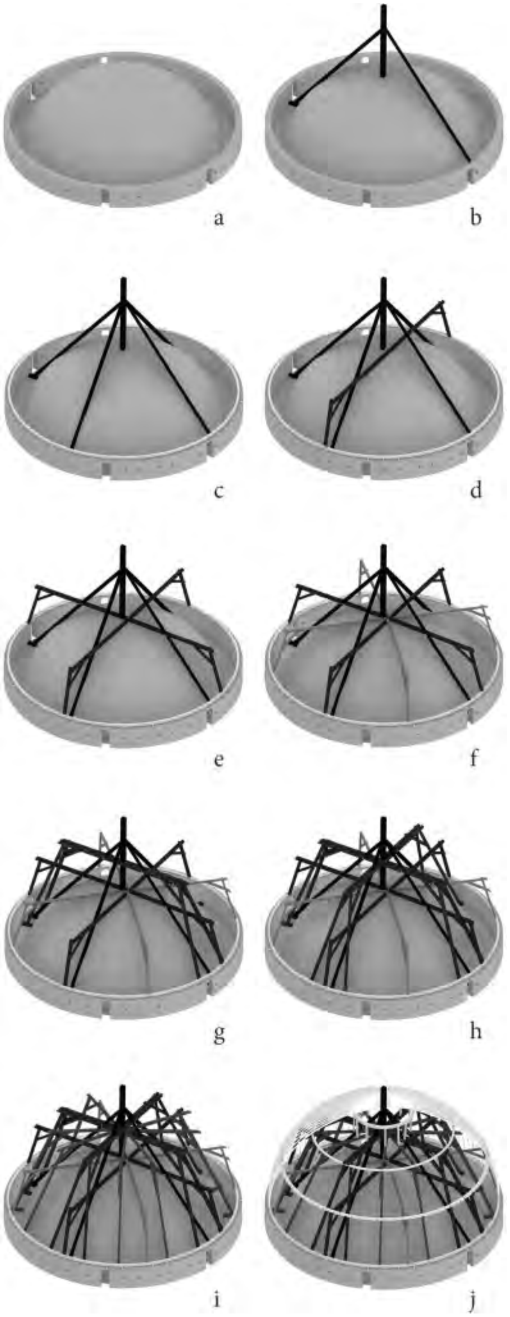

Figure 12. Construction sequence hypothesis. a) Preliminary stage with the masonry vault; b–c) placement of the main struts and king-post; d–f) placement of the lower collar-beams, resting on minor posts; g–i) placement of the upper collar-beams supported by lateral struts; j) placement of the rings and ribs (3D model: author).

Then, the outer couples of struts could have been placed to support the ends of the upper collar-beams, similarly to the current solution. It is likely that the

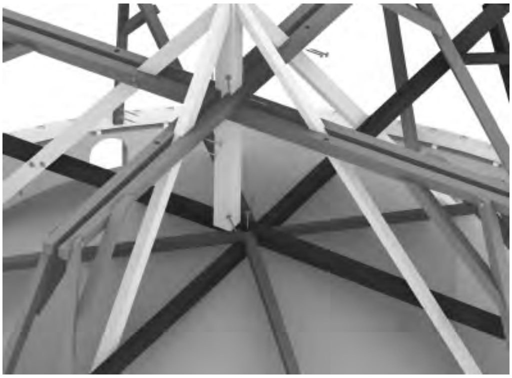

Figure 13. Nailed connections of the collar-beams with the struts and king-post (3D model: author).

following operation would have included the addition of the upper spokes by lifting these horizontal components and putting the last external struts in place.

The final stage would firstly consist of the placement of the wooden rings on the ends of the collar-beams, fixed with nails. The joints between the curved sections were likely shaped on the ground during a preliminary preassembly. Then, circular sectors of planks could have been lifted and reassembled on the collar-beams. Eventually, the last ring was placed after the installation of short vertical posts into the mortices, on the top side of the upper collar-beams (Figures 12j and 14).

Interestingly, in the second dome of the nave (d02), the third ring was seemingly not replaced in the 19th century. Unlike the more recent ones that are composed of two or three layers of nailed boards connected to the ribs with iron strips, it is a one-layer chain. The ribs are clamped in notches around its external profile following the probable original spacing.

Likewise, the settlement of the ribs included a preassembly on a horizontal level to join the segments, and their placement to match up with the notches shaped on the rings.

The construction process was concluded with the covering by an external shell. The internal wooden boards were nailed to the ribs and external lead plates were fixed on those. This external lead cover, replaced several times, assured the protection of the whole system during centuries and the exceptional preservation of 13th-century elements.

5.2 *Lifting techniques*

Despite the lack of documentation, historical depictions and descriptions can contribute to understanding ancient strategies to erect timber roofs. Furthermore, medieval scaffoldings and hoisting devices changed little over time, at least until the early modern period (Holzer 2021).

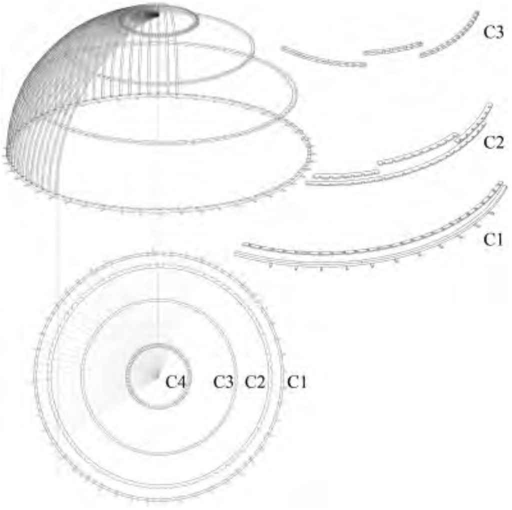

Figure 14. d02. Preassembly of the wooden rings on horizontal level. Detail of the board arrangement. C1 19th century replacement; C2 undated replacement; C3 supposed older single layer configuration (drawing: author).

Because pre-existing putlog holes were obviously reused to secure the 19th-century provisional structures, the above depictions might give an approximate idea of the original scaffoldings in place at the end of the 13th century, when the timber domes were erected on top of the masonry shells. Machines could have been installed on top of the masonries to lift and hoist the long timbers. Windlasses are documented from the beginning of the 13th century in Western Europe (Backinsell 1980; Matthies 1992). However, despite possible speculation about the machinery used, and given the lightness of the structures, the use of simple pulley systems is not unlikely.

The complexity of the round masonries and their height from the ground would not have made the carpenters' task any easier. The lifting of timbers above the brick dome would have required devices installed on the parapet or on external platforms and maintained by ropes attached to the masonry. A first lifting device might have brought the wood up on top of the aisle's roof. A second one, resting on the drum of the dome, enabled the lifting of timbers above the parapet. The four apertures aligned with the floor of each attic likely eased the passage between the inner space and the external temporary floors. Workers could also safely reach the attics through the network of internal corridors of the church.

Unlike in most timber works, carpenters did not use assembly marks in the domes of the Basilica. This can be explained by the simplicity of the assembly relying mostly on lap joints. Connections were likely shaped on a case-by-case basis during the erection phases. Hence, this simplicity and the widespread use of iron nails might have resulted in the interchangeability of timbers, eliminating the need for marks.

6 CONCLUSION

The preliminary dendrochronological analyses confirm the presence of original elements still in place in three domes of the Basilica of St Anthony, making them the likely oldest preserved timber domes in Europe. Moreover, these results could be related to the various interventions on the domes cited in archival reports.

When brought into an overall perspective, the data gathered provides a comprehensive understanding of the original timber layout and the assembly sequence of the structural components. Despite later interventions, the preservation of the original scheme confirms the continuity of the same modus operandi between the 13th and the 18th centuries, hence shedding light on a particular niche in construction history.

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Simply complex: Case studies on complex stone constructions of High Medieval courtly chimneys

J. Lengenfeld
Brandenburgische Technische Universität Cottbus-Senftenberg, Cottbus, Germany

ABSTRACT: When it comes to medieval chimneys, we usually think of their frame or coping as a topic for art or architectural history. The construction of the lintel, mantel or shaft itself has been mostly ignored. Based on detailed studies regarding the chimney systems of keeps in Regensburg (1211–31) and Schönburg (1201), along with further examples, this paper shows the great complexity and variations in the construction of High Medieval chimneys of the late 12th and early 13th centuries in central Europe. Furthermore, it focuses on their building progress and the advanced processes applied, reaching from complex falseworks to pre-produced Ashlars.

1 A SYMBOL OF POWER

When contemporary authors such as Chrétien des Troyes or Wolfram von Eschenbach described the fireplaces of castles and palaces in their novels as vast and flamboyant structures consisting of marble and bronze we are well advised to not read this as a firsthand record regarding their construction. Nevertheless, the focus of the authors on this object and the exaggeration of its grandeur points to the importance of the fireplace as a sign of power and wealth within the context of High Medieval European courts.

The ruins of huge mantelpieces often reaching through several storeys, like in the ruins of the Münzenberg castle (ca.1150-74) (Figure 3), or the lavish ornamented columns, corbels and decorative plates of the fireplace at the imperial palace in Gelnhausen (ca.1170) (Figure 2), give us a hint of how important fireplaces and chimneys were for the medieval individual, and what a task it must have been to plan and build these symbols of wealth and power.

One of the best known and most publicized fireplaces of this era in Germany can be found inside the ruins of the palace at Wildenberg (Figure 1). Dating to 1190–1200 it is located between a pair of mullioned windows and consists of two massive sandstone corbels each weighing approximately four to five metric tons supporting a monolithic lintel featuring an early example of an ornamented front varnished with lion heads and geometric patterns. But while it is an imposing sight and with a clear opening of 5.2m^2 regarded as the biggest Romanesque fireplace in Germany it has lost its chimney so only the fireplace can be surveyed.

Figure 1. Photograph of the fireplace in Wildenberg castle. Note the 3m level pole on the right.

Figure 2. Photograph of the fireplace in the "small hall" of the imperial palace within the court district of Gelnhausen.

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Figure 3. Photograph of the fireplace and the back wall of its chimney in Münzenberg castle.

2 THE CHIMNEYS IN THE RÖMERTURM AT REGENSBURG

2.1 *The keep of the Bavarian dukes*

In the court district of the Bavarian dukes at Regensburg located directly adjacent to the Gothic cathedral in the north a lesser known chimney system has survived to this day which is in significantly better condition.

Dating to 1211–31 it is situated in the upper section of the keep commonly referred to as the Römerturm (Roman Tower), a building towering 26m high above a floor area of roughly 14x14m. The system includes two fireplaces located in the north-east corner of the fourth and seventh storeys connected by a 20m high chimney erected simultaneously with the 1m strong outside walls in coursed quarry stone masonry.

2.2 *Fireplace in the fourth storey*

The first fireplace is located in the north-east corner of the fourth storey which also served as the entrance floor accessible over a wooden bridge leading to the hall on the first storey of the palace.

The original floor of the fireplace is not preserved thus the crown of the thick walls below forms the present day walking level. The basic shape of the fireplace forms an irregular circle of which three quarters are located within the outer wall constructed in coursed quarry stone masonry and the fourth is defined by the form of the mantelpiece in the room. It is flanked by two cut stone pilasters of sandstone featuring late Romanesque – early Gothic bases and capitals. At an unknown time, the shaft of the eastern pilaster was removed. Above each pilaster the remains of upright standing cut sandstones are visible within the surrounding masonry. Since they are broken close to the wall their original form is unknown but are most likely parts of the construction (corbels?) supporting the chimney mantel. At an unknown time, this stonework collapsed which led to a partial collapse of the quarry stone mantelpiece until a self-supporting corbel arch developed which prevented further destruction.

Figure 4. Photograph of the fireplace in Querfurt. Note the marked closed bearing and its position aligned with the intrados zenith of the arch.

Because the possible corbels broke very close to the wall it is not possible to reconstruct the construction carrying the mantel based upon them alone. Yet the bearing for a beam walled up during the construction of the fireplace gives us a hint about its possible construction and form. Found in the middle of the back wall and measuring 30x30cm its lower edge matches those of the possible corbels. The position, size and singularity of the hole makes it unlikely to be referred to as a putlog hole nor does it seem to be a part of the falsework for the shaft which is located a few meters above.

In the former Querfurt castle (late 12th century) a similar bearing, closed during the building process, can be observed in the coursed quarry stone back wall of a fireplace. In contrast to Regensburg, it features a preserved segmental arch consisting of small sandstone voussoirs carrying a quarry stone mantel, whose intrados zenith matches exactly the upper brim of the walled up bearing. We can assume that a beam restrained in the bearing and supported by an unknown temporary structure on the other end supported the falsework of the arch during its construction. After the completion of the work this beam was removed and the bearing closed (Figure 4).

Based on its position and size we can expect the same use for the walled up bearing in Regensburg.

Taking into consideration the form of the mantelpiece and the remains of the possible corbels there are several possible ways how the construction supporting the chimney mantel could have been constructed.

The most elementary geometrical solution would be the use of two corbels whose ground plans describe the segment of a circle. Due to the position of the beam whose upper edge would reach half way up the possible corbels a third ashlar would be needed to close the resulting gap. We can find constructions of similar geometry consisting only of the corbels, in Katzenstein castle (1225).

This construction however is highly unlikely and very daring considering its position. The outer circumference of the mantelpiece at the height of the corbels measures 3.08m while the sandstone corbels which would have to carry the load of the 16.4m high mantelpiece weighing approximately 9.75 metric tons only measure 31 × 38cm in cross section.

A faulty construction could of course be the reason for the collapse, but taking into consideration that all examples for this construction are much smaller and feature additional field reducing elements like additional corbels it seems unlikely.

A segmented arch would be laborious but more resilient. If we take the upper brim of the closed bearing for the zenith of the intrados this segmental arch on the ground plan of a quadrant would reach an elevation of 22cm. Such shallow spatially bent segmental arches from cut stone often tilted following the form of the mantel can be observed on several sites dating from the late 12th and early 13th century. For example, this is constructed from voussoirs in Querfurt castle (late 12th century), Falkenstein castle (late 12th century) and the tower of St Blasius in Altenberg (1143!) or in combination with corbels in the keep of Neuenburg castle (second half 12th century) and Schönburg castle (1201).

It is not certain which construction was used to support the chimney mantel in the Römerturm. However, the position of the assumed falsework beam and the dimension of the sandstone fragments compared with preserved contemporary chimneys of the late 12th and early 13th century suggest a shallow spatially bent segmental arch made of cut stone tilted following the form of the mantel as the most likely geometry. Further, taking into account that an impost block is preserved above the eastern pilaster of the fireplace in the seventh storey, a construction consisting of multiple smaller voussoirs is probable.

2.3 *Construction of the chimney*

Like the fireplace the chimney rising 19.5m over it is, to this stage of my research, still unmatched regarding its size and construction. Erected in coursed quarry stone masonry on a falsework divided in seven segments each varying in shape, diameter, height, and orientation it is a construction of high complexity (Figure 5). Due to the demanding geometry and the height of the chimney it was impossible to measure using a laser scanner or tachometer. It was therefore measured by hand hanging from a rope using a system of Plumb bobs.

The first 3.46m high segment is formed by the vertical walls of the round fireplace in the fourth storey. Its surface of coursed quarry stone masonry was further smoothened by hewing the edges.

It is followed by the 2.42m high second segment of octagonal ground shape. In four of the eight corners of its base niches for falsework, beams measuring 16x10x80cm are reaching down into the first segment. The other four corners are drawn in over the edge of the first segment creating small supports for four additional vertical beams. Between them horizontal imprints of poling boards give a further idea of the chimney's construction. At its upper end the segment conveys into the square shaped ground shape of 2.14m high segment three.

Figure 5. The chimney shaft of the Römerturm photographed from the fireplace of the fourth storey. The changing ground plans and directions of the segments are clearly visible.

At their transition, a stone was placed over each corner forming a support for four vertical falsework beams inside the chimney shaft. In contrast to the first and second segments the surfaces of the stones in the four upper segments are not smoothed.

Segment four is of special interest. Not only is it the shortest segment measuring only 1.73m, it also branches off at an angle of 15° bending towards the tower corner. Since no other segment is leaning at an angle above 5° this is hardly to be taken as a measuring mistake. It seems more likely that it shows a change in plans. It was possibly planned to lead the chimney out of the wall of the tower in or near the north-east corner. This practice was common, and numerous good examples have survived for example at the keeps of Saalburg (late 12th to early 13th century) or Schönburg castle (1201) which will be described in detail later.

Segment five however returns to a vertical orientation while retaining the square as its ground shape. It differs significantly in its height of 4.82 meters.

Furthermore, the technique to form a support for the vertical beams of the falsework changes a last time.

To obtain the supports for them the segment was turned by 45° on its vertical axis, thus creating four triangle shaped supports on the top edge of segment four (Figures 5 and 6).

This procedure of turning the segment by 45° while containing the ground shape is easier and more stable than the method of using stones placed over the corners featured between segments two and three.

Segment six equals segment five regarding form and construction only with a slightly lower height of 3.46m. The same can be stated for segment seven which is cut off by the present day roof truss dating to 1573.

In addition to the supports and imprints of the falsework beams, two outstandingly well preserved poling boards were found and documented in segments three and four. Contrary to the picture one might have in mind regarding a high medieval falsework they are no hasty cut pieces of scrap wood.

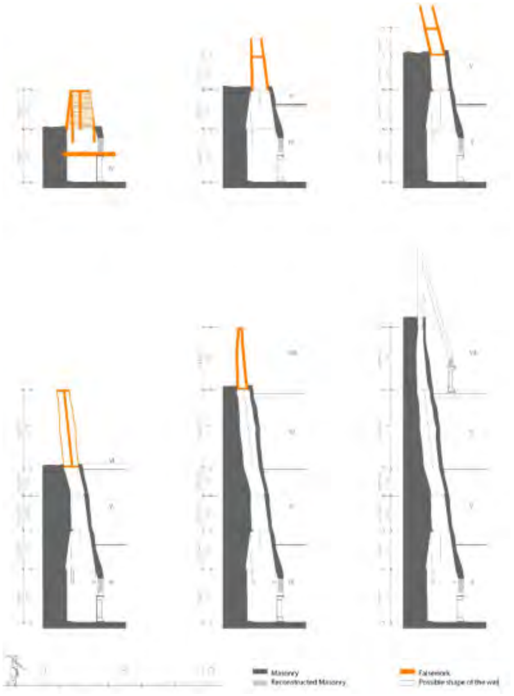

Figure 6. Cross section of the chimney system showing the possible construction process and the reconstructed falseworks.

Both are 10cm high and 2cm strong pieces of pine split wood varying only in length due to their position in different segments. Particularly interesting are their edges which were cut mitred using a very fine saw leaving traces similar to that of a Japanese saw.

Due to the lag on nails or their traces within the boards, we have to assume that they were either glued to the beams or more probably fastened with hook shaped nails found between one of the boards and the wall as it was removed to prevent it from falling down (Figure 7). Furthermore, the removal of this board allowed for dating the construction of the chimney system and tower to 1211–31 using dendrochronology.

2.4 *Fireplace in the seventh storey*

The second fireplace is located in the north-east corner of the seventh storey. Although its ground shape is significantly smaller, its construction is identical to the fireplace in the fourth storey. The mantelpiece and the construction supporting it are missing completely but judging from the features remaining on the walls, it bent towards the chimney and would have joined it a few centimeters above the top edge of the recent walls (Figure 6). This solution to connect two fireplaces located on different storeys with one chimney is, contrary to late medieval buildings, relatively uncommon in German speaking territories at the given time. Most buildings equipped with more than one fireplace feature a separate chimney for every single one. Good examples of this practice are the tower houses of Neuenburg castle, two chimneys (1225–6) and Querfurt castle, two chimneys (1214–34).

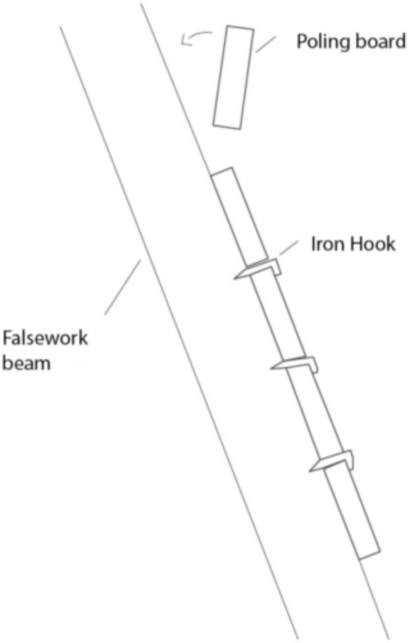

Figure 7. Schematic representation of the possible technique used to secure the poling boards on the falsework beams, based on the imprints of the beams and the preserved poling boards and nails.

Figure 8. View of the segment arch and the dressed stone mantel seen from below. Note the quality of the stonework and the capitals.

3 THE KEEP OF THE SCHÖNBURG

3.1 *The Bishop's keep*

The second case study tackles the chimney system located in the keep of Schönburg castle, built from

1201 onwards by the bishopric of Naumburg within an existing castle on a hill above the Saale river.

The keep, built over a circular plan with 9.6m diameter, reaches a height of 29.6m and is built with dressed sandstone ashlars laid in pseudoisodonic courses. Its chimney system consists of a fireplace in the first storey with a 7.2m high chimney built within the 3m strong outside walls, and made of dressed sandstone ashlars as well.

3.2 *The fireplace*

The fireplace is located in the north-east section of the wall in the first storey. As in Regensburg, this was originally the entrance storey of the tower, accessible by a door with an adjacent corridor in the west. A small window in the east allowed for further ventilation.

The ground plan of the fireplace describes a semicircle with a radius of 0.9m within the wall of the tower (Figure 9). Its floor is raised 0.38m above the walking level.

The rising walls of the fireplace are constructed from curved dressed ashlars laid in pseudoisodonic courses, like the walls of the tower, but with different levels of the bed joints. The fact that these two systems are consistent within themselves, but incompatible with each other, suggests that the fireplace, like other more complex parts (windows, portals), was produced by specialists in advance of the building process and then slotted in when the tower reached the height for their installation. This explains the use of smaller atypical ashlars around the fireplace that were used to fit both parts together. This practice is well known to us regarding the construction of cathedrals but was rarely documented in castles.

At a height of 1.78m above the fireplace floor, upon early Gothic capitals a shallow segmental arch with spatial curvature, made of dressed stone with two corbels and a keystone, spans 1.6m wide across the fireplace and bears the mantelpiece (Figure 8). Contrary to Regensburg, no traces of a falsework could be identified, but the laying of the keystone makes the presence of some sort of falsework a necessity even if the corbel's center of gravity would lie within the wall preventing it from dropping, without the abutment of the rising wall above it.

The cross section of the arch shows a peculiar form: its upper edge is tilted three degrees towards the chimney, possibly to prevent the first layers of the mantelpiece from sliding off when under pressure. Furthermore, the outer and inner edges of the arch are tilted by five and thirteen degrees of the vertical axis in direction of the chimney.

3.3 *The mantelpiece*

The reason for this is that the arch is following the form of the mantelpiece which features different ascents in the room and the chimney.

Inside the room, the mantelpiece describes a 2.6m high figure that can best be described as a tilted paraboloid of revolution intersecting the cylinder of the tower shell (Figure 10). Thus, each course of ashlars is curved vertically and horizontally according to the segment arch in plan and the parable in the cross section. The elegant connection to the walls with a narrow joint bears witness to excellent craftsmanship.

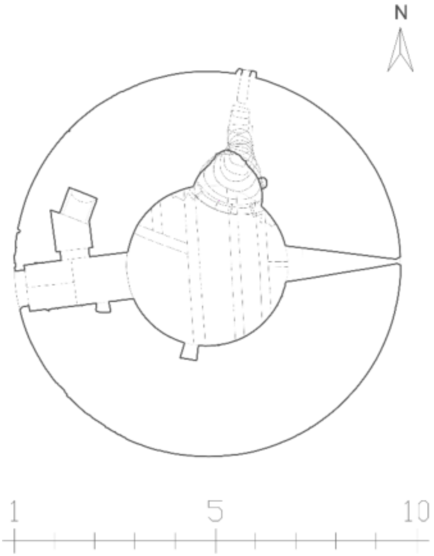

Figure 9. Floor plan of the first storey in the keep of Schönburg. The dotted lines show the height evolution of the chimney shaft.

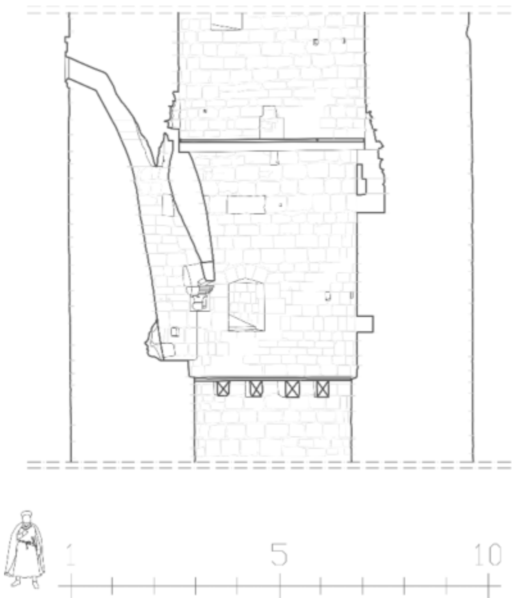

Figure 10. Cross section through the chimney system showing the curved mantelpiece and the bed joints inside the chimney and the room.

Inside the chimney, the mantelpiece describes the same figure at an increased recline, this time cutting

Figure 11. View into the chimney shaft from the fireplace. On the right, the ashlars of the mantel are fitted layer by layer until they share a bed joint with the ashlars of the chimney. Note the smooth transition between the steeper mantel and the back wall.

the cone shaped back wall of the chimney. Therefore, the ashlars are curved horizontally as well as vertically, with the difference being that they are carved concave where the ashlars inside the room were carved convex.

We do not know what lay behind the builder's intension to decouple the course of the chimney shaft and the outer form of the mantel. Maybe it was the wish to build a more representative mantel.

To handle this task, however, they designed a mantelpiece featuring at least an inner and an outer shell of ashlars, as we could observe in the survey. The outer shell shares the bed joints of the room indicating that they were built simultaneously with the room shell in contrast to the fireplace. While the inner shell's bed joints are positioned slightly lower, this is most likely indicative of an attempt by the workers to level the inside of the chimney back wall to the mantelpiece and the room shell on one bed joint. This possible goal was achieved in the height of the bed joint of the fifth course of ashlars above the arch of the fireplace.

3.4 *The chimney*

Thus, the bed joints of the chimney above this layer correspond with those of the inner and outer shell of the tower. The fifth to eight courses maintain the cylindrical form of the chimney. The characteristic feature of the chimney in this segment is the smooth transition between the inner shell of the mantelpiece and the steeper back wall of the chimney.

Above the ninth layer the chimney decouples from the shape of the mantelpiece, merges into a square plan, and changes direction: it turns 17 degrees to the north and the ascent drops to 26 degrees from the vertical axis. The combination of these factors and the consistency of the following segment makes this unlikely to be a measuring mistake: it rather seems to be an intentional change of plans. Whether the reason for this change of direction could be related to the wind affecting the stack effect or other aspects, has yet to be discovered.

Figure 12. Detail of the chimney exiting the wall. The irregular bed joints show that this component was pre produced and fitted in.

The last 0.8m of the chimney shaft shows a further change in its ascent, while orientation and ground shape remain the same. This drop to 67 degrees was most likely carried out to lead the shaft trough.

The chimney shaft finally exits from the wall at a level of 16.2m above the ground through a 60cm high opening with the shape of a gable crowned by the remains of an early Gothic finial (Figure 12).

4 EXAMPLES OF FURTHER CONSTRUCTIONS

Apart from the described chimney systems, further objects were surveyed whose detailed description would go beyond the scope of this paper. Nevertheless, I will present a few examples featuring a design feature or system that cannot be found in the two main examples.

High Medieval chimney copings are very rare. Of the few chimneys that survive relatively intact to our day many do not even feature a chimney reaching above the eaves of the building. This is primarily a result of construction choices. Many chimneys never reached above the eave. Their fume exited through more or less decorated holes in the wall described in Schönburg. Other chimneys that did reach above were placed on the long sides of the building, a position that once the building lost its roof was very unstable compared to chimneys constructed in the gable of a building.

Luckily a surviving coping from the 13th century crowns the battlements of Neipperg castle (1220–4) and gives us an idea of how these could be constructed (Figure 13). The dressed stone construction, made from sandstone, is laid out on a square ground shape and resembles two gable roofs intersecting each other. Underneath every gable a semicircular arch allows the fume to leave the shaft. This lavish construction makes it most literally the pinnacle of the chimney system.

Figure 13. Detail of the chimney of the keep of Neipperg (modern replica of the original), resembling the top of a Gothic pinnacle.

Figure 14. The fireplace in Besigheim featuring its mantel in dressed tuff blocks.

While both case studies featured mantelpieces erected above a segmental arch, constructions resting on horizontal corbels and a lintel were common as well during the same period. We have already seen an intact example of this horizontal corbel and lintel construction design from dressed stone in Wildenberg. While this fireplace was missing its mantelpiece and thus the main part of the chimney, a smaller but significantly better-preserved object has survived in the keep of the margraves of Baden in Besigheim (1220–30) (Figure 14).

Its corbels and lintel are carved from dressed sandstone in accordance with the inner shell of the keep. The mantelpiece meanwhile is constructed using tuff ashlars laid in courses. While we do not know if this construction was chosen due to its lower weight compared to sandstone or because of the heat resilience of the tuff, it is important to note that the tuff mantel is constructed independently from the wall, only connected by two stones reaching out of the wall. This separate construction may explain why the mantelpiece often left almost no trace within the building.

Our last example tackles a further construction method, often leaving no traces due to the transience of its materials. Due to the risk of fire, we usually do not expect to find wooden components in chimneys and fireplaces. Still wood was often used for fireplaces even by clients who could well afford a construction in stone. The reasons for this can be found in statics as well as optical considerations. In the Logis de Clergeons at the Cathedral Monastery of Le Puy-en-Velay (mid 13th to early 14th century) (Figure 15) we find an example of a fireplace with two wooden corbels supporting the mantelpiece and chimney which is constructed from dressed ashlars similar to Schönburg.

Figure 15. Detail of the wooden corbels under the mantelpiece of a chimney in Le Puy-en-Velay. (Photo by S. Schlosser).

5 CONCLUSIONS

These case studies and examples show that the construction of chimney systems and fireplaces was a substantial and complex task for the contemporary planners and masons. The constructions reaching from coursed quarry stone masonry, with up to 20m high complex falseworks, to elaborate constructions in dressed stone which, regarding their complexity and quality, stand not far from aspects in the erection of cathedrals.

Furthermore, the changes in plans documented, and the broad spectrum of different solutions shows the great attention paid by builders. This demonstrates the architectural complexity of these components, revealing them as one of the most complex structures in High Medieval Central Europe, and a subject worthy of continued study.

ACKNOWLEDGEMENTS

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Medieval transformations of the Basilica of St Anthony in Padua based on an analysis of the original brickwork

L. Vandenabeele
Eidgenössische Technische Hochschule Zürich, Zurich, Switzerland

ABSTRACT: The imposing appearance of the Basilica of St Anthony in Padua (Italy) results from several major transformations carried out after an initial construction phase between the 1230s and 1260s. Due to the lack of medieval building archives, the successive forms of the pilgrimage landmark remain uncertain. Based on a recent survey of the church and a detailed analysis of its original brickwork, this contribution provides a fresh set of evidence casting light on the early appearance of the Basilica as intended by its 13th-century builders. The results pave the way for an unequivocal dating of the building, together with a finer understanding of medieval building techniques in Northern Italy.

1 INTRODUCTION

1.1 *Brief history of the Basilica*

The oldest document related to the Basilica of St Anthony attests to an active construction site on the outskirts of Padua in 1238, seven years after the death of the Portuguese-born Franciscan friar (Lisbon, 1195-Padua, 1231). Although the laying of the first bricks can hereby be situated between this date and the Saint's swift canonization in 1232, little is known about the next 150 years, which saw the erection of the church. Indeed, only a tiny handful of construction-related documents have survived the passage of time.

The early history of the massive brick Basilica and its wooden domes is thus only sketched from secondary sources such as municipal funds, religious celebrations, donations or indulgences. Based on these documents, a widely accepted chain of events has emerged in recent literature (Baggio & Bertazzo 2012; Heinemann 2012), as summarized in Table 1. Additionally, two rare city reliefs on tombs dated 1329 and 1345 show that the Basilica was already covered by several domes in the first half of the 14th century (Hein 2012). More precise events can be traced from the 1390s onwards, starting with the unfortunate collapse of a campanile tower in 1394. The last major intervention consisted in the decorative painting of the interior, following a renovation campaign carried out by architect Camillo Boito around 1895 for the 7th centenary of St Anthony's birth.

Table 1. Main historical events.

1232–38	Start of the construction.
1237–56	Occupation of Padua by Ezzelino da Romano.
1256–63	Papal indulgences to finance the construction.
1263	First translation of the relics to the new church.
1265	Municipal financing.
1267–95	Construction of radial chapels.
1307	Municipal financing.
1310	Second translation after *varia et inmensa mutatio*
1350	Third and last translation to the current tomb.
1382	Construction of the Chapel of Luca Belludi.
1394	Collapse of a campanile tower, followed by municipal financing and papal indulgences.
1690–1745	Construction of the Chapel of the Relics.
1749	Fire destroying four timber domes.

1.2 *State of research*

The large body of art history research on the sequence of the Basilica's construction was initiated in the mid-19th century with the monograph by Gonzati (1852). Several hypotheses were formulated over the following decades, notably the postulate of a previous two-level ambulatory – like that of Notre-Dame in Paris – (Dellwing 1975) or a first single-nave church on the model of the Basilica of St Francis in Assisi (Salvatori 1981). Although the single-nave theory has been discredited in recent research, there are still different views on the aspect of the Basilica around the turn of the 14th century. For example, Valenzano (2012) considers that the church was covered by six domes as early as 1263, when the relics were moved to the western transept. The next translation in 1310 – probably to the last chapel of the ambulatory – would correspond to a convenient relocation to the newly built eastern part. On the other hand, Heinemann (2012) comes to the conclusion that the translation of 1310 was motivated by the start of the vaulting above the crossing area, until then protected by provisional roofs.

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Figure 1. Basilica of St Anthony, north-western view (photo: author).

Figure 2. Basilica of St Anthony, south-eastern view (photo: author).

As can be seen, key questions remain open after almost two centuries of art history research. The remaining mysteries mostly surround the form of the church before the junction with the eastern transept, the dating of the domes and the scale of damage caused by the collapse of a tower. In the absence of further onsite surveys and absolute dating, none of the current hypotheses prevails undisputed, as reflected in the latest major publication on the Franciscan Basilica (Ruzza 2016).

1.3 *Scope of investigations*

In 2019, the Institute of Construction History and Preservation (IDB, ETH Zurich) launched a research project under the direction of Professor Stefan M. Holzer, in collaboration with the *Veneranda Arca di Sant'Antonio* and financed by the Swiss National Science Foundation (SNSF). Drawing on existing research, the project aims to establish a coherent timeline for the construction of the Basilica of St Anthony using state-of-the-art building archaeology methods (laser scanning, photogrammetry and thermal imagery) as well as absolute dating techniques (dendrochronology and ^{14}C).

After one and a half year of investigations, this paper provides a first set of results casting light on the construction techniques, the architectural influences and the dating of the Basilica. It focuses particularly on one key question; namely, the early appearance of the church as intended by its 13th-century builders. The outcomes are based on an in-depth survey of the Basilica, including all walled-in corridors, and an early attempt to sort its original brickwork using mensiochronology (i.e. dating of bricks based on dimensions and patterns). Preliminary results from dendrochronological dating of the domes are included in this paper, although further discussed by Diaz *et al*. in this same volume. Finally, ongoing research steps and hoped-for results are briefly presented at the end of the paper.

2 CONSTRUCTIVE FEATURES

2.1 *Western part*

In the oldest part of the church initiated in the 1230s (Figure 1), the bearing structure consists of large brick pillars (about 4 × 4 m) supporting 3-metre-thick semicircular arches spanning about 13.5 m. The exterior walls are formed of thinner brick infills (73–96 cm) inserted below the arches. The nave and the transept are covered by five masonry domes of similar diameters (14.40–14.48 m) and thicknesses (32-43 cm); the higher dome on top of the crossing is slightly smaller (14.30 m). On top of these brick shells, lightweight timber structures elevate the silhouette of the church with four domes and a truncated cone under which the relics were placed in 1263. The thrust forces of the arches are taken up by several buttresses positioned on the lateral sides of the Basilica, some of them integrated into the façade or transept walls.

This structure inevitably echoes the shining example of the Basilica of St Mark in nearby Venice, raised two centuries earlier in the competing lagoon city. Following a Greek-cross plan, St Mark's is, in turn, considered to be inspired by oriental models such as the Church of the Holy Apostles (4th century) or Hagia Sofia (6th century). Despite the different plans and slightly larger proportions in Padua, the structural similarities between St Mark's and the western part of St Anthony's are striking (Figure 3). However, the domes of St Anthony's rest on higher drums, while the profile of the masonry shells is ogival rather than semicircular. Knowing the competitive climate between the two cities, one might reasonably wonder whether these soaring domes were not part of a symbolic race in the flat coastal landscape. Indeed, the original timber roofs of St Mark's – completely destroyed by fire in 1419 but still visible in mosaics – were only added on the masonry shells between the second quarter of the 13th century and ca.1270 (Piana 2019).

Preliminary results from dendrochronological dating of the domes of St Anthony (samples analysed by the Laboratory Dendrodata in Verona) indicate that three of the cupolas (façade, intermediate and *arca*) are still largely original from the early 1280s (Pignatelli unpubl.). These structures, which miraculously survived fire and moisture for more than

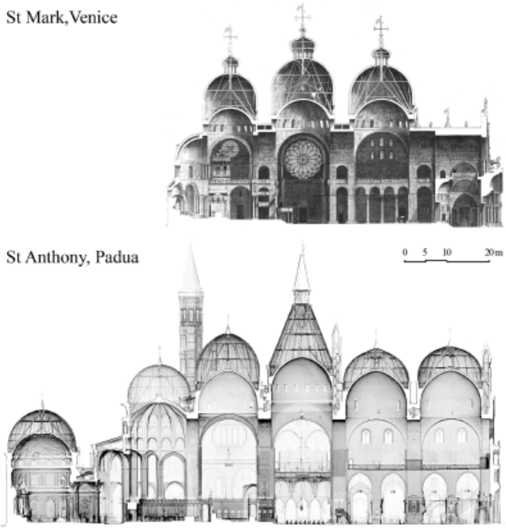

Figure 3. Longitudinal sections of St Mark's and St Anthony's at the same scale (drawings: Visentini 1761; author).

seven centuries, might thus be the oldest timber domes preserved in Europe. The larch trees cut in the 1280s position the construction of these timber structures to shortly after those of St Mark's. As the Basilica of St Anthony would have been higher even just with masonry domes, did the Venetian authorities attempt to raise their landmark in reaction? Could the timber domes of St Anthony be the result of another outbidding? These questions might soon be answered after a second sampling campaign.

A particular feature of the western side of the Basilica lies in the intricate network of corridors meandering inside arches and buttresses. Giving access to every attic and external roof, this "*intricato Laberinto*" (*sic*) already dazzled 16th-century observers (Polidoro 1590). As noticed by Valenzano (2012), walled-in passages are common in Romanesque churches of Lombardy, but no other building exhibits such a complex network. Thanks to recent developments in laser scanning technology, the until now neglected galleries could be surveyed with great precision in the scope of the current investigations (Figure 4). These untouched passages provide fresh evidence about the original appearance of the Basilica which will be discussed in the next section.

2.2 *Eastern part*

This part of the church was likely built between the late 1260s – marked by the laying of the foundation stone of a radial chapel – and 1310, date of the second translation of the relics to the new part of the church (Table 1). The timber domes and attics of this zone were destroyed by fire in 1749. An unusual secondary transept, covered by a dome and two cross vaults, is connected to the older part of the church at the centre of the western transept's gables (Figure 2). In this area, a construction joint is clearly visible between the two transepts at the level of the balustrades, highlighting two different building phases. The diameter of the dome overhanging the presbytery (13.95 m) is noticeably smaller than the western ones (14.30–14.48 m), although its thickness (37–39 cm) is comparable to the others (32–43 cm). On the north side, the transept is flanked by the Chapel of the Madonna Mora, usually considered – and this hypothesis is seriously challenged by ongoing analyses – as the remaining part of an older Church of Mary.

Beyond the two campanile towers, the choir is covered by a 15-part vault on top of which stands another timber dome dated by archives to 1424. The structure of this choir surrounded by an ambulatory with radial chapels is likely inspired by French Gothic churches such as Notre-Dame in Paris or the Cathedral of Chartres. A closer source of inspiration might have been provided by the Basilica of St Francis in Bologna (1236–1263), an early example of Italian Gothic. Based on those dates and the architectural similarities, Heinemann (2012) does not exclude a transfer of builders from Bologna to Padua.

The tower collapse of 1394 inevitably damaged the choir area, yet the extent of the ensuing reconstruction is still unclear. Dellwing (1975) suggested that the choir and the ambulatory were torn down and largely rebuilt. He supported the hypothesis of a previous two-level ambulatory, from the observation that the bases of the towers exhibit arches bearing traces of an open gallery. In another vein, Bresciani Alvarez (1981) suggested that the previous ambulatory's vaulting reached the same level as the radial chapels, like in St Francis's in Bologna. However, a close examination of the masonries does not reveal traces of major modifications of the current ambulatory. Moreover, such arches do not necessarily correspond to an opening: they could also enable a load transfer from the tower to the underlying pillars. Similar arches may for example be observed on the tower of the church of St Francis in Udine (1260–1266). At the current stage of the investigations, it seems that the reconstruction was rather limited to the vaulting of the choir.

Lastly, the Chapel of the Relics was built in the first half of the 18th century where stood the fifth radial chapel, providing the Basilica with a final dome. Interestingly, its timber roof structure and those rebuilt after the fire of 1749 do not differ greatly from the medieval models. Compared to the more elaborate details applied in the neighbouring church of Santa Giustina in the early 17th century, the timber structures of St Anthony mostly rely on simple lap joints fastened by large iron nails.

3 L'INTRICATO LABIRINTO

3.1 *A rational network*

The upper corridors running through the arches and buttresses of the western part of the Basilica connect the attics of the domes to the side aisles, to the

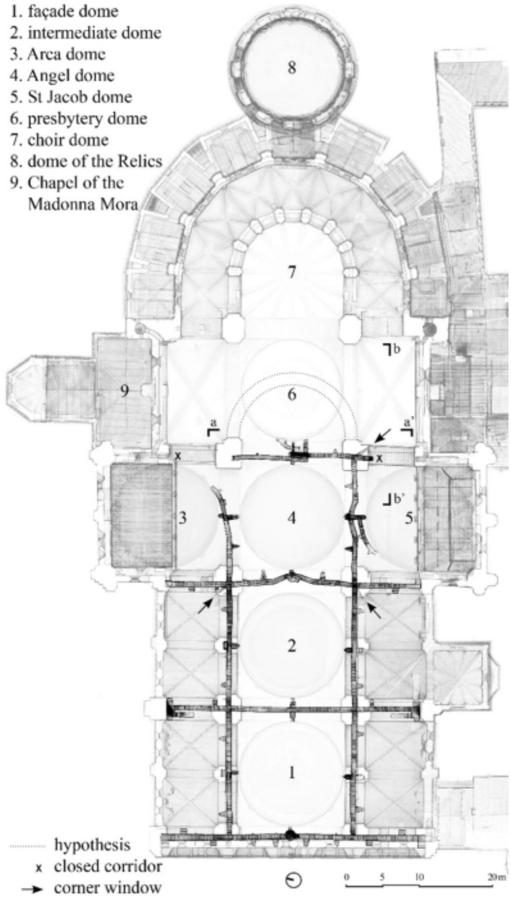

Figure 4. Basilica of St Anthony, plan of the intermediate attics and the upper corridors (drawing: author).

balustrades of the western transept (obsolete after the construction of two chapels) and to the upper gallery of the façade (Figure 4). Another corridor is situated a few metres below in the front façade to access a lower gallery and, via a small staircase, the cloister on the south-western corner of the church.

Once precisely surveyed, this network appears much more rational than the confusing labyrinth experienced onsite and presented as such in literature. A first observation of these 60–90 cm wide corridors reveals a remarkable continuity between the arches and the buttresses, hence disqualifying the possibility of a single-nave predecessor. To bring light into these dark and steep passages, medieval masons opened a series of tiny windows, the position of which is a key to understanding the original plans. Indeed, around the façade and intermediate domes, the longitudinal corridors are illuminated from the outside by two lower windows and a central upper one, positioned just below the Lombard band (Figures 1–4). On the opposite side of each gallery, a small central window opens towards the inner side of the domes, lit by four larger windows placed above each pendentive. The situation is different around the Angel dome, where there are no lateral light sources. However, as the upper part of this dome features no less than 18 windows (Figure 3), light was brought into the corridors from the inner side by simply switching the direction of the lower openings towards the interior. Moreover, the perilous crossings between perpendicular staircases at the junction between the nave and the transept are illuminated by dedicated corner windows (Figure 4).

The implacable logic behind this original network of passages in symbiosis with the system of arches and buttresses – as their wisely arranged openings – supports the idea of an earlier T-shaped basilica crowned by five domes (the tau cross, associated with St Anthony of Egypt and later adopted by St Francis of Assisi, would have drawn a clear distinction from the Basilica of St Mark). Hence, these observations reinforce the hypothesis that the domes were planned from the start of the construction. The theory that the masonry shells were already in place for the translation of 1263 is not impossible, though still uncertain at this stage.

As previously discussed, the connection between the two transepts marks different building phases, separated by a visible joint at the level of the balustrades. In light of the rational arrangement of corridors, the easternmost passage is revealed to be of utmost importance to picture the appearance of the Basilica before the addition of its eastern part. This corridor is abruptly interrupted on its southern end by an open arch in the transept's wall. Only a one-layer brick wall prevents the drop from the corridor into the transept. A similar interruption can be observed at a lower level in the northern arm of the transept, where a corridor used to connect the balustrade to the ground floor, thereby closing the circuit. These interruptions, together with the unusual profile of the pillars, indicate exactly where the previous wall of the transept stood.

Furthermore, a series of bricked-up openings following the logic described above has been recorded on the eastern side of the upper corridor (Figures 5 and 6).

Thanks to the accuracy of the digital survey, their positioning within the overall brickwork can be appreciated for the first time. Firstly, a corner window similar to those on the opposite side of the transept shows that the original construction continued further to the east. Its perfect alignment with the lower support indicates that the latter likely once formed an exterior corner pilaster. Secondly, a few steps higher, a lateral window provided additional light to this corridor. Above the centre of the arch and perfectly aligned with the previous opening, a final window confirms that an external wall stood here. Since there are no openings on the opposite wall, builders clearly counted on this side to illuminate the passage. Thirdly, between these two windows, a door seemingly provided access to a roof, connected to the body of the church between these three openings and the lower arch. On the left side of this door, inside of the construction joint, a blind arcade of the typical Lombard band type can be

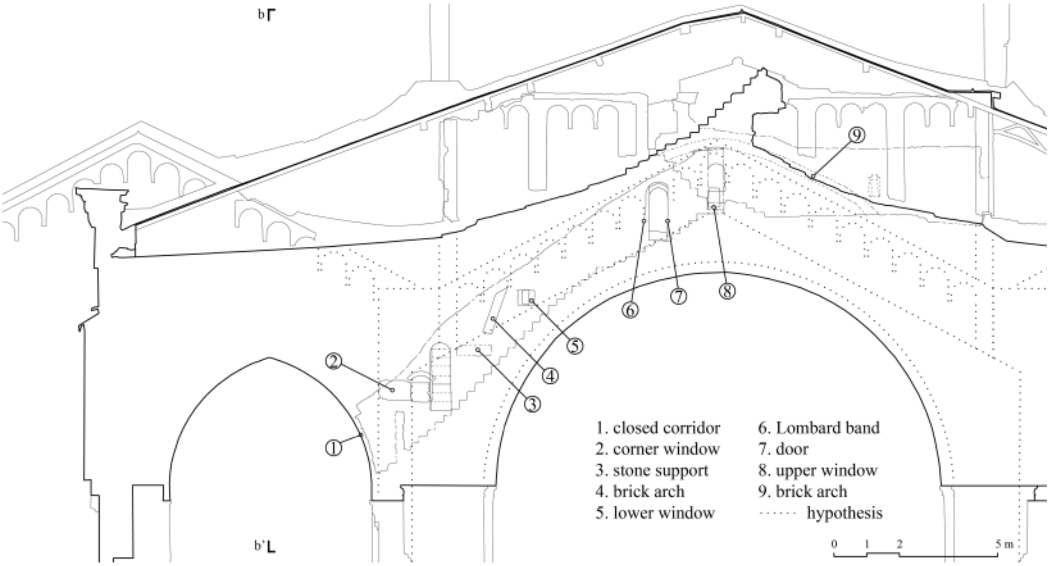

Figure 5. Basilica of St Anthony, transversal section a–a', looking west (drawing: author).

observed. This important hint provides further proof of an exterior wall, and also a means to position the rest of the arcade. Moreover, the first steps of a spiral staircase are visible at the level of the ridge, suggesting the presence – or at least the planning – of a third small tower on the eastern side of the Angel dome. Both the radius and the shape of the stone steps indicate that it was similar to the two central towers on the west.

A last noteworthy observation concerns the western side of this corridor, where a brick arch corresponding to the higher pendentives of the Angel dome can be seen in two places. Shortly below the landing of this arch, a large stone was inserted into the masonry to diffuse the load. These structural features contemporary to the rest of the lower masonry confirm that a higher dome above the crossing was planned well ahead but not raised subsequently.

3.2 *Hypothetical plan*

The analysis of the brickwork tends to indicate that the original plan consisted in a T-shaped basilica covered by fives domes: two above the nave, one above each transept arm and a higher one on the crossing. Furthermore, the openings in the eastern gable suggest that the plan likely ended with a semi-circular apse covered not by a full dome, but rather by a simple roof. This apse was probably similar to the one of the Basilica of St Mark in Venice (Figure 3) and covered by a half masonry dome. This common architectural feature can be observed not only in St Mark's but also in other nearby Romanesque churches such as Santa Sofia in Padua, the Cathedral of Verona or the Cathedral of Modena. Beyond a hypothetical silhouette proposed here, the precise appearance of this apse is still, and will certainly remain, undefined. Yet a ground-penetrating radar survey might provide valuable insights into its original floor plan.

At this point, a more precise picture of the *varia et inmensa mutatio* recorded around 1310 emerges: it could refer to the piercing of the first transept walls and the demolition of the apse, as final steps of the enlargement works started around 1265 with the construction of radial chapels. The municipal financing of 1307 would have thus helped accelerate the final junction between the two parts of the church. From a structural point of view, it cannot be ruled out that, after the completion of the new choir and campanile towers, the eastern transept was erected around the existing apse, a sequence which would have encroached less on liturgical activities. This practical way of proceeding would also explain the very unusual presence of this transitional space now referred to as a second transept.

4 BRICKWORK

4.1 *Mensiochronological analysis*

The above investigation has provided a first set of evidence leading towards an original T-shaped plan. This hypothesis can now be contrasted with a preliminary analysis of different brickworks applied in various parts of the building. The dating of bricks based on the evolution of their dimensions and arrangements was progressively established in Italy with the works of Kleinbauer (1968), Mannoni (1984), Pittaluga and Quirós Castillo (1997), Varosio (2001), Causarano (2017) and others. In Padua, a mensiochronological curve was drawn by Scillia (2011) based on the survey of 11 buildings (40 to 50 bricks per case study). According to this study, the dimensions (height × width × length) averaged 5 × 12 × 27 cm in

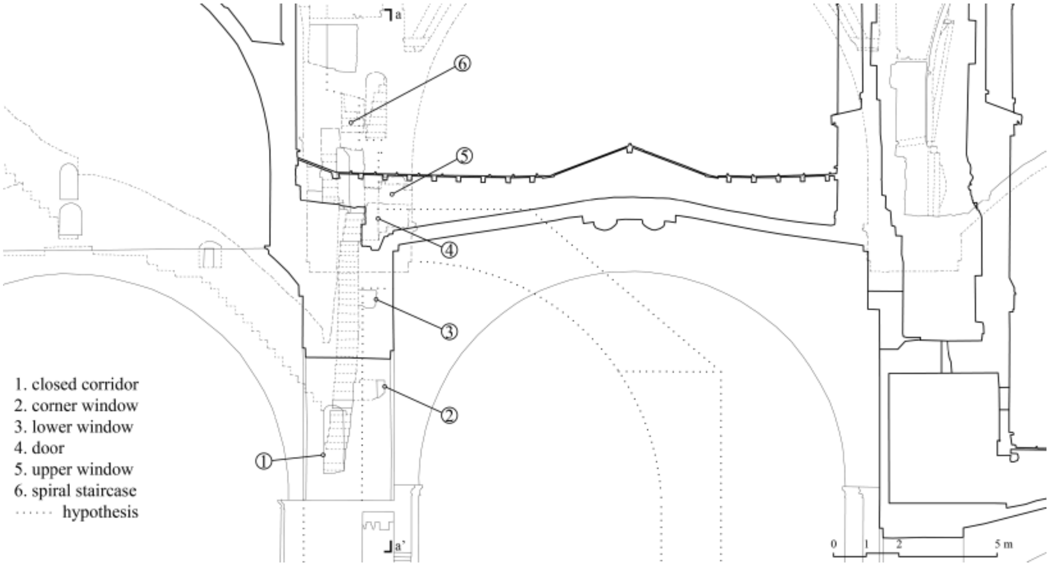

Figure 6. Basilica of St Anthony, longitudinal section b–b′, looking north (drawing: author).

the 14th century and had increased by about 2 cm in all directions by the end of the 15th century. Unfortunately, the start of the curve is flawed by an erroneous dating of the Chapel of Luca Belludi (1382), making further comparisons delicate.

In the scope of the present study, a first analysis of brickworks was performed on 10 homogeneous parts of the Basilica: on the exterior drums of the domes, on the eastern transept and on the lower part of the southern tower. As a first step, sample areas including about 200 to 300 bricks were redrawn on the high-density point cloud with a precision estimated to 3 mm. Each wall was surveyed on two separate positions to exclude local repairs and anomalies; only one sample is presented here for the sake of clarity. The resulting frequency distribution of brick dimensions can be represented by two curves (vertical and horizontal measurements) peaking three times: these turning points provide the height, width and length used to characterize brick formats (Figure 7). Each brick pattern can be further described by its module, defined here as the median height of five bricks and four mortar joints. Clearly defined bond patterns do not emerge at the current scale of the survey, except on the 18th-century Chapel of the Relics where layers of headers alternate with layers of stretchers.

The resulting overview reveals a remarkable stability of formats from one side of the Basilica to the other. Even the bricks of the Chapel of the Relics fit within a close range of sizes of 4.7–5.4 × 11.2–12.2 × 25–26.7 cm. This result, which obliterates a dating based on the sole record of brick dimensions, can likely be explained by the financing and ensuing surveillance of the construction site by civil authorities from 1265 onwards. Municipal statutes already referred to standard formats in 1236 and 1277. That second year, an official model for brick moulds (still visible on a corner of the Palazzo della Ragione) was enforced in the furnaces firing the bricks of the Basilica (Heinemann 2012).

Beyond this apparent uniformity, the distribution of sizes reveals a second level of information: whether masons mostly used entire bricks (steep peaks) or smaller fragments (flat peaks). From this point of view, the dome of the presbytery shows a much higher proportion of intermediate formats. Moreover, the module of this drum is higher than in any other surveyed part of the church: it averages 28.8 cm and, locally, up to 35.1 cm. Hence, this set of evidence tends to allocate the dome of the presbytery to another building phase which seemingly made a more extensive use of salvaged bricks. A last observation concerns the proportion between headers and stretchers. In the western part of the Basilica (from the façade to the *Arca* dome), the proportion of headers exceeds half the number of stretchers. In contrast, the number of stretchers is much higher on the walls forming the eastern part of the building (from the presbytery dome to Chapel of Relics). On the latter chapel, stretchers are even more numerous than headers.

The outcomes of this mensiochronological analysis are thus perfectly in line with the previous hypothesis. At this stage, one can indeed confirm that the masonry of the presbytery dome differs from those on the western side, not only in terms of overall diameter as previously discussed, but also in terms of modules and proportion between headers and stretchers. This last parameter can also contribute to delineating the Basilica in two distinctive parts. However, these preliminary conclusions still have to be contrasted with a broader analysis of brickwork on the entire church, covering much larger sample areas. To this end, automated tracing techniques based on photogrammetric surveys will be applied to entire façades, using recent

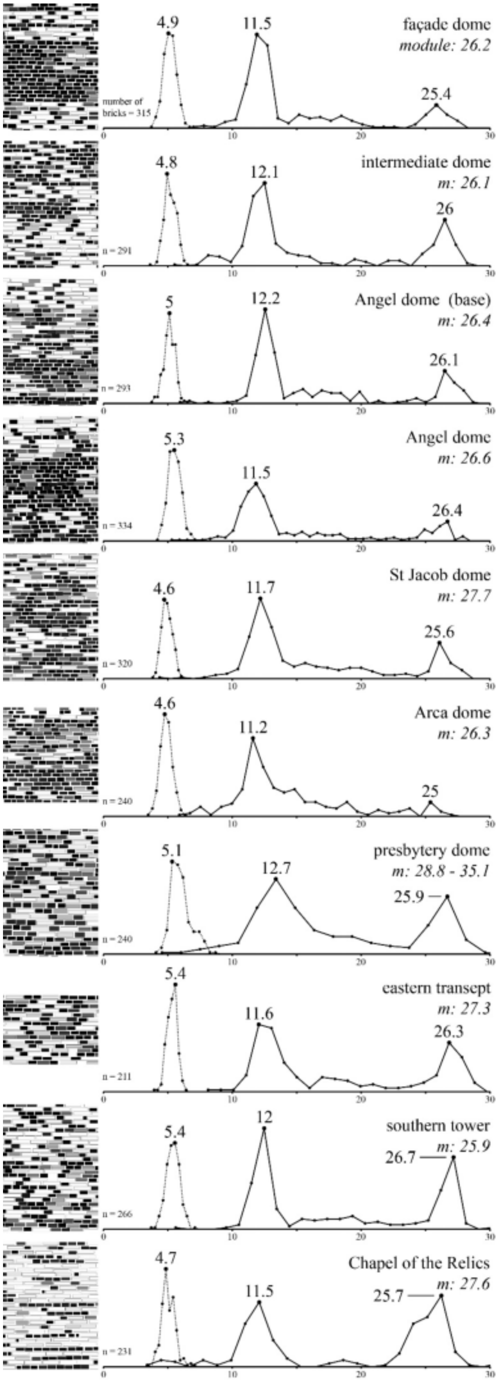

Figure 7. Distribution of brick dimensions (height, width, length) in different parts of the Basilica of St Anthony. Module = 5 bricks + 4 joints. All dimensions in cm.

tools developed at ETH Zurich (IDB) (Potgeter in press). Finally, the erection techniques of the plastered dome shells are currently being investigated based on thermal imagery. For example, detected traces of timber centerings might provide yet another key for establishing a chronology.

5 FURTHER STEPS

Beyond deepening the survey of the original brickwork discussed in this paper, simultaneous investigations focus on the absolute dating of different parts of the Basilica. A second campaign of dendrochronological analyses should irrevocably date the erection of the western domes untouched by the fire of 1749. Moreover, original boards of spruce used for the vaulting of the corridors are currently being analysed in the hope of dating the construction of the walls in which they are embedded. Due to the lack of dendrochronological curves for spruce in 13th-century Veneto and Trentino, those could not be dated in a straightforward way with this technique. Samples will thus be collected for radiocarbon dating at the Laboratory for Ion Beam Physics (ETH Zurich).

Such ^{14}C analyses will also be applied to mortar samples collected from all over the church. Since organic material has already been detected in the mortar, one can hope for a successful dating of the lower brick structures of the Basilica. Moreover, the chemical composition of these mortar samples will be determined, which could offer an additional key to reading the construction sequences.

Finally, numerous testimonies of medieval building techniques (e.g. tool traces, stonecutter's marks, scratches on bricks, inscriptions, transport marks or traces of scaffoldings) are systematically being recorded. Contrasting these observations with current hypotheses based on accurate onsite surveys and absolute dating could portray a very detailed picture of the successive construction sites and the evolution of building techniques from the 13th to the 18th century. A three-dimensional model of the church is currently being prepared to visualize these findings and test various scenarios.

6 CONCLUSION

The Basilica of St Anthony begins to reveal its secrets. Driven by advanced surveying methods and absolute dating techniques, the present research provides fresh insights into the construction techniques, the architectural influences and the dating of the emblematic brick church.

The analysis of the original brickwork puts forth an original T-shaped basilica generally inspired by the model of St Mark's, featuring five domes and a semicircular apse. As proposed in the present paper, this apse was likely demolished around the turn of the 14th century to make place for an eastern part started in the mid-1260s.

These preliminary results obtained in a relatively short time confirm the soundness of the approach and place the answers to the next key questions within reach, namely the dating of the domes (masonry and timber) and the remodelling of the eastern part after the collapse of a tower. In this perspective, the present study paves the way for an unequivocal dating of this major pilgrimage landmark, together with a finer understanding of medieval building techniques in Northern Italy.

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Two- and three-dimensional geometry in tierceron vaults: A case study of the cloister at Norwich Cathedral

N. Webb, J. Hillson & A. Buchanan
University of Liverpool, Liverpool, UK

ABSTRACT: The cloister at Norwich Cathedral has one of the most contested construction histories in English medieval architecture. Built in 1297–1430 under a succession of patrons and master masons, the cloister's complex building sequence has invited a wide range of interpretations by architectural historians. However, these discussions have rarely taken account of the two-dimensional and three-dimensional geometry of the tierceron vaults above. A key exception to this is the work of Robert Willis (1800–75). This paper uses a variety of digital surveying and analytical methods to re-examine the concept of the middle plan and its potential as a tool for comparing forms and geometries in medieval vaulting. By considering the potential implications of the observations made for the building's construction sequence, the paper represents a comprehensive re-evaluation of the middle plan as a method for architectural study, suggesting new directions for research both for the cloister and construction history more generally.

1 INTRODUCTION

In his 1842 essay "On the Construction of the Vaults of the Middle Ages", Robert Willis introduced the concept of using a "middle plan" to analyse the geometries of medieval vaulting. This method involved taking a horizontal section of the vault at the midpoint of its height, using the points of intersection with the rib intrados lines to plot a pattern corresponding to its specific three-dimensional form. The resulting middle plan was used as a comparative tool for identifying similarities and differences between the designs of individual bays, most notably in his study of the tierceron vaults of the cloister at Norwich Cathedral in East Anglia. Begun in 1297 and completed by 1430, this cloister was the product of a long and complex construction process including many changes in design distributed over several generations of patrons and master masons. Through detailed measurements taken using rods and plumb lines, Willis attempted to use the middle plan to quantify these changes graphically, identifying a sequence of four distinct forms corresponding to the cloister's east, south, west and north walks (Figure 1).

The following discussion is an attempt to reassess the middle plan and its usefulness as a comparative method for analysing forms and geometries in medieval vaulting. The starting point for this is a digital survey of Norwich Cathedral Cloister conducted using a terrestrial laser scanner under the "Tracing the Past" project at the University of Liverpool (www.tracingthepast.org.uk), a far wider series of investigations into the design and construction of vaults in England between the 11th and 16th centuries.

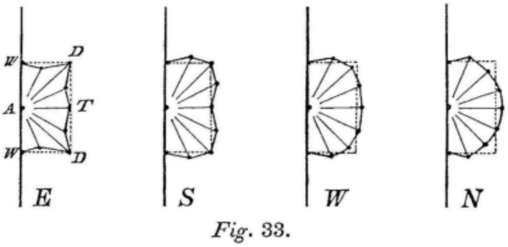

Figure 1. Norwich Cathedral Cloister, middle plans drawn by Robert Willis, published 1842.

By converting our scans into 3D models, we were able to analyse the vaults at Norwich in unprecedented detail, extracting a wide range of geometrical data relating to their plans, dimensions and rib curvatures. This data was then used in conjunction with the middle plan to compare similarities and differences between individual bays, allowing us to identify at least eight distinct designs within the north, south, east and west walks (Figure 2). Focusing on the 12 regular bays within the cloister's east walk (labelled E1–E12 from north to south), this paper examines how digital techniques can be used to investigate the relationship between the middle plan and the two-dimensional and three-dimensional geometries of medieval vaulting. In the process, it demonstrates how such a method can be used for identifying constructional differences between individual vault bays, as well as its implications for interpreting the wider building sequence and chronology of the cloister at Norwich.

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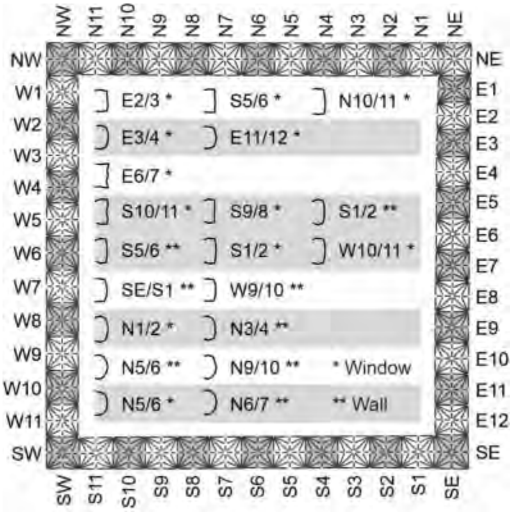

Figure 2. Norwich Cathedral Cloister, vault plan.

2 CHRONOLOGY

The chronology of Norwich Cathedral Cloister is one of the most contested in the history of English medieval architecture. This is in part because the evidence relating to its dating and construction sequence is not only extensive, but often inconclusive and at times can even appear contradictory. Surviving documentary records vary greatly in their level of detail, architectural and archaeological investigations have identified numerous points of significance in its material fabric and the stylistic developments in its window tracery and sculpture have invited diverse interpretations by architectural historians. The difficulty of interpreting this evidence is further compounded by the iterative nature of the cloister's construction, with each bay consisting of a series of a separable elements that could have been designed, manufactured and installed at different stages of the building's history (Figure 3).

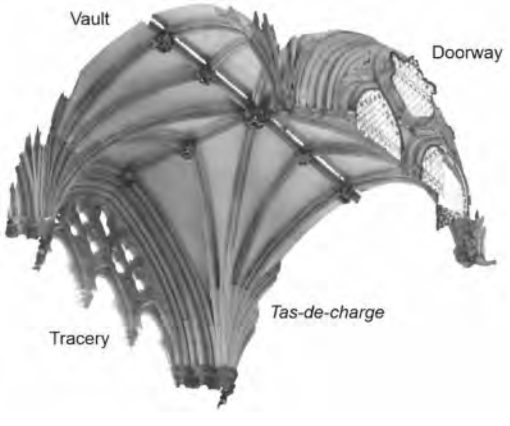

Figure 3. Norwich Cathedral Cloister, bay E7, mesh model, perspective view facing northwest.

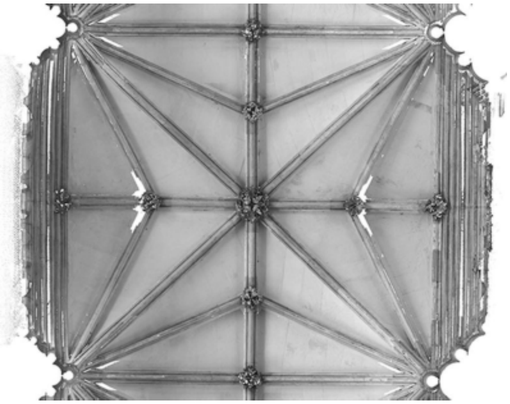

Figure 4. Norwich Cathedral Cloister, bay N7, orthophoto.

The outer walls were provided by the previous Romanesque fabric of the cloister and the surrounding buildings, defined by the treasury, chapter house and dormitory on the east side, the refectory to the south, the guest house to the west and cathedral church to the north (Harris 2015). These were refaced in ashlar masonry and the floor level lowered, resulting in the installation of a seat and Purbeck marble columns. The forms of these were echoed on the window side of the cloister, which open out onto an approximately square garth (Figure 2). Above the capitals are the *tas-de-charges* for the vault above, which in the east walk appear to have been integrated into a single block along with the springers for the wall arch. This implies that both were planned and executed as a cohesive unit, presumably including the buttresses beyond. The window tracery, however, (as well as the numerous doorways on the wall side) may have been designed and installed separately, as might the wall above with its small window openings and the wooden roof. Lastly, the vaulting was not necessarily installed at the same time as the *tas-de-charge* stones. Consequently, though many aspects of the vault's design would necessarily have been set out at this earlier stage, others such as the style and iconography of the boss sculptures may not have been conceived until considerably later.

Given the variability of the evidence in the material fabric and the frequent ambiguity of the documentary records, it is unsurprising that a wide variety of interpretations of the building's chronology have been proposed. The earliest dates from the Middle Ages, consisting of an account in the cathedral's Primum Registrum written at some point between 1430 and 1558 (Fernie 1993: 166–67). This provides a date range of 1297–1430 for the cloister, stating that work began with the entrance to the chapter house followed by the adjoining three bays (E6–E8), with the rest of the east walk (NE-E5, E9-SE) and the first ten bays of the south being built under Bishop John Ely (John Salmon) (S1–S10). The account was based on a variety of documentary sources some of which are still extant, the most notable being the apologia of John Worstead which gives a date range of 1313/14–1329/30 for the south walk. This evidence was picked up by the historians Eric Fernie and Arthur Whittingham (1972, 1993), who suggested that the whole east walk was completed 1297–1314, starting with E6–E8 (1297–99), before moving south (E9-SE) and concluding with the northeast corner (E5-NE) (1299–1314). Francis Woodman (1996), by contrast, proposed a separation between the execution of the vaulting and the walls below, with the walls being completed ca.1297-1309 and the vaults constructed after a significant gap in the works, advancing sequentially from E7–E9 (ca.1316–17) to E10-SE (ca.1317-19) to E5-NE (ca.1327-29). Veronica Sekules (2006) concurred with Fernie and Whittingham regarding the walls, but suggested a revised date of 1320-30 for the vaults based on the sculptural style of its bosses. This dating was questioned by Paul Binski (2015), who proposed an earlier date of 1297-1315 for the vaults E6-SE and 1315-20 for E5-NE. These positions have been further challenged by Robert Hawkins (2019), who has identified a slower, more iterative set of changes in sculptural style with the bosses, dating the vaults of E6-E8 to 1297-1305, E9-SE to 1305-10 and E5-NE to 1310-14. However, none of these approaches have attempted to take account of the variations in underlying geometry between the vault's bays, something which can only be accomplished through detailed measurement and analysis.

3 VAULT PLANS

The starting point for any geometrical survey of a medieval vault is its plan. By taking digital laser scans at strategic points throughout the cloister, we created detailed point cloud models made up from hundreds of thousands of individual measurements for each of the vault bays. These were then converted into mesh models and imported into Rhinoceros, an advanced 3D modelling software platform, where the intrados lines of the ribs could be re-traced in three-dimensions, producing wireframe models that were then converted into best fit arcs to quantify their curvatures. The resulting point clouds, mesh models and wireframes could then be exported as orthographic representations, producing a set of detailed and highly accurate plans for the purpose of comparison between bays.

All four walks of the cloister at Norwich are covered by a relatively simple tierceron vault (Figure 4). Wall ribs and transverse arches provide the boundaries of the bay, with the remaining vault surface being divided up by diagonals and tiercerons that rise to meet the longitudinal and transverse ridge ribs. The design is remarkably consistent throughout the cloister, with only minor differences occurring from bay to bay. The principal point of variation is in the orientation of the tiercerons. Though our analyses of tierceron vault plans at other sites has often revealed the use of proportional systems for laying out rib patterns, this does not appear to be the case at Norwich. The point of intersection for the tiercerons along the ridge rib does not correspond to any known proportional division of the vault's plan, and the extended intrados lines do not converge on any other defined point within its boundaries (Figure 5). Instead, the intrados lines converge on points just beyond the apexes of the transverse and longitudinal arches. While similar methods of construction have been observed elsewhere in English medieval vaults, these largely made use of circular geometries, a method which does not seem to have been used at Norwich. Furthermore, the degree of deviation from the vault plan in these external points of convergence varies considerably from section to section, leaving it unclear exactly how the orientations of the tiercerons were derived. One possibility is that they were determined by the radial cuts flanking the boss stones rather than a single point, with the changes in angle corresponding to variations in masonry. Another is that it represents a more ad hoc optical correction to the vault's form, analogous to the minor geometrical manipulations which we have previously identified in the choir and nave vaults at Exeter Cathedral (Buchanan & Webb 2019).

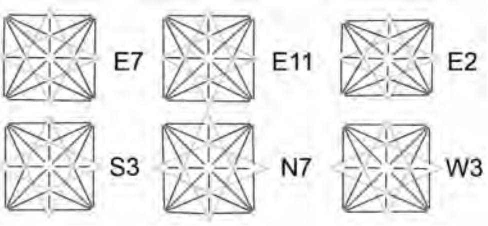

Figure 5. Norwich Cathedral Cloister, vault plans with best fit arcs (black) and tierceron intrados lines (grey).

Throughout the vaulting of the east walk, the layout of the tiercerons is relatively consistent, with the main differences being in the proportions of the individual bays. Bay sizes are variable throughout the cloister, with differences appearing both between walks and internally within them. The south walk is perhaps the most consistent, with approximately square bays averaging 4.05 m on the longitudinal axis (east-west) and 3.97 m on the transverse axis (north-south). By contrast, the vaults in the east walk are slightly wider in the transverse direction (averaging 4.15 m) and the distances spanned by the longitudinal axis vary considerably from bay to bay. The longitudinal dimensions of bays E5-E11 sit at a consistent average of 3.93 m, but those of bays E4 and E12 (average 3.75 m) and E1-E3 (average 3.39 m) are significantly smaller. This has long been ascribed to the location of the chapter house entrance, as this is slightly offset from the position which would be necessary for an even distribution of the bays.

If E6-E8 are the earliest part of the walk to be constructed as has been suggested, then it appears that the initial set of dimensions were continued southward for as long as possible, with some compression being required to span the uneven gaps left at the north and south ends. Yet whilst the dimensions of the vault plan might vary from bay to bay, the fundamental geometry on which it was based appears to have remained fairly consistent through its 133 years of construction, especially within the east walk.

4 MIDDLE PLANS

Such consistency in two-dimensional geometry does not seem to have extended into the vault's three-dimensional form, which can differ significantly from bay to bay. The most straightforward means of visualizing these changes is provided by the middle plan, which could be drawn digitally using Rhinoceros. Starting with the wireframe models of intrados lines traced from the cloister vaults, we identified a horizontal plane at the midpoint between the apex height and impost level given by the abaci of the capitals below. The "section" command was then used on the wireframe, identifying the points of intersection between the plane and the rib intrados lines. These points were then connected together to form a two-dimensional plan, which could then be exported as a more accurately measured digital equivalent of the middle plans produced by Willis. Whilst the height of the ridge rib does fluctuate slightly from bay to bay, the resulting sections nevertheless provide a reasonable method for identifying formal changes within a run of vaulting, their particular forms corresponding directly to the differences in their geometry and proportions.

Detailed study reveals a range of different types of middle plan within the confines of the east walk alone (Figure 6). Bays E5-E9 share a common pattern, with the diagonals taking the distinctive form of prominent spikes. It was this which was the middle plan identified with the east walk by Willis (1842), suggesting that the bay which he selected lay somewhere within this run (Figures 1 and 2). The *tas-de-charges* connecting E9 to E10 and E4 to E5 are both transitional, one half reproducing the plan of E5-E9 and the other the more rounded form found in bays E11-E12. This rounded type can also be found at the intersection between E3 and E4, but for E2 to E3 the middle plan changes again, taking on a new, more rectangular form. Sections of the ribs taken at the level of the abacus reveal that all of the *tas-de-charges* in the east walk had a similar pattern at their springing point, yet as the ribs rose their curvatures began to diverge. As the underlying geometry of the vault plan was relatively similar throughout the east walk, there were therefore only two possible causes for these changes in three-dimensional form: differences in bay sizes or differences in the curvatures of the ribs.

5 RIB CURVATURES

As our far wider study of medieval English vaults has demonstrated, the majority of ribs in medieval vaults were laid out in two dimensions as curves constructed through simple geometrical operations. Using the best fit arcs derived from the tracing process described above, we were able to extract geometrical data for each of the vault ribs in Norwich Cathedral Cloister, specifically their springing points, spans, notional apex heights, radii and the vertical and horizontal positions of their centres. Through fixing some of these variables in advance, vault designers were able to provide a set of parameters within which a rib's curvature could be defined, deriving the remaining variables by selecting an appropriate geometrical method. Through studying the patterns presented by these geometrical data, we were able to propose hypotheses regarding the design process for each rib within the cloister. Each vault's hypothetical design process was then modelled digitally and the resulting wireframe compared directly to the traced intrados lines, allowing us to assess its accuracy both in terms of geometrical data and visual congruity. Through a rigorous process of trial and error, we were able to discover at least three different geometrical designs within the east walk alone, as well as number of minor variations from bay to bay.

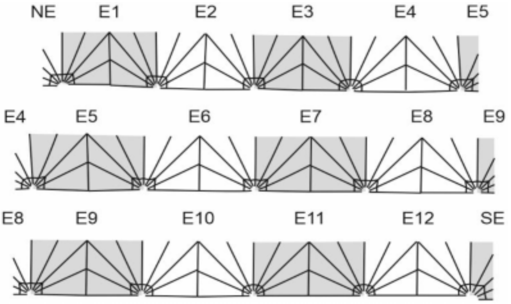

Figure 6. Norwich Cathedral Cloister, east walk, window side, middle plans.

Perhaps the earliest of design of vaulting can be found in E6-E8, the three bays which directly front the entrance to the chapter house (Figure 7). The apex height of the longitudinal ridge appears to have been defined in advance (average 2.07 m), though it is not at present clear exactly how it was derived. The springing points and spans for each rib would have been defined on the vault plan, perhaps using 1:1 scale drawings conducted on a tracing floor or another large two-dimensional surface (Pacey 2007). For the transverse ribs (AF, BG, CF and DG), the centre appears to have been positioned on the plane of the impost, suggesting that they used the "chord method". This involved constructing the perpendicular bisector of a chord drawn between the apex and springing point of the rib, defining the centre using the line's point of intersection with the impost level. The same method appears to have been applied to the longitudinal ribs (AE, BE, CH and DH), though the apex heights of these are slightly higher than the ridge in order to accommodate the window and wall arches below (average 2.17 m). A similar radius to the transverse ribs can also be found in the tiercerons (AJ, AK, BJ, CK etc.), but the level of the centre also approximates that of the impost. Either the chord method was used again, or the "three circles" method was used to transfer the radius from rib to rib. This involved drawing two circles of a defined radius centred on the apex and springing point of the rib, with the lower point of intersection between them giving the missing centre. For the diagonal ribs (AZ, BZ, CZ and DZ), the best correlation which we found involved using the "two chord" method. This involved defining a third point along the circumference of an adjacent rib's curvature, in this case the transverse rib. Using the vault plan, the horizontal position of this third point could then be projected orthogonally, allowing it to be relocated along the diagonal rib's span. By constructing the perpendicular bisectors of the two chords formed by springing point, third point and apex, it was possible to define the centre using the intersection between the two perpendicular lines. When viewed in section along the vault's tunnel, the result would be a similar apparent curvature for the two ribs, although not an identical one. This hypothesis is further supported by the middle plan, in which the position of the diagonals and transverse ribs can be located fairly closely along the same line perpendicular to the wall, strongly suggesting that the third point was located roughly at the midpoint of the vault's height.

The same design appears to have been used for bay E9, but from E10 southwards the geometry of the diagonals changes. When tracing their curvatures, it quickly became apparent that the rib intradoses could not be reproduced using a single centred arc. Instead, it seems more likely that they were designed using a two-centred arc. However, this possibility introduced the problem of how to identify the point of transition between the two curvatures. Focusing on bay E11, we adopted a parametric approach to testing, creating best fit arcs by dividing the traced data incrementally at 5% intervals of the vault's apex height. The closest results were found markedly above the level of the middle plan, situated firmly within the 55–65% margin (~1.14–1.35 m). Yet the problem with this approach was that it was based on a theoretical point defined mathematically and did not take account of the physical structure of the masonry. By using orthophotos, photographs and other survey data, we were able to identify the horizontal and radial cuts of the component *tas-de-charge* stones and voussoirs for each of the diagonal ribs. By transferring the positions of these cuts onto the traced intrados lines within Rhinoceros, we were able to test the effects of constructing best fit lines divided at different joints. The closest match which we could find between model and reality was produced by defining the point of transition at the first radial cut of the *tas-de-charge*. This varied considerably from bay to bay, but was usually within the 55–65% margin that had previously been observed. It therefore seems likely that the lower curvature of the diagonal was applied to the *tas-de-charge*, with the upper belonging to the voussoirs above.

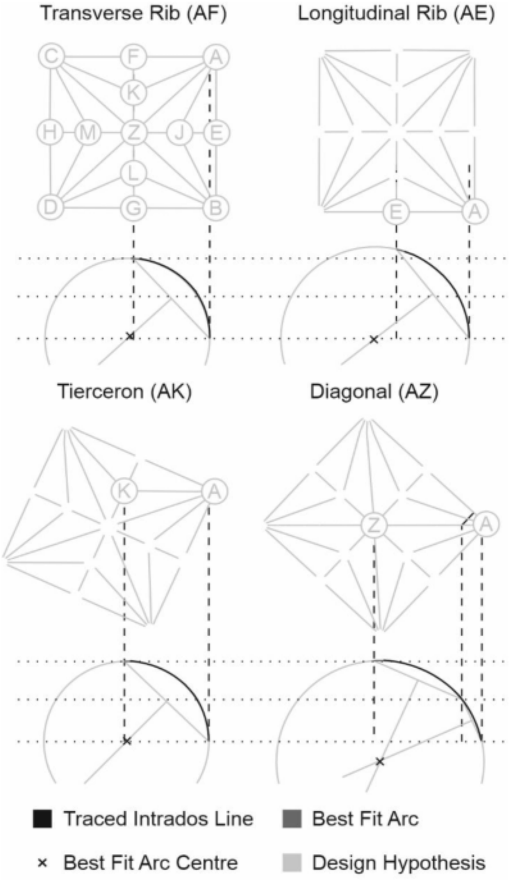

Figure 7. Norwich Cathedral Cloister, bay E7, rib geometry.

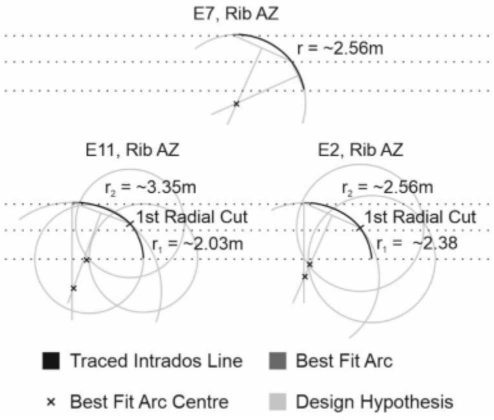

Figure 8. Norwich Cathedral Cloister, diagonal rib geometries.

As the lower radius of the diagonals in E10-E12 is close to that of the transverse arches and tiercerons and the centre appears to be on the impost level, it is likely that it was set out using the "two circles" method (Figure 8). This involved drawing a circle of

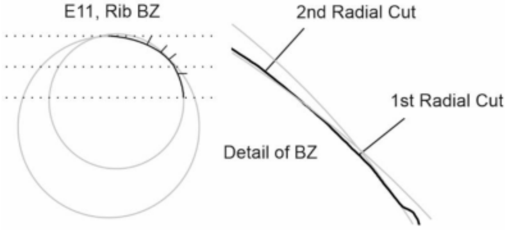

Figure 9. Norwich Cathedral Cloister, diagonal rib geometries.

the previously defined radius centred on the springing point, using its point of intersection with the impost to define the centre. The point of transition would then be set according to the *tas-de-charge*, providing an effective springing point for the upper curvature of the rib. However, the derivation of the upper radius is more difficult to define. While the best fit arc does generally fit the traced data closely, it consistently pulls away slightly as it approaches the point of transition to the lower arc (Figure 9). This raises the possibility that there may have been some kind of transitional block or voussoir between the two arcs. However, such a disparity would also be consistent with many of the best fit lines we have constructed for single-centred arcs, and could therefore be either an inherent flaw in the retracing process or the result of some form of settlement. The closest result which we found for reproducing the upper curvature involved constructing a segmental arch, using a variation of the chord method where the centre was defined by the intersection between the bisector and a vertical line descending from the apex of the rib.

The process described above marks a significant departure from the methods proposed by Willis (1842), who set out two more complex geometrical processes for ensuring a smooth transition between the two curvatures. However, when these were tested using parametric modelling, the results for the east walk were very different from the traced intrados lines. Closer inspection of the diagonals reveals that there is a sharp, visible disjunction in curvature between the upper and lower arcs.

A more complex situation can be seen at the north end of the east walk. As in the case of bays E9-E12, the vault in bay E5 follows the same design as E6-E8, and the diagonals in E4 are modified to reproduce the same geometry as E10-12. In bay E3, however, the setting out method for the diagonals appears to have changed again, with the southern half corresponding to those in E4 and the northern half employing an entirely different two-centred curvature (Figure 8). The lower radius is significantly larger than those on the south, approximating the radius of the longitudinal rib, and the level of the centre is significantly below that of the impost. This suggests that the three circles method may have been used, with the radius being transferred from the longitudinal rather than transverse arches. It is not clear how the apex height of this lower curve may have been derived in this instance, but the upper radius appears to have been set out using the same segmental arch method as that used in bays E10-E12.

The differences in geometry described above correspond precisely to the differences in middle plan between the vault's bays. However, geometry is not the only feature to change between these sections, as the longitudinal dimensions of the bays in E1-E3 are radically different to those in E4-E12. By using parametric modelling, we able to investigate the relative effects of changes in geometry and changes in bay size on the form of the middle plan. The resulting models demonstrated that the effect of the bay dimensions on the middle plan was relatively negligible, suggesting that it was the geometry which was the principal difference in three-dimensional form between the different sections of the walk.

6 CONCLUSIONS

As the preceding discussion has demonstrated, the middle plan remains an effective means of identifying changes in the design process and constructional technique between individual vaults. Digital surveying and analytical techniques allow for fast, accurate comparison between vault bays, allowing a far more detailed comparison of sections and three-dimensional geometries than was possible using analogue methods. Our study of the cloister at Norwich has revealed a far more graduated series of design changes than Willis' original investigation had identified, further complicating the contested design sequence of this building. Whilst the evidence does support the traditional sequence starting with E6-E8 then advancing southwards before continuing north, the disparity in middle plan and geometry between E4-E3 and E3-E1 suggests a more convoluted design and construction process than has hitherto been suspected, perhaps taking the form of an additional interruption in building at *tas-de-charge* level within bay E3. Whereas it has often been supposed that architectural designs were particular to individual master masons, the transitional forms of the *tas-de-charges* at E9/E10 and E5/E4 suggest that they were instead quite capable of reusing old designs even whilst in the process of adopting their new replacements.

Though the reasons behind these design changes remain inscrutable, some possibilities are suggested by details in the material fabric. If there was a significant gap between the installation of the *tas-de-charge* and the vaulting, then a division between two curvatures at this level for diagonals could be advantageous as it would allow for more flexible adjustments at a later stage. Such a change may have been prompted by a flaw within the original bays, as the window side *tas-de-charge* stones for bay E7 include evidence of later modifications to increase their height (Woodman 1996). However, as the transitional voussoirs in bays E10-E12 demonstrate this was not always successful, an observation which may well have prompted the further changes found in bays E3-E1. Alternatively, it may simply have been an attempt to modulate the vault three-dimensional form through geometrical manipulation, perhaps in order to obtain a specific optical effect.

A final point arising from this study is that the middle plan is not solely a modern analytical tool, but may also have had a degree of real design value for medieval masons. Though it remains unlikely that middle plans were actually drawn out during the design process, the use of the two-chord method in bays E6-E8 suggests that the midpoint of a vault's height could at times be a significant part of the design process. Something similar could also be argued for the two-centred arcs, though the point of transition which defined them was more variable and usually significantly above the level of the middle plan. It is possible that further study of the cloister and other sites may reveal the involvement of additional types of level-based geometry in setting out rib curvatures, with the middle plan serving as a critical means for identifying the methods involved.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Vaults, centring, and formwork of the Late Gothic period in Southern Germany

C. Voigts
Eidgenössische Technische Hochschule Zürich, Zurich, Switzerland

ABSTRACT: The construction of Gothic rib vaults not only required centring for the ribs, but usually also substantial formwork for the masonry of the vault compartments. In the Late Gothic architecture of southern Germany, characterised by vaults with elaborate networks of ribs and advanced building technology, formwork could be largely reduced. At the same time, the centring for the ribs became more complex. This article presents evidence of such auxiliary constructions from various buildings, including the remains of a 15th-century centring that was discovered reused in the roof of a church. Advantages and implications of the constructions are discussed in order to better understand the reasons for the technological changes.

1 INTRODUCTION

In the course of the 15th century, the construction of Gothic vaults in southern Germany underwent considerable changes. Some innovations in the architectural form of the vaults are evident: the French-style, quadripartite rib vault, which had predominated in German religious architecture of the 13th and 14th centuries, was replaced by vault forms with a more complex network of ribs. Important impulses came from designs that Peter Parler realised in Prague during the second half of the 14th century. Parler varied the traditional scheme by inserting additional ribs (liernes) that subdivide a bay into more and smaller compartments, forming decorative patterns such as rhombic figures. The patterns often extended beyond the borders of the bays and thus began to dissolve the strict order of the vaults in favour of a more unified spatial impression. This paved the way for the development of Late Gothic vaulting in southern Germany. In the 15th and early-16th century, the invention of increasingly complex and sophisticated vault forms with star-shaped and reticulated figures led to magnificent buildings such as the churches in Landshut, Munich, Nördlingen and Ingolstadt.

Less obvious than these changes in the architectural form of the vaults are innovations in their construction. As is generally assumed, ‘figurated’ vaults of the Late Gothic period – in contrast to the older quadripartite rib vaults – could be built without formwork. The reduced size of their webs undoubtedly facilitated such a technique. However, it is not clear whether there was a direct causal connection between the formal and constructional changes, i.e. whether these developments were interdependent. The motivation for abandoning the use of formwork is also not quite clear. Was it just a matter of saving expenses for the woodwork?

In the following, evidence from various buildings is presented that sheds light on the use of formwork and centring. This will provide a basis for discussing the reasons for the developments described.

2 VAULTING WITH FORMWORK

A well-known example of the construction technique of 13th- and 14th-century vaults is Regensburg Cathedral, where significant traces of the building process have been documented (Schuller 1989, 206-8; Schuller 2016, 473-4). On the intrados of the vaults, imprints of boards demonstrate that the brick masonry of the webs was built on a formwork. The boards were closely spaced so that the bricks could be laid in a bed of mortar. After stripping the formwork, the coarse intrados was covered with a smooth plaster.

In the nave, the lateral vault compartments directed towards the clerestory have a relatively large span of up to 6.4 m at the crown. Here the boards of the formwork had to be supported by additional planks, which rested on the diagonal ribs and the ribs of the clerestory. For this purpose, bedding holes were cut into the upper rims of the ribs at intervals of about 50 cm. The holes were observed only in the upper part of the ribs, where the masonry of the webs is inclined at an angle of less than about 50° and thus needed additional support. Further down, a simple formwork of boards was probably sufficient, whereas the steep parts of the webs at the springing could most likely be built without any formwork at all.

Another important observation in Regensburg, characteristic of vaulting on formwork, is a slightly sagging shape of the webs. As Schuller (2016, 474) convincingly explains, this sagging already occurred during the bricklaying process, when the formwork

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began to bend under the increasing weight of the masonry. Only after the last bricks were inserted and the vault was completed did the structure arrive at a more or less stable state. Interestingly, it is this sag that Fitchen (1961, 115–8) predicted in his discussion on formwork of French Gothic cathedrals and that made him argue for a vertical arrangement of the boards instead of a flat one. Whether the French vaults, which unlike those in southern Germany were executed in stone masonry visible from below, actually have such a sagging form can only be determined by precise measurement.

The vaulting technique attested at Regensburg Cathedral is characterised by a formwork that rested on the stone ribs. Thus, the shape of the vault was primarily defined by the ribs. Even though the webs were built on a formwork, a certain tolerance in their shape had to be accepted due to the flexibility of the boards. The layout of the ribs, on the other hand, was precisely determined by a wooden centring, which in this case has left no traces, but must be assumed with certainty.

This method of vaulting on a formwork supported by the stone ribs was probably widespread in southern Germany during the 13th and 14th centuries. Evidence of a similar construction method can also be found in Switzerland, for example in the former church of Klingental Monastery in Basel (Figure 1). The vaults of the chancel were probably erected in the late 13th century (Schwinn & Jaggi 1990, 14). Here, the intrados of the webs does not abut exactly on the upper edge of the sandstone ribs, but is rather located a few centimetres above them (Figure 2). The gap between the rib and the intrados, which is filled with plaster, is mostly about 3–4 cm; towards the top of the vault, it increases to about 5–6 cm, while it decreases towards the bottom and disappears completely just above the springing. Evidently, the gap originates from boards that were put on top of the ribs to serve as a formwork. The boards could have rested only on the outer edge of the ribs, leaving a sufficient support for the webs in the middle of the rib.

Dismantling such a formwork may not have been easy. Only after the uppermost boards had been removed in some way or another, could the lower ones be pushed upwards in the resulting groove and then taken out. Finally, after the formwork was dismantled, the remaining groove was closed with mortar and plastered, as was the intrados of the webs.

3 VAULTING WITHOUT FORMWORK

It is commonly accepted that figurated vaults in Germany were built without the use of formwork (Bürger 2007, 322, 348; Nußbaum & Lepsky 1999, 176). This becomes apparent from their shape, which is characterised by a multitude of spherically curved webs, as for example in St George's Church in Nördlingen (Figures 3 and 4). While this is not always easy to perceive from below, a glance at the extrados makes it clear. It would be extremely complicated and inefficient to realise such a shape on a formwork. On the contrary, the slightly dome-shaped form of the webs allows them to be constructed without formwork. In this way, each course of the brickwork forms an arch spanning from one rib to another.

Figure 1. Klingental Monastery, Basel. Vaults of the former chancel during restoration (photo: author).

Figure 2. Klingental Monastery, Basel. Detail of the vault, the white marks indicating the gap between the rib and the intrados (photo: author).

As soon as an arch is completed, it becomes quite stable and can support the subsequent arch.

In southern Germany, Late Gothic vaults were almost exclusively executed in brickwork, with ribs of stone or terracotta elements. The lime mortar used at that time needed considerable time to set, usually a few weeks. However, the freshly prepared mortar instantly had sufficient adhesive strength to allow a smooth vaulting process. To improve adhesion, special bricks for vaulting were produced. Endres Tucher, for example, mentions in his *Baumeisterbuch* from Nuremberg from the years 1464–75 that sawdust was added to the clay for these bricks (Lexer 1862, 95). In

Figure 3. St George's Church, Nördlingen. Vault above the chancel, easternmost bay seen from below (photo: author).

Figure 4. St George's Church, Nördlingen. Vault above the chancel, extrados of the easternmost bay (photo: author).

this way, the porosity and thus the capillary effect of the bricks were increased.

This construction method, which was brought to perfection in the course of the 15th century, made very thin vaults possible. In most cases, the brickwork consists of stretcher courses, and thus the thickness of the shells is equivalent to the width of a brick, i.e. only about 14–18 cm. Because of the relatively light weight of these structures, there was no need for an extensive system of buttresses. This reduced the structural requirements and the costs of vaulting projects at the same time. All this certainly contributed to a veritable boom in vault construction in the late-15th and early-16th centuries, when vaults could now be realised in numerous older buildings that had until then remained without such a covering.

4 COMBINATION OF METHODS

The advantages of vaulting without formwork could lead to the idea that this technique, once it was established, completely replaced vaulting with formwork. An example that this is not the case is provided by the Church of Our Lady in Ingolstadt. This magnificent building, which is almost 90 m long, was vaulted by Hanns Rottaler in just one year, from March 1503 to March 1504 (Hemmeter 2007, 137–8). The vaults above the nave and chancel have a span of about 11 metres. Basically, their shape is that of a barrel vault with pairs of lateral lunette compartments and a rib network creating patterns of large rhombic forms. There is evidence that the individual compartments were built with different construction methods (Voigts 2015, 246–50). In a contour plan of the extrados that was created from a 3D laser scan, the ribs become visible as shallow steps (Figure 5). Some of the webs have a cylindrical, slightly sagging shape, which – as we have seen – is characteristic of vaults built on formwork. Others are slightly dome-shaped and must therefore have been built without formwork. This is also confirmed by the structure of the masonry: in the compartments presumably built on formwork, the bricks are laid in horizontal, radially-inclined stretcher courses typical of this kind of construction. In the dome-shaped sections at the apex of the vaults, by contrast, the brick courses form sloping arches.

However, these latter sections were probably not built entirely without auxiliary constructions. A few shallow kinks, which are only faintly visible in the contour plan but were also observed when inspecting the intrados from a scaffolding, indicate that some minor supports were used. They must have had the form of segmental arches; probably they were composed of boards. In addition to serving as support, they would also have helped the bricklayer during construction to create a uniform vault shape. The large lateral vault compartments were probably also executed without formwork. This is suggested by the fact that in their lower portions the brick courses are not horizontal, but slope upwards from the lateral wall to the diagonal rib.

A shallow kink in the apex of the compartments indicates that another thin, supporting element might have been positioned there during construction (Figure 5).

The question of how exactly the above-mentioned formwork was constructed cannot be answered with certainty in this case. Very likely, its boards were not placed on the ribs as in the case of Basel, since the profile of the ribs would hardly allow such an arrangement. The upper side of the stone ribs, which was examined in a small sondage opening, is indeed bevelled at its outer edge (Figure 6). However, the resulting space between rib and brickwork, 3–4 cm deep and 2–3 cm high, does not appear to be sufficient as a bedding for the boards. It therefore seems more likely that the formwork was attached to the centring of the rib. The question of how this centring might have been constructed, so that it could possibly have supported the formwork, will be discussed in a moment.

The finding that specific compartments of the vaults in Ingolstadt were built on a formwork is in contrast to the common opinion that figurated vaults were generally erected without such an auxiliary construction. In fact, the way in which both methods were combined

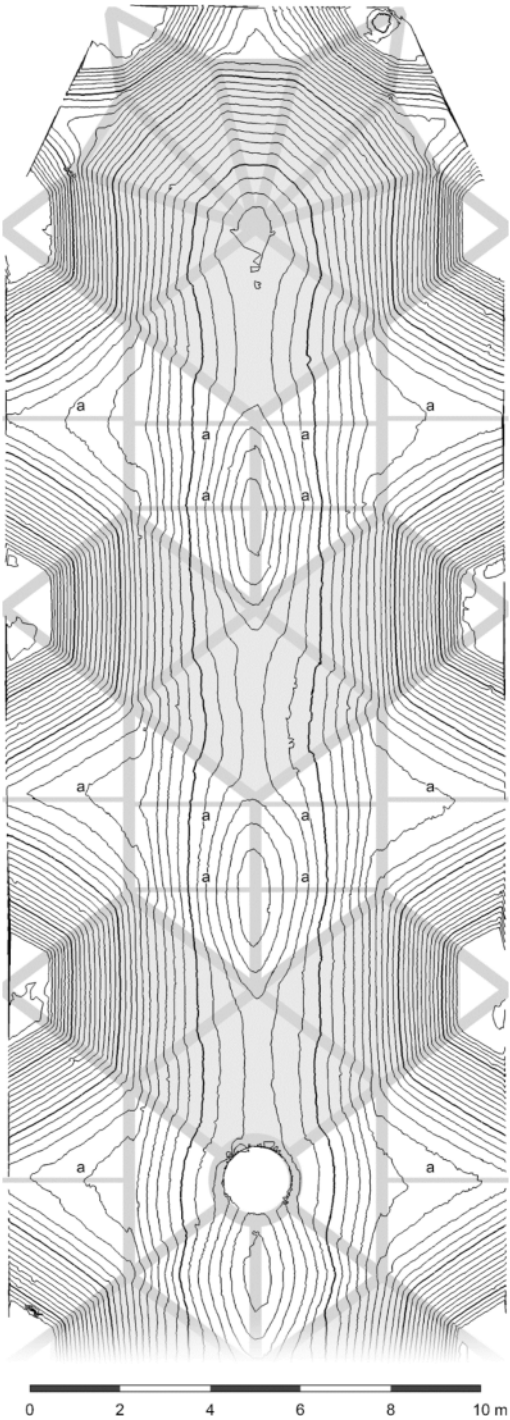

Figure 5. Our Lady's Church, Ingolstadt. Vaults above the chancel, contour plan of extrados, contour interval 0.1 m. Grey lines indicating the centring for the ribs and additional supports (a), light grey areas indicating formwork (graphic: author).

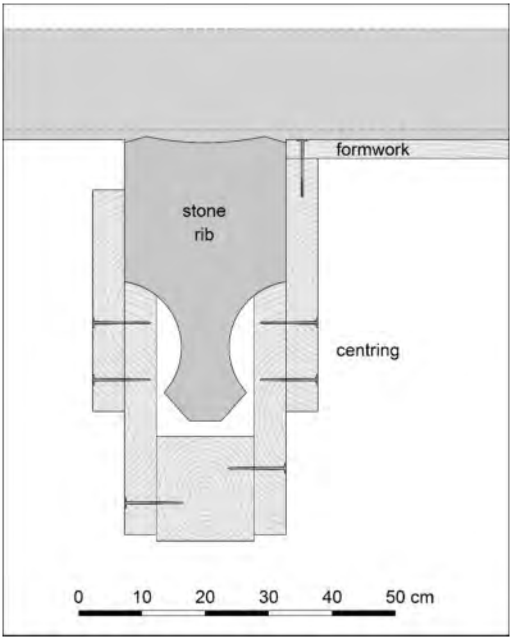

Figure 6. Our Lady's Church, Ingolstadt. Vaults above nave and chancel, hypothetical reconstruction of centring and formwork (drawing: author).

here suggests a careful planning, which aimed at an efficient and safe construction process and a saving of material at the same time. It becomes tangible how the master builder took into account the workflow on the construction site and the costs when he designed this building. Artistic and technological considerations were coordinated and brought into harmony with each other.

5 CENTRING

Our idea of what medieval centring might have looked like is strongly influenced by Fitchen (1961). Based on the broad rib profiles of French cathedrals, Fitchen proposed a pair of arches made of squared timber as support for each rib. Such massive centring was certainly not necessary for the figurated vaults of the Late Gothic period in Germany. Here, the spans of the centring and its wooden arches were much shorter, since usually a support by a vertical post can be assumed for each rib intersection. This is because the construction of the centring intersections could hardly have been accomplished in any other way. Furthermore, the existence of such vertical supports is suggested by measurements of vaults, which showed that the intersections systematically have a more precise height definition than the rest of the ribs (Müller 1990, 161–2; Wendland 2015, 77–8; Wendland 2019, 14–5). As a consequence, depending on the density of the rib network, the centring often had to span only about 2–3 m from one post to the next, especially in the central sections close to the crown of the vault.

Another aspect relevant to the centring is that the ribs of the 15th century generally have a profile that tapers significantly towards its bottom, where it ends in a narrow bar or even a sharp edge. For such ribs, a centring with a U-shaped cross-section would be preferable, so that the rib elements could be set into a channel.

All these general considerations would suggest that the centring for Late Gothic vaults consisted of arches that were composed of boards rather than squared timber. Two or three layers of boards nailed together with staggered joints could form a very stable girder. This could easily be constructed in the shape of an arch with an intended radius. As already proposed by Kotrba (1961, 211), two such arches made of boards together with some wooden spacers in the middle would have provided a very efficient centring (cf. Figure 6). Structures of this kind were actually realised as is shown by the large quantities of boards and iron nails explicitly listed for the construction of centrings in building accounts of the 15th and early-16th centuries (Mai 2014, 161–3).

In any case, the economic and technical prerequisites for such constructions were given in the 15th century: boards, which until the 12th and 13th centuries had to be manufactured with great effort either by splitting or sawing by hand, could increasingly be produced in water-powered sawmills in the Late Middle Ages. In Augsburg, for example, it is documented that several sawmills existed as early as the 14th century (Finsterbusch & Thiele 1987, 105). In consequence, boards became the more and more inexpensive building material that we know them as today.

The fact that the centring for figurated vaults usually implied short spans and could be realised with relatively light wooden arches does not necessarily mean a saving of timber. The reduction of material that was possible for the individual arches was most likely cancelled out by the greater number of arches, but above all by the vertical supports that had to be installed at close intervals. Presumably, even the timber saved by omitting the formwork was compensated by these supports – depending on how they were constructed.

6 SUBSTRUCTURES OF CENTRING

In connection with the centring, the building accounts frequently mention a large quantity of undressed timber, which was obviously used for the vertical supports (Mai 2014, 161). As long as the vaults were not particularly high above the ground, these poles could simply be placed on the floor. But at a height of more than about 8–10 m, which was easily reached when vaulting churches, two or more of these poles would have had to be joined together. Such joints are often imagined to have been made simply with rope, similar to those of historic scaffolding. But this would have compromised the stability and precision that the vertical posts were supposed to give to the vault construction.

Figure 7. St Jacob’s Church, Wasserburg. Timber reused in the roof above the nave (photo: author).

Figure 8. St Jacob’s Church, Wasserburg. Timber reused in the roof above the nave (photo: author).

For this reason, the existence of a working platform at the level of the springing has been postulated, which would have served as a base for the vertical posts of the centring (Wendland 2019, 16–7). Of course, such a platform would have had to be very stable and immovable so that no deformations could occur during the vaulting process. Possibly it could have been supported by the lateral walls; however, relatively strong beams would have been required to span the entire width of the vaults without sagging. Alternatively, a wooden substructure could have supported the platform, but it would have had to be constructed with squared beams and carpentry joints to provide the required stability.

Evidence of a wooden structure meeting the latter criteria was recently found in the roof of St Jacob’s Church at Wasserburg (Voigts 2020, 61–2). In the roof above the nave of the church, which dates from 1414 or a little later (Gschwind 2012), a substantial reinforcement was subsequently installed. This secondary structure is partly made of wood that shows obvious traces of reuse (Figures 7 and 8). Empty mortises and sockets of lap joints, some of which still contain wooden pegs, demonstrate that the beams had previously been used in a different context.

At the same time, the form of the joints indicates that the timbers, which are now laid horizontally, were arranged vertically in their first use. Since the beams still have a considerable length of 7.10–7.80 m, they must have originally belonged to a relatively high construction. Particularly interesting is the chronology of their primary and secondary use: dendrochronological dating has revealed that the trees that the beams were made from were felled in the winter of 1449–50 (Gschwind 2012). The reuse in the reinforcement of the roof occurred only three years later, in the spring of 1453, as we learn from building accounts (John & Nadler 2007, 76). Obviously, in the original construction, the beams were in use only for a short time. It therefore seems reasonable to assume that they were parts of some kind of auxiliary construction that was only used during a building process. Strikingly, the dates of the felling and reuse of the timbers coincide quite precisely with the beginning and completion of the vaulting of the chancel of St Jacob's (Voigts 2020, 62). However, the beams are certainly not components of a conventional scaffolding. The careful execution with elaborate carpenter's joints would rather correspond with the idea of a solid working platform described above.

7 CONCLUSION

As we have seen, Gothic rib vaults in southern Germany were usually built on formwork. Vaulting without formwork, which has a long tradition in other regions of Europe, seems to have been introduced here only in the late-14th or early-15th century. The exact circumstances of this development, when and by whom the impulses were given, are not clear at the present state of research.

The reason why vaulting without formwork prevailed in Late Gothic times is probably not that the wood for the formwork could be saved. This advantage was offset by the greater expense of the centring with its dense network of wooden arches and vertical supports. But the thin and relatively light vaults that could be erected with the help of this network did not require massive buttresses. All in all, the lower structural requirements are likely to have made vaulting with this method more efficient.

If we also include the scaffolding for the masons in this consideration, it becomes clear that an enormous amount of timber was necessary for vaulting – regardless of the method. Finally, this is also confirmed by the findings from St. Jacob's Church in Wasserburg, which suggest the existence of a solid working platform carefully constructed by carpenters. Temporary structures of this kind, erected with great precision, were the basis for the construction of the Late Gothic vaults that we still admire today.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The frame vault of the anti-refectory in the Olivetan Abbey of St. Nicholas in Rodengo Saiano

C. Stanga
Politecnico di Milano, Milan, Italy

ABSTRACT: The paper describes the frame vault construction technique of the anti-refectory of St. Nicholas Abbey in Rodengo Saiano, the oldest still-functioning Olivetan monastery founded by the Cluniac Order in the 11th century in the province of Brescia. The vault covering the anti-refectory is one of the first examples of 16th-century frame vaults, widely disseminated in Northern Italy, that mirrors the Renaissance wooden-coffered ceilings with painted panels surrounded by brackets. Flat vaults cover the space between the brackets and the central panel. This type of vaulting was usually built-in masonry and easily constructed, using light centering. However, the anti-refectory is covered by a mortared rubble vault, which raises some questions about constructing this vaulting type. The understanding of the vault construction technique is carried out through historical research, geometric, thermographic, photogrammetric surveys, and 3D modelling.

1 INTRODUCTION

Frame vaults have been widely disseminated in Northern Italy, mainly in Lombardy and Piedmont, since the second half of the 16th century. They are characterized by brackets or skene arches that divide the space to be covered with different vaulting types, mainly flat or surbased barrel vaults or cloister vaults.

Around the second half of the 16th century, wooden ceilings started to be replaced by vaults, even on the noble floor. The transition was accompanied by the transfer of shapes and construction typical of wooden structures to the masonry. The first examples are cloister vaults or cloister vaults with a central panel (*volta a schifo*), which mirror coffered ceilings through paintings and stucco moldings. Later, wooden ceiling structures and shapes were re-elaborated for the brick-masonry, through vaults with brackets or arches supporting flat lunettes. The construction technique was then refined by forming a frame-band structure made of brackets or arches that divided the room into different spaces that could be covered by different types of vaulting. Studies on frame vaults are missing in architectural literature, although some studies are going in this direction (Dusi 2008; Grimoldi 2009).

The paper aims to shed further light on frame vault construction techniques by analyzing the covering of the anti-refectory of St. Nicholas Abbey in Rodengo Saiano, founded by the Cluniac order in the 11th century, the oldest, still-functioning Olivetan monastery in the province of Brescia. The anti-refectory and the frame vault are part of the 16th-century renovations of the building complex. The vault construction technique is compared to other Lombardy examples, derived from literature and the research carried out by the author, examining the particular case of Rodengo Saiano since the vault is mortared rubble and not the more common brick-masonry.

2 BRICK-MASONRY FRAME VAULTS IN NORTHERN ITALY

2.1 *Some notes about frame vaults in the architectural literature of the 16th-17th century*

Frame vaults are characterized by skene arches or brackets built from one wall to the other, resulting in a frame-band structure covered by different vaulting types. Guarino Guarini wrote one of the first descriptions of frame vaults in his treatise *Architettura Civile*, published posthumously in 1737: "Compartisco adunque la Camera, e vado tirando da muro in muro, o in quadro, o per linea diagonale varie fascie, le quali facciano in se stesse qualche compartimento, e poi gli spazj, che rimangono, riempio di diverse Volte secondo la capacità del campo […] Questa maniera mi ha somministrato una gran varietà di Volte, le quali fanno nobilissima vista, e lasciano campi egregi per la pittura" (Guarini 1737: 189). The term "*fascia*" is geometrically described by the architect as a part of a semicylinder (barrel vault) or a semicone, which are cut by two parallel planes (Figure 1). Guarini highlights that frame vaults are particularly suitable for paintings, especially framed easel paintings (*quadri riportati*).

Bernardo Vittone, the editor of the Guarini treatise, pointed out that the "*fascie*" could be built at both the intrados, forming the frame-band structure, and at the extrados, creating light vaults with limited thickness (tile vaults): "sono alla sussistenza delle Volte di gran

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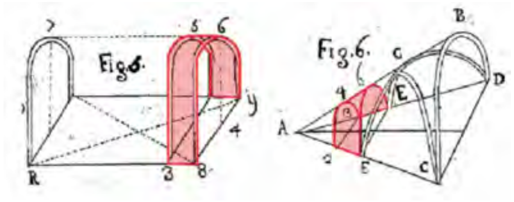

Figure 1. "Fascia" (or arch) derived from a semicylinder and "*fascia obbliqua*" derived from a semicone by Guarino Guarini 1737 (Lastra XIX, figs. 5–6).

sussidio le fascie, che a discreti intervalli si sotto, che sopra in quelle si pratican [. . .] sicchè più non restando in questi necessaria tutta la grossezza dal sostegno della Volta senza fascie richiesta, colla diminuzione, che dell'eccesso fare ad essi si può, egualmente che con quella delle Volte stesse, men dispendiosa a render se ne viene la lor costruzione" (Vittone 1760: 506).

2.2 *Brick-masonry vault distribution*

Frame vaults have been primarily documented in 17th-18th-century architecture in Piedmont (Piccoli 2001), also known as *fascioni* vaults (Passanti 1990). However, they were already scattered throughout Northern Italy, mainly Lombardy, starting from the second half of the 16th century (Grimoldi 2009).

Progressive use of vaults in buildings, even on the noble floors, gradually replaced wooden ceilings, started from the second half of the 16th century. The transition from wooden structures to brick-masonry involved integrating wooden ceiling shapes and models to novel formal and structural vaulted system experiments.

The assimilation was probably due to many reasons, such as the lack of wood for buildings, the need to build more comfortable spaces, and the economic benefits since masonry could last longer than wood.

The vast use of frame vaults in Lombardy is mainly found in Brescia and Cremona, where the oldest examples of frame vaults are documented. Around the 16th century, there had probably been the need to change from the elaborate construction of wooden ceilings to brick masonry.

Scholars referred to the "wood crisis" in the 17th century for the countries of Northern Europe. However, recent studies, such as the one by Pozzati (2012), highlight that the "crisis" was not due to a real lack of wood. It is much more likely that there was a conflict between the different uses of wood. Wood was used for forging iron in furnaces, manufacturing lime and bricks in kilns, for glassmakers, for plant dyes, for making various artifacts of every daily life (household tools, agricultural tools, furniture), and for heating. In the construction sector, wood was required as a building material (roofs, slabs, walls, vaults, intrados or extrados rods) for auxiliary (scaffolding) and non-load-bearing components (windows and doors) and interior fittings and furniture.

These different wood uses could be much more felt in a city like Brescia where wood was even used in the metallurgical sector, which made the city the most famous producer of weapons in Europe and was active in Val Trompia, Val Sabbia, and Val Camonica. Furthermore, Brescia was under the Republic of Venice's control and could probably feel a certain pressure from the Venice Arsenal that required wood to construct ships. In all the Venetian provinces of the mainland, oak wood was bound to the Arsenal's exclusive use, despite the various needs of the other regions.

Therefore, around the mid-16th century, it is possible that the need to optimize resources emerged including the reduction of the use of wood in construction. Frame vaults were easily and quickly constructed because the arches were made first, forming a band-like structure, then the vaults between them. They allowed material saving because one could use the same centering for each arch. Furthermore, one could save bricks if the vault was made *in foglio* (bricks arranged flat). Frame vaults make scenographic effects possible by maintaining a short rise, so they are suitable for ground floors or atria and in the case of building renovations, where rooms should usually keep a fixed height due to existing wooden slabs.

Comfort benefits of frame vaults, and vaulted structures in general, are described by Guarini when speaking about the problem of wooden ceilings that create dust and house mice (Guarini 1737: 190). Scamozzi, in his treatise, *L'Architettura Universale* (1615), highlights that vaults are more durable than wooden ceilings so that the cost-benefit ratio led to building vaults. Moreover, masonry vaults were safer against fire than wooden ceilings. Fire problems were very common from at least the end of the 16th century, but they would persist for the next two centuries and still found great resonance in the second half of the 18th century as proven by the well-known booklet by the Count d'Espié.

2.3 *Brick-masonry frame vaults in Lombardy between the 16th and 18th centuries*

During the second half of the 16th century, vaulted structures, especially cloister vaults and cloister vaults with lunettes or central panels (*volte a schifo*), were inspired by the shapes of wooden coffered ceilings, enhancing the integration between structure and paintings. The integration of structure and paintings was a typical feature of the so-called "Venetian ceilings" (Schulz 1968), such as the one realized by the Brescian artists, the Rosa brothers, around 1559, for the hall of the Sansoviniana Library in Venice. The construction integrates wood and stucco brackets, dentils, rosettes, and frames, with the central canvas in an octagonal frame by Tiziano Vecellio depicting the Allegory of Wisdom (Piazza 2016). A slightly later example is the wooden ceiling with the paintings by Paolo Veronese, realized around 1562, for the Church of St. Sebastian in Venice (Brusegan 2007). The wooden ceiling has circular, oval, and rectangular frames of dentils with canvases by Veronese.

The transition from wooden coffered ceilings to brick-masonry gradually took place, firstly by placing paintings on the vault intrados surface, in a more decorative way, then at a structural level with brackets or arches forming a band-supporting structure. The Large Apartment of the Castle in the Ducal Palace in Mantua, designed by Giulio Romano around 1536 for Duke Federico II Gonzaga, was enlarged under the Bertani prefecture (1549–76). The hall on the noble floor, which overlooks the Cortile dei Cani, located on the north-west corner, is covered by a surbased cloister vault with lunettes. The rectangular central panel is defined by small dentils, around an elongated oval. The remaining vault surface is decorated with stuccos and paintings.

The ceiling of the *caminada* (room with the fireplace) of Palazzo Avogadro (Spada) in Bagnolo Mella (Brescia) is a cloister vault with a central panel set on a dentil frame. The building was commissioned by Camillo Avogadro, Venetian leader and governor in Friuli, and was probably finished around 1560 (Lechi 1974: 298–321). Similar vaulted structures are found in two other buildings in Manerbio: in the *caminada* on the ground floor of Palazzo Luzzago, where the cloister vault with lunettes is characterized by a central panel with a dentil frame, dating back to the 16th century (Lechi 1979; Villari 2009); in the hall of Villa Il Castelletto, where a cloister vault covers the large rectangular space with a dentil frame (Masetti Zannini et al. 1999).

The vault of the *Sala delle Stagioni* of Palazzo Moneta in Belfiore (Verona) has an impressive decoration, represented in an extraordinary and rare preparatory drawing, made by Bartolomeo Ridolfi and Bernardino India, dating back to the second half of the 16th century (Zavatta 2015). The cloister vault with lunettes has an oval central panel and four circles tangent on the main axis, with dentil frames. The lunettes, the circles, and the central panel are painted with personifications of the four seasons, while the remaining part is decorated with floral patterns. India and Ridolfi adopted the same configuration for the cloister vault of the main hall of Palazzo Murari Bocca Trezza in Verona, whose construction was commissioned by the Counts Murari Della Corte Bra around the second half of the 16th century.

According to a procedure that refines the techniques and the structural aspects, the paradigm shift occurred when the wooden ceiling shapes and structures were reworked to form brick-masonry vaulted systems. One of the first examples is the frame vault on the ground floor of Palazzo Biondelli-Uggeri in Via dei Musei, Brescia (Lechi 1974: 40–45). The palace was built starting from 1554, on the foundations of a previous building. Around 1558 it was probably already finished (Jacks 1995). The revival of the ancient and Renaissance stylistic features of the façade is mirrored in the living room, characterized by a frame vault. The vault is made of nine compartments: a flat central panel surrounded by eight flat lunettes. Two pairs of brackets, cyma reversa profile, are placed on each side of the room, matching the lesene on the walls. Frescoes and stuccos embellish the vault. The vault model refers to the Gugliemo Gonzaga's studio wooden coffered ceiling in Palazzo Ducale, which is well-known thanks to a drawing in the Devonshire collection dating back to the 16th century, attributed to the well-known Lombardy artist, Giulio Campi (Grimoldi 2009). The drawing shows a square, coffered ceiling with two pairs of brackets for each side and a central panel with God, the Father, surrounded by angels. In the 18th century, Lord Burlington used the same drawing for building the wooden coffered ceiling of the Blue Room at Chiswick House (Kingsbury 2001).

Figure 2. Top: Frame vault of St. Sigismondo church refectory in Cremona: frescoes by Antonio Giuseppe Natali 1658. Bottom: Southern exterior wall with four end-plate anchors (red arrows).

Frame vaults in Northern Italy are mainly built in brick-masonry. The refectory of St. Sigismondo church in Cremona is covered by a frame vault, similar to the ceiling of the anti-refectory in Rodengo Saiano. The frame vault is characterized by five brackets on the longitudinal walls and two brackets on the transversal walls. The arrangement is similar to the Rodengo Saiano vault, but the compartments have different shapes: a central panel between three brackets on the longitudinal walls, two transversal compartments after it, and three-square compartments on the transversal walls. St. Sigismondo church was founded in 1463 on a former building that hosted the wedding between Bianca Maria Visconti and Francesco Sforza in 1441. The church has one nave with chapels on its sides, and it was embellished with frescoes by Camillo Boccaccino, together with Giulio and Bernardino Campi, starting from 1535. The church frescoes are one of the most important pictorial cycles of Mannerism in

Figure 3. Frame vault of the ballroom of Villa d'Adda-Borromeo in Cassano d'Adda (Milan), Arch. F. Croce 1765.

Northern Italy. The refectory was arranged around the beginning of the 16th century. In 1508, Tommaso Aleni painted the fresco of the Last Supper on the west wall. In 1511, other payments provide evidence of the building of the refectory ceiling (Gritti 2009). It is still challenging to understand whether the frame vault was built around the beginning of the 16th century or later. However, the decoration was painted by Gian Battista Natali in 1658, as proven by the inscription on one bracket, and it is a *terminus ad quem* for the vault construction (Maccabelli 2015). By looking at the intrados, no clue can be found about the vault construction technique, which should be deepened through a thermographic survey. However, the south exterior wall has no plaster, and it shows brick-masonry, helping to form hypotheses on vault construction technique. On the wall, in correspondence to the brackets, end-plate anchors are visible. Even if no tie rods are visible on the intrados, they may be located on the vault extrados, both from wall to wall and inside the brackets. The presence of tie rods inside the brackets (one vertical and horizontal and one curved) occurs in the frame vault of the hall of Palazzo Soncini in Provezze (Brescia), probably built around the 16th century (Giuriola et al. 1995; Grimoldi 2009).

The frame vault covering the main hall on the ground floor of Villa Obizza in Bottaiano (Ricengo, Cremona) is another example of frame vaults (Figure 2). The Villa was commissioned by Giò Matteo Obizzi, noble councilor of the city of Crema, and completed in 1702 (Dusi 2008). The vault consists of three brackets on the longitudinal sides and two brackets on the transversal ones. Surbased barrel lunettes cover the central panel and the spaces between the brackets. Bricks are arranged in a soldier course, bound together with earthen mortar, typical of Cremona. Mortar composition is an essential element for the construction of frame vaults. Lime could be added to the earthen mortar helping to set the brick during the construction.

Another example of a brick-masonry frame vault covers the ballroom of Villa d'Adda-Borromeo inCassano d'Adda (Milan) (Figure 3) (Stanga 2020). In 1781, the Marquis Giovanni Battista D'Adda commissioned architect Piermarini to renovate the Villa. He respected the general layout and the main building, defined by architect Francesco Croce around 1765. The frame vault covers the ballroom on the first floor of the main structure. Eight arches form the frame vault, four smaller and four larger, among which sixth surbased barrel vaults are built, two larger and six smaller, which support a central "elongated circle" panel (racetrack shape). The arches correspond to the wall lesene and are set on a frame that marks the upper floor level balconies, with iron-shaped parapets. Inspection of the extrados and the thermographic survey, carried out in September 2020, allows an understanding of the construction technique. Small brick walls (*frenelli*) with tie rods are aligned to the longitudinal wall arches. The four lunettes on the room's main axis are built with soldier-laid bricks parallel to the lunettes' axis. The bricks of the corner lunettes are arranged in diagonal courses, following concentric squares, showing how the vault arches could be used as guides on which movable or light centering set while building the lunettes.

3 THE OLIVETAN ABBEY OF ST. NICOLAS IN RODENGO SAIANO

The monastery of Rodengo Saiano, formerly dedicated to St. Peter, was founded by the Cluniac Order between 1090 and 1095 in Rodengo Saiano, Brescia. Many Cluniac monasteries were founded in the region between the Oglio and the Mella rivers (Franciacorta). Those became part of the sphere of influence of the Rodengo Saiano monastery, probably due to its strategic position (Figure 4).

After a period of decline (1399–1432), the monastery was renovated. The Olivetans, which followed the Benedictines in 1446, started the renovation from the second half of the 15th century. It is quite challenging to retrace the monastery history because the archive disappeared around the end of the 18th century when the Cisalpine Republic suppressed it in 1797.

However, thanks to historical research and stratigraphic analysis of the building complex, Breda formed hypotheses on the monastery construction phases (Breda 2000). Following Breda's hypotheses, the anti-refectory was built in the first phase of the Olivetans renovation (1478–85), including the church and the two cloisters (II–IV in Fig. 4) on the south side. The *Chiostro Grande* (III in Fig. 4) was added on the south side in the second phase. Recent studies agreed with Camassei (Spinelli et al. 2002), abbot of the monastery in the 18th century, ascribing the work for the renovation of the dormitory and the anti-refectory to the abbot Giovanni Paolo Rovato, around 1559.

According to archival documents analyzed by Camassei, the construction of the frame vault of the anti-refectory (Figure 5) was finished around 1561

Figure 4. St. Nicholas Abbey, Rodengo Saiano, schematic plan of the Abbey with the anti-refectory marked with a red box (redrawing after Fé D'Ostiani 1886): I) church; II) *Chiostro della Chiesa*; III) *Chiostro Grande*; IV) *Chiostro della Porta o della Cellaria*; and building construction phases (after Breda 2000: 157): Romanesque building (red); Medieval building, 14th–15th century (purple); I Olivetan construction phase, 1478–85 (green); II Olivetan construction phase, end of 15th-beginning of 16th century.

Figure 5. Frame vault of the anti-refectory of St. Nicolas Abbey in Rodengo Saiano: stuccos by Francesco Oselli (1560); frescoes by Lattanzio Gambara (1561).

when it was embellished with stuccos by the Mantuan, Francesco Oselli, (1560) and frescoes by Lattanzio Gambara, one of the foremost 16th-century Brescian artists (1561).

4 THE MORTARED-RUBBLE-FRAME VAULT OF THE ANTI-REFECTORY

4.1 *Geometric, photogrammetric, and thermographic survey*

The geometric survey was carried out using standard tools such as metric tape, laser distance meter, optical level, and calipers. It was integrated with photogrammetric and thermographic surveys (June 2020). The photogrammetry was performed to get the vault intrados orthophoto and generate the point cloud that could be later used to enrich 2D drawings in AutoCAD and create the 3D model. The intrados vault photograph dataset was acquired through a Canon EOS 1-D Mark IV. The camera was set on a tripod, lens parallel to the ground, facing the vault. Photographs were acquired following a 50 × 70 cm grid to ensure the overlapping between two adjacent pictures. The 194 photographs were processed in PhotoScanPro, gathering a scaled point cloud of the vault. PhotoScanPro made it possible to obtain the intrados orthophoto with a pixel resolution of 1.08 (suitable for a 1:20 scale).

The point cloud was then exported in .e57 and opened in RecapPro, saved in .rcs. The .rcs file was used in AutoCAD to enrich the 2D drawings: floor plan with vault projections, cross and longitudinal sections (Figure 7). The 3D model was created following Banfi's modelling approach that allows an accurate 3D model using the point cloud coming from either laser scanning or photogrammetric survey (Banfi 2019b). The point cloud in .e57 format was imported into RecapPro2020 to decimate its points, thus reducing the file size. In Recap, the point cloud was cleaned by eliminating the points that provided 'noise' or created errors in the next phases.

The point cloud was then exported in .pts format and imported into Rhinoceros 6 for the 3D modelling. The point cloud was anchored to the vault intrados dwg floor plan, which was imported into Rhinoceros 6. Subsequently, following Banfi's procedure, the geometric primitives (profiles) of the brackets and vault compartments were defined through point interpolation. Afterward, the vault surfaces were created, following the Grade of Generation 9 (Banfi 2019a: 141). Grade of Generation 9 allowed a 3D model that accurately follows the vault geometries (Figure 6).

The thermographic survey was carried out in June 2020. After considering that it would not have compromised the state of conservation of frescoes and stuccos, active thermography was chosen. It was performed by heating the room, increasing the temperature difference among the building materials. It was performed two times to assure better results. The first set of photos was acquired by heating the room from 10 a.m. to 11 a.m.; the room temperature was raised from 24.8°C (UR 61.2%) to 29°C (UR 55.2%). The second set of photos was captured by heating the room from 11.30 a.m. to 12.20 p.m.; the room temperature was raised from 26.7°C (UR 57.2%) to 30°C (UR 54.6%). There were no significant differences between the two sets of pictures.

4.2 *Frame vault-construction technique analysis*

The anti-refectory is about 7.40 × 9.70 m; the vault spring line is 4 m (the line where the brackets are set) and the overall height is 5.75 m. The central panel is about 6.15 × 4 m, and the compartments at the corners are about 1.45 × 1.45 m, while the four on the longitudinal walls are 1.30 × 1.40 m, and the two on the transversal walls are 1.60 × 1.70 m. Brackets measure 0.35 m thickness and 1.60 m width. The pairs of brackets are placed 1.75–1.80 m one from the others

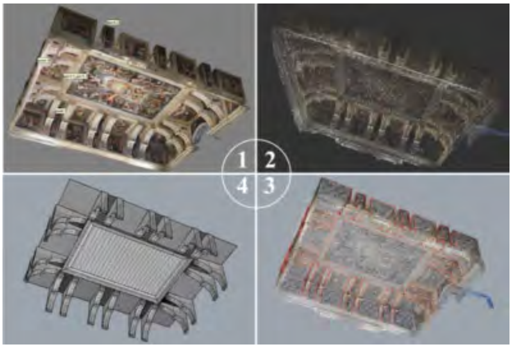

Figure 6. From photogrammetry to 3D modelling: 1) image data acquisition and dense point cloud generation (Agisoft PhotoScanPro); 2) Point cloud decimation (RecapPro); 3) Primitives extraction through point cloud interpolation (Rhinoceros 6); NURBS surface generation (Rhinoceros 6).

(middle line), while the space between the brackets is about 0.8 m.

The same vault compartment configuration is used for the wall's top section (between the spring line of the vault and the intrados), which is part of the vault pictorial cycle. The first hypothesis was that the frame vault was built in brick-masonry, like the other Lombardy examples.

The thermographic survey, however, revealed a different technique. The central panel is a mortared rubble vault (stone blocks of different dimensions bound by mortar – the term is derived from Lancaster 2015). Stones, probably lightweight stones, of different diameters and shapes, and perhaps bricks, are used to create the central panel, as one cloud presumes from the thermal imagery (Figures 8 and 9). Moreover, it seems that the four corners of the central panel have smoother edges as if they were intentionally created to prepare a proper continuous surface for the frescoes. The construction technique is coherent with the walls, ashlar masonry built of stones with the same height within each course, but which courses may vary in height. Even with the thermal imagery, the bracket construction technique is still unclear, probably because they are covered by a thick layer of mortar and stucco. Are they made of mortared rubble? Or are they made of one stone?

Stonemasonry is not unusual in the area of Rodengo Saiano, particularly on Brescia's west side, close to the Prealps. Examples of mortared rubble vaults can be seen in Adro, Esine, Gardone Riviera, Salò, and Rovato. However, this is probably one of the first examples of the mortared rubble technique applied to a frame vault that dates back to the second half of the 16th century. Nevertheless, it is challenging to understand why they chose a technique that seems unsuitable for this vaulting type.

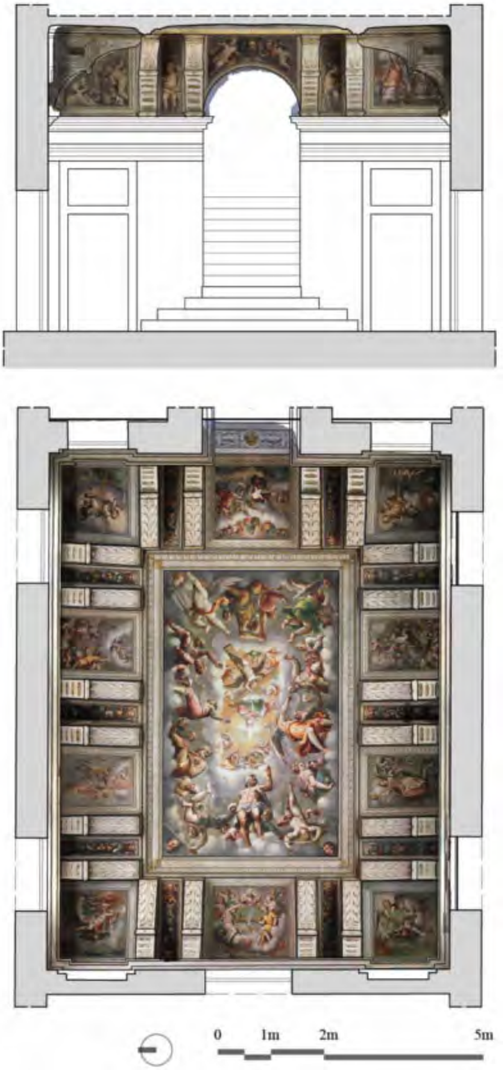

Figure 7. Plan of the anti-refectory and the projection of the frame vault intrados with orthophoto and cross-section.

Brick-masonry frame vaults were easy to build because firstly, a frame-band structure made of arches or brackets was set, and then the vaults to cover the spaces, using the arches as guides. They allow material saving by using the same centering for the arches and the bricks arranged flat (*in foglio*). The frame vault of Rodengo Saiano probably needed a whole centering for the central panel to support the mortared rubble.

If the brackets are made of stones, the craftsmen presumably did not need a complete formwork because the brackets themselves helped to reduce the central panel formwork space. Furthermore, brackets reduce the vault clear span and spread the load on specific points. Perhaps by doing this, it was unnecessary to use tie rods for the vault, not visible at the intrados nor through the thermographic survey; however, tie rods might be placed along with the central panel, not visible in the thermal imagery due to the moldings.

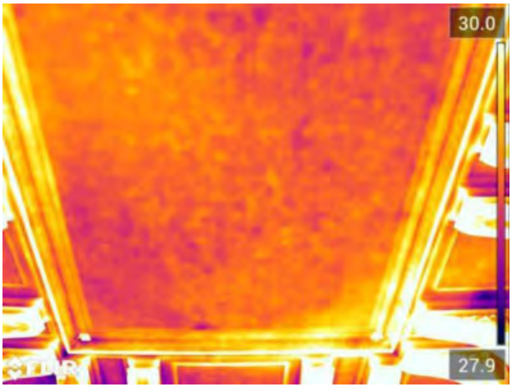

Figure 8. Thermal imagery of the central panel, frame vault of the anti-refectory of St. Nicholas abbey in Rodengo Saiano.

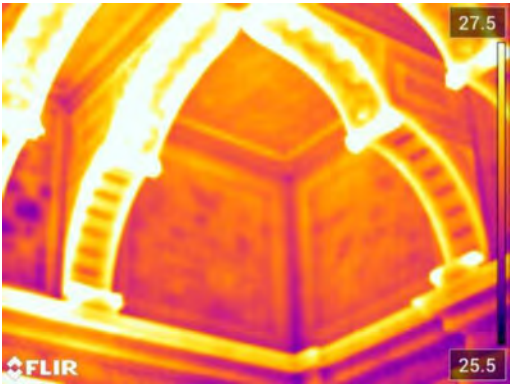

Figure 9. Thermal imagery of the brackets, north-east corner, frame vault of the anti-refectory of St. Nicolas abbey in Rodengo Saiano.

5 THE LEGACY OF FRAME VAULTS

Since the second half of the 16th century, frame vaults have been widely disseminated in Northern Italy. They were re-elaborated versions of the wooden coffered ceilings that integrated paintings with the main structure, creating framed canvases. In the case of brick-masonry vaults, the reasons they were widely disseminated were formal and constructive due to the quick building process. However, the frame vault of Rodengo Saiano was created in mortared rubble, which probably needs a complete centering. It is significant how the will to realize a specific architectural element – the frame vault – overcame the problems linked to a traditional technique, such as mortared rubble. The vault construction technique is coherent with that used for the room walls, consisting of squared stone ashlar courses. The technique is also widespread in the area, and by using lightweight stones, the ceiling resulted in a "light" structure. Even if wood was required for centering, craftsmen created a less expensive structure using local resources (stones). On the other hand, frescoes and stuccos were probably much more expensive, considering the works' high quality, especially the frescoes by Lattanzio Gambara, one of the foremost 16th century artists.

Renaissance humanism influenced the anti-refectory arrangement (by 1561), which is part of the humanistic renewal program carried out by the Olivetans, to which the monastery was sold in 1446 by order of Pope Eugene IV (Gatti Perer 1981). The high level achieved by craftsmen in building Rodengo Saiano's vault shows how it was already a mature period for constructing frame vaults, probably due to previous experiences.

The appreciation of 15th-century architecture might explain the *long durée* of this particular type of vaulting, which lasted until the 18th century, as proven by the work of many architects, such as Faustino Rodi in Cremona (i.e. Palazzo Comunale, Palazzo Soldi) or Filippo Juvarra in Turin (i.e. Palazzo Martini di Cigala).

The frame vault integrates structure and paintings. It means that architects, painters, and artisans probably worked very closely together. Some questions remain about the vault construction. Who was the real author of the vault? Were there specialized craftsmen for its creation? In the Northern Italy building sites, local artisans worked together with specialized craftsmen, such as the *ticinesi* and *luganesi*. Besides Gambara and Oselli, no other name or origin of craftsmen working in the anti-refectory came out of the historical research. Further studies are needed to shed light on those aspects by understanding other frame vault construction techniques and comparing each case study.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Building a Castle in Japan: Analysis of the masonry construction process through the folding screen *Chikujō-zu byōbu*

D. Vomscheid
Centre de Recherche sur les Civilisations de l'Asie Orientale

ABSTRACT: In this paper, we intend to lift the veil on masonry construction process in Japan, through the analysis of the early 17th century folding screen called *Chikujō-zu byōbu*. The great pictorial richness of the screen allows us to reveal many aspects and stages of the masonry construction process of a castle in early modern Japan (1573–1867): stone transportation methods, folk traditions related to stone hauling, implementation of stone materials (especially large ones), and social hierarchy on the construction site. Their analysis and comparison with other paintings and actual remains of early modern Japanese castles will reveal one of the building culture in Japan. Indeed, this paper shows the influence of the social context on the building process and over all on the building result itself. Thus, the great Japanese castles known today as major heritage sites must be understood as the materialization of the early modern social context.

1 INTRODUCTION

Discussions about Japanese architectural techniques most often focus on wooden construction, a centuries-old and highly refined tradition. However, there is also a tradition and culture of masonry construction in Japan, which has long been ignored by Western scientific literature and which we would like to discuss here.

1.1 *Masonry culture in Japan*

It is undeniable that the Japanese preferred wooden structures, notably for seismic resistance reasons, but one should not deny the fact that masonry structures were erected very early. Archaeological evidences show an early presence of stone constructions in Japan. During the ancient (592–1185) and medieval (1185–1573) periods, masonry construction was solely practiced in the highest classes of society and knowledge was passed down from generation to generation (Tabuchi, 1975). Besides, according to Ōmori Masae (2004), masonry related knowledge came from Korean and Chinese masons, from the 3rd century through the 8th century, who played a great role in the development and dissemination of masonry culture in Japan.

One of the most important milestones in the history of masonry in Japan is the so-called Age of Warring States (1467–1590), a violent period during which warlords built castles in all parts of Japan. In 1576, Oda Nobunaga (1534–1582), one of the great warlords of Japanese history, started the construction of his castle in Azuchi (current Shiga Prefecture), involving for the first time, a group of masons called Anō, living nearby in Ōmi Province (Kitagaki, 2006). Before that time, castles were mainly earthen structures. Azuchi Castle therefore represents a turning point in castle architecture and masonry construction European travellers were even impressed by those monumental structures, such as Luís Fróis (1532–1597), a Portuguese Jesuit who said in his reports: “On top of the hill in the middle of the city Nobunaga built his palace and castle, which as regards architecture, strength, wealth and grandeur may well be compared with the greatest buildings of Europe. Its strong and well-constructed surrounding walls of stone are over 60 spans in height and even higher in many places” (Cooper, 1965)

The beginning of the early modern period (1573–1867) marks the start of the “castle boom” and the generalisation of masonry structures in castles. Major castles, such as Osaka and Himeji, could be built on plains or hills, not high mountains anymore, because their strong masonry structures allowed an effective defence of the site. Stone walls were mainly used to fortify the land and the terraces that were laid out. Above these massive structures were erected the buildings, such as donjons, made of wooden structures.

1.2 *Historical context of the folding screen Chikujō-zu byōbu*

In 1601, a year after the great Sekigahara battle, Tokugawa Ieyasu (1543–1616), who was to become the new shogun of Japan, engaged in the reconstruction or the repair of the main castles under his control, such as

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Edo, Sunpu, Nagoya, Hikone, and Osaka. To do so, he ordered all local warlords (daimyo) to contribute financially and provide labourers. This system is called *tenka bushin*. On the one hand, it allowed the Tokugawa shogunate to build and repair its castles quickly, and on the other hand, it was a way to control both the finances and loyalty of the daimyo, as it was an expression of their allegiance to the new shogun.

The folding screen called *Chikujō-zu byōbu*, “Illustrated folding screen of a castle under construction”, is probably related to the *tenka bushin* system. Details of the context of its creation are not perfectly clear, but according to Takahashi Osamu (2011), the castle under construction depicted in this document is Sunpu Castle (current Shizuoka Prefecture) owned by Tokugawa Ieyasu. Important repair works had to be done on the castle in 1607, and the screen is a vivid depiction of the construction site, showing in particular the masonry construction process that we intend to reveal in this paper. This six-panel screen, of a relatively modest size of 55.8 cm high and 210.2 cm long, was made during the Keichō era (1596–1615) and is preserved in Nagoya City Museum (a digital version is available online on the museum’s website).

1.3 *Methodology and objective of this paper*

This folding screen is a unique and interesting piece of art that lifts the veil on a series of practices related to masonry construction of castles in early modern Japan. We aim to lay bare the techniques and construction process of the Japanese masonry. This document is a valuable source depicting the entire scene of a construction site, including material transportation, labourers, techniques, and the associated folklore. We are particularly interested in scenes relating to the construction of masonry. How did they transport the stone blocks, some of which exceeded 10 tons? What tools did the masons use? What were the folk traditions associated with stone construction? What was the social and hierarchical organisation?

We will bear in mind that the scenes depicted in the screen do not represent the entire process of stone construction, and that this paper therefore offers a partial view. In addition, comparisons with other paintings and actual historical sites will be made to overcome the problem of the single source, and to confirm or moderate our observations. Since Sunpu Castle has undergone many modifications, a comparison with its remains will not be relevant.

2 TRANSPORTATION OF STONE MATERIALS FROM THE QUARRY TO THE CONSTRUCTION SITE

The main theme of the *Chikujō-zu byōbu* is the transportation of stones from the quarry to the building site, using different methods (tools, machines, animals, etc.), according to their size and weight.

2.1 *Pulling the stones*

First of all, transportation of the largest and heaviest blocks of stone, that can exceed 10 tons, is the highlight of the screen. It involves not only substantial manpower and great manual strength, but also folklore practices, which we will analyse in part 3. As we can see in the picture below (Figure 1), the stone is placed on a kind of sledge, called *shura* in Japanese. The word *shura* comes from Ashura (or Asura), a Buddhist divinity who fought the god Taishakuten. According to the *Great Dictionary of Buddhist Vocabulary* (Ishida, 1997), although Ashura lost the battle, he made the deadly and ferocious Taishakuten tremble. From this legend, it was said that only Ashura (transformed in *shura*, sledge) could make Taishaku move (written which means big stone). The Buddhist reference reminds that a nearly supernatural power was necessary to transport these huge stone blocks. Indeed, the *shura* is pulled by a hundred bare foot workers. At the rear of the sledge, labourers use the principle of leverage with wooden sticks to push and pry, while a large number of labourers join forces to pull the stone with hemp ropes from the front. Moreover, timber logs, covered in oil or seaweed like *wakame*, are placed underneath the sledge to make the heavy stones slide better (Takahashi, 2011).

Other paintings and folding screens from the early modern period, called *Ishibiki-zu* “Illustration of the stone-pulling” depict this technique of transportation and confirm its common use. Indeed, we observe the similar use of a sledge, pulled from the front and pushed from the rear with the leverage principle. Furthermore, in these cases, the transportation of stones by pulling force is the main theme of the paintings, if not the only, as the title suggests it. For example, the two folding screens called *Ishibiki-zu byōbu*, preserved in Hakone City and in the Hyōgo Prefectural History Museum, depict both in particular the manpower involved in this process and the difficulty of the task. Indeed, according to studies about Kanazawa Castle construction (Ishikawa-ken Kanazawa-jō chōsa kenkyūjo, 2009), transportation of heavy stones was a dangerous process, especially in uphill and downhill roads. The path had to be secured with wooden spikes, around which ropes were wrapped in order to control the speed of the sledge.

The painting kept in Hakone City also shows that boats were used to transport stone materials, especially the heavy ones. As an archipelago, many Japanese cities benefit from the proximity of the sea and sea routes. For example, during the construction of Osaka Castle, stones were transported from different places around the Seto Inland Sea, more than 350 km apart at the most from the construction site (Hirai, 2002).

2.2 *Using wheeled carts*

Secondly, heavy stones are also transported with two-wheeled carts, called *daihachi-guruma*, which was

Figure 1. Left part of the folding screen *Chikujō-zu byōbu* showing the pulling-stone process. Reproduction made by the author.

Figure 2. Right part of the folding screen *Chikujō-zu byōbu* showing several scenes such as transportation methods (two-wheeled cart, oxcarts, baskets, etc.), stone wall building, samurai drinking sake and contractors with abacuses. Reproduction made by the author.

commonly used in early modern Japan to transport all kinds of goods. We observe in the screen above (Figure 2) two sorts of wheeled carts: one pulled by three labourers, and two oxcarts called *ushiguruma* or *gissha*. In the case of oxcarts, two or three workers are walking by the ox without making any effort of pulling the carts. The use of animals is indeed a very big help in terms of efforts and manpower.

This observation can also be confirmed in the folding screen *Ishibiki-zu byōbu* preserved in Osaka Castle. According to the inscription written at the bottom of the painting, mentioning Lord Ii, it would be a stone used for the construction of Hikone Castle.

This painting depicts a two-wheeled oxcart, carrying a large stone, pulled by an ox and some 20 labourers. Their expressive faces and their bodies are showing the physical effort, especially by the front workers who are pulling the cart with the rope wrapped around their chests. Unlike the screen analysed in this paper, the *Ishibiki-zu byōbu* shows that the ox is not pulling the cart by itself but the labourers join it in the effort.

2.3 *Lifting the stones*

Thirdly, medium-sized stones, between one and two tons, are lifted by groups of workers. As we can observe in the picture above (Figure 3), groups of 30 labourers are lifting a wooden frame on their shoulders, made of criss-crossed round beams, to which a stone is attached and suspended with hemp ropes. This is

Figure 3. Central part of the folding screen *Chikujō-zu byōbu* showing the lifting-stone process. Reproduction made by the author.

why this technique is called *ishi-zuri* "stone fishing" in Japanese language.

The screen also shows that this technique is adaptable to the size of the stone. For example, there is a group of 24 labourers lifting a slightly smaller stone, and a group of only eight labourers lifting a smaller stone with only two wooden beams.

2.4 *Carrying the stones*

Lastly, smaller stones, cobblestones or paving stones, are being carried individually or by groups of two people (Figure 2). They are carrying baskets on their back, called *shoiko*, which is a cone-shape wooden rack, with shoulder straps for carrying loads on one's back. The other type of basket is called *mokko*, which is made out of bamboo or rope and is suspended in the middle of a horizontal wooden pole, carried from the front and the back on the shoulders of two labourers. They unload their merchandise on the upper part of the painting, in a stone storage area set up on the building site and guarded by a man.

The folding screen is depicting about 30 of these labourers, coming to the site with baskets full of cobblestones and leaving the site with empty ones. Some of them seem to be rushing, showing the frenetic pace of these construction sites.

3 JAPANESE FOLK TRADITIONS RELATED TO MASONRY CONSTRUCTION

One of the particularly interesting elements of this screen is the depiction of the Japanese folk traditions related to stone transportation.

3.1 *Encouraging the workers*

The transportation of the largest stones is the great moment of the construction process and is highlighted in the painting by a golden background, which makes the scene stand out among all the others. As it requires a very high level of manual strength, artists are cheering up the labourers with music and dances. The scene is particularly festive and reminiscent of *matsuri*, the Japanese traditional festivals.

If we take a close look at the scene (Figure 1), we can see six people on top of the stone, playing music, singing and dancing. On the front, a character is playing a large size drum vigorously, which indicates that the noise must be significant. On top of that, another character is playing the triton's trumpet, a large sea shell called *horagai*, while the man placed at the front of the stone seems to be dancing and singing loudly. Moreover, we can see dancers and entertainers performing in the crowds, encouraging the labourers from the ground. All of these characters let us imagine a very cheerful scene, loud and festive in the centre of the construction site, which is of great contrast with the hard work of the labourers

We are able to confirm this folkloric practice in other paintings, showing, however, some differences. For example, the painting called *Ishibiki-zu*, preserved in the Ristumeikan University (Art Research Centre), depicts the transportation of a large stone on a sledge, with only one character on top of it, who seems to be encouraging the workers in a much simpler way, without music or dance. On the contrary, the screen *Ishibiku-zu byōbu* of Hyōgo Prefectural History Museum is depicting a very cheerful event, with five people standing on top of the large stone covered with a red carpet, and playing music instruments such as a drum.

According to Tabuchi Jitsuo (1975), a popular song called "Ise ondo", listed today as a cultural heritage in Ise City (Mie Prefecture), has its origins in a folk song sung during the transport of stones for the construction of Nagoya Castle. The song known today goes like: "*Ise wa Tsu de motsu, Tsu wa Ise de motsu, Owari Nagoya wa shiro de motsu*" ("Ise [Jingu Shrine] thrives due to [the port of] Tsu, [the port of] Tsu thrives due to Ise [Jingu Shrine], Nagoya in Owari thrives due to a new castle"), whereas the original 17*th* century song goes like: "*Ishi wa tsutte motsu, tsutte motsu ishi wa, Owari Nagoya no shiro he motsu*" ("We are hanging the stone, the stone that we are hanging, is going to the castle of Nagoya Owari"). The stones were indeed "hanging" from the boat to float on the water, when transported by the sea, which was the case during the construction of Nagoya Castle. The phonic filiation is obvious between the two songs, even if its meaning has changed, excluding the mention of the transport of the stones but keeping the reference to Nagoya Castle. This song became particularly popular in the pleasure districts of Ise, where the lyrics were changed over time. Thus, this case shows that the folklore practices related to the construction of castle masonry have a lasting influence on local folklore cultures.

3.2 *Costumes and accessories*

On the screen *Chikujō-zu byōbu*, the characters standing on the stone and walking with the labourers are wearing outlandish masks and costumes (Figure 1). In particular, we can recognize *tengu* (red mask with a long nose and black hair) and *okina* (old man face) masks. *Tengu* reference is of particular interest because according to popular beliefs, *tengu* are legendary creatures supposed to be experts in military art (Frédéric, 1996). *Okina* masks, however, represent an old man face, with white hair, used in noh theatre, a popular art in early modern Japan. Furthermore, a person can be seen yelling or singing on the front of the stone, dressed as a foreigner (*nanban*), with black pants, a red jacket and a white ruff, which was the usual way to depict the "southern barbarian" in this period However, Ronald Toby (2019) points out that there is nothing really Portuguese about this character and that foreigners are usually depicted in paintings of festive scenes with lavish attires

4 IMPLEMENTATION OF STONE MATERIALS ON SITE

The next step of the construction process is the implementation of stones, that is to say, the wall construction. The screen does not depict stonemasons cutting stone blocks on the site, since the cutting and faceting of the stones were executed in quarries.

4.1 *Use of large stones and aesthetic considerations*

Stone wall construction played an important role in the display of power by the warriors. Indeed, castles were the reflection of the lord power and aesthetic taste. Masons' skills were, of course, valued for their defensive interest, in order to build strong walls that resist to firearms attacks, but as the Edo period (1603–1867) progressed, there was a growing interest in the aesthetic value of these walls. The largest stone blocks, which require a lot of manpower for transport, are used in many castles as a symbol of power and authority.

The donjons were the most impressive architectural element of castles and were supposed to show the political and economic power of a daimyo, but the exhibition of huge stones at the entrances of the fortresses was yet another way to impress visitors and opponents. The blocks could exceed 4 m high, and their implementation was a demonstration of technical skills. The case of the huge stone of the Sakura-mon gate in Osaka Castle (Figure 4) shows the massive material and the human force mobilised for its transport and implementation.

Moreover, this demonstration of human and financial resources was particularly strong in the context of the *tenka bushin* system. During the construction of the Tokugawa castles, daimyo were indeed competing for the best construction work, especially stone walls. It was a way to show the shogun their total loyalty and obedience, as well as a way to show their financial and technical superiority to other daimyo engaged in the construction work. In this context, implementation of huge stone blocks was perhaps the most spectacular way to win this competition. The rivalry can still be observed in the monumental masonry works of Osaka Castle, for example in the Sakura-mon gate area built by Lord Ikeda of Okayama clan and in the Ōte-mon gate built by Lord Katō of Kumamoto clan.

Figure 4. Large stone of Sakura-mon gate in Osaka Castle, with an estimated weight of 108 tons. Source: Wikimedia Commons.

In the folding screen *Chikujō-zu byōbu*, a big stone implemented in the right side of the gate leading to the donjon and shogun palace can be observed in the already built main compound.

4.2 *Building stone walls*

The document also depicts some techniques used in the implementation of the stones and the wall construction (Figure 2). First of all, we see that an earthen ramp is set up for the transport of large stones to the upper part of the walls, whereas a wooden scale is used by labourers carrying baskets to bring the smaller stones up to the upper area.

A wooden scaffolding (probably bamboo) is planted in the wall, as it is being built, so that the masons can be positioned facing the wall to place the blocks. Stones are handled and positioned using crowbars, called *kanateko*, or carried by hand for the lighter ones. The tools used by the masons seem quite simple. One is using a kind of pickaxe while the other is using a kind of hammer (called *gennō*) and chisel, for scrapping and flattening the surface in order to improve the aesthetic aspect and to make impossible the climbing of the wall.

In this painting, the drawing of the walls suggests that masons used the masonry technique called *uchikomihagi*, which is characterised by the use of lightly cut stones, the joints of which are being filled with small stones without any mortar (Figure 5). In Japanese masonry, three main techniques can be used to build a stone wall: the *nozurazumi* (random), the *uchikomihagi* (patchy) and the *kirikomihagi* (compact) (Hirai, 1980 and 2017). The first one, *nozurazumi*, was mainly used in a period between 1573 and 1596, at the beginning of the boom of castles. It uses natural stones, such as river stones and stones collected as they are in the quarry. This technique is the less stable because the round and irregular shape of the materials leads to its eventual fall. Besides, it is very difficult to build high walls with this method That is why the *uchikomihagi* and *kirikomihagi* techniques were developed, the

Figure 5. 1:1 scale model of a *uchikomihagi* stone wall in Kanazawa Castle. Source: author.

latter being the most sophisticated one with precisely cut stones without any gap between them. In the case of *uchikomihagi* technique depicted in the screen, corners are reinforced with the *sangizumi* method, using cut blocks to avoid landslides.

4.3 *Masonry related knowledge and secret treatises*

After the construction of Azuchi Castle in 1576, Anō masons developed their skills in castle construction and were appreciated by many daimyo (Tabuchi, 1975). Thus, they played a central role in early modern castle construction in Japan. When Tokugawa government established the rule called "One province one castle" (*Ikkoku ichijō*) in 1615, many medieval castles were destroyed and mason masters returned in the countryside, developing massively the use of masonry structures and improving techniques

One event of importance in the dissemination of masonry techniques in Japan is the construction site of Nagoya Castle in Hizen (current Saga and Nagasaki Prefectures) in the west of Japan, for the great siege of the Korean War in the late 16*th* century (Takahashi, 2011). All the daimyo took part in this construction site and the techniques used in the west spread throughout the country. Therefore, techniques were learned by masons during the construction process and the knowledge was brought back to each province. Nevertheless, specificities developed by some groups of masons should not be ignored. Indeed, as we have already mentioned, there was a rivalry between daimyo in the construction of stone walls. This competition led eventually to a certain secrecy about specific techniques. For example, we know that in Kanazawa, local masons wrote many "secret masonry treatises" (*ishigaki hidensho*) which include explanations and drawings regarding the stonecutting techniques, the way to calculate the inclination of the walls and so on (Kitagaki, 1974).

5 SOCIAL HIERARCHY ON THE CONSTRUCTION SITE

Many people are working together on the construction site: warriors, labourers and masons. A strict hierarchy was observed in order to build the castle in a fast and effective way.

5.1 *Warriors' leadership*

During the early modern period, warriors (daimyo and high-ranking retainers) were supervising the construction work of castles. On the screen we can observe several figures with swords, which do not mix with the crowd of workers. When a daimyo was taking part in a construction work, he sent several high-ranking retainers with the labourers and masons in order to supervise their work. For instance, Maeda clan of Kanazawa sent many workers and masons from Kaga domain during the construction of Osaka Castle masonry walls. In order to supervise the site, Lord Maeda Toshitsune (1594–1658) sent two of his most loyal retainers, Honda Masashige (1580–1647) and Yokoyama Nagachika (1568–1645). They were to return to Kanazawa only once the masonry work was finished, but the construction magistrate (*fushin bugyō*) of the Shogunate, who was supervising the whole site, ordered them to repair the wall where a deformation was spotted. Yokoyama threatened the magistrate of *seppuku* for such dishonour and the case was eventually closed (Ishikawa-ken Kanazawa-jō chōsa kenkyūjo, 2009)

Besides, some daimyo were particularly involved in the masonry construction process and were known as building experts all over the country. Tōdō Takatora (1556–1630), daimyo of Imabari and Tsu domains, who was also a *fushin bugyō* in the Shogunate administration, has remained in history for its role in the construction of castles such as Uwajima, Zeze, Nijō, and Tsu. He paid particular attention to the construction of high stone walls, and was often compared to Katō Kiyomasa (1562–1611), another daimyo expert in masonry. The document called *Owari meisho zue*, an illustrated guide of famous places in Owari, dated from the 19*th* century provides interesting information (Tabuchi, 1975). One illustration depicts the transportation of a huge stone, on a four wheeled cart, pulled by many workers for Nagoya Castle construction. Katō Kiyomasa is standing on top of the stone and leading a group of six people cheering the labourers Kiyomasa was particularly famous for his skills in masonry construction in the beginning of the 17*th* century, and still has today its own statue, standing on a stone block, in Nagoya Castle (Figure 6)

In the screen, however, the warriors are particularly depicted as enjoying the construction site, rather than controlling it. Indeed, above the stone-pulling scene, a samurai, probably a daimyo, can be spotted on a white horse. He is accompanied by his daughter or wife and his retinue composed of more than 30 retainers (Figure 1). They are carrying all sorts of goods, probably gifts to the shogun residing in the castle at the time. At the other end of the screen (Figure 2), a festive scene takes place, where warriors are drinking sake, probably celebrating the progress of the work (Takahashi, 2011) These two scenes of calm, sophistication and luxury, are in striking contrast to the hundreds

Figure 6. Statue of Katō Kiyomasa leading the stonepulling in Nagoya Castle. Source: Wikimedia Commons.

of surrounding labourers who are displaying considerable physical strength and efforts. The building site can therefore be described as a social place, where all the hierarchies of the Edo period manifest themselves.

5.2 *Working force management*

On the construction site, the erection of stone walls is the most demanding in terms of working force. During the so called *tenka-bushin*, Tokugawa Ieyasu ordered his daimyo to provide this labour force according to their income (calculated in *koku*, a rice production value): every 500 *koku* of income, they had to mobilise three men of their domain (Takahashi, 2011). For example, Kuroda Nagamasa (1568–1623) and Katō Kiyomasa, daimyo of Fukuoka and Kumamoto, whose wealth was estimated at about 500 000 *koku*, were to provide 3,000 men for the Nagoya Castle erection. This workforce was selected from their rear vassals and from peasants in the countryside Thus, many labourers were members of the warriors' class (*bushi*), samurai of low status, such as foot-soldiers (*ashigaru*) and came to work in different construction sites from various provinces all over Japan. At this time, lowranking warriors were not exclusively recruited by blood, especially in the lower status. Physical abilities and strong physiques were important factors in the recruiting process. Those soldiers must then have been particularly suited for manual work such as stone transportation.

In early 17th century Japan, management of the workforce must have been a great task for all daimyo as the castles built with the *tenka bushin* system were being erected in the span of 15 years. Not only did many groups of workers had to work together on the building sites (up to 64 daimyo families in Osaka, so potentially as many or more groups of workers) but the daimyo had to dispatch their workers over the building sites of the shogun's castles all over Japan. For instance, Maeda clan was engaged in at least four different projects (Takada, Nagoya, Osaka, Edo) situated in four different provinces (Takahashi, 2011).

Involvement of the daimyo was even materialized in stone walls. Indeed, masons engraved the symbols of their clans to show what part of the castle they built. Today, stone walls containing around 2 000 different symbols on between 50 000 and 60 000 stones can be observed in Osaka Castle (Hirai, 2002).

5.3 *Building economy*

The cost of this labour force (travel, meals, accommodation, etc.) was fully paid by the daimyo who mobilised it (Takahashi, 2011). This economic aspect of the building site is represented on the screen by three men: two with abacuses and one who seems to be writing on a register (Figure 2). If the role of these characters is not perfectly clear from the painting itself, we can make some assumptions about it They must be contractors managing force tasks and budgets. Workers were coming in the construction site in great numbers and their management was crucial for the organisation of the site. In addition, the three men are surrounded by a group of workers, waiting for orders or payment. They are carrying tools, such as long pickaxes and crowbars suggesting they are masons.

6 CONCLUSION

The folding screen *Chikujō-zu byōbu* is a wonderful fresco that illustrates the masonry construction process in almost its entirety. Its analysis reveals one of the facets of building culture of Japan, rather unknown in the West. As Howard Davis (1999) describes it in his book *The Culture of Building*, human systems are at the core of building culture, and the masonry construction process, studied in this paper, exemplify this in a very clear way. The construction of stone walls, can undeniably be viewed as the result of a social process. We have particularly observed its manifestation through the use of monumental stones, a result of daimyo competition. It reflects the *bakuhan* system, i.e. the political hegemony of the shogun through the unification of the whole country, together with a certain autonomy of the provinces led by the daimyo. Masonry related knowledge was definitely shared and disseminated throughout the country, but daimyo and masons' groups were able to develop their own skills through treatises and sites experiences. Although very expensive for the daimyo, the *tenka bushin* system allowed them to practice masonry, to gather knowledge, which ultimately led to building remarkable castles in their own castle towns. Another illustration of this dual global and local scales are folk traditions related to stone construction practised in various parts of the country, but which eventually led to the development of local cultures.

Therefore, famous castle sites we know today, such as Himeji (Figure 7) or Kumamoto, can be seen as the result of the Edo period social system. Their resistance to the passage of time is yet another illustration

Figure 7. Donjon and stone walls of Himeji Castle. Source: author.

of the constructive quality that has resulted from the practices set out in the paper. In the end of the 19th century, Japanese imperial government issued a law in order to destroy many castles, but the sturdiness of the stone walls has often made their dismantlement impossible. Westerners, who visited Japan in the late 19th and the early 20th century were often impressed by these structures, which surpassed many western stone monuments according to their written testimonies (Vomscheid, 2021).

Further research on Japanese masonry techniques, knowledge, workers and construction process must be conducted in order to provide broader perspective on this rich subject. Late 16th and early 17th century Japanese castles are indeed more than aesthetics and technical wonders. They are the result of the unification of Japan, based on a feudal regime, that can be seen as the foundation of modern Japan. This consideration makes it possible to read this built heritage in a different way, not just as a work of military art, but as the materialization of the society of the Edo period and the hierarchy of warriors' class.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The Gothic town hall model of Augsburg

M. Schöll & C. Weber
Universität Innsbruck, Innsbruck, Austria

ABSTRACT: The wooden model of Augsburg's Gothic town hall is the first of seven architectural models referring to the planning process of the new early 17th century Augsburg town hall. It is part of the Augsburg Model Chamber (*Modellkammer*), today in the Maximilian Museum Augsburg, which is considered one of the most important collections of historical models. Despite its extraordinary importance, neither art historical nor architectural historical methods have been able to clarify the function nor date of the model. The methodological approach of this work is therefore to analyze the model in terms of construction history, to verify previous research results by comparing them with the surviving sources, and to clarify whether this model is a contemporary memorial after the new construction of the town hall or a design model from an earlier period.

1 AUGSBURG, TOWN HALL AND MODELS

The city of Augsburg, located in south-west Bavaria at the confluence of the rivers Wertach and Lech, is one of the oldest cities in Germany. Originating from a Roman army camp and occupying a prominent position in Roman times, it experienced its real prosperity in the High Middle Ages (Gottlieb 1984, 11–43). Besides being the leading place of artisan production, the convenient location of the town permitted its rise to one of the most important economic centres in Europe (Roeck 2004, 11–13). Merchants, such as Fugger and Welser, maintained economic relations with the entire known world. As an expression of the resulting wealth and intense exchange with Italy, an urban construction programme was set up in Augsburg at the beginning of the 17th century, which permanently changed the cityscape with numerous representative Renaissance buildings (Roeck 1985, 172–87). The most outstanding work of this building programme is the Augsburg Town Hall by the master craftsman Elias Holl (1573–646), which was built between 1615 and 1620 in place of the previous Gothic building. Its construction and planning process has been subject to controversial discussion since the beginning of the art-historical debate surrounding Elias Holl and is well documented thanks to numerous historical sources. Based on the remains of the original, then existing, building of the old town hall, which was demolished between 1614 and 1616, numerous planning documents, but also seven architectural models, give an insight to the development of the planning steps. At the very beginning of this process is the model of the Gothic town hall, whose function and date could not exactly be clarified until now by art historical research. With the help of constructive history investigation methods, new discoveries can be made, which will allow a more precise classification of the model in the planning process.

2 THE MODEL OF THE GOTHIC TOWN HALL

2.1 *Description of the model*

The model of the Gothic town hall (*städtische Kunstsammlungen und Museen Augsburg,* Maximilianmuseum Inv.Nr. 3453), as well as the six other architectural models that are related to the construction of the new town hall, are part of the so-called Augsburg Model Chamber. This is an urban collection of models which was originally housed in Augsburg's Renaissance town hall and contained an extraordinarily large number of exhibits. An inventory from 1838 provides an overview of about 120 architectural models, 102 mechanical models and six casting models (Rathaus 1838, 23–34). In the 18th century the important hydrotechnical models were added to the model chamber. Most of the valuable models were transferred to the Maximilian Museum, which today has one of the most important collections of its kind, and is part of the list of national cultural monuments. The seven architectural models, which are directly related to the planning history of the new Augsburg Town Hall, already attracted research around Elias Holl from the beginning of the 20th century. The affiliation of six of these town hall models to the design and planning process of the new building, as well as their classification, has meanwhile been largely scientifically proven, whereas the function of the model of the previous Gothic building, as a design model of a 16th century rebuilding or as a memorial model, is still disputed and its dating is therefore also controversially discussed.

The wooden model on a scale of 1:48, which is based on the inch system commonly used at that time, is

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Figure 1. West façade of the Gothic town hall model (*städtische Kunstsammlungen und Museen Augsburg*, Maximilian Museum Inv.Nr. 3453).

made of solid maple and spruce boards (Pfister 1938). It shows three nearly parallel gabled houses whose western façades represent a uniform show-façade facing the characteristic historical main axis of Augsburg (Figure 1). The northern building is the more representative part of the complex, higher and wider than the other two.

The model can be dismantled floor by floor and shows the building from the first basement level upwards. Lower-lying rooms, not shown in the model, can only be identified by references inserted as written room notes. Despite the remarkable slope of the building site, with its west-east gradient, the topography is not reproduced, so that, due to the basement shown, the entrances of the model are a few centimetres above ground level (Lepik 1985).

The exterior of the building is dominated by the representative west façade with the tower and the windows on the ground floor, which are structured by a Gothic buttress. In the south of this façade there is a subordinate portal, as the large main portal is part of the northern façade, which takes up the Gothic windows of the west façade. Above the corner between the west and north façades, a magnificent oriel at the level of the first floor emphasises the main portal below, the entrance from the *Fischmarkt* at the corner. The other façades do not have any design worth mentioning, as the Gothic town hall was integrated into the surrounding buildings on these sides.

The seven parts of the model reproduce the town hall floor by floor, whereby the components of the first floor, the second floor and roof are divided because of the different heights used for the representative and administrative wing. The interior of the model components shows the irregular and small-scale floor plans, which correspond to the various uses of the medieval town hall. The basement (Figure 2) contains storage rooms, as well as dungeons and rooms with increased security/protection requirements, such as treasure chambers. They were only accessible via a separate entrance from the administrative rooms on the first floor. The market function of the little stores in the basement, which were all individually accessed by stairs from the west façade, is continued on the ground floor with the large vaults of the furriers and loden makers in the northern part. The southern part of the ground floor, in contrast, is characterised by small-scale administrative and infrastructure rooms. On the ground floor there is an access corridor behind the prominent Gothic windows. Entering the main portal, a magnificent staircase opposite leads up to the large council hall, which occupies almost the entire first floor of the northern building (Figure 3). The balustrade of the staircase and the characteristic round columns of the hall are reproduced in the model. In the southern part of the piano nobile the rooms are more spacious than on the ground floor because there the most important rooms of the city administration were located, such as the council and court chambers. Many of these rooms are furnished with circumferential benches, as shown in the model, and large stoves.

Figure 2. Basement model section (source: the authors).

A second fully developed upper floor is only to be found on the higher northern building and contains the room of the sovereigns as well as access to the tower. The rooms in the two roof sections are not displayed by the model (Hilbich 1968, 39–68).

The model is thus to be understood as the most important witness to the Gothic town hall and, despite its importance, has never been the focus of research. By examining the model as a constructive historical document with construction historical methods, new insights into the building and architectural history of the town hall are to be gained.

2.2 *Results of the model investigation*

In the context of the research, the model was disassembled into its seven individual parts and each component was documented. The documentation process was carried out, on the one hand, as a deformation-compliant measurement, which was transferred on site into a detailed 3D model (Figure 4), and, on the other, photographic documentation recorded all details and processing traces, as well as the joining

Figure 3. First floor model section of the northern building (source: the authors).

Figure 4. Rendering of the 3D model (source: the authors).

techniques and other characteristics. This construction survey provides the comparison basis to other sources/representations handed down elsewhere and for checking previous scientific theses.

Investigation of the joining techniques showed that each model section stands on a base plate. The walls, as well as the inlaid panels, are glued to it, the roof areas are connected to the base panels with wooden nails, as well as the butt-jointed parts of the outer walls of the northern and central building in the east. Otherwise, the boards of the outer walls are mortised in the corners by dovetail joints (Figure 5). In the case of the inner walls, the wall ends are mortised with a vertical dovetail into the longitudinally adjoining wall mainly for wall thicknesses more than 10mm. Thinner walls are mortised without a dovetail. Only a few walls ending at the adjoining wall are glued, as are the columns, ovens, benches, railings and all the more filigree components shown inside the model.

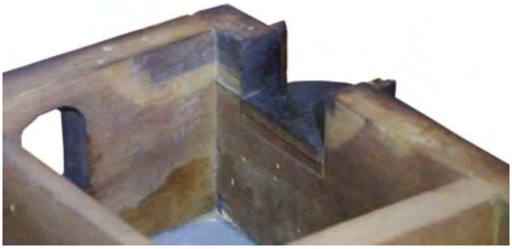

Figure 5. Dovetail connection of the outer walls. Second floor model section of the northern building (source: the authors).

The wall openings were probably cut out from the planed boards before they were assembled, as can be concluded from the still visible lines and markings on the walls. The accuracy of fit of the individual floor sections is relatively exact and is precisely fixed by blocks attached to the underside of the ground plates of the model sections. Only the sections of the 1st and 2nd floors of the representative hall wing use a recess in the upper inner wall and the lower outer wall to allow a plug connection because of their different height levels compared to the other sections.

Regarding later alterations and traces of processing, the plate of the large clock, which was added later, stands out on the outer construction (Hilbich 1968, 31). Its colouring does not correspond to the surface character of the rest of the gable and it is fixed with screws that were not made during the construction period.

Inside the model, the lower floor shows several later modifications. In the north-western area, for instance, the floor plane is missing, which corresponds to the portal and would have made the ground floor accessible by means of a few steps. Discoloration on the inner wall still shows the contours of the former level and stairs (Figure 6).

To find out what was under the closed section of the lowest floor, these were opened in 1942. A written note on the model gives the year of this investigation, in which the wooden nails were cut through and two small rectangular recesses were made in the closing boards.

The most important processing traces can be seen in the part of the lower floor. Tapping -holes and marks as well as discolouration on the walls indicate that a different floor configuration originally existed. This was changed in a subsequent work step, which appears original in terms of the model construction technique. Because one of the walls, later removed, overlaps with one of the inserted room labels, it can be assumed that these labels were added later. However, as all walls and all labels have the same colour according to their position, it can be concluded that all these changes were made shortly after completion of the model. Later closed wall openings can also be seen on the ground floor.

In relation to the visible surfaces, it can be stated that their discolouration is clearly related to light incidence and superficial deposits. Unfortunately, the outside

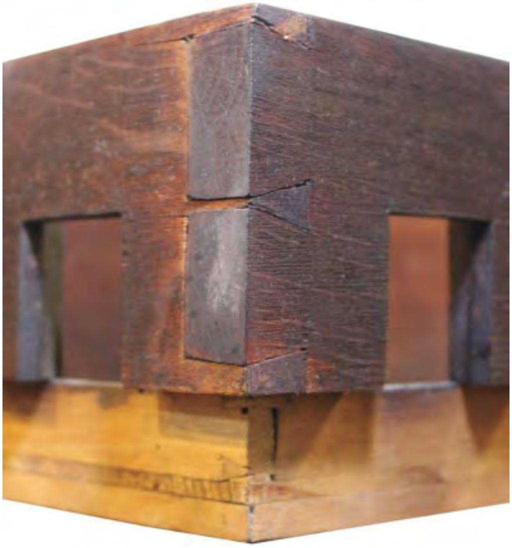

Figure 6. Contours of the former stairs (source: the authors).

of the model, as well as some interior areas, were given a relatively unprofessional wood stain. As models dated later, but belonging to the model chamber, have the same surface sealing, it can be assumed that this measure was carried out much later.

A great number of the interiors are described in the model by means of inserted notes, which refer to the room function and its furnishings; these are sometimes severely damaged, depending on their exposure to light and dust. The inscriptions on the basement floor also refer to the underlying rooms in the substructures of the Gothic town hall, which are not displayed by the model. As explained above, it is certain that not all of the inscriptions correspond to the original state of the model. This supports the thesis that the inscriptions were only added after the old town hall was demolished (Lieb 1955, 234).

What is striking about the façades is the varying level of detail in the individual areas. The tracery of the Gothic windows on the ground floor, for example, is extremely filigree as is the entire oriel or top part of the tower. This contrasts with the simple design of the other window openings, which exclusively reflects the shape of the reveals, but does not display a more detailed representation of the window. The difference in execution could indicate that in this part a differentiation is made between details worked in stone – which are shown on the model – and wooden components which are not shown (Hilbich 1968, 31). Inside the model no furnishing of subordinate rooms is represented.

The various rooms, which provided the most important functions for the imperial city's leadership and therefore characterize a representative claim, are shown with surrounding benches and elevated sitting areas. The heating and cooking areas are emphasized in the form of heating chambers with small fire hatches, tiled stoves in the representative rooms and open cooking places with smoke vents. Even more detailed are the columns in the large council hall and the richly decorated balustrade of the ceremonial staircase. There are also staircases depicted, where their gradient was adapted to the scale of the model (Hilbich 1968, 30).

The model thus reflects the last stage of construction of the Gothic town hall after the rebuilding measures of the 16th century. In the 15th century, the 14th-century building was already fundamentally restructured, whereby the original angular arrangement was abandoned in favour of the parallel arrangement of three gables by adding a second storey to the main building. In addition, the oriel and a new bell tower were built, wooden ceilings were replaced by vaults and paintings were applied to the west façade. Also documented in writing are the last alterations carried out in 1515/6, which mainly concern the interior, specifically 12 marble columns in the council chamber, and two new parlours, but also include an addition to the tower, a renovation of the north portal, and the design of the Gothic windows on the ground floor (Hilbich 1968, 19–25).

2.3 *Divergencies between pictorial/graphical traditions and the model*

To investigate the question of dating and thus also the function of the model in a more differentiated way, it is necessary to consult pictorial and graphic sources in order to make comparisons and a temporal classification of the development and changes of the model. The most important document of this tradition is the building survey of 1609 by Elias Holl (*Stadtarchiv Augsburg* KPS 4254, KPS 4245 and *städtische Kunstsammlungen* Augsburg G 848). However, there are also numerous representations of the Gothic town hall in bird's eye maps and drawings or paintings, which also focus on the most prominent building in the town.

The urban scale model by Hans Rogel (1532–92) is a particularly good source of comparison for the exterior construction and façades. It reflects the appearance of Augsburg around 1560 and was built from 1560–3 (Reuther & Berckenhagen 1994, 47). Because of the urban planning scale and the resulting low level of detail of the individual buildings, only a rough comparison is possible. Clearly recognisable, however, is the town hall in its three-gabled state, whereby the town hall tower is lost in Rogel's model. Most striking, though, are the adjoining buildings east of the town hall, which belong to the so-called *Eisenhof*, the prison, including the extension in the south-eastern part of the town hall, which was drawn in Holl's plans but not displayed by the model. Lined up arches on the west and north façades of the town hall in Rogel's city model are probably intended to show the Gothic windows, whereby all windows are painted on the façade in a stylized grid pattern and thus do not correspond to the more precise representation in the town hall model due to the scale. In contrast to contemporary sources, the façade does not have any wall paintings, probably also due to the scale. In addition to the clock in the northern gable, the middle gable has a painting that can be interpreted as a clock.

Probably the oldest bird's eye plan of Augsburg (Grünsteudel et al. 1998), the so-called "Seldplan", which was printed as a woodcut in 1521 on the basis of measurements by the goldsmith Jörg Seld (1448–1526/7), shows the town and the old town hall from the west (Gottlieb 1984, 365). The triple-gabled façade of the town hall, with oriel and tower, which is much lower than that of the model representation, is exactly visible. The entrances to the little stores, however, seem to be accessible at ground level from the square – in reality, taking into account the real topographical situation, they were located below street level and were individually accessed via stairs. The portal of the west façade is not shown explicitly in the Seldplan. The Gothic windows displayed in the model are also not present in this woodcut, as well as the two small oriels of the south façade. Although the depiction does not represent the sloping terrain towards the east, one can nevertheless recognize numerous adjoining buildings behind the town hall to the east, which were probably part of the town prison.

A better impression from the east is offered by the bird's-eye view of Augsburg in Sebastian Münster's Cosmographia of 1550, whose depth of representation is limited to the most important buildings of the city, as well as the city fortifications (Grünsteudel et al. 1998). According to its importance, the three-gabled Gothic town hall can be found in it. Although the depiction does not show the prison buildings located east of the town hall, it shows adjoining buildings south of the east façade and a structure in the northern part of the east façade, which could also be just a staircase.

Further pictorial representations of the old town hall are limited to its representative main sides and thus allow only conclusions about the design of the northern and western façades. Of particular interest is a coloured pen-and-ink drawing, owned by the *Staats- und Stadtbibliothek Augsburg* (Graph. 17/1 (16,2)), dated 1580 (Hilbich 1968, Fig. 2). It shows the town hall with a considerably lower tower. Since the tower was already raised from 1515/6 onwards (Hilbich 1968, 24), either the dating of the drawing or the realistic reproduction of the town hall in this drawing is questionable. In contrast to the other representations mentioned above, it shows an entrance with stairs in the area of the tower pillars and no portal in the south of the west façade. However, like Elias Schemel's painting *Perlachplatz* around 1600, it gives an impression of the wallpaintings of the town hall, an aspect that is not taken into account in the wooden model. The two consoles with canopy between the Gothic windows in the southern part of the west façade, which are indicated in the model (Hilbich 1968, 52), are not reproduced by any pictorial representation.

At the beginning of the 17th century, the building no longer seems to have fulfilled the requirements of a representative town hall of the free imperial city and in 1609 Elias Holl was ordered to record the state of the town hall in a building survey (Haberstock 2016, 149). From this set of plans, a façade plan and the ground and first floor plans have been preserved, which are very similar to the ground structure of the model. On the basis of this building survey, Elias Holl then designed a rebuilding plan for the Gothic town hall at the beginning of 1610, which was not realised. In the building survey the ground and upper floor plans of this design project have been preserved, as well as an associated façade plan. Accordingly, it is of utmost importance to make a comparison with these plans. The plans are besides the model the only technical representations of the old town hall and provide insights into the layout configuration.

For this purpose, the data obtained from the building survey on the model were configured into floor plans and a façade view, which were then overlaid with Elias Holl's, now digitalised, plans. However, only the floor plans of the ground floor and the first floor have been preserved from this building survey, which, like the façade plan, are dated and signed by Elias Holl at the end of December 1609 (Haberstock 2016, 225–7).

In a next step, the 17th century ink plans, which are provided with a scale bar, were scaled to 1:48 of the model. With few exceptions, Holl's façade plan shows the façade of the model in detail. However, deviations appear in the position of the windows and details in relation to each other, which cannot be differentiated more precisely due to the poor state of preservation of the plan. The oriel, as well as the tower, appears distorted in perspective and thus slightly tilted into the background of the plan, which also results in a lower tower height compared to the model. The window openings on the first floor of the northern building are placed on the plan directly above the surrounding cornice, whereas they are higher in the model, because the floor levels behind them are also elevated. Accordingly, Holl's floor plan of the first floor would have to show a lower floor level here. Because that diverges from the representation in the model, two different conclusions can be drawn. Perhaps the platform shown in the model, which is also shown in Holl's plans, is actually a lower level in the plan. On the one hand, this would correspond to the access level of the bay window in the façade crack, but at the same time it cannot be ruled out due to the unmarked direction of the stairs and due to its location above the access corridor of the ground floor. On the other hand, the entire floor level of the first floor could be lower in the plan than shown in the model. This would mean that the windows of the first floor would have sat very high.

When overlaying Holl's two floor plans with the corresponding plans of the model's building survey, a divergence of individual lines of more than 15mm is revealed, which cannot be explained by age-related wood deformation. In a more detailed view, this divergence is minimised by the fact that the dimensions of the rooms in the model, to a large extent, correspond to the floor plans. Not shown in the model is the eastern extension of the southern building, which is only displayed in Holl's plans as belonging to

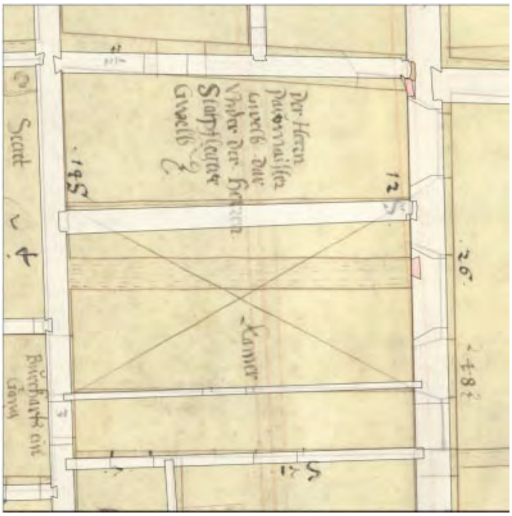

Figure 7. Differences between Holl's building survey (*Stadtarchiv Augsburg* KPS 4254) and the overlaid plan of the model.

the prison according to the plan inscription (Hilbich 1968, 39).

The model does not show the vaults and their corresponding pillars. From Holl's plan it is possible to determine their position. And with the help of the model one can determine that, with one exception, they have adequate supports in the basement below. This exception is the eastern pillar of the so-called *Kürschnergewölbe* (vaults of the furriers), which stands centrally above the room below.

On the ground floor in particular, there are several discrepancies between the floor plans and the model. For example, the corridor which runs behind the northern façade and provides access to the heating chambers is separated in the plan by a wall. The differences in the southern building are even more striking. The northern wall of the so-called *Baumeisterstube* (chamber of master builders) is thicker in the plan and runs at a different angle than in the model. But the model shows traces of machining which, due to the original wide mortise, suggests that the course of the wall corresponds originally to that in the plan. Together with the partition wall to the southern chamber, which is many times thicker in the model, it can be stated that the plan displays the less favourable solution from a static point of view, where a groined vault appears to be supported on a very thin wall. In combination with a southern wall, which only appears in the plan and cuts through the vault and a window, an inaccessible room would result. However, in the model, at the point where this wall meets the window of the outer wall, a later closed mortise can be seen. This is the position where later changes were carried out on the model that no longer corresponded to the status of the rooms represented in Holl's building survey (Figures 7 and 8).

A further observation is that the representation of the staircases, especially their step dimensions, diverge between the model and the plans of the survey. An eastern external staircase is not considered in the model.

Figure 8. Later closed dovetail mortises (source: the authors).

3 CONCLUSION

The described traces of processing, as well as the changes to the model, suggest several phases of creation/handling of the model, so the thesis of a pure memorial model (Dirr 1907) after Holl's construction of the Renaissance Town Hall (Baum 1907) is definitely contradicted, which is also supported by the distinct discrepancy between plans and model.

The different degrees of detailing of individual components suggests the creation of the model in the context of a conversion project, which in the case of the Gothic town hall can only be connected with construction measures undertaken in 1515/6. By comparing the Holl building survey with the traces of work on the model, it can be proven that they took place after Holl's building survey. These subsequent changes allow the determination that the model was used in the planning phase, when reconstruction of the Gothic town hall was under discussion. This means that the model originates from a time when the Gothic town hall was not supposed to be demolished, which would indicate a date between 1609 and 1614. As the traces of the work do not reveal any major fundamental changes to the building, the model does not represent an independent planning step in the reconstruction plans for the old town hall.

Those responsible for these minor changes to the model cannot be determined definitively. The authorship/contribution of Elias Holl, who was responsible for all municipal building projects after his appointment as *Stadtwerkmeister* (city master builder) in 1602 (Haberstock 2016, 29), is obvious with regard to the subsequent changes to the model.

The fact that at the time there were fierce discussions about alternatives for the old town hall or in addition to it, which probably did not fulfil the representative requirements, is proven by the project of a generous urban loggia diagonally opposite to the old town hall. Two extraordinarily artistically designed models in the Augsburg Model Chamber still give evidence of this today (Jachmann 2008, 90).

In the end, Augsburg decided on a completely new design of the town hall, which resulted in the demolition of the Gothic town hall in 1614–6 (Roeck 1985, 203). During the planning process for the new building in the sense of the imperial city's building programme according to Holl's plans, several wooden models were made, ranging from a working model to a prestigious design model (Pfister 1938). A detailed examination of these models dated between 1607 and 1614 may produce a new interpretation of the model of the Gothic town hall.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Haft-rang tile workshop in Qajar Iran: Production and craftsmen

A. Seyed Mousavi
Independent scholar

ABSTRACT: Tilework holds a particular position among the numerous styles of decoration in post-Islamic Persian architecture. While several techniques of producing tiles were used in the Islamic period of Iran, the *haft-rang* method gained great popularity in the Qajar period (1783–1924). In this technique, the different shapes are applied with differently colored glazes on a single tile. Several tile workshops were active in the late 19th century in the historical city of Shiraz. This study means to introduce the structure of the Shiraz Qajar tile workshop and the traditional production process of haft-rang tile. It investigates the traditional system of apprenticeship in a Qajar tile workshop and the tasks of the main craftsman and his professional skills, exploring a wide range of natural materials in creating tiles and colored glazes in the Qajar tile workshops.

1 INTRODUCTION

Tiles with colored glazes and delicate motifs have embellished Persian architecture from antiquity to the present. In Iran's Islamic period, the art of tilework became one of the most significant ornamental elements of architecture, in response to decorative concerns and environmental ones alike; tiles protect architecture against Iran's generally arid climate, while their colorful glazes and wide variety of patterns lend a strongly vibrant, visual appeal (Hillenbrand 1979: 545–554; Scarce 1989: 271–294).

Persian tilework in the Islamic period experienced a variety of tile-production techniques, including: tile mosaic (*moʿarraq*), which is produced by fitting together small pieces of monochrome, glazed tiles to create patterns; underglaze painting, such as lustre painting, whose metallic glaze reflects the multiple colors that are applied directly beneath it; and overglaze methods, which comprise various techniques, the most popular being Persian *haft-rang* or *haft-rangi* (seven-colors: *haft*: seven, *rang*: color), also known in much of the West as *cuerda seca*, in which different shapes are applied with differently colored glazes on a single tile (Lane 1957: Figure 1; Porter 1995).

Persian tile craftsmen developed the aesthetic principles of tilework in both technique and design very gradually during the long history of this art. The splendid heritage of several centuries of expertise informed the artistic productions of the Qajar period (1779–1924), during which time tilework became one of the most popular artistic practices of its era. Qajar tilework – and particularly the haft-rang technique – introduced new patterns, themes, and color palettes which were unique and highly innovative when they appeared in the history of Persian architectural ornamentation (Seyed Mousavi 2018).

The historic city of Shiraz located in the Fārs Province of southwestern Iran holds the largest number of buildings with haft-rang tilework from this period. The style's popularity resulted from a combination of the fact that wealthy sponsors were fond of it and from the custom of displaying art publicly or semi-publicly. Hādi Seyf, an Iranian expert on Qajar popular art, describes Shiraz tile painting with the words "the Shiraz school" to emphasize the distinctive style of this art that existed in the city during the Qajar period (Seyf 2014). Although some scholars have examined Qajar tilework through the lens of historical analysis or according to its technical and thematic aspects, the haft-rang tile workshop in Qajar-era Shiraz in particular has not received adequate scholarly attention (Peterson 1979; Riyāżi 1394/2015; Scarce 1978, 2001; Seyed Mousavi 2018).

Therefore, the current study sets out for the first time to highlight the unique value of the traditional techniques and artistic practices of Shiraz's tile craftsmen. Methodologically, this research is based on the author's extensive fieldwork in Shiraz, where he collected data primarily through interviews with the last surviving generation of traditional tile making artists and direct observation in their workshops.

2 THE HISTORICAL DEVELOPMENT OF PERSIAN HAFT-RANG TILE

2.1 *Terminology*

Before outlining the haft-rang tile technique and discussing its major features in Shiraz, a short note on terminology is in order. Haft-rang (seven-colors) is the author's preferred term for the Persian style of the overglaze techniques commonly known elsewhere as *cuerda seca*. According to recent tests, however,

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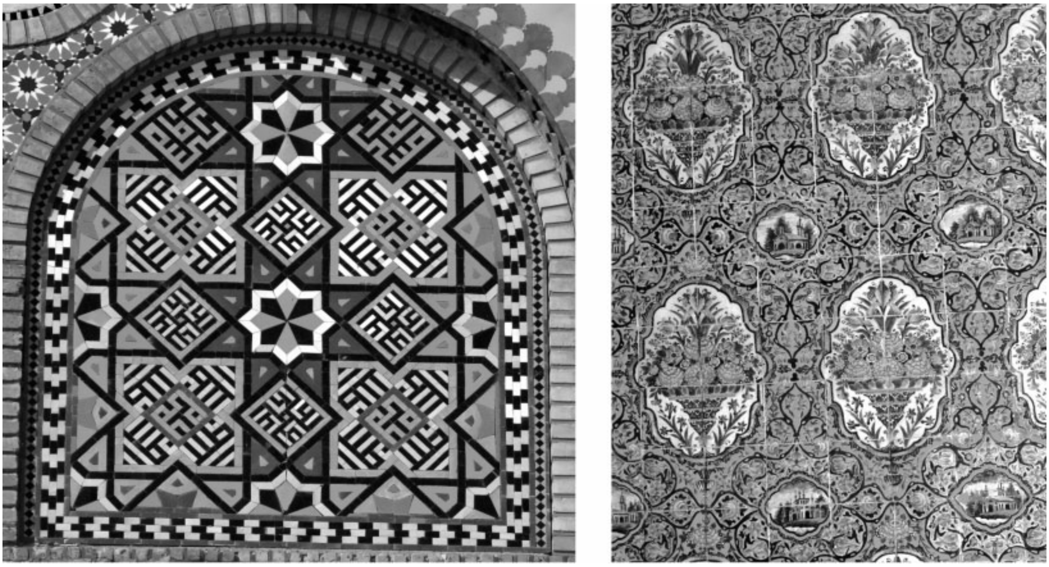

Figure 1. Tile mosaic in the Moshir mosque in Shiraz (left); haft-rang tile panel in the Naṣir al-Molk mosque in Shiraz (right). © Atefeh Seyed Mousavi.

the Persian technique does differ from the Spanish *cuerda seca* with respect to mediums and technical properties (Holakooei et al. 2014: 447–460; Tite & Salter 2011, 200–203). In addition to this, two surviving Persian treatises compiled by local tile-makers, including one by Abol-Qāsem dated 1301 and one by ʿAli-Moḥammad Eṣfahāni dated 1888, used the term “haft-rang” in particular for this technique (Allan 1973: 111–120; Scarce 2005: 21–35). While Persian tile craftsmen evidently choose this term because of the number seven (a prime and highly symbolic number in Persian culture), the term haft-rang (i.e., “seven-colors”) is actually a bit of a misnomer, in the sense that the tiles did not necessarily reflect the seven colors of the visible spectrum, nor a consistent palette of colors across all haft-rang art – nor even did each such work have exactly seven colors. Producers of haft-rang tile used a wide range of pigments and, moreover, each period and region had its own favorite combinations of colored glazes (Interview with Aḥmad Shishegar 14 November 2012, Porter 1995: 17). For instance, purple, pink, grass green, and especially yellow were more popular than cobalt and turquoise during the Qajar period in Shiraz (Seyed Mousavi 2018: 33–34).

2.2 *The flourishing of haft-rang tile*

The history of Persian tilework in the early Islamic period developed parallel to the production of ceramics, which often employed the same techniques and designs with the same craftsmen (Allan 1973: 111–120). It was, in fact, not until the late 14th century that tilework and ceramics came to be manufactured in separate workshops (Porter 1995: 8, 15, 64; Scarce 1989: 271–294). The Timurid period (1370–1507) also began around this time, and it was in this period especially that the haft-rang style of tilework was developed and gradually gained great acceptance in architecture in Iran, for the fact that its production was much quicker and cheaper than other techniques. The style also allowed artists to practice more creativity in their designs and motifs. Nonetheless, the dominant tile-art technique in the Timurid period was still tile mosaics, especially in the form of calligraphic inscriptions, geometric patterns, and interlacing floral motifs (Golombek & Wilber 1988: 117–173). As such, the haft-rang style only developed to its full potential in the Safavid era (1501–1722), particularly during the reign of Shāh ʿĀbbās I (1588–1629), who pursued ambitious plans for the development of Eṣfahān (Hillenbrand 1986: 759–842).

At first, the dominant backdrop glaze of haft-rang tiles was cobalt blue; in a later era, additional colored glazes, such as chrome yellow and white, were applied. *Eslimi* (arabesque), with its vegetal designs and spiraling foliage, represented the principle ornamental patterns in the Safavid era, specifically in religious buildings, although figural and thematic motifs gradually emerged as well (Porter 1995: 68, 76).

During the rule of the Zand dynasty (1750–1794), many buildings in its capital, Shiraz, were decorated with haft-rang tiles, although a large part of these buildings were then damaged by an earthquake in the 19th century (Scarce 1989: 271–294). The Zand tile makers in Shiraz further developed the thematic motifs and colored glaze palettes of the Safavid period and employed new glazes such as grass green, purple, rose, and yellow. They preferred a white background for their colorful motifs, a tradition that continued in the Qajar period (Scarce 1989: 271–294; Seyed Mousavi 2018: 33–34).

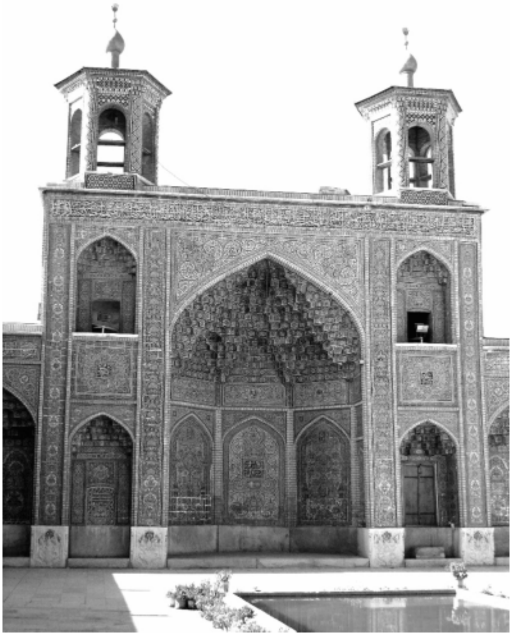

Figure 2. Haft-rang tilework in the Naṣir al-Molk mosque in Shiraz. © Atefeh Seyed Mousavi.

2.3 *Shiraz haft-rang tile*

The Qajar period saw extensive construction projects throughout Iran, from the capital, Tehran, to other major Persian towns such as Shiraz. Haft-rang tiles were one of the period's most popular decorative elements.

Most of the buildings in Shiraz that are decorated with haft-rang tile were constructed during the reigns of Nāṣer al-Din Shāh (1848–1896) and Aḥmad Shāh Qajar (1909–1925). Haft-rang tiles in Shiraz were revitalized by new visual elements such as bouquets, vases, garlands, different types of local flowers and birds, and even European pictorial materials. Furthermore, the depiction on the haft-rang tiles of narrative scenes inspired by Persian classical literature and religious literature lent a special popularity to this art (Seyed Mousavi 2018: 33–36). While the application of tilework in the Islamic period in Iran was frequently limited to religious buildings, such as mosques, schools, and shrines, this art spread during the Qajar period in Shiraz to the elegant homes and gardens built by the elite; to public and commercial places, such as bazaars, warehouses, public wells (*saqqā-khāne*), caravanserais, baths, and gates; and most significantly to the private houses of ordinary people (Figure 2).

Essentially, in Shiraz, all strata of Qajar society considered haft-rang tilework to be fashionable; thus, each group decorated its architectural spaces with tiles according to its budget (Seyed Mousavi 2018: 33, 40).

Several local tile workshops were active during the Qajar period in Shiraz, although they were not a large-scale industry. In the following sections, this paper investigates the structure and traditional characteristics of Shiraz's Qajar haft-rang tile workshops comprehensively and in detail; by contrast, details of this art's technical features and materials will only be mentioned in passing.

3 TRADITIONAL SHIRAZ TILE WORKSHOPS

3.1 *Source of information*

The main body of the present discussion comes from information that has been collected from interviews (November-December 2012) with the last surviving generation of traditional tile makers and tile painters in Shiraz's tile manufacturing community. In addition to this, direct observation from extensive time spent in the Shishegar traditional tile workshop in Shiraz afforded the author a great opportunity to become familiar with traditional production and local terminology in Shiraz's historic tilework industry. In the opinion of Shiraz's tile production community (as expressed to the author), the Shishegar family are considered the foremost experts in manufacturing traditional haft-rang tile in Shiraz.

During the author's time at the Shishegar workshop, he interviewed two generations of the Shishegar family. The head of the workshop, Aḥmad (d. 2019), and his brother, Masʿud (b. 1959), have executed many restoration projects at historical sites in Shiraz, such as the Vakil Mosque and the Naṣir al-Molk Mosque. Aḥmad and Masʿud's father was also a tile craftsman; they worked in his father's workshop since childhood and visited some of the other well-known tile masters and their workshops in Shiraz. During the time of the author's fieldwork in Shiraz, Aḥmad and Masḥud's sons were also active in the Shishegar workshop.

In addition to these sources, the author also draws on a short documentary (Director: Vaḥād Zāreʿ) produced in 1388/2009 by the Fārs Cultural Heritage Organization regarding the technical aspects of the traditional Shiraz haft-rang tile.

3.2 *General description of a traditional tile workshop*

Shiraz tile workshops in the Qajar period were not limited to the production of haft-rang tiles. Rather, they manufactured a wide range of items that were frequently geared towards people's daily needs, such as turquoise clay grills (*shabake*), glazed bricks, clay fences, pottery containers, and monochrome tiles for toilets. The workshops used the term *gel-kāri* (which roughly translates into "work with clay to build new things") to describe these activities collectively. Other types of tilework, such as tile mosaics, were also produced in the workshops.

Large-format, illustrated, haft-rang tile panels were often produced to order for wealthy customers. In fact, the quantity of haft-rang tiles that were used in a given location was a reflection of the clients' or sponsors'

Figure 3. The special stamp of the Mirzā ʻAbd al-Razzāq's tile workshop on the back of the tile (left); square wooden tile mold (right). © Atefeh Seyed Mousavi.

wealth. However, the workshops commonly made single, ready-made haft-rang tiles available for purchase, as the great popularity of this medium encouraged ordinary people to pay for it. In general, the costly production process for haft-rang tile panels was the reason for the limited number of tile workshops in the same period of time. Aḥmad Shishegar claimed that manufacturing a single haft-rang tile could cover living costs for two days in the late Qajar period.

The fixed number of members in a tile workshop was around three to five people, although several additional workers, painters, and calligraphers might be hired temporarily to meet increases in demand; during busy days, around 20 to 25 people worked in the workshop.

As tilework was a family trade, different generations of a family were active in the same workshop at a given time. In this way, each workshop had its own specializations with respect to technique, along with its own special stamp derived from the name of the master craftsman, who was known as *ostād-kār*. This stamp was embossed on the tile molds, such that the back of each tile bore the workshop's mark (Figure 3). However, not all workshops had their own official stamp, as not all workshops produced all of their own materials; some instead sourced tile and certain colored glazes from other workshops. Ultimately, workshops endeavored with the utmost care to create high quality tiles, regardless of the economic and social status of the patron.

3.3 *Glossary of key terms in Shiraz's tile workshops*

Although haft-rang tiles were quicker to manufacture than other styles of tilework, traditional haft-rang tile production still involved a long and complicated process. The following is a brief (verbal) sketch, in list form, of the general features of tile production, arranged more or less in the order in which the steps would have been undertaken. The list gives some attention to the individual duties of the craftsmen and other workers, and introduces the local terms and titles that describe those individuals and their tasks. While no literal translation is possible, the terms' meaning will be explained:

a) *Gel-kub*: the individual who broke up the soil until it was soft. This worker also sifted the soil, added water to it, and let it rest for one week; b) *Gel-lagad-kon*: the individual who treaded the mixture of soil and water to make the clay (a composite paste) and who kneaded it very well; c) *Chune-kon*: the individual who divided clay into equal, small parts for the *bār-zan* to work with. A young novice often served as *chune-kon*; d) *Bār-zan*: the individual who fit the clay into a square wooden mold of 20 × 20 cm, the traditional haft-rang size. He pressed and pulled the clay at the mold with his hands in order to form it into the desired shape. Two narrow, rectangular carvings in the base of the mold served to form two legs for the tile; these legs helped with installing the tiles and fixing them more securely to the wall (see Figure 3); e) *Taqqe-kon*: the individual who used a mallet to release the tile from the mold; f) *Bār-shur*: the individual who washed the tiles after drying, thereafter puttying them with a mixture of soft sand and glass powder. After this step, the workers put these unglazed tiles into the kiln for the first firing; g) *Loʿā*b-k*ā*r: the individual who applied the background glaze (usually white) to the tiles after the first firing. Glazing tiles is one of the major phases of tile production and should therefore be done by a professional craftsman. Furthermore, *loʿā*b-k*ā*r worked simultaneously with two additional workers. Afterwards, the glazed tiles were fired for a second time, in a process called "second firing"; h) *Ājor-tarāsh*: the individual who shaped the edges of the tiles by hatchet – without damaging the glaze – in order to adjust the glazed tiles side by side and provide a large, flat surface, similar to a canvas; i) *Suzan-kār*: the individual who transferred the decorative patterns to the tile panel (one panel consisting of several tiles each). A painter, meanwhile, marked the designs onto paper beforehand. Specifically, with thematic motifs (such as religious narratives and Persian romances), the painter illustrated the entirety of the desired scene

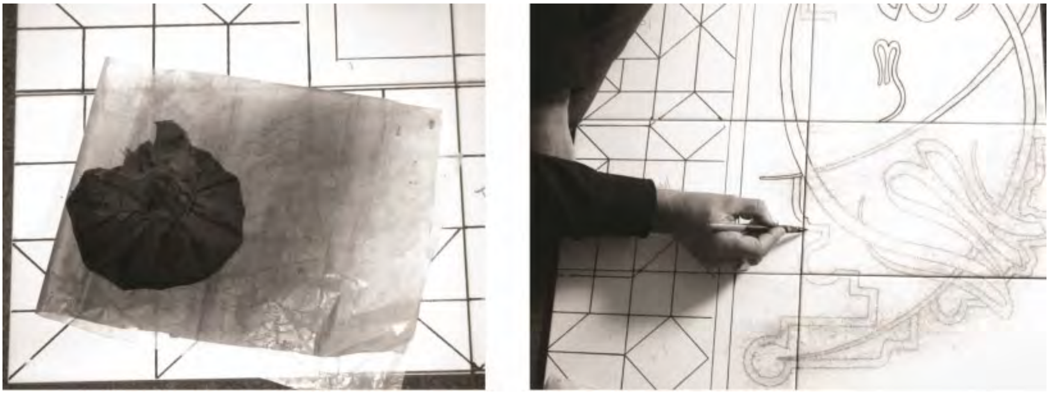

Figure 4. The process of transferring the motifs to the tile panel by Suzan-kār (left and right); outlining the patterns by *Q*alam-*gir* (right). © Atefeh Seyed Mousavi.

on paper in advance of painting the tiles. By contrast, with floral patterns, the painter drew only part of the motif that covers a quarter of the tile panel and for the rest of the parts, the *suzan-kār* repeated the same patterns. At first, the *suzan-kār* transferred the motifs from the original paper to an onionskin paper and perforated the patterns with a needle (*suzan*). Then, to transfer his pattern onto the tile panel, he placed the perforated onionskin paper onto the panel, used a small cloth to rub coal dust onto the onionskin paper, and allowed the coal dust to pass through the holes (Figure 4); j) Q*alam-gir*: the qualified craftsman who thinly outlined the patterns with a greasy substance, usually black, in order to separate the patterns and prevent the glazes from mingling during the glazing process; k) *Āsiyāb-kesh* or *Rang-sāb*: the individual who ground the colored glazes into a powder. The glazes themselves were already produced with a natural base by the master craftsman and were therefore available for the *asiyāb-kesh* or *rang-sāb*; l) *Rang-kon*: the individual who applied the colored glazes to the patterns with a brush. After finalizing the painting process, the backs of the tiles were numbered carefully according to their sequence of placement in the planned design sketch (Figure 5); m) *Kure-chin*: the skilled craftsman who arranged the tiles in the kiln for the third firing (the final firing). Due to his experience, he knew each glaze's heating time and its proper placement in the kiln. He arranged the tiles so that lighter glazes, which need less heat (e.g. yellow, white, and turquoise) were placed in the lower part of the kiln, and darker glazes, which need more heat (e.g. cobalt blue, known as *lājevardi*, and black) were placed in the upper part of the kiln, on account of the fact that heat rises (Figure 6); n) *Kure-suzun*: the experienced craftsman who determined the kiln temperature and heating time (Rabi'i 1390/2011: 24–49; Seyed Mosavi 2018: 57–60).

Shiraz tile craftsmen applied a wide range of natural materials for producing different colored glazes, including minerals, such as flint or quartz (*sang-e chakhmāq*) and lapis lazuli (*sang-e lājevard*); a variety of plants, such as gum tragacanth (*giyāh-e katirā*) and rose madder (*giyāh-e ronās*); and alloys and metals, such as lead, tin, copper, and iron. The majority of the required materials for haft-rang tile production were locally accessible. The glazes' components were gradually developed to be more compatible with the local climate. For instance, over the years, Shiraz tile makers determined that the use of gold in the composition of red glaze made the glaze resistant to fading from the sun (Rabi'i 1390/2011: 23–41).

Figure 5. Applying the colored glazes to the patterns by *Rang-kon*. © Atefeh Seyed Mousavi.

3.4 *Master and apprentices*

The aforementioned process, involving specialized tasks and often specialized craftsmen as well, demonstrates that a strict hierarchy existed within every tile workshop in Shiraz that was, in effect, under the supervision of a master (*ostād-kār*) who was also the head of the workshop (Figure 7). Highly proficient and vastly experienced, the master craftsman was knowledgeable with regard to all processes involved in tile production, even skills such as calligraphy and painting, as he frequently painted the more complicated parts of the tile patterns (especially human faces). His expertise went beyond the artistic to the technical, including an ability to evaluate local soil quality (one of his principal competencies) and to set the kiln temperature and heating

Figure 6. Arranging the tiles in the kiln by *Kure-chin*; tiles with darker glazes in the upper part (left) and the tiles with lighter in the lower part of the kiln (right): © Atefeh Seyed Mousavi.

Figure 7. The process of pottery and tile production in a traditional workshop; a man at a table makes a clay pot with a potter's wheel (right side), the steps of designing and painting on the tiles (in the middle) and the step of firing tiles in a kiln (left side). © Atefeh Seyed Mousavi.

time appropriately in an era when precise instruments of measurement for such functions did not exist.

The master craftsman performed administrative duties as well, including hiring temporary craftsmen and artists, preparing necessary equipment and materials for the workshop, taking orders from clients, and negotiating with clients. He decided how to furnish a location with tilework in accordance with its size (and, of course, considering the client's ideas) and likely would have developed a kind of blueprint to plan the tile panels' installation in every part of the work site. He also determined the quantity of tile panels required and often considered particular places, based on the architectural structure of each building, to be associated with certain patterns. The latter skill was especially important in narrative tile painting, which depicted different episodes of a given theme (e.g. a religious story; Seyed Mousavi 2018: 59). However, all this said, since the preparation of colored glazes required a high level of proficiency, the master's most exclusive task was the creation of colored glazes. The components used for producing glazes were discovered empirically down the generations by a master's family. To guard the recipes, the name of each element and its specific proportions were written in code in *siyāqi* calligraphy, a style of Persian calligraphy that was popular in the Qajar period. The application of special symbols and numbers, along with abbreviated words, make this calligraphy difficult to read; tradesmen and bookkeepers used *siyāqi* in writing calculations, numbers, quantities, and weights (Ṣafi-nezhād 1388/2010). Furthermore, for reasons of secrecy, the main craftsman produced the glazes in a special room in his workshop; some masters even devoted a separate room within their private houses to making colored glazes. In fact, although some of the acids used in the production of glazes released toxic gases, the masters still avoided preparing the glazes outdoors (where fresh air could have made the process healthier and more pleasant) to keep the recipes closely guarded.

A traditional system of apprenticeship (the master–apprentice relation, or *ostād-shāgerdi*) allowed tile makers and tile painters to learn the technical features and principles of visual arts. Apprentices commonly worked in a workshop from adolescence and, through several years of effort, learned the techniques of the trade from their master. Nonetheless, they were usually unable to work independently due to the secrecy surrounding the master's glaze and soil recipes. The main craftsman ultimately only transmitted the professional skills and formulas used for the clay, colored glazes, and other important details to his son or to a very select apprentice. Therefore, every workshop possessed its own unique formulas.

The tile craftsmen of Shiraz generally came from the grassroots of society and therefore were familiar with the general public's aesthetic preferences. As such, the designs and colored glazes chosen by Shiraz tile artists reflect the beliefs and interests of the ordinary people of the Qajar period. Out of the respect for the holy scripture, the tile craftsmen performed the ritual ablution when working on tiles that were decorated with verses from the Koran – a practice that perfectly reflects the fusion of devotional life with art in Qajar society (Seyed Mousavi 2018: 62).

AḥmedShishegar also mentioned in the interview that Shiraz tile craftsmen usually gathered in a specific coffee house after work and discussed their recent experiences, both with respect to technical considerations and to new commissions. From this practice we can presume that tile craftsmen enjoyed close friendships with each other, without a great degree of rivalry.

4 CONCLUSION

Shiraz tilework enthralls the viewer with its vibrant patterns and abundant colored glazes and is a unique phenomenon within the larger history of Persian tilework. Ordinary people were the primary patrons of this art form in the late Qajar period, since it offered them a perfect opportunity for embellishing their private spaces with their favorite images and themes.

With new treatments and themes, along with an extensive range of bright glazes, Shiraz's tile craftsmen improved spectacularly upon Persia's techniques for producing haft-rang tile. The reputation of the city's tile makers and tile painters in the Qajar period thus spread beyond the city, attracting commissions from other cities such as the capital, Tehran (Interview with Shishegar, 12 November 2012). Since the haft-rang production process involved so many craftsmen working in close cooperation with one another, the illustrated tile panels in Shiraz often bear the name of the workshop, rather than the names of individual artists; tile production was a team effort. This is why, even if the name of a particular master ever did appear, it did so only modestly (ḥ*aqir*) alongside the name of his workshop: for example, *dar kārkhāne-ye* ḥ*aqir* Mirzā ʿAbd al-Razzāq-e *kāshi paz* ("in the workshop of the tile maker Mirz*ā* ʿAbd al-razz*ā*q"). The haft-rang tile of the Qajar period of Shiraz continues to inspire art and artists to this day, however, this art gradually lost its earlier widespread popularity. Therefore, very few contemporary tile craftsmen in Shiraz are still acquainted with the traditional methods, and they are mainly employed for the restoration of historical monuments. Altogether, the traditional processes and materials involved in the production of traditional haft-rang tiles are prohibitively expensive. Although some workshops in Shiraz are active in producing haft-rang tiles, they use industrial tile and glazes rather than the old methods of creating their own from scratch. AḥmedShishegar expressed that he believed contemporary haft-rang tile production to be an incomplete assembly (so to speak), sharing only one factor in common with the traditional haft-rang art form: both bear the name "haft-rang tile". Nonetheless, the Qajar era tile craftsmen of Shiraz, with their exceptional expertise, created brilliant art that still – more than 200 years later – lends great vibrancy to the historical buildings it graces.

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Erudite vaults by anonymous builders: The vaulted houses of Fuzeta (Portugal)

M.B. Pacheco
Universidade NOVA de Lisboa, Lisbon, Portugal

ABSTRACT: The fishing village of Fuzeta, in southern Portugal, provides a remarkable and yet unique example of Mediterranean vernacular architecture. Although most of the buildings in the historical centre were built between the 19th and the first half of the 20th century, the underlying urbanism dates to the 17th century with the first fishermen settlements located on the seafront. The homogeneous architecture is particularly relevant because of the pervasive use of a typology of houses with terraces on brick vaults with different shapes and geometries – lowered barrel, sail and cloister – still preserved today. This paper characterizes, analyzes and compares the types of brick vaulted houses in Fuzeta. The conducted research indicates that these anonymous constructions were nourished by an erudite source, the church of *Nossa Senhora do Carmo*, built at the same time and sharing builders and knowledge, blurring boundaries between vernacular and erudite.

1 INTRODUCTION

Fuzeta is located in the eastern Algarve, on a beach that extends up to a small hill, on the west bank of the mouth of the Ribeira do Tronco River. It is protected from north winds by mountains, and exposed to high temperatures and low rainfall, which are characteristic of Mediterranean weather (Feio 1949, 107). Its privileged location within the salt marsh region of Ria Formosa, near the *Barra da Fuzeta*, is that it is the only maritime waterway to the high seas between Olhão and Tavira. Its proximity to the cities of Faro and Tavira, made Fuzeta a strategic point. Since the 16th century, the region has been protected by watchtowers, with the one closest to Fuzeta located in Bias, later reinforced by the Battery of Fuzeta, built in the 17th century (Vaz 1986, 8–10).

Urbanism of Fuzeta dates from the 16th century with the first fishermen seasonal settlements in huts located at the beach on the west side of the river, which became permanent due to the enhanced security provided by the construction of the battery. In the second half of 16th century, it was already considered a place of residence (Mascarenhas 1953). The dwellings were displayed in parallel rows facing the sea, creating a proto-orthogonal grid enclosed by the outer streets. The 18th century legislation contributed to the regularity of the Fuzeta's urbanism. Particularly, the law of 1776 which related to the calculation of rent in county lands. It recommended standardization of the size of the allotments and the prevalence of regular streets. This condition is visible in the regularity of the lot fronts of 19th century allotment campaigns, contemporary with the construction of most buildings of the historical centre (Pacheco 2018, 293–7).

This paper aims to characterize, analyze and compare the typology of the Fuzeta houses covered by vaulted terraces and to place and frame their constructive system in the tradition of the building treatises and the erudite buildings influences. The work also aims at discussing the importance of the transmission of erudite constructive knowledge into popular building practices and techniques. As there are no previous publications about the urbanism or architecture of Fuzeta, the study is based on in situ works, which included conducting house-to-house surveys of 140 houses.

2 VAULTS IN CONSTRUCTION HISTORY

The discipline of construction history still has little research on the construction of vaults in vernacular houses before the diffusion of materials and construction processes introduced by industrialization. Apart from few authors (Caldas 2009, 2012; Luna 2009; Rei & Gago 2016a, 2016b), studies on vernacular vaulted houses in the Iberian Peninsula are scarce, with the exception of some interest in noble houses and in religious architecture, in particular medieval architecture with an erudite root (Ramalho et al. 2002). These studies have generic approaches in the field of art history, sometimes specific in the framework of the rehabilitation of structures and pathologies. Archaeology and ethnology have also shown some interest in rudimentary vaulted buildings, and in buildings to support rural activity, while the vaults as a construction system used to cover current houses remain to be studied.

Until the end of the 19th century, vault construction was widespread throughout Europe, in erudite and vernacular constructions, about whose knowledge was

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disseminated through structural calculation manuals, as happened in Portugal. In the international context after the Industrial Revolution, it gradually slowed down, at the same time that the first patrimonial views of vaulted buildings started to emerge.

Auguste Choisy (1841–1909), engineer and architectural historian, was one of the first researchers to investigate the constructive system of vaults. His study of notable constructions by the Roman and Byzantine civilizations and the knowledge acquired through direct contact with the buildings resulted in the following books: *L'Art de bâtir chez les Romains* (1873), *L'Art de bâtir chez les Byzantins* (1883), and the *Histoire de L'Architecture* (1899). In these publications he highlighted the differences between vault systems according to geometries, construction processes and materials used (Choisy 1883).

According to Choisy, the Romans used different types of systems to build a vault, all requiring the use of a removable wooden formwork that guaranteed the geometry: i) the vault made of a concrecional material on the formwork; ii) the vault in stonework with the stones assembled in a formwork; iii) the vault with lost formwork; and iv) the vault made by bricks assembled in the formwork and filled with a concrete material. Therefore, the Roman brick vaults, with a concrecional conception, differs from the Byzantine brick vault that does not require the use of formwork during the construction process due to the way the bricks are assembled between themselves, from the walls to the closure, generating the intrados (Choisy 1883, 19).

In the Roman system, the brick vaults are built by rows perpendicular to the front wall and with bricks placed with the stretcher face seen which requires the use of a formwork. In brick vaults built without formwork, classified by Choisy as a "Byzantine system", the rows are inclined over the front wall and the bricks are also placed with the stretcher face seen. The inclination is given by the placement of the bricks, more accentuated at the base than at the top, which causes a curvature that increases stability and prevents the sliding effect. The two construction processes in rows perpendicular or inclined in relation to the front wall, can be combined in the same vault, starting with perpendicular rows. The front wall in the springing that does not need the formwork due to the little curvature, is completed with rows of bricks inclined against the front wall. This is a solution with practical advantages and currently used in the Byzantine constructions (Choisy 1883, 34–6).

Some authors relate the development of the construction process of the vaults without formwork with the scarcity of timber (Ribeiro 1961; Villalba 1995) and others justify its presence in the Iberian Peninsula as the inheritance of Syrian civilization (Luna 2009, 494). In Portugal, there is an interpretive trend, formed in the transition from the 19th to the 20th century, regarding the cultural aspect of vaults and terraces construction, which defends a hypothetical persistence of the constructive uses of Islamic origin in the Portuguese fringe of the south-west peninsular. This trend still prevails today, mainly in tourist publications, although it is not supported by historical studies or scientifically based.

Contrary to what has been argued by Orlando Ribeiro (Ribeiro 1961), the vaults of the Modern Era only began to be used in aristocratic houses of the Algarve in the mid-18th century, and were probably first employed in common houses at the end of the same century. Despite the logic of a natural transfer over the centuries of knowledge across the Mediterranean Sea from the East to the West, there remains a hiatus of significant construction examples that relate to the examples known in Portugal built between the 18th and 19th centuries (Caldas 2007; 2009, 2012).

In Portugal, the buildings with the oldest vaults date to at least the Roman period, as, among others, the vaults of the cryptoportico on *Rua da Prata*, in Lisbon, built between 1st BC and 1st AD centuries. In Baixo Alentejo, other Roman vault examples were built in the *villa* of São Cucufate, in Vila de Frades, Beja, before the 4th century. The same system is found in the São Bento chapel, in Monsaraz, built in the late 16th and early 17th centuries, attesting to the permanence of constructive knowledge in the region.

One of the first Portuguese publications referring to the constructive process of the vaults was the manual of the architect João Nunes Tinoco (ca. 1610–89) entitled *Taboadas gerais para com facilidade se medir qualquer obra do officio de pedreiro, assim de cantaria como de alvenaria, com outras varias curiozidades da geometria pratica* (General tables to easily measure any work of the mason, as well as stonework or masonry, with other curiosities of practical geometry) (1660). The manual provides geometric notes for the construction of double (*dobradas*), simple (*singelas*) and lowered (*abatidas*) brick vaults, specifying the necessary materials and procedures in tables and drawings. The manual has sections dedicated to the construction of vaults: "How is it known how many a *braça* [old measurement unit correspondent to two open arms, around 2.2m] bricks to use in a double or simple vault?" (Tinoco 1660, 34); "Form of lowered vaults (*sarapaineis* or *abatidas*) by the 5th part and by the 6th part" and "Form of lowered vaults by the account of the 3rd and 4th part" (Tinoco 1660, 43).

Tinoco's tables appeared at a time when the teaching institution *Aula de Fortificação e Arquitetura Militar* (1647–1709), based in *Paço da Ribeira*, in Lisbon, encouraged both the translation of foreign works representative of the most advanced defensive systems; and the publication, in Portuguese, of specialized works, marking the beginning of a new way of teaching Military Architecture. In this context, Luís Serrão Pimentel (1613–79), senior royal engineer since 1671, and teacher of Fortification in the Mathematics and Fortification Class, developed the *Methodo Lusitanico* (Lusitanian Method) (1680) to support his classes and teach how to draw regular and irregular fortifications.

Later, in the 18th century, in the framework of the Enlightenment, several international publications emerged revealing concerns about the graphic representation of arches and vault sections. In addition, printed works dedicated to ornamentation, measurements, regulations, and standard specifications, helping to unify the measurement units and methods emerged. At the same time that general treatises and manuals of perspective and drawing appeared, a new category of works dedicated to the mechanics of arches and vaults featured in the Enlightenment thinking (Mateus 2002, 40). In Europe, the treatises sought to respond jointly to the requirements of architecture, civil engineering and military engineering. This is the case of *O Engenheiro Português* (The Portuguese Engineer) (1728–9), written by Manuel de Azevedo Fortes intended for teaching at *Academia Militar da Corte* (1707–79). In book V, entitled "Effective fortification" the question of waterproofing the vaults is addressed, among other topics.

Contemporaneous to the construction publications of the European vanguard, another Portuguese manual was written, *Advertências aos Modernos que Aprendem o Ofício de Pedreiro e Carpinteiro* (Advertences to Modern Learning in the Profession of Mason and Carpenter) (1757), by the master Valério Martins de Oliveira. This manual aimed to transmit knowledge about the art of building through traditional and learned processes, and brought together the work of Renaissance architects to the Portuguese construction panorama, such as the arch of Sebastião Serlio published in the architectural treatise *Tutte l'opere d'Architettura et Prospettiva* (1537-early 17th century) (Oliveira 1757, 41). The Martins de Oliveira manual compiles erudite knowledge for practical transmission about construction planning, measurements and quantifications of bricks for different types of vaults – doubled, simple, in stone, in brick, groined, in brick with round turn to the way of barrel, lowered, hemispherical, through geometric drawings and tables (Oliveira 1757, 26, 28) (Figure 1).

In 1896, a new manual was published entitled *Curso Elementar de Construções* (Elementary Construction Course) by Luiz Augusto Leitão. The chapter "Construction works: Masonry walls, walls and stone vaults (…) and vaults formwork", addresses the different types of vaults and their regional nomenclatures (lowered, sail (*asa de cesto*), cloister and hemispherical with pendentives) and their construction processes (Leitão 1896, 251–3). The vaults' construction procedures refer, among other issues, to the use of formwork and to the specificity of the vaults and brick vaults of the type *abobadilha* (barrel, groined (*abobadilha de percinas*), cloister (*abobadilha de engras*) and vaults from Alentejo region that "do not require the use of formworks or supports of any nature" (Mateus 2002, 77–8).

3 THE VAULTED HOUSES OF FUZETA

There is no documentation giving the date of the construction of the first houses in Fuzeta. However, according to the similar context of the nearby village of Olhão, where huts began to be replaced in 1715 at residents' requests "to build masonry houses since they lived in huts" (Romba 2015, 56–7), in Fuzeta the replacement of huts happened also during the 18th century (Vaz 1986, 16).

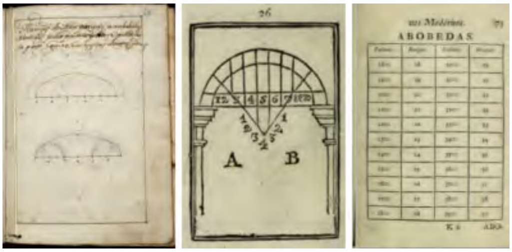

Figure 1. (left) Three-centred arch profile geometry (Tinoco 1660, 43); (center) Arch of Sebastião Serlio; and (right) Table of vaults' measurements (Oliveira 1757, 26, 75).

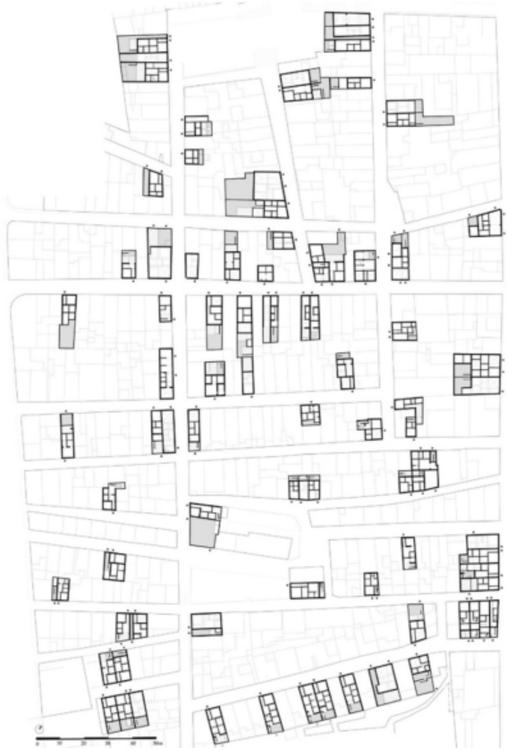

Figure 2. Fuzeta urban centre (western side of *Rua da Liberdade*) with the ground floor plan of the vaulted houses analyzed (author's drawing).

The construction of masonry houses in Fuzeta, whether original or to replace huts, was associated with a current house type, corresponding to contiguous dwellings with a single floor, located in lots currently with homogeneous widths, around five to six *varas* (5.5m to 6.6m) in the standard lots (Figures 2 and 3).

The houses have a modular composition, organised in two or three sectors – façade, middle and back – with individual brick vault ceilings with terraces above covering the majority of rooms, except the main room in the façade sector that was sometimes covered by a pitched roof (*telhado-de-tesouro*) currently absent. The main façade of the houses in standard lots is composed by two windows and a door, topped by a frieze protecting and hiding the terrace and covering the constructive systems.

The houses in standard lots can be composed of two or three sectors, usually the middle one is covered by lowered barrel vaults perpendicular to the façade and the back one with a parallel lowered barrel vault. On the façade sector is the living room, called *casa de fora*, with a square layout covered by a pitched roof, a sail vault (*abóbada de vela*) or a cloister vault (*abóbada barrete de clérigo*), and a corridor covered by a lowered barrel vault. The middle sector consists of two or three alcoves covered by a continuous lowered barrel vault, an interior living room, called *casa de dentro*, and a kitchen, usually in the back sector covered by a lowered barrel vault parallel or perpendicular to the previous sector. The indoor kitchen may be complemented by a covered outdoor space with a fireplace and oven, embedded in the roof terrace's stairwell, extended by a porch to the back courtyard, frequently where there is a water well (Figure 4).

The houses in narrow lots, with less than 5m front, are also composed by two or three sectors. The difference stands in the façade sector, without corridor and just the main room *casa de fora*. The middle and back sectors are covered by lowered barrel vaults perpendicular or parallel to the façade.

The house settled in large lots, with greater than 6m front or resulting of the junction of two standard lots is composed of two or three sectors.

It has an internal distribution with a central corridor, similar to the Portuguese traditional house called *risca ao meio* (symmetrical plan and façade), and has also a symmetric façade composed by a door in the middle flanked by one or two windows, and a courtyard in the back, depending on the geometry and location of the lot. The façade sector made up of two rooms, the living room and the bedroom, is covered by cloister vaults and separated by a corridor with a lowered barrel vault. The middle sector is covered by two continuous and parallel lowered barrel vaults, one covering the bedrooms or alcoves; and other covering the interior living room (*casa de dentro*) and the kitchen. These types of houses have a modular character emphasized by the independent vault coverage of the rooms with the extradoses identified on the terrace. The curvature of the extrados was softened by filling the spandrels, and lined with plain ceramic tiles or lime washed, ensuring insolation, and allowing its use.

The constructive system of the vaults as structure of the terrace is suitable for the Mediterranean environment. The terrace is an extension of the house used for domestic and fishing activities, in particular for drying fruit, fish or clothing, maintenance and storage of fishing gear, as well as for collecting rainwater stored in underground cisterns. Also, the thermal inertia of the vaults provides a positive thermal balance between indoor and outdoor temperature and humidity (Pacheco et al. 2015).

Figure 3. Fuzeta urban centre (eastern side of *Rua da Liberdade)* with the ground floor plan of the vaulted houses analyzed (author's drawing).

According to the vault terminology used by Mascarenhas Mateus (2002, 82–4), the brick vaults on the Fuzeta houses belong to the category of "ordinary masonry" (as opposed to "concrete masonry" molded on formwork filled with concrete and mortar). Lowered barrel vaults or lowered hemispherical vaults (sail vault) can be considered as "simple" type. Cloister vault with a square base and obtained by the intersection of two lowered barrel vaults are "composed" type. The choice of the arch profile results from several factors: the function of the vault; the dimension of the span to be overcome and the section and height of the support wall (pier); the volume of masonry and the charge supported by the extrados; the type of masonry used; and the available manpower (Mateus 2002, 8, 80).

The lowered barrel vaults in the houses of Fuzeta are built in brick with the stretcher face seen, according to a process that does not use a formwork for placing the bricks. Those are placed in inclined rows in relation to the front walls, similar to the Byzantine system for building brick vaults described by Choisy (1883). The springer (area of the beginning of the intrados curvature) is made with stone masonry, arranged conically in straight rows perpendicular to the front walls, supporting the staring of the curved rows of brick, placed with the stretcher face seen, and oblique

Table 1. Vaulted houses and lot typologies according to the “house-to-house” surveys covering 140 houses in the urban centre of Fuzeta village.

Lot typology	House typology	n°	%
Standard lot (between 5m and 6m front)	2 sectors, the middle one covered by lowered barrel vaults perpendicular to the façade	37	27
	3 sectors, the middle one covered by lowered barrel vaults perpendicular to the façade and the back one with 1 lowered barrel vault parallel to the façade	17	12
	2 or 3 sectors, the middle one covered by lowered barrel vaults parallel to the façade	10	7
Narrow lot (less than 5m front)	2 or 3 sectors, the middle one covered by lowered barrel vaults perpendicular to the façade	36	26
Large lot (more than 6m front) or 2 standard lots joined	2 sectors	10	7
	3 sectors	17	12
	House without typology	3	2
	Warehouse	10	7
	Total	140	100

in relation to the front walls, where the arch profile is drawn (Mateus 2002, 91–2). The slope of the first brick rows in direction to the front wall is maintained along the length of the vault, giving stability when transmitting loads to the side and front walls, ensuring that the arch pressure line is within the thickness of the vault. The intrados consists of rows of bricks placed with the stretcher face seen, filled with concretion material of sands, lime mortars and various inert, including shellfish contributing to the insolation, reaching more than 80cm of thickness, decreasing to the top of the vault with just over 30cm, corresponding mainly to the thickness of the bricks and the extrados coating on ceramic tile.

The type of brick assemblage of the vault construction is mainly imposed by the construction method. In the execution of the last part of the barrel vaults, in the central area, is used a spine assembly method, in which each brick is assembled from the perimeter, ending in the centre (Choisy 1883, 39).

In the sail vault construction, the assemblage of the bricks is carried out with a slight inclination composing concentric rings over the springers made by limestone masonry. Occasionally, small blocks of the same stone appear in rows between the bricks (Figure 6). On the top of the vaults, in the last rows the bricks are placed perpendicular to each other.

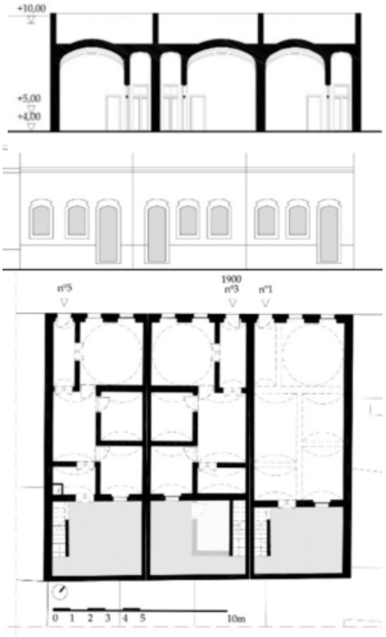

Figure 4. Elevation, section and ground plan of the set of houses located in standard lots in *Travessa das Amoreiras* (author’s drawing).

In the cloister vaults, two types of brick assemblage are combined: lying bricks composing the two crossed arches shaping the geometry of the vault, and bricks standing vertically filling the intrados (Cabral & Aranha 1996; Mateus 2002, 93–5) (Figure 6).

Traditionally, the intrados of the vaults is finished with plaster and stucco, and often decorated with friezes and ornaments that enhance the geometry of the vault, although hiding the stereotomy of the bricks’ assembly in rows. Frequently, the rehabilitation works carried out in the last decade have removed the interior coating, leaving the bricks and the laborious assembly work seen.

In fact, the constructive process of the vaults of the Fuzeta houses is a knowledge based on an oral and practical tradition, whose calculations were made using empirical rules and methods based on geometric proportions compiled in tables (Mateus 2002, 133). This dimensioning process was the only existent technique until the end of the 17th century, when the first applications of Mechanical Engineering to the study of the structural performance of vaults appeared. Its use continued until the 20th century, coexisting with other more advanced techniques based on logarithmic calculations.

The rules contained in the tables were applied to the main structural elements: arch, vault and pier height (supporting wall); to the profile of the arches (once the vaults were classified by their representative arches – round, lowered or pointed); and the type of masonry (stonework, brick or concrecional) (Mateus 2002, 131).

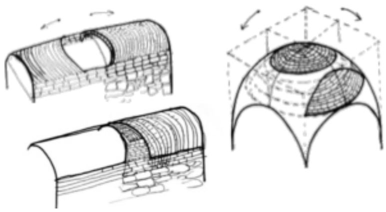

Figure 5. Scheme of the constructive systems of lowered barrel vault (left) and sail vault (right) (author's drawing).

The stability concept of the arches and their piers (*pé-direito*) is studied in a simplified and synthesized version, according to two extreme moments: the "shoot down" moment, caused by the impulse transmitted by the arch and proportional to its thickness; a "stabilizing" moment proportional to the weight of the piers.

Also, the calculation of the vault's thickness, constant or variable, was done according to empirical rules, as mentioned in the works of Francesco Milizia, *Principii di architettura civile* (1781), by Girolamo Masi, *Teoria e pratica di architettura civile per istruzione della gioventu specialmente romana* (1788) and Charles Leroy, *Traité de stéréotomie* (1877). The thickness of the support walls of the vaults is also determined empirically, based on geometric constructions that considers the span distance, the profile of the arches and their peers. According to Gustav Adolf Breymann, in the treatise *Allgemeine Bau-Constructions-Lehre* (1849), the rule has a medieval origin. Its first representation is due to François Derand in *L'architecture des voûtes* (1643), later included in several treaties: in the *Cours d'architecture*, by François Blondel (1675–83), in the treaties previously mentioned by Francesco Milizia (1781) and Girolamo Masi (1788), and also in the *Traité théorique et pratique de l'art de bâtir*, by Jean-Baptiste Rondelet (1804).

The traditional method used to calculate the thickness of the supports of the vaults implied the difference of thrusts caused by different types of profiles (although it disregards the materials' resistance, the voussoirs' thickness, the loading system and the height of the piers). Breymann determines that the thickness of the walls of the brick barrel and lowered barrel vaults is 1/4 of the span (L), with a rise greater than 1/8 of the span (L) (Mateus 2002, 132–3, 135).

Rondelet's studies contributed to 19th century treatises due to their easy application through formulas and graphic schemes, although with methodological limitations and simplified calculations. In the chapter *La Théorie de Voûtes* (section VI of Book IX) of *Traité théorique et pratique de l'art de bâtir*, Rondelet presented empirical formulas for determining the thickness of barrel vaults using reference values for lowered or pointed arch profiles, based on the tests carried out at the end of the 19th century by M. Lavezzari and presented by Marcel Daly in the Portuguese magazine *Construção Moderna* in 1900. (Mateus 2002, 142).

4 THE GEOMETRY OF VAULTS: A CLUE TO ITS ERUDICITY

The lowered barrel vault is the most common type of vault used to cover the rooms of the Fuzeta houses, also used as structural support of the terraces. Lowered barrel vaults, in which the rise is less than half the span are vaults in an arch of a circle or three-centred arch (Leitão 1896, 252). The lowered barrel vault can have different arch profiles obtained from different geometries: round, semi-elliptical or lowered, the most common. The lowered arch is outlined from an odd number of circumference arches, joined tangentially. The lowered arch profile is used when the ratio between the span (S) and the rise (R) varies between 2 and 5 ($2 < S/R < 5$). The simplest lowered arch profile is composed by the three-centred and used when the ratio between span and rise varies between 2 and 3 ($2 < S/R < 3$) (Mateus 2002, 82).

Geometrical studies of the arch profile in 30 rooms of Fuzeta houses were carried out based on *in loco* measurements and further geometrical construction following the traditional treatises (Pacheco 2018; 224–6). According to this approach, the arch profiles of the lowered barrel vaults have different ratios between span and rise (S/R): around two, with greater rise and almost a round arch, others closer to five, with lesser rise, with a more lowered geometry. The most common ratio between span and rise varies between three and five, and corresponds to most of the vaults, including the oldest ones. Ratios greater than five refer to semi-elliptical arches whose geometry appears occasionally in vaults that are more recent or with larger spans, as well as some vaults with profile arches based on segments of circumference (Figure 6).

The lowered barrel vault is present in all sectors of the house, with different ratios between spans and rises according to the dimensions of the compartments. The set of lowered barrel vaults supports most, or all, of the roof terrace. The vaults with narrower spans are found in the corridor covered by a vault with a lowered barrel, located in the sector of the façade. In the middle sector, the lowered barrel vaults that cover the alcoves have spans around 2m. The room *casa de dentro*, also in the middle sector, and the kitchen in the back sector are also covered by lowered barrel vaults, with spans of various dimensions, upper 2m (Costa 1971, 12).

The sail vault is related with square layout compartments, which vary between 2m and 4m in span, and are found mostly in the *casa de fora* and *casa de dentro*, but also can appear in the alcoves. These vaults do not present a risk of collapse in their construction: once during the process each of the rings that composes the geometry, is closed before starting the next one. Also, the assembly of the bricks inclined in each row, convert the vaults into a stable element that "do not give horizontal impulse because they charge vertically on the piers" (Leitão 1896, 91; Villalba 1995, 91) (Figure 5).

Less common is the use of the cloister vault, "the reverse construction of the groin vault" (Costa 1971, 13). It results from the intersection of two-barrel

Figure 6. (top) Intrados and extrados of the sail vaults located in the main room *casa de fora*; (middle) Intrados of cloister vaults in the main room *casa de fora*; (below) Geometrical construction of arch profiles of lowered barrel vaults with three-centred arch, based on *in loco* measurements (author's photos).

vaults, preserving the imposts at the same level, allowing cover of the regular plant spaces with four or more sides, meeting at the same closing point. Its use in Fuzeta houses is associated with a more recent type of housing, built in the transition from the 19th to the 20th century, as roof coverage of the two *casas de fora* built on lots with large fronts or two regular jointed lots.

The use of vaults as a roofing system for the current house is not exclusive to Fuzeta; although it is there that its use occurs to a greater degree. Vaulted houses are also found in the neighbouring towns of Moncarapacho and Olhão and in rural areas of inner Algarve, where the vaults are used either as terrace support or as a floor support of the first floor, or just as a specific cover for a certain compartment. However, its geographic scope has yet to be studied.

As it seen previously, most of the vaults were built from the second quarter of the 19th until the first half of the 20th century, contemporary with the beginning of the church of *Nossa Senhora do Carmo* construction, which replaced the primitive chapel (Figure 7).

The use of vaults as a roofing system for the current Fuzeta house is implicitly related to the opportunity created by the presence of master builders in the village during the construction of the church, and the functionality of terrace use in the everyday life of a fishing village. The vaults' intrados show an excellent mastery of the constructive technique, observed in the geometry of the vault and in the precise placement of the bricks in the rows and coatings. Therefore, the construction of the church was a key moment and the main cause of the dissemination of the erudite constructive knowledge used in current houses.

Figure 7. Lowered barrel vault in the church of *Nossa Senhora do Carmo,* in Fuzeta.

The geometries and the constructive processes used by vault master builders reinforce the hypothesis of the transmission of a constructive knowledge from an erudite source to a popular context. The lowered barrel vault, the most common geometry covering the middle and back sectors of the houses is built according to a three-centred profile arch, already mentioned in the 17th century Portuguese buildings' manuals. The sail and cloister vaults, intentionally covering the main rooms *casa de fora* and *casa de dentro,* are the pinnacle of erudite construction in this fishing village.

5 CONCLUSIONS

The unprecedented study of Fuzeta's vernacular vaulted houses, based on 140 surveys, aimed to characterize, analyze and compare its types, to understand the relationship between constructive systems, the geometries of the vaults and the use of the rooms. Since no documents or registers related to the houses or vault constructive systems or chronology were found, the question about the origins of these vaults and who built them was raised.

Placing the Fuzeta vaults in the history of construction, mainly due to their study through the buildings' treatises approach, allowed placement and framing of its constructive system in the field of erudite buildings influences. These vaulted houses are a testimony of the anonymity of the local masters who built them and about whom there is no information. The only plausible clue was found in the most erudite building of the village, the local church. The forms and construction processes of the church inspired, influenced and may have been intended as an example to be emulated in the popular houses.

The erudite features transmitted locally are reflected in the accuracy of the arch profile geometries (drawn by geometrical knowledge of construction manuals), in the precision of the laying of the bricks, and in the excellence of intrados surface coating. These features are distinct from other Mediterranean vaults with a more popular origin, usually made by concrecional processes based in the use of formwork and volcanic stones, which tend to have approximate geometries and rustic coatings. In addition, the need for new dwellings, and the replacement of precarious huts, took place during the 19th century, and led to the construction of houses with laboured constructive processes (particularly the vaults) and to use standardized architectural typology adapted to the homogeneous allotments. These sets of houses, forming urban ensembles, using erudite constructive systems and standardized dimensions, suggest they were part of a projected plan. Nevertheless, research carried out at main archives (municipalities of Tavira and Olhão and district of Faro) discounted this hypothesis once no building request documents were found. The constructive influence attenuates the popular origins, fomenting a cultured appearance to the village. The study of Fuzeta's vaulted houses and their underling geometries, constructive systems, materials made by anonymous builders, contribute to a deeper understanding of empirical knowledge transmission. Further, it establishes the importance of these constructive systems in the history of traditional architecture and construction within the wider context of the Algarve and Mediterranean region and raises the question of the difficulty in establishing boundaries between popular and erudite knowledge, bridging these two terms, usually perceived as being opposites.

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Pneumatic foundations in the bridges of the first Italian railways

M. Abita & R. Morganti
Università degli Studi dell'Aquila, L'Aquila, Italy

ABSTRACT: In the first half of the 19th century the French geologist Jacques Triger developed a construction process useful for excavating waterlogged soils that applied a caisson to pump compressed air into the working site. His invention was widely deployed in construction engineering, especially for sinking bridge pier foundations in riverbeds. This technology was first used in Italy in the 1850s under the supervision of British and French building companies. It served for the construction of many bridges in the new Italian railway network and resulted from a fruitful collaboration between Italian and foreign technicians. This essay will describe the evolution of cast iron and wrought iron caissons in Italy, a country which provided a favorable environment for the experimentation of this new technology.

1 ITALIAN RAILWAYS: PNEUMATIC FOUNDATIONS FOR NEW BRIDGES

In the first half of the 19th century, the political division of the Italian territory led to the discontinuous and complicated development of the railway network. In 1840s, after the first line between Naples and Portici was completed in the Kingdom of the Two Sicilies in 1839, initial railways began being built by the peninsula's individual states with their different technical and economic means. Furthermore, there were no coordinated plans between the states that guaranteed efficient connections between the country's main cities (Briano 1977).

In addition to difficulties in attracting resources and the complicated dialogue between governments, other problems arose due to geographic obstacles. They sometimes entailed the choice of irregular routes in order to avoid the inevitable technical and financial commitments needed for the construction of bridges and viaducts, necessary for more direct connections between destinations.

One of the greatest difficulties related to bridge building was the construction of bridge foundations in riverbeds. This was usually solved using traditional techniques that had various limitations. For example, the Venetian Lagoon railway bridge, inaugurated in 1846 under Austrian rule, used deep foundations built of larch and oak poles. These were fixed into the ground and connected at the top to wooden boards that supported the masonry required for the over two hundred arches that made up the bridge. For other bridges over narrow and shallow rivers, centuries old technology was used requiring the deviation of the watercourse or the insertion of bulkheads in order to carry out excavations in the open air. However, the use of these techniques was only possible in shallow waters when the foundations did not reach more than 6–7 meters below ground level (Predari 1867).

In the 1840s, the development of pneumatic foundations, tried out first in Britain and France, revolutionised the way of building underwater: the new procedure avoided the insertion of bulkheads and allowed for deeper and continuous excavations and required a smaller workforce.

Pneumatic foundations were required in Italy for the construction of the bridges necessary for an efficient national rail network but the backwardness of local companies and industries led to the initial assignments for these works being awarded to foreign companies already able to apply the new technology. In particular, between the 1850s and 1870s, firstly in the Kingdom of Sardinia and then in the Kingdom of Italy, British and French companies, finding an ideal place of application and research in the country, collaborated with local technicians and deployed different types of pneumatic foundations for the first time in Italy.

2 ORIGINS AND DEVELOPMENT OF PNEUMATIC FOUNDATIONS

The mining industry was one of the main promoters of studies concerning the use of compressed air. Already in the 17th century, the requirement for underground ventilation had led to the development of the first compressors, able both to produce air at a higher pressure than the surrounding atmosphere and to diffuse it into any work space through a network of pipes (Drinker 1883).

Compressed air played a crucial role in the extraction of coal from underground and underwater deposits. In 1841, Jacques Triger used it to extract coal from a deposit below the River Loire near the town

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of Chalonnes. In order to guarantee a dry work space, Triger developed a sheet iron tube, open at the base and closed at the top, from which the water was expelled by pumping compressed air into the tube. The tube was composed of rings with a diameter of one meter. These were connected to each other with fishbolts and made watertight using leather strips. In the upper section, an airlock regulated the air pressure and the entry and the exit of workers.

The airlock was an evolution of the early diving bell, also known as "cloche de plongée", developed in the 18th century that enabled the carrying out of the first deep underwater explorations, aimed at recovering cargo from sunken ships. The physicists Smeaton and Coulomb saw its potential value in the building sector (Curioni 1868).

The tube was gradually sunk into the riverbed with the help of upper loads with the interior lighting provided by stearic candles or gas lamps. The air pressure had to be kept below four atmospheres in order not to compromise the health of workers.

Triger's process received coverage in the publications of the time and showed more advantages than the Potts' system patented in the same period in Britain. The Potts' system was based on reducing the air density inside the tube so as to suck up water and sediments and to ease penetration into the soil but also entailed the regular suspension of work in order to empty the tube when full of deposits (Dempsey 1855).

The process developed by Triger began to be applied in other sectors and within a few years was being used in the construction of underwater foundations in incoherent soils. Previously they had needed very long poles which, due to their length, were susceptible to shear stresses. By the late 1840s, Triger's process was under applications in France, Britain and the United States for constructing bridge piers.

In 1851, for the construction of Rochester Bridge, the British engineer John Hughes introduced important innovations: he enlarged the airlock, equipped it with a double compartment in order to improve the regulation of the air pressure (Figure 1) and optimised the construction process by combining the Triger and Potts systems (Hughes 1859).

A few years later, the company responsible for building the bridge over the River Medway was involved in the construction of bridges in the new Italian railway network.

3 PNEUMATIC FOUNDATIONS WITH CAST IRON TUBES: THE SAVOY BRIDGES

Under the governance of the Count of Cavour, there was a decisive turning point in the drive towards industrial and infrastructural progress for the Kingdom of Sardinia. The Piedmontese statesman, who considered railways an effective means for economic and cultural development, initiated a series of projects for the construction of new railway routes that played an important role even after the Unification of Italy.

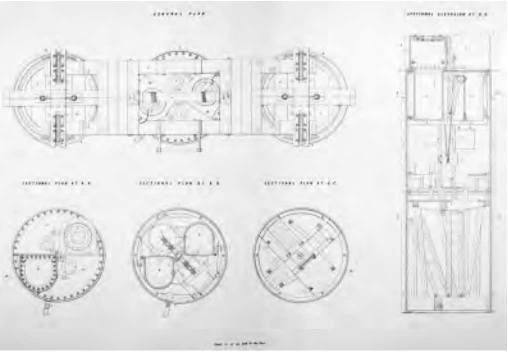

Figure 1. Rochester Bridge: the caissons built in 1851 by Fox & Henderson Company (Hughes 1859).

Between 1852 and 1853, Cavour worked on completing the line between Turin and Genoa but, above all, he provided for the construction of new lines dedicated to international connections, in particular links with Lombardy, then in Austrian territory, France and Switzerland (Cavicchioli 2009).

For the line between Turin and Novara, which was later extended to connect with Milan, Cavour signed an agreement with a group of British entrepreneurs guided by the well-known contractor Thomas Brassey (Stefani 1853), the designer of several railways in Great Britain and Europe and who had managed to complete 100 km of railways in three years. For the line between Turin and Culoz, also known as the Fréjus railway, the Vittorio Emanuele company was founded in 1853, backed by French financiers who also acquired control of the line to Milan after a few years.

The crossing of rivers in a mountainous area involved the construction of railway bridges and viaducts, which required recourse to pneumatic foundations.

3.1 *Pneumatic foundations of the bridges built in the railway line between Turin and Novara*

Thomas Brassey entrusted the construction project for the railway line between Turin and Novara to the British engineer Thomas Jackson Woodhouse. The two had already collaborated in Italy, building the the line between Prato and Pistoia. The engineer Edward Francis Murray, who was involved in completing the railway line between Turin and Genoa, together with Woodhouse and the Italian engineers C. Bermani and V. Ferrari designed four bridges built over the Rivers Stura, Orco, Mallone and Agogna (Murray 1883).

They used the same layout: continuous deck bridges sustained by four supports, two of which were placed in the riverbed. Two wrought iron girders, stiffened using a riveted lattice between the chords, and vertical members supported the single rail (Figure 2).

The use of cast iron tubes sunk into the ground using Triger's pneumatic process was chosen for the bridge

Figure 2. Railway bridge near Novara: the piers built in 1855 by the same company of Rochester Bridge (Fassò 1880).

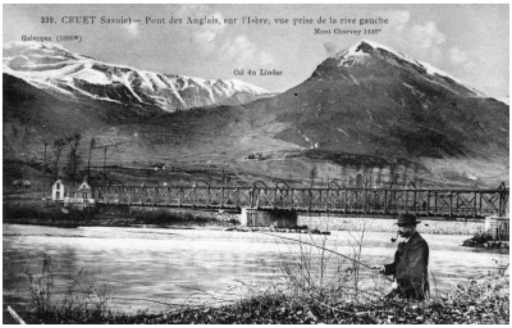

Figure 3. Railway bridge over the River Isère near Cruet: the continuous wrought iron truss (Goutagny Postcard 1889).

piers and the project was managed by Fox & Henderson Company, known for their participation in the construction of Crystal Palace in London and also for setting the foundations for the bridge over the River Medway in Rochester (Casalis 1855).

For each pier they used two cast iron cylinders, which were between 7 and 10 meters long and made of rings, with the height and diameter both measuring 1.5 meters. The sinking was carried out by creating an airlock at the top of the tubes that ensured the regulation of compressed air which was injected by a steam pump. Once the water had been expelled from the tube, the excavation was carried out by two workers, assisted from the outside by two co-workers.

The sinking of the tubes was rapid: for the bridge over the River Agogna near Novara, each cast iron cylinder was sunk to a depth of 7 meters in a period of between two and three days. Once sunk, the tubes were filled with concrete and then connected at the top by wrought iron beams that supported the masonry works.

Above the tubes, walls also acted as the formwork for a further cast of concrete that stabilised the sinking of the cylinders (Pozzi 1892). The technology applied in the piers of the four bridges of the line between Turin and Novara was also used in Savoy, where some innovations developed in France were also introduced.

Figure 4. Cruet Bridge: a pier and its upper rubble masonry sustained by pneumatic foundations (Decker 2020).

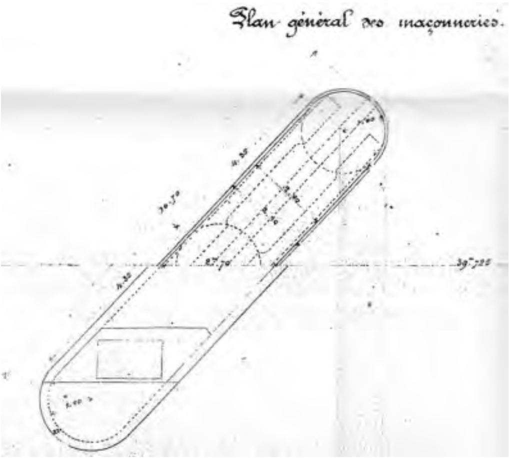

Figure 5. Cruet Bridge: the arrangement of the cast iron tubes and their connections (Courtesy of ACN&P).

3.2 *Pneumatic foundations of the bridges built in the railway line between Turin and Culoz*

The rail connection between Turin and Savoy, which was part of the Kingdom of Sardinia until 1861, was a complex challenge. The Alpine mountains did not allow for any direct route and furthermore needing the construction of a tunnel through Mount Fréjus.

For the laying of the track beyond the tunnel, between Modane and Chambéry, the Vittorio Emanuele Company once again involved Thomas Brassey. George Neumann, a British engineer who had trained in Switzerland and France, was commissioned to design the railway line (Neumann 1867).

Neumann also oversaw the construction of two important bridges: one over the River Isère near Cruet and another over the River Rhone near Culoz on the French border. Both involved the use of large spans, greater than 150 meters, and a structure with a continuous truss supported by multiple piers (Figures 3 and 4).

The truss was built of riveted profiles with different sections and was visually characterized by the way in which these diagonal braces were inserted in the spaces between the chords and vertical members with the arch shaped portal struts (Messiez 1992).

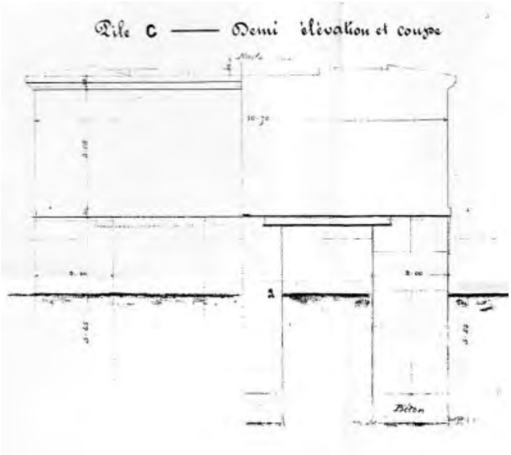

Figure 6. Cruet Bridge: the depth of the cast iron tubes and their concrete filling (Courtesy of ACN&P).

Figure 7. Culoz Bridge over the River Rhone: the same truss used near Cruet (Ministère des travaux publics 1873).

The piers of the two bridges were built with pneumatic foundations. Different companies were involved in their construction, each with their own technical solutions.

The same company as commissioned by Brassey for the bridges on the line between Turin and Novara participated in the piers for the Cruet bridge, also known as Pont des Anglais. The larger dimensions of the bridge required the adaptation of devices used in the construction process.

Three cast iron cylinders were used for each pier, each with a diameter of two meters (Figure 5). These were sunk to a minimum of four meters below ground level. In addition to the wrought iron beams joining the top of the tubes, the connection was also made using a one meter high iron sheet to delimit the edge of the masonry (Figure 6). The upper part of the piers was a rubble masonry with stone ashlars on the perimeter and a concrete filling that formed a massive and compact element (Decker 2020).

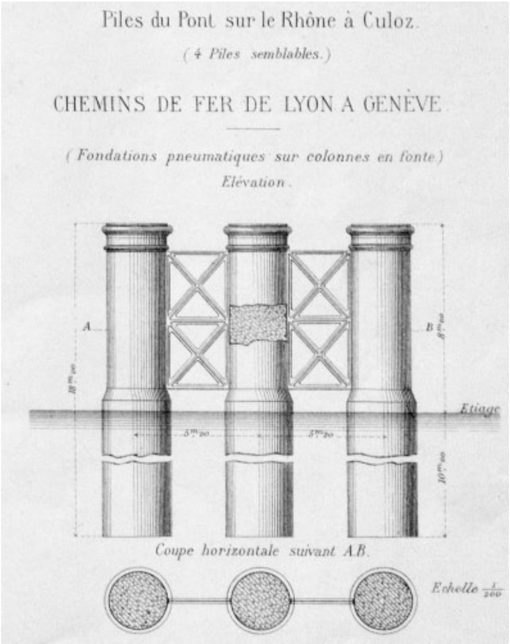

Figure 8. Culoz Bridge: the geometry and connections of the cast iron cylinders (Goüin 1878).

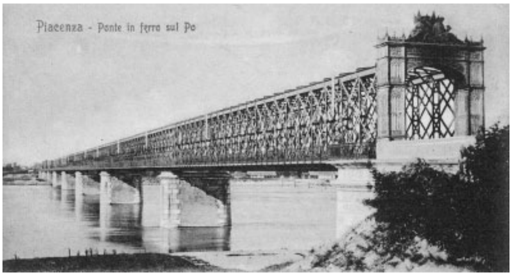

Figure 9. Railway bridge over the River Po in Piacenza: the piers built by a French company (Bernardi Postcard 1890).

The construction of the Culoz bridge, which marked the border between the Kingdom of Sardinia and France, entailed a collaboration agreement between different companies from the two countries. The iron deck was built by the Vittorio Emanuele Company, who chose the same deck designed for the Cruet bridge and decorated it with the French and Savoy coat of arms. The foundations and other riverbed improvement works were managed by the Society of Lyon-Geneva Railway Line, which commissioned Ernest Goüin et Cie Company to build the piers (Figure 7). Between 1856 and 1857, twelve cast iron cylinders were sunk below the riverbed to a depth of 10 meters using Triger's procedure and filled with concrete (Park-Barjot 2005). Unlike on previous bridges, the Parisian company did not carry out masonry work but extended the height of the tubes. These were connected three by three by wrought iron trusses and directly supported the deck (Figure 8). With this solution, the piers were less bulky giving the bridge a greater visual permeability (Goüin 1878).

Figure 10. Railway bridge near Pontelagoscuro: the piers built with wrought iron caissons (Prampolini Postcard 1902).

Other railway bridges were built after the Unification of Italy with all benefiting from the technical advancements surrounding pneumatic foundations.

4 PNEUMATIC FOUNDATIONS WITH WROUGHT IRON CAISSONS: THE BRIDGES OVER THE RIVER PO

Developing the railway network also remained one of the main objectives for the new Kingdom of Italy, which was finally able to link the partially built lines in its different regions.

In particular, the government focused on connecting the lines between Lombardy, Emilia Romagna and Veneto, separated by the River Po, which was difficult to traverse and between 300 and 400 metres wide in places. After the examination of the available resources and possible technical solutions, the construction of various bridges over the river began in 1861. These included the four bridges necessary to complete the Milan-Genoa, Milan-Piacenza, Ferrara-Rovigo and Mantua-Modena railway lines (Besso 1870).

The respective locations chosen were Piacenza, Mezzana Corti, Pontelagoscuro and Borgoforte with the same structural layout chosen: a wrought iron truss in the upper part, which was able to outdistance the supports as much as possible, and with tall piers in the lower section to contain the river in case of flooding. The piers had to be fixed into the riverbed using Triger's process, which had itself undergone some improvements.

At the end of the 1850s, for the Saltash bridge over the River Tamar near Plymouth, the engineer Brunel improved the process by dividing the space between the walls of the cast iron cylinder with diaphragms. This was useful for differentiating the compressed air input channels from those for excavated materials and workers. For the bridge over the River Rhine in Kehl near Strasbourg, the engineer Fleur St. Denis, mindful that the greater depth of the tubes sometimes compromised their verticality, experimented with using a wrought iron caisson which was as large as the upper part of the pier and had a cutting edge at the base (Bruno 1892).

Thanks to the Fleur St. Denis innovation, wrought iron caissons were rapidly preferred to cast iron cylinders, indeed the new devices were used for the piers of the River Po bridges. In particular, the bridges in Piacenza and Pontelagoscuro represent the most significant cases regarding the first Italian application of this foundation type (Figures 9 and 10).

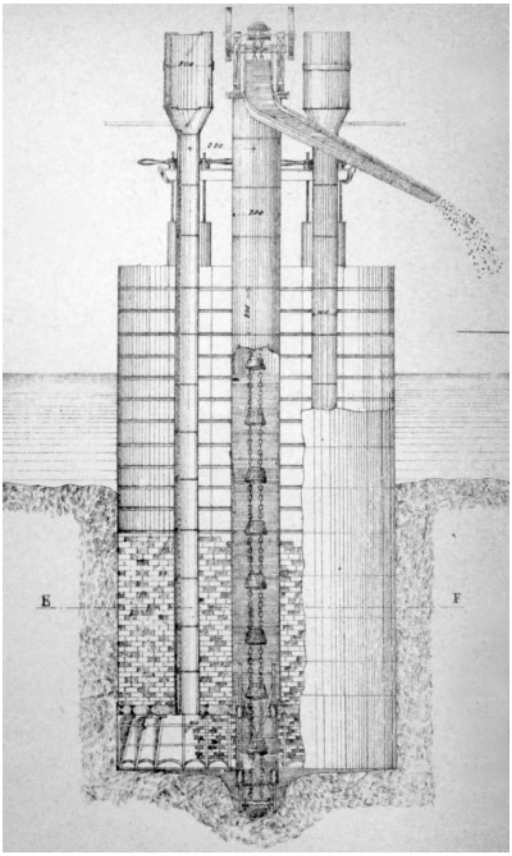

Figure 11. Piacenza Bridge: the sinking process and wrought iron caisson equipped with three tubes (Biadego 1886).

4.1 *Pneumatic foundations of Piacenza Bridge*

The design of the bridge linking the railway line between Milan and Piacenza was supervised by the engineer Giovanni Battista Biadego, who chose a continuous wrought iron truss 280 meters long and supported by seven piers placed in the riverbed. The works were entrusted to the Parent, Schaken, Caillet et Cie Company, based in Fives-Lille and directed by the engineer Félix Moreaux, who had also participated in constructing the bridge in Culoz.

All the piers were 30 meters high. They were sunk into the ground reaching a depth of 20 meters using pneumatic caissons similar to those used two years earlier in Kehl and now applied in Italy for the first time. Each caisson was made of riveted wrought iron sheet that was 1.2 cm thick. It was open at the base with a cutting edge and closed on the top, forming a work space 2.2 meters in height. Three wrought iron

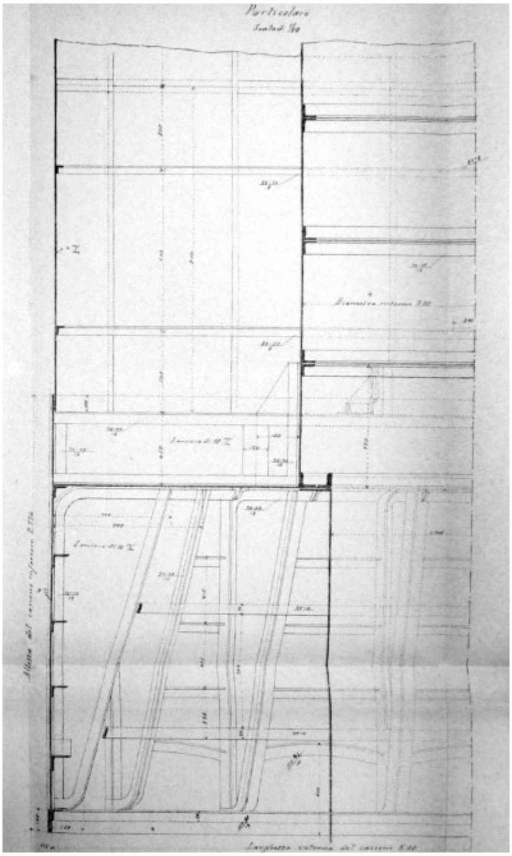

Figure 12. Piacenza Bridge: the construction details of the wrought iron caisson (Biadego 1886).

tubes were joined to the ceiling of this space: two were equipped with airlocks on the top and were used for the compressed air regulation and the passage of workers; another included a dredge which excavated and lifted earth (Figure 11).

The ceiling of the caisson was stiffened with iron I beams and served as formwork for the upper masonry works (Figure 12). The Piacenza Bridge was also the first in Italy to be equipped with new systems of natural and artificial lighting: convex lenses were located in the airlock roof and electric lamps illuminated the work space and had the advantage of not consuming oxygen.

The construction of each pier from start to finish was carried out by a team of only ten workers. They were also responsible for the eight hoists used to keep the caissons horizontal. The hoists were set on a temporary wooden bridge, built to facilitate construction. The workers also undertook the filling of the work space and chimneys with concrete at the end of the sinking phase.

The construction of the piers began in August 1862 but the collapse of a section of the temporary wooden bridge caused a year-long suspension of work. After the reorganization of the construction site and the recovery of the materials, work continued and was completed in 1865 (Biadego 1886).

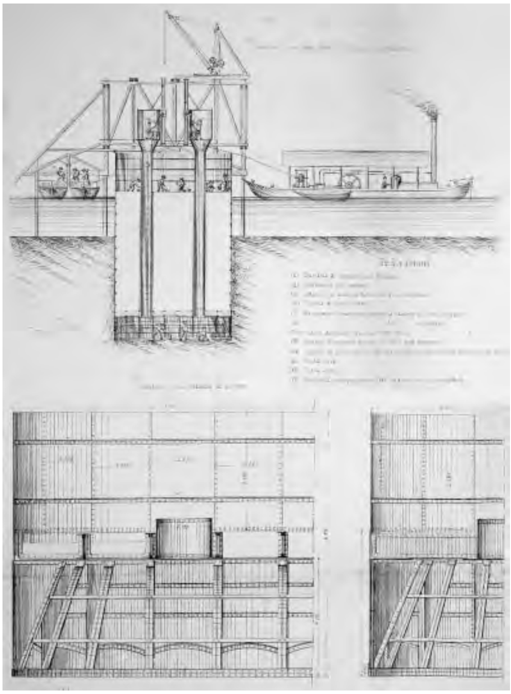

Figure 13. Pontelagoscuro Bridge: the sinking process of the piers and construction details of the caisson (Ratti 1876).

4.2 *Pneumatic foundations of Pontelagoscuro Bridge*

The line between Bologna and Pontelagoscuro had opened in 1862 and connecting it with Venice required a bridge over the River Po spanning over 350 meters.

The bridge was designed by the engineer Gaetano Ratti with a continuous wrought iron truss supported by five piers set in the riverbed. Unlike the bridge in Piacenza, the truss was composed of U profiles for the chords and I profiles for the diagonal braces, without any internal vertical members. The works were conducted by the same French company, with the collaboration of the entrepreneur Jean-François Cail, who had also been involved in the construction of several European railways.

As with the Piacenza bridge, the company applied wrought iron caissons for the piers and developed a new system for transporting the excavations. This was designed by the director Moreaux and partially experimented the works of Mezzana Corti Bridge.

The dredger usually placed in the central chimney, often caused imbalances in the compressed air in the work space and sometimes the chimney got obstructed by excavated material. In order to solve these problems, Moreaux developed a caisson that was 11 × 5 meters wide, with two chimneys equipped with airlocks that participated in the excavation movements

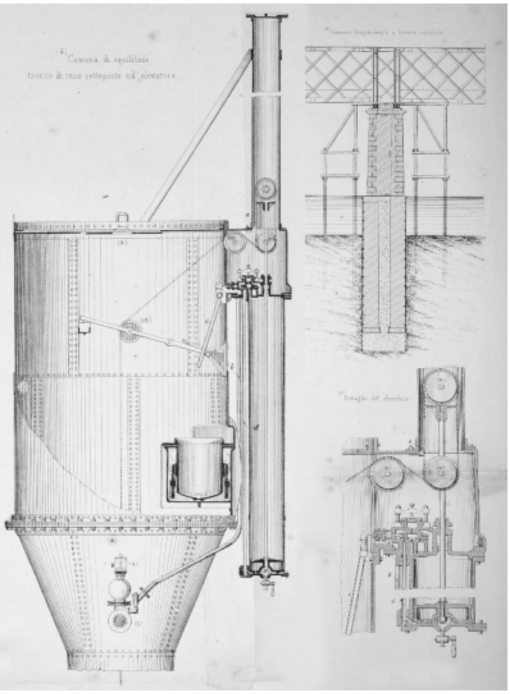

Figure 14. Pontelagoscuro Bridge: the airlock designed for the side piston and the airtight bucket (Ratti 1876).

Figure 15. Sesto Calende Bridge: the piers built by the Italian Industry of Metal Construction (Fotocromo Postcard 1902).

while limiting the loss of compressed air. A three meter high cylinder, with a diameter of 25 cm, was joined to the airlocks with a compressed air powered piston inside (Figures 13 and 14). This piston controlled ropes and pulleys that were managed by a worker who received the excavated material coming up from the work space.

The full buckets emptied into a container affixed to a trolley which, on being pushed outside, automatically introduced an empty container into the airlock.

Local materials, such as concrete made from Palazzolo and Domegliara limestone, were used for the upper masonry. The works began in 1870 and finished the following year in accordance with the system patented by the company (Ratti 1876).

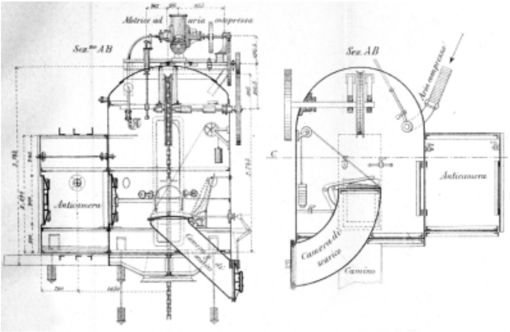

Figure 16. Sesto Calende Bridge: the addition of an antechamber and a discharge pipe to the airlock (Bruno 1892).

Further innovations to the construction process did not change substantially. Advancement focused on mechanizing the airlock, optimizing the compressed air seal and more efficient removal of the excavated materials.

5 CONCLUSIONS

Between the 1850s and 1870s, the deployment of pneumatic foundations was crucial in the conception and construction of the infrastructures necessary for national economic and commercial growth.

The early assignment of these works to British and French companies highlighted the backwardness of the Italian construction sector with this scenario only beginning to change at the end of the 1870s with the affirmation of national companies such as the Italian Industry of Metal Construction. It was the first to use cast iron cylinders for constructing the Ripetta Pedestrian Bridge, built in Rome in 1878, and wrought iron caissons for the railway bridge built over the Ticino River in Sesto Calende in 1882 (Carughi 2003).

For the bridge in Sesto Calende, designed by the engineer Giovanni Battista Biadego (Figures 15 and 16), the company directed by Alfredo Cottrau applied airlocks that followed the model of those used at Pontelagoscuro with the only changes being the addition of an antechamber and further means for casting concrete (Biadego 1886). These technical solutions demonstrated the skills built up by national companies, now finally able to manage imported technological innovations and compete at the European level.

ACKNOWLEDGEMENTS

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Reclamation work and stone masonry at the Nagasaki Harbour wharves (1889–97)

Y. Chen
Gunma University, Gunma, Japan

ABSTRACT: This paper analyses (1) the layout of Nagasaki Harbour and the plans of individual stone masonry wharves in 1889; (2) the relationship between water, tides, and the structure of stone masonry wharves in Oura; (3) the supply of stone and the stonework of the wharves in Oura; and (4) the reclamation process of the Mitsubishi Shipyard and its stonework in the Tategami area in 1897, to illustrate the technology of masonry stonework and wharves used in modern Nagasaki Harbour.

1 INTRODUCTION

Nagasaki is famous for Dejima, a reclaimed island in Nagasaki Bay as a settlement, first for the Portuguese and later for the Dutch merchants from 1634 to 1849. Most scholars have focused on the reclamation work and technology of the stonework of Dejima (Obayashi Gumi Project Team 1994). However, after permitting a new foreign settlement to be opened in the Oura area in 1858, the Japanese Government and Mitsubishi Nagasaki Shipyard began to extend Nagasaki Harbour by reclaiming new portions of Nagasaki Bay and those parts became new harbour areas of the city. Although attention has been paid to the reclamation process of the modern Nagasaki Harbour (Takatoshi Okabayashi and Masaru Yoshida 1992), the detailed reclamation process establishing the harbour foundations from the seabed and the technology of stonework of the wharves have not been clarified. However, stone walls were most widely used in harbour construction in Japan before the Japanese Government started importing new harbour construction technologies from Europe in the late 1890s.

Hence, the purpose of this paper is to analyse (1) the layout of Nagasaki Harbour and plans of individual stone wharves in 1889; (2) the relationship between water, tides, and structure of the stone wharves in Oura; (3) the supply of stone and stonework of the wharves in Oura; and (4) the reclamation process of Mitsubishi Shipyard and its stonework in the Tategami area in 1897, so that the technology of stonework and wharves used in modern Nagasaki Harbour will become clear.

After being opened to foreigners for international trade in 1865, the Japanese government and foreign merchants put emphasis on building wharves in the bay of Dejima, Shinti and Oura, however, Mitsubishi started constructing shipbuilding yards in Tategami, which is located on the opposite side of the above three areas (Figure 1). This paper focuses on these four districts which shaped the main harbour area of modern Nagasaki.

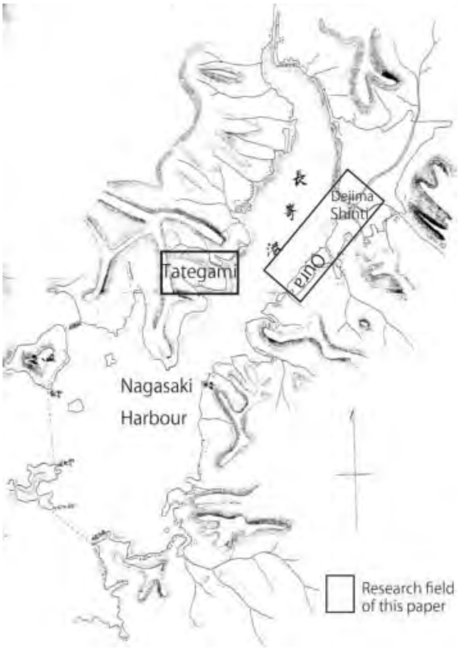

Figure 1. Nagasaki Harbour in 1893 (Meiji 26).

The primary research resources are the proposal to repair wharves in the Nagasaki Foreign Settlement, the plan to repair the wharves, the plan for the bund of the Nagasaki Foreign Settlement and the proposal for the Tategami area, which is located on the opposite side of the above three areas (Figure 1). This paper focuses on these four districts which shaped the main harbour area of modern Nagasaki, reducing the wharves in Nagasaki, and the dredging of the seabed and its

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Figure 2. The plan of Nagasaki Foreign Settlements in 1866.

design or arrangement of the location, all of which are preserved at the Diplomatic Archives of the Ministry of Foreign Affairs of Japan. Apart from the above archival research, the author also carried out a survey about the stone masonry walls in Nagasaki Harbour in September 2020, the outcome of this survey project is illustrated in this paper, too.

2 LAYOUT AND HARBOUR FUNCTION OF NAGASAKI FOREIGN SETTLEMENTS

As with Hakodate, Yokohama, and Kobe, the Japanese government did not open the harbour frontage of the Nagasaki Foreign Settlements to foreigners. As shown in Figure 2, big steamships from foreign countries were forbidden from entering the inner bay area of Nagasaki Harbour and they had to be anchored in the outer bay area. Therefore, fleets of small boats were used to land goods and people from steamships to the inner bay area. To that extent, comprehensive harbour facilities with a large scale such as London Docks in the historic Port of London, England did not appear in Nagasaki harbour in the 19th century, however, the stone wharves built in the inner bay area had played an important role in shaping the harbour's function. However, the harbour of foreign settlements became a location "full of" small private pontoons in 1871 (Figure 3).

By counting the number of wharves from Kozone, one can see that there were 11 wharves on the shore of Nagasaki Harbour and one on the riverbank of Sagarimatsu canal. In total, 12 stone wharves were built on the waterfront of the Nagasaki foreign settlements at that time. Particularly, wharves in front of the No. 51 lot and the No. 44 lot were both private pontoons for landing coal; another one in front of the

No. 49 lot was also a private pontoon for machinery owned by a British merchant (Diplomatic Archives of the Ministry of Foreign Affairs of Japan, classmark: 3.12.1.60). The three above-mentioned private pontoons were located in the bay area of Kozone. The remaining eight public wharves were all located in Oura, Shinti and Dejima. Apart from one wooden pontoon floating in the canal of Sagarimatsu, there were three pontoons on the waterfront of Oura, two in Shinti and two in Dejima.

Shinti was a Chinese settlement in Nagasaki from the late 17th century. The two wharves there were mainly used by Chinese merchants. However, Chinese merchants were suspected of exporting refined tea as unrefined tea in order to leak tax from Nagasaki Customs House, this became a reason for the local government of Nagasaki to start reducing the pontoons in the entire harbour area in order to maintain the order of the harbour (Diplomatic Archives of the Ministry of Foreign Affairs of Japan, classmark: 3.13.1.3,p. 254).

Figure 3. The jetties and wharves in Nagasaki Harbour in 1871 (Meiji 2).

Figure 4. The wharves would be demolished in 1871.

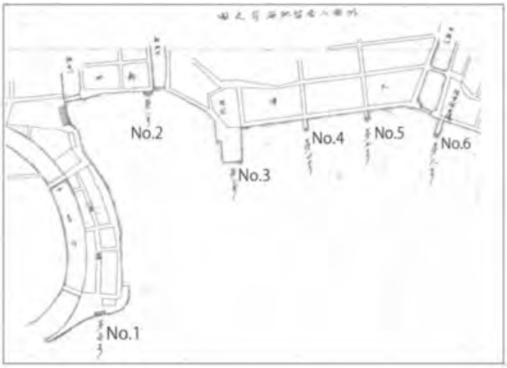

Figure 5. The wharves in the harbour of Nagasaki Foreign Settlement in 1890.

Since pontoons and wharves were strongly related to the profits of foreign merchants, the Nagasaki Government had to negotiate with the foreign ambassadors or consuls from the 12 countries which had concluded treaties with Japan (Diplomatic Archives of the Ministry of Foreign Affairs of Japan, classmark: 3.13.1.3). However, the international consul body in Nagasaki only agreed to demolish the wooden pontoon in the canal of Sagarimatsu and the stone pontoon in front of Guang Rong Hao, a Chinese company based in Shinti (Figure 5). As a result, the Nagasaki Government put the official numbers one to six in front of the wharves in Dejima, Shinti and Oura (Figure 5). On the other hand, the private pontoons in nearby Kozone were allowed to be kept by private owners.

Hitherto, the functions of Nagasaki Harbour were supported by these six public wharves and three private wharves under the management of Nagasaki Customs House until 1897 (Isamu Hiroi 1926), at the time when the Nagasaki Government started building a new modern harbour outside of the foreign settlements.

3 REPAIRS OF STONE WHARVES IN NAGASAKI HARBOUR IN 1889

Due to the importance of Nagasaki Harbour in international trading in the Modern Period, many map producers had paid attention to the layout and plan of the entire harbour to date. However, the plans of stone wharves in the harbour had not been recorded until their architectural drawings were produced by the Nagasaki Government for the purpose of wharf repairs in 1889 since those wharves were heavily damaged and eroded after being used for over 30 years (Diplomatic Archives of the Ministry of Foreign Affairs of Japan, classmark: 3.13.1.9, pp. 445-6). By analysing those architectural drawings, the plan, material, structure and masonry of the wharves would therefore become clear.

3.1 *The No. 2 wharf in Shinti*

The No. 2 wharf (Figure 7, No. 2 wharf) in Shinti was built in front of Chinese store houses and especially for Chinese merchants to land goods. It was made of stones, and its stone wall, stairway and landing were built directly from the seabed at the point of the low-water mark. Its inside was filled with rubble. Its height from the foundation stone at the low-water mark (F) to the surface of the landing place (A-B) was 12 syaku (3.74 m). Initially, there was no stairway opened in front of the wharf towards the sea, the depth of the wharf from the bank to the sea was 6 ken (10.8 m) and the width was 11 ken (19.8 m).

From the wharf's size, one can imagine that only small boats could be accommodated in the bay area of this wharf. Apart from repairs, the Nagasaki Government also decided to extend the capacity of landing and accommodation of this wharf by widening its width from 11 ken (19.8 m) to 13 ken (23.4 m). Additionally, in order to enhance the convenience of the approach from the sea to the landing place, it was decided to open a new stairway in front of the wharf. Finally, since the original stones were too soft, the Nagasaki Government decided to change all the stones to Misumi stone, highly reputed for its hardness. Misumi in Kumamoto Prefecture was a centre for producing and supplying stones to traditional Japanese castles since the Edo Period (Koyama Ichiro 1913). The original stones would be recycled as infill of the stone wharf.

Figure 6. Oura and Dejima, viewing from the southern mountain in 1897.

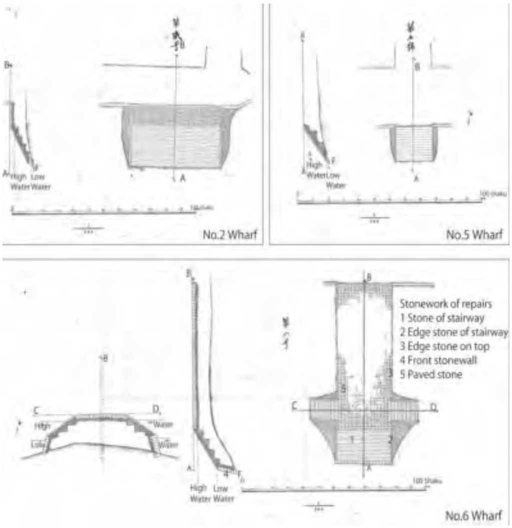

Figure 7. The plan and section of wharves in Nagasaki foreign settlements in 1889.

3.2 *The No. 5 wharf in Oura*

The No. 5 wharf was a public wharf located in front of the No. 8 and No. 9 lots, directly connecting to a public road in Oura Foreign Settlement (Figure 7, No. 5 wharf). The wharf was made of stones and its stone wall and stairway were built directly from the seabed at the point of low water mark like the No. 2 wharf. Its inside was filled with rubble, which supported the

Table 1. The estimation of wharf repairs in foreign settlements of Nagasaki Harbour.

	Stonework	Length	Width	Thick (heighl)	Total cost	Price	Total
Shinti No.2 Wharf	Stone of stairway	210ken	1.4syaku	0.8syaku	210.0ken	2.830yen.	594.300yen
	Edge stone of stairway	8.0ken	0.9 syaku	0.8syaku	8.0ken	2.030yen	16.240yen
	Front stone wall	10.5ken	0.5ken	5.25tsubo	5.500yen.	28.875yen	
	Paved stone on western side	13.0ken	1.75ken	22.75tsubo	4.000yen.	91.000yen	
	Paved stone on top	10.0ken	2.00ken	20.00tsubo	4.000yen.	80.000yen	
	Edge stone on top	10.0ken	0.8syaku	0.7syaku	10.000ken	1.240yen.	12.400yen
Total 822.815 yen							
Oura No.5 Wharf	Stone of stairway	52.0ken	1.4syaku	0.8 syaku.	52.0ken	2.830yen.	147.160yen
	Edge stone of stairway	6.0ken	0.9 syaku	0.8 syaku.	6.0ken	2.030yen	12.180yen
	Paved stone on	6.0ken	1.5ken	9.00tsubo	4.000yen.	36.00yen	
Total 195.340 yen							
Oura No.6 Wharf	Stone of stairway	90.0ken	1.4syaku	0.8syaku.	90.0ken	2.830yen.	254.700yen
	Edge stone of stairway	6.0ken	0.9syaku	0.8syaku.	6.0ken	2.030yen.	12.180yen
	Front stone wall	6.3ken	2.0ken.	12.6tsubo	5.500yen.	69.300yen	
	Paved stone on 8.0ken western side	3.0ken	24.0tsubo	4.000yen.	96.000yen		
	Paved stone on top	15.0ken	6.0ken	90.0tsubo	4.000yen.	360.000yen	
	Edge stone on top	6.0ken	0.8ken	0.7syaku.	6.0ken	1.240yen.	7.440yen
	Stone of side stairway	60.0ken	1.4ken	0.8ken	60.0ken	2.830yen.	169.800yen
	Edge stone of stairway	12.0ken	0.9syaku	0.8syaku.	12.0ken	2.030yen.	24.360yen
	Paved stone on two sides	6.0ken	1.5ken	9.0tsubo	4.000yen.	36.000yen	
Total 1029.780 yen							

Table 2. Stonework of wharf repair.

	Price.	Length	Thick(height)
Stone of stairway	2.830yen.	1.4syaku	0.8syaku
Edge stone of stairway	2.030yeb.	0.9syaku	0.8syaku
Edge stone on top	1.240yen.	0.8syaku	0.7syaku
Front stone wall	5.500 yen per tsubo		
Paved stone	4.000 yen per tsubo		

whole structure of the wharf. It was 11 syaku (3.34 m) high from the foundation stone to the landing place on the surface, 3.5 ken (6.3 m) deep and 3.5 ken (5.49 m) wide in total. The stairway in front of the wharf was two ken (3.6 m) wide.

After a survey of the wharves carried out in 1889, Nagasaki Prefecture noted that No. 5 wharf would no longer be capable of landing more goods because of its narrow width and damaged stones. As a result, the Nagasaki Government decided to broaden the width from 3 ken (5.4 m) to 5 ken (9 m), and the stairway from 2 ken (3.6 m) to 4 ken (7.2 m). All the damaged stones of the stairway, stone walls and landing dock would be replaced by the hard Misumi stones. Those damaged stones would be recycled as infill of the wharf.

3.3 *The No. 6 wharf in Oura*

The No. 6 wharf (Figure 7, No. 6 wharf) was built in the bay area of Umegasaki, behind which was the Nagasaki Customs House. As well as the other two wharves, this wharf was also made of stones and its stone wall and stairway were built directly from the seabed. It was also infilled with rubble which supported the whole structure of the wharf.

This wharf was built far beyond the low-water mark at the seabed. In details, the wharf was 21 syaku (6.55 m) high from the foundation stone at the seabed to the landing place (A-B), 24 ken (43.2 m) deep and 6 ken (10.8 m) wide. The stairway opened in front of the wharf was 3 ken (5.4 m) deep and 2 ken (3.6 m) wide. Beside this front stairway, two side stairways with the same size opened on each side of the wharf. The side stairway was 3 ken (5.4 m) deep and 2 ken (3.6 m) wide. As described above, because of its location, deeper water and larger accommodation for boats, this wharf was one of the primary landing places in Nagasaki Harbour.

In 1889, this wharf was also reported heavily damaged due to the soft nature of original stones and the bumpy landing dock without repairs for long years. Thus, Nagasaki Prefecture decided to remove all the paved stones on the landing dock and the stone walls, and then use the Misumi stone to pave the new landing place and to build stone walls. Those removed stones would be recycled to infill the No. 5 wharf which was going to be broadened.

4 THE STONEWORK OF WHARF REPAIRS

4.1 *The stone and its price and supply*

According to the surveys of individual wharves, Nagasaki Government produced a systematic plan for the repairs of the three wharves. The details of the proposed repairs, materials, size of stone blocks and payment for labour were all included in Table 1.

Nagasaki Prefecture estimated the repair costs for each wharf (Figure 8), however, through investigating the data shown in Figure 8, it was found that the common places to be repaired in the three wharves were "(1) stone for stairways", "(2) edge stone for stairways", "(3) front stone walls", "(4) paved stones on paraments and for wharves landing zone".

The way of estimating the cost of the masonry wall in front of the wharf was based on different types of stone blocks. (Table 2). The size of new stone on the stairway, the stone of the stairway's edge, and the paved stone were standardized and the price of each different type of stone was the same, too. Therefore, the complicated data in Table 1 could be simplified as Table 2. For example, the stone used on stairways was 1.4 syaku (0.46 m) long and 0.8 syaku (0.24 m) thick, its price was 2.83 yen. On the other hand, the paved stone on the two edges of stairways was smaller, which was 0.9 syaku (0.27 m) long, 0.8 syaku (0.24 m) thick, the price was 2.03 yen. The paved stone on the two edges of the landing dock was 0.8 syaku (0.24 m) long and 0.7 syaku (0.21 m) thick, the price was 1.24 yen, estimated 5500 yen per tsubo (3.2 m^2). On the other hand, the price of the paved stone on the landing dock was 4.0 yen per tsubo (3.2 m^2).

By referring to the standard price and size of different types of stones in Figure 10, it is possible to understand the data shown in Figure 9, therefore, the supply, measurement and sculpturing of stone in the late 19th century in Japan becomes clear.

For example, as for the No. 6 wharf in Oura, new stones would be used in the stairway in front of the wharf (Table 2), measuring 90 ken (162 m) long in total. It would be cut into 386 stone blocks; each block was 1.4 syaku (0.46 m) long and 0.8 syaku (0.24 m) thick. The price of stairway's stone per ken was 2.830 yen, thus, the total cost of the 90-ken-wide stairway stone would be 254.7 yen. On the other hand, the new stones to be used on the two edges of the stairway were 6.0 ken (10.8 m) long in total. It would be cut into 45 blocks of stone, each of which was 0.9 syaku (0.27 m) long and 0.8 syaku (0.24 m) thick. The price of edge stones per ken (1.8 m) was 2.030-yen, total of 12.180 yen. In this manner, following the data shown in Figure 8, the entire stone walls in front of the three wharves were measured 6.3 ken (11.34 m) long, 2.0 ken (3.6 m) high, its total area was 12.6 tsubo (40.8m^2), which would cost 69.300 yen to be built.

As a result, the total cost of repairing the entire No. 6 wharf in Oura was calculated as 1029.780 yen, which is equivalent to 20,000,000 yen today (1 yen in the Meiji period is approximately 20,000 yen or $185 today). This cost included the payment for paved stones, stones for stairways on two sides of the wharf, stones for one side of the wharf, paved stones on the deck platform, paved stones on the two edges of the dock platform, block for the two edges of side stairways, and paved stones on the two sides of the wharf.

Through the measurement and calculation in the same way, the cost of repairing the No. 2 wharf in Shinti was 822.815 yen and the No. 5 wharf in Oura was 195.340 yen (Table 2).

4.2 *The work of stoneworkers and their salaries*

The standard price of stones of different types also included the salaries of stoneworkers in the wharf repairs. Table 3 shows the price of stone block, salaries of stoneworkers and their assistants for sculpting stones.

For example, 2.5 stoneworkers and 2 assistants were employed for the repairs of stone stairways of the three wharves. Stoneworkers were required to cut the stone blocks with the stairway's width to a standard size, positioning them into the right places. The assistants were required to help stoneworkers and to fill the inside of wharves with rubble. In the construction of new stone walls, stoneworkers sculpted stone blocks into the designated shapes first, then put them into correct places and finally hammered (*Genno Tataki* in Japanese) their surfaces in order to stabilize the structure of new stone walls.

The daily salary for a stoneworker was 0.30 yen and for an assistant was 0.20 yen, which were the same for other stoneworkers and assistants employed in the constructions of stones on the edges of stairways, stone walls in front of wharves, paved stones and edge stones of landing docks, though the details of stonework in different places were slightly different (Table 3).

On the other hand, the standard salary of a carpenter from 1879 to 1890 in Japan was 0.50 to 0.54 yen, thus, the salary of a stoneworker for repairing wharf in Nagasaki was much lower than a contemporary carpenter. But since it was thought that the building skills required for a carpenter were generally higher than a stoneworker, the salary of a stoneworker employed in the wharf repair was reasonable in the late 19th century.

As analysed in the second and third sections, the Nagasaki Government carried out the wharf repair in a well-organized way through a survey of the wharves, identifying the damaged places, plans and estimations of repairs, supply of stones and the employment of stoneworkers. The repaired wharves would continue providing services for small-sized boats until 1927 when the comprehensive construction project of Nagasaki Harbour officially started.

Table 3. Price and content of stonework.

Stonowork	Payment for material And stonework	Unit	Price	Cost	Content
Stone Of Stairway	Stone block	6.72blcoks	0.250yen	1.680yen	Each stone of stairway is 6 syaku long, 1.4syaku wide, 0.8syaku thick, Misumi Hard Stone
	Stoneworker	2.5person	0.300yen	0.750yen	Cut the stone of stairway, Fix the stone into correct place
	Labour	2.0person	0.200yen	0.400yen 2.830yen	assistant of stoneworker, fill inside of wharf per ken
Edge Stone Of Stairway	Stone block	4.33blocks	0.250yen	1.080yen	Each edge stone is 6syaku long 0.89syaku thick. Misumi Hard stone
	Stoneworker	2.5person	0.300yen	0.750yen	Cut the stone of stairway, Fix the stone into correct place
	Labour	1.0person	0.200yen	0.200yen 2.030yen	Assisstant of stoneworker per ken
Front Stone Wall	Stone blocks	16blocks	0.250yen	4.000yen	Each stone is 2.5syaku long, 1.5syaku in square. Misumi Hard stone
	Stoneworker	3person	0.300yen	0.900yen	Hammer the surface of stonewall, fix the stone
	Labour	3person	0.200yen	0.600yen	Pave stone, hammer stone, cut and fix stone 5.500yen per tsubo
Paved Stone	Stone block	25blocks	0.120yen	3.000yen	Each stone is 2.3syaku long, 1syaku in square, Misumi stone
	Stoneworker	2.0person	0.300yen	0.600yen	Pave stone hammer stone, cut and fix stone
	Labour	2.0person	0.200yen	0.400yen 4.000yen	Assisstant of stoneworker, remove the old stone, fill inside of wharf per tsubo
Edge stone Of paved Stone on Landing Place	Stone block	3.36blocks	0.250yen	0.840yen	Each edge stone is 6syaku long, 0.77syaku in square, Misumi hard stone
	Stoneworker	1.0person	0.300yen	0.300yen	Cut the stone, fix the stone into correct place
	Labour	0.5person	0.200yen	0.100yen 1.240yen	Assisstant of Stoneworker

*1 Ken=approximately 1.8 m, 1 syaku= 0.303 m, 1 Tsubo= 3.3m^2

5 EXTENSION OF MITSUBISHI NAGASAKI SHIPYARD AND ITS RECLAMATION

Mitsubishi started shipbuilding from 1879 and built shipyards in the Awanoura and Tategami districts, which are located on the opposite side of old Nagasaki in 1882 (Figure 7) (Mitsubishi Heavy Industries Nagasaki Shipyard & Machinery Works 2008). The No. 1 dock of Mitsubishi was dug in 1872 by the Nagasaki Iron Company, which was the former organization of Mitsubishi Nagasaki Shipyard. In the early 1860s, Mitsubishi employed local stoneworkers in Nagasaki to build the foundation of the dock and reclaim the sea in front of the Tategami area. In other words, as well as stone wharves in the harbour of old Nagasaki, stone was also the primary material for building Mitsubishi's shipyard.

5.1 *The sea reclamation and masonry of stone walls*

On 13 December 1897, Mitsubishi Nagasaki Shipyard applied for permission from the Nagasaki Government for reclaiming a portion of the sea in Tategami area in order to extend their shipyard (*The dredging of the seabed and its design or arrangement of the location*). The Nagasaki Government immediately issued an instruction to the company.

Figure 8. Tategami shipbuilding yard in 1897.

First of all, the Enmi district in the Tategami area in front of Mitsubishi Nagasaki Shipyard (Figures 7 and 8) was designated as the place for reclamation. According to the previous survey carried out by Mitsubishi, due to a rock sitting on the seabed, the Enmi district was not suitable for constructing a public harbour. Mitsubishi Nagasaki Shipyard therefore decided to reclaim that portion in addition to their existing shipyard. The proposed reclamation area was 913.65 tsubo (2,960,226 m^2), the average depth reclaimed above the rock was 18 syaku (5.45 m). The soil and rubble used in sea reclamation would be transported from the mountains owned by Mitsubishi in the Iwasedou and Jinba areas which were near the Enmi district in the Tategami area.

Secondly, a new stone wall would be constructed in order to contain the land reclaimed by soil and rubble. On the basis of the total area of the reclaimed land, Mitsubishi estimated the length of the new stone wall should be 213 ken (383.4 m) in total. The new stone wall would be built directly from the rock and the seabed. However, if there was some soil accumulated on the rock, a dredge of that soil would first take place. This was an effort to build an even stone wall from the uneven seabed.

Apart from the dredge, the stones used beyond and below the low-water line were also carefully distinct. In details, from the seabed to the point of 0.606 m under the low-water line, the hard Matsushima stones were used. Each Matsushima stone was 0.909 m long, 0.67 m high and 0.606 m wide, the surface of which was un-sculpted and in a rough condition. In order to make the stone wall fixed and not easily washed away by tides, an Aikake (= a connection, 0.303 m wide, 6 cm deep, Figure 9) was sculpted both on the surfaces of bottom and top of the

The aiba (= a connection) of each stone was 0.303 m wide. After each stone being fixed, rubble called *Dogai-ishi* and *Shiligai-ishi* were used to fill the inside of the stone wall. Furthermore, with the aim of protecting the stone wall beyond the low-water line from erosion caused by sea water, a 0.303 m deep berm (Inubashiri) was also created in the stone wall below the low-water line. The slope of the stone wall under the low-water mark was approximately 87 degrees and the stone wall's average height was 2.2 m.

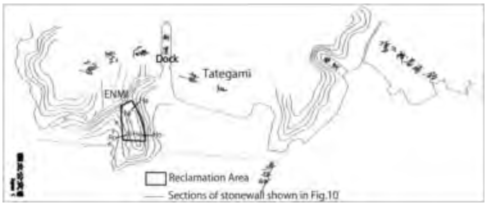

Figure 9. Map of Tategami shipbuilding yard in 1897 and the reclamation area.

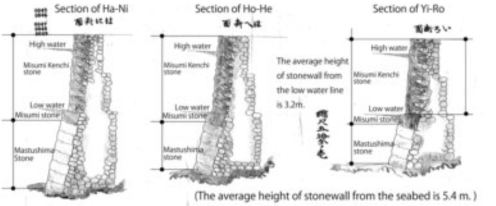

Figure 10. Sections of stonewalls of reclamation Land in 1897 stone.

Regarding the stone wall above 3 syaku (0.909 m) of the low-water mark, Misumi Kenchi (stone with a wedge-shaped end) stones were used. A Misumi Kenchi stone was 1.5 syaku (0.45 m) wide on the surface and 1.65 syaku (0.50 m) high (Figure 9). In order to fix the stone wall, a 6 sun (18.2 cm) wide and 1.5 sun (4.5 cm) deep Aikake was also sculpted both on the bottom and top surfaces of the stone. The Aiba of each stone was 6 sun (18.18 cm). The stone wall beyond the low water line was 10.65 syaku (3.22 m) high. Thus, a new stone wall with an average height of 5.4 m was built in Tategami shipyard of Mitsubishi Nagasaki Shipyard, which still stands in the waterfront of Nagasaki Harbour.

Finally, the rubble for infill of the stone wall was also supplied from the mountains owned by Mitsubishi in Iwase and Jinba districts near Tategami. The hardest stones were selected for infill and the initial stone block was 1 syaku (0.33 m) square and 67 sun (203.01 m) high.

Through the above analysis, it is clear that traditional Japanese masonry was employed in building Mitsubishi's reclaimed land. In particular, the supply of different types of stones beyond and below the low-water mark, and rubble for infill were well planned. Apart from the stone, the soil and rubble for infill were produced from the mountains in Nagasaki owned by Mitsubishi.

5.2 *The types of stonework and their cost*

Referring to Mitsubishi Nagasaki Shipyard's *The proposal of sea reclamation,* the cost for the stone wall, reclaimed land and a bridge connecting the new land to the former shipyard were included in the construction. However, this paper mainly focuses on the stonework of the harbour, so this section will choose the types of stonework and their cost to analyse the process of the reclamation.

Table 4. Proposal and estimation of reclamation.

Stonework	Shape and size	Total measurement	Price	Cost	Content
Negiri (Foundation)	213ken long 2.5ken wide 3ken high in average	159tsubo	75.40yen	6390yen wall	Dredge the seabed and Rock below the stone
Mastushima Stone	3.5syaku long,1 sayku wide, syaku high	2.2 2880blocks	4yen	11520yen mark	Below the low water
Sculpture	Same	2881blocks	0.60yen	1728yen	same
Fix	same	2882blocks	1.30yen	3744yen	same
Misumi stone	3syaku long 1.5 Syaku wide, 1.65 high	6100blocks	1.10yen	6710yen	Beyond the low water mark
Sculplure	Same	6100blocks	0.50yen	3050yen	same
Fix	same	6100blocks	0.30yen	1830yen	same
Misumi stone	3.5syaku long,2 syaku wide, 2.5	640blocks	9.00yen	5760yen mark	Below the low water
syaku high					
Sculpture	same	640blocks	1.00yen	640yen	same
Fix	same	640blocks	1.70yen	1088yen	same
Misumi stone	3syaku long, 1.5 Syaku in square	2520blovks	0.90yen	2268yen	Beyond the low water mark
Sculpture	same	2520blocks	0.30yen	756yen	same
Fix	same	2520blocks	0.20yen	504yen	same
Misumi stone	3syaku long, 2.5 syaku wide, 1.5 syaku thick	54blocks	5.00yen	270yen	For stairways
Sculpture	same	54blocks	1.00yen	54yen	same
Fix	same	54blocks	0.50yen	37yen	same
Misumi stone	3syaku long, 1.5 Syaku in square	12blocks	2.50yen	30yen	For stairways and landing place
Sculpture	same	12blocks	0.50yen	6yen	same
Fix	same	12blocks	0.70yen	8.40yen	same
Rubble		1200tsubo	4.00yen	4800yen	For infill
Fix		1200tsubo	2.00yen	2400yen	For infill

*1 ken = approximately 1.8m, 1 syaku = 0.303m, 1tsubo=3.3m^2

The types of stonework and cost were determined according to the stones used in different places (Table 4), however, the cost for stoneworkers and labour were not shown separately, which were included in the stonework of “sculpture” and “fix”. In other words, Mitsubishi Nagasaki Shipyard designed different types of stonework, and stones were purchased as ready-made including stone’s “sculpture” and “fix”.

For example, in the construction of “Negiri”, (= soil foundation of stone wall), it was 230 ken (414 m) long, 2.5 ken (4.5 m) wide and 3 ken (5.4 m) deep. The depth of Negiri was equivalent to the height of the new stonewall, which was also 5.4 m high. After dredging the soil on the seabed, Negiri was dug deeply into the reclaimed land. A part of the construction of Negiri had to be made under water, thus the cost of which was 75.40 yen per tsubo and the total cost was 6390 yen, which was quite high (Table 4).

On the other hand, the cost of different types of stones used beyond and below the low-water line were distinguishably different as well as the stone’s sculpture and fix.

In details, the stones used below the low-water line, such as the cost per Matsushima stone was 4 yen, which was 3.5 syaku (1.06 m) long, 1 syaku (0.303 m) wide and 2.2 syaku (0.67 m) high, the cost of sculpting each Matsushima stone was 0.60 yen and fixing it was 1.30 yen; the cost per Misumi stone was 9 yen, which was 3.5 syaku (1.06 m) long, 1 syaku (0.303 m) wide and 2 syaku (0.606 m) high, the cost of sculpting each Misumi stone was 1.0 yen and fixing it was 1.70 yen. In total, 2,880 blocks of Mastushima stone and 640 blocks of Misumi stone were used to build the stone wall below the low-water line.

Beyond the low-water mark, a type of Misumi Kenchi stone was used. For example, the cost per Misumi Kenchi stone was 1.10 yen, which was 3 syaku (0.909 m) long, 1.5 syaku (0.45 m) wide and 1.65 syaku (0.50 m) high, the cost of sculpting each Misumi Kenchi stone was 0.50 yen and fixing it into the new stone wall was 0.30 yen. In total, 6,100 blocks of Misumi Kenchi stones of this type were used. Another type of Misumi Kenchi stone with smaller volume was used, too. The cost per stone was 0.9 yen, the cost of sculpting was 0.30 yen and fixing it was 0.20 yen.

In total, 2,520 blocks of Misumi Kenchi stone with smaller volume were used.

Finally, the Misumi stone was also used in the stone stairway of the reclaimed land. The cost per Misumi stone (3 syaku long, 2.5 syaku wide, 1.5 syaku high) was 5 yen, cost of sculpting it was 1.0 yen and fixing it was 0.50 yen. 54 blocks of this type of Misumi stone were used to build stairways. 1,200 tsubo (3840 m^2) rubble was used as infill of the stone wall and the cost per tsubo was 4.0 yen and filling it was 2.0 yen.

Through the investigation of the stonework, it became clear that the reclamation work of Mitsubishi Nagasaki Shipyard in 1897 was carried out with a detailed plan and the costs were high. One year later, Mitsubishi Nagasaki Shipyard conducted another reclamation project in the bay area of Tategami, however, only the cheaper Misumi Kenchi stones were employed to build the entire stone wall without any material distinctions beyond or under the low-water line.

6 CONCLUSIONS

This paper has analysed the function and characteristic of wharves in Nagasaki Harbour, repairs of wharves and the construction process of Mitsubishi Nagasaki's Tetegami shipyard.

Firstly, due to the shallow water and lack of access to Nagasaki Harbour for big steamships from foreign countries from the late Edo Period to the early Meiji Period (mid-19th century), the harbour functions were shaped by stone wharves and pontoons laid in front of foreign settlements. Only small-sized boats which were capable of navigating in shallow water were allowed to land goods and people from large steamships to the harbour via wharves and pontoons. Apart from stone wharves, the shipbuilding yard of Mitsubishi Nagasaki Shipyard on the opposite side of Nagasaki Harbour also played an important role in shaping the function of the harbour.

Secondly, it needs to be emphasised that the local government of Nagasaki had effective control over the maintenance and management of the harbour, such as checking the functions of wharves in the harbour and the decision made to demolish private pontoons and keep public wharves, an elaborate plan made to repair the damaged and eroded wharves.

However, Nagasaki's situation was completely different from the cases of the Yokohama and Kobe Foreign Settlements. For example, foreign merchants in Yokohama laid many private ladders on the stone walls of the bund for landing without getting permissions from the Japanese Government (Yunlian Chen 2020). In Kobe, a British machinery and iron company built a 10.4 m long private pier on the shore of Kobe Bay (Diplomatic Archives of the Ministry of Foreign Affairs of Japan, p. 364, classmark:3.13.18). As analysed in this paper, these kinds of private landing places without official permission from the Japanese Government were not seen in Nagasaki.

Thirdly, stone was the chief material to build the harbour and traditional masonry was used in repairs of the wharves and the construction of the shipyard in Tategami before the new Nagasaki Harbour construction started in 1897. As a result, stone walls built with traditional masonry became a symbolic scenery in the waterfront of Nagasaki Harbour (Figure 6) in the Modern Period. As well as Nagasaki, foreign settlements in Yokohama, Kobe and Osaka in the same period, stone walls built with traditional Japanese style also shaped the landscape of the waterfront of those harbours, though most portions of those stone walls have been demolished or hidden inside of today's new harbour.

It seems that the Japanese used stone to build harbours, however, the British and Chinese used different materials to build harbours in the contemporary East Asian region. For example, the British machinery and iron company in Kobe used wooden piles to build their piers in Kobe and wooden piles were also used to build the harbour of Tianjin Japanese Settlement in 1901 partly because of its cheaper cost. As a result, wooden piles had shaped a completely different waterfront compared with the stonewalls in the waterfront of Japanese harbours in the Modern Period.

In conclusion, it should be mentioned that the different materials employed in the construction in the harbours of East Asia still need to be clarified further.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Ipiranga Museum: 3D laser scanning as a contribution to Construction History

R.C. Campiotto & B.M. Kühl
Universidade de São Paulo, São Paulo, Brazil

ABSTRACT: This study on the Ipiranga Museum of the University of São Paulo (USP) aims to assess the potential of 3D laser scanning to examine aspects related to construction history. Based on bibliographic studies and on the examination of the building itself, this study explores the building's characteristics, and presents data on its construction and the main changes it has undergone over time. The study then analyzes the characteristics of the scanning carried out by the Development of Integrated Automatic Procedures for Restoration of Monuments (DIAPReM-Unife) for restoration purposes, which offers highly consistent morphometric data and information about the characteristics of the surfaces. The results of the scanning, when properly analyzed and articulated with bibliographic, iconographic and documentary sources, can provide important historiographical clarifications. This is explored at the end of the text with the goal of highlighting the importance of interdisciplinary works as a means of mutual enrichment.

1 INTRODUCTION

The present study assesses the Ipiranga Museum building of the University of São Paulo (USP), in Brazil. The aim is to evaluate the potential of 3D laser scanning – articulated with documentary, iconographic, and bibliographic studies – to examine aspects related to construction history. The present text explores the characteristics of the scanning carried out in 2017 under the scientific cooperation agreement between the Center for Development of Integrated Automatic Procedures for Restoration of Monuments (DIAPReM), the University of Ferrara, and USP. The scan, made for restoration purposes, offers highly consistent morphometric data and information about surface characteristics. Its results, if properly investigated and articulated with other sources, will facilitate historiographical clarifications, since the method provides a thorough examination of construction features that could not be obtained with the same precision using other methods.

Construction of the Museum began in 1885 and it was inaugurated in 1895. Brazil-based Italian architect Tommaso Gaudenzio Bezzi designed the building, and the contractor in charge was Luigi Pucci, also from Italy. The work, predominantly of brick masonry, was built as a memorial to Brazilian independence, but since it opened it has been operating as a museum.

The Ipiranga Museum is a landmark in the history of São Paulo, not only because it commemorates a major event that changed the fate of the country, but also because of its importance in the history of architecture and construction history. It was one of the most relevant buildings of the time to affirm the use of an erudite architectural language in the city. It was also a milestone of the shifting from the construction tradition of rammed earth (*taipa de pilão*, in Brazilian Portuguese) – which had prevailed in the plateau of the State of São Paulo from the 16th to 19th centuries – to brick masonry. The museum building played a key role because it was the first large and prestigious building to predominantly use brick.

Ceramic materials such as tiles and baked bricks were not unknown in the city, but their use was limited. Brick was sporadically employed in walkways and bridges, for example. The first documented use of bricks in public works dates back to 1610 (D'Alambert 1993: 50). As of the 18th century, its use is documented in the construction of arches and vaults in the city of São Paulo. However, at the time, it was difficult to find suitable mud, for the soil of the region did not contain quality clay and had high concentrations of river sand. This resulted in low-plasticity, highly porous and low-resistance bricks that were difficult to bake.

In contrast, rammed earth – the most common technique in the region, inherited from a well-established construction tradition from southern Portugal – was less costly and relatively easier to execute. These factors culminated in a three-century tradition of rammed-earth buildings, which shaped São Paulo's vernacular architecture. The prevalence of rammed-earth constructions was also due to a lack of a labor force acquainted with other construction systems and a lack of financial resources to import bricks and lime. In the region, lime deposits were located on the coast, and transportation to the plateau where the city of São Paulo is located was not an easy task. Additionally, the type of lime found on the coast was too hygroscopic and was mostly used in painting. These factors limited

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the use of other materials and construction systems in the city of São Paulo at the time (D'Alambert 1993: 48–54).

Only in the 19th century, with the wealth generated by coffee plantations – which began to expand on a larger scale in the state in the 1830s – did the dissemination of brick masonry take off. Coffee production leveraged and was boosted by railway development (Matos 1990) which, in turn, amplified the use of brick. The first railway in São Paulo was implemented in 1867 and expanded greatly from the 1880s on (Kühl 1998). This process was also associated with the gradual replacement of slave labor by free labor, with increased numbers of European immigrants as of the middle of the century, especially from Italy, Spain and Germany. Within this contingent of immigrants there were civil construction professionals with different qualifications who helped renew the region's architecture and construction techniques, in a period when both the province and the city of São Paulo were experiencing enormous population growth and economic development.

Coffee farms were pioneers in the large-scale use of bricks, both in the construction of different buildings and in laying down coffee-drying terraces. In the second half of the 19th century, pottery shops were a common feature of farms. Subsequently, with the influence of farmers and the work of foreign contractors, bricks also spread throughout urban areas. Brick masonry was adopted on a massive scale, together with neo-classical and eclectic architectural languages. By the third quarter of the 19th century, brick constructions had surpassed rammed earth, changing the physiognomy of the city of São Paulo.

In his classic landmark book *São Paulo: três cidades em um século* (1982) (*São Paulo: Three Cities in a Century*), Benedito Lima de Toledo offers an innovative reading of the history of architecture in the city, based on the succession of pivotal construction materials. Toledo sees a city that rebuilt itself over itself within the arc of a century (1875–1975). The city of rammed earth back from the 16th century turned into the city of bricks, a transition that was accelerated in the last quarter of the 19th century. Brick, in turn, gave way to a city of reinforced concrete, mainly in the second post-war period.

2 IPIRANGA MUSEUM: CONSTRUCTION FEATURES

The Ipiranga Museum is a pivot in this context, as it is one of the most significant buildings in the city in the late-19th century, a physical and symbolic landmark of the decline of the rammed earth construction method and the rise of brick masonry and the dissemination of classical language of architecture.

The origin of its construction goes back to the initiative of a group of citizens who in 1823 requested permission from the city council to build a commemorative landmark to the nation's Independence at the place where the Proclamation of Independence occurred, on the banks of the Ipiranga Brook (Barro & Bacelli 1979: 33). However, there was no consensus on how to proceed with its implementation, which, coupled with scarce financial resources, resulted in its postponement until 1875, when a commission was formed to select the architectural project for a monument-building.

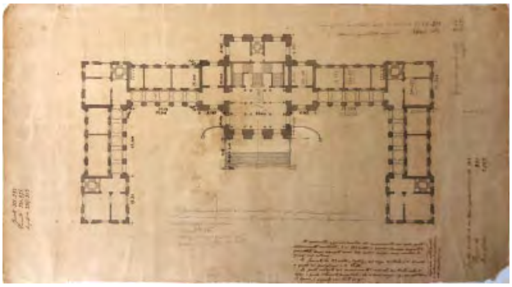


Figure 1. Ground floor plan of the monument-building designed by Architect Bezzi in 1882. On the bottom, it reads: "The façade is 123 meters long, the central body is 31 meters high, and the galleries are 23.80 high." Source: Bezzi Fund, Paulista Museum of the University of São Paulo (MP-USP). Photographic reproduction: Hélio Nobre e José Rosael.

The project, by architect Bezzi, was chosen in 1882. It is characterized by a robust building with an E-shaped floor plan: a large linear body, wings at each end, and a marked central volume, symmetric in its latitudinal axis (Figure 1). The monument-building has three floors: ground floor access, the noble floor, and the attic, where there would be an observation deck. This large building volume would rest on broad foundations and on an equally broad ventilation basement.

The use of basements in buildings persisted until the early 20th century, and their use was linked to health and hygiene issues: they were needed both to ventilate the structural masonry and to function as counterpoint to the alcoves, interior spaces with no light or ventilation common in Brazilian houses, especially during the colonial period (Petrella 2008: 17). This solution was very much needed in the case of the Ipiranga Museum because the foundations, a monolithic arrangement of "cyclopean concrete" base – that is, masonry of large lapidary fragments with lime mortar – were not waterproofed (Fusco 1997: 61).

A richly ornamented style is another important feature of the building. The façades are composed of large horizontal lines that span the entire built volume: the base, balustrades, cornices, and moldings. They create a well-defined rhythm, and their projections and recesses accentuate the intended architectural expression of monumentality and refinement (Figure 2).

Bezzi adopted the system of superimposed orders: each floor was organized according to a classical order – inside, Ionic on the ground floor topped by the Corinthian order on the noble floor; outside, the Corinthian order upon a rusticated podium – denoting

Figure 2. Front elevation of the monument-building designed by Architect Bezzi in 1882. Source: Bezzi Fund, MP-USP. Photographic reproduction: Hélio Nobre e José Rosael.

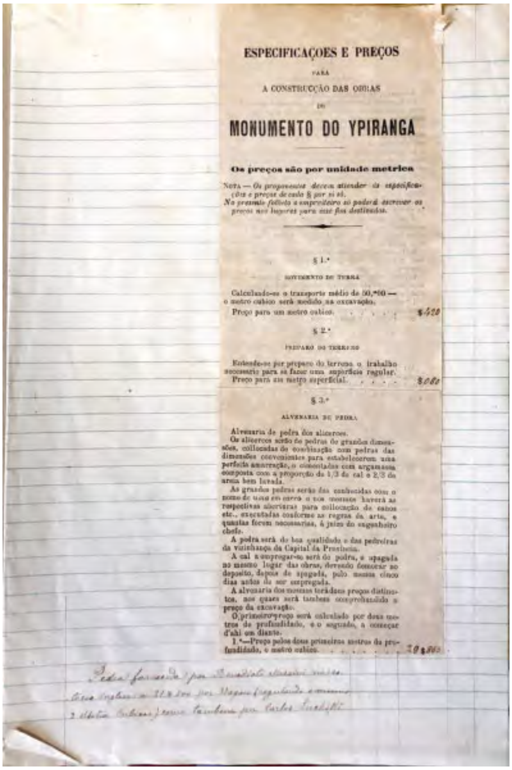
the monumental route to be followed by the visitor. This route is also linked to the symbolic narrative of the celebration of the Independence, progress and civilization of a nation, and reaches its peak in the Noble Room, located on the upper (noble) floor of the building (Petrella 2008: 166). The structural solutions adopted are deeply connected to the concept of architectural decorum and to the ornamental repertoire, materialized through the brick masonry construction technique, a symbol of modernity at the time.

The years following the selection of Bezzi's architectural design in 1882 were turbulent and saw the architect's contract terminated, public bids held to select contractors, and a proposal to reduce the scale of the project to cut construction costs (Elias 1997: 243). In the end, the side wings were not built, and the building formed a large monolithic block, marked by the volumes of the central body, the galleries (*loggias*), and two towers at each end.

Construction work began in 1885 following a solemn foundation stone laying ceremony and a parade of the 300 workers, mostly immigrants, involved in the undertaking (Salmoni & Debenedetti 1981: 44). The master builder responsible for the work was Luigi Pucci, an Italian *capomastro* "respected, if not feared by the workers, who did not hesitate to demolish any piece if it were not in strict conformity with the project specifications". (Toledo 1997: 349). The first step was the installation of a steam engine at the construction site to draw the wagons that carried construction materials through a designated line of the railway (Elias 1997: 251) because, at the time, the monument-building was located on the outskirts of the city, distant from downtown São Paulo.

Part of the commercial proposal sent by Pucci and his team to carry out the work, including their price and a definition of the services to be provided, is preserved in the Historical and Iconographic Documentation Sector of the Ipiranga Museum, the Bezzi Fund. This document (Pucci 1883) allows an analysis of some of the materials used, their origin and cost (Figure 3).

These include: earthmoving, land preparation, stone masonry foundation (including all the materials and services required, such as stone, lime, sand, lime slaking, mortar making, transportation, water), *béton*, brick masonry (four- and eight-hole bricks, and half-bricks for the execution of vaults, and "appropriately-shaped" bricks for the columns), thick timber, tiles, partitions, stonework, marbles, glazed tiles, enameled clay works, plastering and grout, stucco, and hardware.



ESPECIFICAÇOES E PREÇOS
PARA
A CONSTRUCÇÃO DAS OBRAS
DO
MONUMENTO DO YPIRANGA

Os preços são por unidade metrica

Figure 3. Initial page of the document "Specifications and Prices for the Construction of the Works of the Ypiranga Monument" with a list of materials and services to be undertaken. Source: Bezzi Fund, MP-USP. Photographic reproduction: Renata C. Campiotto.

It is noted that Brazilian materials were mostly used to execute the main construction elements, such as the foundations, walls, arches, vaults and roofs. The document reads: "The stone should be of good quality and from quarries in the vicinity of the Province's capital. (…) The walls should be made of first quality bricks, like those used in luxurious buildings in the Capital of the Province. (…) The woodwork should be made of hardwood, very healthy (…) The tiles shall be national, selected and of common mold. (…) Cladding of the building's base, sidewalks, and exterior staircase shall be done with Santo Amaro stone, or similar" (Pucci 1883). In the case of the wet areas floor coverings, "French red clay tiles, (…) from manufacturer Roux Frères. (…) Cement tiles by Villeroy & Boch" (Pucci 1883) were chosen. There are indications that also the marble staircase, hardware, and glass came from abroad (Petrella 2008: 172–173). The demand for high-quality materials for the construction of the building was recurrent in all the specifications,

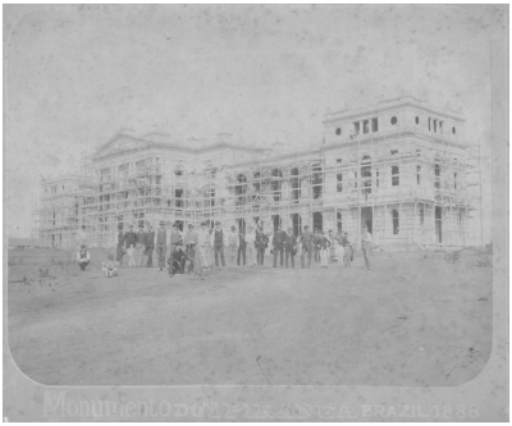


Figure 4. View of the construction site of the monument-building still under construction, in 1888. In the foreground, construction workers. Source: MP-USP website. Photographic reproduction: Hélio Nobre e José Rosael. Available at: http://www.mp.usp.br/museu-do-ipiranga.

Figure 5. View of the damage identified in the external area of the building. In addition to the rising moisture stains at the base of the balustrades, there is a serious detachment of cementitious mortar and water-based paint, resulting in the exposure of the bricks without any protection or surface treatment. Source: Beatriz M. Kühl, 2019.

and consistent with the monumental image that it was intended to embody.

One year after work commenced, when the emperor paid a visit to the construction site, records show that the building's foundations, the basement and ground floor were completed. At the time there were 160 workers on the site (Elias 1997: 256).

The progress of the works was remarkable, given their size and complexity and taking into account that it was necessary to wait for the large foundation structures and masonry monolites to settle on an unstable clay soil to proceed with the construction of the first floor. However, late arrival of imported materials and the lack of resources to complete the finishes led to a delay in completing the work. In a photographic record taken in 1888 (Figure 4), the building can be seen partially completed, with scaffolding on the lower floors throughout its perimeter. When it opened in 1900, the Museum still lacked entrance doors, access ramps, and part of its ornaments (Petrella 2008: 186–188).

Since its completion, the building has undergone several modifications, especially in the basement structure, which was continuously excavated and occupied over almost three decades (1931–1959) to meet the demands for more administrative and exhibition spaces. Similarly, maintenance works such as painting and roof repairs did not consider the particularities of the construction of structural brick masonry with lime-based mortar. Without the restraints of a comprehensive conservation policy, these actions resulted in several damages to the building (Figure 5), and as a consequence, the Museum was closed in 2013 for the safety of visitors, employees, and the collection.

Since then, a series of studies and diagnostics have been conducted to understand the origins of problems such as water infiltration in the roof, walls and ceilings, the constant humidity rising from the soil, and areas of mortar detached from the façades. The goal is to remedy these problems through a major campaign to restore and expand the building so that the Museum can reopen to the public in September 2022 as part of the celebrations of the Bicentennial of Brazil's Independence.

According to Petrella (2008), several studies on the construction technique were facilitated by the detailed definitions and specifications of the elements, all organized and legible, found in the original records of the project in Bezzi Fund archives. However, the lack of a precise metric survey, with details of the installations and recording the building that was actually built as opposed to the one designed (and not fully executed), has hampered an understanding of important structural and construction features. This has led to interventions that have not always been appropriate (Appleton 2013; Mascarenhas Mateus 2013b), such as the rainwater and groundwater drainage system.

The same is true of the mortars and paints, both originally made with lime and applied throughout the building. The constant repainting of the surfaces with paints based on synthetic polymers that were not compatible with the building's natural evaporation process coupled with the occupation of the Museum's basement which resulted in the excavation and waterproofing of its foundations led to an increase in humidity rising from inside the masonry. With no way out of these materials, the moisture ended up damaging the wall mortars and plasters. Despite these damaging dynamics being known about, the deteriorated sections continued to be replaced with cement mortars and synthetic resin-based paints until recent repair campaigns, the last of which in 2002 (Vivio 2013).

Given the need to increase knowledge about the composition and the materials of the original mortars and their incompatibility with coatings applied successively over decades, the Institute for Technological Research of USP extracted samples of the building's surfaces for laboratory analysis. Based on the results, the diagnosis of the damage to the façades prepared by Sarasá (2013) points to the need to remove all the layers of synthetic resin-based paints, in addition to cutting out sections where Portland cement mortar has replaced the original mortar. The report also suggests adopting paints based on lime or potassium silicate, also as per Petrella's recommendation (2008).

The Museum's restoration will involve significant changes to the structural arrangement of the building, since the intended extension would take place in the basement and under the so-called Esplanade. The latter is the underground area limited by the retaining wall where the Independence Park begins along with the access stairs to the museum. An extensive structural diagnosis was commissioned to give solid bases for the construction drawings to be produced by the winning architecture office in the Paulista Museum Expansion and Restoration Competition.

This is the context in which the 3D laser scanning campaign was carried out, mainly to obtain morphometric data and assist in the diagnostic processes of the building. It is a part of a scientific cooperation agreement between the University of São Paulo (USP) and the University of Ferrara (Unife) that was signed in 2015. Data scanning and processing was performed by DIAPReM, which trained USP students and researchers to work with the point cloud. The scanning products were also used by the architecture office responsible for the Museum's restoration and expansion project (H + F Arquitetos), which extracted from the point cloud the set of drawings of the Museum "as built" – essential for the development of the construction drawings.

3 THE POINT CLOUD OF THE IPIRANGA MUSEUM: CONTRIBUTIONS TO THE ANALYSIS OF THE BUILDING

The use of 3D laser scanning for cultural heritage has evolved remarkably in recent decades, gradually becoming more efficient and accessible. In Brazil, however, there are still few examples of the use of this technology. The method enables the development of models based on reliable measurements. Nonetheless, if the survey does not have clear goals, the whole operation can be fruitless. In Brazil, scanning is often viewed as an automated procedure that provides automatic answers when, in fact, it requires that its purpose is previously defined so that the desired density of points can be specified and the scanning operation planned accordingly. It also requires accuracy in execution and in data processing, in addition to a detailed analysis of the building for correct interpretation of the data. Therefore, all stages require a critical approach, something that many are still unaware of in Brazil.

In the case of the Ipiranga Museum, the scanning campaign started with the actions of the Paulista Museum 2022 Working Group, formed by the Dean's office of USP. The goals were to create guidelines and monitor the evolution of the restoration and expansion project of the Museum. These actions involved the collaboration between the Faculty of Architecture and Urbanism of USP (FAU-USP) and DIAPReM to form a team of researchers to critically operate and manipulate the point cloud (Kühl et al. 2019), and to provide a reliable basis for the architecture firm H+F that won the tender to expand and restore the monument-building.

The survey began in August 2017, followed by the point cloud processing phase and the training of part of FAU-USP team and the architects' office. Training took place between April and May 2018 at the University of Ferrara. The final delivery and the closing of the works occurred, respectively, in April and September of the same year.

Laser scanning goes beyond a simple metric-architectural survey to obtain drawings to develop a construction project. By obtaining a set of precise geometric data on the constructed building and its surfaces, it offers the possibility of a new understanding of its construction logic. The results show the thicknesses of the masonry that was actually built, the exact equivalences among the floors levels of the several wings of the building (Figures 6–8). It also allows for an examination of elements that cannot be assessed through direct measurement such as the ratio between a given ceiling and its support structure (Figure 9). By comparing the results with Bezzi's design, it is possible to analyze the construction and explore the differences between what was designed and what was actually executed, and deepen the knowledge available on the material characteristics of the building.

These data, together with information from bibliographic, iconographic and documentary sources – such as the calculation reports by master builder Pucci, letters exchanged between the members of the construction commission of the monument-building and the architect in charge – and the vast studies carried out *a posteriori* helped the researchers understand the alterations that might have occurred during the construction process.

This procedure adds important data to the history of the construction (Huerta 2011) in a way that ties in with Mascarenhas Mateus (2011: 15): "It is necessary to study the techniques, the programmatic requirements, the constructive solutions, the materials, machinery and tools, the teaching of construction and transferring of know-how, the technical literature, the different forms of labor organization, trades and construction management, and aspects of the economic and social history related to the construction".

The investigative process also increases knowledge about the construction techniques and structural systems of the building, corroborating the idea that knowledge and methods from different disciplines must be applied to enhance a "holistic understanding of the construction processes of each culture, joining scientific methods, theory and practice" (Mascarenhas Mateus 2013a: 31). In addition to forming a highly accurate database on the constructed building,

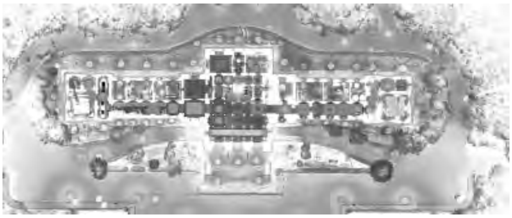


Figure 6. Ground floor plan of the Ipiranga Museum extracted from the point cloud. Elaboration: DIAPReM, Unife, 2017.

Figure 7. Front elevation of the Ipiranga Museum extracted from the point cloud. Elaboration: DIAPReM, Unife, 2017.

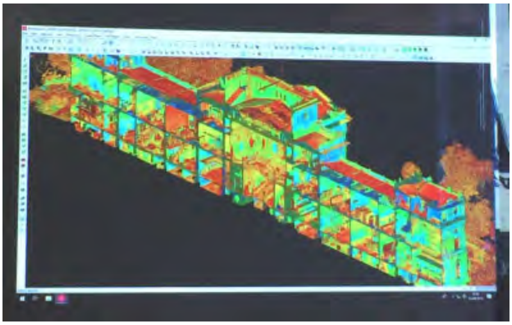


Figure 8. Visualization of the Ipiranga Museum point cloud in the longitudinal section of the building. It is possible to assess the equivalence among the floor levels and the thickness of the masonry. Elaboration: DIAPReM, Unife. Source: Renata C. Campiotto, 2018.

Figure 9. Visualization of the Ipiranga Museum point cloud, transversal section of the building: structural elements of the roof and the position of the plaster ceiling. Elaboration: DIAPReM, Unife. Source: Re-nata C. Campiotto, 2018.

the point cloud also enabled a detailed assessment of the morphology of the surface degradation and of the structural deformations in comparison with a previous diagnosis (Grupo Falcão Bauer 2017). Another advantage of this method is that it is a non-destructive investigative procedure, unlike other types of diagnosis, which in Brazil sometimes use exploratory windows in a way that is not appropriate for heritage conservation.

It is also worth discussing methodological issues and the dangers associated with the poor execution of the scan: a poorly made cloud can result in misdiagnosis. The execution of the point cloud involves (or should involve) a high degree of specialization of those who operate the device and process the data. It is a job that requires rigor at all stages, starting with planning: the professionals must have a deep understanding of the building and of the objectives of the scan to stipulate the density of points needed to accurately obtain information, thus being able to plan the survey campaign properly. The data obtained must be interpreted carefully and then compared with the knowledge derived from other sources that complement it. To this end, it is essential to know the building, its construction characteristics, the project, and how it was executed. The point cloud is also a way of conserving the geometric memory of a given construction at a given time, providing input for assessing how this structure behaves over time (Balzani & Raco 2020). In this regard, in the case of the Museum, the comparison of the scan results with the analysis of the structural diagnosis (Grupo Falcão Bauer 2017) and the survey of the façades (Sarasá 2013) made it possible to explore the differences in results between the traditional and advanced methods of analysis and diagnosis.

The use of 3D laser scanning – especially in complex objects, as is the case of the Ipiranga Museum – is a tool that, if used conscientiously and in coordination with other sources, offers contributions of interest to several fields, including construction history. It also provides support for the Museum’s conservation over time.

When Carbonara (2015) advocates the virtuous cycle of survey/history/restoration, he is not proposing a hierarchy between the areas, nor is he stating that each field should give up their respective epistemological bases. He does not mean that history in general – and construction history in particular – have an operational function in restoration. Rather, Carbonara wants to show that the fields are not impermeable and isolated; when they work together, the process is mutually beneficial. Historiography is a construction of a given time and it is not totalizing. It depends on the questions arising from the goals in mind, which affect how the theme will be approached (Le Goff 2003: 126–171). Construction history associated with restoration is still construction history, but it is stretched by the questions posed by problems associated with the restoration. In turn, by using the data obtained by the survey, through the analysis of structures and materials, and the work of restoration, historiographical issues can be clarified by the building fabric. Thus, the connection of history, survey, and restoration is mutually enriching.

4 FINAL CONSIDERATIONS

The analysis of the Museum's point cloud, articulated with bibliographic, iconographic, and documentary research, clarifies a series of questions about the construction characteristics of the building. This process resulted in some changes to the architectural solutions proposed in the restoration project.

Scanning as a tool has increased – and will continue to increase – our knowledge of how the Museum was effectively built in terms of its metric-morphological features (Georgepoulos 2017). Every architectural organism has complexities, and the Ipiranga Museum is one of the most intricate examples of São Paulo architecture at the time in question. Understanding its complexities requires going beyond the surfaces. But in order to reach an in-depth understanding of how it was actually built, in addition to the documentary, iconographic, and bibliographic sources, we must rely on the building fabric itself. This includes, essentially, its surfaces and the way in which they shape the space – unless there are missing or collapsed parts, and destructive methods of analysis are requested. Architectural surfaces, including the materials that form the construction systems, have within them features and data, which are not merely juxtaposed. An architectural work is not the sum of its parts and materials; it is an organism that must be read in its entirety, and its materials explored in its fabric. As stated by Doglioni (2008: 191–205), surfaces have an intrinsic quality and a narrative capacity that can be analyzed in different ways over time. For this very reason, they must be documented and examined in studies focusing on the history of architecture and construction. Restoration must meticulously preserve this narrative capacity and the material articulation of the surfaces.

In this regard, laser scanning is of great interest as it offers more comprehensive data on architectural surfaces and preserves the building's geometric memory in a given time. Additionally, it enables the methodological separation between the objectivity of the acquired data and its interpretation, allowing them to be investigated in the present and in the future, from different perspectives and fields of knowledge, different from that which initially motivated the scanning.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Black concrete power: The Tuskegee block and Low Cash-Cost Housing

Vyta Pivo
George Washington University, Washington, D.C., USA

ABSTRACT: Concrete is a material that has received increased scrutiny in recent years – it has been used as a vehicle to study the politics of climate change and the culture of architecture. This paper presents an opportunity to examine concrete in the context of vernacular building cultures in southern United States. Focusing on the Tuskegee Institute's Low Cash-Cost Housing program, which taught low-income Black farmers how to mix and pour concrete to build low-cost yet modern homes, the paper shows how the material performed as a tool for economic and social liberation. In addition to the specific case study, the paper links local building cultures to a broader history of global tabby construction. Most significantly, the paper contributes to scholarship on construction history by privileging experiences of Black working-class people instead of private enterprises or governments.

1 INTRODUCTION

In 1947, the Tuskegee Institute in Alabama organized an exhibition to encourage Black farmers to embrace modernity on their farms. To illustrate the benefits of such a radical departure to farming and homemaking, organizers developed "before-and-after" displays that showed the possible transformations of a typical cabin. Visitors were first led through a one-room shack reminiscent of the disorder and paucity of slavery: "The doors and shutters [are] half off; window panes out and pillows stuffed in the openings, the walls papered with newspapers; a bed and two chairs the only furniture; a large fire-place and a log fire over which were two skillets in which were being cooked the proverbial two things–a hoe-cake of corn bread and bacon–on which so many farmers subsist". Outside the cabin sat scattered wooden wash tubs and boards and dirty pots, rags, half burned wood, and "other filth". In contrast to such "eye-sore to any plantation", otherwise referred to as "Cabins in the Cotton", stood a modern farm home, built with modern materials like concrete and equipped with "labor-saving devices and other conveniences which promote health, happiness, and comfort". The contrast between the two residential settings aimed to show exhibition attendees that the introduction of domestic hygiene was simple, affordable, and could have significant improvements on the health of livestock, the family, and the entire community. Most radically, the modern farm had the potential to give rise to Black empowerment in southern United States.

Especially central to the modernization of the southern farm was the introduction of concrete, a material of modernity that promised to bring hygiene to the most underserved parts of the country. Pushed by cement businessmen and federal and state governments alike, concrete prevented the spread of disease among animals and humans; it also improved the appearance of farm landscapes, making them comparable to affordable urban dwellings. By improving working and living environments in southern United States, concrete could also improve productivity and manufacturing capacity. As rapid urbanization in the first half of the 20th century shifted urban and rural demographics, with scores more people living in cities than on farms, rural districts had to become significantly more efficient and productive to keep up with such changes. Although Black farmers were traditionally dismissed by the white plantation elites, they now took on a central role in the agricultural industry.

Historically Black agricultural colleges and institutes went to work to disseminate information about best farming and domestic management practices. These institutions saw agriculture no longer as an industry that kept Black communities subservient and impoverished, but a line of work that could improve their overall standard of living. And learning modern construction skills, in addition to modern farming techniques, promised to expand employment opportunities for Black families. Especially important for this prospect was the Tuskegee Institute's development of its concrete block and low cash-cost housing system. It offered an avenue for Black farmers to manufacture their own concrete blocks at low cost, using materials sourced largely for free from their own farms, including water, gravel, and sand. Working with the Institute, farmers learned to build their own formwork, mix the material, and pour it to create sustainable construction components. The federal government envisioned that Tuskegee's block and construction system could transform low-income housing across the United States and even overseas, from war-ravaged Europe to impoverished communities in the Global South.

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While the Tuskegee Institute is well known internationally for its contributions to agriculture and, perhaps to a lesser degree, its brick manufacture and construction, this paper shows that the Institute's innovative pedagogies were not limited to 19th-century materials. Indeed, Tuskegee played an important role throughout the first half of the 20th century, introducing modern materials to underserved communities. Through close readings of primary source materials, particularly photographs of classrooms and manufacturing processes, the paper provides insight into how the introduction of concrete shifted faculty, student, and farmers' thinking about labor and construction work on the farm. It also offers a unique narrative on construction history that is from the perspective of working-class and underserved communities, rather than the more common large-scale manufacturing companies, contractors, or governments.

2 FARM IMPROVEMENTS

By the early decades of the 20th century, Black and white farmers were looking for ways to diversify their agriculture. Indeed, they discovered that by focusing on planting cotton, many farmers were ill-equipped to grow their own food and livestock – they regularly imported their food, paying exorbitant fees for produce they could grow themselves. Many Black farmers were also motivated to divorce themselves from cotton because of its connection to slavery. In one interview, Mrs. Campbell explained why and how her family decoupled their farming from cotton: "When my husband and I began farming, nothing would do him but cotton. He believed in cotton. I fussed against it. He could make the children farm, but not me. He said he was compelled to have cotton, otherwise he couldn't get a merchant to 'run' him. I told him that I was actually tired of a merchant 'running' me. I said from now on I'm going to run myself at my own leisure". However, to introduce new crops and agricultural techniques, farmers in southern United States first had to transform their farm infrastructure.

Knowledge of cement manufacture and concrete construction became especially critical for expanding and modernizing the rural farm. And concrete on the farm became such a significant topic, it even materialized its own journal, *Farm Cement News*, regularly published by Universal Cement. The outlet disseminated information on how concrete could transform a messy and unruly farm into a modern factory-like operation. Extensive plans, diagrams and photographs of farm buildings and their interiors provided literal blueprints for how farmers might attain a modern life outside the city. One highly publicized barn, for example, adopted the crucifix plan with the horse stable as the apex, silos and covered passageways as the transepts, feed and driveway paths as alleys, and bull and calf pens as the benches. Master-planned with Frederick Winslow Taylor's scientific management principles, the functionally interconnected farm made sure that people, animals, and feed moved around the building efficiently. This new arrangement not only appealed to farmers' religious commitments, but also showed the broader public that agriculture was a serious business that involved planning and preparation. And concrete served not only as a technology that literally restructured the farm, but also as a symbol for agricultural modernity more generally. Cement men argued that large concrete buildings were evidence of farmers' sophistication: "These silos are sign posts that point to prosperity. They mark farms upon which they stand, declaring them to be owned by men who are alive to the best interests of their business". Some men went as far as to adorn their silos with unique features like saw-tooth roof lines that resembled European medieval turrets; others constructed piazzas – entertaining but entirely impractical components of the new rural landscapes.

While building concrete silos was a novel experience for Black workers in southern United States, concrete on the farm was a more familiar undertaking. Indeed, in the late 18th and early 19th centuries, enslaved laborers employed tabby concrete to construct farm and residential buildings on plantations. Tabby concrete – a concoction made by burning oyster shells, crushing, and mixing them with sand and water – appeared across Florida, Georgia, and South Carolina. First used by Spanish colonists to construct their communities in the 16th century, the material's laborious manufacture quickly fell into the hands of enslaved workers who spent a significant portion of their working time collecting oyster shells and acquiring the necessary heat to burn them (Carney 2002, Carney & Rosomoff 2009, Fields-Black 2014). The construction process was challenging and involved building large wooden formwork into which the tabby mixture was poured; each layer had to solidify before another could be added. And since the material was thick and chunky, builders relied on its large mass and weight to keep together. When poured to construct agricultural buildings or slave dwellings, the partially-burned shells exposed their sharp edges and presented a cold and unwelcoming surface ready to scrape and injure unsuspecting passersby. Some enslaved people painted their dwelling in white color while others covered their interior walls with newspapers that promised to keep away the haints: legend had it that the evil spirits had to read every word on the walls before they could practice their voodoo magic on the inhabitants (Gwin 1953).

Although tabby concrete in North America was limited geographically to states bordering the water navigation routes, the material had a broader international history. By some estimates, early forms of tabby, or *tabi*, were brought to Spain by the North African Moors. Historian Thomas Glick, for example, argued that the material may have originated in North Africa in the Carthaginian period; Christian Spaniards then introduced it to the Canary Islands and eventually to the New World (Glick 1976).

Tabby manufacture and construction was immensely different from other construction methods and instead closely resembled other domestic forms of farm labor. From the scavenging and collecting of oyster shells, their burning, and mixing with water and other ingredients, to its pouring into wooden molds, tabby was not unlike cooking. And much like enslaved people's maintenance of slave gardens that carried familiar medicinal plants, tabby too connected them to their African roots. Indeed, the manufacture of tabby resembled that of mud brick, created by mixing agricultural soil with leftover straw from the grain harvest, thus further cementing the familiarity of these sibling building traditions (Rael 2009). This early form of concrete therefore existed not in isolation but as part of a constellation of material linkages that connected enslaved people to their geographical and cultural origins and therefore left a meaningful impact upon the local building cultures.

Tabby concrete was meaningful preparation for the later advent of concrete, but its manufacture and use ended with the passing of the Thirteenth Amendment since compensating for tabby manufacture was too costly. White residents of southern United States grieved the loss of this building tradition: recollecting a tour of St. Simon's Island, home to some of the earliest and best-preserved examples of tabby architecture, one Chattanooga writer remarked in 1888 that "the ignorant but polite negro, standing on one foot over by the gate gained his liberty, but his master lost his home, his property, his peculiar civilization". With the end of slavery, building practices likewise changed to accommodate new financial and labor regimes. Yet, the region's engagement with tabby ensured that concrete would receive an enthusiastic reception and praise and monopolize the construction of all modern infrastructure.

Although tabby as a building material vanished, its connection to Black culture and especially religion persisted. Indeed, to offer concrete as a natural substitute, cement men had to recognize the importance of religion to Black rural farmers – Booker T. Washington recognized that "any program of education or agriculture needed the support of the Negro preacher". Within the Black community, the preacher occupied the highest post as the "biggest person" and local reverence for his work was "woven into every activity of rural Negro life". Black farmers were convinced that preaching and farming went hand-in-hand and regularly learned lessons on agriculture and construction in religious ceremonies. When teaching government workers how to reach their rural farmer audiences, Tuskegee leaders articulated that "the clergymen can assist your work by making announcements from the pulpit, and will welcome the opportunity to preach sermons on the spiritual significance of the homes, religious training in the home, and the ways to promote character building in the home". These lessons taught farmers not only the specifics of how to mix and pour concrete, but the philosophy of modern living and its shaping of personhood: "Instead of picturing the beauty of the pearly gates of heaven, [the preacher] would have to preach to his people the disgrace of broken hinges on the gate before his house". The lure of modern infrastructure was therefore laden with righteous undertones, which suggested that caring for roads and buildings was a way to improve individual morality and reach salvation.

3 TUSKEGEE INSTITUTE AND CONSTRUCTION PEDAGOGY

In order to disseminate the gospel of concrete and modern construction, historically Black agriculture and industrial schools integrated courses on concrete paving and road construction into their curriculum to meet rapidly growing demand. The Tuskegee Institute, founded in 1881 by Booker T. Washington to educate rural Black farmers, had long enabled students to pay for their education through the labor in community and industrial settings: women typically fulfilled domestic roles of cleaning and cooking, while men participated in constructing and maintaining university buildings. Indeed, because so much of the campus was excavated for its clay to manufacture brick, the Institute developed its own authentic topography full of ridges and high inclines. And the brickmaking quickly became a key local industry, so much so that students began to manufacture the construction material for commercial sale. While brick manufacture and construction defined 19th-century building activities at Tuskegee, concrete quickly took over.

Concrete made an appearance at Tuskegee in the early years of the 20th century. Nearly all newly constructed campus buildings had some amount of the material in them, be it extensive pours for foundations, floors, and porches, to the more minimal applications in windowsills, columns, and steps. The earliest use of substantial concrete in Tuskegee was displayed in a 1906 photograph that documented a march across campus in celebration of the Institute's 20-year anniversary; as the students and alumni marched in the middle of the dirt street, one side of the sidewalk displayed a fresh concrete pour. Built to occupy a significant portion of the road, the new clean and permanent walking path promised to protect students' clothes and offer opportunities for a leisurely stroll across campus. Starting in 1910 and especially by 1915, many communal and agricultural buildings, ranging from the student dining hall to the power plant, dairy barn, and veterinary hospital, featured concrete foundations and floors to ensure a hygienic environment.

Tuskegee students first received their introduction to concrete roads in 1903 and only eight years later they were mastering how to mix, proportion, distribute, and test concrete; the Institute also purchased a machine used specifically to manufacture cement blocks. An undated photograph of one of such lessons showed students working collaboratively and displaying the mixing process: the young man on the right

Figure 1. Tuskegee students learn to mix and pour concrete. Published in L. Albert Scipio II, *The building of Tuskegee Institute* (Silver Spring, MD. Roman Publications 1987): 241.

Figure 2. Tuskegee Institute's brick classroom, ca. 1910, Tuskegee University Archive.

shoveled sand while the one next to him mixed the material with other ingredients; the remaining students organized the concrete blocks, perhaps stacking them for the construction of columns or foundations (Figure 1). It is notable that the space in which this learning was taking place was not dedicated to concrete work – the large furnace on the left and the adjacent shelves filled with metal gadgets reveal that the room was the Institute's metal workshop. The five pupils partaking in this work received minimal supervision and largely directed their own efforts. Although the students avoided making eye contact with the camera – a common trait in photographs that advertised Tuskegee workers' skills and subordination – the image differed significantly from the earlier representations of carceral concrete laborers (Goodman & Lucking 2019). Whereas the latter merely emphasized the great numbers of available anonymous workers, the quality of their labor and degree of necessary supervision, the former highlighted the individuality of the students and their instructional capacity. Indeed, after learning the concrete trade, these young men could return to their communities and materially transform them.

The photograph of the concrete classroom reveals even more about the Tuskegee Institute's attitudes toward concrete when compared to a documentation of the brickmaking classroom. Unlike the borrowed space of the former, the latter was housed in a spacious, modern, and clean built environment with large windows and lamp shades covering light bulbs – an uncommon and impractical luxury (Figure 2). The room was not merely a classroom but also an exhibition space to showcase the range of skills that Tuskegee imparted upon its students, ranging from various brick binding techniques to decorative columns that integrated various materials for a unique aesthetic effect. Although filled with students busy at works, instructors could nevertheless be easily identified by their professional attire and large project drawings in their hands. Much like the image of inmate road builders, the photograph concerned not the individual workers, but the group of laborers and their efficiency. A Dixie Brick Co. calendar hanging near the window further emphasized that the brick making and laying operation is primarily concerned with business rather than learning. The space too appeared less like a classroom and more like a job site: the elevated balcony with a door to a private room on the second level most significantly recalled the centrality of the factory overseer, or in the case of the southern United States, the planter surveilling his fields from the porch of the big house.

Closely reading the two classrooms reveals that while Tuskegee students learned about the importance of concrete for the construction of roads, sidewalks, and foundations, they were not taught to think of it as an especially noble or lucrative material. Indeed, the photograph of the brick masonry classroom was thoughtfully staged to encourage the purchase of locally manufactured brick and labor of Tuskegee students. The image of the concrete classroom, in contrast, sent a different message. With its repurposed classroom and low-tech tools like containers and shovels, the photograph communicated that concrete was accessible to every farmer interested in utilizing this medium; furthermore, building with concrete was not especially complicated and could be performed one step at a time with the help of family members or close neighbors. Unlike brick construction, which required an army of laborers, concrete work was significantly less elaborate and even domestic. And in that way concrete was the most fitting medium for Black workers. Indeed, in 1917 the United States Office of Education advised that "the hope of the South for an improved labor supply is not immigration but the effective education of their white and colored youth" (US Office of Education 1917). While the former were expected to fill intellectually rigorous roles of highway design and engineering, the latter were assumed to take up smaller construction projects on the local scale: "for the young men, they should endeavor to provide training in the elements of carpentry, blacksmithing, bricklaying, cement and concrete construction, adapted to small towns" (US Office of Education 1917).

And the Tuskegee Institute did not merely preach the gospel of modern environments, but also equipped farmers with the information and tools necessary for constructing affordable concrete housing. By upgrading their homes, farmers could improve the efficiency and profitability of their operations. The Portland Cement Association enthusiastically confirmed this, arguing that "there is no farm improvement that pays better than concrete" (Portland Cement Association 1924). Starting in the 1930s, the Institute began to experiment with ways farmers could utilize their assets to build housing. Concrete was a fitting material for these improvements since farmers could provide their own labor, mixing and pouring concrete periodically to slowly acquire the necessary construction components over time. They could also fabricate much of the technology they needed for mixing concrete. Indeed, journal articles highlighted clever farmers who utilized basic household equipment to put together homemade mixers that could be turned manually using a simple crank system. Such ingenious problem solving also brought the community together, promoting cultures of innovation and sharing to collectively modernize the agricultural landscapes.

For Black farmers, concrete offered an attractive vision of social and material independence from the white community. Indeed, because so much of the financing and construction labor could be performed by farmers and their families, white businessmen of all stripes no longer played as critical a role. And this was a long-held desire for the Black community in southern United States, as president of the local Tuskegee bank voiced: "When every farmer in the South shall eat bread from his own fields and meat from his own pastures, and distributed by no creditor, and enslaved by no debt, shall sit amid his teeming gardens, and orchards, and vineyards, and dairies, and barnyards (…) then shall be the breaking of the fullness of our day". Concrete therefore offered an opportunity to not merely build a modern southern United States, but also a modern Black United States.

One of the most important innovations for realizing these aspirations was Tuskegee Institute's 1946 development of low-cash cost housing, also referred to as "self-help" homes.

Perfected over a ten-year period, the project was funded with grants from the General Education Board and developed as an effort to provide modern housing facilities for Black farmers; the first experimental concrete house was built on the campus by Tuskegee students. The project proposed that farmers could erect such structures on their own by utilizing the free labor of their family and locally available materials to manufacture concrete blocks in wintertime (Figure 3). At the outset of the experiment, the Tuskegee faculty experimented with various possibilities, building houses of timber, rammed earth, and soil-cement mixtures. However, these options were problematic because of high cost and requirements for specialized facilities and skilled construction labor. Program leaders finally settled on concrete, mixed by farmers with largely freely available materials: "on most of the eroded cotton farms in the South, deposits of sand and gravel can be found in ditches and creek banks" (Tuskegee Institute 1950). farmers had to purchase cement at $47.50 for 50 sacks of cement which could materialize 20 blocks per bag.

Figure 3. Self-help house built by the Felton family. Published by the Housing and Home Finance Agency in "Building Self-Help Homes" (Housing Research (Fall 1951): 34).

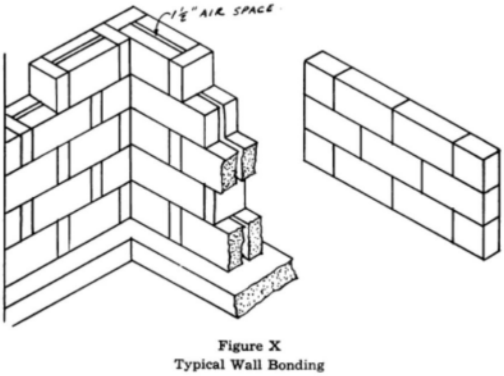

Figure 4. Tuskegee concrete block construction system. Published by the Tuskegee Institute (1950).

To keep the construction process simple, the Tuskegee faculty focused on producing a basic yet well-designed element – the building block and its formwork (Figure 4). The latter was simple and could be built by "one man with crude carpentry skills". Indeed, project leaders calculated that one farmer could construct enough wooden forms in one day to hold 100 blocks; he could then mix and pour 10 blocks per hour and with a month's worth of practice, he could lay 160 blocks in an eight-hour day, or 20 blocks per hour. Tuskegee's concrete block compared well with commercially available alternatives yet cost significantly less to manufacture.

And the only skilled labor that had to be hired was for the laying of the corners, roofing, wiring, plumbing, and chimney building. The project's proposed technique of wall bonding, which included a critical three-inch air space, ensured that the blocks remained thin, cheap, and easy to manufacture, yet produced homes that were sturdy and appropriate for the local climate. While the concrete low-cash cost housing provided an avenue for an affordable and improved life on the farm, it was by no means free. Indeed, while farmers relied on their families for labor and employed locally sourced materials, they still had to accrue debt to cough up the $2056 (or $2.52 per square foot) necessary for the average four-room modern cottage. For many families, their new concrete homes therefore represented years of saving and planning.

Photographs documenting educational workshops for concrete low-cash cost housing showed rural youngsters learning to lay the concrete blocks using trowels. One image featured six young men working on the pouring of concrete blocks into homogeneous formwork as another man in a trench coat and a hat directed their labor. The workshop participants were situated in an unfamiliar yet domestic-looking space with two doors leading to the outdoors. Much like earlier photographs of student laborers at Tuskegee, the young men avoided eye contact. Yet with the camera positioned low and close to the floor, it is clear that the viewers were meant to inhabit the bodies of the workers and see clearly what type of work was involved in building low-cash cost housing. In other words, farmers from all over the region, regardless of their literacy, could view the image and understand the processes involved in concrete mixing. And Black farmers were used to interpreting visual information – historian Stephanie Camp has shown that enslaved people half a century earlier decorated their living spaces with abolitionist literature not because they could read it, but because they interpreted the imagery as a visual representation of the possibilities of freedom (Camp 2004). Thanks to the clarity of visual instruction in concrete mixing, farmers could imagine themselves performing the labor and helping their communities embrace the new material of modernity.

Another telling photograph showed Tuskegee's well-dressed agricultural leaders congregated outdoors, inspecting the formwork and concrete blocks that were created as part of the demonstration. Once again, it is clear that the workshop along with the manufactured product were meant to be consumed by Black farmers. Unlike the brick classroom of some years earlier, which displayed and advertised attractive final products to potential white clients, this image showcased an organized but by no means professional workshop. And the concrete blocks were not shown to present a neat and pleasing appearance to illustrate the skills of Tuskegee workers, but instead were stacked vertically to simply provide more ground space for formwork and more concrete pours. Everything about the concrete block, from the construction techniques to the workshops and their organization, addressed the practical needs of Black farmers and their communities. Even the centrally positioned pulley cart anticipated that upon the conclusion of the demonstration, workers will return to the site to move the concrete blocks to continue the construction process.

5 LEGACY OF TUSKEGEE EXPERIMENTS

On the interior, low-cash cost homes presented environments of unparalleled comfort, marked by individual bedrooms with built-in closets, well-equipped kitchens, and single bathrooms. A heater positioned in the center of the building made sure that the homes were warm in the winter and covered porches kept them cool in the summer. Large windows, included in every room of the house, ensured that the residential accommodation was naturally well-lit and thus saved energy. With ample land to spread out horizontally, low-cash cost housing was always limited to a single level, thus eliminating the additional cost of staircases and overbuilt foundations. Homemakers decorated the new domestic environs by putting to work various discarded papers and fabrics to add color and whimsy to the interior. Since the experiment largely focused on structural questions and issues of labor, Tuskegee leaders promised to examine how interiors too could be made cheaper and more efficient through sensible design. They planned to integrate movable and interchangeable walls, compact furniture and storage units, and new panel material for floors and ceilings (Thomas 1948).

By constructing their own concrete housing, Black farmers revealed the liberatory potential of the material. Indeed, concrete did not have to be restricted to a medium of paternalistic civilization, but could also be an empowering tool for self-sufficiency and independence. Sociologist Monica M. White has written about how agricultural resistance inspired the Black freedom movement. She traced the importance of agricultural work to enslaved Africans, for whom agricultural work provided a connection to national origins and cultural traditions. Many of these men and women maintained their own gardens to provide subsistence, but also to preserve their personal histories and memories. Slave gardens thus can be "understood as a strategy of resistance to a corrupt system and an effort to create food security" (White 2003). Concrete too offered the opportunity to resist construction practices that were regulated by white power. Instead of relying on lumber, brick or other materials procured by white manufacturers, Black farmers could collect their own materials independently and mix them together with cement to manufacture their own construction media. The new approach thus enabled the farm to challenge its associations to oppression and instead create conditions for sustained collective struggle and community building.

As Tuskegee's experiments with concrete block construction expanded opportunities and independence of Black farmers, they also drew national media recognition. Indeed, the projects attracted not only coverage but also financial support from white individuals and institutions, like the Southern Research Foundation.

Tuskegee President Patterson remarked that such housing projects defined the beginning of the rebuilding of local race relations and "expressed his profound appreciation for another opportunity to extend the Institute's usefulness to the community and to the South." Meanwhile, the United States Housing and Home Finance Agency noted that low-cash cost housing was not merely an experiment, but swiftly transformed the construction of rural and suburban dwellings in the southern United States due to concrete's capacity to resist house fires. And the ripple effects of this new mode of rural modernization were felt not only in the southern United States, but also the Global South: both Tuskegee and the federal government entertained the idea of using the low-cash cost method to construct housing in the developing world as part of President Harry S. Truman's Point Four Program. In 1950, the federal Housing and Home Finance Agency granted Tuskegee a two-year, $60,000 research contract to examine cooperative construction labor and peg down the technical aspects of the housing plan. And a year later, the Paley Commission's 1952 report *Resources for Freedom* identified the importance of the concrete block, stating that it is "one of the most spectacular developments of the last few decades" (Paley Commission 1952). While enthusiasm for low cash-cost housing was rampant, the building system did not become as widespread as initially imagined. Nevertheless, the moment in construction history presents an opportunity to consider what a widespread disinvestment from oppressive labor regimes might look like.

6 CONCLUSION

The Tuskegee Institute's Low Cash-Cost Housing program illustrates that concrete provided access not only to a new kind of material modernity, but also to important Civil Rights goals of equal economic and political opportunity. Concrete was first introduced to the Institute's educational curriculum to teach students useful skills, to be applied in the construction of concrete highways, silos, and other important agricultural infrastructure. However, the material soon found new utility in the construction of low-cost residences that allowed Black farmers to embrace urban comforts, including private indoor bathrooms and kitchens. Most significantly, the introduction of concrete to the southern United States farm allowed Black farmers to erect modern homes using materials found for free on their land and maintain independence from the white construction market. Tuskegee's Low Cash-Cost Housing therefore soon became a symbol of self-help and empowerment that could transform low-income communities across the United States and beyond.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Bridge replacement due to structural obsolescence. The case of the Ciudad Real-Badajoz railway bridges (Spain)

P. Plasencia-Lozano
Universidad de Oviedo, Mieres, Spain

ABSTRACT: The great railway bridges built in the 19th century are magnificent examples of the rise of civil engineering, and especially of the development of iron structures. Over time, however, the increase in railway rolling stock complexity and weight made some structures obsolete, and their replacement became indispensable during the 20th century. Such is the case of some bridges built in a section of the Spanish Ciudad Real-Badajoz railway line inaugurated in 1865, which crossed watercourses as important as the Guadiana River, the Aljucén River or the Gévora River. At two different times, during the 1920s and 1950s, the original iron lattice girder bridges were replaced by new concrete structures built in the same places. This study analyzes those structures, both old and new, and especially how the replacement construction was carried out without interrupting rail services. The original construction projects and the new bridges, some historic photographs of the replacement work, which include piers, formwork, arches and decks and dismantling of obsolete iron girders, are thus studied. The study provides evidence of their importance not only as territorial landmarks or major structures but also as elements with a construction history remarkable and extremely interesting in itself. Lastly, the destiny of the obsolete iron structures, sale for scrap, contributes to the discussion of the future of outdated bridges of our time.

1 INTRODUCTION

Throughout the 20th century, a diversity of technological advances took place in railroads. The engines became more powerful as the years went by and could therefore pull heavier loads; as a result, many of the bridges and overpasses became obsolete and had to be reinforced or replaced by others.

This text describes the replacement of four bridges in the railroad line between Ciudad Real and Badajoz. Several studies have approached aspects connected with this line (Blanch Sánchez 2013; Esteve García 2008; Peris Torner 2012), however, the literature contains hardly anything published on the replacement of its bridges.

The study is backed by several different documents kept in the *Archivo General de la Administración* (AGA) and in the *Archivo Histórico Ferroviario del museo del ferrocarril de Madrid* (AHF-MFM), in particular photographic reports made during construction by two photographers, Juan Salgado Lancha and Vicente Garrido Moreno, who made numerous reports on railroad construction throughout their professional careers.

2 CONTEXT

2.1 *The Ciudad Real-Badajoz Railroad*

The Ciudad Real-Badajoz Railroad was the first corridor built between Extremadura and the center of the peninsula. The construction of the line was divided into two sections. The first, which ran between Ciudad Real and Mérida, was planned in 1858 by civil engineers, Pedro Sierra and Santiago Bausá. The second, between Mérida and Badajoz, was also planned in 1858 by civil engineers, Carlos María de Castro and José Barco. Both sections were given an execution period of five years. Construction was begun in 1860, and shortly afterwards, on March 26, 1861, was legalized as the "Compañía del Ferrocarril de Ciudad Real a Badajoz", presided over by Alejandro Mon y Pidal, and directed by civil engineer, José Canalejas y Casas. The line was inaugurated by Queen Isabel II on December 11, 1866.

2.2 *The first bridges*

Some of the bridges in the project were never built: on December 25, 1860, the Guadiana River surged and flooded the valley and, as a result, in 1861, it was decided to draw up a new project for eleven of the structures located between Don Benito and Badajoz to enlarge the drainage capacity of the structures in the original project (AGA 25-07035). The author of the new designs was Manuel Peironcely, one of the most outstanding civil engineers of the 19th century and the company's technical director (Larrinaga Rodríguez 2006).

Almost all of the projected structures consisted of lattice girder sections on masonry piles. Even though the line was planned and built with a single track, it

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Table 1. Metal truss bridges designed by Peironcely.

Bridge	Length	Cost (real de vellón)
Ortiga	15.3 m + 19 m + 15.3 m = 49.6 m	687 137
Guadálmez	15.3 m + 19 m + 15.3 m = 49.6 m	687 137
Guadiana	42.6 m + 9 × 50 m + 42.6 m = 535.2 m	8 522 779
Aljucén	27 m + 7 × 32 m + 27 m = 298 m	2 678 029
Lácara (seven bridges)	2 × 10 m; 10 m; 2 × 10 m = 20 m; 4 × 10 m; 10 m; 4 × 10 m = 40 m; 10 m	744 516
Alcazaba	27 m + 32, 4 m + 27 m = 86.4 m	769 355
Guerrero	30.5 m	271 905
Aguas Blanquillas	8 m	74 785
Gévora (two bridges)	27.4 m + 32.4 m + 27.4 m = 87.2 m; 27.4 m + 3 × 32.4 m + 27.4 m = 152 m	2 420 925

was thought that future traffic might require widening to a double track, and so the abutments and piers were twice as wide as those strictly necessary for the single track.

The most prominent was the Zarza bridge over the Guadiana. Peironcely wrote that it was "The most important construction on this railroad and perhaps one of the bridges of most substance the Spanish railroads will offer." Located 14 km from Mérida, it consisted of eleven iron sections on abutments and masonry piers. Each of the end sections had a 42-m span and with the rest rising up to 50 m. The bridge was oblique, and the axes of the piers formed a 70-degree angle with the track. The total length was 565 m. This notable structure has been described in detail several times (Anon 1865; Lavado Rodríguez 2015).

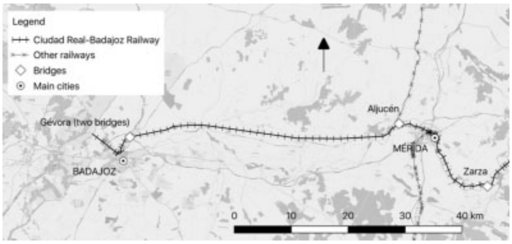

Figure 2. Emplacement of the bridges discussed. By the author.

Other significant bridges were those at Aljucén and the two bridges in Gévora (Arévalo Hernández 2015; Plasencia-Lozano 2019). They were similar to the bridge over the Guadiana, although their spans were somewhat shorter: the Aljucén bridge consisted of nine arches, 27 m at each end and seven 32 m central arches.

The two bridges over the Gévora on the outskirts of Badajoz were consecutive. The smaller of the two had three arches and the larger five. The latter received the same length sections as the Aljucén bridge with both having arches 27 m long at the ends and 32.4 m in the center.

The origin of the metal structures is unknown but were probably built by *Parent, Schaken, Caillet et Cie* (Lavado Rodríguez 2015). They were delivered to Lisbon by ship and then taken by train to the construction site.

2.3 *Lifetime and end of the first bridges*

These bridges were put into service in 1863 and met their purpose efficiently for decades. On June 5, 1902, the *Instructions for drafting plans for metal bridges*

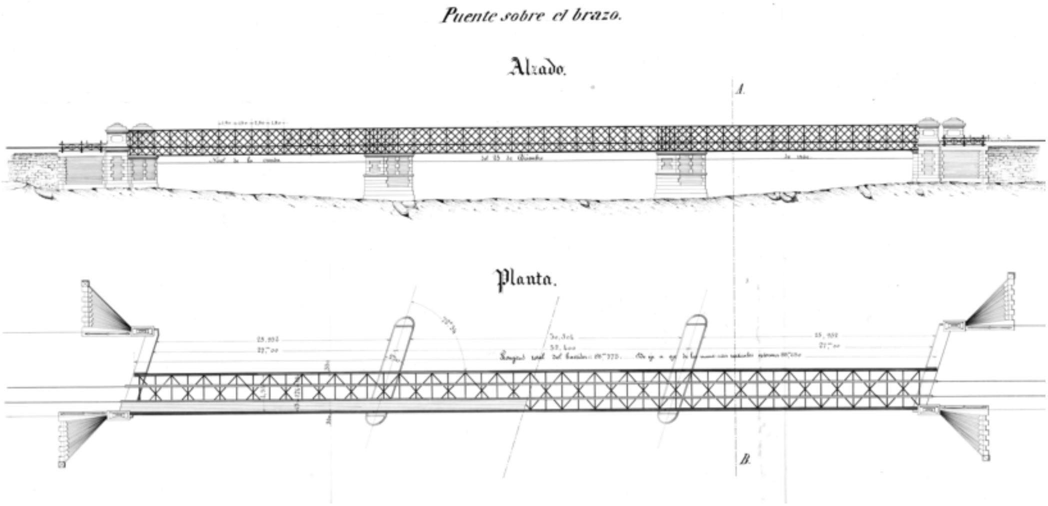

Figure 1. The first bridge on the Gévora river. Piers designed for double tracks (AGA 25-07035).

required that existing metal bridges be subjected to a load test and prior inspection. The bridges on the line were subjected to this inspection and, as a result, it was found necessary to add a series of reinforcements to several of them. Thus, from 1907 to 1909, reinforcements were added to the beam heads and lattice bars in the Zarza, Aljucén and the two Gévora bridges (AHF 0745-002).

In 1925, the new *Instruction for calculating metal sections*, among other measures, prohibited the use of iron as a structural material in bridges, and required biannual inspections of all existing bridges and load tests every ten years. The requirements were considerably stronger in this case and caused some bridges to have to be directly replaced as this was more economical. Such was the case with the Aljucén bridge and the two over the Gévora (AHF-MFM C-0750-001). That is also when the iron sections of the bridge over the Guadiana at Mérida were replaced with new metal sections similar to the previous sections in 1928 (Plasencia-Lozano 2016), or the one over the Guerrero stream, built with a Pratt truss in 1926.

Years later, in August 1956, a new *Instruction for calculating metal sections and predicting the dynamic effects of overloads in reinforced concrete* was published, which again increased the requirements for tolerable deformation under freight trains from those issued in 1925 and required the replacement or reinforcement of those sections that did not comply with this *Instruction*.

3 THE REPLACEMENTS

3.1 *Aljucén Bridge*

Aljucén Bridge did not meet the requirements of the 1925 Instruction and, therefore, its metal sections were replaced with mass-concrete arches according to a project by civil engineer, Rafael Ceballos (Ceballos Pabón 1930).

The structure was located near the Aljucén station. Past the bridge, there was a detour to the branch line to Caceres. However, as transferring that detour from the other side of the bridge to the station itself was of interest to line operations, it was decided that the new bridge should have two tracks: one going directly to Cáceres and the other to Badajoz.

The first action taken was to reinforce the pier footings at both ends as arches of various spans, and therefore with different pressures, met at them. The foundations of the abutments were also reinforced, as was Pier 7. The excavation was done manually and water was pumped out to facilitate the work.

Then the first half of the bridge on the longitudinal axis was executed making use of the existing piers (the width, as mentioned above, was dimensioned to support a double track). Half of each pier was taken apart down to the footings, although the cutwater was kept, and later rebuilt with a new geometry, making use of the existing foundation.

Arch centerings were mounted on provisional concrete supports. They consisted of a triangulated wooden structure to which braces were added, supporting a total of four metal arches, with a series of battens placed over them. A total of five sets of centerings were used for construction. To facilitate mounting, a temporary wooden catwalk was built supported by the lattice girder of the existing bridge as a sort of brace.

Once the arches were concreted, the spandrels were closed off and filled in; the exposed side was closed with ashlars from the piers that had been dismantled and the other side was closed off with a temporary stone masonry wall. After these operations, the track was laid and the first half of the bridge, now completed between both abutments, was opened to traffic. With the new track now in service, the metal bridge was dismantled using a mobile crane. The scrap was removed, and space was thus left for construction of the second half of the bridge in accordance with the same procedure.

This work sequence ensured track service continuity. We would finally note that the construction was executed by employees of the railroad company itself.

3.2 *The Gévora Bridges*

The metal sections of the Gévora I and Gévora II Bridges did not comply with the Instruction of 1925 either so it was decided to replace them with mass-concrete arches similar in length to those already in place, projected by the engineer, Rafael Ceballos (Ceballos Pabón 1931).

The construction procedure was similar to that used for the Aljucén Bridge. Likewise, the construction was also done by the company itself, which allowed them to take advantage of the previous experience acquired, and the centerings for that bridge (used for the Alcazaba Bridge as well) as their spans were very similar.

A work train with a 10-ton crane, which carried materials and auxiliary elements to and from the construction site, served for the construction work. At night, the train was kept in either the Badajoz or Talavera station, and during the day was temporarily left on the track on the bridge. As this track was still in service, a dead-end siding was laid nearby for the work train when a commercial train was passing. This dead-end siding was 600 m long and was connected to the main track at km 505.722 of the line, about 100 m from the Gévora River. The detour had a position signal and Bianchi bolt, and included Bouré locks and keys. For maneuvers, a document was drafted which included management of this siding, including the signals the switchmen should show and the sequence of telephone communications that should be made between this siding and the Badajoz Station. An operator always had to be on duty at the siding.

The timing of work on the bridge was also noteworthy: concreting and decentering took less than 48 days. When the centering was removed from an arch, a telegram was sent. For example, at 1:47 pm on November 13, 1929, the following telegram was sent from Mérida

Figure 3. Aljucén Bridge. Top: soil excavation near the abutments; dismantled pier; rebuilt pier. Middle: centering; frame in the top of the arch; spandrel made of ashlars. Bottom: a train in the first half of the bridge; crane dismantling the metal bridge; new bridge already completed. Photos by Juan Salgado Lancha (AHF-MFM MZA- 0232-IF_10-20-; MZA- 0276-IF_10-23-; MZA-0282-IF_10-23-; MZA- 0284-IF_10-23-; MZA- 0271-IF_10-22-; MZA- 0235-IF_10-20-; MZA- 0241-IF_10-20-, MZA-0250-IF_10-21-; MZA- 0229-IF_10-19-). The collection consists of 64 photographs taken from 29.09.1926 to 05.11.1929.

to Mr. Ceballos, Assistant Engineer for Fixed Materials: “Centering removed from Gévora Arch nine. Nothing new to report.” After removal of the centering, reinforced concrete spandrel walls were built on the arches before the bridge deck was built on top. The design of the spandrels was therefore different from the Aljucén Bridge.

When the new track had been put into service, the metal structure was dismantled. Unlike the previous case, the first structure was moved sideways to temporary supports: in August and September 1929, it was dismantled and taken by train to the Seville and Villaverde Bajo to be scrapped. The metal sections replaced in the first bridge were estimated to weigh 169 tons, and in the second 294 tons, and the scrap was sold for 1.15 Pesetas per kilo.

The whole construction project was executed in 20 months at Gévora II and 14 months at Gévora I (AHF-MFM C-0751-001).

3.3 *Zarza Bridge*

The Zarza Bridge over the Guadiana River was replaced from 1954 to 1958, two years before the 1956 Instruction. The company itself may have been aware that the structure could not support modern rolling stock and decided to go ahead with its replacement before the official regulation required it. We do know, furthermore, that the bridge structure had already been reinforced in 1907 (AHF-MFM C-0742-002) to comply with the 1902 *Instruction*.

This situation shows some similarities as regards the other two: the original bridge piers were wide enough to house a deck for a double track even though only a single track was laid. Therefore, the construction procedure had points in common with those already described.

However, there were also notable differences from the bridges replaced three decades before: the new arches had a different parabola directrix, new intermediate supports were also built between those previously existing in all the bays, except at the Northern end, and the new bridge could take only a single track.

The foundation consisted of a rectangular footing. The first stage of the piers up to the arch springers was built on top in reinforced concrete. These piers were designed with a different geometry from those already there; with a pointed cutwater. In some photographs from 1954, they can be seen emerging from the waters of the Guadiana. The construction must have been interrupted for over a year as there is another photograph from May 1956 in which the bridge still looks the same.

The next stage consisted of formwork and pouring concrete for the arch springers. Formwork was produced with the wooden shuttering supported on the foundation and the first stage of the piers, which stood out from the upper stage. At the same time, the part of the old piers that was going to support the new deck was dismantled down to the foundation as well as half of each abutment. The ashlars in these piers were then reused to cover the new piers and the old modified ones to provide a more uniform look.

The arches were constructed using a set of centerings. These consisted of two semi arches held up by a Warren truss connected at the keystone. Braces were arranged at the base. According to photographs, there were up to four sets so the work would go faster. When the arches were finished, the spandrels, consisting of two outer walls and filling from the quarry, were completed. Last, the deck was completed with concrete slabs on which the ballast and track were laid.

The bridge was built from the two ends toward the center. Thus, in March 1958, it could be observed how on the left side it had progressed to the seventh arch and on the right four arches had been built. We think that the personnel reached the base of the foundations by crossing the Guadiana in carts pulled by donkeys. In the photographs, at least two carts can be seen, and they may possibly also have served to distribute small machinery and utensils during construction.

The new bridge was probably opened in 1959. The metal sections were removed after it was put into service.

Figure 4. Gévora first bridge; temporary supports for metal bridge, first bridge moved; new bridge already completed. Photos by Juan Salgado Lancha (AHF-MFM MZA- 0356-IF_10-28-; MZA- 0366-IF_10-29-; MZA- 0364-IF_10-29-; MZA- 0371-IF_10-29-). The collection consists of 46 photographs taken from 20.06.1928 to 12.06.1930.

4 CONCLUSIONS

The research above enables some conclusions to be reached.

First, this demonstrated the importance of photographs as a documentary source for ascertaining out how construction was done.

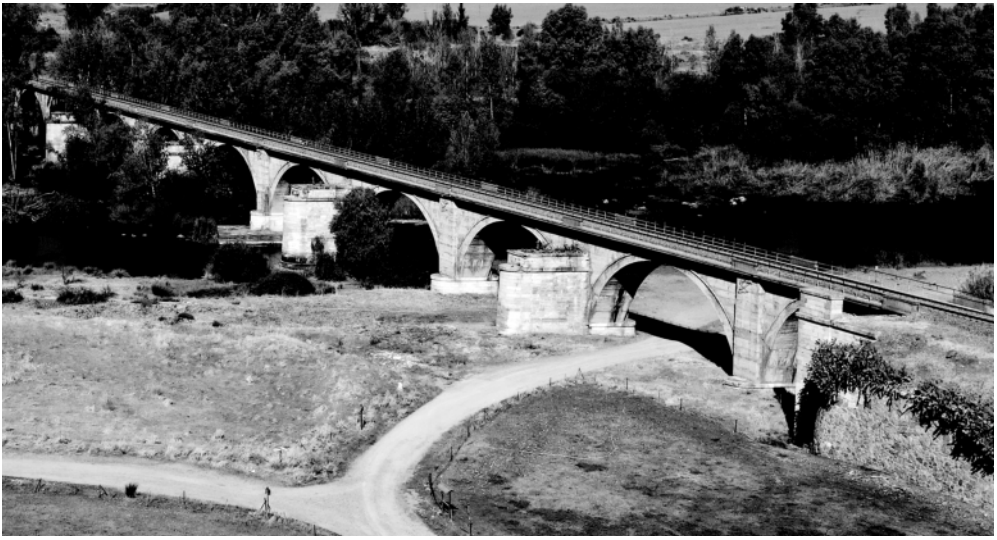

Figure 5. Section of Zarza Bridge, present state. (Photo by Pedro Plasencia-Lozano).

Figure 6. Zarza Bridge. Top: old bridge; execution of the new piers while former piers are being dismantled. Middle: piers already executed; centering. Bottom: groups of centerings; train on the old bridge while the new bridge is under construction. Photos by Vicente Garrido Moreno (AHF-MFM VG-IF- 2229-; VG-IF- 2244-; VG-IF- 2257-; VG-IF- 2256-; VG-IF- 2264-; VG-IF- 2288-). The collection consists of 68 photographs taken from 1954 to 28.03.1958.

Furthermore, the study of three cases enabled similarities and differences to be found. The importance of repeating the structures in a linear infrastructure over the Aljucén and Gévora to save costs was confirmed. However, this repetitiveness of spans did not impede design of distinctive elements in the structures, such as the spandrel.

The 1862 planning of wide piers, able to support two tracks, proved an excellent idea as, although they had no immediate use, they were useful years later when it became necessary to replace the decks. The 1920 bridges were constructed with a view to the future (the Gévora bridges currently have a double-width but only one track); however, by 1954, that future vision had been lost.

Finally, the demolition of the metal structures is to be regretted as their current value as heritage would certainly exceed the price of scrap at the time. Fortunately, current heritage regulations would not allow the same thing to happen again and would require the restoration of such historic structures.

ACKNOWLEDGEMENTS

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The Sant'Elia Kindergarten in Como: Structural behaviour and the issue of durability

A. Greppi & C. Di Biase
Politecnico di Milano, Milan, Italy

ABSTRACT: Giuseppe Terragni's Sant'Elia Kindergarten offers a good opportunity to examine in greater depth the disputed issue of modern buildings' "impermanence". This paper aims to plot the salient phases in the complicated process of the building's construction and to outline the material history of the kindergarten. The reinforced concrete structure of the kindergarten is completed by non-load-bearing walls which define the volumes and interior spaces; however, since construction some of these walls have shown signs of cracking due to land subsidence. These manifestations of structural instability continued over time, making various programs of interventions necessary: demolition and reconstruction of different parts and the repair of the construction framework. The paper will describe the extent and importance of these interventions, suggesting how, though they have apparently not altered the building's form, they have resulted in major changes to its material components.

1 INTRODUCTION

In recent months, the Sant'Elia Kindergarten in Como (1934–37) has once again become the topic of lively public debate. Registered as a Listed Building in 1991, the building is at risk: not only as its continuing function as a kindergarten has been put in doubt, but also because recent work on the structure was suspended soon after it had begun. This interruption of the latest intervention on one of the most famous of Giuseppe Terragni's works recalls various past episodes in the history of the building – episodes which themselves reflect issues regarding the collective use of the structure (and guarantees for the safety and well-being of those using it) and the problems posed by the ageing and obsolescence of 20th-century architecture and its materials.

This paper arises from an on-going PhD research project (Greppi) that examines the architecture of kindergartens built in Italy – and, in particular, the area of Como – in the 1920s and 30s. In this context, the Sant'Elia Kindergarten is a good example of the ideas which inspired the designs of architects who are linked with the "Modern Movement" and Italian Rationalism (Figure 1), illustrating as it does concerns that were recurrent in their work: the definition of a new relationship between internal and external space, and the use of uninterrupted bands of windows to guarantee the largest possible amount of light and air.

In the specific case of kindergartens, there were additional concerns: the need for a building that was "to the measure of children", with reception areas and spaces for learning, play and rest; and particular attention to hygiene and the provision of outdoor recreational areas. As Terragni himself would write: "When adapted to meet such needs, building norms generate an architecture that throws walls open, towards sunshine, greenery, light and nature. The result is a naturalistic architecture that takes its form from Rationalism and its spiritual content from the noble social mission it is to perform (…)" – all of which, he observed, owed a great deal "to the important course of moral regeneration that *Il Duce* has charted out for Our People" (ASCo, 7 March 1935). Furthermore, the achievement of these goals was facilitated by exploiting the discernible potential of new building materials and structural systems, starting with the reinforced concrete structures whose use was becoming ever more widespread.


Figure 1. Sant'Elia Kindergarten after the completion of building work, Archivio Terragni (AT, 43/006/E/S ca.1937).

While over the course of decades Terragni's buildings – and his residential buildings in particular – have suffered extensive loss of fixtures and fittings, replaced during work undertaken by private owners

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(Casanova 2020; Facchi & Greppi 2017), the vicissitudes faced by the Asilo per il Rione Sant'Elia in Como (the Sant'Elia Kindergarten) have been rather different since it has been plagued by structural problems from the very beginning of its existence. It is these issues that the present paper intends to focus upon, particularly with regard to the structural techniques adopted in response to the difficulties posed by the site itself, and the resulting partial instability in the structure. It is true that there have been numerous studies of Terragni's architecture, as well as publications that chart the emergence of the final design for the kindergarten and highlight its significance for the development of the architect's own "poetics" and the history of modern architecture in general. However, these have made little contribution to knowledge of the specific aspects discussed here.

In examining these aspects, the documentation to be found in public and private archives is an essential source of information. In particular, the documents to be found in the municipal archives entitled Asili di Carità per L'infanzia di Como (Kindergartens of the Congregation of Charity Foundations in Como), Lavori Pubblici (Public Works) and the Archivio Terragni itself.

2 FROM DESIGN TO CONSTRUCTION WORK

It was in the late 1920s that the charitable institution the Congregazione di Carità in Como set about looking for a site for the construction of a new kindergarten to serve children from the heavily-populated working-class area in the south-west of the town. Terragni's architectural studio would then become involved in the design of the structure in the early 1930s. However, it was not until 1934 that, after many false starts, a decision was taken to acquire a plot of land between Via dei Mille and Via Alciato (ASCo 23 January 1935); the engineer Attilio Terragni, who as of September 1934 had been the Fascist *podestà* (mayor) of the city of Como, was appointed to design the building. However, it was his brother, Giuseppe, who more directly oversaw all the various phases of the planning phase, drawing upon the principles and forms of modern architecture whilst also taking due account of the 1925 "Norms for the Designing of School Buildings" and the contents of Luigi Secchi's 1927 book *Edifici scolastici italiani primari e secondari* (Primary and Secondary School Buildings in Italy).

The troubled history of the financing for the project – and the repeated demands made by the commissioning client – resulted in Terragni drawing up various versions of the design (Vitale 1996). The first of these (17 September 1934) was presented to the Congregazione di Carità in October 1934; envisaging the presence of three classrooms, it was characterized by a mixed structure to be made of brick-built load-bearing walls with pillars and beams in reinforced concrete. In December of the same year, Terragni would then get rid of a series of features in order to reduce the estimated costs.

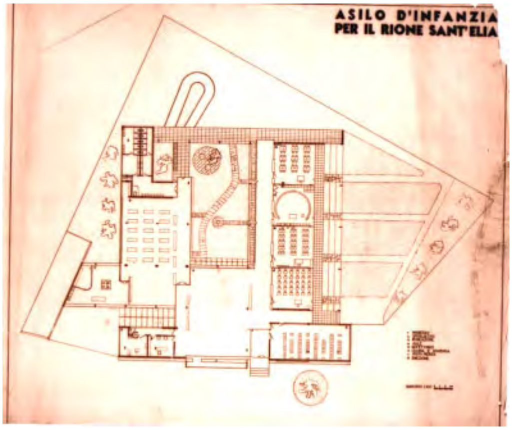

Figure 2. Asilo di infanzia per il Rione Sant'Elia', floorplan of raised level, (AT) 40/063/B1/D/L ca. 1937).

The second version (5 August 1935) is the one whose Project Report is now available in the archives. It envisaged reducing the external height of the building from 5.6 m to 5 m and internal height from 5 to 4.5 m to meet requests for increased capacity; it also added a classroom and a changing room, with the service facilities being relocated and the room for rest-periods being moved to the new attic space. In this version, the weight-bearing structure in reinforced concrete was made up of pillars that, at the foundation level, rested on plinths laid out in a rectangular grid.

In the following months, difficulties in guaranteeing financing led to various solutions being proposed and evaluated. Ultimately, the final version, presented to the Town Council on 10 March 1936, had to make do with the limited financing available. The kindergarten, which Terragni said should house 230 children, was only slightly raised with regard to ground level "in order to reduce the entrance steps to a minimum". The "C"-form layout of the ground plan was rotated with respect to the boundaries of the site in order to make it possible to have different and separate outdoor spaces. The layout along a N.E.-S.W. axis made it possible to locate the classrooms in the south-east of the building so that they overlooked the garden. The cubic volume of each of the rooms was also calculated in order to guarantee "perfect ventilation and natural light" (ASCo 7 March 1935). However, the rest-room dormitory in the attic space was eliminated, as were a number of other features from previous versions of the design; these included the projecting cantilevered canopy at the entrance and the curved ramp linking up to the terrace (this was replaced with a flight of steps). At the same time, the Eraclit sheeting initially intended for the ceilings was replaced with a cheaper "Perret" ceiling; the glass-brick areas of the walls and skylights were reduced by a third; and the use of iron was limited to just the rebars in the reinforced concrete (as required by recent government rulings). In this version there was also no separate service block (Figure 2).

Figure 3. Sant'Elia Kindergarten, worksite with the structures in reinforced concrete completed (AT, 43/004/C/S ca.1936).

Figure 5. The glazing surfaces with their "T"- and "L"-section window-frames, (AT, 43/001/I/S ca.1937).

The structure which determined both the volumetric layout and the architectural composition of the final building – that is, "the network of pillars and beams that form the skeleton of the building, and the roof frame" – were the result of collaboration bet-ween the two Terragni brothers (ASCo 14 August 1935) (Figure 3). Writing in admiration of the final building, Mario Labò would praise "the structure's dynamic elasticity; the pillars seem to be allowed to vibrate" (Labò 1947).

Of all the various problems that arose during the building phase itself, one of the most serious was that posed by the consistency of the terrain, "which was very unsuitable to support such weight burdens". The site was, in fact, in a marshy area that had recently been overlaid with around 3 m of soil. The results of the geotechnical tests carried out (ASCo 20 June 1936) led to the decision to stiffen ground resistance by inserting nine larch-wood piles and "buffers" (thickness approx. 50 cm) made up of compacted rubble beneath each foundation plinth to achieve better distribution of the weight load (Figure 4). Furthermore, the vertical components of the structure were linked by a number of tie beams.

In spite of all these measures, the building would present serious structural problems not long after completion of the roofing (ASCo 23 June 1937). Cracks had begun to appear in the wall along Via Alciato. The cause of the land subsidence was then identified as the changes in the water flow through the terrain resulting from the installation of new drains and culverts, with various solutions to the problem being put forward. These were: reduction of the current weight of the Via Alciato wall through demolition and replacement with hollow bricks (ultimately considered insufficient); widening the base of the foundation in order to better distribute the weight load (but this would not have addressed the issue of lateral shift in the wall); and packing the terrain with wooden piles in order to increase resistance and contain the flow between different strata in the ground. The last of these three was the solution adopted, with the terrain being extensively packed with piles of chestnut wood rather than larch, which was more expensive (ASCo 16 June 1937).

Among the various modifications made during the actual construction work, one was a basement which had not been envisaged in the final version of the

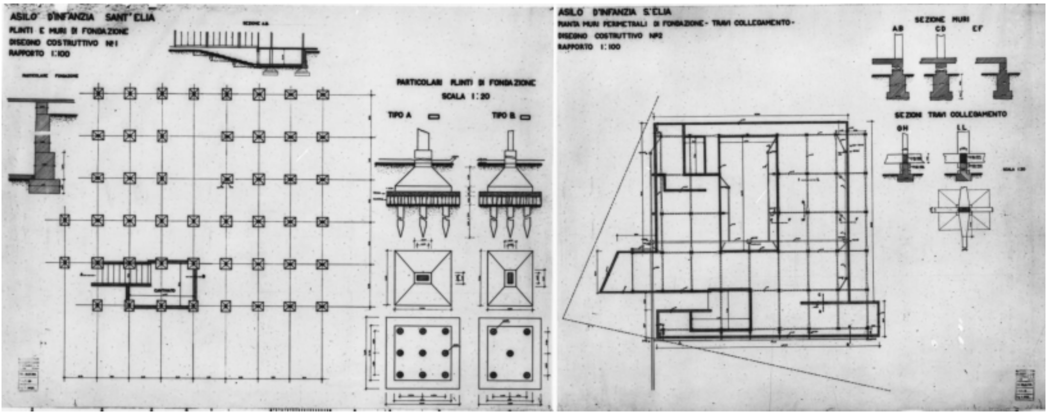

Figure 4. Executive design, foundation plinths and walls (AT, construction drawing n°.1, 14 July 1936, 40/002/E1/D/L); Ground plan of perimeter foundation walls and tie beams (AT, construction drawing n°.2, 23 July 1936, 40/001/E1/D/L).

designs but was necessary to house the heating system; to cover the increased costs of this, the glass-brick areas in the walls and ceilings were eliminated, sun blinds were not installed, and linoleum was only used for the floors in the classrooms and the *ricreatorio* (recreation room). Similarly, the semi-double glazing in the doors was replaced with panes of simple glass (Figure 5) and the accessible area of the external cantilever slab roof was reduced (Vitale 1996).

The kindergarten was certified for public use on 22 December 1937 (ASCo 20 January 1938).

3 STRUCTURAL ISSUES AND SUBSEQUENT PROJECTS (1966–2020)

As with many other buildings designed by Terragni – as well as numerous other works of modern architecture – the kindergarten would suffer because "lack of maintenance over time, and the use made of the building during the war and in the immediate post-war period, led to a rapid decline in the state of the structure" (AT June 1982). In 1963 Como Town Council recognized the need to provide funds for restoration work, which was by then considered indispensable. A study drawn up in 1965 points out sizeable cracking in the north-west and south-west sides of the building, as well as large-scale unevenness in the flooring: "the entire structure's state of preservation is so bad that one can envisage that in no time at all (a few months) the building will no longer be fit for public use. Measures must be taken with the greatest urgency" (ASCo 30 October 1965) (Figure 6). The kindergarten was closed down and, in June 1966, the engineer Alessandro Pedroni was appointed to examine what intervention was necessary to consolidate the building and make it fit-for-purpose once more. The decision to define this whole project as one of *ripristino* (attempting to return the building to its pristine state) was no accident: Pedroni aimed to safeguard Terragni's work by drawing primarily on the original designs – even if, given the current state of the building, this would mean demolishing a large part of the walls and horizontal structures and replacing all the fixtures and furnishings, at a cost that would equal that of constructing an entirely new building.

His project also envisaged the construction of separate premises for the school keeper, in a block alongside the kindergarten – as had been intended in Terragni's original designs. However, once again, it was not possible to construct this separate block, and the solution ultimately adopted would make a decisive change to the distribution of rooms in the north-west wing of the building. The space intended for the school keeper would occupy what had previously been the kitchen, which in turn was transferred to the final bay of the refectory space, with some visual sense of the original size of that dining area being maintained by the use of a partition in glass and iron to define the new kitchen space (ASCo 5 November 1966). Access to the accommodation for the school keeper was obtained by opening a new door in the external wall (AT June 1982).

Figure 6. Diagonal cracks in the wall giving onto Via Alciato due to land subsidence (AT 25 February 1967).

The structures in reinforced concrete turned out to have resisted the passage of time rather well: on-site inspections and tests carried out in May-June 1967 demonstrated there were no permanent deformations or defects. Inevitably, the beams and pillars exposed to the elements showed signs of cracking and spalling, and in these cases the project of "renovation" envisaged the sanding-down of the rebars (to remove the rust caused by corrosion) and the replacement of missing concrete.

On 13 June 1967 direct load-bearing tests were carried out on the double portal that supported the roofing over the entrance area; in particular, these tests focused on the two beams that had two symmetrical diagonal fissures. Similar tests were performed on the cantilevered roof that links the block housing classrooms with stairs leading to the *solarium* (terrace); this structure had been shored up in a rather summary manner by the company responsible for the building's maintenance (Figure 7). The tests showed that the materials were in a good state of preservation and that the reinforced concrete structures "were perfectly suited to bear the loads envisaged by the calculations" (ASCo 24 June 1967).

Though inspired by the best intentions, this "renovation" project – designed by a competent engineer – raised more than a few questions among architects.

When visiting Como to admire Terragni's architecture once again, Luigi Snozzi, Livio Vacchini and Aurelio Galfetti had the chance to see the work in progress on the kindergarten and, on 30 May 1968, would write to Bruno Zevi to complain that "this work of renovation lacks the necessary guidance and over-sight by qualified personnel".

As examples, the Swiss architects mentioned: the metal door- and window-frames used by Terragni were lying around the worksite, and had been replaced by frames in folded sheet metal that had a much larger cross-section and even a different design; the stone-covering at the base of the main entrance wall may have been similar to the original one (which could still

Figure 7. Provisional propping of the external cantilever roof (AT 25 February 1967).

be seen on the back wall) but was finished in an entirely different manner. They also raised doubts with regard to the roof guttering, the parapet of the outside steps, the heating system and the thermal radiators. On the basis of all this, they called for a timely intervention to avoid "damage to a work of such importance, which exemplifies a fundamental moment in the history of modern Italian architecture; a work with which we feel a deep bond (…) We dare to hope that you will take this intervention of ours into due consideration (…) in the hope that one can return the Sant'Elia Kindergarten to being an authentic expression of Terragni's architecture" (ASCo 30 May 1968).

Zevi then forwarded this letter to Luigi Zuccoli, who – together with the architect Emilio Terragni – applied to the Mayor of Como for an assessment of the work being carried out. In reply, the engineer Pedroni stated that he had the greatest respect for the work of Terragni but that "this building is neither a museum nor a listed monument; it is a structure which continues to have a function to fulfil – a function which consists in providing [adequate] school accommodation for around 180 children from the San Rocco neighbourhood" (ASCo 5 August 1968). For example, the young pupils should not have to go on putting up with the freezing temperatures in the classrooms during the winter months – temperatures which were, in part, due to the poor closing of the warped metal window-frames made of simple "T-" or "L"- section components devoid of any seal. The Town Council would then express full support for the work that had been carried out, judging it to "deserve appreciation by all the people of the town for having, without any additional burden to local finances, renovated a work of architecture of the importance of the Sant'Elia kindergarten, which is not subject to the limitations of a listed building" (ASCo 30 August 1968).

However, 10 years later the local press was again drawing public attention to the state of the building: "There is constant deterioration in the condition of the Sant'Elia Kindergarten, a work that not only in Italy but throughout the world stands as one of the most representative achievements of Rationalist archite-cture." On the intervention of the 1960s, the newspaper observed "had not produced the results hoped for" (s.a., La Provincia 23 November 1979).

Figure 8. Worksite during the second restoration project: the reinforced concrete structure with the stairs giving access to the solarium. There is visible non-structural cracking, trickling and staining in the plastering surfaces; spalling of the concrete cover in the pillar's corner; evidence of previous repairs. (AT ca.late 1980s).

By June 1982 the building appeared to be once more in a critical condition, with gaps between the slabs of the flat roof (and subsequent water linkage into the interior) and door- and window-frames again showing signs of corrosion damage. At this point, Giuseppe Terragni's nephews Emilio and Carlo Terragni (an architect and an engineer respectively) were appointed by the Como Town Council to work on the restoration of the building. Their Project Report (AT June 1982) would then describe the current state of the structure and point out that though the extension of the foundations below the level of the walls built in 1968 had limited the movement of the structure, it had not halted it altogether.

Emilio Terragni interpreted restoration as an operation that required a "rigorously philological" approach to the existing building: "It is held that the building over the course of almost half a century has taken on a physiognomy that has become consolidated over the years, and is that which one sees nowadays. It would, therefore, be arbitrary to make additions thereto, even if such spaces might be present in the intentions of the original designer" (AT 1982). Starting from these premises, the restoration envisaged work that fell into one of three categories: re-establishment of the distribution of the internal spaces; structural consolidation; and intervention on the fixtures and fittings (door- and window-frames, flooring, painting).

The internal spaces were returned to their original layout, the accommodation for the school keeper was abolished and the kitchen and refectory were returned to their original size and location.

As for structural consolidation, the subsidence in the site terrain was resolved through "a radical program of packing the ground with wooden piles". At the same time, the work on the roof made it possible to install efficient heat insulation; insulating glass mounted in frames with the same profiles as those used by Giuseppe Terragni led to reduced energy consumption.

Painstaking repair work was carried out on the concrete surfaces (Figure 8) and on the components in reinforced concrete (the projecting entrance structure, the external steps giving access to the terrace, the pillars, etc.). The initial budget for the work of 750 million lire had to be increased by a further 200 million to cover the creation of a crawl space, which was unavoidable in order to guarantee the necessary level of damp control required of buildings for public use (M. 22 August 1987).

With work completed in 1987, the Kindergarten was re-opened and the restoration project was covered in various publications, including *L'Architettura Cronache e Storia* (Marcianò November 1986) and *Recuperare. Edilizia Design Impianti* (Colombo March-April 1988). Then, in March 1988, *Costruire* published an article by Alberto Ferrari entitled "The Work of Giuseppe Terragni: That Kindergarten is a Historic Monument" (Ferrari 1988); in fact, more than 50 years had passed since the creation of the building, so the minimum age required for listing as laid down by the Italian law on protection of the architectural monuments (1089/39) had been reached. Now the kindergarten could be officially recognized as a listed building, with the decree finally being issued on 12 December 1991. The citation stated that this recognition was due "to the valuable typological characteristics of the building. Its substantial significance within the Italian architecture of this century; the importance of its designer, one of the greatest of [modern] architects at both an Italian and international level; the degree with which it is identified with the town of Como itself – all these mean it is of considerable interest as part of our cultural heritage" (ASCo 12 December 1991).

The sequence of work carried out on the building had not, however, alerted the relevant authorities to the damage the lack of maintenance was causing, especially to the more fragile structures. By the end of the 1990s, there was substantial rust damage to the structure supporting the sun blinds, unprotected by weathering; this had been accentuated by the sizeable cross-section of the iron components used, with the usual signs of cracking and spalling. The steps giving access to the terrace showed similar problems; these were so serious that those steps no longer seemed safe so, together with the terrace, they were declared unfit for use. Furthermore, the cantilever roofs did not guarantee adequate run-off of rainwater, and the narrowly-projecting windowsills meant there was water seepage down the walls (Artioli 1999). Once again, in April 1998, the local council turned to Emilio Terragni, who reiterated his philological approach to restoration and requested that preliminary tests be carried out to determine the state of decay in the concrete surfaces and components, suggesting the intervention of "specialists in the field of structures in reinforced concrete" (ASCo April 1998).

Preliminary inspections at last being considered an essential methodological step in any conservation process, a diagnostics survey was initiated in 1999 (ASCo 2 July 1999) in order to evaluate the current state of the materials and the mechanical behaviour of the structures themselves. Tests were carried out on the components in reinforced concrete: sampling to determine the depth of carbonation in the most damaged structures; concrete rebound hammer tests; mapping and testing of the rebars (non-direct tensile test). These tests showed that the concrete used in the pillars was of "medium quality"; hence "for most of the structure, it is not considered necessary to proceed with large concrete repair, except in those places where there is obvious spalling" (ASCo 2 July 1999). Nevertheless, the Director of Works on the project, architect Elisabetta Terragni, believed the structures in reinforced concrete required "more radical structural renovation, due primarily to an accentuation in the process of carbonation and of spalling" (ASCo 15 January 2001).

Meanwhile, the Superintendency for Architectural Heritage laid down that the structural components had to maintain their original size. As a result of this, in accordance with the work done in the 1960s, the project envisaged in-depth removal of the more decayed parts of the structural components, this time using low-pressure water blasting and protective treatment of the iron rebars (judged to be of good quality).

During the progress of work, a part of the structure (to the left of the entrance) exposed further problems: when samples of the concrete cover were removed, the size of the stirrups revealed that it would be impossible to proceed with the installation of a steel grid and new concrete without altering the size of the pillars and beams. The low-pressure water-blasting was, however, carried out on all the external structures, while the iron rebars underwent passivation treatments and the areas of concrete that had come away were fixed. Thus, while there had been relatively little work on the pillars and beams during previous intervention on the building, these parts of the structure now underwent radical and wide-ranging renovation rather than just repair. And it is not difficult to understand why: after in-depth scarification of the pillars supporting the external sun blinds there were certain problems of oscillation in the pillars themselves. Here, Elisabetta Terragni opted for a solution that had previously been suggested by Emilio Terragni: the installation of an electrical mechanism to release and retract the sun blinds so that the structure could withstand the pressure exerted by wind load.

Finally, following the collapse of ceilings in various Italian classrooms, tests were ordered throughout the nation's schools. The examination of the Sant'Elia Kindergartens ceilings – "four tons of materials spread over 1,000 square metres to form a ceiling attached to the floor slab above" (Congregalli 17 June 2019) – produced "non positive results". Hence, it was decided to close the structure yet again, for a sequence of work that also involved intervention on some of the fixtures and fittings.

The work began in September 2019, but the very first measures to sand the window-frames – carried out without due care and attention – caused scratching to the window glass which was visible from the exterior; fortunately, this was noticed immediately and reported, with work on the site then being halted. At this point, a petition with 400 signatures calling for the safeguarding of the Kindergarten was presented to Como Town Council and then forwarded to the Ministry for Cultural Heritage and Activities and for Tourism (Ed. 12 October 2019). In turn, the presidents of the Order of Architects in both Rome and Como wrote to the relevant minister, Dario Franceschini. The local press also got involved in the issue, and *Abitare la Terra* carried an article entitled "An Insult to Terragni. Save the Sant'Elia Kindergarten" (Bernitsa 2019). The restoration work undertaken was judged to be merely "ad hoc", and Paolo Portoghesi was cited when claiming "Terragni's Kindergarten was a building that innovated; its importance lies not only in its form but also – and above all – in the techniques used to create it. Ill-considered alterations could undermine the inestimable value of the structure". Nevertheless, one can no longer deny that the building as it stands is already a palimpsest of superimposed reproductions, which were more or less faithful to the choices and decisions originally made by the great Giuseppe Terragni.

4 CONCLUSIONS

On 14 October 2020, the *Corriere di Como* newspaper published an article entitled "Terragni: A two-speed approach to the Sant'Elia Kindergarten. Tomorrow the new rooms in the Art Gallery open, but the restoration of the building is at a standstill". (Morandotti 14 October 2020). The reference was to the fact that, on the one hand, two rooms in the 20th-century section of the town's Art Gallery were being dedicated to Giuseppe Terragni and his kindergarten, complete with the few surviving original furnishings designed in the 1930s (a few desks, toys, coat rails and lockers for the pupils), while on the other hand work had been suspended on the site of the kindergarten and its future use was a matter of uncertainty. For her part, the architect from the Superintendency for Archaeology, Fine Arts and Landscape responsible for the Como area drew attention to the issue of the link between the building itself and the use for which it was initially designed. True, there had been changes in the design of schools and in the safety requirements imposed on public buildings; however, she argued, one had to recognize the continuing importance of that link.

It has often been said that premature decay in modern architecture results from the "experimental" character of the construction techniques and components used. The truth is that the use of reinforced concrete in building work was already widespread in Europe by the mid-1930s, and was regulated also in Italy by precise government regulations (norms which Terragni's studio would certainly have respected). The disadvantages of the composite material had been known about for some time – and the issue of "durability" was already being discussed in building manuals at the end of the 19th century (Di Biase 2009). However, there was insufficient knowledge regarding the effective durability and behaviour of exposed reinforced concrete. The same was also true of various construction techniques and materials that had perhaps been patented for only a couple of decades or so.

The history of the Sant'Elia Kindergarten is similar to that of a number of iconic buildings dating from the 1920 and 30s. Indeed, given the issues relating to its specific geographical and cultural context, plus the technical difficulties posed by site and building's related instability, it stands as an example from which we can learn. By breaking down the image of a structure which only *appears* to be constant over time, one gets some understanding of the actual substance of the building – something which is essential when reflecting upon the delicate issues raised by the "restoration of the modern" and attempting to develop appropriate solutions to the problems involved. More generally, consideration of the building in terms of the construction process that produced and changed it, of its inherent complexity and fragility, is a step toward proper understanding of issues still unresolved. All of this is necessary to discuss how the building can endure over time, and what function it will perform as it does so.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The innovative application of the curtain wall in the Galfa Tower

C. Costantino, A. C. Benedetti, C. Mazzoli & R. Gulli
Alma Mater Studiorum – Università di Bologna, Bologna, Italy

ABSTRACT: In the US, after the Second World War, buildings' outer shells made of glass and steel were the result of highly specialised technical processes and industrialization in compliance with the requirement framework of the emerging use of the business centre. In Italy, however, the curtain wall would not be used before the end of the 1950s. The Galfa Tower (102.37 m high), was built during this period in Milan, and was designed by Melchiorre Bega. Every component of the project (façade, plan, internal arrangements, load-bearing structure) was defined by a precise rule referring to modularity, but different criteria were used to offer space adaptability and flexibility. The study about curtain wall evolution and Galfa Tower highlights the innovative application of this technological solution in this representative Italian building, in terms of architectural composition together with the refurbishment necessity to ensure the contemporary use while respecting the original language.

1 INTRODUCTION

1.1 *The curtain wall overseas*

The curtain wall is the expression of the long evolution of windows over time. In fact, during the 19th century, the construction of tall buildings with reinforced concrete or steel structure responded to the emerging interest in reducing both soil occupation and load bearing foundations. Also, the great progress in steel and glass manufacturing techniques, the dissemination of processes of industrialization, and the development of new "office blocks" had a significant role in the definition of outer glass envelopes. In fact, the production of large glass panels that progressively occupy the totality of the surface among the structural elements, was the result of technological innovation. At the same time, they addressed health issues by ensuring respect of natural lighting and ventilation standards. These new high buildings required high internal space adaptability and reversibility to meet changing needs and did not have a specific function. The structure and external surface were the only elements to be designed.

In the US, there are examples of progressive formalization of curtain wall systems between the late 19th-century and the early-20th century. For instance, in the Second Leiter Building (1891) by Jenney, the traditional hung sash window had been replaced by the "Chicago window", the tripartite window where the central panel cannot be opened, while the lateral windows provide for fresh air and lighting; this is clearly recognisable in the Carson, Pirie, Scott and Company Building (1899–1904) by Sullivan. During the first half of the 20th century, before the Second World War, the interest in internal and external space relationship grewprogressively, and some early relevant examples of uninterrupted glazed shells can be found, e.g. in the sketches for a skyscraper in Berlin (1921) by Mies van der Rohe, in the Empire State Building (1930) by Lamb and Harmonn, and, in Italy, in the Olivetti ICO Centrale building (1935) by Figini and Pollini. At that time, the application of the glazed envelope introduced the issue of indoor comfort: huge glass panels, which can be partially opened but with no solar shadings, causing significant overheating problems. Many protection systems from solar irradiance were later developed, such as the *brise-soleil* by Le Corbusier. Finally, from the second half of the 20th century, the curtain wall became a product of industrialization. These were manufactured by companies able to realise highly specialised solutions (Croce & Poli 2013). Mies van der Rohe had a very important role in the definition of the curtain wall system. In his opinion, the application of the industrial production concept to architecture brings high-quality results in terms of production information, avoiding the negative standardization of solutions and implementing the creative idea at the root of architectural design. Thanks to the strong connection between architecture and technology, Mies van der Rohe used, for the first time, the external glass envelope attached to the load bearing structure in the Commonwealth Promenade apartment building (1953–56). The pillars are not visible on the main fronts, so that the rhythm and the compositional scheme of the façades is clearly defined by the vertical mullions of the window frames, which are only interrupted by floors: here it is the curtain wall (Romanelli & Scapaccino 1979).

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1.2 *Curtain wall production in Italy*

The development of curtain wall systems in Italy is very dissimilar to the international scenario. In fact, the first innovative experimentations started in the 1950s. Growing business centres expressed their identity with “office blocks”, the representative building of companies in terms of production, progress and economic power and availability. Together with symbolic aspects, these constructions had to meet specific requirements: well-lit spaces and flexible internal arrangements. The volumetric shape did not relate to a specific function. The leading design elements were the maximum exploitation of intervention areas, in line with regulatory standards, and the greatest freedom in space distribution. In this regard, the load-bearing structure is “a grid with the unique intention of ensuring the minimum number of rules and ties” (“*una maglia, con l’unico intento che essa “leghi” il meno possibile*”). The curtain wall follows a simple scheme: highly specialised firms are responsible for deepening technical and quantitative issues in accordance with the architects involved in the project, then they elaborate the specific construction solution and directly carry out the work (Romanelli & Scapaccino 1979). Thus, many glass and opaque panels have been progressively defined to be universally applicable to both steel and reinforced concrete structures by means of special components and respecting the same modularity in structural and window frames. In this context, companies gradually increased their role and influence in the construction process as they directly studied and assembled curtain wall panels, defining the finishing and the connection with load-bearing structures. At the same time, a mutual interdependent relationship between architects and companies became more relevant.

In Italy, in the post-World War II period, many examples of curtain wall application have been realised by large, distinguished Italian companies, such as Curtisa (Bologna, Figure 1), Feal (Rome), F.lli Greppi (Milan) and Alsco Malugani (Milan). These construction firms completed many buildings including Palazzo Olivetti (1954) and the Pirelli offices (1956) in Milan, Palazzo Fassio (1958) in Genoa and the RAI-TV offices (1964) in Rome by Curtisa; the Via Torino office building (1958) and the Casaccia nuclear power station (1961) in Rome, and Palazzo del Lavoro (1961) in Turin by Feal; Palazzo E.N.I. (1957) in San Donato Milanese and Galfa Tower (1959) in Milan by F.lli Greppi; the S.G.P.E. building (1967) in Bari, the Banca Popolare di Novara building (1962) in Genoa and the Uffici Tecnici building (1967) in Milan by Alsco Malugani.

2 ARCHITECT MELCHIORRE BEGA

Architect Melchiorre Bega is considered an example of great professionalism in the Italian and Milanese architectural scenario during the second half of the 20th century (Zironi 1983). His professional activity can be divided into two significant periods, interrupted by the Second World War. There was a first period of study and training at the *Belle Arti* Academy in Bologna, with intensive work at his father’s factory, Vittorio Bega & figli, producing furniture and other interior elements, and a second period in Milan (Greco 2012). In fact, the company was very active in Milan and Bega progressively became close to the city and to its rich cultural context and finally, following the Second World War, he transferred his professional office there. During the first half of the 20th century, many Italian industrial excellences stood out, and great businessmen promoted significant architectural interventions in Italy and around the world. In Milan, the main clients were from the “business-oriented” bourgeois class that promoted the dissemination of a new, modern avant-garde style and used their works to express a desire of internationalization and “deprovincialization” (Canella 2010). From the 1930s, Bega’s first activities were strictly linked to two big Italian companies, Motta and Perugina, that ordered the realization of shops, patisseries, cafés, and exhibition pavilions in many Italian cities. In these projects, interior design and furniture embodied the idea of modern. In Italy, as a consequence of Post-WWII reconstruction and the booming economy, the interest in prefabrication and industrialization of the construction sector gradually increased, together with the development of business centres. Therefore, the second period of Bega’s activity

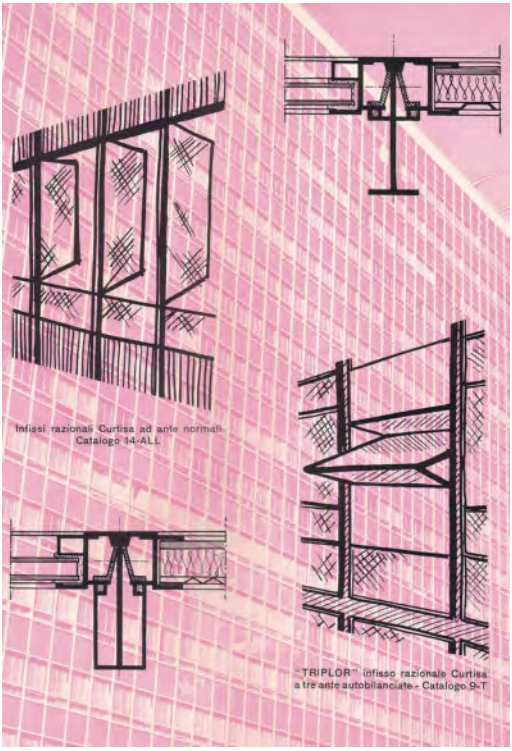


Figure 1. Examples of the application of *Curtisa* window frames to the curtain wall system (source: *Curtisa* catalogue).

was influenced by this new cultural context, marked by the consolidation of the relationship between industrialists and designers, and it is characterised by a growing interest in tall buildings, searching for essentiality shapes and looking at an international scenario for inspiration with the main objectives to respect the existing context and to enhance the image of the modern city. In fact, during the ‘60s, the creation of a business centre, where the typical, modern-city services and offices are situated, became an urgent necessity. The Milanese skyscrapers of that period looked at American culture in terms of high construction, but they did not follow the maximum building usage allowed by the regulatory framework or planning restrictions. This trend can be defined as “Manhattanism” (Bono & Vercelloni 1979) as it refers to the US model, despite the Milanese situation being rather different than the New York one. In fact, the Milanese approach took some elements from International Style, but, at the same time, it recognised the pressing importance of construction traditions and historical events of the city. In this perspective, studies and projects for the urban management plan (“*Piano Regolatore Generale*”) promoted the same guidelines aimed at the transformation of the historical centre into a new business centre while respecting the existing context.

Bega is one of the architects who actively participated in post-war reconstruction, and, in the period of 1956–64, he designed a significant number of buildings for the new Milanese business centre, i.e. the Galfa skyscraper, the Stipel building, some buildings for Milano Fiera, the Reader’s Digest building, the Aerhotel and the office location for African countries. His activity gradually extended to the totality of Italian territory: he realised the SIP skyscrapers in Genoa, in collaboration with the architects Gambacciani and Viziano; the building for the Italian-Latin American Institute in Rome; San Giovanni Battista Church, some large hotel complexes, the Congress Palace in Bologna, as well as some motorway restaurants on the A1 and A4 highways (Pascucci 1974).

Moreover, Bega’s activity opened to the international scene: he realised the skyscraper for the Axel Springer publishing house (Figure 2) in West Berlin, in collaboration with the architects Heinrich Sobotka, Gustavo Muller, and Gino and Tommaso Franzi. This glass tower in the heart of the city became one of the most significant buildings at the international level, in particular, as an expression of political values: the glazed construction is clearly the opposite of the thick separation wall between West and East Berlin, because of the visible “reflections of façades with the sky entering all over the place” (*riflessi di facciate in cui il cielo entrava da tutte le parti*, Zironi 1983). The building was designed in 1956 and built in 1966, and the glazed façades of the 18-storey building follow a bipartite module with light variations. On the last two levels, the vertical mullions are uninterrupted up to the roof without any horizontal elements. Bega’s research activities on tall buildings was connected to the study and use of highly specialised techniques of the International Style. However, for the design of facades, the aspects related to architectural composition always had a more relevant role than the requirements related to industrialization.

Figure 2. Curtain wall façade of the Axel Springer skyscraper (source:https://it.m.wikipedia.org/wiki/File:Berlin,_Kreuzberg,_Axel-Springer-Strasse_56,_Axel-Springer-Hochhaus_01.jpg).

The architect designed two other skyscrapers in Milan between 1958 and 1964, the Grattacielo a cuspide and Domus Omnium, but these were not built due to the many difficulties related to planning regulations and execution. The Cuspid Skyscraper was to be 185 metres high and it would have been built on land owned by Attilio Monti, the same client of the Galfa Tower. This building was conceived as a symbol of the City and a declaration of modernity: a unique parallelepiped without basement volumes and with the tripartite division of the building envelope in accordance with International Style. The Domus Omnium refers to a slab skyscraper model, with a lower central volume adjacent to a 90-metre tower and a tripartite outer shell, with one glass panel and two opaque panels. (Greco 2012).

3 GALFA TOWER

3.1 *The Galfa Tower project by Melchiorre Bega*

Galfa Tower is situated in the Milan business district, north of the historical centre, a few steps from the central railway station. Located on the corner of Via Galvani and Via Fara, the iconic name “Galfa”, which identifies the tower, comes from the union of the first letters of these two street names (Gal-Fa). Since its creation, minimalism has been a distinctive feature of this building, in its structure, internal distribution and the external volume. Both Italian and international critics have classified the skyscraper as one of the most important Milanese vertical structures, together with Velasca Tower by the BBPR studio, Pirelli Tower by Gio Ponti and Breda Tower by Eugenio and Ermenegildo Soncini and Luigi Mattioni (Zironi 1983). "This is the most simple and chaste of Milan skyscrapers. It neither wants to show technological solutions nor gimmicks, nor does it aim to astound…The credit of this success belongs to the author who has been able to concentrate his dedication to seeking the most essential values, neglecting any superfluous complacency, any exercises" (*Dei grattacieli di Milano questo è il più casto. Non vuole esibire invenzioni o trovate, né mira a sbalordire…sicuro merito dell'autore, che ha saputo concentrare il proprio impegno nella ricerca dei valori più essenziali, trascurando ogni compiacimento superfluo, ogni esercitazione,* Vaccaro 1959). Indeed, the purity and the "perfect proportion of volumes" are enhanced by the double order of mullions that form the curtain wall (Figure 3). The façades, therefore, reach to thirty floors "in a simplicity of lines whose vertical structural origin is expressed with wisdom and truth, with classicism" (*in una semplicità di linee la cui ascendenza strutturale è espressa con sapienza e verità, con classicità,* Ponti 1961).

Built between 1956 and 1959, the skyscraper was the headquarters of Italian British Petroleum and SAROM (*Società Anonima Raffinazione Olii Minerali*), one the most important Italian oil refining companies at the time, founded in 1950 by Attilio Monti (Cingolani 1990).

The tower became the symbol of the Milanese economic miracle, together with the other buildings of the business district (Bono & Vercelloni 1979), and it also represented the company's success. In fact, its International style was wisely used to enhance the grandeur of the property.

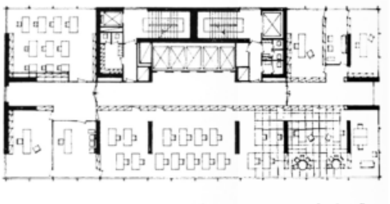
The building is made of two volumes, a two-storey lower body and a 102.37 m high tower, and glass and aluminium curtain wall façades are installed on a reinforced concrete structure (Diamant-Berger 1959).

The skyscraper is located in a 2,690 m^2 irregularly shaped site (Figure 4), with two underground floors with garages and machine rooms. At the ground level, the smaller dimension of the T-shaped plan offers space for gardens and parking. Then, the remaining 28 floors have a rectangular plan of 49.63 m × 10.70 m (Grandi & Pracchi 1980). Inside, the ground floor hosted a bank, exhibition halls, a mechanographic centre, and a projection room, while on the upper floors there were company offices, executive offices, and meeting rooms (Domus 1958).

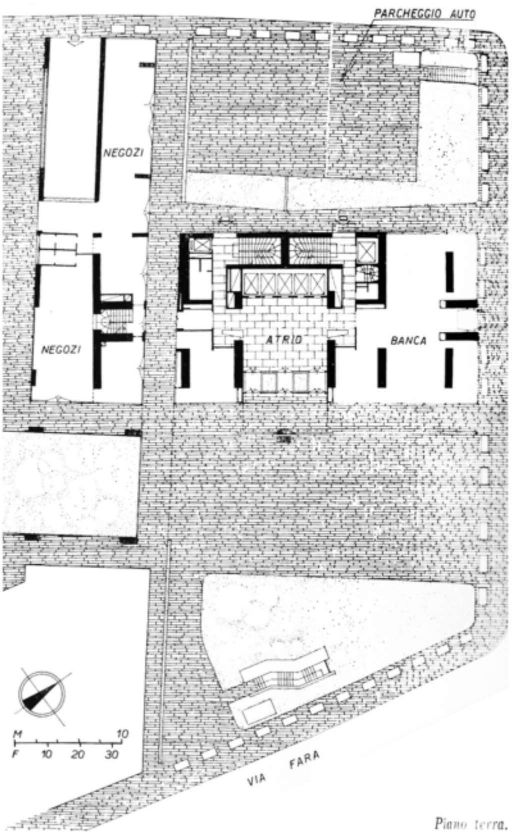
Following the latest trends in terms of functionality and comfort, the offices were organised in flexible and adaptable open spaces, despite their different dimensions depending on the structural grid (Gramigna & Mazza 2001). Furthermore, even the inner walls that separate the large, open office spaces from the corridors were prefabricated and removable. Based on a module of 80 cm, which was also the size of internal doors, the partitions were made with duralumin studs and three typologies of panels: entirely glazed, glazed with an opaque base panel, or entirely opaque with glazed fanlight (Greco 2012). The office surface floor was made with plastic material laid on fibre glass panels, on a concrete screed containing electrical plants (Vaccaro 1959). Designed and produced by the Bega family factory, all the wood furniture consisted of sophisticated pieces characterised by an essential and modern line, suitable for an international company.

Figure 3. Main façade of Galfa Tower from Via Galvani (source: Vitrum, lastre di vetro e cristallo, n. 116, 1959).

The tower is made of reinforced in-situ concrete. The tower structure consists of a large core, which



Piano tipo con esempio di sistemazione degli uffici.



Piano terra.

Figure 4. Typical floor plan and ground floor plan (source: Vitrum, lastre di vetro e cristallo, n. 116, 1959).

occupies more than a quarter of the back façade, and six inner shear walls called "*quinte*". The concrete core is used for staircases and elevators, and its main function is to reduce the lateral displacement providing bending and torsional resistance, while the rest of the structure consists of reinforced concrete and beam-and-block floor systems. The length of these elements is variable between 3.90 m and 9.70 m while the span varies up to 8.50 m. Structurally, the shear walls perform like cantilever elements under lateral forces; therefore, their plane section gradually slims down until dividing into two different pillars towards the top floors. This structural behaviour is particularly suitable for high-rise buildings, solving the bracing problems. The walls are connected to the foundation by two slabs of 0.60 m and 0.70 m, reinforced with a grid made of 2.00 m high cross beams (Greco 2012). In the Italian context, this kind of solution had already been tested by the engineer Arturo Danusso in the Velasca Tower and the Pirelli skyscraper, inspired by the Executive House in Chicago, designed by Milton N. Schwartz, the tallest reinforced concrete construction in the United States at the time (Mornati & Greco 2015). In 1957, the structure was tested at the *Istituto Sperimentale Modelli e Strutture di Bergamo,* whose director was Danusso himself, using a 1:5 scale model. Indeed, the irregularities of spans and wide overhangs required an experimental model to evaluate stability and deformations (Mornati & Greco 2015).

The architect, as the owner of a furniture company in Bologna, had always thought that industrialization was the natural evolution of handcraft production without resulting in the loss of detailed accuracy or material quality (Zironi 1983). The tower is organised on a 75 cm square grid, respected in both the plans and curtain wall structure, and industrialization was a key element of the building. Despite the systematic use of prefabricated elements, the façades never result in negative standardization. In fact, using a single type of curtain wall panel (Figure 5), divided into six parts, and common compositional rules between them and the shear walls, Bega designed four different elevations. These were divided into three parts, offering a new interpretation of the classical subdivision in base, main body, and the top part: the base was disconnected from the central body by a space of 0.60 m; the middle part developed identical up to the last level that was formed by a VIS crystal terrace banister, and covered with a canopy. Furthermore, the shear walls were moved back from the façade line of 2.50 m so that external surfaces were free and could be covered with aluminium-framed glass curtain walls. The "*quinte*" were laid out in an orderly grid pattern, but neither the symmetry nor the distance between them were respected, and they defined the elevations design by changing the ratio between opaque and transparent surfaces in each façade. The main south-west elevation appears as a unique glazed façade; on the north-east front, the connection core is identified by a large opaque portion; in the south-east façade the shear walls are arranged longitudinally while they are transversely arranged in the north-west elevation.

The uninterrupted glass corners (Figure 6) provided elegance and formal purity to the headquarter in such a way that some critics of the time considered that "there is no other example of a building in the world in which the development of the glass façade has the continuity of this one" (*non vi sia nel mondo un altro esempio di fabbricato in cui lo sviluppo delle pareti vetrate abbia la continuità di questo,* Vitrum 1959).

Curtain wall windows, prefabricated by Fratelli Greppi di Donato, were attached on duralumin mullions, a metal alloy composed of aluminum, copper, manganese and magnesium with excellent extrusion behavior, high durability and great resistance. Window panes were made with 11,000 m^2 of "Thermopane" glass produced by the company, V.I.S. – Vetro Italiano

Figure 5. The curtain wall with Pirelli Tower in the background (source: Vitrum, lastre di vetro e cristallo, n. 116, 1959).

Figure 6. The offices and the integrated plants of the curtain wall (source: Vitrum, lastre di vetro e cristallo, n. 116, 1959).

di Sicurezza, achieving the European record for the largest glass surface in a single building (Greco 2012). The gap between glass panels was filled with dry air in order to ensure high levels of insulation and noise reduction. The curtain wall element was divided into six parts and only the larger central one could be opened; it was realised with two orders of duralumin elements: the first one was made of silver opening window frames which were not aligned with the second one of dark colour, whose elements run vertically along the entire façades. In fact, this solution made it possible to obtain an entirely glazed envelope, from the floor to the ceiling.

Furthermore, the air conditioning channels, the heat pipes, and Venetian blinds were placed within a cavity in the depth between the curtain walls and the concrete slab in order to not interfere with elevation continuity.

Therefore, the integration between structure, facilities, and curtain walls had a double purpose: to ensure the best conditions of indoor comfort in the offices and to emphasise the purity and essentiality of the architectural language defined by the design of the window frame composition, in particular at the building corners where the alignment of the mullions highlights the tower's verticality. The execution of the steel-glass outer shells was the result of the close collaboration between Melchiorre Bega and the engineer, Greppi, the producer of the curtain wall façades. Highly specialised modular processing techniques, characterised by the use of traditional building materials, such as steel and glass, were employed to align the architectural needs to the functional ones. These solutions constituted a novelty in Italy at the time, where the building sector was still largely dominated by traditional techniques which were not suitable for the extreme precision imposed by the systematic use of prefabricated curtain wall elements. Furthermore, in the case of Galfa Tower, the dialogue between designers, producers and contractors led to an innovative application of this technological solution in order to respond to both the compositional needs and to the functional aspects. In this way, the technological element became the main architectonic characteristic of the tower.

3.2 *The restoration project*

The Galfa Tower was the SAROM headquarters until 1980 when it was sold to the Banca Popolare di Milano due to the financial difficulties of Attilio Monti's company which began with the 1970's oil crisis. Thanks to the inner space flexibility, the building has not really changed during these years and works have only concerned the adaptation to fire-safety frameworks and the installastin of new chimneys. The building was the bank's headquarters from 1980 to 2006 when Banca Popolare di Milano sold the skyscraper to the real estate company, Società Immobiliare Lombardia, a subsidiary of the Fondiaria Sai Group, today Unipol-Sai, the current owner. Some interior works have been carried out in these years such as the renovation of the entrance hall, the refurbishment of existing spaces and the creation of a company canteen. After the sale in 2006, the building was abandoned and, in May 2012, occupied by students and local artists to create an arts centre named MACAO. On 29 April 2015, the renovation project designed by Milanese studio, BG&K Associati, got off the ground.

The key topic of this kind of project is to preserve the industrial identity of the building, consisting mainly of the curtain wall façades. The intervention was more or less invasive on the basis of the curtain wall conditions and the energy-consumption achievement: adaptation of some components, such as panes or seals; renewal of single parts without changing others; and complete replacement of technological elements preserving only the architectural language. Frequently, in this type of intervention, glass panels are not considered as a material to preserve but only as one of the most important factors influencing energy consumption (Del Curto & Stanga 2019). Nevertheless, replacing the original envelope was generally necessary due to the presence of both degradation and wear of surfaces and in order to ensure current standards of internal comfort and low energy consumption. Indeed, the curtain wall restoration usually presents significant technical and financial difficulties, especially when experimental solutions or materials with different life cycles among them have been employed (Greco 2012). Moreover, other factors, such as the lack of documentation and the necessary adaptation of industrial elements to traditional construction techniques, should be considered to get an overall picture of the issue. Like other International Style buildings, the Galfa Tower is not protected by the Superintendence of Archaeology, Fine Arts and Landscape for the Metropolitan City of Milan. Only the drawings by Melchiorre Bega are now available while the executive drawings of the company have been lost.

The renovation project of Galfa Tower has been designed by Milanese studio BG&K Associati. The floors are not tall enough to contain offices according to the new regulatory framework (Bolognesi 2017). Consequently, new life has been given to the building, transforming the internal function from office to mixed-use: from the basement to the 13th floor, there is a hotel with 146 rooms, restaurants, meeting rooms and fitness rooms, while from the 13th to the 28th floors there are private residences of different sizes and types. The project gives a renovated aspect to the building: on Via Galvani, a crystal cube reflected in the surrounding water mirrors and defines the entrance to the hotel, restaurant, and commercial area. Meanwhile, on Via Campanini, there are the entrances to the residences, located in a hypogeum meeting space characterised by marble seats and bushes. Furthermore, the building shape has been modified by the addition of a new technical volume, containing new staircases, panoramic lifts, and vertical escalators. This transparent glass and steel volume are placed against the opaque wall of the north-east elevation and makes it possible to satisfy the current fire and safety regulations and the removal of architectural barriers. This consequently made it possible to free the terrace from the technical rooms and to create a panoramic restaurant on the 29th and 30th floors, taking on an idea that had originally been considered in the original project but precluded due to regulatory and technical needs at that time (*Corriere della Sera* 1959). The mechanical systems were decentralised in the underground floors: a water loop heat pump (WLHP) supplies the VRF units which in turn supply the hotel rooms and the private residences. In addition, to provide better management and modularity of the system, sub-plants for each storey have been created. Moreover, the solar installation on the roof will provide green electricity to the building. From a structural point of view, seismic improvement of the existing structure was carried out, reinforcing the shear walls, while the new staircase volume is structurally independent (Colombo 2018). The main design challenge is related to the renovation of the curtain wall. The replacement of original windows with new triple glazing, made with anodised aluminium profiles, was necessary to achieve the A energy efficiency classification. However, a steel beam, connected transversely to the reinforced concrete overhangs, was necessary due to the greater weight of the new prefabricated windows (Modulo 2018). The original drawing of the curtain wall, on the other hand, is preserved, thus maintaining one of the main landmarks of Milan’s economic miracle intact.

4 CONCLUSIONS

The language of International Style became the symbol of the economic miracle in the years of the post-World War II reconstruction. Indeed, as a modern icon for offices and headquarters, the curtain wall quickly became a widespread system during the late 1950s in Italy. Furthermore, the flexibility and ease of assembly on framed structures made this technology the ideal solution for new functional and image needs.

The production of prefabricated curtain walls made with lightweight materials constitutes one of the first successful attempts to industrialise the building sector in Italy. Consequently, many companies, such as Fratelli Greppi di Donato who made the curtain wall of Galfa Tower, operated in this field. The building designed by Melchiorre Bega fits perfectly within the cultural context of Milan, one of Italy’s most important cultural, media, and economic centres at the time. The pure volume and the essentiality of the elevations define the Galfa Tower as one of the most significant examples of curtain-wall application in Italy. Indeed, behind the apparent simplicity of the façades, the project hides a meticulous study to always obtain different elevations but without neglecting the main front. The curtain wall elements, divided into six parts, were not aligned in order to break the symmetry among them, maintaining, however, a perfect uniformity in the envelope. Furthermore, this element plays a double role in the building: functional on one hand, as a vertical closure and part of the plant system; while on the other hand, it became the central element of the architectural language and composition. Intervening on this building, about 60 years after its construction represents a considerable challenge. Unfortunately, as is often the case in similar situations, it was necessary to replace the original curtain walls with a more performing envelope to reduce energy consumption and improve indoor comfort. However, the original drawing has been respected, preserving the architectural language. Consequently, new life was given to this building, an icon of the era and the city, that reflects the idea of the architect who saw perfectly proportioned volumes and sober language as symbolic of the new Italy that was being built.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Masonry and its role in the mid-20th century: G area houses in the Le Vallette district of Turin

M.L. Barelli & C. Tocci
Politecnico di Torino, Turin, Italy

ABSTRACT: The paper focuses on the housing complex designed by A. Cavallari Murat and the younger R. Gabetti, A. Isola and G. Raineri (1958–69) for the Ina-Casa public housing district of Le Vallette in Turin. The load-bearing masonry structure initially adopted by the designers, with upward tapered pillars projecting from the façades (a solution which seems to be reminiscent of the work of Alessandro Antonelli), was abandoned during the construction phase in favour of a reinforced concrete one. If this choice had no consequences as regards architectural image, it triggered a process of technological re-elaboration which is interesting to analyze in terms of the various solutions adopted by the four construction companies involved, as concerns both the organization of the load-bearing structure and its relationships with brick cavity walls.

1 INTRODUCTION

The great public housing neighbourhood of Le Vallette was built in Turin, Italy, on the extreme north-west city limits, between the second half of the 1950s and the 1960s. Within it, the residential complex of the area known as “zone G”, designed by A. Cavallari-Murat and the younger R. Gabetti, A. Isola and G. Raineri, represents a significant example of the ways the technical aspects of construction were interpreted by some of the protagonists of Italian architecture from the 1950s onwards. It is also a “definitive” example of the transition of masonry from load-bearing to non-bearing, also in the context of the Ina Casa Turin experience.

In contrast with the setup of the neighbourhood’s organic urban plan, the architects organized the area available around large courts, “something between a farmyard and a city courtyard”, as they underlined in the report published in the magazine *Casabella-Continuità* (1962) to evoke perhaps one of the most evident traits of the design: its reference, among other things, to rural architecture. The general system is based upon a distribution lay-out that combines buildings and makes them function as a coherent whole, whilst offering people who would find themselves living close to one another the opportunities to meet and socialize. The frontal H-shaped buildings, boasting five storeys above ground (six on the side facing the courts, and coupled two-by-two by one-floor above-ground wings), are connected to the long low-rise (three to four floors) internal slab blocks, and the latter, by means of a path overlooking the courts, are positioned over a thin ring-shaped portico. Never built, the portico was conceived to outline a wide play area and to funnel the flow of pedestrians reaching the homes from the centre of the neighbourhood, and vice versa. Three more H-shaped buildings complete the organization of this part of the neighbourhood (Figure 1).

But the aesthetic strength of these houses is, along with the richness of morphological-spatial and distribution solutions, related especially, in the design delivered to and approved by the municipality in 1958, to the unique masonry system of the load-bearing structure, with pillars projecting from the façade and tapered upwards, a system which, in the finished version of the project, was destined to survive only as a simulacrum (Figure 2). In fact, when the construction site was opened (1959), the construction company that won the tender to build the entire complex proposed the adoption of a fully reinforced concrete structure, which was approved. The events that followed underwent a long and rough realization process. In 1960, the building company went bankrupt. A succession of trusted companies was selected by the commissioning institution (IACP – Istituto Auto-nomo Case Popolari, an independent institution for public housing in Turin) to complete a first lot of buildings and, only several years later, in 1966, were three new sites opened to finalize the construction of this part of the neighbourhood (1969), which, nevertheless, would remain partially unfinished.

The reconstruction of the design and building process is the result of research undertaken at the National Archive of Turin (AST, 1; AST, 2; AST, 3) and the ATC (formerly IACP), the local housing agency of Turin (ATC, 1; ATC, 5735; ATC, 14563; ATC, 19447), and a comparison between what gradually emerged from this research and the tangible reality of the buildings.

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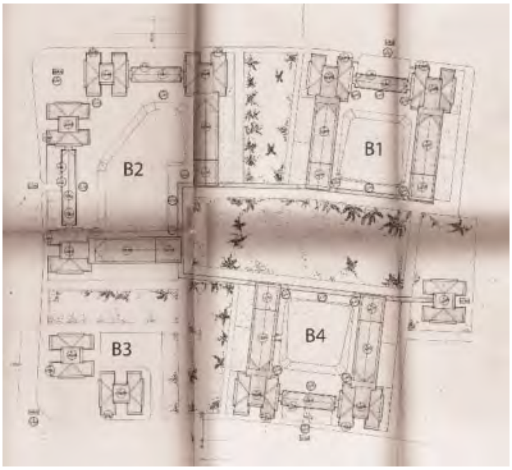

Figure 1. Le Vallette, general plan of the zone G (1:500) (ATC, 14563). Blocks numbering (B1, B2, B3, B4) is referred to in §3.

2 A MASONRY DESIGN

In 1958, the project for zone G houses, developed in the context of the Ina Casa plan, was delivered to the municipality. The plan, as is well-known, was aimed to promote construction methods with low mechanization and high manual labour demand (Poretti 2008), and suggested the adoption of a masonry load-bearing structure for lower buildings, two/three floors above ground, highlighting its low cost-effectiveness for higher ones, starting at a height of five or six floors above ground, exactly what was envisaged for the front buildings of zone G.

Indeed, for the Le Vallette housing complex, the choice of load-bearing masonry seems to respond to greater requirements than simple compliance with the traditionalist premises of the Fanfani plan. On the one hand, construction costs related to its employment were viewed by the architects as still competitive (Guerra & Morresi 1996); on the other hand, above all, the architects seem to have seized, in this assignment, the chance to reconnect to a technology that was by then outdated in the Turin market (and, given the epilogue of facts, even in Ina Casa public housing) with the aim of adapting its design values, which they believed to still be valid, in an original direction, which, when observed carefully, appear completely intrinsic to their specific interest, as well as to the development of architecture and construction in the Piedmont region.

This was a direction that had already been taken, in particular, by Gabetti and Raineri in cooperation with Massimo Amodei, in the design of a number of small Ina houses from the early 1950s (Barelli 2020). A notable example of these houses is the one built in San Maurizio Canavese (Turin area, 1952-3), a building of almost didactic clarity, resting on a system of masonry pillars connected by cavity walls and conceived, as specified in a detail drawing, as solids “of uniform strength” (ATC, 5735) whose taper, rotated (as opposed to its traditional orientation) towards the wall plane, is visible on the façade, as with the houses in Le Vallette (Figure 3). Here too, as with Le Vallette, joist slabs with hollow tiles are given the function of transferring forces to the perimeter shear walls and the central stairwells, providing lateral bracing for the whole building. They are supported by “reinforced concrete ring beams as thick as the slab” (ATC, 5735; ATC, 14563) resting on (and connecting) the load-bearing masonry walls. In Le Vallette, the difference is that the ring beams are “covered by bricks on the visible parts of the outer walls” (ATC, 14563), because the idea was to have a continuous masonry façade.

The architects’ view, upon designing the San Maurizio Canavese house and, though less notable, also the housing in Le Vallette, seems to look backwards, towards that “Antonelli system”, on which Roberto Gabetti would linger in a famous long essay in 1962, and which had been developed, pursuing an ideal that could be traced back to the aim (Rosso 1989) of reducing architecture to its essentials, i.e. single load-bearing columns, aimed at minimising cost and structural weight. This system is based on a grid of single

Figure 2. One of the courts in zone G with the porticoed side slab block and the H-shaped building overlooking it, ca. 1960 (ATC 1).

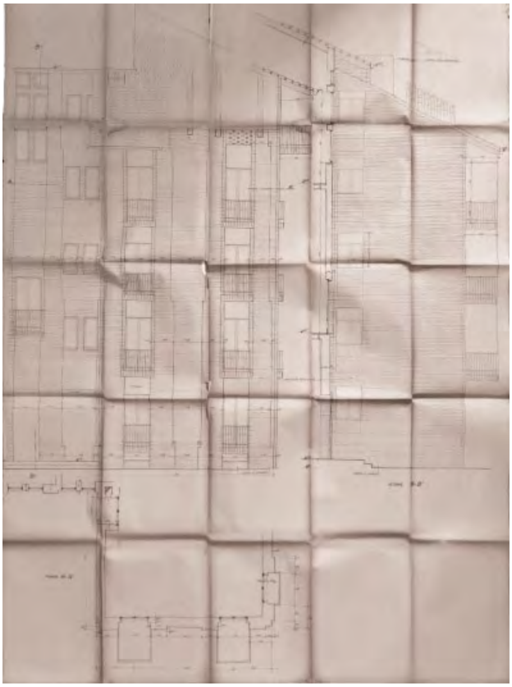

Figure 3. Detail drawing with the elevation of an H-shaped building with the system of tapered pilasters (1:10) (ATC, 14563).

"brick columns and pillars (…), designed precisely to support only vertical loads" (horizontal thrusts being counteracted by a system of metal tie-rods embedded in masonry) and, for the external walls, on "cavity walls, with two 12cm masonry wythes (one external, one internal) connected by legs every 70-80cm", namely by orthogonal half-brick walls bonded with facing and backing wythes (Gabetti 1962). The building systems perfected by Antonelli, states Gabetti, had by then established themselves in current construction and, as emerges in subsequent studies (Barrera 1982), even in early 20th century public housing in Turin. The specifications of the aforementioned Ina houses refer recurrently to masonry load-bearing structures with lightened cavity walls (Barelli 2020).

Nevertheless, in the documentation collected to date, the design for zone G housing contains certain intrinsic ambiguities related, in particular, to the actual presence of the cavity walls.

On the one hand, the specifications, which are rather generic overall (probably deriving from template specifications applicable to all IACP sites), describe in detail the unique characteristics of the structure, underlining that "Where specified in the drawings, the load-bearing structures shall be made of masonry pillars of the specified thickness, which will be tapered upwards", and specifying the presence of "intermediate cavity walls whose outer wythe is bonded with the pillars themselves, and once again made of a 12cm solid brick facing and a 8cm hollow brick backing" (ATC, 14563). It is worth noting here the different role assigned to the wythes of the cavity wall, with the half-brick facing bonded with the load-bearing pillars, thus contributing to overall stability. As further proof, another specification states that "the half-leaf partition walls, though made of solid shiners, may not be considered load-bearing", whilst "the 12cm single-leaf walls" may indeed be, albeit "only for 70% of the transverse section, and depending on their height and connection conditions".

However, it is important to note how the drawings included in the specifications, even the detail drawings, never indicate the presence of cavity walls (which are, instead, represented precisely in the design for the house in San Maurizio Canavese), nor where we should expect to find them. The hollowing of certain pillars (to insert garbage chutes), as well as the weakening, rather than the strengthening, of corners (although less evident in the initial design version), might lead us to think that, in Le Vallette, the architects were inspired by Antonelli's system mostly in terms of aesthetics – no longer single supporting pillars and cavity walls, but continuous, solid walls strengthened by projecting pilasters tapered upwards.

Thus, on this matter, research has yet to achieve certain results. Although the design documents do not resolve the ambiguities between description and representation, they nonetheless seem to take on an interlocutory form, which, within a shared framework of a construction art that is still traditional, requires certain essential choices to be made in the building phase.

The masonry walls on all storeys have a constant thickness of 40cm, with a half-brick increase for the pilasters (52cm thick). The latter are organized quite flexibly in plan view, as seems to be highlighted, for instance, by the different rhythm of the two opposite façades of the long inside slab blocks, and the freedom with which the ones facing the court are designed. In the vertical layout of pilasters, the recesses, half a brick in thickness (12cm), are positioned usually every two floors, thus becoming one of the distinctive aesthetic elements of the complex.

The analysis of the drawings allows us to reconstruct, more or less, the evolution of the solutions proposed for the load-bearing structure, which would undergo certain adjustments in terms of internal organization.

In some of the initial drawings, most certainly the first ones delivered to the institution (though undated), the vertical load-bearing structure is made entirely of brick.

In the H-shaped front structures, the continuous partition walls in the two wings at the sides of the central stairwell act as an intermediate support for the 7.5m span slabs and this explains the somewhat rigid (as it was in the past) circulation of the apartments (Figure 4, left). In the rear side buildings which outline the court, a spine wall runs lengthwise, becoming thinner at certain points, or coming to an end where there are openings, which is also typical of 19th century masonry construction. But due to the presence of rigid horizontal r.c. slabs, the only transverse shear walls, along with the short side façades, are those surrounding the stairwells. Thus, the design relies on the ability of the slabs to wind-brace the structure.

In the later versions, the design was gradually aligned to the recurring building methods of Ina Casa constructions, used, for example, from 1953 to 1958 in the La Falchera neighbourhood, also in Turin (Bardelli et al. 2003). Rows of inner pillars appeared in the lateral wings of the H-shaped front structures, initially laid out with close centre-to-centre distances (about three metres), which became longer in the approved version, clearly taking on the composition of reinforced concrete columns (Figure 4, centre). Likewise, the central spine of the long internal slab blocks turned into a succession of pillars.

But the decade was by then coming to an end. The choice of a mixed solution, masonry and reinforced concrete, would actually represent, as noted in the introduction, the first step towards the adoption of a fully reinforced concrete frame (Figure 4, right). This was proposed as soon as the site was opened by the winner of the tender, Saicca, and was a subject of dispute which would see the architects as the losing party.

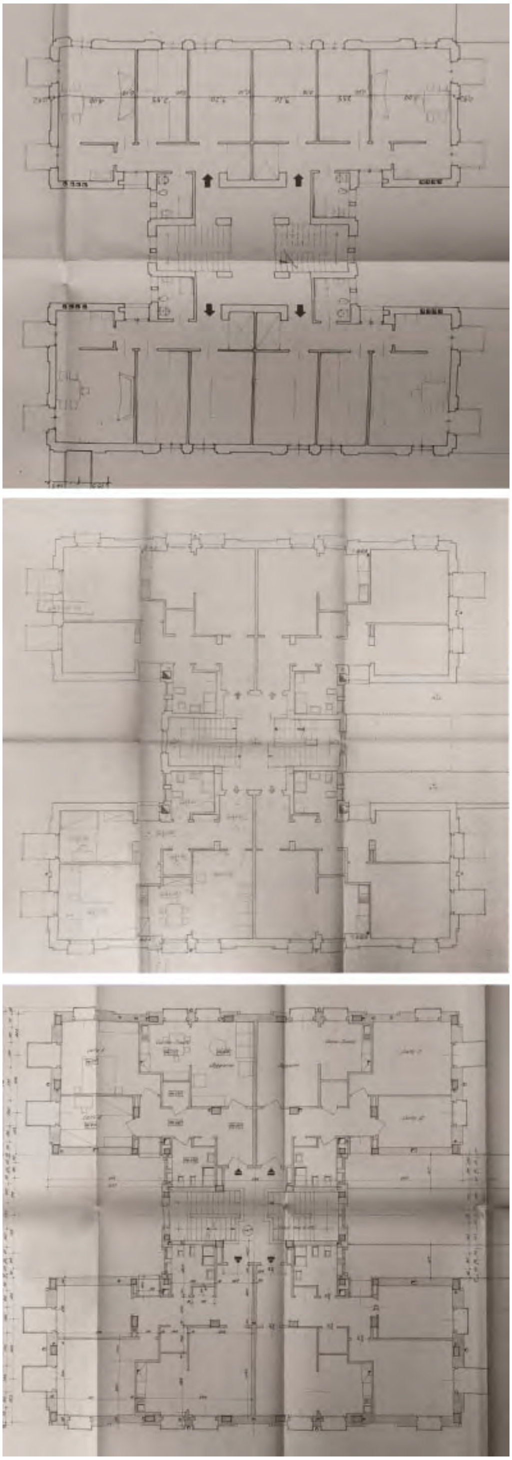

Figure 4. Changes in the internal distribution and the load-bear- ing system from design to execution: details from the plans of masonry (top), mixed (centre) and r.c (bottom) versions (1:100) (ATC, 14563).

3 THE CONSTRUCTION SITE AND THE ADOPTION OF THE R.C. STRUCTURE

The construction of the zone G housing complex would last much longer than the time planned (just over a year) in the handover report delivered to Saicca on 1 April 1959. A number of photographs show the first houses completed (the ones in blocks B1 and B4) in a mostly undeveloped neighbourhood. The company went bankrupt in 1960, and the work was newly launched in 1966, though the area was subdivided into three lots, perhaps to prevent eventual new construction slowdowns. The assignments went to Bracco (block B3) (AST, 4), Borini (buildings south-west of block B2) (AST, 3), and Simet (buildings north-east of the same block) (AST, 2), each making use of trusted civil engineers, developing their own structural designs (Figure 1).

The adoption of a reinforced concrete structure in place of the original masonry system was probably due to the advantages brought "to the organization of the construction site schedule" (Guerra & Morresi 1996), even with an ineluctable increase in manufacturing costs. Besides, this choice was not incompatible with the *Capitolato Speciale d'Appalto* (special tender specifications), which, as mentioned, was characterized by substantial flexibility, not to say indifference, towards different technical choices. In fact, it envisaged the possibility of using either load-bearing masonry or a reinforced concrete frame for the vertical structure, whilst the horizontal ones were to be joist slabs with hollow tiles.

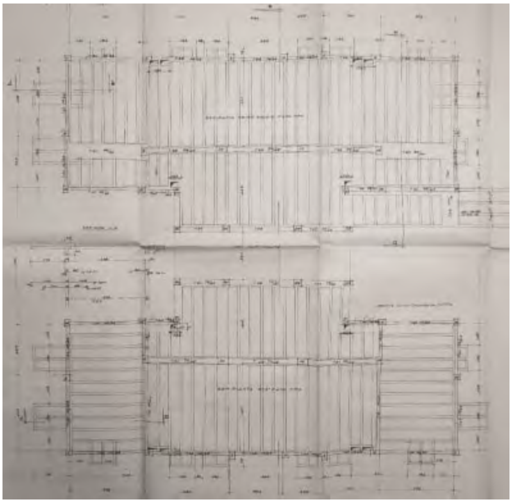

Figure 5. Bottom floors structural plan (detail 1:50) adopted in blocks B1 and B4 by Saicca (AST, 1).

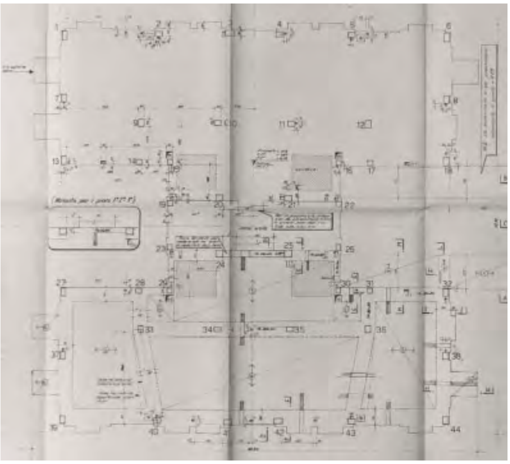

Figure 6. Bottom structural floor plan (detail 1:50) adopted in blocks B2 by Borini (ATC, 14563).

Once adopted for the houses erected in 1959 by Saicca (in the first construction phase), this choice was never again questioned by construction companies Borini, Bracco, and Simet (second phase), as can be seen from an adjustment made to the specifications, among the few relevant for the purposes of this paper, where the only accurate reference to the organization of the masonry structure in the original design, the tapering pillars, disappears. Another specification, in this case perhaps due to the difficulties emerging throughout phase 1, was the floor and roof precast slabs ("reinforced hollow tiles or prestressed concrete joists"; ATC, 19447) to be site-cast.

The evolution of the reinforced concrete technique that took place in Italy over nearly 10 years from the first to the second phase, which within a few years would lead to the replacement of the early 20th century standards then in force with the first modern ones, seems to reflect in the peculiar features of the frame types developed by the different construction companies, though within a general conception that was indisputably traditional in character.

The load-bearing structure is indeed still essentially one-way, like that of the first-ever early 20th century reinforced concrete buildings, in which frames were laid out only in a longitudinal direction, often ignoring the misalignment of columns between parallel frames, and were connected by floor slabs, which represented the only stiffening transverse element. The longitudinal frames thus replaced masonry walls in one direction, whilst the other was dependent, though not as efficiently, upon the in-plane stiffness of horizontal diaphragms.

The Le Vallette housing complex reintroduces this structural organization, adopted in the first-ever framed constructions, working "by subtraction" on the old style masonry box, without undermining the logic behind it. In this sense, the construction site "is still a nineteenth century site, with the insertion of reinforced concrete in the masonry work, without any substantial transformations" (Poretti 2012). In this case the insertion is almost literal, in that the reinforced concrete frame was lowered into an initially masonry-based grid, with a somewhat "eclectic" operation, conducted regardless (it could not have been otherwise) of the original location of the brick pillars in the building envelope (Figure 4, right).

Nonetheless, the reinforced concrete frames of phases I and II are different, and almost seem to relate to successive steps of the aforementioned evolution process. Two general considerations, which cannot be discussed in detail in this paper, clarify this statement (Figures 5 and 6).

First, it is interesting to note how the very graphic features of the Saicca drawings, as opposed to the more modern ones produced by Borini (as well as Simet and Bracco), are somewhat "old style". The beams and columns represented, with their double lines, point to the classic chamfer at the corners applied by the first-ever Italian licensees of the Hennebique patent (Iori 2001).

Secondly, and certainly more significantly, the technical solutions implemented by Saicca highlight a less-than-ignorable distance from those adopted by Borini, especially considering the few years separating the two. One example, perhaps the most illuminating among the many that might be considered, concerns the beam sizes, so strictly correlated to the spans to be covered, and almost completely shy of solid sections (a solution not fully justified by the use of precast joists), as to seem more like the architraves of a masonry wall, the one, indeed, replaced by the reinforced concrete colonnade, rather than the horizontal bending elements of a rigid frame. Nothing could be more different to the simple and rigorous lay-out of the hidden beams of the Borini design.

4 FROM LOAD-BEARING TO NON-BEARING WALLS

In the changeover from the original masonry design to the reinforced concrete frame, and in the consequent transformation of the façade walls from load-bearing structures to a non-bearing supported enclosure, two issues that already existed took on new meaning and called for specific reflection. It was, in fact, necessary not only to define a construction solution for the cavity walls, which were no longer bonded with load-bearing masonry, but also to resolve the more complex relationship between the masonry envelope and the concrete frame. These were by then recurring issues at Italian and Turin sites of the 1950s and 60s. In this case, they were resolved by the firms involved, and in very different ways.

It may be interesting to note how the two issues have certain analogies with those arising in the transition from a masonry to reinforced concrete structure, even in terms of the construction setup of the outer stone wall surface (Poretti 2008). In fact, the latter was traditionally considered either a stone facing bonded to a backing masonry, and exerting a common action under load, or a thin, independent, and self-supporting veneer, though anchored to the backing wall to restrain lateral movements. When a discrete frame replaces the continuous backing wall, "the self-support by means of superimposition to the thin veneer" (Poretti 2008, 35–6) may no longer be possible for certain parts of the building, and calls for different solutions.

Something similar occurred in the case of Le Vallette, both in the transition from masonry to reinforced concrete design, and in the different solutions that the firms involved in phases I and II of the construction. In fact, while in the masonry design (at least the one based, in accordance with the "Antonelli" system, upon pillars) the facing of the cavity wall was bonded with the load-bearing brick system, thus conceptually comparable to a structural layer, in the reinforced concrete design, it became a de facto independent curtain wall, for which suitable solutions were required to guarantee its stability (indeed, it is these solutions that distinguish the proposals of each construction company).

In the built version, the cavity walls preserved the thicknesses envisaged in the masonry design (40cm, 52 at the pilasters) and were made of two half-brick masonry walls. The specifications, regardless of their successive versions, always state that the 8cm backing must be made of hollow tiles, and the 12cm facing (to be protected with "a transparent and waterproof coating"; phase II specifications) of common, solid bricks, which means, before the 1980's standards (UNI 8942, issued in 1986, in particular), without cores at all. Nevertheless, we can see from certain decayed areas of the façades that the bricks actually used are different. In the houses built by Saicca, bricks with horizontal cells were alternated (we do not know to what extent) with solid or semi-solid ones required to change the wall direction at the pilasters. Houses built in the second half of the 1960s, instead, reveal the use of bricks with vertical cells, comparable to semi-solid bricks. The architects insistently asked for the colour to be kept consistent for the entire supply, but, unsurprisingly, suspension of work at the site would lead to the use of bricks that at first sight are similar but appear different when viewed close-up. Those used in phase I are redder and irregular, while the ones used in phase II are of a lighter colour and more regular. Moreover, certain areas of the façades, in the buildings of phase II, show noticeable irregularities, with level courses not exactly horizontal, which are indicative of all the difficulties of a construction site managed in the name of cost savings (certainly very different to the ones the same architects were engaged in, in the very same years, for private housing), at a time (in the 60s) when it was increasingly difficult to find good bricklayers, and it was common for firms to make use, instead, of piecework by unspecialized labourers.

We may find certain clues on the cavity-wall creation methods in the specifications. In phase I specifications, it is stated that "if the load-bearing structures are planned to be made of reinforced concrete", the two wythes need to be bonded "every 50cm" (ATC, 15463). It is a rather vague recommendation that could refer to connections made by means of either masonry "legs" (according to construction methods derived, indeed, from the "Antonelli" system, then "transferred" to reinforced concrete construction) or the use of metal ties.

This ambiguity is removed in the phase II specifications, which only refer to regularly spaced (again, every 50cm) metal ties made "with ø 6mm reinforcing bars, duly shaped and coated or galvanized" (ATC, 19447), a solution which, moreover, made it easily possible to make the facing wythe with a simple running bond (overlapping stretchers).

As for the elements to ensure the lateral stability of the cavity walls, first, we may observe that their relationship with the reinforced concrete framework is solved in two different ways in the designs of the different companies (Figure 7). In the first solution (implemented by Saicca), the outer facing of the cavity walls is completely separate from the reinforced concrete slabs (Figure 7c). In the second solution (adopted by Borini and Bracco), the facing partially rests upon each floor slab, and also leans on the columns. Thus, the reinforced concrete structure bears its weight and restrains its lateral movement (Figure 7b). In both cases, the facing wythe is always supported on the lower edge by a projection from the reinforced concrete walls of the basement (a method which, in reality, we see only in the Saicca and Borini drawings, but was probably, if not certainly, also applied to the houses built by the other two companies). This facing is, in any event, an external curtain (fully or partially self-supporting), and the changes simply involved the way in which its stability was ensured.

From this point of view, the second solution seems more "traditional", so to speak, than the first, in that its end purpose was an interaction with the load-bearing structure (though, of course, differently from what the

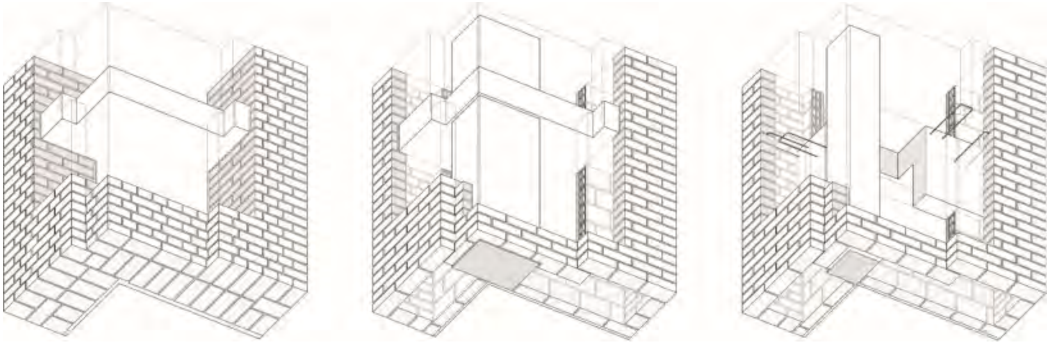

Figure 7. Relation between masonry walls and r.c. structures. The original design load-bearing masonry (solid) walls with joist slabs (left) and the r.c. frames with cavity walls actually created, in two versions adopted respectively by Borini (centre) and Saicca.

masonry design would have involved). This solution is expressed in incredibly refined terms, a manufacturing precision that pointed to the "handcrafted" characteristics of early reinforced concrete structures, in the buildings erected by Borini (Figures 8 and 9). To guarantee the most "extended" support possible for the facing wythe on the floor slabs, these are shaped to follow the outline of the façades, at the height of the last tapering of the pilaster section, with a constant recess, with regard to the outside edge, of 6cm (taking into account the column position, this generates a slab overhang of only 2cm around the same), namely half the thickness of the face bricks (referring to the 12cm stated in the specifications, although preliminary on-site surveys show an actual size of 11.5cm).

As for the first solution, it inevitably points to a form of connection between the outer side of the façade and the floor slabs. If, indeed, the distributed metal ties between the two wythes of the cavity walls involve horizontal constraints that reduce the slenderness of each, and guarantee their stability, these are unilateral constraints, thus not effective in preventing inward reciprocal movements, especially in points where, at the level of the pilasters, the facing is completely separate from the slabs and the spacing of the two wythes is greater.

Nevertheless, an explicit indication in this sense is only included in the Bracco drawings, which state: "leave ø 6mm reinforcing bars to anchor the *muroni*": where the word *muroni* ("big walls") (AST, 4) makes it clear that it refers to the pilasters, where, indeed, the note is positioned in the drawing. There is no trace of similar specifications in the drawings of the other companies but, as aforementioned, it is highly probable they were in any event implemented.

Finally, still in terms of lateral stability, we note that the articulation of the outer facing generates a form-resistance, at the pilasters and the opening jambs, which cannot be relied on in limited portions of the façades, which have in part, unsurprisingly, suffered collapses in recent times. Besides, it is possible that, due to the greater local out-of-plane stiffness of the outer facing, this form-resistance could be related to a differential response to thermal-hygrometric variations, with the consequent possibility of triggering cracks (which are indeed recorded, on lower floors, perhaps due to the concurrent presence of greater compressive stresses, and thus more pronounced transverse strains).

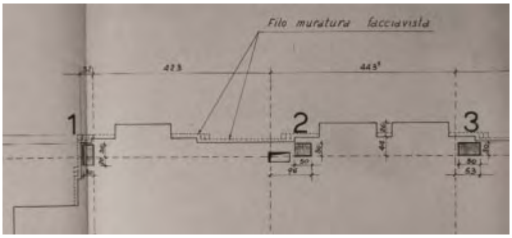

Figure 8. Joist slabs shaped to follow the outline of the façade (Borini's bottom structural plan, detail 1:50) (ATC, 14563).

Figure 9. One of the Borini buildings under construction, ca. 1967 (photo by R. Moncalvo) (ATC, 19447).

5 CONCLUSIONS

Upon investigating the houses of zone G both in general and in their slightest details, they seem to breathe an air of history, along a timeline which, especially in the 1950s, distinguished the specific position of the architects involved in their design on the Italian architecture stage and, more specifically, within the Ina Casa plan; a plan that ? in this case as in others already subject to in-depth investigations (Vittorini & Capomolla 2003) ? takes on the role of a large canvas that guided architects and included different interpretations of the same topic.

In terms of building history, what emerged is the peculiarity of the reinterpretation of one of the most interesting experiments in 19th century architecture, “Antonelli” architecture, still seen as a vital body from which to extrapolate suggestions for the present, as well as the object of “transpositions” to a modernity which, upon careful analysis (not only in the interpretations of architects but also in the translations of the workers) is highly nuanced.

The retracing of the construction site events, as far as this has been possible to perform to date, leaves the architects in a blurry position, and puts the spotlight on the multiple actors governing, and sometimes hindering, the building process. In the actual translation of the design to a constructed architecture, the compromise applied, representative of a well-defined adoption of reinforced concrete techniques in public housing construction in Turin in the late 1950s, does not mean that the architects ignored an element they considered essential, construction quality, as they underlined in the report published in the *Casabella-Continuità* magazine upon conclusion of the first lot: “we have strictly followed the technology of each element with constant care and attention, as we believe the few pictures of the houses realized to date (no more than this) prove” (Cavallari-Murat & Oreglia d’Isola 1962, 48).

The central matter that the architects and labourers needed to deal with to guarantee quality, no longer simply based upon traditional standards, regarded the erection of cavity walls, which the final part of this paper focuses on. But besides the specific results, strictly linked to the comprehension of this work, this research aims to contribute to the broadening of knowledge of the architectural heritage of Turin from the second half of 1900s, which in terms of tangible consistency seems still mostly uncharted.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Modern dwellings after World War II: An Italian experience of wooden prefabrication by Legnami Pasotti

L. Greco
Universitá della Calabria, Rende, Italy

ABSTRACT: The paper deals with the spread of prefabrication techniques in Italy after World War II with specific reference to the diffusion of the wooden construction system manufactured by the company Legnami Pasotti and applied to the production of prefabricated homes delivered as “Garda houses”. The system was based on the use of uprights and wall elements and provided for the integration of fixed furniture elements into the wooden construction system. The section of the uprights was shaped so as to allow corner, crossing and linear connections with the wall elements using a single coupling scheme. The research considers the Pasotti case in the post-WWII context and with reference to the pioneering prefabricated systems developed by Pasotti in the 1930s. Sources are both Legnami Pasotti’s technical catalogue, as well as the written sources (drawings and technical notes) preserved by the Central State Archive of Rome.

1 INTRODUCTION

After World War II, European countries faced a substantial housing demand. They also had to tackle the reconversion of manufacturing, which had been engaged for years in the war effort and, more generally, planned socio-economic recovery, taking advantage of the industrialization and building prefabrication evidenced by the many measures already launched by governments during the conflict. It is worth mentioning some of these events to outline the cultural framework which gave rise to the Italian experience.

European leadership came from Germany and Great Britain, which as early as the 1920s and 1930s had become major players in prefabricated construction with wooden and metal structures with construction systems such as the Germans Wohr and Blecken and the British Weir and Telford.

In 1942 the Burt Committee was established in the United Kingdom to study possible housing solutions, including temporary and typologically innovative schemes, and in 1944 the Temporary Housing Program (THP) was promulgated (Vale 1995). Initiatives included prototypes such as the Portal Bungalow, as well as solutions developed by Uni-Eco Structures and Arcon, whose dissemination also had an impact in Spain (Cassinello 2015).

In France many measures emerged, such as the collaboration of Jean Prouvé with the Bureau Central de Construction (1941–42) and the work of the French designer with Edouard Menkès for the reconstruction of the Saar region (Cinqualbre 2009).

The United States had the most advanced prefabrication know-how. They had a particular preference for prefabricated wooden buildings (derived from the balloon-frame tradition) and the use of the metal frame, first introduced in skyscrapers and then adapted to the construction of small houses. A key-experience of this context is the well-known system promoted by Walter Gropius and Konrad Wachsmann in the General Panel System based on a wooden modular panel that, by varying the insulation and strength characteristics, could be used as a wall, floor and roof component thanks to the universal joint designed by Wachsmann.

In Italy, the use of wooden systems in the residential sector was limited, and the topic has so far been little considered by studies on construction techniques of the 20th century. Yet analysis of this technique enriches knowledge on prefabrication developments in Italy in the field of small constructions, exploring themes of standardization (of components and connections), of rationalization of assembly sequences, and the wider framework of building construction after the Second World War.

The study presented in this paper focuses on the work of Legnami Pasotti, a leading company in the sector of wooden construction systems in Italy whose role in the national framework has not yet been established. The research is based on the catalogue of Garda houses and on the 1937 patent for temporary houses by Legnami Pasotti. The documents analysed, largely unpublished, highlight aspects of continuity and originality between the company’s work in the 1930s and its post-war work, outlining a representative Italian case.

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2 LEGNAMI PASOTTI AND BUILDING PREFABRICATION IN ITALY

The Pietro Pasotti company, later the Società Anonima Legnami Pasotti and then Legnami Pasotti s.p.a., was founded in Brescia by Pietro Pasotti in 1879. Initially specializing in the production of furniture, windows and floors, it gradually gained visibility in the building prefabrication sector, participating in the reconstruction of Messina, the Southern Italian city destroyed by an earthquake in 1908.

Legnami Pasotti perfected its approach to the unification and standardization of building components and registered a patent linked to the construction of *pannelli a compensazione*, undeformable wooden panels intended for floor and wall cladding designed to prevent the deformation of plywood components (also made available in France and in the United States). A second patent was to do with the development of a system for producing straight and curved glued wood beams for large spans.

In 1922 Legnami Pasotti participated in the first International Trade Fair Exhibition of modern construction that took place in Turin. Its products enjoyed success there, as evidenced by a gold medal award “for the perfect unification of types” and silver medal for “the excellent performance of the materials”. Taking advantage of the development of Italian colonial countries (Libya, Ethiopia and Albania), during the 1930s, Pasotti’s production diversified and advanced, and they opened offices in Rome, as well as branches in Ethiopia and Albania.

Among the innovations introduced was a light and waterproof roof system made up of populite, cork and Cel-bes plates, used together with metal sheets. But most resounding of all were their structural achievements, in which the straight and curvilinear glued wood beams developed by Pasotti with the consultancy of the engineers Gino Bettoni and Mario Moretti found applications. In 1939 the company employed 600 workers. In these same years, Legnami Pasotti competed in the market for temporary constructions in the colonial territories of East Africa with other brands such as L’Invulnerabile from Bologna.

Patent no. 353302 of 11/05/1937 concerning “Demountable building constructions obtained by means of elements that form the beam and wall at the same time” (ACS-UIBM 1937), was used in Pasotti’s submission to the national agency *Azienda Miniere Africa Orientale* (AMAO) for the construction of removable buildings. The patent defined a demountable wall consisting of wooden uprights connected together by steel tie rods fixed with bolts and covered with sheet metal panels, fibre cement and wood fibre. This system involved a layer of insulating material (Cel-bes) placed in the cavity of the wall between the two cladding panels. The wall elements, stiffened by connections with the floors, could be dismantled and reused for other constructions.

After World War II, Legnami Pasotti faced the debate on construction techniques for reconstruction.

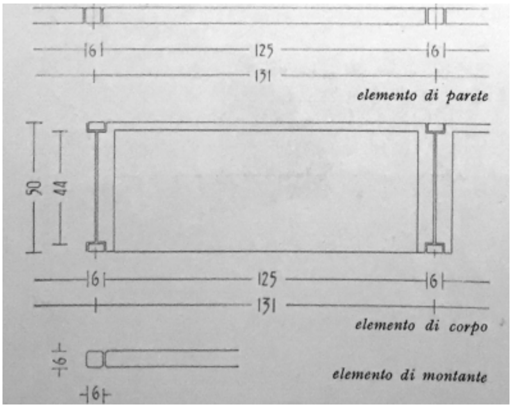

Figure 1. The module of the system (131 cm) corresponded to the width of a wall element (125 cm) plus the sum of two half uprights (each 3 cm wide)- Source: Garda houses catalogue.

Between the 1930s and 1950s the theme of prefabrication in Italy was inspired by an artisan approach that particularly affected the evolution of cementitious processes (thanks to the work of Pier Luigi Nervi), tracing an Italian method of prefabrication based on the use of small elements prefabricated on site with sophisticated craftsmanship techniques and then assembled with reinforced concrete ribs cast on site (Iori 2012). Nevertheless, the mood established by the public reconstruction programs did not favour methodological progress in the management of building processes to review the relationship between building design and manufacturing in the wake of the conditions (reconversion of the war industries, demand for reconstruction) that predominated in many countries after the war (Graf 2012). On the contrary, the political and economic condition led to inertias that postponed the actual impact on construction practice of the theoretical debate surrounding prefabrication to the 1960s.

The first national conference on reconstruction was held in Milan in 1945 and in June of the same year the National Research Council (CNR) announced a competition for prefabricated house prototypes in which Legnami Pasotti also participated. The effects of these events on the evolution of construction practice were very limited (Gardella 1946). The exhibition on the CNR competition presented the developments of the prefabrication in the field of residence in three sections (metal frame constructions, reinforced concrete panels and linear reinforced concrete elements), summarizing the influences of the more advanced English and French experiences with the Italian approach, based above all on breaking down the structure into simple and light prefabricated elements.

The house presented at the 1945 exhibition by Legnami Pasotti contemplated a single-family dwelling designed by the company in collaboration with the architects Cino Calcaprina, Tito De Micheli and Silvio Radiconcini, with reference to the aforementioned patent no. 353302 of 1937 and to the contemporary Garda houses. In the following years, Legnami Pasotti received major orders from the Australian Department of Work and Housing (Canberra) and from the War Service Homes Division (Victoria).

3 THE GARDA HOUSES: MODERN DWELLINGS AND WOODEN PREFABRICATION

Legnami Pasotti launched Garda houses after the war (exact date unknown), trusting in commercial success favoured by the housing demand and the contemporary debate on prefabrication.

The manufacturer indicated “the main characteristic of the prefabricated Garda houses in the interchangeability of the components and in their modular dimension, established on the measure of 131 cm, corresponding to the width of a wall element (cm 125) plus the sum of two half uprights (each 3 cm wide)” (Pasotti n.d.). To allow a quick and economical assembly of the parts, submodules were also provided, solving specific nodes and junctions. All the elements of the construction therefore corresponded to the total, fractions or multiples of the basic measure (131 cm).

The modularity and interchangeability of the system components allowed buildings with different layouts and surfaces, illustrated in the Legnami Pasotti catalogue. The repertoire provided 19 schemes of single-family houses that could be joined with configurations including up to three-four units. These were solutions intended for permanent use in urban and holiday areas (by the sea, in the mountains, by the lake), or for temporary use.

The analysis of the different layouts of the Garda houses highlights the use of basic functional units such as the bedroom (3.87 m × 3.87 m), the entrance and the bathroom (1.69 m × 2.56 m), obtained with the composition of basic construction modular elements also combined with submodules of the basic construction module. In all combinations there were complex components (called *corpi*), intended to integrate plans and furniture in the construction system.

From a construction point of view, the system was based on the use of uprights and wall elements (Figure 1). The section of the uprights was shaped so as to allow corner, crossing and linear connections with the wall elements using a single coupling scheme, as made by Pasotti in the house displayed at the CNR exhibition held in 1945.

The external walls of the 1945 exhibition house were formed by panels (112 cm × 280 cm) with a wooden frame and covered internally with masonite and externally with a vertical wooden beading. As observed in number 193 of *Costruzioni* dedicated to the exhibition, the 1945 self-supporting panel house was characterized by the “panel joining system which allows linear or cross connections and an interesting autonomous bathroom-kitchen group made of sheet metal with the piping equipment, appliances and connections already installed” (Costruzioni 1946). The joint between the panels was protected by special pieces to make the cladding a continuous layer.

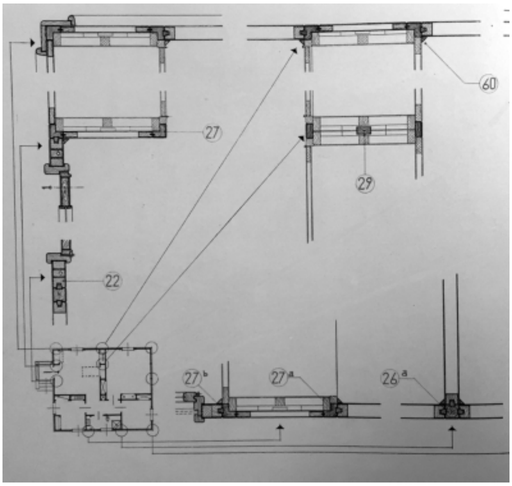

Figure 2. Typical connections of Pasotti’s system. Both the uprights and panels were connected by mortise and tenon joint. Source: Garda houses catalogue.

Figure 3. Houses under construction in Brescia. Realization of stone plinth and of raft. Source: Garda houses catalogue.

Both the uprights and panels of the Garda houses were connected by mortise and tenon joint thanks to the shape of the sections of the elements, so as to reduce the use of skilled labour (Figure 2). The panels had a timber frame and a masonite or hardboard cladding on both faces. The cavity was filled with insulating material, according to a practice proven in demountable constructions for colonial territories in East Africa and which was also proposed in the CNR exhibition house.

There were 12 types of uprights as follows: internal and external connection uprights (with two, three or four couplings), internal and external corner, uprights for the connection between two plant or furniture blocks, register uprights to regulate the connection between two furniture or plant blocks.

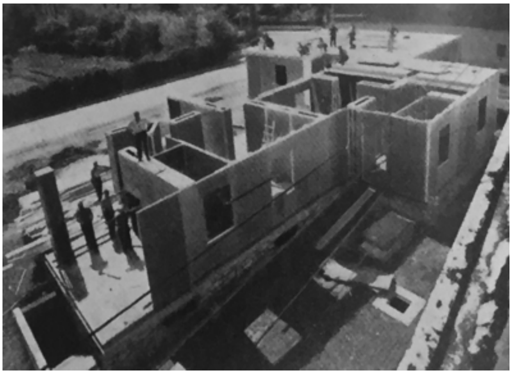

Figure 4. Houses under construction in Brescia. Wall assembly. Source: Garda houses catalogue.

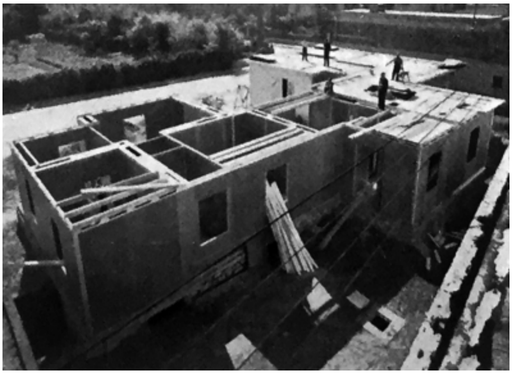

Figure 5. Houses under construction in Brescia. Roof assembly on one wing of the building. Source: Garda houses catalogue.

Several types of wall elements included opaque elements (without openings for windows and/or doors) with different standard dimensions (125 cm × 296.5 cm × 6 cm; 81 cm × 296.5 cm × 6 cm; 59.5 cm × 296.5 cm × 6 cm; 38 cm × 296.5 cm × 6 cm), equipped opaque elements for bathrooms with integrated aluminium pipes for hot and cold water, elements with external and internal doors (125 cm × 296.5 cm × 6 cm) and elements with windows (125 cm × 296.5 cm × 6 cm). The Garda repertoire included a catalogue of flat and pitched roofs, with varying complexity planimetric articulations. The roof was placed on the wooden loadbearing walls by means of the headtree.

In the case of a flat roof, the roof structure was formed by a framework of rectangular section beams (60 cm × 50 cm) joined to the headtree at one end and on the other side placed on the loadbearing walls. The roof boarding (16 mm thick) on which a straw and cement layer formed the pitch of the roof, rested on the beams. Bitumen cardboard protected by gravel or a layer of concrete composed the waterproofing layer. On the perimeter, the roof was completed by the brackets of the cornice and by a wooden frame covered with hardboard that formed the overhanging ceiling.

The pitched roofs were solved with trusses, on which a secondary frame of beams (50 mm × 25 mm) or the roof boarding were arranged, according to the type of roof covering, which could consist of brick tiles (flat or curved), flat or corrugated sheets of asbestos or aluminium. The intrados of the roof was made of a ceiling of flat elements consisting of a wooden framework, covered on both sides with masonite or hardboard, and fixed to the roof frame by means of screws.

As anticipated, the Garda houses provided for the integration of fixed furniture elements into the wooden construction system. The furniture blocks, when present in the building, constituted the main structure and represented a partial furnishing of the rooms (Pasotti n.d.). These special parts of the system were 131 cm wide and 50 cm deep. They included blocks for the bedroom (cabinet-chest of drawers, wardrobe, bed-wardrobe), for the living room (table-sideboard, bookcase-cabinet), for the kitchen (stove bod, kitchen table, sink) and the fireplace.

Figure 6. Houses under construction in Brescia. Completion of the roof. Source: Garda houses catalogue.

One interesting solution was the Garda G.T. type independent bathroom, consisting of a central core group that included bathroom, sink, bidet and bathtub. This solution involved the passage and connection of hot and cold water distribution and drain pipes through an inspectable parapet, on whose faces all the sanitary fittings were arranged. On the other hand, for different functional layouts of the bathrooms, the system included the autonomous elements of the sink, bidet, bathtub, toilet.

The archive documentation available describes the assembly sequence of a group of three houses installed in Brescia (the case cannot be dated). The prefabricated structure was laid on a natural stone plinth with a hollow block slab and an overlying floor (in linoleum, stoneware, cork oak). Part of the building also had a basement. The assembly of the houses was completed in 15 days.

The work on site was organized with two teams, one of masons who carried out the works of preparation, excavation, foundation and construction of the stone plinth (Figure 3). A second team of fitters took care of the assembly of the wooden parts and finishes. To mount the prefabricated structure above the stone plinth, a raft was set up on which uprights and wall panels were grafted (Figure 4). Taking advantage of the C-shaped layout of the project, they proceeded with the assembly of the roof on one wing of the building while completing anchoring of the walls to the rest of the building (Figure 5). While the roof was completed, the external finishes of the walls were carried out and the electrical and water systems were installed inside (Figure 6). The final layers of the roof were created while the walls and ceilings were painted inside. The construction site closed with the arrangement of the outdoor area.

4 CONCLUSIONS

The slow spread of prefabrication in Italy conditioned by post-war reconstruction programs did not hinder advances in the pioneering trend begun in the 1930s for proto-industrialized solutions with metal and wooden frames. These experiences, albeit niche in the national construction context, constituted a reservoir of ideas, products and experiments whose effects re-emerged after the war, as demonstrated by the case of Legnami Pasotti.

The solution of the wall of the Garda houses derived its organization from the system patented in 1937 and from the prefabricated house presented at the CNR exhibition in 1945. Unlike the 1937 patent, the post-war Garda houses and the CNR exhibition house did not require the use of tie rods and reversible anchors to ensure the dismantling of the buildings but used the features of the 1930s construction system, updating it to the renewed requirements of the domestic market.

Once the colonial experience had ended, Legnami Pasotti updated its production after the war to address the domestic market and then the housing project took care of the functional aspects to bring together comfort and construction economy and to provide for a complete and autonomous housing solution. Moreover, the presence of different equipped parts for bedrooms, living room, dining room and kitchen confirms Pasotti’s intention to offer comfort and interior finishing standards comparable to traditional homes and oriented towards the evolution of the domestic space that distinguished the housing market of those years.

Legnami Pasotti aimed to validate prefabricated houses as an effective alternative to traditional masonry houses, as evidenced by the introduction to the catalogue in which the Brescia-based company noted that prefabricated houses were suitable for the immediate supply of the necessary number of houses and to “guarantee high requirements of comfort, hygiene, solidity, durability and safety” (Pasotti n.d.). From a typological point of view, the proposals of the Brescia-based company recalled the vision of Bruno Zevi who, at the I Convegno Nazionale sulla Ricostruzione (1945), proposed the experience of American prefabricated houses as an option for the Italian reconstruction (Signori 1986). However, this hypothesis proved to be difficult to implement in an urban and social context that was not very compatible with the mass use of the single-family houses, so much so that it succumbed to the multi-storey types that inspired the public reconstruction program of the Ina-Casa. This aspect, and a different custom in the industrialization of the prefabrication techniques, restricted the commercial success of Pasotti production, which in the 1950s expanded into the foreign market with orders in Australia from the Department of Work and Housing and from the War Service Homes Division, while in the 1960s the production of prefabricated solutions for the Italian school building sector took off, as evidenced by the development of the “P63 System”, which earned the Brescia company the Compasso d’Oro in 1970.

In any case, the link between Legnami Pasotti’s work in the 1930s and that of the post-war period, when referring to the broader context in which the history of the company took place, confirms the analysis proposed by Franz Graf when he notes that “industrialised production during 1920s and 1930s, uncommon but earnestly deliberated, served as the wellspring from which ideas for reconstruction, and later for the post-war boom could be drawn” (Graf 2012). Thus, we can link this case with the more general trend in building prefabrication in Italy, in which post-war developments were inspired by the research conducted during the 1930s in different fields and with reference to the metal structures at the Triennale of Milan in 1933, the concrete technique with Pier Luigi Nervi’s ferrocement experiments, and, finally, wooden prefabricated construction by Legnami Pasotti.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Morandi (1957–1962) and the cable-stayed Bridge over Lake Maracaibo: Pioneering contributions

F. Mustieles
Universidad Iberoamericana, Puebla, Mexico

I. Oteiza
Instituto de Ciencias de la Construcción Eduardo Torroja, Madrid, Spain

S. Delgado
Gilsanz Murray Steficek, LLP, New York, USA

Pedro Romero
Universidad del Zulia, Maracaibo, Venezuela

ABSTRACT: This presentation aims to highlight the historical importance of the Bridge over Lake Maracaibo (or General Rafael Urdaneta Bridge) (1957–1962) within the framework of the cable-stayed bridge work by Riccardo Morandi, as well as its main structural and constructive contributions. This was the first modern cable-stayed bridge with multiple spans, and one of the longest in the world for many years. The result of an international competition won by the Morandi team, its design, calculation and construction was executed by a range of international and national companies, while its construction marked an important milestone for innovation in bridge building in general. Currently, after almost 60 years standing, and following the collapse of the Morandi bridge in Genoa, maintaining the structure is more important than ever, due to what it represents for the economy of Venezuela and for the history of bridge construction.

1 INTRODUCTION

Venezuela in the 1960s saw oil revenues that allowed for major investments. Large-scale equipment works included the Caracas-La Guaira Highway with three viaducts (1948–1953) by Eugène Freyssinet (1879–1972), as well as what locals would call the Bridge over Lake Maracaibo, later the General Rafael Urdaneta Bridge (1957–1962) (Figure 1), which spanned the strait of Lake Maracaibo. It was designed by Riccardo Morandi (1916-1989) with a length of 8678 m for a country of 916,445 km^2 with just 5 million inhabitants.

Morandi built just four bridges in the entire American continent: three in the Caribbean (Caracas 1951–1954, Maracaibo 1957–1962 and Barranquilla 1970–1974), and one in Canada (Castlegar 1960–1965). The Maracaibo and Barranquilla bridges were cable-stayed type (steel) bridges in prestressed concrete. This paper sets out: a brief history of the project and construction of the Maracaibo Bridge and review of documentary sources; the significance of the Maracaibo Bridge within Morandi's cable-stayed bridge work; and the importance worldwide of this forerunner in infrastructure works and its innovative structure and construction, through a review of documentary sources and direct consultation with bridge engineers.

2 THE WORK: HISTORY OF THE PROJECT AND CONSTRUCTION

2.1 *A brief history*

The Maracaibo Bridge project was the result of an international consultation launched by the dictatorial government of General Marcos Pérez Jiménez (1952–1958), who would go down in history as a great modernizer of the Venezuelan infrastructure and equipment. As he was overthrown in January 1958, the General's government did not complete the hiring process, and the new democratic government of Rómulo Betancourt (1959–1964) put it out to tender again in 1958. Construction was completed on 24 August 1962, and in just 40 months, the longest bridge in the world had been built.

The Venezuelan economic context at that time was very favorable for the realization of a work of such magnitude. Venezuela was at that moment the second world producer of oil behind the United States of America and the top exporter in the Western world. Some 70% of Venezuelan oil production came from the Lake Maracaibo basin, and oil exports were carried out across the lake right in the strait where the bridge would be built. Thus, the bridge had to allow the transit of large tanker ships until the present day – hence its

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Figure 1. Bridge over Lake Maracaibo (1957–1962) (source: Taringa@ZuliaPrensa 2014).

vertical clearance of 45 m, which is also respected by the new "Cacique Nigale" bridge (10.8 km) planned for the same strait, and whose construction is currently suspended. This second bridge would reinforce the integration of the most western province of Venezuela into the country, a process that started 58 years ago with the Maracaibo Bridge.

2.2 *Participating actors*

The Maracaibo Bridge project was the subject of an international competition that was awarded to the Maracaibo Bridge Joint Venture comprised of the companies Precomprimido C. A. (based in Caracas) and Julius Berger A. G. (Wiesbaden) for 330 million bolivars (approx. US$100M in 1957). It envisaged a reinforced concrete structure according to the design by Morandi. This offer was successful because lower maintenance costs were expected of a concrete structure, fewer supplies had to be imported and a large number of local engineers were able to gain experience in the construction of prestressed concrete, a requirement made by the democratic government.

According to Simons et al. (1963), many Venezuelan engineers as well as engineers from various other countries participated in the team involved in the project and that carried out the work. A group of Italian engineers, among which L. Sbalzarini, of Professor Morandi's team, was responsible for the project development from the initial ideas during the first contest. The examination of the structural analysis and drawings were carried out by the professors from the Zurich Polytechnic: Lardy, Stussi and Schnitzer. Professor Kerisel was the consulting engineer appointed to handle the particular complex aspects of soil mechanics. The engineers Otaola and Benedetti, from the Venezuelan construction company, were in charge of the execution program and construction details. The inspection of the works by the Ministry of Public Works of Venezuela was performed by the engineers González Jaime (director) and González Bogen. Trials were done on scale models at the National Institute of Civil Engineering in Lisbon and at the ISMES Institute in Bergamo. The surveying work was carried out by a team led by engineer Heinz G. Henneberg.

Table 1. Bridge over Lake Maracaibo: subdivision into sections (source: PGRU 2020).

Sections	m/unit	Total m
1	22.60	22.60
1	35.80	35.80
19	36.60	695.40
77	46.60	3588.20
2	46.65	93.30
2	65.80	131.60
26	85.00	2210.00
2	160.00	320.00
5	235.00	1.175.00
135	8271.90	
Embankment		406.70
Total (m)		8678.60

2.3 *Work description*

The bridge, located south of the city of Maracaibo, joins the eastern and western shores of Lake Maracaibo at one of the narrowest parts of the strait of the lake. The Maracaibo Bridge is 8678 m long and has 135 sections; it also has an embankment that extends for a length of 406.7 m on the eastern shore of the lake (Tab. 1).

The cross section of the bridge (17.4 m) is subdivided into four traffic lanes, each 3.60 m wide, with a central island of 1.20 m to separate the two directions of traffic and two lateral platforms 0.90 m wide. There are no sidewalks or cycle paths.

The navigable channel that spans the bridge allows the navigation of 65,000 t oil tanks. This channel is 100 km long, 300 m wide and 15 m deep.

"The approach spans to the main navigation channels are formed by a series of piers and precast girders (Piers 1–3 and 38–134). Intermediate piers have the shape of a X, rigidly connected to a top beam (post-tensioned) with double cantilevers (Piers 4–9 and 37). As the height of these piers increases to approach the navigation channels, the X-shape rises while resting on two columns that carry loads to the pile cap, forming an approximately H-shape. In all cases, piers receive eight precast prestressed concrete girders (four at each side) with lengths of either 36.60 or 46.60 m. The structure has 528 precast beams that cover nearly 3/4 of the bridge length" (Fargier-Gabaldón 2020).

A long ramp rises from Maracaibo (west of the bridge) to the main navigation opening of the bridge with six pylons and five cable-stayed spans. After the last pylon to the east, the descending part, a long ramp at the end, a flat section just a few meters above the water, reaches the eastern shore with an embankment (Figure 2).

In constructive terms, the numbers are impressive, as well as the time in which the bridge was built (Tab. 2).

Before Maracaibo Bridge's final design with five sections of 235 m span, Morandi had proposed another

Figure 2. Bridge over Lake Maracaibo (source: Imago/ZUMA Press/ JC Hernández 2018).

Table 2. Construction data. Source: From Simons et al. (1963).

Concrete	270,000 m^3
Drilling piles	35,660 m
Driving piles of 91,4 cm diameter	27,170 m
Driving piles of 50/50 cm diameter	6260 m
Prestressed cables	5000 t
Rods	19,000 t
Workers	2600
Total construction time	40 months

with only one section or central span of 400 m (Morandi 1957, Sbalzarini 1962a), but which was eventually scrapped although many of its components would be retained.

3 THE MARACAIBO BRIDGE’S IMPORTANCE IN MORANDI’S WORK

The Maracaibo Bridge represented for Morandi his first concrete cable-stayed bridge, as well as being his longest and largest construction work and, at that time, the longest bridge in the world.

After designing and building the Maracaibo Bridge, Morandi would design four more cable-stayed bridges in prestressed concrete (Tab. 3 and Figures 3–6), strongly influenced by and resembling the design and structural and constructive system of the Maracaibo Bridge, but in fact quite different to that design.

It is worth mentioning that, of these five cable-stayed bridges, only the first one in Maracaibo and the one in Potenza are still in operation. The Maracaibo Bridge continues to be the longest cable-stayed and the second longest bridge in Latin America today, almost 60 years later. His Morandi system of prestressing (Morandi 1960) was largely replicated in the subsequent four bridges. Wai-Fah Chen and Duan (2014) add that this bridge “not only is the first multi-span cable-stayed bridge having six pylons and five main spans of 235 m, but it is also the first application of concrete as structural material in the pylons and stiffening girder of a cable-stayed bridge”.

Figure 3. Polcevera Bridge, Genoa (source: Fundación Mag-dalena 2014).

Table 3. Morandi’s cable-stayed bridges (all cast-in-place and precast) (source: Podolny & Scalzi 1976).

Morandi’s cable-stayed	Date	Length (m).	N°. of cable-stayed spans	Total length of cable-stayed spans (m)
Maracaib	1957–62	8678	5	1175
Genoa	1963–67.	1182	3	550
Wadi Kuf	1965–72.	477	3	475
Potenza	1977.	242	2	198.6
Barranquilla.	1970–74.	1536	3	279

Morandi’s cable-stayed. bridges.	Major Span length (m).	Ratio of of total length to major span	Girder depth (m)	Span to girder depth ratio
Maracaibo.	235	5	5	47
Genoa	210.	2.6.	4.6	45.7
Wadi Kuf	280	1.7	4 to 7	70
Potenza	145	1.37	–	–
Barranquilla	140	2	3.	47

Figure 4. Wadi el Kuf Bridge, Libya (source: YouTube 2018).

Figure 5. Carpineto Bridge, Potenza, Italy (source: Angelo, S. & Della Sala L. 2020).

The Maracaibo Bridge “held the world record for concrete cable-stayed bridges until the Wadi el Kuf Bridge in Libya was completed in 1971 by the same designer. The Wadi el Kuf Bridge with a single main span of 287 m followed the same design principles as Maracaibo”, but nevertheless, they add, that “despite the pioneering these bridges have not set a precedent in design of cable-stayed bridges”.

Figure 6. Pumarejo Bridge, Barranquilla, Colombia (source: Fundación Magdalena 2014).

4 SOME INNOVATIVE STRUCTURAL AND CONSTRUCTION CHARACTERISTICS

Engineer L. Sbalzarini (1962b), from the Morandi team that worked on the project, confirmed that the design complies with: i) Italian standards for the prestressing, and ii) the American HSS and the German DIN for mobile loads. Morandi, when tackling this project, was guided by the most advanced regulations of the times, and working with project considerations exacerbated by the conditions of the place led to innovative foundations and piles, and a superstructure of colossal dimensions that placed it among the largest in history.

4.1 *Foundations*

The depth of the foundations, corrosion and especially the particular characteristics of very fragile soil on the surface meant that it was possible to foresee, in the case of a work of this magnitude, a problem of potential local differential settlements or settlement by zones; in either case, the effects of this phenomenon would have been catastrophic.

"The superstructure is supported by 2184 piles that transfer loads to layered deposits of fine and coarse sands, silts, and normally consolidated clays. Nearly 56,000 m^3 of concrete was used in the piles (…) Piles were designed so that the tip transfers load preferably to the layers of coarse or fine sands to layers of silts at locations where the sand layers are at greater and impractical depths while avoiding the tip of the pile in the layer of normally consolidated clays" (Fargier-Gabaldón 2020).

The depth of the lake at the bridge site is up to 18 m, with the bottom covered with a layer of mud 2 to 28 m thick. On the west coast there are rocky layers of sandstone and conglomerates. At a depth of about 90 m below the water level, there is a layer of hard clay. This made the foundations of the bridge particularly difficult, especially in the central piers that had to transmit the enormous loads (around 40,000 t). "It was finally agreed to consider the piles fixed to two meters below firm ground of the bridge. At the zones nearest the shores and therefore of lesser depth it was sufficient to resort to short piling, using normal prefabricated piles of a maximum safe bearing capacity of 300 tons. For the deeper foundations on the other hand, larger piles were studied with larger bearing capacities (variable from 500 to 700 tons)" (Morandi 1960).

Drilling piles of different sections and depths with extraordinarily high bearing capacities were chosen. Thanks to a new technique of lateral and tip injection of cement mortar with load-bearing capacities up to 2000 t, all the piles were prefabricated and prestressed in the plant (Figure 7) that was prepared at the head of the bridge, allowing the placement of one-piece piles of up to 57.5 m, thanks to the use of powerful cranes.

Figure 7. View of the pile factory (source: Simons et al. 1963).

Three types of piles previously tested were used, according to Sbalzarini (1962b):

1. Circular section drilling piles with 1.35 m outer diameter with a bearing capacity of 675 t.
2. Cylindrical piles, for direct driving, 91.4 cm outer diameter, with a bearing capacity of 675 t.
3. Square section piles, for direct driving, 50 × 50 cm, solid and with a bearing capacity of 75 t. These piles are intended for the sections with 36.6 m span.

The drill piles were manufactured in sections of 1 to 6 m long, which were later combined and joined together with prestressed cables.

Depending on the load corresponding to each support, four to five drilling piles were planned for each support of the 46.6 m span sections, 10 to 12 for the 85 m sections and 62 piles for the 235 m sections.

The preparation of these piles required large auxiliary facilities in the prefabrication workshops.

The importance of these lies in the 67,000 linear meters of piles that were assembled and concreted in these workshops.

The handling of these heavy elements (up to 110 t), as well as their transport across the lake to the location, required a heavy type of auxiliary material" (Figure 8).

"Truly extraordinary equipment was set up for the drilling of the well and the laying of the tubes. Among them the platform and crane called *Elefante*, which was transported by flotation, but extended four legs that dug into the bottom, provided with a 65 m high tower, a 20-tonne machine and a 250-tonne crane" (Fernández Casado 1962) (Figure 9).

4.2 *Superstructure*

The most iconic part of the structure of the Maracaibo Bridge is made up of six large trestle piers and towers (piers 20 to 25) with five sections, each with a 235 m

Figure 8. Track tensioned and manufacturing of the piles: already finished on the right; and placing the reinforcement and prestressing anchor on the left (source: Simons et al. 1963).

Figure 9. Lifting of a 60 m driving pile, "*Elefante*" platform and crane with up to 250 t lifting load (source: Simons et al. 1963).

span and with a horizontal slope in all of them, exceeding a vertical clearance of 45 m, to allow the passage of oil tankers.

Fargier-Gabaldón (2020) states that "main piers have the three distinctive details found in many designs by Morandi: (1) two parallel A-shape pylons emerging from a pile cap; (2) X-shape struts, also emerging from the pile cap and rigidly connected to the deck; and (3) a simple arrangement of cable stays to support the deck. The A-shape pylons (Piers 20–25) and the X-shape struts lead to the rigid system introduced by Morandi, which has proven to be effective in stabilizing the deck under unsymmetrical live-load patterns while maximizing the effectiveness of the cable stays. The segment of the deck at the pylons is formed by a 5 m deep prestressed concrete box section, which receives four simply supported precast prestressed beams, 46.60 m long, at either end".

Conceptually, regardless of size, the difference in components of the main piers compared to the rest is that the first have cable-stayed ropes.

The horizontal slope of the bridge begins to descend towards both banks of the lake with two inclined viaducts with spans ranging from 22.60 to 160 m, supported by piles of variable shape built "in situ" and on which fixed beams of 22.60, 36.60 and 46.60 m are supported, which were prefabricated in pairs of beams.

In the 235 m long sections, the trestle piers have two towers, one on each side of the road; each tower is shaped like a triangle with a height of 92.5 m tall from the water level upwards. At the level of the road surface, the towers are connected to each other by 5 m high inclined bracing beams, which, together with two secondary structures in the shape of an "X", support the slab of the bridge. The entirety of the slab is the pier cap girder; this is an element 189.5 m in length, made up of an upper slab 0.25 m thick, another 0.25 m thick lower slab, four longitudinal beams 5 m high and six diaphragms, together forming a three-cell configuration in the longitudinal direction.

Additionally, Sbalzarini (1962b) specifies that "this central structure suspended by means of cables or winds has a piece of deck 189.05 m in length, and, therefore, it is necessary to insert, between one piece and another, four Gerber beams, 46 m long, in order to achieve the total length or span of 235 m of the section. The 235 m spans replace the 420 m single span foreseen in the initial project.

The trestle piers continue upwards from the deck slab in the form of two 92.50 m high tower above the lake level. At the top of these towers the cable-stayed ropes are supported. 16 cables make up each tie on both sides of the stack. They introduce a horizontal component of force into the pier cap girder that acts as a prestressing from both ends towards the intermediate part, throughout the entire cell box.

This configuration of compression forces means post-tensioning is only required in the anchorage zone of the cable-stayed ropes and at the point of support on the outer ends of the 'X' to resist gravitational loads, while in the rest of the structure of the pier cap girder only requires a minimum steel to attend shrinkage effects and temperature changes.

The cable-stayed ropes are anchored in a large inclined cross beam, concreted in the place provided for the anchorage of the aforementioned cables.

When the bridge was built, each tower had a single saddle at the top (two per stack) on which the cables passed from one end to the other continuously; this made it difficult to replace the cables, individual replacement being impossible.

When all the cables were replaced (1980), it was decided to build a double saddle on top of the original ones, to make the anchoring of the cables on each side of the stack independent and allow individualized replacement of any of the cables leaving the original saddles out of use; Figure 10 shows the configuration of the new pair of saddles on the original.

In the other sections of the Maracaibo Bridge, the trestle piers begin as walls of four vertical elements, passing from a certain height to V elements that open as the height increases, until the V is prolonged below

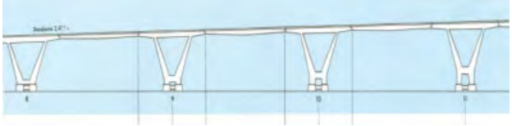

Figure 10. Top: Current saddle configuration in central piers. Bottom: Before (originally) (source: Precomprimido C.A. 1980).

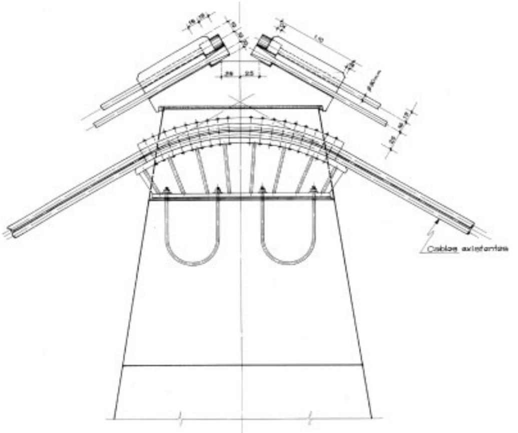

Figure 11. Supports with variable shapes from V to H in the 85m span sections. Source: Simons et al. (1963).

to form a X or an H, keeping a larger opening at the top than at the support level" (Figure 11).

The upper parts of these support some 39 m beams that span out 9 m on each side, leaving span voids of 46.6 m that are filed with series beams, hence obtaining 85 m spans that are most commonly found (26 voids) in both accesses.

At that time, the Ministry of Public Works introduced a proposal for the cable-stayed system to be replaced with a normal type of rope in emergency conditions or partial destruction in case of war, which allows a rapid repair and immediately put into operation, and effectively the cable-stayed ropes have been replaced entirely once, and later partially due to corrosion and lack of maintenance (Otaola 1982).

4.3 *Prefabrication plants and auxiliary marine machinery*

On the west bank of the bridge, on the side of the city of Maracaibo, a vast plant (assembly of reinforcements, loading dock, concrete manufacturing, etc.) was installed for the intensive prefabrication of all those structural components that were required, and that would simplify the construction of the bridge, and at the same time it was arranged for its transport by means of flotation.

The technology for offshore construction was designed entirely by Venezuelans, given their expertise in oil exploitation platforms on Lake Maracaibo, which involved the design of barges for driving piles (hammer barges) and piles for the type of bed the lake has, as well as accessories for the distribution of the loads to be hoisted, technological milestones that have gone unnoticed and of which there are few historical records.

The metal formwork was also assembled for concrete casting "in situ", and additionally, a 52 m span gantry crane, with a load capacity from 25 to 95 t, carried the pieces directly to the barges that transported them to the job site with auxiliary maritime machinery, which Sbalzarini (1962b) details:

a) The floating platform and crane, *'Elefante'*, whose central tower has a 250 t capacity crane, with a height of up to 70 m.
b) An 'Ajax' floating crane with a 300 t capacity, 52 m headroom and 135 t capacity if this height is raised to 75 m.
c) A 'Dixie' type dredge with two 248 and 82 CV engines, equipped with a 25 cm diameter suction tube.
d) Automatic, floating concrete mixer plants with different hourly capacities that vary from 10 to 30 m per hour.
e) For the central piers, special cranes were used that could reach up to 100 m in height".

5 CONCLUSIONS

The Bridge over Lake Maracaibo, older brother of the recently fallen and demolished Polcevera Bridge in Genoa, not only became the longest bridge in the world in its time, but also the pioneer bridge in R. Morandi's work in cable-stayed bridges and his largest work ever projected and carried out.

The Maracaibo Bridge significantly marked not only the work of the engineer Morandi, one of the 20th century's great bridge engineers, but also the history of cable-stayed and prestressed concrete bridges. This vast work allowed the participation of a large number of professionals, many of them international experts in large structures, bridges, and in reinforced and prestressed concrete.

For the foundations, all the piles were prefabricated and prestressed, totaling 67 km in length, never seen in the construction of a bridge. The truly innovative feature of these piles was their hollow cylinder shape filled in with reinforced concrete.

The length of the piles dug into the subsoil in the case of the six trestle piers with 235 m span. Measuring some 57.5 m, they were at the time the tallest piles in the world. They were built in segments, joined with post-tensioning cables and were placed in a single piece. Such piles would become known as "Maracaibo" piles (Simons et al. 1963).

Unlike the other cable-stayed bridges designed by Morandi, in the Maracaibo Bridge the cable-stayed ropes were left exposed, without being embedded in concrete, which has allowed visual verification of its deterioration and the need for maintenance and replacement at different times, which if carried out would extend their useful life (Otaola 2018). In Genoa the cable-stayed ropes were embedded in concrete.

Another innovation in the bridge over Lake Maracaibo was the replacement of the cables in 1980, and the construction of a new double saddle on top of the original ones, to make the anchorage of the cables on each side of the stack independent and allow individual replacement of any of the cables (Otaola 2018).

Finally, its construction required the use of large cranes that would reach up to 100 m in height, as well as platforms, cranes, dredgers, and concrete mixers, all of them floating, equipment not previously used.

6 RECOMMENDATIONS

Fargier-Gabaldón (2020) states that "structures like the bridge spanning Lake Maracaibo as well as the Bridge in Genoa have no redundancy, and the failure of one group of stays leads to the failure of the entire structure.

Although different structures, it is impossible not to think of the recent collapse in Genoa, apparently due to corrosion (…) Efforts shall be directed in the short term to monitor and maintain the cable stays.

Although it is nearly impossible to anticipate the service life of the structure, it is certainly related to the durability of the cable stays and integrity of the dapped ends.

The performance of foundations is also a concern because of the extensive corrosion that is affecting the entire structure".

He also recommends "that a comprehensive field investigation is required to assess the current the condition of the entire bridge".

Corrosion is definitely the main enemy and maintenance is the main guideline to follow for the preservation of the bridge.

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To all the participants in the design and construction of the Maracaibo Bridge, especially H. G. Henneberg (1926–2016), an engineer from the Technical Universities of Braunschweig and Hannover, who directed the surveying works of the Bridge over Lake Maracaibo in Venezuela. Professor at the University of Zulia (LUZ) in Maracaibo-Venezuela since 1961 (Drewes 2016).

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The USM HALLER stahlbausystem MINI-MIDI-MAXI, designed by Fritz Haller, 1959–1987

C. Nozza
Università della Svizzera Italiana, Lugano, Switzerland

ABSTRACT: A specific feature of the USM HALLER MINI-MIDI-MAXI prefabricated modular steel construction system, designed by the Swiss architect Fritz Haller, a pupil of Konrad Wachsmann, in collaboration with the engineer Paul Ulrich Schärer, is its potential adaptability and versatility intentionally programmed over time. The same architectural thinking, building logic and materials, spans three different technological thresholds, building scales and programmes: houses, schools and factories. Wohnhaus Schärer was the first private house built with the USM HALLER stahlbausystem MINI.

1 INTRODUCTION

When the architects Walter Gropius, Ludwig Mies van der Rohe and Konrad Wachsmann were forced to emigrate to the United States due to persecution in Germany during the advent of Nazism, they took both a full cultural endowment of knowledge and experience and consolidated technical and professional know-how.

The American Modern Movement thus developed in part thanks to the fecundation and subsequent maturation of innovative ideas brought from Europe by some of the leading masters of modern architecture. Once in the dynamic American context, they found fertile ground for conducting their research. These men of great culture and concrete design and technical abilities had the undisputed merit of intuiting and understanding the potential of the cultural context and technical production methods that had arisen in the new society overseas. This was the product of needs dictated by the typical instances of a young society, open to innovations, affluent and in the midst of its cultural, technological and commercial expansion.

At the end of what is termed Californian Modernism, characterized among much else by the works of Richard Neutra and the innovative Case Study House program commissioned by Arts & Architecture publisher and editor John Entenza, at various times between 1966 and 1971, the Swiss architect Fritz Haller also visited the United States to collaborate with Konrad Wachsmann at the Construction Research Institute at the University of Southern California in Los Angeles. There he took part in some experimental research into innovations in steel construction resulting from post-war reconversion of US military industry. Documents consulted in the Fritz Haller record group in the gta Archiv ETH-Zurich, made it clear that the Swiss architect, across the whole span of his career, never lost his interest in the design of industrialised prefabricated modular construction systems in steel. He always kept up close and continuous contacts with the circles engaged in research into and production of innovative industrialised building materials and systems for the North American market.

On his return, Fritz Haller was a leading exponent of the Solothurn school, a group of young Swiss architects that included Franz Füeg, Max Schlup, Alfons Barth and Hans Zaugg, all active in the canton of Solothurn. They never presented themselves under a shared manifesto but what they had in common was an approach that laid great stress on the architectural order, favoured industrial-looking materials and valued prefabricated construction systems and assembly. Matching the general mood of optimism in the 1950s, the designs of these architects liberated post-war Swiss architecture from traditional methods while simultaneously creating a basis for resisting the trends of later postmodern fashion. The new buildings could be simple and transparent, made of steel and concrete with large glass façades.

2 USM-HALLER/MINI-MIDI-MAXI SYSTEMS, 1959–1987

Fritz Haller was always active in the cultural debate surrounding him and, when having the opportunity, he openly expressed strong dissent towards a large part of contemporary Swiss construction practice, as completely uninterested in technological and industrial advances. This was particularly true of the metallurgical sector, which public opinion and some fellow designers considered unsuited to buildings for civil

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uses. Hence, thanks to his specific interests in industrial construction, towards the end of the 1950s he came into contact with the engineer and entrepreneur Paul Schärer and they began to collaborate on the design of an industrial plant in France, intended to be built with a load-bearing steel frame and lightweight, modular metal infill elements in the façade. The factory was never built but the development of this first construction system marked the start of a long process of design, diversification and specialisation that lasted several years. It eventually led Paul Schärer, as engineer, financer and director of the technical office of his company and Fritz Haller as architect, to patent the USM-Haller/MINI-MIDI-MAXI systems.

The three systems, designed for architecture, were progressively developed and initially used to create some of the buildings and pavilions that are still part of the USM industrial complex at Münsingen owned by Schärer's heirs. Together they were designed to construct buildings at different scales, degrees of complexity and characteristic flexibility in use. Each system included elements and techniques of assembly that enabled the buildings to be adapted, expanded or reduced over time, in terms of both the general volumetric configuration and the distribution of the internal functional programme. In this way, much of the USM-Haller/MINI-MIDI-MAXI design system was developed directly in the factory, defining different production and construction processes that would enable each single piece to enter into a modular relationship with the other components of the same system, a typical feature of closed prefabricated systems.

USM-Haller/MAXI was the first prefabricated modular steel structural system to be designed. It was generally used for the construction of single-storey buildings with large spans and was made up of elements for composing the load-bearing structure, roof, external walls and internal partitions. The structure, consisting of columns and lattice beams, could be expanded horizontally in all directions and the elements of the external and internal walls were removable and replaceable, but only by respecting the modular grid. MAXI was suitable for the construction of production plants that required very large clear spans and heights and the potential for easy expansion or adaptation over time.

In turn, USM-Haller/MIDI was a prefabricated modular steel structural system suitable for creating multistory buildings. All the components were coordinated so as to create, depending on the modular combination chosen, both simple buildings and more complex structures. In the 1980s, when Haller was teaching and researching at the University of Karlsruhe in an advanced programme that he proposed and directed, he made further innovations in the design processes for this system. He applied the new IT tools to the integrated design of both metal structures and the systems necessary for the construction of buildings versatile, efficient and complex in technological terms. This process he called "Armilla", a name chosen in homage to Italo Calvino's famous story published in Invisible Cities in 1972.

USM-Haller/MINI was a prefabricated modular steel structural system for the construction of buildings with one or two floors and load-bearing spans with centre-to-centre distances of up to 8.40m. The structure, consisting of pillars and beams made from cold bent sheet metal profiles, could be expanded horizontally in all directions. The external casing pieces were removable and replaceable but always in keeping with the predetermined form. The foundations, basement and underground sections in general were made to measure, adapted according to the programme and the final structure under construction. The MINI structural system was suitable for creating buildings with a variety of uses such as private residences, offices, small schools and medium-sized exhibition pavilions. Short construction times, rapid and easy installation, as well as the various assembly options, were the main advantages of this construction system.

In more recent years Paul Schärer and Fritz Haller designed and put into production yet another, the fourth USM-Haller/Möbel system, in a certain sense a synthesis of the first three, consisting of modular components devoted exclusively to the production of furniture initially made of wood and published for the first time in 1965 by the magazine "Bauen + Wohnen". Following the great interest aroused, industrial production began in 1969, this time with three-dimensional elements and joints entirely in steel. This fourth system was also patented. It still enjoys exceptional success today and is unanimously recognised as an icon of international design.

Between 1967 and 1970, the USM-Haller/MINI system was used with minimal variations in the construction of numerous residential and office buildings, such as the Schärer houses in Münsingen and Hafter in Solothurn, and the Imfels office pavilions in Sarnen and Mikron in Boudry. The potential programmable adaptability in width and height of the USM-Haller/MINI-MIDI-MAXI systems was then applied for the construction of many more complex public and private buildings such as schools and factories. An exemplary use was the set of pavilions with different functions and sizes that make up the current USM industrial complex in Münsingen, all built with one of the three systems or their variants.

3 WOHNHAUS SCHÄRER, USM-HALLER/MINI PROJECT, 1967-1969

Wohnhaus Schärer was an experimental project conducted in Münsingen deploying the USM-Haller/MINI modular prefabricated steel construction system to create an architecture capable of guaranteeing the potential for future changes in the general configuration of the building and interior spaces over time all the way through to its eventual complete dismantling.

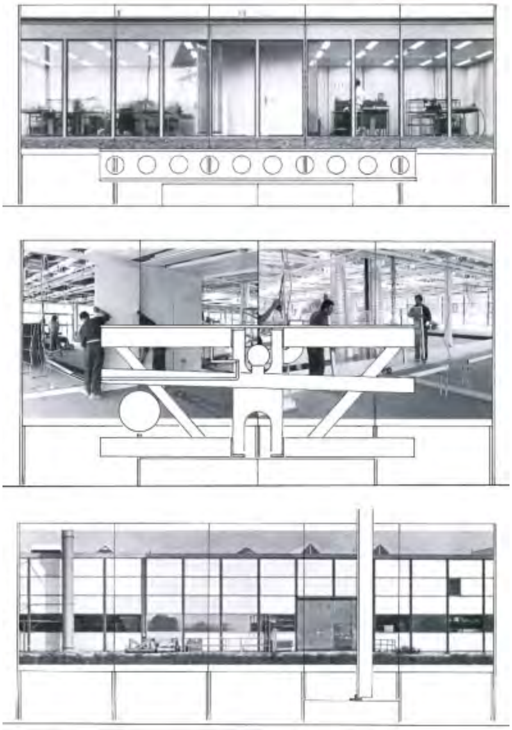

Figure 1. USM HALLER stahlbausystem MINI-MIDI-MAXI, typical structural frames – USM U. Schärer Söhne AG archive.

By consulting the documents kept at the gta Archives ETH-Zurich – Fondo Haller – folder USM-Haller/MINI-Wohnhaus Schärer 1967–1969, it has been possible to establish the precise dates of the various project phases. The preliminary drawings date from 1967–1968 while the detailed drawings delivered to the client, the engineer Paul Schärer, are dated 1969. The study of the USM-Haller/MINI construction system began with the entrepreneur Paul Schärer's idea of entering the world of prefabricated metal construction by starting to produce a modular construction system suitable for one- or two-storey buildings. To evaluate the feasibility and effectiveness of this system, both technically and in terms of problems with producing and marketing its products, Schärer decided to build a prototype house near his factory. He awarded the commission to the architect Fritz Haller, who in the period 1959–1964 had already designed the nearby production spaces by developing and then applying the USM-Haller/MAXI innovative construction system.

Wohnhaus Schärer was laid out on three levels. The ground floor contained the entrance and some distribution spaces. On the first floor there were the daytime quarters including the kitchen and a large living room, and the sleeping quarters with two double bedrooms, possibly adaptable to one double and two singles via a system of movable and sliding walls, a main bathroom and a service bathroom. The semi-basement level had a private office, a bedroom, a bathroom, the utility rooms and the bunker. The different levels were connected to each other by a prefabricated metal spiral staircase.

The structure of the two floors above grade was built out of steel elements typical of the USM-Haller/MINI system, while the basement was made completely of reinforced concrete and served as a base and foundation for the building above. The system was designed to build houses of one or two floors above grade, with clear spans of up to 8.4m between the vertical supports. This provided a typical supporting pillar consisting of a square through tube, main load-bearing beams 8.4m in length and secondary beams from 1.2m up to 6m. Every piece respected the 1M = 10cm dimensional grid and the 6M = 60cm module.

4 THE BUILDING OF WOHNHAUS SCHÄRER

As described by Fritz Haller himself in the numerous original documents consulted at the gta Archiv, the USM-Haller/MINI construction system is mainly based on the combination of modular elements assembled mechanically in situ, in principle either interlocked or riveted. Wohnhaus Schärer is located on a natural slope and the main habitable floor is supported above ground by thirty-six metal pillars of different heights, arranged to form a precise modular grid. Of these, one section rests on the perimeter of the basement built with perimeter walls in 20cm thick reinforced concrete, originally without any particular precautions for isolating the surrounding soil from humidity. The other pillars, external to the perimeter of the base, rest on isolated plinths embedded in the ground, also made of non-waterproofed concrete.

The primary vertical structure of the building is made of steel with through tubular pillars with a square section of 76.2 mm and a thickness of 6 mm. It has main beams with a "C" profile of 280 mm x 30 mm and thickness of 6 mm. The latter are characterised by numerous holes to make them lighter, each with a diameter of 160mm and spaced 300mm apart. The solution adopted thus made it possible to create a lightweight horizontal structure. Although it has proven not to be sufficiently rigid over time, it does guarantee considerable flexibility in the distribution of the electrical and ventilation systems as all of them can only pass through the thickness of the floors via the lightening holes inserted in the beams (Figures 4 and 5).

The typical connecting joint between the vertical and the horizontal structure, designed to be quick and easy to assemble, was initially conceived as a simple mechanical joint, consisting of a metal plate subsequently connected to the tubular pillars by means of two projecting T-shaped elements, in which the shaped heads of the beams are housed and anchored during assembly.

Once the primary structure has been erected, it is made stable with the installation of the prefabricated modules that constitute the framework of the horizontal reticular metal structure of the plates of the first floor and the roof. Finally, the structural framework of the building is completed with the further laying of the secondary C-beams in the floors, ordered according to the 120cm modular grid.

The corner supports of the iron structure of the horizontal floor plates are made by folding a suitably shaped metal sheet three-dimensionally and then fixing it with aeronautical rivets (Figure 6).

A further interesting aspect of the load-bearing modules of the floors, in addition to their considerable resistance to vertical loads, is their low weight and ease of transport. This is due to the general reduction in their thicknesses and the numerous holes to lighten them also present in all the secondary profiles.

To ensure the maximum freedom and flexibility of the internal space, which is the main feature and final architectural result of this construction system, the bracing of the pillars is achieved by twelve steel profiles shaped to an elaborate C section, bolted to the external front of the perimetral vertical tubular load-bearing elements, with a square and hollow section, corresponding only to the main structural axes. In turn, these stiffening elements are connected to the reinforced concrete foundations by means of point-loaded metal plates placed at the lower ends and embedded in the casting, which raise them elegantly clear of the ground (Figure 7).

In all of the structural load-bearing connection points, the joint between the primary and secondary elements is achieved by using threaded tie rods of the butterfly type that unite the pillars and main beams with the floor plates and make them stable.

The envelope of the façade rests aligned above the edge of the profile-covers of the beams on the perimeter of the floor plate and consists of fixed modular panels of 120cm x 240cm, consisting of double glazing connected to the support structure by means of a continuous neoprene profile, shaped to interlock around the whole perimeter (Figure 8).

Among the documents consulted at the Haller Fund, catalogues were found showing that the architect wanted to use a curtain-wall type system sealed in rigid neoprene, at the time mainly in use in the North American market. The set of these panels, with their relative uprights already at the time made up of two separate C-shaped profiles to avoid thermal bridges, contributes substantially to the structural rigidity of the first floor. The only elements that can be opened are the hinged French doors on the ground floor, which give entry to the building, and on the first floor, which allow access to the two terraces.

The external ceiling of the ground floor entrance area is covered with pure glossy white lightweight honeycomb panels, placed to protect the insulation above and attached to the structure of the ceiling plates.

The roof plate is made up of corrugated sheets supporting a layer of thermal insulation, the waterproofing layers and a layer of gravel, which serves both to drain rainwater and as protection for the underlying waterproofing membranes.

Figure 2. Wohnhaus Schärer, overall view of the southeast front, 1969 – gta Archives/ETH Zurich, Fritz Haller.

The interior finishes were advanced for the time. The support surface of the floors is made up of chipboard panels, resting directly on the metal structure to create a uniform support, covered in the communal and living areas with a uniform light gray carpet and in the wet service areas with black rubber Pirelli dot-type flooring. The internal ceilings all consist of lightweight and pure white glossy honeycomb panels attached to the structure of the ceiling plates.

For the division of the interior spaces on the first floor, Fritz Haller envisaged hollow-core insulated wooden walls, which were therefore light and could easily be repositioned and interchanged. Some of them contain hanging and sliding doors of varnished glass. The frames of these walls are connected to the supporting structure by means of continuous wooden guides, fixed to the intrados of the floor and ceiling slabs. Finally, each finishing panel is connected locally and by means of simple screws to the corresponding base and top in order to guarantee both the necessary stability and their easy repositioning if required over time.

The whole distribution network of the systems is built into the thickness of the floors and passes through the circular openings that lighten the metal beams, which are all acoustically insulated. The electrical system, the heating and air cooling system are distributed through flexible corrugated pipes that can potentially reach every area of the living space. This fully guarantees flexibility in the articulation of spaces, including the kitchen and the wet service areas.

5 FIRST UPGRADING OPERATION, 1986

In 1986, following a design by Fritz Haller himself, the embankment at the foot of the slope on the top of which the house is located was enlarged to support a small service pavilion for the swimming pool. This small, structure, which is neither heated nor cooled, is particularly interesting as it is built with a variant construction system, which simplifies and lightens the basic USM-Haller/MINI system to better adapt it to the specific new programme. Although it has never been codified or patented by the author, this variant is today confidentially called USM-Haller/MINI-mini.

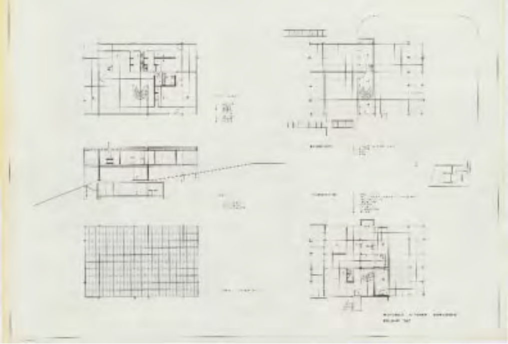

Figure 3. General drawings – gta Archives/ETH Zurich, Fritz Haller.

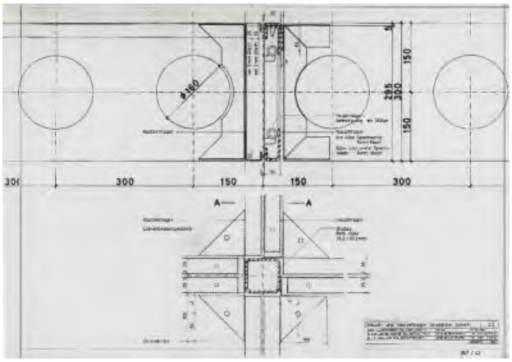

Figure 4. Typical joint between pillar and beam – gta Archives/ETH Zurich, Fritz Haller.

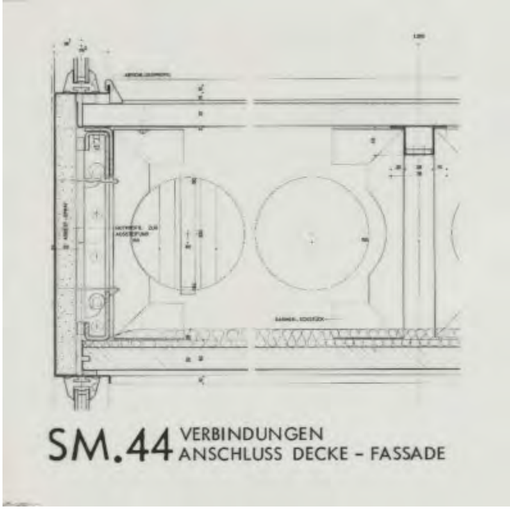

Figure 5. Typical section of the floor slab on the first floor – gta Archives/ETH Zurich, Fritz Haller.

Figure 6. Corner supports in shaped sheet metal – gta Archives/ETH Zurich, Fritz Haller.

Figure 7. Support on the ground of the load-bearing pillar – gta Archives/ ETH Zurich, Fritz Haller.

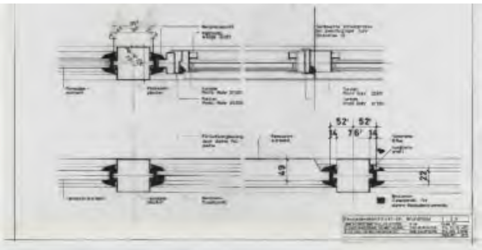

Figure 8. Assembly of the façade panels – gta Archives/ETH Zurich, Fritz Haller.

Figure 9. View of the completed structural framework – gta Archives/ETH Zurich, Fritz Haller.

The second main adaptation is of a structural nature and consists of reinforcing the metal floor plate of the main building's first floor in which new secondary beams were installed in addition to the existing grid, which has proved unstable with usage. These beams have long remained visible in evident contradiction with the general logic and overall proportions of the system.

Figure 10. View of the interior spaces – gta Archives/ETH Zurich, Fritz Haller.

Figure 11. View of initial phases of work on the integral conservative restoration – photo Nozza C., 2015.

6 RECENT CONSERVATIVE RESTORATION

Between 2015 and 2019, after the Schärer family moved permanently from Münsingen and a consequent short period when it was derelict, the Wohnhaus Schärer, now renamed Wohnhaus Buchli, underwent major redevelopment and restoration work on the main building as well as the annexes. The purpose was to recover their use as service guest quarters for the company USM. Architect Philippe Castellan of the Vuotovolume Architekten GmbH office in Bern was commissioned to design its restoration.

In July 2015, during a first visit in the initial phases of the work, it was possible to note the urgent need for he overall restoration and energy requalification of the whole complex of structures and buildings, and the incongruity between the solutions proposed in the original project and some local choices made later, or supported by Haller himself, during the subsequent stages of implementation.

During this inspection, the sensitive architectural and constructional ambivalence of the detail of the ground support of the C-bracing of the main pillars was of particular interest. While there is no doubt that it confers considerable elegance on the whole, it has nevertheless proven over time to be the most fragile constructional detail, which often required repeated intervention for its maintenance and consolidation. The particular tectonics of this detail, combined with its incorrect binding to the reinforcements of its respective foundation, the problems of condensation inside the pillars and the lack of waterproofing of the foundations, have constituted the main causes of the structural failures of the building that have occurred over the years.

Furthermore, the continuous welds of some connections between the main load-bearing elements then appeared immediately contradictory. Although they express the building's character as a prototype, at the same time they seriously negate the general principle of "pure" mechanical assembly, jointed or fixed with aeronautical rivets, intended to make for the fullest and easiest adaptability and reversibility over time, initially proposed for the whole USM-Haller/MINI system.

In October 2020, during a visit after the completion of the restoration work and upgrading of the energy performance for the reuse of Wohnhaus Buchli as guest quarters, it was found that this second intervention was able to recompose most of the main incongruencies found during the first site inspection.

Careful analysis and assessment was made of the state of preservation of the individual structural elements. After this, the Schärer Family, today represented for the fourth generation by Alexander Schärer CEO USM, given the prefabricated and modular nature of the original construction system and in consultation with the team of specialists, decided to dismantle the whole building and then reassemble it using almost exclusively the restored original elements. An exception was made for the thirty-six pillars, which were too badly decayed and therefore replaced with new profiles, but identical to the originals in material, shape and finish. Furthermore, most of the technological systems have been replaced to adapt them to the new comfort and energy saving needs, while keeping all the original exposed terminals in use, after restoration. In the same way, the thermal-acoustic insulation has been replaced to adapt it to the new regulations on environmental sustainability and safety. Finally, even the materials, the interior finishes and all the visible service accessories, when not fully maintained and restored, have been reproduced to precisely resemble the originals.

As for the above-mentioned fragility of the point of support on the ground of the pillars and the reinforcement bracing, the point-loaded foundations were completely replaced in order to correct the connection to the reinforcement and execute it as planned in the original project. This fact alone has unexpectedly made it possible to guarantee a new stability for the whole building that enabled the removal of the exposed beams added during the first intervention in 1986 and to eliminate the spot or continuous welds, reactivating only the joints and rivets.

Figure 12. View of final phases of work on the integral conservative restoration – USM U. Schärer Söhne AG archive – photo Opladen S., 2019.

Figure 13. Overall view of the north-west front after restoration – USM U. Schärer Söhne AG archive – photo Opladen S., 2019.

7 BUILDING PHYSICS ANALYSIS OF RECENT RESTORATION

The main construction and durability problem encountered in the original project is that it did not provide waterproofing and insulation for the underground structures. This decision, although very common for the time, has now been corrected by waterproofing and isolating all the elements.

As for climate control, the original project from the beginning envisaged the use of a ventilated system for both heating and cooling the rooms. Initially the thermal power plant was fueled by diesel and with this today replaced by a heat pump system that allows the rooms to be conditioned using renewable energy produced on the adjacent USM industrial complex.

Figure 14. View of the restored interior spaces – USM U. Schärer Söhne AG archive – photo Opladen S., 2019.

For the envelope, the double glazing on the façade, already planned as double in the original project, was replaced with sheets in the same colour and thickness as the originals but shatterproof, of low emissivity and with the air chamber filled with krypton gas to improve its heat-insulating performance to the greatest extent. The mobile screens were replaced and, according to the original project, placed only inside, identical to the originals and with the main function of protecting the sightlines.

The natural ventilation of the rooms is favoured by the position and orientation of the building, which allow sufficient air exchange through only the French windows, facing north-east for the sleeping quarters and south-west for the living quarters and the entrance.

Finally, while always intervening without any contradiction to the original construction system, thermal bridges were eliminated, for example by separating and insulating the surfaces of the facade elements in contact with the internal spaces, from those in contact with the exterior.

8 CONCLUSION

The architectures built mainly in Switzerland with the USM-Haller/MINI–MIDI–MAXI systems continue to prove functional and offer a high degree of comfort and liveability. This shows how greatly the design principles of adaptable evolutionary flexibility programmed in the design phase are an integral and living part of the history of the architectural construction. These appear among the decisive ingredients in the search for a general improvement to the habitability of built spaces over time. These principles determine spaces with a high degree of comfort and considerable aesthetic quality. They also prove to be all the more valid and effective the more they are programmed from the start of the integrated architectural design process in both private homes and in more complex buildings for productive or tertiary purposes. Finally, it should be noted that, as often happened with most prototypes of experimental architecture, Wohnhaus Schärer was initially built with craft methods. This is because it was intended to be a laboratory for testing the proposals and criticalities of the building system during its evolution with a view to its possible industrial mass production.

This construction system was the outcome of an era in which the issue of energy saving was not as urgent as it is today. The drawings and figures (Figures 2–10) tell us of its original simplicity, lightness and versatility but also the need for careful reflection on the themes linking construction to the issue of energy saving and the level of comfort of living spaces.

The challenge is to preserve the idea underlying the architectural project while using the original materials entailed in this type of intervention to protect and reuse the heritage. In each case, this involves identifying the most appropriate tools and methods. It also means preserving the original material of buildings with apparently fragile characteristics, while understanding the reasons for the original system and ensuring continuity of use and therefore maintenance.

For Fritz Haller, design and construction coincided and this architectural form is the direct experimental result of this. The work of the Solothurn school came to an end with the onset of the oil crisis at the start of the seventies. Today, it deserves to be rediscovered and critiqued.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The Catalan vaults of Roberto Gottardi's School of Theater in Havana: Some discoveries on the construction technique

M. Paradiso, S. Galassi & S. Garuglieri
Università degli Studi di Firenze, Florence, Italy

ABSTRACT: Despite their current state of high degradation, the National Art Schools (*Escuelas Nacionales de Arte*) in Cuba are currently considered the most iconic examples of the use of *tabicadas* vaults within modernist architecture. A wonderful example of organic architecture, these schools were designed in the 1960s by Italian architects Roberto Gottardi and Vittorio Garatti and the Cuban architect Ricardo Porro. They consist of five buildings set in a natural park of 660,000 m^2 dedicated to teaching dance, music, theatrical art, plastic arts and ballet. The Catalan or Valencian technique has been widely used in the schools. The actual technique used is not a pure Catalan technique, but mixed, aided by reinforced concrete members. Recent visits by the authors were dedicated to the study, in situ, of the vaults using non-destructive investigation and diagnostic techniques (thermography, ultrasound, video cameras). The paper describes these results and proposes them for public discussion.

1 SHORT HISTORICAL ESCURSUS

Las Escuelas Nacionale de Arte de Cubanacan, in La Havana, were founded by order of Fidel Castro Ruz in 1961, in the aftermath of the Triunfo de la Revolución. The site where they were to be built was the Country Club of Havana, an exclusive club for Cuban and North American upper middle class at the time of the US protectorate over Cuba (1899–1959) which culminated with the dictatorship of Fulgencio Batista y Zaldivar. The Country Club was founded at the beginning of the 20th century by the American entrepreneur Fredrick Snare, who had been a golf champion (León Valdéz 2018).

The Country Club, by order of Castro, was to be transformed into a campus for teaching classical arts: Theater, Music, Classical Dance, Modern Dance, Plastic Art. It was not only intended for young Cubans but also for young people from all over the Caribbean. The campus was to be built quickly, which meant using local materials such as brick, and limiting the use of reinforced concrete as much as possible to minimize the use of wood for formwork. Fidel Castro commissioned the architect Selma Díaz Llera, the very young director of the National Institute of Urban Planning, who turned to the architect Ricardo Porro (1925–2014), a Cuban who had just returned from exile in Venezuela. Porro involved two young Italian architects, known in Venezuela, the Venetian Roberto Gottardi (1927–2017) and the Milanese Vittorio Garatti (1927, alive).

The two Italian architects, the first graduated in Venice with Carlo Scarpa and the second in Milan with Ernesto Nathan Rogers, had both worked in the BBPR studio (Banfi, Belgioioso, Peressutti, Rogers), and then emigrated to Venezuela. The three architects chose, in the 660,000 square meters of the wonderful landscape of the Country Club, to place the buildings at the boundary of the area which they wanted unfenced, to give everyone the opportunity to cross it, enjoying the beautiful landscape, which in the past was exclusively enjoyed by only the upper middle class (Figure 1; del Toro 2003). Proponents of organic architecture, they chose free forms of dialogue with the landscape. Roberto Gottardi took charge of the School of Theater, Vittorio Garatti of Music and Classical Dance, Ricardo Porro of Plastic Art and Modern Dance. Having to use exposed brick as the construction technique for elevation walls and having to respect the same constraint for roofs, they immediately remembered the construction technique of the Catalan vaults. The three architects, the *Ministerio de Obras Públicas*, later *Ministerio de la Construcción* (Micons), were joined by a team of engineers and 2000 workers. Because of the long spans that the 1vaulted system had to cover, the engineers did not trust that the thrusts of the vaults on the supporting walls could be absorbed by the elevation walls. Therefore, they strengthened the buildings with reinforced concrete elements arriving, as in the case of the vaulted pavilions of the School of Classical Dance of Vittorio Garatti, with a structure of covered reinforced concrete. They designed the guides for the construction of the vaults. However, many changes were made from the executive project to the actual realization, because the technicians were forced to carry out many tests in the laboratory on scale models to verify the stability of the vaults. The result of these experimental verifications led to substantial changes in the execution phase and revealed that there was a lack of detailed knowledge of the various steps of this process.

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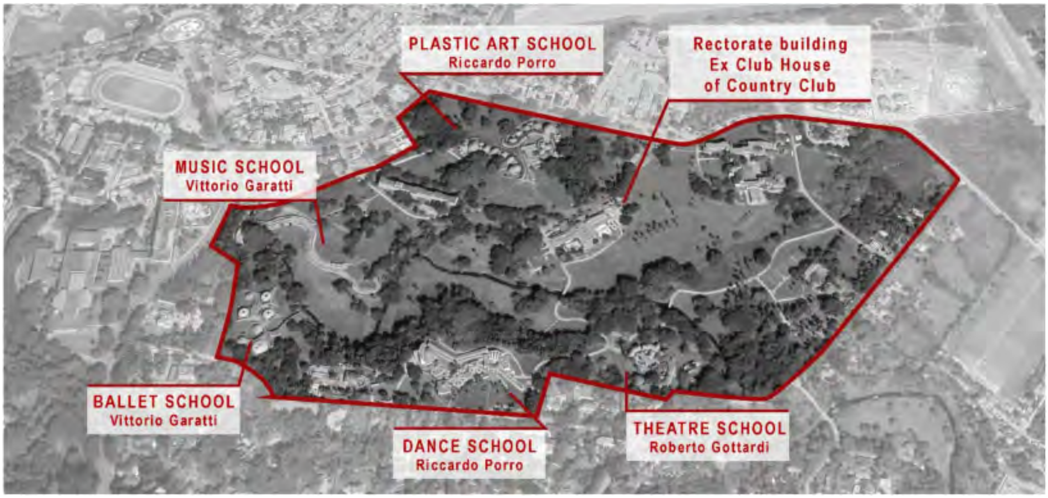

Figure 1. Plan of the National School of Art in Havana into the Country Club area.

The work began in 1962 and was interrupted in 1965 due to both the consequences of the Bay of Pigs crisis and a line of thought of Cuban architectural culture strongly opposed the school of organic architecture. This was linked to the wide internal debate, opened with the relationship between Cuba and the Soviet Union, regarding the meaning of "*Arquitectura de la Revolución*". After the closure of the construction site, the three designers continued to work for MICONS on the projects that were assigned to them according to the priorities of the Cuban Government, aimed at the construction of schools, hospitals, barracks, and buildings for civil housing, following the construction ideas of the Soviet model. However, shortly afterwards, Ricardo Porro was able to emigrate to Paris where he lived until his death.

Vittorio Garatti, accused of being a collaborator of the North American government, was expelled and returned to Milan where he still lives. The only one who, despite being subjected to the humiliation of a period of confinement in labor camps, chose to stay in Havana was Roberto Gottardi.

The Art Schools, at the time of the interruption of the works, were in the following constructive condition: the School of Plastic Art was 95% finished, the School of Modern Dance was 95% finished, the School of Classical Dance was 95% finished, the School of Music was 55% finished, missing the two great amphitheaters, and the School of Theater was only 40% finished. Despite these shortcomings, the training activities continued making the most of the available space, but without respecting the intended use.

The Classical Dance School was never used. The reason is attributed to the opposition of Alicia Alonso, who was the main reference for Cuban classical ballet. In 1974 cracks occurred in the buttresses supporting the Catalan vaults of the entrance corridors of the School of Plastic Art which marked the beginning of decades of little or no ordinary maintenance work (Figures 2 and 3). In 1977 a didactic reform flanked the ENA (Escuela Nacional de Arte), primary, secondary and pre-university schools, with the Instituto Superior de Arte (ISA), a university institute. This forced the teaching of ENA students in the School of Modern Dance alone. Decades of impoverishment of the built structures followed, until the Art Schools lost the international visibility that Fidel dreamed of and which the three architects had aroused in the 1960s. It was John A. Loomis' book (Loomis 1999, 2015, 2020) that led to the international rediscovery of the Schools and gave strength to DO.CO.MO. Cuba (International working party for DOcumentation and COnservation of buildings, sites and neighbourhoods of the MOdern Movement) to indicate the need for restoration and completion by Fidel Castro himself.

Figure 2. M. Paradiso (2006), detail of the buttresses supporting of the School of Plastic Art.

Castro publicly declared that it had to be done, yet took into account the changes in the teaching methods of the Arts, which foresaw new forms of Art at the beginning of the third millennium.

Figure 3. M. Paradiso (2003), cracks in the buttresses supporting in the entrance corridors of the School of Plastic Art.

The restoration and retrofitting works began around 2002 and were managed by MICONS. The works began at the Schools of Plastic Art and Modern Dance of Ricardo Porro, but several errors were made both from the point of view of structural strengthening techniques (Paradiso 2016), and of the landscaping. In particular, paved roads inside the complex and small reinforced concrete (hereafter r.c.) bridges over the river that crosses the campus (Rio Quibú) were built.

Furthermore, since in previous years the entire campus had been completely fenced off, entrance sentry boxes were added to each of the Schools overlooking the outer perimeter. These decisions were not welcomed by the three designers who perceived these interventions as a distortion of the identity and authenticity of the original complex, betraying the spirit of the 60s. The restoration of Porro's two schools was completed in 2008 and, in the meantime, Roberto Gottardi was encouraged to redesign the missing part, considering the educational reforms of the teaching of Theater Art. In fact, in 2008, the restoration of the Theater School was also carried out, starting with the replacement of the first intrados and the last extrados layer. In 2011, the Cuban Government greatly reduced the budget for restoration, leaving ordinary funding to ISA and ENA, which was insufficient even for minimal maintenance work. Thus, the schools returned to oblivion. In 2014, the first author of this paper began to investigate at the *Ministerio de Cultura* of Cuba, which has long been in charge of the complex, and at the Italian embassy, the possibility of drawing up a Human Development Cooperation project aimed at the restoration and qualification of at least one of the five schools. MINCULT chose to intervene on Roberto Gottardi's School of Theater. From 2014 to the end of 2017 the cultural and political foundations for its approval were built. With a complex work of various bureaucratic steps, both in Cuba and in Italy, the project was approved in December 2018 by the Italian Agency for Development Cooperation (AICS-MAECI), which entrusted the technical advice for the restoration, strengthening and refunctionalization of the School of Theater to the Department of Architecture of the University of Florence, at the suggestion of MINCULT. The funding of the Italian Cooperation is 2.5 million euros, which is matched with similar funding by the Cuban Government. The activities, which began in early November 2019, will last four years.

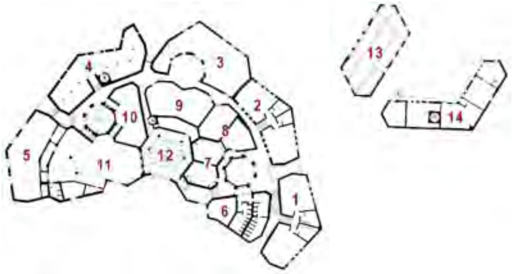

Figure 4. Blocks numeration of the School of Theater by Roberto Gottardi.

2 THE STRUCTURE OF THE COOPERATION PROJECT ACTIVITIES

Onsite activities began in September 2019 but stopped in late March 2020 due to the Covid emergency. The project, titled "¡*Que no baje el telón*!", provides input in the first-year training courses for students of ISA and the Universities and Research Centers of Havana, as well as Architects, Engineers and officials of these institutions. The courses deal with the topics of digital survey of built historical heritage, material degradation and restoration, degradation and structural strengthening, organization of the restoration site, BIM techniques for restoration and the final course dedicated to the drafting of an Atlas of the Built Historical Heritage of the Playa Town Hall, to which the ISA Campus currently belongs.

The training activities are expected to develop in the first year, together with studies and research useful for the drafting of the complex executive project of restoration and strengthening, in order to leave, in the following years, time for purchasing the materials necessary for the worksite and the site itself. In this article, the activities related to structural restoration, particularly dedicated to the "Catalan vaulted structures", are discussed.

3 THE CATALAN VAULTS OF ROBERTO GOTTARDI'S SCHOOL OF THEATER

Of all the five Art Schools, the buildings of the School of Theater have a vaulted system that at least formally retraces the "Catalan vaults" (Figures 4 and 5). They present a state of deterioration of materials, the result of decades' long lack of maintenance, and structure due to the presence of some cracks in the intrados and the interruption of the last layer of brick replacement works at the time of the restoration from 2008 to

Figure 5. M. Paradiso (2008), Top view of the vaults and state of decay of *rasillas* in the School of Theater by Roberto Gottardi.

2011. The executive project drawings from the 1960s had always been kept in the Historical Archives of MICONS until 2007, when they were acquired by the Historical Archives of the *Oficina del Historiador* (OHC) in Havana. Therefore, the first activity was the retrieval and study of historical maps, but, surprisingly, the documentation present at the OHC was much reduced compared to what was known from the story of the protagonists at the time. In addition to this, other archives have been consulted and studied, such as Roberto Gottardi's private archives. However, no document explaining how these vaults were actually built has been found. However, this information, even if found, would still have been necessarily unreliable because the trials and tests on models carried out in situ led to changes with respect to the design indications. The stories and oral testimonies of the coprotagonists of the 1960s, as well as Roberto Gottardi himself, collected from 2003 to the present day, have not clarified whether, nor to what extent, the thickness of the r.c. elements in Catalan vaults were determined, whether they were transverse beams to stiffen the vaults, or whether they were real reinforced concrete layers. To partially clarify the question, a copy of a magazine from the time of the construction, *Ceramica Convencional*, has been found (AA.VV. 1961–1962). It is a kind of manual for the construction of different types of Catalan vaults that provides precise technical specifications for their execution. It is the result of an experimental work by a group of researchers of MICONS in the 1960s, useful especially to compare the size and thickness of the vaults of the School of Theater with the specifications contained in the manual. In the last part we present photos of examples of vaulted architectures realized in Havana previously or in the same period of the construction of the ENAs. It is surprising that the date of publication reported is 1962, but it refers to laboratory experiments carried out after this date, until the photographs of Vittorio Garatti's Ballet School, was just finished. Therefore, a clear contradiction. In the authors' opinion, this is a publication made after 1964, deliberately backdated for future reference to give the idea that there was vast experience and knowledge in Cuba of the construction technique of the *bóvedas tabicadas*. However, as the study progressed, the suspicion of the presence of reinforced concrete in the thickness of the vaults grew stronger and stronger, especially with the consideration that the heavy reinforced concrete rings that surround the skylights could never rely on the strength of the slender vaults, which are structures typically resistant by shape. For this reason, it was essential to deepen the research both through the study of historical photos and the few project drawings found and through invasive and noninvasive diagnostic investigations on some of the FAT (Facultad de Arte Teatral). Considering the above, it was necessary to carry out further diagnostic investigations to fill the gaps regarding the construction techniques used. From the study of the few drawings of the project preserved in the Archives of the *Oficina del Historiador* of Havana referring to the early 1960s, details emerged that immediately confirmed the hypothesis that inside

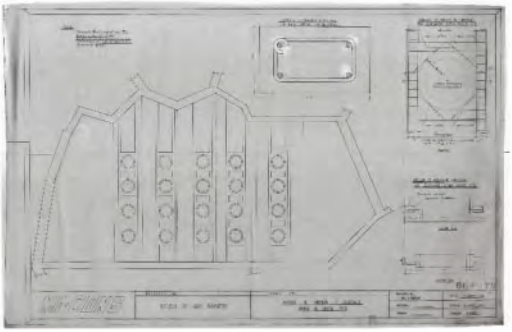

Figure 6. Project drawing representing the block 9 (1963), Oficina del Historiador of Havana archive.

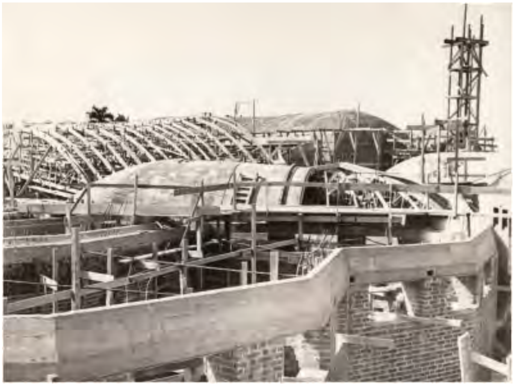

Figure 7. Historical photo of the construction site. In the background it is possible to see the ach centerings or guides used for the construction of vaults. R. Gottardi archive, date n.d.

Figure 8. Historical photo of the construction site stamped by Cuban Ministry of Public Works. R. Gottardi archive, 1962.

Figure 9. S. Garuglieri (2020), Thermographic image realized in collaboration with Arch. Luca Valisi, part of Prof. Del Curto's Research Group of Milan Polytechnic in Getty Foundation project. Thermographic image representing the vault of block 9 in the intrados.

the vaults, but especially in relation to the skylights, there was the presence of r.c. elements to support them (Figure 6).

Moreover, from the study of the historical photos of the construction site, present in the private archives of Gottardi, it was possible to make further observations regarding the executive techniques of the FAT buildings. From the images found, some of which are not dated but can be attributable to the years 1962 to 1965, it is possible to notice the presence of centerings, or guides, useful for the construction of the brick *tabicadas* vaults as shown in Figure 7. Sometimes the arch centerings seem to be "coupled" and arranged at such regular intervals that one would think they are real form works used for the insertion of ribs inside the vaults. In any case, this hypothesis is unlikely because the intrados surface of the vaults is continuous and entirely made of bricks. Therefore, the ribs, if existing, should have been built after, at least, the first layer of *rasilla*s (long thin bricks).

In this regard, Figure 8 shows a discontinuous arrangement in the layers of *rasillas* that seem to be interrupted at regular spacings where "voids" are clearly visible, especially when looking at the head of the vault. The most probable hypothesis is that the "voids", which have a shape that can be traced back to the ribs visible in the drawings of the project, were made in order to become themselves brick formworks for the casting of the reinforced concrete ribs directly inside the thickness of the vaults. Finally, the construction site phases for the construction of the vaults have been hypothesized: (1) positioning of the first two layers of continuous *rasillas*; (2) arrangement of the additional upper layers of *rasillas* with the creation of voids with the function of formwork for the subsequent casting for the realization of the ribs and arrangement of the prefabricated reinforced concrete skylights; (3) drilling of the two layers of intrados *rasillas* to create the opening of the skylights.

First, to definitively address the issues about which many words and theories have been spent, but which, however, lack a direct match with the artifact, thermographic investigations have been carried out, in particular in the intrados of the vaults of those blocks whose project drawings were available and which could, therefore, be compared with the thermographic images obtained that, once again, seem to confirm what had been hypothesized (Figure 9).

Figure 10. M. Medero Peréz (2020), Core drilling B in the top of vault of BLOCK 9 carried out by ENIA company.

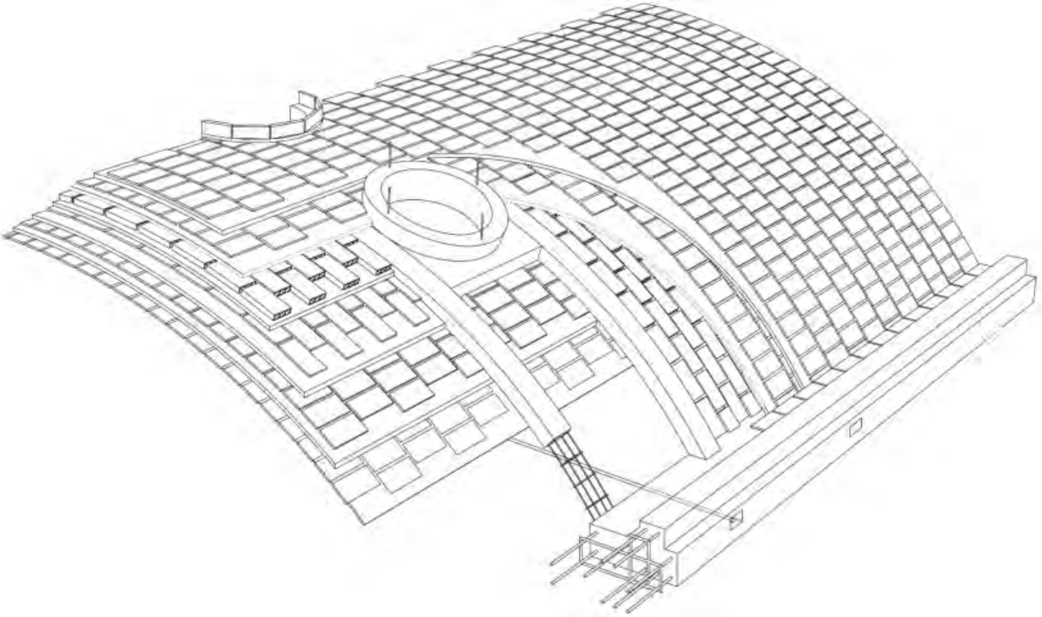

Figure 11. S. Garuglieri, Graphic artwork: hypothesis about the stratigraphic structural composition of the Catalan vault of Block 9.

Also, in this regard, due to the impossibility of finding other nondestructive instrumentation in situ, it was decided to carry out invasive investigations. The thermographic images directed the core drilling performed in early March 2020 by the company ENIA (*Empresa Nacional de Investigaciones Aplicadas*, Havana) on a block considered significant, referred to as BLOCK 9. The core drillings have been performed respectively where the presence of possible r.c. ribs had been hypothesized, therefore in tangent with one of the skylights (Core drilling B) and in a generic point of the vault in order to understand the stratigraphic composition (Core drilling A).

In the latter case, it was possible to do a thorough core drill that made it possible to understand the nature of the vault at this specific point. This vault seems to be composed of five layers of *rasillas* of about 1 to 1.5 cm of thickness, the second layer of which, compared to the extrados, seems to be constituted of perforated bricks about 4.5 to 5 cm thick with 2.5 cm thick mortar joints (Figure 10).

In any case, it is highly probable that this block may have been affected by the above mentioned 2008 restorations and that it, therefore, lacks the last layer of *rasillas* in the extrados part and, consequently, that the vault may have originally consisted of a total of six layers.

As far as “Core Drilling B” is concerned, the core drill, which cannot cut the reinforced concrete iron bars, was able to make a non-through hole due to the interception of a metal reinforcement.

The portion removed is composed of a layer of extrados *rasillas*, a layer of mortar and a layer of reinforced concrete.

In so doing, it was possible to definitively confirm, the initial hypothesis about the presence of r.c. ribs inside the vault, in correspondence to the skylights. Thanks to the study of the stratigraphy and the technical details contained in the various project drawings of 1963, a three-dimensional reconstruction was carried out that could better describe the structural and technological composition of the vaulted system of BLOCK 9.

Instead, the details related to the bars of the reinforced concrete are taken from the 1963 tables where the dimensional indications of the iron bars are also reported (Figure 11).

In any case, although on BLOCK 9 it was possible to rely on thermographic investigations and core drilling and, therefore, possible to deduce and elaborate a technological and structural detail, it would not be advisable to believe that this model can be extended to the whole complex. In fact, starting from the technical indications of the MICONS engineers, responsible for the executive drawings of the reinforced concrete structures, it seems that during the execution phase of the vaults each team adapted to the specificity of the vault of the building where they had to work. This means that for this and other reasons, at the current state of knowledge and the results of the in-situ investigations, it is not possible to determine in detail a single execution technique for all buildings. Only further and more in-depth investigations, even during the execution of the restoration works, can resolve these doubts (Tempesta & Galassi 2019; Galassi & Tempesta 2019).

4 CONCLUSIONS

Las Escuelas de Arte de Cubanacan are still considered the most beautiful and complex example of “Catalan style” vaults outside the Iberian Peninsula. The reference to *tabicadas* vaults was made by the designers themselves and reiterated in all the texts and articles that have spread outside Cuba over time. However, almost no one in the technical literature, has addressed the problem of studying and verifying the real construction technique. Neither John Loomis’ nor Gulli’s works address this issue, while John Ochsendorf has dealt deeply with the Guastavino’s family but never with the Schools of Art. Not even the work of Eladio Dieste can be taken as a reference in the authors’ opinion, because the fantastic forms with inversion of curvature analyzed do not fit with the Catalan vaults, given the inversion of curvature of the forms of Dieste that required the use of the inner reinforcement. However, if the Catalan vault is strengthened by an inner layer of reinforced concrete, the mechanical compatibility between the two different materials is not assured. In fact, the deformability of r.c. is 10–15 times less than that of ceramic material which leads to malfunctioning of the r.c. *rasillas* coupling, especially under dynamic action, such as those provoked by strong winds or cycles of strong thermal excursion during the wet and dry season.

If in the last 20 years the idea that a mixed technique could be defined, such as that used in the Schools, our first results of field investigations show that these vaulted coverings are very different from the pure technique of *tabicadas* vaults. This may be due to the ancient conception, which fortunately is gradually being overcome, that the world of architecture and the world of civil engineering are separate worlds. And therefore, during the years of the construction, the engineers and the workers of that time had to resort to a series of expedients and improper inclusions that only served, in the uncertainty that this forgotten technique in Cuba could work, to make the free forms, conceived by the three designers, feasible. The authors do not expect any more surprises from further studies, only confirmation of what has already emerged. However, it is obvious that it makes no sense to carry out any structural strengthening and/or restoration work if the construction and technological corpus of the building is not known in detail. We trust that our efforts will contribute to a more truthful knowledge of the history of the National School of Art in Havana, convinced that this architecture, for the cultural context in which it was born, for the few economic resources used in the attempt to support its construction, and for all that has been mentioned above, remains a unicum in the history of building.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Plovdiv concrete: Modern, bold, valuable? Houses of youth and of science and technology

Iva Stoyanova
Independent scholar, Plovdiv, Bulgaria

ABSTRACT: This paper presents two important examples of reinforced concrete construction from the 1970s and 1980s in Plovdiv, Bulgaria. These are large-scale, public buildings and examples of in-situ concrete construction with some precast concrete elements. This paper is the first to argue that the buildings represent significant local accomplishments in concrete construction, a conclusion based on an examination of the structural and architectural use of concrete in each building. The paper draws on unpublished archival documentation and personal onsite investigations as well as the discussions in architectural textbooks and magazines of common building practices at the time. This study also compares the two buildings, which were built at the same time and had similar design and construction requirements. Finally, the paper considers if the use of concrete was approached differently in the two buildings and the 'concrete' heritage value of each building.

1 INTRODUCTION

1.1 *Standardized design, industrialized construction*

The processes of project design and construction in Bulgaria from 1944 to 1989 were largely shaped by the political and economic organization of the reigning Socialist regime. One of the main state goals at the time was advancing the technical development of the country. This period was marked by the large-scale construction of various architectural typologies, such as residential complexes and public and industrial buildings, as well as the creation of powerful production facilities serving mass construction.

As in other sectors of life, building design and construction were planned and carried out through regional subdivisions representing centralized state power. In the field of project design and urban planning, architects, various engineers and technicians were assigned to such subdivisions after graduating from universities or specialized high schools. Likewise, construction was executed by regional building units representing the state, such as the Plovdiv Construction and Assembly Combine.

The state's pursuit of fast yet high quality technical progress resulted in the implementation of standardized designs for building projects and the industrialization of construction. The methodology of standardized building design was taught in university-level architectural programs, as can be seen in a number of textbooks on architectural construction used at the time (Angelov 1989; Lazarov 1975, 1976; Popov 1972). According to these books, standard design was the main prerequisite for industrialized construction. Standardization and simplification were taught as leading design principles. They were achievable by means of the modular coordination of building dimensions, and thus, each building had to be developed through a modular system.

The application of the modular system to structural elements resulted in the structural grid of each building. For each type of building, typical structural modules were developed, taught and applied in practice: for example, for residential housing, they varied from 2.40 m to 6.00 m (multiples of 30 and 60); for industrial buildings and warehouses from 3.00 m and 6.00 m; and for agricultural buildings, 1.50 m (Popov 1972).

1.2 *Prefabricated or in-situ concrete construction?*

Textbooks on architectural construction strongly recommended prefabricated construction because of its high degree of standardization and industrialization, which made it cheaper and allowed projects to be completed in less time than in-situ concrete construction. Prefabricated design was promoted in textbooks for both the load-bearing structure of the building and the finishes (Angelov 1966, 1973). Thanks to mass production of prefabricated building components, 30% of housing and 12% of public buildings were partially or entirely built with them by 1963 (Angelov 1966, 3).

That fewer public buildings were prefabricated was due to their variability: the specific differences every project presented as spatial concepts, including their architecture, functional requirements and integration with surroundings. Thus, prefabricated elements were used less for the construction of public buildings than for other architectural typologies.

Instead, in-situ construction in reinforced concrete was favoured for public buildings. Textbooks

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recommended it for its advantages such as the ability to be shaped in a range of forms, stiffness of structural connections, fire safety and anti-corrosive features and the minimal cost of long-term maintenance (Angelov 1989; Popov 1972). Exposed concrete in particular was appreciated not only as a modern material in architectural design but also as the time- and cost-effective alternative to traditional finishes that were executed by hand and difficult to mechanize (Angelov & Petrov 1970, 12).

1.3 *Modern tendencies in architecture and construction*

Bulgarian architecture at that time was influenced by contemporary architectural trends in the West and the Soviet Union. Ideas from both worlds were combined in the architectural design of many buildings. Foreign examples were taught in the universities and reached practitioners in the local state agencies for building design and urban planning through current periodicals, which were kept at the agencies' libraries. The influence of the Soviet Union was very strong in the areas of architectural engineering and building construction. The principles of standard and modular design, simplification and industrialized construction were the products of this influence.

The use of exposed reinforced concrete followed one of the modern architectural tendencies for public buildings: expression of the load-bearing structure. Inevitably, the geometric forms and exposed concrete surfaces conveyed an architectural reference to Brutalism, which was among the popular architectural trends.

This tendency of structural expressionism derived from the theory that a public building was the unity of architecture, function and structure (Lazarov 1975, 8). This theory affected all the design phases starting with the functional layout of the floors and ending with the architectural details. As for the latter, the concept at that time was to expose through the architectural design the technical nature of construction details, such as the connection between the columns and beams (Angelov & Petrov 1970, 5).

1.4 *Plovdiv, the District House of Science and Technology and the District House of Youth*

As the second largest Bulgarian city, Plovdiv was a national leader in the fields of light industry, education and culture. The city was the administrative center of the homonymous region, and its economic and industrial growth was consequential for the technical progress of the whole region. The rapid development of Plovdiv resulted in the need for new public buildings. These would reflect the regional importance of the city and house the activities of various administrative, public and cultural agencies that served the region. Two of the new buildings were a District House of Youth (DHY) and a District House of Science and Technology (DHST).

The main purpose of the DHY was to accommodate cultural events and initiatives for young people. Before it was built, such gatherings took place in one of the pavilions of the International Plovdiv Fair known as 'Hambara' hall [the 'Barn'] (D"reva 1978). As for the DHST, it had to house the services offered by the 12 technical and scientific unions representing 12 economic sectors (Dom na naukata i tehnikata – ideen proekt 1967). Most of all, this new building was necessary to offer an appropriate space for international exchanges with the technical unions of other countries during the International Fair in Plovdiv, which is still held today. Eventually, both buildings were built in close proximity to two different parts of the centrally located Tsar Simeon's Garden.

The design and construction of both buildings received wide coverage in the local press and periodicals as significant examples of modern architecture and large constructions in reinforced concrete. DHY has a ground floor measuring 1 500 m^2 and the larger DHST building spans a 2 500 m^2 ground floor (Boyadzhiev 1976). The local newspaper *Komsomolska iskra* was in charge of publishing regular updates on the construction of the DHY, including various construction problems and deadline delays (Iskrov 1974). The DHY, begun a few years before DHST, was reported to be the largest reinforced concrete building project in the country at the time, and even if that claim cannot be confirmed, it was probably the largest local one (Boyadzhiev 1976). As for the DHST, its project was featured in the national *Arhitektura* magazine: the magazine of the Ministry of Construction and Architecture and the Union of Architects (Grekov 1976).

Both buildings exist today and have been adapted for uses similar to the original purposes. The DHST accommodates the seat of the non-profit organization 'Scientific and Technical Unions of Plovdiv', as well as commercial establishments, spaces for lease and exhibitions, and a cinema. The DHY houses the seat of Plovdiv Municipality Council, and spaces for lease and recreation. Yet, as often happens with Socialist-era architecture, the inevitable association of both buildings with the past regime and its ideology hinders an appreciation of the buildings as potential heritage architecture. Both have received little attention from scholars, especially from a construction-history point of view.

Are these buildings unrecognized local feats in reinforced concrete? What are their architectural and structural merits? Did they conform to the design principles for standardized design and industrialized construction? Did they answer to the above-mentioned modern tendencies in architecture and construction? What were the design and construction challenges and their solutions? Does their comparison reveal different approaches to architectural and structural design for the same problems in reinforced concrete construction?

2 GOING BIG IN CONCRETE

Reinforced concrete was reported to have been first used for construction purposes in Bulgaria in 1905

(Angelov 2011, 154). One of the first structures built with reinforced concrete column-and-beam frames dates from 1920. From then on, this construction system diffused widely throughout Bulgarian building practice. Its structural and architectural potential was largely developed in the period after the Second World War.

With respect to the DHY and DHST buildings, analysis of the technical drawings of their structural designs and the proportions of their volumes reveals the bold attitude of the architects and structural engineers at that time with respect to reinforced concrete. Their work pushed local construction practice forward.

2.1 *The District House of Youth 'Yordanka Nikolova' (DHY)*

The building is composed of a parallelepiped-like, three-storey volume, with a higher cube-like volume accommodating a meeting hall (Figure 1). The volumes are organized around a semi-internal courtyard that once had a water mirror, which referred to the large lake with fountains in Tsar Simeon's Garden. All building parts are topped with flat roofs used for outdoor retreat. The roof areas are accessible through several external staircases, built in exposed concrete. The DHY was integrated with Tsar Simeon's Garden by means of a system of outdoor spaces such as the courtyard, the staircases and the rooftop terraces.

The architects at the head of the DHY design team were Vesel Rakshiev, Iglika Belyakova and Emiliya Todorova, all from Sofia. They worked with the famous local structural engineer Lyuben Sofkarov (1922-2004) and others as employees of 'RPO – Plovdiv', which was the local agency for building design and urban planning.

The DHY accommodated numerous cultural activities for youngsters from the whole district including a literary club, a cinema club, a string orchestra, two choirs and a youth mini-theatre. The building was designed with a spacious foyer for art exhibitions, a meeting hall (400 seats), an art hall, five rooms for extra school activities, two pastry shops with dancing floors, a café on top of the roof and three gaming rooms.

The facilities for centralized building services and a garage were placed in the basement. The outdoor staircases provided separate entrances to the different functional units of the building. The concept of independent entrances was recognized as a valuable feature of the functional design (Milchev 1978).

Construction lasted four years, from 1973 to 1977. Newspapers reported various problems during construction that caused numerous interruptions. The reason quoted most often was delays in the submission of detailed technical drawings (Iskrov 1974). Eventually, the building opened; its official inauguration was on November 5, 1977 (D"reva 1978).

2.1.1 *The big cantilever*

The available archival documentation includes only architectural drawings from the technical and detailed design phases. The structural plans and information on treatment of the surfaces of the exposed concrete were not kept in the Plovdiv State archive.

Figure 1. The DHY today. The meeting hall is located in the cube-like volume to the left. Image: Iva Stoyanova, 2020.

Nevertheless, the architectural drawings show the structural components of the building (Mladezhki dom – chertezhi arhitektura tehnicheski proekt 1971). Analysis of the drawings reveals that the load-bearing structure consisted of rectangular columns and beams cast in place in reinforced concrete. The structural grid of this building was developed through several modules varying from 6.60 m x 3.30 m (the largest) to 4.20 m x 1.50 m (the smallest). They comprise a grid of 17 vertical and 6 horizontal axes.

The meeting hall has a square plan (19.55 m x 19.55 m), 6.50 m high, and is elevated 4.35 m from the ground floor (Mladezhki dom – chertezhi arhitektura raboten proekt 1972, 10). The whole space of the hall is column-free, which is achieved by the use of 'waffle' slabs for the roof and for the floor. The slabs are 0.10 m thick, and the joists are 0.90 m deep. The whole cube-like volume containing the hall was designed as a structurally autonomous part, separated from the rest of the building by a 5 cm construction joint.

The large dimensions of the building volumes were inseparably bound to the architectural message of the DHY. It can be argued that the large Brutalist building volumes were intended to communicate the idea of youthful boldness and determination. The meeting hall, the dominating building volume, was a place where youngsters from the whole region gathered for special events; it was the functional and ideological heart of the building. It highlights the main entrance by projecting over it with an 8-metre cantilever.

This cantilever stands out as one of the most characteristic structural features of the DHY. A projection of 8 metres is still considered to be a significant length considering local seismic activity. For comparison, the Bulgarian building code today allows a standard cantilever projection to be no more than 1.80 m.

2.2 *The District House of Science and Technology (DHST)*

The DHST is a step-like building comprised of a three-floor volume and a five-floor volume separated by a construction joint (Figure 2). Just like the DHY, a basement contained a garage and centralized facilities for building service systems. The step-like structure

Figure 2. The DHST today. Image: Iva Stoyanova, 2020.

is shaped by the 4-m cantilevers of the balconies, which integrate the building with the neighbouring Tsar Simeon's Garden.

Construction work on this building took ten years to complete, from 1975 to 1985. The project was headed by architect Milcho Sapundzhiev (1934-2016) along with architect Kolyu Kolev (1934-2009). They were among Plovdiv's most renowned local architects. For this building project they worked together with the famous local structural engineer Dragiya Aleksiev. All members of the design team were employed in the 'RPO-Plovdiv'.

Arhitektura magazine stated that the load-bearing structure was assembled from prefabricated columns and beams (Grekov 1976). Yet, onsite investigation and analysis of the recently located archival documentation testify to its construction in reinforced concrete cast in forms on site. The archival documentation of the DHST includes drawings of the structural design showing formwork and reinforcements (Dom na naukata i tehnikata – konstruktsii raboten proekt 1973), records that are not available for the DHY (Mladezhki dom – kofrazhen plan konstrukcii tehnicheski proekt 1971). This allows for more detailed analysis.

2.2.1 *Standardization and functional flexibility*

The DHST had to accommodate multiple functions usually found in separate public buildings: conference halls, teaching rooms, a bookstore, a library, an exhibition hall, offices for inventors and researchers of working-process improvements, a business club, a pastry shop, a cinema and a restaurant.

At the same time, the application of the concept of modular coordination of building dimensions for the sake of standardization produced a two-fold problem. First, the various functions called for different typical design modules. Therefore, the DHST had to either adopt a modular system based on one function or on several. Second, the application of any modular system would inevitably result in a fixed geometrical pattern of the structural grid that could limit functional flexibility.

As archival technical drawings of the structural design illustrate, one structural module was chosen for the DHST – 9 m x 9 m (Dom na naukata i tehnikata – konstruktsii raboten proekt 1973). On the ground floor, which is the floor with the largest enclosed area, the grid is comprised of five horizontal and seven vertical axes. This relatively large structural module was chosen no doubt in order to gain functional flexibility by generating a wide span between the columns.

Analysis of the archival drawings reveals that the requirement for standardization was very strictly applied to all the components of the load-bearing system. Rather than decreasing in size on the upper levels, where they support less weight, they have the same shape and dimensions on all building levels. The typical column has an I-section (0.65 m x 0.65 m). Beams are typically paired sections (2 x 0.20 m x 0.80 m). The floor slabs are always two-way slabs with beams spanning between the supports. Slabs also have a consistent section height on all floors (0.18 m).

The archival drawings of the structural design reveal that the concrete parapets are another standard building component, because all the parapets were designed with the same section and dimensions (1.52 m x 0.12 m). Long and solid concrete parapets were rare in in-situ concrete construction because of the difficulty of executing precisely-shaped corners and surfaces (Angelov 1973, 192). This was the case in the DHST, where all the parapets are very long, yet thin. The reinforcement plans show that some parapets are reinforced like beams and labelled as such. This allows classifying these parapets as another load-bearing element.

Given the variety of functions in the DHST, the necessary building services were challenging to standardize, especially in terms of their location and installation slots. Space was secured for most of them wherever a reasonable route for their installation route could be found, horizontally and vertically. Holes made in the floor slabs to install vertical services were not closed up. Special attention was given to the rainwater downpipes. These were accommodated by placing them against the web of the I-section columns.

2.2.2 *The Vierendeel beams and the hangers*

The technical drawings reveal how reinforced concrete was intentionally adopted for two large-scale beams. These structures are labelled the Vierendeel beams in the drawings. The first was used in the façade wall of the cinema (Figure 3). It was designed as a single beam (2.85 m x 0.25 m x 18.10 m) with eight openings (1.65 m x 1.63 m) and placed above the band of windows.

The second instance was a fork-like beam – a panel with a section cut out on the top, with a series of posts through the cut out; the small openings (0.35 m x 0.37 m) between the posts accommodated the building services infrastructure (Figure 4). Nineteen of these beams support the concrete floor slab under the main staircase. If the first example clearly corresponds to the usual profile of a Vierendeel beam, the second instance deviates from that typology. It was probably given this name because of the small web perforations.

The structural use of reinforced concrete also can be seen in the design of special hangers on the third, fourth and fifth floors. These hangers are braced between the two beam sections, and they carry the lower floor slab.

Figure 3. The wall behind the pyramids and over the window band (above) is actually a large beam with openings (in black below). Images: Iva Stoyanova, 2020.

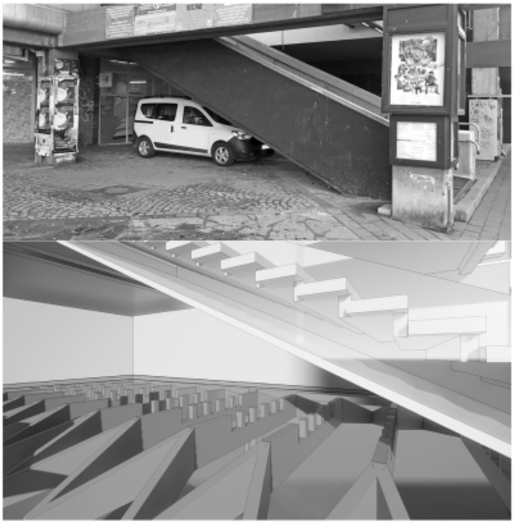

Figure 4. The slab under the main staircase (photo, above) is supported by fork-like beams (drawing, below). Images: Iva Stoyanova, 2020.

Thus, a part of the load of the lower slab is transferred to the upper beams, which contain an excess load-bearing capacity since they have the same dimensions as the lower ones yet support the smaller loads of the upper floor (Figure 5).

3 DECORATING IN CONCRETE

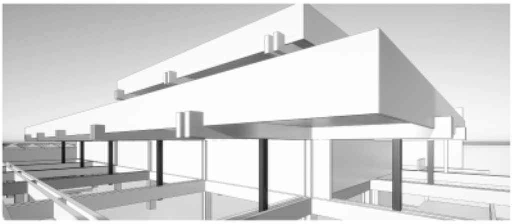

Figure 5. Concrete hangers (in black) on the fourth floor. Image: Iva Stoyanova, 2020.

Figure 6. Flat-roof outfall in exposed concrete. Image: Iva Stoyanova, 2020.

The use of exposed concrete characterizes both buildings. In the DHST, exposed concrete and brick masonry are the principal materials of the walls. Such a combination was typical in the designs of public buildings (Angelov & Petrov 1970, 19). Departing from this approach, the architects of the DHY combined exposed concrete with a variety of other finishing materials such as wood and stone cladding on the exterior.

3.1 *Exposed structural concrete*

In the case of the DHST, the structural concrete adopted for the columns, beams and interior staircase was left exposed. A text note on the technical drawings specified that planed wooden material be used for the formwork boards. As visible onsite, these boards had a vertical pattern for the columns and a horizontal one for the beams.

In the case of the DHY, exposed concrete can be observed in the external staircases, façade walls and cantilever beams. The flat roof parapet walls and their outfalls were also built of exposed concrete (Figure 6). The architecture of structural concrete of the cantilever beams is two-fold: first, the exposed texture of the concrete cast in-situ and second, the curved pattern of the joists of the 'waffle' slab, which follows inscribed and semi-inscribed circles. This decorative pattern is not found in the archival documentation. It recalls the pattern of the original decorative sign next to the entrance of the building (Figure 7).

Unlike those in the DHY, the columns and beams of the DHST have chamfered corners. Such corners are indicated only in the case of the columns in the technical drawings. However, they were necessary for both the columns and the beams to facilitate the dismantling of the formwork without damaging the newly-formed concrete corners that would remain exposed afterwards.

Textbooks on finishing work and exposed concrete give insights into several formwork practices taught at that time. For example, Angelov explained that

Figure 7. The decorative pattern of the ‘waffle’ slab over the main entrance. Image: Iva Stoyanova, 2020.

formwork made of planed wood produced a smooth finish to concrete cast in-situ as can be observed both in the DHST and the DHY. Usually, such formwork was assembled from planks that were sawn from softwood. The planks needed to be at least 2.5 cm thick and 10 cm wide in order to form a solid board. They fit together with a tongue-and-groove connection (Angelov 1973, 82–83).

Angelov also gave several significant tips with regard to casting concrete in-situ in deep formwork, tips that can apply to the column formwork for both the DHST and DHY. The crucial requirements were to pour the concrete gradually for a short distance in layers no more than 30 cm thick and then to vibrate them well, preferably with a needle vibrator (Angelov 1973, 89).

As for the treatment of exposed concrete surfaces post-construction, no information has been found so far for either building. In building practice at the time, three main groups of impregnating materials were usually adopted: saponified metals, silicone resins and sodium and potassium methyl siliconate (Angelov 1973, 93–94). Other alternative materials were bituminous substances with additions of phenolic and vinyl resins or artificial rubber as well as plastic resins. These materials were mechanically applied as protective water-repellent coatings. Further investigations including lab tests of samples from the less deteriorated surface areas of both buildings should verify what post-construction treatments may have been applied.

3.2 *Precast architectural concrete forms*

In both buildings, the architectural use of concrete can be observed in modular shapes particular to each case. While the buildings used in-situ concrete construction for the structure, they also incorporated precast elements. For the DHST, these were the pyramids used in the roof and the façade of the cinema hall, for concrete slats and for parapet and wall panels. For the DHY, the vents and slats were made of precast concrete.

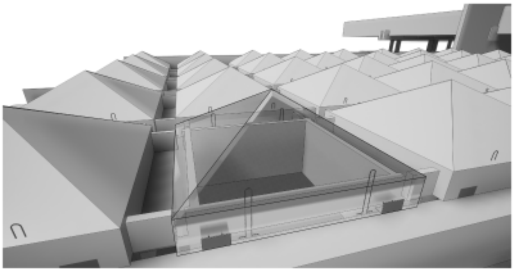

Figure 8. Decorative pyramids cover the roof; also shown are the installation hooks. Image: Iva Stoyanova, 2020.

Figure 9. Almost identical parapet and façade panels. Image: Iva Stoyanova, 2020.

3.2.1 *Pyramids and ribbed panels for the DHST*

The pyramids were designed with bases that could fit perfectly into the cassettes of the ‘waffle’ roof slab. Additional concrete parts allowed the pyramids to be placed and attached to the slab by means of metal planks (Figure 8). The same detail is indicated for the installation of the pyramids on the façade of the cinema. As the technical documentation indicates, the concrete of the roof pyramids was cast with special installation hooks embedded, which protrude vertically from the sides. They facilitated lifting and manoeuvring the pyramids during their installation.

The concrete parapets and the façade walls of the upper floor were clad with similar types of panels that featured a ribbed finish (Figure 9). The latter differ from the former in the lack of an indentation for decorative purposes. As can be seen onsite, the panels were precast in light concrete. Common building practice at the time offered two main ways of getting a decorative ribbed pattern like this (Angelov 1966, 17–18).

One way was to apply it by hand to the concrete surface while it is still plastic enough, by means of a specially shaped roller. The other way was to cast the concrete in a formwork with a specially shaped, ribbed bottom. The precise and regularly shaped ribs of the existing panels suggest the use of the second method.

The regular panels form a continuous finishing layer on the external surface. This means that the vertical joints were subsequently processed and concealed in the vertical groves between two neighbouring panels. Most probably the ribbed design of the panels was chosen because it offered a safe way to conceal the vertical joints. For this reason, it can be deduced that the panels were produced with great precision in dimensions which guaranteed the same width of vertical joints between them.

3.2.2 *Slats and vents for the DHY*

The technical drawings for the DHY reveal the decorative use of concrete in the ventilations system vents

Figure 10. The missing concrete slat (to the left), digitally reconstructed in place. Image: Iva Stoyanova, 2020.

Figure 11. The vent shafts. Image: Iva Stoyanova, 2020.

and horizontal slats (Mladezhki dom – detaili 1972, 42-43).

The slat grid was placed in front of an exhibition hall window on the ground floor facing the main street, probably not only for decorative purposes but for blocking sunlight. This slat is no longer present on the building. It was comprised of seven horizontal slats (15 cm x 10 cm x 10.55 m) attached to four posts (10 cm x 15 cm x 3.70 m) (Figure 10). All were precast in reinforced concrete as noted in the text part of the project design. The drawing suggests that each slat was composed of two equally long parts (3.60 m) and a third shorter one (3.35 m). The parts were spliced at their connections to the posts. The posts were connected to the building structure by means of metal planks. Such slats were widely diffused in the architectural language of many public buildings (Angelov & Petrov 1970).

The vents were two identical shafts that served to supply fresh air supply to the building. As text notes on the detailed design specify, all the elements were precast and the concrete was left raw. An analysis of the drawings shows that each vent is composed of two parts with square bases (1.40 m x 1.40 m) that fit together (Figure 11). Although it is not specified, their connection was most probably grouted with cement or concrete in-situ. The upper part has triangular openings with metal grids.

4 CONCLUSIONS

The DHY and DHST were among the important new public buildings designed according to the architectural trends of the time, notably the popularity of Brutalist style architecture. As large-scale constructions in reinforced concrete, they signified the rising significance and technical progress of Plovdiv and its region. Both buildings had to accommodate various public functions, to abide by the principles of modular coordination and standardization, and yet offer functional flexibility. Although both examples were designed with in-situ concrete structures, the two buildings differ in their overall design approach to the structural and decorative use of concrete. The DHST can be defined as an example of concrete construction with a very high degree of standardization applied to all the load-bearing components. The spatial grid of this building is based on only one structural module. In contrast, the structural grid of the DHY can be defined as a ‘patchwork’ of several structural modules and one dominating structural field – the meeting hall. In both buildings, load-bearing elements had difficult-to-cast shapes and dimensions. Such complex forms were not recommended in architectural textbooks because of their construction challenges. Nevertheless, their presence today testifies to the successful handling of this risky construction. For the DHST, the most challenging elements were the long and thin solid parapets and the Vierendeel and fork-like beams. For the DHY, they were the ‘waffle’ slab under the roof with its curved pattern. Another notable feature of the DHST with regard to the structure was the employment of reinforced concrete not only in its supporting capacity but also in its ability to ‘hang’: the so-called hangers skillfully make use of the excess load-bearing capacity of the upper-floor beams. As for the decorative use of concrete, raw concrete was a preferred finishing material for the DHST. It was used in various forms and shapes: from exposed structural concrete to concrete molds. The DHY mainly relied on exposed concrete texture in combination with other finishing materials. Although these buildings are unknown internationally, they are important pieces of local construction history in reinforced concrete, notable efforts to realize the goal of a unity of architecture-function-structure. Their architectural and structural merits testify to the success with which the design requirements and construction challenges of the time were successfully met.

The study of these two buildings also shows that their value as heritage architecture lies in their structural features as well as their architecture. They deserve to be officially listed as heritage buildings. To properly assess them in context, studies of similar buildings in other Eastern European countries should be developed, which would also serve as the basis for proper and timely conservation of such concrete structures.

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Open session: Building services and techniques

History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Observations on the design and building of the Roman Segovia Aqueduct

J. Tomlow
Hochschule Zittau/Görlitz, Zittau, Germany

ABSTRACT: The dry masonry structure of Segovia Aaqueduct (ca 100 AD), in granite, is a masterpiece of Roman construction design. Observation of hoisting holes and scaffold holes are analyzed on their impacts. Photographs show the existence and position of the holes. Since the brittle material reduces detailing options, only traces of simple holes have survived over time. Hypotheses on the origin of these holes are discussed, also by comparing aspects to other insights on Roman scaffolds. A possible light scaffolding system is presented for the aqueduct's piers. They were mainly work platforms, not to be used for storing granite blocks. Possibilities of safe wedging of the blocks at high altitude, necessary because of the hoisting device iron forceps, are presented, also in respect to ergonomics. In drawings, phases of the construction process and its careful preparation by skilled staff are illustrated. The current contribution adds substantial new insights.

1 INTRODUCTION

"To summarize, it does not seem unlikely that (…) in order to create very tall and safe scaffolds whose elements could be used flexibly, all wooden parts were relatively small in size, but joined in a clever, easy way" (Albrecht & Döring-Williams 2018, 315).

Looking up at the aqueducts of Segovia (Figure 1), or Tarragona (Figure 2), one wonders, how such slender structures, built 1900 years before our time, can still exist. How to work at such heights? How did the builders lift weights up to 1 ton? In May 1984, the author visited Segovia and observed certain holes in the dry masonry surface, the position of which seemed to be relevant for the building process which resulted in a publication (Tomlow 1989a).

In the current paper, chapter 3 is a revised, abridged version of the author's quoted publication of 1989. All the rest has never before been published.

Figure 1. Segovia Aqueduct 728 m long, max. 28 m high, 112-116 AD. (Photo Peter Bak, 1984).

2 STABILITY OF AQUEDUCTS

Mağlova Kemer Aqueduct, crossing the Alibey Stream (near Kayseri, Turkey) was built by Mimar Sinan in the

Figure 2. Tarragona Aqueduct/Aqüeducte de les Ferreres, Catalonia, Spain, 217 m long, max. 27 m high, probably 1st century AD. (Photo Jos Tomlow).

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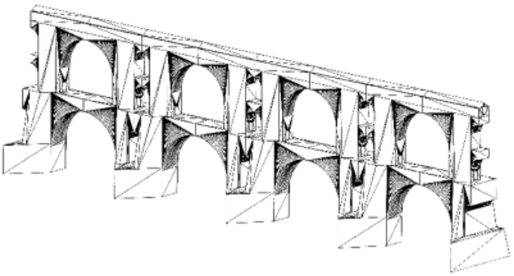

Figure 3. Mağlova Kemer Aqueduct by Mimar Sinan (CAD drawing by Jochen Maier 1994).

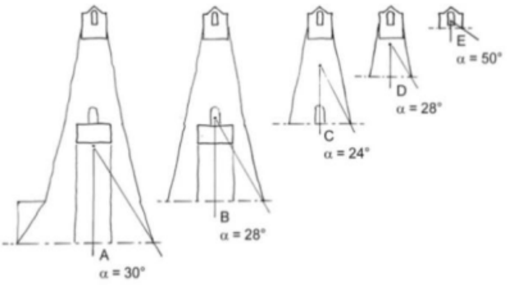

Figure 4. Mağlova Kemer Aqueduct. Five sections A-E with gravity point and tilt-angle. (Scheme drawing Jos Tomlow based on Mayer 1994).

Ottoman period (start of the works of the water supply system 1555, 1563 flood incident, restored 1564, 258 m long, 36 m high, top width 380 cm, base width 11 m.).

The purpose of the survey is to identify gravity points of structure sections, Mayer 1994. A technical model concept by Prof. Frei Otto, Institute of Lightweight Structures (IL), Stuttgart University, states that a tall slender structure may tilt – thus becoming unstable – not only at its base level, but also at any higher level. By dividing the structure in discrete design sections, gravity points of these parts may be simulated in a CAD-model (AutoCAD 11), or in a physical model. The result on Mağlova Kemer Aqueduct, like similar studies for the Tarragona and Segovia aqueducts, showed that the structures were very well designed, thanks to the stepped or pyramidal shape, as in Figure 2. The main gravity point in Mağlova Kemer Aqueduct is in a position 14.05 m above fundament top or 39% of the total height of 36 m.

Mağlova Kemer Aqueduct is much less slender than the two named Roman Aqueducts. Mimar Sinan took account of earthquake effects based on documented observations of his time (Çeçen 1992).

From modern static calculations, the 1992-99 restoration architect of Segovia Aqueduct, Francisco Jurado Jiménez, concluded that the Segovia Aqueduct was designed properly for its own weight loading. The pier sections grow in their area along with the increase of load. He also calculated what would happen if one of the lower arches were to fail and collapse. The result is that the thrust of the next lower arch does not force a pier to collapse (Jurado Jiménez 2001).

3 HOISTING GRIP HOLES

The use of hoisting grip holes – in German, *Zangenlöcher* – is well known in Western Europe as typical for the building process since the Romanesque and Gothic periods and often depicted (Binding & Nussbaum 1978). In a normal stone block, the holes are positioned on two opposite long faces, not far from the top. The depth of these roughly conical holes or cavities is a few centimeters. In them, a scissor-like hoisting grip may find hold to lift the block.

In Roman times the tool was called *ferrei forfices* (Vitruvius 1629, book X). The scissor-like iron forceps are held by a short flexible rope or chain (Figure 7). When the forceps is lifted, the grip on the block is held as long as the hoisting device is under tension. This method was considered to be secure and save.

3.1 *Common knowledge on Roman construction*

Half-circle voussoir arches which span the space between the piers have been executed by arranging the prepared stone blocks on heavy wooden scaffolding. Such wooden scaffolding rests on piers at either side, on a cornice. When the arch is closed, the wooden scaffolding may be removed after careful lowering and is ready for installation in the next bay (Adam 2010).

A further observation concerns the stepped shape of the piers, almost pyramidal at all four sides (Figures 1 and 2). On the one hand, the stepped shape adds stability to the general structure for side forces like wind or earthquakes and for decay of material substance over time, because it implies a low position of the overall structure's gravity point. On the other hand, each pier section shows a cornice with a sloping top surface. Jean-Pierre Adam interprets some cornices to be there for practical reasons, along with stylistic concerns (Adam 2010 174-6). The same kind of cornice may serve as a base for a working platform for the pier section above. Thus, a wooden scaffolding structure does not need to stand on ground level, which means that one saves precious wood. Given that a pier section weighs, for instance, 60 tons, it may be clear that any scaffolding can easily suspend from this huge mass.

3.2 *Hoisting grip holes in Segovia Aqueduct*

The position of holes in a normal, straight block resembles the way two handles are made along the top of a ceramic pot. They are at the same height and exactly opposite. In a more abstract definition: The holes in the block's face are made according to the middle axis – vertical gravity line – on a safe distance from the top edge. In this way, the block is held balanced and with a horizontal top face, when it is lifted. But how would a Roman know where a voussoir block – of trapeze shape – gets the two holes? From the two arches observed, all visible holes are depicted in the drawing in their correct position (Figures 5 and 6a).

Figure 5. Segovia Aqueduct. Top arches on piers. All granite blocks show hoisting grip holes. (Photo Peter Bak 1984).

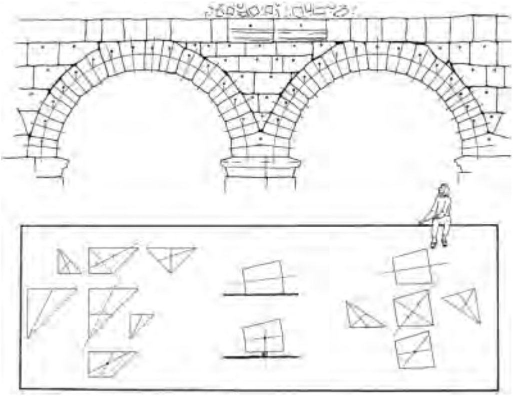

Figure 6. Top. Segovia Aqueduct. Top arches on piers. Hoisting grip holes appear in upward distance from the gravity points (Drawing Jos Tomlow). Bottom: Possible graphical methods, to locate a gravity point, following the Greek mathematician Archimedes of Syracuse (c. 287 – c. 212 BC). In the middle, an empirical method for locating a gravity point: crossing of two gravity lines (Drawing Jos Tomlow).

The set of rules on how the hole position is conceived seems to be the following (Figure 7). Each voussoir block is treated as an individual case. For each block, the gravity point is marked on the side face. The way the voussoir block is part of the masonry lay-out is considered relevant for the correct hole position. The lay-out of an arch is checked empirically, by assembling the voussoir blocks turned 90˚ on their side face, on a flattened soil area. This compares with a working platform on a cleaned and flattened level of wood or gypsum – in German, *Reißboden* – which was to try out the tracery or rib design in the Gothic period (Wendland & Ventas Sierra 2018). Subsequently, the position of the hoisting grip holes was marked by taking some distance vertically over the gravity point. Finally, the holes were carefully executed, also on the opposite side. Alternatively, this could have been done in their normal position, on wooden scaffolding at ground level and eventually the arch lay-out could be prepared in a scale drawing. It should be checked whether the distance of the hole to the top border is sufficient, depending on the stone quality and block's weight.

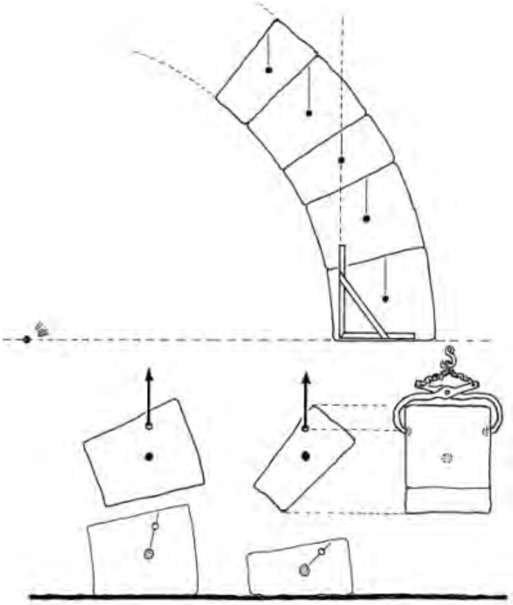

Figure 7. Method to find the correct locations of hoisting grip holes upwards of the gravity point of a voussoir block. The lay-out of the arch is considered to be tested on ground level, turned all blocks on their side (90˚). During hoisting with iron forceps (*ferrei forfices*), the block turns naturally in the position it will take in the arch lay-out (Drawing Jos Tomlow).

This results in hypothesis 1: *All blocks are prepared with a pair of hoisting grip holes in a position, which ascertains that during hoisting, the block turns naturally in the angle it needs in the voussoir arch.*

Following this, the workers do not need to turn the suspended blocks in the right position (Tomlow 1989a). Given a block of 500 kg, a person weighing 70 kg would have problems handling such a task, namely that of turning the block suspended from the forceps.

According to Alonso Zamora Canellada, the low areas of the piers (related to the original soil level) do not show hoisting holes, which he interprets as a sign that the lowest blocks were positioned by other means than with a crane and forceps (Zamora Canellada 2013, 33–5).

4 MORE HOLES AT SEGOVIA AQUEDUCT

Many years after this discovery, the author, preparing architectural history classes about the Roman Empire, was intrigued whilst looking again at the photographs of his fellow traveler, Peter Bak (Figure 8). In the pier blocks there is an abundance of small holes showing a strange pattern.

The shape of these holes is shown in the drawing in Figure 9. The top edge of the block is carved at a depth of approx. 7 cm. Each hole is shaped like half a

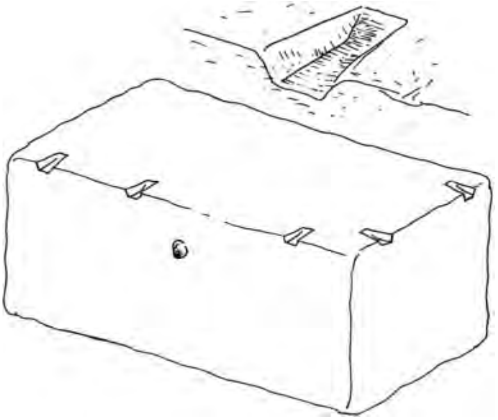

Figure 8. Segovia Aqueduct, stepped pier sections divided by cornices with *scaffold holes* at the blocks' top edges (Photo Peter Bak, 1984).

Figure 9. A large granite block showing edge holes on its top – depth approx. 7 cm – in an irregular position, when compared to the block itself (Drawing Jos Tomlow).

hexagonal pyramid or rather as the negative of a pencil, sharpened by a knife.

The author wants to express the function of these new holes, as hypothesis 2: *At Segovia Aqueduct, certain holes, to be indicated here as scaffold holes, appear at the top edge of façade blocks, in a specific position on each horizontal joint level.*

They serve to hold short, up to approx. 1.5 m, sharpened poles, which are elements of a scaffold for the pier section.

4.1 *A cantilevered scaffolding based on putlogs*

In literature, these holes were observed but not yet documented in detail (Prieto Vásquez 2000, Zamora Canellada 1995, 2013, Adam 2010 p. 53–5, Figures 121, 123). Adam, referring to Aqua Claudia in Rome (before 52 AD) calls them *spike holes*, positioned along the top edge of big blocks of dry masonry, which serve to move the block backwards to its final position, with the help of a metal crowbar. Based on Adam's interpretation, Alonso Zamora Canellada refers to them, partly in accordance with the author in this current contribution, as wedge (or spike) holes (Zamora Canellada 2013, p. 33-5). An interpretation of these holes as remnants of the splitting process in the quarry, contradicts the author's view, because such holes for wedge tools are more regularly spaced apart.

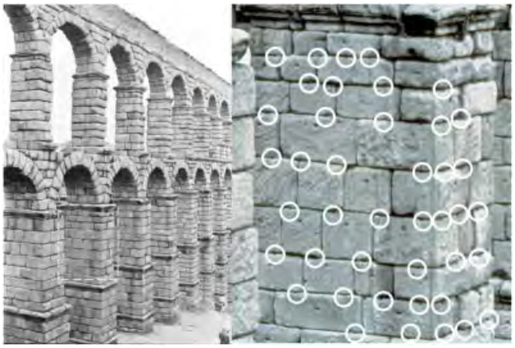

Figure 10. Segovia Aqueduct. Pier with indications of visible scaffold holes in center of rings (Photo Peter Bak 1984/Interpretation Jos Tomlow).

In conclusion, the author accepts the reading of Adam and Zamora Canellada, but with a certain difference. Figure 9 shows that the observed shape is conical, and not as a deepened socket like Adam suggests. And also, the use of a crowbar, which Adam takes as the most proper instrument to wedge the blocks, is not necessarily needed as the following analysis suggests.

A closer view discloses a pattern of these holes in Segovia Aqueduct.

Two layers of blocks have to be regarded as related to each other (Figures 10 and 11). Blocks of the top layer may count on two scaffolding holes beneath them on the top horizontal edge of the blocks of the bottom layer. In the ideal case, these two scaffold holes are in a symmetrical order not far from the top block's sides. In cases where the top layer block is narrow, only one scaffold hole below is considered to be enough. Since the masonry bond is irregular of size and order, except for the defined length of a row, the intended position of the holes is frequently somewhat disturbed by a vertical joint. In those cases, the position of the scaffolding hole below is improvised. In one row of the considered pier section 5-7, scaffolding holes appear.

According to hypothesis 2, these holes are prepared to hold the horizontal poles, which carry the scaffolding planks of the working platform.

When a pole end is inserted horizontally in such a scaffolding hole, its position is secured when the next layer of blocks is laid. In the author's view, these holes are part of a scaffold system, which resembles a type that Jean-Pierre Adam calls cantilevering scaffolding (Adam 2010, Figure 190, right). They consist of a putlog, the horizontal pole that inserts into the wall's face and carries the scaffold boards, oblique braces (poles) and a standard, which is a vertical pole along the wall. All knots are firmly bound together with thread, leather strips, or other rope material.

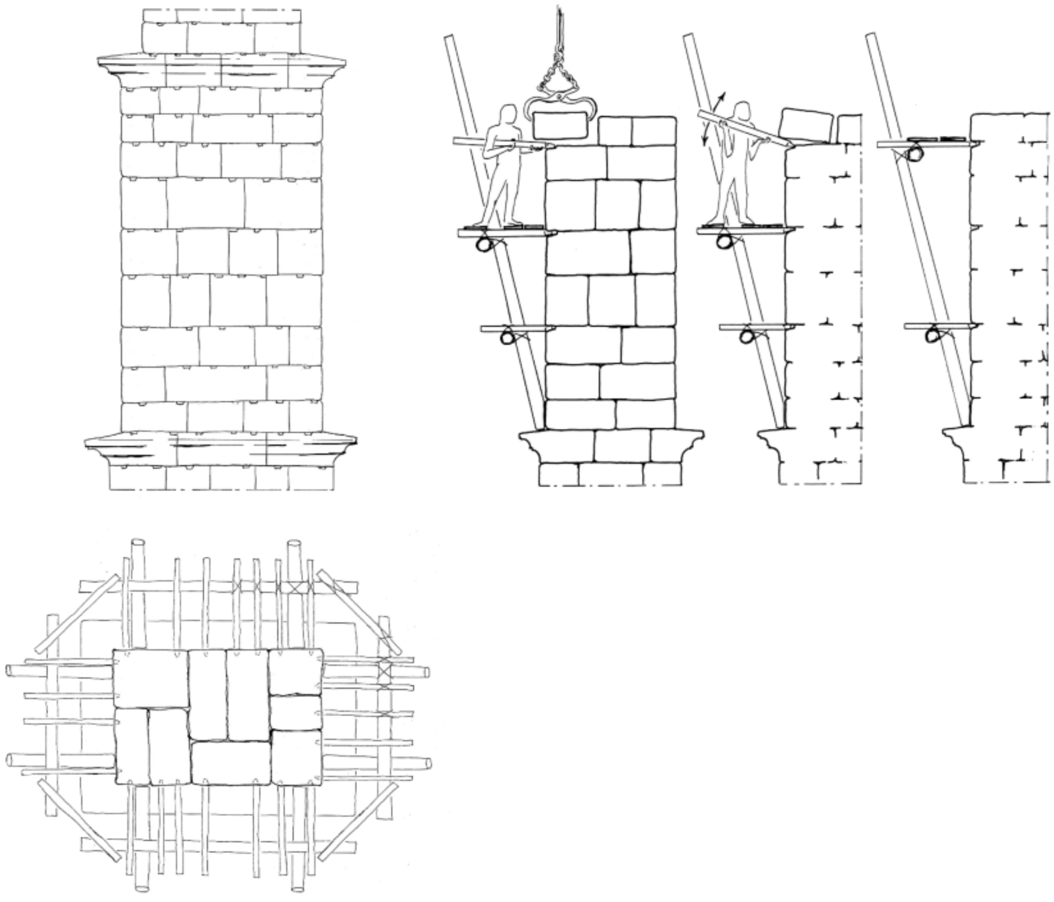

Figure 11. Reconstruction of scaffolding type for Segovia Aqueduct piers (Drawings Jos Tomlow).

Differences exist to Adam's cantilevering scaffold. The author holds the opinion that the scaffold type for Segovia Aqueduct piers was designed following a more complex concept, in order to better serve the work process. When one of the top layer blocks arrives, suspended from a hoisting device with a grip, already positioned blocks may disturb the intention to put the block in its proper place, because the forceps needs a space of approx. 10 cm outside of the block's side face. So, such blocks land on an odd position and have to be wedged in their final position. The author suggests that the scaffold holes may help the wedging process. When in the two scaffold holes below, two poles are held somewhat oblique by two workers, they can guide the block, by small alternating movements that make the block slip backward. The poles work like two crowbars, using the lever phenomenon. In that way, two 70 kg men can move a block of 500 kg. But another aspect is relevant as well.

For ergonomic reasons, the worker has an optimal position towards the block's height between 40 cm and 130 cm. Ideally the scaffolding is rising with each new layer. This can be exactly established by changing the position of the horizontal putlogs, which hold the platform planks, to a higher joint level. Long oblique brace elements, which ought to be thicker than a simple putlog, keep their position in the building sequence, together with a "ring beam", described below. They are held at the base by ropes that secure their position on the cantilevering cornice of the pier section beneath. The ropes go around the pier. The reconstruction drawing reveals the optimal position of the brace elements, in this pier section estimated to be eight. Ledgers shape an octagonal ring beam. Such a ring beam, positioned on the height of the horizontal layer joints, give the putlogs a support at their outward end, in the same instance assuring that these do not slip from the scaffold hole.

So, for every one or two layers, a complete platform is built with a rather high number, like 23, of putlogs. With increasing height, the lower platforms are partly dismantled and the material used again, if possible.

Substantial observations were made on Roman scaffolding in earlier surveys, confirming aspects of the current vision (Albrecht & Döring-Williams 2018; Rasch 1984). Although different in masonry material, the scaffolding type reconstructed in Albrecht & Döring-Williams 2018, Figure 6 shows a similar layout. The depth of the putlogs into prepared holes in the Basilica of Maxentius in Rome (307–313 AD) normally vary between 17 and 45 cm, so much deeper than in Segovia Aqueduct. Although the holes are mostly square (edge 8 cm, the height of a long brick type called *bipedales*), the authors regard the putlogs as being cylindrical (natural) poles, diameter up to 8 cm.

They refer to a sensational finding by Jürgen Rasch of the remains of a wooden putlog, among other rests found at the Mausoleum of Maxentius in Rome, early-4th century AD (Rasch 1984, p 46,47 and Tafel 49, 5,6). His documentary drawing shows a fairly intact wooden pole part of 46 cm length, found in situ in a putlog hole with a 5 cm diameter. Microscope analysis states that the wood is oak.

Rasch mentions vertical distances of 140–160 cm, and horizontal distances between 50 and 150 cm but mostly around 1 m between putlog holes. The issue of ergonomics was also looked at by Luise Albrecht and Marina Döring-Williams. The reconstructed height of the specific scaffolding is approx. 150 cm for a thick brick masonry wall.

4.2 *Open questions*

A question concerning the reconstruction description of hypothesis 2 may be whether putlogs, poles of small dimension, would fit strongly enough to carry the load of boards and two men working there, let's say 100 kg in 1 m length. Referring to pole diameters in Rasch 1984 of only 5 cm (oak) and Albrecht & Döring-Williams 2018 of up to 8 cm, the author estimates – regarding also the scaffold hole dimension – the putlog diameter to be 6–8 cm. The wood type is also relevant. Oak or chestnut may be strong enough but tend to be too brittle, pine may be better suited.

Another question is whether a wood pole would stand comparison with an iron crowbar, a singular tool type which has proved its success on several occasions to reach an Olympic force. The presented reconstruction efforts start from an empirical approach, and real scale tests could bring more evidence. However, in respect of the current vulnerable material state of Segovia Aqueduct, the author does not recommend a reconstruction in real scale of the scaffolding at the monument itself.

The question may arise as to what degree such holes as in Segovia Aqueduct may be finely worked. The brittle granite material implies a basic approach in the hole design. This can be illustrated by a rural fence post of similar granite, in which apparently only rather rough details seem permitted (Figure 12a, b). Following this conclusion means that a deepened hole type like the one depicted in Adam, Figures 121, 123, is unlikely for the Segovia Aqueduct.

It seems relevant at this point to illustrate a common scaffolding of the 19th century in the Netherlands. It is simply stunning how much the elements like poles, ropes and planks, resemble the described scaffoldings of the Roman Empire (Figure 13).

This includes signs of improvisation, like stiffening locally a crossing of poles, with an additional bar. One can sense the search for strict economy, balanced by the fear of accidents.

Figure 12. Rural fence post in Olbersdorf, typical for Saxony from 17th–19th century. The illustrations reveal standard features of details in granite material. The L-shaped hole to hold a fence is large with rounded edges to avoid splitting. The detail is very convenient to take out the wooden fence quickly (Photo Jos Tomlow).

Figure 13. Typical 19th-century scaffolding type, with features similar to the Roman ones. Oil painting by Willem Bastiaan Tholen (1860-1931), Huizen in aanbouw, 1895, KM 108.927, Kröller-Müller Museum, Otterloo, NL (Photo Jos Tomlow).

My dear former teacher, Jan Molema, asked the author to comment on how the scaffolding would be pulled down. It is clear that the workers, when the pier was completed, could walk back to the start of the aqueduct, along the water channel at the aqueduct's top.

Before this, they could have fixed parts of the scaffolds with ropes and lower them with a crane. Or they could simply throw certain parts down. A comparison is technically possible with tent roofs over Roman stadia. Discussing the Colosseum and the way the textile shadow screens were installed – or pulled back quickly in case of a storm – Rainer Graefe has cited Lampridius, the ancient Roman author of *Vita Commodi* (Graefe 1979, 16), with proof of sailors doing such dangerous work, partly without ladders.

5 CONCLUSIONS

Types of professionals like engineers had a role in establishing the building process of Segovia Aqueduct.

Of decisive importance was the hydraulic engineer, responsible for an overall design suitable to bring enough drinking water to Segovia. Second in charge was the geodetic engineer, who had to measure all distances, necessary to control the verticality of a wall or the expected fall of the water channel towards the city.

The static engineer conceived harmonious proportions and determined the pile and arch dimensions, with regard to the specific compression strength of the granite masonry and the fundaments. However, a fourth category – thus concludes the author – should be a person who was responsible for locating and controlling all necessary holes for erecting this monument of construction history, aimed at an economic and safe work process. Such a person could be named a process management engineer.

One may further ask whether the methods applied were unique or rather a copy of other experiences. Construction history teaches us that excellent, huge structures like this one are invariably the result of a specific and singular solution, in which all aspects were reflected upon before or after early experiences in the building sequence. The author wants to compare the achievement of Segovia Aqueduct with more recent singular structures: the Oka electricity pylons (1929) by the Russian engineer, Vladimir Grigoryevich Shukhov (1853-1939) (Beckh 2012; Graefe et al. 1990; Tomlow 2010), and the roof of the 1972 Olympic Games in Munich, by a team directed by Günter Behnish, Frei Otto, Fritz Leonhardt/Jörg Schlaich, and Jürgen Linkwitz (Tomlow 2016).

The current survey may strengthen knowledge about and trust in a vanishing amount of heritage of humankind and Nature itself.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Medieval geometry and the Gothic style at the Cathedral of Tortosa

C. Lluis Teruel, I. Ugalde Blázquez, J. Lluis i Ginovart & M. López Piquer
Universidad Internacional de Cataluña, Barcelona, Spain

ABSTRACT: The construction of Gothic cathedrals is among the great achievements of medieval science as it is defined in terms of *theorica* and *practica*. This study introduces the original sources of the Codex of the Cathedral of Tortosa (Catalonia, Spain). A documental survey of masonry books (11.o. ACTo), the Guarc parchment (ca.1345–1380) and the geometric layout of Tortosa Cathedral carried out over the last decade provide some details that afford an understanding of some of the conditions of execution and construction of what has become known as *geometria fabrorum*. Two main sources allow a bijective assessment of the built masonry: the ACTo chapter archive and the parchment known as *la traça de Guarc* (ca.1345–1380). These sources show a heptagonal apse with an arithmetical and geometric dimension based on a metrological and tonal musical proportion of 9/8, which is perfectly compatible with the bases of the *quadrivium*. The lateral and radial chapel, as the basic unit and feature element in 14th-century Gothic cathedral design, can be used as a pattern and its measurement established as the basic unit for the overall proportions of the cathedral.

1 INTRODUCTION

The Arxiu Capitular (Chapter Archive) of the Cathedral of Tortosa (hereinafter ACTo) contains a large collection of codices and manuscripts. This paper does not intend to offer an exhaustive analysis of those sources but to present the mathematical and geometrical knowledge applied in the construction of the cathedral included in those documents. The cathedral is a synthesis of the knowledge of both clergy and builders. The clergy acquired knowledge from codices, while the master masons learnt through the practice of their craft. The members of the Cathedral Chapter worked closely with the master builders and, despite a lack of primary sources regarding the transfer of knowledge between them, the evidence found when studying the completed cathedral links to the sources available at the Archive. This paper is the result of the work *El quadrivium y la Catedral gótica* (Lluis i Ginovart & Lluis-Teruel 2019: 195-2018)

It is, therefore, worth considering which methods the canons and architects used when designing Gothic apses (Beaujouan 1963: 555–563, 1975: 437–484; Høyrup 2009: 367–377; Sarrade 1986: 27–40). Mathematical ideas spread throughout Europe during the Gothic period thanks to the book *De Scientiis* by Dominicus Gundissalinus (fl. 1150), although that work was preceded by the *Enumeration of the Sciences* by al-Fārābī (ca.870–950). According to al-Fārābī, mathematics, a *sciencia doctrinali*, is one of the five known sciences. Mathematical sciences include arithmetic, geometry, optics, astronomy, music and the science of weights and mechanics. In arithmetic and geometry sections, he makes a distinction between *theorica* (theory) and *practica* (practice) (González Palencia 1932: 97–105). Gundissalinus used the same terms in the third chapter of *De Scientiis* (Alonso François 1955: 85–112).

2 THE THEORICA OF THE CANONS OF TORTOSA'S CATHEDRAL

After carrying out an in-depth analysis of the contents of a number of codices, the sources listed below were identified. Canons had access to these sources prior to the construction of the Gothic cathedral (begun in 1345). In what follows, we outline part of the content of the sources, in which we focus on the knowledge regarding arithmetic and geometry, which relate to the aspect known as *practica*. It is not the objective of this paper to track the origins and genealogy of these sources.

1) Commentary on Euclid's *Elements* (ca.325–ca.265 BC) by Al-Ḥajjāj ibn Yūsuf ibn Maṭar (786–833), ACTo 80 (fol. 161r.6-13), 12th c. (Lluis et al. 2015a, 884–885). This commentary (fol. 161r.6-13) is based on Euclid's *Elements* by Al-Ḥajjāj ibn Yūsuf ibn Maṭar (786–833): *Hec est de abecedario. Ait Elhageth dic [it] quia linea longior cum proporcionaliter in potencia. [Biteg dixit]*. The *Commentarii* reads as follows: *Quem prima Surdare erit latus, post ea erit secunda latus Latans, deinde erit tercia latus lateris* ... (The first of the irrational numbers will be the first side, the second one will be the second side, the third one will be the third side, and so on for each successive number…).

2) Saint Augustine's *De Civitate Dei (The City of God)* (354–420), ACTo 20, (fols 1r-408r), 12th c. (Denifle & Chatelain 1896: 7). Saint Augustine's *De*

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Civitate Dei (354–420) contains 22 books (fols 5v-407v), an introduction (fols 1r.5r-4v), including five graphical representations, and an appendix (fol. 408r), one of which represents the creation and the symbolism of the numbers five, six and seven. The first book begins with "*Gloriosissimam Civitatem Dei, sive in hoc*… " (fol. 5v), and Book XXII finishes with "*Explicit Liber vicesimus secundus…Finito libro Reeddamus gracias Christo*" (fol. 407r). In Book XI, *Civtatem Dei dicimus cuis ea Scriptura*…(fol. 156r-170v), the number six is cited as the number of perfection. Therefore, number six is the first number made up of its own parts added together, 6 = 3 + 2 + 1 (XI.30). To Saint Augustine, the number 10 was also significant: its divisors are one, two, five and 10, and it is made up of number three, representing the Trinity; and number seven, which represents the seventh day, known as the day of God, as the sum of four and three (fols 168v-169v) (XI.31). The number 12 has six, four, three, two and one as divisors (XI.30). At the end of Book XX, from "*De die ultimi judicii Dei, quod ipse donaverit*…" to "…*et posse facere quod imposible est infideli*" (fols 333r-359r), new proportional references appear. The number 1000, which is the perfect number in the fullness of time, appears as the measure of past or future time. This number represents the cube of number 10, since 10 x 10 = 100. Therefore, 100 would represent a square, a plane. In that order, 1000 would make a solid figure with volume, since 10 x 10 x 10 = 1000 (XX.7.2).

3) Translation of one of Plato's dialogues, the *Timaeus* by Calcidius (fl. 350), ACTo 80 (fols 146r-155v.14) includes part of his commentary (fol. 155v.15-66), 12th c. (Waszink 1975, CXXV). It contains Plato's *Timaeus* translated by Calcidius (fols 146r-155v), and includes a summary of his commentary (fol. 155v.15-66). The commentary starts on fol. 146r.1, "*Socrates in exortationibus suis virtutem*… " (Moreschini 2003, 4–109; Waszink 1975: 5–52; with the translation of the first part and continues with "*nancisceretur imaginem. Liber Platonis Timaeus explicit* on fol. 152v.3. At the end, there is a commentary on *Timaeus*, from "*[Quis igitur] primae portionis numerous*… " (fol. 155v.15-66) to "*qui unt in formula*". The work only shows one commentary by *Timaeus*: "*Descriptio tertia, quae est armónica"* (XLIX), accompanied by [tab. 9]. One of the codex peculiarities is the figure inserted between fol.150.1 "*cuncta intra suum ambitum*" and fol.150r.41 "*a Graecis epitritum dicitur*", in the right margin (fols 150r.20-150v.16). The figure explains the passage devoted to generating mathematical proportions. In Calcidius's translation, they are generated as follows: 1, 2 (= 2 x 1), 3 (= 2 + (1/2) x 2), 4 (= 2 x 2), 9 (= 3 x 3), 8 (= 1 + 7), 27 (= 27 x 1). In the intervals it defines: the whole plus its half part (1 + 1/2); the whole plus its third part (1 + 1/3), which he called *epitrite*; the whole plus its eighth part (1 + 1/8), which is called *epogdus*; the double, triple and quadruple, and the ratio between (243:256). The figure accompanies *Timaeus* throughout his comments. XXXII [tab. 7] and XLI [tab. 8] (Moreschini 2003: 186–191; Waszink 1975: 89–91) are summarized in a single figure. The first one is dedicated to the origin of the soul with the numbers 1, 2, 4, 8 and 1, 3, 9, 27; while the other one refers to harmonic modulations with the series 6, 8, 9, 12, 16, 18, 24, 32, 36, 48 and 6, 9, 12, 18, 27, 36, 54, 81, 108, 162 (Figure 1).

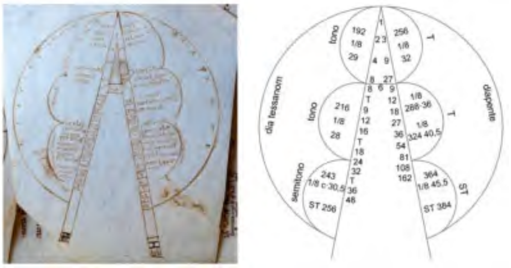

Figure 1. *Comentarii In Somnium Scipionis* (ACTo. 236 fol. 51).

4) Another part of the commentary on *Timaeus* by Calcidius (fl. 350), inserted in ACTo 236 (fol. 39), 13th c. (Lluis et al. 2016: 89–97). In the middle of Macrobius's commentary on *Somnium Scipionis (The Dream of Scipio)*, there is a part of the commentary on *Timaeus* by Calcidius, "De modulatione siue Harmonica" (XL, XLI, XLII), [tab. 7], [tab. 8] (Moreschini 2003: 186-19; Waszink 1975: 89–91). Chapter XL is complete, "Itaque figura similis eius quae paulo superius" (ACTo 236, fol. 39r.7), and so is XLI, "Quia VI numeris facit unum limitem et item XII" (ACTo 236, fol. 39r.10). Chapter XLII is incomplete: the beginning, "Haec eadem ratio", is cut off by the binding.

5) Commentary on *Somnium Scipionis (The Dream of Scipio)* by Macrobius (fl. 400), ACTo 236 (fol. 1r-61v), except fol. 39, 13th c. Both books constituting the commentary are complete (Rubió i Lluch & Rubió i Balaguer 1914: 329). Book I goes from fol. 1r, "*Inter Platonis et Ciceronis*" (I.1.1) to fol. 35v.18 "*disputationem sequentium reseruemus*" (I.23.13) (Armisen-Marchetti 2001: 1-134; Willis 1970). Book II goes from fol. 35v.19, "*Superiore comentario Eustathi*" (II.1.1) to fol. 61v.28, *philosophiae comtinetur integritas* (II.17.17) (Armisen-Marchetti 2001: 1-869; Willis 1970), from which passages I.5.7 to I.5.13 (fol. 6r) are missing. In the first part of the commentary (fol. 6r.4) the first citation of the dream (I.5.2) starts by mentioning the notion of plenitude of arithmetic, "*Ac prima nobis tractandam...*" and goes to fol. 12v.69, which concludes with the arithmetical excursus (I.6.83) "*singulos certa lege metitur*". In the left margin (fol. 6v.19-22), where he talks about the virtues of the number seven (I.6.3), a diagram appears with the two series 1, 2, 4, 8 and 1, 3, 9, 27, recalling God as the creator of the soul, taking even and odd numbers with doubles and triples. It defines the virtues of the main numbers 8, 7, 1, 6, 2, 5 and 3, 4 (I.5.15 and I.6.23). He calls the number eight *justicia* (justice): 8 = 7 + 1; 8 = 2 x 4; 8 = 2 x 2 x 2; 8 = 5 + 3. Macrobius called the number seven

pleno (full): 7 = 1 + 6; 7 = 2 + 5; 7 = 3 + 4. He calls one *monás* (monad): one is both male and female, and even and odd at the same time. The number six has 1/6, 1/3, 1/2, 1: 6/3 = 2, 6/2 = 3, 1/6 = 1; 1 + 2 + 3 = 6. The number two, called *diada* (dyad) is considered the first number after one. The number five is the supreme God, and is the total sum of the universe. The number three is the number situated between numbers one and five. The number four is the first number to obtain two means. In Book II, the part dealing with music, the harmony of the spheres (II.1.1) appears, and he explains why we do not hear the music of the spheres (II.4.15) *non capitat audium* (fol. 43r.4). Both fols 46v-47v, diagrams of the earthly and celestial orbs, and fol. 51bis, contain the figure with the definitions of diapente and diatessaron. The diagram explains the harmonic relations (II.1.15) similar to the way they are described in Calcidius's commentary on *Timaeus* XLIX (Waszink 1975: 98-99). He defines the harmonic relations (II.1.4), as well as the concepts of *epitrite* (3:4), *hemiolia* (3:2), double (2:1), triple (3:1), quadruple (4:1), and *epogdus* (9:8) (fol. 36v.23). The *dià tessàrōn* comes from the ratio of the *epitrite*, the interval *dià pénte* from the *hemiolia*, the *dià pason* from the double, the *dià pason kaì dià pénte* from the triple, the *dis dià pason* from the quadruple and the *tónos* (II.1.15-20) from the *epogdus*, which is completed with the definition of a semitone 243:256 (II.1.15-22), which the Pythagoreans called *diesis* (fol. 37r.13).

6) An excerpt from Book VI, *Geometria*, in *De Nuptiis Philologiae et Mercurii* by Martianus Capella (fl. 430), ACTo 80 (fols 160v.28-161r.5), 12th c. (Lluis et al. 2016: 89–97). The excerpt is from Book VI, *Geometria*, of the *De Nuptiis Philologiae et Mercurii*, and goes from "*Ergasticis Schematibus*" (715) to "*Ex his aloge XIII fiunt, quarum prima dicitur Mese Alogos*" (720) (Capella 2001: 486–491; Willis 1983). It defines the different types of plane figures: *ergastic* figures contain the precepts to form any figure; apodictic figures provide evidence. The methods used are *systatikós*, which creates a triangle from a few lines; *tmēmatikós*, which shows how lines can be cut for a procedure, *anágraphos*, which shows how a line can be joined and described, *éngraphos*, which shows how a figure can be inscribed in a circle; *perígraphos*, which shows how a figure circumscribes a circle; *parembolikós*, equivalent polygons; and *proseuretikós*, for finding the mean proportional between two lines of different lengths. It defines three types of angles: regular angles, which are right and always identical; narrow angles, which are acute and variable; and finally wide angles, which are obtuse and variable like acute angles, and wider than right angles. The lines are: *isotes* when two equal lines are in proportion to a mean line, the length of which is equal or double; *homólogos*, when the lines meet; *análogos*, when a line is twice longer than another line but half the length of a third one; and *álogos*, or irrational, in which there is no proportional coincidence. All lines are either *rhētós* or *álogos*. The first one is rational, and it can be compared with a common measurement, while the second does not match any measurement, so it cannot be compared. Lines may also be classified as those that are the same as others, *symmétrus*, and those that are not, *asymmétrus*. It is not only the length that makes them commensurable but also their strength, which is referred to as *dynámei symmétroi*. Those lines with the same length are called *mếkei symmétroi*, while those that differ in either length or strength are *asymmétros*. These lines give rise to another 13 irrational lines.

7) Part of Books III and IV of *Geometria Incerti Auctoris* by Gerbert of Aurillac (Silvester II, c. 940–1003), ACTo 80 (fols 159r.1-160v.27), 12th c. (Denifle & Chatelain 1896: 16). The codex does not appear in the main editions of the work. The text was part of Caput XIV-Caput XXXII (Silvester II 1853: 115–127), Cap. XIV-XXXII (Olleris 1867: 427–441) from Liber IV and Liber III (Bubnov 1899: 317–330, 336–338). *Geometria* consists of 20 propositions from different sources (Lluis et al. 2015a, 808–809). The definitions P-1 and P-2 are gromatic, while P-3, P-4, P-5, P-6 and P-7 are utilities of the astrolabe of Arab origin, such as P-8 and P-9, though the latter had its foundations in optics. P-18, P-19, P-20 and P-21 are ascribed to Euclid's *Optics*, as are P-10, P-11, P-13, P-15 and P-16. Finally, triangle proportionality is defined in P-12, P-14, P-17 and P20, including isosceles (P-18) and Pythagorean (P-19) triangles. These proportions use a proportional base, whose unit is 12, which can also be divided as follows: 1:1, equality, 2:1, dupla or diapason, 3:2, sesquialtera or diapente, 4:3, sesquitertia or diatessaron. Of particular interest in this codex are the different interpretations given of proposition P-20. In the editions of Olleris (1867) and Bubnov (1899) an auxiliary construction on the mount is built with an auxiliary vertical element, which may be either a rule or a plumb line *uhz*, unlike the Migne edition (1853) and ACTo 80, fol. 161v, in which *uhz* is constructed horizontally. In the diagram included in ACTo, a set square is used on the line-of-sight *bd* at point *d* to determine point *u* and *uh*, unlike the Pez edition. Pez extends the line-of-sight *bd* until it meets the horizontal line *hz* and he also shows a comparative analysis of these interpretations.

8) The positional number system, ACTo 80 (fol. 162r.1-3), of Adelard of Bath (1090–1160), 12th c. (Bayerri 1962: 228). Indo-Arabic numbering is found in ACTo 80, fol. 162r.1-3), arranged in three lines. In the first line appear the figures 2, 3, 4, 5, 6, 7, 8, 9, in the second the numbers 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 and in the third the numbers 30, 40, 50, 60, 70, 80, 90 and 100 (Figure 2). The notation of the number zero, represented by the approximate shape of the letter tau (τ), is used to write the tens precisely. The Mozarabic tradition of codices *Vigilianus* written in 976 and *Aemilianensis* written in992, orders the numbers in descending order: 9, 8, 7, 6, 5, 4, 3, 2, 1 (Menéndez Pidal 1959: 45–116). Likewise Abraham Ibn Erza (1140-1167), in *Sefer ha mispar* (Silberberg 1895, 2), Leonardo Pisano (1180–1250), *Liber abaci* (Boncompagni 1854: 253), and Alexandre Villedieu, (c.1175–1250) in *Carmen de Algorismo*

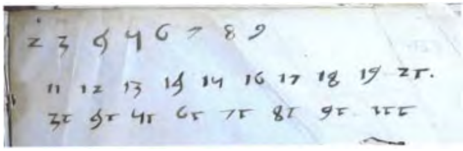

Figure 2. Numbering ACTo 80 (fol. 162r.1-3).

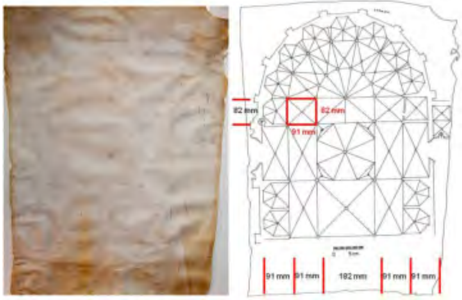

Figure 3. Plan by Guarc, ACTo Fábrica no. 49 (ca.1345–1380).

(Halliwell 1841: 3–27, 73–83), as well as in El *Algorismus vulgaris* by Joan Sacobosco (1200–1256) (Curtze 1897: 1–19). Pedro de Dacia (c.1235–1289), Rector of the University of Paris and canon of the cathedral, introduces it in this sphere, with *Commentun Magistri Philomeni de Dacia* (Curtze 1897: 20–92) and the medieval manuscript MS 1 from Cashel Cathedral in Tipperary, Ireland, held in the G.P.A. Bolton Library (Burnett 2006: 15–26). The notation τ, for the formation of numbering the position of the tens, from 20 to 90, and the hundreds was used by Johannes Ocreatus (fl. 1200) and the followers of Adelard of Bath (1090–1160) (Burnett 1996: 221–331).

3 PRACTICA VERSUS THEORICA. THE GEOMETRIA FABRORUM

The Tortosa Cathedral Chapter Archive contains a parchment ACTo Fábrica no. 49 (917 x 682 mm), which depicts the plan for a heptagonal chancel of a Gothic cathedral proposed by the master-builder Antoni Guarc (c.1345–1380). Although it does not match the one built, it is very similar to it with regard to the main decisions made. Guarc divides the width of the cathedral into six parts (91 mm), as a standard unit. The rectangle beside the keystone of the chancel has a ratio of 91:82 mm. The proportion between the width of the chapels and the separation wall is 8:1, and the module of the lateral and the central nave has 18 units (Figure 3).

The Cathedral's double ambulatory (1383–1441) was built within the structural free space of the wall between the radial chapels of the apse, creating a concentration of the weight in the abutment. The chapels' geometric solution consists of a square ribbed vault organized with nine chapels around a heptagonal apse, creating a belt around the old cathedral. The vaults were covered, consecutive and sequentially, between 1377 and 1424.

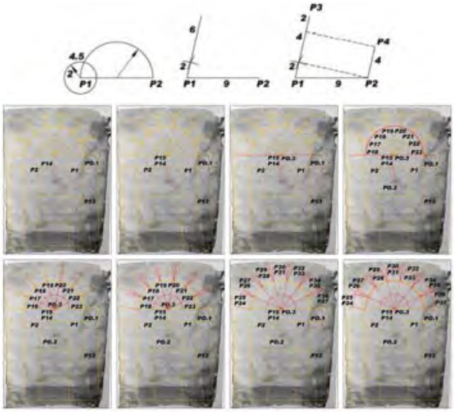

Figure 4. Sequence of the heptagon layout. Plan by Guarc (ACTo Fábrica n°. 49).

The basic units of measurement that appear in the *Llibres d'Obra* (Construction Books) are the *cana* (eight palms) and the palm (12 fingers). The Tortosa *cana* is defined in Book IX.15.5 of the *Consuetudines Dertosae* of 1272 (AHCTE cod. 53, fol. 256r). By comparing the documents regarding the unification of the Tortosa *cana* with that of Barcelona, we observed that the Tortosa *cana* used for the cathedral measures 1.858 m, and the palm measures 0.2323 m.

The entire apse of the cathedral has the proportions of 150 palms wide x 100 deep x 100 high. The radial chapels are square and have an interior measurement of 21 x 21 palms. The interior points of the pillars of the apse, where the work was laid out, were equidistant at 24 palms (= 3 Tortosa *canas*). They were equidistant at 54 palms from the centre of the presbytery. There is a ratio between the radius of the circumference (54 palms) of 18 modules, and the side of the polygon of 14 sides (24 palms) of 8 modules, establishing a ratio of 9/4.

Guarc's plan ratio, 9/4, is equal to that of the construction of the first phase of the apse, in 1383–1424. The solution is both arithmetic and geometric. According to the theory of proportionality, if the presbytery has a width of 18 modules, the chapels must have 8 modules. To build a chapel of 3 *canas* (= 24 palms), the radius must be of 6 *canas* and 6 palms (54 palms). These metrical structures are directly related to some sources found in the ACTo. This has been described widely in (Lluis i Ginovart et al. 2013) (Figure 4).

Among others things, the catalogue ACTo 300 contains the *Tractatus varii de rebus philosophicis et mathematicis* by Caroli Bovilli Samarobrini (Bayerri 1962: 473–474), a collection of philosophical and mathematical texts by the humanist Charles Bouvelles (1478–1567), published in Paris (Bouvelles 1510). There it was acknowledged that a figure as important to Christian symbolism as the heptagon (Chap. 2.57) does not appear in Euclid's *Elements* (Bouvelles 1542, 25v). In spite of this fact, architects from the 14th century knew how to draw the heptagon. They used the 9:8 ratio, the ratio of a musical tone.

The heptagon layout used in practical geometries is the one proposed by A. Dürer (1471–1528) in the *Underweysung der Messung, mit dem Zirckel und Richtscheyt: in Linien Ebnen vo gantzen Corporen* (1525), which is constructed as a corollary of the pentagon's plotting (LII.15) rather than as a heptagon (LII.11). (Dürer 1525: 27v-28v). The method using the equilateral triangle and the projection of half the radius was disseminated (Istruzione. 25, fig. 9) by F. Galli-Bibiena (1657–1743) (Galli Bibiena 1711: 10). The method was formulated by Abū al-Wafā Al-Būzjānī (940–998) in the *Kitāb fī mā yaḥtāju al-ṣāni' min al-a'māl al-handasiyya* (*Book on Those Geometric Constructions which are Necessary for Craftsmen).* (ca.993–1008) (Aghayani-Chavoshi 2010, W47) and in his Arithmetic (P2, C.IV-V) (Saidan 1974: 367–375). The drawing of the heptagon using geometrical instruments was refuted by J. Kepler (1571–1630) (Kepler 1864: V5, 101–108) and C.F. Gauss (1777–1855) (Gauss 1801: 454–463).

These methods cannot be applied to the drawing of apses. The problem is accentuated because the centre of the circle was not accessible, since other buildings usually occupied it. The *magister operis* had to solve three geometrical problems: the drawing of the heptagon; the construction of the geometric figure without knowing where its centre was; and, finally, the ratio of proportionality between the radial and side chapels. Thus, learned methods are far from *Guarc*'s construction of the heptagon. Only the *Manifiesto Geométrico* (1684) by the Dominican mathematician Fray Ignacio Muñoz (1612–1685) determines that the side of the heptagon has a ratio of 4:9 with the main diagonal of the figure (Muñoz 1684). In the treatise, he refutes J. Kepler (1571–1630), takes issue with the cosmographer Luis Serrano Pimentel (1613–1679) and says that he has added to the trigonometric tables by P. Joseph Zaragoza (1627–1679).

The layout of the dome drawn on Guarc's plan requires a method for constructing the octagon (Figure 5). Guarc, therefore, takes the mainline T2.1 at the presbytery's back area as the base and constructs the structural square that contains the dome. A compass point is observed at P1, P2, P3, and P4. That was how the centre of the square, PO.2, was traced. This point is determined by the intersection of the diagonals P1-P3 and P2-P4, where the auxiliary traces of graphite are still visible. The opposite vertices of the square, P1 and P3, have two compass marks, unlike the rest. The points P5 and P6 are obtained by rotating the segment P1-PO.2 on the vertex P1. The same sequence is carried out on point P3, obtaining points P7 and P8. The distance P5-P7 and P6-P8 is the measure of the side of the octagon. Points P9, P10, P11 and P12 are obtained by the reiteration of this measure with a compass, the marks of which can be seen on each point. The dome was laid out based on this octagon (Lluis i Ginovart, et al. 2017).

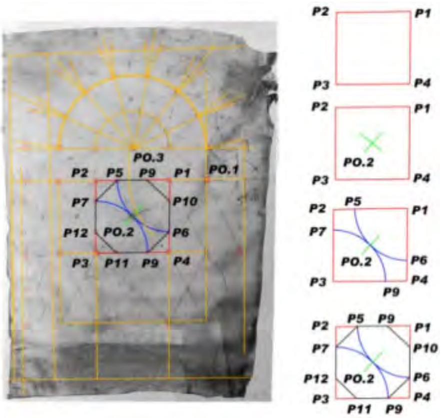

Figure 5. Sequence of the octagon layout. Plan by Guarc, ACTo Fábrica no. 49.

Practical methods for the construction of octagons were used in the late classical period. This method is described in *Fragmentum de hexagono et octogono*, a gromatic text ascribed to Marcus Terentius Varro (116–27 BC) (Bubnov 1899: 552). It contains the drawing of an octagon; whose square construction was widely used in Roman flooring (Watts 2015). It was also considered by Heron of Alexandria (c.20–62) in his work *Metrica*, LI.XVIII XVIII (Schoene 1903: 57–59). This method is taken as a reference for the plan of the *Horologion des Andronikos* (Svenshon 2010) and in some apses with an octagonal layout (Özdural 2002). What is considered the pseudo-Heronian *De mensuris* also contains the construction of an octagon inscribed in a square (Heiberg 1914: 206–207). The Gothic design of the octagon appeared on fol. 3r of the *Geometria Deutsch* by Matthaüs Roriczer (ca. 1435–1495). It is drawn using an octagon inscribed in a square and performing an abatement of its semi-diagonal (Roriczer 1999: 56–60). An operating system was produced to simulate the construction WG 18 in the Frankfurt book (1560–1572) (Bucher 1979: 219). The method is similar to the one used 100 years earlier by Antony Guarc. It is also similar to W 79, by Abū al-Wafā Al-Būzjānī.

Because of the modular structure present in Guarc's plan, it can be speculated that the parchment's measurements could be carried out as an arithmetic operation. In Guarc's case, the floor plan of the radial chapel is 8 × 7.5, and the dome has a square layout of 18 × 18. The octagonal side is close to the depth of the radial chapel 7.5, which is obviously an arithmetic approximation for 7.456. Heron's measurement errors 13, 10, 13, and 13, 9.950, 13, which are like Guarc's, are completely negligible in Gothic building measurements.

The keystone of Tortosa Cathedral was 10 palms in diameter at the base, 3.5 palms in diameter at the neck, and 5.5 palms high from the upper surface of the rough tiling of the roof. The keystone volume has been calculated to be 3.64 m^3 and its weight 87.47 kN. Thus, in the quarry, the stone block used for the keystone must have been approximately 8.77 m^3. The block's grinding, carving and sculptural decoration is attributed to the sculptor Bartomeu Santalínia, who came from a family of goldsmiths and was employed to work on the construction of the cathedral for 59 days in the summer of 1439. The final cut of the keystone had to resolve both the problems involved in carving the iconography of the Coronation of the Virgin Mary and the problems related to the geometry of the Gothic stonework. The lower carving is set out on a circumference and the neck of the keystone had to accommodate the nine diagonal arches of the presbytery that converged on it. There must be a relationship between the circumference length, its diameter and the dimensions of the diagonal arch that meets the keystone (Lluis et al. 2015b).

As a result, this circumference had to be divided into seven equal parts. The keystone was cut prior to the completion of the diagonal arches, and the size of the mould of the arch was dictated by the mould of the base of the column placed at the presbytery. The geometry of the neck needed to accommodate the diagonal ribs. Its size can be determined using simple proportion, 9:4, using either the ratio of the circumference to the rib or vice versa. The ratio 9:4 (radius of the circumference to the side of the inscribed polygon) is highly effective for the division of the circumference into 14 equal parts. The arches' axes are equidistant, 36 cm, and the neck of the keystone has a radius of 81 cm, corresponding to the ratio of 9:4.

The keystone of the presbytery of Tortosa Cathedral, which represents the Coronation of the Virgin Mary after her Ascension into Heaven surrounded by a choir of 10 angels, is a highly symbolic element that overlooks the high altar and was the culmination of the cathedral's construction. The keystone was placed during a public ceremony on Sunday 27 September 1439, the feast day of the Virgin Mary's Assumption. The geometric and topographic metrology of Tortosa's Cathedral *clau major*, its keystone, is strongly based, in symbolic terms, on St Augustine's number theory (10 x 100) (Figure 6). Following his teaching, the keystone's theoretical diameter is 10 palms (2.32 m) and its position is at a height of 100 palms (23.23 m). It thus represents the number 1000, the perfect number in the fullness of time that St. Augustine defined in *De Civitatis Dei* (XX.7.2). The keystone represents the volumetric concept of space. The square figure is flat, and it is given height to make it three-dimensional or volumetric. This appears in the codex ACTo. 20, fols 337v-338v.

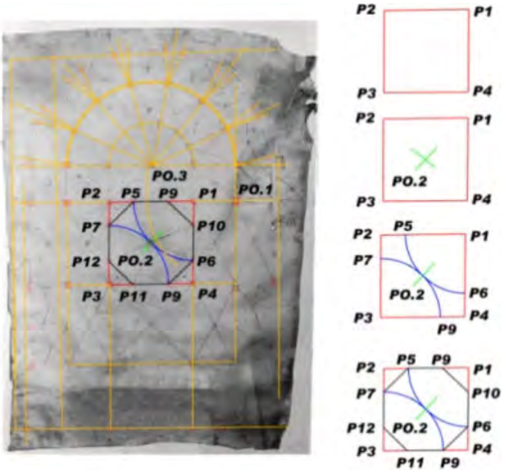

Figure 6. The Coronation of Virgin Mary in the main keystone of Santa Maria Cathedral, Tortosa.

4 CONCLUSION

In ACTo 80, Capella describes two kinds of lines, *rhētós* and *álogos*. The plot of the 14-sided polygon used in Guarc's elevation, as in Tortosa's apse, uses the ratio 9:8 to define the width of the nave and the chapel. This makes the chapels in the straight section of the apse and those located on its plumb line commensurable and equal. In Capella's terms, it is *rhētós*. The ratio 9:8 appears in Calcidius (ACTo 80) and in Macrobius (ACTo 236) as the whole plus one-eighth (1+1/8), which is called *epogdus*. The geometrical layout of Guarc's octagon is similar to the one published in the *Geometria Deutsch*. This layout is *álogos*, which is incommensurable. The arithmetical transposition of the octagon may be based on Heron of Alexandria's *Metrica*. It enables the drawing of a 7.5 side, equal to the depth of a lateral chapel and a dome with an 18-module base. When Tortosa's Gothic cathedral was constructed the remains of a previous Romanesque cathedral still existed. The builders were, therefore, unable to draw the chord of the circle within the apse. Using Guarc's ratio, 9:4, circumscribing the polygon, it was possible to draw it. Furthermore, using a 2-9-9 triangle and a 9-8-9-4 trapezium and by gradually rotating the two polygons on their sides, the apse could be designed without knowing its center. Moreover, the 18:8 ratio and the 9-8-9-4, trapezium are similar to the 13-18-13-8 trapezium in the *Hibbur ha-Meshihah ve-ha-Tishboret* of 1116 by Abraam Bar Hiia (1070–1136) (L II. 77) (Millàs 1931: 62) and the *Practica geometriae* of 1223 by Leonardo Pisano (ca.1180–1250) (Boncompagni 1854: 78–81) and has similar solutions (Levey 1952). Guarc's ratio, 9:4, does not appear in learned treatises, but it is an instrument of the *Geometria Fabrorum* that provides a geometric and arithmetic solution (Sanabria 1982: 281–293) (Huerta 2007: 519-532), (Fuentes ; Wunderwald 2019). In the Cathedral of Tortosa, taking as a starting point the measurement of the chapel, which is 3 *canas* (24 palms), all the measurements of the apse, both in the floor plan and in the cross-section, are implemented as an algorithm. The large measurements are related to the numerical modulations *diapente* and *diatessaron*, which were well known to the canons who had read ATCo 80 and ACTo 236.

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Acoustic vases in the Portuguese synagogue of Tomar: Analogies with other coeval worship buildings

A.M. Moreira
Instituto Politécnico de Tomar, Tomar, Portugal

ABSTRACT: Since ancient times, European construction history has been confronted with the existence of ceramic pots inlaid in walls often related to acoustic purposes. This paper focuses on the ceramic pots embedded in the masonry walls of the synagogue of Tomar, built in the 15th century. Although acoustic vases in Christian and Muslim worship buildings are relatively well known and documented, no similar studies published in English were found reporting similar devices in other synagogues. This paper attempts to shed light on the presence of embedded ceramic vases in the walls of this synagogue building in Tomar. The study considers the research on ceramic vases in ancient worship buildings as well as current acoustic research on the context of cavity resonators as an ancient building technique. The origins of Tomar synagogue were also investigated in order to argue this practice can be regarded as an expression of a coexistent tradition.

1 INTRODUCTION

The synagogue of Tomar is one of the oldest Jewish worship buildings in Portugal: built in the 15th century and converted into a museum in the 20th century. One of its features is a set of inlaid ceramic vases, located at the top corners of the walls.

The use of ceramic pots embedded in the walls became common practice in churches during the Romanesque and Gothic periods. Ceramic vases (the ‘sebu’ technique) were also applied in some Ottoman mosques in Turkey in the 16th century. Since restoration works revealed the presence of these cavities in the walls, increasing attention has been paid to their significance and influence on the perception of sound inside these spaces. Recent studies investigated the relationship between that practice and acoustic purposes (Desarnaulds et al. 2001; Gül & Caliskan 2014; Kayili 2005; Valière & Palazzo-Bertholon 2017).

Although acoustic vases in Christian and Muslim worship buildings are relatively well known and documented in the literature (Arns & Crawford 1995; Desarnaulds et al. 2001; Kayili 2005; Valière & Palazzo-Bertholon 2017), we found no similar studies published in English reporting on the usage of acoustic cavities in other Jewish temples.

This study attempts to provide a better understanding of the presence of embedded ceramic vases in the walls of the Tomar synagogue, observing the importance of acoustics in Jewish ancient worship buildings. The main goal of the work is to place the ceramic vases of synagogue of Tomar within the general context of the historic relationship between acoustics and construction, emphasising the importance of acoustics in the History of Construction.

The genesis of the synagogue building of Tomar is hereby investigated while presenting a literature review on the usage of ceramic pots in Churches and Mosques, highlighting the results of experimental tests conducted to evaluate their acoustic efficiency. The paper also explores the main features of each type of worship building, with special regard to the specificity of the liturgy, and the acoustic challenges that architects and builders had to overcome in those days. Finally, the main findings on their function, position and acoustic efficiency are summarized and discussed to understand the similarities with those of the Portuguese Jewish House.

2 THE SYNAGOGUE OF TOMAR

Tomar is a small Portuguese town in the centre of the country about 150 km north east of the capital, Lisbon. The town is famous for the UNESCO World Heritage listed “Convento de Cristo”, an impressive Templar monastery and the remnants of its previous fortress. Less well known is the synagogue building of Tomar, restored and re-opened in 2019.

Iberian Jewish communities, Sephardic Jewish, were established in the peninsula by the 8th century as a minority people among the existing (majority) Christians and Muslim invaders (Adams et al. 2008). In the 15th century, the Jewish presence in the village of Tomar was significant enough to permit the establishment of the synagogue.

Nevertheless, in 1496, religious intolerance resulted either in the expulsion of the Jews from Portugal or in their conversion to Christianity, where they continued to reside as “novos cristãos” (new Christians).

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Figure 1. General view of the left corner of the worship hall of the Tomar synagogue (in relation to the current main entrance).

Thereby, the Tomar synagogue served as a place of worship for the local community only until 1496. After its decommissioning as synagogue, the building experienced different uses: a Christian chapel, wine cellar and warehouse (Teixeira 1925). In 1923, the building was rediscovered as an ancient synagogue and purchased by Samuel Schwarz, who donated it to the Portuguese State in 1939. Nowadays, the building houses a Hebraic museum, the “Museu Luso-Hebraico Abraão Zacuto”, which is valued as a cultural tourism asset (Figure 1).

Inconspicuously located in downtown Tomar and surrounded by other buildings, the synagogue has its ground floor approximately one-half metre below the level of the street. The lowering of the floor level was also carried out in other coeval synagogues in order to provide a higher ceiling without conflicting with the legal constraints on the height of the Jewish building, which could not exceed the height of neighbouring constructions (Afonso 2016; Stiefel 2011).

The building displays a rectangular floor plan with a length of 9.5 m, a width of 8.3 m and a height of 6.5 m. Afonso (2016) mentions other ancient Iberian Jewish worship buildings with similar floor plan dimensions, namely Arón del Rubio (10.0 m × 7.5 m), Bembribe (10.5 m × 7.5 m) and Tarazona (10.0 × 8.0 m).

The current white-painted façade, with the main entrance surrounded by two iron-grated windows, faces to the North. In the opposite wall there are two narrow windows (Figure 2). The roof structure comprises a set of ribbed vaults, supported on the walls by limestone corbels and by four central limestone columns (Figures 1 and 2). In each corner, near the corbels, two side by side cavities are visible (Figures 1 and 2), which tally with the openings for the clay vases inlaid in the wall. The cavities do not have the same alignment in all corners, e.g. the two cavities located in the left corner are below the corbel (Figure 1), while the cavities on the right side are above the corbel (Figure 2). Detailed features of the ceramic vases are presented by Carvalho and Vieira (2020). The local oral traditionally associates the eight cavities with acoustic purposes.

Figure 2. The visible cavities on the right corner (in relation reference to the current main entrance) above the corbel.

While some authors (Teixeira 1925), (Krinsky 1985, Dodds 1992 and Simões 1992 cited in Afonso 2016) attribute the construction of the synagogue of Tomar to Muslim workers from North Africa, Afonso (2016) puts forward the hypothesis that the building, as well as another Christian church in the neighbouring village of Ourém, was built by an Italian master builder in the same century. This Christian church, namely its space of worship, was destroyed by the 1755 Lisbon earthquake, and later rebuilt in a new architectural style. However, the crypt of the church remained intact, displaying similar characteristics to those of the ribbed vaults of the synagogue building of Tomar (Afonso 2016). As the church was destroyed, there is no way to know whether its walls included ceramic pots.

Although acoustic vases were a common practice in church architecture throughout Europe between the 10th and 17th centuries, there are no examples of this tradition in other places of worship in Portugal (Valière et al. 2013), (Valière & Palazzo-Bertholon 2017).

3 CERAMIC POTS IN ANCIENT WORSHIP BUILDINGS – A LITERATURE REVIEW

A ceramic pot inlaid in the masonry with its free aperture directed to the room acts as a cavity resonator. A cavity resonator or Helmholtz resonator, named after the German physicist and scholar Hermann von Helmholtz (1821–1894), is a hollow sphere (containing a volume of air) with an open hole through a small-diameter neck. A cavity resonator performs at once as sound absorber for an array of frequencies, and as amplifier for the resonance frequency.

Although the phenomenon of air resonance in a cavity was scientifically demonstrated in the 19th century, the Roman architect Marcus Vitruvius Pollio (c. 90–c. 20 BCE) mentioned, in his treatise *De Architectura Libre Decem* (Vitruvius 1st century BCE), the use of resonant cavities as a coetaneous solution to improve acoustics in Greek theatres. The treatise comprises ten books detailing his knowledge based on ancient Greek scripts and some Roman building practices of the time. Book V, devoted to acoustics, specifies bronze pots, named 'echea', currently known as cavity or Helmholtz resonators. Before the Vitruvius treatise, Aristotle (c. 380–c. 320 BCE) also highlighted the relationship between the quality of sound and the presence of a cistern or a well or buried empty pots in a building (Aristotle 4th century BCE, Book XI).

According to Vitruvius, and apart from other practices to enhance sound distribution to the audience, bronze pots were laid out on the ground or under the steps of Greek theatres built of stone. In fact, the Greek theatres of Dionysius and Syracuse (5th century BCE) reveal, even nowadays, an impressive knowledge of acoustics. The Vitruvius text also contains recommendations to improve acoustics in the Roman Senate House, an important public building where senators expounded on their ideas, through speech and long reverberation times were hence undesirable. Those recommendations included the dimensions of the building and the materials that should cover the cornice (stucco or woodwork).

Vitruvius also denoted the use of earthen vases in small Greek theatres as a similar and more affordable solution than bronze pots (Vitruvius 1st century BCE, Book V). Nevertheless, acoustic science demonstrated that the material of the vessel, the way it is mounted (loose or fixed to the base) and its geometry influence the behaviour of the sound field inside the cavity, and thereby the perception of the sound inside the room. Moreover, the number and the location of cavity resonators, besides the position of the sound source, affect the distribution of sound into enclosed spaces.

Despite the Vitruvius descriptions, such acoustic pots have never been found in ancient theatres. As Vitruvius claims to be unaware of any example in Rome, it is plausible that he only became aware about sounding vessels through oral transmission or reading, and had thus never used or seen them. In this regard, Crunelle (2009) noticed a historic curiosity: almost everything that is known about ancient Greek resonators resulted from the Vitruvius text, even without any actual archaeological findings; furthermore, despite the existence of several examples in medieval churches, no written records on the function of embedded ceramic pots have ever been identified.

The potteries installed in Romanesque and Gothic churches, and in Ottoman mosques, are generally vases, vessels, jars, urns or pots with or without handles. They are manufactured of red or grey clay whose primary function appears, in most cases, to be typical of utilitarian use (Arns & Crawford 1995; Desarnaulds et al. 2001; Ergin 2008; Kayili 2005). The employed vases are of small but variable size and shape, even within the same building (Crunelle 2009; Desarnaulds et al. 2001; Kanev 2020). The vases are generally embedded in the masonry with the visible openings placed on the plan of the wall, which are sometimes visible while others stand integrated into the surrounding pictorial decoration (Desarnaulds et al. 2001; Kayili 2005). However, in some worship buildings, the openings of the ceramic vases are not visible as they were covered with mortar and decorated with fresco paintings (Mijic & Sumarac-Pavlovic 2002) or filled with bricks and plastered over during later restoration works (Ergin 2008; Kayili 2005).

The number of embedded ceramic pots in churches and mosques ranges from a few units to some hundreds in the same building. The Chartreuse du Val de Bénédiction in Villeneuve-lès-Avignon (France) includes three ceramic pots (Arns & Crawford 1995). The Süleymaniye Mosque in Istanbul has about 255 embedded ceramic pots open towards the space of worship (Ergin 2008; Kayili 2005). The Russian Orthodox church of St. Nicholas in Pskov has about 300 pots inserted into its walls (Kanev 2020).

As the inlaid ceramic pots are widespread to different building construction traditions and architectural cultures, their functions are approached in different ways. Arns and Crawford (1995) argue that besides acoustic purposes, ceramic pots found in churches may been burial urns unearthed during construction, or their openings used for the suspension of ornamental hangings, or even to reduce the weight of the walls. In Byzantine constructions, empty ceramic amphoras and pipes were incorporated in the church buildings with a view to lightening the structure and to avoid moisture problems resulting from the improper drying of the massive wall masonry. Hence, no acoustic purposes were behind their use. However, as the vessels were embedded into the masonry with their openings facing the inner space, the architects and builders certainly perceived their benefit for acoustics (Kanev 2020), as Aristotle had also highlighted centuries before.

Arns and Crawford (1995) mention 17th century scripts that relate church vases to those described by Vitruvius for Greek theatres. These authors also noted that ancient Greek and Roman theatres were linked to pagan practices, thus it would be surprising if a prescription for those (heathen) auditoriums was approved for worship buildings. Furthermore, Vitruvius described a solution to improve the acoustics of theatres, i.e. open-air space buildings, which suggests that the vases installed in medieval churches might reflect a different practice for enclosed spaces (Arns & Crawford 1995).

Different studies provide detailed information about the location and characteristics of ceramic pots in Romanesque and Gothic worship buildings in several countries. The most common positionings of the wall embedded vessels are in their upper portions, in the vaults/ogives, in the corners/angles and around the windows (Arns & Crawford 1995; Desarnaulds et al. 2001; Đorđević et al. 2017; Zakinthinos & Skarlatos 2007).

Crunelle (2009) argues that the vases inserted in the masonry represent a conscious attempt seeking to endow a specific acoustical character to a space. Ars and Crawford (1995) state that ceramic vases had been installed in medieval European churches in a systematic and purposeful way and probably for acoustic purposes. Đorđević et al. (2017) analysed the position and physical characteristics of embedded ceramic vases located inside fifteen medieval Serbian churches; this study pointed out that the recourse to acoustic vessels can be considered an expression of the musical traditions of Serbian medieval worship architecture.

In order to demonstrate the influence of ceramic pots in the sound absorption of Christian churches, experimental tests were carried out according to two different approaches: in situ measurements, i.e. inside the buildings, and in laboratory facilities. Desarnaulds et al. (2001) analyzed the speech intelligibility in two Swiss Christian churches with four embedded ceramic pots and similar volumes by in situ measurements. These authors concluded that the weak variations observed in the measured parameters make any audible improvement in the room's acoustics due to the existence of the pots highly unlikely. Carvalho et al. (2002) performed experimental laboratory measurements of ceramic pots similar to those used in some medieval churches; the results demonstrated that sound absorption does increase. Therefore, regarding the same authors (Carvalho et al. 2002), this conclusion confirms the relevance of the tradition that often involves usage of acoustic pots inside the churches, especially near the corners. Zakinthinos and Skarlatos (2007) studied the effect of 480 cavity resonators with the same resonance frequency placed inside an orthodox church by measuring and analysing the impulse response of the building. The authors concluded that the vases located in the corners were acoustically more efficient (compared to other positions in the building), which conveys some kind of knowledge on the acoustic performance of enclosed spaces. Mijic and Sumarac-Pavlovic (2002) carried out laboratory experiments with ceramic vessels found and removed from some medieval Serbian churches in order to measure the reverberation time under simulated real conditions; these authors conclude that the ceramic vases inlaid into the walls and domes of the buildings resulted from an orally transmitted tradition without any real knowledge of their function.

Ceramic vases were also embedded in the walls of some Muslim worship buildings, which is believed to have become a tradition in Ottoman mosques to overcome acoustic problems resulting from their geometric configuration (Kayili 2005; Sü & Yilmazer 2008). Ottoman mosques are generally domed structures. The concave shape of these structures imposes specific challenges, because within these forms incident sound energy reflects back and forth several times, making speech unintelligible. Cavity resonators placed in a dome prevent the multiple reflections of sound energy. Hence, the incident energy is reradiated in all directions, the sound field becomes diffused and the inconvenient echoes, due to delayed reflections from the dome, are eliminated. In addition, the sound coming from the dome shortly after the direct sound, creates an appropriate effect for this worship environment (2005).

(2002) measured and compared the reverberation times of six Ottoman mosques with cavity resonators with free (in four mosques) and plastered openings (in two large-size mosques); the experimental results indicate that the mosques with cavity resonators with free openings present lower reverberation times at low frequencies. Thus, the cavity resonators control excessive low frequency content, and contribute to lessening the weight of the dome (Gül & Caliskan 2014), this latter factor of particular importance in large-size structures.

Carvalho and Vieira (2020) characterized the acoustic effects of the eight embedded ceramics in the synagogue of Tomar by measuring the in-situ reverberation time values. These experiments were carried out with and without the occlusion of the vase's openings. The results demonstrated a small contribution to the acoustic absorption of the worship hall by the presence of the opened ceramic vases.

4 LITURGY IN ANCIENT WORSHIP BUILDINGS

Judaism, Christianity, and Islam claim descent from Abraham. These monotheistic religions are based on literature considered, by their believers, of divine origin (sacred). Each has different rituals and consequently specific building features and requirements, to provide the accurate worship environment for their believers. In this context, a proper acoustic ambience is essential not only for good communication and understanding the liturgy but also for the praying of the worshipers.

The next sections summarize the main features of each worship building, with special regard to their ritual activities and sound environments.

4.1 *Synagogues*

The spiritual Jewish heritage, embodied in the Hebrew Bible, was integrated into the liturgy, first in the Temple of Jerusalem and later, after the destruction of the Temple (70 CE), in houses of prayer, study and community assemblies known as synagogues. As much as synagogues provided these main three functions, they also reflected the conditions and the way of thinking of those who built and used them (Simha 1995; Weissbach 2011) in the different countries where Jewish people settled.

According to Burton (1896), the main elements of the ancient Jewish service were worship and instruction. The spoken liturgy was the dominant sound source and the Torah its basis. In Sephardic synagogue buildings, the Torah was read from a centred raised platform. During the service, the worshipers were arrayed around this central raised platform which, apart from the symbolic meaning, also suggests acoustic purposes (Carvalho & Amado 2011; Weissbach

2011). Therefore, a clear perception of sound was certainly of high relevance in the synagogue worship hall.

In European countries, synagogue buildings should be oriented toward Jerusalem, i.e. to the East, with no specific exterior shape or pattern. Throughout the Middle Ages and the Early Modern period, synagogue buildings were raised according to the norms of vernacular architecture that prevailed in the country in which they were built (Steifel 2011; Weissbach 2011).

4.2 *Churches*

Churches are the houses of worship for Roman Catholic Church, Eastern Orthodox and Greek Catholic congregations. In Western Europe, several Christian worship buildings erected between the 11th and the 17th centuries include earthen vases in their masonry walls (Crunelle 2009; Valière & Palazzo-Bertholon 2017). Orthodox churches, in the same period of construction, also reveal the presence of ceramic vases (Kanev 2020; Mijic & Sumarac-Pavlovic 2002; Zakinthinos & Skarlatos 2007).

In the 1st and 2nd centuries CE, the newly emerged Christian Church used catacombs, underground Roman galleries, with long reverberation times, for clandestine religious rituals. This circumstance, besides the inherited Hebrew tradition, relating with the ceremonies of religious text intonation, would influence the later development of the Church service, such as the presence of the choir in the liturgy (Girón et al. 2017). Hence, the dominant sound source in Romanesque and Gothic Christian worship buildings was mainly based on monophonic chant, traditionally performed by male vocalists. The human voice was similarly dominant in Orthodox services (Đorđević 2017). In this sense, the use of cavity resonators can be understood as modulating the acoustic environment, emphasising the mood and the ambience for worship. However, it is important to highlight that cavity resonators operate in a narrow frequency band in the vicinity of the resonant frequency, it is therefore entirely unreasonable to assume their influence over a wide range of speech frequency.

4.3 *Mosques*

Islam’s most important text is the Qur’an. In Islam, the concept of scripture closely links to the acoustic ambiance created by the recitation of the Qur’anic text. The oral nature of the Qur’an imposes the ability not only to hear but also to understand the sacred text. The high relevance placed on the experience of Qur’anic recitation must have been an essential requirement of Ottoman mosques, and a priority for their architects and builders (Ergin 2008). Therefore, mosque design and its construction were almost certainly influenced by worship considerations needing high levels of speech audibility and intelligibility.

Recent restoration works revealed the existence of inlaid ceramic vases in the walls surrounding the domed structures of the complexes of the Shehzade Mhemet (completed in 1548), the Süleymaniye (completed in 1557), the Sultan Amhet or Blue Mosque (completed in 1616), all located in Istanbul, and the Selimiye (completed in 1575) mosques, located in the city of Edirne. However, the openings of most vases were sealed during some previous repair works, denoting a lack of knowledge about their original function.

5 DISCUSSION

Architectural acoustic concerns date back from antiquity as reported in the Vitruvius treatise. The text describes some coeval solutions to overcome acoustic problems in the most important public spaces of those times. Acoustic vases were proposed for open-air spaces, while specific materials, ceiling shape and dimensions were recommended for enclosed spaces. Vitruvius’ treatise lasted through the ages, with relevance in Medieval and Renaissance periods.

Several Christian Romanesque and Gothic churches present cavities in their masonry walls formed by inlaid ceramic vases. These pots were found in different countries, e.g., France, Switzerland, Serbia, Russia, Britain, Italy, Cyprus, Greece or Spain.

The vases, with different shapes and sizes, were installed, mainly during construction, in diverse positions of their buildings, including in the corners. Traditional Byzantine construction included hollow spaces in masonry walls and vaults both to lighten the structure and to overcome moisture problems. This practice also hosted acoustic changes inside the buildings, perceived by their architects and builders, who probably did link the effect to acoustic benefits. In fact, long reverberation times result in insufficient intelligibility and audibility of speech, especially in large-size enclosed spaces with stone walls.

Although ceramic vases may perform as Helmholtz resonators as shown by laboratory tests, when inlaid in walls that behaviour depends on different factors, e.g. the number of cavities, their placement, the geometry and the building’s characteristics.

Recent experimental tests carried out in churches with inlaid ceramic vases revealed a perceptible reduction of reverberation, for low frequency content, which was more evident for those placed in the corners of the building. These studies also highlighted that this practice probably derived from a kind of awareness on the perception of sound inside enclosed spaces. Moreover, despite monophonic chant being the prevailing sound source in Romanesque and Gothic churches, it would be necessary to select the number of suitable cavity resonators, i.e. size and shape, to act successfully across that wide frequency range.

Experimental tests conducted in Ottoman mosques with inlaid ceramic vases, revealed a reduction of reverberation times at low frequencies. Large-scale Ottoman mosques were masterpieces of building techniques and fine arts with their architects also aware of acoustic problems due to their dome’s shape, and thereby used ceramic containers, or Helmholtz resonators, to overcome those difficulties.

It seems plausible that beside the Vitruvius descriptions on the benefits of 'echea', the practice to embed ceramic vases in the walls would also arise from the constructive tradition for decreasing the weight of masonry walls and avoiding moisture problems, which would together have contributed to the belief in an effective technique to overcome acoustic issues in enclosed spaces. In this regard, given the importance of worship buildings back in those days, and as well the predictable existing problems due to undesirable reverberations inside worship spaces, it is also probable that the 'technology' became a practice for acoustic intents.

Throughout the Middle Ages and the Early Modern period, synagogue buildings were inconspicuous edifices, with no specific external signs and built according to local rules and following the prevailing vernacular construction styles. The synagogue of Tomar was closed and devoid of religious functions in 1496, however, the building and its main constructive features lasted well preserved. This circumstance seems to be an exception, given the historic context and Jewish religious persecution: most of these buildings were destroyed or radically altered to accommodate other functions, with few remaining original specimens. The Tomar synagogue building has been studied by historians who related its constructive origin and architectural features with the crypt of a coeval Christian church, located in the area. A recent study puts forward the hypothesis that the synagogue was built by an Italian master builder who also built the neighbouring Christian church. Moreover, there is no evidence of the practice of embedding ceramic vases in the walls in other Portuguese worship buildings.

Experimental evaluation of the reverberation times in the Portuguese synagogue worship hall revealed that, despite a slight decrease in the overall values with free openings, that reduction does not reflect an acoustic improvement in the synagogue worship hall. These findings seem consistent with those of the experimental in situ tests carried out in two small churches with four wall embedded ceramic pots irrespective of the differences between these buildings and the Portuguese synagogue (e.g., volume, architectural shape, vases-volume ratio).

Despite the specificities of the liturgies and rituals of each religion, Judaism, Christianity and Islam, the dominant sound source in synagogues, churches and mosques would have been mainly based on the intonation of human male voices duly conveying the divine message. Therefore, it is predictable that the demand for a high level of speech intelligibility and audibility was shared across the three religions, correspondingly emphasising the importance of architectural acoustics in their buildings. The architects and builders of ancient worship buildings were certainly aware of this demand.

In light of the above, the construction of some synagogue houses would have been conducted by architects and builders who also would have designed and built other types of worship buildings. In this perspective, it seems probable that the synagogue building of Tomar followed the prevailing constructive practices adopted by other worship buildings. It is also plausible that the builders that incorporated the eight ceramic vases in the walls at the corners of the synagogue hall had the main intention of improving its acoustics. Although there are no findings on this tradition in other Portuguese worship buildings, this circumstance seems congruent with the hypothesis that the construction of the synagogue was conducted by a foreign master for whom the technique was familiar.

6 CONCLUSIONS

This paper reports on the eight embedded ceramic vases in the corners, near the corbels, of the synagogue of Tomar, in Portugal. This building is one of the few preserved synagogues built in the 15*th* century. Furthermore, while these vases had been orally attributed by residents to acoustic purposes, there were no published English language studies on the use of ceramic vases in other coeval synagogue buildings nor in other Portuguese worship buildings. In fact, only a small number of synagogue buildings survived destruction over the course of history.

According to some experimental tests conducted in different churches, the usage of ceramic vases probably rested more on a tradition than on effective knowledge of the laws of acoustics, namely in small size buildings with few specimens of acoustic embedded vases. Despite this finding, it should not be forgotten that ancient buildings and their technologies are not yet completely understood because, in most cases, there are no written records on them, or those records have been lost over the centuries.

Specific research on ancient construction practices and even unsuccessful technologies, as seems to be the case with the acoustic vase practice, may offer the opportunity to fully understand ancient buildings, and thus draw their constructive history. Besides the benefits of increasing knowledge in the field of History of Construction, research on ancient building techniques, specifically on this topic of acoustics, also contributes to accomplishing more accurate restoration works in such buildings. Additional advantages may be associated for other domains: supporting the conservation of intangible heritage, increasing cultural understanding and consequently benefitting cultural tourism.

A multidisciplinary approach, i.e. building techniques, acoustics, psychoacoustics and ancient religious studies, would be helpful in order to understand whether acoustic related problems held the same importance in synagogues as they did in Christian and Muslim worship buildings.

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The vaulted systems of the colonial city of Quito, Ecuador

F.S. López-Ulloa & A.A.López-Ulloa
Universidad Técnica de Ambato, San Juan de Ambato, Ecuador

ABSTRACT: The vaulted systems of the colonial city of Quito are key to the construction history of its former main churches, mostly made of brick and stone masonry; whose singular structural characteristic bears continuous earthquakes. Recently, several restoration and structural reinforcement interventions have taken place to ensure their conservation. This in turn, has produced some studies with a number of architectural surveys. These have been compiled and systematized with comparative tables, aimed at presenting a graphic resource with schematic plans and sections, which at the same time, collect various data related to their origin and construction. As a result, it is possible to have the first comparative graphics of these structures from ten of the most important colonial churches in Quito.

1 INTRODUCTION

The construction system of arches, vaults and domes in the colonial city of Quito has hardly been studied through the theory of limit analysis of structures. However, several studies have been carried out using modern engineering methods, which has left an important record of architectural surveys, through which these types of structures can be studied in greater detail. Therefore, it is possible to have a range of analyses from the formal field to more technical in the structural sense. Additionally, these graphic resources offer an opportunity to systematize information about materials and construction techniques.

Consequently, this study presents this graphic information, collected and systematized around the structural systems of arches, vaults and domes, of ten of the most representative colonial churches (Figure 1).

The work consists of a compilation of schematic plans and sections which allows a general overview of the whole structure, with a quick appreciation of its shapes, dimensions, scales, proportions, types, construction techniques and locations.

Likewise, it has been necessary to update some data, including a new photographic record, using techniques commonly applied today, such as laser scanning and photogrammetry.

Most of the colonial churches in Quito have a pattern related to the basilica ground plan, which consists of three aisles plus a transept, shaping the Latin cross plan. According to the Catholic tradition, the three aisles facing the head of the church, from left to right, are known as Gospel aisle, Central aisle, and Epistle aisle.

Through original plans, the geometry of these structures is practically invisible, and little or nothing is known about the rules used by their designers and builders, such as proportions or possible geometric relationships. For this reason, the recent architectural survey executed in several works of restoration and structural reinforcement, and implemented by several institutions as projects, have allowed an approach to obtain real measurements and construction details, in addition to unpublished information.

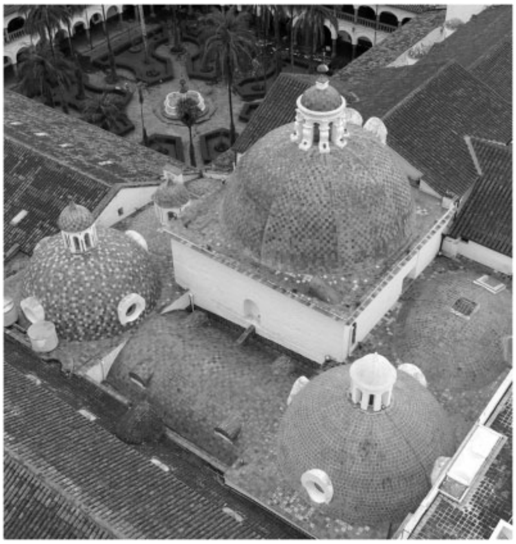

Figure 1. Quito, San Francisco church, presbytery and side chapels domes (Authors' photograph).

Therefore, the present study shows a graphic comparative record among churches through which some similarities and differences can be appreciated.

2 SELECTED CHURCHES AND LOCATION

The ten selected colonial churches were mostly made of brick and stone masonry structural systems that have remained in the historic center of Quito for centuries

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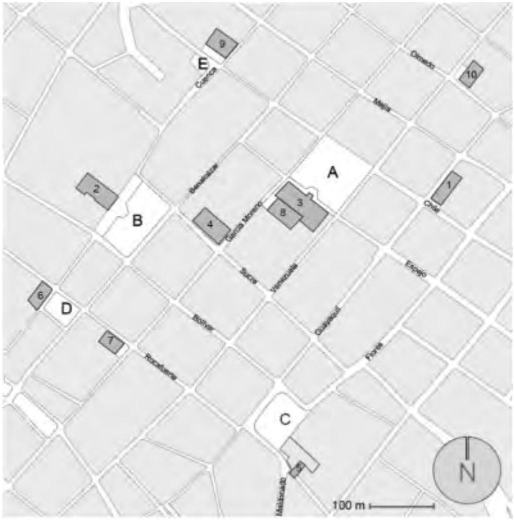


Figure 2. Quito, Historic Centre, location on the ten main colonial churches (Authors' map).

and whose stability and mechanical behavior have an evident relationship with geometry, in terms of planning and materials. The main colonial buildings were built between the 16th and the 18th centuries. The list below indicates the centuries in which the works began. The numbers have been assigned according to the map (Figure 2).

1. Church of San Agustín (16th century), Chile St.
2. Church of San Francisco (17th century), Plaza de San Francisco.
3. Catedral Metropolitana (16th century), Plaza Grande.
4. Church of La Compañía de Jesús (17th century), García Moreno St.
5. Chapel of Rosario (17th century), church of Santo Domingo, Plaza de Santo Domingo.
6. Church of Santa Clara (17th century), Cuenca St.
7. Church of Carmen Alto (17th century), García Moreno St.
8. Chapel of Sagrario (17th century), church of Santo Domingo, García Moreno St.
9. Church of La Merced (18th century), Plaza de La Merced.
10. Church of Carmen Bajo (18th century), Olmedo St.

A. Plaza Grande
B. Plaza de San Francisco
C. Plaza de Santo Domingo
D. Plaza de Santa Clara
E. Plaza de la Merced

3 COLONIAL CHURCHES

The colonial churches of Quito have semi-circular or pointed arches, vaults or wooden structures on roofs, and domes. These structures hold construction variations that respond, as everywhere, to geographic conditions, budgets, requirements of its owners, and in the particular case of Quito, to the strong seismic conditions that in some cases caused the collapse of several vaults and domes. However, there were also cases of poor execution before which the structural systems were adapted or exchanged for structures of different materials. In other cases, structures were reinforced or adjusted through extensions or remodeling. Take as an example the church La Compañía de Jesús, which initially had a coffered ceiling that was replaced by the current vault. This replacement forced its builder, Brother Marcos Guerra, to reinforce the entire structure (Piñas 2008).

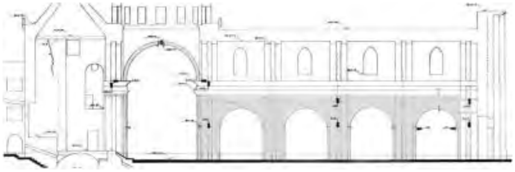


Figure 3. Quito, Compañía de Jesús church, longitudinal section, semi-circular arches (IMP 1995).

4 GRAPHIC TOUR

In order to offer a general view of shapes and schematic section profiles, a graphic tour of the most representative sections of the selected churches was designed, including arches, vaults and domes. It is also possible to appreciate main and formeret arches, as well as various types of vaults.

Finally, the graphic tour offers the opportunity to see the height and span dimensions of the distinctive domes of the transepts, presbyteries, side aisles, adjoining chapels, and some domes that cover almost entirely the central aisle. This feature facilitates certain aspects, such as having a comparative look at their scales.

4.1 *Arches*

The most important arches are related to those that define the structure of churches. Among these, it is possible to find the transepts' main arches, the formeret and transverse arches, which are those that can either separate aisles, hold some minor domes or be part of the barrel vaults.

There are two types of arches in the studied churches; semi-circular and pointed. The former are part of most church structures; for example, those of the church La Compañía de Jesús (Figure 3), while the latter are distinctive of the Cathedral (Figure 4) and those of the transept of the church of San Francisco.

4.2 *Vaults*

The main barrel vaults are located in the central aisles and transepts of the churches of La Compañía de Jesús, La Merced, chapel El Sagrario and a part of Santa

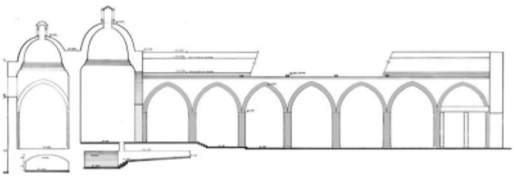


Figure 4. Quito, Catedral Metropolitana, longitudinal section, pointed arches (IMP1989a).

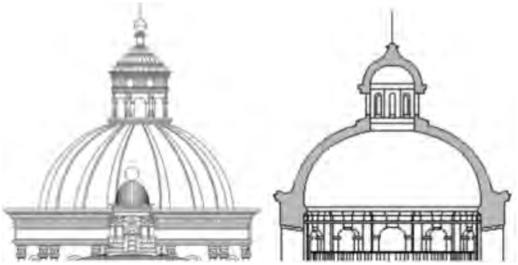


Figure 5. Quito, (Left) La Merced church, transept dome (IMP 1991); (Right) Compañía de Jesús church, section, transept dome (IMP 1989).

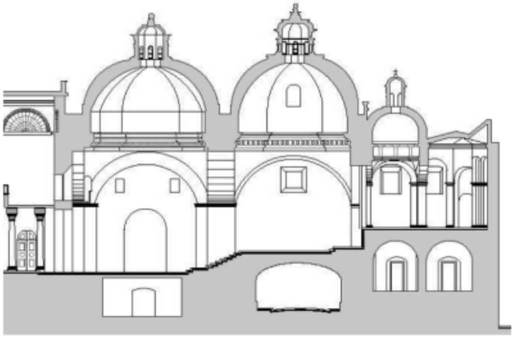


Figure 6. Quito, chapel of Rosario, longitudinal section (IMP 1999; López 2015).

Clara. These vaults maintain an alignment of formeret arches of important dimensions, according to the span of the vaults. In the case of the churches of San Agustín (CIMPC 1985) and Carmen Alto (IMP 2002), it is important to highlight the rebuilding of the original vaults, after the first vaults had collapsed in the earthquake of 1868. These vaults were fixed with wooden structures that used the support of the original walls and formeret arches (López 2015). Additionally, there are some surbased vaults, similar to those of the church of Santa Clara.

4.3 *Domes*

Regarding the domes, a great variety can be found. The large domes on drum on the transepts of the chapel of Sagrario stand out, as well as the ones in the churches of La Merced and La Compañía de Jesús (Figure 5).

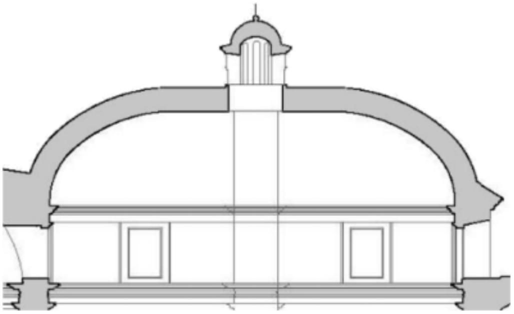


Figure 7. Quito, Santa Clara church, longitudinal section, central aisle oval dome (CIMPC 1993a; López 2015).

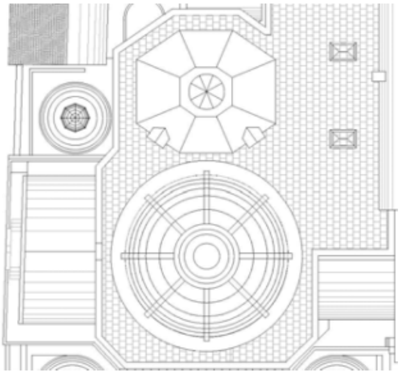


Figure 8. Quito, San Francisco church, detail of roof plan, presbytery and side chapels domes (IMP 2003).

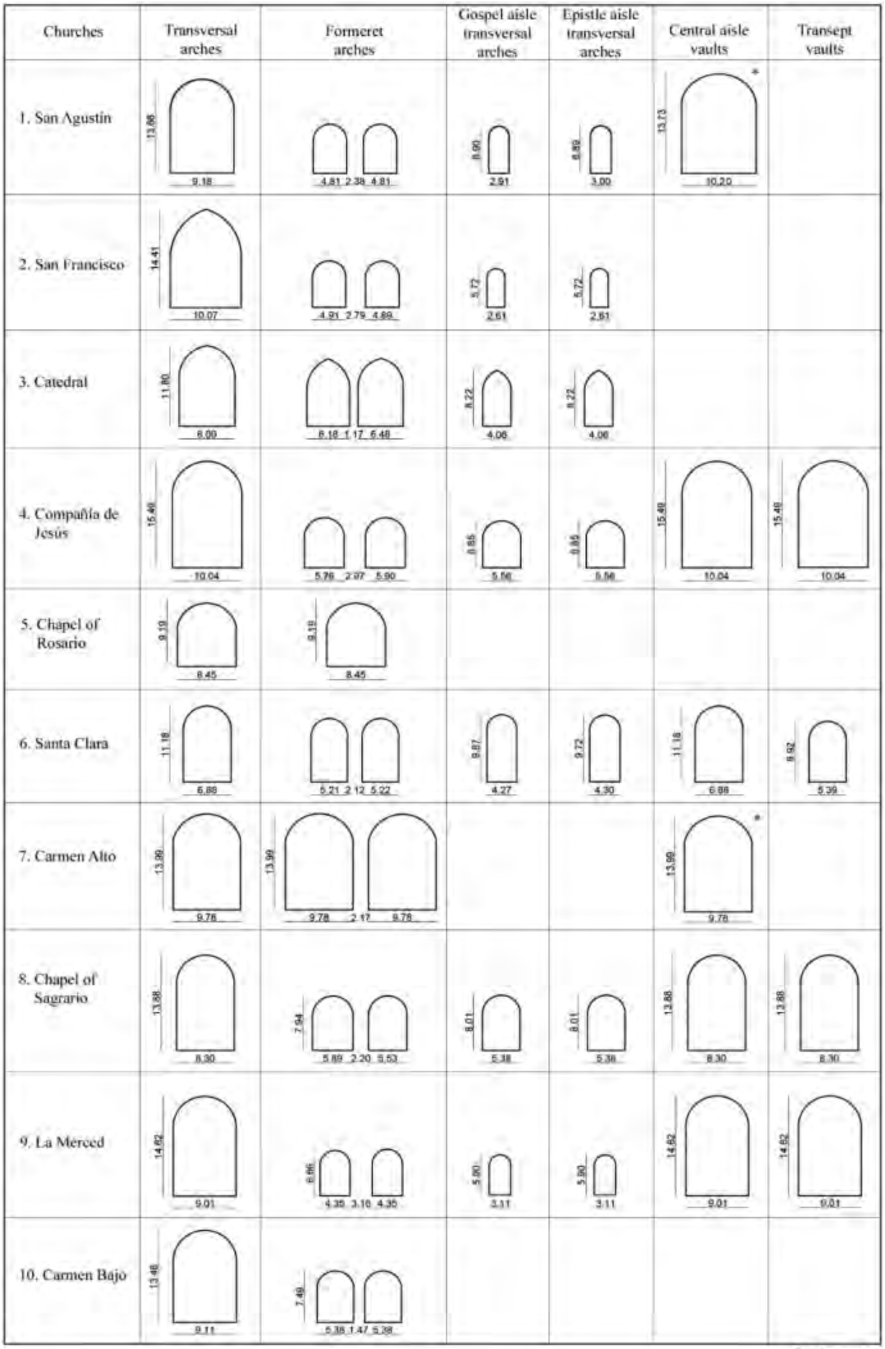
Some other highlights are appreciated in those that are located directly over the main arches; for example, in the presbyteries of the churches of San Francisco, Catedral, La Merced, Carmen Bajo; and the octagonal domes of the Cathedral, Santa Clara, chapel of Rosario and La Compañía de Jesús. Other minor domes exist as well, which cover the side aisles and chapels and other spaces, with several shapes, either semispherical, surbased, bulbous or oval. Finally, the particular domes of the central aisle, in the chapel of Rosario (Figure 6) and the singular oval dome of the church of Santa Clara (Figure 7) can also be mentioned.

Concerning the roof plans of the domes, it is possible to see the different designs and proportions, most notorious those that make up the transepts and presbyteries of almost all of them and whose detail is shown in the following figures (Figures 8–15).

5 TABLES OF SCHEMATIC PLANS

In the following tables (Tables 1–3) information about the arches, vaults and domes of the selected churches has been systematized, facilitating its comparison, as well as the presence or absence of some types in one or another church. Measurement is shown in meters.

Table 1. Arches and vaults, schematic planas (Authors's table).



Churches	Transversal arches	Formeret arches	Gospel aisle transversal arches	Epistle aisle transversal arches	Central aisle vaults	Transept vaults
1. San Agustín	13.86 9.18	4.81 2.38 4.81	8.90 2.91	8.89 3.00	13.73 10.20 *	
2. San Francisco	14.41 10.07	4.91 2.79 4.89	5.72 2.61	5.72 2.61		
3. Catedral	11.80 6.00	6.18 1.17 6.48	8.22 4.06	8.22 4.06		
4. Compañía de Jesús	15.49 10.04	5.76 2.97 5.90	8.85 5.56	8.85 5.56	15.49 10.04	15.49 10.04
5. Chapel of Rosario	9.19 8.45	9.19 8.45				
6. Santa Clara	11.18 6.88	5.21 2.12 5.22	9.87 4.27	9.72 4.30	11.18 6.88	8.92 5.39
7. Carmen Alto	13.99 9.78	13.99 9.78 2.17 9.78			13.99 9.78 *	
8. Chapel of Sagrario	13.88 8.30	7.94 5.89 2.20 5.53	8.01 5.38	8.01 5.38	13.88 8.30	13.88 8.30
9. La Merced	14.62 9.01	6.86 4.35 3.16 4.35	5.90 3.11	5.90 3.11	14.62 9.01	14.62 9.01
10. Carmen Bajo	13.48 9.11	7.49 5.38 1.47 5.38				

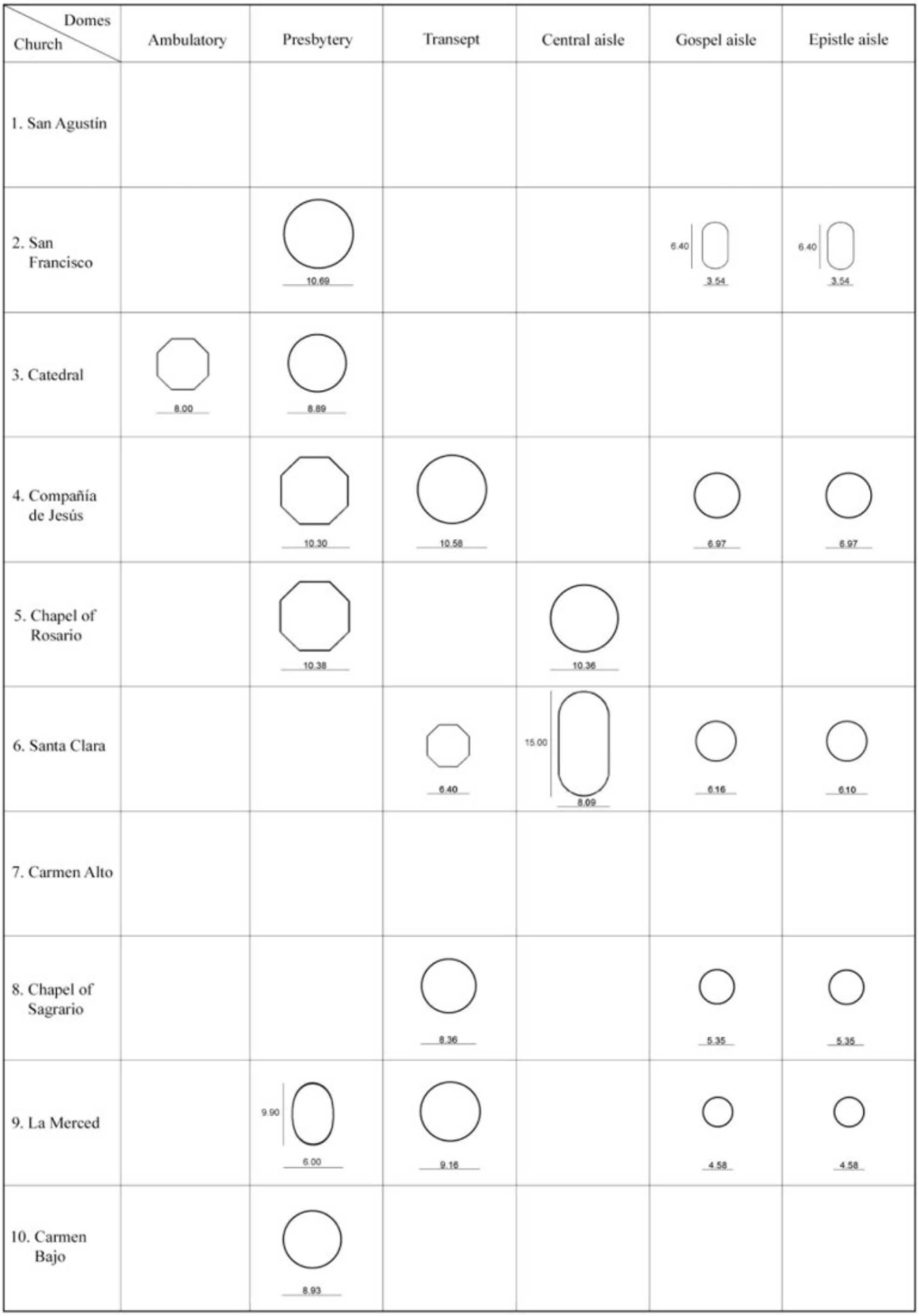
* False vaults

6 CONCLUSIONS

First, the range of construction possibilities in terms of arches, vaults and domes in the selected churches is wide. There are a number of series cataloged, allowing the appreciation of the differences between one and the other. The overall vision of typological series allows us to see the variety in scale, as well as the similarities, especially in layout schemes.

Secondly, it is possible to see how the span of the aisles in the same church does not always respond to a pattern, but rather, it presents notable differences

Table 2. Domes, schematic floor plans (Authors' table).

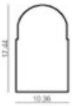
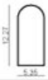


Domes Church	Ambulatory	Presbytery	Transept	Central aisle	Gospel aisle	Epistle aisle
1. San Agustín						
2. San Francisco		10.69			6.40 3.54	6.40 3.54
3. Catedral	8.00	8.89				
4. Compañía de Jesús		10.30	10.58		6.97	6.97
5. Chapel of Rosario		10.38		10.36		
6. Santa Clara			6.40	15.00 8.09	6.16	6.10
7. Carmen Alto						
8. Chapel of Sagrario			8.36		5.35	5.35
9. La Merced		9.90 6.00	9.16		4.58	4.58
10. Carmen Bajo		8.93				

in scale; as seen for example, in the churches of La Compañía de Jesús and La Merced. There are also exceptional cases where the three aisles are similar in their dimensions. This, compared against the basilical characteristic ground plan, makes it atypical of its kind, for example, in the church of Santa Clara.

The building characteristics of the selected churches are evidence of the importance and hierarchy

Table 3. Domes section, schematic plans (Authors' table).

Church \ Domes	Ambulatory	Presbytery	Transept	Central aisle	Gospel aisle	Epistle aisle
1. San Agustín						
2. San Francisco						
3. Catedral						
4. Compañía de Jesús						
5. Chapel of Rosario						
6. Santa Clara						
7. Carmen Alto						
8. Chapel of Sagrario						
9. La Merced						
10. Carmen Bajo						

of the first religious groups that settled in the colonial city of Quito. They are located in strategic places and used the best technical, technological and design resources there were. The structures had the intervention of well-known European and national architects, who contributed to their improvement and reconstruction with important budgets. Appropriate structural adaptations were carried out through which

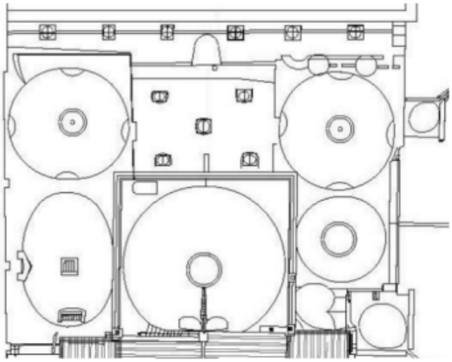


Figure 9. Quito, Catedral Metropolitana, detail of roof plan, presbytery, ambulatory and side chapels domes (IMP 1989b).

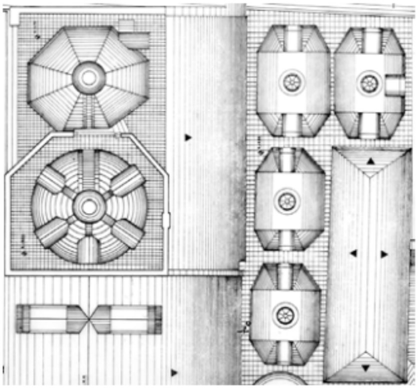


Figure 10. Quito, chapel of Rosario, detail of roof plan, nave, presbytery and sacristy domes (IMP 1999).

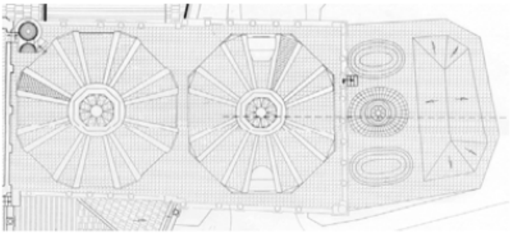


Figure 11. Quito, Compañía de Jesús church, detail of roof plan, transept and presbytery domes (IMP 1995).

it was possible to respond in a better way to earthquakes. To all the above can be added the use of the best artistic resources of the period in every finishing touch in both the inside and outside; as seen, for instance, in the monumental Monastery of San Francisco, the biggest in Latin America, and most remarkable representative of the Renaissance and Baroque tendency of the continent.

Finally, this study opens up new possibilities of analysis about these construction systems in the colonial architecture of Quito, in terms of techniques and materials. Furthermore, it sheds light on the mechanic

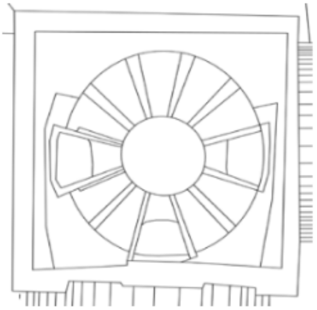


Figure 12. Quito, Carmen Bajo church, detail of roof plan, presbytery dome (IMP 2011).

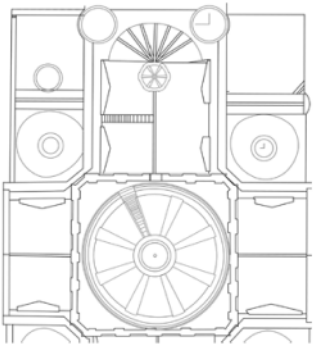


Figure 13. Quito, chapel of Sagrario, detail of roof plan, transept and presbytery domes (IMP 2009).

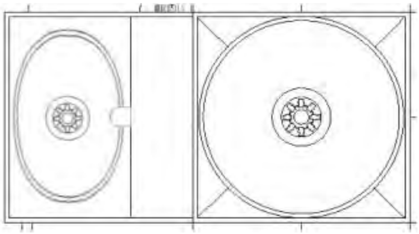


Figure 14. Quito, La Merced church, detail of roof plan, transept and presbytery domes (IMP 1991).

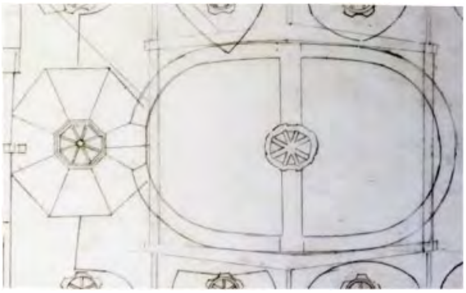


Figure 15. Quito, Santa Clara church, detail of roof plan, transept and central aisle domes (CIMPC 1993b).

behavior and geometric rules within the field of the limit analysis of structures.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Pursuing comfort in late 19th century school buildings in Milan: Technical knowledge and role of the enterprises

A. Grimoldi & A.G. Landi
Politecnico di Milano, Milan, Italy

ABSTRACT: After 1860, in European states, laws made public education compulsory and the obligations, which had already been sanctioned for nearly a century, were made effective: until then, they had hardly been applied. Urbanization was advancing ever further and the increase in the population required the construction of large school buildings in the cities. The best-known architects of the time participated in the implementation of a new building type. Ventilation was essential for the hygiene and heating was necessary to pursue school comfort. School construction stimulated the evolution of techniques, both in studies and in production. In Italy, studies in applied engineering promoted the development of a specialized mechanical industry in Milan, which met the high needs of the city and the region, attaining a dominant position in the rest of the kingdom. The city archives keep extensive documentation on the construction of the Milanese schools, the application of new technologies and the company roles and strategies in applying them.

1 INTRODUCTION

In the ancient Duchy of Milan, compulsory education dated back to the end of the 18th century. By the decree of Count Gabrio Casati, formerly mayor of Milan (1859), the newly founded Kingdom of Italy extended this obligation to its entire territory and attributed municipalities with the burden for school management, from the cost of personnel to the maintenance or construction of school buildings.

In cities, school classes were often located in private homes, rented and adapted, or in the monasteries or even the oratories of brotherhoods, suppressed at the end of the eighteenth century and, from the mid-19th century onwards, in purchased aristocratic residences.

The need for adequate buildings was soon encountered and became unavoidable when the Coppino law (1877) made effective the obligation established in 1859. Faced with the financial difficulties of municipalities, subsidized loans were granted for school buildings by law no. 4460/1878, establishing minimum requirements for new buildings and subsequently reiterated by law no. 5616/1888 (Grimoldi, Landi 2019).

The hygiene and functionality of spaces actually took crucial importance and gave ample space for the application of technological planning, in particular for centralized heating and natural and artificial ventilation. The Milanese experiences are particularly significant.

2 AIR HEATING, A PECULIAR MILANESE ACHIEVEMENT

The city had its own tradition in the heating sector. In the 18th century, large Milanese majolica stoves or simply brick stoves were commonly used, and hot air heating, known in the nineteenth century as *calorifero*, was installed in the Palazzo di Corte in 1750 (Forni 1997), before then spreading to every large house in the entire region. Meanwhile, the system had evolved: the first brick stoves were gradually replaced by cast iron furnaces and then all the improvements proposed by Meissner in the 1920s-30s were implemented (Forni 2017). A furnace heated a brick “chamber”, having sufficient thickness to ensure good insulation. The heat of the smoke was also exploited, making it circulate along iron sheet ducts, which sometimes crossed the chamber in several turns. Both the brick and iron components were affected by the heat and its variations. The joints were sealed with clay and had to be constantly renewed: the combustion gases and smoke were not to enter the hot air ducts through cracks and diffuse into the heated rooms. To avoid introducing too hot and dry air, the exchange surfaces between the furnace and the air, as the exchange chambers, had to be very large.

An air heater required continuous monitoring and adjustment. The stove could be placed in a room other than that to be heated, usually in a mezzanine, below the rooms, or in the cellars: this possibility was

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much appreciated. The distribution of the heat was relatively simple, requiring only ducts in the walls, which were generally vertical. The changes in the direction of the ducts reduced the speed of the air, while attempts were made to increase its quantity and decrease its temperature. In the two editions of his pamphlet, Meissner (Meissner 1821) proposed ducting systems with horizontal tree paths of decreasing width, or diagonals; he even suggested the use of metal ducts within the wall cavities; however, these devices, which would have involved the implementation of cavities (similar to those required by the chimney flues in multi-storey rental houses), were not detected in all the cases studied. In the second half of the 19th century, sub-horizontal ducts in the cellars were frequent, with their length not exceeding fifteen meters (Ferrini 1876, p. 387) and formed by metal profiles that supported plastered tiles.

3 ITALIAN TECHNICAL LITERATURE AND ITS EUROPEAN REFERENCES

Attempts to eliminate the defects of these air heating systems had necessarily to focus on the production of heat in the stove. An effective synthesis of its ensuing implementation, especially in the German technical literature, is provided by Scholtz in the third edition of *Baukonstruktionlehre* by G.A. Breymann (Breymann 1893).

An extensive bibliographical survey on this subject is carried out in several languages by Hermann Fischer in the *Handbuch der Architektur*, the most extensive and complete manual of the late 19th century (Fischer 1881; 1890). Even if we cannot analyse Fischer’s manual, it would be useful to understanding how, at that time, the expert technicians assimilated this technical evolution. In France, the fourth, posthumous edition of the manual by Péclet (Péclet Hudelo 1878) and by Planat (Planat 1880) played a similar role. Thus, recourse will be made to this general literature only if strictly related to the case studies considered.

Specialized publications, including those in English, circulated in Milan among the most up-to-date clients already in the first half of the 19th century. The cost of iron and the difficulty in providing coal – necessary to power sophisticated plants – hindered the development of the sector, in particular due to the lack of training of technicians. The *Museo Industriale* (Industrial Museum), founded in Turin in 1862 (Codazza 1873), was directed by an engineer, Giovanni Codazza, former Rector of the University of Pavia whose studies included the physics of heat (Ferola 1982). The collaboration between the Museum and the *Scuola di applicazione per gli ingegneri* (Application School for Engineers) in Turin and the foundation of the *Istituto Tecnico Superiore* in Milan (then named the Polytechnic) drew up the curriculum of studies for an industrial engineering degree. This model was proposed in accordance with an analogous course which had been taught in the Polytechnic of Vienna since 1815.

In 1870, Francesco Bongioannini discussed his thesis on heating and ventilation systems at the Turin *Scuola di applicazione per gli ingegneri* (Bongioannini 1870), with this then a novelty in the Italian technical literature. Bongioannini – an eclectic figure equally dealing with building services and the protection of monuments – concluded his manifold career as a superintendent for Education in Alessandria (Grimoldi, Landi 2019, p. 108). He finally published a collection of model projects for school buildings, including also heating system plants: circulation stoves heated the classrooms from the corridors (Bongioannini 1879).

Rinaldo Ferrini (Pozzato 1997), a professor at the *Milan Polytechnic*, was the author of the most systematic text, titled *Tecnologia del calore* (Ferrini 1876), which was translated into French in 1880 and also into German in 1887. The book was mostly updated on the French, English and German literature, even if lacking in bibliographical references, and described the state of the art in 1875, on the eve of significant changes. A very successful manual followed in 1886, published by Hoepli (Ferrini 1886), and intended for a wider audience of technicians.

The *Politecnic*o – the fusion of the technical part of the famous magazine animated by Cattaneo with the *Giornale dell’Ingegnere* (1869) – devoted rare and short articles to heating and ventilation systems, either in the bibliographic review or in the “technological physics” sector, which also included both electricity and industrial plants. The author was almost always Ferrini. The famous physicist was not very interested in applications: for example, he only reported the air heater by *Fischer and Stiehl* (Ferrini 1883), which was already illustrated eight years earlier (*Stumme’s Ingenieur* 1875).

Only at the turn of the century did he deal with steam heating and hot water heating but he pointed out conceptual problems that are still somewhat relevant today (Ferrini 1898). In proportion, the magazine*L’ingegneria civile e le arti industriali* – edited by Giovanni Sacheri since 1875 – seems more accurate although published in monthly issues of thirty-two pages, less than half of the *Politecnico* issues. Sacheri himself illustrated the *Eisenwerk Kaiserlautern* hot air system displayed at the Milanese Exhibition in 1881 (Sacheri 1882). In Italy, it was assembled by the *Besana e Carlon*i company in Milan. Engineer Francesco Corradini defended the usage of finned tubes (Corradini 1882), while a text in two parts illustrates the advantages and disadvantages of the most common systems, and bears the signatures of the two owners of a famous company, founded in 1872 in Berlin, Hermann Rietschel and Rudolf Henneberg (Rietschel, Henneberg 1883). They were presented as Viennese, but Rietschel became professor at the Berlin Polytechnic in 1885: he founded the Institute that still bears his name today, and developed the teaching of technical physics (Usemann 1993). He was also the author of research on heating schools (Rietschel 1886).

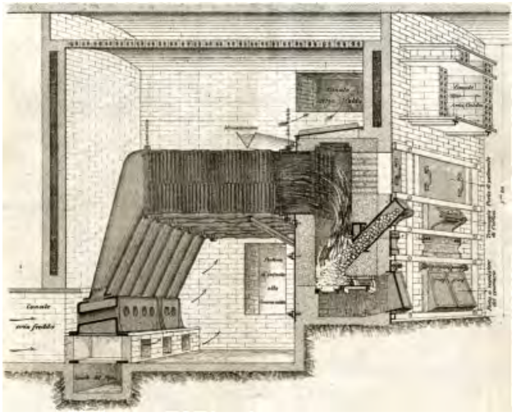

Figure 1. The *calorifero* (hot air heater by F. Corradini), in *L'ingegneria sanitaria*, no. 9, 1890, tav. 7.

A branch, the company *Kurz, Rietschel und Henneberg* operated in Vienna and realized many heating systems in public buildings (Usemann 1993, p. 155), including the Neues Rathaus (Weiß 1883) by Friedrich Schmidt, who was closely linked to the Milanese cultural *milieu*.

Sacheri himself presented an air heater – visibly derived from the *Eisenwerk Kaiserlauter* model – by his collaborator Corradini (Sacheri 1886), a mechanical engineer from Thiene, who graduated in Turin in 1876 (Curioni 1884, p. 238)

Specialized magazines, also entirely dedicated to civil construction, such as *Edilizia Moderna* – published in Milan since 1892 – or *Architettura Italiana* – published in Turin since 1890 – devote increasing space to heating systems but the demand in the sector had grown so much that Corradini had been able to publish a monthly magazine entitled *L'Ingegneria sanitaria* since 1890; he ran that magazine until 1905 when this merged with *L'ingegnere igienista*. In the issue of July 1890, Ferrini himself illustrated Corradini's air heater (Ferrini 1890), whose patent was sold to the G.B. Porta company and, in the same year, the *Politecnico* recommended this new magazine to its readers.

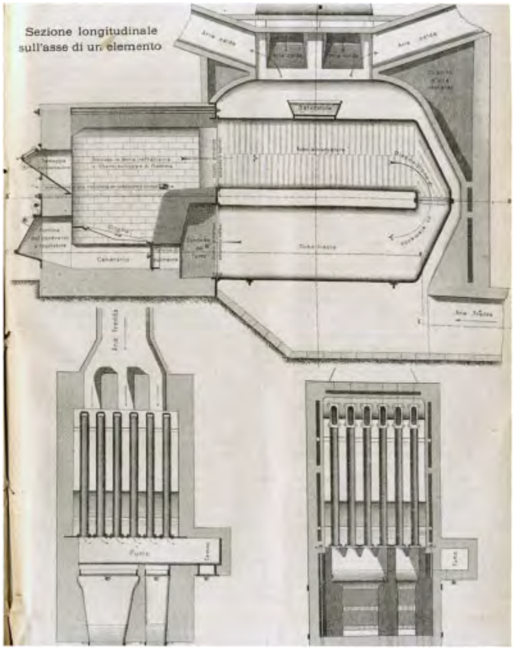

Figure 2. The *calorifero* (hot air heater patented) by the firm G. B. Porta), in *L'ingegneria sanitaria*, July 1890, tav. 7b.

In half a century, the close relations between the technical *milieu* of Milan and Turin, among climate experts and companies, were strengthened. However, the approach quickly changed: in 1890 the magazine acknowledged the new low-pressure steam regulation system, implemented by the Körtning company in Hanover: it allowed for varying the temperature in every singular *stufa* (stove) without introducing (or removing) the air (Gibelli 1890). There followed a further local improvement, which was carried out by the Milanese company *Piazza & Zippermayr*: the lower quantity of steam determined by the regulation of the "stoves" (radiators) activated a simple conical valve, which decreased the production of steam in the boiler. The owners themselves signed the article (Piazza & Zippermayr 1892). The valve eliminated the presence of a licensed stoker to control the boiler. The contrast between the technical evolution and the persistence of legislation lagging behind and hindering any kind of innovation, is well explained in the magazine *Edilizia Moderna* (Baseggio 1892) by engineer Nicolò Baseggio, a supporter of the new system and a future expert in accident prevention.

In 1895, Corradini reviewed – or better summed up – a book on heating systems by P. P. Morra, a professor of technical physics at the *Museo Industriale* (Ferraris 1906). It was a copiously illustrated 130-page extract (Morra 1895) from the *Enciclopedia delle Arti e Industrie*, coordinated by Raffaele Pareto and Giovanni Sacheri (Corradini 1895). The long article briefly deals with air-heaters and evaluates the high-pressure system – both steam and water – as outdated. In this last field, the Milan and Turin experiences were very scarce, and with the gradual abandonment of air-heating systems in private and public buildings.

4 FROM THE FUMISTI TO THE ENGINEERS

In fact, the difference between a stove and an air heating system, according to an undisputed authority, Eugène Péclet (Péclet 1861), are conceptually limited. The former, even when it provided cavities to heat the air by convection (the "circulation stoves") did not renew the ambient air, while the latter let in external air. It was, therefore, possible to make «calorifères placés dans les lieux à chauffer» (Péclet 1861, pp. 338–346) and «calorifères placés loin des lieux qui doivent être chauffés» (Péclet 1861, pp. 346–364). The exchange of air was essential for collective health and school buildings were relevant in this regard: the great physicist wanted to write a booklet (Péclet 1846), describing a real experience he made with the help of a specialized engineer, Léon Duvoir. A large classroom was heated by two high cylindrical circulation stoves, placed on the platform of the desk, so that the teacher could check their functioning. They heated external air, while thin metal smoke ducts crossed the entire classroom horizontally, up to chimneys in the opposite wall.

In Northern Italy, until the mid-nineteenth century, the air heating system was integrated into the construction, and therefore a task for architects or civil engineers. The executors were simple masons, assisted, for the stove installation, by the *fumisti*, a very widespread Gallicism. This word designated skilled assemblers of refractory ceramic panels, sheet metals and cast pieces produced by local foundries. The *fumisti* worked within a brick construction, adapted on-site. This organization of work progressively changed after 1850, following a process already developed in France and Great Britain. The goal was to simplify maintenance, abolishing the annual renewal of seals and heating a greater quantity of air at lower temperatures. Supply had to be simplified by providing automatic fuel loading, with simple devices based on elementary physical principles. The exchange of the heat, produced by the fuel in the furnace and by the smoke in its loss of temperature, had to be concentrated in a somewhat sealed apparatus. Only leading industrial engineers could conceive of such furnaces-exchangers, produced and assembled by specialized mechanical workshops, participating in defining the design of the entire plant.

In Milan, the company founded by the Duke Antonio Litta in 1857, who had bought Chaussenot's French patent, set the pace (Landi 2017). The exchanger consisted of a furnace from which the smoke climbed up into a sort of cast iron hemisphere, before then descending through a double row of cast iron ducts into a similar lower hemisphere connected to the flue. Péclet was very sceptical about this apparatus, which produced a low performance in comparison with the high cost of the cast iron used.

In his book, Ferrini owes many illustrations to Péclet (Ferrini 1876); he makes very little reference to the subject and underlines the analogy with a "circulation" stove model, which heated both by radiation and by convection using the same device in smaller dimensions. It was a typical initiative of a world on its way out, where the high aristocracy of the Hapsburg empire also held the public role to support technological innovation; on the death of the Duke in 1866, the company, which had offices in Turin and Milan, continued to be run by Gian Battista Monti. He renewed production with the help of engineer Carlo Cochard, a large landowner from Adro, in the province of Brescia: he was an expert in applying heat to the processing of agricultural products. The company then passed to the engineer G. B. Porta and survived until the end of the nineteenth century. The advertising brochures not only illustrated the company patent, which dated back to 1839, but also gave an idea of the business. The company could also take charge of the design. Customers usually had to provide plants and sections of the rooms to be heated. Until 1864, about 200 installations of very different sizes were executed, including nursery schools for the Municipality of Turin. In the same year, a "Litta heating system" was planned for the new large school building in Corso di Porta Romana in Milan (Archivio del Comune di Milano, hereinafter ACMI, Beni Comunali, Finanze, cart. 209), but it is not mentioned in the *brochure*. Not only were air heaters available, which however might coincide with circulation stoves in the current language, but also heaters with "heating" or even simply "interiors for fireplaces".

Bartolomeo Zanna had working experiences in Vienna until 1840/50, and in 1852 he started his company, while simultaneously opening a branch in Milan (Manfredi 2013, pp. 171-173; Manfredi 2017, pp. 52-53). The company was taken over by C*aligaris & Piacenza*, and was still active in the 1890s when it developed a type of air-heater mixed with air and steam (Corradini 1895, pp. 187-188).

Its qualities – as attested to by the Milanese prison of San Vittore in 1874 – were effective coordination, availability and rapid execution, while the technical background probably still linked to Meissner's texts. The proposals for elementary schools in Via Santo Spirito in Milan, and the contract (10 July 1878), describe three radiators in which iron and cast iron were quoted by weight, that is, an "iron serpentine", a flue passing from the furnace through the air heating chamber (ACMI, Beni Comunali, Finanze, cart. 220). The described works are disparate, including a "hot-air stove" and required numerous masonry works, including the demolition of an old air heater, as attested to by the final balance in 1879. In the same building, the subsequent steps of works include not only other heaters, but also some *Franklins*, a fireplace and another stove. For the schools in Via Santa Marta (ACMI, Beni Comunali, Finanze, cart. 224), the installation of an air and steam heater was negotiated in 1883: a single boiler produced the steam which in turn heated the air, condensing in special coils in mixing chambers at the foot of vertical ducts. Although the correspondence is incomplete, it would seem that, in the end, the Office of the Engineers did not trust the technical innovation suggested by *Besana e Carloni*, and turned to Zanna in 1885. The municipal engineers preferred a clearly antiquated (but reliable) solution or, more likely, an executor they had consolidated a relationship with, and therefore all the administrative procedures were simpler and faster.

Additionally, in Turin, the Castellamonte furnaces, traditional producers of terracotta and majolica stoves, had extended their range of action to *fumisteria*, air heating, offering a composite product that aggregated metal, terracotta and majolica parts. Although the products were largely designed for private homes, public demands, centralized systems and, in particular, school buildings were also given great attention.

In 1882/83 the catalogue of the *fumista* Buscaglione proudly highlighted not only the date of the foundation of the company (1830) but also bore as an epigraph a passage from Narjoux's book (Narjoux 1877) on public schools in France and Britain. In 1895, Corradini deemed these products obsolete (Corradini 1895, p. 187).

5 FROM AIR TO STEAM

Conversely, like the *Società anomima Duca Litta*, other Milanese companies also based their fortunes on the application of foreign patents. The entirely cast-iron stoves had spread rapidly in the early decades of the 19th century, imported mostly from Bohemia and Moravia. Milan was the natural outlet of trade flows from Switzerland and Rhenish Germany. Business relations with the territories that were left to the Habsburgs after 1859 continued to be strong. The reference technology, however, was that of the new German empire which, after the two banking crises of 1873 and 1889/1893, had also become decisive in finance, and offered effective support to its companies. The German model, where the engineers, *Rietschel and Henneberg* or *Fischer and Stiehl* became entrepreneurs exploiting the innovations they had conceived, was reproduced on a smaller scale by Milanese companies. In turn, the commercial relations and the import of technologies from France decreased: while those with the English-speaking world remained marginal, although the language, the technical literature and their achievements were well known. Like Turin, Milan and its mechanical industry certainly played a prominent, though not exclusive, role in exporting their technologies and products throughout the kingdom. The air heater was an effective *passe-partout*: new, complex stoves could be purchased, while the distribution - more extensive but less specialized - remained a mason's work and could be carried out on site.

The best organized company belonged to Edoardo Lehmann. He was of Swiss descent, and settled in Milan in 1879. In 1886 he had completed his factory, which occupied an entire block next to the train track square of the Central Station, between the current streets Lazzaretto, Casati and Tunisia. Following the decline of air heaters, the company developed its own variant of low-pressure steam heating (Corradini 1895, pp. 192–193) and remained active until 1906, when *Haeberlin Gerra & C.* took over until 1913 (Grimoldi, Landi 2019, p. 122). Lehmann proposed a Geneva patent, that of L.F. Staib (1812-1866), which dated back to the 1850s.

Péclet considers it a very well-studied patent, however it was subsequently perfected (Candolle 1867, pp. 288-90; Wartmann 1873, pp. 68-69). Bongioannini illustrates it and Ferrini describes and links it to the name of his successors Weibel (Weibel 2006) and Briquet. The pyramidal furnace facing upwards was contained in a cast iron parallelepiped with accordion-like sides. An inclined hopper allowed coal to be loaded every eight or twelve hours. The smoke lingered in this vast combustion chamber and was drawn under the furnace. The particular profile of the perimeter walls increased the exchange surface and the heat at a lower temperature was transmitted to a more abundant quantity of air that circulated in a masonry chamber, formed by a double wall in solid bricks inside, and perforated bricks towards the outside.

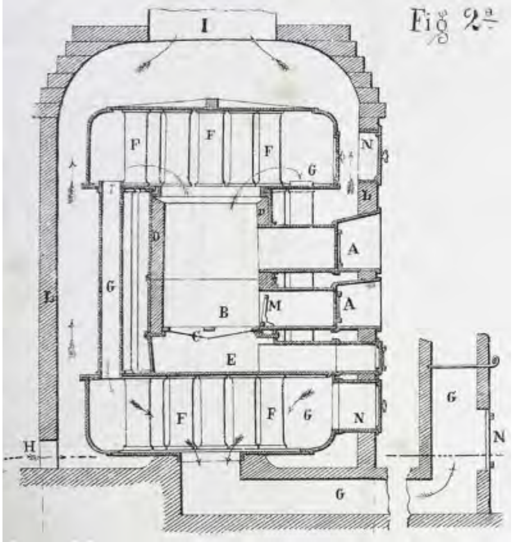

Figure 3. The *calorifero* (hot air heater) Litta, from (Bongioannini 1870, tav. 2, fig. 3).

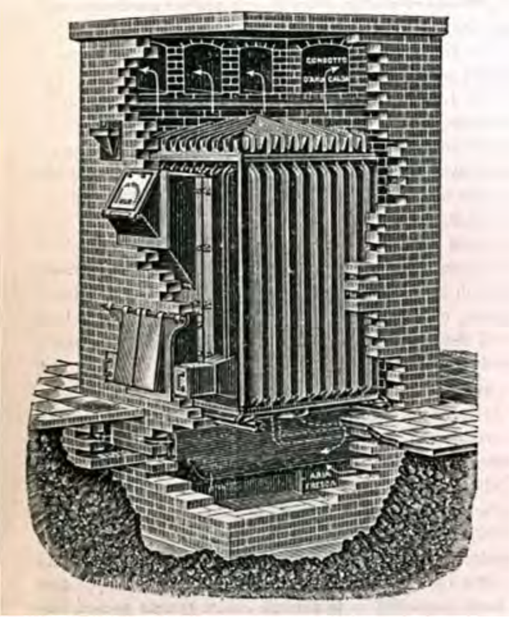

Figure 4. The *calorifero* (hot air heater) Staib, by Edoardo Lehmann in Milan, in*L'ingegneria sanitaria*, n. 9, 1895, p. 174.

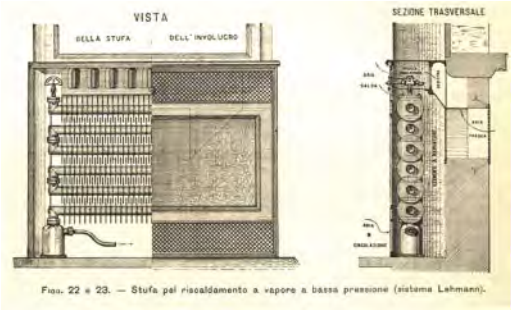

Figure 5. Low pression steam heating system by Lehmann, Milan, the “stoves”. In *L’ingegneria sanitaria*, no. 10, 1895 p. 189.

A similar solution was developed in France by *Giraudeau & Jalibert*, who also recommended it in a special version for schools (Planat 1880, p. 337). These apparatuses resolved the lively debate on the finning of pipes and more generally of containers in the 1870/80s.

Finned pipes were also introduced into the Litta-Chaussenot radiator, a difference that enabled a Turin company, Carlo Crivelli, to circumvent the patent (Corradini 1882). As often happens, the contenders aimed at different objectives: the transmission of heat did not significantly increase, because the fins decreased in temperature towards their ends. According to Planat, the heat exchange did not increase over 50% by doubling the surface by means of fins. However, the temperature decreased over a greater extension with this a useful effect for a good heater performance.

The ownership of a patent was a commercial resource: the specificity and exclusive use of the technical solution allowed the assigning of public tender contracts even against lower bids: thus, Lehmann was awarded the heating of the school complex in Via Anfossi (1888) and also of the schools in Via Galvani (ACMI, Beni Comunali, Finanze, cart. 214, f. 8) Boito and Ferrini had accepted this heating system on the basis of its technical superiority. In their opinion, the problems of regulating low-pressure steam heaters had not been solved yet even though endorsed by the Municipal Health Commission (November 24, 1887); so they rejected a single steam boiler to feed the air system, which was also proposed, in this case, by the *Besana & Carloni* company (ACMI, BC-Fi, cart. 227, f. 7).

Lehmann, as a system builder, proposed a mechanical summer ventilation system. He was not favourable to passive ventilation systems, which the two renowned scholars instead recommended. Boito had precisely followed the instructions contained in his colleague’s book (Ferrini 1876, p. 451) in designing the school’s ducts in Padua, and also in via Galvani he had envisaged special air intakes at the level of the floors integrated into the design of the façade.

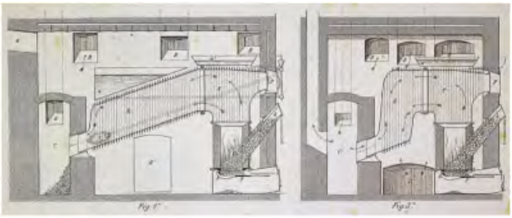

Figure 6. The *calorifero* (hot air heater) by *Eisenwerk Kaiserlauter*n represented in Italy by the firm *Besana e Carloni*, in *L’ingegneria civile e le arti industriali*, 1882, tav. 7.

The most reliable competitor, the *Besana e Carloni* company owned a large factory in Via San Rocco in Porta Romana, in the district where companies producing railway materials were located. Their representative office was in the centre, in Via Torino, in the former Giuseppe Besana’s office, one of the two engineering partners who founded the company, for directly carrying out projects that were formerly entrusted to various craftsmen. The 1888 Besana list of works includes numerous hospitals, and the contract, just received, for the heating system of the Roman headquarters of the Bank of Italy. They could count on a real national network of correspondents in the main cities and on other engineers who collaborated first on the projects and then on the direction of the works (in Turin, that representative was Francesco Corradini). The company had already added high and low-pressure steam heating to air heaters. In the offer letter directly addressed to Camillo Boito for the school in Via Galvani, Giuseppe Besana claims to produce all the necessary material in his own factory, while, in his opinion, other companies just assemble all the imported pieces; he concludes with a biased apology of the protectionist policy, pursued by the *Sinistra* then in power. More specifically, Besana presented his company as a “precision foundry”.

To attain an economic equilibrium, a large amount of other activities, in addition to civil and industrial heating systems, were required. The company supplied bathrooms, kitchens and special cast pieces to order. It probably imported the most sophisticated apparatuses from Germany, despite the protectionist faith of its owners. For hot air heaters, *Besana e Carloni* was a patent holder on behalf of *Eisenwerk Kaiserlautern*. a company specialized in metal heating appliances. The system was made up by an exchange chamber crossed by an inclined smoke duct and the furnace used the long-life loading system for column circulating stoves, patented by a professor at the Karlsruhe Polytechnic, Heinrich Meidinger.

Other producers, working for the Municipality of Milan, had not yet made the leap yet from the professional practice to an enterprise. Guzzi and Ravizza are engineers, respectively mechanical and civil. Their activity began in 1870 as representatives of patents belonging to other holders and managing all of the procedures necessary to obtain the patent. They will

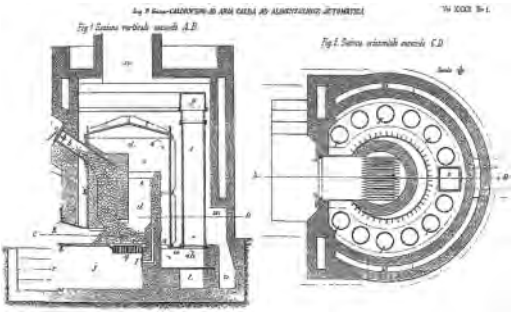

Figure 7. The *calorifero* (hot air heater) by the company *Guzzi & Ravizza*, in Milan in *Il Politecnico – Giornale …* , vol. XXXIII, tav. 1.

take the final step towards the mechanical industry within the following two years but, in particular, they will deal with the equipment for the fledgling electrical industry.

Ravizza published several articles on the structural problems of rural buildings in the *Politecnico* magazine, while Guzzi repeatedly wrote in defence of patents and above all on the theoretical aspects of heat transmission; Ferrini himself considered him a significant interlocutor to the extent of sending him a public letter (Ferrini 1878). Guzzi also published a model of an air heater, with a circular plan with cast iron pipes, yet another reworking of the Chaussenot heater (Guzzi 1885).

Unfortunately, the accounting relating to the Lazzaretto school heaters has not been preserved but the four heaters, one installed in each wing, certainly corresponded to this model. The upper part of the flues was flanked by the final part of the ducts, that went up into the spine walls, thus activating thermal ventilation. In summer, it sufficed to light a gas flame in the ducts. Fresh air flowed into the classrooms from the double-walled window sills. The air penetrated through an external circular grate and came out of an adjustable vent at floor level. The vasistas windows and sliding wooden shutters were also designed to regulate the heat exchange. Angelo Savoldi, the designer, had entrusted the thermal comfort to the constructive elements no less than to the system (ACMI, BC-Fi, cart. 223).

The next generation of school buildings will focus on a simplified construction to reduce costs, entrusting the ventilation to the windows, reduced from one-third to one-sixth of the floor surface (Ferrini 1892, f. VII, p. 5) and therefore having to focus on installation. The technical office however continued to use air heaters (*ibidem*, f. VIII, p. 6); but in the following year, in 1893, in the large complex of Via Ariberto, *Piazza & Zippermayr*, owners of the automatic boiler regulation system, created and implemented a low-pressure steam heating system, with “stoves” in 46 classrooms (ACMI, BC-Fi, cart. 216, f. 3). Only the maintenance costs of 1896 attest to the presence of a similar low-pressure steam heater, entrusted however to the *Mussi and Koerting* company, in the schools of Via Pastrengo.

6 CONCLUSIONS

The *Statistica industriale della Provincia di Milano* was published in the Bulletin of the Ministry of Agriculture, Industry and Commerce in 1893; its information dates back to 1891, and enables the integration of printed advertising with comparable data. The six companies, Lehmann, Besana and Carloni, De Franceschi, Piazza and Zippermayr, Mussi&Koertning, employed 346 workers, a motive force of 132 HP, with 19 forges, 30 lathes and 78 machines of various kinds. The six companies producing railway materials employed 3,120 workers and 1,242 HP, hence, ten times more, while all of the other mechanical industries (including small items and other objects of use), employed 11,547 workers with 2,271 HP. The relationship between workers and motive force was similar to the railway material producers, while in the rest of the sector, technical and manual skills prevailed, as in the case of measuring instruments that require a high degree of expertise. However, the *Mussi&Koertning* company was in fact a representative office, of a large company in Hannover for the regulation of low-pressure steam heaters. The rapid success of the system led the German company to set up its own factory in Sestri Ponente, destined for the Italian market. This was managed by a member of the family and produced all the components, which had hitherto been imported. This relocation – as it would be called today – was one of the signs of the industrial launch in northern Italy. The diffusion of more sophisticated plants also marked a substantial leap forward in the size of companies, the organization of their production and their relationship with the applied research.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Space funicular polygons and their applications by Émile Foulon

T. Ciblac
École nationale supérieure d'architecture de Paris-Malaquais, Paris, France

ABSTRACT: In the thesis he presented for his *agrégation* qualification at the Faculty of Applied Sciences of the University of Liège in 1939, Émile Foulon, a University of Liège Civil Engineer of Construction with a doctorate from the University of Paris, focuses on the transposition to space of the funicular polygons traditionally used in the plane and their applications to the calculation of three-dimensional constructions. Surprisingly, his approach was an original one as apparently no systematic study of space funicular polygons, as he defined them, had been published before. Foulon systematically studies the existence and degrees of freedom of space funicular polygons as a function of the number of forces considered. He further proposes to make use of descriptive geometry and develops practical methods which he applies to spatial structures. This article aims to shed light on Foulon's approaches, their specificities and how they relate to other historical methods of space graphic statics. In particular, Foulon's theoretical and practical motivations will be compared to the radically different approach of Benjamin Mayor. This also explores why Foulon's methods fell into oblivion.

1 INTRODUCTION

The transposition of plane funicular polygons to space has apparently not been the subject of a precise and detailed study apart from that which Émile Foulon completed in 1939 as part of his thesis for the *agrégation* qualification, roughly the equivalent of a doctoral thesis, at the Faculty of Applied Sciences of the University of Liège (Foulon 1939). Maurice Lévy (1886) defined space funicular polygons by analogy to plane funicular polygons and set down the conditions that they must verify. He quickly abandoned their study, mainly because they could not be built for any number of fully defined space forces. Benjamin Mayor (1910) considered an analogy linked to the general properties of funicular polygons that should be preserved in space. To this end, he constructed specific concepts and proposed the *funicular chain* notion which differed significantly from that of funicular polygons.

The lack of theoretical and applied studies on space funicular polygons makes the work of Émile Foulon unique and particularly interesting in relation to knowledge of the graphic statics of space. However, despite the originality and potential applications of Émile Foulon's approach, it was not widely disseminated and failed to leave any enduring mark on science. Moreover, little biographical information on its author is available. His publications inform us that he was a civil engineer in construction from the University of Liège, who held a doctorate from the University of Paris (Foulon 1938), and who presented his thesis for the *agrégation* qualification at the Faculty of Applied Sciences, the University of Liège in 1939 (Foulon 1939). His research work, funded by an endowment from the Francqui Foundation, was carried out at the Swiss Federal Institute of Technology in Zurich, which he describes as "the parent school of graphic statics" and where he worked with Professor F. Stüssi in particular. His thesis for the *agrégation* sets forth a graphical method of composition and decomposition of forces in space based on the traditional knowledge of engineers and requiring few plots compared to other graphical methods. For this, he relies on the use of space funicular polygons, the existence and properties of which he systematically studies according to the number of considered space forces. He also makes use of descriptive geometry to achieve a purely geometric method. This article first discusses how the question of the transposition to space of funicular polygons was approached by Maurice Lévy and Benjamin Mayor. Then, it sets forth Foulon's theoretical and practical approach and addresses the question of its failure to leave an enduring mark.

2 THE QUESTION OF TRANSPOSITION OF FUNICULAR POLYGONS FROM PLANE TO SPACE

2.1 *Plane funicular polygons*

The construction of plane funicular polygons was introduced by Varignon (1725). The usefulness of the force polygon and funicular polygon concepts for the graphical resolution of static problems was recognized by Carl Culmann (1864). He contributed to disseminating these approaches by formalizing the methods of graphic statics. We shall first briefly present the main elements relating to funicular polygons. A funicular polygon with vertices M, a_1, a_2 …a_n, N (Figure 1,

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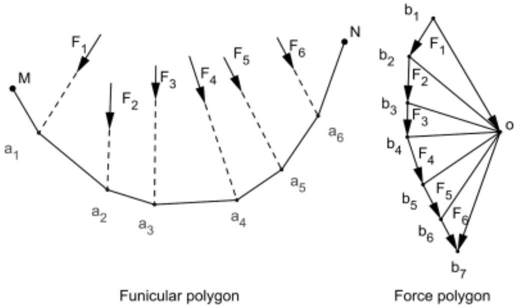


Figure 1. Funicular polygon and force polygon in the plane.

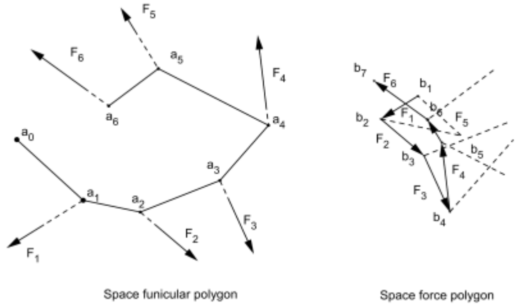


Figure 2. Space funicular polygon geometrically constructed for a given system of space forces and space force polygon incompatible with the equilibrium of the sides.

left) can be defined as the equilibrium shape taken by a wire fixed at its two ends (M and N) to which *n* forces are applied ($F_1, F_2, \ldots F_n$) whose lines of action, directions and magnitudes are known. The equilibrium of each vertex a_i of the polygon results in the equilibrium of three forces: the force F_i, and the tensions in the two adjacent sides. The balance on either side of the funicular polygon requires that the two forces that apply to the sides are directly opposed. This is reflected in the force polygon (Figure 1, right) by the decomposition of each force from a single point o, called the pole. A funicular polygon can be constructed by choosing any point a_1 on the line of action of F_1, which corresponds to one degree of freedom, and any pole in the plane of forces, which corresponds to 2 degrees of freedom. Plane funicular polygons therefore have 3 degrees of freedom for a fully defined force system. That is to say that one can construct 3 infinities of funicular polygons for a given system of forces. A major advantage of funicular polygons is that they allow a system of any *n* forces in the plane to be reduced to two forces.

These two forces are those applied to the outermost sides of the funicular polygon and correspond to the vectors b_0o and ob_n in the force polygon.

Depending on the case, the two forces can in turn be reduced to a non-zero resulting force or to a non-zero resulting torque, or else they can be in equilibrium. The funicular polygon concept can be extended to space if one is interested in the equilibrium shape taken by a wire fixed at its ends to which are applied any *n* forces of space ($F_1, F_2, \ldots F_n$). It is just such a conceptual extension that Maurice Lévy introduced.

2.2 *Definition of space funicular polygons and the conclusions of Maurice Lévy*

Maurice Lévy (1886) addresses the question of funicular polygons in space by first giving their definition by analogy to funiculars in the plane, when considering any space forces.

As in the case of a plane, each vertex of the funicular polygon is subjected to three forces in equilibrium. Moreover, Lévy noticed that the three concurrent forces of space in equilibrium are necessarily coplanar. By also considering the equilibrium on each side of the funicular polygon, he deduced the following two conditions (Lévy 1886, 429):

"Thus, it is necessary: 1° that each force be situated in the plane of the two sides of the polygon which are adjacent to it;

2° that the two components of the given forces, directed along each of the intermediate sides of the polygon, be equal and opposite."

Lévy assumes that the forces F_1 to F_n of space, as well as the first side a_0 $a_1$of the funicular polygon (Figure 2, left), are known. The first condition makes it possible to successively construct $a_2, a_3 \ldots a_n$ only by intersections of planes and lines. Therefore, vertex a_2 is the point of intersection of the plane containing F_1 and a_0 a_1 with the line of action of F_2. Likewise, vertex a_3 is the point of intersection of the plane containing F_2 and $a_1 a_2$ with the line of action of F_3.

Thus, if one knows a side of the funicular polygon, the condition of coplanarity of the sides adjacent to the vertices of the funicular polygon give a geometric means of constructing the funicular polygon from successive intersections of these planes with the action lines of the following forces. Note that in the case of a plane, the first condition is always true and does not allow for this construction, which leaves the possibility of building the funicular polygon by imposing the balance on its sides.

It then remains to check the equilibrium condition on each side of the funicular polygon (second condition set forth by Lévy). This condition implies, as in the case of a plane, that two consecutive forces must be decomposed according to their common adjacent side in such a way that the forces are balanced.

In the general instance, Lévy points out that there is no reason why this should be the case. If this were the case, there would exist, as for a plane, a pole where the lines parallel to the sides of the funicular polygon would converge, passing through the ends of the force vectors of the space force polygon, thus forming what Foulon calls the force pyramid (see 3.1). Figure 2 illustrates the construction of a space funicular polygon when a first side is known and taking into account only the first condition. We observe in this figure, on the right, the space force polygon amounting to the sum of the forces $F_1 \ldots F_n$ and we observe that the lines parallel to the sides of the funicular polygon, shown as dotted lines, do not converge.

Lévy concludes that, in the general case, the conditions of equilibrium on each side are not satisfied and the generality of the construction of funicular polygons is not found in space. He does not pursue the study of space funicular polygons any further. Foulon for his part contests Lévy's conclusion. He points out that the hypothesis of fixing the first side a_0 a_1 is arbitrarily restrictive. He also indicates that, even in this case, if one limits oneself to a set of two space forces, a funicular polygon does exist. In his thesis, he aims in particular to systematically study the conditions of existence of these funicular polygons and to deduce their practical uses. To this end, he considers the conditions of planarity and equilibrium simultaneously in relation to the number of forces in space.

2.3 *Reduction of a system of forces in space to two equivalent forces*

If we manage to determine a funicular polygon for a system of forces in space, we immediately obtain two equivalent forces by considering the forces applied to the outermost sides. One of the consequences of the construction of funicular polygons is thus to determine two forces equivalent to a system of forces in space. Part 4 details the approach proposed by Foulon using funicular polygons. A different approach is proposed by Lévy with the funicular pyramid method.

2.4 *The funicular pyramid according to Maurice Lévy*

Lévy considers the case of any number of forces in space and proposes a method for reducing this system to two forces, one of which passes through an arbitrary point O.

This allows him to set forth the following theorem: "Forces distributed in any way in space can be reduced to two, one of which passes through an arbitrary point" (Lévy 1886, 433).

The method by which he proves his theorem involves the decomposition of each force F_i into three concurrent forces at point a_i in the line of action of F_i, one of which passes through O. Figure 3 details the construction in the case of six forces F_1 to F_6 after Lévy (1886, 430).

Force F_1 is broken down into three forces by a first known force in magnitude, line of action and direction, and passing through fixed a_1. The second force goes through a_1 and O. The third force is based on the line of action of F_2. Lévy also proves that such a decomposition is always possible. Gradually, we arrive at the decomposition of F_6 whose last force is based on the line a_0 a_1, which simultaneously defines a_0, which was not yet fixed. Thus, the forces F_1 to F_6 are reduced to the sum of the forces passing through O and to the two outermost forces passing through a_0 which in turn are reduced to a single force.

This method does not make use of funicular polygons but does show that the decomposition of each force F_i into three concurrent forces. instead of two, makes it possible to carry out a single construction to reduce the system to two forces, one of which passes through a fixed point O.

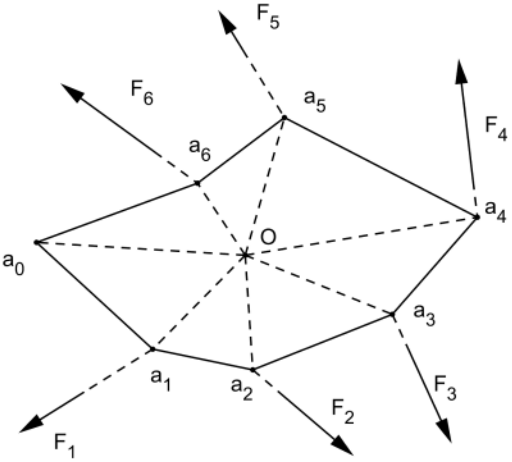


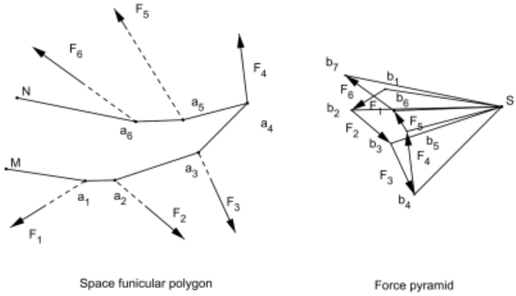
Figure 3. Funicular pyramid after Lévy (1886).

2.5 *The Benjamin Mayor approach*

Benjamin Mayor (1866–1936) aspired to propose a method that could generalize the methods of graphic statics developed in the plane so they could be applied as much as possible to space. A description of these approaches is presented by Ciblac (2018). Mayor chooses to rule out the use of descriptive geometry and rely instead on ruled geometry, in particular on the notion of linear complex, to take advantage of the dualistic character associated with lines in space.

The method thus developed, called "graphic statics of the systems of space", consists in transforming a spatial problem into a plane problem that can be treated by the conventional methods of graphic statics. Mayor introduces the notion of action complex of a system of forces in space as follows: "A system of forces, acting on a rigid solid, is completely defined by the linear complex formed by its straight lines of zero moment and by the magnitude of its general resultant. This complex, which can play the same role as the line of action of a force belonging to a planar system, will be called, for this reason, the *complex of action* of the considered system" (Mayor 1896). The lines of zero moment must be understood as being the axes with respect to which the sum of the moments of the forces of the system is zero. Mayor then introduces the notion of a funicular chain relating to a system of forces using action complexes. He shows that these funicular chains have geometric and mechanical properties which correspond exactly to those possessed by funicular polygons.

This approach contains the major drawback, emphasized by Foulon, of taking recourse to the theory of ruled geometry, which is not part of the theoretical background taught to engineers, thereby making it difficult to use. Émile Foulon also considerd



Space funicular polygon

Force pyramid

Figure 4. Space funicular polygon, force pyramid and pole S.

that rejecting descriptive geometry deprived users of powerful methods for solving spatial problems.

3 DEFINITION AND EXISTENCE OF SPACE FUNICULAR POLYGONS

3.1 *Definition of the space funicular polygons and force pyramid*

Foulon (1939, 13–16) reworks Lévy's definition (see 2.2), laying down the following two conditions:

- First condition: "Two successive sides of the funicular polygon must be in the same plane as the force that they intercept and must intersect on it."
- Second condition: "The components, according to any intermediate side, of the two forces on which it rests at its ends, must be equal and opposite."

He deduces the following theorem:

"For a funicular polygon to exist between a system of given forces in space, it is necessary and sufficient that we can find a continuous broken line whose vertices lie on the lines of action of the given forces and such that if, through the vertices of a polygon of these forces, we lead the rays parallel to its respective sides, these rays all converge at the same point, which is the apex of the corresponding force pyramid. The vertex S of the force pyramid will, in the continuation, often be called pole S of the corresponding funicular polygon."

Figure 4 represents a funicular polygon assumed to exist for 6 forces of space with the force pyramid indicating satisfaction of the second condition. The conditions of existence of the space funicular polygons are presented below.

3.2 *Demonstration of the existence of space funicular polygons*

In his study, Foulon first presents the demonstrations regarding the existence and the number of degrees of freedom of funicular polygons depending on the number of forces. To do so, he relies on the consequences of the two conditions that define them. He begins with the case of three forces and proves that there is a double infinity of space funicular polygons relating to three forces in space corresponding to two degrees of freedom (Foulon 1939, 19). He also determines analytically and geometrically the locations of corresponding poles and proves that these are quadric-type ruled surfaces. In the case of four forces of space (Foulon 1939, 45), he proves that there is an infinity of funicular polygons and that the location of the corresponding poles is the intersection curve of two quadrics. He deduces that, unlike plane funicular polygons, the existence of space funicular polygons is linked to the number of forces considered and that the addition of a force reduces their degrees of freedom by one. He establishes that in the general case of space forces arbitrarily defined in magnitude, line of action and direction, the degrees of freedom are as given in Table 1. By naming *n*, the number of space forces completely determined by the line of action, direction and magnitude, and *p*, the number of degrees of freedom of funicular polygons that can be constructed by considering these forces, we reach the following equation:

$$p = 5 - n \tag{1}$$

Table 1. Number of degrees of freedom of funicular polygons depending on the number of space forces given.

Number of space forces	1	2	3	4	5	6	7	8
Number of degrees of freedom	4	3	2	1	0	-1	-2	-3

The previous results prove it is possible to determine funicular polygons in an infinite number for fewer than five forces and in a finite number for five forces. Beyond five forces, *p* being negative, it is not possible to construct a funicular polygon if all the forces are arbitrarily chosen. For this to be possible, the forces must then meet as many conditions as there are negative degrees of freedom.

3.3 *Space funicular polygons relating to one and two arbitrary space forces.*

In the case of a single force F_1 of space, the four degrees of freedom correspond for example to the possibility of decomposing this force into two concurrent forces using pole O freely chosen in space (three degrees of freedom) and a freely chosen intersection point a_1 on the line of action of F_1 (one degree of freedom).

The three degrees of freedom relating to the construction of a funicular polygon for any two space forces F_1 and F_2 to correspond for example to the possibility of freely choosing points a_1 and a_2 on their lines of action and of freely choosing pole O on a parallel to a_1a_2 passing through b_2. Thus, for a_1, a_2 and O fixed in this way, the three degrees of freedom are blocked and a single funicular polygon can be constructed.

Figure 5 shows the construction of the funicular polygon according to these assumptions in descriptive

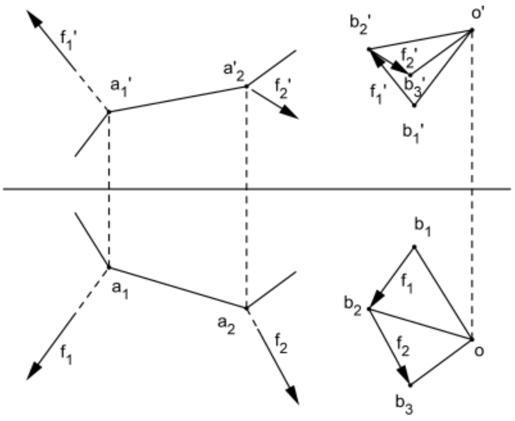


Figure 5. Descriptive geometry construction of a funicular polygon for two forces of space (left) and a force pyramid (right).

geometry. The funicular polygon is shown on the left. By convention, forces F_1 and F_2 are represented in horizontal projection by f_1 and f_2 and in frontal projection by f_1'and f_2'. The two projections of the force pyramid are shown on the right. Constructing the force pyramid makes it possible to deduce the outermost sides of the funicular polygon and the two space forces that are applied to it, which are vectorially equal to $\mathbf{b_1O}$ and $\mathbf{Ob_2}$. These two forces are statically equivalent to forces F_1 and F_2.

A different way to fix a funicular polygon, blocking three degrees of freedom, is to choose any pole O in space to build the force pyramid. In this case, points a_1 and a_2 and the last sides are deduced from the funicular pyramid and from the first condition.

Another consequence of the existence of three degrees of freedom for building the funicular polygon in the case of two space forces is that one can also arbitrarily give oneself the first side of the funicular polygon, that is to say, any straight line passing through any point a_1 of the line of action of F_1.

Thus, in particular, the last side of the funicular polygon is uniquely defined. Conversely, if we take the last side of the funicular polygon, passing through point a_2 of F_2, the first side is uniquely defined. Foulon deduces from this that the two outermost forces correspond to the combined forces used by Mayor, among others (Foulon 1939, 80).

He also notices that the line a_1a_2 is a line of zero moment of the force system. It therefore belongs to the action complex defined by Mayor in his theory of funicular chains. He thus links the construction of the funicular polygon in the case of two forces to the concepts of conjugate forces and action complex of Mayor's theory. He also proposes adapting Mayor's method of calculation of reticulated structures. To do so, Foulon utilizes space funicular polygons and descriptive geometry in order to make Mayor's method purely graphic and also to avoid any errors in signs arising due to recourse to analytical calculations.

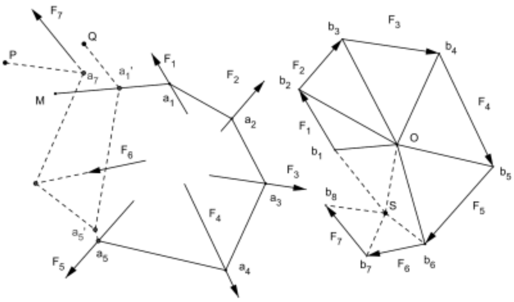


Figure 6. Reduction to two forces of a system of seven forces of space using two space funicular polygons.

4 REDUCTION OF A SPACE FORCES SYSTEM TO TWO EQUIVALENT FORCES

Whenever it is possible to determine a funicular polygon for a set of forces, we deduce two statically equivalent forces. Émile Foulon proposes an iterative method for reducing a system of *n* space forces (*n*>5) to two equivalent forces. To this end, we begin by reducing at most five of these forces to two equivalent forces. We then consider these two forces and the remaining forces. This allows us to decrease the total number of forces that are to be reduced.

The same procedure is then applied as many times as necessary until two forces are obtained. Figure 6 illustrates the example of seven space forces (Foulon 1939, 70). It first considers the funicular polygon associated with the forces F_1 to F_5 according to pole O and deduces from it two resulting forces b_1O and Ob_5 on the sides Ma_1 and a_5a_5'. These two forces, associated with the remaining forces F_6 and F_7, form a set of four forces for which a funicular polygon is built with the pole S. The overall system is reduced to the forces $\mathbf{b_8S}$ and $\mathbf{Sb_1}$ acting on the sides Qa_1' and Pa_7 of the last funicular polygon.

5 APPLICATION TO STRUCTURAL CALCULATIONS

5.1 *Seeking reactions in support of rigid structures*

Foulon presents a systematic approach for determining the reactions of rigid structures based on the types of bonds and their combinatorics in order to treat the externally isostatic and rigid constructions for which the reactions can be obtained graphically.

He considers three types of links according to the fixity of the support point (type a, three link bars) or its mobility on a line (type b, two link bars) or a surface (type c, one link bar). Externally, isostatic and rigid constructions can be supported according to one of the six general arrangements described in Table 2.

These arrangements are not sufficient to ensure the complete connection of the rigid solid under any load. Conditions on the positions of the bars must be given in order to ensure complete bonding. Foulon

Table 2. Arrangements according to the number of types of joints

Number of the arrangement	Number of types of joints		
	a	b	c
1	1	1	1
2	1	0	3
3	0	3	0
4	0	2	2
5	0	1	4
6	0	0	6

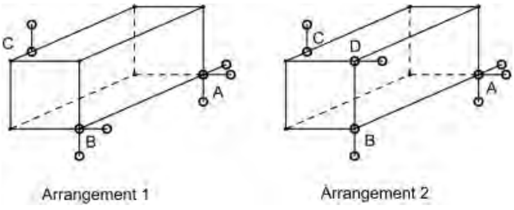


Figure 7. Examples of cases of arrangements 1 and 2.

systematically details these provisions as well as the restrictions concerning the relative positions of the bars.

By way of illustration, Figure 7 shows, in axonometry, examples of connections of a rigid solid in the cases of arrangements 1 and 2. On the left, arrangement 1 with, respectively in A, B and C, connections of type a, b and c. On the right, arrangement 2 with, in A, a type a connection, and in B, C and D, a type c connection. For each of the arrangements, Foulon proposes the use of space funicular polygons in order to determine the reactions in the supports as a function of the number f of external forces applied to it and the number a of supports. He first determines the number s of degrees of freedom of the funicular polygons that can then be used for the graphic determination of the reactions according to f and a. Equation (2) provides this relation (Foulon 1939, 103):

$$s = 6 - (f + a) \tag{2}$$

Foulon gives the proof of this equation as follows. The number a of supports corresponds to the number of external forces of connections, and the number $f + a$ corresponds to the total number of forces relating to the funicular polygon. From equation (1) we deduce:

$$p = 5 - (f + a) \tag{3}$$

In all cases, the a forces of connection must satisfy six equilibrium conditions which correspond to six additional degrees of freedom of the funicular polygons. Foulon deduces the number of degrees of freedom l of the funicular polygons between the f given forces and the a reactions that are sought:

$$l = p + 6 \tag{4}$$

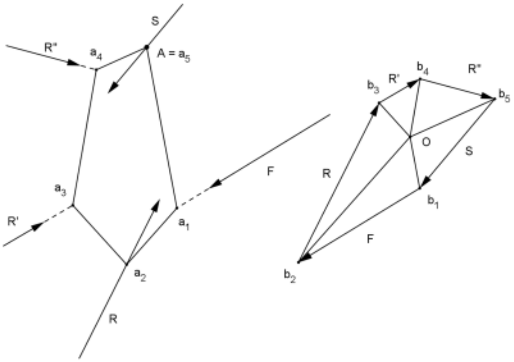


Figure 8. Solving the problem of determining the reactions for the second arrangement of supports in the case of a force.

To these conditions are added the equilibrium conditions resulting in the closure of the funicular polygon (four degrees of freedom) and the force pyramid (one degree of freedom), totalling five degrees of freedom to be removed. Thus, we obtain the following relation which, by considering (3) and (4), allows us to deduce the relation (2) yielded by the following calculation:

$$s = l - 5 = p + 1 = 6 - (f + a) \tag{5}$$

5.2 *Example of resolution for the second arrangement of the supports*

The second arrangement of supports considers a rigid construction which has a fixed support and three supports whose reactions have given lines of action. The reactions are called R, R', R" and S. The first three have their given line of action, the last passes through a fixed point A. In this case, $a = 4$ hence, according to (2), the number s of funicular polygons making it possible to determine the reactions is equal to 2-f. In the case of a single force F, $f = 1$ and therefore $s = 1$, there is therefore a degree of freedom and therefore an infinity of funicular polygons giving the four reactions to be determined.

Figure 8, on the left, illustrates the construction of one of these funicular polygons passing through A, inspired by a figure of Foulon's (1939, 124). Point a_2 is built at the intersection of plane (A, F) and line of action of R. Point a_4 is at the intersection of plane (a_2, R') and the line of action of R". Point a_3 is at the intersection of the plane (A, R") and the line of action of R'. The point a_1 is at the intersection of the plane (a_3, R) and the line of action of F. The closed funicular polygon (A, a_1, a_2, a_3, a_4) is thus fully determined. Figure 9, on the right, shows the construction of the force polygon and the force pyramid. The vector b_1b_2 relating to the force F is given. The pole O is constructed at the intersection of the parallels to Aa_1 and a_1a_2 passing respectively through b_1 and b_2. The sides Ob_3, Ob_4 and Ob_5 of the funicular pyramid are parallel to the sides a_2a_3, a_3a_4 and a_4A of the funicular polygon. We deduce the vectors R=b_2b_3, R' = b_3b_4, R" = b_4b_5 from the reactions that are sought by successively taking the

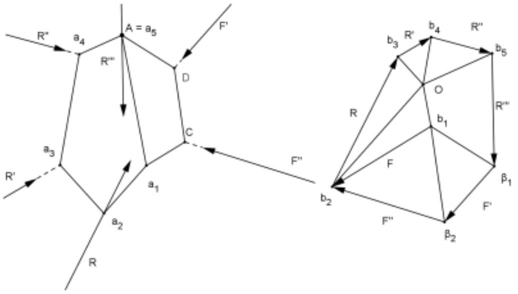


Figure 9. Resolution of the problem of determining the reactions for the second arrangement of the supports in the case of two forces.

parallels to the lines of action of the reactions R, R' and R" passing through the vertices of the force polygon. Lastly, the force vector S = b_5b_1 of the force S is determined by the closure of the force polygon. We finally deduce the line of action of S passing through A.

Figure 9 also illustrates the case of two forces F' and F", and therefore with $s = 0$, which means that only one funicular polygon can be used. A solution proposed by Foulon consists of using a funicular polygon relating to two space forces F' and F", one of the two outermost sides of which passes through A and a point D of the line of action of F' and the other, Ca_1, does not rest on R. Point C is first constructed at the intersection of the plane (A F') and the line of action of F". Point D is taken anywhere on the line of action of F'. The force polygon $\beta_1\beta_2b_2$ is first constructed knowing F' and F". The pole b_1 of the funicular polygon relative to F' and F" is deduced from the AD and DC sides of the funicular polygon. F' and F" are equivalent to the forces β_1b_1 applied in A and b_1b_2 =F applied in a_1.

The problem is thus reduced to the previous problem. The reactions are then R, R', R" and finally R"', the reaction passing through A.

The case of three Forces F', F" F"' is resolved by Foulon by considering an auxiliary funicular polygon relating to F' and F", and that is then reduced to the case of a single resulting force F of F"' and of c'. In the case of more than three forces, Foulon proposes methods using auxiliary funicular polygons.

5.3 *Resolution by descriptive geometry*

The methods presented above convey the feasibility of determining the reactions of structures using funicular polygons. Figures 8 and 9 show only a projection of the forces considered without putting into practice their spatial construction. Their significance is therefore purely illustrative. From a practical and graphically computational point of view, Foulon shows how a spatial problem can be completely determined by the use of descriptive geometry. He relies in particular on conventional methods of determining intersections of planes and lines used in the construction of space funicular polygons. The construction procedure is the same but it is entirely defined in space thanks to the two correlated projections.

5.4 *Application to the calculation of reticulated frameworks in space*

Descriptive geometry was used in the calculation of isostatic reticulated spatial structures by Föppl (1900) but without applying the concept of space funicular polygons. Émile Foulon provides concrete applications of his approach involving space funicular polygons and descriptive geometry through studies of a triangulated pylon, a triangulated dome and a bridge.

6 A METHOD THAT LEFT NO ENDURING LEGACY

Émile Foulon's work on space graphic statics was not widely disseminated. Apart from his *agrégation* thesis, we found traces of only one publication in a journal (Foulon 1940). It seems that no further work by Foulon about space funicular polygons was ever published. Nor does it appear that this approach was widely taught or included in textbooks. Moreover, this research has hardly ever been cited in the scientific literature. Corentin Fivet (2013) does, however, cite Foulon's work in his doctoral thesis on the development of a numerical approach to space graphic statics, which allowed us to discover this source. The non-dissemination of the approach by its author probably suffices to explain its lack of enduring impact. The competition of alternative graphic methods and analytical approaches can also explain the lack of interest in the developments he contributed. Nevertheless, the theoretical and practical contributions seem sufficiently important for his approach to have aroused the interest of the scientific community. We can also hypothesize that Mayor's approach, little used but cited by Pirard (1967) in his reference work on graphic statics, might have been enhanced by the adaptation proposed by Émile Foulon, had it been disseminated.

7 CONCLUSION

The study of space funicular polygons by Émile Foulon constitutes an original development of graphic statics of space, bringing into play knowledge of plane graphic statics and descriptive geometry that were still in use by construction professionals in the mid-twentieth century. Space funicular polygons possess properties that are not as general as those of plane funicular polygons, but the former type of polygon can be applied iteratively to solve spatial problems. The proposed methods thus allow the composition and decomposition of forces in space as well as the fully graphic resolution of calculations of isostatic reticulated spatial structures. Émile Foulon emphasizes the reduction of the number of graphical plots resulting from the use of these methods compared to other spatial methods. If this research work left no lasting mark on scientific history, it may not have been due solely to its author's failure to disseminate it but also perhaps because of the existence of alternative graphic methods and a context in which graphic statics methods were beginning to decline in importance.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Lighting and visual comfort systems in administrative buildings in 1950s Milan

G. Sampaoli
Università della Svizzera italiana, Mendrisio, Switzerland

ABSTRACT: In the first part of the 20th Century, architects began to experiment with the use of electric lighting as a “new building material” applied or integrated into buildings but this was interrupted due to the Second World War when cities lay cloaked in darkness. The end of the conflict redefined visual parameters and administrative centres served as a testing ground for industrialization as well as lighting techniques in the post-war phase. This paper, based mainly on perusal of articles from the period and documents from Archivio Civico of Milan, the Lombardy region archive, CSAC of Parma, and the Mendrisio Archivio del Moderno, aims to examine the issue of lighting and climatic comfort in relation to the administrative buildings erected in Milan in the 1950s. In these buildings, the various plant engineering systems attained such a level of integration as to make them intrinsic to the architecture, the spatial and visual conception of space, and structural forms, as is also reflected by the exterior appearance of the buildings and by the city’s night-time appearance.

1 THE NIGHT-TIME PLANNING OF BUILDINGS

“Only modern architecture is nocturnal architecture today: ancient architecture at night disappeared in the dark or only appeared in its profiles, through the linear lighting of torches, without any relief, or was transfigured, through projection lighting, into wonderful and stormy reliefs, like an extended flash of lightning. But only modern architecture – the most modern architecture – provides this play of light, whereby whole walls become transparent, while other, isolated ones appear twice as thick. It is an architecture of the negative, and it is the first and purest abstract art. Machines naturally inhabit this architecture: they too are abstract art” (Ponti 1948a).

Over the course of the 20th century, the importance of artificial light not merely as a complementary element but as an essential facet of architecture emerged as a concept that gradually became self-evident. Yet, in the interwar period most people, including most architects, still took little interest in lighting or believed it could be regarded as a fortuitous and nocturnal addition to the true structure of buildings (Sampaoli, in press). The Second World War redefined visual parameters: throughout the years of the conflict, cities were hidden in the dark. With the war ending, the dimension of nocturnal urban life finally reappeared and was rediscovered after the forced blackout. Those who had experienced darkened cities during the war could rediscover the pleasure provided by the lighting of billboards and the electric lighting that once again became part of the architectural composition of buildings. If we look at major European cities, we find they once again started offering the spectacle of artificial lighting as had already long been the case in American cities in which the nocturnal appearance of buildings was a prominent aspect – as described by Gillo Dorfles in relation to New York in 1956 (Dorfles 1956).

Therefore, in the aftermath of the Second World War, in Europe as much as in America, one of the most dynamic developments in the approach to architectural planning – in line with interwar experiences – was the attempt to combine the daytime planning of buildings with their night-time profile. This need chiefly derived from two factors: the increasingly frequent use of glass in architecture, and more efficient and cost-effective electrical lighting compared to the past. The new constructive potential of glass abolished the old relationship found in all buildings: the relationship between the voids represented by windows and the solids constituted by walls. Through the large sizes of the new panes available, this relationship between solids and voids was replaced by that between opaque and transparent surfaces. It became possible to create unbroken surfaces made of the same material. In Milan, the architectural theme of the facade as an unbroken surface was already foreshadowed in the pre-war period by Gio Ponti’s Palazzo Montecatini. Here, the exterior glass panes and door and window frames are perfectly flush with the Apuan Cipollino marble of the building. In 1947, architects Bianchetti and Pea took up this theme when designing the Palazzo delle Nazioni for the Fiera di Milano, whose curtain wall features prominent utilisation of glass, compared to other elements in the facade (Ponti 1948b). At night, the internal electrical lighting becomes part of the exterior appearance of the building, creating a negative

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of its daytime facade. From this moment onward, architects were required to take account of the urban prominence of the lighting of buildings at night, and to propose plans for night-time hours in addition to daytime plans. As the editor-in-chief of *Domus*, Gio Ponti launched a debate on the theme from the pages of the magazine, emphasizing the leading role of electrical lighting as a means of giving architecture a second life. He further confirmed this concept during the presentation of the building he had designed for the Fondazione Garzanti in Forlì (Ponti 1954), which was described as "a genuine night-time architecture". This building, set back from the street, serves as the backdrop for an extensive garden and reflects itself in a body of water. In the project, these two aspects – the diurnal and the nocturnal – are quite evident: lighting becomes a constitutive element of the architecture, and light brings out the airiness of the building, separating its exterior surfaces, as well as the frontal surface from the side ones. These surfaces do not meet at an angle, so at night the angles of the building are completely lit, as is evident in the photographs published of the scale model especially created to study the structure's appearance at night. "Only now are we starting to also design night-time plans, and these must not be based on exterior lighting, but on the radiation of light from the building itself" (Ponti 1954). These and other architectural designs by Gio Ponti are often based on the same principles: "the detachment of the walls and roofs, in such a way as to emphasize their limited thickness and the typical lightness deriving from modern construction methods, the windows flush with the exterior wall, which extend rather than pierce the surface, the self-lighting of the building at night – which is to say not the kind of interior lighting that creates an effect of solids and voids, but a plastic effect whereby light shapes the building's formal appearance" (Ponti 1955).

2 THE INTERIOR LIGHTING PRODUCED BY BUILDINGS WITH A LIGHT FAÇADE

After a period when the fundamental theme in European cities was that of post-war reconstruction and swiftly providing affordable new housing for those who had lost their homes, a new design theme emerged with the beginning of the economic boom in the early 1950s: the creation of office buildings. In 1953, in line with post-war experiences and thanks to the approval of a new urban planning scheme that replaced that of 1934, Milan was among the first Italian cities to engage with the urban theme as an administrative centre. It was followed by Turin in 1962, Florence in 1977–1978, and Rome and Naples in the 1980s (Crippa & Zanzottera 2004). The office building became a type of building that all leading architects were keen to work on. Administrative centres, business and trade areas became the primary testing ground for industrialization methods and new planning trends on account of the large size of these architectural structures, the scope for constructing them in prominent areas within the expanding urban fabric – or at any rate in areas that had yet to be redeveloped in the post-war period – and the considerable financial resources of the commissioning parties.

In this respect, critic Reyner Banham has stated that an aesthetic of office buildings certainly emerged in Milan. We might speak of 'black diamonds' here, since – compared to the pre-war buildings, which were often clad in stone – these new buildings featured simple cladding in transparent, opaque, or glazed glass, often set in oxidized aluminium metal frames (Banham 2003). Among the most prominent examples of constructions erected in Milan, there is the building by Caccia Dominioni in Corso Europa (1953–1959), Palazzo Galbani by Soncini, Pestalozza and Nervi (1954–1955), the building by Magistretti in Corso Europa (1955–1957), the Tirrena Tower by Soncini (1956–1957), the Pirelli Skyscraper by Ponti and Nervi (1956–1961), the Galfa Tower by Bega (1956–1959), and the office building by Minoletti and Chiodi in Piazzale Loreto (1957–1963) (Ponti 1960). These buildings are unique in the context of 1950s Italy: they are not imitations of a foreign culture – say, of American skyscrapers – but a typological reinvention. These structures ought to be regarded as prototypes for 1950s Milan that present a marked degree of innovation and originality, and represent valuable objects located in the city centre (Aguzzi 1961a). Their significance can be appreciated by considering the fact that, in all likelihood, it was Walter Gropius who drew inspiration from the Pirelli Skyscraper for the construction of his Pan Am Skyscraper in Manhattan, and not the other way round (Bucci 2006). France too witnessed extensive construction of office buildings. One of the most striking examples of this is the district developed in the west of Paris in the aftermath of the Second World War: known as *La Défense*, it consists of office skyscrapers, apartment buildings, and shopping centres. One of the recurrent features of these office buildings is the presence of curtain walls, based on the combination of horizontal and vertical modular systems, which in most cases involve the use of a metal frame constructed in a workshop and then assembled on site (S.n. 1958). Curtain walls became one of the main sectors within the construction industry in this period, and clearly illustrate the problems posed by the industrialization of construction work (Aguzzi 1961b).

During daytime, these glass walls look opaque, shiny, and reflective, but at night they provide lighting from the inside out, making these architectural elements shine, and achieving a far more satisfactory effect when viewed from the outside than when looking out from inside. This does not occur in the same way in all the Milanese buildings just mentioned. For example, in the Palazzo di Fuoco, Minoletti and Chiodi chose to set fluorescent lamps in especially designed recesses running along the upper section of the 685 identical windowpanes that make up the curtain wall (Aguzzi 1960). These special colour-changing lighting appliances, consisting of three fluorescent tubes, determine the measurement of 102 cm that serves as

Figure 1. View from the outside at night of some Milanese office buildings. 1. “Palazzo di Fuoco” office building (Postcard, G. Minoletti collection, Archivio del Moderno, Mendrisio); 2. “Galbani” office building (*Superfici*, n.2-3, 1961); 3. Pirelli Skyscraper (*Domus*, n.379, 1961); 4. Galfa Tower (*Domus*, n.377, 1961).

the basic module for the project and as a means to coordinate the whole building, from the layout of the structure to the size of the window and door frames, from the extension of internal spaces to the layout of the utility areas. This sophisticated system for lighting the facade was developed in collaboration with the Phoebus company and with the electric lightbulb manufacturer Osram (Soc. riunite Osram, Edison, Clerici S.p.a., Milan) (Morgan 1963), achieving a very scenic effect that conveys the urban prominence of the building at night. The building further extended the lighting communication plan that Minoletti had previously developed for several buildings of his, such as the Liquigas building in Corso Venezia (1952) and the Upim in Corso San Gottardo (1957) (Sampaoli 2016). This facade lighting system differs significantly from other night-time designs, such as those for the Pirelli Skyscraper and the Galfa Tower, where the nocturnal exterior appearance is determined by the interior lighting. In the case of the Pirelli Skyscraper, it was again collaboration with the Osram company that helped define the lighting plan, which in this case entailed the usage of over 10,000 fluorescent tubes evenly distributed across all floors. This lighting was not only functional to everyday life and work activities but became a crucial feature of the kind of “integral planning” which all architects were turning to in this period, and that also included night-time plans for buildings (S.n. 1961b).

3 THE RELATIONSHIP BETWEEN NATURAL AND ARTIFICIAL LIGHTING, AND THE ISSUE OF HEATING

In his book *American Building: The Environmental Forces that Shape It*, architect James Marston Fitch devotes much room to the relationship between natural and artificial lighting in buildings, and to the exchange of light between the interior and the exterior through the presence of glass curtain walls (Fitch 1967). While some building types, such as department stores and workshops, have little or no need for natural light in their interior, in other cases – such as homes and schools – natural light is essential. Museum spaces are instead hybrid spaces, insofar as they can function by predominantly using either natural or artificial light. Evidence of this, from the same period, can be found in the French museums Musée Maison

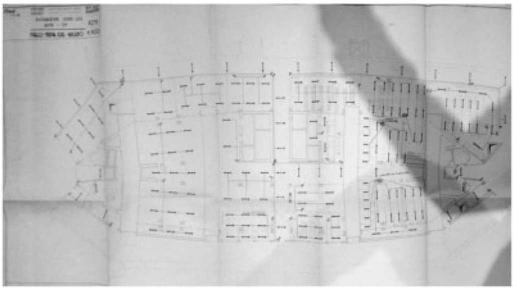

Figure 5. Arrangement project of fluorescent lamps in a typical plan for the Pirelli skyscraper (G. Ponti collection, CSAC, Parma).

de la Culture in Le Havre and Musée des Arts et Traditions Populaires in Paris. By contrast, office buildings and factories require both forms of lighting, so buildings of this type pose the problem of finding a way to integrate the two kinds of light into a single, efficient environmental lighting control system. In particular, in the case of office buildings with a curtain wall, it is necessary not just to develop a night-time plan, dealing with the aesthetic and decorative aspect of the buildings' exterior appearance at night but also to carefully balance natural and artificial light by finding ways to integrate both forms of lighting into the architectural artefact. As far as the lighting of interiors is concerned, one concept that was developed from the post-war period onwards, alongside the theme of the coordination of systems, was the idea of *confort visuel* (Salomon 1969). This consists of the usage of artificial light to create an environment which does not strain the human eye through glaring lights or strong luminosity contrasts in the visual field. Particularly in the case of these collective buildings, the lighting must be measured and distributed in the right areas. Artificial light must resemble natural light in colour. The luminosity of the interior must be tailored to the visual tasks to be performed in the various rooms of the building. To ensure a balanced distribution of natural light, *brise-soleil*, curtains or Venetian blinds may be used. However, given that natural lighting is not always available throughout the day, electrical lighting is used for three different purposes: to compensate for natural lighting on days with little sunlight, to enable the complete lighting of the building at night, and to enable circulation throughout the building, or its maintenance, at any time, by preserving the same level of lighting even in the innermost areas of the building (Coulon & Genes 1959). So, the need emerged to find a suitable solution to avoid any excessive imbalance between daytime and night-time in the lighting of interior spaces, and between the innermost and the outermost parts of the building. Moreover, it was necessary to come up with a solution to the problem posed by the large glass panes created in this period, which were not thermally broken and so let the cold in during winter and the heat in during summer to a greater extent than traditional cladding. Hence the need to design interior heating and ventilation systems to limit these problems and to ensure the correct functioning of the buildings, in combination with the lighting system, without spoiling the overall aesthetic effect. In the case of the Galfa Tower, for instance, an attempt was made to thermally insulate the uprights of the curtain wall. *Termopane* glass panels were also used, consisting of two glass panes joined together by a metal spacer filled with dehydrated air, along with Venetian blinds, which helped manage the amount of sunlight. In addition, as far as the air-conditioning and heating of the building is concerned, the system is based on high-speed air pipes and fan-coils supplied by the Dell'Orto-Chierigatti company.

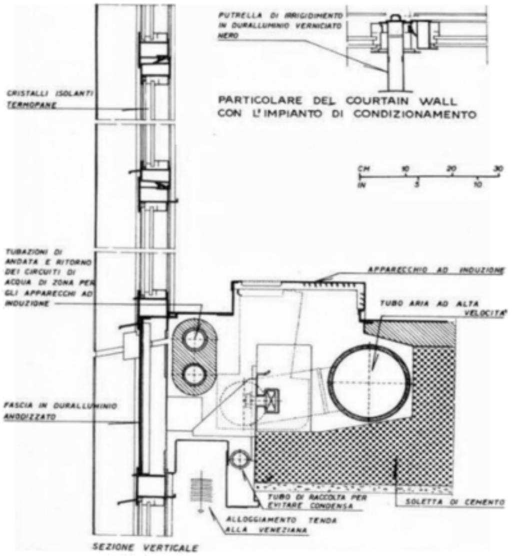

Figure 6. Detail of the curtain wall of the Galfa Tower with the airconditioning system (*Domus*, n.377, 1961).

These are arranged along the perimeter of the building and are especially designed to be almost entirely fitted into the floor slab in such a way as to keep the facade as visually uncluttered and clear as possible (S.n. 1961a). In the case of Palazzo di Fuoco, Minoletti instead opted for a mixed heating system: heating, cooling, and air-conditioning were balanced by combining a system of radiant panels in the floor slab, a system of radiant hot and cold water pipes running along the soffit of each window, and finally an air-conditioning system with a central air duct. The choice was made to place radiating pipes along the perimeter of the building to at least partly counterbalance the heat loss due to the broad glass facade, which might have caused some thermal changes and unbalances between the outermost and innermost areas of the building.

In these two cases, despite the use of large heating and air-conditioning systems, the architects designed discrete ways of integrating them into the overall complex system of their building so as to avoid making the technological appliances visually independent and to emphasize instead the volumetric unity of the building. By contrast, in the Pirelli Skyscraper, Ponti highlighted

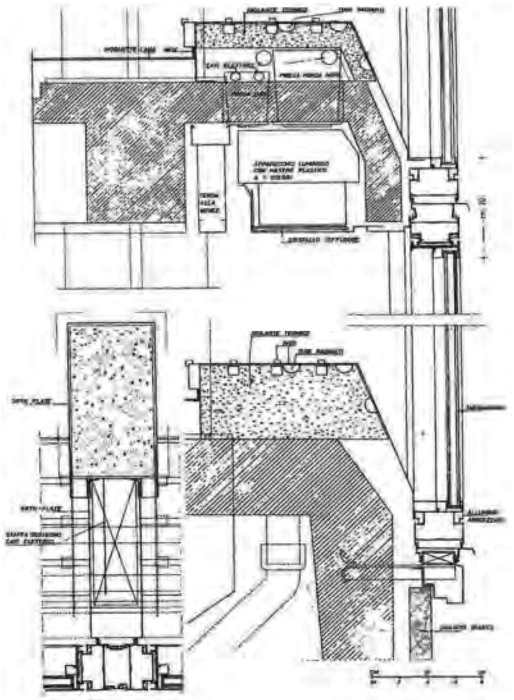

Figure 7. Detail of the curtain wall of the Palazzo di Fuoco with the lighting system and heating system (G. Minoletti collection, Archivio del Moderno, Mendrisio).

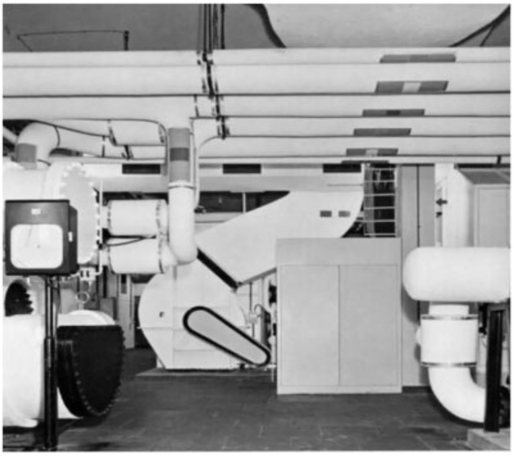

Figure 8. The "theatre of systems" of Pirelli Skyscraper (*Domus*, n.379, 1961).

the importance of the various systems, even going so far as to paint the machines that ensured the running of the building in red, yellow, and white. In this building, the various systems have their architecturally defined space: a glass gallery even allows them to be viewed in all their "truth and beauty", as a genuine "theatre of systems" (S.n. 1961c).

4 INTEGRATED LIGHTING SYSTEMS AND THE INTEGRATION OF LIGHT, AIR, AND SOUND

The integration of lighting systems into architectural structures is not a new feature of post-war planning, as this also appears in many buildings designed before the Second World War. Solutions of this sort are described as integrated because, in order to develop them, the architect must design them in parallel to the general building plan. In the field of architecture, in the interwar period, the modernist movement was largely responsible for the increase in integrated lighting methods: in an effort to rationalize buildings and reduce the number of visual components, architects looked for ways to really make electrical lighting part of the discipline of architecture. Other requirements also led to the increase in these integrated artificial lighting systems, including the demand for higher lighting levels, which were impossible to achieve by using too many lighting sources in a building as these would have a negative impact on the overall perception of the architecture itself. This led to the conclusion that instead of adding individual lighting systems, it was necessary to design specific artificial lighting plans that would affect the whole ceiling of a room and shape its appearance: in other words, architects started preferring to achieve an overall effect rather than using individual lighting devices. This tendency to adopt integrated lighting systems went hand in hand with a growing desire to control interior spaces through artificial systems. Architects gradually realized that the lighting system and electrical distribution scheme could no longer be separated from the other systems in any building's interior, such as sound control, heating, ventilation, and fire control systems. Each of these physical problems, associated with different control systems, found a unitary, overall solution that made the lighting equipment a visual and functional method in relation to all other services. The time had come for architects to accept that other specialists should take part in the planning process right from the start – or that they themselves needed to consider the problem of lighting from the very outset of the design process as it would be difficult or even impossible to make changes at subsequent stages. One possibility was to design technical ceilings or service grids, which is to say systems integrating lighting sources with the other systems, such as the heating, ventilation, and sound control systems. However, in each case a different solution could be adopted for the lighting problem, even when dealing with architectural plans of the same sort, requiring the same visual functions and lighting levels, as in the case of office buildings, since the decisions made chiefly derived from architectural considerations, notwithstanding any differences due to the lighting function alone. One feature shared by all lighting systems for office buildings in 1950s Milan was their recourse to fluorescent light sources, which is to say artificial light sources that were more cost-efficient than incandescent sources

9-10

11-12

13-14

Figure 9. The lighting systems of the offices and passageways of some Milanese office buildings. 9-10. Pirelli Skyscraper (*Domus*, n.379, 1961); 11-12. Galfa Tower (*Domus*, n.377, 1961); 13-14. “Palazzo di Fuoco” office building (G. Minoletti collection, Archivio del Moderno, Mendrisio).

and produced less overheating in the rooms where they were employed (Phillips 1964). The use of fluorescent lighting takes widely different forms in the examples presented so far. For example, in the Galfa Tower, we find an alternation between the fluorescent lighting produced by linear tubular light fittings on the office floors, and the use of round light fittings individually applied to ceilings in transit areas and along with chandeliers by the Stilnovo company suspended over the tables in the meeting room on the administrative floors (Bega 1961). In Palazzo di Fuoco, the office floors are equipped with state-of-the-art lighting systems designed together with the Phoebus company. To ensure ideal lighting in work areas both during the daytime and at night, each office module, which is to say roughly each metre, is equipped with a high bay Perspex lighting device, consisting of two fluorescent tubes, which also ensures maximum flexibility for the interior spaces. The corridors connecting the various offices are instead furnished with a drop ceiling formed by a grid of Edilglas panels lit by fluorescent tubes, which provide balanced lighting in the space below. In this building, moreover, a metal box girder connects the vertical load-bearing structure with the thin vertical structure of the curtain wall. This box girder encases the electrical wiring running between floors. This enables the complete connection of the systems network across the various floors of the building: a highly effective expedient to solve electrical problems across the entire height of the building. Moreover, a system of key cable ducts extending for 7,500 m in total is present on all floors of the building and used to set in place or ground electrical outlets according to the arrangement of the partition walls between one office and another. The planning of interior lighting for the Pirelli Skyscraper is even more sophisticated. For Ponti, the problem of artificial lighting in workspaces was crucial to the successful development of a project. According to the technical sheet published in issue 379 of *Domus* magazine, in the interior of the Pirelli building, the lighting “must be even and not glaring”, and this result was achieved through the technical contribution of Fidenza Vetraria (S.n. 1961d). This company helped the architect to develop the lighting design and to practically install the light fittings in the soundproof ceiling panels on all floors of the building. The distribution of light fittings is based on the 95 x 95 cm modular system that makes it possible to change interior spaces through the use of movable walls. The Fidenza Vetraria company suggested the “Padova” device from the Efolight series, which was suited to the soundproof ceiling of the interior and combined it with a fluorescent light source jutting out from the soffit of the ceiling by a few centimetres, in such a way as to provide balanced lighting for the entire ceiling. This device ensures a soft and even light that avoids shadows on the ceiling, turning the latter into a reflecting element that contributes to the overall lighting. More specifically, the lighting appliance used consists of a metal frame of the same size as the fluorescent tube, which can be of either 20 or 40W. While the upper part of the lighting appliance’s frame is closed and encases the reactor and light starter, the lower part, where the lighting tube is fitted, was left in plain view and stove-enamelled, to give it a reflective, opaque white hue. The metal frame is attached to the gridwork of the soundproof panelling. After the panels were set in place, the empty spaces for the light fittings were covered with aluminium cover plates supporting semi-transparent plastic bowls serving as diffusers. The soundproof panel remains inside the cover plate, the plastic bowl, and the gridwork, so the precise connection of the various levels ensures no shaft of light will issue from the contact surfaces.

5 CONCLUSION

To conclude, the Milanese examples just examined show that no standard lighting solution can be adopted for an architectural project and, indeed, none has ever been suggested. What have been set out are a number of design ideas for the usage of electrical lighting, which have grown increasingly varied and complex over time. When dealing with lighting, it is necessary to take many different aspects into account in order to come up with a suitable solution that meets both functional and architectural requirements as a fair architectural result may be defined as a compromise between these two. The use of electrical lighting in architecture, therefore, raises many questions. Over the years, electrical lighting has evolved from being a simple means of providing light when necessary – in a somewhat random way – to becoming a crucial material in construction to be coordinated with the other systems ensuring the functioning of buildings. This new ‘material’ has led to various changes in terms of architectural style and design, societal expectations, and service technologies. Electrical lighting has acquired increasing centrality to the point of becoming a symbol of the urban condition: a powerful means of transformation (precisely because of its capability to redefine real-world hierarchies), a deeply expressive art form that enriches and modifies our experiences, and a utilitarian means to enjoy our living environments in comfortable and efficient ways.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Energy-aware construction within the Modern Movement: Erskine's approach

E. Poma
Università della Svizzera italiana, Mendrisio, Switzerland

ABSTRACT: This paper proposes discussing how the application of climate-specific construction technologies contributed to the definition of valuable energy-aware examples of Modern architecture. The technical features of three projects by Ralph Erskine are investigated to highlight the qualities deriving from the critical implementation of building technology for a regional interpretation of the principles of Modern design.

1 INTRODUCTION

The rise of mechanization in building technology and the growing availability of fuel contributed significantly to the achievement of unprecedented construction and spatial quality within the architecture of the Modern Movement. However, the extent to which the application of energy-conscious technology played a part in the pursuit of architectural quality has yet to be extensively debated. The architectural outcomes of the 20th century are often identified as highly dissipative in terms of energy consumption (Moe 2014). The quest for an international architectural style determined a gradual and widespread rejection of traditional site-specific construction technologies in favour of new construction methods.

The progressive abandonment of long-standing historical practice in the construction of the envelopes of buildings was conceived to enhance the potential of Modern design. This could eventually be perceived as jeopardizing the advancement of energy-conscious architecture and even considered, to some extent, as the only technological regression in the millennium (Butera 2004). Nevertheless, it is possible to demonstrate that, in a limited range of Modern examples, innovation in construction was adopted as a means to relate architecture to the local climatic context by controlling the resulting thermal behaviours.

The first part of this paper describes some traces of an energy-aware technological approach within the Modern Movement by recalling significant contents from CIAM (Congrès Internationaux d'Architecture Moderne). Subsequently, the figure of Ralph Erskine is introduced, pointing out how his personal and debated approach as a Modern architect involved the quest for climate-attentive design. The fourth section displays the analysis of construction features of three selected projects built in Sweden by Erskine between 1950 and 1965: Lassaskog residential buildings in Växjö, Ortdrivaren district in Kiruna and Erskine's own villa and office in Drottningholm.

The study of the technologies implemented is intended as a tool to argue in support of the architect's success in producing buildings attentive to energy efficiency, without giving up on the architectural ideals promoted by the Modern Movement.

2 THE MODERN MOVEMENT AND ENERGY AWARENESS

The advent of "full mechanization" (Giedion 1948) irreversibly affected the construction technology sector from 1919 onwards. The availability of new building strategies, based on industrial processes, determined a sudden change in building production. The innovative application of concrete, steel and glass expanded the horizons of architectural design, overcoming the limits of pre-industrial construction models. This technological revolution subverted the dynamics of energy management in the design, construction and operation of buildings by liberating the envelope from its historical functions. Previously unexplored spatial experiments were also made possible by implementing innovative artificial climatization tools, regardless of local climatic conditions (Banham 1969). The international adoption of Modern features, launched by architectural exhibitions and promoted by the commitment of CIAM, allowed for the codification of an International Style, moving away from traditional local construction methods. Nevertheless, it is possible to identify a few representatives of the Modern Movement who chose rather to consider constructional innovations as a means to connect Modern Architecture to local specifics.

Recalling some of the contents transmitted by CIAM activities between 1928 and 1959 is an effective strategy to evaluate the extent of the commitment of Modern architects towards energy management and interrelations between the built environment and the context. This acknowledges that sustainability and ecological issues were not an explicit topic in debates

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among figures in the Modern Movement, who were significantly engaged in defining the principles for disseminating the International Style based on the application of new technologies. A glimpse of an interest in improving energy usage and indoor climate can be traced back to the first congress in Las Sarraz. Domestic education, in the interest of shaping a new generation of Modern customers for architecture, was discussed in this meeting as a method for spreading knowledge regarding building physics and energy management (Steinmann 1979). The importance of user behaviours constitutes a factor impacting on energy saving in operating buildings, which is still under research today (Pasini et al. 2017).

The second CIAM session, devoted to the theme of "Existenzminimum" (minimum needs of life) encouraged debate around the definition of features for efficient and minimal Modern residential construction. The contribution by Walter Gropius, focused on the need for economy in the production of dwellings, arguing that the optimization of resource usage was a key factor. In addition, the chance to separate the load-bearing structure from the envelope made it possible to introduce a variety of outer envelopes, transparent or opaque, capable of benefiting from sunshine and reducing the negative impact of outdoor climate on interior space.

Further interest in energy-aware architectural technology was brought to the attention of CIAM by Helena and Szymon Szyrkus, involving the enhancement of Modern buildings by deploying limited resources. The latter's contributions to CIAM IV and V underlined the necessity of experimenting with new technological solutions, driven by the application of knowledge about building physics (Urbanik 2006). In 1939, the Szyrkuses edited a survey on technologies for the construction of outer walls, addressed to architects from the countries participating in the CIAM. A Dutch delegation of architects and engineers responded exhaustively by publishing an inventory of construction solutions applied within their works in the magazine *De 8 en Opbouw* in September 1939. The examples published, including some projects by Johannes Bernardus Van Loghem and Johannes Duiker, showed their distinctive approach in considering the Modern building not only as a functional machine but above all as an integrated system, attentive to the application and optimization of comfort devices within construction (Jonge 2006).

The last CIAM in Otterlo, in 1959, was the decisive moment in the chronology as participants were invited to present architectural design and practice in relation to the local context, both geographical and cultural (Newman 1961). An impactful outcome was the presentation of the "Habitat Evolutif" (Evolving Habitat), by the French architectural and urban planning partnership Candilis-Josic-Woods. They illustrated urbanization schemes based on the need to modulate light, sound and heat exchanges between building typologies and the exterior context by taking the local climate into account in urban design. Another topic addressed was the urgency of rooting the Modern Movement's functionalism in the features and resources of traditional local construction. Within this scope, it thus becomes possible to acknowledge the contribution of the Dutch architect Herman Haan, who presented his documentation of Saharan traditional housing in Otterlo. Haan meant the study of vernacular cultures as a tool for understanding the fundamental life patterns shaping the built environment. However, Ralph Erskine's contribution to the last CIAM meeting is undoubtedly the most significant one on this research topic. The British architect, at the time active in Sweden, presented his proposals for the definition of a Modern "Sub-Arctic Habitat". Exhaustive documentation of extreme climate constraints and the indigenous milieu anticipated the description of his architectural ideas. Subsequently, he exemplified, with the aid of effective schemes, the thermal behaviour of different construction strategies and the architectural shapes corresponding to the diversity of climate conditions. Planning for severe sub-arctic weather was intended as the test bench to apply a climate-aware design method, potentially replicable in any geographical area to improve architectural standards.

Even if the need for ecological awareness as we experience it today within the construction field was never a clearly stated goal for Modern architects, examples and references related to climate and energy management occasionally recurred. Analysis of the exemplary architecture designed by Ralph Erskine offers the opportunity to assess how far efforts to organize construction in relation to local climate and energy efficiency resulted in architectural quality.

3 RALPH ERSKINE'S MODERN APPROACH

Ralph Erskine is a much debated figure in the history of Modern architecture, thus the analysis of construction features in some of his designs has to be preceded by remarks on his distinctive approach to architectural practice. In 1939, at the beginning of his professional career, fascinated by the work of the Nordic Modern masters and attracted by the opportunities in the local architectural sector, he moved to Sweden. The encounter with the Scandinavian climate and the local vernacular culture encouraged Erskine to challenge the potential of Modern construction technologies for improving habitats in northern climes. His attentive study of traditional architectural types is to be considered not only as of cultural or historical interest but as the application of scientific analysis to the definition of architectural possibilities.

A similar approach may be noted in the interest in rural construction of the Italian architect Giuseppe Pagano, who significantly contributed to the spread of knowledge of Italian pre-industrial models within Modern architecture (Sabatino 2010). The catalogue curated in 1936 by Pagano and Werner Daniel for the Milano Triennale exhibition "Funzionalità della casa Rurale" (Functionality of the rural house) testifies to a Modern concern for traditional construction. Pagano found in rural types a significant anticipation of functional architecture (Pagano 1935). He saw the forms of vernacular architecture as responding to the local function, climate and availabilities, independent of styles. In this sense, Modernity may be understood as a method to apply within the technological specifics of each age as theorized by Walter Gropius (Gropius 1956). Therefore, Ralph Erskine's approach to the consideration of traditional elements cannot be misinterpreted solely as a nostalgic or aesthetic impulse but rather constitutes a necessary tool for understanding the relationship between the built environment and its context. Accordingly, the legacy of his Modern designs lies precisely in the method applied in his design and construction choices, driven by case-specific functional needs.

Furthermore, it is relevant to observe how Ralph Erskine considered architecture as an instrument to improve human well-being and social integration (Erskine 1975). His early education in a Friends' school might have been influential in shaping his professional attitude as an architect, determining his outstanding attention to social patterns (Collymore 1982). The preliminary investigation of future user habits and needs actually contributed to the design of his projects. Erskine's choice of specific typologies and construction techniques, as well as his challenge in achieving acceptable maintenance and operational costs, were therefore intended primarily to benefit the occupiers. His care for the well-being of the inhabitants reached its highest point in the user-involvement design process applied to the housing project in Byker, Newcastle-upon-Tyne (1969–81). Yet, this attitude was also already clearly recognizable in Erskine's earlier designs. In fact, "social sustainability" and "cultural sustainability", together with "environmental sustainability" and "economical sustainability" have been argued as substantial dimensions of Erskine's work (Caldenby 2014). It is thus paramount to consider the constructional and typological quality of Erskine's production as subsequent to the anthropological inclination to improve the quality of life and society: a truly Modern dream.

4 CASE STUDIES

Three examples from Erskine's Swedish production are here presented by highlighting their relative construction specifics. Archival research at the "ArkDes" archive (Sweden) has been carried out with the purpose of displaying how far the technological choices were meant to improve building performance in terms of operation, functionality and costs. The decision to focus on case studies from the 1950s and 1960s was motivated by the intention of documenting the application of innovative post-war construction methods as well as Erskine's ideas contributing to the definition of Modern features of sub-arctic architecture, presented by Erskine within the CIAM debate. The selected projects contain, non-exclusively, residential typologies and were constructed by using lightweight aerated precast concrete components. The first example, the Lassaskog residential buildings in Växjö (1953–54), and the last, Erskine's own villa and office in Drottningholm (1963), are situated in southern Sweden, whereas the second, the Ortdrivaren district in Kiruna (1960–62), was built inside the Arctic Circle, where the extreme climate is particularly harsh. The case studies are presented in chronological order.

Figure 1. Ralph Erskine, Lassaskog buildings, Växjö. Two of the six apartment buildings, view of the southern facades, 1960. The picture shows the original envelope and balconies supported by iron cables before changes were made to the buildings in more recent times. From ArkDes Collections (ARKM.1988-111-X1898-6).

4.1 *Lassaskog residential buildings, Växjö, Sweden, 1953–54*

The six residential towers completed in Växjö in 1954 consist of seven floors of functionalist dwellings plus a ground floor for storage and facilities (Figure 1). The design was commissioned by the town of Växjö for the densification of the area at the time of the spread of industrialized construction methods in Sweden. The project was developed by Erskine, with the contribution of his collaborator Aage Rosenvold and the engineer Arne Larsson. The design process was an opportunity for the studio to develop affordable dwellings, minimizing waste and consumption of resources.

The architectural firm designed the buildings to an extremely strict plan, based on modules of 4 by 5 metres so as to allow the application of different optional building technologies, from heavy prefabrication to lighter construction. Following the submission of various tenders, "Skånska Cementjuteriet", a

Figure 2. Construction site of Lassaskog buildings, Växjö. Air-heated Masonite hoods moved by cranes were used to cast concrete regardless of the weather. Construction continued through the Swedish winter. Photo: Sallstedts Bildbyrå / Nordiska museet.

Swedish concrete construction company, obtained the building contract by tendering the lowest price for both categories (Egelius 1990). Thereafter, the heavier solution was favoured in order to explore innovative advanced prefabrication technologies. The buildings were erected as "Allbetonghus" (all-concrete houses) with a load-bearing box-type structure, poured using prefabricated shuttering units, built of wood on a steel frame. All non-load-bearing concrete components were precast and positioned using cranes. The striving for the economical use of resources motivated the architect to arrange the layout of the towers so as to reduce the number of cranes needed to only three units that moved along rails to assemble all six buildings (Figure 2). Load-bearing walls, consisting of 12 cm of poured unreinforced concrete, were positioned to divide each floor plan (11 m × 20 m) into ten equal-sized modules. The different apartments, organized with the arrangement of precast partitions and cupboard/wardrobe-walls, were all provided with a south-facing living room and cross-ventilation. All concrete vertical surfaces were cast in jute-clad moulds, to allow easy wallpapering or painting without plastering. Electric systems were cast in, while heating, plumbing and drainage were prefabricated and mounted in ducts.

Innovative features of the construction were the non-loadbearing facades, made of 8cm-thick concrete panels of 4 m by 2.9 m (Figure 3). These elements, with an exterior ribbed surface, were precast at the construction site, using moulds of mahogany plywood with teak screwed strips. Designed only to protect the internal insulation from the weather, the panels were accordingly realized in aerated lightweight concrete, with higher resistance to frost. Each piece contained anchor irons, used for lifting and assembling the elements in place with the aid of cranes. Stainless-steel adjustable loops, attached to the poured structure, ensured the correct positioning of these pieces. The concrete floor slabs, 21 cm thick, did not carry the weight of the façade pieces, which were, in fact, bricked on top of each other. A 10 mm air gap for ventilation divided the outer panels from a wooden structure, equipped with diffusion-proof cardboard and aluminium foil to secure protection behind vertical joints. On the interior, the insulating layer (10 cm stone wool) was enclosed by wooden fibreboard. Continuity of the air gap behind the envelope was preserved by placing cork boards with vertical grooves against the exterior surface of the concrete slabs. The overall thickness of the envelope was 20 cm. The load-bearing walls at the shorter side of each building were also insulated

Figure 3. Construction site of Lassaskog buildings, Växjö. Positioning a precast facade panel. Photo: Sallstedts Bildbyrå / Nordiska museet.

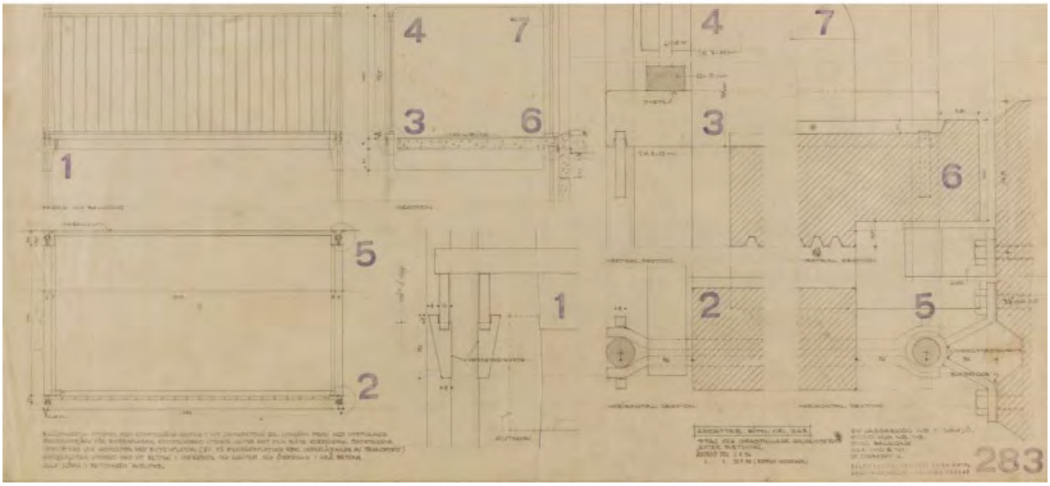

Figure 4. Ralph Erskine, 1:1 and 1:10 drawings of the balcony supported by iron cables designed for the Lassaskog buildings in Växjö, May 1954. From ArkDes Collections (ARKM.1986-17-2874-003).

externally and covered by the same exterior precast panels, ensuring the continuity of the insulation and the air gap. Rounded elements were applied to shield the corners and further reduce frost effects.

White concrete hanging balconies were designed to equip the dwellings with outdoor space for summer use. The monolithic elements, cast in concrete so as to obtain maximum resistance with the lowest weight, were originally hung with round iron cables 22 mm thick and 22 m long. The weight of the balconies was carried only by precast beams, placed on the rooftop. The two inner round irons were guided in loop-fittings fixed to the facades. This strategy avoided any contact between the balconies and the structure, eliminating cold bridges (Figure 4). The design of the roof surface also prevented snow from sliding, enhancing insulating performance.

All the construction solutions adopted were customized to cope with the local climate and to reduce production and operation expenses. Therefore, a first proposal, recalling the Modern stereotype of residential building with a recessed ground floor was discarded. The facades were instead designed to continue to the ground level, where the soil, moved for excavation, was relocated for further thermal protection. The resulting low cost of each house (Bouvin 1955) demonstrated that the construction methods applied were very market competitive. Furthermore, the project proved that the application of industrial methods to the building site was not only a solution to reduce production times but a method to be further developed for improving construction in qualitative terms, adjustable to different climatic regions.

4.2 *Kvarteret Ortdrivaren, Kiruna, Sweden, 1961–62*

Kiruna, located 145 Km inside the Polar Circle and in need of urban expansion in the post-war period provided the optimal context to experiment with Modern typologies and construction techniques in extreme weather conditions. Ralph Erskine had been studying the potential development of the town and its local climate on his own initiative since the 1950s (Egelius 1990), and was willing to test his ideas for a Modern "Sub-Arctic Habitat". When he was asked to design a proposal for the renovation of Kiruna, he had already acquired extensive knowledge of its exposure to the sun and meteorological phenomena.

The district built was originally conceived as the central area of a masterplan involving a much larger portion of the town, which was instead redeveloped according to a different urban pattern. The neighbourhood is composed of three low-rise buildings, painted yellow, and two towers and a church, painted shades of brown (Figure 5). There is a total of 138 apartments, 12 facilities and 85 garage spaces. The district contains an open square framed by commercial activities. The highest tower has 13 floors and it is connected at the bottom with the other 10-storey- high tower and the church. A courtyard with a playground and parking areas was obtained by the positioning of the parallel three low rise buildings in the west side of the neighborhood.

Due to the severe climate, all the energy-conscious innovations already put into practice in Lassaskog and Erskine's other projects in Sweden had to be enhanced to achieve improved control of energy consumption for operation and maintenance costs. The district plan was organized so as to allow internal circulation, minimizing heated spaces. The management of snow was also kept in mind when planning the distribution of each block and its structure. Whereas in Växjö the construction technology drove the definition of the typologies, in Kiruna the shape of the blocks appears to be planned in the first place, in order to implement the thermal optimization strategy. All the buildings were designed with rounded edges to reduce heat losses. In addition,

Figure 5. Ralph Erskine, Kvarteret Ortdrivaren. The neighborhood in the 1960s, view from the South. The high-rise buildings, in darker shades, are placed behind the lower ones, in lighter shades. The original balconies, here visible, aesthetically recalling mine lifts, have been modified in recent times. From ArkDes Collections (ARKM.1986-122-2148).

the volumes were slanted towards the north to increase the surface area of the southern façade and to limit the shadowing effect. The shape of the metal-coated roofs prevented frozen snow loads from dangerously falling onto pedestrian areas. High buildings allow for good solar exposure of the dwellings, despite the low position of the sun above the sub arctic horizon.

Each apartment was equipped with a small balcony (approximately 1 m^2) made of precast concrete elements minimally anchored to the floor slabs and detached from the insulating envelope to avoid cold bridges. This device was designed for different seasonal use: in winter it was meant as a natural deep freezer, whereas during the sunny summer it provided an additional outdoor space. The plans of the dwellings were organized to limit usage of perimetral areas during the colder season and to encourage it in the warmer months. The surface areas of windows, with wooden frames and fitted with triple glazing, were limited to reduce heating needs.

The separation of the loadbearing structure from the envelope, achieved in Växjö with only two loadbearing walls located close to the envelope, took a new step forward in Kiruna. The perimetral vertical loadbearing structure was reduced to T-shaped concrete pillars, with minimum contact with the external walls. The envelope was designed in lightweight aerated concrete panels, insulated by the application of polystyrene and anchored to the loadbearing concrete frame. The precast elements, painted on the exterior, are 50 cm wide and rise to the full height of a floor or the window sills. Particular care was dedicated to the detailing of the ground-floor level, where the precast panels encounter the poured concrete structure of the basement, reducing thermal transmission (Figure 6). Additional insulation was placed to control heat losses in the round corner facing north at the street level. Here, the pillars are designed with a round profile and completely separated from the building's envelope. In designing the buildings in the Ortdrivaren neighborhood, Erskine demonstrated the adaptive potential of the Modern concept of the suspended façade. In the Polar Circle, the hung wall is materialized, not as a transparent envelope, but as a device to improve the building's comfort and thermal performance. Erskine was able to prove that the advent of innovative concrete construction strategies could be successfully used to improve the quality of building standards internationally, regardless of climate differences.

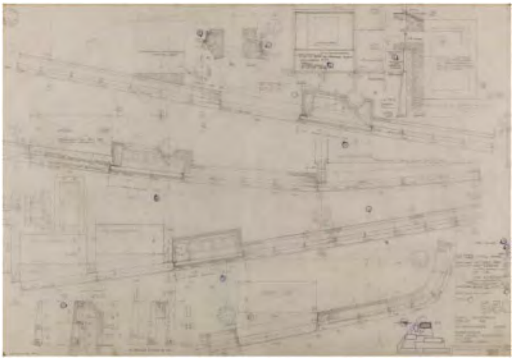

Figure 6. Ralph Erskine, 1:10 drawing of the envelope of the ground floor and the basement of the highest building of Kvarteret Ortdrivaren, 1959. From ArkDes Collections (ARKM.1986-17-2288-001).

Figure 7. Ralph Erskine, villa, garage and office building in Drottningholm, view from the South at the time of completion. From ArkDes Collections (ARKM.1986-122-0217-01).

4.3 *Villa Erskine, Drottningholm, Sweden, 1963*

In Erskine's own house and studio in Drottningholm, west of Stockholm, the absence of a vertical internal loadbearing structure reduces thermal transfer from the exterior envelope. The three modest-sized parallelepipedal buildings, designed to contain the villa, the office and a garage, were realized as shells of white aerated concrete blocks. (Figure 7). The house contains an open-plan double height living room, facing south. Here, a rotating fireplace dominates the scene, making it possible to adjust the direction of the heat source, depending on the usage. Bedrooms and bathrooms are organized on two levels at the northern side. The cooking area was designed as a box within the box at the centre of the building. An atelier space for kids was placed on top of it, looking down towards the living room. The office building is also organized on two levels and equipped with a kitchen and a bathroom. The larger windows of the atelier face west to provide more privacy to the villa.

The buildings were erected during the summer of 1963. Arne Larsson, the same engineer involved in the design of the buildings in Växjö, participated in planning the construction process. The lightweight concrete elements were assembled on top of reinforced concrete foundations. The façade pattern was obtained by the disposition of the 30 cm-thick block types. The exterior face of each element was grooved by hand to liven up the dull surface using a special sled-like tool equipped with metal teeth. The type of construction applied to the buildings allows free positioning and varied dimensioning of windows in the facades according to the needs of each indoor area. Special curved elements are used to join perimetral walls, limiting heat losses. The floors were also built as 15 cm-thick lightweight concrete elements, carried by perimetral foundation walls and central supporting beams in reinforced concrete. The laminated parquet floor finishing was insulated with 7 cm of mineral wool. The roof was obtained by placing 25 cm-thick precast elements to form a barrel vault. The vault is supported with T-shaped steel trusses. Internal metal tie-rods that cross the indoor spaces ensure the stability of the curved surface. Dark corrugated metal elements were positioned on supports anchored to the exterior of the vaults (Figure 8). This device protects the concrete shells from rain and snow falls, preventing the formation of dangerous icicles. Additionally, the heat of the interior spaces is not transmitted directly to the snow accumulating on top of the buildings (Porteus 2002). Water is collected in perimetral drain pipes and transported away from the envelope.

The outdoor spaces require minimum maintenance and large rocks in the garden work as heat accumulators on sunny days. Access to indoor spaces is via wooden decks, mounted on autonomous structures to avoid unnecessary thermal transmission and to reduce the effort of snow removal in winter. The interior surface of the envelope is finished with white paint. The buildings are heated by means of heaters connected by exposed pipes running around the indoor perimeter. The concrete elements therefore remain untouched by the heating system.

The Drottningholm complex is the materialization of Erskine's experimentation with open-plan and free façade composition. These principles of Modern architecture are adjusted to the local climate constraints by means of appropriate construction technologies. In a colder climate, freedom in displaying indoor spaces and openings could be obtained by eliminating the contrast between structure and envelope.

Figure 8. Ralph Erskine, villa, garage and office building in Drottningholm. Detail of the roof of the garage. The upper layer of the roof construction is completely separated from the building's structure. Photo: Elena Poma, 2020.

5 CONCLUSIONS

Analysis of the technological applications in Erskine's design demonstrate how the customization of construction to the local climate resulted in energy-aware buildings that responded to Modern ideals. In addition, the chosen case studies seem to reveal progressive improvements in Erskine's approach to energy-conscious construction by a climate-aware revisitation of a few Modern architectural principles, such as the use of pilotis and the free design of plan and facades. The architect's understanding and enhancement of technological innovation were, in fact, crucial for the production of the architectural quality of his designs.

As proposed by the Olgyay brothers, when promoting the development of a regional Modern architecture (Olgyay 1963), Erskine saw prior climate analysis as essential to architectural design. Therefore, the local climate can be recognized as a "force" (Fitch 1975) that contributed to the shaping and improvement of Modern architecture through a technologically-aware approach. Besides, the "Environmentalism" identified by Banham in Wright's production (Banham 1967) could likewise be ascertained in Erskine's works. The careful interrelationship of technological solutions and spatial organization define a method for producing high-quality built results, attentive to indoor comfort.

In conclusion, the research behind this paper seeks to demonstrate that investigation of the technology applied by Modern architects could play an important role in assessing the value of the energy-aware legacy of the Modern movement. Even though the technological applications discussed here are obviously outdated by the standards of current practice, the lesson behind their incisive application by a small group of Modern pioneers remains valuable for further debate.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

We're not in Kansas anymore: ASHRAE and the global growth of thermal comfort research

A. Cruse
The Ohio State University, Columbus, USA

ABSTRACT: This paper outlines the changing role of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) in shaping thermal comfort research during the second half of the 20th century. During that time, the comfort research community grew considerably, while ASHRAE's role became smaller. Yet, it remained vital. ASHRAE engineers established the basic comfort research methods and ASHRAE funding supported subsequent scientific advances fundamental to the two principal comfort models, the Predicted Mean Vote index and the Adaptive Thermal Comfort model. The Society's changing role highlights how a multi-disciplinary approach was embedded in comfort research, how industrial and academic ties shaped inquiry, how opposing viewpoints were addressed within the research community, and how the network of comfort researchers expanded from the Unites States to Europe, Australia, and Asia.

1 INTRODUCTION

In 1961 Ralph Nevins, chair of mechanical engineering at Kansas State University (KSU), published "Psychrometrics and Modern Comfort" in *ASHRAE Transactions*, the research journal of the American Society of Heating, Ventilating, and Air Conditioning Engineers (Nevins 1961). There, Nevins sketched an American-focused history of thermal comfort research and outlined his plan to continue this work at the University's soon-to-be-opened Institute for Environmental Research (IER). ASHRAE had provided key equipment to the Institute and would sponsor much of its work on comfort over the following decades. This included support for P.O. Fanger and his widely-used Predicted Mean Vote thermal index. Twenty years later, Richard de Dear and Gail Brager proposed the adaptive thermal comfort model that challenged the dominance of the PMV approach. They too relied on ASHRAE's support in furthering their efforts. Nevins, Fanger, de Dear, and Brager were all important participants in the network of comfort researchers during the second half of the 20th century. This paper outlines ASHRAE's changing role in directing and shaping this network. During this time, the comfort research community grew considerably while ASHRAE's role became smaller. Yet, it remained vital. ASHRAE engineers established the basic comfort research methods and ASHRAE funding supported subsequent scientific advances. The Society's changing role highlights how a multi-disciplinary approach was embedded in comfort research, how industrial and academic ties shaped inquiry, how opposing viewpoints were addressed within the research community, and how the network of comfort researchers expanded from the Unites States, to Europe, Australia, and Asia. Less than 60 years after Nevins summarized the Society's comfort research from his Kansas office, an article by 60 researchers from 21 countries announced ASHRAE's Global Thermal Comfort Database II (Földváry Ličina et al. 2018).

2 ASHRAE RESEARCH AND THE IER

ASHRAE was formed in 1959 by the consolidation of the American Society of Heating and Air-Conditioning Engineers and the American Society of Refrigeration Engineers. One of the newly formed Society's earliest decisions was to close their Research Bureau, which had been founded in 1919. A principal task of the Bureau had been to determine thermal comfort standards based on scientific research and useful to the growing air conditioning industry (Cooper 1998). By 1923, F.C. Houghton and C.P. Yaglou published the first comfort chart, showing "equal comfort lines" superimposed on a psychrometric chart (Houghten & Yaglou 1923). Bureau researchers, most of whom were trained as mechanical engineers, continued to expand and refine this work over the following decades. During the war, the Society had begun to plan revisions to the comfort chart. But, after the merger that formed ASHRAE, the group's board decided instead to close the Bureau's laboratory. They believed that by shifting research to universities and other established laboratories, they could support more work for less money.

Comfort research remained a priority for ASHRAE even after closing its laboratory. Although the group's organizational structure changed over the years, generally the Society's Research Committee set overall priorities and then formed Technical Committees to

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oversee specific topics. After closing the Bureau's laboratory, the Technical Committees took on the added responsibility of reviewing and administering financial grants for research projects. Between 1959 and 1967, comfort work received the largest share of ASHRAE's research budget. ASHRAE's grant to the IER was one few multi-year grants (it lasted from 1963 to 1971) and the largest that ASHRAE awarded (Nevins 1968).

Under Nevins's leadership, the IER inherited the mantle of American comfort research from ASHRAE. It also literally inherited ASHRAE's climate chamber, which was brought to Manhattan, Kansas from the decommissioned laboratory in Cleveland, Ohio. A climate chamber – also called a psychometric or air-conditioned chamber – is a mid-sized windowless room in which different environmental parameters can be precisely set and independently controlled using a sophisticated air conditioning system. More than a piece of laboratory equipment, the climate chamber represented a research methodology based on empirical observation under carefully controlled experimental conditions. The Society preferred laboratory-based comfort research to the other dominant research methodology, field studies, because research parameters could be better controlled and measured in the laboratory.

Climate chamber comfort research was based on the idea of heat balance. This is the premise that a person feels comfortable when the heat produced by their body is balanced with the heat in the environment. From their earliest climate chamber experiments, Society researchers had recognized the role of different factors in achieving comfort by heat balance. These included the environmental variables of air temperature, radiant temperature, humidity, and air speed; and the personal ones of clothing and activity level. Researchers often varied two of these parameters to see how they affected the conditions subjects found most comfortable. Most early building-related research focused on air temperature and humidity since these were thought to have the largest effect on comfort, and both could be easily controlled with a climate chamber's air conditioning system. Houghton and Yaglou had combined these two parameters into the widely used Effective Temperature (ET) thermal index. ET conditions could be graphically represented on the two axes of the psychrometric chart. Sometimes a third parameter, often air speed, was also included, and the results plotted on a Mollier diagram or a nomogram. In outlining research goals for the IER, Nevins cited over a dozen studies showing different combinations of temperature and humidity as the most comfortable. Suggesting that this previous research did not conclusively establish the parameters of thermal comfort, he wrote that research at the IER would focus on producing a "'complete' comfort chart" (Nevins 1961).

To develop this complete picture of thermal comfort, ASHRAE-funded researchers relied on a more detailed understanding of heat balance based on a rational understand of heat exchange. This work was done at the Pierce Laboratory in New Haven, Connecticut. Founded in 1933 through a trust left by John B. Pierce (whose Pierce Company was a forerunner to the American Radiator Company), the Pierce Lab's mission was to connect comfort research to the biological sciences. The Lab's first Director, C-E. A. Wilson, was the founder of the Yale School of Public Health and had long been a member of ASHRAE's Technical Committees on human physiology and comfort. Many of the lab's researchers had joint appointments at the Yale School of Medicine, located next to the Pierce Lab building. Although the Pierce Lab had a climate chamber, its design was based on models used to test the effectiveness of radiators, not air-conditioned environments like ASHRAE's chambers (Winslow et al. 1934). Instead, the most significant early work at Pierce by Wilson and his collaborators L.P. Herrington and Pharo Gagge dealt with quantifying heat exchanges between the body and its environment using a partitional calorimeter. Unlike the climate chamber, which relied on subjects to report their subjective experience of comfort, the partitional calorimeter allowed researchers to individually measure the body's different avenues of heat exchange – conduction, convection, radiation, and evaporation (Winslow et al. 1936). Although this work did not result in practice-oriented comfort charts like ASHRAE's, its rational expression of heat exchange allowed researchers to predict the effects of the different environmental variables in greater detail. This, in turn, led to more precise formulations of comfort. Pharo Gagge, who had trained as a physicist at Yale before joining Pierce, developed the Standard Effective Temperature (SET) thermal index based on this more detailed understanding of heat exchange (Gagge 1940). SET incorporated radiant as well as convective heat sources to determine comfort. Unlike the ET index, SET did not address humidity, which was seen as having only a small role in thermal comfort for building occupants.

While physiologists modelled the body's reaction to the physical stimulus of heat exchange, psychologists sought to understand how such stimulus related to sensation. Sensation cannot be measured in a direct way like stimulus. Rather, it is up to the psychologist to define what people mean when they say they are comfortable. The study of the relationship between stimulus and sensation, called *psychophysics*, began in the mid-19th century and was one of the earliest branches of psychology. ASHRAE considered the psychological dimension of comfort fundamental to its work. Since issuing its first comfort standard in 1966, ASHRAE has and continues to define thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE 1966, 2004).

Starting in the 1930s, comfort researchers had using a rating scale to quantify the sensation felt by test subjects. The best know early example of such a scale was by the Englishman, Thomas Bedford. Sponsored by the UK Medical Research Council, Bedford conducted field studies of factory workers engaged in light and sedentary work (Bedford 1936). He asked the workers to describe their "sensation of warmth" with one of seven terms that ranged from "comfortable" to "much too warm" and "much too cold". He then assigned numeric values to each category. These values allowed him to analyse statistically workers' comfort votes using linear regression to correlate sensation with environmental conditions. His seven-point scale, known as the Bedford Scale, was later adapted by ASHRAE researchers. Significantly, they changed Bedford's terms to more closely corresponded to sensation. On the ASHRAE scale, the central value corresponded to "neutral", rather than Bedford's "comfortable", while "much too warm" became "hot" and "much too cold", "cold". Despite its origins as a field study technique, the ASHRAE scale became the standard tool used in climate chamber research to relate physical stimulus to psychological sensation.

ASHRAE researchers were not simply interested in sensation, but in how such sensation affected performance. Nevins was explicit about this in outlining goals for the IER, stating that their research would study "the effects of the thermal environment on learning rate and achievement and on productivity" (Nevins 1961).

Doing this, Nevins recognized, would require further psychological work. At the IER, this work was done by Frederik Rohles, who joined the lab when it opened in 1963 with a joint appointment to KSU's departments of psychology and mechanical engineering. Rohles was trained as an experimental psychologist and had spent much his career in the Air Force, assessing how airmen performed in extreme environments. This included working with Pharo Gagge at Wright-Patterson Air Force Base and training chimpanzees for spaceflight. At the IER, Rohles studied how indoor climate affected performance. He found that subjects' reactions to moderate environments were more difficult to predict than their reactions to the extreme ones he had studied in the Air Force. He believed this was because, in moderate environments, more factors affected the sensation of comfort. Rohles represented this range of factors in a diagram depicting a gridded cube. The x-axis represented the physical factors addressed by most thermal indices such as temperature and humidity. The y-axis showed "organismic factors" – "those conditions man brings with him to the environment" – such as age, sex and genetics. And the z-axis shows "reciprocative factors" – "those factors that interact between man and his environment". These included the well-recognized effects of clothing and activity and also more vaguely defined "social incentive" (Rohles 1971).

Comfort research at the IER built upon ASHRAE's methods and equipment, while incorporating new physiological insights from medicine and psychological ones from the military. With its roots in hygiene and ventilation, American comfort research had long been interdisciplinary, involving public health professionals, and mechanical engineers. Yet each profession tended to conduct their own research with its own methods. ASHRAE's shift from conducting to sponsoring research increased interdisciplinary exchanges with actors trained in different fields collaborating in new ways. The network of researchers was largely American although it was soon to expand to Europe.

3 P.O. FANGER AND THE PMV INDEX

When he arrived at the IER for the 1966-7 academic year, P.O. Fanger stepped into an academic laboratory doing industry-sponsored comfort research. At the time Fanger was an assistant professor of engineering at the Technical University of Denmark (TUD), in Lyngby, north of Copenhagen. The TUD had a long tradition of academic research focused on the interior environment. Its professorship in heating and ventilation was established in 1885, only one week after Hermann Rietschel became the first professor in the field at the Berlin Technical University. TUD's Laboratory of Heating and Ventilating had opened in 1935. Fanger earned his MSc degree there in 1957. As Fanger was starting his academic career in the early 1960s, Danish building researchers and public health officials were increasingly concerned about the poor indoor air found in much post-war housing. In 1962, G.R. Lundqvist and I. Anderson, an engineer and medical doctor respectively, had started the Indoor Climate Research Climate Group at the University of Aarhus to study these problems. Anderson claims that Lundqvist, a friend of Fanger's, encouraged Fanger to shift his research to thermal comfort from oil burner efficiency to help in this effort (Andersen & Gyntelberg 2011).

At the IER, Fanger first formulated his comfort equation. He had two goals for this work. It had to address all significant factors researchers agreed affected comfort. And it had to be practical for engineers to use. As Fanger later wrote: "thermal comfort is the 'product' which is produced and sold to the customer by the heating and air-conditioning industry. It is therefore obvious that quantitatively expressed comfort conditions are of great importance" (Fanger 1970). Working with data Nevins and Rohles had collected from KSU students in their climate chamber, Fanger developed a comfort equation. This included the six environmental and personal variables long held by comfort researchers to be the most important. To this, he added skin temperature and heat loss through sweating. Partitional calorimetry work by Gagge and others at Pierce had shown that these values were effective indicators of thermal stress. When they were within a normal range, Fanger reasoned, subjects did not experience thermal stress. Fanger associated this absence of stress with both thermal neutrality and thermal comfort, which he treated synonymously. Fanger published a series of charts (calculated by "digital computer") showing various solutions to the comfort equation under different circumstances. Engineers would find the chart that applied to their design problem and use it to determine the ideal comfort conditions.

ASHRAE was fundamental to developing and broadcasting Fanger's comfort equation. His work at the IER was financed by its ASHRAE research grant. He first presented his findings at the 1967 ASHRAE annual meeting in Minneapolis, Minnesota. And he first published the comfort equation in *ASHRAE Transactions* that same year (Fanger 1967).

After returning to TUD, Fanger expanded his comfort equation research as part of his DSc. thesis. One of his first tasks was to build a climate chamber at the TUD that matched the specification of the one in Kansas. This was only the second chamber in Scandinavia, and the first built specifically for comfort research (Andersen & Gyntelberg 2011). Duplicating the IER chamber at the TUD ensured reproducibility, an essential aspect of scientific comfort research (Murphy 2006). Inter-laboratory standardization of equipment, along with a standardization of methodology and the adoption of common units, allowed Fanger to aggregate data collected from the TUD chamber with that from the IER. Fanger first repeated Nevins and Rohles' experiment with KSU students – and on which he had based his comfort equation – with Danish college students. To ensure consistency in clothing insulation, Fanger imported KSU uniforms for the Danish student to wear. Fanger's experiment showed that Danish students preferred the same comfort conditions as the American ones had. Fanger repeated these preferred temperature studies to understand if any "special factors" influenced the comfort equation. These included age, sex, and body build – many of those same "organismic factors" Rohles had outlined. Based on the results of his tests, Fanger concluded these factors had no significant effect on the neutral comfort preferences among his climate chamber test subjects (Fanger 1970).

By 1970, Fanger published *Thermal Comfort: Analysis and Applications in Environmental Engineering* based on his doctoral research (Fanger 1970). There he restated his comfort equation with some updates based on his work at the TUD. Fanger then introduced the Predicted Mean Vote (PMV) thermal index. He explained that while the comfort equation allowed engineers to calculate ideal conditions for a space, the PMV index would allow them to predict occupants' thermal sensation. The "vote" in the index's name refers to a hypothetical subject's vote on the ASHRAE scale. The PMV predicted this vote based on a reworking of the comfort equation where the variables of skin temperature and sweating were used as deterministic indices of sensation. As Fanger explained: "we will assume that the thermal sensation at a given activity level is a function of the thermal load of the body" (Fanger 1970). As with the comfort equation, Fanger provided a series of charts showing how comfort votes would deviate from neutral based on different combinations of variables.

In developing his comfort equation and PMV index, Fanger acknowledged those who had helped him. Not surprisingly, he offered the largest thanks to his American colleagues at the IER and Pierce Lab – Nevins, Rohles, and Gagge – and to the TUD's Laboratory for Heating and Air Conditioning.

In the book's literature review section, Fanger explained his preference for laboratory-based climate chamber research. Although he recognized that field studies provided insights into specific situations, Fanger, like ASHRAE, found field studies often incomplete in that they did not collect data on the range of factors affecting thermal comfort. Fanger also observed that field instruments were less precise than laboratory ones, meaning field data was not useful for predicting comfort. As he later explained, "poor input data will provide a poor prediction" (Fanger 1994).

Fanger also recognized gaps in his research and potential shortcoming of his models. These included a series of questions about non-steady-state thermal conditions. Comfort researchers had long debated experimental design for their climate chamber research. One agreed-upon principle was that, for heat balance comfort to be valid, subjects needed to spend an extended amount of time (on the order of an hour or more) inside a chamber with fixed, or steady-state, environmental conditions. In recognizing that the PMV index might not work under non-steady-state conditions, Fanger anticipated future research to address thermal transients or step changes (when the temperature changes over short periods of time), asymmetrical radiant heating, elevated air speeds, and other novel thermal conditions.

Another concern Fanger raised with his and ASHRAE's research was that it was done largely in temperate climates with residents of those climates. Fanger questioned whether the PMV index would work for people acclimated to other climates, specifically tropical climates. Acclimatization refers to the body's ability to adjust its balance point with the thermal environment. The time scales of such adjustments varied, from physiological changes caused by seasonal changes to genetic ones that take generations to happen. Acclimatization had been a hotly contested topic in the 19th-century science (Livingstone 1987). The International Biological Program's Human Adaptability Project revived interest in the 1960s. Some researchers associated with the Project worked at Pierce Lab (Weiner 1964).

In his literature review, Fanger cited several field studies from the tropics done during the 1940s and 1950s suggesting a role for acclimatization in comfort. However, he sided with a group of laboratory researchers, who argued that such difference had to do with clothing habits rather than physiological changes. Fanger concludes the section on acclimatization with something less than his typical scientific certainty: "comparison of field studies in the tropics and the comfort equation suggests that the equation can also be used under these conditions" (Fanger 1970).

With his formulation of the comfort equation and PMV index complete, Fanger set about building consensus around his models. In the decade following the publication of *Thermal Comfort*, Fanger was elected a member of the Danish Academy of Technical Sciences, the Danish representative to REHVA (the Representatives of European Heating and Ventilating Associations), and the vice president for the IIE (International Institute for Refrigeration), in addition to continuing his involvement with ASHRAE. He also sat on editorial boards of peer reviewed journals *Energy* and *Energy and Buildings*. His ability to generate interest in thermal comfort research was not always seen positively by his Nordic colleagues, two of which commented that he was "a better salesman than scientist in the promotion of indoor air climate matters" (Anderson & Gyntelberg 2011). Yet through this involvement Fanger enlarged the network of researchers who worked with on climate chamber-based laboratory research, accepted the PMV index as the research standard, and embraced its knowledge gaps as sources of vital questions.

One can identify the wider impact of Fanger's work in two international conferences. The first, Indoor Air, took place in Copenhagen in 1978. Intended to highlight Danish leadership in indoor air research, it brought together 200 academic and government researchers from 20 countries. Fanger was Chairman of the organizing committee. About half of the 47 invited presentations dealt with the thermal environment. Several were by TUD and Pierce Lab researchers. (The two labs had built matching state-of-the-art climate chambers in 1975.) Others papers were by German, English, Belgian, and French researchers (Fanger & Valbjørn 1979). Their work dealt largely with non-steady state thermal conditions that Fanger had outlined in *Thermal Comfort*.

Seven years later, Fanger organized a second, much larger, international conference, the CLIMA 2000 World Congress on Heating, Ventilating and Air-Conditioning. Sponsored by REHVA, ASHRAE, and the IIR, (on all of whose boards Fanger sat), CLIMA 2000 broadly addressed the "artificial climate industry". It included sessions on building performance, energy management, HVAC systems, solar energy, and indoor climate. The indoor climate session had 80 papers, over 30 of which dealt specifically with thermal comfort. These were by many by the same European and North American researchers who had presented at Indoor Air and again addressed many of the same research questions Fanger had previously outlined.

As CLIMA 2000 was taking place in mid-1980s, the pioneering phase of heat balance comfort research was over. While this research began with ASHRAE in the United States, its centre had shifted to Europe under Fanger's leadership, and ASHRAE's influence had begun to wane. The energy crisis that began in the 1970s had shifted ASHRAE's focus to indoor air quality and its chemical composition, rather than its thermal properties. Starting in the mid-1970s, ASHRAE had used the energy crisis to push into a larger, international arena, as its sponsorship of CLIMA 2000 showed. However growing awareness of the limits of the PMV index related to its energetic costs would soon help an alternative approach to comfort grow within the research community. ASHRAE would play a significant role in its development.

4 ADAPTIVE THERMAL COMFORT

Among the CLIMA 2000 thermal comfort papers, two stand out as signalling a shift away from PMV-related research questions. The first, by Japanese academics Ken-ichi Kimura and Shin-ichi Tanabe, shifted the focus of comfort research to warmer climates in Asia. Their paper describes a new climate chamber they built at Waseda University, where Kimura was a professor of architecture (Kimura & Tanabe 1985). As a student, Kimura had participated in Solar Energy Project at MIT before returning to Japan where he built an academic career focused on solar energy. Tanabe had studied with Kimura for his BArch degree before spending two years at Fanger's TUD lab. In their paper, Kimura and Tanabe situate the new chamber within the lineage of chambers at the ASHRAE, IER, TUD and Pierce laboratories. While they explained these earlier chambers were used to test comfort in cooler climates, the high energy demands of summer air conditioning in hot, humid climates highlighted the need to reconsider comfort in the tropics. Tanabe and Kimura would later present preliminary results of this work as the opening address of ASHRAE's first Far East Conference on Air Conditioning in Hot Climates, held in Singapore in 1987 (Tanabe & Kimura 1989). This explicit connection of comfort and kilowatts in tropical Asia would form the basis for future comfort work in the region.

A second paper by Richard de Dear and Andris Auliciems stands out as signalling a shift towards an adaptive comfort approach (de Dear & Auliciems 1985a). The Latvian-Australian Auliciems had completed his PhD in social biometeorology in 1969 at the University of Reading, studying the effects of climate on the performance of school children (Auliciems 1970). His advisor O.G. Edholm was an expert on extreme physiology in cold climates. Auliciems joined the University of Queensland in 1973, where he later directed the Applied Climate Research Unit. De Dear completed his PhD with Auliciems in 1985. Their CLIMA 2000 paper [published the same year in the *ASHRAE Transactions* (de Dear & Auliciems 1985b) and the Australian *Architectural Science Review* (Auliciems & de Dear 1986)] was based on de Dear's doctorate work. It tested the validity of the PMV index through field studies of air conditioned and naturally ventilated building in three different climate zones in Australia. De Dear had surveyed the building occupants about their comfort preferences and compared his findings to two different indices. The first was the PMV index, which embodied what they called a "constancy hypothesis". As Fanger had argued in *Thermal Comfort*, and confirmed in subsequent climate chamber research, this view held that thermal comfort was constant and that neither acclimatization nor any "special factors" such as age, race, or sex affected one's comfort vote. The second was a new thermal index derived by Auliciems that combined interior temperature and mean monthly outdoor temperature to determine comfort conditions. De Dear and Auliciems explained that his approach embodied an "adaptive hypothesis". That is it predicted building occupant's comfort preferences would change, or adapt, in concert with the outdoor climate. Auliciems had derived this index based on a regression analysis of data from 50 years of field studies (Auliciems 1983). When comparing results of the two indices to the responses of building occupants, de Dear and Auliciems found that the adaptive index better predicted their preferred conditions than the PMV index. They attributed the success of the adaptive hypothesis to a "climate signal" influencing sensation. This conclusion, they argued, was consistent with the tenets of adaptive theory in environmental psychology. Environmental psychology held that one must consider the cognitive context of a person's thermal perception. This psychological perspective was much more inclusive of thermal and non-thermal factors than the deterministic psychophysical model embedded in the heat balance approach.

The adaptive hypothesis did not contradict the PMV index per se. Instead, the "experiential realism" of field study meant that comfort researchers could detect aspects of thermal experience that were not evident in laboratory-based climate chamber studies. Although ASHRAE researchers generally and Fanger specifically had rejected field studies, they had been widely used in allied research in industrial, military, exploration, and architecture-related fields (Chang 2016; Heggie 2019). Many early thermal indices were derived from this work (Macpherson 1962). Researchers affiliated with the English Building Research Establishment (BRE) made extensive use of field studies. Charles Webb, head the BRE's thermal comfort section, spent the war years in Singapore, where he conducted field studies with residents of Malaysia and Singapore (Webb 1959). His work connects strongly to the postcolonial network of tropical architecture that has come to recent scholarly attention (Chang 2016). After returning to England, Webb continued this field study-based comfort work at the BRE with young researchers Michael Humphreys and Fergus Nicol. Humphreys had presented some findings showing adaptive comfort response at Fanger's 1978 Indoor Air conference (Humphreys 1979). And Auliciems' adaptive index was based on a statistical analysis of Humphrey's work (Auliciems 1983).

While this field study-based comfort work developed outside of the ASHRAE/Fanger research network, de Dear established it as respected research methodology within this community. At the *CLIMA 2000* conference, de Dear met Bjarne Olesen, a former student and colleague of Fanger's from the TUD. Olesen invited de Dear for a post-doc at Fanger's lab, where he worked (along with Tanabe) on what was the lab's first ASHRAE-funded research project, a climate chamber study on the effects of humidity and step changes. De Dear moved to the National University of Singapore in 1988, where they were building a climate chamber. There he was awarded an ASHRAE-funded research grant to continue the preferred temperature experiments Fanger had done at the TUD, and Nevins at the IER, with Singaporean students (de Dear et al. 1991a). (Like Fanger, he acquired KSU student uniforms to control for clothing insulation.) In parallel with his climate chamber work, de Dear conducted a field study comparing the comfort expectations of workers in air-conditioned office to residents of naturally ventilated apartments (de Dear et al. 1991b). His results showed that these occupants had different comfort expectations in these two different contexts, suggesting that thermal expectations played a role in comfort and further supporting the adaptive hypothesis.

Importantly, de Dear called this work "field experiments", rather than field studies. This was more than a semantic shift. Field experiments entailed using laboratory-grade instrumentation and measurement procedures. With these, he took high-quality recordings of all the parameters necessary to calculate contemporary comfort indices, including PMV. By improving fieldwork to laboratory standards, de Dear addressed Fanger's objection to such work. The superior data gathered from field experiments would allow for the superior comfort prediction just as with climate chamber work in the laboratory.

De Dear began to bring together different field experiments supporting the adaptive hypothesis at the conference Thermal Comfort: Past, present and Future, organized by Humphreys and the BRE in 1993 (de Dear 1994). There, he discussed his work from Australia and Singapore, as well as ASHRAE-funded research by Gail Schiller and her colleagues at the University of California Berkeley, in San Francisco, and Berkeley researcher John Busch in Thailand. De Dear argued that collectively their work showed that while laboratory-determined heat balance indices could predict neutral conditions in air-conditioned buildings, adaptive equations derived from field experiments best predict comfort in naturally ventilated ones. He was not, however, ready to draw larger conclusions about global comfort preferences from this limited number of studies. For his part, Fanger, who also presented at the conference, expressed confidence that the PMV index could be modified for local circumstances, while characterizing naturally ventilated buildings as "third world" (de Dear 1994).

With growing awareness of the adaptive hypothesis, ASHRAE's research committee issued a proposal to develop an adaptive thermal comfort model in 1994 or early 1995. They received three proposals, one from a Chinese research team, a second from the Humphreys and Nicol, and the third from de Dear. De Dear's proposal won (in part, he thinks, because of the favourable exchange rate between American and Australian dollars). Working with Schiller (who had since changed her name to Brager), de Dear cleaned and standardized 21,000 sets of raw thermal data taken from 160 buildings to create a global database of thermal comfort field experiments (de Dear et al. 1997). This included correlating studies with meteorological data, standardizing units to meet ASHRAE norms, and sorting air-conditioned buildings from naturally ventilated ones. Based on this larger data set, de Dear and Brager observed that occupants of naturally ventilated buildings preferred a wider range of comfort conditions than the PMV predicted. They attributed this to adaptive mechanisms – behavioural, physiological, and psychological – that the field experiments revealed. They eventually referred to this idea of a variable indoor comfort standard as Adaptive Thermal Comfort (de Dear & Brager 1998).

Developments leading to the Adaptive Thermal Comfort standard significantly enlarged the network of comfort researchers. While Fanger had expanded the initial group of mostly Americans to include Europeans, the adaptive hypothesis was supported by work of an international group. This expanded network followed postcolonial patterns with many BRE-affiliated researchers, most notably Humphreys and Nicol. It also grew through ASHRAE networks, as was the case with Tanabe, de Dear, and Brager. Similarly, field experiments freed ASHRAE-related comfort research from the fixed location of a laboratory, allowing for research sites across the globe.

5 CONCLUSION

In 2004, ASHRAE adopted both the PMV index and the Adaptive Thermal Comfort model into their comfort standard (ASHRAE 2004). Comfort standards are lagging indicators of comfort research, but the simultaneous adoption of the two approaches is emblematic of ASHRAE's continuing involvement in comfort research during the second half of the 20th century. Comfort research changed dramatically during this time. While the Society's first climate chamber experiments recorded two environmental variables, today's Global Thermal Comfort Database captures data from the personal to the meteorological in over 80,000 field experiments from around the world. During this time, ASHRAE played a key role in building state-of-the-art climate chambers to allow for inter-laboratory research fundamental to the constancy hypothesis. Their participation helped to integrate new physiological and psychological insights into comfort research. ASHRAE also sponsored field experiments fundamental to the adaptive hypothesis. The flexibility of fieldwork, coupled with the global spread of air conditioning, helped to expand comfort research from its initial location in America and Europe to a wider world, especially tropical and semi-tropical areas of Asia and Australia.

Adaptive thermal comfort researchers seem to be following a similar pattern to PMV researchers before them. They have gathered around a comfort model and an established research method (Földváry Ličina et al. 2018). Ongoing research at de Dear's and Brager's home institutions, as well as new centres in China and elsewhere, are investigating recognized knowledge gaps and promising opportunities based on adaptive ideas (de Dear et al. 2013). These include the cooling potential of elevated air speed, personal comfort systems, and mixed-mode buildings that can operate with both air conditioning and natural ventilation. De Dear and Brager attributed the interest in adaptive comfort research to a growing awareness of global warming, and the role indoor comfort plays in energy use (de Dear et al. 2013). With its wider range of acceptable temperatures, the adaptive model can save more energy than the constancy model. While ASHRAE was fundamental to adaptive research, some have questioned their commitment to pushing adaptive ideas in practice, specifically in building standards. ASHRAE's current comfort standards significantly limits how and when the adaptive model can be used (Deuble & de Dear 2012). This suggests a commitment to, as Fanger wrote, comfort as a "product" sold by the air-conditioning industry rather than a resource to be conserved. Certainly, to maintain their relevance in a resource-constrained world, ASHRAE will need to find a way through this dilemma.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

‘Sirapite for Sopranos’: Tempered construction and designing for musical tone

F. Smyth
Trinity College Dublin, Dublin, Ireland

ABSTRACT: London’s Royal Festival Hall opened its doors on 3 May 1951. The first concert hall to be built in Britain after World War Two, it was not just an iconic piece of architecture but would also become an archetype in design for musical tone. Its design fused architecture, music, and science, and its construction process was interspersed with a series of experiments that were implemented throughout 1950 and 1951 to allow for acoustic adaptation as the building was finalised. This paper examines the interdisciplinary collaborations that informed the process, and the differing forms of experience and expertise that formed a valid part of the hall’s construction. It highlights the manner in which the final stages of the construction process were tempered and revised (over the course of three months) to take account of these, and the contemporary social and cultural priorities which were brought to the fore as a result.

1 INTRODUCTION

> “Today in this country the number of public halls designed primarily for musical tone – halls in which music rules – are few.”

This appraisal appeared in print in 1950, in the January issue of the *Royal Institute of British Architects’ Journal* (Bagenal 1950). At the time, construction was underway on a new concert hall for London. What would become known as Royal Festival Hall was not just destined to become an iconic piece of architecture but would also become an archetype in design for musical tone. The procedure fused architecture, music, and science and was predicated upon a tempered construction process.

The approach to tempered construction at Royal Festival Hall took place in a series of experiments throughout 1950 and 1951. During this, the final stages of construction were implemented in phases and interspersed with data collection and tuning concerts to allow for acoustic adaptation as part of the process. Scientists, musicians, architects and the general public were all involved. Objective measurements were aligned with subjective observations. As the construction process progressed, the design of the hall was refined to incorporate their contributions and a new body of building-science data was amassed. As such, the outputs of the construction process were manifold.

As “Britain’s first post-war, non-austerity and non-essential building”, Festival Hall also represented a change in national priority that reflected societal and cultural needs. In the pre-war years, building science research in acoustics had formally concentrated on issues of noise exclusion and housing. However, with Festival Hall, the prominence of acoustics for music was cast firmly into the national spotlight, officially endorsed by government-sponsored research. It was the subject of scientific enquiry at the Building Research Station (BRS) and made manifest in the acoustic design of three post-war concert halls that year, albeit most publicly at Royal Festival Hall.

Colston Hall in Bristol and the Free Trade Hall in Manchester also benefited from a similar acoustic approach, with the final stages of construction completed in phases to allow for fine-tuning and test concerts. This paper focuses on Royal Festival Hall, as the archetype. It was the first and largest of the three. Ultimately Royal Festival Hall was not just an archetype in designing for musical tone, but also demonstrative of nascent international collaboration in acoustic testing and design which began on an informal footing in Copenhagen some two years previously with theoretical testing of the acoustic design of new concert halls by a group of international experts. (Arch. Corr. 1949a; DSIR 1949).

The significance of the architectural and acoustic history of Festival Hall have both been the subject of excellent scholarly work, notably by Barron, Bullock, Cox, Glendinning, Hawkes, and Shield. This paper contributes to that body of work through a discussion of the phased construction process of its auditorium, the interdisciplinary collaborations that informed that process, and the contemporary social and cultural priorities which were brought to the fore as a result. In this discussion, it examines how differing forms of experience and expertise formed a valid part of the Hall’s construction and it highlights the manner in which the final stages of the construction process were tempered and revised (over the course of three months) to take account of these.

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2 THE NEW CONCERT HALL

London's Royal Festival Hall on the South Bank of the Thames was formally opened with a gala concert on 3 May 1951, exactly 100 years to the day since Queen Victoria had opened the Great Exhibition at Crystal Palace (Mus. Cr. 1951b).

The Hall had been under construction since 1949 (Arch. Corr. 1949b). London had lost one of its premier venues for music – Queen's Hall – during the Blitz. Although the city had a number of other concert halls, none of them was deemed ideal for orchestral music. Emergency (and temporary) acoustic accommodations had been made to the Albert Hall during the war to permit the established series of Promenade concerts to continue (Smyth 2018). However, a dedicated concert hall was required, and suggestions were made that a new cultural centre be included in the plan for post-World War Two regeneration of the city. That idea was solidified in 1947, with the new cultural centre, incorporating a concert hall, intended to form a part of the centennial celebration of the 1851 Exhibition (Atkinson 2012; Banham 1976; Turner 2011). What would become known as "The Festival of Britain" was conceived of as a "tonic for the nation" and designed to celebrate national achievements in Science and Art. Ultimately Royal Festival Hall would embody both: in its conception and in the manner of its construction.

The overall process struck a very fine balance in coordinating functional design, scientific analysis, and nuance. This was demonstrable in the scope given to fine-tuning (which paralleled objective and subjective assessments) in the latter stages of construction, and in the manner of merging ideas, language and expertise at every stage from design through to construction and post-construction assessment. An intrinsic part of the process was defining an inter-disciplinary language that drew together the perspectives of musicians, as well as scientists and architects to encapsulate aspirations of subjective acoustic criteria.

Royal Festival Hall was a building that broke new ground in terms of interdisciplinary collaboration and its impact on what would become known as environmental design (then known as "efficiency of buildings").

The site on which Royal Festival Hall was constructed was a noisy one, located next to a busy overground railway – the Hungerford Bridge – and with an underground railway line running directly below. As such, designers of the new concert hall were presented with two acoustic challenges: designing against noise and designing for musical tone. The "egg in a box" solution, with the auditorium raised above ground and buffered by circulation space and foyers, and the nested structure of two separate concrete skins of the auditorium that was adopted to insulate the auditorium against external noise is well known and has been detailed in the literature.

Shaping the acoustics of the auditorium in terms of designing for musical tone, however, was a more complex and nuanced undertaking. It was also a very public undertaking, and it incorporated the expertise of those who would ultimately use the hall, as listeners and as performers.

3 DESIGNING FOR MUSICAL TONE

Designing for musical tone was a concept first mooted by the acoustician Hope Bagenal in the 1920s. The basic principle was that a building should be regarded as an instrument that would shape the nature of the sound within. Volume and geometry were of course fundamental, but exploring materials that responded to different frequencies – and building up a body of data as to how materials functioned acoustically – was also a core concern (Smyth 2015). Sirapite, it was noted from the early experiments, was good for reinforcing sopranos (Sirapite was a form of plaster slaked with petroleum, with a very hard finish that reflected high frequencies).

Prior to Royal Festival Hall, the ideas on musical tone – and using materials to achieve balance in musical tone – that Bagenal propounded were largely explored in private commissions. National research in acoustics and building science in the first half of the 20th century was, for the most part, concerned with construction techniques for improved sound insulation (Smyth 2014). Post-World War Two, with a national focus on the regeneration of spirit as well as the regeneration of cities, came the opportunity to put the theory into practice in a large-scale, flagship building dedicated to musical tone, in a process that brought cultural priorities to the fore. After decades of acoustic research in Britain that had been dedicated to housing and noise exclusion, the social and cultural priority given to musical tone in the context of wartime regeneration marked a definite shift in perspective and the integration of a range of voices and opinions.

Both designing for musical tone, and assessing its effectiveness as construction progressed, required design criteria; design criteria that bridged disciplines, and expertise. Effective design criteria also needed to bridge numbers and experience, and to align the objective with the subjective. It required a specific language. This was an important starting point. As noted by those involved directly in the acoustic design, "… musical criteria themselves are still difficult to establish, largely because musical views have seldom been linked to scientific studies" (Allen & Parkin 1951). Precedent work incorporating the perspectives of architects, musicians, and scientists as well as construction interspersed with testing and adaptation began to link these.

Phased construction to allow for acoustic fine-tuning was proposed from the outset by the Building Research Station (BRS) who, led by William Allen and Peter Parkin in conjunction with the acoustic consultant Hope Bagenal, were responsible for both acoustic testing and acoustic design (DSIR 1949). To provide data for this tuning process, preliminary work linking objective data with critical subjective opinions began in 1947, a year before design work commenced, when a plan of "operational research" was put into play by the BRS (DSIR 1948). Ten concert halls were acoustically measured with equipment calibrated by the National Physical Laboratory. In conjunction with this, the opinions of "listeners" – defined as music critics, composers, and professors of music – on these halls were solicited by questionnaire. The results of the survey were statistically analyzed and the halls were ranked by preference, tabulated against volume and the measured reverberation time (the sole objective acoustic criterion then available) (Parkin et al. 1951). At this juncture, attention was focused on the identification of what constituted "good" in halls for music and the extrapolation of numbers to move towards a corresponding objective definition.

Design work began in August 1948. The architects for Royal Festival Hall were drawn from the London County Council design department, headed by Robert Matthew. The deputy architect was Leslie Martin with Edwin Williams as Senior Architect in charge and Peter Moro as associated architect.

In early 1949, the sketch design was taken by acousticians to Copenhagen for review at an international congress on acoustics. The International Commission on Acoustics with its triennial congresses had not yet been formed, it would be instigated in 1951, the same year that Royal Festival Hall opened, with many of the same acousticians involved. However, an informal working group with representatives from France, Denmark, Holland and Britain had been established (DSIR 1949). The group's aim was to standardise methods of measurement in acoustics, a crucial component of the tuning and phased construction process that would be implemented at Royal Festival Hall. International collaboration on acoustics, although it had existed within personal networks for decades, was just beginning to be formalised.

The foundation stone for Festival Hall was laid by the Prime Minister, Clement Atlee, in October 1949 (Arch. Corr. 1949b). Phased acoustic testing and adaptation to the auditorium began 10 months later, in August 1950. Discussions on tone – in its many varieties from singing tone, through to warm tone, and full tone – and what the terminology meant to musicians, architects and scientists continued, as the design work picked up pace.

A meeting of the Acoustics Group of the Physical Society invited musicians and music critics as well as architects to participate and share their perspectives. Presentations were made to the Royal Institute of British Architects with musicians and scientists invited to participate in the ensuing discussions. At every stage, the opinions of those who would play and conduct within the hall and those who would attend concerts, was solicited. Identification of differing definitions to terms like "singing tone" and "resonance" added clarity to the discussions.

Royal Festival Hall was to be built of reinforced concrete. In following the principles of "building as instrument" careful consideration of the absorptive and reflective qualities of internal surface materials was required. To mitigate the effect of the concrete on the acoustics, timber panels were proposed, offset from the wall with a degree of absorbent in the air gap. Data was required to analyze the effect of the panels, and a series of tests were instigated utilising an "irregularly shaped" and highly reverberant room in London County Council repurposed as a laboratory (Parkin & Purkis 1951; Smyth 2019).

One of the outcomes extrapolated from the "operational research" surveys of auditoria was a sense of how contemporary tastes would prefer music to be sustained (expressed in terms of reverberation time) at different frequencies. This was mapped as a time-frequency curve. For Royal Festival Hall, this began as a flattish curve that rose upward slightly at one end. It was described as "… relatively short bass reverberation and longer 'tops' …" (Bagenal 1951). Tops referred to reinforcement of the soprano, similar to the theories on using sirapite which had emerged from the experiments in the 1920s (Bagenal 1928). An idealised curve – based on calculations and not in situ measurement – was already in existence (Bagenal & Wood 1931). The in situ measurements flattened that curve further. It would be adjusted once again, to reduce low frequency absorption and accommodate a longer bass. (Bagenal 1951).

4 ADAPTING FOR MUSICAL TONE

The changing acoustics of the hall were charted and adapted on eight separate occasions between August 1950 and May 1951; as the scaffolding was removed, floors were laid, and insulation added. Objective data – in the form of reverberation time and sound intensity – were gathered electronically on each occasion using Western Electric type 640 AA condenser microphones at four specified positions throughout the hall. In the first four tests, the reverberation time dropped (from a relatively substantial figure at mid-frequencies) with each phase, and then rose (Parkin et al. 1953a, 1953b).

Data existed for certain materials, notably the insulants which were used: rock wool and Copenhagen absorbent as well as the ceiling plaster (vermiculite) and the timber panels which had been tested in the improvised laboratory at London County Hall. By a process of extrapolation, measurements of the overall auditorium at each stage yielded approximate absorption coefficients for all other internal elements that were either introduced or removed, augmenting the body of existing materials data, and confirming the measured data for the timber panels (Parkin et al. 1953a, 1953b).

Subjective assessment was introduced midway through the testing and adjustment process in parallel with the ongoing objective data collection. Tuning concerts – intended to assess the performance of the auditorium rather than the performance of musicians – began on 14 February 1951.

The first concert featured a performance of Beethoven's *Coriolan Overture* (Journ 1951a). The overture was performed three times, by an orchestra of 80 musicians drawn from the Guildhall School of Music. To measure the reverberation time, the music was punctuated by a counterpoint of shots fired from a Colt revolver. On 30 occasions throughout the evening, the orchestra played a loud staccato C Major chord followed by utter silence.

The intent was to identify any continuing defects such as echo, and also to gauge the hall's acoustics in terms of musical requirements which were not yet scientifically quantifiable. Noise infiltration was measured "during pauses in quiet passages of music". The majority of those surveyed were categorized as "ordinary concert goers" (of whom there were 260). Six smaller groups, each composed of two to three listeners with training in acoustics, were also surveyed. These groups were strategically positioned at changing locations throughout the hall, to give their preferences as to the overall acoustic, its variation by location, fullness of tone and definition, and how to optimise balance in the latter two.

A further group of listeners described as the "normal audience" filled the auditorium to capacity so that concert conditions – and the absorption provided by an audience – were accurately represented. In the combination of surveyed data and the measured data, localised acoustic defects were identified towards the rear of the Grand Tier. Absorption was assessed – to both horizontal and vertical surfaces surrounding the area (Parkin et al. 1953a, 1953b). Wood-wool margins and the wood-wool absorbent to the ceiling to that area (an absorbent gangway) was plastered over before the next tuning concert, and the rock-wool insulation behind the timber panels was removed.

Music critics were involved in the second test, instigated one month later on 14 March 1951. Described in contemporary newspapers as "a further and more extensive test of the acoustics" (Journalist 1951b). Beethoven's *Coriolan Overture* was repeated, this time played by the London Symphony Orchestra, conducted by Basil Cameron. For this test, the intricate piano solos from Debussy's *La Mer* were integrated into the musical repertoire. By this stage a false floor and overall ceiling had been added, and the fit-out included one-third of the upholstered seats. Attention was focused on the musical requirements of definition and fullness of tone. Definition was decidedly present with respect to the piano solos, opinion was divided on whether or not tone was sufficiently "full".

Consideration was given to how best to accommodate fuller tone by reducing absorption, in a manner that would not introduce echo. To assess the success of these measures, a further tuning concert followed, on 15 April 1951. Architectural critics joined the music critics at the third concert. Little change was noted in the objective reverberation time measurements, but critical opinions noted an improvement in fullness of tone as wall absorbents were removed and the fit-out continued with carpets and the remainder of the upholstered seats.

5 CONCLUSIONS

Tone was fundamental to Royal Festival Hall and to its legacy. Defining tone, designing for tone, and the processes involved in adapting the construction to shape tone, involved the recognition of expertise beyond the design team. Embodying that expertise in the building as it took shape validated that input as a crucial component of the design and construction.

The significance of integrating that interdisciplinary expertise is summed up best perhaps, in a subsequent article in the scientific journal *Nature w*hich described the major contribution of science to Royal Festival Hall as "an attempt to assess and define the musical requirements" (Parkin 1951). Although made manifest in the design and construction of the building, it was not a visible component of the final product. Yet, designing for musical tone, and the work towards defining the intangible and previously unmeasurable – that continued as the building was under construction – made tremendous inroads in what we now term environmental design. The process broke new ground. Royal Festival Hall itself is an iconic building, of striking composition with clean modernist lines. Yet its environmental design moved beyond that framework. It moved beyond contemporaneous strictures of rational science and measurement to create an environment that transcended discrete disciplinary specialisms and took shape via tempered construction.

In the September following the official opening of Royal Festival Hall, the building was temporarily given over to another purpose. On the 20th September that year, it hosted Division Three of the 1951 Building Research Congress: the first international congress to address "the problem of building as a whole" and not just building in its constituent parts (DSIR 1952). It was a fitting coda to a process that had integrated so many forms of expertise. Division Three focused largely on environmental design, defined then as "efficiency in use". Naturally, the congress featured a substantial panel on acoustics, with the acoustics of auditoria taking prominence.

At that congress, acousticians from Denmark, France, Germany, the USA, who had been involved with varying degrees of formality as the acoustic environment of Royal Festival Hall took shape, had the opportunity to gather formally and review the effectiveness of the process and its final output. 1951 was a pivotal year for the acoustics of buildings as international collaborations were formalised, and the results of precedent collaborations could be experienced in a landmark concert hall (Smyth forthcoming). Underpinning this was the recognition that, "the determination of what are good and bad acoustics is an artistic, and not a scientific decision, and all that science can do is analyse the requirements and provide means of meeting them. But that in itself represents a substitution of knowledge for chance" (Spec. Corr. 1951). It involved the alignment of numbers with experience and integrating forms of knowledge that extended from the quotidian to the specialised.

Ultimately, the processes which were implemented and collaborations which accompanied them would lead to further discussions on the utility of objective parameters in acoustics, and on how these tools might be standardised and expanded: how new parameters might evolve from combinations of data types, and how experience might be quantified. The results of the trajectory of development that followed were made manifest in the design of concert halls throughout the 20th century, and are expressed in the current ISO standards for acoustics.

In the afore-mentioned article in *Nature,* authored by one of the acousticians involved in the design of the hall, it is telling that despite the challenges of the noisy location of the site at the Hungerford Bridge, the achievement in respect of sound insulation was described as the *second* contribution. Musical requirements remained the primary one.

It is generally accepted that at Royal Festival Hall, brilliance of tone was achieved, if not the fullness of tone that had been hoped for. Its acoustic design was not perfect. It was an experiment, and a work in progress. It integrated numbers and experience into the construction process and it opened a dialogue.

"*We have given you a building which brings into aural consciousness not only all the parts of an orchestral score (presumably intended to be heard) but also all the parts of a musical note – transients, fundamental, harmonics*" (Bagenal 1951).

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The 1968 Integrated Facade System by Josef Gartner

R.S. Grom & A.W. Putz
Technische Universität München, Munich, Germany

ABSTRACT: In 1968, the company Josef Gartner & Co. was granted the patent for an “external building wall with water-filled hollow steel columns”. This patent defines the principle behind the Integrated Facade System, which conflates the supporting structure, building envelope and building services. Hollow steel columns are connected to the water heating and cooling system. For the first time, the new system was presented as a prototype pavilion at the “BAU 68” international trade fair in Munich. Translocated to Gundelfingen soon after, it has since survived as a gatehouse to the factory premises. The Integrated Facade System has since been applied to numerous objects, not least icons of late 20th century architecture. However, the integration of building services and the building envelope, once a mark of technological achievement, poses serious challenges for maintenance and repair.

1 INTRODUCTION

The Integrated Facade concept is based on a simple idea. The facade combines two functions, protecting and demarcating the interior from external environmental conditions as a passive layer and actively regulating and controlling the internal climatic conditions (Jensen & Jacobs 1980). In uniting the supporting structure, building envelope and building services in one component, this thus dissolves the boundary between architecture and building technology. By breaking the separation between structure and function, the Integrated Facade created something completely new.

The department store La Rinascente in Milan, built from 1957 to 1962, stands out as an example of this idea. As lately studied by Giulia Marino, the building displays a still early form of air conditioning. Warm and cold air ducts run in the outer walls in a so-called “dual-duct system”, which tempers the open sales floors. Warm and cold air flows are separated before meeting in a mixing chamber where the temperature and pressure are regulated before being blown onto the sales floors. The cross sections of the ventilation ducts are a disadvantage in their size but these can be perceived in terms of the facade design within the department’s steel super structure that is clad with reddish and greyish stone slabs (Marino 2016).

In turn, the water filling of structural elements was primarily aimed at ensuring structural stability in case of fire. This idea can be traced back to the 19th century. Responding to the great fire in Chicago in 1871, a US patent from 1884 describes a solution for a multistoried structure in cast-metal columns. The columns were to serve as a water reservoir. The head and base of each column were connected together via a pipe on each floor for the initial water filling. The head of a column was perforated but sealed with a heat-dependent substance, to prevent the water from evaporation under normal circumstances. In case of fire, the sealing would melt to allow the boiling water and steam to eject and cool the outside of the column (Wright 1884). From the mid-1960s onwards, buildings with water-filled load-bearing structures were constructed in the United States, and also in Europe a few years later (Jensen & Jacobs 1980, 14). The load-bearing steel structure would be connected to an internal water circulation system through a ring line, which starts running in case of fire, dissipating the heat occurring and preventing the building from collapsing (Fisher 1970). Such water cooling was applied to vertical columns, diagonal elements and also horizontal floor beams. As the direction of water flow can only be forced by interconnection with vertical elements or support pumps, the last was structurally problematic. Of course, all the components had to be welded together to turn the entire skeleton into a network (Hart et al. 1991).

To provide an example, an eight-story building for the State Institute for Occupational Health and Safety in Karlsruhe, Germany, planned by the building authority itself, was designed with a load-bearing facade made out of water-cooled steel columns in the late 1970s. This made a finely structured facade with a slim column section feasible without any conventional fire-retardant coating. The delicate structure was not just an architectural expression on the outside, the exoskeleton structure also provided modular flexibility for the interior office space. In addition, the cooling water in the columns had beneficial effects on the climate but these were only considered in terms of the thermal expansion of the steel as material. In all buildings of this type, the load-bearing structure and, in a broader sense, the technology is placed on the outside of the facade ([s.n.] 1979a).

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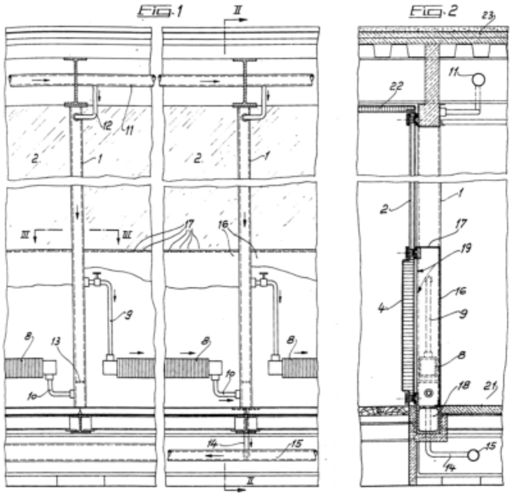

Figure 1. Patent drawing Nr. 1 784 864 of the operating principle of the pavilion prototype: Fig. 1 elevation detail from inside. Fig. 2: section detail of external wall. (Gartner 1968)

2 IDEA OF THE INTEGRATED FACADE

After 1945, the company Josef Gartner GmbH in Gundelfingen an der Donau, founded as a small metal workshop in 1868, developed into the leading expert for metal facade constructions in Germany. Until the post-war period, Gartner had mainly manufactured gates for industrial plants. Additionally, starting in 1946, the firm produced coupled windows in aluminium. The construction of the first aluminium facades followed a few years later and became the main field of activity in the post-war boom years. As a result of numerous other technological inventions, Gartner developed into an internationally renowned facade specialist.

The so-called Integrated Facade marked a structural breakthrough that secured Gartner's technological leadership after 1970. Authorship is attributed to Karl Gartner, who carried on the inventive spirit and craftsmanship of the company founder in the 3rd generation of the family. With the company's everyday operations run by his brother, among other things, Karl worked in the company's department for the construction of central heating and water supply systems. It is anecdotally reported that Karl's original considerations were aimed at meeting in creased building code fire protection requirements for metal-glass-facades, similar to the known examples mentioned above. Just as there is no fire risk from water-filled pipes, water-filled facade profiles should also allay concerns. Apparently, Karl's achievement consisted of recognizing the previously neglected possibilities of function and building technology of the American models and combining them into a new unit. The water-filled vertical load-bearing structure is no longer placed in front of the facade, which is problematic in terms of building physics, and was now integrated within the building and the facade (Jensen & Jacobs 1980). For this invention, the German Trademark and Patent Office granted, on September 28, 1968, Josef Gartner GmbH, a patent for an "external building wall with water-filled hollow steel columns" (Gartner 1968).

In the same year, the new construction was tested and shown in a 1:1 model at the international building trade fair in Munich.

3 THE PAVILION AT BAU 68

The GARTNER pavilion was built as a prototype for the BAU 68 international trade fair in Munich and served for the demonstration and information purposes of this new invention. Designed by local architect Helmut Haberbosch, the pavilion was constructed in a square grid structure of 3750 mm, the dimensions are 30.00 x 22.50 m with a total area of 675 sqm. In addition to three meeting rooms, a small kitchen and plant room, as well as an outdoor terrace, it provides for app. 280 sqm of exhibition space. The inner walls or partition walls were mobile to allow for new layouts. This new type of steel construction combined structure and heating, the building's external columns were designed as rectangular brackets with a cross-section of 60 x 120 mm and connected with the warm water heating system (Figure 4). The flat roof overhung the terraces on three sides of the building by 3.75 m. The surfaces of the wall elements and roof frieze were made of anodized aluminium sheets in various dark colors while the edge panels were steel sheet (Gartner 1968). The pavilion was almost entirely built from products manufactured by Gartner itself. The three entrances were equipped with fully glazed sliding doors with fixed side panels that could be opened via a contact mat on the floor. In front of the steel structure, 54 mm thick GARTNER panels were placed, wall elements in insulated honeycomb sandwich construction with aluminium sheets outside and insulated glazing elements with dimensions of 3720 x 2220 mm made from CUDO-glass, an early insulating glass dating from 1934 (Gartner 1964; DETAG 1969). A double floor system, the so-called GARTNER-ELECTROMA floor, in adjustable steel beams forming a grid of 1.25 x 1.25 m, provided flexibility for the layout and cable ducts (Gartner 1963). Rectangular inner columns structured the exhibition area and drained the flat roof. The roof itself and the terraces outside were sealed with GARTNER-EYTUL foil, a synthetic rubber for different kinds of sealings (Gartner 1965).

The pavilion was fully air-conditioned, with fresh air provided through air supply ducts within the floor. This fresh air was heated by radiators, that were attached between the heated steel structure. The exhaust air was then extracted through the ceiling. The pavilion facade offered many functions and benefits and represented an economical concept. The steel framework absorbed vertical loads and horizontal forces, while the outer supports also formed a heating surface. The warm water filling of the

Figure 2. Overall view of the pavilion prototype at the exhibition site in Munich in 1968. (Josef Gartner & Co. 1968, 2).

Figure 3. Left: big exhibition area inside the pavilion. Right: close-up facade-corner in 1968. (Josef Gartner & Co. 1968, 5).

supports provided internal corrosion prevention, and the constant circulation of the liquid also ensured fire prevention and structural stability. In case of fire, the heat occurring was to be dissipated. As coating with non-combustible materials became unnecessary, the elegance of the delicate steel construction was retained. The warm water-heated structure prevented the concentration of cold spots on the steel surface and the formation of condensation on the glass panes. Insulated glass surfaces and the wall features radiated less cold and ensured a comfortable environment, especially closer to the window surfaces (Gartner 1968).

Immediately after the trade fair, the prototype was rebuilt with some major changes in Gundelfingen. With a new additional basement to accommodate the building services, the pavilion received a stationary and prominent position. Ever since translocation, the pavilion has served as the entrance building to the Gartner plant. Since 1971, the pavilion included a porter's lodge, rooms for dispatching incoming goods, a telephone switchboard, meeting rooms and waiting rooms for visitors, as well as sanitary installations. The south entrance was no longer needed and therefore removed. Ceiling-high window casements have been integrated into the normally fixed glazing, mainly for natural ventilation. Additionally, an openable window in the porter's lodge makes it easier to communicate with arriving traffic (Figure 6).

It might appear the pavilion was designed directly for re-use as an entrance building because the original room layout fits so well in the current layout. We assume that there have been more slight changes over the years. The pavilion floor plan had to react

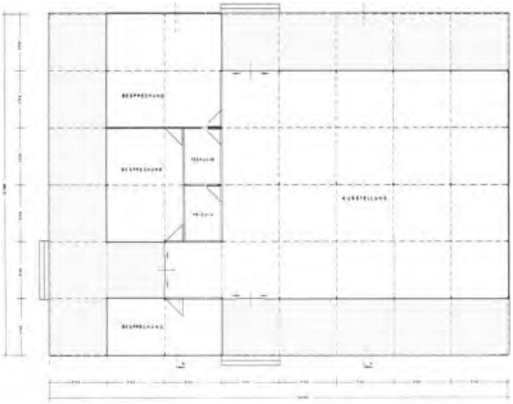

Figure 4. Layout of the pavilion prototype in 1968, north oriented. (Josef Gartner & Co. 1968, 3–4).

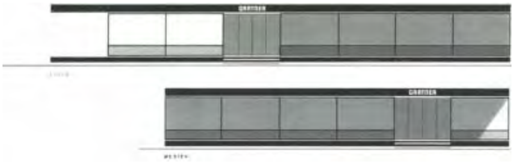

Figure 5. Top: south elevation. Bottom: west elevation of the pavilion prototype in 1968. (Josef Gartner & Co. 1968, 3–4).

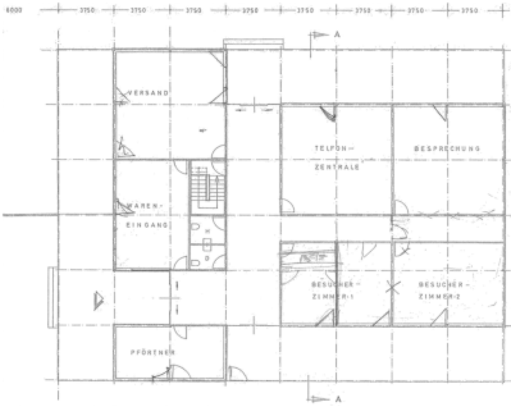

Figure 6. Layout of the pavilion after translocation in 1971, window openings drawn by hand, oriented to south. (Josef Gartner & Co. 1970).

to the changing and growing structures of the company. The company's manufacturing program reached its peak in the mid-1970s and, at the end of the 1980s, Gartner began to specialize in fewer products. There are two main visible interventions dating from 1971 and 2009. In 2016, the pavilion was extensively renovated (Cornette et al. 2018, 49), especially the interior equipment.

Since the previous renovation in 2009, the pavilion has contained a porter's lodge and visitor waiting area, as well as meeting and training rooms for apprentices. The whole entrance has been redesigned. In addition to the installation rooms in the basement, the number

Figure 7. Current situation of the pavilion on the Gartner Campus. (Photo: A. Putz).

of sanitary facilities on the ground floor increased alongside the equipment. The ceiling panelling in aluminium has been renewed in some rooms. The porter's area has been refurnished with steady workstations on a steel frame construction and shelves, in addition to the new walls and glass panes installed inside. All additional radiators from the original concept of heating and cooling were removed, probably already in 1971 (Josef Gartner GmbH 2009). However, the Integrated Facade is still working.

4 FUNCTIONAL PRINCIPLE

The operating and construction principle of the Integrated Facade is quite simple. The basic functions are heating and cooling. Heated water circulates in a closed circuit through hollow metal profiles and emits heat through thermal radiation from the profile surfaces into the room. In order to keep the loss of heat to a minimum, the water-filled profiles must be thermally isolated from the outer wall, glass surfaces must include insulating glazing with reflective layers and wall elements must also be insulated accordingly. The otherwise cold window and wall surfaces offer an almost homogeneous heating face. Compared to conventional radiators, there are no spots of cold and heat concentration. The temperature on the outer wall can be adjusted to the room temperature more evenly. In high-rise buildings, especially close to windows, there are often temperature differences due to the drop in cold air that make a workplace permanently unusable, which can be avoided in such heated rooms. The radiation through a heated wall or facade comes closest to natural solar radiation, and thus achieving a high level of thermal comfort. The Integrated Facade is classified as a low-temperature heating system. Due to the large heating surfaces the flow temperature is very low, which saves heating energy.

No structural changes are necessary for cooling. As before, water circulates through the hollow profiles and is now used for cooling. Inside, directly behind the glazing, the gain of heat is greatest. The heat of the sun is partly absorbed directly on the profiles' surfaces and transported away through the cooling water, while another part of the heat is extracted from the room air by convection or long-wave radiation exchange. As a result, a comfortable room temperature can also be guaranteed in the summer months. The facade can be controlled by temperature sensors inside and outside, whether as an entire component or in functionally dependent sections (Gartner 1994). The Integrated Facade is usually part of a non-load-bearing curtain wall but, in special cases such as low buildings, it can also be load-bearing. Metals like steel or aluminium can be used for the water-filled elements, the profiles are primarily determined by the static requirements, secondarily by the material itself and the required heating power. To guarantee the proper functioning of the system, internal corrosion of the water-filled components has to be avoided by using special liquids. Low-oxygen water in the closed heating water

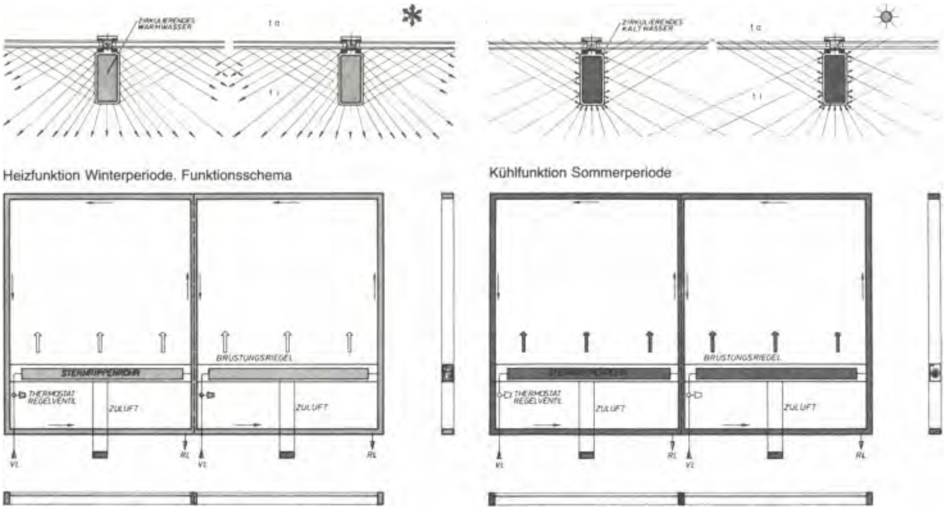

Figure 8. Operating principle of the Integrated Facade System. Left: heating function in the winter period. Right: cooling function in the summer period. (Gartner [1975]).

circuit prevents the internal corrosion of steel profiles; completely demineralized water prevents aluminium profiles corroding inside (Kocyigit 1993).

5 FURTHER DEVELOPMENTS

The first patent was followed by further patents worldwide. Gartner further developed combinations of heating, cooling and ventilation, also combining water and air systems. Soon, the Integrated Facade System also allowed for air-conducting mullions and transoms. Heated or cooled air will be blown out directly on the glass pane through the side blow-out nozzles in the facade mullions. Parapet or floor transoms are then designed as discharge ducts for the air supply. One early example for heated air conditioning is a seawater swimming bath in Borkum, Germany, completed in 1971 out of a cantilever steel construction with perforated mullions (Gartner 1971). A construction system with the combination of water and air is particularly suitable for swimming pools, because with a heated construction, the energy-consuming air exchange and the water evaporation can be reduced to low levels (Gartner 1975, 32-35). Another example is the Gartner design office on the factory premises in Gundelfingen, built by Hermann Blomeier in 1979. The building combines a steel structure and curtain wall with integrated heating, cooling and ventilation. The load-bearing building columns incorporate water circulation for fire protection, heating and cooling ([s.n.] 1979b). The combination of warm water-heated and air-conducting mullions and transoms created a variety of options. Each system was tailored to the specific project requirements and building usage (Gartner 1994). The Integrated Facade became incorporated into a wide variety of construction tasks, applied in residential and administrative buildings as well as in buildings for education, healthcare and sports. In the healthcare sector in particular, the lack of radiators benefits room cleaning and hygiene.

Inevitably, the targeted integration of several functions in one building component has a positive effect on the overall construction. The water filling is operational fire prevention, when functionality is ensured with a water reservoir. There is thus no need for structural fire prevention when the components are flushed with cooling water and the metal profiles can then be designed with slim cross-sectional sizes (Kocyigit 1993). However, there are limits to the height of a building when the heated facade is loadbearing. The support framework would have to be very large in dimension in order to guarantee the appropriate cooling capacity. In a fire test carried out successfully in 1970, water-cooled steel columns were exposed to a firing temperature of up to 1,000° C for 90 minutes. The steel column remained well below the maximum permissible temperature. The fire resistance period is practically unlimited in time whenever the cooling water remains constantly in motion (VDEh 1970). Overall, this multiple usage returns an enormous effect on the economic efficiency of facade construction.

6 CONCLUSION

The emphasis on building services increased in the second half of the 20th century as a design option and architectural trend with the rise of high-tech modern architecture. Technology became ornamental as exemplified by the Lloyd’s of London Building, a multi-storied office building by Richard Rogers from 1978 to 1986. The most prominent feature of the building, in addition to its technical shiny metallic architectural appearance, is the visible installation of supply lines, stairs and lifts on the outside. All facades of the high-rise were produced by Gartner (Cornette et al. 2018, 85-87). Among others, the company also realized the facades of architectural modern icons like the SAS Hotel, Copenhagen by Arne Jacobsen in 1960, the Connaught Center, Hong Kong by Palmer & Turner in 1983, the Bank of China Tower, Hong Kong by I. M. Pei in 1990, the Commerzbank Tower, Frankfurt am Main by Norman Foster in 1997 and, more recently, Apple Park, Cupertino in 2017, to list just a few examples.

Today, Gartner is a specialized provider of highly individual and technically demanding facade elements. Gartner is no longer a hidden champion from the Bavarian Swabian region but a renowned global player.

From 1968 onwards, numerous objects with Integrated Facades have been realized by Gartner around the world. The utilisation of Integrated Facade Systems, however, reached its peak in the 1970s and 1980s. Today, the system is only used occasionally for special projects as there have since been so many company-own technical innovations in facade construction that supersede the Integrated Facade (Cornette et al. 2018).

The range extends from complex three-dimensional frameworks and dome structures to simply heated winter gardens with flat steel-glass facades. Seemingly beyond the limits of feasibility, probably the most prominent recent building with an Integrated Facade system is the so-called BMW Welt in Munich, designed by Austrian architectural company Coop Himmelb(l)au in 2001. The most distinctive part of it is a double cone made of integrated steel facade parts that carry the entire load of the roof. Sprinkler lines, as well as smoke and heat extraction cables are also integrated into the welded steel construction (Lother 2007).

Knowledge of structural calculations, durability, building physics, heating and air conditioning are considered as “integrated” as are the investment costs, the maintenance costs and operating costs. Although the Integrated Facade System may guarantee low heating costs, the investment costs are very high. It is therefore not easy to answer whether the high investment costs are justified. Since the 1970s, in the times of the energy crisis, low-temperature heating systems such as heat pumps and the like have certainly gained in importance. There is a clear energy saving effect.

The quality of the cooling and heating water in the facade profiles should also be checked annually in order to ensure their proper functioning. For this purpose, a “lifelong facade maintenance contract” is offered by Gartner (Kocyigit 1993). No one else will be able to maintain the system directly without special knowledge, which means the customer's loyalty is unavoidable.

The extent and complexity of building technology has been increasing for decades and is often now getting out of hand. Usually, technical assembling is handed over to specialists independent of the completion of the structure and designed covering. The result of this labor division are buildings with increasingly complex technology and functional limitations. The complexity of these systems results in high error rates in planning and design and, above all, in overwhelmed clients as their users is forced into certain behaviors (Nagler et al. 2019). No information is available about the lifespan of the Integrated Facade but Gartner pointed out a few examples in 1996 that had been running without problems for at least a decade (Kocyigit 1993). And well maintained as any showcase, the pavilion system in Gundelfingen from 1968 still remains in use today.

The advantages of integrating different requirements in one technical system go hand in hand with disadvantages in subsequent servicing, maintenance and repair as there are many different dependencies. According to the current Energy Saving Ordinance, a replacement for heating systems is demanded in Germany no longer than 30 years after commissioning. However, modernization should be considered after 20 years (EnEV 2016). For the preservation of historic monuments and the structural conservation of the almost 50-year-old Integrated Facade, there are technical as well as legal and maintenance challenges. Principally, building services are repair-prone and usually the fastest to breaking down. They are usually the earliest building components of the late 20th century architecture to be replaced and lost.

However, the trend for integrating several technical functions in one component continues and not only in the area of facade constructions. In the thermal activation of structural elements, such as concrete walls or ceilings, building mass is used here for temperature regulation. Pipes, carrying water or air within building elements to warm or cool building interiors, are becoming inseparably connected to the raw structure.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The *aditus maximus* of the Roman Theatre in Málaga: An early model of Roman stonework vault

R. García-Baño, M. Salcedo-Galera, P. Natividad-Vivó & V. La Spina
Universidad Politécnica de Cartagena, Cartagena, Spain

ABSTRACT: The authors of this paper performed an architectural survey to approach the study of the south *aditus maximus* of the Roman Theatre in Málaga, which is covered by a sloping barrel vault topped by a round arch, all made with stonework. The analysis of the survey has generated valuable information to deepen knowledge of Roman stonework techniques, above all those related to stone stereotomy, which involve the resolution of geometric problems in space and their material execution. The authors have formulated hypotheses about the design and construction strategies used, such as the division into parts and their assembly, the number of courses, locking systems, the orientation of the bed joints, vault springers and their transition to the walls, or carving methods. The solutions used in this vault are compared to others used in Roman times, analysing possible knowledge transfers and establishing analogies in the construction resources used.

1 INTRODUCTION

Málaga's Roman theatre was discovered in June 1951 when some works were undertaken for the gardens in calle Alcazabilla, next to the building housing the Provincial Archives, Libraries and Museum of Málaga. This building, known as the Casa de la Cultura and designed by the architect Luis Moya Blanco, was a work under construction at the time. It was finally inaugurated in 1956 (Corrales Aguilar 2007). There were already indications of the existence of an important Roman building in the area as of the 18th century, and some late Roman remains had even been visible as of 1928 (Campos Rojas 1975). One of the entrance galleries to the *proscenium* stands out among the first findings from 1951 (Figure 1). Of particular interest is the gallery on the right facing the hemicycle, which still conserved the masonry arch of the inner opening, and beside it the remains of the barrel vault that extended to the exterior of the building (Gómez Moreno 1952).

At first, the remains were considered as a part of one of the gates of the wall of the Roman city of Málaga. However, some tiered steps made with similar ashlars were also discovered, so it was concluded that it was the remains of the southern *aditus maximus* of a theatre building and part of its *cavea*. The rest of the theatre had to lie partially under the foundations of the Casa de la Cultura.

The archaeological studies carried out dated the Roman theatre to the early 1st century AD, the time of Emperor Augustus when the city was called Malaca. During the Roman Empire, numerous public works were carried out. This theatre was built on the remains of previous republican constructions in the context of monumentalizing public spaces (Corrales Aguilar 2007). After its construction, the theatre was rebuilt several times but fell into disuse during the 3rd century AD. As a consequence of its abandonment, the area where the theatre was located was occupied by the salting industry, and by a necropolis as of the 5th century AD. Later, in the 16th century, the site was urbanized and became a residential neighbourhood.


Figure 1. Discovery of the *aditus maximus* of the Roman Theatre in Málaga in 1951. Archivo fotográfico UMA. Fotografía de prensa 1951. ES 29067.AHUMA AF08-07-01-1951-19510000_2221_0008L302 (photo: Arenas).

From a construction point of view, it is a mixed theatre. While it partially takes advantage of the hillside where the Alcazaba Moorish complex and the Gibralfaro fort would be later built, it also relies on artificial foundations. It is a medium-sized theatre which preserves a large part of the *cavea*; the *orchestra*, richly decorated with marble slabs; and the *scanea*. In the theatre, there is the noteworthy south *aditus maximus*, which is the main entrance gallery to the *orchestra* that

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Figure 2. View of the *aditus maximus* (photo: R. García).

allowed access to the *proedria*. It shows a significant difference in level between its extremes as it descends towards the *orchestra*. The *proedria* was the sector of the *cavea* reserved for priests, magistrates and other prestigious figures.

Today, the Roman Theatre constitutes a fundamental landmark in the city's architectural heritage (Noguera Giménez & Navalón Martínez 2015). After the first findings in 1951, consolidation and restoration works were carried out on the *cavea* in 1963, in the 1970s and 1980s, under the direction of Pons Sorolla, B. S. J. Isserlin and Gran Aymerich, respectively.

However, it was not until 1989 and the following years that excavations began in the courtyard of the Casa de la Cultura, which was eventually demolished in 1995. In 1999, excavation works were carried out to partially recover the theatre. The following year, Rafael Sánchez rebuilt the *cavea* and several more excavation, consolidation and restoration works took place on the complex up to 2009. Finally, an Interpretation Centre was added to the Theatre in 2010 to provide the starting point for visits to the monument.

The set of elements that make up the *aditus maximus* (Figure 2) has been studied from historical and archaeological points of view, but it has not been analysed from the specific aspects of stereotomy. These aspects are especially important given the scarcity of singular pieces of stone construction surviving from Roman times, which merited the study presented here.

2 METHODOLOGY

2.1 *Architectural survey*

The authors performed an architectural survey of the *aditus maximus* by using photogrammetry techniques. To do this, firstly a data capture consisted in taking 187 images. A digital reflex camera was used, ensuring a 60% minimum overlap between photographs. The images were processed into .jpeg files with sizes between 5,115 and 12,670 Kb. The photographs were then processed using Agisoft Metashape automated photogrammetry software. The workflow consisted of an initial phase of aligning the photos, detecting tie points and matching points and estimating camera locations. After that, a coloured dense point cloud was built from which we could generate a three-dimensional model made up of triangular faces called a mesh. Finally, the mesh texture was obtained by creating a bitmap image that gives colour to each face. As a result, we obtained a cloud formed by 14,488,969 points and a polygonal mesh of 965,931 faces (Figure 3).

Figure 3. Dense cloud of points (image: authors).

2.2 *Model processing*

The survey resulted in the point cloud and the polygonal mesh. The set was processed with CloudCompare software in order to obtain the most significant orthogonal projections. Plans, elevations, longitudinal sections and cross sections were obtained, including those made of planes perpendicular to the sloping axis of the vault. In addition, we obtained an orthophoto of each projection. Next, we worked on the three-dimensional model and the projections obtained using Rhinoceros in order to precisely determine the geometric characteristics of the set. This software simultaneously offers the functionalities of processing three-dimensional models and CAD assisted drawing (Figure 4).

3 DESCRIPTION OF THE SET

The set of stone constructions that make up the *aditus maximus* is formed by four constructive elements: a slightly skewed opening arch, a cylindrical intrados vault with sloping axis, a lintelled arch and the side walls on which the set is supported.

3.1 *The opening arch*

This is the element that makes up the façade of the set facing the *orchestra* and the *proedria*. It is formed by

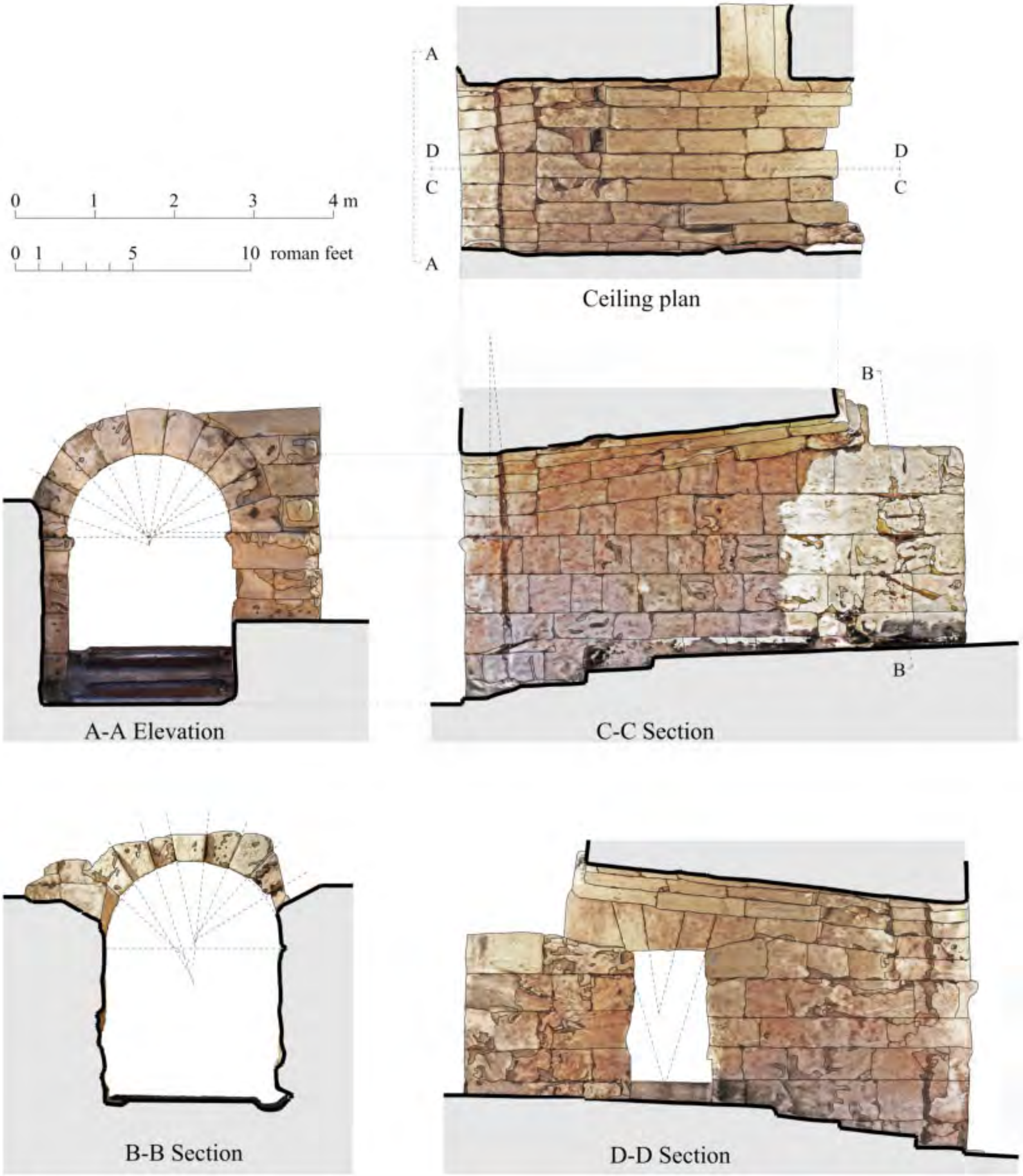

Figure 4. Plan, elevation and sections of the aditus maximus (image: authors).

a set of 11 voussoirs (the central keystone and five on each side), which present different sizes. Its springers are located at different levels and the height difference is equivalent to 3% of the arch span. The carving of the voussoirs is carried out by means of a set of radial planes. In elevation, these planes tend to converge at a point located in the centre of the arch at the level of the lower springer. A singular detail is that the bed joints of the springers are both horizontal despite the height difference.

In addition, the arch is slightly skewed, since its front and the longitudinal axis form an angle of 88.3°. Taking deformations and irregularities into consideration, its dimensions approximate 7 Roman feet span and 3 Roman feet deep. The voussoirs have different thicknesses, which means that in the head of the arch we do not see two concentric semicircles (Figure 5).

The set of the arch voussoirs presents three clearly differentiated sectors in its development. The first sector corresponds to the outside front. It is approximately half the length of the voussoirs, around $1^{1/2}$ Roman feet, and corresponds to an arch whose directrix approaches a semicircle. The intrados joints remain

Figure 5. View of the *aditus maximus* through the entrance arch to the orchestra (photo: R. García).

Figure 6. View of the sloping vault and its meeting with the opening arch (photo: R. García).

horizontal and its intrados surface tends towards a half cylinder.

The second sector includes the inner area that connects with the sloping vault. Its span is greater than the one of the initial sector, close to $7^{1/2}$ Roman feet. The intrados joints have a slight slope, which is intermediate between the horizontal and the slope of the vault. The directrix tends to be a semicircle concentric to that of the initial section, although the initial voussoirs on the right-hand side deviate slightly from the directrix approaching the vertical.

The inner limit of this sector is not determined by a single vertical plane, but rather each voussoir has a different alignment that connects with the adjacent one at the common joint. Some of the voussoirs even present irregular posterior faces formed by more than one plane adapting to the edge of the vault.

The third sector, located in the middle zone, is the one that connects the intrados surfaces of the two previous zones. It is an irregular carved surface without a clearly defined geometry that overcomes the span differences of the two directrix of the inner and outer sectors.

3.2 *The sloping vault*

After the opening arch, we find a vault with a cylindrical intrados surface, whose axis presents a slope of 10% ascending as it moves away from the orchestra. The vault is made up of eleven courses of voussoirs with different widths (Figure 6). Each course presents between four and seven voussoirs with different lengths. In most cases, the joints between adjacent courses are locked, although in a few cases the joints are aligned. The span of the vault is the same as that of the inner sector of the opening arch, that is, around $7^{1/2}$ Roman feet.

The bases of the first voussoirs of the vault present the same height difference of the arch springers. The bed joints of the courses of the vault tend to be radial. However, as in the opening arch, those corresponding to the left part deviate slightly from this orientation. Furthermore, these bed joint planes do not coincide with those of the opening arch. That is, there is no continuity of the joints between both elements, which causes a constructive interlock between arch and vault.

The seven upper courses of the vault (the keystone and three on each side) formally and constructively belong to the vault and present a tendency in their intrados joints to be parallel to the slope of the axis, despite the irregularities. On the contrary, the four lower courses (two on each side) are constructively part of the walls although they formally belong to the vault, as they define its starting point. These four courses have a notably higher dimension.

This situation corresponds geometrically to the surface of the intrados of the vault. The successive sections perpendicular to the sloping axis of the vault made on the 3D model show that the surface tends to approximate a barrel vault with a semi-circular directrix with slight deviations. These deviations may be caused by the construction process, by structural deformations, or by the effect of the restoration actions carried out, as well as those corresponding to the directions of the bed joints. In the seven upper courses the adjustment is greater. On the contrary, in the lower courses, those integrated in the walls, it deviates slightly from the arch adopting a more closed curve that makes the transition towards the vertical under the springers.

3.3 *The walls*

Under the opening arch, the courses of the walls extend to the ground level the molding that makes the transition between the inner and outer spans. The inner surface of the walls is currently very irregular with deterioration and stone mass loss. Puertas Tricas (1982) indicates that its average width is 2.25 m, a dimension very close to $7^{1/2}$ Roman feet. The supporting walls are formalized by between three and five horizontal courses up to the springers due to the height difference at the base. From this level, the next two courses are simultaneously part of the wall and the vault, with different situations on both sides.

Figure 7. View of the walls on the left side (photo: R. García).

On the left side, in the direction away from the *orchestra*, the wall attached to the *cavea* has the function of containing the ground. We can distinguish in it two sectors of length close to half that of the vault. In the initial sector, the first course of the wall has a horizontal lower bed joint. The upper bed joint presents a slope which is slightly greater than that of the vault. The next course presents both sloping bed joints, with an intermediate slope between that of the springer and that of the vault. In the final sector, the first course of the wall in the first sector has both horizontal beds. Consequently, in this sector the next course has the horizontal lower bed joint and the upper bed joint has a slope slightly higher than that of the vault (Figure 7).

On the right side, both faces of the wall are exposed and it has a significant thickness to counteract the thrusts of the vault. In its initial section, it presents the same arrangement as the left side: a first course with horizontal lower joint and sloping upper joint. In the final sector, there are special circumstances as it integrates the lintel arch. The slope of the upper bed joints of the first course is reversed to counteract the thrusts of the arch. Meanwhile, in the final sector after the lintel, the lower horizontal joint of the first course is at a higher level. This arrangement makes the difference in the starting levels of the vault even greater on both sides.

3.4 *The lintelled arch*

This is a singular element formed by five voussoirs arranged transversely to the axis of the vault that span the entire thickness of the wall in a single piece. Since the arch is simultaneously integrated into the vault and its supporting walls, the inner face of the voussoirs has the cylindrical shape of the vault while the upper face presents the slope of the vault. The two extreme voussoirs rest on the wall with slightly inclined bed joints to facilitate the transmission of the horizontal thrusts of the arch. For the same purpose, the three central voussoirs are divided by inclined joints towards the centre of the span, approximately, although their lines do not converge at one point. The voussoirs located beside the keystone are mounted slightly on the wall (the left-hand one in a greater length) to improve the support conditions. The vertical surface of the jambs has deteriorated so it does not present a clear vertical direction, but its span at the base of the lintel is close to 3 Roman feet.

Figure 8. View of the lintelled arch (photo: R. García).

This lintel structure was restored years after the discovery of the *aditus maximus*, so its originality has been questioned (Corrales Aguilar 2007). In our opinion, there are enough indications to suggest that the structure of the flat arch is original. Its jambs are defined in some of the photographs taken in 1951, the voussoirs fitting quite precisely with the adjoining voussoirs despite the numerous irregularities in their execution, with surfaces far from the theoretical joint planes. Furthermore, the intrados surfaces are integrated into the curvature of the vault, showing continuity with the pieces that were still standing at the time of the vault's discovery (Figure 8).

4 THE STEREOTOMY OF THE SET

The stone construction of sloping axis vaults, with a difference in level between their ends, poses geometric problems of some complexity. Taking into account that the opening arch corresponds to a vertical section of the inclined cylinder, if it is executed as a semi-circular arch, the intrados surface of the vault corresponds to a lowered semi-elliptical directrix. Conversely, if the intrados of the vault corresponds to a cylinder surface, the opening arch is a raised ellipse. In both cases, the design of the opening arch voussoirs is complicated by the shape of the arch itself and because all of voussoirs have different angles between the head and intrados surfaces.

However, the executors of the *aditus maximus* in Málaga planned a set that presented semi-circular directrix simultaneously on the head and the vault. To do this, they designed two different elements: the opening arch and the sloping vault, whose intrados surfaces approximate revolution cylinders. In this arrangement, the main geometric problem consisted in resolving the meeting point between the two cylinders whose axes formed a certain angle. If both cylinders had the same diameter, the intersection curve would be a raised ellipse located on the bisector plane of the orthogonal planes to the axes of both cylinders. With the dimensions and the slope of the vault, the length difference between the circle and the ellipse's major axis is 1.27% of the span, and the slope of the intersection curve is 2.85°. This does not have a significant impact in practice, taking into account the construction systems used. The constructive, structural and carving problems posed by the set were solved by adopting a series of design decisions (Figure 4). The most important decision was to completely separate the opening arch from the sloping vault. Once the problem of solving the intersection between cylinders is known, the arch is designed with whole voussoirs arranged in radial planes and limited by two vertical planes. The span of the arch at the head is smaller than that of the inner one, which helps to hide the complicated intersection from direct view. Thus, the carving process of each voussoir gives three different surfaces on their intrados. The outer one, which corresponds to a revolution cylinder with horizontal axis; the inner one, also cylindrical, which provides the connection with the vault; and an intermediate zone between the two. It is an indeterminate fitting surface with more or less inclined generatrix between both edges and irregular carving. This shows the difficulty the executors would have had conceiving and carving surfaces with complex geometry.

As we have commented before, the arch remains constructively independent from the vault. This is due firstly to its inner boundary surface, which is close to a vertical plane – despite its irregular carving; and secondly to the fact that the intrados joints of both the arch and the vault remain locked without continuity. We can hypothesize that this independence is due to several reasons. Given the difference between the axes' slope, resolving the arch and vault bed joints with the same fan of radial planes implies an important geometric complexity in tracing and carving the voussoirs. Therefore, using two different set of radial planes would have been easier. In addition, the different arrangement and span avoid the problem of precisely determining the intersection edge between cylinders and hide it, allowing a joint capable of assimilating irregularities and dimensional differences between the intersecting directrix curves.

Finally, there is a constructive reason, since the slope of the vault produces longitudinal horizontal thrusts that could move the arch voussoirs outwards. In this way, the lock between the joints of the intrados helps to avoid such displacements.

As for the vault, as indicated above, it is divided into two parts. The upper one, formed by the seven upper courses of voussoirs, is arranged according to a fan of planes that tend to be radial. The lower one is formed by the two lower courses on each side that are actually part of the supporting walls in which the inner face of each ashlar is carved with the curvature of the inner surface of the vault.

This special arrangement is also due to constructive considerations, according to our hypothesis. The lower courses of the vault are located in the area where the horizontal thrusts of the vault are greater. The fact that these courses are part of the wall significantly minimizes the effect of the thrusts. Furthermore, these courses are thicker than the vault and keep their outer face vertical, thus increasing the mass of stone that counteracts the thrust. This fact is particularly significant on the right side, which is free in its two faces as it is not attached to the ground. Its thickness reaches around half the span of the vault.

This hypothesis is reinforced by the arrangement of the bed joints in the first courses. The intention is to maintain the horizontal plane as much as possible within the lower courses of the vault, forcing the load transmission in a vertical direction. On the contrary, the upper beds of the courses that receive the vault present a slightly higher slope than that of the vault, attesting to the independence of elements.

In addition, this strategy would allow the construction of the vault without the need to place a complete formwork throughout the whole development of the cylinder. The lower part would be resolved without formwork, directly placing the courses of the walls that represent the springer of the vault. Formwork would be necessary only in the upper part, which corresponds to the surface of the seven central courses.

We must consider the design and the carving process of the voussoirs located in the flat arch in a similar way. This could have been resolved with several prismatic voussoirs arranged longitudinally and which would have extended across the whole span. In this way, the carving process would have been immediate; however, a continuous horizontal joint would be required at the critical thrust point, posing a risk of displacement of the lintel segments outwards. The executors of the set in fact proposed a solution involving five transverse voussoirs with sloping bed joints: three in the span area and two over the jambs, all of them integrated into the wall area. The arrangement adopted, in which all the voussoirs are different, is more complex. Thus, the resolution of the gap itself is more complex and the lower face of the voussoirs belongs to the cylindrical surface of the vault while their upper face displays the slope of the vault axis.

Regarding the carving of the voussoirs, it can be seen that there are no clearly defined edges in a few units, and intersections between adjacent faces are rounded. And this is without taking into account the existing deficiencies and mass losses due to the passage of time and the situation in which the monument has been preserved. We can also observe numerous irregularities both in the arrangement of the courses and in the alignment of the intrados joints. This is also true of the the way the bed joints between adjoining pieces are executed, in which we can often find irregular areas, recesses or projections that deviate from the theoretical plane of the joint affecting both segments. Despite all of this, the voussoirs display an acceptable adjustment. Nevertheless, the opening arch is the piece of the set where we can appreciate a greater care in the carving of the voussoir faces.

From the point of view of the carving, there are two types of voussoirs whose geometry poses problems: the voussoirs of the opening arch and the voussoirs of the sloping vault that come into contact with it. The assumption that they meet on a vertical plane allows us to establish a carving hypothesis. The voussoirs of the sloping vault are all carved like conventional voussoirs with their heads perpendicular to their axis. But those that intersect with the opening arch have an oblique slope in one of their heads: the one that faces the arch. The slope of this face with respect to its axis is difficult to obtain by means of graphic procedures.

Now, this could be solved with a carving process organized into two phases. Firstly, a conventional barrel vault voussoir could be carved. Then, the voussoir would be placed on the inclined formwork. The joint would be carved as a vertical surface and the work would be checked in situ with a plumb. Finally, the voussoir would be placed beside the vertical face of the voussoirs of the opening arch.

The voussoirs of the opening arch would also be carved in two phases. They would first be carved as conventional semi-circular arch voussoirs and placed in their specific location within the factory. Afterwards, the vault would be executed as a sloping vault applying the procedure described above. Once this was done, the intrados of the inner part of the voussoirs of the opening arch would be finished fitting the intrados of the sloping vault. To do this, the stone would be checked with a rule to see if it fits the intrados of the sloping vault. The transition part between arch and vault would emerge naturally in the carving process and would assume eventual irregularities in the execution process and the placement of the voussoirs. This two-phase carving system has already been suggested by several researchers over time (Choisy 1883: 59-60; Sakarovitch 1997: 111–113) and recent studies propose similar hypotheses for voussoirs of groin vaults and arches in round walls (Calvo López et al. 2020; Piccinin & Natividad Vivó 2020).

5 RELATIONSHIP WITH OTHER ROMAN MASONRY PIECES

Although stonecutting is not the usual vault construction system in Roman period, there are numerous unique pieces built in stone, some of which pose problems similar to those of the *aditus maximus* in Málaga. Zaragozá Catalán (2008) has revealed the existence of some stone sloping vaults from Roman times. This is the case of those built in the temple of the goddess Anahita in Bishapur in Iran, dating from the 3rd century AD; in the Odeon of Herod Attic of Athens in Greece, built in the 2nd century AD; or in the Odeon of the Amman theatre in Jordan, also from the 2nd century AD. The latter is especially significant due to its similarity to the vault built in Málaga.

It has a similar situation, since it gives access to the *orchestra*. It is also resolved with an opening arch with a smaller span than the vault with a lowered directrix. This would indicate a construction system similar to the hypothesis formulated above, in which the surface of the vault itself does not reach a complete half cylinder, being reduced in the upper part to integrate the lower courses in the walls. The intention was probably to facilitate the placement of the formwork and to improve the structural performance.

Something similar has been noticed in other stereotomic elements from Roman period; for example, in the hemispherical dome and in the barrel vaults of the Ummidia Quadratilla mausoleum (Piccinin & Natividad Vivó 2020: 36–38).

The similarities between the aforementioned pieces indicate the existence of a common body of knowledge about stone construction in the Roman period. The executors of these works addressed the need to solve geometric problems and tackled questions related to the conception, process and technique of stone construction with elementary methods, still a long way off stonecutting knowledge of the Modern Age.

6 CONCLUSIONS

The *aditus maximus* of the Roman Theatre in Málaga is a unique structure built at the beginning of the 1st century AD. It has a special interest because it contains vaulted pieces built in stone, a rarity in Roman construction.

The architectural survey and the analysis carried out by the authors make it possible to identify that the whole set is composed of four elements: a slightly skewed semi-circular opening arch, a sloping vault, a flat arch and the walls that support the set, whose upper courses match the intrados surface of the vault.

The main geometric problem is the intersection of two cylinders, one of which has an inclined axis. The execution is resolved with constructive criteria proposing two different pieces, arch and vault, which are attached to both sides of the intersection curve. The number of courses varies between the two, creating locked joints in both directions – longitudinal and transversal – with a final carving process in situ.

Additionally, the executors decided to merge the upper courses of the wall and the voussoirs of the flat arch with those of the vault. This, together with the design of the orientation of the joints, contributes to reducing the effects of horizontal thrusts and facilitates the construction of the vault by reducing the need for formwork in the upper part of the vault.

We must highlight the existence of other examples of Roman pieces built in stone in remote areas which address similar problems and where similar solutions are adopted. This suggests the existence of a body of common knowledge in the field of stonecutting with a basic level of stereotomy that nevertheless made it possible to address the design, carving and execution process of the voussoirs.

ACKNOWLEDGEMENTS

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Experimental analysis to define the stability conditions of the temple of Vesta in *Forum Romanum*

F. De Cesaris & A. Gallo
Sapienza – Università di Roma, Rome, Italy

ABSTRACT: The round temple of Vesta - located in the Roman Forum and connected to the House of the Vestals on the Via Sacra – was the site of religious practices predating the founding of the city. The temple was reassembled by the Fascist regime in 1936 as background for the Via dell'Impero. This reconstruction was made by anastylosis with significant additions. The few original marble elements were composed with travertine pieces to partially restore the ancient image recovered from coins and descriptions. Investigating the building's structural condition verified the reconstruction methods for the N-W sector. Here, two rows of three columns are arranged in concentric circles in a system of pendular elements, which is made asymmetrical by the presence of partition walls between the inner columns. The reduced-scale model - commensurate with the prevailing building conditions - highlighted the behaviour of collapse and the possibilities for improvement.

1 HISTORICAL OUTLINE

The restoration of the Temple of Vesta was based on recompositing the ancient building remains by anastylosis. Today, this operation appears questionable due to the low percentage of original elements and the partiality of the reconstruction compared to the entire monument. However, this intervention brought about the creation of an easily recognizable visual and ideal identity-node in the Forum central area crossed by the Via Sacra. The cult of Vesta – dedicated to the conservation of the sacred fire – was, in fact, an essential aspect of the most ancient history of the city, linked to the myth of the founders.

The original temple, probably already rebuilt several times in the classical period, was closely connected to the House of the Vestals overlooking the Via Sacra. This was inspired by the tholos typology that constituted an impenetrable envelope in which fire burned perpetually, guarded by the Vestals. From the outset, the architectural form is not configured as a *templum* but as a *sacrarium* as evidenced by its original name "Aedes Vestae" (sacred residence of Vesta). In the 1st century configuration, after one of the most important reconstructions, the cell was formed by columns inserted in the inner circular wall and surrounded by the colonnaded perimeter covered with a lithic ceiling.

The classical profile was recovered both from ancient coins and descriptions that allowed for recompositing the building components found during the extraordinary excavation campaign supported by the fascist government.

This campaign belongs to an exceptional period in the history of archaeology and restoration that transformed the faces of a neighbourhood and the modern city; this was a vast operation that led to the demolition of an entire Renaissance sector to bring to light what remained of the ancient monuments and obtain the current layout of the archaeological area of the Roman Forum.

Figure 1. Two imperial coins of Tiberius (14–37) and Titus (79–81) preserved in Oxford's Ashmolean Museum (RIC I, 99, 74 and RIC II 34 n.162) (a); Bas-relief from Lateran, ascribable to the temple of Vesta, currently preserved in the Florence Uffizi Gallery coming from Villa Medici (b).

It was a process in which the political objective, aimed at opening the Via dell'Impero and the scenographic preparation of the Forum area, was

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Figure 2. Site plan showing the temple with the remains of the foundations, the erratic pieces and the reconstructed sector formed of three columns. The original building must have been of 22 columns per row.

tightly interwoven with archaeological purposes. Great archaeologists such as Giacomo Boni, Corrado Ricci and Alfonso Bartoli himself, who was to support the reconstruction project of the Temple of Vesta through to its completion, all contributed.

The reconstruction of a portion of the temple was debated. The choices underlying the current relocation of erratic parts on the remains of the classical foundations also stemmed from the environmental context contrary to the first positioning proposed only according to the archaeological study. In a photograph taken by architect Torquato Ciacchi, Bartoli's collaborator, the prototype appears to display a different placement to that of the actual reconstruction. In fact, in the background, we may depict the Palatine structures which are currently on the southern side. Despite the different position, the real reconstruction maintains the same components of the prototype, with double rows of three columns, the wall partition between the inner intercolumns and the ceiling on the trabeation, with the dark colouring of the additions highlighting the original parts. The re-composition was completed in 1936 after a phase of proposals, rethinking and modelling. Nowadays, the intervention represents a classic example of partial reconstruction through anastylosis with significant additions.

Political needs presumably favoured a reconstruction made with a few marble elements and many travertine blocks and bricks. The execution was entrusted in two phases to the firm of engineer G. Cozzo; technical control, which was not attributed to the archaeologist Bartoli, was first based on the contributions of the architects G. B. Milani and T. Ciacchi and, in the execution phase, the engineer L. Crema, but especially on the advice of Gustavo Giovannoni.

The base was completely rebuilt with massive new masonry, lined with travertine slabs in which the fragments of the original covering materials are set.

Figure 3. Photographic documentation (1929). Analysing the background, we can presume that the gypsum model is rotated compared to the current placing of the elements.

The reconstruction was justified by the need to reposition the columns in an elevated position. This allows for a correct perception of the monument and the site's scenography, recalling the high podium in the tradition of Roman sacred building.

The columns are largely original but integrated with cabled shaft sections which, according to some scholars, re-proposes the lathwork of the archaic hut and symbolizes the idea of closure and protection. The two trabeation sections and the ceiling were also obtained by assembling the original marble portions with local travertine additions well-distinguishable from the originals, which were probably imported from eastern quarries.

The integrative portions were obtained by replicating in travertine the model made with gypsum during a preparatory phase. In fact, gypsum makes it possible to quickly obtain shapes that blend perfectly with the original stones but does not guarantee resistance and durability due to its typical hydrophilic behaviour.

Once the prototype was finished, the elements to be reproduced in stone were obtained from those in gypsum. In order to connect the different elements mortars and metal pins were chosen. During assembling, bronze connectors fixed with lead casting were certainly used while small concrete reinforcements with smooth steel bars could not be avoided.

Reinforced concrete inserts were applied to put together the trabeation where new portions joined the historical remains that would otherwise have been unable to sustain themselves.

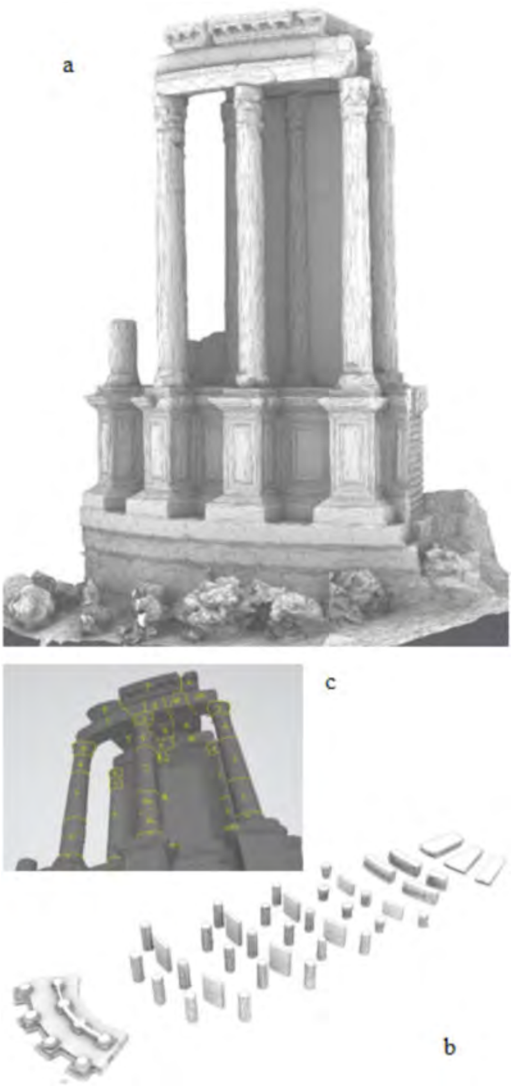

Figure 4. Perspective view of the laser scanner 3D model (a). The physical model was obtained by printing all the pieces separately (b), according to coded numbering, as shown in the study scheme (c).

Mostly, it emerged that these concrete works were widely used to recompose the lithic ceiling coffers by modelling them by moulding the ancient pieces.

We assume there are pins between pieces even in the columns, where they are inhomogeneous but are able to exclude the insertion of continuous metal cores. The wall partitions between columns are composed of slabs in which there are metal blocks at the edges, connecting them to the columns and the upper plates.

Tests conducted with electromagnetic instruments (georadar) have confirmed the use of connectors, which had already emerged from analysis of archival documents. However, the shapes and sizes remain undefined.

The binders present good consistency and toughness, both in the small additions and in the castings that give continuity to the elements. In the ceiling, you can see the connections obtained with small beams carved into the stone and cast with a concrete conglomerate, with small aggregates, which protects and connects the reinforcements. The connection of the architraves was obtained with similar reinforced castings put in fluting dug into the extrados of the old and new stone elements so they do not appear on the intrados. An understandable choice to preserve the image and to reunite the architraves with the ceiling, but apparently less effective than the similar and more common intrados reinforcements.

Although more than eighty years have passed since the building's completion, no significant signs of deterioration appear, neither to the mortars and conglomerates nor to the metal elements.

2 AIM OF THE EXPERIMENTATION

During the last few months, a monument maintenance cycle has been activated by the Parco Archeologico del Colosseo. No structural interventions are proposed and only conservation actions on the surfaces are planned as no symptoms of structural decay have been detected. However, we simultaneously gained the chance to verify – with instrumental investigations - the execution construction methods, the structural stability of the building and the potential of theoretical solutions for increasing its capacity.

Non-invasive investigations were carried out aimed at determining the state of conservation, identifying the presence of hidden connections and their state of conservation. Furthermore, the structure's behaviour was determined by means of accelerometers able to capture the effects of environmental micro-tremors.

Indeed, the structure - greatly reduced compared to the original intact building - appears as a pendular system consisting of two series of almost aligned columns and an important mass on top that connects them; the wall podium is instead solid and rigid, perfectly stable, so much that it can be considered equivalent to rigid ground.

As previously mentioned, it is a sector that represents about one seventh of the entire peristyle, consisting of two rows of three columns arranged radially on two concentric rows. The entire columns (3 out of 22 of the entire perimeter), made of original marble portions and reinstatement pieces, constitute the system of pendular elements that is symmetrical in the radial direction, but strongly asymmetrical in the frontal direction tangent.

The partition wall in travertine blocks, occupying the spaces between the inner columns, makes the internal colonnade more stable in the tangential direction; at the same time, however, this modifies the behaviour of the inner row of columns compared to the external row. In fact, it strongly differentiates the structural response of the two main axes by strengthening the

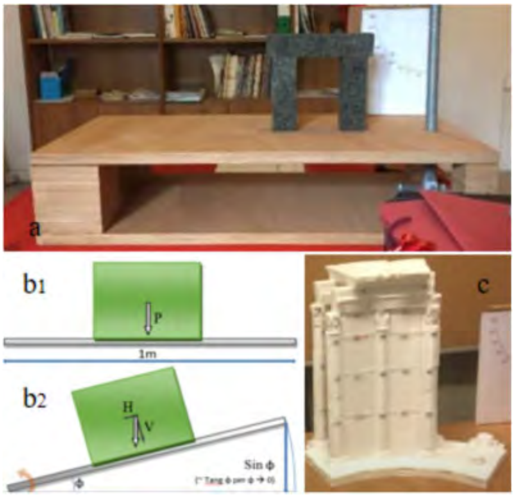

Figure 5. The inclinable table in horizontal position with a model placed on (a). Increases in inclination are obtained by screwing a bolt onto the vertical threaded bar on the right side of the table. (b). The 3D model used during the tests (c).

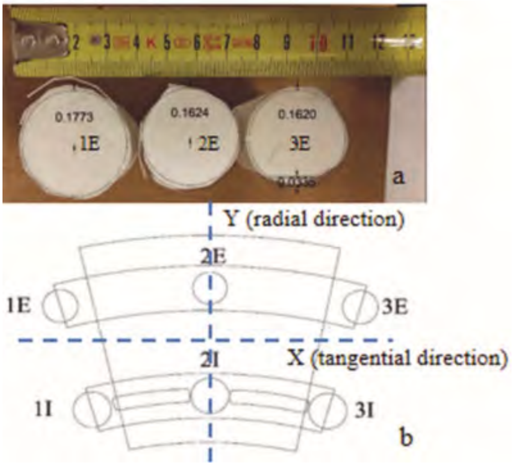

Figure 6. The column bases with their dimensions in the model representation scale (1:14.5) and the chipping of column 1E (a). The planimetric diagram with the elements coded (b).

in-plane behaviour of the internal columns compared to the others.

On the other hand, the structural response in the radial direction is not particularly enhanced by the walls, which are very thin compared to the columns.

The sustain system of the columns is linked at the top by curved trabeation sections and by the recomposed lithic coffered ceiling which is laid - sometimes in an apparently 'adventurous way' - on the capitals. Actually, the supports are constrained by means of special anchoring devices that are only visible close-up from scaffolding.

The original portions of the columns show flaking and deterioration due to aging and previous damage. Defects in the lithic material appear relevant, especially when corresponding to the nodes expected to contain hinge formations. In these cases, any lacking can strongly influence the kinematic behaviours of the entire system.

The first analysis identifies the structure's seismic vulnerability while remaining, however, almost intact despite the earthquakes occurring in Rome over the last century.

3 DEFINITION OF THE STUDY MODEL

This structure is unusual because it is an incomplete portion of a building that would find its own stability in a closed conformation based on the circumference. This is thus an almost real 'macro-element' extracted from the ideal integral structure.

This portion can behave as a rigid body. The radial action is well-defined but - due to the aforementioned asymmetry - it is difficult to delineate the response to actions tangential to the peristyle and perpendicular to the radial direction.

The definition of the kinematics implies the determination of the nodes in which the hinges form, and their positioning can be influenced by the fragmentation of the recomposed elements.

To deepen the study, the behaviour of the structure brought to collapse also involved a physical model produced by printing the results of a 3D laser scanning survey.

The model was obtained from a three-dimensional printer making all the pieces separately, following the discontinuity lines between the historical elements and modern additions.

The model's scale of representation is 1:14.5. The printing was carried out by depositing a filament of synthetic material - layer-upon-layer - until the object was fully formed. This material has a density of about 13 kN/m3, obviously different from the travertine and marble of the lithic elements, but the shapes are effectively simulated. The physical model presented some problems relating to the reconstruction of pieces in the posterior portion and the coplanarity of the overlapping bases.

These problems were partially solved by correcting the discretization of the non-matching pieces and re-printing them. A progressively inclinable plane served to check system behaviour. The gradual leaning increase makes it possible to evaluate, – as in some experiments begun in the late 1980s – the model's behaviour in comparison with a horizontal stress equivalent to the component of its own weight parallel to the plane.

The inclination transforms the weight into stress corresponding to the horizontal static action ($H = V \text{ tg } \phi = V \alpha$) proportional to the inclination and to load multiplier α.

Contextually, some theoretical calculations related to limit-behaviour schemes based on the application

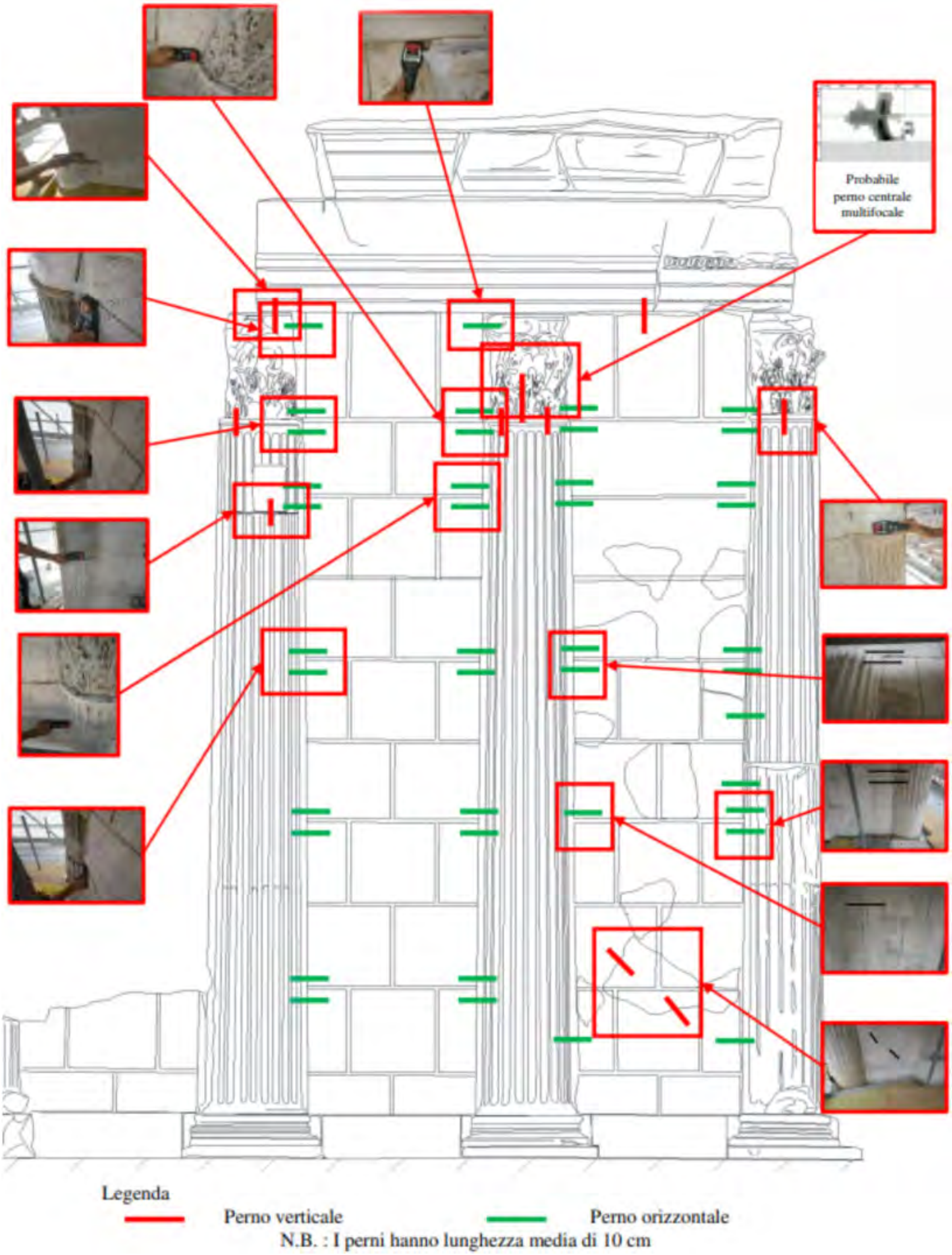

Figure 7. Working notes on the connections reported by magnetometric and thermal instrumental analysis.

of the PLV were made and also defined according to the results achieved in physical modelling.

The physical model underwent minor adaptations to make it more similar to the real monument in keeping with the research outcomes on the presence of metal connections and the registration of the response methods to environmental vibrations.

Analysis and the study of site documents highlight the presence of connection devices largely not visible from the outside: concrete castings with steel

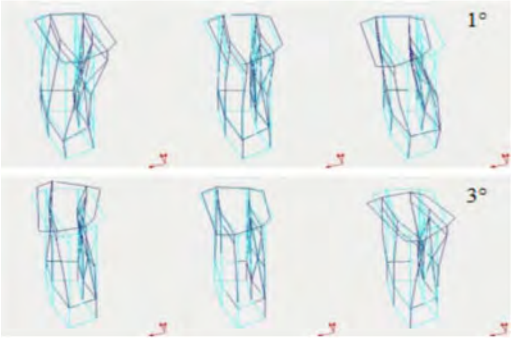

Figure 8. Wire frames of the structure with its vibration modes produced by environmental micro-tremor. The main modes (1° , 3°) are compatible with the behaviour of the model.

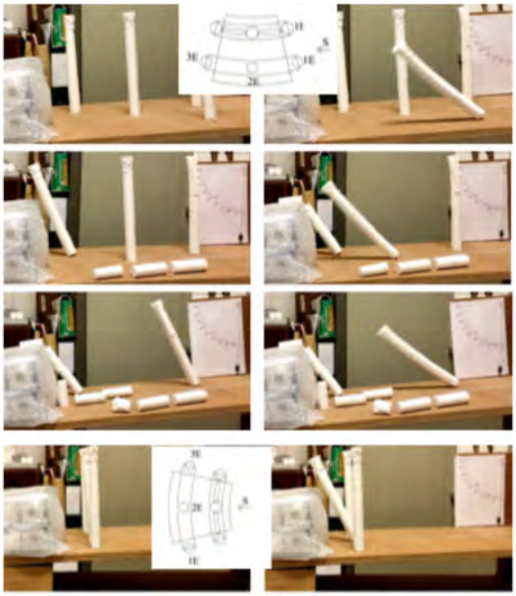

Figure 9. Results of the experimentation on single columns.

reinforcements that strongly constrain elements of the ceiling and portions of the entablature anchored to the capitals, especially at the ends where the connection appears less solid. The wall partition between the internal columns is provided with cramps that bind the single travertine panel to the upper section. It is presumable that pins have been inserted centrally between the elements composing the columns.

In the physical model, the elements were simply placed against each other and so the results are thus highly preliminary. Strings were inserted only in the horizontal planes of the inner row to simulate the actual massiveness of the wall obtained with the cramps.

Some simplified experimental tests were initially conducted to calibrate the reliability of the model. These took into consideration the columns individually and they displayed fewer resistant behaviours than the corresponding theoretical schemes. Nevertheless, the most macroscopic defects were considered only in the schemes. On the other hand, the re-proposal of the exact geometry of the columns, including the irregularities in shape and verticality, leads us to consider the experimental result as more realistic than the theoretical, abstract and simplified model.

Subsequently, the behaviours of the entire model were tested alternately on the two main axes and in the two opposite directions. Finally, having identified the greatest criticality, improving the resistance capacity was tested by inserting a holding device consisting of two stays placed in the rear section of the building.

4 VERIFICATION RESULTS

Comparing the results obtained experimentally with the physical model with the results of the theoretical calculations reports a decent level of convergence; however, certain numerical differences must be highlighted between the homologous values determined with the different methods. We presume this difference is attributable to the simplification of the theoretical model and to the eventual limitations of the physical model.

The overall result in determining the modalities of the final behaviour remains reliable with the limitations of a test conducted only with equivalent static stress. For this reason, we intend to verify the dynamic behaviour of the model in the future. Both methods have their own trustworthiness and a real intermediate behaviour between the two series of results obtained can be considered valid. The greater attention paid to the individual external columns came from their significant influence on the behaviour of the entire model.

Frames 1 to 6 in Figure 9 concern the three external columns and one of the internal columns when the inclination solicits the tangential direction. In the same figure, frames 7 and 8 resume the three external columns arranged in a radial direction, 90° rotated by the previous position. The mechanism is firstly activated in column 2E; columns 1E and 3E follow. Based on the results obtained by theoretical calculations and by considerations about the geometry of these columns and the defects that we incorporated into the test, we decided to repeat the test for column 2E only.

The result confirmed expectations: the mechanism is activated firstly for column 1E, then for column 2E and finally for 3E. This response mainly links to the presence of chipping at the base of column 1E. Therefore, this anomaly determines a decrease in the width of the support with a consequent reduction in the stabilizing work. The columns of the internal peristyle - stabilized by the dividing wall - exhibit a distorted behaviour in the tangential direction for which they were tested separately only in the radial direction. Figure 10 details how the anterior columns precede the movement with less contribution from the column located in a prominent position, which initially follows

Table 1. Single column.

Code	numerical meth.	experimental meth.
Tangential direction		
1Ex	$\alpha = 0.096$	$\alpha = 0.047$
2Ex	$\alpha = 0.090$	$\alpha = 0.087$
3Ex	$\alpha = 0.102$	$\alpha = 0.070$
1Ix	$\alpha = 0.096$	$\alpha = 0.090$
Radial direction		
1Ey	$\alpha = 0.063$	$\alpha = 0.049$
2Ey	$\alpha = 0.093$	$\alpha = 0.058$
3Ey	$\alpha = 0.102$	$\alpha = 0.090$

*E = external peristyle I = inner peristyleigure 10. Model response when stressed in the radial direction.

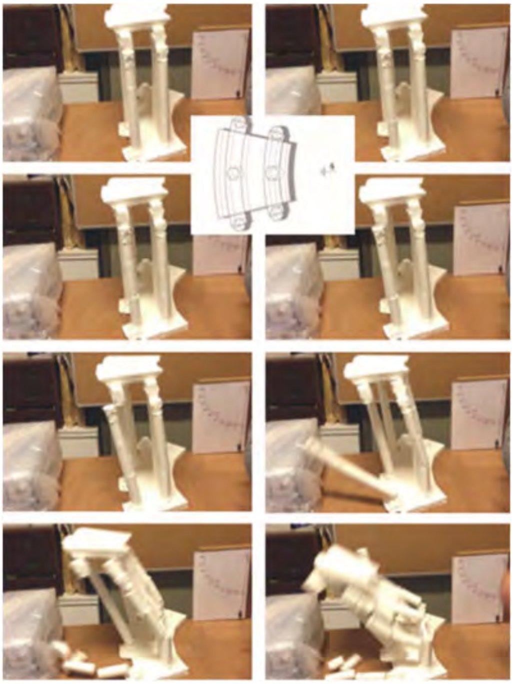

Figure 10. Model response when it is stressed on the radial direction.

Table 2. Complete model summary.

Tangential	numerical meth.	experimental meth.
North	$\alpha = 0.145$	$\alpha = 0.090$
Radial	numerical meth.	experimental meth.
East	$\alpha = 0.096$	$\alpha = 0.090$
Radial	numerical meth.	experimental meth.
West	$\alpha = 0.096$	$\alpha = 0.081$

*we consider the force acting towards the cardinal point.

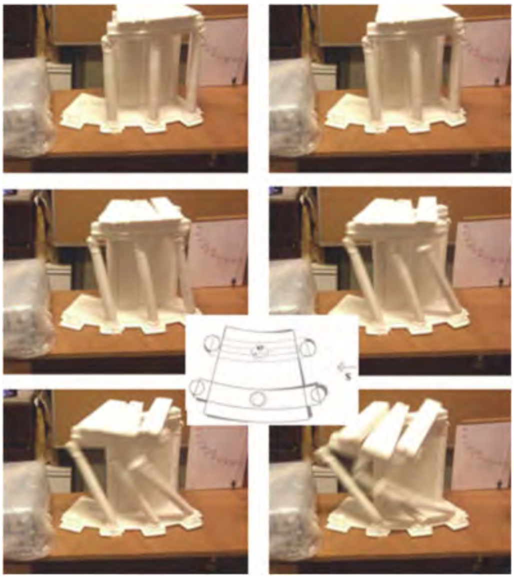

Figure 11. Model response when the pushing direction is tangent to the peristyle.

the global movement and then releases. Recording the experimentation with continuous photographic shooting allowed us to study the collapse mechanism by extrapolating the most significant frames. In fact, the collapse occurs with extreme rapidity which sometimes does not consent to fully observe its evolution and, particularly, its trigger.

The tests all considered the two directions - radial and tangential - and the horizontal multiplier values of load α, which involve the activation of the mechanism, were determined. The most significant values are collected in Tables 1 and 2. This column anticipates the kinematic collapse that involves all the elements except for the base of the inner peristyle which, linked to the base and to the wall, does not participate in the collapse. The ceiling and the architraves follow the movement of the columns although remaining substantially compact.

Figure 11 depicts how the columns represent the weak part of the vertical bearing system and how the trigger of the kinematics begins with the overturning of the three columns in tangential directions to the horizontal trajectories with the centre in the median zone of the posterior wall; simultaneously, the left column of the inner peristyle folds towards the back. Subsequently, the failure of the floor due to friction brings about a release between the horizontal masses and the wall which loses its balance and collapses almost completely.

5 HYPOTHESIS FOR THE STRUCTURAL IMPROVEMENT AND CONCLUSIONS

The results obtained showed global stability but also a greater sensitivity of the structure in the radial direction. Therefore, we suggest inserting suitable devices

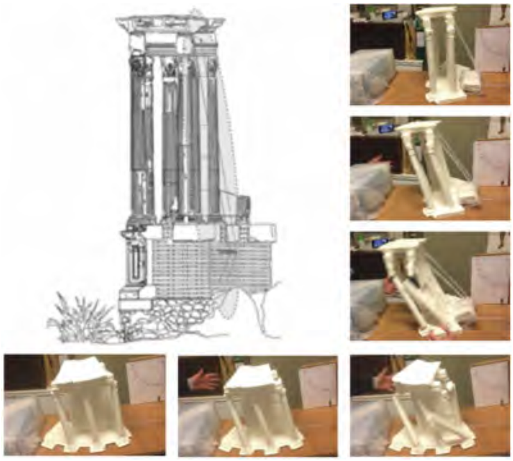

Figure 12. Lateral view of the reconstructed portion showing the stays designed to anchor the structure and to reduce its vulnerability especially in the radial direction which is that most exposed to a potential seismic event (a). Model response when stressed in the radial direction with the application of strings anchored to the ballast (b). Model response when stressed in the tangential direction with strings anchored to the ballast (c).

Table 3. Complete model summary experimental meth.

Tangential	without strength	with strength
North	$\alpha = 0.090$	$\alpha = 0.110$
Radial	without strength.	with strength.
West	$\alpha = 0.081$	$\alpha = 0.105$

∗considered the force acting towards the cardinal point.

to improve resistance to overturning in this direction, especially towards the outer areas. In order to respect the construction and the historical documents and because of its special location, we decided to verify the possible positive contribution of a minimal intervention. This can consist of a stayed system formed with two ropes placed on the rear face, out of sight from the gaze of observers, distinct from the stone artefact and totally reversible. These devices can be fitted with minimal alterations to the existing material, while also capable of significantly improving the resistance to overturning in this direction, especially outside.

The upper anchoring could be placed on the internal entablature, in correspondence with the less exposed face, limiting the invasiveness to the two holes that would be necessary for the passage of the wire ropes. To allow for a suitable inclination of the stays (increasing the horizontal component of the constraint) two battens inclined on the bisector of the two linear sections were hypothesized. The advantage obtainable with this device is summarized in the table above. This was verified in the model applying two strings corresponding to ropes anchored to a ballast. We presume that the positive effect would be greater than in the model, which is made of lighter materials than travertine and does not reproduce the real limit conditions for sliding. The expected advantage is thus obtained in both directions, radial and tangential. In the second case, the tensioned stay helps delay the triggering of rotation due to the torsional effect, while the other one remains inert. Overall, the experience was useful to deepening the study of archaeological artefact reconstruction techniques with metal connections and well-preserved reinforced concrete mortars; the experiments highlighted the behaviour generated by the geometric shapes of the perfectly reproduced masses and guided the analysis carried out numerically by applying the principle of virtual work on mechanisms determined by physical modelling.

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Geometry by eye: Medieval vaulting of the Anba Hadra Church (Egypt)

H. Lehmann
Technische Universität Berlin, Berlin, Germany

ABSTRACT: At first glance, the vaults and domes made of adobe bricks in the medieval monastery church of Deir Anba Hadra appear simply typical to the region. However, a closer look at their construction enables new insights into form-finding processes and the combination of specific vault forms to produce differentiated formation of space. Tracing of historical origins reveals relationships in the development of vault forms and building typologies. The paper describes the church's vault construction and explains the principles of determination of their geometry. In order to consider how this could have been implemented at a medieval construction site, experiences derived from traditional adobe construction in the area will be included. A comparative view of the Anba Hadra monastery church along with Nubian buildings as well as Christian and Muslim buildings in the Aswan region allows conclusions to be drawn regarding the intertwined handicraft tradition and cultural exchange in the region of the First Cataract of the Nile in the 10th century CE.

1 INTRODUCTION

The monastery of Deir Anba Hadra is located in the south of Egypt, at the First Cataract of the Nile. The monastic complex occupies the northeastern edge of a sandstone plateau in the western Sahara, opposite the city of Aswan and the island of Elephantine. The topography was skillfully integrated into the construction, as the exterior walls in the north were placed directly on the vertically sloping rock edge of the plateau; another rock edge divides the ground plan of the monastery into an upper terrace in the west and a lower, slightly smaller terrace in the east (Figure 1). This rock edge is perforated by grottoes, which constitute chambers of an ancient gallery quarry (Klemm & Klemm 2008: 206).

The monastery church, as the spatial and spiritual center of monastic life is the largest building on the lower terrace. It occupies nearly the entire width of the terrace in its east-west extension. The building is attached to the rock edge; its northwestern corner is connected with an elaborately painted grotto, rendering it accessible via a narrow passage leading from the church (Figure 2). This grotto, still honored today as the Hermitage of Anba Hadra, was probably the origin of the development of the monastery (Lehmann, in press).

No written sources provide information concerning the ways in which Coptic monastery construction sites were organized in the Middle Ages or regarding the possible existence of specialized builders among the monks or of itinerant building teams in the region. It can be assumed, however, that the vaults, in particular, were built by specialist master masons. How the individual types of vaulting came about will be explained, on one hand, by observing the construction process in contemporary traditional vaulting and, on the other, by examining their historical origins to draw conclusions about the development of the history of building in the region of the First Cataract.

1.1 *Research history and new approaches*

The first scientific approach was applied to the ruins of the monastery as early as the last decade of the 19th century (Clarke 1912: 95–111; de Morgan et al.

Figure 1. Panoramic view of the huge qasr on the upper terrace and the large cubic church on the lower terrace of the monastery (Lehmann).

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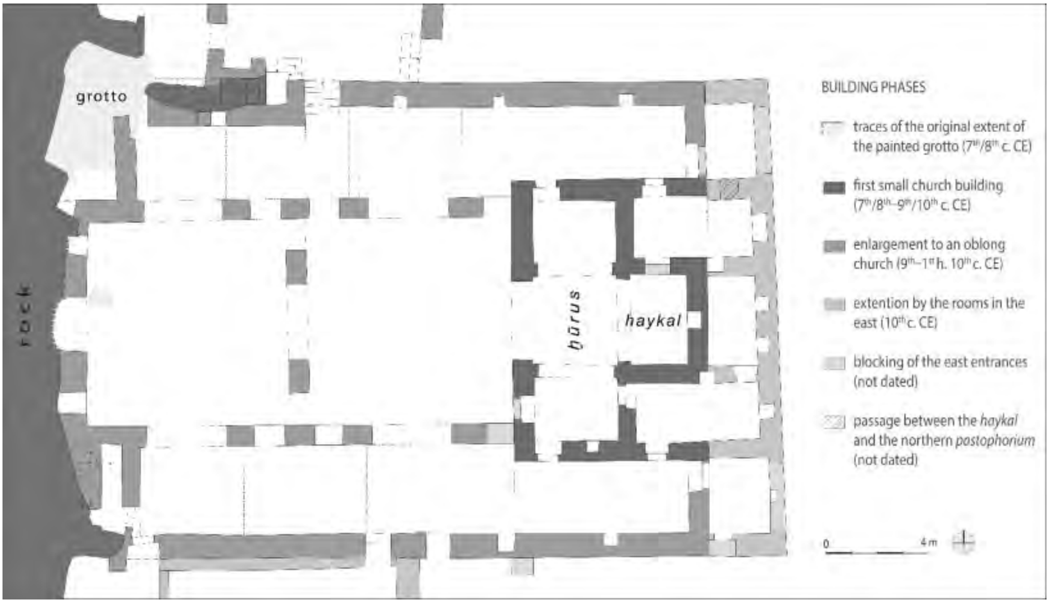

Figure 2. Floor plan of the church with indication of construction phases (Lehmann).

1894: 129–141; Gayet 1892). The site was almost completely excavated in the 1920s by a mission of the Service des Antiquités under the direction of Ugo Monneret de Villard. Their publication contains the first comprehensive description of the architecture of the monastery church, a schematic floor plan, and proposals for reconstruction of the vaulting (Monneret de Villard 1927: 39–65, figs 50–76).

New investigations conducted by Peter Grossmann in the 1970s corrected some details of the vault reconstruction, but his main focus was on the typological classification of the church as an octagonal domed building and as a special form of oblong domed church, based on the assumed use of Byzantine octagonal domed churches, which appeared in Greece from the 11th century onwards, as role models (Grossmann 1982: 7–13, figs 3–4; 2002: 563–564).

In 2013, a joint project involving DAI Kairo and TOPOI FU Berlin adopted a multidisciplinary approach to the research at the monastery (Lehmann 2016: 7–8; Richter et al. 2019). Within the framework of the current project, the building history of the monastery church was studied anew during several intensive field campaigns between 2015 and 2018 (Lehmann 2016, 2018, in press). For the first time, a detailed building survey was carried out, using structure from motion (SfM) methodology in combination with tachymetric measurements. A ground plan, vertical sections, and elevationson a scale of 1:20, as well as a 3D model built at that time, formed the basis for new studies of the architecture of the church and its building phases.

This new approach, combined with datable inscriptions by pilgrims, lead to the conclusion that the completion of the main building phases of the church must have taken place by the 10th century CE at the latest (Figure 2. The building is therefore older than the Greek models assumed by Grossmann, and new explanatory models had to be sought for the derivation of the building tradition.

1.2 *The church of Deir Anda Hadra*

The monastery churchis a cubic and rectangular building, aligned east-west, up to 30 m long and 18 m wide. The walls consist of locally quarried sandstone up to the spring levels of the vaults. The wall parts above and the vaulting shells were made of air-dried mud bricks, apart from some special features in the dome construction which will be discussed later.

Rectangular pillars divide the naos of the church into three naves, and additionally divide the central nave into two square rooms vaulted with gigantic domes (Figures 2–5). To the east of the central nave is the sanctuary, set off by massive walls. The central wall opening of the sanctuary towards the naos of the church was fenced off with wooden grilles. The sanctuary itself is divided into a central room in the eastern end, the so-called *haykal*, where the main altar is supposed to have been placed, and a transverse row of rooms in front of it, the so-called *ḫūrus* (definition of *ḫūrus* and *haykal* after Grossmann 2002: 72–76, 96, 565). Together, the *ḫūrus* and *haykal* form the shape of a rectangular trefoil, thus creating a kind of triconch. To the north and south the *haykal* is bordered by *pastophoria*(definition after Grossmann 2002: 113–115). The *ḫūrus* is slightly broader than the central nave of the naos; thus, the lateral naves alongside the sanctuary continue to narrow as far as the eastern rear wall of the *haykal*.

Figure 3. View of the ruins of the monastery church, looking southeast (Lehmann).

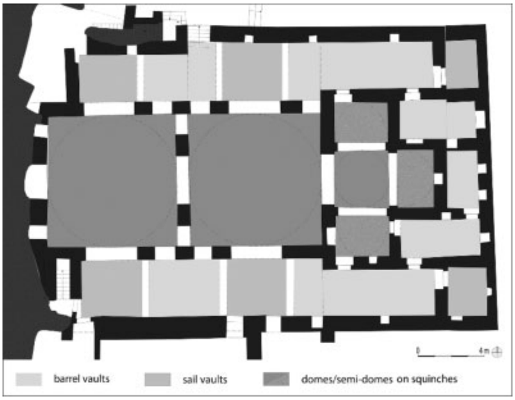

Figure 4. Distribution schema of the various vault forms (Lehmann).

2 VAULTS AND DOMES

Apart from one zone which is still intact in the east, the vaults have mostly collapsed (Figure 3). Nevertheless, the traces that have been preserved are sufficient to deduce at least their basic forms: parabolic-like barrel vaults, sail vaults, and domes on squinches (Figure 4). A particular constructional feature can be noted in the spandrels of some of the room-spanning vaults: secondary vaulting barrels, the so-called “shoulder barrels”. All of these different forms were constructed as single shells of inclined ring courses, which could be built without formwork.

2.1 *Parabolic-like barrel vaults*

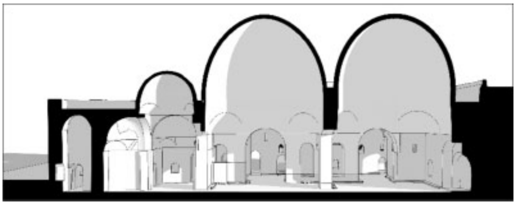

Figure 5. Longitudinal section through a schematic reconstruction model of the church, with a variant reconstruction of the domes (Dzembritzki/Lehmann).

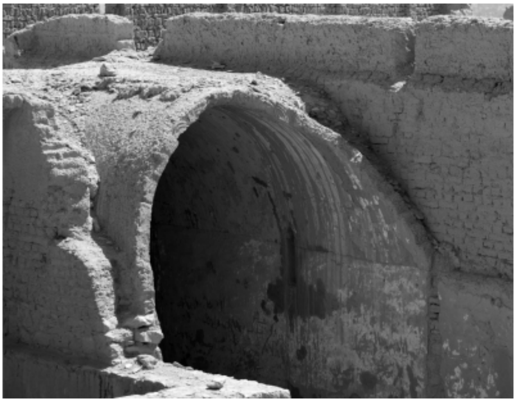

Figure 6. Barrel vault of the southern lateral nave (Lehmann).

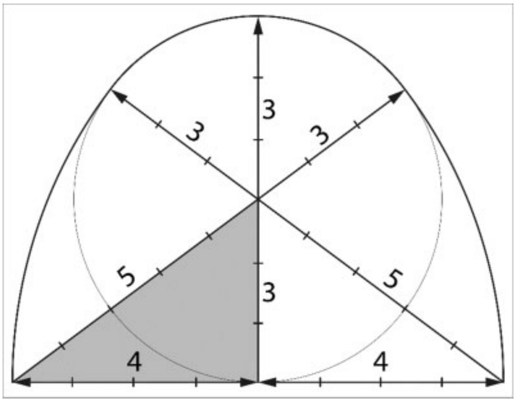

Figure 7. Geometric determination of the barrel vault shape using the Pythagorean theorem (Lehmann).

The long rectangular rooms behind the sanctuary and sections of the lateral naves were covered with mudbrick barrel vaults consisting of only one shell of inclined ring courses built against a supporting front wall (Figures 4–8). Vertical ceramic tubes were incorporated into the apex line of the barrel vaults, which, in addition to the few high and relatively small windows, probably facilitated the ventilation of the rooms.

In Deir Anba Hadra, one can trace a basic formula that served as the model for the geometry of the parabolic-like barrels, even if the vaulting shell seems to have been designed based on a purely visual sense of proportion (Figures 7 and 8). The measurements of all intact vault cross sections show that their most important construction points can be determined by a simple geometric formula with integer ratios (Figure 7). The basic module of dimension results from

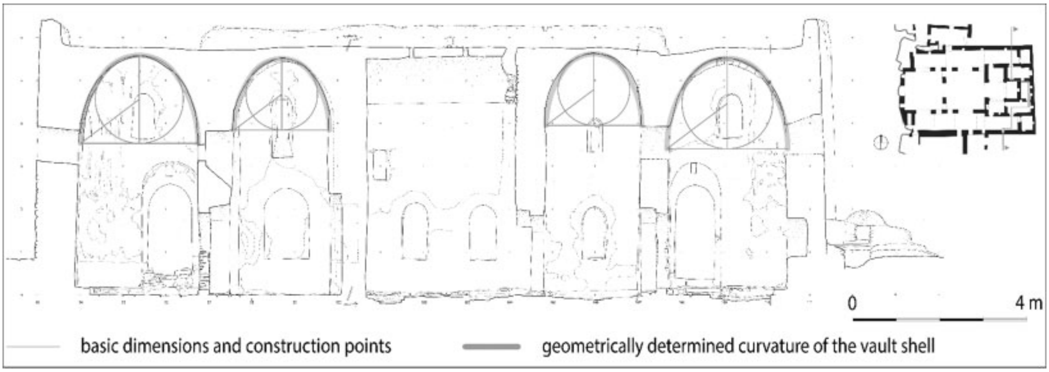

Figure 8. North-south section through the lateral naves and the rooms east of the sanctuary: ideal shape and "by eye" execution of the barrel vaulting (Dzembritzki/Lehmann).

the span of the barrel divided by 8. The vertex height of the barrel is 6 modules; the control points for the line of curvature result from a diagonal which, starting from the bearing of the vault, intersects half the height of the vertex (3 modules), and upon which the length of the span (8 modules) is measured. The initial figure or model for this procedure is a triangle characterized by the lateral relationship 3-4-5, i.e., the Pythagorean Theorem, for the determination of the right angle.

Examples of vaulted barrels with a near-parabolic shape can be found in Pharaonic architecture dating from the middle of the third millennium BCE (Kemp 2000: 78–103; Spencer 1979: 10–11, 11 fig. 3; Fauerbach, pers. comm.), for example, a burial chamber in Ain Asil (Dachla, 6th Dyn. 23rd c. BCE) and the magazines in the Ramesseum (Thebes, 19th Dyn. 12th c. BCE). Auguste Choisy assumes that, as early as in Pharaonic times, the form of parabolic-like arches was geometrically determined with the use of a right-angled triangle with the aspect ratio 3-4-5 (Choisy 1904: 46–48, 46 fig. 38, 47 fig. 40). No constructed examples are given for this assumption; moreover, there is a controversial discussion among Egyptologists concerning the method used in ancient Egypt to construct right angles (Schneider 2015: 99). However, knowledge of the principles of arcs and ellipses in geometrical construction incorporating the 3-4-5 configuration known as the Pythagorean Theorem is proven by an ostracon from the burial district of Djoser (Saqqara, 3rd Dyn. 27th c. BCE) and the 1:1 constructional drawing of an elliptical vault at the entrance to the tomb of Ramses VI (20th Dyn. 12th c. BCE) (;ightbody & Monnier 2017; Rossi 2003: 10, 64, 113–118)

Rules of thumb aimed at determining an ideal parabolic shape for the creation of vault shapes without complicated calculations of pressure lines to optimize load transfer are still used in traditional vaulting today (AVEI 2020). Due to the inclined ring course technique, no falsework is required to construct such a vault. The form just needs to be outlined on the supporting front wall. Nevertheless, aids for height control may have been used for large and long barrel sections. From today's traditional vault construction, we know that horizontal cords stretched between end walls serve to control the cross section. In addition, there are wooden model arches that move along with the construction almost like a sliding formwork. Often, however, master builders at construction sites manage without geometric formulas or additional construction aids, since these rules of proportions pass along as part of traditional construction knowledge (Fathi 2000: 9–11, figs 7–18).

Figure 9. Sail vault in the northeastern corner room (Arnold).

2.2 *Sail vaults*

Sail vaults cover the corner rooms to the east as well as the compartments of the lateral naves connected to the two large domed rooms by wide arch openings (Figures 4 and 9). Thus, also keeping in mind that the corner rooms used to be the vestibules of the subsequently blocked eastern entrances, all rooms with sail vaults mark transitional areas in the church. The sail vaults are similar to barrel vaults in that they are single-shell constructions built in ring courses without formwork. However, their shape is nearly that of an ideal spherical segment rather than a parabolic curve.

The dome shell is connected to the rising wall surfaces via an abutment in the form of shield arches which result from the intersection of a fully formed external circular dome with the room floor plan. This abutment surface is inclined towards the center of the room; the dome shell is built up with ring courses of air-dried mudbricks starting simultaneously from the shield arches on each side of the room towards the dome apex. In the corners of the room, the ring courses interlock in a herringbone bond.

The northeastern corner room of the church is not even nearly square, therefore the shield arches, with common starting points in the room corners, were stilted on the narrower sides of the room and were constructed as segmental arches only on the long sides. Thus, the arches are characterized by the same apex height despite different spans. It was then necessary to compensate for deviations from the square basic shape when creating the dome shell in a slightly ellipsoidal shape.

The construction of domes has been documented in Egypt since the time of the Old Kingdom in sepulchral architecture and silo constructions. There are several examples of sail vaults from the Pharaonic period, and the earliest known ring layer dome made of mud bricks is part of the tomb of Seneb (Giza, 4th–6th Dyn. 27th-22nd c. BCE) (Junker 1941: 29–33, 23 fig. 2, 25 fig. 3). Sail vaults have been in widespread use since late Roman times and were applied in the Middle Ages in both Coptic and Islamic architecture (Grossmann 1982: 249–254).

Dome geometry can be defined with the use of a lath or a string compass (Clarke 1912, 29–30, 29 fig. 5; DWF 2020; Heindl 2009, 140 fig. 10, 143 fig. 13;. A bar is placed in the middle of the room and a lath or string is attached to the upper edge, defining the radius of the dome and, at the same time, the inclination of the individual brick courses circling around this pivot. In the case of deviations from the ideal spherical shape, as described for the slightly ellipsoidal sail vault in the eastern corner room, several compasses, eccentrically placed in the ellipse foci, could theoretically have been used. Considering the irregularities in the geometries of the vault shells, however, the compensation of the dome distortion was most likely calculated by eye.

2.3 *Domes on squinches*

The third vaulting form comprises full circular domes on squinches (Figures 5 and 10), a term applied to the two large domes in the central nave and in all rooms of the sanctuary, and thus to all rooms in the central axis in which liturgical acts were performed, as can be concluded from the installations found here. Only a part of the painted semi-dome above the *haykal* and fragments of the corner squinches in the west wall of the church have been preserved. The vaulting base of these domes consists of a layer of fired bricks. The domes themselves are single-shell mixed constructions of air-dried and fired bricks. During archaeological investigations in the two large domed rooms, fired bricks with decorated head sides – probably remnants of the collapsed domes, which must have been characterized by polychrome painting – were found in some debris.

Figure 10. Semi-dome on squinches over the haykal with shoulder barrels in the spandrels (Lehmann).

Figure 11. Barrel vault with shoulder barrels in the qasr (Lehmann).

The construction of the shell of the semi-dome in the *haykal*, approximately 30 cm thick, is divided into two sections. The bricks are laid in horizontal courses slightly corbeling up to approximately 1.15 m from the upper edge of the vault abutment. Only above this are the bricks placed on edge, in ring courses inclined to the center of the room (Figure 9). The inclination of the bricks is supported by flat stones and ceramic shards in the joint mortar. In addition, small sticks protruding inwards were worked into the joints, to support the adhesion of the plaster in the calotte. The geometry of the preserved remains of the hemisphere is so irregular that it cannot be described either as a deformed hemisphere or as an approximately parabolic shape. Instead, in the lower areas the dome is still very steep and almost angular, whereas towards the apex the curvature increasingly resembles a horizontal ellipse. This suggests construction by eye rather than the use of control mechanisms to maintain geometry.

The exact shape of the full domes remains uncertain because both parabolic and hemispherical domes, each with its own advantages and disadvantages in terms of weight and load transfer, are feasible here (Figure 4). Unfortunately, even a glance at comparable Egyptian buildings is no help, because the dome shapes vary not only from one building to another but even within a single building. Various possibilities also exist in the detailed design; this can no longer be verified in Deir Anba Hadra. The domes may have been perforated with ceramic tubes, or may have included windowed or solid tambour zones characterized by circular or octagonal shapes, to name just a few possibilities.

Domes on squinches are not part of the ancient Egyptian building tradition. Horizontal corner bridges, whereby wooden beams, stone beams, or stone slabs diagonally span the corners of the room, thus forming an octagonal basic form for support of the dome, are statically less loadable Egyptian forerunners of squinches. Egyptian examples of horizontal corner bridges with full-circle domes can be found in the monastery churches of Deir al-Suryani and Deir Abu Makar in Wadi Natroun, among other sites (Hauser 1973).

As a source of inspiration for the construction of the domes on squinches, the Sassanid building tradition must be taken into consideration. The earliest known examples of domes on squinches derive from the Mesopotamian-Persian region, including the main dome of the Sassanid palace of Sarvestan (ca. 350 CE) and the domes of the temple and the Ardashir palace at Firuzābād (ca. 250 CE). These domes are made of adobe bricks and are characterized by a parabola-like shape of the dome shell typical of Sassanid architecture (Ashkan & Ahmad 2009: 101, 112–113, 101 figs 3, 4; Thunnissen 2012: 73–74, 125–126, 36 figs 4, 4a).

The earliest domes on squinches in the Egyptian region, which vault above large rooms, are found in the mausoleums of the Fatimid cemetery of Aswan (Monneret de Villard 1930; Speiser 2019; Speiser et al. 2013) and at several medieval monastery complexes, such as the monastery churches of Deir al-Shuhada and Deir al-Fahuri near Esna (Grossmann 1982: 267). As yet, none of these buildings has been dated with certainty; thus, as far as the author is aware, the two large domes of the monastery church in Deir Anba Hadra, which were erected during the first half of the 10th century at the latest, must be regarded as the earliest large domes on squinches in Egypt.

2.4 *Shoulder barrels*

A remarkable construction feature of the Anba Hadra monastery comprises the so-called "shoulder barrels" in the spandrels of the vaults spanning the rooms (Grossmann 1982: 242–243; Lehmann 2018: 178–181; Monneret de Villard 1927: 125–126; 1957: 119–120). In the monastery church, remains or negative imprints of such shoulder barrels can be seen above the barrel-vaulted sections of the lateral naves as well as in the spandrels between the walls and the semi-domes above the *haykal* and the outer *ẖūrus* rooms (Figure 10). Opinions are divided regarding the static significance of these shoulder barrels. Monneret de Villard sees them as statically meaningful relief arches, "*Voltini di Scarico*"(Monneret de Villard 1927: 125, 132; 1957: 119). Deichmann and Grossmann, however, assume that the load point in the upper third of the arch shell imperils the safety of the overall construction (Deichmann & Grossmann 1988: 152). There is no doubt that the shoulder barrels offer a practical advantage in creating a plain accessible surface above them, as they save material and weight in comparison to complete filling of the spandrels (Deichmann & Grossmann 1988: 152; Monneret de Villard 1957: 119).

The shoulder barrels in the vault construction of the *qasr* on the upper monastery terrace (Figure 11) are better preserved than those in the church. Their insides are carefully coated with plaster and accessible from above via vertical shafts. The shafts were covered with stone slabs and could probably be closed from the inside, as some suitable stone slabs found next to such shafts include notches and cut-outs at the lower edges. The cavities in the shoulder barrels could therefore have served the monks as storerooms as well as hiding places or escape tunnels during raids.

The shoulder barrels are no more a part of ancient Egyptian building tradition than are domes on squinches. In the Aswan area, however, there are some medieval examples, such as in the *qasr* and the church of the nearby monastery on Qubbat al-Hawa, as well as in the now-destroyed Qasr al-Mullah on the Aswan city wall. Shoulder barrels were also observed on ancillary buildings in the Deir al-Fahuri monastery near Esna (Grossmann 1982: 242–243; Monneret de Villard 1927: 125–126, figs 144–147; 1957: 119–120). The northernmost, and earliest, evidence known to the author of this vault form in Egypt is the temple of Umm el-Dabadib in the northern Kharga Oasis, possibly built in Roman times(Rossi & Ikram 2006: 283, 293–296, 295, fig. 5). More widespread are shoulder barrels, especially in the Nubian area where they appear both in sacred and profane architecture, in very different designs (Deichmann & Grossmann 1988: 67–94, plates 15, 18, 151–153; Grossmann 1982: 242–243; Monneret de Villard 1927: 125–126; 1957: 119–120). Early examples are the vaults of the Meroitic palace of Karanog (300 BCE-550 CE) and the late antique to early medieval insula construction of Ihmindi (city foundation, second half of the 6th century CE).

3 THE INTERTWINED DEVELOPMENT OF VAULTING CONSTRUCTION AND SPATIAL ORGANIZATION

Different types of vaulting are used, depending on the proportions of the space to be vaulted; however, they also shape spatial communication within the church and create a certain hierarchization of rooms. The two large dome rooms have a decisive influence on the structure of the entire naos, in terms of both ground plan and elevation, because the dome construction determines the rhythm of the supporting rows of pillars, to which the division of the vault sections above the lateral naves is also linked (Figure 4). Further segmentation of the vaulting of the lateral naves results from their narrowing north and south of the sanctuary.

The spatial organization of *ḫūrus* and *haykal* rooms in Egyptian monastery churches can be observed from the 7th century onwards. The replacement of basilical with new types of floor plans as well as the transition from timber beam roof to vaulting had become characteristic of church construction throughout Egypt by the Fatimid period at the latest (Brooks Hedstrom 2012: 27–28; Grossmann 2002: 73, 79–81;. However, the so-called type of the oblong domed churches is found only locally in Upper Egypt and Nubia.

The re-dating of the Hadra Church to the late 9th or early 10th century now raises far-reaching questions, as the church is earlier than the Byzantine octagon domed churches which have thus far been accepted as role models (Grossmann 1982: 13, 2002: 90–93, 564). An important question is whether the process of evolution of church architecture in Egypt in general can be seen exclusively as part of the Byzantine tradition of sacred architecture or whether it is more inspired by contemporary Islamic architecture and, especially in the Upper Egyptian region, by Nubian church architecture as well. In any case, the particular type of the Hadra Church provides strong arguments for independent development derived from regional predecessors. In Upper Egypt and Nubia there are older buildings in which relatively small domes with maximum diameters of 5 m are supported on four L-shaped pillars (Grossmann 2016). Causally connected with the monumentalization of the rooms with domes on squinches up to 8 m wide, the L-shaped pillars are subdivided into separate square pillars (Lehmann in Richter et al. 2019: 25). This transition can be seen very clearly in the domed church of Kulb in Nubia (Grossmann 1982: 61, fig. 20). The penetration of the L-shaped pillars by passageways, doors, or windows enables great variety in the interconnection of the large dome rooms with adjoining room groups, ambulatories, or lateral naves, as in the Hadra church.

Furthermore, the dating of other Egyptian and Nubian churches needs to be reconsidered, as the previous dating of the Deir Anba Hadra church to the 11th century and the derivation of the building type from Byzantine prototypes are often cited in the dating of typologically similar churches, e.g. the church of Deir al-Kubaniya (Grossmann 2002: 562), the second phase of the church of Deir al-Fahuri (Grossmann 2002: 559), the domed church of Kulb in Nubia (Deichmann & Grossmann 1988: 47–53), or the predecessor of the apostle church in the St. Antonius monastery (Blid et al. 2016: 146), to name but a few of many examples.

4 CONCLUSIONS

The analysis of the vaults in the Deir Anba Hadra demonstrates the dependence of construction principles on local conditions and a building tradition over a thousand years old, as well as strong interdependence within the region, including the Nubian area south of the First Cataract.

In terms of building construction, the Deir Anba Hadra fits basically within the Egyptian tradition; this includes, for example, the cubic overall shape of the church or the inclined barrel vaults built without any need for formwork, from Nile mud bricks that could be produced locally just in time. Nevertheless, comparisons with vault construction with shoulder barrels in the spandrels above the large barrel vaults and domes can be found above all in the Nubian area and, in Egypt, concentrated in the area around Aswan (Grossmann 1982: 242-243, Deichmann & Grossmann: 151–153, Lehmann 2018: 185–186).

In oblong domed churches, various vault forms are combined; both the basic form of the room and the desire for a hierarchization of the room zones in the church played a role in the choice of the respective vault form. It has become obvious that the building typology of oblong domed churches developed in the 9th or 10th century from previous regional Christian models; it can also be observed how closely related the development in typology is to the introduction of domes on squinches in the region. With regard to the latter, however, one cannot speak of a “Christian” development, because its introduction and further development in dome construction began in Egypt in Fatimid and Coptic architecture at about the same time. In order to make further statements, however, more fundamental investigations are needed within the framework of case studies.

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The construction and stereotomy of the medieval vaults in Notre-Dame: Planning, stone-cutting and building of the double-curved shells

D. Wendland, M. Gielen & V. Korensky
Brandenburgische Technische Universtität Cottbus-Senftenberg, Cottbus, Germany

ABSTRACT: The construction of the vaults in stone masonry in Notre-Dame in Paris, which are an essential feature in the cathedral's architecture, was a challenging task for the medieval builders, and certainly can be seen as a milestone in technical and artistic innovation. Not only the ribs, but also the shells are made of dressed stone: their double-curved surfaces are built in exposed masonry with a remarkably regular texture. During the devastating fire, the vaulted ceiling stood for good part to its task in confining the flames to the roof structure. Even though some portions were destroyed by heavy impact, it nevertheless played a key role in avoiding major damage to the interior of the cathedral. This study aims to clarify the historic position of this construction and to understand the builders' technical knowledge. We also hope to contribute valid information for repairing the damaged vaults and integrating the destroyed portions.

1 INTRODUCTION

All ceilings in the Cathedral Notre-Dame in Paris, the construction of which started around 1160, are rib vaults built with exposed masonry of carefully dressed stone: including the shells where the courses are arranged in a special, regular pattern. These vaults have a prominent precedent some decades earlier in the Abbey church of Saint-Denis, compared to which, however, they have significantly evolved. The type is taken up again and further developed in the great cathedrals that were built in the following decades. In this phase of the development of Gothic vaults, the high vaults of Notre-Dame (Figure 1) play a key role.

The regular layout of their masonry pattern is remarkable because the surfaces of the shells have a pronounced curvature, and because, due to the general characteristics of their design, their shape is not geometrically determined. This raises the question of which methods the builders could have used for planning, setting-out, and building the vaults.

There are no contemporary records of their design and construction. The current interpretation of their structure is mainly based on the writings and drawings by Viollet-le-Duc (1846, 1854;, which refer to detailed analyses and to his restoration project, and therefore have undoubtable practical relevance.

Nevertheless, they must be seen as a historical position from the early 19th century, which is rooted in the beginning of modern architectural theory and certainly not representing the perspective of the mediaeval builders.

Moreover, it has become apparent that the consistency of the geometric description models and the practicability of the description of building technique, especially their relation with the evidence on the original, are problematic and in any case require critical revision (Wendland 2008). Currently, no relevant technical information is available. The only primary source is the building itself.

Figure 1. Notre-Dame in Paris: high vaults in the eastern end of the nave (DW 2009).

In the research in progress, preliminary observations on the vaults are reflected and interpreted by means of experimental studies carried out in a large-scale prototype (Figure 2) where possible procedures for planning, setting-out and assembly focusing in the present stage on geometrical aspects are tested and analysed. In later stages we plan to carry out on-site archaeological investigations.

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Figure 2. Experimental reconstruction of the vault (scale 1:3): the ribs are assembled on the centring, further centring arches guide and support the ridges (MG 2020).

2 THE HIGH VAULTS IN NOTRE-DAME

The high vaults in Notre-Dame were built in four campaigns, the first and largest of which was supposedly realized well before 1200 (Bruzelius 1987; Erlande-Brandenburg 1992; and extends over several parts of the Cathedral that had been erected during the preceding decades: the high choir, the crossing, the inner bays of the transept, and the two eastern bays of the nave next to the crossing (Figure 1). Unlike the architectural features of the walls, and leaving apart some different construction details we could observe, these vaults are rather homogeneous in their design, with similar rib profiles and keystones. A second campaign of vault construction covered the remaining two western bays of the nave, closing the gap to the western towers and completing the building.

The third campaign consisted in the addition of the outer bays in the transepts in conjunction with their great transformation in the middle of the 13th century (Albrecht 2020; Erlande-Brandenburg 1992). Finally, in the 19th century the mediaeval vault in the crossing was replaced with a cross-vault designed by Viollet-le-Duc.

Apart from the crossing and the outer transept arms, all bays of the high vaults are sexpartite vaults upon an approximately square plan. The dimensions in the eastern part of the nave, where our study focuses, are 13.26 m in transversal direction and 11.60 m in axial length of the bay (Maira 2016). The total height is ca. 33 m, the fleche of the vault 8.26 m.

2.1 *The design of the vault*

Our interpretation of the design is mainly based on the orthogonal projection of scan data given by Maira (2016, 2:671), but coming to different conclusions, as well as on the available drawings (Erlande-Brandenburg 1992, 241-9) and photographs.

The figure of the sexpartite vault combines the cross ribs that diagonally span the whole bay with transversal arches between and also in the middle of the bays. Along the clerestory, the formerets span only half the length of the bay, resuming the close rhythm of the main arcade. The ribs in the different arches have different dimensions (Maira 2016, 2:665): the transversal arches are the strongest (ca. 43 by 42 cm), the cross ribs are narrower but have the same height (ca. 25.5 by 42 cm), and the formerets that are embedded in the clerestory wall have a much smaller section. While the transversal arches according to their greater section are apparently intended to be the primary structural elements, they have different elevations, because in the geometric concept they are subordinate to the cross ribs.

The elevation of the vault, in fact, depends primarily on the cross ribs describing semi-circles; this determines the level of the summit of the bay where the great central keystone is located. The central transverse arch that also connects to this keystone is semi-circular as well, with a smaller radius because of spanning directly over the width of the nave, and stilted according to the constraint at the summit. Whereas the other transversal arches in the boundaries of the bay are traced as pointed arches, apparently with a radius of 3/5 of the span, rising from the common springing level; their summits remain a little below the central keystone. Finally, the formeret arches between the springers of the main ribs are drawn as pointed arches with a radius of 2/3; although springing from a higher level, their summits remain well below the vertex of the vault.

The ridges of the shells (i.e. the sharp edges between the vault surfaces rising from the ribs) that run in longitudinal direction along the centre or rise diagonally from the summits of the formerets to the central keystone, describe arches.

Their curves are given a priori and apparently defined as circle segments with a uniform radius equal to the free transverse span of the vault.

The entire geometric concept of the vault is therefore based on the spatial system of curves defined as circle segments in vertical planes: the ribs and the ridges of the shells. During the construction process, all these were supported by wooden arches which could be easily provided according to this elementary geometrical description (Figure 2). The surfaces of the shell, instead of being defined by geometric primitives, adapt to these autonomous curves, resulting in a rather high geometric complexity: The concave double-curved surfaces cannot be described in simple geometrical terms. This is the essence of Gothic vault design.

2.1.1 *The construction and its elements*

The vaults are entirely built of dressed stonework visible on the intrados, comprising the ribs, keystones, and shell masonry. The ribs are composed of rather short elements that are not cut as voussoirs, but as cubic blocks with parallel beds and plane intrados – as usual in early Gothic vaults (Figure 10). In spite of the profile carved on the intrados, they maintain a block-like appearance: the curvature of the ribs is obtained only through the variable thickness of the mortar joint. The ribs remain below the shell, resulting in a continuous mortar joint between rib extrados and shell masonry.

In contrast, the central keystones penetrate the shell and are likely to be visible on the vault extrados (as it is the case in Reims and still common in Gothic vaults of the 15th and 16th century). The large format piece is composed of a central volume with an open ring, and six departing arms for the diagonal and transverse ribs. In longitudinal direction, two heads emerge – Christ and the Devil – resulting in an octagonal layout. The masonry of the shells is built of rectangular blocks with courses running strictly parallel to the ridges, except for the lowest parts. Considerable variations of the heights of the courses are visible. The rectangular blocks have no curvature on the intrados (Figure 3), and the section of the blocks is perpendicular instead of being radial. At least in the samples from the debris we could analyse, no ad hoc dressing of the beds could be observed.

In the ridges of the shells, special stone elements are visible that comprise the edge and the two adjacent vault surfaces and have radial beds – similar to the keystone of an arch (Figures 6 and 8). Apparently, these elements also exist in Reims Cathedral, while in other comparable vaults they are absent: for instance, in the narthex vault in St Denis, there is a continuous joint in the ridge instead (Figure 10).

Other features of the vault, such as the masonry structure on the extrados or the detailing of the springers, also subject to current research, will have to be discussed elsewhere.

3 GEOMETRIC CHALLENGES IN BUILDING THE VAULT MASONRY

The main difficulty for creating the regular pattern of block masonry in the shells of the vault is given by the fact that the concave double-curved surfaces are not geometrically defined. In the characteristic pattern, which is already present in Saint-Denis (Figure 10), the courses are parallel to the ridge and therefore not horizontal in most parts of the shell (Figure 7): this is due to the inclination of the ridge and also to the different curves of the ribs resulting in different lengths.

If, on the contrary, the shells were built with horizontal beds from the bottom to the top, for the same geometric reasons a pattern would result where the courses intersected the ridge line in an angle, requiring a seam or ad hoc cutting of the blocks in the summit of the vault. This is visible e.g. in the high vaults of Durham Cathedral (11th century), and also in vaults with exposed masonry from later times (Wendland 2008). Within the surface geometry of Gothic rib vaults, it is generally impossible to obtain courses parallel to the ridge just by proceeding with horizontal beds.

Another characteristic feature of the shell masonry is given by the different heights of the courses: the carefully dressed blocks (Figure 3) have the same height only within the same course, but their dimensions are not uniform throughout the surface (Figures 1 and 6). A similar pattern also occurs in walls and pillars built in stone, where it has been correlated with the characteristics of planning and building organization in the development of the mediaeval building workshops (Kimpel 1977; Kimpel & Suckale 1995, 36).

Figure 3. Recovered stone block from the high vaults in Notre-Dame, at the LRMH (DW 2019).

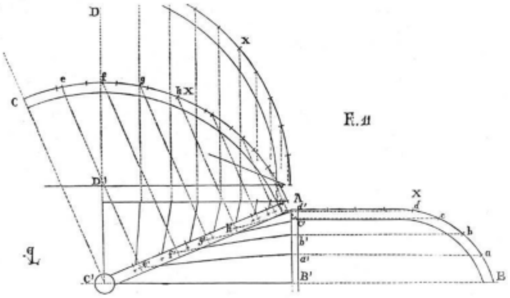

Figure 4. Viollet-le-Duc, construction of the masonry pattern in a cross vault (1847, 195).

The ridges, following very regular curves, during construction were surely guided by centring on which the ridge stones, similar to keystones, could be laid (Figure 8). The surface continuity on the intrados suggests that these stones were put in place first, and the upper courses of the shells were then set against them. As mentioned, Viollet-le-Duc developed a description model for the texture of the vault masonry (Figures 4 and 5) that turns out to be inconsistent at closer look. He started the construction of the masonry pattern with the division of the extradoses of the formeret and the transversal arches, respectively, in regular intervals. This was carried out in the elevation, providing a joint in the ridge. The extrados of the cross rib was then divided into the same number of intervals as the

Figure 5. Viollet-le-Duc, construction of masonry texture with deviation in the block dimensions (1859).

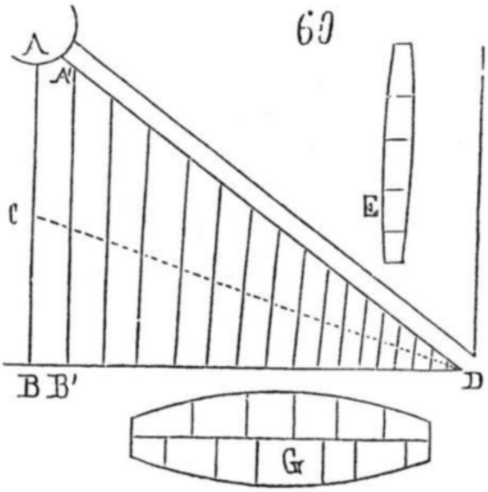

Figure 6. Notre-Dame, detail of the vault in the eastern bay of the nave: masonry pattern and ridge stones (DW 2009).

corresponding arch, in order to draw the lines that define the footprints of the courses in the triangular vault surfaces. This, however, did not ensure the equidistance of the courses at both ends. The drawings also show that Viollet-le-Duc assumed a joint in the ridge, instead of the ridge stones that can be seen in Notre-Dame (Figure 6).

The courses of the shell masonry are finally defined by vertical circle segments over these lines, with a uniform radius. Due to this curvature, Viollet-le-Duc sees variations in the height of every course (Figure 5, E and G), which had to be corrected by cutting the blocks down to the right size as they were laid. At both ends of the courses, the height was less than in the middle. This was supposed to happen especially in the highest courses. The ad hoc cutting for correcting the dimensions of the blocks, as he reckoned, could be carried out directly on site without the need of drawings by the mason proceeding “without even noticing it”.

As to the construction process, the steep lower portions were easily built free-handed, while in the upper portions the single courses had to be supported each by a centring. Once a course was completed, it was stable due to its curvature. These centrings could be easily produced because of the uniform radius. They had to be placed in vertical planes, as Viollet-le-Duc points out in the second version of his description (1859), where he also proposed the use of a sliding centring that adapted to the length of the course to be built.

The systematic ad hoc corrections that would be necessary according to this description, however, don’t correspond to the evidence on the samples of blocks we analysed (Figure 3). Although some oblique cuts with rough axe blows are visible where a block rested on the extrados of a rib, in general the surfaces in the beds show the fine chisel marks from their production in the stone workshop, without secondary alterations. In reality, these deviations must have been very small: by modelling the masonry pattern based on parallel lines and applying the curvature, we found deviations of ca. 2 mm, which would be easily compensated in the mortar joint and certainly not require any cutting of the blocks. Ad hoc cutting surely occurred in some courses where the direction of the pattern had to be corrected, but definitely not in the systematic manner described by Viollet-le-Duc.

However, the major problem in Viollet-le-Duc’s description model is the fact that with the proposed procedure the constant height of the courses is not ensured, because their starting points are not necessarily equidistant.

The constant height within a course is essential in block masonry:

Even if, like in the case of the vaults we analysed, the heights differ from one course to the other, by all means, within one single course the height is constant and the blocks from serial production can be freely placed in any position. The courses with constant height can be modelled by drawing a straight line in the ridge, and then constructing equidistant lines between the ribs (Figure 7): the linear dimension in space from one line to the next must be the same in both ends.

Upon these lines, the bed joints visible on the shell intrados can be constructed with circle segments in vertical planes, again with a uniform radius (Figure 7, top).

In practice, the setting-out of the masonry texture can be performed directly on the ribs, using the centring for the ridge as reference (Figure 8).

The parallel lines that determine the direction of the courses can be drawn starting from the ridge and proceeding downwards: By means of a square, a fixed distance is measured perpendicular to the centring, and marks are applied on the rib extradoses. On these marks a ruler is placed, and the procedure is repeated as many times as needed (Figure 9). The resulting lines for the courses will not be horizontal, but result strongly tilted especially in the lower portions (Figures 7, 9, 10). Probably only generic lines for guiding the direction of the courses could be

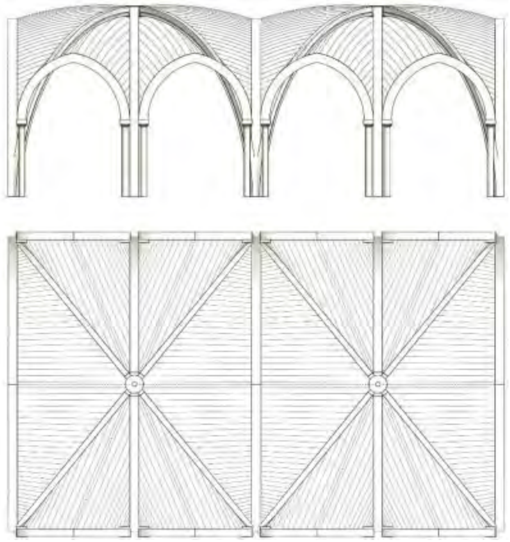

Figure 7. CAD model of the masonry texture, with courses running parallel to the ridge with uniform curvature (MG).

Figure 8. The ridges of the shells are made with special pieces that were assembled on the centring, cf. Figure 6 (DW).

drawn, as the heights of the courses were obviously not predetermined: hence, the exact position of the beds couldn't be planned beforehand. But numbered marks on the ribs could have helped to guide the direction and apply the necessary continuous corrections.

As mentioned, the pattern cannot be created by building the caps with horizontal beds. Both in Saint-Denis, where the courses are straight (Figure 10), and in Notre-Dame, where they are curved as arches, only the very first courses of the shells are horizontal or randomly tilted. Already in the lower portions, the precise direction parallel to the ridge is assumed by more or less sudden changes in the courses. It must be stressed that in order to determine this orientation, suitable guidance and a system of position control were absolutely necessary.

For the construction of the shell, the straight courses in Saint-Denis had to be supported, which could be accomplished very easily with wooden laths spanning from one rib to the other: this formwork had to remain in place until the vault was completed. Whereas in the high vaults of Notre-Dame each course could be stable as soon as it was closed, working as an arch. However, for proceeding with self-supporting masonry courses, which enables free-handed vaulting, the courses could as well be arranged with both ends in the same level, without constraining their direction parallel to the ridge (Wendland 2008).

Figure 9. Setting out equidistant lines to the ridge on the rib extradoses, for guiding the masonry courses of the shell: this is easily done using a ruler and a square (DW).

Figure 10. Saint-Denis Abbey Church, vault in the narthex, ca. 1135. The vault masonry is in exposed stone masonry with courses arranged parallel to the ridge, except for the lower portions where they are horizontal. Unlike in Notre-Dame, the courses describe straight lines (DW 2012).

4 CONTEXT AND SIGNIFICANCE

4.1 *The high vaults of Notre-Dame in the history of Gothic vaulting*

The close direct relation of the vaults in Notre-Dame with those of the Abbey Church of Saint-Denis (Figure 10), where the building of the western portions started around 1135 (Crosby 1987), is obvious and universally recognized. Unfortunately, many other structures within the immediate context that would be important for understanding both in their significance and historical position, no longer exist in their original state. This is the case, for instance, for the sexpartite vaults in the Norman churches of St.-Étienne and Ste-Trinité in Caen, which can be seen as a key reference for Saint-Denis. Both vaults have been dismantled and reconstructed in much later times (Frankl & Crossley 2001), obviously completely altering their shape. What still remains is the construction of the ribs with profiled blocks, very similar to Saint-Denis and also Notre-Dame in Paris, while in earlier examples (e.g. in Speyer and Moissac), the ribs were built with plain blocks. The spatial conditions given by the curves of the sexpartite rib system and the boundaries suggest that the geometric concept was that of the Gothic vault, with simple geometries in the ribs and arches and complex geometries in the surfaces. This definitely applies to the next existing great Norman rib vaults: the high vaults in Durham Cathedral built around 1115 (Frankl & Crossley 2001). In Saint-Denis, in the vaults of the narthex and in the ambulatory this constructive and geometric system is also clearly developed and, as an additional feature, combined with stone masonry in the shells arranged in a regular pattern parallel to the ridges, as we have seen: the construction is essentially different from that in Durham, where the vault masonry, probably not meant to be visible, is built with horizontal courses that reach the ridges with an angle. A precedent of vault surfaces in exposed, dressed stone may be seen in the crypt of the Abbey Church Saint-Gilles in the south of France, also from the early 12th century: Here, the geometric difficulties of arranging the courses parallel to the ridge are minimized because the shape of the vault is strongly surbased. The effort of creating perfect stone surfaces in the shells is more than obvious in this building.

We cannot say whether or how this visible stone pattern was applied in the original high vaults of Saint-Denis or in the later related constructions, the cathedrals of Noyon and Sens (Kimpel & Suckale 1995): all these vaults have been replaced in later times. But what we can say for sure is that the high vaults in Notre-Dame in Paris mark a crucial step in the development of the design coined in Saint-Denis for sheer dimension: it was the first time that this vaulting system was used over such a huge span and in such tremendous height. Many details in this pioneering construction differ from what we are used to referring to as "typical" Gothic vault design which developed in the interrelation between the later great cathedrals' construction sites, and then also radiates back on the high vaults of the second campaign in Notre-Dame. For instance, the ribs were built individually from the springing onwards: in some parts we observe refined connections between the lower rib portions and the wall, but the tas-de-charge is not yet present in the way we are familiar through Viollet-le-Duc's drawing from Amiens. Nor has the *en-délit* shaft yet been translated into longer rib voussoirs. In all these formal and technical aspects, the high vaults in Notre-Dame become tangible as a key work in the development of Gothic vault architecture.

While the regular stone surfaces in the shells of the vaults are obviously a guiding theme in Saint-Denis and Notre-Dame, and also appear in later great cathedrals such as Reims and Amiens, this feature is not at all mandatory: It is absent not only in earlier structures, but also in ambitious churches that are contemporary and closely related, e.g. Saint-Germain-des-Prés in Paris – and even in great cathedrals such as Cologne, where the vault masonry is plastered on the intrados and only the ribs are in exposed stone. We must therefore underline that it is a special feature, and ask for the significate.

Figure 11. Stereotomy in the curved arches of the chevet of Notre-Dame (M. J. Ventas Sierra 2009).

4.2 *Vault construction and stereotomy*

Compared with the narthex of Saint-Denis, the shells in the high vaults of Notre-Dame are more refined in their design with the apparently regular double curvature of the surface, and with the introduction of the ridge stones: this element with shaped intrados and radial beds goes beyond the concept of masonry. Yet, shells and ribs were conceived and constructed as block masonry: with shells, this is reasonable due to the shape that is not geometrically defined. But with ribs, the routines for stone planning in arches with radial voussoirs could have easily been applied.

This is peculiar because, on the other hand, stereotomy plays an important role in the architecture of Notre-Dame – just like before in Saint-Denis, and, in close geographical and chronological vicinity, in the Parisian abbey churches of Saint-Martin-des-Champs and Saint-Germain-des-Prés. In particular, we refer to the arches in the chevets and radial chapels, curved both in elevation and in plan, which are composed of voussoirs carefully planned and cut according to their three-dimensional curvature (Figure 11) – "twisted voussoirs" as explained in the lodge book by Villard de Honnecourt (Hahnloser 1972, pl. 39; Wendland 2019, 50). This contrasts with the construction of the ribs. But the common denominator is that in the architecture of Notre-Dame, all surfaces are decidedly in exposed, dressed stone assembled in the greatest perfection, consistently avoiding any sight of stones cut ad hoc.

4.3 *Construction and symbolic meaning*

As pointed out, we couldn't perceive any major technical advantage of the peculiar masonry pattern in the vaults compared with possible alternatives. It seems that this construction cannot be considered to have been motivated by improved or efficient working techniques. On the contrary, we find extra difficulties. From the merely structural and constructive point of view, there isn't even the necessity of building the vaults in dressed stone instead of rendered masonry. This draws us away from interpreting this structure in the terms established in the 19th century, as perfect construction driven preliminarily by structural and procedural rationality.

The meaning of this construction is therefore likely to be not only, or even other than, technical. We may try an interpretation related to the symbolic significance of the Cathedral, as von Simson elaborates it (1954). Among other aspects, there is the reference to Solomon's Temple, which is explicitly found in written sources, e.g. in the text of the inauguration liturgy. This reference is plausible also regarding the close connection between the building of Notre-Dame and the King (Kimpel & Suckale 1995, 148): the image of the Temple built by King Solomon is more than apt for valorising the position of the King of France. Citations of the Temple can be seen in some aspects of the architecture of the cathedral, even in the galleries and the crown of chapels that surround the apse – typological elements that are not stringently motivated in their function, but have a straight-forward relation to the Biblical description of the Temple having raised galleries and "side chambers all around" (1 Kings 6:5). We propose to interpret in this sense as well the great importance of dressed stone surfaces, so particular in the architecture of Notre-Dame, e.g. the ostentatious presence of complex stereotomy in the curved arches in the apse as well as the vaulted ceiling entirely made of dressed stone. Here, the masonry pattern gives a special sense of regularity: of perfect assembly without needing to cut any stone to its shape.

Richard Etlin speaks of "an iconography of stereotomy" (2012) when he reads the efforts of creating conspicuously complex structures in dressed stone in Early Modern architecture as references to the Temple, built "with stone prepared at the quarry, so that neither hammer nor axe, nor any tool of iron was heard …while it was being built" (1 Kings 6:7). A similar early modern example is the royal monastery El Escorial, where flamboyant stereotomic solutions are a main feature of the architecture, and where the reference to the Temple is unambiguous (Wendland & Ventas, in prep.). In the same line, we could think that the very special stone construction of the vault in Notre-Dame, like in the narthex and choir chapels of St-Denis, could be seen as an architectural expression of the symbolic reference to the Temple: stonework that appears to be assembled without working the stones on site, the ceiling of the Temple.

5 CONCLUSION

The architecture of Notre-Dame, and the vaults in particular, can only be understood through the integration of visual arts, architectural design, and construction. Thus, through detailed analysis of the planning and building processes, the construction of the vaulted ceiling becomes understandable as a historical source. This reveals the extraordinary historical value of the construction – of the masonry shell! – in view of the further steps to be undertaken in the restoration. Literally, every part of the vaults and every single stone must be conserved in its original state with the maximum care. The integration must be carried out with the highest fidelity to the original: any repair or reconstruction based on the problematic description model established by Viollet-le-Duc, or on any other modern ideas of construction, will adulterate the original fabric in its quality of historic document.

Both for understanding the historic artefact, and for its recovery and restoration, detailed archaeological surveys are as mandatory as a thorough understanding of the structure, of its making and of its design – studies for which we propose a methodology.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Geometry and construction of the severies of the vaults in the Cathedral of *Notre Dame de Paris*

R. Maira Vidal
Instituto de Historia, Consejo Superior de Investigaciones Científicas, Madrid, Spain

ABSTRACT: The fire at Notre Dame de Paris Cathedral shocked the world, which watched in disbelief as flames devoured one of the most important early-Gothic cathedrals in medieval Europe. Some vaults in the transept and in the main nave collapsed completely or in part. Reconstruction will require addressing one of the most complex challenges of recent decades.

The results of the geometric and construction analysis carried out before the fire on a three-dimensional model created using a laser scanner have brought to light extremely important information for the restoration works based on the thorough knowledge of medieval construction. The severy surfaces of the Parisian cathedral have double curvature. By comparing all the courses with each other, we were able to confirm the geometry rules governing these structures and form hypotheses about the auxiliary structures used.

1 RELEVANCE OF THE DATA: LOSSES AFTER THE FIRE

The fire that broke out at the Parisian cathedral two years ago, in April 2019, caused considerable damage to its vaults. The quadripartite vault in the central transept collapsed while the sexpartite vaults in the north transept and the first two sections of the nave disappeared in part. The severies were particularly damaged (Mouton 2019).

The vault analysed is one of the vaults affected and is in the second vaulted section of the nave from the transept, which makes the results presented here especially relevant. Five of the six vault compartments have survived. The large east severy has been lost completely, after collapsing together with the west compartment of the adjoining vault to the east. The severy surface of its north-east splayed side compartment, which also suffered significant damage, has a large hole in the centre of its east half (Figure 1A).

This article presents the results of the first comprehensive analysis of the severies of the Parisian cathedral's vaults carried out using a laser scanner survey that was conducted before the fire (Figure 1B). This data will be of use for future restoration work, which will soon have to be undertaken on the damaged vaults.

The vault severies are the least studied elements in this type of structure (Palacios Gonzalo 2009). Some original documents and illustrations in stained glass windows and miniatures dating from the 12th and 13th centuries still exist, but no illustrations or texts that describe the construction of these stone surfaces, nor the scaffolding that was used, have been preserved (Ibáñez Fernández 2019).

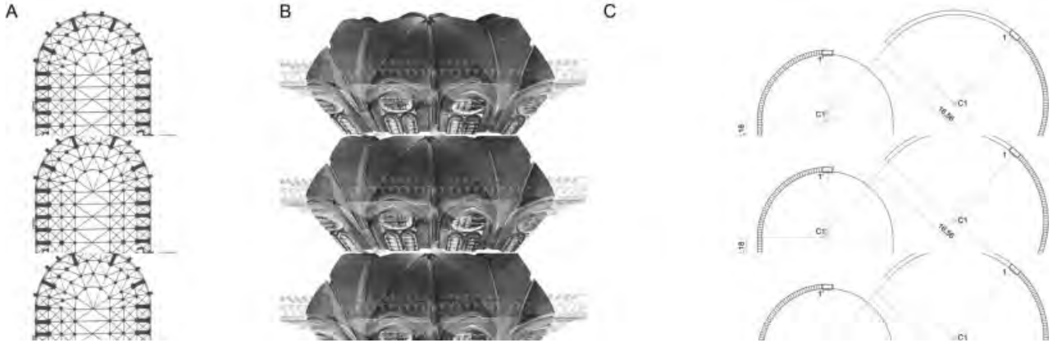

Figure 1. A. Collapsed vaults and vault analysed in the Cathedral of Notre Dame de Paris. B. Laser scanner survey of the vault analysed. C. Full size drawing. Author's drawings.

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Figure 2. Vaults in the nave in 2013. Author's photograph.

In these vaults, each course of severy stones forms a different arc on the supporting ribs; the rise of each course, measured at the centre of the span formed by the straight line between the two ends of each arc, varies. Curved courses reduce the time required to dismantle the formwork that provides stability, but it complicates the setting out and design enormously, which will present a challenge for future reconstruction.

The Parisian vaults are among the largest European sexpartite vaults, covering spans longer than 13 metres. Their severies bear witness to the knowledge and technological development at the dawn of the Gothic period.

These vaults are one of the main examples of sexpartite vaults in Europe (Figure 2). Their geometry served as a model for many medieval buildings. They constitute the most important and influential example of one of the most widespread typologies of sexpartite vault in the north-eastern half of France and in the central part of Europe, territories belonging to the ancient Carolingian empire (Maira Vidal 2017a, 2017b). The geometry of the central rib, which is semi-circular and stilted 2.18 metres above the impost line, is the vault's most distinctive feature and complicates the auxiliary structures used for construction as the formwork had to be raised above this rib (Maira Vidal 2016b). The centres of the semi-circular diagonal ribs are on a level with the impost line and the transverse ribs are pointed (Figure 1C). The geometry of the central rib distinguishes the sexpartite vault from other typologies and determines the shape of its side severies.

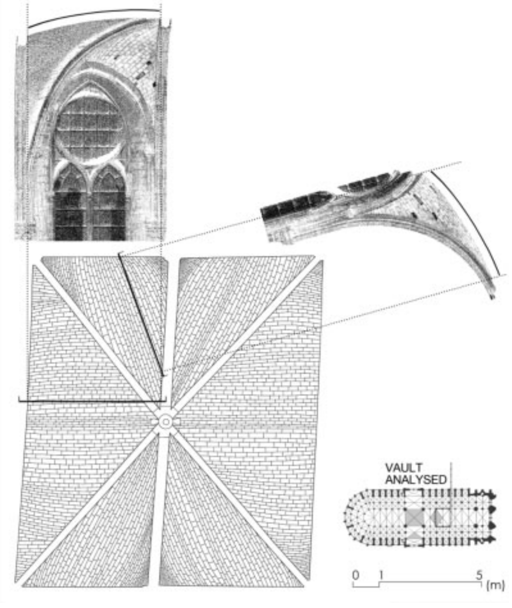

Figure 3. Methodology used to analyse the curvatures of each course of severy stones. Cross-section of two courses showing the circle arc considered. Author's drawing.

2 MEASUREMENT, DATA PROCESSING AND ANALYSIS METHODOLOGY

The geometry was analysed using the point cloud obtained with a laser scanner. First, its life-sized drawing was analysed (Figure 1C), defining the geometry rules that governed the design of the ribs (Maira Vidal 2017b). Subsequently, the severy surfaces were analysed based on cuts in the three-dimensional model, made in the centre of each of the severy stone courses. This thorough process allowed each course of severy stones to be studied separately, defining the maximum rise, the distance and the difference in height between the two supporting ribs (Figure 3). These data were subsequently processed in numerical tables to obtain the rise-to-span ratio and the inclination of the course. After separately analysing each different course in a compartment, an overall analysis was carried out comparing the different courses in both the same compartment and the different compartments. The numerical analysis was complemented by the overall comparison of the curvature of the different courses. The findings enable prior design patterns, if any, to be detected, and to define the geometry used in construction and the resources used in assembly.

Error in the point cloud model used for study is minimal, less than one centimetre, but deviations from the actual vaulting geometry can be appreciated when interpreting the values. The rise was analysed using the ideal curvature that best matched the actual curve of the course. In some courses, there are slight differences, not exceeding two and a half centimetres, where the severy surface diverges from the ideal curvature, probably due to movements during assembly or subsequent deformations. These are such small errors that they are considered acceptable when interpreting the data, allowing reliable conclusions to be reached.

The point cloud also enabled an exploded view of each course of stones to be obtained, in order to determine the number of stones and their size (Figure 4). It is interesting to understand the stereotomy of the pieces and the tools used.

3 STANDARDISATION IN THE EARLY GOTHIC: SEXPARTITE VAULTS

My doctoral thesis studied the construction of the sexpartite vault in Europe (Maira Vidal 2016a). I measured and analysed a total of 59 vaults in the principal European countries: France, UK, Spain, Germany, Italy and Switzerland. In previous publications, I broadly compared the shape and construction of the severy surfaces of the European sexpartite vaults analysed (Maira Vidal 2017a, 2017b). These studies allowed me to confirm that the vast majority have ruled surfaces, that is, their severy courses were laid horizontally between the supporting ribs. Only in some of the great European cathedrals, such as Notre Dame de Paris, Bourges, Lincoln, Bremen, Piacenza or Lausanne, and some others, did the vaults have double-curved surfaces, where the severy stones form small arches between the supporting ribs.

This system has many advantages during construction, but it also involves certain difficulties for setting out.

4 GEOMETRY AND CONSTRUCTION CHARACTERISTICS OF THE LARGE SEVERIES

Large severies form the most unstable surfaces of the vault, and the damage caused by the fire is proof of this. In all three instances of vaults that partially collapsed, the area affected is in one of these large compartments. The spire, built by Viollet le Duc, that topped the transept, fell onto one of the vaults (Del Ser & Romero 2019; Mouton 2019). But, the smaller adjacent compartments withstood the collapse and the related movements and vibrations, despite the extreme temperatures to which their intrados surfaces were subjected.

The higher courses of stones in the large severies form lowered, practically horizontal, arches. This, in addition to the enormous span they cover, which reaches nearly 5.50 metres, constituted one of the greatest difficulties for construction. The curvature of the courses reduces the risk of collapse during construction, but it complicates auxiliary resources and previous setting out to a greater extent.

4.1 *The missing large east compartment*

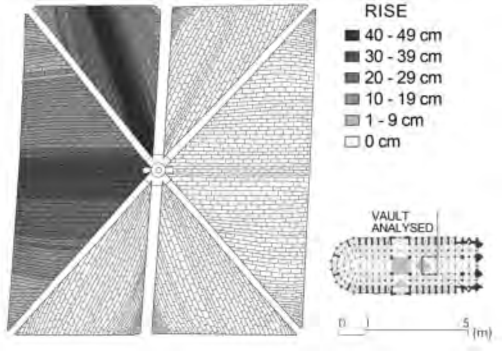

Figure 4. Exploded view of the vault severy analysed. Each sector indicated groups together courses with the same rise. Author's drawing.

Although this surface appears to be symmetrical on its longitudinal axis, if we divide the compartment into two halves along the ridge, the number of courses, rise and curvatures show that the two sides are asymmetrical (Figure 4). Although the rise of the severy stone courses increased as they neared the keystone, it did not increase equally on each side. The curvature was, therefore, different in the two halves, but the difference was practically invisible to the naked eye. While in the north half the rise gradually increased in consonance with increasing spans between the supports, on the opposite side the rise remained relatively low up to the top six courses.

We divided the north half into four sections, each with a similar number of courses based on the rise (Figure 4), which in the lowest quarter ranged between 1 and 10 cm, in the next quarter between 11 and 20 cm and then varied between 20 and 30 cm. In the last quarter, it exceeded 30 cm. In contrast, in the south half, the rise of each of the top six courses ranged between 20 and 36 cm, while the remaining area could be divided into another two distinct sectors: in the top sector the rise of the courses ranged between 10 and 20 cm, while in the lower sector it remained below 10 cm. The north half had only 44 courses while the south half had 50. This difference in number involved using the same rise in courses covering different span lengths between the supports on either side of the compartment ensuring the required height was covered up to the keystone.

When comparing the ratio between the rise and the span covered by each course, there are noticeable differences between the two halves of the severy. In the north half, rise-to-span ratios ranged between 1/17 and 1/11. Here, the first course of severy stones above the springing did not have a rise at all, and the courses were laid as lintels on the supporting ribs. In the south half, the rise-to-span ratio ranged from 1/15 to 1/35. Only the first courses on the springing exceeded these values, reaching a rise-to-span ratio of 1/9, despite covering the shortest lengths between supports.

This comparison between the rise and the span of each course confirmed the absence of a constant relationship between the two values, indicating that the arches had not been built to a previous design based on the rise-to-span ratio. This hypothesis is reinforced by the fact that several courses with the same rise cover different distances between supports. While in the south half courses covering distances between 5.40 and 5.50 metres were found to have a rise of little more than one foot, in the north half this same rise was used for courses with a 4.50 metre span. In addition, the increase in rise was not linear; although it increased as the courses needed to cover longer spans, in some courses it was lower than in preceding shorter courses. These differences were small, equal to or less than 2 cm, and, in no case, greater than 4 cm.

The rise of the courses covering the longest spans of 5.50 metres between supports, ranged between 36 and 37 cm. At the bottom of the severy surface, the courses immediately above the springing were required to cover distances between supports of approximately 50 to 90 cm with an almost non-existent rise of just 1 to 2 cm. They were lintel courses. The function of these low rise-to-span ratios would have been to provide stability to the whole severy during assembly and would not have been noticeable after the structure was finished.

The courses of severy stones were slightly inclined towards the transverse rib because the supports on either side were at different heights (Figure 5). The most inclined courses were in the third quarter, near the top of the vault. In the south half, the height difference between supports in the first 20 courses began at zero and increased to half a metre. Just before reaching the top half of the surface, this height exceeded 60 cm. The same data were reproduced in the north half, but, in this case, the distance between supports was longer, exceeding half a metre after the first ten courses. Again, the data show the surface to be slightly asymmetrical.

By superimposing the curves of the different courses to compare the geometry, we can confirm that they are not the same arc of a circle. They are different lowered arches with inclinations that increase with the height of the compartment. The first courses are shorter with a lower rise, while the upper courses are much longer and more curved.

The ridge course comprises 19 severy stones. After that, the number of stones per course gradually decreases until the bottom, where the course comprises one single lintel stone from side to side.

4.2 *The surviving large west compartment*

The two halves of this compartment are also asymmetrical, with 52 courses in the north half and 47 courses in the south half (Figure 4). The rise sequence also varies as the courses approach the ridge in both halves, as already seen in the opposite severy. The absence of a constant rise-to-span ratio enables us to affirm that they were not built to a previously designed model but were improvised during the building process. The master builder had to supervise the building of the courses to ensure they formed low-rise arches, in order to facilitate safe formwork removal after assembly.

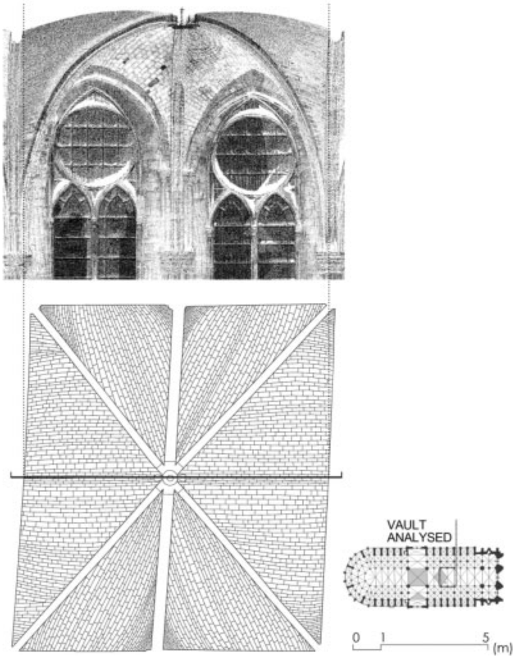

Figure 5. Longitudinal section of the vault along the ridge course. Author's drawing.

5 GEOMETRY AND CONSTRUCTION CHARACTERISTICS OF THE SPLAYED SIDE COMPARTMENTS

The double-curved severy surfaces of the four side compartments are splayed and distinctly vertical (Figure 1B). Although the ridge course covers a span around one and a half metres longer than the ridge of the larger compartments, the surfaces are more stable because they are splayed, providing greater resistance to movement, as evidenced by the collapses caused by the fire. On the other hand, this shape does not favour setting out and construction owing to the narrow supports and the difference in length of the diagonal, transverse and wall ribs that support the severy courses. The direction of the severy stones had to be corrected by using wedged courses to overcome the differences (Maira Vidal 2016b).

The surfaces are asymmetrical around their longitudinal axis along the ridge course that joins the central keystone to the wall rib (Figure 4). Neither the number of courses nor the curvature of the surfaces, as defined by the rise and the span of each one, are the same on either side. The shape of the surface above the vault springing is different on each side because of the angle between the wall arch and the diagonal and transverse arches. While the diagonal rib forms an acute angle with the wall rib, making the surrounding severy surface narrower, the transverse rib is perpendicular to the wall rib.

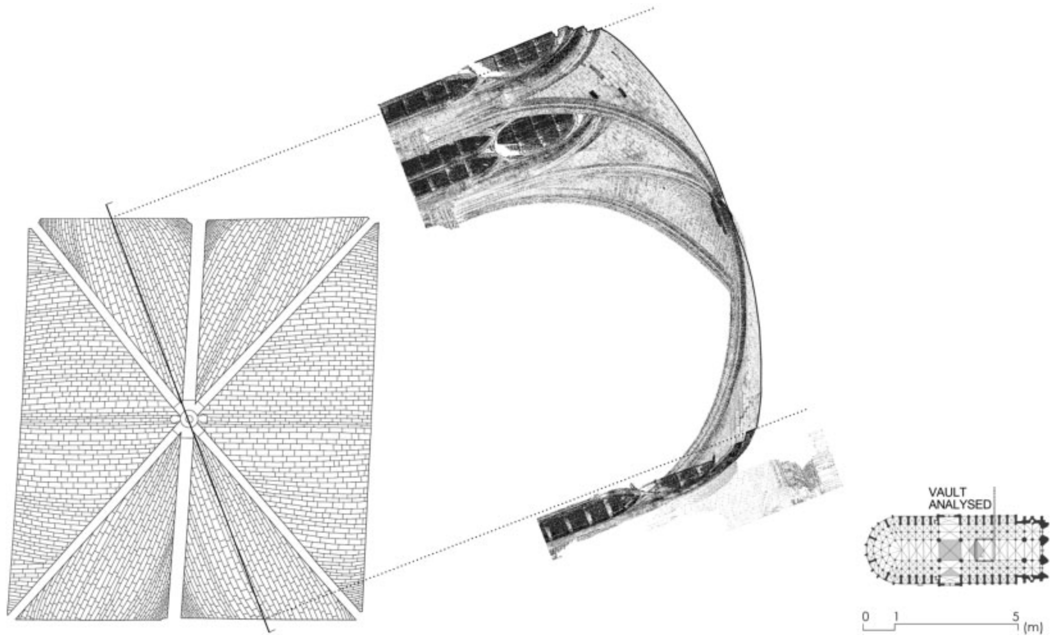

Figure 6. Cross-section through the ridges of two small severies on opposite sides of the vault. Author's drawing.

5.1 *The curvature of the courses in the splayed side compartments*

The severy surfaces of the four side compartments can be split into two halves around the central axis along the ridge course. Both surfaces are asymmetrical due to the vault's inherent characteristics, but, in addition, the rise does not increase equally on each side, producing different curves (Figure 4).

The geometry and construction characteristics of the severy surfaces of the four splayed side compartments are similar, which allows the same conclusions to be reached. Below are the results of the analysis of one of the side compartments, the one in the south-east corner of the vault.

The west half of the south-east splayed side compartment can be divided into four quarters according to the rise (Figure 4). The lower courses, located on the vault springing, have no rise. These are lintel courses, laid horizontally on the supporting ribs, which are 70 cm apart at most. In the next quarter, each rise is less than 10 cm and covers spans ranging from 0.5 to 2 metres in length. In the third quarter, this distance varies between 2 and 4.50 metres and the rise ranges between 10 and 20 cm. The rise in the higher courses, which cover spans between 5 and 7 metres, increases from 20 to 50 cm. In contrast, the east half can be divided into three sections according to the rise (Figure 4), which was less than 10 cm in the lower third where courses cover a distance between supports ranging from 0.50 to 1.30 metres. In the middle third, the rise increases from 10 to 20 cm in spans between 1.80 and 3.30 metres. In the top third, it ranged between 20 and 50 cm on distances between 3.50 and 7 metres in length. The asymmetry of the severy surfaces is especially visible at the bottom, since in the west half the first ten courses are lintel courses while in the east half only the first course has no rise.

Analysis of the relationship between the rise and the span of the different courses confirms again that the ratios are not constant. In the west half, the rise of the higher courses is considerable, with ratios ranging from 1/14 to 1/17 of the span. In the two central sections of the splayed compartment, the rise decreases notably despite covering long spans. Rise-to-span ratios vary between 1/21 and 1/27, although occasionally the rise-to-span ratio of some courses is as low as 1/56. This reduction could be related to the verticality of the surface, which is more pronounced in the lower half of the splayed compartment. In the east half, the rise-to-span ratio varies less, between 1/23 and 1/14 of the span between supports.

Differences in the rise of consecutive courses vary between 1 and 2 cm in the west half of the splayed compartment, except for the upper courses, where rise differences vary between 3 and 7 cm. In the east half they vary between 2 and 5 cm.

On both sides of the splayed compartment, there is less difference in height between the supports of the lower courses, not exceeding one metre. In contrast, in the upper courses, the difference increases markedly between one and two metres since the wall rib keystone is 1.88 metres lower than the central keystone of the vault (Figure 6).

There are 23 severy stones in the ridge course, the number gradually decreasing in successive courses. Again, the lintel courses allow us to affirm that the stones are straight, cut without a curve, which simplified work and reduced labour costs by requiring less skilled workers.

6 DIFFERENCES AND SIMILARITIES BETWEEN LARGE AND SMALL SEVERIES

Splayed severies are asymmetrical along the longitudinal axis as a result of their general configuration and vault characteristics. In contrast, large severies are symmetrical. In both cases, however, the rise and number of courses progress asymmetrically on either side of the longitudinal axis, producing a slight asymmetry in curvature.

In the case of the side splayed compartments, the higher courses cover a significantly longer span, with a distance between supports of 7 metres, while in the large compartments the span is 5.50 metres.

When comparing the rise of courses in both types of compartments, similarities were found where courses cover similar spans between supports. For example, in the north half of the east compartment, course number 23 has a span of 2.53 metres and a 0.16 metre rise, while the span between supports of course number 12 in the east half of the south-east splayed compartment is 2.43 metres with a rise of 0.15 metres.

However, when grouping the courses by rise height, they are seen to correspond to different ranges of span in each half of the compartment, although some areas overlap allowing courses with similar values to exist in different severy compartments (Tables 1, 2, 3, 4):

There is a less pronounced difference in height between supports in the large compartments, ranging from zero to one metre, which progresses irregularly. Differences reach a maximum in the second third or third quarter, depending on each case, and then fall back to half of the maximum reached.

In contrast, the maximum difference in height between the two ends of the courses in the side splayed compartments is greater, up to 1.88 metres. However, height differences progress regularly, reaching their maximum at the severy ridge (Figure 6).

This increase in inclination of the higher courses in the small severies produced more thrust on the wall rib which had to be counteracted properly during assembly to avoid serious stability problems (Huerta 2004). By making these courses curved, the thrust was less horizontal and more vertical and thus the wall arches became more stable (Heyman 1999).

The severy stones are the same size in both types of surface, where ashlars ranging between 0.10 and 0.20 metres in width, and 0.15 and 0.45 metres in length were used. The thickness of the ashlars was estimated from the photographs of the collapses after the fire (Del Ser & Romero 2019), by comparing the thickness of the ribs, which is a measured value in the model, to

Table 1. Ratio of rise-to-span between supports. South half of the large east compartment.

Courses	Span between* supports metres	Maximum rise* metres
H1-H4	5.50-5.40	0.36-0.30
H5-H7	5.40-5.00	0.30-0.20
H8-H28	5.00-2.00	0.20-0.10
H29-H50	2.00-0.16	0.10-0.01

* The figures have been rounded in these tables for easier reading and comparison.

Table 2. Ratio of rise-to-span between supports. North half of the large east compartment.

Courses	Span between* supports metres	Maximum rise* metres
H1-H8	5.50-4.50	0.36-0.30
H9-H21	4.50-3.00	0.30-0.20
H22-H31	3.00-1.50	0.20-0.10
H32-H34	1.50-1.00	0.10
H35-H44	Less than 1.00	0.00

* The figures have been rounded in these tables for easier reading and comparison.

Table 3. Ratio of rise-to-span between supports. West half of the south-east splayed side compartment.

Courses	Span between* supports metres	Maximum rise* metres
H1-H3	7.00-6.15	0.50-0.40
H4-H5	6.15-5.50	0.40-0.30
H6-H7	5.50-4.50	0.30-0.20
H8-H14	4.50-2.00	0.20-0.10
H15-H21	2.00-0.70	0.10-0.05
H22-H32	Less than 0.70	0.00

* The figures have been rounded in these tables for easier reading and comparison.

Table 4. Ratio of rise-to-span between supports. East half of the south-east splayed compartment.

Courses	Span between* supports metres	Maximum rise* metres
H1-H2	7.00-6.50	0.50-0.40
H3	6.50-6.00	0.40-0.30
H4-H8	6.00-3.50	0.30-0.20
H9-H14	3.50-2.00	0.20-0.10
H15-H21	2.00-0.50	0.10-0.03
H22	Less than 0.50	0.00

* The figures have been rounded in these tables for easier reading and comparison.

the severy stones that remained attached. The average thickness must be approximately 0.27 m.

7 CONCLUSIONS: STEREOTOMY AND AUXILIARY STRUCTURES IN COMPARTMENT CONSTRUCTION

The comparative analysis of the geometry and construction of the severy surfaces, studying each compartment and each of the courses of stone they contain, enabled us to confirm the absence of a prior design defining the curvature of the surfaces to be built.

We did not detect a constant relationship between the spans covered by the courses and the rise of each course. The rise of higher courses of stone near the top of the compartment increases differently in the two halves of one compartment. In addition, the two halves do not have the same number of courses; the number of lintel courses on the springing of the vault is also different on each side, and even the rise used over similar spans is different. These inconsistencies are the result of the work of different crews of workers, each working on one side of the compartment and not using a geometry previously defined in a full size drawing. However, they all worked to the same guidelines: build small, lowered arches with a minimum rise to reduce the risk of the course collapsing until the severy surface is completely filled in and becomes self-supporting. Each crew would build the courses with different arcs, defining their curvature in situ depending on the preceding course. The first courses on the springing were lintel courses between the supports. The rise then gradually increased until reaching a rise a little over one foot. Work would have been done on the two halves of the same compartment at the same time, and construction of all the compartments was likely to begin at the same time, so that the thrusts of the structure remained symmetrical during construction.

Comparing the geometry of the arch formed by each course of severy stones confirmed them to be different arcs of a circle, indicating that small sections of curved formwork (Fitchen 1981) that were moved from one course to the next were not used, as some authors such as Viollet Le Duc (1996) have suggested. Rather, simpler less sophisticated methods would probably have been employed (Archilla Salido 1931-50). Perhaps slightly roughened wooden logs would have been placed between the support ribs on which stone or wooden wedges would be placed to support the courses, raising them little by little until they reached the maximum rise in the centre of the span (Figure 7). These auxiliary structures would have allowed costs to be reduced and logs and uprights could be used in successive courses, after safely removing the scaffolding once the arches were completed, provided that their horizontal thrusts had been properly counterbalanced in the absence of the adjacent vaulted sections.

The lower courses of the compartments, with no rise and built with several severy stones, confirm that these pieces were straight. Quarry work presented no difficulty since prismatic ashlars were used, cut without curvature, which simplified and lowered costs as the workers who cut them did not need to be as skilled as those cutting the stones for the ribs, which were much more complex. By not using curved wooden formwork, lower-skilled carpenters could be employed.

Figure 7. Reconstruction of one of the vaults in Sigüenza Cathedral after Spanish Civil War. Archilla’s photograph (Archilla Salido 1931-50).

After analysing the severy surfaces at the beginning of the Gothic period in detail, we can once again admire the adaptability and flexibility of the system, which enabled large, curved severy surfaces to be created using simple construction processes.

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Vaults on the water: A systematic analysis of the vault construction in the *Wasserkirche* Zurich

M. Maissen
Eidgenössische Technische Hochschule Zürich, Zurich, Switzerland

ABSTRACT: This paper examines the vault construction in the Wasserkirche in Zurich, Switzerland with regard to its geometrical design and the structural engineering of the building itself. Similar to numerous vault constructions in the Late Gothic period, the vault pattern of the Wasserkirche appears rather simple in its ground plan, but unfolds a highly complex geometry in its spatial configuration. In the following, the complexity of the vault construction is analysed, deciphered and simplified with state-of-the-art technical equipment and precise reverse engineering techniques. To provide additional support and better illustration, various visualisation methods are applied. In a final step, the results obtained are brought into a historical context by comparing them with contemporary and regional vault constructions.

1 INTRODUCTION

The Wasserkirche (“Water Church”) is located not far from Lake Zurich on the right bank of the Limmat between the two main churches Grossmünster and Fraumünster. The somewhat peculiar name of the church derives from its original location on a small river island, which is no longer directly recognisable today, as the church only borders the water directly on its left-hand side, whereas the right side facing the Grossmünster was backfilled during the reconstruction of the Limmatquai in 1839 (Figure 1).

For a long time, nothing was known about the early building history of the Wasserkirche. According to legend, the city’s later patron saints Felix and Regula, alongside their servant Exuperantius, were executed as members of the Theban legion on the small island in the Limmat in around 300 AD. After their beheading, Felix and Regula are said to have carried their heads 40 steps up the hill to the east, where they were eventually buried. Later, the Grossmünster was erected at this exact place while the Wasserkirche was built on the site of their martyrdom on the river island. It was not until an archaeological excavation in the years 1940–1941 (Vogt & Herter 1943) that the prehistory of the Wasserkirche and its predecessor were determined. The significant results of the first excavation campaign were confirmed and extended by a recent archaeological survey (Wild et al. 2005).

On the location of the Wasserkirche, pagan or Roman and even prehistoric cult sites have been assumed in historical sources, although any archaeological evidence in this regard is absent (Wild et al. 2005, 5). The first predecessor building (Building I) can archaeologically be dated to around 1000 – a first written reference of the Wasserkirche is only found in a document from 1250 (Baraud Wiener & Jezler 1999, 204–206). Building I was reconstructed twice before the small Romanesque church was replaced by a new Gothic church (Building II) in 1288. Building II was the first church in Eastern Switzerland to be built entirely in the Gothic style and, as a single-nave church with no external distinction between chancel and nave, corresponded to the type of palace chapel that emerged in France in the 13th century, such as the Sainte-Chapelle in Paris, or to mendicant churches. After severe structural damage, the demolition of Building II and the construction of today’s Wasserkirche (Building III) was considered in 1475.

Figure 1. The Wasserkirche from the west with the adjoining Helmhaus on the left and the Grossmünster in the background.

2 BUILT ON WATER

For the first time, the city council of Zurich itself acted as the main client of the Wasserkirche. For the construction of the new building, a master builder

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named Hans Felder the Elder, originally from Öttingen im Ries near Nördlingen (Bavaria, Germany), was recruited by the city council. Until 1472, Hans Felder was the *Werkmeister* of the city of Lucerne and was thereafter responsible for other church constructions in the canton of Zug. After becoming a citizen of Zurich on February 1, 1475, Felder only began to rebuild the Wasserkirche in the fall of 1478 at the earliest, but certainly over the course of 1479 (Baraud Wiener & Jezler 1999, 219–220).

On the new construction of the Wasserkirche a priceless contemporary manuscript has survived, which was written probably between 1485 and 1490 by a chronicler named Martin von Bartenstein. Today, the manuscript is kept in the Zentralbibliothek Zürich as *MS. A 118*, with parts of the text transcribed and reprinted by Ribi (1942). One passage on fol. 49v and fol. 50r is particularly interesting with Bartenstein recalling the construction of the foundations: he recalls that in the winter of 1479 the water level of the Limmat was unusually low, which made it possible to drain the substructure and work on the foundation. The predecessor building was subsequently demolished down to the ground level, with the existing foundations reinforced and reused (Ribi 1942, 103). According to Bartenstein, the reinforcement of the foundation was built on a pile foundation with a grid of oak wood, which was additionally filled with clay. The archaeological excavation of 1940/41 was able to confirm the sequence of work described by Bartenstein (Vogt & Herter 1943, 31). Moreover, this procedure corresponds to the contemporary approach of constructing pile foundation systems, which was such a complex and expensive process that it was quite common to reuse elements of the substructure of predecessor buildings (Maissen 2020, 245–247).

By reusing the foundations, which already occupied the maximum spatial extent of the island, the new building corresponded in its dimensions and ground plan to its Gothic predecessor. The Late Gothic building was thus rebuilt again as a single nave church with no external separation of chancel and nave. Similar to its predecessors, the Late Gothic Wasserkirche was built with a substructure and a crypt, in which the legendary execution stone of Felix and Regula as well as wall remains of the previous structures can still be seen. In addition to the exceptional reticulated vault, which will be discussed in detail, the Wasserkirche also contained rich interior decoration (Vogt & Herter 1943, 62–68, Plate 14).

Hans Felder completed the Wasserkirche in as early as 1484 after only five years of construction, with the ridge turret added in 1487. The new splendour of the Wasserkirche did not last long, however, as the Reformation hit Zurich particularly hard, which led to an iconoclastic fury and the devastation of the interior decoration in 1524–1525. After the Reformation, the Wasserkirche was converted into a warehouse, hence, two intermediate floors were added in 1580/83. In 1633, the Wasserkirche became the home of the public library, which would eventually become today's Zentralbibliothek Zürich. Due to the increase in books and works of art, the church and especially the adjacent Helmhaus were altered and extended throughout the 18th and 19th centuries. In the Wasserkirche, the intermediate floor was cut open into an oval in 1717, creating one of the first gallery libraries in the southern German-speaking region (Baraud Wiener & Jezler 1999, 228–242). After the Zentralbibliothek moved to its present-day location at the Zaehringerplatz in 1917, the Wasserkirche was once again used as a storage for comestibles.

Figure 2. Detail of the vault construction of the Wasserkirche.

After the First World War and lengthy disputes, it was finally decided to thoroughly restore the Wasserkirche. Work on the exterior had already begun in around 1927 but it took until 1939–1943 for the architect Hermann Herter to restore the original Late Gothic interior of the church. At the same time, the excavation campaign by Emil Vogt was conducted. Since 1943, the Wasserkirche has again served as a church but is also open to the public as a space for cultural, social and socio-political content.

3 VAULT CONSTRUCTION

In the following, the planning and construction of the vaults in the Wasserkirche (Figure 2) will be examined more closely. Although there are no references to the construction of the vault in the historical written

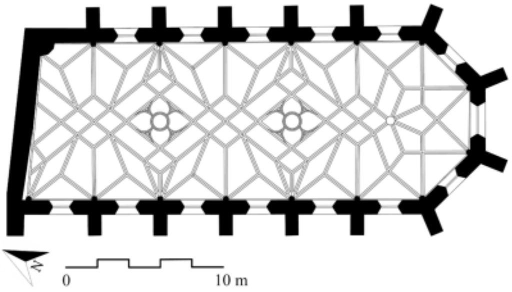

Figure 3. Ground and vault plan of the Wasserkirche generated and drawn from lasers scans and total station surveys.

sources, Hans Felder probably completed the vault just before 1484. However, the archaeological investigation by Vogt and Herter (1943) provides significant evidence and rare insights into the vault construction, since the plaster of the vault webs was also removed during the restoration of the interior. These findings, which have so far received little attention, will be discussed in the relevant sections.

3.1 *Designing the vault pattern*

The vault of the Wasserkirche (interior 27.6 × 9.9 m) unfolds on a rectangular ground plan over six bays of 4.2 × 9.9 m each and the directly adjoining 3/8 chancel bay (Figure 3). The northern wall facing the Helmhaus is slightly inclined towards the lateral walls of the church, since the northern wall was inherited from the previous Gothic building (Vogt & Herter 1943, 30).

The vault pattern itself is actually composed of two different systems, which will become increasingly important in the rib geometry. In the nave, we find a reticulated vault of parallel extending ribs, which additionally contain two tracery rosettes in the apex. The second system evolves after the middle of the southernmost bay, where the ribs extend into the chancel (see Figure 3): Here in the chancel apse, the ribs suddenly form a reel-star vault, which is a quite common vault pattern in Switzerland. This particular pattern can be created by repeating ribs of uniform length and radius (Maissen 2020, 45–50), thus simplifying the otherwise complex pattern in the vaults of the nave.

However, both of these systems can easily be designed in the ground plan with a compass and straight edge using an auxiliary grid (Figure 4): in a first step, the bays are drawn as well as centrelines in longitudinal and transverse directions. Then, the diagonally oriented auxiliary grid can be drawn by connecting the bay corners or springers at A and C as well as the bay's centre points at B across three full bays to A', B' or C' (1). By elaborating the auxiliary grid, almost all intersection points are already given and can be connected further – for example, the middle diamond pattern is already set and the lateral centre D can be connected to the intersection point E of the lunettes (2). Steps 1 and 2 can now be repeated for the remaining bays in the nave (3). To complete the vault pattern in the nave, only the short tierceron ribs F and F' from the springers to the first rib intersection are missing and can be added (4).

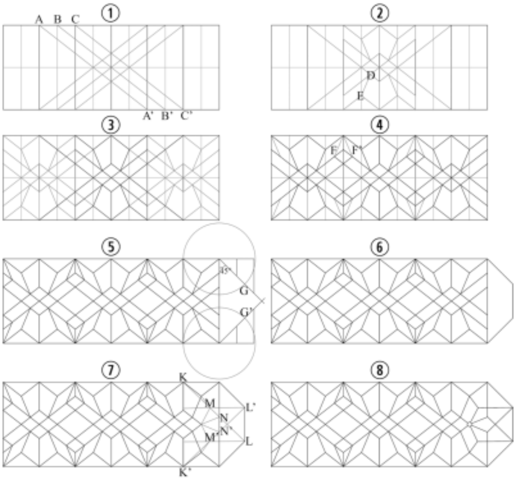

Figure 4. A possible reconstruction of the design process.

In the next step, the vault in the chancel area is designed (5): To draw the 3/8 chancel, the bay width is taken off at a 45° angle. The 45° angle can be drawn by an auxiliary construction or by a bisector. The intersection points G and G' can now be connected, thus completing the ground plan (6). The last few needed intersection points are defined by connecting the springers K with L and K' with L', so that the intersections M, M', N and N' are given and can be connected (7). The vault pattern is now – aside from the tracery decorations – complete (8).

3.2 *Constructing the ribs*

The vault pattern in the ground plan of the Wasserkirche must be considered with caution, because the real vault geometry only becomes apparent in the three-dimensional space (Figure 2). An essential detail is that not all ribs originate at the springers at the same height. The reason for this is that in the planning of the main parallel rib sequences, one bay was skipped at a time, thus creating differently weighted springers: the main springers with five ribs and the subordinate springers with only three ribs (Figure 3). The most obvious difference is in the transversal ribs, which arise at the main springers almost 3.3 m lower compared to their position at the subordinate springers.

Furthermore, this results in the necessity to widen the lateral ribs at the subordinate springers massively in order to have any contact with the vault webs above. Another remarkable detail is that the vertex of the ribs in the chancel area is slightly higher than the vertex of the nave ribs. This causes the apex in this part of the vault not to be directly at the keystone, but rather to shift towards the intersection points M and M' (see Figure 4, step 7).

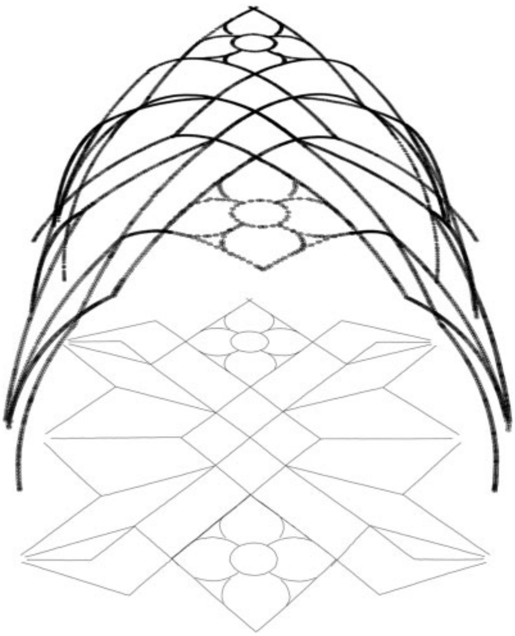

Figure 5. Total station survey of the central part of the vault.

Table 1. Computed radii of tierceron rib sequences.

	Radius (m)	Max. Dist. (m)	Mean Dist. (m)
T01	6.6225	0.007923	0.001752
T02	6.6587	0.007076	0.001731
T03	6.6032	0.004299	0.001490
T04	6.5959	0.006852	0.002447
T05	6.6249	0.005520	0.002068
T06	6.6482	0.003788	0.001005
T07	6.6756	0.005914	0.002225
T08	6.4231	0.004121	0.000826
T09	6.6603	0.004299	0.001490
T10	6.5839	0.006660	0.001757
Ø	**6.6096**	**0.0056**	**0.0017**

For a more precise analysis of the rib geometry and the applied radii, 3799 individual positions were measured axially along the ribs at intervals of 0.05 to 0.07 m with a total station (Figure 5) and later evaluated with a computer program developed by Prof. Dr.-Eng. Stefan M. Holzer. Initially, an attempt was made to calculate the radii of the longest rib sequences from the springers to the apex but this produced varying results and a significant spread within the sequences. However, this is a clear indication that more than just one radius was applied for different sections of the vault.

Thus, for the vault of the Wasserkirche, uniform radii for the tierceron and lierne ribs can be verified. In the evaluation, ten different tierceron ribs from the lower areas of the vault and ten different lierne ribs from the apex were computed. For the tierceron ribs, the evaluation (Tab. 1) resulted in an average radius of 6.6096 m with a mean standard deviation of 0.0465 m. The lierne ribs in the apex, however, have a larger radius, averaging 7.5438 m with a mean standard deviation of just 0.0164 m (Tab. 2).

Table 2. Computed radii of lierne rib sequences.

	Radius (m)	Max. Dist. (m)	Mean Dist. (m)
L01	7.5511	0.014686	0.007687
L02	7.5282	0.027422	0.010376
L03	7.5545	0.017254	0.007094
L04	7.5496	0.011097	0.001275
L05	7.5448	0.017085	0.004475
L06	7.5761	0.017872	0.006899
L07	7.5219	0.022975	0.006815
L08	7.5327	0.027596	0.010344
L09	7.5684	0.015102	0.007562
L10	7.5102	0.016817	0.004221
Ø	**7.5438**	**0.0188**	**0.0067**

* The two “Max Dist.” and “Mean Dist.” values both indicate the divergence of the measured points within the sequences.

By applying a larger radius in the apex, this area becomes more skene or flatter in relation to the lower parts at the springers. Thus, the cross section of the vault does not describe an exact semicircle, but a slightly pressed three-centred arch, which will be discussed in the next subchapter. The method described herein for the construction of the ribs in a three-dimensional space using several uniform radii also corresponds to the contemporary standard (Wendland 2019, 24–29). By reducing the rib geometry to merely a few uniform radii, not only the rib voussoirs could be produced more easily, but also the falsework required for the assembly.

The brief descriptions by Vogt and Herter (1943) allow a more profound insight into the construction of the vaults as, during the restoration work, the plaster was removed from the vault webs and ribs (Figure 6). In their explanations, they are astonished to note that the ribs do not tie into the vault webs (Vogt & Herter 1943, 68), which has become recognised as the standard condition in the research on vaults (Barthel 1991, 280–281) since their investigations. More remarkable, however, are the references to the use of iron in the construction. For example, the tracery panels in the apex were anchored with strong irons through the vault webs and the individual voussoirs, either very short or attached at particularly planar areas, were further secured by flat iron braces (Vogt & Herter 1943, 69). Some of these iron anchors and braces were removed during the restoration of the vault, others are still visible today (Figure 2). Unfortunately, these iron anchors cannot be examined more closely, because the extrados of the vault is not accessible. It is hence not possible to determine conclusively whether the iron was applied during the initial construction phase or added later.

Another striking observation is that the individual voussoirs are freely adjoining each other without being connected by lead dowels – although a few iron wedges have been found in some of the joints (Vogt & Herter 1943, 70). The use of lead joints can be proven for comparable Late Gothic vaults in the region (Maissen

Figure 6. Detail of a rib intersection (Vogt & Herter 1943).

2020, 52–54) and would have been expected for a vault as daring as that of the Wasserkirche – consider here the location of the church on an island with abutments that border the water directly on the western side.

As a final note on the construction of the ribs, it should be added that after the plaster was removed, all the stonemason marks on the voussoirs, probably made of limestone (De Quervain 1962, 7), were also recorded (Vogt & Herter 1943, 72). A total of forty stonemason marks can be distinguished, which suggests a rather large workshop or *fabrica* – this may well explain why the construction of the church was completed in only five years.

3.3 *Building the vault webs*

The removal of the plaster during the restoration of the vaults in the early 1940s also enables a closer look at the construction of the vault webs (Figure 7). In the historical photographs, the exposed vault webs show a regular stretcher bond of flat bricks. The regular arrangement of the bricks and the exceptionally straight alignment of the layers may indicate that the webs were built on formwork. In order to examine this further, a laser scan of the entire church was conducted and thereafter the contour lines were computed at 0.10 m elevation intervals for the entire soffit of the vaults (Figure 8). The elevation plan likewise reveals very straight masonry bond layers. This is a strong indication that the vault webs were not built freehand as this would necessitate a clear double curvature of the planes. Since the individual areas between the ribs are not double-curved, they had to be laid on a formwork or at least on a supporting auxiliary construction of battens placed between the ribs (Schuller 1989, 206–208).

Both the historical photo (Figure 7) and the elevation plan prove that the bricklayers were always arranged at a right angle to the alignment of the ribs. Furthermore, it can be seen on the photo that the mortar layers between the bricks become thicker in the flatter areas of the vault. This facilitates the construction of the apex area, which, as mentioned above, is much flatter, now clearly visible on the elevation map as the contour lines in the apex area are further apart (Figure 8). A not perfectly semi-circular cross-section is quite common in Late Gothic vaults and it is both possible that the vaults are either superelevated or slightly flattened at the vertex (Trautz 1998, 21).

Figure 7. The vault webs without plaster (Vogt & Herter 1943).

With the use of flat bricks with dimensions of 29 × 13 × 5 cm (Vogt & Herter 1943, 68), a lightweight structure was achieved. One way to illustrate the lightness of the vault construction is the ratio between the minimum radius ($R = 6.6$ m) and the thickness ($t = 0.13$ m) of the vault of 50.7, whereby a ratio $R/t > 20$ is already considered a thin shell today (Heyman 1995, 28–29). The construction of such a lightweight shell structure on a small island in a river must be considered a remarkable structural achievement even from today’s perspective.

4 CONTEMPORARY CONTEXT

The 15th century was a time of prosperity and economic growth throughout Central Europe, which led to a boom in the building industry in the German-speaking regions. However, while monumental cathedrals were built in the Gothic era, these were superseded in the Late Gothic period by urban and rural church buildings commissioned and financed by the local population. Thus, in southern Germany and Austria, major hub cities of Late Gothic architecture such as Landshut or Salzburg developed between 1400

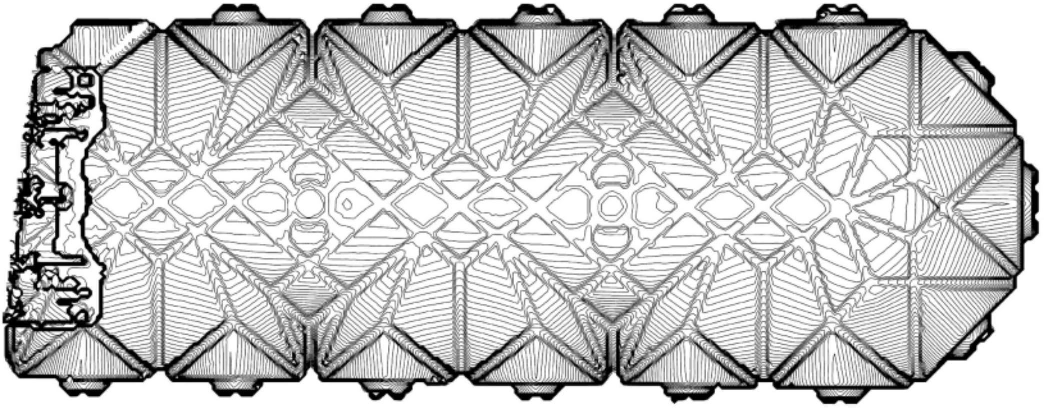

Figure 8. Elevation map of the soffit of the vault with contour lines generated at height intervals of 0.1 m. The distortions in the area to the left are caused by the built-in organ.

and 1430. From these cities, Late Gothic architecture began to expand around 1450 into the territories of present-day Switzerland.

Due to the spread of the new architectural forms and the construction techniques from southern Germany and Austria, the eastern regions of Switzerland were particularly affected by the construction boom. A particularly steep increase in construction activity occurred in the region around Zurich up to Lake Constance, with around 125 churches affected (Knöpfli 1969, 163–169), and in the canton of Grisons in the southeast of Switzerland, where at least 118 churches were built or rebuilt by 1525 (Maissen 2020, 255–262). In both regions, the amount of church buildings completed after 1450 initially increased rather slowly, only to rise abruptly in the late 1470s and throughout the 1480s. In Grisons, one of several reasons for this massive rise was the reconstruction of the parish church of St Martin in Chur after a devastating fire. In Zurich, a similar effect could be attributed to the Wasserkirche, as it too stood at the beginning of the construction boom and thus set a new aspiration standard for a contemporary church architecture.

However, the Wasserkirche has to be brought into a construction-historical context. The first noticeable feature is the use of bricks for the construction of the vaulting webs. Although brick was the preferred building material of the Late Gothic period in various regions, this material was not available everywhere. For instance, in the entire territory of the canton of Grisons, there was only one brick kiln in the capital Chur, which is why just three Late Gothic churches in Chur itself have brick vaults (Maissen 2020, 38–40). In Zurich, on the other hand, a brick kiln can be traced back with certainty to 1364; however, written sources suggest that the first occurrence of the material dates back to the 13th century (Guex 1986, 57). The advantage of using bricks in vault constructions is that the webs could be built freehand and without the need for extensive formwork. For this purpose, each brick layer must be arranged as an arch so that every layer can carry itself (Wendland 2008, 11–15). However, this would produce double-curved surfaces, which would be clearly evident in an elevation plan (Wendland 2008, 39–46), something that cannot be observed in the case of the Wasserkirche (see Figure 8). Despite the use of light bricks, the actual potential of the material was not fully utilised here so that the webs were at least laid on a load-bearing batten construction.

The fabrication of the rib voussoirs with only a few uniform radii also conforms to common practice in the 15th century. The application of a single or several uniform radii has recently been successfully demonstrated on a wide range of objects (Maissen 2020, 239–241). The situation is quite different with the use of iron; for the short rib voussoirs in the flatter areas in the apex at least lead dowels would be expected. However, there have only been a few studies on the use of iron and lead dowels in vaulting so far (L'Héritier et al. 2012, 557–564), as without a metal scanner the dowels can only be observed in damaged vaults or at defective points (Maissen 2020, 53–54). In this respect, no conclusive statements and comparisons about the use of iron and lead in the Wasserkirche can be offered with any certainty at this point.

5 CONCLUSION

Despite the unusual building site and the complex structural design, the new construction of the Wasserkirche was completed in just a few years. To enable this, the master builder Hans Felder had to maintain the most efficient building operations possible. Thus, regionally available building materials were selected in order to avoid long transport routes and reduce costs. The bricks needed for the construction of the vaults were produced directly across the river at today's Rennweg (Guex 1986, 30); the natural stones, on the other hand, could be cut at the quarries located outside the town and transported directly to the worksite by boat or raft along the waterway (Guex 1984, 62–75). In addition, a rather large workshop is indicated by the forty stonemason marks on the vault ribs, which allowed the construction of the Wasserkirche to proceed quickly.

The rather short construction period of the Wasserkirche and its intricate vaults, however, is not only due to the building materials and the artisans but rather largely due to the engineering skills of the master builder, whose geometric understanding has made it possible to greatly simplify even complex structures. This was most impressively exemplified by the vault geometry, whose components, despite their spatial complexity, could be planned and manufactured with only two different radii. The use of uniform radii for different segments of the vault construction can also be verified in vaults of similar intricacy (Maissen 2020, 239–240), thus analysis of the vaults in the Wasserkirche contributes another paragraph to our understanding of Late Gothic vault constructions. For once, the extensive restorations were also a fortunate coincidence as they provided rare insights into the actual construction, which is largely due to the meticulous documentation of all the findings by Vogt and Herter (1943). Thus, some of the results of the archaeological investigation could be further verified by the surveys conducted as part of the present study and, concurrently, the conclusions drawn on this basis susceptible to corroboration by the existing historical photographs. All these different sources, from historical manuscripts to archaeological excavations and modern surveying methods, not least highlight how diverse the discipline of construction history is and how much potential is inherent in its interdisciplinary nature.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Stone and brick flat vaults from the 16th century in Spain

M. Perelló & E. Rabasa
Universidad Politécnica de Madrid, Madrid, Spain

ABSTRACT: Flat vaults expand the boundaries of knowledge on flat vault techniques, stepping away from the conventional rules. At first sight, flat vaults can be easily defined. They are a kind of vault without curvature. However, there are not many examples of strictly flat vaults; low vaults are much more common. We have located a group of vaults that seem flat: those located in Magalia Castle, in the Monastery of El Escorial and in the Casa de Campo's Garden Pavilion. They belong to the same historical period and their builders are linked. The analysis of these vaults, built in stone or brick, and located in buildings with different purposes, military or monumental, allows us to know their geometric and constructive parameters to review the flat vault idea, and to conclude if they are a useful resource or an arrogant construction.

1 INTRODUCTION

During the 16th century, new formal issues were faced despite their geometric complexity or construction problems. The adaptation of previous solutions to new requirements involved innovation. The use of stone instead of brick for the construction of structures imported from the classical world that were built in brick would also lead to new problems. Experimentation with new structures could be also justified as a need to showcase the technical skills of stonemasons and architects; these skills, on the other hand, are necessary to carry out the construction of uncommon structures.

Vaults located in the basement and under the choir of the Monastery of El Escorial, vaults located in the basement and ground floor of the south tower of Magalia Castle in Las Navas del Marqués and vaults located in Casa de Campo's Garden Pavilion are examples of these new formal issues. These vaults have a flat appearance, but not all of them have a flat intrados. (Figures 1–5).

If we considered flat vaults those that are almost flat, perhaps we should establish a threshold to distinguish them from those vaults that are simply diminished. This limit would be related to geometric parameters, such as concavity, or construction parameters, such as the relationship between keystone height and spread. The analysis of this group of vaults aims to shed light on this meaning.


Figure 1. Vault in the basement of Magalia Castle.


Figure 2. Vault in the ground floor of the Magalia Castle.

2 STONECUTTING IN THE 16TH CENTURY

The 16th-century stonecutting books collect the most used structures and speculations about more complex ones. Occasionally, the authors directly address the subject showing firstly more complex and advanced solutions, disregarding the simplest examples. In other cases, the content is ordered from the least to the greatest complex ones, providing possible variations of the basic examples. Philibert de L'Orme (1567) wrote his treatise following the first schema and Alonso de Vandelvira (1575-1591), the other one (Calvo 2009). In Alonso de Valdelvira's manuscript, we find simple structures and forms derived from the basic ones, such as lowered vaults.

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Figure 3. Vault in the basement of the Monastery of El Escorial.

Figure 4. Vault under the choir of the Monastery's Church.

Figure 5. Northern vault in the Casa de Campo Garden Pavilion.

We have found no references to the trace of flat vaults in the 16th-century treatises. However, we can find some notes about the construction of ovals, diminished arches and vaults, and flat arches. Methods to draw ovals with any proportion between the axis were unknown at this time, and ovals with predetermined sizes were usually used. Obviously, in some cases, these fixed proportions are not valid, and it was required to use lower ovals, probably testing (López Mozo 2002). Regarding flat arches, Serlio suggested the use of convergent joints at a single point. He gave no indication on the position for this centre of convergence. His drawings of flat arches have been drawn following the equilateral triangle rule (Fantin 2017).

In the 17th century, Torija (1661) said that diminished barrel vaults and diminished hemispherical vaults "are built in rooms where the ceiling height is not enough in order to build a round arch". Next, he gave some indications to draw layouts of 40-feet spans and 13-feet-high vaults. The treatise of the Majorcan, Joseph Gelabert, explains the construction of a basket arch and also a flat arch, which he calls Roman door, and its variant with vertical joints. In order to draw the three-centred basket arch, Gelabert divided the span into as many parts as needed; then he drew a line with an inclination of 60 degrees through the first division point. This point will be the centre of the small arches. Gelabert also noted that if we increase the number of division, the smaller arch will become more diminished. In relation to the flat arch, Gelabert gave no information regarding the methodology used to obtain the inclination of the bed. The arch that Gelabert named "Portal de Apotecari" (pharmacy's gate) is an unusual flat arch. It has vertical beds in the front face, but these beds converge in the back face (Rabasa 2011).

In the 18th century, T.V. Tosca, who had copied Milliet Deschalles' Latin Treatise, said that "all arches which are not round, that is, their height is lower than their horizontal semi-diameter, are called diminished arches, among which we include segmental arches because they have only one portion of the round arch".

He also defined as *degenerated arch* "those arches whose voussoirs are joined together as in arches, but they are not circular". When the geometry of some arches is defined by a straight line down, Tosca, in the same way as Milliet, named the arch as *straight-line degenerated arch*; the arches which have a straight line down and up are named either *flat arch* or *level degenerated arch*. Tosca included in this group of arches those composed of polygonal lines. That is, round arches can degenerate into basket-handle arches and pseudo three-centred arches and these into flat arches (Tosca 1727).

To the authors' knowledge the first reference about the construction of flat vaults is in Frézier's treatise, *La théorie et la pratique de la coupe de pierres et des bois pour la construction des voûtes et autres parties des bâtiments civils et militaires, ou traité de stéréotomie à l'usage de l'architecture*, published in 1737 (Figure 6). Frézier explained three types of flat vaults from the construction point of view. He named as *plate-bande* those supported by two parallels walls; as *voûtes plates* those structures supported by four walls; and *trompes plate,* those supported by two contiguous walls and "inclined towards the horizon". He also distinguished between *voussoir* and *claveaux. Claveaux* was the appropriated word to designate the flat vault pieces and *voussoir* for the rest. Before that, in 1699, an article entitled, "Voûte Plate inventée par M. Abeille" was published in *Recueil de machines approuvées par l'Académie*. Frezier took this idea and went further with new approaches, including Truchet's solution, which solved the original problem: to make the extrados continuous in order to support a floor.

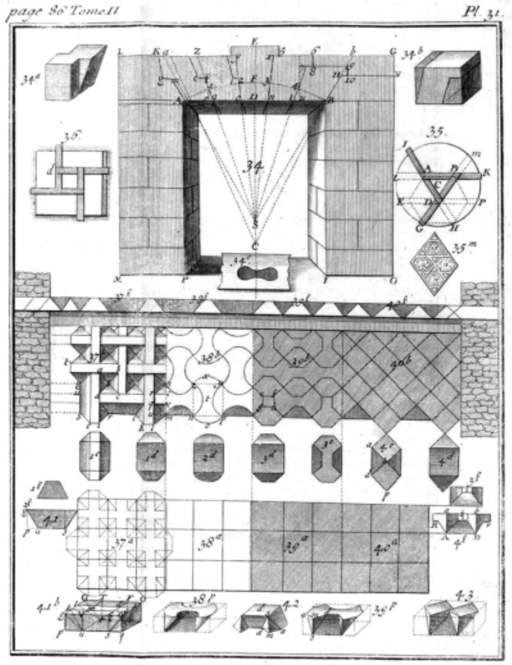

Figure 6. Flat vaults studies by Frèzier, 1737. *La théorie et la pratique de la coupe des pierres, print 31.*

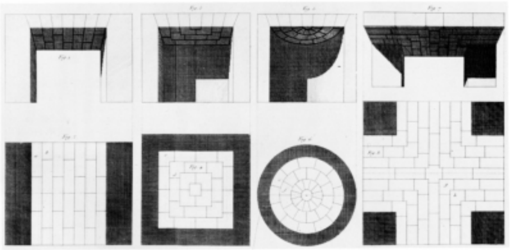

Figure 7. Flat vaults by Rondelet, 1842, round course flat vault included. *Traité théorique et practique de l’art de batir, print 30*.

One of these new approaches was used by the engineer, Lucio del Valle, between 1851-58 in Pontón de la Oliva (Madrid). In 1775, Julián Sánchez Bort built two flat vaults in Lugo’s Cathedral using the Abeille solution, but he smartly turned the pieces upside down to get a continuous extrados (Rabasa 2012).

The 19th-century treatises written by Rondelet, *Traité théorique et practique de l’art de batir* (1842) (Figure 7), and Rovira y Rabassa, *Estereotomía de la piedra* (1897-99), contain examples of flat vaults, those which Frezier called plate-bandes, and Abeille’s invention.

3 LAYOUT AND CONSTRUCTION

The group of vaults studied was built at the end of the 16th century. Magalia Castle’s vaults were built before 1571. On this date, Pedro Dávila y Córdoba, the second Marqués de las Navas, who was very close to Felipe II, included the works carried out in the Castle in his entailed estate (Parada & Palacios 2020). López Mozo (2003), in *Planar vaults in the Monastery of El Escorial*, explains the construction chronology of those flat vaults. She defined the end of the construction of the vault located under the choir of the basilica as 24 May 1583, when the measurements of the space under the choir had already been made. She also estimated that the vault located in the basement of the Monastery was built around 1567. Brick vaults in Casa de Campo’s Garden Pavilion were built after 1562; on this date the Vargas Country House had been bought by Felipe II (Ramón-Laca & Menéndez 2020).

3.1 *Vaults in the south tower of Magalia Castle*

The vaults of the south tower of Magalia Castle are the simplest from the point of view of the layout (Figures 1 and 2). The tower is circular and is connected to the main building with a narrow corridor. The rooms where both vaults are 7.33 metres in diameter and a maximum height of 3.43 metres, measuring from the keystone. The rooms of the tower have a circular shape, the same shape the courses have; thus creating harmony between both elements. It seems like the vaults have been built following the same layout: the geometry of both vaults has been drawn according to a segmental arch; however, the analysis of the 3D model – made from a photogrammetric reconstruction – shows that they are two different solutions to the same construction problem. The basement vault has a rise of 0.527 metres and a radius of curvature of 12.9 metres. The ground floor vault has a rise of 0.33 metres and a radius of curvature of 18.7 metres. The thickness, measured in the centre of the room, is also different: 0.56 metres in the basement vault and 0.34 metres in the ground floor vault, including the floor in both cases (Figure 8).

As a result of this analysis, we can observe that the dimensions and shapes of both vaults are proportional. The ground floor vault is approximately an affine transformation of the basement vault. The affine transformation of an arch of circumference is an arch of ellipse; however, we have verified the difference between both layout and, in this case, we have found that the difference is negligible (Figure 13 A-B).

According to Rankine’s theorem, published in *A manual of applied mechanics* (1858), which describes the stability in the transformations of the blocks constructions, and Huerta’s (2004) interpretation, "if a construction formed by blocks that support the action of a system of forces represented by a system of vectors is stable, any parallel projection will also be stable and will present the same degree of stability, under the action of a system of forces projected from the original". That is, the horizontal component of the thrust is constant in the affine transformation of an arch; the inclination of the force vector obviously changes. This is the performance of the vaults of Magalia Castle. The architects of these vaults may

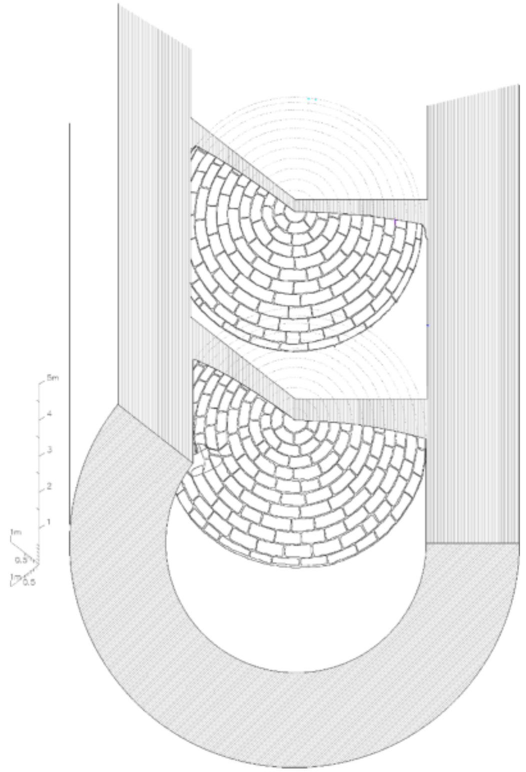

Figure 8. Current state of the vaults in Magalia Castle.

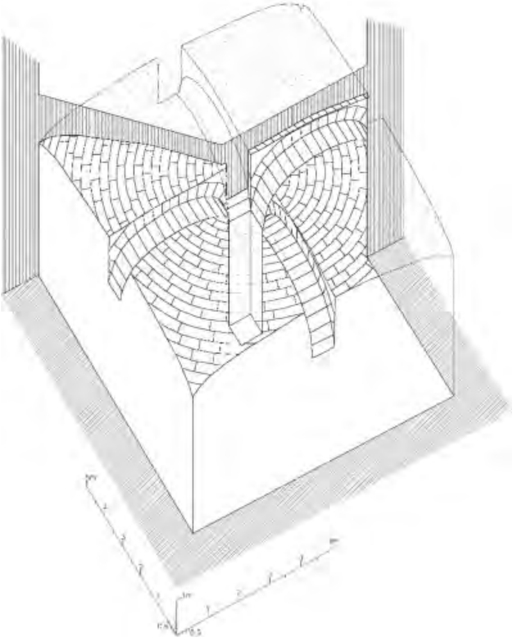

Figure 9. Current state of the vault in the basement of the Monastery of El Escorial.

have had an intuitive knowledge about Rankine's theorem when they designed the vaults. They were able to build the ground floor vault slimmer than the basement vault, under the same condition, without compromising the tower stability, because the horizontal thrust is the same.

Regarding the construction techniques, the problems are reduced as much as possible because the geometry of the rooms is the same as the geometry of the courses. That is, there is no transition surface, as we will see on the other vaults. The voussoir carving does not present any complication either since we understand that being a curved intrados; the beds are convergent in the centre of curvature.

3.2 *Vault in the basement of the Monastery of El Escorial*

In the room known as Platerías, located in the basement of the Monastery of El Escorial, there is a pillar in the centre of the room, four arches which are supported by the pillar and the perimeter walls and four segments which could be part of a diminished vault with circular courses (Figure 3). According to the hypothesis of López Mozo (2003), the pillar and the arches were built after the vault and their purpose was to prevent the vault from collapsing. She noted that building construction was delayed in this area and she pointed out that this delay may have been due to the construction of the central pillar and the arches to achieve it, so the vault courses would be supported by the arches. As a result, the courses would complete a circle and some courses, and the keystone, would be hidden behind the pillar and the arcs. The vault covers an almost square room which dimensions are 8.34 per 8.618 metres (Figure 9). These dimensions are very similar to those of the other vault in the Monastery.

To find out how this vault had been built, we analysed at first both sections, the diagonal and the transverse or longitudinal ones, obtained from the 3D model, to get the layout geometry. The vault could be made up of two different surfaces: an almost flat surface, which takes up almost entirely the vault, and a concave surface in the room corners that serves as a transition to a square plain. We have noticed there is no dependency relationship between the layout of the two parts. We are interested in the geometry definition of the first one, which in turn is now divided into at least two segments: one ascending and one almost flat. We can formulate different hypotheses about their original geometry. If we considered the current state as a project state, that is, the segment which seems almost horizontal was designed with this geometry; the layout of this section would be composed of broken straight lines, the first ascending and the second horizontal, as pointed out by López Mozo (2003). If we considered the current state as a result of a loss of shape, that is, the segment which seems almost horizontal was not designed with this geometry; the layout of this section would also be composed of a single arch (Figure 13 C).

It is difficult to define whether the vault has a concave shape or flat shape, because both obstacles, deformation of the shape and the pillar and the arches, leave an information gap. After the analysis of the photogrammetric 3D model, we have not been able to distinguish between the straight and curved shape in the first segment of the central area of the vault because the difference is negligible. To sum up, we could draw the central area with arches of circumference or with straight lines. In this last case, the shape of the vault could be built from a cone.

The choice between curved or straight geometry does not have any impact on the definition of the voussoir beds. We consider that the voussoir beds located in the flat area of the vault might be convergent as in a flat arch.

3.3 *Vault under the choir of basilica of Monastery of El Escorial*

Currently, the vault under the choir of the Monastery of El Escorial is the reference for a *flat vault* (Figure 4). It is a vault of round courses on a square plain of 7.81 metres of side. We use the same method as in the previous case to make a hypothesis about the construction process of the vault. We again analyse the diagonal and transverse or longitudinal sections, obtained from the photogrammetric model, to get the layout geometry.

We can consider that the vault could be made up of two different surfaces, as in the previous example: the flat surface and the concave surface in the square corners serve as a transition to a square plain. The geometry of the flat part is simple: a straight line, as pointed out by López Mozo (2003). Its objective allows us to cover a room where we cannot build a round arch. The geometry of the transition courses from the square to the central plain, including the one that rests on the keystone of perimeter arches, are perhaps the ones that generate the most doubts and the ones with the most complex design. Its objective is allowed the transition from round courses to a square plain (Figure 10). In summary, the rules to draw both surfaces are different, that is why, we could consider them as independent parts (Figure 13 D).

Nowadays, the central part of the vault is not strictly flat. In the longitudinal and transversal sections, the central part defines a slightly ascending line that follows a descending trajectory when it reaches the fifth course; in the diagonal sections the same descent can be observed around the keystone. López Mozo (2003), who carried out a data capture using a total station, also quantified the descent of the vault at 0.096 metres. Frèzier, in his aforementioned treatise, published in 1737, already pointed out the possible deformation that a vault of this type can suffer (Frèzier 1737).

To avoid this, he proposed that the centring must be arranged with a small curvature. This same deformation has been verified by the experiment s carried out in the UPM Stonecutting Workshop in which a 1:10 scale stone model of this vault was built. In this experiment, the bed of the voussoirs was drawn convergent at the vertex of the equilateral triangle. This approach was also studied by Ávila (1998) who, in addition, rejects the proposed with tongue-and-groove pieces of Martín Gómez.

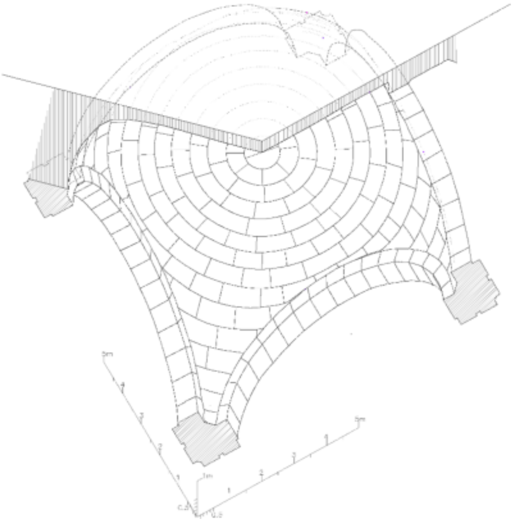

Figure 10. Current state of the vault under the choir of the Monastery's Church.

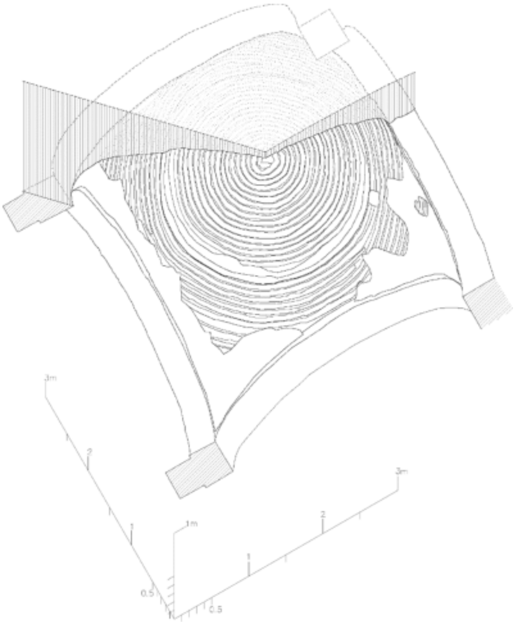

Figure 11. Current state of the southern vault in the Casa de Campo Garden Pavilion.

3.4 *Vaults in the Casa de Campo's Garden Pavilion*

In the Casa de Campo's Garden Pavilion, we find two vaults of round courses on a square plant. It seems to have a flat shape (Figures 11 and 12). Pedro Navascués describes the construction as "a biabsidial space,

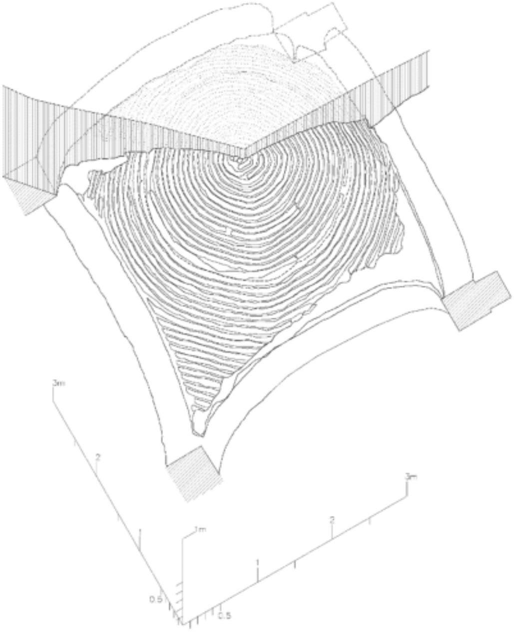

Figure 12. Current state of the northenr vault in the Casa de Campo Garden Pavilion.

composed of five vaulted areas, each one of them independent from the others. At the same time, they are distanced from the perimeter walls. Consequently, the diminished vaults have their own supports, which are resolved with columns in the central and immediate area and with pillars in the last area" (Navascués 1991). Today, the building is partially destroyed.

As in previous examples, these vaults are formed by two different surfaces, but in this case, it is clear, and it would not be necessary to study the sections geometry. There is an interruption between the two round courses. The bricks in the first course of the second surface have been placed slightly backward. Thus, a continuous step is formed, a kind of moulding. Both surfaces are drawn according to an arch (Figure 13 E-F).

Vicente Paredes expounded how to build flat brick vaults without centring in his treatise, *Construcción sin cimbra de las bóvedas de ladrillo con toda clase de morteros* (1883). He said the round courses form a cone frustum. It is a stable structure when the course is closed, that is, after placing all the bricks that form it. This stability is achieved thanks to the adhesive force of the mortar and the friction force. In addition, Vicente Paredes points out that the inclination of the beds will prevent their sliding. He draws the beds of the courses converging as usual in a flat brick arch. Furthermore, he explains the origin of a flat vault with circular courses as a flat arch turning around its vertical axis, and he adds that the round courses that do not complete the circle are stable because they rest on the side walls of a square room. This had been written long after the Casa de Campo's vaults were built; however, the construction of these vaults follows the same rules.

4 USEFUL RESOURCE OR ARROGANCE CONSTRUCTION. ADAPTATION OR EXPERIMENTATION

Vaults located in the basement and under the choir of the Monastery of El Escorial, vaults located in the basement and ground floor of the south tower of Magalia Castle in Las Navas del Marqués and vaults located in Casa de Campo's Garden Pavilion have similar traits in relation to their layout and construction, such as, very low profiles, which became flat or almost flat in some areas, and circular geometry of the courses.

The profile is very low; however, the way this profile has to approach to the horizontal line is different in all studied cases. The layout is defined by a segmented arch with a very large radius of curvature or by an extremely diminished arch (Figure 13). In any of these last studied cases, the methods to draw ovals with predetermined sizes developed during the 16th century were used. The rise is limited by a room built over the vault. The course's geometry has been drawn following a round pattern, regardless of the room geometry. So, the vault plain could be square, almost square or circular depending on the geometry of the room on which they were built.

Regarding its construction, the carving of the voussoirs which belongs to any kind of arch or vault with curvature is not difficult. It is only necessary to know the intrados curvature to carve the intrados face and the centre of curvature to obtain the direction which defines the bed inclination. In practice, we use the bevel to draw the geometry on the stone and to check the dressing of the stone blocks. In the case of the vaults, the most common procedure is to use the intrados template first. In those vaults that have a slightly curved trace, and we could be confused with a straight line, the definition of the beds is still the traditional one, that is, convergent at the centre of curvature or, what is the same, perpendicular to the arc of circumference. In those vaults in which the curvature tends to zero, the definition of the joint beds is close to the problem posed by a flat arch (Fantin 2017). Therefore, further research is needed to understand those joint beds.

On the other hand, this group of vaults has been built in spaces that, in some way, guarantee the stability of the entire building, despite the thrust produced by a vault with a very diminished or flat profile. The vaults of Magalia Castle are located in a tower, with walls approximately 2.5-metres thick; in El Escorial, the vault built in 1568 is located in the basement under a missing tower (Rabasa et al. 2003); the *sotocoro* vault occupies the central space of a rectangular grid of vaulted vaults (Ortega 1988), like the vault in Casa de Campo's Garden Pavilion.

This group of vaults has a close relationship through their promoters and builders. According to the research of López Mozo (2003), the vault of the basement of

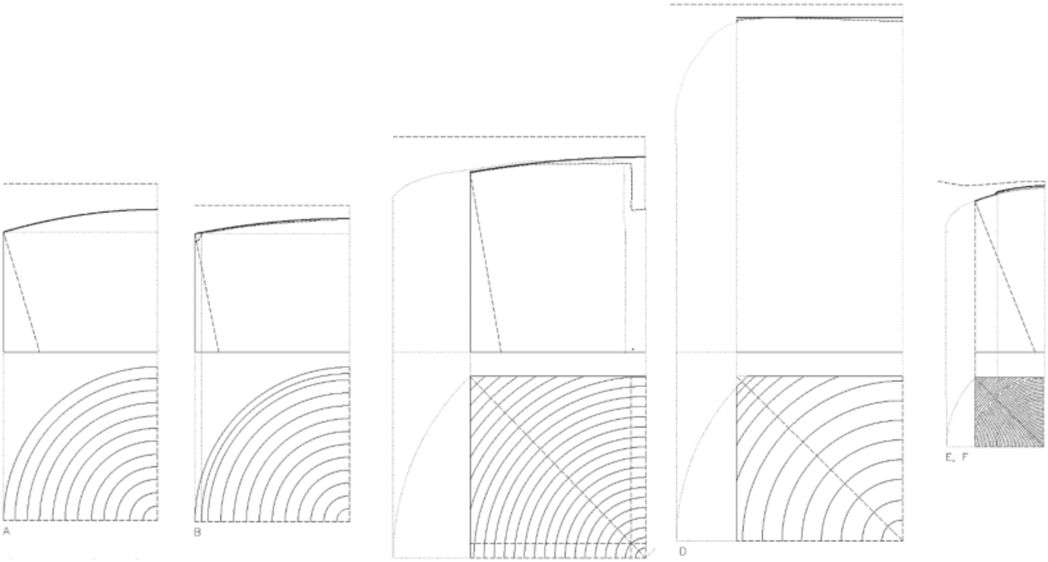

Figure 13. Hypothesis of the ideal geometry of the vaults compared to the current state. Vault in the basement (A) and vault in the ground floor of Magalia Castle (B), vault in the basement (C) and vault under the choir of the Monastery of El Escorial. (D), north and south vaults in the Casa de Campo Garden Pavilion. (E, F).

El Escorial was drawn by Juan Bautista de Toledo, and the vault of the *sotocoro,* by Juan de Herrera. Juan Bautista de Toledo is also credited with the authorship of the Gruta de la Casa de Campo (Navascues et al. 1991). According to M. Parada (Parada & Palacios 2020), the refurbishment works of the castle during the marquisate of Pedro Dávila y Zúñiga (1533-67) and Pedro Dávila y Córdoba (1567–74), can be attributed to Alonso de Covarrubias and Pedro de Tolosa, who worked at the Monastery of El Escorial.

In view of the development achieved by the discipline of stone carving at this time, it is likely that builders had more empirical knowledge, based on practice, than theoretical knowledge.

In addition, it seems that a knowledge network between the promoters and builders above enabled the exchange of experiences.

5 CONCLUSION

These vaults, whether extremely diminished or flat, were not common in the 16th century. As we have seen, what allows for the success of these vaults had to be the experience and the mastery of the trade, because there was not a theory as a guideline for their construction. Their construction could be justified by the need to adapt a conventional type to initial project conditions, such as insufficient rise. Sometimes, this need could be an excuse to search new forms, in stone or brick. In fact, this was an emerging research, and we could notice it in the doubts that the geometry of the layout reflects. The construction of the vaults is justified as an answer to a need, and, at the same time, it is an opportunity for experimentation.

Finally, distinguishing these extremely diminished vaults or flat vaults from other less diminished vaults is not very relevant. The name “flat vault” is confusing because vault and flat are opposite concepts. From a geometric point of view, if we consider vaults whose intrados is a horizontal plane as flat vaults, of all those studied vaults only the one under the choir of the basilica of the monastery of El Escorial would be a flat vault. From the point of view of stability, the possibility of containing a pressure line of thrust at any vault is conditioned by shape and thickness. The flat vault or extremely diminished vault behaviour is similar because the pressure line of thrust hardly comes out of the shape. Perhaps it would be more fortunate to call them degenerated vaults, as Tosca and Milliet Deschalles did.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The renovation of the Church of San Benito Abad in Agudo (Ciudad Real, Spain) through a 17th-century drawing

R. Ramiro Mansilla
Independent scholar

F. Pinto-Puerto
Universidad de Sevilla, Seville, Spain

ABSTRACT: This article addresses the architectural study of the renovation process of the Church of San Benito Abad in Agudo, Ciudad Real, Spain, through a 17th-century drawing attributed to the master builder, Antonio de Piña. The drawing is unique in that it records the construction phases of the building and includes an exceptional working drawing of a Late-Gothic vault that is currently concealed by a more recent sail vault. The authors conduct a comparative analysis between the document and the material traces in the building, revealing a modus operandi adopted by master builders at the time.

1 INTRODUCTION

Agudo, in the province of Ciudad Real, is situated in a natural enclave of the Mediterranean ecosystem. The last town on the western edge of the region of Castile-La Mancha, it has been historically linked to the Campo de Calatrava area, although its hills and pasture lands have little in common with the flat plains that characterise the rest of the region.

The natural wealth of the valley and its strategic location may account for its foundation as a new settlement or repopulation town to secure a border territory during the latter days of the Christian reconquest of Spain because "from the 15th century to the 18th century, the tithe collectors at least always referred to Agudo as a town" (Gómez 2012) (Figure 1).

From the outset, it formed part of the *encomienda* [landed estate] of the Order of Calatrava, representing one of its most important possessions. During the 15th century, its population grew significantly due to the boom in textiles and the arrival of settlers, and the increasing wealth of the area prompted the need to provide it with amenities on a par with the size of the population and the status of the town. This was probably the reason for the renovation of the church in Agudo, which is architecturally superior to the churches in the nearby towns. As well as featuring building solutions and designs which the same stone masons used in other works in the region, the church in Agudo reveals the stylistic references of one of the major art centres of the day – the town of Almagro – with which it enjoyed fluid relations.

Figure 1. The Church of San Benito Abad, the old quarter of Agudo and the Umbría range in the background. Aerial drone photograph by J.A. Palomares (August-September 2019).

2 DISCUSSION FRAMEWORK

Spanish architecture of the Modern Age has traditionally been studied from a historiographic perspective based on universal values, and the evaluation of a particular work therefore involved comparing it with the supposedly representative models of each period and culture on a national or international level. As a result, some of the works in the towns and villages located farthest away from the most important production centres were either ignored or classed as minor, leading to considerable gaps in the knowledge of our heritage.

Today, the recovery and promotion of that heritage takes into account multiple parameters and sources of knowledge, shedding light on a more complex and richly nuanced reality. In these cases, the local variables are sometimes highly significant.

The architectural drawings made by the old master builders are one of the sources of knowledge. These documents are very scarce if we compare them with the volume of the heritage that has been preserved. As well

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as reflecting the knowledge of the day, they offer valuable written information and metric guidelines about the building processes followed.

Drawings of floor plans, elevations and perspectives became an integral part of the preparation of a project, adding an essential element over and above the long tradition of medieval drawings based strictly on the construction aspects (Cabezas 1992). Before the advent of the Renaissance mindset, medieval architectural drawing tended to make less use of paper and parchment and primarily consisted of full-scale drawings of stonework. These simple sketches are known as *monteas*, or working drawings, and they were vital for controlling the execution of the more delicate formal and structural works, such as domes, ribbed vaults, splayed arches and other types of arches, and pendentives. However, unlike the scale drawings on paper that have been preserved in certain archives, most of these full-scale working drawings have disappeared because the material on which they were made during the work was discarded. More often than not, these drawings were made through incisions on wooden planks, as explained in Rodrigo Gil de Hontañón's manuscript, which mentions the creation of working drawings for vaults on a scaffold "made of so many strong planks that the entire ribbing can be drawn and demarcated at full-scale", which were then removed (Calvo et al. 2015, 5). On other occasions, they were drawn on walls or paving stones that were subsequently concealed, in spaces specially created for this purpose (Calvo & Rabasa 2016) or on flat roofs, which were used as a type of alternative drawing board, as in the case of the *montea* for the vault over the chancel in Seville Cathedral (Pinto & Jiménez 2015), the scratched remains of which have miraculously survived. Specifically, working drawings for vaults served a practical function by resolving a particular moment of the work, basically consisting in drawing the floor plan and elevation of the arches, and plans that include these Late-Gothic drawings are therefore quite rare. In Spain, as Rabasa explains, drawings of vaults are virtually non-existent, whereas full-scale working drawings of archivolts, rosettes and buttresses are more common and have been preserved to this day on the stone paving of the buildings in question (Rabasa 2000). For example, of the 200 inventoried drawings in the book, *Trazas, muestras y modelos de tradición gótica en la Península Ibérica entre los siglos XIII y XVI* [Drawings, Samples and Models of the Gothic Tradition in the Iberian Peninsula between the 13th and 14th Centuries], the result of a research project led by Javier Ibañez Fernández, only two contain this type of drawing, one for the church in Priego (Cuenca) and the other included in the Manuscript by Hernán Ruiz the Younger (Ibáñez 2019). In view of the exceptional nature of these drawings and the very small number that have survived, the working drawing describing the construction of the subject of this study, the church in Agudo, offers a valuable and crucial testament, as highlighted by our research and explained in more detail below (Figure 2).

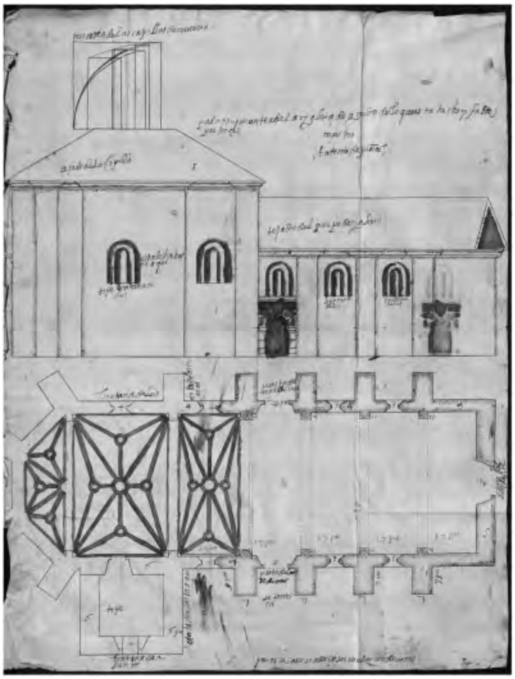

Figure 2. Drawing of the church in Agudo by the master builder Antonio de Piña (1610–1613). *Planimetría Ministerio de Cultura y Deporte. Archivo Histórico Nacional*, inv. no. OM.MPD.201.

3 THE DOCUMENTARY TESTIMONIES OF THE CHURCH IN AGUDO

The documents that have provided the most information about the description of the church in Agudo are those that record the requests to extend the parish church, a historical claim sustained over the course of many years before the works were finally undertaken. These texts contain the constant complaints about the lack of funds and suits "brought by the Council of Agudo against the Commanders on the grounds that the latter were deliberately failing to fulfil their obligations, specifically those related to the necessary improvement and repair of the church" (Jiménez 2012a). The most important files refer to the period between 1592, when the church extension was requested (Jiménez 2012a) and the legal action in 1610 when the works were finally approved (Jiménez 2012c). The events that occurred thereafter and subsequent testimonies from the technicians who appraised the works provided a crucial aid for studying the graphical document analysed here and its relationship with what was finally built.

The approved lawsuit of 1610–13 makes reference once again to the need for a series of ornaments and repairs to the church. This manuscript is important because it is accompanied by a drawing that contains some very valuable information: a detailed description of the building by means of supplementary flat projections of the floor plan and elevation with graphics and texts describing two separate building phases – "what is done and what remains to be done"; a working drawing for the arches of the ribbed vault, rarely found in this type of plan because these drawings were usually full-scale; and the literary description of certain aspects to clarify and supplement the graphical information. The drawing is signed by Antonio de Piña, "master builder of similar works" and "mason, resident of the town of Almadén, specialist witness of the Council of Agudo..." (Jiménez 2012b), who in the year 1606 was commissioned to appraise and cost the works.

It is a large drawing on a single piece of yellowed laid paper, dimensions 50.50 x 30.50 cm, which was folded – as confirmed by the ink marks and horizontal and vertical creases in the paper – and included in the lawsuit file. The top half of the paper shows a drawing of the north elevation of the church, while the bottom half contains the corresponding floor plan, both with measurements and notes by the author. In general, it is a drawing with careful lines and proportions accompanied by somewhat hastily written texts containing words that have been crossed out. Thicker lines in a darker ink were used for the ribbed vault in the floor plan and the windows and roof in the elevation. These darker lines denote a rapid, casual hand, to the extent where they appear quite clumsy. It is an ink drawing with no signs of the use of drypoint or any pencil lines. Although there is no graphical scale, it does include several measurements that refer to the thickness of the walls and width of the nave sections, which suggest a scale of 1:200 for the plan, and the annotations in feet coincide fairly closely with the actual dimensions of the building.

The supplementary flat projections are an early example of what came to be codified as dihedral projections – cylindrical and orthogonal – and which in this case express the configuration of the building at the date of the drawing and the pending elements. The design which was finally built contains certain differences with respect to the plan, but the working drawing nevertheless gives us a very approximate idea of the original design that was partly completed and whose traces can still be found in the building today.

The drawing shows the church floor plan, comprising a five-section nave, plus the main vault over the crossing and the polygonal apse. The first two-vaulted sections correspond to the chancel, which is higher than the rest of the nave and covered by ribbed and chamfered vaults, as shown in the drawing. There are two rectangular ribbed vaults with tiercerons, a large one over the chancel and a narrower one. The four remaining sections of the nave are lower in height and resolved with barrel vaults and buttresses of the same size. The drawing shows two facing doors in the third section of the nave and a third door in the west facade, and there is a tower on the north side. From the second section of the nave, the walls are shaded with freehand slanting strokes, coinciding with a murky, darker mark underneath, which differentiate them from the apse and tower walls. In addition to the murky mark, it is possible to make out the words "completed up to here" on both walls, therefore differentiating the two building phases: the walls of the completed chancel and the design for the body of the nave.

Measurements in feet are included for the apse and crossing, as well as on the right-hand side of the plan that represent the elements pending construction and, at the time, would have required more specifications. In relation to the preserved building, the plan broadly coincides with the dimensions of the floor plan and the apse – but not the chamfered vault, which seems narrower in reality – as well as with the number of nave sections and the position of the tower and the openings. However, there are also certain differences, mainly in the apse. These inconsistencies are particularly remarkable because they correspond to the part that was supposedly already completed and it would have been easy to avoid errors. In the plan, the position of the buttresses that absorb the thrusts of the main vault are turned with respect to the walls, whereas in reality they are built perpendicular to them, in the same position as the other buttresses in the nave. Furthermore, the plan does not show the spiral staircase excavated in the buttress adjacent to the tower, which at the time the plan was made must have already been under way, as noted in the accompanying lawsuit with the words "complete the spiral…" (Jiménez 2012c). In the plan, the ribbed vault is not entirely accurate because, although the main vault shows tiercerons, whose dimensions are a perfect match, it omits the liernes and the other keystones that complete the design, even though these would have been visible from the inside if they had been built.

Today, it is still possible to distinguish the two building phases represented in the plan because the stone walls in the apse are higher as well as being the only ones that display a decorative double-line filling around each piece, something which is not found in any of the other churches. This technique is known in Spanish as *a raspa-terrón* [literally, "scrape-clod"] and is performed by making a pattern on the mortar that covers the stones with a rod or reed cut in half lengthwise (J.A. Fernández, personal communication, 28 June 2019). The second phase on the plan coincides mainly with the construction of the brick and lime mortar sections.

The most remarkable aspect of this building phase is the absence of the second ribbed vault in the present-day building, which features in the drawing but was never built. In its place was a barrel vault, confirmed by the inspections conducted of the vault plans, and like the ribbed vault, it was concealed by a subsequent intervention. In the elevation, the drawn windows differ considerably from the actual windows, both in terms of their form and position. The openings, which would be lower than the actual ones, trace a line in the chancel walls and in each section of the nave, except for the last one. There are still traces of the existence of these windows on the walls today, and, in fact, they are increasingly visible due to neglect and the lack of cladding.

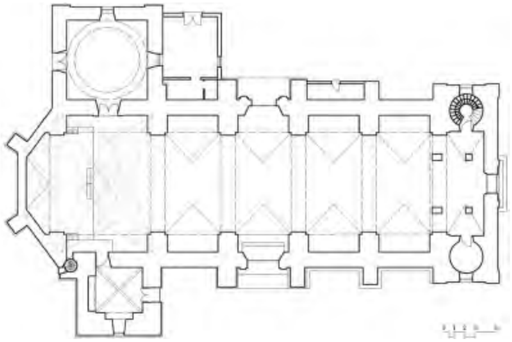

Figure 3. Plan of the Church of San Benito Abad. Drawing by the authors.

Lastly, there are minor differences with respect to the original design if we compare it to the floor plan (Figure 3). For example, there is no spiral staircase in the tower. There is no evidence of the stone portal planned for the north door, which today is a lime mortar and brick portal. None of the stonework for any of the church doors has been preserved, although if it had survived it is reasonable to suppose that it would be found in the "palace door", as the south door is still called by virtue of its location opposite the old palace of the Order of Calatrava (Cabrera 2019). Still present today are the traces and absence of what probably corresponded to the old "pinnacles flanking a central opening" (Cabrera 2019, 3), which suggests that a portal once occupied this position.

4 THE WORKING DRAWING

At the top of the drawing, above the elevation of the church, is a sketch that corresponds to the working drawing for the ribbed vault. It is not a full-scale working drawing of the type made on the platform that was mounted across the scaffold to reach the vault's tas-de-charge, but it does reproduce the geometric logic because it superposes the lower lines of the vault arches on the horizontal plane of the platform. These arches served as guides, enabling the carpenters to assemble the formwork and the masons to align the stone voussoirs radially before placing them on top of the formwork. Once the vault had been completed, the horizontal platforms were dismantled, which explains why so few working drawings have survived, and it is therefore rare drawings like the one examined here that provide evidence of their existence.

The working drawing corresponds to the floor plan, so both projections enable us to reconstruct the vault. By editing the plan digitally in a CAD environment and redrawing the arches of the working drawing on top it, we can check its accuracy in spite of the tiny scale. The floor plan shows the lines of the ribs and the awl points at the centre of the keystones, which permit the necessary turns of the compass to superpose one of the arches on to a vertical plane, coinciding with the top of the rectangle.

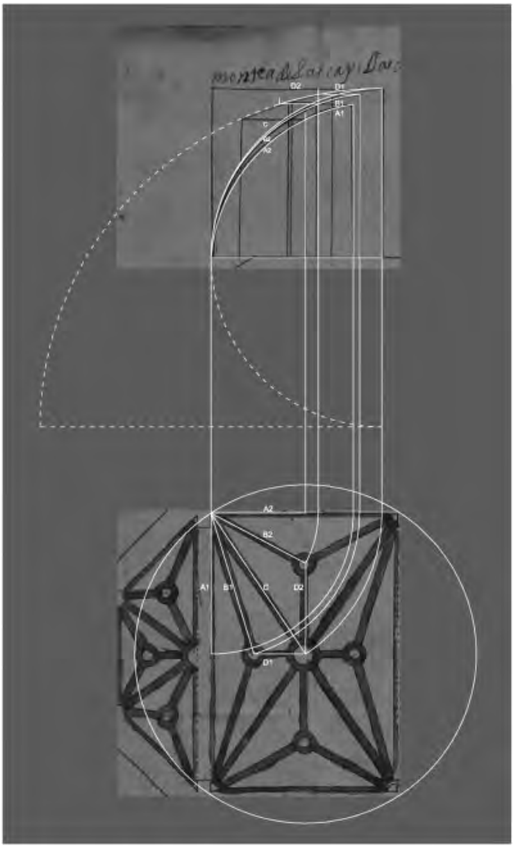

Figure 4. Checking the accuracy of the plan and the elevations of the arches. Drawing by the authors.

The graphical procedure consists in drawing each arch both in the plan of the vault and in the group of circles and then finding their centres. In keeping with the initial hypothesis, the diagonal and tierceron lines in the plan are turned to a supposed vertical plane situated on the short side of the plan.

When the turns are elevated to the working drawing, which represents the superposed arches, we can confirm the accuracy of the drawing (Figure 4). The rectangular plan, with its 3:2 ratio, corresponds to the sesquialtera vault, in keeping with the system of proportions in Simón García's treatise (Palacios 2009), which fits with Antonio de Piña's drawing as well as with more recent plans. The geometric figure of the ribs forms a star with diagonal, rampant and tierceron ribs, which are obtained by following the usual lines for these types of vaults that were so frequent on the Iberian Peninsula between the late-15th and early-16th centuries (Palacios 2009; Rabasa 2000). They are built through a series of steps: a circle is drawn around the rectangle of the vault to provide the basic reference for obtaining the tiercerons; lines are drawn from the corners to the intersection of the axes of the rectangle inside this circle; the point where these lines intersect with the axes of the rectangle indicate the position of the keystones for the tiercerons.

5 THE BUILT LATE-GOTHIC VAULT

The 1610–13 plan defines ribbed vaults for the first two sections of the church in Agudo. However, the interior of the actual building presents a different reality: a large sail vault covers the entire crossing and five barrel vaults cover the remainder of the nave. What we see today corresponds to a subsequent intervention carried out during the 18th century to unify the style of the church and conceal the old Late-Gothic vault built in the 16th century. While a small group of parishioners were aware of the existence of this vault, the majority knew nothing about it. We were able to verify the existence of this ribbed vault underneath the cavities formed by the sloping roofs when we inspected the extrados of the vaults. As well as the exterior volume and the “segments” that differentiate it from the other vaults over the nave, crucially there are two small perforations in the severy that must have been made at some point in the past to check for the existence of the vault (Figure 5).

These perforations provide access to a narrow interior space between the sail vault below – visible from the interior – and the ribbed vault, recognisable from the vault plans. The two openings, one situated at one axis of the vault and one at the other axis, each offer a view of half of the vault and it is therefore possible to identify the design of the whole vault, which is more complex than the one represented on master builder Piña’s plans (Figure 6).

The ribbed vault at the church in Agudo dates to around 1553 and was therefore built in the Late Gothic period when ribbed structures became more sophisticated and included a larger number of ribs, even though they played a less prominent role than in the Early Gothic period.

As shown, the vault in Agudo has a design that is practically identical to the vault and chamfer in the nearby village of Alcolea de Calatrava, which means that we can imagine what this one would look like if it were on view (Figure 7).

The proportions vary only very slightly, the Alcolea vault being smaller and lower in height than the Agudo vault. There are also fewer keystones, and at Acolea. Eight of them have been replaced by more complex and more efficiently resolved pieces that receive a large number of ribs, demonstrating the skill of the Basque stonemasons to whom the work is attributed. The arches rest on corbels and some of the tas-de-charges display traces of reddish paint, as can also be observed on the ribs at the church in Agudo.

The keystones are simple with no other decoration than the flat boss. If we analyse not only the ribbed vault but the complete intervention in the apse, we continue to perceive similarities in the design of both projects. In Alcolea, the tower is situated on the opposite side to the one in Agudo but they adopt the same model: the two lower stages are square plan and the top one – two in the case of Alcolea – are octagonal, with the greatest similarities between the lowest stage. Both projects adopt the model of the tower at the parish of Valdepeñas (Barranquero 2016), the first building renovated in this area at the beginning of the 16th century (Barranquero 2013).

Figure 5. Ribs (tiercerons and liernes) and hidden keystones of the Late-Gothic vault. Photograph by the authors.

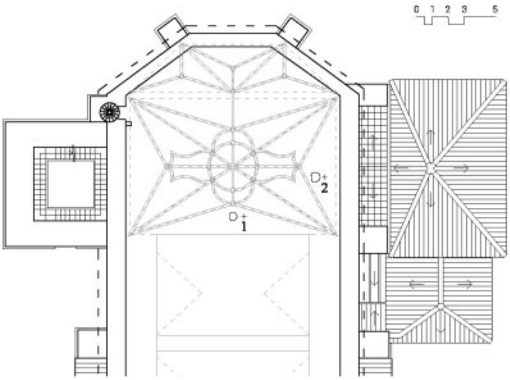

Figure 6. Design of the ribbed vault and perforations in the severy. Drawing by the authors.

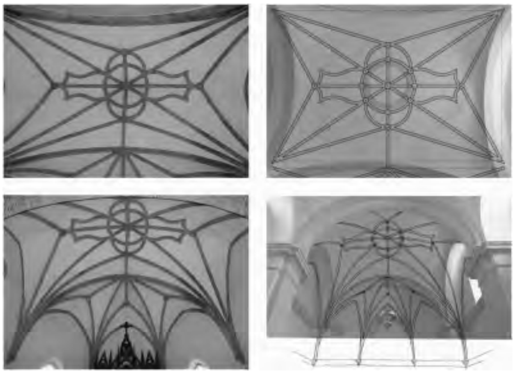

Figure 7. Comparison between the ribbed vault at the church in Alcolea de Calatrava (left) and the concealed vault in Agudo (right). Photographs and drawings by the authors.

5.1 *Ribs*

Ribbed vaults are created by dividing the shell of the severy into cells. The folds are defined by a rib and all the ribs are interconnected, generating a complex three-dimensional network covered by the severy. The geometry is defined by arches or primary ribs, such as transverse, stilted and rampant arches (Palacios 2009). The intersection of the two diagonal arches – or transverse arches – determines the height of the crown keystone. In the case of the concealed vault in Agudo, it is a semi-circular arch and the height at which the keystone is placed must be more than 14 metres since this is the free height above the sail vault immediately below. It is impossible to specify any details with regard to the stilted arch, the vertical section from which the springing line rises, because both elements are concealed.

The two rampant arches of the vault are also concealed but thanks to Antonio de Piña’s working drawing we know that a vault with a round rampant arch was designed, and this was confirmed when we inspected the interior space between the concealed ribbed vault and the sail vault. The liernes are secondary ribs in a ribbed vault in the sense that they are not self-supporting arches. Stonemasons needed to exercise very accurate geometric control of the vault when making the liernes because these are the ribs that connect the keystones located on different planes and at different heights of the vault surface (Palacios 2009), and, in fact, it is the liernes that lend complexity to the design and make each vault unique. This is precisely the case with the church in Agudo, where the original design includes liernes in both directions around the crown keystone.

The moulding is reminiscent of the classical lines that were commonly used in the Late-Gothic period when ribs gradually lost their structural function and the severy acquired more importance. We were able to obtain the section of the liernes and of some of the primary ribs by collecting data in situ, therefore gaining a very approximate idea – notwithstanding possible errors of accuracy due to the uncomfortable conditions in which the data were gathered – of the profile of these arches (Figure 8). The ribs must have been whitewashed at some point because they are still white today. On the parts where the white layer has been lost completely, it is possible to discern traces of the reddish paint that must have decorated the stone.

5.2 *Tas-de-charges*

The intervention in the church in Agudo in the 18th century did not only completely cover the ribs of the main vault but also the springing lines of the arches from the walls, which makes it impossible to gain clues about the building solutions adopted for the vault. Tas-de-charges are pieces of stone laid horizontally as part of both the wall and the arches. Firmly embedded in the wall, they form the springing line for ribbed vaults and connect the different ribs (Palacios 2009). As the same author notes, from the 16th century onwards, these were represented with a circular section on plans, creating clusters of the different arches. On Antonio de Piña’s plan they appear at each springing line in the vaults. We assume that this solution was chosen since we can see a similar one in the vault over the sacristy situated beneath the tower, which has been preserved intact. That vault only has two pointed arches and a crown keystone, and the solution adopted is therefore simpler.

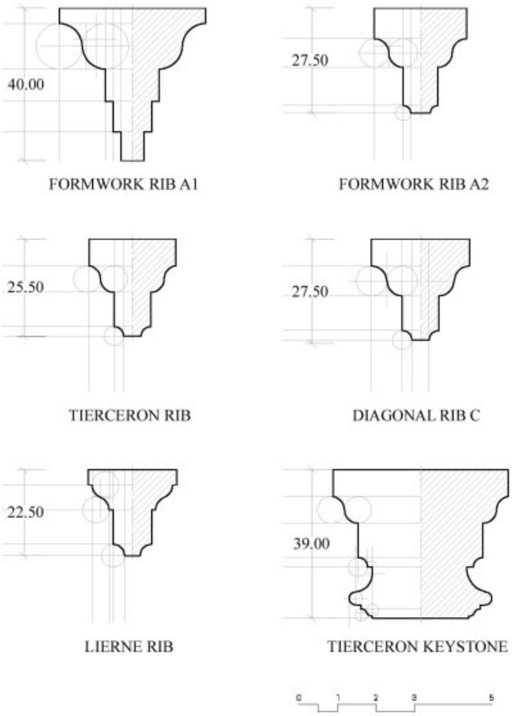

Figure 8. Section of the primary ribs studied. Drawing by the authors.

5.3 *Keystones*

The keystone is the cylindrical piece that resolves the junction between different arches, and arms branch out radially from them to accommodate the ribs. One way to highlight the beauty of a vault was through the delicacy of these pieces, which expert carpenters and masons decorated with carved details and mouldings. The complexity and richness of a vault is partly defined by the number of keystones it generates and there are multiple designs, from the simple vault with a single keystone, like the one over the sacristy at the church in Agudo, to more complex vaults with numerous keystones like Segovia Cathedral with 45, “probably the vault with the largest number of keystones in Spain” (Palacios 2009, p. 111). The tierceron vault examined here generates five keystones. Besides, the liernes are connected to the ribs by another keystone, bringing the total number of keystones to 13. The only ones for which we were able to collect data from the vault are the keystones that connect tiercerons and rampant arches, resolved in both directions with the same design. From what we were able to observe, the profile of the rampant arch keystones, which serve the circular liernes, is similar to the previous ones but has one less rib.

The shape of the diagonal arch keystone appears larger, although it is difficult to view it with complete precision. The crown keystone is barely recognisable since it is located too far away from the point from which it is possible to see the ribs. It is also impossible to determine whether it has more decoration than the flat stone boss because there is not enough space to check the underside of these pieces. Once again, we would have to compare it with the vault at the church in Alcolea, with which we have twinned it.

5.4 *Severy*

Severy is the term used to describe the surface that forms the shell of the vault, which may be resolved with different types of bonding. In the case of the church in Agudo, we were unable to identify the exact bonding used for the vault because a thin layer of plaster on which rows of stone are simulated conceals the original pieces. However, due to the section of the severy, we can affirm that it is composed of several rows of solid brick and is approximately 22 cm thick. A remarkable aspect of this surface is the top coat of *calicostrato*, an amalgam of lime and fragments of ceramic material thicker than is usually found. Extremely hard, it lends the vault a certain monolithic quality and may correspond to a subsequent repair or reinforcement.

6 CONCLUSIONS

The surviving graphical documents of architectural designs and working processes dating back hundreds of years are very valuable objects because of the information they provide. They are testaments to a particular period and modus operandi, but they also shed important light on the history of the buildings concerned, making it possible to create a timeline of events through the ages.

When these records offer data about the actual construction process, they can be compared with the material reality of the building and therefore furnish significant conclusions. In the case of the Church of San Benito de Abad in Agudo, they not only enabled us to establish a timeline for the construction phases but to discover and appreciate the details of an element that had been concealed: the Late-Gothic vault over the chancel. The data gathered at the church itself, the detailed observation of the traces of its construction and careful interpretation of the drawing that has survived all provide a valuable insight into the building. Besides, by comparing it with other local examples we can determine the final configuration of the vault in the concealed elements.

This analysis and the results obtained transcend the merits of the building in the local context as a constructed work of architecture because they also provide a testament to a working method during a particular period. As well as being appreciated by local residents for its symbolic aspects, the church is a valuable testament of a series of architectural works that explain the history of building at a specific time.

The design of the vault also demonstrates the continued use of medieval knowledge as late as the 17th century, and how these drawings not only played a role in the material execution but adapted to new requirements, in this case as part of the standard graphical description of the building. The design of the vault contained in this drawing defines the vault during the construction phase, in the absence of an elevation as we know it today, which in any case is not necessary at this time. In this drawing, the vault is represented as an abstraction of the lines of its ribs and the geometry of its plan, in contrast to a drawing of the floor plan and elevation that acquire a higher degree of iconicity, to the extent permitted by a type of drawing made for people with sufficient knowledge to interpret it.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The geometric design of the "Guarinesque" vaults in Banz and Vierzehnheiligen in relation to the treatises of stereotomy

R.E. Schmitt
DFG Research Training Group 1913 "Cultural and Technological Significance of Historic Buildings", Cottbus, Germany

D. Wendland
Brandenburg University of Technology Cottbus-Senftenberg, Germany

ABSTRACT: Johann Dientzenhofer's Banz Abbey Church (1710–18) and Balthasar Neumann's Church of Vierzehnheiligen (1743–72), both located in Upper Franconia (Germany), are characterized by their masonry vaults, sequences of oval domes separated by double-curved arches. This Late Baroque architecture has been called "Guarinesque"; however, the conceptual connection between the vaults and Guarino Guarini's architecture remains to be thoroughly investigated. This paper discusses the geometric definitions of these vaults using the modern methods of geometric analysis and reverse geometrical engineering, based on 3D-laser scanning. Analysis of these scans reveals a design process based on plane circle segments and ovals, while more complex geometric procedures are not necessary to describe the vaults. Further, the relationship between these designs and the procedures of geometric design described in the treatises of stereotomy since the 16th century can be shown. Based on this background, the relation to Guarini's *Architettura Civile* (1737) is discussed.

1 APPROACHING GUARINESQUE VAULT DESIGN WITH NEW METHODS

1.1 *The vaults of Banz and Vierzehnheiligen as examples of "Guarinesque" vaults*

Near the town of Bad Staffelstein in Upper Franconia, (Germany) and within sight of each other, two churches dominate the landscape aptly referred to as "god's garden".

They are Banz Abbey Church (1710–18), designed by Johann Dientzenhofer, and the pilgrimage Church of Vierzehnheiligen (Fourteen Holy Helpers, 1743–72), designed by Balthasar Neumann. Both churches are prominent examples of an emblematic group of sacral buildings that emerged in the central European regions of Franconia and Bohemia (Czech Republic) during the Late Baroque.

The interiors of these churches have undulating walls covered with vaults. Their complex geometries create extraordinary spaces.

This kind of architecture was employed by a small group of people, including members of the Dientzenhofer family of master builders and the famous architect Balthasar Neumann. Due to a perceived conceptual connection to the work of the Piedmontese architect, mathematician, and Jesuit priest Guarino Guarini (1624–83), the architectural style of these buildings has been described as "Guarinesque" (Brinckmann 1932).An especially interesting aspect of these churches is their vaulted ceilings built in masonry. Their shape is determined by sequences of oval domes, separated, and enclosed by boundary arches with spatial curvature. Analyzing these double-curved arches, also referred to as warped ribs, may help to identify some characteristics of the geometric concepts and procedures that were used by the architects designing and planning these complex vaults (Figures 1, 2).

Figure 1. The vaulted ceiling of Johann Dientzenhofer's Banz Abbey Church (1710–18).

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Figure 2. The vaulted ceiling of Balthasar Neumann's church of Vierzehnheiligen (1743–72).

1.2 *Previous research on "Guarinesque" vaults*

The sacral architecture created by Johann Dientzenhofer and Balthasar Neumann, especially the vaults and double-curved arches, have been a subject of scholarly debate for a long time.

It has been suggested that the designs for the churches and their vaults were based on bent or deformed rectangular bodies (Franz 1987) or on intersecting geometric figures, such as rotation bodies (Holst 1981; Reuther 1953, 1960). Based on this background, a close connection to Guarini's designs and ideas has usually been recognized (Brinckmann 1932; Müller 2002b; Norberg-Schulz 1993). Because the original drawings of these vaults are often inaccurate or partially missing, they offer little insight into the concepts developed by the architects. However, it has recently become possible to carry out analyses on the buildings themselves; these analyses can be used to ascertain the geometric principles behind the designs (Wiesneth 2011). Consequently, the design principles of the Guarinesque churches in Franconia and Bohemia have received renewed scientific interest (Compán et al. 2015).

Nonetheless, the conceptual connection between these Guarinesque vaults and the architectural designs and geometric solutions developed by Guarino Guarini, which were spread by architects in Bohemia and Franconia and were widely disseminated through his architectural writings and prints, still remains to be understood.

1.3 *3D laser scanning as a method for geometrical analyses*

Using Johann Dientzenhofer's Banz Abbey Church and Neumann's Church of Vierzehnheiligen as examples of Guarinesque vault architecture, the modern method of geometric analysis based on 3D-laser scanning has been used to shine a new light on the vaults' underlying design principles. In July 2020, both churches were scanned using a Leica RTC360 time-of-flight laser scanner. The scanning data gathered (Figure 3) has enabled an analysis of the shape of the built objects in their three-dimensional complexity and the reconstruction of their original design.

Figure 3. Triangulated scans of the vaults of the church of Vierzehnheiligen (left) and Banz Abbey Church (right); isometric top view.

In contrast to previous research in which the original building plans or plans drawn by conventional building documentation have been utilized, this method enables the researchers to analyze the shape of the structures as they were actually built, instead of having to refer back to the idealized forms of building plans. Using the methodology of reverse geometric engineering, the scans can be compared to three-dimensional models representing hypotheses of the designs, in order to test them. The quantification and visual representation of these comparisons enable critical revision of the analyses and their scientific discussion (Wendland 2012). The high density of the scans also reveals characteristic geometric irregularities that have the potential to provide evidence on the construction process. The analyses presented herein are preliminary, as the research is in progress.

Discussing these findings and assumptions concerning the design process in relation to the methods described in contemporary treatises on stereotomy and design practices is necessary to provide context and put the results into perspective.

2 THE GEOMETRIC DESIGN OF THE VAULTS

2.1 *Banz Abbey Church*

Banz Abbey Church was built between 1710 and 1718 (Hotz 1993, 63–73). Master builder, Johann Dientzenhofer, who had previously worked on the Benedictine Collegiate Church in Fulda (Vilímková and Bruckner 1989, 46–7), designed and oversaw the construction of Banz Abbey Church in his role as the court architect of Bamberg.

The building is made up of a high and wide nave, structured by three pairs of wall pillars. A narrow entrance and a narrow, elongated choir are attached on either side of the nave (Figures 4, 5). The main vault is intersected by transversal lunettes that span between the wall pillars, widening the space.

The vaults are made of brick; there are structural ribs on the extrados. The vaults' surface is composed of a series of domed areas on an oval plan, separated from each other by pairs of double-curved arches. The spatial curves described by these arches, which can be

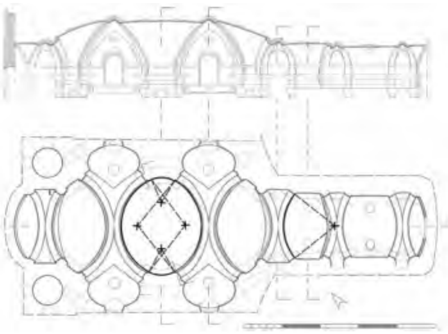

Figure 4. Longitudinal (top) and horizontal (bottom) sections of Banz Abbey Church. The crosses mark the center of the circle sections and the dashed lines mark the radii. The lines indicating the outer edges and extrados are based on Wiesneth 2011. The horizontal section shows a view from above.

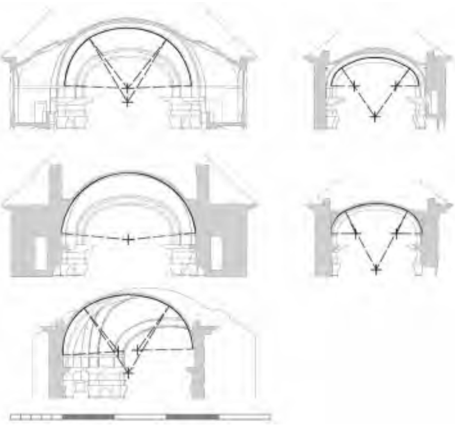

Figure 5. Cross-sections of Banz Abbey Church. Sections of the main double-curved arches (top left), the double-curved arches in the choir (top right), main vault (middle left), choir vault (middle right) and the main vault cut diagonally (bottom left).

seen in Figures 1, 3 and 4, made the arches the object of research interest for decades.

2.2 *State of research*

Reuther described the church's main vault as the fusion of a barrel vault with an oval section and an ellipsoid, trimmed by spherical arches (1954, 362–4).

Hotz described the vaults as spherical barrel vaults, joined by double-curved arches and lunettes (1993, 115). A thorough tachymetric survey of the vaults, including the extrados, has been carried out by Wiesneth. He concluded that the vaults and arches cannot be described by elementary geometrical bodies or rotation surfaces and he attempted to trace their shape back to the wooden centering used in their construction process. According to his hypothesis for the construction of the double-curved arches, the first step was the creation of a barrel-shaped wooden formwork. Upon this formwork, circle segments could be plumbed down to draw the curve of the arch (Wiesneth 2011, 40–47). The most recent research on the vaults of Banz Abbey Church by Compán et al. described the design of the ribs as the "intersection of two perpendicular cylinders of different diameters" (2015, 195).

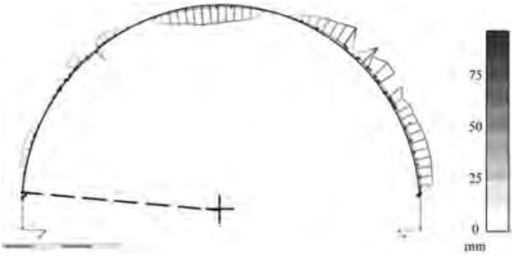

Figure 6. Cross-section of the main vault in Banz Abbey Church. The maximum deviation of the scan data (dotted line) from a fitted circle segment (black line) is 80 mm. Stucco decoration disturbs the findings in the area showing the maximum deviation.

2.3 *Geometric design*

According to the drawings and deviation analyses produced from the laser scan, and corresponding with the most recent research, the geometric design of the vaults of Banz Abbey Church can be described as being based on simple circle segments or, in some cases, oval arches with two radii. As shown by the horizontal section in Figure 4, the projections of the double-curved arches on a horizontal plane are inscribed into circle segments. The domed vaults span between these arches. Their shape can be described by circle segments; the main vault is defined by a symmetrical oval. The cross-section of the main vault (Figure 5) is circular in shape: the first deviation analysis carried out (Figure 6) showed a maximum deviation of ca. 80 mm from a perfect circle. The projection of the double-curved arches on a vertical plane more closely resembles oval arches drawn with two radii. This geometrical feature of the double-curved arches implies that their curves are the primary feature of the design and not simply generated by the intersection of the neighboring vault surfaces. The arches are determined a priori through the intersection curve of two cylinders, while the surfaces of the adjacent vaults are fitted to the curves described by these arches.

The cross-sections of the vault in the choir are based on oval arches with a significantly flatter curve and reduced height. A diagonal cross-section through the main vault reveals a form based on circle segments. Sections drawn in radial direction in respect to the oval plan are defined by just two different radii.

2.4 *The pilgrimage church of Vierzehnheiligen*

Vierzehnheiligen was built as a pilgrimage church over a period of almost 30 years between 1743 and 1772.

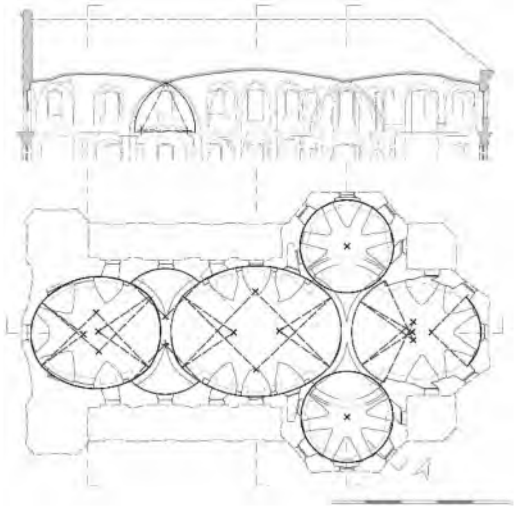

Figure 7. Longitudinal (top) and horizontal (bottom) sections of Vierzehnheiligen church. The lines indicating the outer edges and extrados are based on the documentation by Albertini and Roth, 1913. The horizontal section shows a view from above.

The renowned architect, Balthasar Neumann, had to drastically alter his designs after construction had begun because the executing builder Krohne had made changes to the plans. These changes resulted in a "displaced" crossing (Ruderich 2000, 131–58). At the time of Neumann's death in 1753, the bare structure had only been completed up to the springing of the vaults, built in brick masonry (Ruderich 2000, 171–74). Even though Neumann did not personally oversee the construction of the vaults, it can reasonably be assumed that his successor, the local builder, Nißler, refrained from making major alterations to the great architect's designs. Nevertheless, the construction of the high vaults is substantially different from Neumann's other vaults, and from those of Dientzenhofer's. Vierzehnheiligen's vaults are built with limestone tufa instead of brick and have no ribs on the extrados (Wiesneth 2011, 162–68).

The church has a Latin cross plan created by oval and circular shapes (Figures 7, 8). Two ovals in longitudinal direction make up the nave, the third oval marks the choir. Two circular transepts are located to the north and south of the main crossing.

At the level of the ceiling, these same ovals and circles form the bases of gently domed vaults.

The vaults are separated by two pairs of double-curved arches, forming two crossings. The main surfaces of the vaulted ceiling are interrupted by lunettes for the clerestory windows.

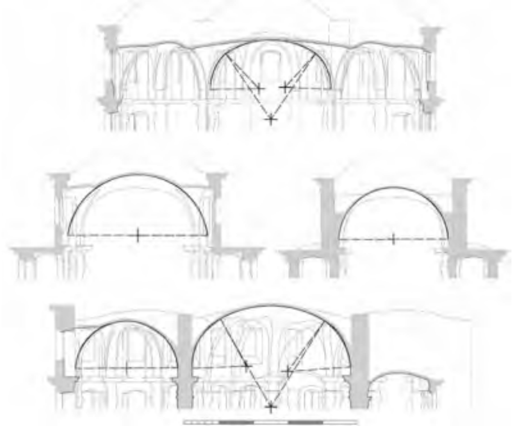

Figure 8. Cross-sections of the church of Vierzehnheiligen. Sections of the crossing's double-curved arches (top), the main vault (middle left), the choir vault (middle right) and the main vault and transept vault cut diagonally (bottom).

2.5 *State of research*

In terms of their geometric design, the vaults of the Church of Vierzehnheiligen have been described by Teufel as approximating ellipsoid shells with blurred edges separated by helical ribs (1939, 103). Reuther described them similarly as a mutual penetration of ellipses, spherical triangles within double-curved arches, and circular transept vaults (1954, 362; 1983, 80). In his comprehensive monograph on Vierzehnheiligen, Ruderich pointed out that ellipses were rarely used in architectural design and that oval constructions were important to Neumann's design. He claimed that the form of the vaults is not based on geometrical bodies, such as rotation surfaces. Therefore, he considered analyses of the geometrical bodies misleading and preferred two-dimensional geometric constructions based on the building plans (Ruderich 2000, 150–95). Müller explained that the design of the double-curved arches of Vierzehnheiligen was the result of the intersection of a vertical cylinder and a horizontal cone (2002b, 44–8). Most recently, Compán et. al. described the projection of the double-curved arches on a vertical plane as composed of circle segments with three different radii (2015, 200–2).

2.6 *Geometric design*

Just like the vaults in Banz, the vaults of the Church of Vierzehnheiligen were designed using circle segments, belonging to single circles or oval arches with two radii. As previous research has already made clear, the horizontal section (Figure 7) reveals a design based on the use of the compass.

Circles are used for the transepts and ovals of different orientation and sizes are used for the main nave and choir. Unlike the projections of the double-curved arches of Banz on a horizontal plane, the projections here are drawn with two different radii, resulting in a "flatter" curve. The double-curved arches are based on circle segments in the longitudinal section. As the cross-sections in Figure 8 show, the double-curved arches' projections on a vertical plane are based on oval arches with two different radii. The cross-sections

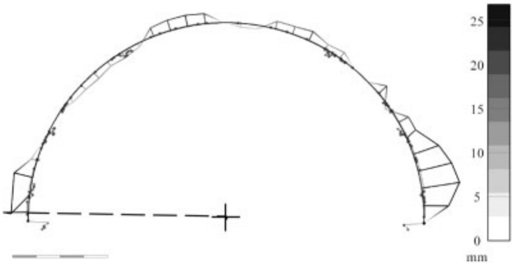

Figure 9. Cross-section of the church of Vierzehnheiligen's main vault. The maximum deviation of the scan data (dotted line) from a fitted circle segment (black line) is 25mm.

through the middle of the vaults themselves (main vault, choir vault, and transept vault), are based on half circles, just as they are in Banz Abbey Church. The deviation analysis revealed the maximum deviation from a perfect circle to be only ca. 25 mm (Figure 9). The diagonal cross-section through the main vault revealed an oval arch similar to that of the diagonal section of Banz.

2.7 *Vault design based on plane geometry*

The survey and geometric analyses of the vaults of Banz Abbey Church and the Church of Vierzehnheiligen revealed that the designs of the two churches' vaults, despite the 30 years that divide them, show many similarities: the most obvious similarity being the use of circles, circle segments, and circle segments combined to form ovals. The preliminary deformation analyses (Figures 6, 9) support this finding, showing a maximum local deviation from the ideal circle of 8 cm (further analyses of this kind are in progress).

Such deviations can be explained by typical vault deformations: the sagging of the summit, the numerous uneven layers of plaster, the stucco decorations that disturb the scan, and the inaccuracies of the building process. It must also be considered that the surveyed surface is the secondary plaster surface. The masonry that was defined by planning lies beneath the plaster. Nevertheless, the deviations are small enough for the results to back up the assumption that circles formed the basis of the design process. The surveys of both churches revealed that the main vaults follow oval shapes and have circular cross-sections. The double-curved arches of both churches are oval arches in the projections on a vertical plane, but the projections on a horizontal plane revealed that the Church of Vierzehnheiligen has oval arches and Banz Abbey Church has arches based on circle segments.

The designs of the vaults of both churches are based on the ovals of the floor plan and the circle segments of longitudinal- and cross-sections. The vault surfaces are simply connecting these geometrically defined curves. The double-curved arches (Figure 10) were not created to function as section curves of the neighboring vault surfaces but were planned geometric elements that defined the design in their own right. Their form can be described by the intersection line of the extrusions of the projections on horizontal and vertical planes (Figure 11). The vertical extrusion is based on the oval shape (consisting of two-by-two different circle segments) of the projection on a horizontal plane. The horizontal extrusion is based on the oval arch (consisting of two different circle segments) of the projection on a vertical plane. There is no part of the vault, neither the double-curved arches nor the vault surfaces, that cannot be defined with simple curves such as circle segments with one or two different radii. There are no curves that derive from intersections, even when cut diagonally. The geometric conception is based solely on geometric construction in the plane. By no means was the use of surfaces of revolution or other more complex surfaces, as some authors have suggested, needed to define the vaults' geometry, and no evidence of such forms has been found in the analyses. Dientzenhofer's and Neumann's reliance on ovals and circle segments is also apparent from the surviving building plans, which show the holes left by their compasses (Ruderich 2000, 51–158; Wiesneth 2011, 41–2).

Figure 10. Triangulated scans of the double-curved arches of the church of Vierzehnheiligen (left) and Banz Abbey Church (right); isometric top view.

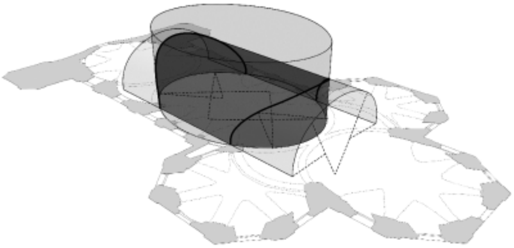

Figure 11. The form of the double-curved arches of the church of Vierzehnheiligen (pictured) and Banz Abbey Church can be described as the intersection curve of the extrusions of the oval of the horizontal projection with the oval arch of the vertical projection. Visualisation by Mark Gielen.

That the designers took this approach to the geometric design of the complex shapes in the vaults is more than plausible. One can suppose that the construction and form control of the vaults was entirely based on wooden centering arches erected in longitudinal, transversal, and radial directions – a feature easily determinable in an oval plan. These centering arches could easily be traced and built as plane oval arches – a geometric description which any skilled mason or carpenter could work with. In these elementary geometric terms, the specification for production of the centering arches could be easily formulated, passed on, and controlled. One can conclude that the astonishingly complex shapes in the vaulted ceilings could be produced by simple geometric control and the use of temporary supporting structures, which were easy, foolproof, and conventional.

3 TREATISES AND DESIGN PRACTICES IN LATE BAROQUE VAULT ARCHITECTURE

The geometric design of Late Baroque vaults must be viewed within the broader context of vault construction in the 17th and 18th centuries. During this period, theoretical knowledge was conveyed through treatises on architecture. Knowledge concerning issues of geometric design were shared in treatises of stereotomy, illustrated books that describe design procedures for complex stone construction. Additionally, the common practices used in execution planning and craftsmanship in this era should be taken into consideration.

3.1 *The design of arches with spatial curvature in the treatises of stereotomy*

Within the Early Modern treatises on the particular subject of stereotomy, a group of several French illustrated printed books refer to the architectural treatise *Le premier tome de l'architecture* by Philibert de l'Orme, (1567). In this work, large sections are dedicated to design procedures for complex shapes (Pérouse de Montclos 1982), and individual work steps are explained. Some of these procedures are exemplified in de l'Orme's own designs of impressively complex stone structures. There is also explicit reference to an existing practice among stonemasons, and some sort of curriculum of standard exercises in stone planning becomes tangible (Wendland et al. 2019, 46–55). While this book and its later editions have never ceased to be in circulation, several treatises solely dedicated to stereotomy adopted and partially adapted the design exercises coined by de l'Orme. François Derand's *L'Architecture Des Voutes* (1643) followed de l'Orme's path and made an important impact on subsequent, influential, published architects and mathematicians, such as Dechales (1674) and Frézier (1737). These treatises, aimed at stonemasons and builders, functioned as instruction manuals that detailed how to execute precision carving of exposed stonework (Müller 1968, 202).

A basic exercise contained in all these treatises addresses the particular problem of designing an arch on a curved plan. The exercise describes how to create an arched door in a round tower – *tour ronde* – and how to draw and cut the single voussoirs according to the geometry of the curvilinear arch. This seems to have been a standard exercise that had been in use since the medieval stonemasons' workshops. A variety of different solutions for the geometric problems of the generation of the curve, shape of the voussoirs, and spatial arrangement of the joints are known (Wendland et al. 2019, 48–51).

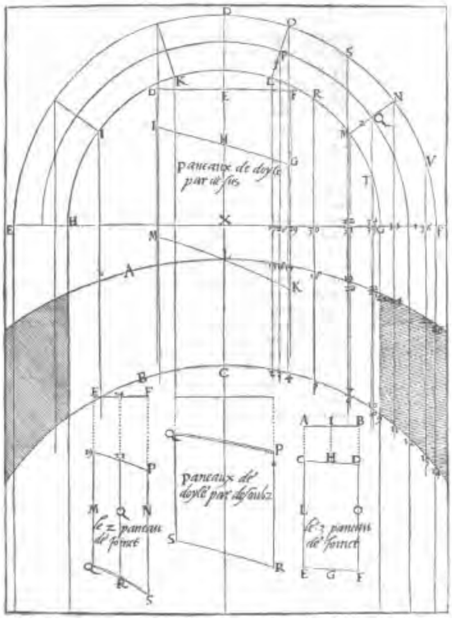

Figure 12. The "tour ronde" in Philibert de l'Orme's treatise Le premier tome de l'architecture (1567, 77); Reproduced from Universitätsbibliothek Bern, MUE Bong IV 783, https://doi.org/10.3931/e-rara-15161 (public domain).

According to de l'Orme and the later treatises, the geometric construction of a curvilinear arch is based on the intersection of two cylindrical surfaces: the vertical cylinder constituted by the wall of the round tower and an ideal horizontal half-cylinder, according to a barrel vault, generating the arch (Figure 12).

It is obvious that the design of double-curved arches proposed in this exercise is based on the same geometric concept that can be encountered in the vaults of Dientzenhofer's Banz Abbey Church and Neumann's church of Vierzehnheiligen.

3.2 *The theoretical approach of Guarini's Architettura Civile*

Even though the comprehensive, printed edition of Guarino Guarini's *Architettura Civile* was not published posthumously until 1737, the plates and other parts of the book were already widely known in the architectural circles of Prague around 1700, where, in particular, they influenced sacral architecture (Hubala 1989, 133).

Although Guarini's work shows similarities to Derand's methods (Calvo-López 2020, 96–100), it is not part of the French tradition of knowledge. In contrast to this group, Guarini's book is less concerned with stonecutting and practical building (Müller 2002a, 80–94). The Italian, who taught and published books on mathematics, produced writing

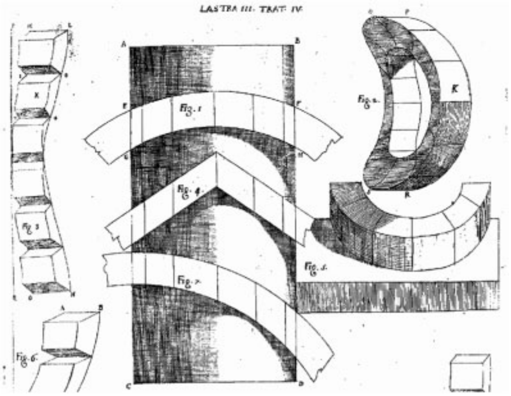

Figure 13. Projections of different forms such as arches on a cylinder, Figures 1–6 of Table 3 of Treatise 3 of Guarino Guarini's "Architettura Civile ADDIN (1737, 349). Reproduced from Bibliothèque Nationale de France, https://gallica.bnf.fr/ark:/12148/bpt6k1118620 (public domain).

that focused on theoretical questions. Guarini himself suggested that his theoretical ideas about projections and sections are necessary for (mathematically proficient) architects (1737, 191).

Architettura Civile is divided into five treatises. The fourth one, *Della Ortografia Gettata*, deals with stereometric problems, such as sections of cylinders, spheres, and cones. Figure 13 shows the projection of arches on a cylinder – this is reminiscent of the *tour ronde* (Figure 12). In his theoretical description, Guarini does not state the practical use for these forms, but their application in a practical building context is apparent.

3.3 *Double-curved arches as an established building practice*

Stereometric problems like the projections on cylinders in Guarini's book must have been very fascinating to well-educated architects with the renown of Johann Dientzenhofer and Balthasar Neumann. However, to recreate Guarini's designs, they had to rely on the established design practices that were available at their Franconian building sites, as his treatise lacked comprehensive instructions. Despite their different creative periods, influences, and backgrounds, when attempting to recreate geometrical ideas such as the double-curved arches made popular by Guarini, both fell back on very similar design methods for the vaults of Banz Abbey Church and the Church of Vierzehnheiligen respectively.

As the descriptions of the *tour ronde* exercise in most contemporary treatises makes clear, the design of double-curved arches from the 15th to 18th century was a standard task in the training of architects – in France for sure – and was made accessible to erudite architects through written treatises. De l'Orme made clear that these exercises were part of the common practice in building crafts. Hence, the design of the great double-curved arches of the churches of Banz Abbey and Vierzehnheiligen was far from being an unusual problem requiring an unusual solution. This was a standard task for architects, planners, and craftsmen. Needless to say, the tracing of oval arches, upon which the whole geometry of the concave vault surfaces is based, was general knowledge on the building sites. The approach to the planning of the vault, which started with creating systems of simple arches, is a sound procedure that goes back to Gothic design practice. In the projects discussed here, Dientzenhofer and Neumann deal with their double-curved arches in the same way. It must be stressed that the design of these extraordinary vaults was achieved in a way that could be realized by means and methods everyone involved in their planning and building would have been familiar with from traditional practices.

4 CONCLUSION

At first glance, the designs of the vaults of Banz Abbey Church and the Church of Vierzehnheiligen appear to be based on complex geometrical concepts. The survey of the buildings and the subsequent geometrical analysis, however, proved that all the surfaces within the vaults can be traced back to simple geometrical curves consisting of circle segments and ovals with one or two different radii. The double-curved arches are not the result of two intersecting vaults. They were designed by what is essentially the same method used in the *tour ronde*, which was described in the building instructions of the Early Modern French treatises of stereotomy. This concept was widely understood by building professionals in Central Europe and was familiar due to the persistence of Late Gothic building traditions. For the purposes of planning, design and construction of these complicated looking vaults, the theoretical descriptions of Guraino Guarini's *Architettura Civile* were neither necessary, nor very helpful. Contemporary mainstream practices were capable of producing the design of the Guarinesque-looking vaults.

ACKNOWLEDGMENTS

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Joseph M. Wilson, Henry Pettit and the iron truss bridges of the Pennsylvania Railroad

D.A. Gasparini
Case Western Reserve University, Cleveland, USA

ABSTRACT: The paper examines the contributions of Joseph M. Wilson and Henry Pettit of the Pennsylvania Railroad (PRR) to the design of iron truss railroad bridges in the US. Wilson and Pettit developed statically determinate truss forms, connection details, and details of built-up compression members that were widely adopted by other US bridge designers. These contributions are examined in context of specific bridge designs: the 1869 bridge over 30th Street in Philadelphia, Pennsylvania (PA), the 1871 bridge over the Juniata River at Mount Union, PA, the 1874 East Span of the Monongahela River Bridge near Pittsburgh, PA, and the Delaware River Bridge at Trenton, New Jersey. These designs reflected a change in engineering judgment regarding appropriate bridge characteristics and were distinctive within contemporary international design practices.

1 INTRODUCTION

The second half of the 19th century was a challenging time for designers of railroad bridges. For one, locomotive weights were relentlessly increasing. Greiner (1895) noted that weights of engines used on the Baltimore and Ohio (B&O) Railroad increased from 10.7 tons in 1835 to 80.4 tons in 1894. Moreover, it became standard to design bridges for trains pulled by two locomotives, implying a 15-fold increase in design loads over that period. Train loads were first modeled as equivalent uniform loads but by the mid-1870s train loads were modeled as discrete axle loads at prescribed axle spacings. Designers then had to determine the position of a train along a span that caused the maximum force in a member, a position that varied from member to member! Moreover, with increasing train speeds, train loads could no longer be assumed to be "static". That is, the fast rate at which axles arrived on a span, unbalanced drive wheels, and track roughness caused dynamic responses with significant stress ranges in many members and connections. These stress cycles caused the newly-observed phenomenon of "fatigue" cracking and rupture. As the spans that could be economically bridged became longer, the truss members became longer, with larger, built-up cross-sections, and their strengths, especially under compression, needed to be verified by physical testing. In general, design, fabrication, and erection processes became increasingly complex, which led to the formation of companies with separate responsibilities, and in turn to new norms of bridge procurement.

This paper discusses some of the above issues in the context of the Pennsylvania Railroad (PRR) and the design work of Joseph M. Wilson and Henry Pettit from the 1860s to the mid-1870s. The forms designed by Wilson and Pettit in that period effectively became the "standard" forms for US highway and railroad truss bridges, used well into the 20th century.

2 THE PENNSYLVANIA RAILROAD

The PRR was chartered relatively late, in 1846, to build a railroad linking Philadelphia, at the eastern boundary of Pennsylvania (PA), with Pittsburgh, 260 miles to the west. This was a modest charter, but with incomparable managerial, financial, and technical leadership, and through formidable political action, by 1875 the PRR owned, operated, or controlled an astounding 6616 miles of railroad (Sipes 1875: 253). Dredge (1879) noted that by 1879 there were 3 miles of iron bridges just on the main line from Philadelphia to Pittsburgh. Churella (2013) provided a definitive history of the early development of the PRR, often referred to as the "Standard Railroad". Much of its explosive early growth may be credited to J. Edgar Thomson, an engineer who began his career as a surveyor and later served as PRR President for 22 years from 1852 to 1874.

The earliest all-iron truss bridges built by the PRR, dating from 1851, combined a tied-arch form with a post-tensioned all-iron Pratt truss (US Patent 3523). Darnell (1988) convincingly showed that the designs were by Herman Haupt, who published a book on bridges in 1851 that illustrated arch-trusses, although not explicitly the PRR bridges (Haupt 1851). By the early 1860s the PRR needed iron bridges that could span navigable rivers and meet minimum "open channel" navigation requirements. Simmons (2018) described how in 1863-5 the PRR realized the first railroad truss bridge that provided the minimum required

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300 ft navigable open channel for the crossing of the Ohio River at Steubenville. The design was by Jacob Linville, a self-taught engineer who joined the PRR in 1857 as an assistant resident engineer and rose to PRR Engineer of Bridges and Buildings in 1863. His design, as described by him (Linville 1869) and illustrated by Cooper (1889), was a complete departure from Haupt's bridges, but still a very highly statically indeterminate form. Concurrently with the Steubenville Bridge, Linville also designed and built a double-track bridge with a 260 ft span over the Monongahela River at Try Street in Pittsburgh, using the "patterns from the channel span at Steubenville" (Linville 1869).

Working alongside Linville were Joseph M. Wilson, who joined the PRR in 1860, and Henry Pettit, who joined in 1862. In 1865, with the apparent agreement of the PRR, Linville left to become President of the Keystone Bridge Company, where he continued designing notable long-span bridges using his patented system. Joseph M. Wilson was appointed the new PRR Engineer of Bridges and Buildings and, together with Henry Pettit, defined a new direction for design of truss bridges.

3 JOSEPH M. WILSON AND HENRY PETTIT

Knap (1903), Pettit (1903), and Vitiello (2002) provided biographical information on Joseph M. Wilson. He was a fifth-generation engineer. His great-great-grandfather and great-grandfather were Scottish engineers. His grandfather, Maj. John Wilson, surveyed the state-owned Philadelphia & Columbia Railroad and mentored the young J. Edgar Thomson (Churella 2013). His father, William Hasell Wilson, became resident engineer on the Philadelphia & Columbia when it was acquired by the PRR in 1857. Joseph M. Wilson (1838-1902) graduated with a degree in civil engineering from the Rensselaer Polytechnic Institute (RPI) in 1858 and then studied analytical chemistry at the University of Pennsylvania for two years. In 1869 he married Sarah Dale Pettit, Henry Pettit's first cousin. His two brothers, John A. and Henry W. Wilson were also civil engineers, also graduates of RPI, classes of 1856 and 1864, respectively. In a unique arrangement with the PRR, Joseph Wilson and his brothers were allowed to establish a private engineering and architecture consulting practice, Wilson Brothers & Co, in 1876. In addition, Joseph Wilson was allowed to retain his position as PRR Engineer of Bridges and Buildings until 1886.

Henry Pettit (1842-1921) was of a prominent Philadelphia family. One great-grandfather, Col. Charles Pettit, was a delegate to the US Continental Congress in 1785-87 and later a trustee of the University of Pennsylvania. Another great-grandfather, Gov. Thomas McKean, was a signer of the US Declaration of Independence (Lamb's 1903). Henry Pettit studied civil engineering at the University of Pennsylvania but left without graduating, very likely because of the US Civil War. However, he received a Master of Science degree, *honoris causa*, from the University of Pennsylvania in 1877. Pettit worked at the PRR for 12 years, until 1874.

Bridge design may be said to consist of three general phases: conceptual design, structural analysis, and detailed member and connection design. Several iterations are normally required to arrive at a complete final design. In the 1860s and 1870s each of these phases was in flux, evolving as engineering science and fabrication processes were evolving and as data on strength and performance became available.

4 CONCEPTUAL DESIGN AND ANALYSIS OF IRON TRUSS RAILROAD BRIDGES

Conceptual design first requires choosing the design actions or loads, deciding on how to model them mathematically, and selecting appropriate magnitudes to achieve a safe design. Self-weight, train weight, and wind pressures were the common design actions. Train weight and wind were modeled as static loads. Wind loads were modeled either as lateral pressures on windward surfaces, usually 30 lbs/ft^2 or 50 lbs/ft^2, or as effective horizontal forces per unit length of span. In the 1830s through the 1860s, train weights were modeled as effective uniform vertical loads, usually 2000 lbs/ft or 3000 lbs/ft. In 1875, the engineer Louis F. G. Bouscaren of the Cincinnati Southern Railway introduced the model of a discrete set of axle loads at prescribed spacings that corresponded to two "design locomotives", while retaining a uniform load model for the freight or passenger cars (Lovett 1875).

A truss bridge consists of the principal vertical trusses, a lateral bracing system, and a floor. The choice of principal vertical trusses elicited a 50-year debate between European (mostly British) engineers and US engineers. British engineers favored lattices, commending their small, simple members, the simple riveted connections, and the overall interconnectedness and redundancy of the diagonals. Iron lattice bridges were used in the US primarily by the New York Central Railroad, initially by the engineer Howard Carroll, a former pupil of Sir John Macneill (Gasparini & Simmons 1997). However, most US iron truss railroad bridges were of the type championed by Cooper (1889), who emphatically stated their principal features: large panels, fewer, larger members, pinned eyebars, and minimal field riveting. But within this conceptual design framework there were important variations. In this context, it is informative to contrast two bridges described by Cooper (1889). One is Jacob Linville's PRR Ohio River Bridge at Steubenville and the other is Albert Fink's Ohio River Bridge at Louisville. Cooper's (1889) drawing of the Steubenville Bridge shows a single-track bridge with a truss form that is statically indeterminate to the 12th degree. Therefore, the diagonals were threaded to allow for some "adjustments" during erection. The transverse floor beams bore directly on the bottom chord eyebars, causing bending. Cast iron was used

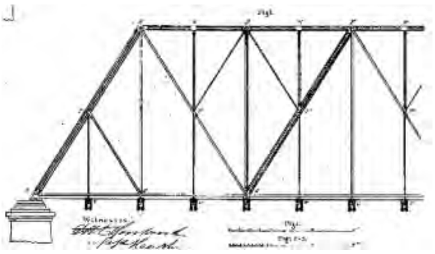

Figure 1. Partial elevation of Albert Fink's Louisville Bridge (adapted from US patent 116,787).

for the joints, the compressive top chord, and the verticals. Linville (1869) noted that both the top and bottom chords had lateral bracing systems and that the "double tube" top chords added to the lateral stiffness. Fink's bridge, also for a single track, was built in 1868-70 with 46 ft deep trusses over a 390 ft span. Both the principal trusses and the floor system were quite different from Linville's design. Fink's design, shown in Figure 1, was based on Warren trusses with very long, 56.6 ft, distances between panel points. Fink then divided this distance into four 14.2 ft panels using vertical members and two sub-diagonals. Fink called the added members "auxiliary trusses", which he patented (US Patent 116,787, 4 July 1871). This subdivision reduced the effective length of the top chord members and the span of the floor beams. Unlike Linville's trusses, Fink's subdivided trusses were statically determinate forms, which did not need adjustable threaded members. Fink used riveted wrought iron compressive members but still used castings for the joints. He designed lateral load resisting trusses at both the bottom and top chords, terminating into elaborate portals. Fink used *sixteen* eyebars in parallel for the bottom chord at midspan! Linville's and Fink's designs, conceived just a few years apart, embodied completely different conceptual design ideas.

With load models and a preliminary conceptual truss design, some structural analyses must be done to estimate the effects of the loads, which in turn may be used for detailed design of the members and connections. In the US, railroad truss bridges were initially analyzed using Navier's analogy of a truss as a framed beam, first by the engineer Stephen Harriman Long in 1829-30 (Gasparini & Provost 1989). Navier's analogy was disseminated at the US Military Academy at West Point through the teaching and textbook of Dennis Hart Mahan (Mahan 1837). The next step forward in the analysis of trusses was the solution of joint-by-joint equilibrium using graphic statics, elements of which had been used for the analysis of masonry arches well before the 19th century. In the US, Whipple (1847) and Haupt (1851) applied elements of graphic statics to the analysis of trusses but Rankine's (1858) and Maxwell's (1864) construction of "force figures" and the seminal book by Culmann (1864) provided the core conceptual and theoretical advances. For statically determinate trusses, Rankine's and Maxwell's force figures represented equilibrium at every joint; Unwin (1869) provided force figures for many common trusses and loads. Fink's Louisville Bridge was statically determinate as a truss and, as a native German and an 1848 honors graduate of a polytechnic in Darmstadt, Fink was certainly able to read, understand, and apply Culmann's graphic statics. However, it is uncertain whether he did so for his Louisville Bridge. The earliest US texts on graphic statics were by Du Bois (1875), Greene (1877) (copyrighted in 1874), and Eddy (1878) but this does not preclude earlier use of Rankine's, Maxwell's, and Culmann's advances by engineers active in bridge design.

Engineers understood that member forces and other responses changed as a train traversed a span and that it was necessary to determine maximum member forces and the corresponding train positions. These needs inspired the concept of "influence lines", graphs that showed how particular responses varied as a single concentrated vertical force traversed a span. Kurrer (2008) provided a historical account of the development of influence lines, primarily by Emil Winkler and Otto Mohr beginning in 1867, although Winkler stated that he used the concept prior to 1864. In the US, Swain (1887) stated that he was "not acquainted with any systematic and complete treatment of this subject in English", and provided a historical account, citing almost exclusively German literature.

Any 19th-century engineer who stood on a truss bridge while a train crossed at a normal speed immediately understood that bridges vibrated dynamically and that the assumption that a train caused strictly static responses was in fact unconservative. But analytical estimation of the actual dynamic amplification of responses was beyond the analytical capabilities of 19th-century engineers. One bound was clearly known. If an object is dropped suddenly on a simple spring scale, the maximum indicated weight is twice the actual weight of the object. Therefore, it was thought that the actual maximum dynamic amplification of responses or "impact factor" was ≤ 2. There were two equivalent approximate approaches used by engineers to account for the unknown dynamic amplification. The first was simply to multiply the design train load by a factor, usually 2, and then use allowable stresses for static loads to size members. The second, suggested by Rankine (1858: 274), was to decrease the allowable stress under moving loads to one-half of the allowable stress used for static loads. S.W. Robinson read a paper on the dynamic responses of bridges at the 1885 American Society of Civil Engineers (ASCE) Annual Convention and later published his work in the ASCE Transactions (Robinson 1887). In 1881, Robinson developed a basic strip-chart recorder and measured 193 actual displacement time histories of 13 bridges during train crossings. He concluded that dynamic responses were not primarily from the "suddenness" of the applied axle loads but from periodic forces caused by unbalanced drive wheels, the vertical motion of the cars, and rough or uneven-stiffness floors. On the basis of his experiments, he suggested that dynamic displacements may be considered to be 28% greater than static displacements for a locomotive and tender and 50% greater than static for a loaded freight train (Robinson 1887).

Dynamic responses from train crossings caused another phenomenon: crack initiation, growth, and eventual failure in iron. The existence of this "fatigue" phenomenon was observed in mine hoists by W. A. J. Albert (1838) and reported in train axles by Rankine (1843). Long-term, groundbreaking experimental studies on fatigue were performed by August Wöhler. His results were published in English in ten issues of the magazine *Engineering,* Volume 11, March to June 1871. In addition, US engineers studied English translations of books by two succeeding German researchers, Weyrauch (1877) and Spangenberg (1876). Data on fatigue life, or the number of cycles to failure, are notoriously "scattered" and difficult to interpret. Wöhler's results and how to implement them in design were still being debated in the US well into the 1890s. Design to provide sufficient fatigue life remains a challenge for bridge engineers to this day. A. P. Boller observed that Joseph M. Wilson during 26 years with the PRR had "unusual opportunities for noting the behavior of iron structures under the wear and tear of actual service, opportunities denied the regular professional bridge-builder" (Wilson 1886, discussion on p. 454). Wilson must have observed and considered *many* fatigue failures, especially in threaded members, beam hangers, and castings.

Because of uncertainties regarding responses and member capacities, rules for sizing members and connections had not been standardized in the US when iron bridges were first used. Widely adopted rules or specifications were formulated only after decades of debate among designers.

5 SPECIFICATIONS FOR IRON BRIDGES

Early bridge specifications generally prescribed design loads, methods for sizing members and connections, material quality requirements, tolerances, and other workmanship requirements that affected quality. The objective was to "guarantee" that if the specifications were followed, a bridge would be safe for the design loads. In the second half of the 19th century, in the absence of US national standards, specifications were written by prominent consulting engineers or engineers working for bridge companies (fabricators and erectors). The development of US iron bridge specifications was described in a committee report (Historical sketch 1906) and in an unpublished paper (Clark 1939). Howard Carroll of the New York Central Railroad likely wrote the first US specifications in 1859 for iron lattice bridges. Numerous specifications were written in the 1870s and by the 1880s most of the prominent bridge designers promoted their own specifications as a way of obtaining work and increasing prestige. Theodore Cooper became *primus inter pares* in writing specifications, continually updating his until the early 20th century.

Joseph Wilson first presented his PRR iron bridge specifications at the ASCE National Convention in June 1885 and later published them in the ASCE Transactions (Wilson 1886). His paper generated 70 pages of discussion by most of the prominent US bridge engineers. Cooper wrote a scathing discussion, prefaced with: "The purpose of presenting this paper before the Society [ASCE] was, undoubtedly, to obtain the benefit of criticism from bridge experts in regard to the accompanying specifications" (Wilson 1886, discussion on p. 415). In his closure, Wilson simply replied that he had been "connected with actual bridge work for over twenty years, during which time more than *20 miles* [italics added] of bridges have been constructed from my plans and specifications" and that they are "free for the use of any who may desire to adopt them, either as they stand or with whatever modification or improvement they may seem advisable, and I trust that they may be of some service to my fellow-laborers" (Wilson 1886: 485-6). Cooper took strong exception to the fact that Wilson, using the work of Wöhler, Launhardt (see Seaman 1899), and Weyrauch (1877), had, for the first time in the history of US bridge design, reduced allowable stresses as a function of the *range in stress* in a member, in an attempt to reduce the potential for fatigue cracking. Cooper did not think that such additional complexity was well-founded nor beneficial. In fact, Wilson's specifications were more detailed and complex than practically all other US bridge specifications. Wilson prescribed not one but three types of locomotives for which a bridge had to be designed. No doubt because of his observations of fatigue failures, Wilson specified that all threaded rods had to be "upset" and that floor beam hangers "must have an additional section of twenty-five percent above" that required on the basis of allowable stresses. Probably because of his observations of derailments on bridges, Wilson specified that cross ties on bridges must have a "width of ten inches... and spaced not over twenty inches between centers..." and that guardrails "six by eight inches are to be placed ten inches in the clear outside of each track rail..." Wilson explained: "In case of wheels getting off the track they will run over these 10-inch clear spaces without difficulty, as practical experience has proved it. The outside timber guardrail, well notched to the ties, is considered necessary to prevent the ties from crowding together, as well as a guard" (Wilson 1886: 488). Wilson's workmanship requirements were demanding. The behavior of eyebars in parallel was especially sensitive to dimensional accuracy. Wilson required that "no variation more than one-sixty-fourth of an inch [0.4 mm] will be allowed in the length between centers of pin holes". This is an astounding requirement especially for members that approached 20 ft to 30 ft in length.

In sum, the 1860s and 1870s were periods of competing conceptual design ideas, developing structural analysis methods, evolving understanding of dynamic responses, and unsettled member design rules. In this context, Wilson and Pettit designed and built bridges that were recognized by contemporaries as some of the best of US practice. A very small sample of four bridges reveals aspects of their design process and their contributions.

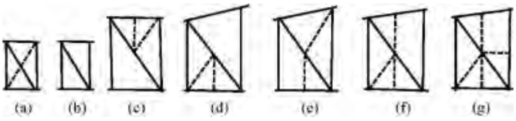

Figure 2. Variations of Pratt truss forms.

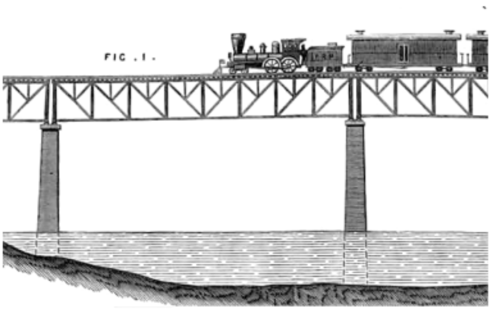

Figure 3. Partial elevation of Juniata River Bridge at Mount Union, PA (adapted from *Engineering* 1871).

6 30TH STREET BRIDGE IN PHILADELPHIA, BUILT IN 1869

Wilson described this bridge in the March 1870 issue of the Journal of the Franklin Institute (Wilson 1870). The bridge had a modest scale, with a span of 64 ft, although its width accommodated six railroad tracks, each track supported by two trusses. Wilson chose to use a statically determinate, three-hinged, wrought iron elliptical braced arch, thus “reducing the calculations to a certainty not possessed by the ordinary form of arch, and annulling the straining effects due to change of temperature and yielding piers” (Wilson 1870). The table and the drawings included with Wilson’s article beautifully revealed the bridge design process practiced at the PRR in the late 1860s. Wilson used graphic statics to draw a force diagram for a vertical load at a top chord joint. He then repeated the analysis for the load at each of the other top chord joints. That is, he computed influence lines for all 31 members that formed one-half of the symmetric truss. Wilson did not compute member forces for a given set of axle loads, but rather computed the maximum compressive and tensile forces in all members for any live load distribution, whether it corresponded to a realistic locomotive or not. He sized each member such that it was able to carry both its maximum compressive as well as its maximum tensile force. Although this was a small bridge, Wilson’s paper shows that PRR engineers in the late 1860s deliberately chose statically determinate forms, drew force figures using graphic statics, and used influence lines to determine maximum member forces. Wilson did not note whether Pettit contributed to the design.

7 PRR BRIDGE OVER THE JUNIATA RIVER AT MOUNT UNION, PA, BUILT IN 1871

The original Pratt truss (US Patent 3523), shown schematically with a single panel in Figure 2a, was a combination wood-iron truss, post-tensioned by tightening the threaded wrought-iron diagonals. Wilson and Pettit were the first US bridge designers to simplify it to its single-diagonal, statically determinate form, shown schematically in Figure 2b. In the eleventh article of their series on the PRR, the editors of *Engineering* noted that: “Two deck bridges of 78 ft and 98 ft were built of this [statically determinate] form in 1870, constructed entirely of wrought iron” (*Engineering* 1877a: 205). For longer spans, with correspondingly larger panels, framing a floor system between two widely-spaced joints became uneconomical, and Pettit designed mid-panel vertical members with sub-diagonals as shown in Figures 2c and d for deck and through trusses, respectively. This modification, which was similar to Fink’s subdivision for his bridge at Louisville, did not change the character of the truss; it remained statically determinate. Therefore, adjustable threaded members were not required. The editors of *Engineering* called such a truss “Pettit’s stiffened triangular truss”, not a name destined to endure. Either because he did not wish to or because he was not able to, Pettit, unlike Fink and most other US bridge engineers, did not patent the form, therefore other designers could freely use it. Pettit used his design for the PRR bridge over the Juniata River at Mount Union, PA. The bridge, completed in 1871, (*Engineering* 1871: 190) had four river spans plus one span over a canal. Figure 3 shows a partial elevation.

Each span had three equal trusses carrying two tracks. In view of the analyses done for the earlier 30th Street Bridge, it is almost certain that Pettit and Wilson performed similar graphic statics analyses and computation of influence lines. The principal diagonals in such trusses, especially those near midspan, could have either compressive or tensile forces, depending on the position of a train. Wilson and Pettit surely estimated both the maximum compressive and the maximum tensile forces and detailed the principal diagonals to carry both. The top chord and the verticals, which are primarily compressive members, were “built-up” from rolled wrought iron sections. The bearings were also of wrought iron, fabricated as per Wilson’s US Patent 112,878. For even longer spans and larger panels, members were added as shown in Figures 2f and g in order to halve the effective lengths of the top chord and verticals. These modifications also did not change the character of the truss; it remained statically determinate. The forms shown in Figures 2b through g became the most widely used forms for US truss bridges because they were efficient and could be analyzed easily using only static equilibrium.

8 EAST SPAN OF THE MONONGAHELA BRIDGE AND DELAWARE RIVER BRIDGE AT TRENTON, NEW JERSEY

The multi-span Monongahela River Bridge was 1622 ft long, with a 260 ft channel span designed by Jacob Linville in 1863-5. A wood Howe bridge was originally built for the span east of the channel span. Wilson and Pettit designed its replacement in 1873-4 “upon the triangular system of H. Pettit” (*Engineering* 1874: 273), as shown in Figure 4. Linville’s and Wilson and Pettit’s designs were both functional and safe, but the differences are striking. Unlike Linville’s truss, the form used by Wilson and Pettit is statically determinate, with fewer, larger, non-adjustable members and much larger panels. It was built entirely of wrought iron. The differences between the two designs reflect a maturation of graphic statics structural analysis and a perception that statically determinate forms were advantageous, as explained by Wilson for the 30th Street Bridge. Wilson and Pettit still elected to support the floor beams directly on the top chord and the outside rails were precariously close to the outside of the deck trusses; it must have been a thrilling crossing.

Wilson and Pettit’s bridge over the Delaware River at Trenton, New Jersey, completed in January 1875, had five spans of through trusses. These were also of the “stiffened triangular [Pettit] form” (*Engineering* 1877b), although slightly different (see Figure 2e) from that of the east span of the Monongahela River Bridge. Figure 5 is a schematic of one of the trusses, which had eight practically square 26 ft wide panels, forming a span of 208 ft.

Each span consisted of three through trusses, separately accommodating two parallel tracks in the south “barrel” and carriage traffic in the north “barrel”. Wilson and Pettit designed a separate floor system as follows: “The cross girders of the railroad portion are of two channels trussed, and are placed at every panel and sub-panel. The track girders consist of two **I**-beams under each rail, upon which are placed white oak crossties and track stringers” (*Engineering* 1877b: 263). They used a uniform load of 3000 lbs per foot of track to design the trusses but a load of 4000 lbs per foot to design the floor beams. This was logical, because an average train weight over a bridge span is smaller than the maximum load that could occur over one panel and because dynamic effects are greater for floor components. As for their other bridges, the main diagonals “in the panels next to the centre of the span are stiffened by internal diagonal bracing, so as to resist compression under variable load” (*Engineering* 1877b: 263). Sketches of the bridge show that Wilson and Pettit installed outside guardrails in this 1874 design, as later prescribed in Wilson’s specifications.

Figure 4. Elevation of the east span and the channel span of the Monongahela River Bridge (adapted from *Engineering* 1874).

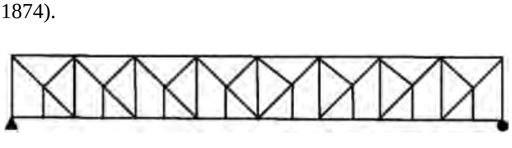

Figure 5. Schematic of one span of Wilson and Pettit’s 1874 Delaware River Bridge at Trenton.

Wilson and Pettit’s practice after commissioning a bridge was revealingly described by Dredge (1879: 68): “In addition to the weekly and sometimes almost daily inspections of the bridges by those in direct charge of them, the engineer of bridges and buildings [Wilson] makes an annual advisory inspection, overlooking them all carefully, noting their action under service, and suggesting any improvements and repairs that may be necessary”. What an ideal way to learn and improve one’s designs!

9 WILSON AND PETTIT’S LATER WORK

In 1874, the City of Philadelphia was planning an international exhibition in celebration of the centennial of the US Declaration of Independence. Pettit resigned from the PRR and he, Wilson, and the industrialist William Sellers became leading advocates and participants in the realization of the exhibition. Pettit was appointed Chief of the Bureau of Installation and, with Wilson, designed both the Main Building and the Machinery Hall. After the success of the 1876 Centennial Exhibition, Pettit consulted with the planning of subsequent international exhibitions and continued practicing as an architect in Philadelphia until ca.1890. He then withdrew from the practice of engineering and architecture and devoted most of his time to travel and travel writing (Lamb’s 1903).

Joseph M. Wilson and his brothers, John A. and Henry W. organized the firm Wilson Brothers & Co. on 1 January 1876. With a client base that included the PRR and its financiers, the firm gained immediate prominence (Vitiello 2002). The firm’s projects were wonderfully illustrated in their *Catalogue of Work Executed* (Catalogue 1885). In a unique arrangement, Wilson remained the PRR Engineer of Bridges and Buildings until 1886 and thus he and his firm continued designing PRR railroad bridges. Two notable designs were the Susquehanna River Bridge, which had 23 spans and a total length of 3680 ft, and the PRR bridge over the Monongahela River at Port Perry, near Pittsburgh, which had 12 spans for a total length of 1406 ft. Wilson described his Port Perry design in the Minutes of the Proceedings of the Institution of Civil Engineers (Wilson 1880) and was awarded a Telford Premium for his paper. As a complement to his engineering and architectural work, Wilson had a lifelong interest in technical education, demonstrated by his long-standing membership in the Franklin Institute in Philadelphia. He was a "Manager" of the Franklin Institute from 1868 to 1887 and served as President from 1887 to 1896. In 1888, supported by PRR financier and philanthropist Anthony J. Drexel, Wilson traveled to Britain, France, Germany, and Sweden to study technical education at "vocational" schools. He summarized his observations in a 160-page report written as a series of articles in nine issues of Volumes 99 and 100 of the Journal of the Franklin Institute (Wilson 1890). Based on their mutual interest in technical education and in providing opportunities for working class students, in 1891 Anthony J. Drexel established the Drexel Institute of Art, Science, and Industry (now Drexel University) and commissioned Wilson to design the institute's main building, which is still extant. Vitiello (2002) noted that Wilson's report served as the foundation for the early curricula and that "as the leading engineer on Drexel's Board of Directors, Joseph Wilson continued to shape the school's curriculum" (Vitiello 2002: 299). He died suddenly, of an apparent heart attack, in 1902.

10 WILSON AND PETTIT'S CONTRIBUTIONS TO US BRIDGE DESIGN

In the late 1860s and early 1870s Wilson and Pettit developed efficient, statically determinate, non-proprietary bridge truss forms that became the standard iron and steel truss bridges in the US for both highways and railroads. Their designs did away with tension-only or "counter" members in the principal trusses. The unprecedented scale of PRR bridge construction, the severity of the train loads, and Wilson's assiduous inspection program meant that PRR bridges served as a test bed for proving new member and connection designs. Wilson and Pettit used up-to-date graphic statics analyses and influence lines well before the publication of US texts on the subjects. As noted by Dredge (1879: 68), the PRR and Wilson "institutionalized" the current US norm of bridge acquisition in which the design engineer is independent of the fabricator and erector.

In his celebrated 1889 paper "American Railroad Bridges", Theodore Cooper noted the early PRR iron bridges built by Haupt and the Steubenville Bridge built by Linville. But Cooper did not mention a single bridge designed by Wilson and Pettit during their long careers with the PRR. It was the British magazine *Engineering* that documented some of their important designs and thus helped preserve their legacy within US bridge design and construction.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Construction of English fan vaults: The tangent plane as a surface of operation

F. Tellia
Universidad Politécnica de Madrid, Madrid, Spain

ABSTRACT: In current historiography on fan vaults, the geometrical method employed to define the shape of the blocks constituting the conoidal shells in joined masonry is based on a horizontal plane opportunely translated to the extrados of the vault, as wonderfully described by Robert Willis. His conclusions came after noticing the flat surface of the extrados of the voussoirs of these vaults. It is worth looking afresh at Willis's theory for two reasons. Firstly, because it cannot be confirmed as no English medieval drawing describing this procedure exists. Secondly, as commented by Leedy in his study on fan vaults, Willis's conclusions were based on built examples featuring a top flat plane, which are the exception, not the norm. It is proposed in this paper that the individual stone blocks may have possibly been defined by a different method, which uses a plane tangent to the vertical ribs, as opposed to a horizontal one.

1 INTRODUCTION

The construction of fan vaults is one of the most striking developments of Perpendicular Gothic and a uniquely English phenomenon, as no comparable examples were built elsewhere in Europe. The earliest fan vaults were erected in the second half of the 14th century in the west of England, possibly as early as c.1351–64 in the cloister of Gloucester Cathedral (Figure 1). Several other examples were constructed well into the 16th century. This form of vaulting was probably a direct evolution of the lierne vaults and brought together many of the constructive innovations of the stonemasons of the West Country. The most distinctive visual feature of a fan vault is the geometry of its intrados, shaped as four trumpets each placed in the corners of a quadrangular bay, with a flat spandrel covering the central space defined by the upper circular boundaries of the fans. The surface of the fan is a conoid generated by the rotation of an arch around its vertical axis; this can also be described as the inner half of a torus. These surfaces have a double curvature and are extremely difficult to carve in stone. At the same time, the multiplication of the lierne ribs makes it inconvenient to build panels independent from the ribs, which were often carved together in the same panel that constituted the shell. From their inception, fan vaults involved a return to the vault in jointed masonry, while the Gothic binary system of construction based on ribs and panels was largely renounced (Palacios 2009). For fan vaults to be constructed, it was essential that each block be drawn and cut according to three-dimensional geometry.

A key problem in the construction of a fan vault, therefore, is related to the cutting of its voussoirs. This procedure may have changed depending on the construction technology used to build the vault, which was made either of jointed masonry, of rib and panel, or of a combination of rib, panels, and jointed masonry. The stonecutting process used for the rib and panel option may not have changed significantly from the traditional Gothic system: the voussoirs with which the ribs were built could have been cut using a template taken from the full-scale elevation drawing of the vault, a bevel to control the curvature while working the stone, and a mould swept along the lower face of the voussoir to obtain the decoration of the ribs. In a few cases where the panels between the ribs are observed to be flat trapezoids, shaping the stones would not have been too difficult. In the case of vaults built of jointed masonry, individual stones had to be individually drawn and purpose-cut for their position in the

Figure 1. The Cloisters at Gloucester Cathedral. Photo by Christopher JT Cherrington. This work is licensed under the Creative Commons Attribution-ShareAlike 4.0 International License.

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vault. Compared to the rib and panel system, the complication of building the vault in jointed masonry adds significant practical challenges when all invariants are considered, which are the saddle-shaped surfaces that are concave in the vertical section and convex in the horizontal section, and the high level of surface articulation of the tracery, which is easier to carve from a single piece of stone.

2 STEREOTOMY OF THE VAULT

In the current historiography on fan vaults, the geometrical method employed to define the shape of the blocks constituting the conoidal shells in joined masonry is based on a horizontal plane opportunely translated to the extrados of the vault: the "surface of operation". This geometrical method is wonderfully described by Robert Willis (1861) through his direct observations of a few built examples. He reached his conclusions by noticing the flat surface of the extrados of the voussoirs of these vaults. Furthermore, as commented by Leedy (1980) in his study on fan vaults, this flat surface seems to be an exception to the norm appearing only in later examples or in vaults of larger spans, as it was used to control the overall shape during construction. It is more usual to find that the extrados follows the intrados very closely (Figure 2). It is worth looking afresh at Willis's theory for two reasons. First, the theory cannot be confirmed as no English medieval drawing describing this procedure exists. Secondly, his conclusions were based on built examples featuring a top flat plane, which are the exception rather than the norm. In this paper, it is proposed that the individual stone blocks may have been worked by a different method that used a plane at a tangent to the arch rib and translated to the midpoints of the upper and lower horizontal arc joints of the voussoir, as opposed to Willis's suggestion of a horizontal plane translated to the extrados of the vault.

According to Willis, therefore, the voussoirs were carved from their two projections, horizontal and vertical, which explains why some vaults have a stepped extrados. However, this method has a drawback: it requires a very large volume of stone. The need to retain the upper reference plane for the cutting of the voussoirs makes the solid stone block containing the volume of the voussoirs considerably larger than the resulting voussoir. When the voussoir occupies a central position in the vault, the volume of stone is not a significant factor, but when it is farther away from the centre of the vault, the volume of stone increases.

Figure 2. The extrados of the vault of the Henry VII Chapel in Westminster. Copyright: Dean and Chapter of Westminster.

This study compares Willis's method and the proposed method based on the tangent plane by using a hypothetical fan vault with flat ridges covering a squared bay, with the radius of the rib defining the conoids being greater than half the side of the bay. A selected voussoir placed in the same position has been drawn and cut to size using the two methods.

3 THE HORIZONTAL PLANE AS A SURFACE OF OPERATION

Willis's method to obtain blocks constituting the fan vaults using the horizontal "surface of operation" is in principle the same as that used to carve the boss stones in lierne vaults. The horizontal and radial joints of the intrados of the vault are drawn on a full-sized plan, as shown in the bottom drawing of Figure 3. The radial joints lie on vertical planes, while the circular joints constitute conical bed surfaces formed by interlacing the upper and lower circular joints of the voussoir. Next, the elevation of the fan is traced. Since the arch ribs constituting the conoid have the same curvature, only one elevation drawing is required to build the vault. It is then possible to project the intrados joints from the plane upwards to meet the arch ribs. The arch of the extrados is then traced at the distance required with the estimated thickness of the vault; this then allows the section lines of the conical beds to be drawn. The newly found vertices of the extrados are then projected downwards to the plan, and in this view the radial and circular joints of the extrados are

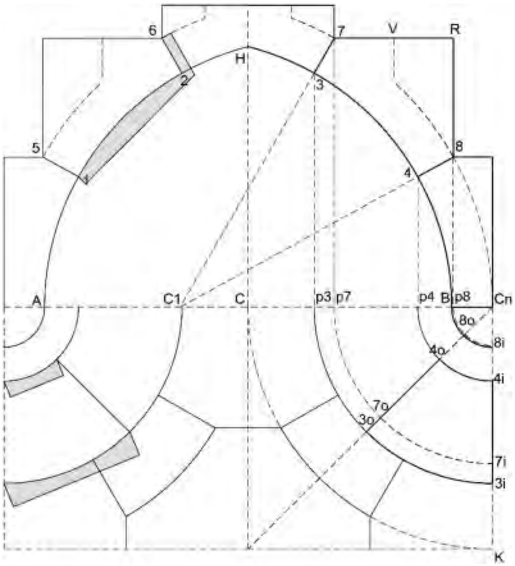

Figure 3. The Horizontal Plane as a Surface of Operation.

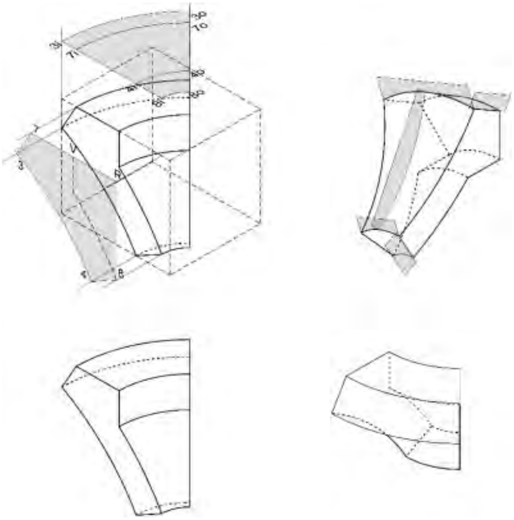

Figure 4. The procedure to work the stone starting from the horizontal plane.

traced-onto the same drawing of the intrados joints. Each stone is designed individually for a particular location, and the templates can be repeated for each circular course of the voussoirs of the fan.

To work the stone (3,4,8,7) defined in the drawing, it is first required to square a stone block with parallel faces (Figure 4). After levelling the upper surface of operation and tracing onto it the mould of the upper face, the stone is cut perpendicularly to this surface in a truncated wedge shape by removing the excess stone. The mould taken from the elevation is drawn onto the side faces that have just been created. Using the mould traced onto the surface of operation as a guide, the other two sides of the stone are worked perpendicularly, resulting in one concave and one convex surface. The stone is then turned to lie on one of its flat side faces.

Willis suggested two ways to form the upper conical bed. The first consists of tracing a horizontal line on the convex surface and working the stone in straight lines by taking as a reference the lines just traced and the arc already traced on the upper bed. The second method requires sliding a bevel set to the angle (4,3,7) from the top plane taken from the elevation drawing. Similarly, the lower conical bed can be made in two ways. It is possible to trace a horizontal line on the concave surface and then to work the stone with a bevel set to (3,4,8). Alternatively, the lower bed can be worked to a horizontal plane passing through point (4) by tracing the outline of the circular joint onto this plane, tracing a horizontal line on the concave surface, and connecting these two arches with straight lines working the conical bed. The cusped surface of the voussoir can be carved out by sweeping along the upper and lower arc joints a bevel with the same curvature of the arch rib, the dimension of which is taken from a true-scale elevation drawing. The surface of operation, according to Willis, can then be chipped away to reduce the weight of the vault and ensure the extrados follows the intrados. The intricate decorations of the intrados were defined on the plan. Using orthogonal projections, the main lines of the tracery can be projected onto the intrados of the vault. The finer details had to be drawn directly onto the smoothed surface of the voussoir, after which the stone was carved perpendicularly to the surface.

The horizontal plane solves the problem of defining the conical beds by taking advantage of a geometrical property of a torus, namely, that all horizontal sections are circles. However, in addition to the larger volume of stone required, the requirement to draw the intrados and then the extrados by projecting downwards from the elevation of the vault may have demanded a careful and accurate tracing to prevent dimensional errors and, therefore, larger tolerances when assembling the vault.

4 THE TANGENT PLANE AS A SURFACE OF OPERATION

No original drawings documenting the construction of fan vaults appear to have survived; moreover, this type of vault was not elaborated in French and Spanish treatises on stereotomy written since the 16th century. There are, however, drawings of annular vaults, which are similar stereotomic artefacts appearing in French treatises of the 17th century and which were also solved by flexible templates and conic developments. These methods involved more approximation than that of orthogonal projection proposed by Willis, since these surfaces cannot be developed and the convex part of the soffit in particular would have been harder to be carved easily due to its protruding curvature. Frezier (1768) proposed a solution with flat templates and explained the procedure to obtain an auxiliary plane that could be used to find the exact geometry of the lower curved edge of the voussoirs. Frezier's solution is very precise and, in comparison to the other methods, allows a notable amount of stone to be saved. Furthermore, some of the geometrical principles outlined in the earlier treatises of Philibert de L'Horme and Vandelvira might prove useful to the construction of the continuous shells of fan vaults.

The different procedure proposed in this article presupposes that the English stonemasons had few advanced geometrical skills and that they would have encountered two main difficulties: finding the dihedral angle between the tangent plane and the vertical bed of the voussoir; and drawing in true dimension the flat template tangent to the arch rib. The idea to use a plane different from the horizontal one comes from the observation that a bounding block inclined at the same slope of a particular voussoir fits more tightly around the voussoir itself than does a bounding block oriented on the horizontal plane. The first step, therefore, is to define the plane tangent to the arch rib for a specific voussoir and to translate this plane to the midpoints of the lower and upper arc joints of the selected voussoir; this can also be referred to as the secant plane passing through the midpoints of the arc beds. This plane will

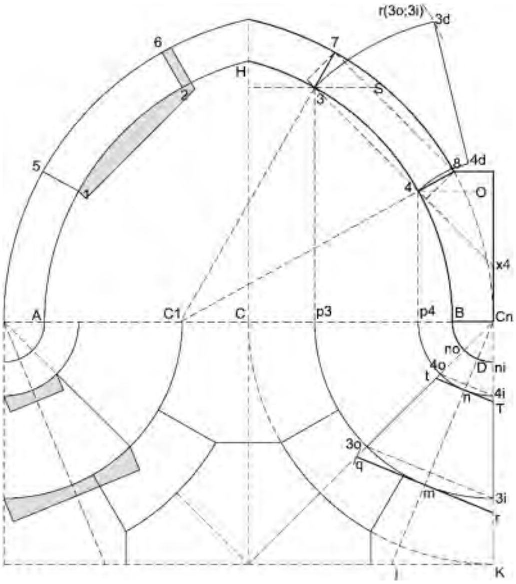

Figure 5. The Tangent Plane as a Surface of Operation.

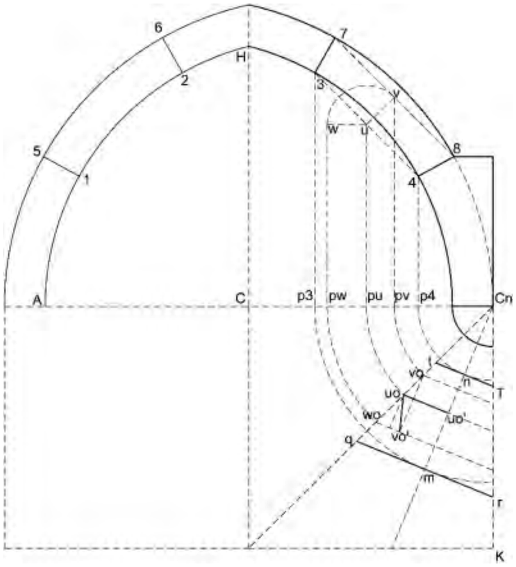

Figure 6. The geometrical procedure to find the Dihedral angle.

be used to reference the dihedral angle and the position of the vertices of the voussoir.

Figure 5 shows a portion of the plan and the elevation of the fan vault. Since all ribs of the conoid have the same radius, only one elevation is required. To begin, the circular and radial joints of the vault are traced onto the plan and the circular joints are orthogonally projected to meet the arch rib in the elevation drawing; next, a line parallel to the arch rib is offset to the required thickness of the vault. The masonry joints must be set with reference to the decorative pattern of the vault: the most intricate parts of the tracery – generally, the panel heads – should be grouped in ashlar rings to isolate the most difficult voussoirs and thus distribute the tasks in the workshop according to the technical skills of the stonemasons.

4.1 *Flat panel*

After selecting the voussoir to cut, the craftsman doing the tracery work must find the true dimension of the trapezoidal flat panel passing through the vertices at the intrados of the voussoir. The distance (3,4) in the elevation is the length of the panel. To find the width of the bases of the trapezoid, it is necessary to refer to the plan for the lines (qr) and (tT), because in this view they are in true dimension. By combining the height and the two bases, the true dimension of the flat panel of the intrados is found.

4.2 *Dihedral angle*

Given that the radial joints lie on the same vertical plane, it is sufficient to find the dihedral angle between the tangent plane and the vertical plane in order to define the face of the block on which they will lie. The stonemason is likely to have known the rudimentary principles of angle revolution. To calculate the dihedral angle (Figure 6), it is necessary to trace an auxiliary line (uv) at the midpoint of the line (3,4); to revolve the point (v) about the axis (u) to (v’); to transfer the distances of the original point (v) and the rotated point (v’) to the radial joint in the plan view; to project them perpendicularly to the bisector of the voussoir; and, finally, to intersect these lines to find the dihedral angle rotated on the flat plane. From this construction, it is possible to set the bevel to the angle that will be used to define the sides of the voussoir.

4.3 *Arc edges*

As previously noted, all horizontal sections of the conoids are circles, so we can use the plan to produce the bevels of the upper and lower arc edges. To orient the bevel on a squared block of stone precisely, it is necessary to find the angle of the bounding volume from the horizontal plane.

This can easily be found in the elevation, as it corresponds to the angle between the section lines of the conic beds and the horizontal plane.

After setting the bevel, it can be transported to the block of stone to be worked. It should be noted that these angles do not correspond to the angle formed between the intrados and the conical beds; rather, they simply define the direction where the vertices of the voussoir are located. Since the conoid is a surface of revolution, each vertex always travels horizontally during the rotation of the generating arch, and each rectangular patch of the arch’s surface will have the vertices of the lower or upper edge lying on the same horizontal plane.

This information would be enough for the experienced stonemason to begin shaping the stone.

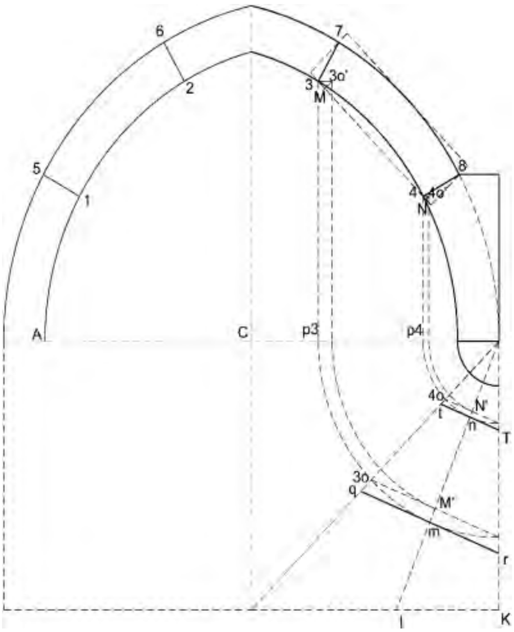

Figure 7. The geometrical procedure to find the arc edges.

However, there is an additional step illustrated in Frezier's treatise that would allow the intrados vertices to be defined univocally in space. Although this treatise was written after the construction of fan vaults, Frezier's suggestion can be interpreted as a mature procedure for tackling this issue. From the elevation of the vault (Figure 7), the projection of the distance between the midpoint of the arc bed and the vertex is measured and, by means of rotation, transferred to the flat template. It is then scored on the top of the stone block, and, by intersecting this line with the line used to orient the bevel defining the arc edges found earlier, the exact position of the vertex on the stone block can be defined. The distances (t,40) taken from the elevation view can also be transferred directly to the stone block without the need to draw them on the flat template.

4.4 *Section*

The template (3,4,8,7) representing the section of the voussoir is taken directly from the elevation drawing, which is also used to manufacture the curved bevel for shaping the vault's soffit.

4.5 *Stonecutting*

After finalising all the required geometrical constructions necessary for shaping the voussoirs, it is possible to carve the stone (Figure 8). Once the projection of the voussoir has been drawn onto the elevation, the stonemason can then work the stone (3,4,7,8) by sizing a prism of stone of the approximate dimensions and creating a flat top surface, equivalent to the tangent plane, on which to trace the outline of the flat template (3,4,7,8).

By placing the bevel of the dihedral angle '(uo'-uo-vo') on the corresponding face, the stonemason can work the radial joints of the voussoir by removing the excess stone. The bevels (3-4-O) and (4-3-S), which are kept perpendicular to the top surface, will now be used to orient the arc joint bevels taken from the plan and to determine the position of the intrados vertices. The arc joints must be made very carefully as they will be used as guides. The template of the section is placed on the radial faces, oriented in such a way that it touches the vertices of the intrados, and it is then traced onto the stone. This outline provides the information about the thickness of the voussoir.

To carve the saddle-surface of the intrados, the bevel with the main curvature taken from the elevation is used. The bevel must lie on the upper and lower arc edges and remain perpendicular to these edges. Next, the bevel sweeps at proportional intervals; that is, if the bevel sweeps by one fraction of the arc length along the lower edge, it must sweep by the same fractional length along the upper edge. The outline of the section will provide the starting point for placing the bevel so that it can be carved from the outside of the block to the inside. Similarly, the conic beds are produced by sweeping a bevel along the arc edges to carve the intrados surface. The bevel has the arm open to the angle (3,4,7) taken from the elevation, and this can be reused for the upper and lower beds. While working the beds, the bevel must be kept perpendicular to the surface of the extrados. One of the benefits of this method is that the stone does not need to be turned until all the faces and the decorative pattern of the intrados are complete.

After working the intrados to a smooth surface, the outlines of the decorations can easily be drawn on top of it while still in the workshop with the help of the tracery pattern drawn on the flat template. In this case, the template should be on a flexible material such as paper or leather. The moulds and decoration can then be carved so that they are sunken into the stone and perpendicular to the surface; this carving might be assisted by the negative of the rib that would have been swept, which would ensure a constant width and continuity of the rib moulding. The extrados can be worked in a similar fashion but with more approximation to reduce the thickness of the stone and make the vault lighter.

Once the voussoir was finalised, it would have been used in the specified order to assemble the vault, with decoration possibly being retouched to ensure the continuity of all the ribs and mouldings.

This method of cutting the voussoir can also be applied easily to the construction of a polygonal fan vault. In this case, the bevel of the horizontal joint would be straight, while the bevel used to connect these two lines would have the curvature of the intrados taken from the elevation. This would produce an effect similar to that of a palm, and the beds of the voussoirs would be flat surfaces.

This alternative stonecutting process results in a notable reduction of the minimum bounding volume

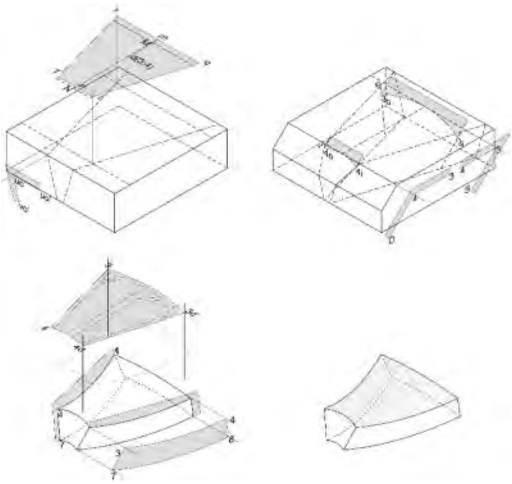

Figure 8. The procedure to work the stone starting from the tangent plane.

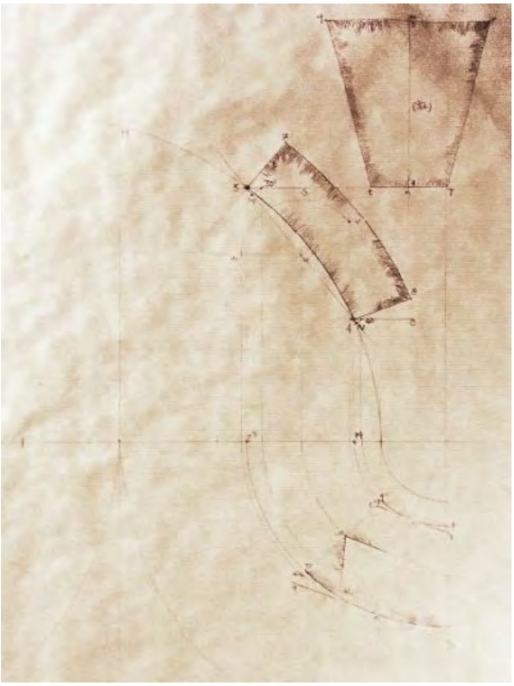

Figure 9. The full-scale tracing of the fan vault.

of the voussoir, leading to a substantial saving of the material required.

5 PHYSICAL MODEL

To prove this theory, constructed models and full-scale tracings (Figures 9, 10 and 11) have been used to reverse engineer the geometrical definition of the voussoirs of the fan vault. The objective was for the results to highlight an important technological development of English Gothic architecture that may have been overlooked. The guidelines described above have been verified in a workshop where plaster blocks were carved out using the proposed cutting protocol to verify the soundness of the theory.

Figure 10. The templates and bevels used to cut the voussoir.

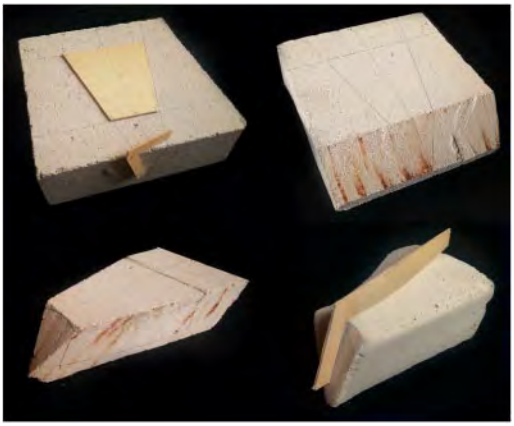

Figure 11. The voussoir was carved out using the proposed cutting protocol.

6 CONCLUSIONS

This paper has outlined a revision of the current assumption of how fan vaults were constructed, with the aim of prompting further investigation. To support this ongoing research, there needs to be an extensive renewed survey that relates the intrados of the vault to its extrados. This would involve digital scanning to identify the exact geometry of the radial joints, as well as an analysis of the vein direction of the stone of the voussoirs. More data on whether stones were chipped away after completion of the vault might be yielded as follows: if the direction of the vein is parallel to the horizontal plan, it was most likely that the stone was cut using the horizontal plane as a reference; if the vein direction forms an angle with the horizontal plan, it is possible that the squared block was oriented to the tangent plane.

Once the geometrical problems are solved, the procedure of working the stone by the method of a

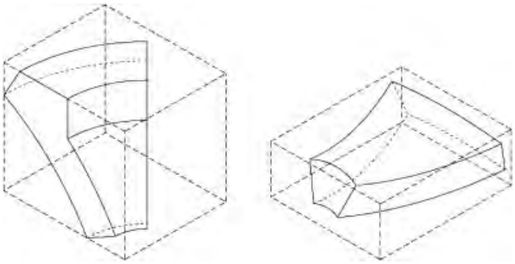

Figure 12. The volume of stone required for the same voussoir worked by using the tangent plane could be half the volume needed if using the horizontal plane as a surface of operation.

tangent plane does not present significant complications. However, there is another more important reason behind this different method: the economy of material. The volume of stone required for the same voussoir worked by using the tangent plane could be half the volume needed if using the horizontal plane as a surface of operation (Figure 12). Furthermore, the nearer the voussoir is to the external of the vault, the greater the difference in the volume of stone required; in particular, the difference is negligible for voussoirs closer to the ridge of the vault. Beyond economic considerations, it is possible to make another observation. To use the tangent plane as a surface of operation requires finding the true size of the angle between the vertical and the tangent plane. It is worth recalling that all classical stereotomy and the cutting of voussoirs for the construction of spherical domes was based precisely on the projection of the stone block onto the face of the intrados. It is extremely interesting to see how both medieval stonecutting and classical stereotomy converged at the same point: projection onto the tangent plane. This method possibly preceded the geometrical operations of the Renaissance whereby stereotomy was based on the surface.

English stonemasons were able to manage the cutting of voussoirs with total precision in coordination with the decoration of their vaults. This geometrical ability was facilitated and ultimately made possible by a precise stonecutting protocol that allowed the construction of some of the most extraordinary vaults in Gothic architecture. This might be evidence of a technological advance in English Gothic construction, because this method presupposes the employment of a sophisticated geometrical system and is in tune with that trait of Gothic architecture which aimed to reduce the construction material irrespective of the complexity of the design.

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Graphical analysis of masonry domes. Historical approaches (1850–1920)

P. Fuentes
Vrije Universiteit Brussel, Brussels, Belgium

ABSTRACT: The idea of the line of thrust appeared in the first half of the 19th century and it was promptly applied to the analysis of domes. Two main approaches were used. On the one hand, the one proposed by Poleni in 1748 for the analysis of St Peter's dome in Rome, considering the dome divided in separated arches, with a two-dimensional behaviour. However, a dome is a spatial structure, and can develop hoop forces. The matter was addressed in an analytical way but also graphical methods were elaborated since the middle of the 19th century. H.T. Eddy, in 1878, applied a graphical method to masonry domes, considering the absence of tensile strength, and obtaining the point where hoop compression changed to tension. In similar ways, different authors struggled with the same problem. This paper summarizes the different approaches, together with application to real cases.

1 INTRODUCTION

Masonry domes have been recurring structural elements for centuries. From the Pantheon or Hagia Sophia to the impressive domes built by Guastavino in the 20th century, many of the most representative buildings in the history of architecture feature this element.

Traditionally, masonry domes, as well as other masonry structural elements, have been designed following geometrical rules. In 1670, Robert Hooke carried out the first scientific study of arches, comparing their behaviour with that of an inverted chain. At the end of the century, Gregory (1697) added a fundamental remark: when an arch of any other form than a catenary is stable, it is because a catenary can be included in its thickness. Two main directions were followed. On the one hand, English engineers tried to obtain the ideal form for arches; on the other hand, French engineers tried to obtain the thrust of the arch in order to design appropriate buttresses. In this sense, the theory proposed by La Hire in 1712, and elaborated by Bélidor (1729) was generally accepted during the 18th century. Later on, Couplet (1730) and Coulomb (1773) developed this theory. The idea of the line of thrust appeared in the first half of the 19th century, and with it, a complete theory of arches. Around 1850, some methods were developed in order to obtain thrust lines with graphical methods. Culmann (1866) proposed a systematic application of graphic statics and by 1900, graphical analysis was the standard tool to analyse arches and vaults. However, the indeterminacy of the position of the thrust line was considered a problem at the time. The elastic theory made it possible to determine what was considered to be the "true" thrust line, and the first elastic analyses of arches were carried out in the second half of the 19th century (Huerta 2004; 2008; Kurrer 2018).

2 FIRST SCIENTIFIC THEORIES FOR DOMES

The development of the scientific theory of domes until the first quarter of the 19th century is thoroughly studied in López Manzanares (1998). A summary is presented below.

The first scientific design of a dome was carried out by Christopher Wren, in collaboration with Robert Hooke, for St Paul's Cathedral, shortly after Hooke's presentation of the problem of arches to the Royal Society (Heyman 1998). In the first half of the 18th century, different theoretical essays were published regarding structural analysis of vaults, and some included the analysis of domes. Bouguer (1734) was probably the first one considering the three-dimensional analysis of domes and some years later, Frézier (1737–39) systematically used the slicing technique considering domes divided in lunes, as a particular case of polygonal vaults.

The first assessments of real domes were done for St Peter's dome in Rome, in relation to the cracks that appeared in the structure. In this context, two reports should be highlighted. The first one was made by the three mathematicians who analysed the stability of the dome employing the principle of virtual work. In the second one, Poleni (1748) applied the catenary analogy, considering the dome divided in lunes, as we will see below.

Throughout the second half of the 18th century, the studies about domes generally followed the La Hire/Bélidor approach for arches, adapted for domes. The method was not correct, but it was easy to apply, and more importantly, it agreed well with traditional geometrical rules. In 1798, Gauthey applied for the first time a collapse mechanism with five hinges to the lunes in which the dome would be divided. The study of collapse mechanisms would be the predominant approach in the first half of the 19th century.

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Lamé and Clapeyron (1823) resolved the equilibrium of the collapse mechanism for vaults and domes, in relation to the reconstruction of the Church of St Isaac in Saint Petersburg. The analysis of domes divided in lunes was also applied by Navier (1826). Throughout the 19th century, other works used similar analytical approaches (;eckett 1871; Durand-Claye 1880; Kobell 1855).

At the end of the 19th century, the elastic theory was generally accepted. However, it was not easy (in fact, impossible at the time) to apply it to three-dimensional structures such as domes. Graphic analysis, calculating different positions for the thrust lines, were considered reasonably safe for practical calculations.

3 POLENI’S APPROACH: THE SLICING TECHNIQUE

In 1748, Giovanni Poleni analysed St Peter’s dome as 50 separated lunes, every two of them forming an arch. The lunes were divided into 16 blocks (Figure 1). Poleni then demonstrated that a chain loaded with proportional weights to that of each block (taking also the weight of the lantern into account) would lie within the arch. Therefore, the dome hypothetically divided in arches was safe and, of course, the dome was safe whether it was cracked or not. This approach of dividing the dome into lunes and every lune into a number of blocks has been systematically used when analysing domes. Poleni used an experimental approach, using a real chain, but the same could be applied using graphic statics and drawing a thrust line inside the lunes. Due to its simplicity, it seems reasonable that this method could be used in practice, however, it has not been found in academic texts (Rehm [2018, fig. 14] published the analysis of a dome built in Munich in 1897 with this method. Although the dome was finally built in concrete, it seems that it was first designed in brick). Poleni’s idea of hanging models has been used throughout history to design structures (Graefe 2021).

In the 1960s, Jacques Heyman demonstrated the validity of Poleni’s analysis within the modern theory of Limit Analysis (Heyman 1967; 1977; 1988). However, during the 19th and part of the 20th century, it was considered impossible that the upper edge (theoretically a line) could transmit a finite thrust. Thus, a different approach was needed.

4 THREE-DIMENSIONAL ANALYSIS: THE MEMBRANE THEORY

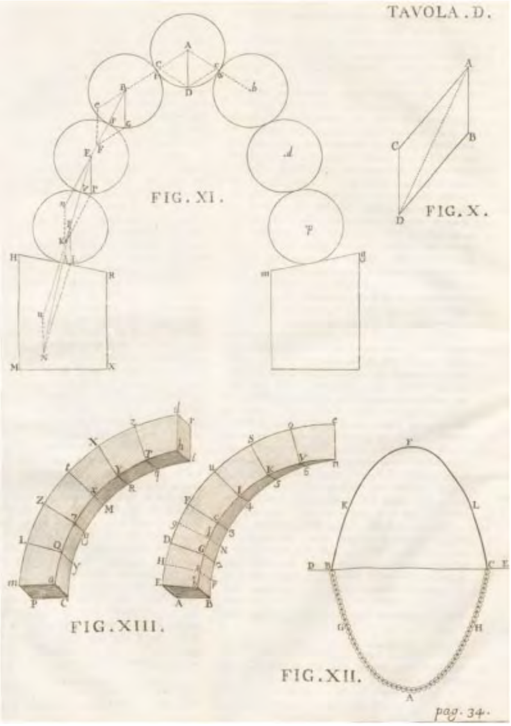

Figure 1. Poleni’s analysis of a dome (Poleni 1748).

A dome is a spatial structure, and it can resist loads as a membrane. Therefore, meridian and hoop stresses can develop. The resultant of the hoop stresses, when combined in the meridian plane, is a horizontal force that will be able to “change” the direction of the meridian forces. In the case of a hemi-spherical dome, both will remain compressive at the crown, while hoop stresses will become tensile at 51.8° from the crown. Such tensile stresses are inadmissible for masonry, and it is not possible to consider them in the stability of the dome.

In 1858, Rankine wrote the membrane equations for a masonry revolution dome. The major step in the development of membrane analysis was taken by J. W. Schwedler. Although he gave an example of a masonry dome, he dealt mainly with iron domes (Schwedler 1863; 1866, 13–15).

4.1 *First graphical approaches (1850–1900)*

One of the first authors considering the development of these hoop forces with a graphic approach was Hermann Scheffler (1857). Scheffler begins his explanation by stating that the previous hypotheses made by authors such as Navier and Rondelet, are wrong. These approaches analysed domes divided in lunes, and then every two lunes were analysed in the same way as barrel vaults and, as explained above, it was considered impossible for the upper edge of the lune to transmit a thrust (Scheffler 1857, 186). Scheffler analyses the equilibrium of a lune, divided in blocks (Figure 2). To achieve the equilibrium, the resultant of the forces in the block must lie inside the joint and fulfil the friction condition. If these conditions are not met, a horizontal force must be applied (Q_1 and Q_2 in Figure 2). These forces will be the resultant of the hoop stresses against the meridian planes. Scheffler considers that these horizontal forces should be exerted in the upper part of the element, in order to make them as small as possible,

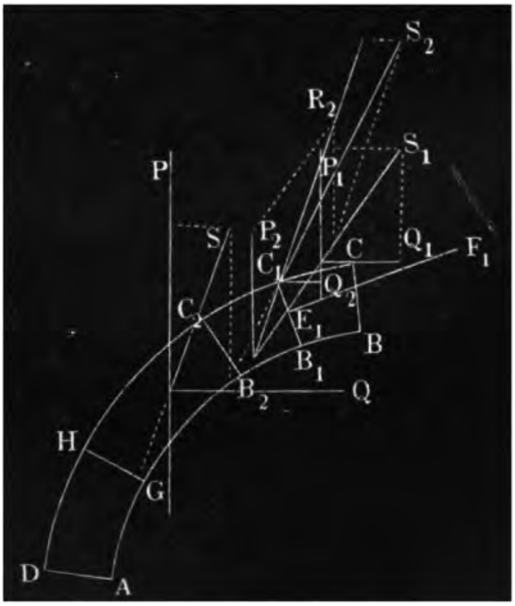

Figure 2. Analysis of a lune (Scheffler 1857).

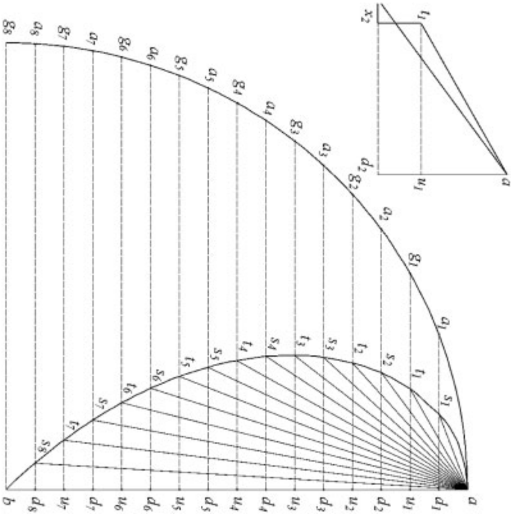

Figure 3. Membrane analysis of a hemi-spherical dome (Eddy 1878, redrawn by the author); Left: analysis of section g_1a_2.

according to the “principle of least resistance” (first formulated by Moseley [1833]). When going down in the dome, at some point this horizontal force will not be necessary in order for the resultant to fulfil the above-mentioned conditions. Scheffler calls this point “the rupture joint”. Below this point, if the resultant acts outside the arch cross-section, or if it forms an angle with the normal to the joint bigger than the friction angle, the dome will be unstable (Scheffler 1857, 186–9).

A fundamental step regarding the application of graphic statics to the membrane analysis was taken by American engineer, H.T. Eddy, in 1878. Eddy first explains the case of a very thin hemispherical metallic dome (Eddy 1878, 53–6), noting that the same procedure applies to any different form generated by the revolution of a curve around a vertical axis. He divides the dome in lunes. As the dome is so thin, the thrust has to be tangent to its section. In order to calculate the thrust and the hoop resultant he proceeds as follows (Figure 3): the height of the dome *ab* represents the total weight of a lune and it is divided in a number of equal parts $d - u$, representing the weight of the parts $a - g$ in which the dome is divided. From *a*, a line parallel to the tangent of the lower point of the section considered is drawn (as_1 is parallel to the tangent in a_1, at_1 is parallel to the tangent in g_1, etc. in Figure 3). The parallelogram of forces $s - t$ represents the equilibrium of the dome and of each section into which it has been divided. Considering, for example, section g_1a_2: g_1 is subjected to a thrust at_1, and at a_2, the thrust must be as_2. To “transform” at_1 into as_2, the weight of this part of the dome, and also a horizontal force s_2x_2 are required (Figure 3). This horizontal force will be the resultant of a hoop compression. As can be seen in the drawing, from t_3 the diagram changes, and in order to change the direction of the thrust, a hoop tension is needed. In the case of a masonry dome with no tensile strength, Eddy considers that below this point, the dome will behave as a series of independent arches working in compression, subjected to the thrust exerted by the upper part of the dome. Besides, Eddy affirms that the thrust line must be contained in the middle third of the dome (the middle-third rule, generally assumed as true in the 19th century, is based on the elastic theory and was intended to avoid tension).

As an example, Eddy analyses a masonry dome with a thickness of 1/16 of the internal diameter (Figure 4). A lune is divided with conical joints normal to the dome, passing through g_1, g_2, etc., being the centres of gravity at a_1, a_2, etc. The weights of each section are au_1, u_1u_2, etc. Eddy draws an equilibrium polygon *c*, starting at the bottom of the dome in point f_8, at the external point of the middle third. The associated polygon of forces has *a* as the pole and the vertical tangent to the curve *st* obtained for the metallic dome w_1w_8 as the weight line. The horizontal thrust of this polygon will be the one exerted by a membrane state in the upper part, that is, considering the forces tangent to the middle line up to 51°49’. But this polygon is under the section of the lune, so Eddy infers that the real thrust will be smaller; applying the principle of least resistance, the thrust will be the minimum necessary for the dome to stand. Thus, Eddy transforms polygon *c* into a new one with a bigger rise, and therefore, a smaller thrust, with two conditions: (1) the thrust line must be within the middle third of the section in the lower part of the dome acting as an arch; (2) the hoop compression will vanish at the level where the thrust line coming from the crown becomes more vertical than the meridian section. At that point, the thrust coming from the upper part will be the greatest thrust that the dome can exert, and it will be equal to the thrust of the "lower arches". Eddy elongates the ordinates of polygon *c*in such a way that the new polygon *e* will be tangent to the exterior line of the inner third (line *m*). To do so, he transforms the latter into a straight line *fo* with *f* being the exterior point of the middle third at the upper part of the vault, and *o* an arbitrary point in line *b*; then he applies the same transformation to polygon *c*, obtaining the line *q*; he graphically calculates the ratio for the elongation of the ordinates drawing a tangent to line *q* (oq_2). Then, it is possible to draw each point, or, as recommended by Eddy, calculate the new pole distance, where the new line of weights will be *vv*. Line *e* will be parallel to the curve of the dome in the points where line *vv* cuts the curve *st.*

Although Eddy does not draw it, in the upper part, approximately up to e_2, there will be a membrane state. From this point to the bottom, the dome will behave as a series of separate arches, and no hoop stresses will develop. Moving upwards, the point of zero hoop stress, Eddy obtained a smaller thrust, allowing a thinner dome thickness than the one obtained considering the membrane solution until the angle of 51°49'.

Eddy noted that the thrust should still be reduced, since polygon *e* is circumscribed about the true equilibrium line, and therefore, the latter will not be tangent to line *m*. He also noted that e_5 is slightly outside the inner third, and that even decreasing the pole distance, this line would remain outside, which for Eddy means that the dome is unstable: "a dome of which the thickness is one fifteenth of the internal diameter, is almost exactly stable." (Eddy 1878, 57–8).

The minimum thickness of a masonry hemispherical dome to be stable is 0,042R (Heyman 1977, 111) that is three times thinner than Eddy's example.

In 1879, Wilhelm Wittmann published *Zur Theorie der Gewölbe*, where he applies graphic statics to arches and vaults.

Besides the arbitrary assumption that the thrust line must be contained in the middle third, the procedure followed by Eddy is correct, and his approach will have great impact in later works. His work was translated to German in 1880 (Eddy 1880).

When addressing the analysis of a dome, Wittmann considers again the equilibrium of an element contained in a meridian lune and a horizontal ring. Wittmann's approach is similar to Scheffler's with some differences. He considers that the force that a block exerts on its base must fulfil friction condition, and in addition, it must be contained in the middle third of the joint. If these two requirements are not met, a horizontal force is needed, that will be applied again inside the middle third. The horizontal force needed for the equilibrium will diminish when going down towards the base of the dome, and at some point, it will become zero (Figure 5). From this point to the bottom of the dome, no hoop forces will be considered, and the thrust line will be the resultant of the combination of the weights of the blocks with the thrust coming from the previous block (Wittmann 1879, 70–74).

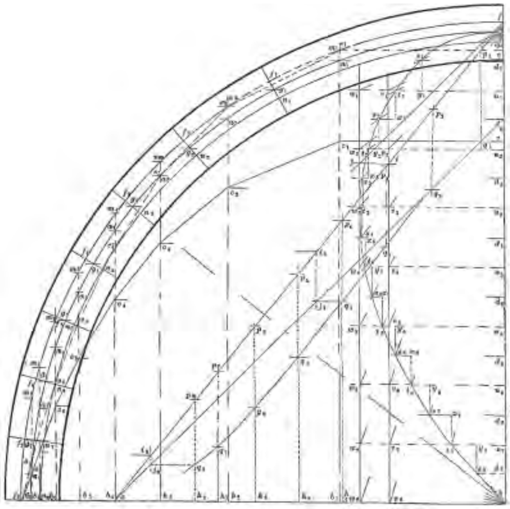

Figure 4. Graphical procedure for the calculation of a dome (Eddy 1878).

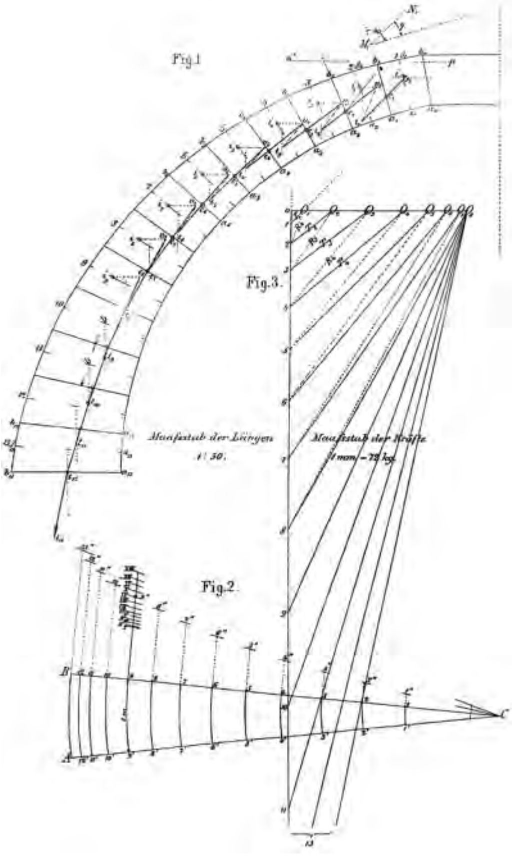

Figure 5. Analysis of a dome with an oculus (Wittmann 1879).

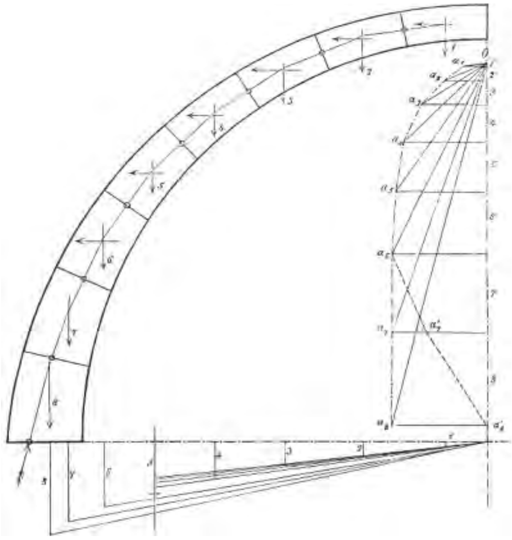

Figure 6. Analyisis of a dome (Föppl 1881).

In 1881, Auguste Föppl in *Theorie der Gewölbe* considers that Scheffler was the first to apply the correct approach to the analysis of domes, although he affirms that the principle of least resistance is not strictly correct. Even though Föppl does not mention Eddy's work, he proposes a similar method, with the difference that Föppl does not move upwards the point where compression hoops become zero. He draws a thrust line tangent to the middle section of the dome until the point where the hoop tension becomes zero. Then, the thrust line will depart from the middle section considering only the weight of the blocks andthe thrust coming from the upper part. In order to have stability he gradually increased the thickness of the dome at the bottom (Figure 6). This is, according to Föppl, an approximate method that can be used in practice. The same approach was published by Max Haase (1900), with a very similar figure.

In 1894, Autenrieth published *Die statische Berechnung der Kuppelgewölbe*, where he compiled and commented on different theories (Navier, Scheffler, Wittmann, Schwedler, Föppl, Hagen and Durand-Claye) and also proposed an analytical method to obtain the variable thickness of a dome for a given intrados. He considers that, for practical calculations, it is better to use simple methods (instead of elastic calculations), based on experience and already built domes (Autenrieth 1894, 16).

R. Gottgetreu cited Scheffler when explaining his approach, and considered as well that the required horizontal forces that keep the blocks in equilibrium must be in the upper part of the joints, so they are as small as possible (Gottgetreu 1880–90, 238). As an example, Gottgetreu analysed St Peter's dome in Rome, concluding that it is stable.

In France, Paul Planat contributed enormously to the dissemination of graphic analysis, particularly through the journal *La construction moderne*. In 1887, he published *Pratique de la mécanique appliqué*, where he dealt with, among other topics, the graphic calculation of domes (Planat 1887, 905–7). Planat considered that the meridian thrust must be perpendicular to the joints, and be inside the middle third of the section. To do so, he assumes any necessary horizontal force. Planat does not mention what happens when, in order for the thrust to be perpendicular to the joint, a hoop tension is required. One year later, Maurice Lévy published *La statique graphique et ses applications aux constructions*, where he applies the same graphical procedure developed by Eddy. In this case, he used a more general example, analysing a dome with a variable thickness (Lévy 1888). In Italy, C. Ceradini (1887) explains Wittmann's theory and gives as an example the analysis of St Peter's dome carried out by Gottgetreu. However, he also considers the possibility of a two-dimensional analysis, with a constant horizontal thrust. He suggests this analysis not as a possible equilibrium solution for any dome, but in the case of domes built as separated arches, and therefore with the disadvantage of the necessity of a centring.

4.2 *Dissemination of the graphical analyses (1900–1920)*

At the beginning of the 20th century, graphical methods were still included in handbooks, but we hardly find significant differences with earlier approaches.

In Germany, Carl Körner (1901) follows Scheffler's approach, and the principle of least resistance, placing the resultant of the hoop stresses in the upper part of each block. Then, he adds that if we consider that the resultants must be applied in the middle third, then this middle third, instead of the whole section, will be used as the limit for the position of the forces in the graphical procedure.

R. Kohnke was mainly interested in the calculation of concrete domes, but he justified the use of methods developed for masonry domes. For the analytical approach, Kohnke cites Rankine and Schwedler. With regard to the graphic methods, he gathers Wittmann's and Föppl's procedures: "For the usual designs, experience has shown that it is enough to prove that sufficient stability exists for any possible thrust line in the vault" (Kohnke 1909, 561). In Germany, Lauenstein and Bastine (1913) followed Wittmann's approach as well.

In the United States, William Cain follows Eddy's approach, and he cites his graphical method. In his analysis of a hemispherical dome, Cain brings attention to the uncertainty of the position of the "true" thrust line. Cain considered that "the true resistance line, even for immovable abutments, depends upon the cutting of the stones as well as the elastic yielding of the dome". (Cain 1906, 174).

Following Eddy's approach as well, William Dunn published a paper for the calculation of thin domes of material capable of resisting tension and compression, with a hemispherical section and of uniform weight (Dunn 1904, 405). In a later paper published in 1908, "The Principles of Dome Construction", Dunn

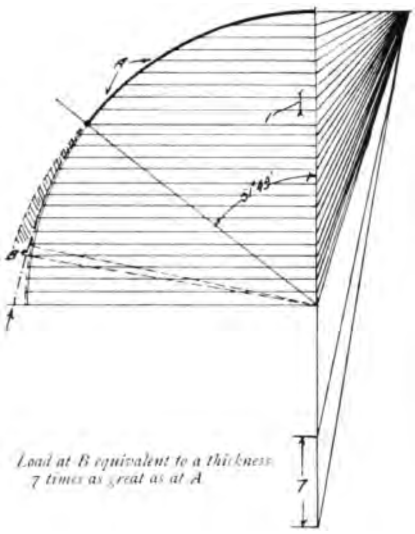

Figure 7. Equilibrium of a dome varying the thickness towards the springing (Waldram 1912).

referred exclusively to masonry domes and he highlighted Eddy's contribution in this matter. He discusses the topic only in a qualitative way. It is interesting the he mentions that cracks do not necessarily mean a lack of stability. If the material cannot resist tensile stresses, "it splits into separate segments (…) which act as a series of radiating arches stressed on the upper and lower beds only (…). It may thus burst apart in radiating lines near the bottom, and yet be quite stable if the abutment is secure" (Dunn 1908, 64–5).

P. J. Waldram (1912), after presenting Dunn's graphical membrane analysis of a dome, tackles the problem of domes with no tensile strength. He suggests two possibilities (besides the use of iron rings): either vary the form of the dome below the point of zero hoop tension or gradually increase the thickness of the dome towards the springing (Figure 7). A similar method is proposed by William S. Wolfe. When the material cannot resist tensile stresses, the thrust line will depart from the middle line (Figure 8, left part of *Fig. 500* and *Fig. 501*). He proposes either adding metallic ties or thickening the section of the dome (Figure 8, right part of *Fig. 500* and *Fig. 502*) (Wolfe 1921, 250–3).

In Italy, Camillo Guidi considers that the thrust line is undetermined, and the elastic theory does not offer a simple and practical solution. Therefore, he explains that the best situation for the dome is having the resultants in the middle point of each joint. The resultant of the hoop stresses should be also in the centre of gravity. Then, it is possible to graphically calculate the dimension of the horizontal forces acting in the meridian planes. In a masonry dome, from the point where the hoop stresses become tension, these horizontal forces will not be considered.For this lower part, Guidi recommends that the thrust line be contained inside the middle section of the lune, unless iron rings are used, in which case it should be contained in the middle third or, even better, coincide with the middle line of the lune, just like the upper part of the dome (Guidi 1915).

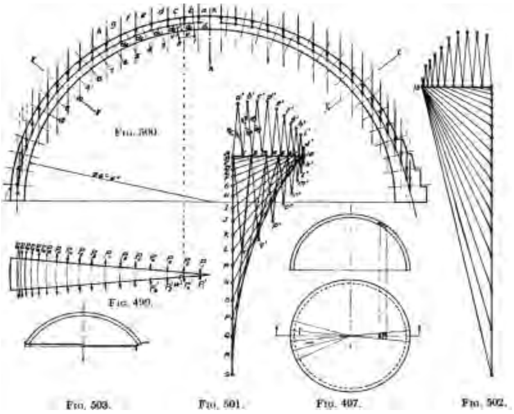

Figure 8. Analysis of a dome (Wolfe 1921).

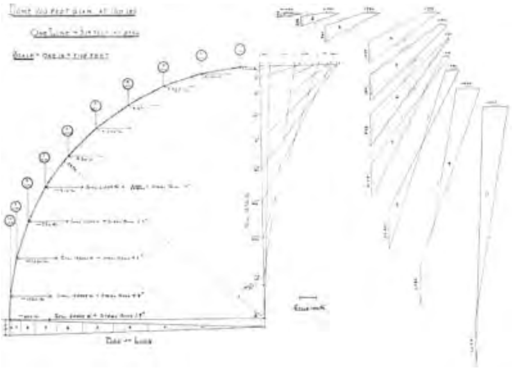

Figure 9. Graphical analysis of a thin dome by Guastavino Jr. (Photograph by the author, Guastavino Fireproof Construction Company architectural records, 1866–1985, Avery Architectural & Fine Arts Library, Columbia University).

5 PRACTICAL DESIGN APPLICATIONS

These graphic methods were not only used for theoretical purposes. They could also be used for the design of domes. The drawings by Rafael Guastavino Jr. show that he perfectly understood membrane behaviour (Figure 9). Following Eddy's method, he designed one of the largest masonry domes, the one for the cathedral of St John the Divine in New York, with a span of 29.9 m, adding rods at the points where tensile stresses are developed (Huerta 2003; Zawinsy et al. 2017). In other domes, he modified the thickness or the form of the dome in order to have compression-only structures (Huerta 2001, 301–13).

An interesting example of the application of graphic statics has been found for the design of the dome of the Congo Museum in Tervuren (Belgium), a double dome with a span around 20 m, by architect Charles Girault. Within the original drawings made by the architect, one has the graphical analysis of the dome (Figure 10, the

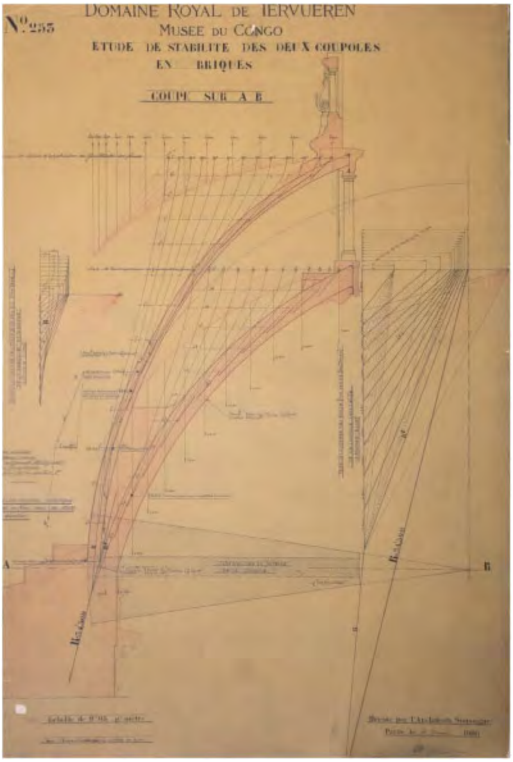

Figure 10. Graphical analysis of the dome of the Congo Museum in Tervuren; Drawing no. 253 (HA.01.0827.19, collection RMCA Tervuren; Charles Girault archives).

drawings are kept in the archives of the Royal Museum for Central Africa). The theoretical approach is similar to the ones already mentioned. However, the specific graphical procedure is new, and no precedents have been found so far. Girault could have used a method taught in the École des Beaux Arts in Paris, where he studied, or a method published in some unknown handbook. Girault analyses one lune that includes a rib in the inner shell. Some missing lines, such as the division of the lune in elements, make it difficult to understand the process followed. Girault considers the horizontal forces resulting from hoop stresses. In the external dome, he allows tensile forces (diagram of forces on the left, Figure 10), while in the internal shell there are only compressive forces (diagram of forces on the right, Figure 10). In both shells he places metallic rings. The resultant of the meridian forces with the horizontal forces seem to be inside the middle third of each shell, a rule that we have seen was very common in this period. After analysing each shell, Girault combines both resultants in the diagram on the right side, obtaining the thrust of the dome.

6 CONCLUSIONS

Graphical methods were very common at the end of the 19th and beginning of the 20th centuries. There were two different approaches to the analysis of domes. The first one applied by Poleni in the 18th century considered the dome divided in arches that will be stable independently. Poleni's analysis, even though it was not graphic, but experimental, was the basis of later analyses with similar assumptions. Despite the simplicity of this approach, it was ignored (at least in texts) until well into the 20th century. The second one was to consider the development of hoop stresses and, therefore, a three-dimensional behaviour. Scheffler, Eddy and Wittmann took fundamental steps and most of the later approaches were based on them. Most authors dealing with this problem considered analytical and graphical approaches. Graphical methods were, in general, considered as an accurate enough solution for practical cases, while the elastic solution was regarded as the "true" solution, although almost impossible to find. The simplicity of these methods compared to analytical methods was the key to their use in practice, both in terms of assessments and design of domes.

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Portuguese timbrel vaults—description and constructive tests

J. Rei
Academia Militar, Lisbon, Portugal

A. Sousa Gago
Universidade de Lisboa, Lisbon, Portugal

M. Fortea Luna
Universidad de Extremadura, Badajoz, Spain

ABSTRACT: This paper presents the main characteristics of the Portuguese timbrel vault, known in Portugal as “abobadilha” or “abobadilha alentejana”, after the region Alentejo where most examples are found. This research is part of an extensive study that culminates in a set of experimental and computational tests which aims to determine appropriate design rules for this type of structure. The rules, shapes and proportions of the timbrel vaults are compared with the geometric features of those described in European treaties of the 18th and 19th centuries. Experimental loading tests were performed on two simple timbrel vaults, the results of which are summarized in the present paper. The numerical model (based on the discrete element method) is intended to be used in the simulation of real structures, anticipating their structural capacity, without the need to perform new experimental tests. A comparison of the experimental results and the predictions obtained is also presented.

1 INTRODUCTION

Throughout the history of construction and into the beginning of the 20th century, overcoming spans in buildings was achieved using vaulted masonry solutions. These solutions developed over the centuries, with an important improvement (and dissemination) during the Roman period.

Given the mechanical characteristics of masonry, without tensile strength, low shear strength and moderate compressive strength, the arch shape is the only possible way to overcome spans with that material. In fact, the arch shape allows loads to be transferred to the supports through compressive stress flows. Thus, in masonry vaults and arches shape is an essential element to guarantee the necessary strength and structural stiffness.

Vaults have been found with several variants, both in terms of geometry and construction techniques. A relatively popular solution in southern Europe is the timbrel vault, also known as tile vault. It is a technique that allows the execution of vaults without centering (or with a light falsework) while using relatively light and economical clay bricks (Gulli & Mochi 1995; Huerta 2003).

In Portugal, this technique was common in southern regions (Mateus 2002), mainly in Alentejo where it is known as “abobadilha” or “abobadilha alentejana”. In Spain it is called “bóveda tabicada” or “catalana” (Huerta 2003), in southern France “voûte Roussilon”, “plate” or “mince” (Claudel & Laroque 1850) and in Italy “volta in foglio” or “a la volterrana” (Gulli & Mochi 1995). In addition to these southern European regions, the timbrel vault can be found in Algeria, Morocco and Tunisia. More recently, at the end of the 19th century, the timbrel vault was exported to North America by the Catalan architect Rafael Guastavino, where several vaults were built using this technique (Collins 1968; Huerta et al. 2001; Moreno-Navarro 1999).

With the spread of steel and reinforced concrete structures, presenting unprecedented possibilities (namely high resistance to bending and shear), shape was no longer a crucial criterion for structures to overcome spans. Thus, the use of linear elements, simpler to put in place, apparently less demanding in terms of execution and, above all, introducing fewer constraints to architectural design, began to be the preferred option for builders and designers.

The preference for these new structures by structural engineers also arose from the level of development of structural mechanics at the end of the 19th century. In the late 19th century and first half of the 20th century structural mechanics was sufficiently developed, allowing the analysis of frame structures with sufficient accuracy. Although considering linear elastic behavior, the models were sufficiently accurate to be used in the design of such structures. Thus, structural designers had a tool to safely design frame structures, while the design of masonry structures was based on empirical rules, which are not always reliable.

It was only in the last quarter of the 20th century, mainly through the pioneering work of Jacques Heyman, that appropriate structural mechanical tools

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began to be used to study masonry arches and vaults.

The high structural efficiency of this type of vault and its reduced ecological footprint compared to other solutions is highly valued today. However, even though the scientific community began to study the behavior of masonry arch structures a few years ago, there are still no adequate design rules for use in professional practice. This work is a summary of the ongoing research project that aims to fill this gap.

2 MAIN CHARACTERISTICS OF THE PORTUGUESE TIMBREL VAULT

The timbrel vault is a particular type of masonry vault made of solid clay bricks of small thickness, placed flatly, i.e. with its largest dimensions placed according to the surface of the vault. In Portugal timbrel vaults were made using 30cm x 15cm clay bricks (also called tiles) with a thickness of 3.5 to 7cm.

This particular way of laying the bricks flatly distinguishes the timbrel vault from other types of vaults, that have the bricks placed with the largest dimensions perpendicular to the surface of the vault (Figure 1). However, it should be noted that in some variants of the timbrel vault technique, the two types of brick laying are combined.

Another distinctive feature of the timbrel vault is that it does not require centering during its construction. The use of fast-setting mortar and light bricks (the low weight results from the flat laying) allows the vault to be executed without the use of centering or, at most, with very light formwork.

According to Rodrigues (1954), the performance of the mortar must be such that in less than 20 seconds of air exposure sufficient strength is obtained to support the clay brick on two of its smallest faces. This support capacity should happen for any position of the brick, even when it is placed horizontally. To obtain a mortar with these characteristics Rodrigues (1954) claimed that use was made of a mixture of lime and gypsum, in a proportion, in volume, of three parts lime to two parts gypsum. According to Rodrigues (1954), sand was not used in this composition. In the 20th century lime was replaced with hydraulic lime and more recently with Portland cement.

Branco (1981) refers to another composition used in Portugal for laying mortar, in which lime is not used, but fine sand, in a proportion, in volume, of three parts gypsum to one part sand.

To build a vault without centering means a massive saving, but this requires a skilled and experienced mason. Controlling the "freehand" form is not a task for any conventional mason and requires sensitivity, skill and persistence. To achieve this goal, in addition to using fast-setting mortar, artisans find an ally in the construction process. Generally, vaults are executed from the borders towards the center, in a uniform way. When the surface to be covered is not square, after laying the first row the execution of the vault is continued on the borders of the rectangle, until the surface to be covered is reduced to a square (Figure 2). When the surface to be covered is square, the rows will be executed continuously along the four borders.

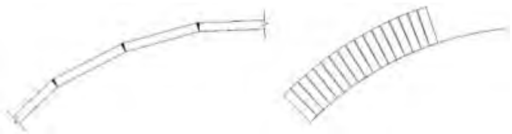


Figure 1. Timbrel vault (left) and current brick vault (right) (Rei et al. 2014).

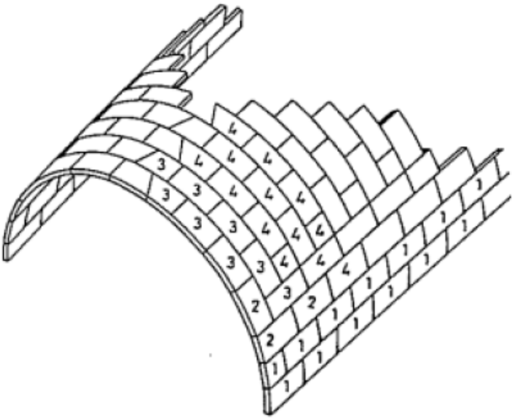


Figure 2. Execution sequence of a barrel timbrel vault (Fidalgo 1994).

Table 1. Typical rise of Portuguese timbrel vaults (Rodrigues 1954).

Span m	Rise % of the span
Up to 4.0*	15 a 20
From 4.0 to 6.0	25 a 30
From 6.0 to 10.0	35

*In Spain and Italy rises of 30 to 40 cm were adopted for vaults of 3 to 4 m, i.e., rises of about 10% of the span.

The most common vault generating lines are the circular curve and the elliptical curve. In the case of the elliptical profile, the rise (free height at half span) is often less than half of the span (Table 1).

When the length of the barrel timbrel vault exceeded two meters, it was common to change the vault cross section in the middle of the vault length (Figure 3) to improve stability during the construction process.

Gurrea (1841) states that this procedure was used by Spanish master masons in the execution of long timbrel vaults (1841): "…se le darán dos ó tres dedos de curva ó montea, á fin de romper la línea recta; pues este pequeño ángulo que forma com su montea, impede y se opone á que puedan desprenderse los ladrillos en su elaboracion" [two to three inches of cutting curvature will be allowed to break the straight line; because

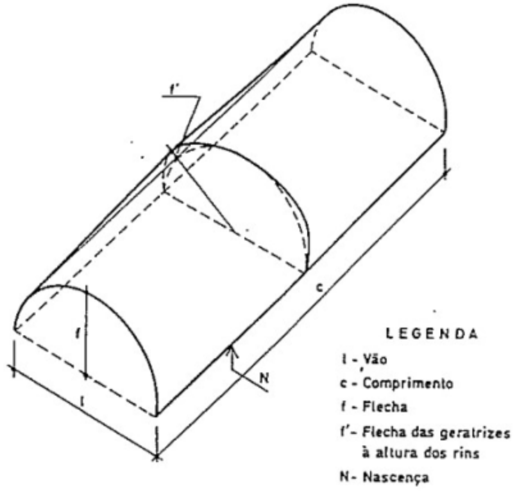


Figure 3. Cross section changing on long timbrel vaults (Fidalgo 1994; Rodrigues 1954).

Table 2. Increasing rise adopted on long timbrel vaults (Rodrigues 1954).

Span		Rise increasing (f' – according to Figure 3)
m	m	mm
3.5	3.5	15
5.0	5.0	30 a 40
5.0	10.0	40 a 50
8.0	8.0	50 a 55
8.0	10.0	50 a 55

this short angle made with the cut works against the mosaics detachment while they are molded].

In these cases, the circular shape of the generating line was transformed to an ellipsoidal shape by increasing the rise of the generating line in the haunches mid-zone. Table 2 shows the increasing rise adopted on long Portuguese timbrel vaults.

Aguiar (1889) refers to another solution of changing the shape of the vault cross section to increase its stiffness and stability. In this technique (called "voamento" in Portuguese) the rise of the double curvature timbrel vaults is increased in the area of the vault crown. This solution is also described in the Spanish timbrel vault and is called "*retumbo*".

Other particularities of the Portuguese timbrel vault apply to the joints: one related to their wedge profile and another to their orientation at the closing of the rows.

The first particularity (wedge profile) is related to the adjustment between bricks (tiles) that should result in joints (in the intrados) of very reduced thickness. The placement of the bricks drives laying the mortar to the vault extrados, filling the wedge-shaped space between the bricks (Figure 4).

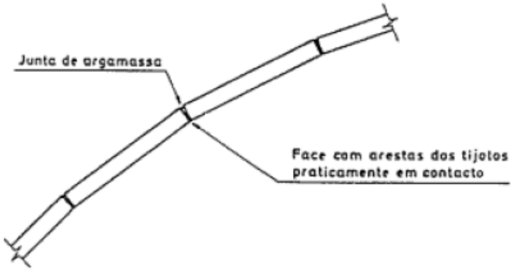


Figure 4. Wedge profile of joints between bricks (Fidalgo 1994; Rodrigues 1954).

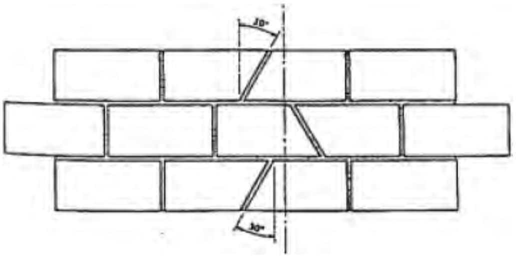


Figure 5. Mismatched joints at the closing of the brick rows (Fidalgo 1994; Rodrigues 1954).

The second particularity occurs in the closing of the brick rows, which should be carried out through mismatched joints, with an angle of approximately 30° (Figure 5).

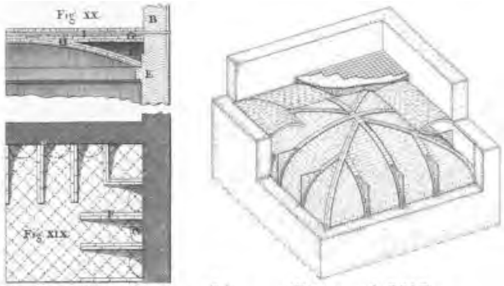
After the vault is closed, its extrados is covered with mortar to increase the strength of the vault and improve the linking between bricks. This operation, called "caldeamento" in Portugal, is also mentioned in the Spanish bibliography.

According to Rodrigues (1954), to reinforce timbrel vaults, and prevent them from rising near the supports when loaded at half span, reinforcement strips 45cm wide, with the thickness of the brick and a distance of 2.5 to 4m, were usually executed (Figure 6). On these reinforced strips solid brick walls were built to the height of the vault closure. These reinforcements have two simultaneous effects, the loading effect that counteracts the effects of other loads, and the effect of increasing the cross-section thickness which increases the vault strength and stiffness.

The loading of the vault extrados, resulting from the construction of the aforementioned solid brick masonry walls, was usually complemented by filling the extrados with lime mortar (with a volumetric ratio of a part lime to four parts sand) up to a height of two thirds of the vault rise. Nicolás (1639) mentioned that in Spain the height of the filling was up to a third of the rise.

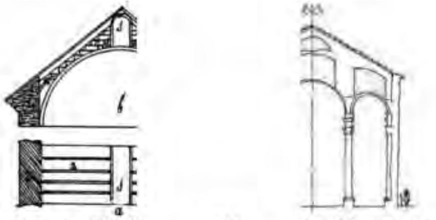
In more recent times, filling was carried out with Portland cement mortar (with a volumetric ratio of one part Portland cement to six parts sand). Sometimes these mortars incorporated brick waste.

Figure 6. Reinforcement strips in Portuguese timbrel vaults (source: the authors).



(a) (Blondel 1777) (b) (Fatta et al. 2017)

Figure 7. Light leveling solutions in timbrel vaults.



(a) Gurrea (1841) (b) San Vicente de Piedrahita Church, Spain (Zaragozá 2011)

Figure 8. Leveling walls in roofing.

In cases where vaults support floors and where an upper horizontal surface is required, it was usual to fill the entire vault extrados, using lime mortar (or Portland cement mortar, in more recent times), agglomerating mortar waste and broken bricks. However, in some cases, to lighten the vault's own weight and to reduce the thrust on supports, small walls were built using the vault bricks placed vertically. These walls supported the wooden beams of the floor, or small timbrel vaults that in turn supported the floor (Figure 7a). This solution was also common in other European timbrel vaults. In other cases (but not as common in Portugal), complementary vaults were built on the main vault extrados (Figure 7b).

This solution to level the vault extrados through small arched walls was also used in inclined roofs (Figure 8). This solution, described in Spanish construction treaties, has not been used, at least not in general, in Portugal.

3 TRADITIONAL DESIGN RULES

For a long time, the design of vaults and their supports (walls and columns) was based on experience. Careful observation of constructed and stable specimens and analysis of failures gave rise to empirical rules that were passed orally from generation to generation. Fortunately, some of these rules were recorded in construction treaties.

In general, the design rules for timbrel vaults in the literature concern the dimensions to be adopted for the walls/piers that support them ("*pés-direitos*" in Portuguese). Although timbrel vaults are light and of small thickness, resulting in moderate thrusts on the supports, a critical point for the stability of these vaults is (as usually happens in vaults and arches) the stability and stiffness of the piers.

Some construction treaties refer to minimum thicknesses for timbrel vaults, as well as limit values for the rise, depending on the vault geometry, but such dimensions were, in general, the result of the execution and practice of the master mason and not of previous calculations. The design of supports (thickness and length) required a knowledge of structural mechanics and, therefore, was usually the only factor referred to in construction treaties.

In Portugal, despite the wide use of timbrel vaults (mainly in the Alentejo region), there are few written references about this technique. The oldest that mentions (indirectly) its design dates to 1896 (Leitão 1896) and establishes the size of the span as key for the use of the simple vault (up to 3.0m) and double thickness vault (over 3.0m).

The lack of Portuguese technical literature and, consequently, the lack of information useful for designing timbrel vaults is mentioned by Aguiar (1889), who presented a design table extracted from a foreign work (Claudel & Laroque 1870). The first explicit reference to practical rules for the design of timbrel vaults in Portuguese literature (and reflecting the Portuguese reality) is from 1954 (Rodrigues 1954). However, the rules described in this document are the result of the practical knowledge of a master mason and are presented for information purposes, without the accompanying proof such as structural calculations.

According to Rodrigues (1954), the thickness of the piers needed to balance the thrust of the timbrel vault could be obtained by the following practical rule: "The weight per linear meter of the wall above the vault supports, including the weight of the vault up to the filling on its extrados, should be three times the weight of the part of the vault above the filling". Based on this, Rodrigues presented a table with thicknesses to be adopted in supporting walls (Table 3).

The Spanish treaty where the "bóveda tabicada" was mentioned for the first time is the pioneering work of Fr Lorenzo (Nicolás 1639). In this work, besides describing the technique in detail, the author presents rules and geometric proportions for timbrel vaults (Table 4), which were reproduced by other authors (Berruguilla 1747; Bru 1738; Camin 1767).

Table 3. Thickness of solid brick masonry walls to support timbrel vaults (Rodrigues 1954).

Vault Span	Thickness
m	cm
Up to 3.0	30
From 3.0 to 4.5	45
Over 4.5 to 6.0	60

Table 4. Fr. Lorenzo designing rules for timbrel vaults (adapted from Nicolás 1639).

Type of support*				
Simple Wall Thickness	Composite Wall Thickness	Buttresses Thickness	Length	Spacing
L/5	L/8	L/4	L/9	L/2

* Considering the usual height/width proportions of the nave in churches.
Note: Thicknesses for churches of a nave with barrel vaults with lunettes, common in 18th century Spain (Huerta 2004).

Table 5. Design rules for the thickness of the supports (walls) of timbrel vaults (Renart ca. 1810).

Timbrel Vault Type	Thickness
Semi-circular without lunettes	L/10
Semi-circular with lunettes	L/11
Low-rise (r=L/6) without lunettes	L/9
Low-rise (r=L/6) with lunettes	L/10
Semi-circular dome	L/10
Low-rise dome	L/9
Seal, groin, semi-circular cloister	L/10
Semi-circular cloister with lunettes	L/12
Low-rise cloister	L/9
Low-rise cloister with lunettes	L/11

Table 6. Design data for 8cm timbrel vaults (Lagarde 1850).

Span	Semi-circular		Low-rise					
			2/3		1/3		1/5	
	H*	t**	H*	t**	H*	t**	H*	t**
m	kg	cm	Kg	cm	kg	cm	Kg	cm
2	148	26	206	31	270	35	282	36
3	222	32	309	37	405	43	423	44
4	296	37	412	43	540	51	564	51
5	370	41	515	48	675	56	706	57
6	444	45	618	53	809	61	847	63
7	518	48	721	58	944	66	988	67
8	592	51	824	62	1079	69	1129	71
9	666	55	927	65	1214	74	1270	76
10	740	58	1030	68	1349	78	1411	80
11	814	61	1133	71	1484	83	1522	85
12	888	64	1236	75	1619	86	1693	89
13	962	66	1339	78	1754	90	1834	92
14	1036	68	1442	81	1889	93	1975	94
15	1110	70	1545	84	2024	96	2117	97
16	1184	72	1649	87	2258	98	2258	100

* Thrust per linear meter of each pier.
** Pier thickness – stone masonry wall with a specific weight of 2200 kg/m^3.

Table 7. Brick courses (Chassinat 1865).

Vault Span	Number of brick courses*
m	#
From 1 to 8	2
From 8 to 12	3
From 12 to 18	4
From 18 to 25	5

* Bricks with a thickness of 5.5cm.

Other significantly less conservative design rules appeared two centuries later by Renart (Table 5).

In France, d'Espie (1754) stands out for being the first to address the technique in some detail. Later, Lagarde (1850), based on the studies by Rondelet and d'Olivier, presented values for vault thrust and for the thicknesses that the supporting walls should present (Table 6). Chassinat (1865), using the results of an experimental campaign, presented a relationship between the number of brick courses and the span of the vault (Table 7). In Portugal vaults with spans of more than 12 meters are unusual. For spans of more than three meters the number of brick layers was usually more than one (Leitão 1896). The use of three layers of bricks was not common in Portugal. However, the required number of brick courses in timbrel vaults depended on the authors. It was usually defined according to the span, the load and the way the filling of the vault's extrados was done. Ultimately, the number of courses is dependent on the thickness of the bricks.

Tables 8 and 9 show some proposed values for the thickness of the timbrel vaults, collected from several construction treaties.

4 EXPERIMENTAL TESTS

Although timbrel vaults were widely used in the past, only a few studies have been carried out with the aim of validating the traditional design rules. Even though there are currently sophisticated models for structural analysis, adequate models and methodologies for structural assessment and design of new timbrel vaults have not yet been established.

The present ongoing research project aims to fill these gaps, using two distinct but complementary approaches. The experimental approach, through loading tests in full-scale models; and the numerical approach, with discrete element models that, calibrated with the experimental results, will allow assessment of the safety of timbrel vaults with shapes not tested experimentally.

In the experimental campaign described in this paper, two simple barrel timbrel vaults, with one a course of bricks and a span of 2.45m were built. The experimental prototypes had a rise of 0.35m (1/7 of the span) and a depth of 0.95m (eight rows of bricks). The extrados of the prototypes was not filled with any type of mortar.

The materials used for the construction of the experimental models were perforated clay bricks of 24x12x3cm^3, laid with a fast gypsum mortar without any other additive, besides water.

The vaults were built on two metal profiles, one held by a fixed support (Figure 9a) and the other on a mobile support (Figure 9b). The mobile support was required to measure the horizontal thrust transmitted by the vault to the supports. Two 8mm diameter steel ties were used to connect the two metal profiles supporting the vault (Figure 10). The horizontal thrust transmitted by the vault was recorded by two load cells attached to these ties.

Table 8. Thickness of timbrel vaults in relation to the span and radius of curvature.

Country	Thickness	Remarks
Spain	L/100	7 > L♠ < 10
	7/8 cm	9 < L♠ > 10
	R/100	
	≥ R/100	Domes¤
Italy	R/50 or > L/48 and < L/36⁑	
	Variable	L♠ < 4.5⁂
	Variable	Arches+

♠ Span size in meters.
¤ Includes filling and bearing walls up to 2/3 of the rise.
⁑ Key thickness for small loads and spans.
⁂ Key, 6cm. Imposts, 12cm. Rise greater than L/10.
+ Key, 12 to 25cm. Imposts, 25 to 36cm.

Two load tests were performed on each timbrel vault model. In the first test the vault model was subjected to a uniformly distributed load, increasing from zero to a maximum value of 2.50kN/m^2 (Figure 10a). No damage occurred with the uniform loading in either of the two models.

The load was materialized by concrete slabs with dimensions of 60x40x5cm^3, with an average mass of 25kg (approx. 250N) per slab (Figure 10).

In the second test, after unloading the uniformly distributed load, the prototype was subjected to a concentrated load (edge load), also incremental, applied at one third of the span (Figure 10b). The specimen was


(a) Fixed Support (b) Mobile Support

Figure 9. Supports of the vault prototype.

Figure 10. Loading of the timbrel vault models.

Table 9. Thickness of timbrel vaults depending on the brick courses.

Country	Variant	Thickness		Bricks	Remarks
		Courses #	Total cm♦	cm^3	
Portugal	Alentejana	1 or 2	3 or 7		3 < L♠ > 3
Spain	Catalana	3 or 4	6.5	30*15*1.5	
		≥ 2	≥ 6	30*15*2.5	Guastavino
		1 or 2	5 or 10		
France	Roussillon	1 or 2	2.7/6.4	27*13.5*2.7	⁂
		1		22*11*5.5	+
Italy		2 to 5			++
		1 or 2	4 or 7		⁂
		3	8	28*14*2	Stairs

♦ Includes 1cm cement mortar thickness between courses (the underlying courses served as formwork for the overlying ones.
♠ One course: span < 3m. Two courses: span > 3m.
⁂ Depending on whether it is a habitable room or not.
+ Small span and pronounced curvature.
++ Depending on the span.

loaded until its collapse, which occurred, in both tests, suddenly without warning, and with little deformability (practically undetectable to the naked eye). This anticipated collapse draws attention to the high risk of conducting load tests on timbrel vaults and to the fact that any sign of degradation and lack of capacity of timbrel vaults should be taken into account.

All the tests were connected to four transducers, used to record the vault displacements: two vertical transducers at half span and one third of the span; and two horizontal transducers on the mobile support, next to each of the tie rods. As mentioned, two load cells (of five tons capacity) were also placed to measure the horizontal thrust on the supports.

The experimental results are summarized in the following tables and Figure 11 showing the load-displacement diagrams obtained in the tests with edge load.

As can be seen in Tables 10 and 11, the 3cm thick timbrel vaults, built with gypsum mortar, supported without collapsing a uniformly distributed load of 2.50kN/m^2, with maximum deformations of 1mm.

Regarding the asymmetric edge loads, the vaults collapsed with loads of 3.68kN and 2.94kN (applied to a length of 0.95m – depth of the prototypes), with maximum displacements under load, just before the collapse, of 1.75 and 1.57mm (Figure 11).

Based on the experimental results, a numerical model of discrete elements (or distinct elements, according to Cundall (1971)) was built and calibrated (Figure 12).

The mechanical characteristics used in the numerical model are summarized in Table 12. Bricks were modeled by rigid elements. The blocks and joints deformability were indirectly modeled on the contacts. It should be noted that with the adopted values for the friction angle and cohesion, sliding did not take place in any joint, as happened in experimental tests. For the contacts' tensile strength, it was considered a relatively low value (0.20MPa), although not zero. This

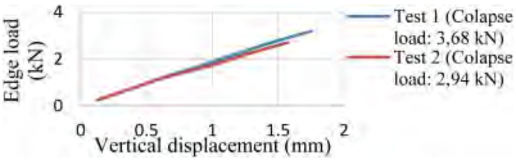


Figure 11. Load-displacement diagrams obtained on the edge load tests.

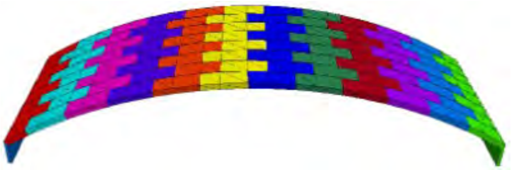


Figure 12. 3D discrete element model of the vault prototype.

Table 10. Experimental and numerical results for the uniformly distributed load of 2.50kN/m^2.

	Displacement				Thrust			
	Vertical		Horizontal		Initial		Final	
	1/3♠	1/2¤	T. 1*	T. 2**	T. 1*	T. 2**	T. 1*	T. 2**
	mm	mm	mm	mm	kN	kN	kN	kN
Test 1	0.96	1.04	0.54	0.75	2.7	1.3	4.4	3.4
Test 2	0.95	1.31	0.41	0.68	1.7	1.0	3.4	3.0
Average	0.96	1.18	0.48	0.72	2.2	1.2	3.9	3.2
3DEC	0.44	0.49	0.34	0.35	1.3	0.3	2.7	1.8

♠1/3 span; ¤1/2 span; *Tie rod 1; **Tie rod 2.

Table 11. Experimental and numerical results for the edge load (immediately before the collapse).

	Load◇	Displacement				Thrust			
		Vertical		Horizontal		Initial		Final	
		1/3♠	1/2¤	T. 1*	T. 2**	T. 1*	T. 2**	T. 1*	T. 2**
	N	mm	mm	mm	mm	kN	kN	kN	kN
1^{+}	3185	1.75	0.74	0.59	0.47	2.7	1.3	3.8	2.7
2^{++}	2695	1.57	0.64	0.49	0.34	1.7	1.0	2.7	2.3
A$^{\perp}$	2940	1.66	0.69	0.54	0.41	2.2	1.2	3.3	2.5
3^{+}	3000	0.36	0.36	0.24	0.24	1.3	0.3	2.3	1.3

◇Collapse loads: Test 1: 3675 N, Test 2: 2940 N, Numerical: 3185 N; ♠1/3 span; ¤1/2 span; *Tie rod 1; **Tie rod 2; $^{+}$Test 1; $^{++}$Test 2; $^{\perp}$Average; $^{+}$Numerical.

Table 12. Mechanical Properties of the numerical model.

Masonry	Joints				
Self weight	$\varphi^{\spadesuit}$	c_u¤	$\sigma_{t,max}^{**}$	k_n^{***}	k_s^{+}
kN/m^3	°	MPa	MPa	GPa/m	GPa/m
1070,0	35	0,57	0,20	100	100

♠ Friction angle; ¤Cohesion; **Tensile strength; *** Joint normal stiffness; $^{+}$Joint tangential stiffness.

value was necessary for the numerical stability of the model and to obtain similar results to the experimental results. The boundary conditions of the numerical model reproduce the boundary conditions of the experimental model. The effect of the two 8mm diameter metal tie rods was also included in the numeric model.

The results of the experimental tests and numerical simulations are presented in Tables 10 and l1.

The reference parameter in the numerical model calibration was the collapse load. Thus, by adjusting the properties of the numerical model, an attempt was made to obtain a collapse load value close to the average experimental result. The value of the numerical collapse load was 3.19kN which compares with the corresponding experimental average value of 3.31kN. As for the other parameters, such as displacements, the calibration of values was not so close, although with values of the same order of magnitude. For both the uniformly distributed load test and the edge load test, the displacement values numerically obtained were lower than the corresponding experimental values (Tables 10 and 11). This lack of adjustment may be because the deformability was fully modeled in the contacts. However, relatively good approximation was obtained in relation to the intensities of the horizontal thrusts.

5 CONCLUSIONS

The brick timbrel vault, referred to in Portugal by Alentejo as timbrel vault or "abobadilha", is a widely spread variant of the traditional masonry vault. The vaulted timbrel solution presents several advantages over traditional vaults executed with the bricks laid with the largest dimensions perpendicular to the vault surface. First, its execution process, with fast setting mortars based on gypsum, is extraordinarily simple and does not require the use of centering. Simultaneously, it is a lighter constructive solution that induces less vertical and horizontal thrusts in its supports.

Although the technique has received less attention over a long period of time, it is a constructive solution with high potential, satisfying simultaneously demands for comfort and sustainability. The timbrel vault solution was practically abandoned in Portugal and its revival today is due to architects rediscovering this sustainable constructive solution.

This requires the recovery of traditional knowledge about geometric proportions of timbrel vaults and the development of new analytical tools to support the design of new vaults (with traditional geometries or with new and audacious geometries).

The study of the construction history of the timbrel vault, which is briefly described in this paper is part of this knowledge recovery.

The experimental trials recently conducted at the Portuguese Military Academy and at the *Instituto Superior Técnico, Universidade de Lisboa*, part of which is described in this article, is one of the first attempts to study the Portuguese timbrel vault. The experimental tests highlighted the extraordinary strength, a small deformability of the timbrel vaults and the subtle behavior at the collapse.

The mechanical behavior of timbrel vaults is relatively well simulated by means of discrete element models, which require calibration with experimental results.

Research on the Portuguese timbrel vault is ongoing, both through experimental and numerical tests, in order to find methodologies to evaluate the structural safety of existing constructions and to design new timbrel vaults with new shapes.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The bells of Brisbane Cathedral

J. Heyman
University of Cambridge, Cambridge, UK

ABSTRACT: The Anglican Cathedral of St John in Brisbane was built over the course of a century; it was started in 1906, and work continued until 2009. The church is of neo-Gothic style, and almost the final building activity was the completion of the crossing tower and the installation of a ring of twelve bells. An assessment was made of the consequences for the tower that would result from bell ringing.

1 BRIEF HISTORY

In 1885, Bishop Webber commissioned John Loughborough Pearson to design the cathedral, and plans were complete by 1889. The project was agreed in 1896, but Pearson died in 1897, and his son Frank took charge of the work and made many of the drawings. Pearson was the architect of Truro Cathedral, and he designed other buildings in the southern hemisphere, also completed by his son; the very large church of St Matthew's in Auckland, 1902–1905, is particularly fine. In all of these churches John Loughborough Pearson designed in innovative but scholarly and traditional style, using elements of Romanesque, Early and Late Gothic with absolute mastery. The completed Brisbane Cathedral is shown in Figure 1.

There were two construction periods over the century. The first, 1906–10, saw the completion of the east end, including the sanctuary, the Lady Chapel and the South Chapels, the crossing and the transepts, and

Figure 1. The completed Brisbane Cathedral.

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Figure 2. The east end of the Cathedral in 1910.

the first two bays of the nave, covered by the first of the sexpartite vaults. The crossing tower, which was finally to house the bells in the 21st century, was taken to a height of 20 m, just above the ridges of the timber roofs covering the masonry vaults of the sanctuary and transepts (Figure 2).

Building was resumed some 50 years later in 1965–69, when four bays (i.e. two sexpartite vaults) were added to the nave. Construction differed from that of the previous work in that the new bays are essentially steel-framed structures supporting steel trusses for the roof; all steelwork is clad in masonry, and the 1965 additions are visually indistinguishable from the work of the original campaign. It may be surmised that it proved difficult to find expert local craftsmen able to carry out traditional masonry construction.

Indeed, for the final phase, 1989–2009, the Master Mason of Exeter Cathedral, Peter Dare, resided in Brisbane and English masons were employed in the completion of the western façade and of the two western towers. At the same time, the crossing tower was completed by the addition of a ringing chamber, a bell chamber and a pyramidal timber roof (Figure 1).

2 THE BELLS

The consequences of the proposed installation of twelve bells at the top of the crossing tower were of course assessed. The four piers supporting the incomplete 1910 tower were carrying some 500 tonnes of masonry.

These piers are founded on “Brisbane schist”. This schist is foliated rock, and the loads imposed by the piers have caused small settlements. The increase in height of the tower in order to house the bells was estimated to add 400 tonnes to its weight, and the envisaged further settlements were deemed to be acceptable. Similarly, the existing crossing piers had ample strength to accept their increased loads.

A bell, when rung full circle (as in change ringing), imposes a horizontal force on its supports; as a rough guide (although this depends on the precise way a bell is mounted) the horizontal force is about three times the weight of the bell. The tenor bell (the heaviest) of the ring finally installed at Brisbane weighs some 16 cwt; that is, about 0.8 tonnes or 8 kN. Thus, a first question is whether horizontal forces of the order of 24 kN would be acceptable for the existing fabric. This question can be answered quickly and easily. Wind pressures (say 1 kN/m^2) are experienced regularly by the cathedral, and although the exact area of the tower exposed to wind is difficult to define, it is apparent that wind forces are very much greater than the forces that would be engendered by bell ringing, even of several bells sounding together.

However, bell ringers are in any case not concerned with the strength of the structure housing their bells, but with its stiffness. If the tower develops large oscillating sway displacements, then the bells may prove hard to ring. Again, as a rough empirical guide, if the amplitude of the sway is about 2 mm, then the bells will go easily; if it is 20 mm, then ringing may prove to be difficult. Thus, an estimate was needed of the value of the horizontal deflexion of the crossing tower at Brisbane under the action of horizontal forces induced by bell ringing.

What was required, in fact, was a measure of the *stiffness* of the fabric when subject to horizontal loads at the top of the tower. Direct measurement of this stiffness would seem to be impossibly difficult, involving the provision of aerial forces of the order of a tonne or so, and the measurement of tiny displacements. A different approach was needed.

The frequency of the vibrations that could develop during bell ringing depends, of course, precisely on the stiffness of the masonry involved in the motion, and if this frequency could be measured, and could be related to the stiffness, then this would give the required information for the calculation of deflexions. As early as the 1740s (Truesdell 1960), Daniel Bernoulli had studied the lateral vibration of an elastic beam – the ends of the beam, of uniform cross-section, were taken to be free, or pinned, or clamped, in various combinations, and Bernoulli obtained expressions for the frequencies of fundamental and higher modes of vibration.

As a crude model, the tower at Brisbane could be regarded as a vertical masonry cantilever beam, with its base fixed in the ground and the upper end free. Clearly, since the tower is surrounded by abutting masonry, some care must be taken in the assessment of the total mass involved in the vibration. For a uniform cantilever beam, Timoshenko (1928) gives a numerical solution for the period of vibration of the fundamental mode, which involves the determination of the smallest root of the equation cos θ cosh θ = -1. (Since this equation involves hyperbolic functions, the higher frequencies cannot be simple harmonics of the fundamental, as they would be for a vibrating string, and this fact was noted by Bernoulli.) The fundamental periodic time τ is given by

$$\tau = \frac{2\pi}{3.515}\sqrt{\left(\frac{Wl^3}{EIg}\right)} \tag{1}$$

where l is the length of the “cantilevered” tower of weight W,and EI is the flexural rigidity of the tower.

The deflexion δ of the end of a cantilever under the action of a transverse tip load $w$is, of course, $\delta = wl^3/3EI$, so that

$$\delta = \frac{1}{3}\left(\frac{w}{W}\right)\left(\frac{3.515}{2\pi}\right)^2 g\tau^2. \tag{2}$$

3 THE ASSESSMENT

The static deflexion of the top of the tower in response to a horizontal force w can therefore be estimated from Equation (2), and requires knowledge only of the weight of the tower and of its natural frequency of vibration. In units of seconds and metres, the equation becomes δ = (1.02) (w/W) (τ^2). The value of this deflexion will give a guide as to the expected behaviour under the forces arising from bell ringing.

The mass of masonry in the completed tower approaches some 1000 tonnes, but perhaps 2000 tonnes of the fabric might be involved in any oscillations. In contrast to this imprecision, it was possible to determine the natural period of vibration with great accuracy. All buildings suffer from vibration, and this has sometimes proved of difficulty in a laboratory when very accurate observations are required. (In contrast, use can sometimes be made of these vibrations. The 534 nominally identical pinnacles on the Houses of Parliament in London are subject to continual vibration from wind forces and tremors from traffic. The frequency of vibration of each pinnacle was observed from the information carried on a reflected laser beam, and a few structurally defective pinnacles were detected immediately (Ellis 1998).)

In the case of Brisbane, such background vibration was observed and measured. In addition, six men jumped up and down randomly in the tower to increase the signals, and finally the same six men heaved purposefully on a rope attached to the top of the tower. All three sets of observations were consistent; the tower had a natural period of vibration in the E/W direction of 2.8 Hz, and of 2.5 Hz in the N/S direction. At a frequency of 2.5 Hz the periodic time τ is of course 0.4 sec. However, these figures refer to the tower as it existed in the year 2001, before the tower was raised by some 5 m to 25 m, with a corresponding increase in weight of masonry from 600 to perhaps 1000 tonnes. Equation (1) indicates that these changes should lead to a periodic time of the completed tower about 1.8 times greater than the observed 0.4 sec; that is to say, $^3/_4$ sec.

Thus, if a proof load is taken of $w = 2.4$ tonnes (corresponding to the ringing of the tenor bell), and the weight W of the completed tower is assumed to be the bare 1000 tonnes, then equation (2) shows that the deflexion could be estimated as 1.4 mm. Bell ringers sometimes “fire” their bells, ringing them all simultaneously. The total weight of the bells installed at Brisbane is 97 cwt; that is, just under 5 tonnes. If all bells were aligned in the same direction, and if all were swinging in the same sense (i.e. all clockwise or all counter clockwise), then the lateral dynamic force might be 15 tonnes, with a corresponding deflexion of some 9 mm.

This figure would seem to be the largest displacement that the tower might experience, and it would not inconvenience the bell ringers. It is in any case likely to be a substantial overestimate of the actual value, since much more than 1000 tonnes of masonry will be excited.

4 COMPLETION OF THE PROJECT

The first requirement was the provision of a ringing floor on which the bell ringers could stand. Had the first phase of construction been continued after 1910, such a floor would have consisted of timber joists spanning the rectangular area of the tower immediately above the already completed masonry quadripartite vault. The actual 21st-century floor is a reinforced-concrete slab supported on the 100-year-old masonry walls of the tower, serving to consolidate those walls and to provide a footing for the additional 5 m of masonry involved in the raising of the tower. This created a ringing chamber which was capped with a second reinforced-concrete slab, forming the floor of the bell chamber. Both slabs are of course provided with circular (actually octagonal) central holes to allow for the lifting of the bells from the floor of the cathedral, and which correspond with the eye provided by John Loughborough Pearson in the original quadripartite vault.

Conventional timber bell frames are designed to allow the bells to be installed to ring N/S or E/W, and the bell pits are arranged ingeniously so that the ropes hang round the circle taken by the ringers. In Brisbane there is no bell frame; the supports for each individual bell are bolted directly to the upper reinforced-concrete slab. Moreover, the bells are installed not N/S and E/W, but radially, so that each delivers its dynamic forces to the centre of the crossing tower. Such an arrangement has long been advocated to minimize the sway of bell towers, and has indeed been realized in a few installations; the existence of reinforced concrete rather than timber made such an installation easy at Brisbane.

ACKNOWLEDGMENTS

Dr H.E.M. Hunt, a distinguished mechanical engineer of the University of Cambridge, was on leave in Australia at the time of the Brisbane bell project. He organized the tests on the tower, and made the very accurate frequency observations.

Dr Hunt also provided a conjectural explanation of the fact that bell ringers find it hard work to ring bells if a tower is very flexible. If a tower is in a steady state of oscillation (and a peal can last for two hours or more), then there is, of course, a store of kinetic energy in the mass of masonry that is in motion. This energy decays rapidly in an inhomogeneous mass such as the masonry tower of Brisbane, and, if such a tower is vibrating steadily under the action of the bell ringers, then the energy must be continuously renewed. The source for the renewal lies, of course, in the exertions of the ringers; the larger the oscillations, the larger the dissipation, and the harder the ringers must pull on their ropes.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Calculation methods for reinforced concrete structures at the beginning of the 20th century: The Modernissimo Theater in Bologna

G. Predari & D. Prati
Università di Bologna, Bologna, Italy

ABSTRACT: Palazzo Ronzani represents a junction between local tradition and modernity as it collects different construction solutions: a reinforced concrete frame, unreinforced concrete masonry, and load-bearing masonry. The structural design followed the Hennebique system, but the archival documentation contains a limited number of documents about the structural design, and no structural calculation report to confirm the adoption of the system. The paper focuses on the study of its structural calculation, simulating the procedure that technicians must undertake in intervening on buildings dated to the beginning of the 20th century, with calculation and construction documentation often missing. The restoration site of the theater offered the opportunity to carry out specialized structural surveys, bringing to light the traditional stirrups and the huge smooth iron reinforcements. The theoretical simulation of the calculation procedure has highlighted the correspondence between the patent and the real situation, confirming the adoption of the system and its excellent structural performance.

1 INTRODUCTION

In Europe, the modernization process that characterized the season of scientific and technical innovations between the late 1800s and early 1900s was matched by profound parallel transformations of urban structures to adapt them to the new demanding framework.

This change also took place in medium-sized cities such as Bologna, an important administrative, economic, and cultural center within the Papal States in the first half of the 19th century.

Bologna continued to be a city with a predominantly agricultural economy, maintaining a mutual-dependence relationship with the neighboring countryside, being in a peripheral position from the centers of power and still confined within its multi-centenary city walls.

The Unification of Italy changed the geopolitical location of the city in the national context, involving Bologna in a new political, economic and social reality that transformed it into the crossroads of communications between the Po Valley cities and the rest of the peninsula.

The inclusion in the new national framework and a rapidly changing economic and commercial system led to a profound reshaping of the appearance of the city, influenced by foreign models of historical town renovation according to hygiene and decorum rules.

Bologna gradually welcomed these changes, but in a short time, the adaptation process of the historic center to the new functions caused traumatic interventions in the urban fabric and the built heritage. The 19th-century imprint on the city became increasingly evident, with urban modernization works that began in 1860 (Gottarelli 1978) and had their climax in the drafting of the 1889 Regulatory Plan, one of the first to be adopted in Italy.

The Plan made significant changes to the ancient city's urban fabric, starting with the demolition of the city walls and gates to eliminate the physical barrier between the central core and the outer villages, thus connecting the historic center to the outer expansion areas.

In the ancient center, the Plan provided for the widening of some existing avenues and the straightening of minor streets; it was also planned to realize a total of 50 km of new roads. These works were done by tearing down entire neighborhoods and thus destroying the city's appearance, previously characterized by a discreet and curvilinear road network, flanked by buildings with few floors, progressively replaced by higher buildings overlooking wide and straight streets (Gresleri & Massaretti 2001).

2 PALAZZO RONZANI IN BOLOGNA

2.1 *Stylistic features*

Since it was the first building to rise after the demolitions carried out in the historic city center, Palazzo Ronzani underwent a complicated design process due to opposition to large building construction in the old city. After a two-year debate and discussions, no project had yet been approved, while the demolitions had already begun.

The rich archival documentation made it possible to find the early design concept used to define the stylistic features and the planimetric distribution of the

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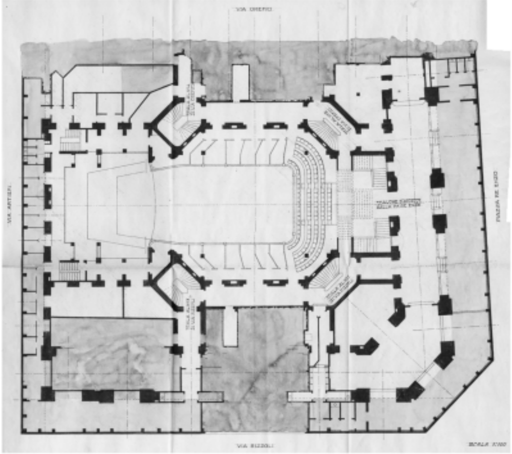

Figure 1. Plan of the first underground floor of Palazzo Ronzani (private collection).

building. The process leading to the final solution went through several intermediate projects by the architect, Gualtiero Pontoni, who gradually became less conservative regarding the historic building design until it became a big "business machine".

In 1912, the design reached its ultimate form, and the final solution was absolutely adherent to the 1889 Town Plan specifications: "*a remarkable example of the character that the new buildings of the center of Bologna should have, a character that is summarized in the word monumentality*" (Giovannetti 1912).

On an area of about 2000 m^2, the architect was able to design a theatre with 2000 seats located in the basement; shops, a café, and a restaurant on the ground floor; clubs, studios, and commercial storerooms in the intermediate and the first floors, and, finally, a hotel on the upper stories (Marchetti 1981). The works were entrusted to engineers Luigi Bernardi and Carlo Prati, and the structural design to the engineer Giuseppe Lambertini, who had more than a decade of experience in reinforced concrete construction.

At the opening of the Teatro Modernissimo, the two underground levels accommodated entertainment spaces (Sicari 2003); the entrance to the first underground floor, where the theater gallery was located, was via an internal staircase (Figure 1). On the second underground floor, four other stairs granted access to the parterre on either side of the hall (Figure 2).

The rectangular hall in the lower floor officially opened on 14 July 1921 and started hosting theatre performances and film screenings. However, a smaller hall, the Cinema Modernissimo, was already active in 1915. It was located on the ground floor and was equipped with 550 seats.

The building was characterized by some typical features of local building tradition and many references to new, foreign architectural styles. In Italy, at the beginning of the 20th century, the traditional historicist eclecticism was usually merged with the French and Spanish architectural styles in a sort of local Art Nouveau, the Liberty style. This building, strictly linked to the local tradition, was conceived with a portico since its first project, emphasizing the corner facades, especially at the intersection of the main streets. In the most visible corner, the top floor was surmounted by a magnificent Parisian belvedere, recalling the French construction tradition of highlighting the intersection of two main streets with an architectural elevation.

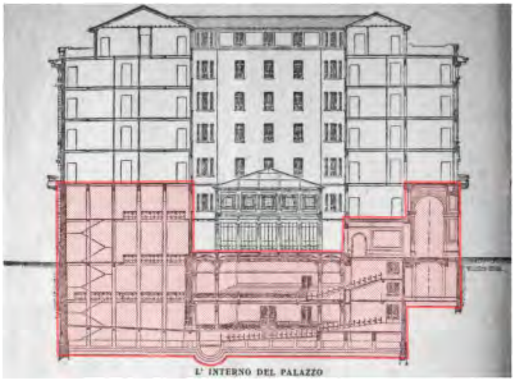

Figure 2. Longitudinal section of the hall of the Modernissimo Theater in the underground of Palazzo Ronzani. Highlighted in red are the volumes occupied by the theater stalls and galleries and all the vertical connection systems. (private collection).

Figure 3. Main facade of Palazzo Ronzani (private collection).

The external decorations were influenced by the Art Nouveau style, which refers to human figures in the plastic configuration and the alternating rhythmic sequence of the sweeping arches of the portico (Figure 3). Inside, the arch theme frames the wide opening between the gallery and the foyer of the underground hall so that direct daylight could reach the lower levels.

2.2 *Structural features*

At the lowest level of the building, the parterre insists on a smaller area than the upper floors. It is set on a grid foundation made of upturned concrete beams, which are surrounded by retaining walls on the perimeter

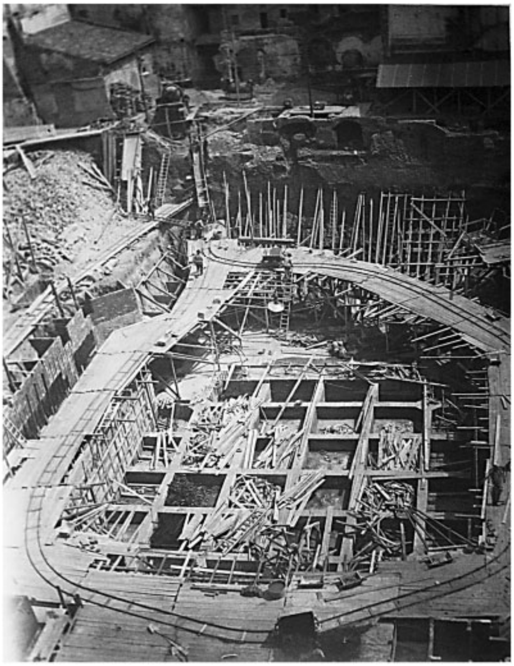

Figure 4. Construction phases of the foundation slab (private collection).

(Figure 4). These walls, made of one-meter-thick reinforced concrete with internal brick lining, were designed to insulate the inner spaces from the ground humidity.

The building core consists of a reinforced concrete frame, which allows the hall to have a clear span of 11 x 12 meters and a height of about 9 meters. Starting from the lowest level, a series of pillars (with cross-sections from 45 x 45 cm to 30 x 30 cm) and reinforced concrete beams support the gallery floor, made of slabs with a thickness of 15 cm. The pillars, beams, and slabs go over the back of the proscenium and are lengthened until reaching the mezzanine level (Mochi & Predari 2012).

The construction site images suggest a mixed technical solution for the two underground floors, which combines reinforced concrete with the widespread use of brick walls. Outside the central core of the theater, where a wide span was necessary, the construction technology has a more traditional character and consisted of 60-45-30 cm thick walls.

The slab covering the large theatrical space is a refined lattice of reinforced concrete beams, connected to the pillar structure and the two large portals at the ends of the hall, towards the proscenium and the access zone (Figure 5).

On the upper floors, the construction technology is more traditional, resorting to brick walls. Images of the first-floor construction phases clearly show the presence of traditional masonry structures behind the decorations. Furthermore, the internal distribution and the alignment of the openings, which are smaller in size than those of the floors below, refer to the typical structure of a load-bearing masonry building, with perimeter walls and a central spine wall.

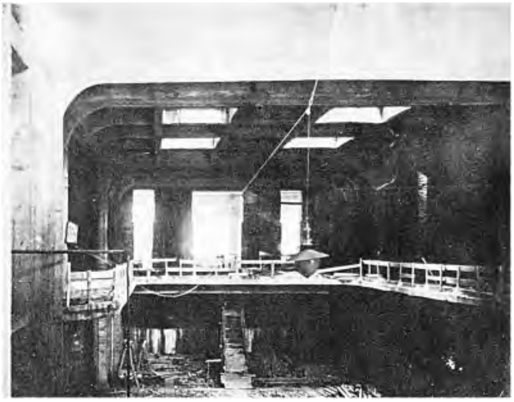

Figure 5. The slab of the theatrical hall from the proscenium (private collection).

3 THE HENNEBIQUE SYSTEM

3.1 *The use of the system in Palazzo Ronzani*

The primacy of "first application in Bologna of reinforced concrete in an entire building, according to the theory and practice of Hennebique" (Marchetti 1981) is bestowed to Palazzo Ronzani based on relatively recent sources. This information is not entirely correct since reinforced concrete was already used in Bologna to build entire residential and industrial construction frames for at least a decade; however, it was probably the first building dedicated to entertainment.

Further information regarding the structural analysis appears inconsistent since (Marchetti 1981) says that "one of the first treatise writers, Eng. Guidi was in charge of the structural calculation. Guidi, having found the groundwater layer a bit high in the terrain specimen, devised, to be sure, that the huge building should rise on 'a monolithic waterproof floating box' foundation, as he called it. Even the much criticized arches of the porch derive from static needs, as suggested by Guidi (...)". The reference to Camillo Guidi as *"one of the first treatise writers"* is quite evident, having been the first Italian professor to teach and publish writings on the new material (Guidi 1914). However, it has not yet been possible to find any document that would prove the professor's involvement in this project. Furthermore, at present, it seems that his role in the evolutionary process of reinforced concrete was only as a scientist and experimenter, never involved in real design practices, if not as a static tester.

An in-depth study of the archival material has made it possible to find only two documents referring to the structural design of the building: the structural layout plan of the slab-on-grade foundation (Figure 6), signed by Eng. Giuseppe Lambertini (and not by the alleged designer, Eng. Guidi) and the vertical section of the

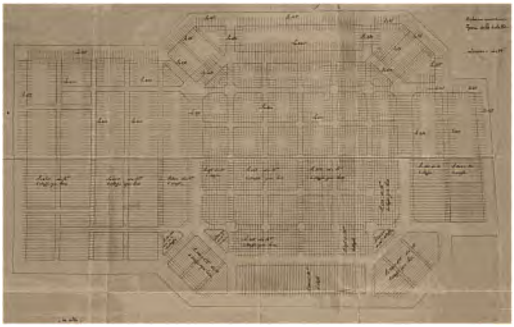

Figure 6. Structural layout plan of the foundation, with the signature of Eng. Lambertini (private collection).

underground walls in the basement. Two occurrences may not seem very substantial if compared to about 200 drawings available for the planimetric distribution, facade solutions, and artistic works; however, they are essential to definitively verify the adoption of the Hennebique system for the reinforced concrete structures, and, at the same time, establish who was directly involved in the structural analysis of this building.

Above all, the cross-section of the retaining walls highlights the characteristics of the Hennebique system: the rebars are placed only in the tension zone (in this case, the outer side of the wall, since it must withstand the ground thrust) and the typical shape of the stirrups, called *étriers*, consisting of small U-shaped folded metal plates, arranged in variable distances, according to the different shear stress value.

An ongoing project of re-functionalization of the spaces of the ancient theater aimed at transforming it into a cinema has followed specific design choices, trying to preserve the historical-artistic value of the building, as early 20th-century evidence of the construction techniques and decorative styles of local tradition. However, the project also provided the opportunity to carry out specialized, detailed investigations; these, on the one hand, made it possible to tackle the consolidation design fully and, on the other hand, allowed integrating the documentary-based notions and definitively recognize how the building site was one of the most extensive and advanced applications of the Hennebique system in Bologna.

3.2 *The Hennebique calculation method*

Starting from its first patent in 1892, the accurate description of the Hennebique system allows identifying its main features due to the characteristic properties of the two-component materials: the position of the reinforcements, the lightness, and high fire resistance of the structural elements depended on them.

In its final configuration, the Hennebique patent defined the construction of a monolithic spatial system through the composition of individual elements, i.e., to obtain complete frameworks consisting of a modular structural mesh. The system allowed the construction of foundation plinths or upturned beams, pillars, beams, slabs.

The pillars generally had a square, rectangular or polygonal section, with particular bevels at the edges; they were reinforced with four rods, with a diameter ranging between 8 and 50 mm, which were arranged near the vertices of the section. The beams were monolithically connected with the 8–16 cm thick slabs and constituted resistant structures with a T-beam, often oriented in the two orthogonal directions of the floor.

In the beams, the straight bars were placed near the tension zone and were alternated with bent bars obtained by raising both their extremities for a length equal to 1/3 of the length of the entire bar due to the inversion of the tensile stress between beam and column in the joint. Since the joint bending moment is lower than the maximum one in the midpoint, it was considered enough to bend one bar of every two alternately (Vacchelli 1900).

The calculation method used by the patent holders seems to have been developed by the Belgian engineer, Paul Christophe, from the Ponts et Chaussées institution, who was the technical consultant of the Hennebique organization (Billington 2020; Zorgno 1988). Christophe worked from 1892 onwards as a civil servant in the Belgian road and bridge building authority. At the start of his career in the civil service, he supervised the construction of several wide span bridges in Liège and was quickly promoted as the vice-secretary of the Central Committee for Public Works in Brussels; in 1898 he was entrusted with the experimental testing of bridges. One year later, he was dispatched to the international congress on reinforced concrete that Hennebique had organized on the occasion of the Paris World Exposition in 1900, for which he carried out careful preliminary studies (Kurrer 2008). Later that year, the journal, *Annales des Travaux publics de Belgique*, published his lengthy report, which shortly afterward appeared as the monograph, *Le béton armé et ses applications*, (Christophe 1902). The book was acknowledged "*as the best-known and the best compendium in this field*" and was translated into several languages, e.g. Russian (1903), and German (Hellebois & Espion 2013).

For a few years, the calculation method was not disclosed, but it soon became the reference for the first scientific studies and prescriptions of the first decade of the 20th century, given the widespread diffusion of the construction system.

The assumptions of the procedure were quite intuitive and straightforward: the compressed concrete – above the neutral axis, which was not barycentric but in an unknown position – and the reinforcements – placed only in the tense part of the section – both absorbed half of the bending moment. In this way, however, only the balancing of rotating and not of translating was satisfied, while the neutral axis position was independent of the overall height of the cross-section (Figure 7).

The method used no homogenization coefficient and considered the distribution of stresses as uniform in the compressed concrete and equal to the average

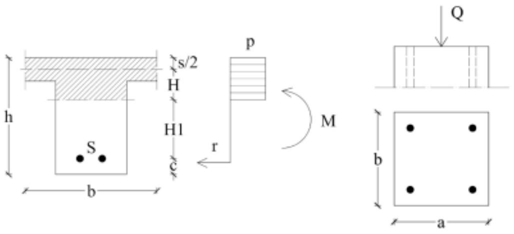

Figure 7. Design schemes for beams and pillars with the Hennebique method.

value of 25 kg/cm^2, while a value of 1000 kg/cm^2 was estimated for iron (Canevazzi 1902).

The first step of the calculation identified the position of the neutral axis thanks to the balancing of rotating equation for compressed concrete; in the case of a ribbed slab or T-beam, it was assumed that the whole slab, and only the slab, was subject to compression stress, neglecting the possible contribution of the compressed concrete part of the rib if the neutral axis passed in it (Donghi 1923). The equation was:

$$\frac{M}{2} = p \times b \times s \times H, \text{so } 2H = \frac{M}{p \times b \times s} \tag{1}$$

Then, to derive the required area of the reinforcement S, it was sufficient to write the balancing of translating equation for the rebars:

$$\frac{M}{2} = r \times S \times H1, \text{so } S = \frac{M}{2 \times H1 \times r} \tag{2}$$

where p = 25 kg/cm^2; r = 1000 kg/cm^2; H1 = h – s/2 – H – c.

The predominantly intuitive aspect of the procedure lay in the calculation of the pillars where, once the load action was assessed, a real calculation was not performed, but rather it was an estimation based on the section of the pillar and the strength of the concrete under compression.

The edge reinforcements had only the function of withstanding transverse actions. The bearing capacity of the pillars, subject to simple compression, was determined on the basis of the sum of the contributions of the concrete and the reinforcements, obtained as the product of the respective sections for the calculation stresses. The bearing capacity of the pillar, which had to be greater than the load action, was:

$$q_p = p \times a \times b + r \times S, \text{so } S = \frac{(q_p - p \times a \times b)}{r} \tag{3}$$

where p = 25 kg/cm^2; r = 1000 kg/cm^2.

3.3 *The calculation method applied to the theatrical hall structures*

Knowing the system and the calculation method adopted in the original structural design was fundamental, given the lack of adequate technical support documentation. During the design phase aimed at the static strengthening of the structures, hypothesizing the positions and dimensions of the reinforcements as deriving from the Hennebique system turned out to be crucial to later verify their presence and consistency through appropriate surveys.

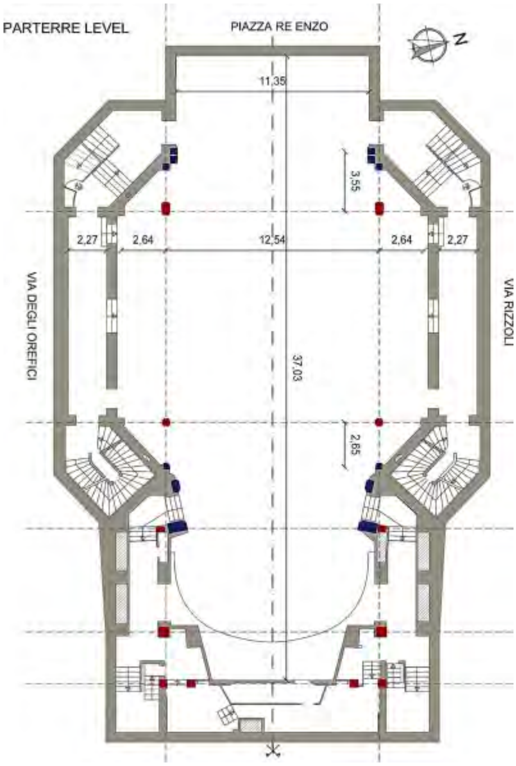

Figure 8. Types of vertical structures at the parterre level: in grey, masonry structures; reinforced concrete structures in red, unreinforced concrete structures in blue.

This structural re-design phase made it possible to simulate the rebar amount and arrangement in the reinforced concrete beams and pillars, precisely identifying the specific areas for the demolition tests, such as the concrete cover removals and bar diameter measurements. The overall diagnostic campaign consisted of 59 investigation spots, with 45 non-destructive tests and 14 destructive investigations. Without such simulation, the number of destructive tests would have been considerably higher and more widespread, harming the structural integrity of the concrete frame.

As already mentioned, the original structural scheme consisted of reinforced concrete beams and pillars, together with extensive brick walls and unreinforced concrete pillars, which were located where the material malleability allowed for the creation of decorative connections, leaving the structural function to the masonry structures.

In the first phase of the investigation, non-destructive tests were carried out using geo-radars to verify that the reinforcements were actually where the Hennebique system intended. SON-REB tests were

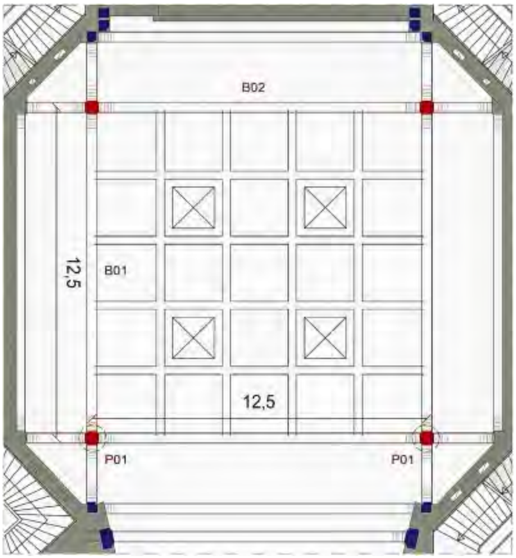

Figure 9. Location of the beams and the pillar subjected to the calculation procedure.

also carried out to determine the presence of flaws (micro-cracks, air bubbles, discontinuity, etc.), the compressive strength of the concrete, and in general, the material homogeneity.

Thanks to this first test campaign, it was possible to definitively demonstrate that the only pillars entirely made of reinforced concrete within the hall space are the four standing alone, placed at a distance of 12.5 m from each other. Originally these were all cross-shaped inscribed on a square base, but during the building's lifecycle, the two placed below the gallery bleachers, at the parterre level, have been doubled in the cross-section due to an extension of the theater gallery itself which required new supports. The additional reinforced concrete pillars are instead placed in the back of the proscenium, in the stage tower, and reached the mezzanine floor height, thus being over about 20 m high. All the slabs and beams are made of reinforced concrete (Figure 8).

As an example of the process followed, the calculation results for the two pillars remaining in their original shape at the gallery floor level (P01) and for one of the beams supporting the ground floor slab (B01) are presented (Figure 9). The latter is one of the edge beams supporting the smaller cross-section beam lattice covering the entire theater hall, where the *cafè chantant* was initially located

The preliminary non-destructive SON-REB investigations allowed detecting the spacing of the reinforcement bars and their position. In the P01 pillar, it was possible to identify the vertical bars positioning, in correspondence with the chamfered corners, their large diameter, and the relatively regular step of the stirrups, equal to 20–22 cm (Figure 10).

The B01 beam was inspected along the side parallel to its axis and showed the typical bent rebars pattern provided by Hennebique at about 1/3 from the edges. In addition, the number of bars and stirrups was identified, but their diameter could not be identified at this stage (Figure 11).

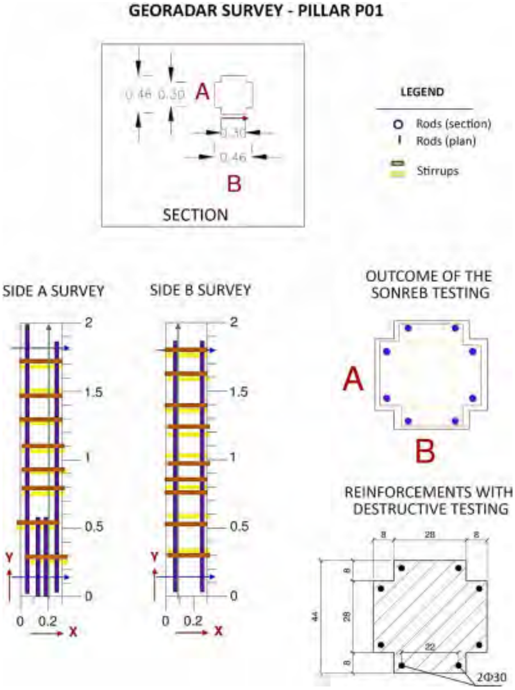

Figure 10. Destructive and non-destructive investigations on pillar P01.

While performing in-situ investigations, the theoretical calculation procedure was carried out. For P01 pillar, the application of the Hennebique calculation method according to the previous formula (3), considering a maximum cross-section of 44 x 44 cm, with 8 cm chamfer in each corner, and assuming a variable load equal to 300 kg/m^2 (a suitable value for the use of the upper floor as open to the public premises), allows obtaining a minimum rebar area S = 58 cm^2.

The on-site destructive tests have allowed detecting a longitudinal reinforcement made of 8Ø30 bars, whose area corresponds to 56.56 cm^2, indeed very close to the required minimum (Figure 12).

With regard to the beams, having a cross-section of a 48 cm base and 90 cm height, the adopted structural scheme provides a double symmetry in both directions for a total length of 12.50 m, so each of the four perimeter beams is intended to bear the same vertical load.

Performing the simplified calculation procedure proposed by Hennebique according to the previous formulas (1) and (2), the calculated value of 2H is equal to 65 cm, H1 is equal to 60 cm, and the minimum rebar area S is equal to 53.21 cm^2.

The destructive tests allowed detecting in the middle of the B01 beam a reinforcement composed of 2Ø32 + 3Ø40 bars, whose total area corresponds to

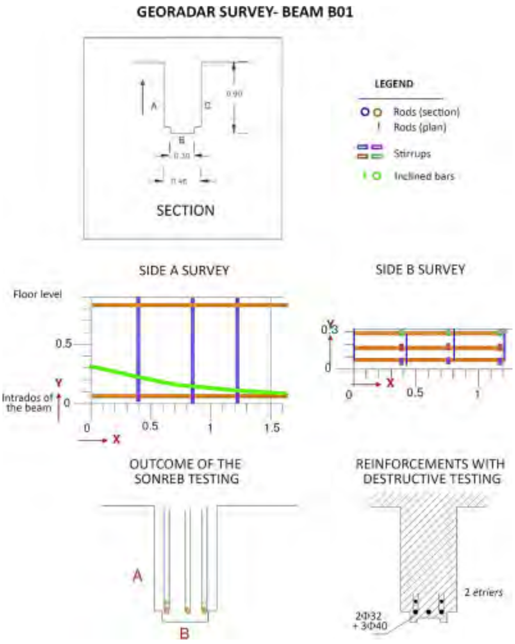

Figure 11. Destructive and non-destructive investigations on beam B01.

Figure 12. Reinforcements at the base of the pillar after the removal of the damaged concrete cover.

53.76 cm^2, indeed slightly higher than the required minimum (Figure 13).

Other destructive tests showed that approximately the same reinforcements had been placed in the other inspected beam on the same level, beam B02, where, however, there is a reinforcement equal to 4Ø42, corresponding to 55.39 cm^2.

Figure 13. Reinforcements of the perimeter beam after the removal of the damaged concrete cover.

4 CONCLUSIONS

Modern construction finds its founding reason in the gradual inclusion of the innovative technology of reinforced concrete in building practice. The history of modern construction has been exploring this field for more than 20 years now.

However, studies have mainly dealt with “exemplary” buildings, well-known to the scientific and technical community. Researchers have only recently started to pay specific attention to the so-called “minor” buildings.

Despite the many studies carried out, there are still many explorable areas of interest, both about the most hidden facets of what is already known and concerning those trends that are currently only hypothesized but not yet demonstrated.

In this context, Palazzo Ronzani becomes a significant reference point for both mentioned areas; it is an emblematic building for Bologna, with its figurative image with strong foreign influences, and the first building of the local “modernity”. It can be considered one of the first buildings constructed in the city where reinforced concrete had been consciously used: the new material was actually positioned only where its potentiality allowed solving otherwise unsolvable construction space design problems.

The new material allowed engineers to obtain wide open spaces and fire-safe constructions, which are essential requirements for a theatre building. Where its use was strictly unnecessary, reinforced concrete still used to be combined with solid brick walls. In these cases, the structure was based on the traditional masonry construction, according to the local practice, or in unreinforced concrete.

The transition of traditional building to modern technique takes on specific features that are locally interpreted in the different, regional study contexts and cannot be generalized. Palazzo Ronzani is a non-secondary piece of this still open research, demonstrating how such a transition has not been instantaneous but has been only gradually implemented, at first constituting contamination of the tradition and then being able to fully establish itself.

Finally, Palazzo Ronani symbolizes one of the significant problems of our time, when contemporary technicians have to cope with listed, historic buildings, dated back to a period where there were no calculation standards at the national level.

The structural analysis simulated according to the Hennebique method is not a mere design exercise. However, it proved to be a very profitable activity since it allowed providing the technicians involved in the renovation project with a preliminary approach of investigation. Besides, it was possible to reduce the burden of the necessary on-site surveys and drastically decrease the number of destructive tests in favor of the non-destructive ones. In this case, the investigation method and the detailed knowledge on the building legitimately makes it possible to include Palazzo Ronzani, its history, design, and construction in the research field of international modern construction.

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The Orense railway station: A shell roof by Eduardo Torroja

J. Antuña
Universidad Politécnica de Madrid, Madrid, Spain

ABSTRACT: A project by Eduardo Torroja made for Orense station platform roofs is presented. This project was never built. The proposed structure employs thin concrete slabs. The arrangement of the structure makes the main mechanism to balance actions that of an isostatic frame with one pillar and a beam. This beam has a section formed by two arches and curved thin sections joined in a thicker central rib. As in other projects for laminar roofs made from 1939 on, small ribs are incorporated on the upper face of the sheets in order to stiffen them. The project is described from the data that is preserved. It is shown that the solution allowed the roof to be made with a reduced amount of material, although more than was the case in the structure that was finally built, which was much less ambitious.

1 INTRODUCTION

The project for the new roof of Orense station dates to 1950. Its purpose was to protect the station platforms, with a total length of 200m and a width of 37.90m in the area in front of the station and 41.90m for the rest. During completion of the work, a new project was presented which included the station canopy formed by a conventional metal structure based on steel frames and trusses. By presenting this proposal, as indicated in the project file, the intention was to go on to study a new solution. With the conventional project carried out and presented, the administrative procedures necessary for contracting the work could be carried out while an alternative solution would be studied.

The new solution was fundamentally intended to reduce the total budget for the work and, above all, the amount of steel and cement needed, as well as to reduce execution time. Reducing the amount of steel not only reduced the budget, as it also reduced the lead time, since steel was scarce as well as expensive and delivery was slow. The same restrictions affected the supply of cement, so a solution with the smallest possible thickness of this was studied.

Under these conditions Torroja proposed a laminar structure of independent sections that were successively repeated. This is a situation similar to other projects that Torroja himself had carried out, such as the canopies of the Instituto Escuela, Zarzuela racecourse stand roofs (Arredondo et al. 1977), and the roof of the Compañía Aeronáutica Sociedad Anónima (CASA) warehouse. In all cases, the roof was resolved with thin sheets of reinforced concrete.

The project was organized on the basis of uniform self-stabilizing independent elements. The same formwork was reused to make all the sections. In this way two objectives were achieved. On the one hand, it reduced the amount of material used. Thin concrete sheets 90mm were used, with the resulting dual savings in reducing the amount of material and weight. On the other hand, by using uniform sections it was possible to reduce the cost of auxiliary equipment, scaffolding and formwork.

2 BACKGROUND

A reinforced concrete sheet roof was the most economic type of structure in 1950. At that time, Félix Candela began to build the first double curvature sheets in Mexico (Colin 1963), although in 1953 Makowski began to study the construction of braced barrel vaults (Makowski 1985) as an alternative to continuous concrete sheets, announcing the decline of reinforced concrete roof structures and their replacement by steel bar structures. In Spain, concrete roofs continued to be used during the following decades. One way to reduce the cost of this type of roof was to divide it into equal independent sections. In this way, the formwork could be reused to construct the successive sections. This procedure had been used by Freyssiet in the construction of the Orly hangars (Fernández 1978) and Ildefonso Sánchez del Río had used it in Spain in the construction of the fourth Oviedo water reservoir in 1928 (Sánchez del Río 1928, 1930) and in several other places in Asturias and Santander that are still in service.

To construct roofs at the entrance of a school building, carried out with the architects Carlos Arniches and Martín Domínguez, Torroja proposed a cantilevered structure that was solved with a variable thickness slab 100mm thick at the edge. The deck width is 5.00m. The cantilever span is 6.30m.

To construct the roofs of the Zarzuela racecourse stands, a series of cylindrical shells parallel to each other and with their generatrices arranged transverse

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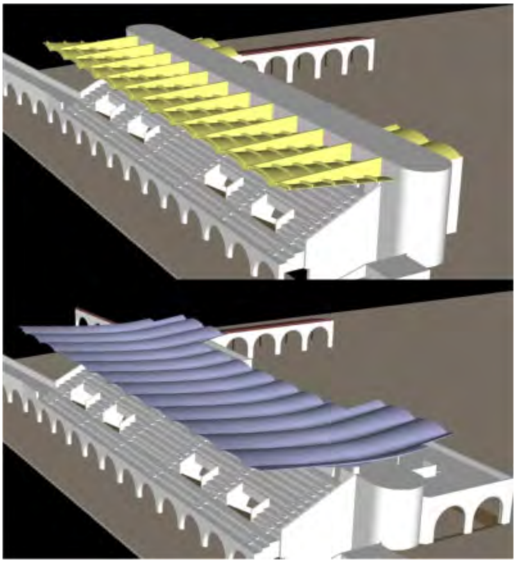

Figure 1. Roof of the Zarzuela racecourse stands proposed in the competition (above), the cantilever beams between which the sections of cylindrical shells with stiffeners placed at the top can be observed. Built cover (below) in which a continuous shell has replaced the original cylindrical one (Image: the author and Fernando Asanza).

to the building was proposed. The winning proposal of the competition was that of the architects Carlos Arniches and Martín Dominguez, with whom Eduardo Torroja collaborated. It was presented in October 1935, and in December the decision of the competition was published. The works began in 1936, and in June of that year, with a significant part of the work already completed, the roof plan was completed (Figure 1).

The proposal actually built, although formally similar to the one in the competition, was a completely different structure. Instead of being a single roof, made up of the same linked continuous elements, it was composed of 5.00m wide independent sections arranged in parallel (Antuña 2003a, b; Moragues et al. 2015). Several formworks were made to build each section. They were reused many times to build the whole roof. The initially planned structure consisted of a series of vaults supported by cantilevered beams. The thrusts of the vaults were balanced between them, and those of the ends were balanced by means of beams that worked in the horizontal plane. Finally, the cylindrical elements placed at the ends of the grandstand buildings functioned as a buttress to counterbalance thrust. The modified construction meant each section could be concreted independently and stripped without the need for the others to be finished. The new structure consisted, in essence, of a cantilevered beam with a particular section formed by two circumferential arcs (Figure 2). In this case, the section of the beam is variable, with a total height of 0.50m at the ends (sections 17 and K in Figure 3) and 1.50m in the central zone on the support (section 0). This variation in shape makes it possible to place a ruled surface on a part of the total surface. With this arrangement, it is possible to put into place the reinforcement bars that support the roof without the need to bend them. The structure consists of a cantilever with a span of 12.60m which, at 1.50m deep, has a slenderness of 8.5. This is a reasonable value for a cantilever.

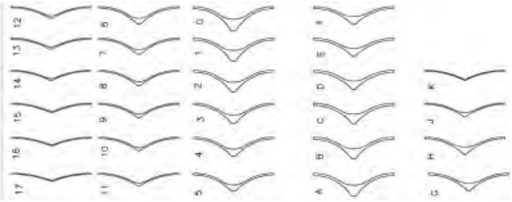

Figure 2. Variation of the cross sections of the racecourse grandstands roof module.

Although we do not know why the competition project was modified, the built solution solves several problems. On the one hand, it reduces the amount of formwork required, since it can be made in sections and the formwork modules can be reused. On the other hand, concreting is significantly simplified. Although the surface is apparently more complex, once the formwork is done, both the arrangement of the reinforcement and the concreting require the same work in both cases. However, in the solution finally built, the concreting is done all at once and it is not necessary to concrete successive ribs on top of the shell, as was the case in the original project. In short, the built solution is much simpler and cheaper.

Previous experience with the roofing of the racecourse stands had shown that it is possible to create a roof that covers a large area with a thin reinforced concrete structure, low self-weight and a small amount of steel, as is the case with concrete shells. Additionally, with suitable organization of the elements the cost of scaffolding and formwork can be reduced. For this it is necessary to divide the roof into equal sections that can be repeated successively.

With this same idea Torroja carried out the project for the CASA warehouse in 1938. The project, which was not finally built, has a rectangular floor plan and is made up of a succession of 81.40m span arches. The width of each section is 8.261m. The total length expected for the building was 190.00m. With a total of 23 sections, it was possible to cover an area of 15,500m^2. The cover element consists of a parabolic arch with a curved transversal cross (Figure 3). The arrangement of the arches allows a skylight to be placed between them to ensure interior lighting. On the other hand, the sections are joined by a series of rolled steel bars, thereby stiffening the edges of the sheets that form each arch. The roof of the entire building can be resolved using the same section of scaffolding and formwork (Antuña 2003a; Oliver et al. 2016).

Although this project was not built, Heinz Hossdorf built a similar solution for a warehouse in Gossau with 30.0m span circular arches organized in the same way (Torroja & Casinello 2007).

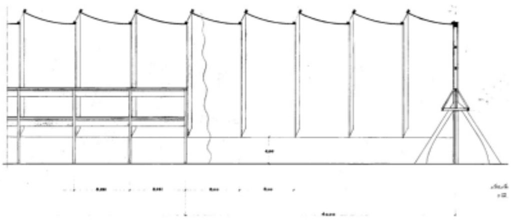

Figure 3. Elevation and longitudinal section of part of the proposed project for the 1938 CASA warehouse (Archivo Eduardo Torroja).

Due to the precarious economic and industrial situation in Spain in 1950, reducing the amount of steel in a building was essential if it was to be built in a reasonable period of time. To make the Orense railway station platform roof, the first proposal was a conventional steel structure with beams, pillars and trusses. The large quantity of steel required by this solution not only increased the budget, but also made the construction itself more difficult due to the increase in the delivery times of the necessary material. To make a wide roof over the entire surface of the station, it was necessary to modify the design and find another form of structure that required less material. Torroja therefore studied an alternative to the initial project that was presented in 1950. The new proposal consisted of a reinforced 90mm thick concrete shell.

On the other hand, since 1941 Torroja had been the director of the *Laboratorio Central de Ensayo de Materiales de Construcción* (LCEMC). From this position he promoted the creation of a model testing laboratory that is still in use. One of the tasks carried out in the small-scale model laboratory was the investigation of new ways of constructing reinforced concrete shells, reducing scaffolding and formwork costs. These studies include a 14.00m diameter dome composed of 12 precast reinforced concrete pieces (Antuña 2019b). This shows one of the strategies that Torroja used later to make shells, which consists of dividing them into smaller sections that can be made successively. A procedure that Freysinet or Sánchez del Río had previously explored, as has been seen.

With this background, Torroja proposed an alternative solution for Orense railway station roof, with the aim of reducing the amount of steel and concrete as much as possible, as well as the necessary auxiliary equipment.

3 PROJECT DESCRIPTION

This project consisted of a roof over a total area of 7900m^2 organized in a series of independent 6.82m wide sections arranged parallel to each other. It had to protect both the main platform and two others located between the tracks along 200.00m. The roof was divided along its length into three parts: a central part 80.00m long coinciding with the existing station building, plus two others, one on each side measuring 38.00m and 77.00m, respectively (Figure 4).

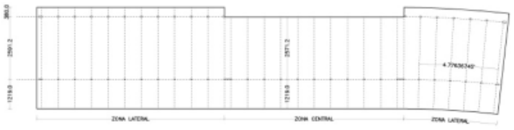

Figure 4. Scheme of Orense station roof plan showing the three different areas into which the roof was divided. (The author, from project documents).

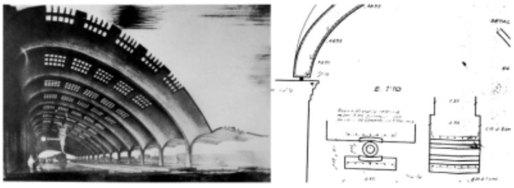

Figure 5. Image of the proposal for Orense railway station roof (left). (Archivo Eduardo Torroja, CEHOPU, reproduced in Arredondo 1978). Support of the roof on the wall of the existing building's façade that allows horizontal displacement. (right). (Archivo Eduardo Torroja, CEHOPU).

In all three cases the cross section of the building was similar, essentially consisting of a single span beam with a cantilever at one side. The length of the canopy was determined by that of the existing platforms and the presence of auxiliary buildings. On the La Coruña side, the horizontal plan was slightly modified to adapt to the curve of the tracks. The entire roof was divided into sections of the same size. The 6.82m width of each section was conditioned by the distribution of the windows in the station building, since the axis of the support was made to coincide with that of the walls of the façade.

To save space on the platforms the supports were not placed on them. They were only placed between two of the tracks where there was enough space for them. This gave a 25.71m span between the alignment of supports and the station building. In addition, to protect the third farthest platform from the station building, a 12.19m cantilever was provided (Figure 5).

The pillar close to the cantilever is a support 4.50m high located between two of the tracks. In the central section of the roof, the other support is on the top of the station building façade at a height of 10.00m above the level of the platforms. This support allows horizontal movement, as seen in Figure 6. In the two lateral sections, the second pillar is a 4.40m tall reinforced concrete support. Thus two different profiles for the roof result, one in the central section and the other in the two sides.

The roof consists of 27 6.82m wide sections, of which 11 are in one of the lateral sections, 11 in the central section and five in the other lateral section. In addition, two other particular sections are arranged to form the joints between the central section and the lateral ones, in which the difference in height of one of the supports and the change in the shape of the roof section are resolved. Although formally different, the structural scheme of all the sections is the same, as

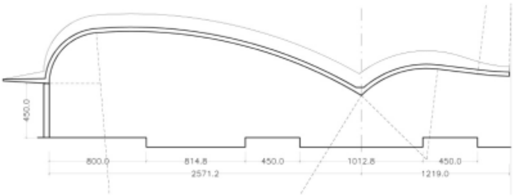

Figure 6. Lateral roof section cross-section. The circumference arcs that define the shape or the section are shown (The author, from project documents).

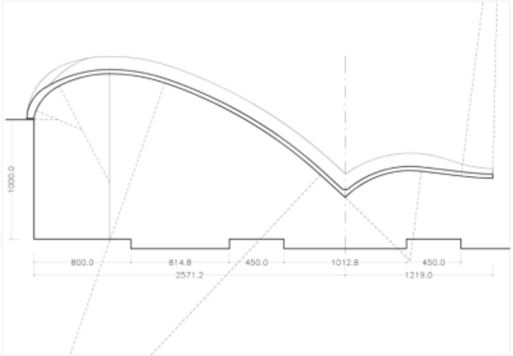

Figure 7. Cross-section of the roof in the section in front of the station building. The circumference arcs that define the shape or the section are shown (The author, from project documents).

a 25.71m span beam with a 12.19m cantilever at one end. All sections are separated by an expansion joint, so that they are all independent.

In each section there are also skylights for lighting and ventilating the platforms. These skylights are square with 2.50m on each side, and they are located in the upper part of the cross section of the roof elements. A glass cover, separated from the concrete sheet, protects the interior while allowing smoke through.

The guideline of the beams that form each section is wavy and has two different lines, as seen in Figures 6 & 7. They correspond to the two different areas of the roof, the one in front of the station building and the two lateral sections. They have a span and cantilever of 12.19m on one side. The support prior to the cantilever is placed between the tracks and the other is on the cornice of the station building in one case and on a new lower support in the lateral areas. The support on the cornice of the building is made such that it only has vertical reactions. The walls of the building are used to support it, thereby avoiding the need for new pillars. Horizontal wind force is counterbalanced by the single reinforced concrete support (Figure 9). Although the geometric description of the beam shape has not been found in the project documentation, it can be drawn as several tangent circumference sections, as shown in Figures 6 & 7. The cross-section of the beam is symmetrical and has the shape of two cylindrical shells joined by the guideline (Figure 8). The path follows the direction of three arcs of circumference tangent to each other. With this arrangement, full-width beam sections are alternated with others that are narrower that permit skylight openings. Thanks to these the interior of the platform can be ventilated and illuminated.

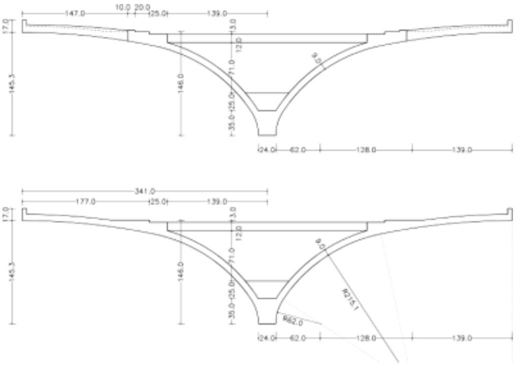

Figure 8. Roof beam cross-section dimensions in the skylight area (top) and between them (bottom). (The author, from project documents).

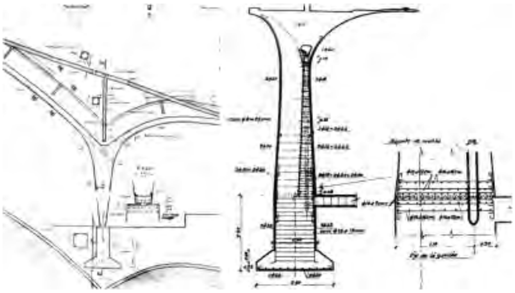

Figure 9. Pillar placed between the tracks (left). Pillar placed at the end of every area that counterbalance horizontal forces (right) (Archivo Eduardo Torroja, CEHOPU).

The shell thickness is a constant 90mm. At the junction of the two lobes they thicken, forming a nerve measuring 350 mm x 240mm in section. To stiffen the sections of the shell, 11 70mm thick transverse reinforced concrete walls are arranged on it at regular intervals. They are 4.00m apart in the central area, and closer when approaching the support on the edge located above the station building façade. In addition to the transverse partitions, the shell is stiffened at the edge by a thickening of 170mm and, in the middle of each lobe there is another 120mm thick reinforcement that is also arranged on the upper face and parallel to the sides of the skylights. The latter coincides with the upper face of the transverse partitions (Figure 8).

These transverse partitions are arranged so that their lower part does not touch the sheet, leaving a hole to drain water which leads to the support area on the pillar containing the downspout.

One of the transverse partitions coincides on the supports and the pillar continues from it up to a height of 3.50m on the shell support. The end of this pillar holds a tie consisting of four steel bars that joins the end of the cantilever to a point inside the span of the beam. This tie is the traction reinforcement of the cantilever. By separating it from the beam a greater arm is achieved, thereby increasing its efficiency. Thus, the depth of the structure is 3.50m for a cantilever of 12.19m, giving a slenderness of 4. This low reduced value ensures the rigidity of the roof. The tie rod bars are provided with threaded sleeves with which the structure can be prestressed and loaded, facilitating the stripping maneuver. Subsequently, the tie was concreted to form a square section bar 170mm on each side (Figure 9).

To guarantee the longitudinal stability of the assembly, the end supports between the central body and the sides are lengthened, forming buttresses. At the ends of the lateral sections there are buttresses of the same type (Figure 9).

In the lateral sections the organization of the roof is similar, with the only difference being the height of the support on the opposite side to the cantilever over the tracks, since in this case it is not necessary to respect the height of the cornice. Another small cantilever is added here, on the side opposite to the tracks.

The difference in height between the central and lateral sections is resolved with a vertical wall that joins the lateral guidelines of the lower and upper roof modules, overcoming the difference in height between them. In this way, a large edge beam is formed that supports the end sections of the roof.

In the description of the project, mention is made of the need to add “substances” to the concrete to improve protection against the effects of smoke from locomotives. Although which substance to use is not specified, this shows the intention to take into account the durability of reinforced concrete.

4 ROOF STATIC

The structural scheme of the roof is simple. It is an isostatic frame with a span and a cantilever in one side in the central area and two in each side in the lateral ones. The support in the existing building has a vertical reaction component, and the support located between the tracks is constructed as a joint and has only two reaction components. In the case of the lateral areas, pillars aligned with the building façade are pinned at the side of the top.

This is therefore an isostatic structure in which specific forces in the different sections are determined. In the project description, the weights of the different parts of the roof are described. For each part the location of its center of gravity is identified and located in the section. The weight of one part corresponds to the section between the skylights (P1 to P3 in annex number 1 of the report, Figure 10), the second weight corresponds to the skylights (PL), the third is the weight of the partitions (Pn) and finally, the weight of the shell sections between the skylights (P4 to P9) is given. In the said annex, the position of each weight is detailed, with which the magnitude of the reaction in the support on the building can be determined, taking into account the bending moment due to the cantilever. With this, the value of the bending moments in each section of the beam is determined. As permanent actions, only the roof’s own weight is considered, without taking into account any coating. As variable actions, only snow with a value of 0.15kN/m^2 was considered. The wind action only produces suction due to the inclination of the roof. As their value is much less than its own weight, they are not taken into account.

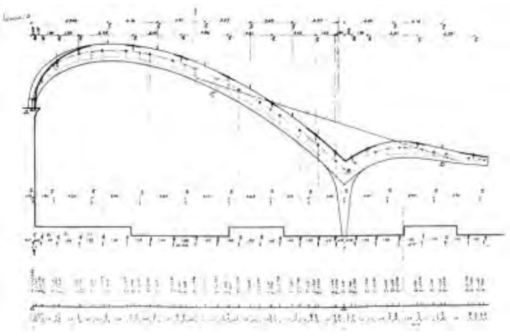

Figure 10. Cross section of the frame showing the distribution of the actions considered (Archivo Eduardo Torroja, CEHOPU).

Figure 11. Equivalent shape of the cross section of the sheet in the area between skylights (left), actual platform canopy of Orense railway station in summer 2009 (right) (author).

The cross section of the roof beam can be assimilated to a solid section with the shape shown in Figure 12, where the cross-sectional area, the position of the center of gravity and the moment of inertia are indicated.

5 THE ACTUAL ROOF

The roof that was finally built is made of reinforced concrete, but it was not the proposed solution. It is a much more modest structure, made of three sections of canopies on pillars arranged on the platforms. Pillars support a beam with two symmetrical cantilevers. The slab between the beams is resolved with a reinforced concrete slab with beams that protrude above the roof (Figure 11).

No documents of the built structure have been found in the Eduardo Torroja archive, so we cannot affirm the authorship of the actual roof.

During the visit carried out in summer 2009 prospecting was visible in the reinforced concrete surface, showing that the state of conservation of the roof

Figure 12. Prefabricated tri-articulated arch roof with prefabricated parts (left), roof modules made up of prestressed shells with a triangular plan (right) (Joedicke 1967).

was under study. Test pieces have also been extracted from the pillars and reinforcement with corrosion can be seen on the surface of the roof.

6 LATER SOLUTIONS

To resolve a warehouse roof using successive sections of elements that are repeated was a strategy followed by Torroja in later projects. One of them was the roof of the church of Pont de Suert. The roof consists of the repetition of 6.00m wide sections of pinned arches in the key, in which each part of the arch is a variable section shell. These shells are made up of reinforced masonry, so that the necessary formwork is eliminated and replaced by a partitioned vault composed of three brick shells and a reinforced concrete layer (Antuña 2005; Oschendorf & Antuña 2003). This solution shows the formal freedom that can be achieved using reinforced timbrel vaulting.

A final attempt to produce roof elements in reinforced concrete consists of the use of precast thin pieces using the prestressed concrete technique. Torroja prepared two solutions that were presented during the celebration of the conference on “Non-traditional processes of shell construction” in September 1959 that led to the formation of the International Association for Shell Structures (IASS) in Madrid in 1959. One solution consisted of rectangular pieces with variable section with which a tri-articulated arch was formed (Figure 12).

The other solution consisted of three-dimensional equilateral triangle shells that were prestressed on the ribs that formed the perimeter of the module. They were designed to be supported at the vertices and to support earth fillings up to 1.00m thick (Antuña & Orta 2019). With a thickness of 50mm, high loads can be supported thanks to the shape of the shell. The two previous solutions were built and tested in the facilities of the Instituto Técnico de la Construcción y el Cemento of which Torroja was director (Joedicke 1967).

7 DISCUSSION

The solution proposed for the railway station follows the procedure used in the roof of the grandstand of Zarzuela racecourse in 1935. It consists of dividing the roof into independent elements that can be built separately. That way the formwork and the scafolding can be used several times. It was a common procedure and has been widely performed in the past. Using shell structures, roofs can be built with a low rate of steel and concrete and repeating the same element several times reduces the cost of construction. In the case of the roof of the Orense railway station, despite the apparent complexity of the form, an economic solution was achieved. However, the project was not built.

At the same time, in Mexico, Felix Candela was building his first reinforced concrete shell and created the company Cubiertas Ala with Fernández Rangel brothers. In the following 20 years more than 1500 projects were studied by the company and more than 800 were built. An average of 40 each year.

The difference between the two situations allows us to answer the question of why some procedures become popular and are widely used in a place and at a particular time.

At the same time, Makowski and other authors started to explore the use of spatial structures formed with steel bars.

In the following years Torroja continued to explore different solutions for building reinforced concrete shell roofs. He proposed two types of solution: one, the use of precast elements, first in reinforced concrete and later using prestress concrete; two, exploring the possibilities of using reinforced title vaults. With the first option industrialization of roof construction was explored and, with the second, he experimented with the formal possibilities of a traditional and artisanal construction system in which neither scaffolding nor formwork were needed. None of these options were studied beyond Torroja’s proposals.

The contrast with the success reached by Candelas’ company is impressive. The economic situation in both countries does not allow for explaining this difference. And neither does the technical development, similar in both countries at that time. If the availability of manpower justifies, in part, Candela’s success, at that time in Spain the situation was not very different and that did not popularize the shell construction procedure.

A relevant issue that differentiates both cases is the existence of an industrialist, a company, that exploited a procedure. That procedure allowed economic solutions, in exchange for using unconventional and original procedures. Although Torroja participated in the creation of several companies related to construction (Obras Metálicas Electro Soldadas OMES, or ICON to carry out tests on models and build precision devices), he never created a construction company as Candela did. Although he collaborated with different entrepreneurs such as Ricardo Barredo (the builder of the dome of Algeciras and patented a prestressing system that was used in the Fedala reservoir) and François Fernández (builder of the Fedala reservoir and with whom he made several bridges and reservoirs in Morocco), he did not establish a permanent relationship to exploit a constructive system.

As the project presented was not built, we cannot know if, in carrying it out, Torroja had made any modifications to simplify the construction. In the past he had done so in previous cases, such as the grandstand roof of the Zarzuela Hippodrome project. At least three aspects of the project can be modified to simplify construction. One is the reduction or elimination of the stiffening walls placed on top of the shell, the other is to replace the external tie with reinforcement for a reinforcement located in the shell itself and, lastly, to simplify the skylights by making them continuous throughout the entire roof width, instead of the small sections of square plan separated from each other.

8 CONCLUSIONS

An unrealized project by Eduardo Torroja from 1950 has been presented in which a 90mm thick reinforced concrete shell is used for a roof of almost 30 meters' span.

The structural scheme of the roof is that of an isostatic frame span with a cantilever at one end, although the arrangement of the elements allows it to take the form of a thin shell, thickened in the appropriate areas to achieve the necessary rigidity.

As in other shell projects made after 1939, stiffening ribs were arranged in the upper part of the shell. Thus, with its transverse reinforcements the structure consisted of a series of frames of beams and supports.

In several previous projects by Eduardo Torroja there is evidence of the evolution of this design, with substantial variations between the solution described in the project and the one finally carried out. Once the proposed design is known, an exercise of great educational value is to explore the modifications that the design admits. Three modifications are proposed that maintain the fundamental form of the project but that modify the construction process. One is to study the effect of suppressing the transverse walls and the effect this has on the stability of the shell. Could it be built without these partitions? The other modification that is proposed to be explored is the elimination of the tie outside the shell, replacing it with the necessary reinforcement in the shell itself. Studying these options may make it necessary to slightly modify the shape of the roof. Finally, enlarging the size of the skylights will reduce the reinforced concrete surface and increase the lighting surface.

Finally, Torroja was never interested in creating a building company and was not able to convince any Spanish builder to use shell structures. Just the opposite to what, some years later, another Spanish engineer, Ildefonso Sánchez del Río, did with his company for building his own system.

9 FUTURE WORK

Before the use of rolled steel structures and the use of prestressed concrete spread, the roofing of all types of ships was made using reinforced concrete. The examples of concrete sheets are few, although a large number of cable-stayed reinforced concrete vaults were made. A large number are currently in use and it would be of great interest to make a catalog of the solutions carried out, their geographical distribution, the state they are in and the lesions they present. All of this will help guarantee their conservation and reuse.

ACKNOWLEDGMENTS

To carry out this study, the files in the archive of the Oficina Técnica Eduardo Torroja kept in the Centro de Estudios Historicos de Obras Públicas y Urbanismo (CEHOPU) of the Centro de Experimentación de Obras Públicas (CEDEX) of the Ministerio de Fomento were consulted. The file is available at the following address: http://www.cehopu.cedex.es/etm/indices/obraindx.htm. Several files were consulted. Not all the information is digitized and consultation was completed with visits to the institution. The project file for Orense station is number 745 from the Technical Office (http://www.cehopu.cedex.es/etm/obras/ETM-300.htm).

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Structural design via form finding: Comparing Frei Otto, Heinz Isler and Sergio Musmeci

G. Boller
Eidgenössische Technische Hochschule Zürich, Zurich, Switzerland

P. D'Acunto
Technische Universität München, Munich, Germany

ABSTRACT: Form finding is an effective approach for the conceptual design of structures. In the 1950s and 1960s, various form finding techniques flourished to create geometries that could not be realized with analytical models or graphical methods alone. The development of contemporary form finding owes much to the seminal work of a number of structural designers of the period, notably Frei Otto, Heinz Isler and Sergio Musmeci. The scientific cultures to which they belonged led to differentiated results in their research and design. This paper examines the approaches to the form finding of Otto, Isler and Musmeci, looking in particular at the inspirations, methods and visions of these protagonists in the history of structural design.

German architect Frei Otto (1925–2015), Swiss engineer Heinz Isler (1926–2009) and Italian engineer Sergio Musmeci (1926–1981) are structural designers who made form finding their main operative approach. Their education is rooted in the engineering culture of their time and their methods are informed by their individual backgrounds and scientific cultures. Although they all advanced experimental approaches to the discipline of structural design, they represent different perspectives on the subject of form finding. Therefore, a comparative study on their design approaches, as well as their written contributions, supports and enhances a broader understanding of their role within the history of engineering. This paper aims to compare the viewpoints of Otto, Isler and Musmeci on form finding by looking back at their writings and original documents in relation to their inspirations, methods and visions.

1 INTRODUCTION

Form finding is the design process, both physical and digital, that leads to the definition of the form of a structure in static equilibrium under given loads and boundary conditions. This term emphasizes that the form of the structure is the output of the design process: a "form-active structure" (Veenendaal & Block 2012) that expresses a "figure of equilibrium" (Linkwitz 1999) in compliance with the external and internal forces. It can also be considered as the result of an iterative procedure based on an experimental approach (Bletzinger & Ramm 2014; Ramm 2004) and subject to the law of causality (Carpo 2015). In the "initial equilibrium problem" (Haber & Abel 1982), other parameters besides structure must be considered, such as constructability and architectural aspects (Isler 1968). From this perspective, form finding goes beyond mere structural optimization to achieve minimal material use (Bubner 1972; Musmeci 1971) while obtaining "elegant forms" (Isler 1979a; Musmeci 1979a; Otto 1984a).

The study of specific physical phenomena to determine the form of structures under given loads and boundary conditions has its roots in the use of scale-independent physical models (Addis 2014). Early examples include Hooke's catenary curve (Hooke 1676) with St. Paul's Cathedral by Christopher Wren (1632–1723) as one of its first applications to architecture (Addis 2014). Further developments are due to Friedrich Gösling (1837–1899) and Antoni Gaudì (1852–1926). In particular, the latter is considered the original master of form finding with his investigation on combinations of catenary curves (Graefe 2020; Tomlow 2011). The exploration of structures under tension is rooted in the Euler and Plateau studies on soap-film membranes (Burkhardt 2020), with relevant applications in architecture, such as the prestressed cable-net membranes and shells by Otto, Isler and Musmeci.

Both Otto and Isler use the term "to shape" to describe the process of finding a form under given loads and boundary conditions (Isler 1959; Otto 1954). Musmeci also defines such a process as a "new philosophy of design" in which the form of the structure - and not its inner stresses - is the actual unknown (Musmeci 1979b). The projects for the German Pavilion in Montreal (1967) and the Olympic

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Stadium in Munich (1972), with their worldwide resonances, undoubtedly accelerated the interest in form finding among the structural engineering community.

The development of digital form finding procedures is strongly connected to the original physical methods (Tomlow 2016). The use of the first computational tools paves the way for the "Force Density Method" by Schek (Schek 1974) and the studies by Argyris on the extension of the "Finite Element Method" to membrane structures (Argyris et al. 1978). Their experiences form the basis for the further development of contemporary digital approaches to form finding, such as the "Dynamic Relaxation Method" (Barnes 1999), "Particle Spring System" (Kilian & Ochsendorf 2005), "Thrust Network Analysis" (Block 2009; Rippmann 2016) and "Combinatorial Equilibrium Modelling" (Ohlbrock & D'Acunto, 2020).

2 INSPIRATIONS

The form finding approaches of Otto, Isler and Musmeci draw their major inspiration from physical phenomena that belong to the natural world, albeit from different perspectives (Neri 2014). For example, Otto studies "nature" as a biological process and works in close collaboration with German natural scientists. In contrast, Isler's interest in the natural world suggests a more formal reference to its materialized physical principles. Musmeci studies the mathematical laws of mechanics in the context of recent developments in the natural sciences.

2.1 *Reproducing biological processes*

Otto's understanding of "nature" is very broad. Considering all the disciplines that belong to the natural sciences (Otto 1995), his goal is to reactivate the role of research in architecture and find a scientifically based connection between natural and artificial domains. In Otto's view, biology provides a model of study for architecture. His research group "Biologie und Bauen" (Otto 1984b), founded in 1961, makes extensive studies on biological processes, exploring, in particular, the physical and mechanical activities of self-formation and self-organization. Otto's form finding approach stands as a methodology based on direct observation and the replication of natural processes. Every element, both animate and inanimate, develops a form that results from an adaptation process and can be expressed by a combination of compressive, tensile and bending forces (Figure 1).

Otto promotes the reproduction of biological phenomena in terms of forms and methods: from his perspective, the form is not the result of the designer's intention (Otto 1971). His interest in natural processes is multifaceted and multiscale: with the same research attitude, he studies diatoms (Otto 1985), radiolaria (Otto 1990a), bubbles (Otto 1988), bones (Otto 1984c), spider webs (Otto 1992a) and territorial networks (Otto 2008). From this perspective, even the city can be studied as an organism (Otto 1984d): as in biological processes, it adapts according to its boundary conditions (Otto 1975a, 1992b).

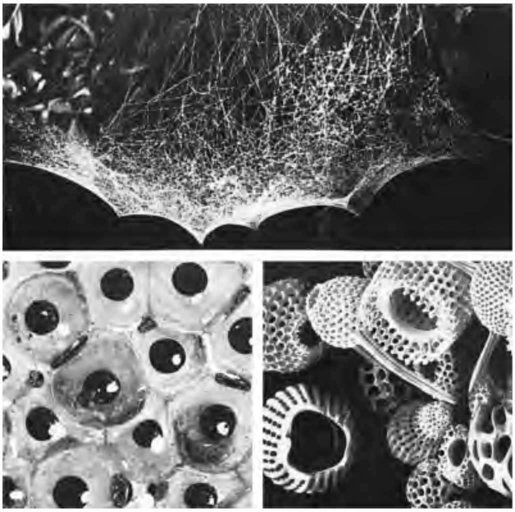

Figure 1. Studies on biological processes (Otto 1982: 15,19,20).

Otto's best-known experiments are those on soap films (Burkhardt 2020; Otto 1969, 1973). They follow the physical laws of minimal surface between given boundaries, characterized by constant stresses, and thus optimal distribution of material (Burkhardt 2020; Otto 1988). Exploring natural phenomena through physical experiments for the design of spatial cablenets enables him to devise forms not yet realized in the artificial world and that go beyond the traditional structural typologies.

2.2 *Observing nature*

According to Isler, the natural world is a source of inspiration for the designer's own imagination (Isler 1992). Originally intending to become a painter (Chilton 2000), his early watercolors are probably his very first formal studies of the natural world. The elements belonging to it - insects, plants, fruits, soil - reveal principles and forms resulting from physical necessities. Their formal clarity provides a reference image (Isler 1983) for the definition of effective structural forms. Since optimal shapes follow natural processes, they are necessarily beautiful according to Isler (Isler 1980) (Figure 2).

Isler's design goal is to recreate "natural" shell shapes through a process of physical form finding. Although the designer is responsible for the experiment's set-up (boundary conditions and selection of materials), the process evolves naturally. Isler's experiments are thus similar to those of Otto but differ in their objectives. If Otto is concerned with studying the process evolution, Isler achieves a particular form thanks to his static intuition. The pneumatic membrane refers to the physical concept of a surface under pressure, whereas the form achieved through the hanging

Figure 2. Isler's photograph of a natural shell, 1963 (gta Archives, ETH Zürich).

membrane is based on the extension of the catenary curve into space.

In his work, biological objects also represent powerful images to promote his design approach. Due to the formal similarity of his shell structures with the natural shells, the communication of his form finding method is possible on different levels and easily reaches the broader public.

2.3 *Exploring natural laws*

Unlike Otto and Isler, Musmeci looks at physical phenomena through an analytical mindset aiming to grasp the universal laws behind them. Like Otto, Musmeci is fascinated by the ever-changing physical and mechanical processes and their dynamic interactions. From his perspective, "nature" represents a collection of diverse entities that are interrelated (Musmeci 1979a). He is not interested in studying individual events: their structural organization is of greater importance. As the temporal synthesis of an unfinished process, form represents the organization of objects in space (Musmeci 1979a). Thanks to a vivid curiosity towards any mathematical theory, he investigates this concept of form and space in various fields, such as astronomy, but most importantly, architecture and structural design (Musmeci 1971). His search for new forms explores the potential correlation between scientific theories and their physical translations into design concepts (Figure 3).

For Musmeci, each element's original nature reveals the geometric and structural principles that contribute to its form. In his structural design conception, the optimal design solution expresses the force flow within the structure through its form. In this way, the form shows the variation of the inner stresses in accordance with its material properties (Musmeci 1960). As "natural" (Musmeci 1979b), the found form is the optimal shape because it manifests explicitly the concept of static equilibrium in the way it materializes.

Figure 3. Sergio Musmeci, Studies on Polyhedra (Musmeci 1979c: 15).

3 METHODS

The different approaches to form finding by Otto, Isler and Musmeci reflect their diverse backgrounds. Interestingly, both Otto and Musmeci had experience in aeronautics, although the former graduated in architecture and the latter in engineering. Among the three, Isler is the only structural designer who has a solely civil engineering education. Although with different objectives, they all establish relations with public and private institutions. Otto's projects represent not only the test field for his theoretical research but more importantly, the best occasions to promote new German technologies at globally important events. Isler's collaboration with a variety of Swiss private industries creates a constellation of fruitful alliances that fosters the development of Switzerland as a modern country. Musmeci explores new design and construction methods, also thanks to his collaboration with the construction company Italcementi (Musmeci 1980). In different ways, their works push the established building industry to envision new structures for new materials.

3.1 *A scientific approach to form finding*

Otto's research group at the Institute for Lightweight Structures in Stuttgart challenges the conventional approach to architectural design. The relation between biology and building becomes the key research objective and reproducing scientifically self-forming processes provides the operative approach (Otto 1971). Design creativity emerges from a synthetizing action (Otto 1990b). Otto's Institute promotes several research projects on long-span and adaptable buildings, all of which related to lightweight construction (Otto 1984a): "with the knowledge of the "principle of lightweight", one can begin to consider the objects of living nature from a technical point of view" (Otto 1982: 8).

Unlike Isler and Musmeci, Otto's design approach results from strong collective research that brings together several disciplines at the University of Stuttgart, including biology, botany, paleontology, zoology, biophysics, photography. For example, within the research collaboration at Otto's Institute, the nature photographer Andreas Feininger (1906–1999) develops innovative photographic techniques to further study natural objects (Burkhardt 1969). At the same time, the design experiences on cable-net structures help the biologist Ernst Kullmann (1931–1996) develop his research on spider webs (Otto 1984b).

Like Isler, Otto considers the physical experiment as the primary source of knowledge. It is the “methodical basis” (Otto 1990b) in every research project. It helps a process of abstraction, from the contingent event to its reproduction under specific conditions. That is, the physical model is the “medium to materialize the idea” (Weber 2020), which helps to test the theoretical assumptions developed by the research team. Among the three protagonists of structural form finding, Otto is probably the one who explores the most, with every material type and principle: sand cones (Schanz 1995), tensile nets (Otto 1954, 1975b), pneumatic membranes (Otto 1975a, 1975c, 1977, 1984c) and soap-film models (Otto 1969).

While Isler follows the same methodology to produce his physical models that is then implemented in all his projects, Otto continues exploring new possibilities throughout his career. His experiments require the development of high-tech instruments at various stages of design. For example, his “soap-film machine” (Figure 4) keeps the soap-film model in a climatic chamber with high humidity, which extends its lifespan and allows studying its geometry using parallel light and a camera (Fabricius 2013).

In the case of physical models with solid plaster casts, a 3D measuring machine surveys the form using an electrical measuring system especially developed at Otto’s Institute. In both cases, photogrammetry and geodesy are used to extract geometric information that forms the basis for further project development. In this process of analysis and synthesis, the Institute of Applications of Geodesy to Engineering directed by Klaus Linkwitz (1927–2017) plays a significant role, as in the case of the project development for the curved roof geometry of the Olympic Stadium in Munich (Tomlow 2016; Weber 2020).

3.2 *Form finding through craftmanship*

In contrast to Otto and Musmeci, who experimented with several structural systems, Isler devotes his work to studying a specific typology: the reinforced concrete shell. His “new shapes for shells” (Isler 1959) are free-form shapes that use physical models - in particular hanging and pneumatic models - as the main design tool. Indeed, Isler’s approach to shell design is highly experimental, from exploring multiple design variations in the conceptual design phase to measurement models before shell construction (Isler 1993). His prolific activity confirms his unique perspective on structural design as an engineer (Isler 1979b). Isler is influenced by his engineering education under the Chair of Prof. Pierre Lardy (1903–1958) at ETH Zürich (Billington 2003; Chilton 2000). Moreover, his experimental methodology is embedded within the Swiss engineering culture, considering that the Swiss codes accept the use of physical models instead of analytical calculations (Lardy 1955) to prove the structural soundness of buildings.

During his “research activity after office hours” (Isler 1979c), Isler works alone in his garden to observe natural processes in their original setting (Isler 1979d, 1992). This formal inspiration is then translated into his form finding models developed in his office. Model makers Anton Friedli and Hans Glanzmann support him in the construction of his gypsum models. However, the final design decision is left to Isler, who enters into a private dialogue with his objects, following a procedure that has been defined “Fingerstatik” (Glanzmann 2019).

In his form finding explorations, Isler acts as a craftsman and follows a rigorous methodology. The initial structural forms are generated by implementing basic principles: air pressure is used to produce pneumatic membrane forms and gravitational forces to define hanging membrane forms. At the same time, the materials employed in these models are simple: rubber membranes cut according to the initial starting shapes and anchored to timber frames (Boller & Chilton 2020). To further study the form, Isler makes use of solid plaster casts. (Figure 5)

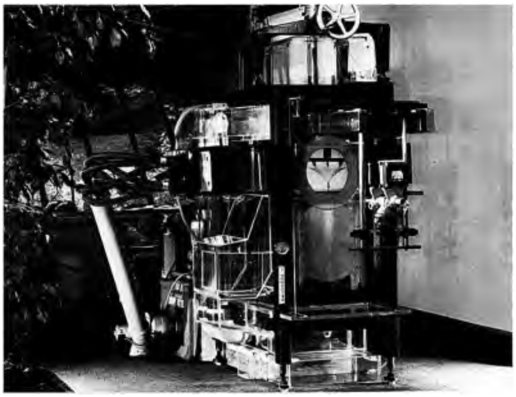
Figure 4. Soap-film machine at the IL (Schanz 1995: 58).


Figure 5. Heinz Isler, Studies on the form finding model of the Sicli project, 1968 (gta Archives, ETH Zürich).

Since this approach is simple, economical and fast, it enables Isler to test several design variations in the form of gypsum models until the shape is found that best fulfils the given structural and architectural constraints (Isler 1959). The structural behavior of this form is then studied in more detail. At first, the chosen gypsum model is measured with a measuring machine to extract its shape in x, y and z coordinates. Afterwards, a wooden mold translates the geometric data into a fiber-reinforced polyester model. A set of hanging timber masses is used to test the structural behavior under different load types through electrical strain-gauges. Whereas the form finding models are the output of Isler's craftmanship and experience, the form-validating models belong to a more established practice within the engineering discipline (Hossdorf 1971; Müller 1971). The translation from the small-scale physical model to the full-scale building is possible if similarity, precision, the quality of the materials used and cleanness of execution are respected (Isler 1979b, 1993, 1994).

3.3 *A mathematical perspective on form finding*

Musmeci's education as a structural engineer is deeply rooted in the Italian scientific culture of his time. His unconventional approach to form finding stems from the analytical approach to structures typical of the Italian school of engineering in which the mathematical perspective on structures is dominant. Musmeci belongs to the "second generation of Italian engineers" (Iori and Poretti 2018). In this context, he envisions a novel approach towards structural design regarding the search for new structural forms as one of its pillars (Musmeci 1971). While the traditional theory of structures considers geometry as a given input, with the assessment and verification of the inner stresses as the ultimate goal of the analytical procedure, Musmeci highlights that in the process of structural design, the form should instead be regarded as the real unknown (Musmeci 1979b). This intuition represents a paradigmatic shift that opens new perspectives in structural design. Thus, the analytical methods become design tools to control the form of the structure and the use of the material (D'Acunto & Ingold 2016). In line with the work of Maxwell (Maxwell 1870) and Michell (Michell 1904), Musmeci defines the notion of "static action" (Musmeci 1967), which is the signed product of the force acting in a structural member (positive for tension and negative for compression) and the length of that member. The algebraic sum of the "static actions" extended to an entire structure in static equilibrium – "total static action" – is an intrinsic characteristic of the system of external forces applied to the structure, and it is independent of the specific structural configuration (Musmeci 1967). This new perspective on structures leads to Musmeci's explorations of different structural typologies, based on accurate consistency between the shape and its corresponding force flow: from continuous surfaces towards spatial lattice structures (Musmeci 1979c). The search for those forms that minimize the amount of material required to resist a given load represents Musmeci's main design objective: it is about the essentiality that achieves the maximum synthesis (Musmeci 1968a).

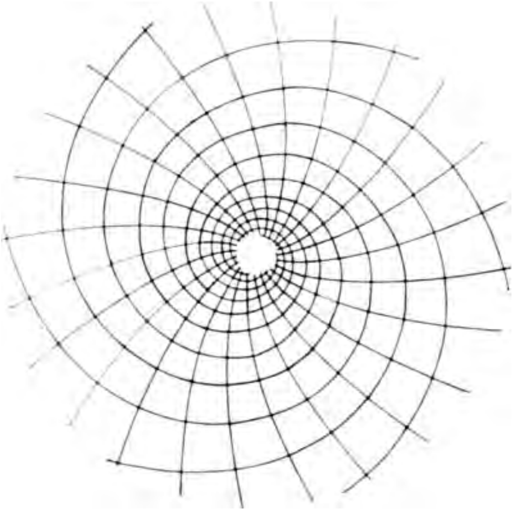

Figure 6. Equiangular spirals that satisfy the equation of the "structural minimum" (Musmeci 1968a: 411).

Unlike Otto and Isler, who use physical models as the primary design tools, Musmeci's physical models are rather instruments to visualize the mathematical theory underlying the design (Ingold 2020) (Figure 6). Musmeci often produces physical models at different scales for the advanced design phase and uses various materials to approximate the form and structural behavior gradually. These include, for example, the 1:100 methacrylate model and the 1:10 micro concrete model for the Basento Bridge (Musmeci 1977), the latter constructed at the national testing center (ISMES) founded by Arturo Danusso (1880–1968).

Musmeci believes in the concept of "static thinking" (Musmeci 1960) as the main starting point for any design exploration. If in the past intuition and experience are the main design factors that do not help envision new structural possibilities (Musmeci 1979b), his research supports a creative approach to structural design that minimizes the use of material. The form results from a precise static choice and should highlight its structural features by explicitly showing the variation of the internal stresses within the material (Musmeci 1979a).

4 VISIONS

Otto, Isler and Musmeci are the representatives of a generation shift between the physical and digital methods of form finding. Their visions of the future of the discipline are crucial at the turning point towards the new century. Otto and Musmeci saw the recently introduced computers as essential tools opening up new design possibilities. On the contrary, Isler found the new computational tools a potential threat to a proper understanding of his form finding methodology based exclusively on the use of physical models and supported by practical experience.

4.1 *Between analog and digital models*

Thanks to its strong network of collaborations, Otto's research group was able to take advantage of emergent electronic tools to support its activities. Since the methodology behind a complex research project requires many iterations, Otto considered the combination of physical and computational methods as an excellent opportunity to reduce the effort required in the design process. Unlike Isler, he managed to find a balance between analog and digital models. In the early phases, he worked mainly with physical models. In fact, Otto argued that mathematical models require a lot of time and energy in the form finding process (Otto 1990b). On the contrary, physical experiments like those with soap-film models are quicker to produce and therefore enable multiple design possibilities to be easily explored. The roof design for the Olympic Stadium in Munich was the first project where the form of the physical model was compared with that generated with early digital tools (Linkwitz 1999). It is no coincidence that Otto's collaborator on this project, Ewald Bubner (1932-), wrote one of the first dissertations on early digital form finding methods (Bubner 1972). Linkwitz, together with Hans-Jörg Schek (1940-), developed a computational approach to control the geometry of the complex cable-net structure (Linkwitz & Schek 1972) and to compare it with the photogrammetric measuring method on Otto's physical model. Similarly, even the calculation phase was the result of a collaboration between the analytical approach of Fritz Leonhardt (1909–1999) and the early digital methods based on the "Finite Element Method" developed by John Argyris (1913–2004) (Argyris et al. 1978).

4.2 *Creativity and the use of digital tools*

Isler's long experience with physical models made him question the potential use of new tools in the design phase (Isler 1998). This aspect became evident in one of his last commissioned works: Stuttgart 21 (1997-). In collaboration with Otto and the British engineering office Buro Happold, he was involved in the form-refining phase (Boller & Schwartz 2020). To recreate the chalice-shaped column proposed by the team winning the architectural competition, Isler made one of his most complex form finding models based on the hanging membrane principle (Isler 1997a). His physical results – two gypsum models - were then compared with the outcomes of the digital form finding method developed by Buro Happold. From Isler's point of view, the outcome of the digital approach was not accurate enough because the definition of the algorithm required too many simplifications. The physical approach refers to the "genuine hanging process" (Isler 1997b) and, therefore, was more reliable than the digitally found shape. He believed that the form finding process needs experience and intuition to achieve a trustworthy result: the apparent simplicity of the process can lead to arbitrary outcomes (Isler 1986), especially when implemented within digital tools.

Isler believed that inventive work needs human minds, and cannot be replaced by automatic processes (Isler 1997c). Contrary to Musmeci, he considered computers were unable to provide creative results (Isler 1992, 1997d) as physical models did.

4.3 *The computer and its new design possibilities*

According to Musmeci, electronic tools within the disciplines of architecture and engineering represented an important step towards a more integrated design approach. He appreciated the scope for accelerating structural calculations in the structural analysis phase (Musmeci 1972). At the same time, like Otto, he anticipated the development of a computationally-driven methodology for rational data analysis that combined knowledge from several disciplines (Musmeci 1979a).

From his viewpoint, "structural design" was to deal with the problem of form optimization to achieve the solution that best approximated the "structural minimum" (Musmeci 1968b). In this respect, computers could be extremely powerful tools. Unlike Otto and Isler, Musmeci foresaw the cooperation between humans and machines to enhance creativity in structural design: "I think that one day, perhaps not very far away, this will be the way a creative structural engineer designs" (Musmeci 1972: 159–160). Indeed, digital methods would then help in both quantitative and qualitative aspects of the design process (Musmeci 1972). If electronic tools could be implemented in the conceptual design phase, this might lead to new shapes. The designer's task was to choose from among all the eventual solutions, that which best met the architectural and structural requirements, taking full advantage of the possibilities offered by new materials (Musmeci 1980). Thanks to digital tools, he foresaw the possibility of controlling a greater number of parameters to study the most complete and diversified structural possibilities. Unfortunately, his premature death in 1981 did not allow him to fully exploit this new digital world and experience the outcomes of his intuitions.

5 CONCLUSION

Frei Otto, Heinz Isler and Sergio Musmeci opened up new ways to form finding. Their broad curiosity in multiple fields and their innovative approaches contributed to changing the perspective on the discipline of structural engineering. The wide-ranging fascination with natural phenomena formed the starting point for the development of their design methods. Otto's biological processes, Isler's natural references and Musmeci's studies of the mathematical laws behind them were reflected in their practical production. For example, Otto became head of a research group at the University of Stuttgart, where experimental activities led to the creation of real projects. Isler established his engineering office to promote his innovative shell design that encapsulated to nature. As an intermediate figure between Otto and Isler, Musmeci balanced his professional collaborations as an engineer with his theoretical studies on structural design. The methods they developed are the basis for today's digital form finding tools. Indeed, the principles behind them translate their approaches in the digital world. The computer enhances the possibility to explore multiple design possibilities following specific protocols without losing the combination of creativity and scientific thinking that are the two main characteristics of Isler, Otto and Musmeci's practices. For this reason, their works rank among the most relevant references for today's structural designers. Even though the design tools have changed, as Isler stated, "What is the best form, or even the correct form? This will remain the crucial question" (Isler 1997e).

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The practical geometry of Persian ribbed vaults: A study of the rehabilitation of the Kolahduzan Dome in the Tabriz historic bazaar

S. Nazari
Brandenburgische Technische Universität Cottbus – Senftenberg, Cottbus, Germany

ABSTRACT: Recognized as a UNESCO World Heritage site in 2010, the bazaar of Tabriz is one of the largest brick complexes in the world. In the mid-20th century, the complex came under the management of the Iranian Cultural Heritage, Handicrafts and Tourism Organization (ICHTO). This article focuses on the rehabilitation of the Kolahduzan Dome in the old fabric bazaar. By the 1970s, the dome was crumbling following decades of neglect. Conservation of the dome began in 1981 under the direction of Reza Memaran Bename Tabrizi, a member of the last generation of local traditional builders. This article delves into the geometrical analysis of the new design and the construction technique adopted by the master builder. The geometrical analysis provides a new perspective on practical geometry in Persian vaulting. It identifies three geometrically different layers: 1. Theoretical geometry, 2. Structural geometry, and 3. Architectural geometry. On-site data collection was performed by the author to record all workable points on the vault. Historical documents have been received from Iran Cultural Heritage Documentation Center.

1 INTRODUCTION

This research investigates one of the monuments built by the master [Ustād] Reza Memaran Bename Tabrizi over the Charsough-i Kolahduzan in the historical complex of the bazaar of Tabriz. The Kolahduzan Dome was redesigned and reconstructed by Us Reza in 1982. Little is known about the original vault and covering of the site. However, interviews with older shop owners in the area reveal that the cupola's original roofing material was lost to untreated earthquake damage and lack of timely restoration. Us Reza was able to reconstruct the dome using solely traditional method. This method, known as kārbandī in Iran, utilizes load-bearing intersecting ribs. kārbandī is a traditional Iranian architecture used to cover large-scale openings in public spaces. This method employs intersecting stellar lines and theoretical mathematical principles.

What supplies the unifying force to Islamic architecture is the geometrization of design, structure, ornament, and space (Golombek & Wilber 1988). Geometry is as much a theme of the architecture as it is of the decoration. The first examples of this kind of stellar vault to be identified by Persian architects as kārbandī appeared in Umayyad Cordoba in the 10th century. Over the next two centuries this technique appears to have made its way to some of the Islamicate world's eastern cities like Nā'īn and Merv. The latter is shown over the tomb of Sulṭān Aḥmad Sanjar (Nazari & Hashemi Nik 2019, 7).

Studying the design of the diminutive cupola of Kolahduzan revealed several keys to understanding the approach and methods of Us Reza. His approach to aesthetics and structural design and his personal affinity for embedded ribs (*taqdozd*) are revealed through the examination of the cupola. Embedded ribs are hidden load-bearing ribs that function as a main design element of a vault.

Because the Kolahduzan Dome was reconstructed 35 years ago by a contemporary Iranian architect trained in traditional methods, and there are compelling documents in the archive of ICHTO (Iranian Cultural Heritage, Handicrafts and Tourism Organization) concerning the dome's construction process, this cupola's reconstruction represents an important case study in the use of practical geometry in Persian architecture. This article presents the results of a study to examine the architectural approach to the geometrical design of the dome's skeleton, the structural role of the transverses and tiercerons, and use of embedded ribs. Before proceeding with the discussion of the structure's technical elements, it is important to provide a glimpse of the history of Tabriz and its bazaar.

2 THE HISTORICAL BAZAAR OF TABRIZ

Tabriz (north-west, Iran) is the Iran's sixth largest city, and it has played an important role in the historical, cultural and political facets of the contemporary history of Iran. Owning to the fact that the city hosted the residence of the crown prince during the Qajar era (1789–1925), Tabriz became the center of the Iranian Constitutional Revolution between 1905 and 1911. During the Qajar era, Tehran became the political capital of Iran. However, Tehran's economic growth was delayed due to Tabriz's importance as the home of First

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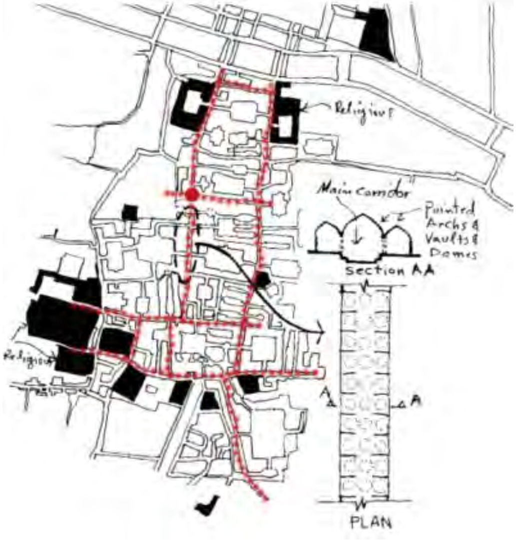

Figure 1. A map of the bazaar of Tabriz, with the axis configuration marked in red (Pourjafar 2012).

Chief of the Persian Chamber of Commerce, Malek al-Tojjar Aqa Mehdi Tabrizi who was instrumental in expanding and improving the bazaar of Tehran (Farmanfarmaian 2012, 203). The task of transforming the bazaar was left to Amīr Kabīr (d. 1851), the reformist prime minister of Nasīr al-Dīn Shah, and Aqā Mehdī Tabrizī Malek al-Tojjar (King of the Merchants of the Protected Domains of Iran).

The result was a vast program of restoration and expansion of the Tehran Bazaar (Keshavarzian 2007, 22). The monumental bazaar has been a symbol of Tabriz’s greatness throughout the centuries. In 1330, the famous Moroccan explorer Ibn Battuta wrote that the bazaar of Tabriz was one of the largest bazaars in Muslim countries (Gibb 1929, 102). Marco Polo and the Spanish traveler, Clavijo, wrote about the architectural glories and economic prosperity of the complex in 1275 and 1403 respectively. The bazaar’s current architectural structure is 230 years old.

The bazaar’s earlier structure had been almost completely demolished by the disastrous earthquake of 1780. The complex (Figure 1) has an organic fabric, wherein a system of land-use and geographic configuration develops naturally out of the interplay of market forces. The main commercial components are the configuration axes (*rastehé-ha*), the chambers (*hojreh-ha*), the caravanserais, and the recessed domed vestibular intersections (*charsough*). Spatial models of charsoughs usually contain a covered central court around which commercial cloisters and axes are arranged. The axes are vaulted vestibules, made up of vaulted vestibules, with a length of 5.5 km and width varying between four and five meters, and flanking chambers. Most of the flanking chambers have two stories. The ground floor is used as a trading space and the second-floor rooms are used for storage.

Figure 2. The construction of Masjid-i Sharif University. Farhad Tehrani archive, the photo was taken circa 1990.

3 REZA MEMARAN BENAM TABRIZI

Ustād (Us) Reza (1903–95) was one of the most famous Iranian contemporary architects of the last century. He was among the last in a line of local traditional builders in Iran, such as Hossein Lorzadeh (1906–2005) and Ali Asqar She’ ’rbaf (1931–2016).

Us Reza began his architectural training at the age of 20 under the supervision of his father, Us Balakazem. In an interview with Dr. Farhad Tehranī , Us Reza notes “I had been studying theology before learning architecture, because the study of theology was not suitable for my personality, at the age of 20, I began architecture” (Tehrani interview 1981).

Us Reza’s name emerged as designer and builder not only of some of the most important projects by ICHTO, like the rehabilitation project of Masjid-i Kabud’s central dome in Tabriz (1975), but also in a number of major projects in Tehran, such as the Masjid-i Sharif University dome (Figure 2), all using traditional construction methods. He was well-known for his vaulting techniques and use of geometrically intricate crossed-arch structures for the bridging of large spans.

Due to the rise in the use of modern construction methods in Iran in the 1960s, traditional architects were no longer in demand. In the 1970s, the establishment of ICHTO and developments in the science of historic preservation, led to the documentation of the professional knowledge of traditional architects, like Us Reza, through their cooperation in restoration projects. The following section presents an analysis of the structure and the geometry on the stellar vault composition of the Kolahduzan Charsough. This analysis was carried out using the following methods: surveying the structure’s present condition, regenerating the plan of the ribs, consulting archival documents from the Iran Cultural Heritage Documentation Center, and using Rhinoceros 6 to produce the 3D model of the intersecting arches. In this article, I shall also address the question of whether traditional master builders based their intersecting vaults on geometrical concepts. Firstly, the geometrical knowledge of the architect behind the design of the ribs shall be investigated. Secondly, the stages of the construction process corresponding to the transverses, tiercerons and liernes will be described. Finally, the construction technique employed in the assembly of the ribs will be described.

4 GEOMETRICAL ANALYSIS

4.1 *The arch profile*

In any geometric analysis of a vault built on pointed arches, the identification of the arch profile and the geometrical knowledge behind the design must be determined. Unlike in the case of semicircular or oval arches, the possibilities of the pointed arch are endless due to the possible width/rise ratios determined by the locations of the arc centers. Multi-centered arches in Islamic architecture, recognizing Persian influence to various degrees, can be grouped into recognizable sets. Most pointed arches in Iranian sphere are three- or four-centered. The origins of the four-centered pointed arch demand a thorough investigation. This model made its debut under the Il-Khanids (1256–1335). A surge in design experiments related to this model occurred in the 14th and 15th centuries.

Four particular profiles of the Kolahduzan Dome are of interest, namely the load-bearing transverses (Figure 5). Since the four transverses are assumed to be equal, only one transverse was scanned. The vault was surveyed using a Leica FlexLine TS 06 which recorded points and vertices. The first plotting attempt revealed that the geometry of the profile is quite similar to the most well-known Persian four-centered pointed arch, colloquially known as *panjo haft* (literally translates to: five-and-seven). The geometry of the arch profile is illustrated in Figure 6.

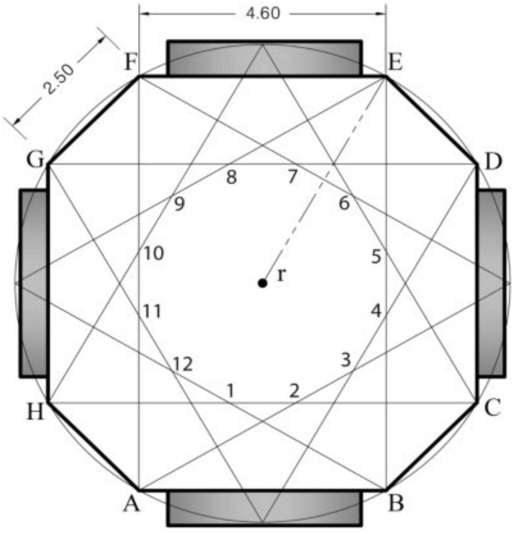

Figure 3. The theoretical geometry of the Kolahduzan vault

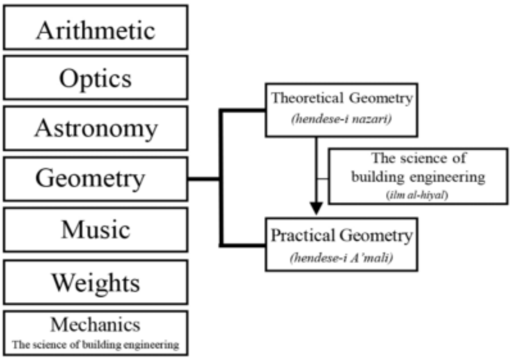

Figure 4. The scientific classifications in the Kitāb'ihsā' al-'ulūm by al-Farabi.

4.2 *Theoretical geometry*

Unlike free-handed vaults, ribbed vaults (kārbandī) conform to strict mathematical principles. Understanding these principles will illuminate the design process behind these ribbed vault structures. The construction methods including projection of a star polygon from the plane onto the rotating surface of a solid (*kārbandī*) is a significant pattern in the Iranian architecture vaulting (Hashemi Nik 2013, 11) that are designed based on a series of theoretical principles of mathematics, known as "Theoretical Geometry." Before introducing the theoretical geometry of the Kolahduzan Dome, it should be mentioned that Al-Fārābī identified seven fields of mathematics. Each of these mathematical fields had a branch of theory and a branch of practice. Carpenters, masons and metal workers deal with the practical geometry as defined by al-Fārābī (Necipoğlu 2017, 20).

In al-Farabi's classification system, theoretical geometry contains definitions, theorems and proofs. He describes practical geometry as "looking into the lines and surfaces, within a wooden body if it is used by a joiner (*najjār*), and within a wall if it is used by a master builder (*bannā*), or within surfaces of land and fields if it is used by a surveyor (*māsih).* Al-Farabi and Abu al-Hasan al-?Amiri (d. 992) also identified another branch of mathematics within the branch of geometry which they called, "The Science of Building Engineering" (*ilm al-hiyal*) (Necipoglu 2017, 20) and it refers to searching for ways for human beings to impose mathematical theories on external objects (Figure 4).

The architectural plan of the charsough is a semi-oblong octagon, its longer sides measure 4.6 meters, opening directly into the main axes (*rastehé-ha*), and its shorter sides measure 2.5 meters. The cupola over the hall is about 9.5 meters high.

It is segmented by four transverses and secondary and tertiary ribs: tiercerons and liernes.

Figure 5. The Kolahduzan Dome construction. In this photo the four transverses have been built as the first phase of the construction. Farhad Tehrani archive, the photo has been taken circa 1981.

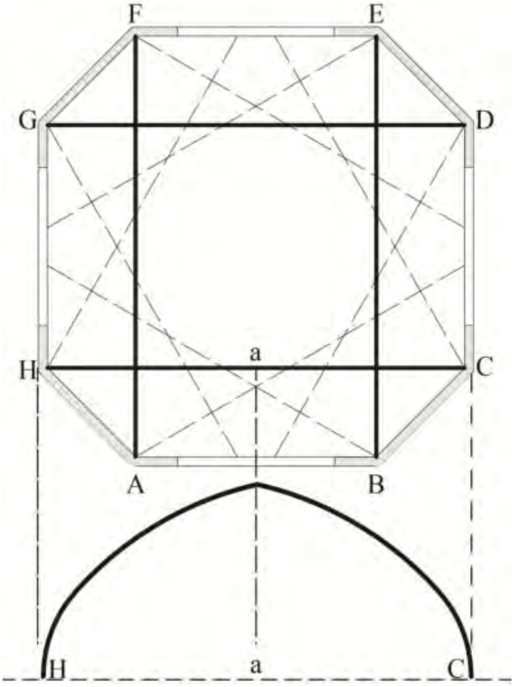

Figure 6. The plan and the arch profile of the transverses.

The key to understanding the composition of the intersecting ribs is to divide an imaginary circle circumscribed around an octagon (here the octagon represents to the charsough plan) into twelve equal arcs, then connect the chords four in between. Assuming this imaginary circle was the modular format on which the vault had been developed facilitates an understanding of the morphology of the composition of the ribs. Therefore, the theoretical geometry of the design can be described in the following way: if the points created by dividing the circumscribed circle around the octagon into twelve equal parts, are connected four in between, a star-shaped polygon, known as "kārbandī/rasmī {12/4}" in Iranian architectural terminology, emerges (Figure 3).

Here the nomenclature is purely mathematical. The first integer denotes the number of vertices on the represented polygon (12), and the second denotes the connection sequence between said vertices (4). The star-polygon shapes a twelve-sided central rosette (numbered consecutively from 1 to 12 in Figure 3), known in Iranian art and crafts as *Shamseh*. The number of the kārbandī is usually displayed in the extremities of its rosette.

The finished geometry (the theoretical geometry) is the horizontal image of the intersecting ribs on the ground whose convex vertices have an internal angle of 30 degrees. In a practical experience, each chord represents a 2D pointed-arch in front view (Figure 6), and a solid, masonry pointed-arch in the finished vault. The whole geometry represents a three-dimensional network of intersecting ribs.

4.3 *From theory to practice*

Structural and decorative functions, construction techniques, and applied geometry in rib-vaulting, particularly load-bearing capacity of the masonry vaults, would make an interesting subject in the study of construction history. Ever since foreign scholars like Arthur Upham Pope, André Godard, and Donald Wilber wrote about Iranian architecture in the early 20th century, scholars interested in Iranian architecture have engaged in speculation and debate about a variety of matters pertaining to the topic.

Referring to the previous argument, theoretical geometry was the basis for the structural design of the Kolahduzan Dome. Hence, Us Reza purposefully selected and applied the kārbandī {12/4} and technical considerations to accommodate the boundary conditions of the site. A point of interest here is that under certain situations, architects eliminate or trim some lines parts of the theoretical geometry for aesthetic or practical reasons. In the following, the construction stages and the geometry of the constructed ribs will be described coining the term "structural geometry".

From the structural point of view, some technical terminology is essential. Transverse ribs are the main ribs in Gothic ribbed vaults. These ribs are used to bridge the nave, connecting two walls on both sides and also separating the cell units in a vault. Tiercerons function as tangential and secondary ribs in a Gothic ribbed vault and liernes are minor ribs in a complex ribs network that do not start from the main springers. The author has chosen to adopt this terminology to categorize the ribs in the analyzed system according to their function.

Observations of the vault revealed the presence of three types of ribs on the structure of the vault. The first type identified was the massive transverse ribs. These ribs bridge the width of the open space, with landings on both sides of the structure composed of a greater number of bricks as evidently serving to carry the bulk of the loads onto the piers.

According to the archival documents (Figure 5), it could be observed that four transverses labeled AF, BE, CH and DG (Figure 6) were built during the first step of the construction process.

The four transverses are two-footed landing ribs, bridging the entire width of the open space, which measures around 10 meters. Each of the transverses represents a four-centered pointed arch in front view. In Islamic architecture, multi-centered arches can be grouped into recognizable sets. The origin of four-centered pointed arches requires further study, but their structural application can be traced back to the 15th and 16th century. Here, we witnessed a famous Iranian arc profile that is colloquially known as *panj-o haft*.

The four transverses are thicker than the other ribs; they have cross-sections measuring around 65×35 cm and seven layers of bricks. The four transverses form two intertwined rectangles on the plan (ABEF and HCDG). These four vaults were constructed in accordance with the theoretical geometry used in their planning. These four vaults will be denoted by calling the transverses the “first layer of the ribs network” in the following.

In the second stage of construction, the vault was fortified by a network of secondary ribs (tiercerons), and fewer brick rows were used here than in the first stage of construction. The use of fewer bricks lightens the tiercerons, and these elements land on transverses on one side, and on the piers on the other side.

In certain situations, master builders may remove or trim intersected lines that occur with the theoretical geometry. For practical reasons, Us Reza trimmed the tierceron lines where they meet the transverse lines. Figure 7 demonstrates that, trimming the extension of the secondary ribs (dashed lines) turns the 12-sided rosette into a square. This mean that the extensions of the tiercerons are not constructed in the finished construction.

The trimming of the lines is left to the discretion of the designer. With a practical approach, trimming the central rosette and turning it into the square is due to the small working space to execute brick groins, according to the author’s workshop experiences and learning from first-hand practitioners. Groins cannot be constructed in close proximity to each other as such an arrangement does not provide the architect with enough space to work. The elimination of the ribs reduces the weight of the structure and the amount of materials required for the construction. It seems likely that the master combined his desire to have a suitable work environment with his desire to reduce the structure’s weight and the cost of materials.

In Figure 7, the bold lines indicate the position of the tiercerons in the Kolahduzan Dome. The tiercerons were added in the second construction phase. The dashed lines in the figure show the parts that the master chose not to include in the construction. The web between the transverses (two-footed landing ribs) and the tiercerons (single-footed landing ribs), are the tertiary ribs, landing on the transverses built in the first stage of the construction on one side, and on the tiercerons on the other side. Parts of the theoretical geometry have also been eliminated in this construction phase. The lines were trimmed and were not extended beyond the junction with the transverse and tierceron lines (Figure 7). Because these ribs are only connected to other ribs, as opposed to being connected to a springer, they will be referred to liernes in the following paragraphs.

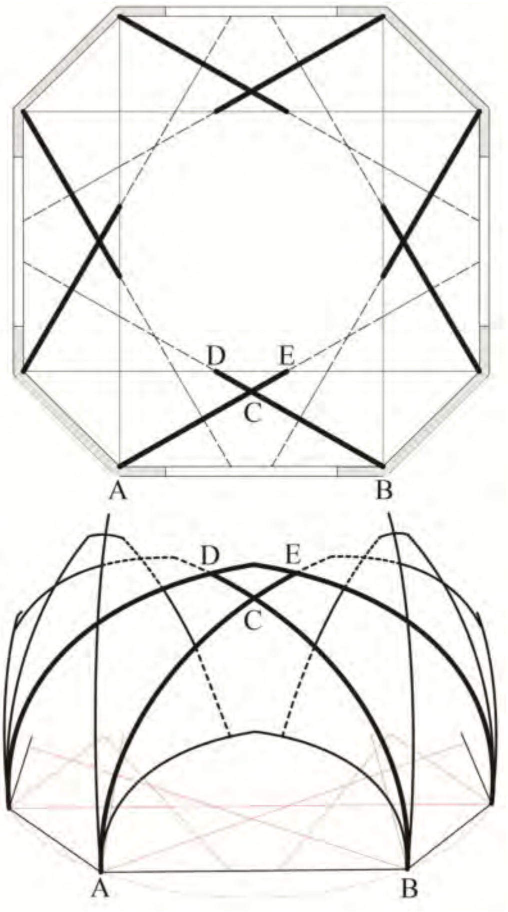

Figure 7. This figure illustrates the tiercerons. The dashed lines represent elements that were trimmed by the master. They were not present in the finished construction.

In the current Iranian architectural discourse, a number of specialists have accepted that the ribs classified as secondary (tierceron) and tertiary (lierne) are not involved in load-bearing capacity of the vaults. They assert that they simply frame the brick shell of the dome. In other words, it is argued that the transverses are solely responsible for transferring the static loads of the cupola to the piers, with the rest elements appearing as symmetrical infill laid out on a layer of veneer. An understanding of the structural function of the elements of the vault cannot be gained without performing a dissection of the star-vault and subjecting

Figure 8. Structural frame of the Kolahduzan Dome, displaying the transverses, tiercerons and liernes. Farhad Tehrani archive, the photo has been taken circa 1981.

Figure 9. The Shrine of Baha'uddin-e Naqshband, Bukhara (16th century). The picture shows the dome's load bearing {8/3} kārbandī covered over by the decorative yazdi-bandi. Hatice Yazar, Aqa Khan visual archives, MIT.

it to a load test, unless illustrative archival documents are available, as is the case for the Kolahduzan Dome.

4.4 *Architectural geometry and embedded ribs*

Identifying the structural or decorative nature of the architectural components of Iranian structures has been a controversial subject for scholars, especially as the issue pertains to ribbed vaults over ceilings. In many cases, the surface of the ceiling is merely a decorative layer such as *muqarnas* (stalactites) and *yazdi-bandi* (Nazari & Hashemi Nik 2019). For example, the decays of the surface of the structure of the yazdi-bandi at the shrine of Bahau'ddin-e Naghshbandi in Bukhara has revealed the structural embedded ribs of its stellar vault, which were once covered by a *yazdi-bandi* pattern (Figure 9).

In other structures, the load-bearing frame is almost traceable from bottom view (Figure 11), as in the case with the architecture of the Tabriz Bazaar. However, a novel application of the embedded ribs can be observed in the cupola in Tabriz. Us Reza trimmed parts of the theoretical geometry, thereby transforming the rosette at the apex of the structure into a square, and trimming the tierceron lines in junction with liernes and transverses. For practical and aesthetic reasons, the geometry of the stellar vaults often ends with a rosette (*shamseh*) at the top of the structure in the Iranian stellar vault tradition. The square over the pinnacle of the vault broke with traditional ideas of aesthetics.

Here, the master's novelty appears in his solution to the aesthetic problem. Us Reza has not displayed the entire skeleton of the vault, the key to understanding his approach in correlation between structure and architecture. He decided to use embedded ribs to hide the apex of the transverses from the field of vision of any observers. Figure 11 is a photogrammetric view of the Kolahduzan Dome, captured using a wide-angle lens, that shows the architectural geometry of the vault. It appears that the builder opted to conceal the apexes of the transverses and tiercerons by shaping a new rosette, in a larger span this time. The dashed lines in the figure indicate the positioning of the segments concealed under the brick shell of the vault. The protrusions on the outer surface of the vault are visible from the roof (Figure 11 bottom). Hiding the crowns of the transverses and tiercerons causes a rosette shape to be displayed. Thus the expected appearance for and Iranian ribbed vault is achieved. This time the rosette covers a larger span magnifying the dome larger in span.

5 THE CONSTRUCTION TECHNIQUE OF THE RIBS

The following description was made possible by the contribution of Dr. Farhad Tehrani, a close acquaintance of Us Reza, who was in charge of the Iran Cultural Heritage Center in the province of Azerbaijan, during the time of the construction of the Kolahduzan structure.

In this section the construction method of the ribs will be described, and the gypsum centering rib method, known as "*lenge gachi*" in Iranian traditional architectural vocabulary will be introduced. The use of this technique dates back to the Sassanid Dynasty (224-651CE) (Acre 2008, 524).

The traditional method of rib construction in Iran differs from the common traditional methods in Western architecture – what was common in Roman architecture and later revived in Renaissance architecture – where heavy, load-bearing wooden formworks were used to build arches. One of the reasons that wooden formworks are not used in Iran is due to a lack of

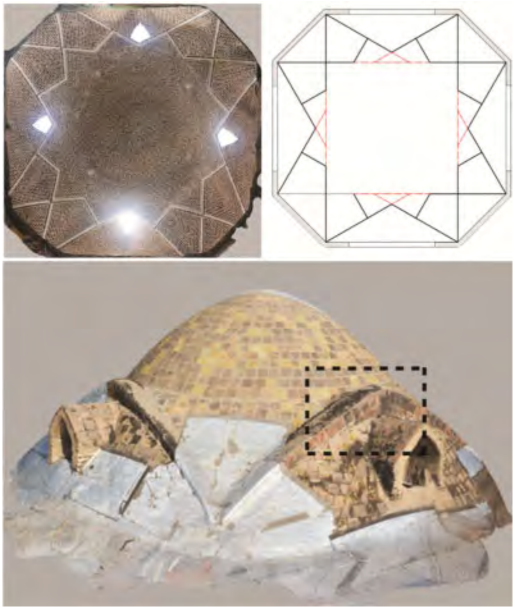

Figure 10. The bottom of the Kolahduzan Dome and a plan of the visible ribs. The rectangle and dashed lines show the hidden parts of the transverses.

Figure 11. The Kolahduzan Dome under construction (photo taken circa 1981). A: Transverses, B: Tiercerons, C: Liernes.

wood. Additionally, Iran's climatic conditions may make wood constructions unappealing.

Iranian arches, especially the multi-centered types, have complex geometry and are difficult to draw. Therefore, they are difficult to implement without formworks. An Iranian solution to this problem is to build a gypsum centering rib, to use as a model and guide. A centering rib is a temporary wooden or gypsum structure that is built to support an arch during construction.

To build a gypsum centering rib, firstly, a full scale of the front view of the desired arch is sketched on the ground. The desired arch can be a pointed arch or of an oval arch type. The front view of the sketch is a two parallel arch with 10–18 cm space between. A mold is formed by placing the bricks on the sketched line. Sand is then poured under the mold to prevent the gypsum rib from sticking to the ground. The frame is then filled with gypsum slurry. In the past, date palm tree fibers, or bamboo stems were placed into the frame to increase the tensile strength of the gypsum centering rib. Today, plastic ropes are often used instead of tree fibers or bamboo stems. The construction of the load-bearing ribs begins after the centering is installed. One or two parallel gypsum centering rib will be set where the load-bearing transverse or tiercerons are to be built. Then, the space between the centering ribs is infilled with brickwork. Figure 12 illustrates different types of brickwork commonly used in rib construction. In order to increase the firmness and load-bearing capacity of the masonry ribs, a mixture of pitched-brickworks and radial-brickwork is used. For instance, for the *Masjid-i Sharif project* Us Reza covered almost one sixth of the area with radial-brickwork, and the remaining area with pitched brickwork. Dr. Tehrani asserts that Us Reza has only employed pitched brickwork at the Kolahduzan, as Figure 5 indicates.

Figure 12. Left: different types of brick works used in ribbed vaulting. 1: gypsum centring, 2: pitched brickwork, 3: radial brickworks, 4: tile brickwork (Memarian 2015, 112).

6 CONCLUSION

This research describes the Kolahduzan Dome in the old bazaar complex in Tabriz that was reconstructed in the early 1980s. While studying the dome's stellar composition, I realized that the vault may reveal the approach to aesthetics and structure taken by an important Iranian traditional architect. Using a surveillance camera to record the points on the vault, and converting these points into AutoCAD revealed that the arch profiles matched those of four-centered pointed arches, *panjo haft.* The arrangement of the transverses, tiercerons and liernes match the theoretical geometry (kārbandī {12/4}). This indicates that theoretical geometry was used in this structure. The master builder expertly manipulated the theoretical geometry; he eliminated the extension of the lines in some areas. Thee manipulations satisfied the builder's desire to reduce the weight of the structure and the quantity of construction materials used during construction. Additionally, these manipulations created ample space for the vaulting process. To distinguish the geometry of the structure from theoretical geometry, the network of the emerged ribs is called Structural Geometry. In Iranian stellar vaults, the geometry of the vaults often ends with a rosette at the top of the structure. Us Reza concealed the crown of the transverses to achieve that aesthetic ideal. We witnessed that by hiding the crowns, the geometry of the visible ribs from the interior view is ended in a rosette, as expected. It may be stated that when a master builder, such as Reza Memaran, took a structure in hand, he followed through on every stage of the work, from the working drawings to the design of the vaults and the working out of all types on decoration and aesthetics. The geometrical approach and construction techniques adopted by the master have been identified; therefore, they can be applied in future restoration projects.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Structure in Villa dall'Ava: Rational order versus conceptual order

L. Burriel-Bielza
École Nationale Supérieure d'Architecture de Paris-Belleville, Paris, France

ABSTRACT: Regarding his approach to structural design, Rem Koolhaas pointed out the necessary intervention of the architect as a "thinker" through a critical dialogue with other disciplines converging on the project. Based on original documents drawn from his Office for Metropolitan Architecture's archives, this paper explores Villa dall'Ava (Saint-Cloud, France, 1984–1991) as a means to address two issues. The first is the difference between rational and conceptual order, where structure operates according to spatial and perceptive conditions. The second encompasses research methodology and tools, where 3D modeling and drawing will be used to re-enact building processes and reveal hidden relations and logics that will help us understand the real value of the final version.

1 INTRODUCTION

Architecture is a collective practice involving an increasing variety of disciplines, all gathered around a specific proposal, regardless of its scale and size. Social, economic, political, and technical conditions must be coordinated and integrated to assure spatial coherence and unity. To play a crucial role during the design and building process, architects should be trained to have a broad base of general knowledge. The current classical division between engineering and architecture gives rise to different tools and approaches. On the matter of structure, a minimum of performance requirements needs to be achieved: safety, serviceability, and restorability. If conceived from a utilitarian standpoint – that is, an approach strictly driven by optimizing material to withstand forces and loads – structure cannot make a significant spatial contribution.

Very often, the structural solution chosen delves into preconceived structural systems which are applied as "recipes", without reflection on their coherence with or relevance to architectural goals, criteria, challenges, and ambitions. Early exchanges between both disciplines during the design stage would allow structure to be fully exploited to meet, convey, reinforce – even define and further stretch – spatial requirements to transform structure into a creative tool. This approach would have further implications for a project. As Rem Koolhaas points out in a 1991 interview published in *El Croquis* 53, it can be extended to the whole concept of services, currently beyond the control of the architect: "We do not speculate about it: it is like accepting that between 30 or 40% of the building is simply not your domain and you have to swallow the ridiculous garbage that mechanical engineers install there" (Koolhaas 1993: 21).

In parallel, this paper also aims to open a debate on research methodology. To make a crucial contribution to architecture, a project must lay at the intersection of three distinct activities – practicing, researching, and teaching – developed by professionals that have undergone different kinds of training. They are deployed at different moments, but they orbit around the same building. From the very beginning, I have committed myself to actively participating in all three. This position strives to take advantage of the synergies that can be established between these three activities, by cross-fertilizing and transferring approaches, logic, or tools from one to the other. While most of the time words are the only means for understanding, reflecting, and communicating, a drawing can become a powerful tool to achieve the same goals – and certainly to reveal and address new challenges. Through his research on Giuseppe Terragni, Peter Eisenman already laid open this path, which I would like to explore further. Can a design tool operate as an analytical tool? Before we begin, we shall agree that this kind of "research drawing" cannot be codified or crafted in the same way as a design drawing because its main purpose is different.

The transition into our current digital world should be integrated as a critical interrogation. Even though computers have heavily impacted our discipline, they have not been integrated into research. How can digital drawing software be actively applied? We should hijack those tools and logics to perform a new function: to unravel the different layers and meanings embedded within a real building. For that purpose, the case study we will be focusing on has been reconstructed as a 3D model. Based on execution plans and construction details from the archives of the Office for Metropolitan Architecture (OMA) and complemented with onsite visits, a virtual model fully re-enacts the act of building from its foundations through to its completion,

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including finishes, determined with full accuracy. In parallel, the pictures taken during the building stage by Rem Koolhaas's close friend and photographer Hans Werleman provide full insight into the hidden logics of the structure. This 1:1 reconstruction is a piece of research in its own right, but the real power of the virtual model lies its capacity to raise, explore, and respond to new questions.

2 VILLA DALL'AVA AS A CASE STUDY

In Koolhaas's opinion, the Netherlands Dance Theater (structure by Polonyi & Finck 1981–1987) was the first project in which engineering became a major tool. But Koolhaas would choose Villa dall'Ava to demonstrate his posture at one of the most important conferences held in 1986 at the University of Illinois, Chicago (Tigerman 1987). Like other architects, Rem Koolhaas positions himself in relation to the Modern Movement. The house, still on paper, strived to prove that modern architecture is a hedonistic movement. His critical and provocative approach operates within the Villa as a radical appropriation of these references. When analyzing the project timeline, one becomes aware of the gap between the building permit granted in July 1985 and the start of the building process four years later. As pointed out by Koolhaas, this hiatus provided critical distance: "The long wait was bad in some ways, but good in allowing endless revision: it began as a beginner's house: strident, colorful, etc.; it became a record of our own growing up" (Koolhaas 1995: 135).

Rather than focusing on the design process, the built version will help us to fully understand the architect's approach to structure. At the beginning of the 1980s, OMA worked with several local engineering firms. In 1985, the Morgan Bank project was OMA's first collaboration with Ove Arup. In the case of the Villa, given the working conditions linked to a precise cultural and technical context, a local office was selected; however, this turned out to have its challenges. Marc Mimram was put in charge. Trained as both engineer and architect, well known for his collaborations with leading French architects such as Yves Lyon and Paul Chemetov, Mimram founded his own practice in 1981. On 11 June 2019, I interviewed him in his Paris office. He remembers this partnership as a true adventure filled with passion. He insightfully summed up Rem Koolhaas's attitude in a few words: "The structural question does not interest him too much. On the other hand, structure by itself does interest him a lot".

3 ON STRUCTURAL ORDER

Figure 1 brings together three sketches made on one sheet during our exchange, addressing the difference between "rational" and "conceptual" order. At the bottom, Mimram traced a squared plan. Applying an approach strictly related to homogeneous load distribution would give us a repetitive pattern of pillars embedded within a regularly spaced grid. However, following Rem Koolhaas's conceptual approach, those structural elements also needed to comply with spatial constraints resulting from a deeper reading of architectural conditions. They had to deal with the "instability" caused when other parameters are added. This network of conceptual forces controls matter. Concrete and steel, unevenly distributed in selectively placed nodes, define each structural element. This gives rise to the second square plan and, in turn, this same principle is applied to the house. Structure is now integrated in a force-field which articulates all the different elements of the project. It is therefore subject to a new form of equilibrium or balance.

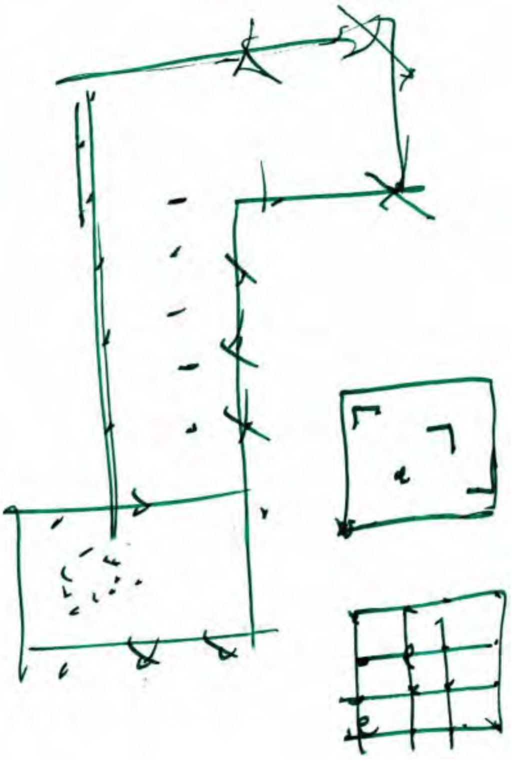

Figure 1. Sketch by Marc Mimram. Paris, 11 June 2019.

One of the copies of the building permit from OMA's archives comes with several A4 photocopies filled with references. The plans of Le Corbusier's Domino system feature, seemingly carrying a subliminal message. Nevertheless, the status of this standardized and repetitive linear framework relies on a completely different condition regarding the role that structure will have at Villa dall'Ava. Hovering over the semi-underground retaining walls that form the socle, each floor of the house (garden or living spaces) fully exploits the capacity of two different types of vertical supporting elements – linear for the garden level or surfaces for the living level – which are depicted in Figure 2. If Le Corbusier's early proposal strives to free the plan from structural constraints, in the Villa each structural device is intimately linked to a certain spatial

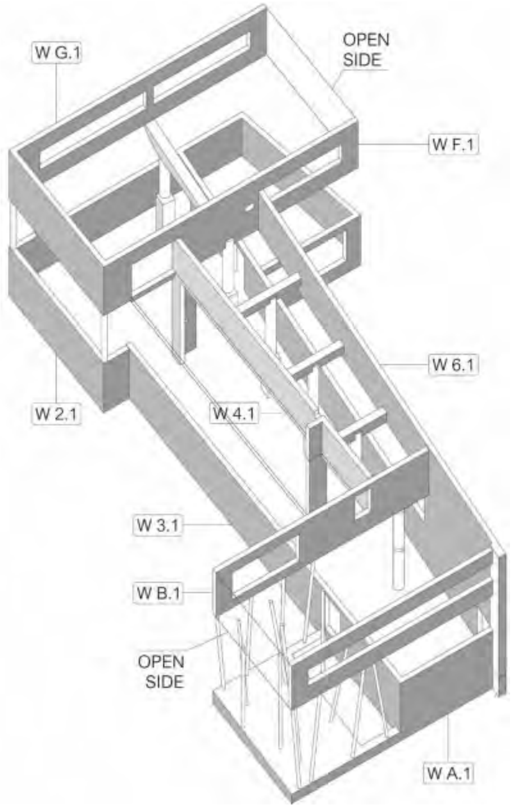

Figure 2. Vertical structural elements (Drawing by the author).

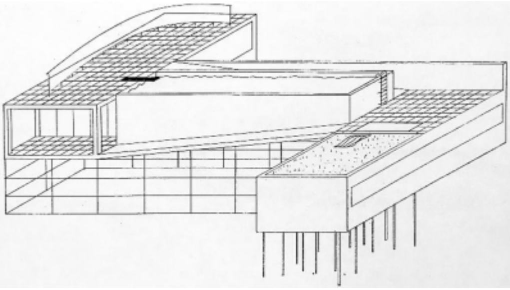

Figure 3. Axonometric view of the second version (OMA).

condition: these mutually define each other following what we call a “conceptual” order.

4 ARTICULATING STRUCTURE AND SPACE

From the very first design stages, the domestic realm was organized into two worlds. Anchored to the ground, the garden level opens into the landscape, greeting guests: a free plan in continuity with the suburban scale typical of Saint-Cloud. Columns and pilotis arise from the foundations like nodal points on this “plateau”. Koolhaas seeks to determine the identity of each mechanism so that it clearly stands out from the others, fulfilling several roles at the same time, forming part of a shared conversation. These devices inhabit the space enclosed by the glass envelope, articulating domestic rituals – whether static or in motion – around clusters, accompanied by other elements such as trees, stairs, or built-in furniture.

Floating in the air, the apartment level opens onto the skyscape, addressing an urban scale conditioned by the Eiffel tower. It contains the most private part of the program: the swimming pool, a space for reflection. Here, the vertical structural system relies on bearing walls. Regardless of their presence, they do not always act as spanning devices, introducing important distortions which Rem Koolhaas will use to his advantage. Of course, these walls are not just his choice. They follow French local construction techniques, where concrete is extensively used as a surface instead of a framework filled up with brick. These walls can be considered diaphragms. No other structural element is to be found inside the apartments. Not only do these walls define the limits of the volumes: they also articulate the inner world of the house with its context through specific bays, textiles in motion and surface finishes.

The pool is a crucial element, but when you stand before the house you cannot discern it; from the inside, no clear signs are offered to reveal its presence to guests. Yet it features in the first draft of the program attached to a letter sent on 26 May 1984. As stated during the Paris interview of 4 June 2019, its position on the roof is the outcome of two conditions stipulated by M. Boudet, who commissioned the work. One: swimming should be an intimate moment, detached from family life. Two: respect the free available surface of the garden as far as is possible. In the early stages, as seen in Figure 3, the sloped underside gave character to the house and cheerfully rested on the daughter’s room’s terrace. Little by little, this dialogue will vanish, the pool remaining unidentifiable from any point. In the end, the visual expression of any form of articulation between the garden and the living spaces will be highly limited and nuanced. This vertical transition applies to two kinds of flows stretching up from soil to roof: fluids and loads.

5 ARTICULATING FLUIDS

The living level needs to be reached by its inhabitants, but it also requires to be “supplied” and “evacuated”: clean and wastewater, rain, electric power, air extraction and heating travel from one floor to the other. At the garden level, L-shaped concrete pillars C7/8 are part of the cross-bracing structural system, but, as seen in Figure 4, they also work as service ducts, integrating pipes which are then horizontally distributed through the complex underside of the first-floor slab. A chimney shaft was planned for this space. However, it is important to notice how both L-shaped pillars are differently treated. The one between the reading space and the living room is completed with an inverted L in

Figure 4. L-shaped pillar during construction (Hans Werleman).

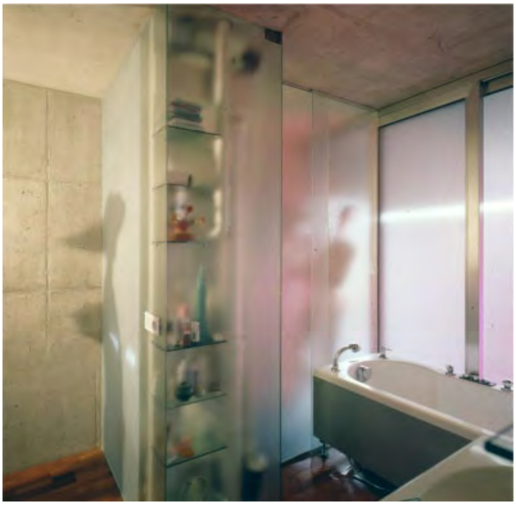

Figure 5. Technical core in main bathroom (Hans Werleman).

concrete finished stucco that resembles an enormous column. The second one, between the kitchen and the dining room, is completed with a layer of white plaster the thickness of a sheet of paper.

In these two worlds, installations are treated differently on each level. On the ground floor, they fully disappear, integrated in the two concrete cores and the forest of pilotis. On the upper floor (Figure 5) they are fully present, exposing its inner complexity. Like the underground networks depicted in Madelon Vriesendorp's drawings for *Delirious New York*, the pipes, ducts, and wiring are displayed in the center of the main bathroom, with bottles, brushes, and towels, articulating the daily rituals. On the southern terrace, a hint of the machinery of the swimming pool and ventilation system is perceived through the frosted glass panels enclosing the vertical shaft.

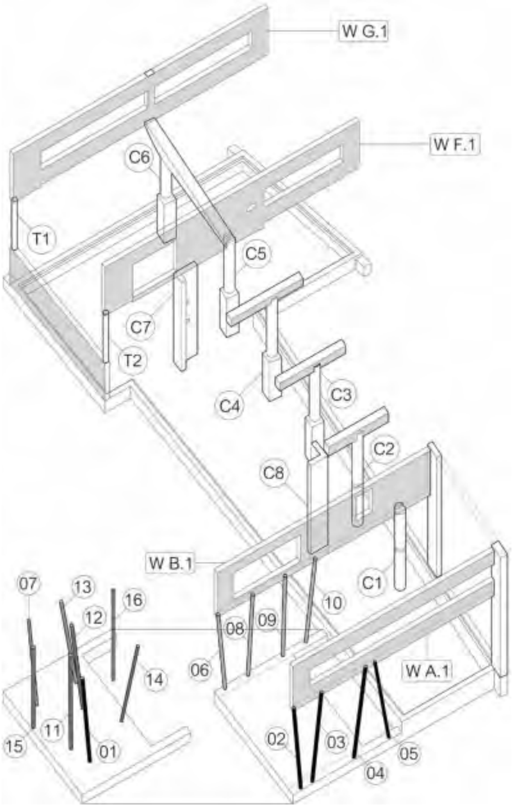

Figure 6. Pillars, pilotis and columns (Drawing by the author).

6 ARTICULATING LOADS

Figure 6: an array of heterogeneous structural components transfer the gravity loads of the swimming pool, the rooms and the forces generated by its cantilevered overhang to its foundations, settled on individual 80 x 80 cm concrete footings, stiffened by retaining walls. There are four types: the 16 slender round Ø12 cm steel pilotis (01/16), the two L-shaped cross-bracing concrete pillars (C7/C8), the six fat Ø40 cm concrete columns (C1/C6) and the two slender Ø20 cm concrete supports (T1/T2) acting as tie bars, counterbalancing the parent's apartment overhang. The false ceiling placed at 2.80 m hides any articulation between bearing walls/slabs to these pillars. Figure 7 shows the interaction of these elements.

As seen in Figure 6, column C1 supports wall beam B1, the daughter's room's west façade. The load transfer from the swimming pool to the round columns C2 to C4 is not as direct as the false ceiling leads one to believe. Those three are topped with perpendicular 40 x 45 cm beams. They support not only the sloping slab and the volume of water, but also wall beams 4.1 / 6.1 defining its sides (Figure 2), from which the southern footbridge-terrace springs out as an overhang. L-shaped pillars C7/C8 take part of the load, but they are mostly working as cross-bracing elements.

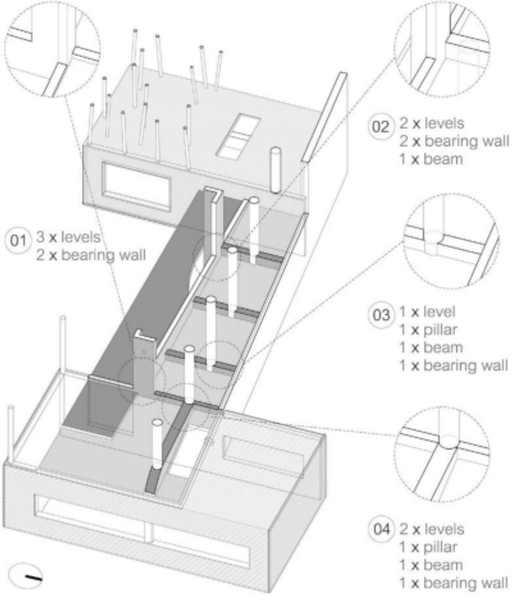

Figure 7. Underside of first floor slab (Drawing by the author).

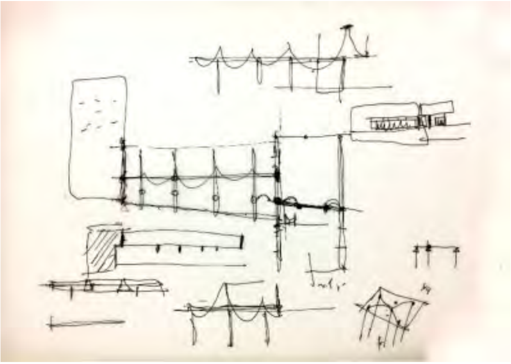

Figure 8. Marc Mimram's manual calculations, 1985 (OMA).

The height of the side pool wall beams 4.1 / 6.1 has not been dimensioned because of the span between axes B and F, but because of hydrostatic pressure, pushing outwards. As we already saw in Figure 7, transitions between structural elements are much more articulated than expected.

Figure 8 shows Marc Mimram's sketches made in 1985, which demonstrate that, in the case of those two wall beams, no bending moment is being transferred to the living spaces' structural façades. They are simply supported on both ends. But the situation is different when we look to the central bay with columns from C2 to C6. Column C5 supports wall beam F1, one façade of the parents' room. However, it also helps to deal with the bending moment induced by the variable cross section beam cantilevering from column C6 seen in Figures 4, 9. The parents' room has a double overhang. The short end of the box cantilevers towards the existing trees, thanks to wall beams F1 and G1, but column C6 has been displaced 1.30 m away from the latter (in fact, west façade). The curved profile of the beam responds to the moment diagram seen in the upper side of the drawing.

Figure 9. Cantilevered beam in construction (Hans Werleman).

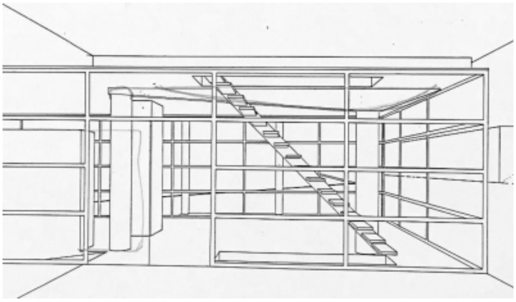

Figure 10. North elevation sketch with beam (OMA).

This beam has been dimensioned in view of optimizing its proportions as much as possible regarding load transfer and bending moment. One could have made it straight, but then it would lose the effect that Koolhaas is looking for, which also explains the final height of the false ceiling. By placing it at that point, we have the feeling that the curved beam never touches column C5. In fact, Figure 10, drawn during the design process, shows a pencil mark attempting to modify the profile so that the beam would appear completely detached from column C5, while the wooden wall stretches further to the right to integrate it. In this way, C6 stands on its own, balancing a beam shaped like a cup, not touching either the façade or the precedent support as seen in Figure 11.

Figure 11. Columns C6/C5 from living room (Hans Werleman).

Figure 12. Site plan from building permit. Ground floor (OMA)

7 A FOREST OF PILOTIS

As we learn in Figure 12, the plot acquired by Mr. and Mme. Boudet was a fragment of a larger sloping site between two streets. Above the site were an existing house, pool and a tennis court. As we read in the building permit, Rem Koolhaas divided the plot into three west-east oriented strips: "the first section, defined as a garden, is inscribed on the continuity of the strip of the upper plot and extends to the pre-existing pedestrian entrance. The desire to preserve an unbuilt strip at the back of the plot allows to identify the concept of 'hollow cross', which enhances new neighborhood relations. The second strip is formed by the longitudinal construction. The third strip, paved, allows access to the garage". This strip organization had already been tested for the Spear House in 1974, but it would be deployed on an urban scale in the competition for the Park of La Villette in 1982.

The longitudinal garden guides our view when entering the property, but no "entrance door" seems available. The pilotis supporting the daughter's bedroom appeared early in the design process, being considered as a spatial unit or open-air room. During my interview with him on 14 August 2019, Xaveer de Geyter explained: "The main argument for these columns is that they are the entrance door to the site. We wanted a kind of screen, a filter before entering the private space". Their number, angle and position will evolve throughout months, finally comprising 16 elements ranging from Ø114.3 to Ø168.3 mm. As seen in Figure 6, eight are aligned with walls A1 and B1, acting as main structural members arranged in pairs. N^{o}.16 is a pipe for rain and wastewater. The rest barely serve to support the 16-cm concrete slab.

When using thin metallic pillars, punching shear reinforcement is essential, but here there are exceptions. For those aligned with façades A/B, the concrete walls regulate load distribution. The rest bear so little weight that this problem can be overlooked. They might have acted as tie bars counteracting lateral loads, but the angle is not acute enough and these will be taken by the L-shaped pillars working along with columns C2 and C5. This freedom will allow Koolhaas to push forward the provocative use of elements borrowed from Le Corbusier. At some point (Figures 13, 14), he will even consider extending two of them, reaching up to hold up the table.

The original wall enclosing the site was respected, as was the flight of steps leading to the strip of garden. Even when the position of the pilotis had nearly been decided, the geometry of the pathway connecting that stair with the "front" door was yet to be set. As the architect points out, "one of the most difficult design issues was how to go from A to B. Straight? Random? Scientific?" (Koolhaas 1995: 182). During the process, a fourth version was drawn (Figure 15). A straight asphalt strip cuts at right angle with a stone "carpet" extending out from the main door. There is a clear collision between these two elements and the position of the pilotis. The final version responds to three criteria. First, it accommodates its geometry to structure, winding its way around the "trunks". Second, it increases the amount of time needed to arrive. And third, it does so by alternatively facing the garden and the door, rhythmically.

8 CONCLUSION: BLURRING THE TRANSFER

Koolhaas wanted the living level to look like a solid block hovering over the site. While the tilted pilotis contribute to achieving that feeling of instability, the presence of the ground floor structure needed to be

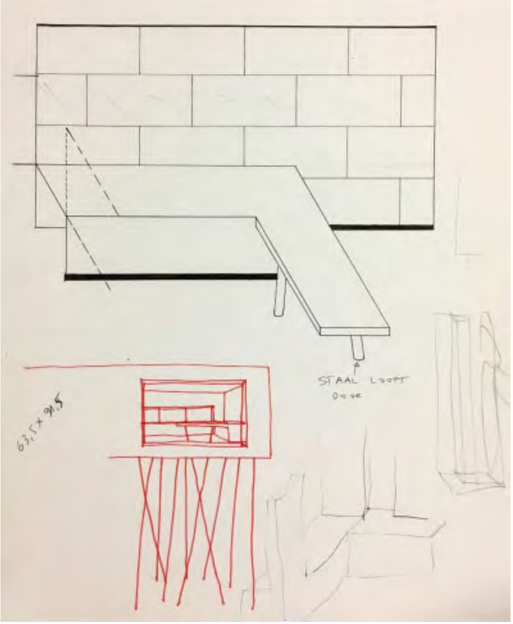

Figure 13. Sketch showing extended pilotis (OMA).

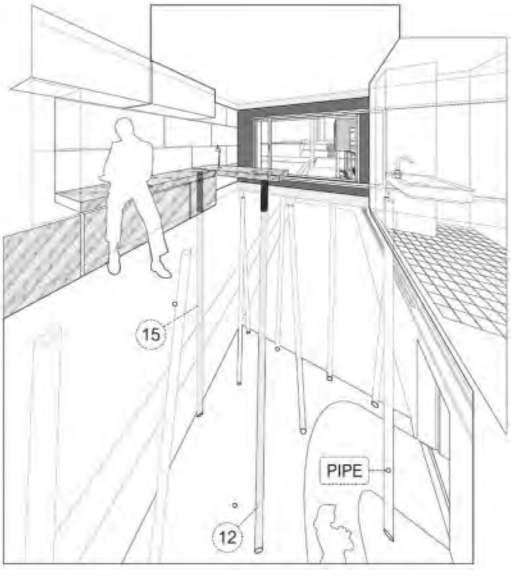

Figure 14. Transparent view inside the daughter's bedroom, showing pilotis and access (Drawing by the author).

counteracted. The columns were pushed inside, off centered, following the ramp and far from façades. Even though they were all Ø40 cm, the wooden wall running along the north façade provides some downscaling, allowing them to be perceived with various rhythms, scales, and proportions. Subject to different manipulations, the repetitive and uniform distribution of round pillars only visible during building process (Figure 16) was transformed into a series

Figure 15. Sketch showing pathway to main entrance (OMA).

Figure 16. On site work. Façade north (Hans Werleman).

of local episodes unfolding along with the domestic rituals scattered over the free plan. The mechanics of load transfer and the complexity of articulations between both levels are hidden behind the false ceiling. Masking this transition is crucial because it allows the architect to blur our understanding of the structural logic.

Actions and strategies in this process do not pretend to fully hide structural elements. Local solutions surgically modulate their presence or question their bearing capacity. The wooden wall atomizes columns, transforming them into smaller concrete fragments, creating a dialogue with domestic elements such as tables, armchairs, cupboards, or stringers. At some point (Figure 17), columns were deformed to deal with

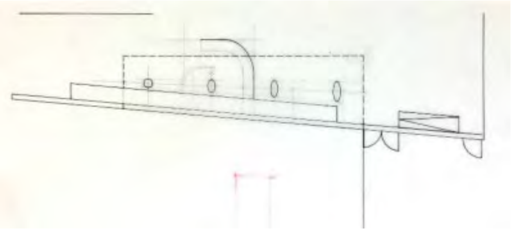

Figure 17. Ground floor level plan (OMA).

Figure 18. Villa dall'Ava / Villa Lemoine (OMA/Author).

perspective, thus recalling strategies developed by Le Corbusier in his Swiss pavilion. More surprisingly, some of the structural solutions finally abandoned in Villa dall'Ava would reappear in Villa Lemoine, designed between 1994 and 98 with engineer Cecil Balmond from Ove Arup & Partners, already a key player in OMA's production. For example, the fat "spider leg" jutting out under the west façade (Figure 18), or the tapered beam end (Figure 19) are both integrated later in this house.

In Villa dall'Ava, columns, pillars and pilotis resolve structural stability requirements. However, they have been positioned to interact with architectural elements. They both fulfil conditions related to movement, domestic rituals, or perception. Except for the forest of pilotis, the other columns appeared when spatial criteria were being identified. Structure joins in to mutually intensify, challenge, articulate and tune up such conditions, serving purposes other than "supporting". The solutions strive to blur any reading of a coherent structural system. Loads travel through concrete and steel, ultimately reaching foundations. But this logic is not revealed to the inhabitant, since components behaving in an identical way are not perceived within the same hierarchy and conversely, elements that would seemingly work together do not do so. Structural matter, concrete or steel, is unevenly distributed as this newly invented state of "conceptual" equilibrium.

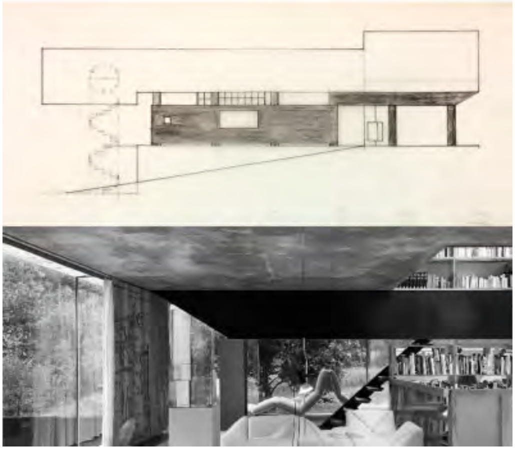

Figure 19. Villa dall'Ava / Villa Lemoine (OMA/Author).

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Open session: Political, social and economic aspects

History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The Manning specification

E. Shotton
University College Dublin, Dublin, Ireland

ABSTRACT: Robert Manning's reputation in the field of hydraulic engineering all but eclipses the impact he had on the design and construction of over 128 harbours as Chief Engineer (1874–91) at the Office of Public Works (OPW) Ireland. His skill in exploiting networks, evident in the development of the *Manning Formula* for estimating water flow, was equally manifest in his adaptation of concrete to marine works. Though pioneering work with concrete in harbours was underway as early as 1850, by the 1880s little coherence existed in practice. Manning's earliest concrete harbours, which drew on work by engineering colleagues as well as contractors, were no more or less precise. However, the passing of the *Sea Fisheries Act (Ireland)* in 1883 enabled the construction of a large number of harbours that Manning, in concert with colleagues and contractors, used to develop an adaptable specification governing cement grade, concrete mix and methods of construction.

1 INTRODUCTION

1.1 *Robert Manning as historical figure*

History remembers the Irish engineer Robert Manning (1816–97) as one of the fathers of modern hydraulic engineering, having developed a formula for computing waterflow in channels and pipes at the end of his career (Manning 1891, 1894), described simply as the *Manning Formula* (Dooge 1989, 1992; Powell 1960, 1968). There had been notable contributions that predated this work, including Manning's own early *Observations on the Flow of Water* published in 1866. The significance of his later formula, developed by comprehensively testing formulas against empirical data from his own work and data compiled by others, was its simplicity and accuracy (Bertrand-Krajewski 2006).

A self-trained engineer, Manning was first employed on drainage projects across Ireland (1846–55) with the Office of Public Works (OPW). He educated himself in the emerging science of hydrology through a methodical reading of published works in French, English and those translated from German to English (Bertrand-Krajewski 2006). This was followed by work as estate engineer on drainage, water supply, bridges, and harbours for the Marquis of Downshire in Ireland (1855–69). Included among this were schemes for the water supply of both Dublin and Belfast (Dooge 1989, 26–7), resulting in his earliest paper on water flow (1866). His final offerings on the subject, which became the *Manning Formula*, drew on the breadth of this experience and extensive reading, coupled with his considerable correspondence with academics and practitioners across Europe. This correspondence led to the formula's early adoption and it remains "the most popular formula in use throughout the world" (Dooge 1989, 50).

Manning's formidable reputation in the field of hydraulic engineering has all but eclipsed his equally remarkable work in maritime engineering. As Chief Engineer (1874–91) of the OPW he designed and built over 128 harbours where, drawing on the systematic methods he used to develop the *Manning Formula*, he skilfully introduced a system to govern the use of concrete in marine works.

Manning was by no means an early pioneer in concrete, despite his presidential address to the Institution of Civil Engineers (Ireland) where he claimed to be "one of the first engineers who used it in Ireland" in 1850 on the foundations of a bridge (Manning 1878, 77). The use of concrete in Ireland in the 1850s was exceptional, though not singular, nor as ambitious as other work underway at the time (Shotton 2018). There had been far more pioneering concrete marine works across Europe and in the English colonies from 1850 onward. However, by the time the UK Select Committee on Harbour Accommodation was formed in 1883, there existed little coherence in the practice, either in the cement content or form of construction (Anon. 1883, 1884), a situation that endured among the broader UK and Irish engineering community for the remainder of the decade (Barron et al. 1887; Coode et al. 1887). Manning's earliest harbour works in concrete in the mid-1870s were no more or less precise. However, with the passing of the *Sea Fisheries Act (Ireland)* (SFI) in 1883, the OPW, with Manning as Chief Engineer, had the opportunity to construct a significant number of harbours, which was used as a vehicle to develop the first coherent, type-set, standardized

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specification to govern the use of concrete in maritime works.

1.2 *The heterogeneous engineer*

Manning's successful development and implementation of a standardized yet malleable specification to govern concrete construction can only be understood within the extended context within which he was operating as well as his own work method. Regarding the latter, W.J. Doherty CE, when questioned at the 1884 Select Committee about a difference of opinion with Manning's testimony, stated that "…anything Mr. Manning reports upon is decided after mature deliberation, and perhaps he has deliberated upon it more than I have …" (Anon. 1884, 200). As with the development of the *Manning Formula*, this mature deliberation reflected an approach that drew on all available evidence to inform a decision – whether from professional colleagues, contractors, published sources, or empirical evidence from Ireland or abroad – moderated by issues of governance and legislation, representing an extended field of disparate elements. In his work method, Manning could be described as a system builder, drawing in various actors and heterogeneous elements to be shaped into a stable network to create a new technological form – the standardized specification (Law 2012, 107). In this role Manning exemplifies the *heterogeneous engineer* described by the actor-network theory (Murdoch 2001, 118).

In marine engineering these actors and networks range from the social (owners, engineers, contractors, workmen, government bodies, regulations), to the physical (the properties of materials, gravity, force, the size and draught of ships) and extend to include natural systems (winds, tides, currents). This complexity, and the influence of natural systems, is aptly illustrated in Law's analysis of the early Portuguese global expansion (2012), understood as a successful network of developments which coalesced to enable it. The development of the Portuguese Caravel, described by Law as "a family of methods for associating and channelling other entities and forces, both human and nonhuman" (2012, 109), when coupled to the introduction of the magnetic compass and the development of the volta, a new navigational technique, created "a network of heterogeneous but mutually sustaining elements" that enabled the expansion (Law 2012, 115).

The relative success of Manning's work on codifying and structuring a set of clauses to better control concrete construction depended on a similarly diverse set of factors aligning simultaneously. Most obvious were the standardization of Portland cement and the evolving experience regarding cement content and construction methods. Though Manning fixed the criteria for Portland cement, cement content and construction methods, both continued to evolve, influenced by contractors, experience in the field, and the spatial conditions of the works – the natural entities of wind, tide and current. The specification became a form of *fluid object,* in that its constituent elements, the clauses, could be adapted to different situations (de Laet & Mol 2000, 226; Law 2002, 100–2).

There were also changes to the systems of organisation and governance of harbour construction in Ireland, brought on by the passing of the SFI Act, that enabled this new approach in the OPW. Even before this Act the use of concrete had led to a greater use of specialized contractors with foreign or domestic experience of concrete use. But the SFI Act, which provided Irish funds for harbour construction, liberated the OPW from previous oversight by the UK Treasury (Wilkins 2017, 199) and resulted in the need to build a significant number of harbours in a very short time, leading to the greater use of external contractors that may itself have provoked the need for a more systematic means of governing the works.

2 THE EXTENDED NETWORK

2.1 *The OPW, the commissioners of fisheries & the UK treasury*

Legislation and the multiple organizations with oversight of marine infrastructure in Ireland, themselves products of diverse influences and actors, established the context which led to the development of a standardized concrete specification. As Law argues, actors are never a single person, but rather "an actor is a patterned network of heterogeneous relations, or an effect produced by such a network" (2002, 384). The opportunity Manning seized to develop such a specification is better understood as a context that enabled or even demanded the need for such a tool, best illustrated by the historical legislative and organizational context.

Before the 19th century, aside from the major ports, Irish harbours were built by landlords (private or monastic) principally for trade, or by local communities to shelter fishing boats. Though the Irish Parliament made occasional harbour grants to support Irish trade (Ireland 1778, 495), they played little role in local harbour development. This changed dramatically in 1819 with the establishment of the Commission for Irish Fisheries and the concurrent onset of Ireland's first famine, or distress, in 1822 (Wilkins 2017, 11). Though initially tasked with promoting fisheries through the fitting out of boats (Wilkins 2017, 19), with the onset of the distress in 1822 their focus shifted to the building of fishing piers. This was intended to address the dearth of such facilities, but more explicitly was "a means for providing work to the distressed poor" (Wilkins 2017, 12). An ill-fated funding structure requiring government funds to be matched by local contributions led to undue influence by estate owners, the primary contributors, who pressed for preferred locales regardless of merit (Wilkins 2017, 21). Though the burden of local contributions was later reduced to one-quarter this did little to relieve the problem. Despite responsibility for fishery piers being passed to the new Irish Board of Public Works in 1831 (Wilkins 2017, 60–1), known also as the Board of Works or the Office of Public Works (OPW), the provision of

Table 1. Proportion of Works undertaken in-house (OPW) versus External Contractors 1849–1891*

	OPW			Contractors		
Years	No.	Mean Value (£)	%	No.	Mean Value(£)	%
1849-69	45	2,432 %	76	15 %	2,864	25
1870-75	7	2,947 %	70	3 %	2,034	30
1876-80	3	5,042 %	33	6 %	3,078	67
1881-85	18	1,446 %	45	22 %	2,474	55
1886-91**	20	1,257 %	32	43 %	5,403	68

* Completion dates (Ireland 1885; Royal 1888)

**3 unaccounted works 1886–91 are attributed to the OPW. If attributed to contractors their percentage would be 73%.

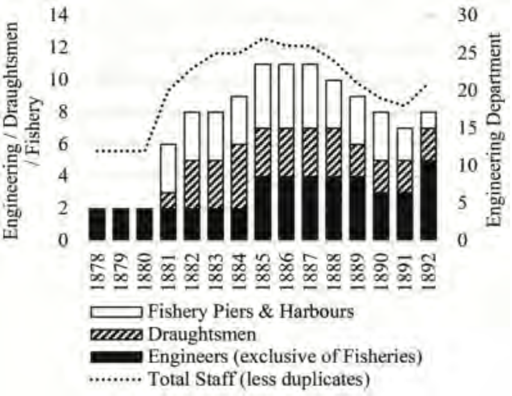


Figure 1. Increase in OPW staffing 1878–92 (Thom's 1878–92).

employment and demand for local contributions continued to influence harbour development in Ireland for another 50 years.

With a restricted mandate of only completing earlier projects or maintenance, the OPW added little to what had been accomplished by 1835. A total of 64 harbours or piers were built (Ireland 1886), using day labour supervised by government engineers, at which point funds were extinguished (Doherty 1884, 17). A second distress sponsored a new Act in 1846, providing £50,000 for piers to the OPW (Doherty 1884, 17). It also introduced a new actor, the UK Treasury, who had authority for project approvals and to limit project sizes. As a result, projects tended to be small and while a handful of works were awarded externally, day labour with Board supervision was a relative constant until the mid-1870s, with 75% of harbour works built using day labour from 1849 to 1875 (Table 1).

Of the modest number of externally supervised works, contractors worked locally, with only one contractor ever awarded two commissions, in the adjacent counties of Galway and Clare (Ireland 1885, 66, 68). However, a number of local and global events sponsored a dramatic shift to the use of external contractors after 1875, rising to nearly 60% of the works built, all mediated by the appointment of Robert Manning as Chief Engineer in 1874.

2.2 *A renewed OPW*

The *Fisheries Act (Ireland)* of 1869, which removed the Fishery Inspectors from the OPW (Wilkins 2017, 126), had little apparent impact on the use of contractors 1870–5 (Table 1). It did, however, create a more cumbersome approval process between the new Inspectors, the OPW, and the UK Treasury, the latter still controlling the scale of funding and approval of projects (Wilkins 2017, 130). Wilkins argues that the appointments made soon after, of Samuel U. Roberts as Assistant Commissioner (1873) and Robert Manning as Chief Engineer (1874), brought a professionalism to the Board that had been wanting (2017, 128), perhaps influenced by their previous work together on OPW drainage projects. Manning's appointment certainly had a measurable impact on the governance of the department and interface with the UK Treasury, but most clearly in the adoption of concrete.

By the mid-1870s the UK Treasury had diverted all funding for 1876–80 to two large harbours, Arklow and Ardglass (Ireland 1876, 22). Though the number of projects in the latter half of the decade remained essentially static, the design of two large harbours coupled with initial Board supervision at Ardglass may have stretched the two engineers on staff, Manning and his assistant, too far (Figure 1). As a result, Manning tendered much of the smaller work to contractors, freeing the Board to oversee the largest works up to 1880 (Table 1).

A delay on starting Arklow released funds at the close of the decade, formalized in the next year in response to another distress as the *Relief of Distress Act (1880)*. Beyond the £45,000 granted under the Act, the distress attracted other donations to the fisheries, including £20,000 from the Canadian Government (Wilkins 2017, 151). This resulted in a fourfold increase in projects compounded by strict start dates mandated by the Canadian Fund Committee that impacted all the projects as the funds were primarily used to offset the local contribution still demanded under the Acts (Wilkins 2017, 154). Though there had always been dedicated teams for drainage and navigation projects, and the Royal Harbours, in Manning's department, engineering expertise was limited, and the department was overwhelmed. In response Manning created a new Fishery Piers & Harbours division to oversee work in three districts, as well as hiring temporary draughtsmen (Figure 1). Even with Fishery Piers & Harbours staff overseeing works, the new works (complete by 1885) were beyond their capacity. As a result, the OPW tendered 55% of the works to contractors with an average value of £2,474, 71% higher than Board-supervised works (Table 1).

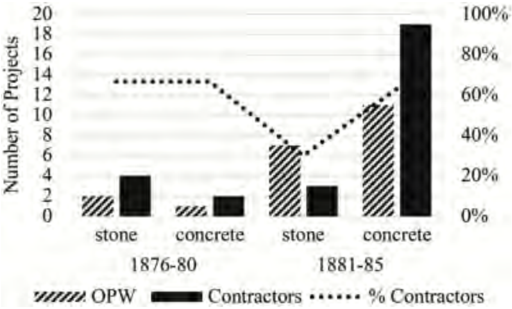


Figure 2. Increase in the use of external contractors relative to material (completion dates) (Ireland 1885; Royal 1888).

2.3 *The introduction of concrete*

Introduction of concrete in OPW marine works, starting in 1874 (Ireland 1879, 53), also played a role in the increased use of contractors. Though Manning had declared in his presidential address of 1878 that he had used concrete exclusively in marine works for the past nine years, this was somewhat disingenuous. Only a handful of OPW works were constructed in concrete by the end of the 1870s, with the greater proportion in stone (Figure. 2). Nor did the increase in work after 1880 displace stone construction, though these were more often Board-supervised, with an increased use of contractors on projects involving concrete.

Specialist expertise in concrete offered by contractors likely played a role in this decision. Evidence suggests that Manning was converted to concrete by virtue of its promise as an inexpensive alternative to dressed stone through the agency of contractors. In the year following his address, Manning reported that Giles Quay, begun in 1874, was the first OPW pier built of concrete (Ireland 1879, 53). The original 1872 proposal and specification by his predecessor William Forsyth (1798–1888), a stone construction, substantially exceeded the available funds when tendered in 1873 (Ireland 1879, 53). The resolution to this impasse was a proposal from a contractor, Martin Farrell, to reduce the cost by half by building in concrete. Though Farrell's proposal was rejected in 1873, on later examining the site Manning recommended to the Board, in his new role as Chief Engineer, to erect the structure designed by Forsyth in concrete (Ireland 1879, 53).

Farrell's 1873 proposal in tandem with Manning's appointment as Chief Engineer in 1874 was a watershed for the future trajectory of OPW marine works. The vast majority of OPW harbour works begun after 1874 until the end of Manning's tenure as Chief Engineer in 1891 were concrete (84%) (Ireland 1885; Royal 1888). Farrell's arrival at this moment was both fortuitous and a harbinger, where the background of the external contractors played an increasingly important role in the work of the OPW. Farrell was son of James Barry Farrell (1810–93), whose practice he joined in 1859 (Anon. n.d.). Both trained as engineers, via apprenticeship, but also worked as contractors. Their professional connections included two of the foremost UK engineers working in concrete, Sir John Coode, CE (1816–92), on Wexford harbour (Anon. n.d.) and A.M. Rendel, CE (1828–1918) on Rosslare harbour (Stevenson 1885, 295). These associations were not unique to the Farrells, but rather illustrate a professional network, across countries, projects, and engineering practices, responsible for the dissemination of knowledge on concrete in marine works, which had a profound impact on works by the OPW following the passing of the SFI Act in 1883.

2.4 *The Sea Fisheries Act*

Whereas earlier works were almost exclusively undertaken as relief works, the SFI Act introduced a new approach to the construction of fishery piers and harbours in Ireland. This Act, granting the OPW £250,000 from funds of the Disestablished Church (Doherty 1885, 5), was the first that targeted the building of piers to facilitate fishing, rather than providing work to the distressed poor. This released the OPW from the mandate to hire as much local labour as possible, paving the way for a greater use of contractors.

Also influential were the specifics of the Act's provisions. With no absolute requirement for local contributions the historical bias in site selection was removed, leaving this task to the new Fishery Piers and Harbours Commission. The OPW would then provide designs and cost estimates, with the first tranche of 23 projects under contract by the end of 1884 (Wilkins 2017, 192). Nor was there a cap on the size of projects, but rather a cap on annual expenditure of £50,000, giving the fund a five-year life span (Wilkins 2017, 191). This narrow window brought additional pressure to bear on Manning and his team, resulting in the hiring of two temporary engineers (Figure 1). While this enabled the design of works to proceed at an increased volume, the oversight of so many projects simultaneously demanded the use of external contractors, increasing their role to 68% of works completed after 1885, the average value of which was nearly five times the Board-supervised works (Table 1). The dramatic shift from the Board-supervised day labour to the use of contractors is evident when works from 1849 to 85 are compared to the work completed after 1885, primarily funded by the SFI, illustrating a near complete reversal in the pattern (Figure 3).

3 THE MANNING SPECIFICATION

3.1 *Developing the specification*

Sixty-one of the 63 harbours completed 1886–91 were SFI-funded, with the remainder funded from previous Acts (Ireland 1885, 53; Royal 1888, 708). The specification developed by Manning (Figure 4) appears to have been intended for SFI projects from its title "Fishery Piers and Harbours", a reference to the temporary Commission established. However, it was first used on Carnsore, one of two harbours not funded by SFI.

Research to date has not located the origins of the form. There is indirect evidence that it may have

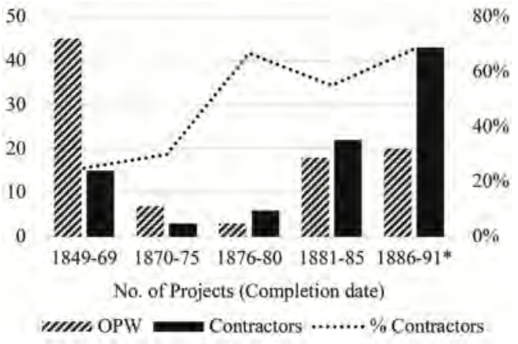
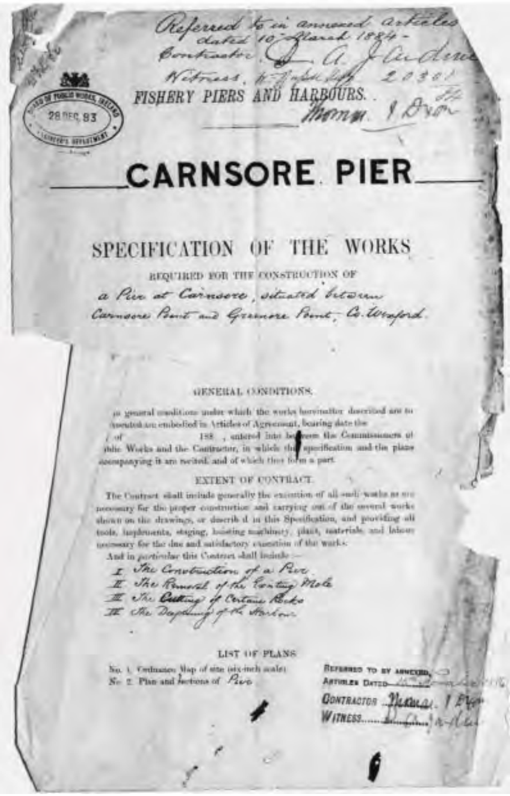


Figure 3. Proportion of works completed by external contractors versus the OPW (Ireland 1885; Royal 1888).

been developed as early as January 1883, based on an order of single-sided forms from the Board's printers, a departure from their typical use of double-sided forms but consistent with the layout of the specification (Shotton 2018). The use of single-sided sheets in the specification facilitated deleting or adding sheets as demanded by the specifics of each project, including the insertion of hand-written notes and amendments. However, though the SFI Act had been introduced as a Bill in February 1883, the Fishery Piers and Harbours Commission referenced on the form was only established when the Act was passed in August (Wilkins 2017, 192). Manning may nevertheless have been working on such a document, prior to the enactment of the SFI, as it was used in December 1883 on Carnsore, in advance of the design and specification of the first SFI projects submitted for approval in spring 1884 (Wilkins 2017, 192). The specifications still extant (26 of 61) all relate to works undertaken by contractors, suggestive that the specification was developed for externally awarded contracts (Table 2).

In Manning's 1878 presidential address he described the profession as having been neglectful in not having made more use of "so admirable a material Portland cement", signalling an ambition to use concrete more comprehensively in OPW works. The enactment of the SFI, unfettered by previous limitations on project size and the use of local labour created the ideal context in which Manning could embrace this relatively new material. The development of a standardized specification that governed, among other things, the properties of Portland cement, the cement ratios, and the methods of construction, be it cast-in-situ or prefabricated blocks, was evidence of Manning's thoroughness and mature deliberation, as earlier cited. As there were but two engineers working in the department in 1883, Manning and his assistant C.F. Green CE, who had no background in concrete, Manning likely drew on the experience of Bindon Blood Stoney, whose works at Dublin Port (Stoney 1874) he referred to in his address. It is noteworthy that the construction methods outlined for Carnsore, the first project to use the specifications, had strong parallels to Stoney's work, using precast concrete blocks below low water that incorporated large stone displacers or boulders with cement packed between them, mirroring the work underway at the port.



Referred to in annexed articles
dated 10 March 1884 -
Contractor
Witness,
20301

FISHERY PIERS AND HARBOURS.

28 DEC 83

CARNSORE PIER

SPECIFICATION OF THE WORKS

REQUIRED FOR THE CONSTRUCTION OF

a Pier at Carnsore, situated between
Carnsore Point and Greenore Point, Co. Wexford.

GENERAL CONDITIONS.

EXTENT OF CONTRACT.

The Contract shall include generally the execution of all such works as are necessary for the proper construction and carrying out of the several works shown on the drawings, or described in this Specification, and providing all tools, implements, staging, hoisting machinery, plant, materials and labour necessary for the due and satisfactory execution of the works.

And in particular this Contract shall include:—

I The Construction of a Pier
II The Removal of the Existing Mole
III The Cutting of Certain Rocks
IV The Deepening of the Harbour

LIST OF PLANS.

No. 1. Ordnance Map of site (six-inch scale)
No. 2. Plan and Sections of Pier

REFERRED TO BY ANNEXED
ARTICLES DATED
CONTRACTOR
WITNESS

Figure 4. Carnsore Pier, Specification of the Works (OPW 8/61, with permission of the Director, National Archives of Ireland).

Displacers would eventually fall out of use in later incarnations in the next five years, reflecting an increased confidence in concrete. In this sense the specification would best be described as a fluid object: "an enacted practice" with a "a core of stable network relations" (Law 2002, 100–2). Law uses the term fluid objects to explain how technological objects can morph relative to spatial conditions, but in a manner that does not cause a rupture in the technology: possibly because the fluid object does not privilege a particular structure of relations or a particular boundary but rather allows for incremental reconfiguration (2002, 99–100). By structuring the specification as a set of interchangeable single-sided sheets, with various elements like cement ratios left blank, Manning engineered a tool that was responsive to spatially varied projects, influenced by contractors and the natural forces placed on the structure.

3.2 *The specification in use*

On the initial use of the specification at Carnsore and at least one subsequent project (Cheekpoint), a cement

Table 2. Geographic distribution of works and number of specifications extant.

Counties	Total Works 1875–1891	Funded under SFI	Specification Extant
Antrim	1	1	1
Clare	9	4	3
Cork	14	7	6
Donegal	17	7	1
Down	5	3	2
Dublin	1	1	-
Galway	23	13	1
Kerry	6	4	2
Limerick	2	1	-
Londonderry	1	1	1
Louth	4	2	-
Mayo	15	7	3
Sligo	5	4	2
Waterford	6	4	3
Wexford	2	1	1*
Wicklow	2	1	1
Total	113	61	26

(Office 1708–1922) * Carnsore in Wexford was only work that used the specification but was not funded by SFI

Table 3. Variation in cement proportion relative to date of contract and exposure.

Contract (M/Y)	Harbour	Cement kg/m3	Exposure* (STC = strong tides / currents)
03/1884	Carnsore	166	Exposed STC (I)
06/1884	Cheekpoint	166	Sheltered STC(R)
08/1884	Knockadoon	166	Exposed (I)
10/1884	Aughris	166 / 266	Sheltered STC (A)
06/1885	Baltimore	266 / 332	Exposed (B)
07/1885	Greystones	199	Sheltered (I)
08/1885	Anascaul	199	Sheltered (R)
03/1886	Brandon	199	Sheltered (A, B)
05/1886	Castletown Bere	199 / 266	Sheltered (B)
06/1886	Ballywillan	199 / 266	Sheltered STC(A)
07/1886	Ballyhalbert	199 / 266	Exposed STC (I)
10/1886	Passage East	199	Sheltered STC (R)

(Office 1708–1922) *https://eoceanic.com/ and where: I=Irish Sea; R=River; B=Bay; A=Atlantic

content of 280lbs/y^3, equivalent to 166kg/m^3, was typeset into the specification (Board 1883; 1884a). While low by current standards for marine works (360kg/m^3 in Ireland), at a proportion of cement to aggregate of 1:8, it was comparable to that used in Dublin Port. Stoney described this as a 1:7 ratio excluding the large boulders (Stoney 1874, 334), which compares to 1:5 in the original OPW specification when the boulders are discounted, which would have occurred on the face of the work.

Cement proportions were still hotly debated at the time, made clear by A.M. Rendel's comments at the Select Committee on Harbour Accommodation a year following the introduction of the specification: "…engineers have been trying to outbid each other with respect to cement, one engineer suggesting that he could do with less than another" (Anon. 1884, 375). Engineers and contractors suggested a range of proportions at the enquiry, from 1:4 to 1:10. Or much less, as Stoney acknowledged his mix as lean when boulders were included at three-quarters of the composition (Anon. 1884, 261), equal to a ratio of 1:55. There was such diverse opinion on proportion and mode of construction that the Committee advised another enquiry be established (Anon. 1884, 558).

In defining the ratio Manning may have drawn on the experience of contractors as well, such as Doherty, contractor on Ardglass. Doherty was also working on Maryport under Sir John Hawkshaw CE, where the proportions were 1:12 in the heart and about 1:6 on the face (Vernon-Harcourt 1885, 417). Whatever the source for this adjudication, by June of 1884 Manning had modified the form, leaving a blank for cement content to allow an adaptation by project. Of the 26 specifications, 12 specified the original cement content of 280lbs/y^3 (166kg/m^3) up to mid-1885. There was nevertheless an evolution in the cement content as early as October 1884: the natural entities of water depth, tides and currents influencing decisions taken by Manning, the contractor, or indeed in unison (Table 3). In the case of Aughris, located in greater water depth than previous projects and fully exposed to the force of the Atlantic, cement content was increased to 266kg/m3 in the foundations to a height of 0.5m above low water (Board 1884b). By mid-1885 the lowest cement content being specified was 199kg/m^3, with higher content for foundations in deep water or exposed to strong tides and currents.

In addition to making cement content malleable, the specification also evolved to allow contractors greater latitude in defining the specification. By July 1885 Manning added a handwritten clause ending: "…the printed pages of specification and deed will be supplied to him to fill in the blanks", inviting contractors to adjust elements of the specification after the award (Board 1885). This increased latitude was likely in recognition of their extensive experience, many holding multiple contracts (Table 4).

Of the most prolific contractors known to have worked on SFI-funded harbours, Doherty, an engineer himself, had worked on concrete marine works with Stoney (Dublin) and Hawkshaw (Maryport); Cunningham, who built Coliemore in the 1860s, the first project that Stoney had designed using concrete foundations (Anon. n.d.), had already built two significant concrete harbours for the OPW.

Experience that Manning capitalized on due to the malleable nature of the specification, to develop a more lateral relationship between the engineer and contractor. Equally there was a shift in how contractors practised. Previous to the introduction of concrete in the mid-1870s, contractors were regional operators, rarely straying beyond their county limits. With the introduction of concrete, the culture of contracting

Table 4. Number, value, and location of works undertaken by principal contractors in concrete.

Contractor	No.	Mean Value (£)	Counties
J. Cunningham	4 + 2*	2,383	Cork, Kerry, Mayo, Sligo
T.I. Dixon	7	4,473	Antrim, Clare, Down, Mayo, Wexford, Waterford
W.J. Doherty	4	10,888	Clare, Donegal, Louth, Wicklow
J.J. Long	3	5,600	Galway, Kerry, Sligo
J. Jameson	3*	1,792	Donegal
Doherty/Jameson	2*	6,465	Donegal, Down

(Office 1708–1922) * Projects were not SFI-funded

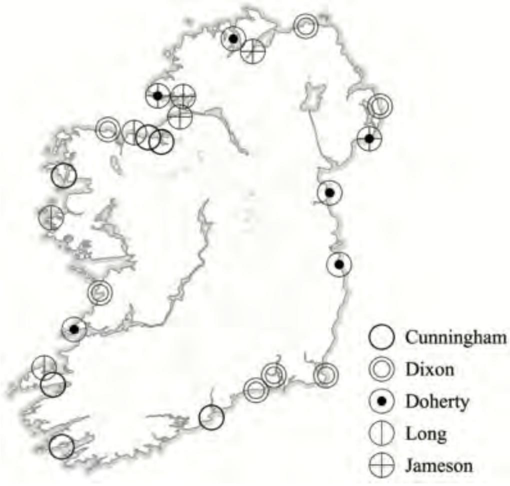


Figure 5. Works in Ireland by Principal Contractors hired by OPW following introduction of concrete (Office 1708–1922).

shifted from regional business to a national industry (Figure 5).

4 CONCLUSIONS

The *Manning Specification* was enabled by the convergence of heterogeneous forces that both demanded its existence and sustained its use. The SFI Act liberated the OPW from previous constraints, allowing them to exploit a growing body of knowledge held by contractors, several with international experience in concrete marine works. Equally, the volume of work generated by the Act sponsored the need for a system to control works being executed in the still-evolving material of concrete. The arrival of Manning, with his deliberate and focused mindset, was essential to recognizing the opportunity and drawing together a still mutable body of knowledge into a tool to govern such a great number of simultaneous works. It is noteworthy that after Manning's retirement in 1891 the specification fell out of use, due perhaps to the completion of the SFI-funded works. Yet it suggests that without the presence of Manning, this tool may never have developed.

Most significant was the nature of the tool itself and how it was deployed. It was adaptable to both natural forces and the experience of the contractors, operating as a fluid object within a heterogeneous network of actors. This promoted a more lateral working relationship between contractors and Board engineers in defining the terms of the specification. As with Law's description of the Portuguese Caravel, the *Manning Specification* operated as "a family of methods for associating and channelling other entities and forces, both human and nonhuman" (2012, 109).

ACKNOWLEDGMENTS

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

From regulation to everyday construction practice: The Lisbon building codes between 1864 and 1930

C. Rodrigues de Castro & A. Gil Pires
Universidade de Lisboa, Lisbon, Portugal

ABSTRACT: The regulations that control urban construction, while simultaneously limiting spontaneous constructive procedures, also contribute to the establishment of new ones. With this purpose, the Lisbon City Council introduced the 1864 regulations, expanded in 1869. These were valid until 1886 and replaced in 1930. These codes defined the volumetry of the buildings and also constructive elements that could interfere with street or sidewalk traffic. However, implementation of these regulations was not a linear process, with amendments emerging with the everyday construction practices and constructive techniques. This article analyzes the regulations related to the drainage of rainwater from building roofs to the ground; maximum height of new buildings and extensions of existing structures; constructive elements suspended above the street; modifications to the shape of doors and windows; and relations between the working site and the public space.

1 INTRODUCTION

Controlling the shape of buildings through legislation in Lisbon was nothing new in the 19th century. Since the Middle Ages, there have been written rules on this topic. According to Pinto (2017), at least since 1444 laws were defined regarding, for example, the relation of vertical expanded buildings that became taller than neighbouring buildings. The biggest concern, in this case, was how to carry the rainwater from the roof of the expanded building without causing damage to those around it. These same laws also regulated the permitted maximum projection of floors built hanging over the public space, which was restricted to one-third of the width of the street where they were inserted.

Except for the plan for the Pombaline Quarter built after the 1755 earthquake – where the façade's configuration had been strictly stipulated, forbidding houses with different heights or with architectural elements other than what had been established – the licensing of works until the Liberal Period in Portugal (1820) was mainly concerned with avoiding any element hanging over public areas affecting circulation in the public space (Pinto 2016).

From this moment, and above all with the subsequent construction codes, this concern remained, but there was also an interest in enhancing the façades of individual buildings and making the relation of these buildings' volumes more coherent at the street level.

This is evident from a law enacted in 1836, in which it became mandatory to present the façade drawings of buildings to the Lisbon City Council, both those to be expanded and those built from scratch.

In the absence of specific legislation, approval became dependent on the municipality's employees, who gave their opinion, often suggested guidelines to be applied for the building approval to proceed (Tojal 2002). An example is Malaquias Ferreira Leal, the director for public works in Lisbon from 1836 to 1855, who expressed this in his notes written in the drawings sent to the municipality by building owners willing to build new constructions or modify those already built.

As already mentioned, after the 1755 earthquake, except for the Pombaline Quarter, the city did not have a volumetric plan that covered its entire area, so these suggestions served as a primitive way to regulate the morphology of the buildings.

After the introduction of the building codes, the rules for construction were clearly set. This started with the national road police regulation of 1864, the basis for the more detailed municipal regulations of *Código de Posturas Municipais* (Code of Municipal Postures) from 1869, which would last until the arrival of the 1886 regulations. This was superseded in the 1930s, when the *Regulamento Geral da Construção Urbana para a Cidade de Lisboa* (General Regulation of Urban Construction for the City of Lisbon) was enacted.

2 REGULATIONS ON SPECIFIC TOPICS

2.1 *Drainage of rainwater from building roofs to the ground*

The emergence of laws that regulated the drainage of rainwater from building roofs arose with the concern to improve the circulation condition of pedestrians on rainy days. It was also concerned with sidewalk floor maintenance, avoiding the damage water falling from

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above caused at pavement level. This was an important issue, since most pavements were either composed of basalt and limestone blocks, creating the *Calçada Portuguesa* pattern, or composed of the more common cobblestone type.

Since the regulations of 31 December 1864, Article 35 foresaw the need for new buildings to provide sewage and rainwater pipeline installation. In the Council's decisions regarding individual projects submitted after 1864, the need to provide pipelines for rainwater was always stated, although without mentioning the technique to accomplish it (Governo de Portugal 1865, 98–100).

In the 1869 regulations (CML 1869) it became mandatory for buildings that underwent works on the roof structure to do the plumbing of rainwater to the proper drainage pipes. According to Article 173, it was stated indirectly that these pipes had to be embedded inside the walls, a procedure believed to be the norm since 1864 (Figure 1). In this case, a new legal imposition forced property owners to make modifications to the building, with the caveat, however, that it was only at the time of general works scheduled for reasons beyond the plumbing, making the introduction of this element gradual.

This regulation indirectly determined that the edge of the roof could no longer be made by eaves overhanging the street, and the need for them to be replaced by a gutter collecting water from the roof. Due to the prohibition of rainwater collecting structures being exposed, this gutter would necessarily have to be hidden. This, in turn, would connect to a vertical pipe located within the masonry of the walls that would flow out to the public sewer system. This legal determination affected constructive solutions, boosting an element that before the mid-19th century already appeared in civil constructions in Lisbon, but that since 1864 became practically the norm.

For combining the aesthetic effect with the practical, the parapet – a border along the top of the wall of a building, in its joint with the roof – became the standard solution. Although the regulations made no mention of the parapet as a constructive solution, which in theory would only allow the use of a gutter with a small wall to hide it, in the individual reports of the Lisbon City Council the parapet, as an architectural element, was suggested.

The insertion of drain pipes inside the wall – defined by the codes as needing to be 10cm in diameter – did not allow for its installation without compromising the integrity of that walls' structure. To get around this situation, an amendment from 12 August 1872 stated that the technicians at the Lisbon City Council, after an inspection, could postpone the installation of the pipes until the building eventually had gone through some improvement that could allow the introduction of the drain pipes (Pimentel de Novaes 1882, 80–4). Meanwhile, water would fall on the sidewalk, from gargoyles placed in the parapet.

This position of the Council demonstrates a certain ambiguity, insinuating that aesthetics had a role that in practice supplanted utility. If the biggest concern was the problem of rain pouring from the roofs onto the sidewalk, for exceptions where it was not possible to embed the pipes inside the wall, the Council authorized that these could be temporarily on the outside.

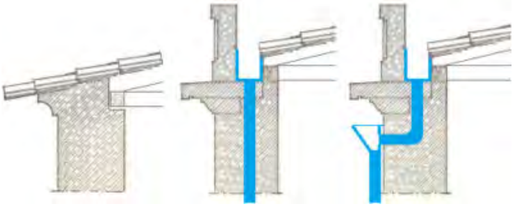

Figure 1. Solutions for the removal of rainwater. On the left, before the 1864 regulations; at the center from 1864 until 1903. Between 1903 and 1930 both the center and right solutions were used; after 1930 the right one became mandatory. (Costa 1955: 7; Pipes drawing inserted by the authors).

The 1872 amendment also added a previously unanticipated situation. It stipulated that in the streets where there was not yet a public rainwater pipe underground, but the sidewalk was above street level, therefore, with a gutter, the buildings that had the parapets with gargoyles were obliged to undo them and insert the pipelines to the curb level. Similarly, if the sidewalk did not have a curb yet, the pipelines should end at the meeting of the building's wall with the street, being later expanded when a curb was built.

The 1886 regulations (CML 1887) maintained what was previously stipulated, which would continue to be valid until the beginning of the 20th century, with the emergence of the *Regulamento de Salubridade das Edificações Urbanas* (RSEU – Health Regulations for Urban Buildings) in 1903 (Governo de Portugal 1904). From here, as noted in Article 27, there was the possibility of inserting the pipes on the outside of the building, without however prohibiting them from being internal to the wall. This was an old demand from the building owners, who constantly had problems with the breaking of stoneware tubes placed inside the masonry walls.

In the new code from 28 August 1930 (CML 1930), there was an inversion of the rules applied until then, forcing the pipes to be exposed on the façades of the new buildings, as stated in Article 148, to facilitate repairs, demonstrating here a more practical than aesthetic concern on the part of the Municipality of Lisbon. However, it is observed that in the architecture practice of that time, in keeping with the practice of the 19th century, it was common for architects to avoid leaving the pipes and gutter on the front façade. The gutter usually flanked the perimeter of the roof until the rear façade, and here the vertical pipes were externally placed.

In cases where the vertical pipes were exposed on the sidewalk of the front façade, Article 72 stipulated that at a height of at least two meters, it should consist of impact-resistant material, and suggested materials such as cast or laminated iron.

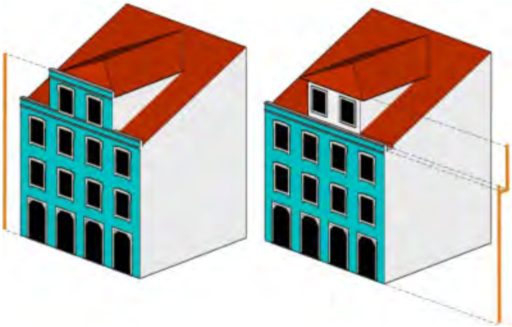

Figure 2. Volumetric shape before the ban on *trapeirões* (left) in 1864, and the solution (right) used after by the builders (source: Authors).

2.2 *Maximum height of new buildings and extensions of existing structures*

The regulations of 1864 provided, for the first time in the history of the city of Lisbon, volumetric regulations regarding the height of urban buildings throughout its entire area. In addition, it defined some volumetric elements of the façades, such as those stated in Article 36, stipulating that above the cornice and on the façade's plan, no construction could be elevated, except the acroterions or other decorative elements.

In practice, this meant the end of the *trapeirões*, a derivation from the common dormer windows, but comprising much more area, sometimes encompassing many windows (Figure 2). This was a regular constructive practice in the vertical expansion of floors in Lisbon since the late 18th century, achieving a usable space that had nothing to do with the narrow attics, being closer to the configurations of the standard downstairs floors.

The modification proposal of the building on Rua Conselheiro Arantes, numbers 21 to 29, dated from 1867, is an example of law enforcement where the request of the owner to add three *trapeirões* above the cornice was expressly rejected by the City Council, leaving the building with a flat top, as it currently stands (Figure 3). To circumvent this imposition, some builders used artifice to obtain approval. The modification project on Rua da Esperança, numbers 31 to 37, dating from 1883, included an attachment on the roof, in a style that resembled the *trapeirão*, but with a setback in relation to the façade plan and behind the parapet with balusters. It was approved without dispute by the Council and remains intact to the present day (Figure 3).

As for the general height of the buildings, the 1864 regulations defined in Article 35 that they should be proportional to the street's width in meters, with different height intervals for the buildings according to this dimension:

- For a street less than seven meters wide, the height could not exceed eight meters;
- For a street with a width between seven meters and 10 meters, the height could not exceed 12 meters;
- For a street with a width of 10 meters to 18 meters, the height could not exceed 16 meters;
- For a street with a width of more than 18 meters, the height could not exceed 19 meters;
- If the building was at an intersection and had façades facing two streets, the height of the building would be determined by the largest street width.

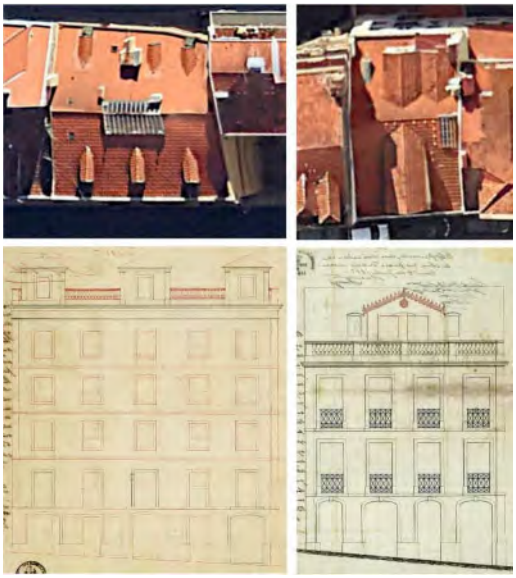

Figure 3. Left: Proposal rejected by the City Council for adding three *trapeirões* to a building in Rua Conselheiro Arantes, 21–29, dated 1867. (sources: Google Street View and Arquivo Municipal de Lisboa. Ref: PT/AMLSB/CMLSBAH/GEGE/023/1081). Right: Proposal to add a stepped back *trapeirão* to the building in Rua da Esperança, 31–37, dated 1883. (source: Google Street View and Arquivo Municipal de Lisboa. Ref: PT/AMLSB/CMLSBAH/GEGE/023/1391). The bottom of both satellite images are the façades shown on the elevation drawings.

The same regulation, on Article 44, dealt exclusively with the cases of height expansion of existing buildings, establishing for them a maximum height of 15 meters, thus differentiating them from cases of new construction. However, the 1864 regulations concerning the buildings' height would be amended in the Decree from 2 July 1867, largely due to the phenomenon of vertical expansion of buildings.

When an owner decided to expand their property, as a way of circumventing the law, they ended up compressing the height of the ceilings of the new floors to fit within the overall height of 15 meters, which resulted in individual floors with a little more than two meters. Another side effect of the law was related to its anti-economic content in the case of simple maintenance works on the roofs of buildings:

> "Last year there was a need to carry out works on a property by rebuilding its timber roof; this property had four floors, and as new roofing

> had to be done, with the fourth floor having a very little ceiling, the owner wanted to give it another two span [44cm] in height. On this occasion, someone appeared from the City Council, calling for the fourth floor not to be rebuilt, and instead to demolish what existed, because since the timbers had undergone works, the building should remain with the height marked in Article 35 of the Decree of 31st December" (Governo de Portugal 1867, 1794. Authors' translation).

After pressure from civil construction professionals, including architects, builders and construction material suppliers (*Idem, ibidem*, 1792) presented through two signed representations and delivered to the Council of Deputies, the 1864 regulation was reformulated and started to require a minimum height of three meters for the ceilings. The criterion for establishing the maximum height was simplified and allowed for taller buildings:

- For a street less than five meters wide, the maximum height allowed was 12 meters;
- For a street with a width between five and seven meters, the maximum height became 15 meters;
- For a street above seven meters, the maximum height allowed buildings up to 20 meters.

These regulations would be maintained until 1903, when concerns related to public health and natural lighting of the street and private spaces brought new modifications to the permitted maximum height. The RSEU adopted positions to be followed not only in Lisbon, but throughout the national territory, to maintain the relationship between the width of the streets and the maximum height resulting from previous laws, but now more detailed and less permissive, as seen in Article 5:

- When the width of the streets was less than seven meters, the height of the façades was not to exceed eight meters (ground floor and first floor);
- When the width was seven to 10 meters exclusively, the height of the façade was not to exceed 11 meters (two floors);
- When the width was 10 to 14 meters exclusively, the height of the façades was not to exceed 14 meters (three floors);
- When the width was from 14 to 18 meters exclusively, the height of the façades was not to exceed 17 meters (four floors);
- When the width of the streets was 18 meters or more and in large squares and boulevards, the height of the façades was not to exceed 20 meters (five floors).

The concern with natural lighting was also present at ceiling height, with Article 6 defining the minimum height of 3.25m for the ground floor and first floor; 3.00m for the second, 2.85m for the third; and 2.75m for the fourth and fifth floors. In this way, the closer to the street, the greater heights would allow more natural light, and as the floors moved further from street level, with less chance of shadows of other neighboring buildings, the height decreased. Those articles were kept intact with the 1930 municipal regulations.

2.3 *Constructive elements suspended above the street*

As described in the introduction, the insertion of constructive elements hanging over public roads dates back at least to the Middle Ages. Over the centuries, laws have sought to inhibit this practice, for reasons primarily concerned with the spread of fires. This led, for example, to the prohibition of lattice windows in 1759 by decree of King José I.

In the 19th century, the main concern was no longer the spread of fire, but the unimpeded circulation of public roads, and with the possible damage that structures above these could cause to the traffic. By this time, the blinds, held by a pelmet, also for coupling to the outside of the building, took the place of the aforementioned lattice windows, keeping the same role as a provider of privacy and protection from the sun.

In the 1869 regulations, the pelmet was mentioned in Article 62, stipulating that it must be placed 2.16 meters above from the sidewalk level, so as not to cause accidents to pedestrians. When placed on the upper floors, however, there was no stipulated regulation, which shows that aesthetics were in the background in this case. Article 61 also demonstrated concern with the accessibility of the sidewalks, by prohibiting ground floor bulge window railings, projecting balconies and the construction of door porches. The latter was a traditional element of Portuguese architecture, providing a transition between the private and the public space, while also offering rain protection. However, for storefronts, the legislation allowed the use of retractable awnings, as long as they were only opened during the day.

The ban on porches would only be lifted in the late 19th century, through the 24 August 1895 amendment (Governo de Portugal 1895, 2345–6), allowed its construction on streets with a width greater than 13.5m. This was not intended to revert to the traditional typology, but instead to allow porches inspired by the typology of Parisian ones in Art Nouveau style (Figure 4). Thus, the 1895 law was clear in stipulating their volume and materiality, such as demanding they must be no less than three meters above the sidewalk, with a maximum projection of 2.05 meters, and be made of glass framed by wood or metal profiles.

The 25 March 1915 amendment allowed projections up to three meters, unless the sidewalk itself was not wide enough to fit it within its width (Morgado & Aleixo 1923, 209–10). This amendment also stated the compulsory use of metal as a structure for porches on streets over 13.5 meters wide, covered necessarily by galvanized iron sheets, zinc, fiber cement, or glass plates. The glass plates had to be protected by wire netting, this being only necessary when wire mesh glass was not used.

This greater variety of materials allowed, after 1915 in comparison to the 1895 amendment, demonstrates the flexibility of the Lisbon City Council regarding

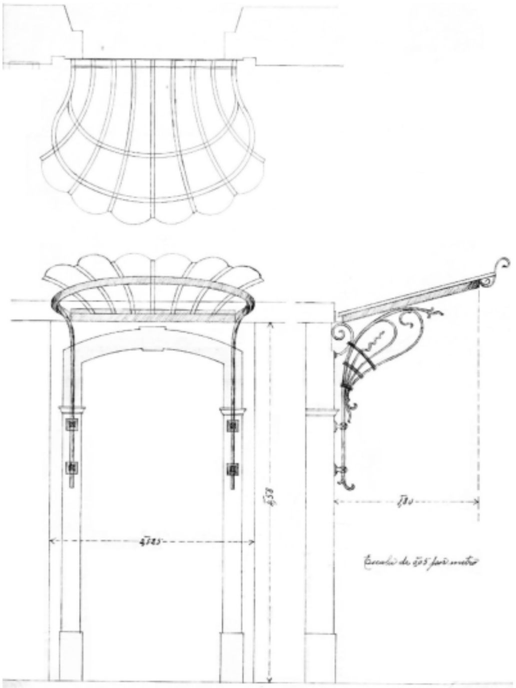

Figure 4. Drawing of a proposal sent in 1913 to Lisbon City Council to add a porch at a store entrance in the Pombaline Quarter. (source: Arquivo Municipal de Lisboa, process number 10708).

glazing roof, by allowing safer materials in cases of impacts. At the same time, by allowing covering materials less costly than glass, the City Council indirectly ended up encouraging the construction of these structures.

The mandatory use of metal on the city's avenues (wider than 13.5m) demonstrates a concern to follow French models of boulevards, just as it is clear that by not mentioning the possibility of using roof tile on the porches there is intentionally a denial of traditional constructive culture.

This impulse for constructive and aesthetic novelties was in line with monumental urban works the city was experiencing, such as the opening of the 90-meter-wide and 1.1km long Avenida da Liberdade (1886), the construction of the Rossio Railway Station (1891), the Santa Justa Lift (1902), and the emergence of large department stores, such as Armazéns Grandella (1891), this later renovated in 1907 in a project by French architect Georges Demay. This situation contrasted, for example, with the Pombaline Quarter, seen at the end of the 19th century in conflict with the taste of the time (Mello de Mattos 1906, 143), when a break with the compositional austerity of its buildings was sought (Martins 2004, 142).

Conversely, there was a stimulus for its use in streets narrower than 13.5 meters, allowing porches conditionally, if covered by transparent glass, to allow natural light to reach the sidewalk below it.

The 1930's regulations, as seen from Articles 89 to 92, were more general and sometimes vague concerning porches. There was no direct mention of the materials allowed, stating only that translucent materials should be the first option, however opaque materials could also be used if it made no impact to natural lighting on the sidewalk.

2.4 *Modifications to the shape of doors and windows on the facades*

The practice of modifying openings in Lisbon's buildings was commonly seen at ground floor level and linked mainly to commercial activity. The main reasons for these transformations were the optimization of natural light inside the stores and the improvement of the display of products.

When doing these modifications, it was common practice to realign the ground level openings with the vertical axis of the upper floor openings, resulting sometimes in the suppression of some doors, and the addition of new ones. Modifications for aesthetic reasons, such as changing the arch types to differentiate them from the neighbors' were also a common procedure during the second half of the 19th century and early 20th century, mainly in the Pombaline Quarter. The 1869 code dedicated Article 172 especially to these interventions. It clearly states that any building owner who intended to modify the doors or windows of their property to some shape other than the original of their respective buildings would need to ask for a license from the City Council presenting a document containing the drawing of the proposed change.

This article, more than a redundancy of Article 155 of the same regulations of 1869, which stipulated that any work that involved modifying the façade of buildings required the approval of the municipality, demonstrates that the regulation of buildings' openings was of great concern to the City Council. With the city's commerce increasingly transforming to create more aesthetically pleasing spaces, the municipality started to follow these changes, which brought constructive specialties hitherto unprecedented.

The regulation code of 1886 followed these specializations, by specifying in Article 274 the obligation to request authorization from the City Council for placement, outside the walls, facing the street, product displays or similar structures for exhibiting objects, and it defined in Article 275 that these new elements could not project more than 10cm into the sidewalk. An appendix to this article stipulated the taxation on these elements, made according to the elevation area (Governo de Portugal 1886, 3758–9).

In the following year, according to the amendment from 4 February, this position was updated, and taxation was revoked (CML 1893, 110). With this, there was an incentive for the proliferation of these type of structures in the city's commerce. In turn, from the first decade of the 20th century, the most sophisticated stores, inspired by the Parisian department stores, began increasing their display area, which were not limited to small displays attached to the

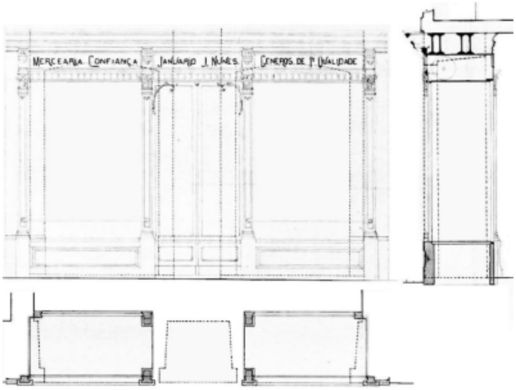

Figure 5. Proposal from 1912 to remove two original arched openings (dotted line) from a store in Lisbon's Pombaline Quarter and replace it with a large showcase supported by four iron beams and four columns located on each side of the store's entrance door. (source: Arquivo Municipal de Lisboa, process number 5).

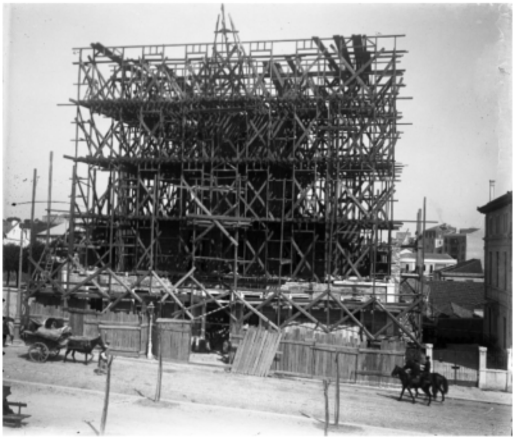

Figure 6. Construction fence made of wood in an early 20th century photograph of a working site in Lisbon (source: Arquivo Municipal de Lisboa. Ref: PT_AMLSB_CMLSBAH_PCSP_004_PAG_000141).

original façade, as before, but involved the entire storefront, suppressing the masonry and replacing the arch support with the iron beam (Figure 5).

An amendment from 3 March 1904 reinstated the taxation according to the elevation area and its projection over the public space (Morgado 1914, 54). The maximum projection limit was set at 0.25m, and the taxation divided into three levels: displays, showcases or similar structures, with projections up to 0.10m would pay 0$70 (Portuguese Réis) per square meter; projections from 0.11m to 0.15m would pay 1$30 per square meter; from 0.16m to 0.20m would pay 2$00 per square meter; and, from 0.21m to 0.25m, would pay 3$00 per square meter.

Pursuing the taxation policy of the municipality of Lisbon, which began in the early 20th century, the 1921 amendment of 1 July stated that permission to open, expand or close door and window spans included a specific fee, applied according to the number of spans modified (Morgado & Aleixo 1923, 122). This fee was added to the one already existing from 1904.

The regulations from 1930 placed special emphasis on the Pombaline Quarter, by stipulating in Article 78 that changes would only be allowed to modify the character of the primitive design when these changes affected the entire façade. As for storefronts, the same article makes an exception, allowing for their modification, establishing an unclear concept that these modifications, however, should not break the architectural harmony of the entirety of the façade.

2.5 *Relations between the working site and the public space*

This topic was of great importance for the 1869 regulations, to which it dedicated ten long articles on protection fences and other security measures, which should be implemented at the working site to avoid damage and obstruction to the public space in front of it. As an example, Article 159 required that all working sites had wood fences (Figure 6) on the sides facing the roads, in addition to prohibiting any type of rubble or construction materials placed beyond it. In contrast, Article 162 required the use of rubbish chutes for removing rubble from upper floors, thereby prohibiting the act of throwing to the ground the mentioned debris.

On 20 August 1896, an amendment allowed the occupation of the public space for small works that had no fences. This permission, however, was valid only to a maximum area of two square meters, and the duration of the workday, and at the end of the day it had to be removed. This was later cancelled in the amendment of 17 March 1898, which conditionally allowed the occupation of the public road during the construction process of a building by paying a fortnightly amount according to the occupied area. The amendment also put an end to the mandatory removal of rubble on the public road by the end of the workday.

The trend of the City Council to tax building elements, mentioned in other sections, is also seen in the working site regulations through the amendment from 1 July 1921. In Article 6, it maintained the definitions from 1898, but expanded taxation for scaffolding and fences, whose fee calculation involved the total area in square meters of each element and was paid monthly. In this amendment, also the suspended working platforms and boilers to melt asphalt attracted a tax according to the number of units available at the working site.

The 1930 regulations dedicated 14 articles to the working site theme (Article 220 to Article 234), without great changes concerning its relation to the public space in comparison with the previous amendment. The novelty here was an extensive description of how scaffolding should be used, to avoid damage both to the public space and to the workers. As a result, it required diagonal braces and protective guards, and it defined that floorboards must be able to withstand three times the weight of the workers and loads of materials they supported. In addition, it prohibited suspended working platforms or any type of scaffolding that was not attached to the walls.

3 CONCLUSIONS

Overall, for the five topics presented in this article, there is a constant updating of the regulations by the Lisbon City Council, sometimes aiming for adaptation of the everyday construction practices, and sometimes oppositely, by regulating construction procedures already settled by the builders. For both cases, during the almost 70 years covered in the text, the regulation updates also took into account technological advances incorporated into the constructive culture.

The topic related to the drainage of rainwater from the roof, whose central issue is conducting water to the public sewer system, demonstrates how the parapet, a constructive element already available for everyday construction in Lisbon, becomes indirectly the norm imposed by the City Council. This led to the pragmatic resolution of the problem and provided aesthetic beautification at the same time. Following the mandatory implementation of the rainwater downpipe within the walls, technical constructive issues arose and the Council was obliged to review the legislation to comply with reality.

In the same way, in the matter of building height regulation, there were also adaptations of the legislation to try to reverse side effects that came up in the everyday practice of construction, as seen in the amendment regarding the expansion of existing buildings. In addition, there was an attempt by the City Council to define systematically not only the maximum height but also volumetric aspects of civil constructions, seen objectively in the ban of *trapeirões* in the façade line. However, to circumvent these regulations, the builders used other geometries to obtain the usable area on the top floor as the *trapeirão* once provided.

Regarding the suspended elements, namely the porches, the regulations initially aimed at prohibiting the traditional model of the porch. Later, while keeping the prohibition for the mentioned porch model, the legislation stimulated the French inspired porch, as a beautification element of the city landscape, without neglecting practical issues, such as security and natural lighting underneath it. Subsequently, concern for natural lighting was pushed aside by the City Council, and the regulations were relaxed as an incentive to the proliferation of porches, intending to echo the typology seen in other European capitals.

As for the modifications on the shape of doors and windows, a practice closely linked to commercial activity in the period covered, until the 1930s there was no direct regulation, except for the projection of storefronts onto sidewalks. In addition, from the late 1880s, the Council started to see this phenomenon as an opportunity to create new taxes and increase its revenue.

In the last topic, about the working site, we conclude that, although there was no relationship between legislation and the final morphology of the building, there was always a constant concern by the City Council for the safety of passers-by and in avoiding obstruction of the public road.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Swing bridges in the 19th century Italian dockyards

R. Morganti, A. Tosone, D. Di Donato & M. Abita
Università degli Studi dell'Aquila, L'Aquila, Italy

ABSTRACT: Italian Unification in 1861 fostered a reorganization of national infrastructures in order to adapt them to the status of other European countries. The strategic Navy sector was implemented with a new equipment supply system in order to achieve functional and autonomous weaponry production and to develop a network of shipbuilding and defensive structures. This infrastructural system pushed a multi-year plan of refurbishment and newly founded Italian dockyards, which included experimentation with the swing bridge built in iron and steel structures. This bridge design was already known on the peninsula with models in a wooden construction tradition. This produced an original variation in the second half of the 19th century due to the influence of French and British models. Its construction combined multiple specializations of Italian engineering, involving national iron and steel construction, eager to obtain its technical and economic affirmation.

1 ORIGINS OF SWING BRIDGES IN ITALY

The swing bridge, which took origin from the drawbridge used in defensive structures such as fortresses and castles, was used to cross navigable canals and guaranteed both the passage of boats and the connection between the banks for the transit of people, livestock and goods. Its short span, the light loads and the structural typology, made possible a rigid rotation around a single pin placed on a bank or sunk into the riverbed, leading to the choice of wood for its construction, incorporating also iron components and ropes for the completion of the structure. For small spans of 6–8 meters, structural layouts would have resembled traditional wooden roofs while more complex solutions were conceived for greater spans, such as the original proposals of Leonardo Da Vinci (Bernardoni 2020). In Italy, several swing bridges were used over narrow rivers and they were characterized by warped deck and wooden frames: paradigmatic cases include the bridges that from the 17th century defined several connections along the Canal Navile in Bologna (Matulli & Salomoni 1984).

The use of wood continued until the early decades of the 19th century, when cast iron and iron construction pieces gradually became common. This transition is well represented by the swing bridge of Senigallia harbour built in 1827 (Mancini 1834).

From the mid-19th century, cast iron and iron began to be applied to the whole bridge structure, with the exception of the deck and secondary frame parts, introducing new technical and figurative potential. Meaningful cases of this conception were: the bridge over the Grand Canal of Trieste built in 1857 (Vio 1887) and the three bridges built over the River Brenta near Venice (Figures 1, 2).

Advancements in this construction typology could later be found in the several swing bridges that the Royal Italian Navy had constructed within the scope of the refurbishment and expansion of dockyards and their infrastructures. This process was characterized by the importation of foreign models with two pins and turning spans, especially used in France, that became the national construction practice reference.

2 THE ROYAL NAVY AND ITS INFRASTRUCTURAL DEVELOPMENT

After the declaration of the Kingdom of Italy, the Royal Navy immediately attained an important position in a country that was "mainly maritime" (Ferrante 2018). The debate on the development of the fleet and weaponry production grew strongly and decisively following the disastrous defeat of Lissa in 1866. This ruinous battle revealed the Italian shortcomings both in terms of military strategies and the navy's equipment.

Ministers Riboty and Saint-Bon started a renewal plan that involved several aspects: the manufacture of efficient warships, the replacement of obsolete vessels, the completion and construction of dockyards and military ports, with the consequent plan for the coordination of the respective fleets. Between 1867 and 1882, the Royal Navy inaugurated three new dockyards (La Spezia, Messina and Taranto) and provided for the refurbishment of the dockyards in Livorno and Venice (Gabriele & Friz 1982).

A leading figure in the modernization program was General Benedetto Brin, initially Director and then Minister of the Navy's Ministry. Brin was the main supporter of the construction of large warships and also promoted the development of heavy industry, primarily the steel industry, to support the production and the equipping of warships. The increasing tonnage of battleships required the construction of increasingly wider canals, docks and dry-docks in the harbours; as

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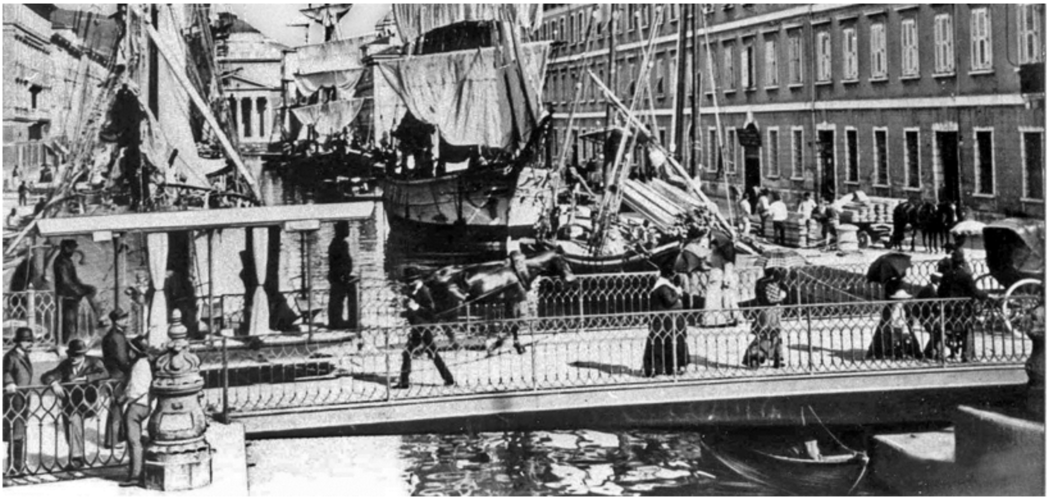


Figure 1. Swing bridge over the Grand Canal of Trieste built in 1857 (Vio 1887).

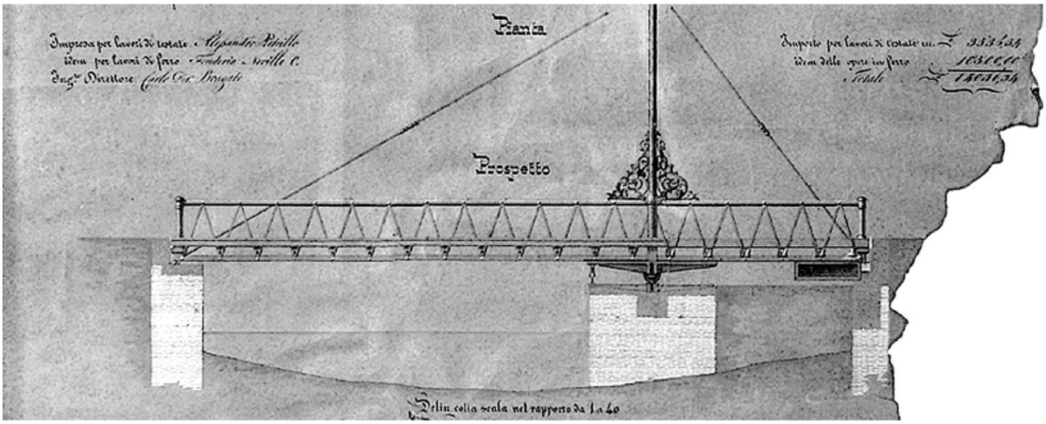


Figure 2. One of the three swing bridges built over the River Brenta near the Venice Lagoon (Comune di Mira 2008).

a consequence, bridges were built in order to ensure connections between the different banks and also to control maritime access.

Large span swing bridges were introduced in Italian military ports; their design concept mainly focused on two construction models: a one or two rotation pin bridge inspired by case studies drawn from countries that already possessed consolidated military forces and port infrastructures suitable for the movement of large warships. In particular, the British and French models represented an important cultural reference for the Italian engineers who were charged with this bridge typology. In particular Italian designers preferred the model with two pins and turning spans as used in the dockyards of Livorno, La Spezia and Taranto.

A common aspect of these experiences emerges in the building company, the Anglo-Neapolitan Guppy & C which was commissioned to build the swing bridges in Livorno and La Spezia. In the case of Taranto, their proposal was rejected and awarded to the IICM (Industria Italiana di Costruzioni Metalliche – Italian Industry of Iron Construction) company directed by the Neapolitan engineer Alfredo Cottrau. Guppy & C boasted a long-lasting relationship with military institutions that started out during the reign of the Two Sicilies and continued after the Unification of Italy. The founder Thomas Guppy had collaborated in the UK with one of the great icons of British engineering, Isambard Kingdom Brunel (Angus Buchanan 2001). After Guppy's arrival in Italy, he founded the Neapolitan company with his partner John Pattinson, which also contributed to the construction of several iron bridges (Doe & Green 2017).

2.1 *The Livorno dockyard swing bridge*

The new programs of the Kingdom of Italy involved deep change for the commercial role of Livorno. The status of free port was removed and the government aimed at transforming the city into a construction

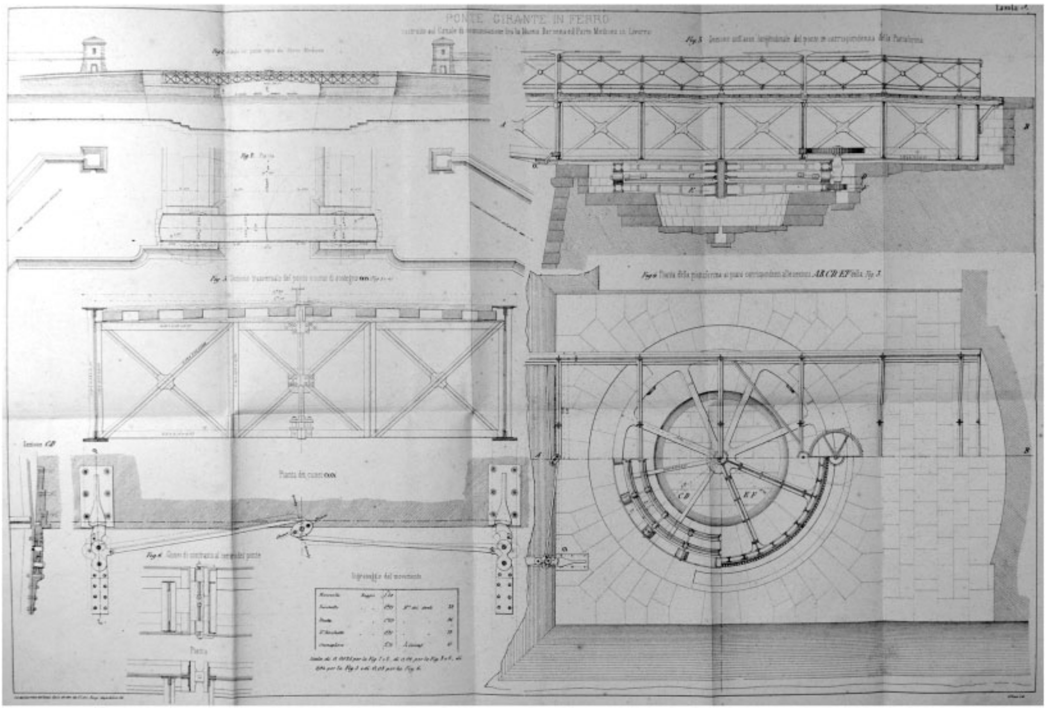


Figure 3. Construction details of the swing bridge built in the new dockyards of Livorno and inaugurated in 1868 (Mati 1869).

centre of large passenger and naval ships (Montgomery Stuart 1876). Therefore, the harbour needed improving and continuing the extension works, already launched in the final years of the Grand Duchy of Tuscany according to the project by the French engineer Victor Poirel.

With the law of July 1861, the Kingdom of Italy accepted the proposal of the colonel and naval engineer Vladimiro Chiavacci, who sought to carry out the works at his own expense in exchange for certain concessions. Observations by the technicians charged by the Ministry of Public Works and Maritime Affairs extended the Chiavacci plan to include the addition of a new dockyard and the construction of two bridges: the first one unmovable for connecting with the city and a mobile second bridge at the port entrance (Marzucchi 1861).

The construction of the new sections of the harbour was managed from 1864 to 1867 by the Fortini, Rinaldi and Comp., which completed the masonry supports of the mobile bridge in eight months. The foundations were sunk to 8 meters below ground level while the abutments rose to 2.5 meters above sea level (Figure 3).

In February 1867, the design for this two pin iron swing bridge, supervised by the engineer Tommaso Mati, was proposed to the Maritime Affairs management and the bridge building contract awarded to the Guppy & C company based in Naples. Each turning span of the bridge was 21 meters long and divided into three parts: the base was 7 meters long, the pin section was 4 meters long with the cantilevered section 10 meters long and forming a low half arch. The bridge deck was 5 meters wide and allowed the passage of people and vehicles when closed and the exit of ships built in Livorno when open.

Work began in October of the same year with the assembly of the pins on the masonry supports, which were shaped with a cylindrical introflexed compartment. The pins were composed of two iron cogged wheels – with a diameter of 5.40 meters, a stiffened rectangular section and eight spokes – connected to two other concentric wheels without spokes. The lower wheel was fixed in the masonry through "screw pivots and a concrete cast"; the collaboration with the upper wheel was guaranteed by 48 iron bearings of different sizes and a mechanism equipped with cogged wheels. The next phases concerned the assembly on the rotation pins of the turning span parts that included the counterweight far ends (Mati 1869).

The iron structure of each turning span consisted of two iron girders, joined by eleven horizontal members. The I shaped section of upper and lower members was composed by different profiles, stiffened according to the influence of the load. The vertical and diagonal members were built of L shaped profiles. Riveted joints were concealed along the truss ladders by iron disks and half-disks. The pattern of the parapet of the side girders was regular and harmonious to the eye (Figure 4).

Figure 4. Swing bridge of Livorno that controlled the canal between the harbor and the dockyards (Soranzo Postcard 1902).

The wooden deck was characterised by three overlapping planks. Above the abutments, two fly-wheels fixed to the parapet transferred the movement to the cogged wheels of the pins. The rotation system was designed to be controlled by a single operator and took one minute to complete. In order to allow for the movement of the spans, it was necessary to release the two clamping keys: the first placed on the crown and the second at the end of the abutments.

The swing bridge of Livorno's dockyards was inaugurated in 1868, the same year in which the National Naval Academy was established in the city and remained in service until the early 20th century.

2.2 *The La Spezia swing bridge*

The Gulf of La Spezia, which formed "the most beautiful port in the universe" according to Napoleon, has been the site for two dockyard construction projects since the time of the French government at the beginning of the 19th century. The first project was designed by Colonel Domenico Sauli, at the request of a commission chaired by Admiral D'Arcollieres; the second by the English engineer James Meadows Rendel in 1853 at the request of Camillo Cavour, head of the government of the Kingdom of Sardinia at that time.

Both projects identified the location near the promontories next to the Lazzaretto del Varignano for the navy yard site (Alderotti 2005). In 1860, this idea was rejected in the plan designed by Domenico Chiodo, a Military Engineer Major. In order to guarantee the necessary space for the dockyards, he chose an area close to the town of La Spezia (Calderai 1871).

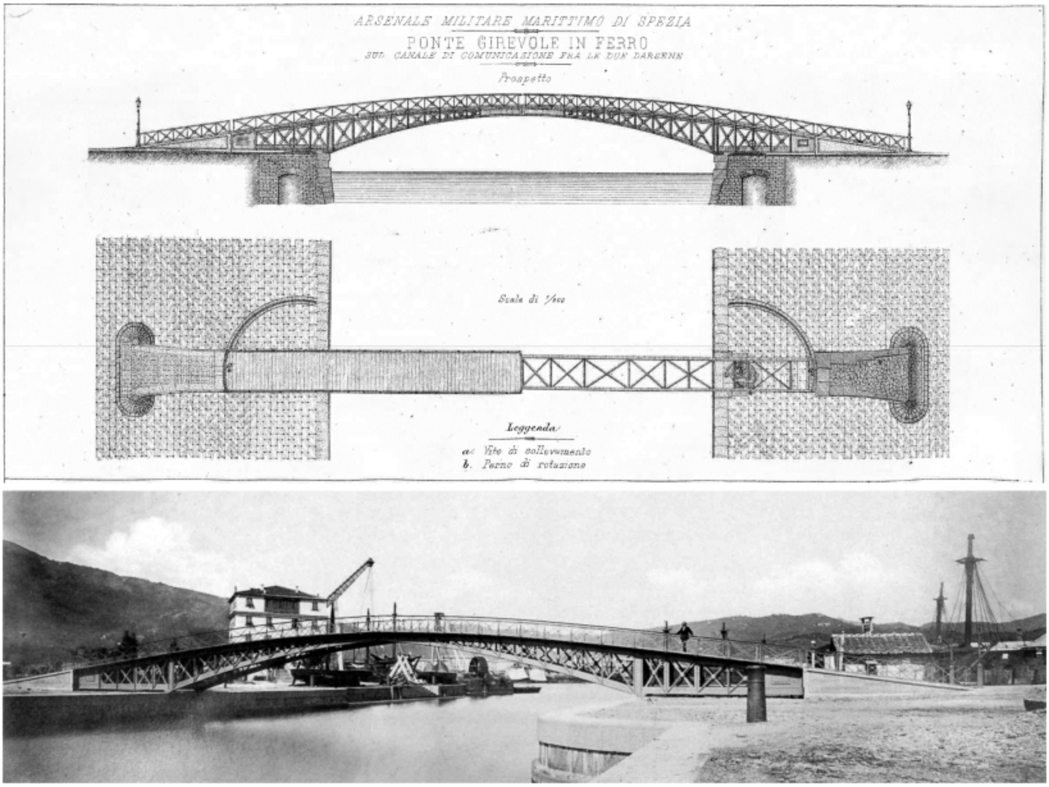
In July 1861, law n.136 established the construction of the dockyard to be arranged in two docks, with four dry-docks, nine construction yards, buildings for management, offices, warehouses and workshops, as well as an area included into the outer limit in order to host future extensions. The La Spezia plant was not fully completed on the date of the inauguration in August 1869, and the works, including the construction of an iron swing bridge over the canal linking the two docks, continued until 1881 (Nascé & Zorgno 1994).

This swing bridge was not the only one in La Spezia; another mobile bridge had already been built at the entrance to the pits intended for the underwater conservation of timber (Galuppini 1969).

The second swing bridge was built after 1871 by the Guppy & C, which had already supplied and installed the mechanisms for draining the dry-docks in 1869–1870.

The bridge was designed by Officer Gio Batta Grassi who chose the double pin scheme, with two turning spans 23 meters long; each turning span had a cantilevered part, 17.20 meters long, and a back end, 5.80 meters long (Figure 5).

The iron bridge was 3 meters wide. Each back end rested on a cast iron platform, which allowed two consequential movements: the lifting and inclination of the turning spans and afterwards, their rotation and alignment to the banks. This sequence of movements was enabled by a pin that was positioned 2.20 meters rearward of the channel border; a screw allowed the initial inclination motion and was controlled from ground level using a special crank placed close to a track that hosted two of the four iron spheres introduced to permit the rotating mechanism. The other two spheres were inserted into an internal track next to the pin. When the bridge was closed, it rested on four bearings; two near the connection between the horizontal and curved lower chords of the turning spans; the others placed on the external track. The movement of each part was allowed by a system of gears consisting of two wheels and three sprockets; in particular by one of the sprockets meshed with a circular ferrule affixed to the ground. Each back end was equipped with a case made of iron sheets, which was filled up with ballast in cast iron blocks in order to ensure the balance of each turning span was shaped as a semi-arch. As with the Livorno bridge, handling was incredibly



Figures 5 and 6. Swing bridge of La Spezia built in the 1870s: the double low arch defined in the drawings above and the bridge in its closed configuration below (Comitato delle Armi di Artiglieria e Genio 1881 – Archive of the Military Engineers of the Navy).

easy, requiring the intervention of a single worker and similarly taking just a minute to complete the operation (Comitato delle Armi di Artiglieria e Genio 1881).

The structure of each turning span was composed of two lateral trusses, with upper and lower chords shaped as two eccentric arches in order to configure the bridge with a profile that progressively tapered from the banks to its centre; in this way enabling the guarantee of a rise of 4.60 meters, permitting the passage of small boats, even when the bridge was closed (Figure 6).

The two trusses were interconnected by horizontal and internal diagonal members. The series of vertical members of trusses was interrupted in the middle of the bridge by the insertion of longitudinal plates that joined lower and upper chords. The deck was made of pine boards, fixed to the iron members with rag-bolts. The iron bridge parapets reproduced the same pattern as the trusses. The two back ends were connected to the ground through two masonry ramps.

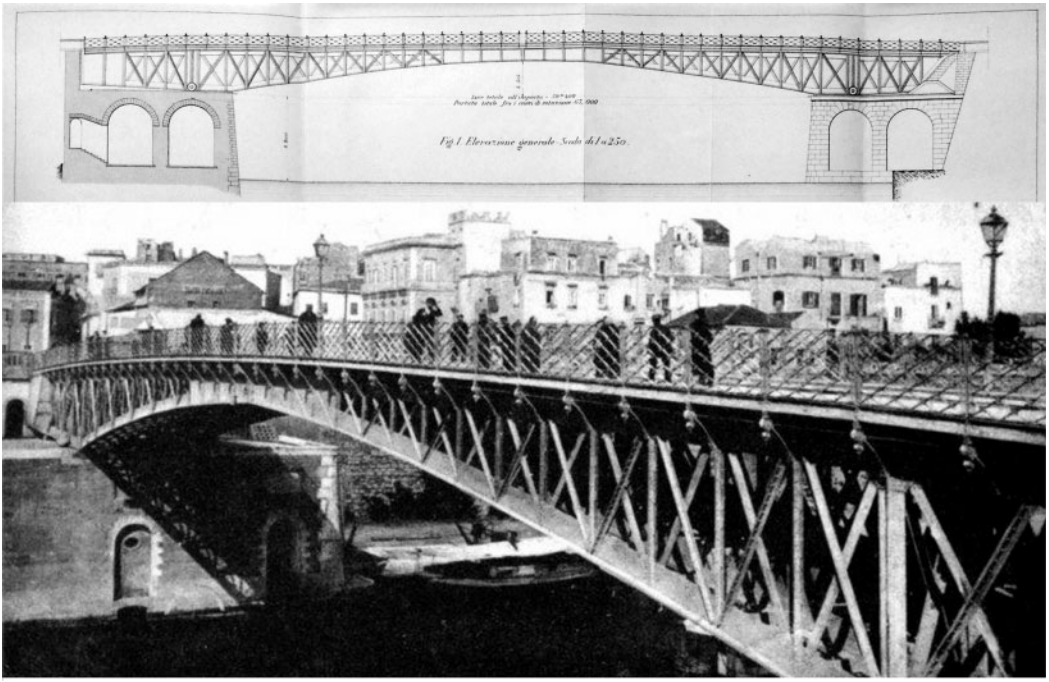
The bridge was widened in 1892 and subsequently replaced in 1914 when the Savigliano Company built a new connection with a longer span situated in a different position.

2.3 *The Taranto swing bridge*

The construction of the Suez Canal signalled a turning point in the urban development of Taranto and relaunched its international role thanks to the feasibility of hosting a commercial harbour and an important naval base. In 1865, the government recognized the city as being strategic for the surveillance of the southern coasts. It provided for an extensive program of improvements which included the inner harbour, the Cala Santa Lucia dockyards, the arrangement of the navigable canal and the construction of the new bridge, already proposed in the urban plan of 1861. In 1874, the enlargement of the Canal and the final decision on the bridge location involved the demolition of several historic buildings (Porsia & Scipioni 1989).

Both the design of the iron swing bridge and its construction were put out to tender overseen by the administration of the Military Engineers. The tender call prescribed: the compatibility of the bridge to the existing masonry abutments, and the cantilever of the turning spans back ends, which could not exceed the pivot by more than 11 meters. The width of the deck was 4.70 meters and with sidewalks 1 meter wide for pedestrians. They used a bridge built in Havre in 1861 as a reference model but, further indications concerned the movement mechanism which, within a maximum time of three minutes, had to guarantee the opening and closing of the turning spans (Messina 1888).

Only two companies were invited to submit to the tender, Guppy & C. and the Italian Industrial



Figures 7 and 8. Swing bridge of Taranto, inaugurated in 1887: the pins placed 67 meters apart in the drawing above and the passage of people on the turning spans below (Crugnola 1888 – Postcard, unknown publisher 1910s).

Company of Metal Construction, which was finally awarded the contract. The first proposal was for a mechanism actioned through "driving machines powered by compressed air at high pressure in cylindrical tanks". Collaboration with Eng. Giuseppe Messina, director of works, and the Military Administration, led to the choice of hydraulic turbines placed inside the abutments (Crugnola 1887).

The 89-meter-long bridge turned on two pins 67 meters apart (Figure 7). The iron structure was divided into “two independent parts” which covered a span of 59.40 meters and had a back end that was 11 meters long. Each turning span consisted of four girders placed at a distance of 2.50 meters in the centre and 5.50 meters on their sides. The iron truss structure involved the use of I shaped elements composed of different profiles for the chords, vertical and diagonal members (Figure 8). The trusses ended with regular beams close to the apex of the arch, which was defined by the turning spans. For the chords, I shaped beams with flanges of different width were used: the upper chords followed a parabolic curve reaching a rise of 1.10 meters; the lower chords, horizontal in correspondence to the abutments, were shaped with a semi-circular arch in the cantilevered parts that amounted to a rise of 3.39 meters. Cross diagonal braces were fixed between vertical members along the ladder and between girders. The turning spans were completed on their sides by a series of iron shelves with a 60 cm cantilever placed according to the vertical member that supported the parapet. The wooden deck was built of oak joists placed in the direction of the girders and thick planks running in the same direction as the girders before thick planks arranged in a herringbone pattern were placed on top (Carughi 2003).

The movement system included two subsequent phases. The first disconnected the turning spans and consisted of a small lifting device. The second defined the rotation of the parts. The weight of the bridge was over 1,014 tons. 540 tons of this was the counterweight built of big iron caissons filled with rubble and cast iron blocks (Figure 9).

The bridge was supported by several "rollers and wheels" and pins laid on a triple bearing system that allowed it to rotate. A central cast iron hinge with a diameter of 1.7 meters was radially equipped with truncated cone rollers and bore the weight of the turning span in the raising movement that disconnected the two parts. A cast iron wheel with a diameter of 10.00 meters, supported the rotation of the spans and collaborated with two other cast iron wheels and a steel shaft, placed horizontally, that also allowed the upward movement. A circular rail with a radius of 10.00 meters guided the driving wheels on the abutments in the rotation phase. The IICM started the construction of the cast iron and iron components in the Naples manufacturing workshops at the end of 1884, after which they were moved to Taranto in March 1886. In just three months, the two turning spans were assembled. In July, the wooden deck was also completed. The rotation of the parts was tested in January of the following

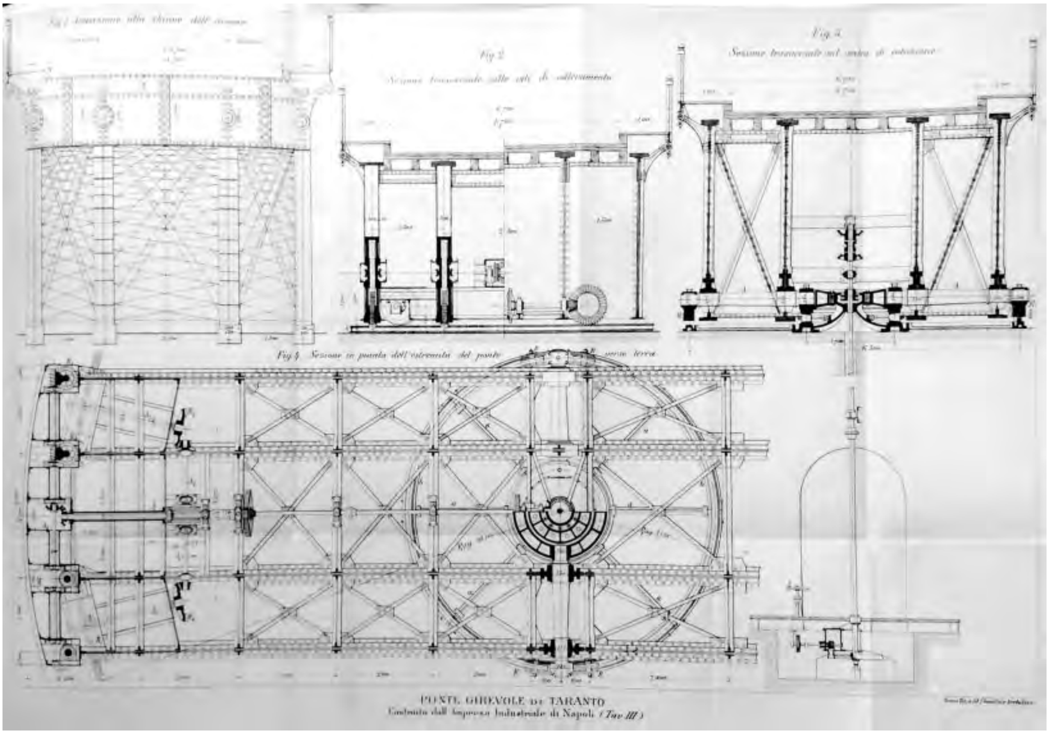


Figure 9. Construction details of the swing bridge of Taranto and sections of the turning mechanism (Crugnola 1888).

year and the bridge was finally inaugurated on May 22nd, 1887.

Since the 1920s, a refurbishment was foreseen but the bridge was replaced only after the Second World War. This replacement bridge was designed by the Technical Office of the Savigliano Company and built by local dockyards in 1958.

3 CONCLUSION

The construction of the Navy's swing bridges represents an epitome of the spirit of the age in the young nation, a 19th century Zeitgeist still uncertain but also vibrant enough to face the technological challenges of a late industrial revolution.

Italian progress in the field of construction techniques and practices was also improving in the effort to bridge the gap with the European countries able to boast of innovations in the fields of mechanical engineering and iron construction. It is no coincidence that the models inspiring Italian examples always came from the most advanced contexts in Europe. Although Italian industry never surpassed this, they managed to advance their technological know-how.

The swing bridges represented an engineering theme that was linked to really fertile research; its importance was undoubtedly related to experiments in the military sector then transferred to the infrastructural equipment needed by the armed forces. As a consequence, the transformative processes which involved the above case studies were the outcomes of coherent research that addressed the search for adequate solutions to the necessary technological progress required by the national war industry. Within these dynamics, "the red thread" which links the case studies is iron construction and the full exhibition of its mechanical and industrial nature. This aspect can also be found in the technical progress experienced in shipbuilding in the same years that affirmed the close original relationship between iron and water.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Early general contracting in Siam, 1870–1910

P. Sirikiatikul
Faculty of Architecture, Silpakorn University, Thailand

ABSTRACT: The paper explores the emergence of general contractors in late 19th century Siam when the corvée system, which customarily provided primary resources for government construction, declined. This period's main features were the introduction of capitalism into construction, the establishment of the Public Works Department, and the abolition of the corvée system. By looking at difficulties that the Siamese government had in dealing with the shortage of labour and the ineffectiveness in supplying building materials under the corvée system, the paper shows how European contractors offered Siamese rulers an alternative way of construction. The introduction of the general contract to tender, enabled both parties to benefit. In short, the rise of contracting in Siam was not purely the result of independent enterprise by individual contractors, but part of a holistic attempt to address the long-standing problems inherent within the corvée system.

1 INTRODUCTION

In Thailand (formerly known as Siam), construction today is more or less an independent process, distinct from other building activities such as building design. However, this division between design and construction processes is relatively recent, and can be traced back within the last 150 years. Under the Siamese mode of building production, building materials and labourers for government construction were supplied through corvée. Siamese officials, like building designers (*naichang*) and directors of building work (*maekong*),took the corvée resources and managed the design and supervision of the building work from start to finish; the demarcation line between design and construction often being blurred. During the last quarter of the 19th century, however, not only had a significant proportion of construction become a separate process, but also the practice of construction had become more and more confined to a group of men, calling themselves general contractors. These general contractors offered to build a whole building for a fixed sum, and used a contracting process to tender for a building project. By looking in more depth at the early development of Siam's building practice during the last quarter of the 19th century and the first decade of the 20th century, this paper considers how Siamese aristocrats accommodated this contracting system.

2 PROBLEMS INHERENT IN THE CORVÉE SYSTEM: CONTROL OF MANPOWER AND SUPPLY OF BUILDING MATERIAL

In the earlier Bangkok era (1782–1873), the corvée was the primary source for workforce and material supplies necessary for government construction. Under the corvée system, the king topped the hierarchy, while at the bottom was the group of commoners called *phrai*, that is the majority of the population who could be conscripted annually by the government for public works or military service. Between the king and the *phrai* were the official classes who were the direct overseers of the *phrai*. Through this social order, the king relied on administrative officials to manage the *phrai*'s services and resources for the government, while allowing them some use of the labour and produce of the *phrai*. The result was of mutual benefit, so long as their partnership remained productive.

In practice, however, such a partnership between the king and his officials could easily be disrupted by disobedient subjects. When the *phrai* were requested to work too hard by their master, they could flee to seek the patronage of influential princes and nobles to shield them from government control or even escape the network of government control entirely. Some officials actually helped the *phrai* avoid registering for corvée to keep their service to themselves. The king's total reliance on his officials through the corvée system, which could prove volatile rather than efficient, led to a shortage of human resources and created anxiety about the administration's loss of control throughout the early Bangkok period (Lysa 1984, 31; Susayan 2009, 72–105).

The manpower shortage was improved during the reign of King Nangklao (1824–51), by which time the influx of Chinese immigrants from the south of China helped to relieve reliance on corvée labour. Even though hiring Chinese labourers was costly, it was more efficient in the changing economic condition. Their status, as immigrants who were free to travel around the country, and their reputation of being capable and industrious, made the Chinese a better

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Figure 1. Phra Samut Chedi, Pranam, Samut Prakan. Source: National Archives of Thailand.

choice of labour than the *phrai* in almost all circumstances. As the historian Walter Vella put it: “the use of paid Chinese labor for construction projects rather than free, but less efficient, Siamese corvée labor, was either introduced or became common during the Third Reign” (Vella 1957, 19). It was clear that wage Chinese labourers were common on construction projects like canal digging and temple building in the early 19th century.

Just as labourers began to be purchased, so too did building material. Like labourers under the corvée system, most of the building materials were obtained from *suai* taxes-in-kind sent by the *phrai*, in place of corvée; while building materials unavailable in the *suai* could be obtained through purchase either within the country or imported from overseas.

In the second half of the 18th century, the purchase of materials for government construction was relatively low compared to *saui* materials; hence the building cost was virtually free as nothing needed to be paid for (Lysa 1984, 46). In the early 19th century, however, the old way of acquiring building materials changed due in no small part to the expansion of the export economy. The increase in overseas trade during the reign of King Nangklao meant that *saui* items to fill the junks were in greater demand than ever before. However, as exportable products offered higher potential revenue than junk trade, the government promoted high selling goods to make a greater profit. Under this new policy, the *phrai* were encouraged to devote their time and labour to produce more profitable products, while government began to prefer payment in monetary form as a substitute for labour service and *saui* items (Eoseewong 2005, 67–9). As money circulated more widely amongst the people, it led to changes in building activities. It comes as no surprise that materials used for government construction not only appeared in greater quantities but exceeded what the *suai* could provide. In a particular building project such as that by Phra Samut Chedi, construction records show that the building materials were entirely purchased with cash (Nangklao 1987, 17). From the second half of the 19th century, purchasing materials became the preferred method for most government construction (Figure 1).

The government’s policy of allowing foreigners to settle freely in the country attracted many Chinese into the Siam building industry. Material merchants and suppliers, for example, were permitted to sell and buy privately, for they had the mobility and connections that made possible the development of material markets. Under these circumstances, Siamese officials found themselves spending more time in material management, such as purchasing rather than extracting *saui* materials as they had before. In particular, *Phra Khang* or the Treasury was responsible for finding and securing, at the lowest cost possible, materials that government needed. Once purchased, construction materials were centralized under the Treasury’s control before being distributed to a building site.

As cash became increasingly important as a medium of exchange for building materials, government records showed that more and more officials were involved in corruption, exposing government’s ineffective control. A significant number of corruption cases during the 1870s highlight the embezzlement of government material by Treasury officials. Another form of corruption was such that a covetous trader conspired in cooperation with a Treasury official to sell Chinese stone slabs to the government for a higher price than market rates (Waiworanart 1883). This episode in 1883 is reminiscent of King

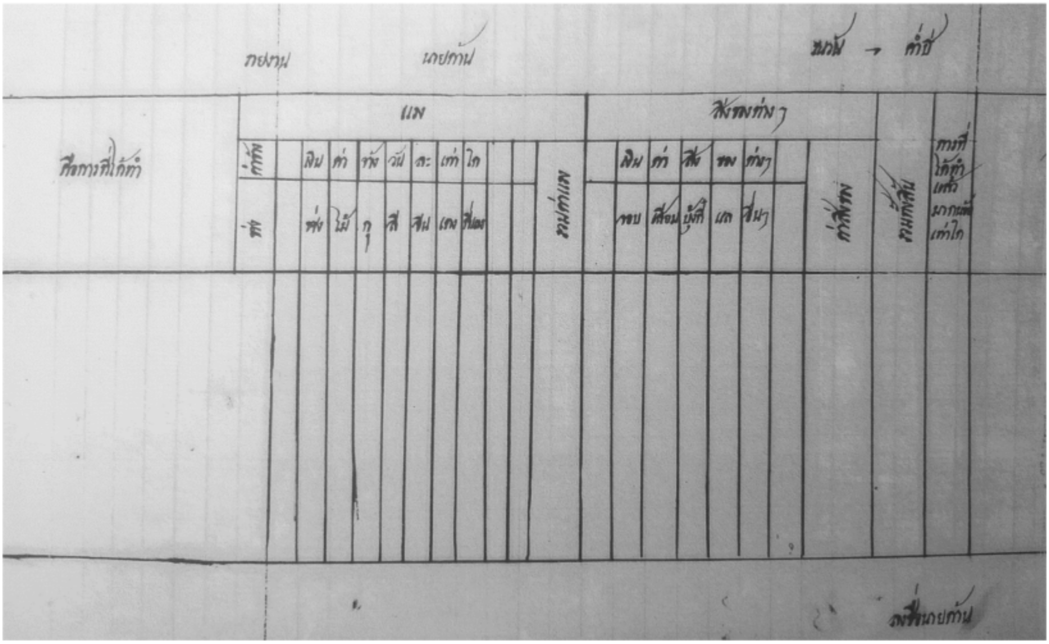

Figure 2. Frey's table for road building estimation. Source: National Archives of Thailand.

Chulalongkorn's cynical remark in 1887 about the dishonesty and misconduct of the Treasury official involved in the transaction of materials:

> "In the beginning, the Treasury's duty was to purchase materials necessary for a building project in advance so that everything would be ready to proceed without delay. So it is essential to have officials who understand this job, that necessary materials were prepared in advance and brought for better price […] however, in later times, some greedy merchants wanted to sell things to the government, trying to lure the officials into corruption; and the officials accepted the deal, at the expense of government. Every year, an enormous amount of money of one thousand *chang* was spent on poor-quality things; thus, unwanted. Apart from that, there is no estimation for the whole building project as the Ministry of Treasury and a master builder did their duties without collaboration. The cost for the whole project is then two or three times higher than standard practice" (Chulalongkorn 1927, 52).

Based on King Chulalongkorn's complaint, the government suffered considerable loss due to corrupt officials in the Treasury involved in sourcing building materials.

However, the situation concerning Siamese building practices had started to change towards the end of the 19th century, especially during King Chulalongkorn's reign (1868–1910). More than before, his administration built many new palaces, government buildings, and urban infrastructure. As building design became more complex, requiring a larger workforce, together with the demand for more rapid completion, the government started to look for alternatives to the old building practices.

3 MR FREY'S 1882 REPORT ON ROAD AND BRIDGE CONSTRUCTION

In 1882, Mr Frey, a British civil engineer and advisor to King Chulalongkorn, presented a report on road and bridge building, suggesting how the practice of construction in Siam could be improved. After surveying local building conditions, he realized there was no practice of estimating the entire construction cost; therefore, it was impossible to procure estimates from several of the best contractors. He therefore suggested that, first, a total estimated cost for the project be calculated before construction could begin, and secondly, that "[…] it should have a contract to specify in detail the amount of work to be done by contractors, as well as a schedule of work and cost." He attached to his report a sample of a table for calculating road building costs. The left column was for the amount of work to be done. The middle column contained lists of labourers, including carpenters, unskilled labour and Chinese coolies, paid daily. Finally, the right column was reserved for recording the cost of individual building materials (Frey 1883). What Frey was suggesting here was a comprehensive way of calculating the total estimated cost – an equivalent of Bills of Quantities, in today's language (Figure 2). Of all the necessary procedures Frey proposed, the process of contracting between the commissioner and contractors in advance was the most important. Although what he suggested was about road and bridge construction, the implication was that in proposing a contract for building work, and in setting a competitive tendering process in which each interested building firm submitted a tender for the project, the government could gain assurance of the work's best value for a guaranteed price.

In the 1870s, the use of general contracting was rare, and King Chulalongkorn was in a position to choose whether to use the contracting process or not. Nevertheless, by the end of the 1880s, when the Department of Public Works was inaugurated, the practice of estimation and contracting became necessary steps through which almost any building project undertaken by the government had to progress. It has been suggested that the commissioning of European builders was due to King Chulalongkorn's strong desire for Western-style buildings, since they offered better service than Siamese builders who were far from familiar with Western architecture. This explanation may be self-evidently true; nevertheless, against a background of the corrupt practices inherent in the corvée system, it can also be said that the adoption of the contracting process by the Public Works Department reflected King Chulalongkorn's desire for more organisational efficiency to prevent wastage of government funds.

Before looking at the characteristics of the new system of general contracting in more detail, it should be remembered that general contractors' business could be possible only because Chinese immigrants provided the foundation upon which business could operate. As Chinese immigrants were allowed to participate in some building activities themselves, either as wage labourers, material traders or entrepreneurs, they helped significantly to lighten the government's burden of the shortage of labourers and building materials. The point to be stressed here is that without the economic change in the 19th century, which generated the expansion of wage labour and material trading in Siam, there would have been no foundation whatsoever on which a contractor could run his business.

4 EARLY GENERAL CONTRACTING IN LATE 19TH CENTURY SIAM

The building industry's growth during King Chulalongkorn's early reign attracted European contractors to base their construction firms in Bangkok. Of all contractors in late 19th century Siam, the Scottish architect-contractor John Clunis, the Italian contractors Stephen Cardu and Joachim Grassi were among the most prominent; especially Grassi, his successful business venture had made him the wealthiest foreigner in the late 1880s (Povatong 2011, 128). Their practice of general contracting for building shared norms and values that differed significantly from Siamese building practice (Figure 3).

Figure 3. Joachim Grassi. Source: National Archives of Thailand.

At this time, the characteristic of general contracting was that building contracts were signed by one person known as the general contractor, who undertook to direct the whole project for a fixed sum. Unlike Siamese building practice under the corvée system, where the building cost was calculated after completion and sometimes not at all, under the new system of general contracting, the general contractor was able to estimate the total expense of the work and concluded an agreement with the commissioner in advance. Once contracted, the general contractor provided all building materials and employed the necessary tradesmen – such as craftsmen, bricklayers and coolies – over whom the general contractor would have direct control, as he paid them. Having the advantage of owning the capital to employ many tradesmen, the general contractor became the one who assumed control over the building work and responsibility for the outcome of the work.

To the commissioner, an advantage of the new system of building was that it enabled him to know in advance how much the building would cost – a benefit that was unavailable under the old system of building. Supporters of the new system, like road engineer Frey, could claim that in theory it offered perfect competition amongst builders, so the commissioner would be able to get the best offer from several tenders, rather than be restricted to just one offer from a builder. Besides, as the contractor now became responsible for building production, the system of general contracting enabled the commissioner to avoid all the inherent problems likely to happen if the building were operated under corvée system. With general contracting, all the risks in building, either concerning the control of manpower or the transaction of building materials which previously rested upon the king's administration, were now transferred to the general contractors.

While this new way of building practice presented considerable advantages both to the commissioner and the contractor, it presented Siamese officials like *maekong* (a director of works) and *naichang* (a building designer) with the significant risk of losing control over the construction of buildings. It should be recalled that it was their job to call for artisans, labourers and building materials and to direct and regulate their work throughout the entire building process under the old building system. Under the new system of general contracting, however, these Siamese officials were displaced by the general contractor, who became the one to select and employ artisans and labourers and regulate the work. Although no opposition to the general contractors has been found at this time, they were increasingly compelled to accept the loss of their authority to emerging general contractors.

Looking at the difficulties that some Siamese master builders in the late 19th century had in dealing with the loss of their control over the building production gives a better picture of the changing situation in building practice. In 1881, for instance, Prince Praditworakan, the director of *Krom Chang Sipmu* (Department of Ten Crafts), received an order to supervise labourers removing the stone slabs to clear the site for a new Buddhist temple whose building contract was being tendered for by contractors. Instead of complying with the order, Prince Praditworakan replied that he could not do this task since "no corvée has been assigned to him for so long" (Putharetthamrongsak 1881). In the end, the government had to turn to prison labour as a substitute for the labourers needed instead. Although some Siamese builders and artisans remained employed and were given commissions for certain kinds of work that required traditional arts and craft skills, such as the building of the Royal Cremation Pyre, the level of supportive resources for work production was substantially reduced. Underlying this was a rapid transformation in building activities when the clans of Siamese master builders found themselves faced with the prospect of declining authority, as their services were gradually discarded.

5 CONCLUSIONS

General contractors offered an alternative to the old building system and the inherent problems of the corvée system which by the late 19th century was already an obsolete organism in Siam. However, the introduction of general contracting in Siam was not an isolated act. Neither was the new professionalism of general contractors purely the result of independent initiative, nor was the Public Work Department's establishment merely the result of administrative reform. Both were part of a solution to counteract the problems inherent in the corvée system.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Pedreño y Deu Pantheon: An example of late-19th-century funerary architecture in Spain

D. Navarro Moreno & M.J. Muñoz Mora
Universidad Politécnica de Cartagena, Cartagena, Spain

ABSTRACT: In the late-19th century, Cartagena experienced great economic development, prompting a profound architectural change in the city, stimulated by the bourgeoisie who used architecture to display social distinction. In addition to their urban palaces, these residents began to build villas in the countryside for status, rest and recreation, and to enjoy the scenery and a healthy environment. This social class was conservative and religious, which meant that spiritual matters occupied an important place in their thinking. This led to the construction of imposing funerary architecture in Cartagena's main cemetery. One of the most significant pantheons is the one belonging to the Pedreño y Deu family. This communication focuses on the study of the aforementioned pantheon, on which an analysis of the architectural, constructive, pathological and restoration processes were carried out. Through the study of this silent dwelling, it will be possible to understand the parallels that exist between the mansions of the living and their eternal dwellings.

1 INTRODUCTION

In the late-19th century, the city of Cartagena (Murcia) experienced great economic development based on mining-metallurgical activity and the intense port traffic it generated (López & Pérez de Perceval 2010), as well as the revitalization of the Arsenal and other industrial sectors.

This period of economic fullness was reflected in both society and the city. A new bourgeoisie emerged and used architecture as a means of exhibiting economic power and social distinction. Immersed in this architectural fervor, wealthy families competed to build luxurious urban palaces following the architectural trends at that time, triggering an architectural metamorphosis of the city (Egea Bruno 1996).

To achieve their objective of social ostentation, the bourgeoisie, cultured and interested in art, turned to the most significant architects of the moment, who left an important repertoire of relevant buildings in the city. Carlos Mancha (1827–88) was one of the most important. He was credited with introducing architectural eclecticism in Cartagena, although the facades of his buildings did not altogether lose their classicist essence. He was followed by a new generation of architects, such as Tomás Rico (1854–1912), Francisco de Paula Oliver Rolandi (1861–1915) and Víctor Beltrí (1862–1935), who represented the transition from 19th-century architecture dominated by historicisms and eclecticisms to early-20th-century architecture characterized by the modernist spirit (Pérez Rojas 1986).

Simultaneously, the upper-middle class also began to make new demands for residential and recreational conditions that went beyond those available in their usual residences. They found the solution in the countryside. There, they began to acquire large tracts of land where they built unique villas to rest and enjoy recreation and social relationships, as well as the scenery and a healthy environment. These villas, formalized according to the model of urban palaces and surrounded by lush gardens, in which the bushy and arboreal flora of the place was combined with exotic plants and some ornamental elements, perfectly fulfilled the requirements of sustaining the habits of the bourgeoisie, accustomed to comfort, and entertaining important guests, as well as serving as a symbol of social status, an indicator of wealth and a marker of identity (Navarro Moreno 2018).

Furthermore, this conservative and religious society was concerned with spiritual matters. This, together with the fact that late-19th-century health regulations had forced the location of cemeteries far from the cities, resulted in the construction of a new city cemetery in which this social class also constructed imposing funerary architecture (Muñoz Mora 2020).

Excellent examples of this architectural legacy have been left by great families of the time, such as the Aguirre, Dorda, Martínez and Pedreño families, who competed in the construction of their urban and rural residences as well as their eternal dwellings. Does the study of the architectural composition and constructive systems of these buildings allow us to identify and understand parallels between the mansions of the living and their eternal dwellings?

This communication focuses on the Pedreño y Deu Pantheon, one of the most significant in the main cemetery of Cartagena. An architectural, constructive

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and pathological process analysis has been carried out. In addition, the ongoing restoration process will be examined. This communication aims to value a building which, despite its municipal protection, has suffered years of neglect and has seen the continuity of its memory in jeopardy.

2 AN EXPANSION PROJECT IN THE CITY OF CARTAGENA

In the late-19th century, Cartagena still conserved the complete layout of its city walls, which consisted of three main gates: the north gate, *Puertas de Madrid*, which connected to the road to Murcia (the capital city of the territory); the south gate, *Puertas del Muelle*, which was the access to the port, and the east gate, *Puertas de San José*, which led to the mining mountains. These accesses converged into a city organized around two main axes, one north-south which connected the gates of the port and those of Madrid, and another east-west that led from the gate of San José to the City Hall, close to the gate of the Muelle.

The buildings of the bourgeoisie are located along these streets. The predominant style is eclecticism based on the imitation of models from the past, with a clear modernist influence through some plant and floral motifs. Its material and constructive characteristics respond to traditional techniques, with the progressive incorporation of new products derived from the industrial revolution, such as metal profiles, cast-iron columns and cast stone.

Among the earliest palaces built was the one promoted by Andrés Pedreño, an industrial businessman and renowned character who left his mark on the social and cultural life of his time. The commission was given to architect Carlos Mancha, who carried out the project in 1872.

The building was located in the middle of the north-south axis, a strategic point where three main streets of the city's layout converged, providing an urban perspective that allowed pedestrians to contemplate its façades. It remains one of the architectural gems of Cartagena. The outer decoration, in which stone predominates, is a sober reference to the classic lines of architecture (attached pilasters, pediments topping the windows, semicircular arches, corbels, carved masks on the cornices, grottos and rosettes). Noteworthy are the expressions of freedom and eclecticism, such as the winged head of Mercury located at the entrance of the building, a figure closely linked to commercial activity and repeated in other works promoted by the local bourgeoisie.

The demographic growth experienced during previous decades due to the impulse of economic growth provoked a need to expand the city. Thus, a Project for the Expansion of Cartagena city was commissioned in 1895 to the architects Pedro García Faria and Francisco de Paula Oliver Rolandi (Archivo Municipal de Cartagena, CH00952).

This project was structured in four areas: the northern area or first area of Ensanche, the eastern area corresponding to Santa Lucía's neighborhood, the western area referring to La Concepción neighborhood, and finally, the area that included the San Antonio Abad and Peral neighborhoods. In addition, it contemplated a large English landscape-style park that included various spaces for recreational activities (Ródenas López 2016).

This new area of urban growth was connected to the old enclosure by means of a large, circular square, the *Plaza de España*, in front of the gate, *Puertas de Madrid*, from which the *Alameda de San Antón* and *Paseo Alfonso XIII* streets began as the new main axes. These large roads, embellished with trees, became the place chosen by the middle class and the bourgeoisie to establish their residences. Consequently, unlike the extensions of other Spanish cities, such as Madrid and Barcelona, which were characterized by the construction of apartment buildings, in Cartagena, the construction consisted of individual houses surrounded by some landscaped space, more like garden cities (Pérez Rojas 1986).

3 THE MAIN CEMETERY PROJECT OF CARTAGENA

At the same time that the city of the living was planned under the new ideals illustrated by the development of its expansion, the other city, the silent city or cemetery, also emerged as a new urban facility. The new main cemetery, known as *Nuestra Señora de los Remedios*, was designed by the architect Carlos Mancha in 1866 and inaugurated two years later (Archivo Municipal de Cartagena, CH00288).

This monumental cemetery was conceived as a silent city, isolated and far from the urban nucleus, designed to dignify the city it served. Its structure was organized in avenues, streets and blocks, which constitutes a scale replica of the city of the living. A gate gives access to the enclosure and to its central boulevard axis that organizes the space and categorizes the areas. The most representative funerary buildings are concentrated on both sides of the landscaped central axis, which ends with a chapel (Figure 1).

The series of pantheons built along the main avenue of the cemetery also constitute an excellent example of historicisms, collecting expressions from the main architectural styles of the past. The words of Nicolai Gogol (1809–1852), remembered by Hugh Honor, perfectly describe this paradigm: "A city must exhibit a great variety of masses if it is to be pleasing to the eye. Within it, the most varied tastes must be harmonized. That in the same street there is a dark Gothic building, a building in a colorful oriental style, a colossal Egyptian structure…We would thus have a street that would be at the same time a chronicle of the architectural history of the world" (Honour 1981).

This funerary architecture, although designed by the same architects and conceived according to the same artistic movements as urban architecture, has not received the same attention and conservation as

Figure 1. The main cemetery of Cartagena, plan of the current state and aerial view. Images: authors, 2020.

the buildings in the city, where many of them have been restored and enhanced. The proliferation of new funerary practices, particularly cremation, has caused these architectures of memory to fall into disuse and oblivion, leading to serious maintenance difficulties.

4 THE PEDREÑO Y DEU PANTHEON: AN ARCHITECTONIC AND CONSTRUCTIVE DESCRIPTION

One of the most significant pantheons in *Nuestra Señora de los Remedios* cemetery in Cartagena is the one of the Pedreño y Deu family. Located very close to the entrance and on the first line of the boulevard axis, it was also created by Carlos Mancha in 1872. As in the family's urban residence, its design was clearly inspired by classicism (Figure 2). In addition, most likely at the request of the family, it consisted of a replica of the Boode Family Pantheon in the Parisian Père Lachaise Cemetery. However, the original building was not used as a model, but a lithograph from 1864 served as a reference. Some decorative motifs found in the lithograph are present in the Pedreño y Deu Pantheon but not in the Paris one (Moreno Atance 2005).

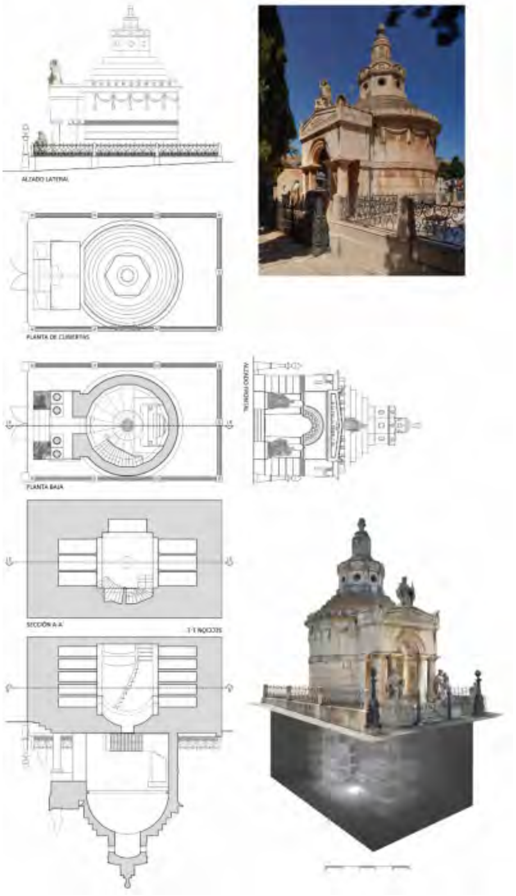

Figure 2. The Pedreño y Deu Pantheon, photography, 2D plans and 3D model. Images: authors, 2020.

The pantheon consists in an underground, rectangular crypt and a circular chapel, with an altar, on the ground floor. The crypt or burial area is accessed by a semicircular staircase which originates on the ground floor. The crypt, illuminated by a skylight in the geometric center of the floor above and by the stairwell, contains niches for burials along its four walls. There are 36 niches altogether, arranged five high on three of the walls and two high under the staircase on the fourth wall. The plot on which the monument is placed is enclosed by a metal fence with some cast-iron elements. It measures 85 m^2 (approximately 7 x 12 m^2) and is completely occupied on the underground level, while the ground floor of the chapel forms a cylinder with a diameter of 6.5 m (Muñoz Mora 2020).

The composition of the funerary chapel refers to the Roman Pantheon with a central cylindrical windowed tower, which is crowned with a carved pinecone shape. Extending from the main facade and framing the door, a portico with Doric columns supports a semicircular arch topped by a pediment bearing the name of the family. The funerary chapel has a crenelated cornice and a stepped pyramid crowning. The ensemble is decorated with plant motifs. Three sculptures represent the three virtues (Faith, Hope and Charity), two in front of the façade and one on the pediment. The decorative motifs and sculptures are attributed to the sculptor, Francisco Requena (1840–1909), who collaborated with Mancha in the decoration of his buildings as well as being the author of numerous funerary sculptures (Ortíz 2012).

The structural system of the main body is made up of load-bearing walls of blocks of natural stone about 55 cm thick. The horizontal structure is resolved with spherical vaults; the top one is a hemispherical vault with a cylindrical roof lantern made out of quarried stone arranged in concentric circles. The vault of the crypt is a reduced segmental vault on pendentives, also made of stone, but in this case, overlaid.

In terms of the roof coverings, different solutions can be observed. The roof of the chapel presents a tiered exterior, while the covering of the entrance portico and the part covering the crypt, which extends beyond the contours of the chapel to occupy the full dimensions of the plot, are flat.

In the interior, the flooring of both levels is of white marble which, on the ground floor, is cut radially and in large pieces, while in the crypt, the pieces are smaller and square. In the underground level, the vertical paraments and the ceiling are also covered with the same marble as that used for the floor or with a continuous covering of plaster which, in the case of the segmental vault and its pendentives, contains remnants of pictorial decoration.

The pantheon was built using natural stone ashlars and large elements made of cast stone (sculptures and decorative elements such as shrouds, hourglasses, etc.). Stone was the principal element of construction, which forms part of the enclosure, the roof and the coverings.

Stone was also the material used in other important pantheons in the cemetery, such as the Aguirre Pantheon (Víctor Beltrí y Roqueta, 1906), the Celestino Martinez Pantheon (Víctor Beltrí y Roqueta, 1921), the Pedro Conesa Calderón Pantheon (Carlos Mancha, early-20th century) and the Hinojal Pantheon (attributed to Lorenzo Ros, 1920–30), among others.

A few kilometers outside the city of Cartagena, there is a quarry whose sandstone, popularly known as tabaire, was used from the late-third century BC up to the mid-20th century to build some of the most emblematic buildings in the city: the Punic Wall, the Roman Theater and Forum, Eclectic and Modernist buildings in the historic center, etc. However, this stone was not chosen for the Pedreño Pantheon. The reason is probably because this soft stone is easy to extract and carve, but deteriorates easily. On the facades of some urban building made of tabaire stone, significant reliefs and chromatic alterations caused by exposure to the elements can be observed.

The stone used to build the pantheon appears to be bateig, which is a biocalcarenite stone quarried from the neighboring province of Alicante and is highly valued for its mechanical characteristics, its appearance and its color.

5 PATHOLOGIES AND RESTORATION OF A CONSTRUCTION SYSTEM BASED ON NATURAL STONE

The action of time has left its marks on these funerary constructions which, in many cases, have not been repaired since their inauguration or are suffering from previous restoration interventions. The Pedreño Pantheon is about 145 years old and its state of deterioration is advanced. Fortunately, after years of neglect, the property was ceded to the Cartagena Town Hall in 2018 and the first phase of its restoration took place in 2020.

The restoration works had to take into account that the building received official protection in 1987, when it was included in the building catalogue of the General Municipal Ordinance Plan of Cartagena (*Plan General Municipal de Ordenación de Cartagena*) approved that year. It was given grade 3 protection, under which "Adaptations or modifications are permitted as long as the essential elements or parts of the building are preserved. Among these essential elements, the facades, as configuring shapes of the urban space, are included".

In the first place, a planimetric survey was carried out using the latest graphic techniques available: drone flight, photogrammetry, computer-aided drawing and 3D rendering.

The different pathologies were also identified and divided in this restoration project according to their pathological processes: physical damage (deformation, cracks, detachment, breakage and damage caused by impact), mechanical damage (humidity, deposits, dirt, and accumulation of dust) and chemical damage (corrosion, efflorescence, biodeterioration, microorganisms, nests).

The first restoration phase surveyed the condition of the building envelope with the aim of keeping water from entering the building. Water damage was seen as the most important problem. In addition, the facade was cleaned and the missing parts of the moldings, cornices and sculptures were replaced (Figure 3).

Before beginning the work, images were obtained with a Dinolite AM 1443 T digital optical microscope. Samples of stone fragments that were about to detach and crystalized salts were also taken. This information allowed us to determine which parts of the building had been constructed with cast stone and which parts with natural stone, as well as dating the superficial color and texture before cleaning.

After the phase of extracting data, the existing biodeterioration in the upper parts of the funerary chapel and some parts of the building envelope was eliminated. Thereafter, the entire exterior surface was cleaned mechanically from top to bottom with high-pressure jets of water. In order to do this safely and not damage the stone, tests were made to determine the

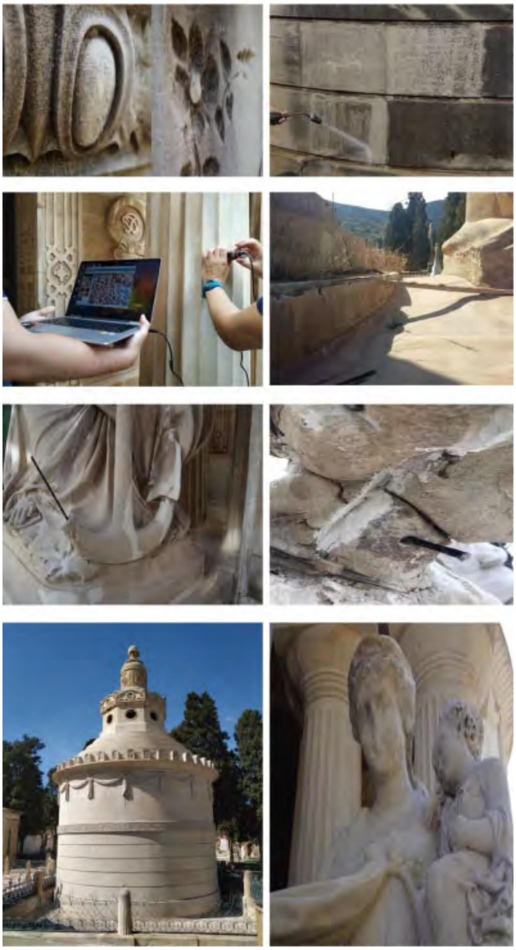

Figure 3. The Pedreño y Deu Pantheon, stone deterioration patterns: analysis and intervention processes. Images: authors, 2020.

correct pressure and angle of the water jets. After this cleaning (at 220 bars), a dark brown crust remained in some areas. In these areas, a slightly more abrasive wet sanding (with siliceous sand) cleaning method was used. This was only applied to the paraments of the facade, while an application of chemical agents formulated by the Instituto Centrale del Restauro di Roma; AB 57, was used on the moldings and cornices. AB 57 is a product made of bisodium salt and other slightly alkali salts (bicarbonate and ammonium) and a surfactant fungicide. The application of this chemical agent to the stone is made using paper pulp of pure cellulose absorbent fibers, which only partially swell with water without dissolving and it is largely insoluble in solvents.

Once the entire exterior surface was cleaned, a fungicide was applied. A concentrated liquid preparation of substances with the principal active ingredients of octylisothiazolinone (OIT) and ammonium salts were dissolved and used in the preservation and repair of microbiological attacks to the stone. Any biological remains that could still exist inside the porous stone would thereby be eliminated.

After applying the fungicide to the entire building envelope, all the vertical and horizontal mortar joints of the hemispherical roof were first cleaned and then sealed with mortar made of Saint Astier Natural Hydraulic Lime (NHL), sand, and specific additives. Then, a bicomponent, salt-resistant elastic covering based on lime and eco-pozzolana and free of cement was applied.

The chosen treatment aims to consolidate the stone and prevent water seepage through the roof without altering the aesthetics of the building. In this sense, inorganic materials are considered highly desirable for consolidating stone because of their chemical and structural compatibility with the substrate. The most suitable inorganic material for stone consolidation is calcium carbonate since it is the main component of the stone itself. However, treatments containing organic materials, such as asphalt, often show insufficient compatibility with substrates, inducing the formation of incompatible, superficial films that can accelerate stone deterioration (Pesce et al. 2019).

At the same time, the volumetric reintegration of some of the eroded pieces or those which had lost a large amount of their original shape including the sculptures was carried out by a sculptor with expertise in restoration. The material chosen for this reintegration was a mortar made of NHL, sand and special additives, which were applied to the cornices and trim elements as long as it could be possible to determine the original shapes of the elements based on their existing parts. Some elements, such as the columns of the pediment or various stone blocks in the cylinder had holes produced by bullets fired during the Spanish Civil War. In this case, they were left untouched, to leave evidence of a bygone era and the traces of time and historical events that impacted the building.

In the interior part of the hemispherical vault under the roof and under the pediment at the entrance, the concentration of mineral salts caused by water entering the pantheon was quite abundant. To eliminate these salts, the affected areas were brushed with a pig bristle brush and demineralized water. This did not achieve the expected result, as salt crust remained. Therefore, sepiolite was used.

The cracks detected in the area of the pediment went beyond the stone that covered it (about 8 cm thick) and produced serious stability problems for that part of the building. For this reason, it was necessary to remove the loose pieces to clean and repair their back side and then affix them using corrugated fiberglass rods and epoxy resin.

The steps leading to the entrance of the monument were in very poor condition. Therefore, it was necessary to reconstruct them using an epoxy mortar made of selected inert materials of various colors and granulometry. After reticulation, the selected mortar offers great mechanical and dimensional resistance as well as chemical inertness and high stability to atmospheric agents. In addition, a product that could be worked on (molded, chiseled, etc.) as if it were natural stone was chosen.

Once all the above procedures were carried out, a water-repellent surface hardener with a base of oligomeric polysiloxanes in a solution of white spirit D40 was applied to all the surfaces, excepting the areas affected by salts (the lower part of the pediment). Polysiloxane provided water-proofing properties to the solution.

To prevent different types of animals from nesting within the pantheon, textile mesh was placed in the oculi of the roof lantern and over the grills that cover their interior access. In addition, to prevent birds from perching on the sills of the roof, bird repelling systems have been placed on the inside of the oculi.

6 CONCLUSIONS

The hygiene and health regulations adopted in the early-19th century resulted in the separation of the living and the dead, people who had shared the same space of the city for centuries. As a consequence, a new urban installation, the cemetery, was created to house the dead. These new silent cities were designed along the same lines as the living cities they served (Saguar Quer 1995).

By the end of the 19th century, most important European cities underwent profound urbanistic and architectural changes in accordance with the thinking in of the time. The silent cities were not exempt from the same tendency, since the most important architects of the moment were hired to design them.

Two models of cemeteries were developed in Europe: the garden cemetery, which was open and more common in northern countries, and the monumental cemetery, which was enclosed and more often found in southern countries, such as Spain.

The cemetery of Cartagena corresponds to this second typology. Its study reveals urban, architectural and constructive patterns similar to those existing in the cities: the cemetery, conceived as a closed enclosure, has its counterpart in the historic walled city and, in both the access, is through a gate that leads to a main circulation axis; in the interior space the axis is materialized by a wide landscaped avenue that organizes and hierarchizes the whole according to a grid, as occurs in the widening area of the 19th-century city; in both the city of the living and the city of the dead, the privileged classes occupy the relevant areas due to their location and perspective, while the common people are relegated to the background. Funerary architecture, like urban architecture, represents the social status of the family, with the bourgeoisie resorting to individual constructions (pantheons) built following the same architectural formalisms and construction techniques used in urban residences, while the common citizen is buried in modest tombs.

The action of time along with socio-economic and demographic evolution combined with the ongoing transforming influence of humans have resulted in the loss of important architectonic creations in the city of the living. The city of the dead, however, has not been subject to such intense urbanistic pressure, and still conserves interesting funerary constructions. Unfortunately, it has been and continues to be the victim of forgetfulness and, consequently, neglect. Funerary buildings constitute valuable cultural heritage as examples of an era and social environment, in addition to their exceptional constructive and architectonic quality.

It is possible to go back to the first architectonic archetypes to find construction systems based on stone masonry. The construction of vertical elements came first, and horizontal construction systems came later with the improvement of building techniques. Since the 10th century, spheric vaults (sometimes of hemispherical domes on pendentives), sail vaults, or rib vaults helped to define different styles and architectonic periods (Rabasa Díaz 2000).

The resistance to the action of time that this constructive system based on stone presents has been evidenced by a great number of buildings that make up the built heritage of our cities. The Spanish late-19th-century cemeteries are, in many cases, enclosures which contain funerary constructions with high heritage value. The pantheon which appears in this work is a good example.

In addition to its stylistic value, this study has focused on the modern stone constructive system of the Pedreño y Deu family pantheon in the main cemetery of Cartagena. The constructive system used 148 years ago to build this silent dwelling is an example of what is currently called massive stone construction. It is quick, fire-resistant and leaves a small carbon footprint compared to concrete. It is not surprising that stone, the great forgotten material of our times, is gaining renewed interest.

The multiplicity of functions offered by the graphic restitution of historic buildings through the use of the latest techniques stands out. In addition to being used for the graphic definition of any intervention project, it constitutes a complete and exhaustive documentary record of the state of the building in a specific moment and this graphic material is, in turn, useful for any dissemination strategy focused on its enhancement.

In summary, this communication attempted to show the importance of taking action to preserve the silent, architectural, funerary heritage through the presentation of the restoration process of a neglected and forgotten building. After the elimination of the pathologies, it has recovered its original excellence.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Building controls in New Zealand: A brief history, 1870 to the 1930s

N.P. Isaacs
Victoria University of Wellington, Wellington, New Zealand

ABSTRACT: From the earliest European settlement in the 1840s to the current day, New Zealand has had a range of building controls. Initially, provincial government legislation covered only larger population centres, but following passage of the Municipal Corporations Act 1867, local authorities could make their own by-laws. Subsequent revisions increased by-law coverage. By 1923, at least 37 towns, boroughs and cities had their own (often different) building by-laws, but it was not until the 1931 Napier, NZ, earthquake that the 1935 national "Standard Model Building By-law" NZSS 95, complete with seismic requirements, was created. This paper reviews the evolution of building by-laws in two major cities – Dunedin and Wellington – from 1876 to the 1930s. It explores the issues and materials controlled in each major change in the by-laws as well as the reasons for change. By comparing the requirements between the two cities over time, it explores how these represent changes in construction systems, methods and materials as well as responses to different natural and man-made disasters.

1 INTRODUCTION

Traditional societies, including the Maori of Aotearoa/New Zealand (NZ), have long had customary rules around the construction and use of buildings. For example, during the English Captain James Cook's first voyage of discovery, the naturalist Joseph Banks recorded on 21 October 1769: "Every House or small knot of 3 or 4 has a regular necessary house where everyone repairs and consequently the neighbourhood is kept clean" (Beaglehole 1962). European colonization led to ever increasing controls for a variety of building types.

The 1840 signing of the Treaty of Waitangi between the English Crown (Queen Victoria) and the indigenous Maori led to increasing European immigration. Once their houses were built, the first national building control was to limit flammable construction – The Raupo Houses Ordinance 1842 (raupo is a swamp reed similar to the bullrush). As towns grew, fire resistant construction (brick, stone, and later concrete) was also promoted by controls. Although initially seismic dangers were not well understood, major earthquakes in 1855, 1869, 1870, 1888, etc. helped the new settlers understand the dangers of living on lively ground (Isaacs 2012).

Local councils of large cities initially relied on Provincial or Central Government legislation as a basis for building controls. By 1867, the cities of Auckland, Dunedin and Christchurch had building controls under provincial legislation covering issues such as structure, fire, chimneys, roofs, verandas, and street front projections, as well as dangerous buildings and the ability to require an inspection fee to ensure compliance (and penalties in case of non-compliance). Nevertheless, Dunedin's Otago Daily Times reported on 18 April 1863: "much still remains to be due in order to transmute these flimsy and perilous structures into more permanent and secure edifices of brick and stone" (Isaacs 2012).

1.1 *Authorization for local government*

The Municipal Corporations Act 1867 allowed local government (councils) to have by-laws to regulate buildings (13th Schedule, Part V), including:

(a) to prohibit or restrain use of combustible or dangerous materials;
(b) the distance between buildings;
(c) wall dimensions & materials;
(d) fireplace & chimney construction & materials;
(e) erection of temporary structures (e.g. tents);
(f) time for the use of non-complying building, roof, fireplace, furnace, or chimney;
(g) to set fees "not exceeding £2 in each case, for any inspection, superintendence, or other service performed by the Borough Surveyor or other officer of the Council" (£2 in 1876 ≈ €190 in 2020).

The Act permitted the replacement of 19 different laws for the management of just 20 incorporated towns (NZ Parliament., vol. 1, pt 1 2 Aug 1867) This coverage was continued and extended by the Municipal Corporations Act 1876 (Part XI, Section 349(5)). This Act also gave adult women the franchise, albeit only as a property-owing citizen (Sutch 1964).

The Abolition of Provinces Act 1875 allowed provincial legislation to remain in force. Sixteen years later, the Provincial Ordinances Act 1892 continued the Auckland Building Act, Dunedin Building and Christchurch Fire Prevention Ordinances. The Auckland and Christchurch legislation was repealed by the

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Statutes Repeal Act 1907, and that of Dunedin by the Building Amendment Act 1993.

The Municipal Corporations Act 1886 further extended the coverage of council by-laws, although buildings continued to play a minor part – less than 8% by count of the by-law coverage for all three acts. Analysis of a part of the chimney by-law shows a direct link to the (London) Metropolitan Building Acts 1844 and 1855 (Isaacs 2018a).

Local government continued to implement and develop their own building by-laws. By 1923, 37 towns, boroughs or cities had their own by-laws dealing with the use of timber in construction (NZ State Forest Service 1924)

1.2 *Early attempts at national building by-laws*

The first attempt to create a national building code, albeit only for timber frame buildings, came from the 1924 "Building Conference Relating to the Use of Timber in Building-Construction", which, in turn, made use of the 1922 American "Recommended Minimum Requirements for Small Dwelling Construction" (Isaacs 2018b). The 3 February 1931 earthquake, which destroyed the Napier City CBD and shook the rest of the country, led to a demand to include seismic issues in building codes. Central Government appointed a Building Regulations Committee which advocated a uniform Building Code and this, in turn, became the ten-part New Zealand Standard Model Building By-law (NZSS 95), first published in 1935 (Galbraith 1939). The ten sections were able to be adopted in part or whole, and/or amended as the Council (or more likely the city surveyor or engineer) desired.

2 BUILDING BY-LAWS 1870–1930

This paper explores the development of building controls under the Municipal Corporations Acts in two major 19th-century cities, Dunedin and Wellington. It covers the period from 1870 to the 1930's, prior to the adoption of NZSS 95. Building controls in Dunedin had been in place under Provincial Government legislation since 1862, but this was not the case in Wellington (Isaacs 2018a).

2.1 *Analysis process*

A complete set of building bylaws for Wellington and Dunedin were identified and then obtained. The Municipal Corporations Acts 1867 (Section 191) and 1876 (Section 340(2)) required by-laws be published, although from the Municipal Corporations Act 1886 only public notification was required. An extensive search of the online historic newspaper database PapersPast (paperspast.natlib.govt.nz) and the official New Zealand Government Gazette provided initial lists of such notifications. Wellington and Dunedin City Archives assisted the researchers to obtain electronic copies of by-laws, regulations, and amendments which were transferred to a word processor file and then to a spreadsheet database for analysis.

2.2 *Dunedin city*

The first Dunedin "Building Regulations" (passed 23 February 1870, in force 25 May 1870, 54 clauses) were part of the 1870 "General By-laws for the City of Dunedin". The 54 building clauses provided for: classifications; permit application processes; construction of footings and pier foundations; party walls; external walls and chimneys; construction of auxiliary buildings close to dwelling houses; the regulation of building districts; and applicability of certain regulations. They were under the control of city surveyor, Samuel H. Mirams (formerly of Melbourne) (White 1993).

These regulations were amended in 1874 (22 July 1874, 55 clauses), possibly in response to major land reclamation increasing the area of the commercial zone, with minor changes plus the addition of requirements for commercial ovens, furnaces, etc., to be made of brick or stone and at least 18 inches (46 cm) away from nearby buildings.

The Municipal Corporations Act 1876 increased council's powers, so amendments were made in 1877 (24 August 1877, in force 26 September 1877, 64 clauses). These included reducing fire risk restricted buildings, planning and the administration of construction. The three main changes were with respect to penalties, chimneys, and walls.

Following the 1879 "Octagon fire" in the central business district, the 1881 amendment (1 November 1881, in force 1 December 1881, 70 clauses) again increased complexity and made minor changes, principally with respect to structure, interpretation and penalties for non-compliance. The use of fire-resistant lath-and-plaster for wall linings was promoted over (timber) tongue-and-groove panelling.

Additional powers were given to councils under the Municipal Corporations Act 1887, so the 1890 revision (12 November 1890, 74 clauses), both consolidated all city by-laws into a single document and continued the focus on protection from fire, structure, and the use of stone and concrete for construction. The erection of tents was, for the first time, constrained in Dunedin.

Following the amalgamation of Dunedin City Council, the Caversham, South Dunedin, and the North-East Valley Borough Councils into the City of Dunedin, the 1912 by-law (24 January 1912, in force 1 April 1912, 217 clauses) consolidated and amended the existing by-laws. The replacement, in 1906, of long-serving city surveyor S.H. Mirams by consulting engineer George Gough (formerly of Scotland) (Cyclopedia Company Limited 1905) helped set the scene for this major revision.

These first by-laws of the 20th century were revolutionary, dealing with larger scale buildings under a more controlled building process. For the first time, clauses were added dealing with open space in new developments, ventilation, safety, and safe egress. The 1906 San Francisco, USA, earthquake had established the benefits of reinforced concrete which were also incorporated.

The next change, not analysed in this paper, incorporated the New Zealand Model Building By-law NZSS 95 into the 1936 Dunedin City by-law (6 July 1936, in force 1 September 1936).

2.3 *Wellington city*

Wellington had general by-laws in 1871 that dealt with nuisance, maintenance of public places, offensive trades, horse and carts, and fire. It was not, however, until the 1873 Building Regulations (23 December 1872, in force 1 June 1873, 43 clauses) that there was coverage for the construction of walls, chimneys, fireplaces or furnaces and architectural elements.

The 1877 Building Regulations (1 November 1877, in force 1 January 1878, 37 clauses) divided the city in to four districts, each with specific provisions, while refining coverage. Before its passing, a draft of the proposed regulations had been discussed at a conference of architects and the city surveyor – a process to be continued in future years.

An amendment was passed on 12 March 1878 which was then incorporated in the 1879 Building Regulations (9 September 1879, in force 1 October 1879, 42 clauses). A fire in the city on 15 June 1879 destroyed 30 buildings across 10 acres (4 hectares) (Evening Post, p. 2, 16 Jun 1879), possibly leading to the requirements for the removal of shingle (timber) and its replacement by non-combustible roofing. Minor amendments were passed in 1880, 1881 and 1882.

The 1888 Building By-law (12 January 1888, in force 1 April 1888, 50 clauses) was the first prepared by new city engineer, Mr. B. Loughrey (formerly of Melbourne) (Evening Post, p. 2, 30 November 1883). Fire continued to be an ever-present danger, with major fires in 1885 and 1887. The primary focus of the by-laws continued to be on walls, chimneys, fireplaces, and roofs but with greater emphasis on planning and permits.

Mr Loughrey finished in 1889 and his assistant Mr G. Wiltshire was promoted to city engineer. Minor changes were made in the 1891 Building By-law (7 January 1892, in force 1 February 1892, 56 clauses).

The 1896 Building By-law (10 February 1896, in force 1 April 1896, 80 clauses) provided consolidation as well as division of the city into three districts and introduction of the city engineer (replacing the city surveyor) as the inspecting officer. Safe loading capacities were introduced for floors and roofs, while bracing and fixings were detailed for wooden buildings.

In 1898, the city's by-laws were consolidated (in force 1 June 1898, 86 clauses), and included new changes in applications, inspections, piles, sites on reclaimed land and open space. A new city engineer, Mr Rounthwaite, started in December 1898. A further amendment in 1903 (22 October 1903, in force 1 December 1903, 18 clauses) dealt with requirements for plans, building frontages, and enforcement.

Mr W.H. Morton became city engineer in March 1904, remaining until 1924. The Iron or Steel Structures By-law 1904 (21 April 1904, in force 2 May 1904) was the first Wellington by-law relating to construction materials other than brick, stone, concrete or timber.

The by-laws were again revised and consolidated in 1908 (30 January 1908, in force 1 April 1908, 228 clauses), and now included the design and construction of reinforced concrete and steel framed buildings. The old by-laws were reported as being "based on the old London by-law which was obsolete years ago" but the new one "resembles very closely the San Francisco by-laws drafted after the recent earthquake and fire" and was expected to offer "a brighter era ahead for building in Wellington than has been the case for the past ten years" (Dominion, p. 5, 10 Oct 1907).

The next changes, not included in this analysis, were in 1934 and 1940. The 1934 amendment (27 April 1934, in force 7 May 1934) added 114 new clauses to the existing by-laws, the last Wellington-specific by-laws, although following the framework of the yet-to-be-published NZS 95. The 1940 amendment (22 October 1940) resulted in NZSS 95 Parts I-VI being amalgamated with the existing city by-laws.

2.4 *Reasons for change*

From the original 1870 Building By-laws in Wellington, there were major revisions in 1896 and 1908 and in Dunedin in 1912. From 1890 to 1912, and again from 1913 to 1936, no significant changes were implemented.

There are many probable reasons for this by-law stability, but one possible reason is the person responsible for the by-law – the city engineer or city surveyor – was long serving. In Wellington, for the 60 years from 1870 to 1930, nine people held this role with 11 significant by-law alterations. In Dunedin, over this period, only six changes were made with four people in this position.

Changes also show a reactive response to disasters – major, local fires led to changes in the fire requirements, just as national or international earthquakes led to increased interest in managing the building response to seismic events.

3 ANALYSIS

For each major change, each clause in the by-law was examined, and its application determined under five main topics:

1. What ISSUE does this clause respond to?
2. What is the physical COMPONENT?
3. Who is concerned (PARTIES) with the clause?
4. What time or stage? (WORK TYPE)
5. What are the specified MATERIALS?

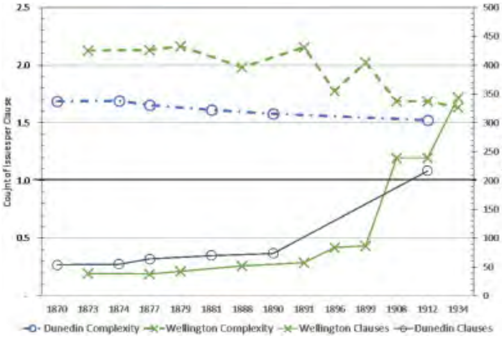

Figure 1. Building By-law Size and Complexity.

Each clause was then entered into standardised templates, allocating:

1. Primary level – Main category
2. Secondary level (refining) – Sub-category
3. Tertiary level (specifying) – Identifying term

To ensure consistency, this process was applied twice: firstly, when each by-law was transferred to electronic form and, secondly, when both cities were complete. Count tables were then generated for each of the by-laws and topics.

It should be noted that not all building by-law clauses deal with a single topic or have only one category level. As a result, it is possible for the counts to be greater than the number of clauses. For this paper, the analysis is based on the counts and, where appropriate, the number of clauses are also given.

3.1 *Comparison*

Figure 1 plots the building by-law complexity and the number of clauses for the various building by-laws. Dunedin is represented by a circle (◯) and Wellington by a cross (x), while the number of clauses by a solid line (right axis) and the complexity by a dotted line (left axis). Complexity is the number of issues divided by the number of clauses – if each clause dealt with a single issue, then the complexity would be 1.

Figure 1 shows two interesting trends – in both cities the number of clauses in building by-laws increased (i.e. grew in size) while reducing in complexity (i.e. clauses were focused on fewer issues). While the complexity trended gradually downwards over the period (reducing from 1.69 to 1.53 for Dunedin, and from 2.13 to 1.63 for Wellington), the number of clauses showed very small growth until the end of the 1890s and then rapidly increased. An examination shows this clause growth was occurring in the coverage of the by-laws.

3.2 *Coverage issues*

As discussed, the coverage of each clause was allocated to appropriate topic categories, the first being the building issue being regulated. Table 1 lists the 12 building issues categories developed by this research, and, for both Dunedin and Wellington, the number under the first (1870 or 1873) and last (1912) building by-law.

Table 1. Count of Building Issues by Category

	Dunedin		Wellington	
Main Issue Category	1870	1912	1873	1912
Access[1]		1		3
Administrative[2]	11	21	13	21
General Provisions	9	53	9	51
Moisture	6	13	5	15
Permit[1]	6	28	4	35
Planning	10	27	6	57
Protection from Fire	30	32	34	44
Safety of Users[1]		13		12
Services & Facilities[1]	4	5	1	15
Stability	15	134	10	146
Utilities[1]		1		
Ventilation[1]		4		4
Sum of Counts	91	331	83	403
Total Clauses	54	217	39	239

For figures combined as: [1] 'Misc.'; [2] 'Administrative + Permit'

The most numerous issues at the start for both Dunedin and Wellington are under the issues of 'protection from fire' and 'stability'. Table 1 shows that by 1912 the number of clauses dealing with stability have the largest increase – in Dunedin starting with 15 clauses in 1870 increasing to 134 clauses in 1912 (8.9 times), while in Wellington stability clauses increased from 10 in 1873 to 146 in 1912 (14.6 times). For this research, 'stability' includes ground stability, structural elements, internal and external forces, structural protection, and durability. Next by count come 'administrative' requirements (measurement, application of rules, etc.) followed by 'planning' (site coverage, encroachments, site layout, subdivision, and town layout).

The number of clauses dealing with 'general provisions' (building classification, permits, interpretation, etc.) increased nearly six times from 1870 to 1912 in both Dunedin and Wellington. The 'utilities' issue related to the planning, owning and operation of electric generation, town gas or water works but it only appeared in the 1870's Wellington building by-laws, as they were moved to more specific by-laws.

There was a large increase in the number of clauses setting out the details of issuing of a 'permit' (required documentation and procedures), but clauses dealing with issues of 'moisture' (rainwater, groundwater, surface water, preventing entry of water) just increased by two in Dunedin and three in Wellington. The provision of 'services and facilities' within a building (hygiene, ventilation, natural and artificial lighting, gas, water, electricity, water and sewerage, management of solid waste) increased in number by just 1.25 times in Dunedin but 15 times in Wellington, albeit from just one clause in 1870 to 14 in 1921.

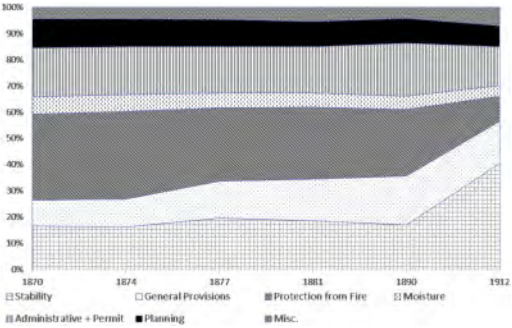

Figure 2. Dunedin Issues Count.

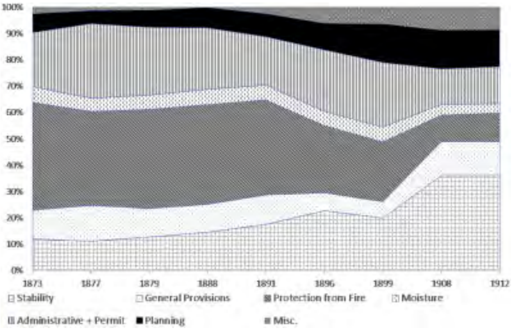

Figure 3. Wellington Issues Count.

Three issues that were not present in the 1870s by-laws appear later: 'safety of users' (safety at heights, hazardous materials, and any other construction work hazards); the provision of 'access' (passageways, exits, etc.) first appears in Wellington in 1908 and Dunedin in 1912, while 'ventilation' for sub-floor moisture management first appears in Wellington in 1891 and in Dunedin in 1912. To graphically track changes in the importance of the various issues over time, smaller categories were combined as noted in Table 1. These are used in Figure 2 for Dunedin and Figure 3 for Wellington which shows the percentage changes over time by count of the different issues. In both Dunedin and Wellington, there is noticeable growth in the relative importance of stability issues. In Dunedin, Figure 2 shows a reducing proportion of clauses dealing with protection from fire but this is a consequence of a relatively small increase in the absolute number.

Figure 3 similarly shows an increase in the count of clauses dealing with stability for Wellington, a reduction in protection from fire as well as administrative and permit clauses, but an increase in the number of clauses dealing with miscellaneous issues.

3.3 *Materials*

Question 5 in the clause analysis concerns the materials subject to building by-laws. Table 2 lists, for the first and last by-law under study, the 11 material divisions developed to categorise each clause. The term 'No material' was used for clauses which did not apply to any material, e.g. issue of permits.

Table 2. Count of Materials by Category.

	Dunedin		Wellington	
Main Category	1870	1912	1873	1912
Concrete & Mortar[1]	13	94	24	104
Concrete Block[1]	-	1	-	1
Exterior Surface[2]	-	8	-	6
Finish[2]	-	7	6	14
Fire Safety	7	9	6	12
Fired Brick & Clay[3]	21	48	20	57
Masonry Elements[3]	1	1	-	3
Metal	20	119	20	124
No material[4]	18	89	12	105
Other[4]	4	7	3	9
Stone	28	44	21	51
Wood	20	47	12	52
Sum	132	474	124	538
Total Clauses	54	217	39	239

For figure combined as: [1] Concrete [2] Finishes [3] Brick, clay & masonry [4] Other + no material

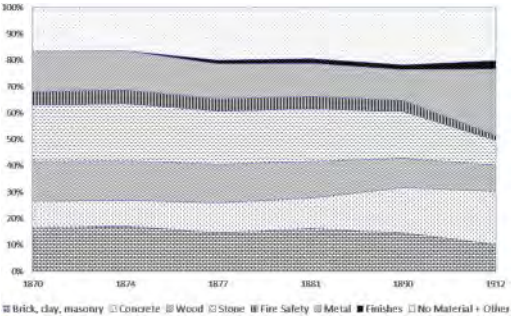

Figure 4. Dunedin Materials Count.

The count increases for all materials, but Table 2 shows that two – 'metal' and 'concrete & mortar' – have very large increases. Although both materials are present in the 1870s by-laws, this increase appears to be a response to changing construction practices with increased use of iron and steel in larger buildings and in-situ or off-site prefabricated concrete in a range of building types. 'Concrete block' refers to solid concrete blocks used for foundations of veranda posts, except in Wellington where 'cinder' or hollow blocks first appear in 1908. Hollow concrete blocks were first used in Wellington in 1904, but they were not widely used until after 1910 (Isaacs 2015).

The notes to Table 2 document the category combinations used for Figure 4 for Dunedin and Figure 5 for Wellington. The figures show the percentage changes over time for the count of the different materials. The counts of 'other' are small in Table 2, so have minimal impact on the combined grouping.

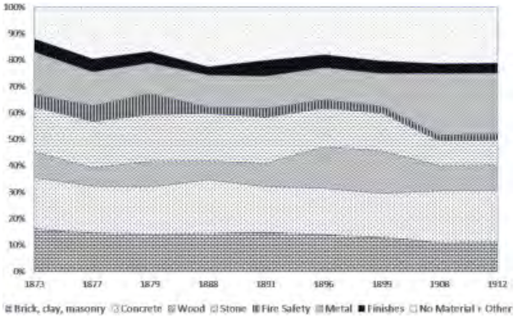

Figure 5. Wellington Materials Count

In Dunedin, the large decline in percentage of ‘brick, clay masonry’ and ‘stone’, along with a smaller decline in ‘timber’, are matched by increases in the percentages of ‘concrete’, ‘metal’ and ‘no material + other’, and the inclusion of ‘finishes.

For Wellington, the changing pattern of materials is similar to that found in Dunedin. The proportions of ‘brick, clay masonry’ and ‘stone’ decline, while ‘concrete’, ‘metal’ and ‘no material + other’ increase. ‘Finishes’ were present from the 1873 by-laws.

4 DISCUSSION AND CONCLUSIONS

This paper contributes to an understanding of the development of the rules around construction, and hence to construction history.

British Prime Minister, Sir Winston Churchill is reported as saying in 1943, referring to the rebuilding of the debating chamber in the House of Commons: “we shape our buildings and afterwards our buildings shape us” (UK Parliament 2020). The same conclusion could be made with respect to building controls. Although building controls seldom specify design requirements, they can be interpreted to create tedious uniformity or interesting variations.

This paper has presented an analysis of the evolution of building by-laws in two key 19th century New Zealand cities – Dunedin and Wellington – over the period 1870 to the 1930s. Lists of 12 building issues and 11 material types were developed by this research. Future research is planned to examine the remaining topics identified in Section 3: component; parties; and work type.

The by-laws of the late 19th and early 20th centuries covered what many still consider to be the central issues of building controls: fire, structural safety, ventilation, management of water and the management of construction, etc. Safety of users, access and subfloor ventilation do not appear until the beginning of the 20th century. Although an issue of structural safety, earthquake specific design first appears after the 1906 San Francisco, USA, earthquake, with the 1931 Napier, NZ, earthquake leading to major changes including the creation of the first NZ Standard Model Building By-law.

As new materials were developed, or older materials were used in new ways, by-laws adapted. Stone, although a permanent material, did not perform well under seismic loads, so it was joined by the better performing iron and steel framing, as well as reinforced concrete. The new hollow concrete blocks provided greater flexibility and lower cost, so they joined with in-situ concrete.

The revision and updating of by-laws, while formally council’s responsibility, on a day-to-day basis, were under management of the city engineer (or city surveyor). New appointees to these positions were more likely to make changes than longer term occupants who responded to new issues or undertook revisions.

Building by-laws have been shown to increase in size and coverage but reduce in complexity from the 1870s to 1930s. While the two are related (fewer issues per by-law clause require more clauses), the coverage also expanded not only to deal with the greater roles permitted in the various Municipal Corporation Acts but also new issues and materials.

Internationally, there is very limited analysis of the reasons for change in complexity and coverage in 19th-century building by-laws and, even more importantly, the consequences of these on modern building controls.

Of particular interest is Harper’s examination of the English Building Regulations from 1840 to 1914. He concluded that “By 1914, all the main building regulations that were considered essential for the safety of the general public had been established”. On the positive side, these led to improved public health and an acceptable level of sound building construction. On the less positive side, it allowed for ‘by-law houses’ (built with minimum design to minimum requirements) and for the development of controls under “a legal profession which was not overfamiliar with the world or practice of building” leaving “a legacy of many rigid, complicated and often archaic regulations” (Harper 1978, 1985).

This research provides a starting point for a similar examination of the consequences of New Zealand’s 19th-century building controls.

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Private responsibility for public safety: The case of Charles Buddensiek

D. Friedman
Old Structures Engineering, New York, USA

ABSTRACT: Charles Buddensiek went to prison in 1886 for manslaughter after a worker died in the collapse of tenements Buddensiek was building in New York. While there is no question that Buddensiek regularly built unsafe tenements of poor quality construction, he did so in a context of poor-quality speculative building and poor governmental regulation. He was used for decades as an example of the evils of corrupt building practice even as regulation to stop such practices lagged. In short, it is easier to blame individuals than the system in which they operate.

1 INTRODUCTION

Construction history is generally concerned with buildings that are themselves interesting because they are large and complex, because they are monuments, or because they illustrate issues in the development of architecture, engineering, or construction. However, the history of background “boring” buildings can illustrate how government regulation of construction works, or does not work, with structures that do not challenge the standards of the era. This paper examines the “old law” tenements of New York, and the experience of one builder, Charles Buddensiek. In 1901, when new construction of these buildings was outlawed, more than 2,300,000 people in Manhattan, the Bronx, and Brooklyn lived in over 80,000 such tenements.

Old-law tenements, named after the Tenement House Act of 1879, were simple buildings, four to seven stories high and rectangular in plan (the 1879 law required every room to have an exterior-facing window leading to air shafts hidden on the sides of buildings, which was an improvement over the 1867 Tenement House Act that allowed rooms with no outside windows) The exterior walls were masonry, but the rest was wood, including stairs, room demising partitions, center partitions that served as bearing walls, and the floor joists. The minimum legal plumbing was one sink per apartment and one interior toilet or one back-yard privy per twenty inhabitants. With the exception of ornamentation on the front facades, these buildings were all essentially identical, which is not surprising given their number and the speed with which they were built. There was little experimentation with other designs: builders put up buildings that matched the minimum requirements of the Tenement Law and the New York City Building Code, and went no further.

Under these circumstances, a builder had to do something remarkable to attract notice. Buddensiek did: in 1878 he sickened tenants by neglecting to not properly connecting interior toilets to the sewer, and then in 1885 eight of his buildings collapsed and he was convicted of manslaughter. He had built hundreds of tenements, all of which were now suspect. The notoriety from the collapses was so great that his name was used for decades afterwards as a synonym for dangerously shoddy workmanship. However, it is unclear that his building practices were so far from the norm, or were always in violation of the laws as written. In other words, the local standards for construction of these buildings may have been so poor that such incidents were inevitable, and Buddensiek was caught because he built so many tenements rather than because the quality of his work was so much worse than average.

2 NEW YORK TENEMENTS

It is difficult to overstate the importance of tenements in New York housing in the 19th century. The population of Manhattan island – not exactly the same as the population of the incorporated city, but a close approximation until 1898, when the city’s boundaries were greatly expanded – grew from sixty thousand to over two million between 1800 and 1900, with no slowing as time went on. Between 1890 and 1900, the population of Manhattan grew by over half a million people (Hunt, 1901, chapter 4, table 4). After 1900, the outer boroughs absorbed most of the population growth, but this geographic spread was a hope rather than an established fact in 1900. This growth was dependent on an inexpensive form of housing. In 1900, approximately 1,585,000 of the 2,050,600 people in Manhattan were housed in 42,700 tenements, cheaply built apartment houses designed for maximum density (Veiller 1903).

2.1 *Regulation of building construction*

While there have been laws regulating building construction in New York going back to the early days of the New Amsterdam colony in the mid-17th century,

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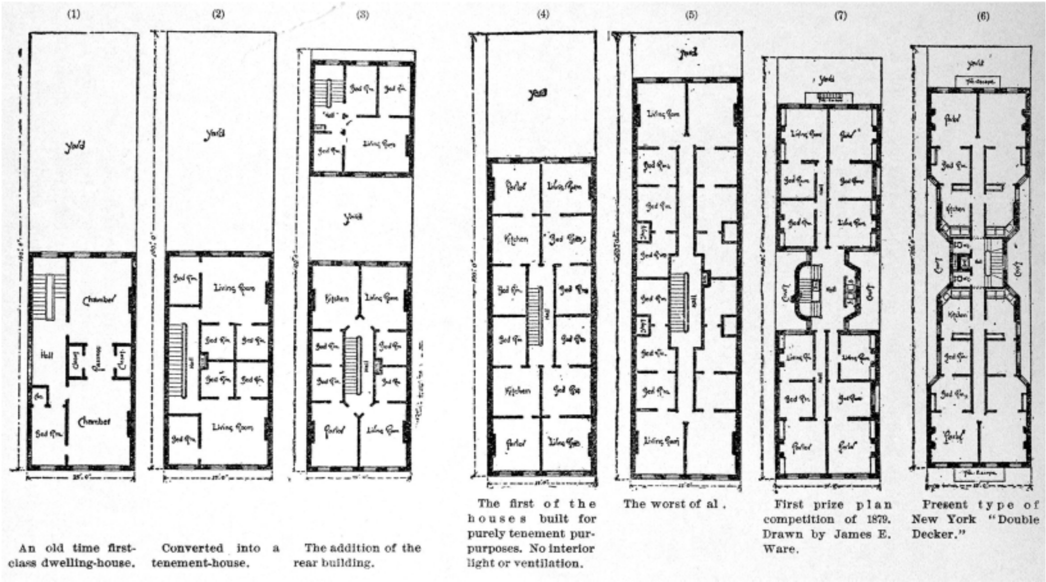

Figure 1. The evolution of the floor plans of Manhattan tenements. From the left, a mid-1800s single-family house; that same house converted to a tenement; a boarding house with a rear tenement; the first purpose-built tenements; tenements built immediately before the 1867 law, showing maximum packing on the lot; the first dumbbell proposal; dumbbell tenements as built under the 1879 law (Tenement House Committee, 1895).

the first comprehensive building code in the city was only enacted in 1882.

The 1887 revision of the building code had more specifics than 1882, and the technical sections of the code were improved through rapid iteration until the 1916 code represented a version that accurately reflected the technology of the time.

The 1882 building code was a mixture of prescriptive language (such as detailed descriptions of the minimum thickness of masonry bearing walls) and subjective descriptions (such as the requirement that exterior walls be "properly bonded and solidly put together, and all such walls shall be built to a line, and be carried up plumb and straight, with close joints"). This mixture of useful information and personal interpretation extended to the description of mortar in section 482, where specific mixtures of sand, lime, and cement were given, but so was less clear language like "No inferior lime or cement shall be used; and all sand shall be clean, sharp grit, free from loam, and all joints and all walls shall be well filled with mortar."

There was a system of city-run inspection that pre-dated the 1882 code, but the small number of inspectors relative to the number of construction sites, and the regularity with which there were bribery scandals regarding the inspectors suggests the system did not work as intended.

2.2 *Regulation of tenements*

The rapid growth of New York meant that housing was always in short supply and that the growth of tenements happened in an unplanned manner. In 1842, Dr. John Griscom, published a report describing 1459 cellars used as residences for 7196 people, with another 6618 families living in courts or rear buildings. Eleven years later, a report by Robert Hartley of the Association for Improving the Condition of the Poor had this as 3742 cellars housing 18,456 people. In addition to those wretched residences, thousands of people lived in single-family rowhouses converted to rooming houses. New York State created the Metropolitan Board of Health in 1866 and enacted a tenement house law in 1867. At that time some 15,000 tenements of various types were already in use. The 1879 revision of the tenement house law (usually referred to as the Old Law) was the first to state a maximum percentage of a lot that could be covered and the first to require all rooms to have a window to the outside. The 1901 revision of the tenement law (usually referred to as the New Law) was the first to require indoor plumbing, at a time when Old-Law and pre-Old-Law tenements still had roughly 9,000 privies in their yards. In 1901, there were more than 350,000 interior rooms with no direct ventilation in pre-Old-Law buildings, reduced to roughly 76,000 by 1914 by the demolition and alteration of old tenements. To give a sense of the continuing growth of the city and tenement use, 22,295 buildings containing 248,815 apartments were constructed under the new law between 1901–1914, housing roughly 1,200,000 people (de Forest 1914) (Figure 1).

3 CHARLES A. BUDDENSIEK AS A BUILDER

Charles Buddensiek was an immigrant, who arrived in New York in 1857 and abandoned his original trade as a butcher for real-estate development and construction in the 1870s. During his 13 years as an active builder, he constructed roughly 2,000 tenements in Manhattan. Following his trial and conviction for manslaughter in 1885, he served seven years in prison and then retired, dying in 1901 (*New York Times* June 17, 1885, p. 3, June 12, 1894, p. 12, and December 25, 1901, p. 5).

3.1 *Plumbing on 51st street, 1878*

In the winter of 1878, the Board of Health examined tenements at 100 and 102 East 51st Street because of a concentration of malaria, typhoid fever, and diphtheria, and because of tenant complaints of the odor of sewer gas. Buddensiek had constructed the buildings in the spring of 1877 for a group of speculative owners including himself. At the time of the court proceedings in February, there were two people ill in 100 East 51st Street and one death in 102 East 51st Street. Thomas Nealis, a "sanitary engineer" working for the Board, described numerous flaws in the indoor plumbing, including gaps in the joints of the clay drain pipes large enough that the sewer gas in some rooms was almost strong enough to extinguish a candle. Nealis's report gave a great deal of technical details about the plumbing, possibly because the governing regulations were vague. For example, the charges against Buddensiek referred to Chapter 636 of the state laws, containing 1874's changes to the enabling legislation of the Board of Health, but rather than mentioning any specific safety violations, referred to a section of the law that stated the board's regulations could be generally used as evidence in court (*New York Times* January 16, 1878, p. 8 and February 19, 1878, p. 2).

The specific text of the New York Sanitary Code relating to this incident is in section 22: tenements had to have "adequate privies or water-closets, and the same shall be so adequately ventilated and in such cleanly and wholesome condition as not to be offensive, or be dangerous or detrimental to life or health. And no offensive smell or gases…shall be allowed…to pass into such house…" In light of this subjective language, it appears that the detail in Nealis's report was an attempt to define such words as "adequately ventilated" and "offensive". Buddensiek was tried for this violation and acquitted (*New York Times* April 15, 1885, p. 2).

3.2 *Collapse on 62nd street, 1885*

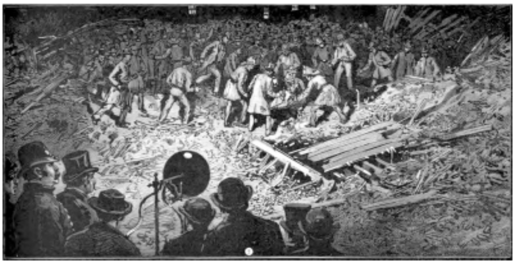

Figure 2. Artist's rendering of the search for wounded workers in the 62nd Street collapse (n.a. 1885c).

In early 1885, Buddensiek was working on a large development on the west side of Manhattan, with rows of buildings on the north side of 61st Street, on the adjacent south side of 62nd Street, and on the adjacent Eleventh Avenue blockfront. On April 13, eight contiguous five-story tenements on 62nd Street collapsed, killing Lewis Walters, a carpenter, and injuring 13 others (*New York Times* April 16, 1885, p. 2, April 21, 1885, pp. 4 and 8, and December 25, 1901, p. 5). Each building was intended for ten families and was 25 feet (7.6m) wide by 83 feet (25.3m) deep, or one standard lot wide and covering the entire lot except for a 17 foot (5.2m) rear yard.

The buildings were nearly complete at the time of collapse, with interior plastering in progress. It came out during the legal investigation that more than 100 men had been working on site the prior day but, because many felt that the buildings showed signs of collapse, only 35 showed up on April 13th (Figure 2).

There were multiple nearly-simultaneous legal proceedings because of the death and the possibility of both criminal and civil violations of law: a police court hearing on April 16 to determine if any crime had been committed, followed by a grand jury investigation on April 17 led to indictments against Buddensiek and Charles Franck (the masonry subcontractor) for manslaughter. A coroner's jury investigated the cause of Walters's death on April 20 and 21. After these preliminaries, Buddensiek was tried in June, convicted on June 18, freed on bail in September during an appeal, and then sent to Sing Sing Penitentiary in June 1886 after the appeal failed. The appeal was reviewed by a higher appellate court and finally dismissed late in 1886. There was testimony from witnesses and experts at each of the proceedings, and the full picture can only be determined by piecing together the five separate court proceedings. Two distinct classes of problems were described: errors in the materials and methods used to construct the buildings, and deliberate obfuscation of responsibility for design, construction, and ownership.

The most damning testimony concerning the physical construction involved the mortar used in the brick walls of the buildings, at the front and rear facades, the end walls of the row of buildings, and the party walls between the individual buildings in the row. The word most often used to describe the mortar was "mud" and "testimony was produced at the trial showing that the loam dug out of the cellars under the collapsed buildings had been used with a little lime shell to serve as mortar." Albert D'Oench, the city's Inspector of Buildings, testified that the mortar was soil from the cellar excavation (loam) mixed with lime, and had no "binding properties" or adhesion (*New York Times* April 21, 1885, pp. 4 and 8, and December 25, 1901, p. 5).

Testimony made it clear how this had happened: August Todenbusch, the masonry foreman complained to Franck about the quality of the mortar; Franck said that there was nothing to be done because Buddensiek would not provide better materials. Todenbusch testified that “We often laid a row of bricks without any mortar between them” and that walls that had been laid up plumb had not remained so because of the poor mortar. Charles Shewerger, a mason, worked on the walls until they were four stories high, and then quit the project because he felt it was unsafe. The conditions were known to Buddensiek, as numerous witnesses testified that he was on site every day (*New York Times* April 21, 1885, p. 4 and 8, and June 12, 1885, p. 8).

James O’Reilly, a mason, testified that Buddensiek supplied the materials, including earth dug on site to be used instead of sand. O’Reilly refused to enter the buildings cellars, and said that he had told Buddensiek that the buildings would fail. W.H. Cornet, a sand dealer, testified that he had never provided any sand to Buddensiek during construction but that a representative of Buddensiek came to buy a load after the collapse and took it to the collapse site, implying that it was used in a cover-up regarding the materials used in the mortar (*New York Times* April 23, 1885, p. 8, and June 12, 1885, p. 8).

Various contractors, including Marc Eidlitz, one of the premiere builders in New York at the time, testified as to the poor quality of the work. Eidlitz made one remark that meant little in the legal proceedings but had larger implications: “He knew of many buildings, which were occupied, in which the mortar was no better than that used by Buddensiek” (*New York Times* April 22, 1885, p. 8).

Besides the well-established technical problems with the masonry, the most damning testimony concerned Buddensiek’s method of conducting business. Testimony showed that he hid his involvement through the use straw-man owners, designers, and builders. For example, Gothold Haug, the reported owner” of the 62nd Street lots, was a watchman employed by Buddensiek, with a standard salary of one dollar per day. George Spitzer, Buddensiek’s bookkeeper, testified that Buddensiek had provided the money that Haug used to paid the costs associated with construction. Spitzer, in those days before professional licensure, was also listed in the filing as the architect for the houses. The coroner’s jury, which was tasked with fact-finding as well as determining responsibility, stated they believed Haug was merely a straw-man purchaser for Buddensiek or others (*New York Times* April 22, 1885, p. 8, and April 23, 1885, p. 8).

Buddensiek’s testimony that he did not know the details of construction but rather hired and relied on experts was contradicted by the testimony that his “experts” were not, that he was on site every day directing the work, and his past history of having complaints lodged against him and his by building department personnel. “Ex-Buildings Inspector Easterbrook” (D’Oench’s predecessor) testified that Buddensiek”used to build many houses and file many plans. Numerous complaints, the witness said, had been made against...He had had contests in court. ‘If I knew that Buddensiek was building a house I would put three examiners instead of one on it.”’ During the initial police court proceedings, D’Oench submitted with his report on the buildings a list of 185 other violations from the building department for the years 1879 to 1885, in the names of seven figure-heads for Buddensiek.” Buddensiek had a similar record with the Board of Health, with numerous violations. Dr. Moreau Morris, Chief of the First Sanitary Division testified“His buildings are of the worst character and have been so for years” (*New York Times* April 15, 1885, p. 2, April 16, 1885, p. 2, and April 21, 1885, p. 4 and 8).


THE HOUSE THAT BUDDENSIEK BUILT.

This is a House that Buddensiek Built.

This is the Mortar used in the House that Buddensiek Built.

This is Greed, the Contractor, a wily old Rat, who supplied the Mortar used in the House that Buddensiek Built.

This is the Cat who caught the old Rat who supplied the Mortar used in the House that Buddensiek Built.

This is the Dog who will worry the Cat who caught the Rat who supplied the Mortar used in the House that Buddensiek Built.

But this is the Cow with a crumpled Horn who will toss the Dog who will worry the Cat who caught the Rat who supplied the Mortar used in the House that Buddensiek Built.

This is a Widow all forlorn, who depends on the Cow with the crumpled Horn to toss the Dog who worried the Cat who caught the Rat who supplied the Mortar used in the House that Buddensiek Built.

This is a Juryman, all shaven and shorn, taking comfort to the Widow all forlorn who depended on the Cow with the crumpled Horn to toss the Dog who worried the Cat who caught the Rat who supplied the Mortar used in the House that Buddensiek Built.

And this is the Cock who will crow in the morn to cheer the Juryman, all shaven and shorn, taking comfort to the Widow all forlorn who depended on the Cow with the crumpled Horn to toss the Dog who worried the Cat who caught the Rat who supplied the Mortar used in the House that Buddensiek Built.

Figure 3. The collapse on 62nd Street as presented in satire (n.a. 1885d).

Perhaps the simplest statement of public understanding of the problems with tenement houses were made in two editorials in the *Times* shortly after Buddensiek was convicted. In the first, they stated that his trade, as everyone familiar with building operations has known for years, and as everybody knows now, was the building of the detestable structures known as speculation houses.

A tenement house of such and such a frontage and depth and of so many stories is a staple article, as much so as a bushel of wheat or a barrel of pork. The price of such a house in such a quarter as is commonly devoted to tenement houses is perfectly well understood. It is understood, also, that the builder of such a house has not built it better than he was required by law to do. A certain average of construction is taken for granted, and enters into the cost of the building. Now, the practice of a number of builders, and very notoriously the practice of Buddensiek, has been to degrade this very moderate standard of construction, to omit precautions necessary to stability and to health, and to use poorer labor and cheaper materials than the law allows for the purpose of cheapening the building, which yet commands the normal tenement house price for a structure of its dimensions. The difference the enterprising 'jerry'builder puts in his pocket." In the second, they stated that "For all these years he has been making and selling houses that he knew to be unfit for human habitation in open violation, or else in evasion, of the law" (*New York Times* June 19, 1885, p. 4, and June 24, 1885, p. 4).

4 SOCIAL CONTEXT

The type of tenements that Buddensiek constructed are not today considered fit for habitation but that type was the norm in New York at that time and not so different from similar tenements in other cities. Even in the context of that era, people understood that there were problems with tenements, both in the architectural compromises made to pack more people onto a given lot and in terms of how they were actually constructed. The first issue shows up in the various government commissions and private organizations investigating tenements; the second was addressed less formally.

In 1887, the *New York Times* reported that the *Sanitary Engineer*, a professional journal not read by the general public, had published a list of prosecutions by the city's Health Department for unsafe traps in drains, unsafe fresh-air intakes, gaps in pipes, and so on. This was a reminder of the words of Chief Shay of the Fire Department of New York in 1885: "In the tenement house districts, comprising the densely populated wards, the greatest danger arises from a disregard of the law in the construction of buildings. The general public has but a very vague and imperfect conception of the extent of that danger" (*New York Times* May 17, 1885, p. 8, and August 2, 1887, p. 4).

A statement of public opinion on this topic came in the verdict of the coroner's jury in April 1885. Testimony had included Commissioner Van Cott of the fire department stating that his department had reported hundreds of violations of law to the Building Department without seeing any action, which he felt showed the inefficiency of having two separate departments. The jurors agreed that the building department was a problem. First, incompetence and neglect of duty by building inspectors Thomas Dailey and Robert Mackey had contributed to Walters's death, because the inspectors had heard a complaint about the site on January 20, 1885, which they dismissed because repairs were supposedly being made, and had filed a report literally days before the collapse saying such repairs were in progress. In addition, the jurors found that the building department "should be an organization of a character and invested with a power commensurate with the dignity and necessities of a great and growing metropolis like New-York, and one under whose administration the construction of anything in the l[e]ast degree analogous to such structures could not be even begun, much less proceed to such an extent as attained by the buildings prior to their fall, and those equally bad and now allowed to stand. We find culpable negligence and looseness of discipline and supervisory control…" (*New York Times* April 22, 1885, p. 8, and April 23, 1885, p. 8).

4.1 *Buddensiek in the national press*

It was common in the 19th century for interesting news stories - read "sensational" for "interesting" - to be reprinted nationally in various forms. Articles from newspapers in major cities might be reprinted in their entirety in small-town papers, might be summarized, or might be summarized with commentary. The last category of reprint is the most informative as it tells us how the national news was seen locally. The examples below are a small sample of the national news discussion of Buddensiek.

One simple summary is an item in the *Ann Arbor Democrat* [Michigan], stating Buddensiek's sentence after his conviction. There is no particular reason for this news to matter in a city of fewer than 10,000 people hundreds of miles away (*Ann Arbor Democrat* July 3, 1885, p. 1). Similarly, the *Daily Evening Bulletin* of Mayville Kentucky reported on Buddensiek's initial appeal (*Daily Evening Bulletin* June 2, 1886, p. 2). Years later, when Buddensiek was released from prison, the *San Francisco Chronicle* stated that "New York and every other city in America is cursed with many Buddensieks, but these fellow generally escape the penalty for their misdeeds" (*San Francisco Chronicle* December 3, 1892, p. 4).

An example of a summary with straightforward commentary is the item in the *Brainerd Dispatch* [Minnesota] on the final review of Buddensiek's appeal that made the news more local by stating "This decision will have a tendency to make contractors more careful, and will prevent such disasters as the falling of the Brackett block in Minneapolis several months ago" (*Brainerd Dispatch* November 26, 1886, p. 1). Less accurate commentary was published in the *Bloomington Progress* [Indiana] which made a passing reference to the collapse killing "about a dozen workmen" (*Bloomington Progress* May 6, 1885, p. 4) The most picturesque commentary, doing the best job of taking this New York story and localizing it, probably is the article in the *Taylor County News* of Abilene, Texas, which called Buddensiek a "wild-cat builder" and stated that he had jumped bail and was fleeing to Canada (*Taylor County News* May 1, 1885, p. 2).

4.2 *Buddensiek as a symbol*

Buddensiek was used as a symbol of social defects before his trial even began. On April 24, 1885, a Socialist Labor Party meeting condemned "the mass murderers, Buddensiek and company" with one speaker stating there were volunteer societies to address crime, but none to look after the safety of buildings, that examiners were as corrupt as contractors, and that the contractors were a disgrace to trade unionism (*New York Times* April 25, 1885, p. 5). This meeting and Buddensiek's history (including the 1878 sanitary incident and the 1885 collapse) were reported in great detail in the *Commonweal*, a London-based journal of the international socialist movement. The article said that the sensation in the press was not caused by the "death of one working man" but rather because "the whole affair is so characteristic of our modern commercial system" including Buddensiek's practices of undercutting union wages and bribing officials (n.a., 1885a).

During Buddensiek's trial, the collapse of a building in Pittsfield, Massachusetts, led the *New York Times* to run an item with the headline "Collapse of a 'Buddensiek' Building in a Massachusetts town." (*New York Times* June 16, 1885, p. 1).

For some years after Buddensiek's conviction, his name was used as journalistic shorthand for "poor quality construction." An 1889 *Times* editorial discussing a boiler explosion in Connecticut that killed 23 people had the headline "Buddensiek in Hartford" and an 1895 *Times* article on the fatal collapse of two buildings had the subheading "Police Reminded of the Buddensiek Disaster – Mortar Described as So Much Dirt." Immediately following the collapse of a small apartment house in 1896, and shortly after two other collapses during construction, a *Times* editorial stated "Buddensiek was tried, convicted, and sentenced for manslaughter and actually imprisoned. But all this happened ten years ago and speculative builders have forgotten that there is any danger in violating the law." As late as 1905, an editorial discussing the collapse of eleven buildings in Harlem, attributed to poor mortar in walls built in freezing weather, was titled The Buddensiek Revival." There was no shortage of poor builders but Buddensiek's name was instantly recognizable (*New York Times* February 22, 1889, p. 4, March 2, 1895, p. 1, September 29, 1896, p. 4, and March 21, 1905, p. 10).

Puck, a satirical magazine, used Buddensiek's name as a synonym for "shoddy" in two political cartoons in July 1885 with regard to news that had nothing to do with him: the quality of ships being built for the US navy (Gillam 1885; Opper 1885).

5 CONCLUSION

Building collapses and lesser, but still serious, failures were fairly common in late 19th century New York. The eleven different building collapses cited in the *Times* editorial of 1905 would be considered a crisis today, while two of the three examples cited in the 1896 editorial concerned serious failures of structural design. In that context, we have to ask why Buddensiek was singled out as a villain. Given the large number of buildings he constructed, it could be argued that having only one major collapse was not so far from the average.

In short, we would consider today that what was criminal is what the laws allowed but he failed to meet even those minimum standards. In terms of sanitary conditions, indoor toilets were not required until 1901 even though New York had a reliable source of water after the completion of the Croton supply system in 1842. Some possibility of fresh air through windows was not required until 1879. In terms of structural safety, there was no legal statement of structural design until 1882 and design criteria were poorly spelled out until 1916. And, of course, having laws on the books means nothing if they are not enforced properly, for example, if building inspectors do not stop poor construction because of either overwork or corruption. An item in the *Albany Law Journal*, which represented the legal community of New York State, congratulated the prosecuting attorneys for their conviction of Buddensiek but also made the point that existing laws protecting human life were not sufficiently enforced. (n.a., 1885b).

An example of action that was legal but at the least showed questionable judgement is that Buddensiek resumed construction on some of his projects while out of prison on bail, after his conviction and before his appeal was denied. (*New York Times* March 19, 1886, p. 3, and March 20, 1886, p. 4). This leads to what is perhaps the most egregious example of the laissez-faire attitude towards safety: three boys were injured in April 1886, a year after the 62nd Street collapse, while playing in Buddensiek's unfinished buildings on 61st Street (*New York Times* April 2, 1886, p. 5). The 61st Street and Eleventh Avenue portions of the development had not been secured in any meaningful manner even though the decision had been made in April 1885 that all of the buildings were to be demolished (*New York Times* April 23, 1885, p. 8). The buildings were finally demolished after Buddensiek went to prison, three months after the boys were hurt.

One possible explanation for Buddensiek's infamy is simply that the collapse was so clear-cut and well publicized in the press: a developer/builder used shoddy materials and killed a man in the process. A short item in *Harper's Weekly* before his trial stated that he should have been charged with first degree murder because the penal code allowed that charge for "an act imminently dangerous to others, and evincing a depraved mind, regardless of human life, although without a premeditated design to effect the death of any individual" (n.a. 1885c). During Buddensiek's trial, his lawyer stated that he was acting in the same manner as rich and powerful developers, that he "believed that the buildings would be secure. He did merely what the Vanderbilts, the Astors, and the Rhinelanders were in the habit of doing. They sought their contractors, and the people whom they believed had reason to believe had the necessary skill and were competent practically and mechanically to do that which they themselves were unable to perform. The District Attorney has told you that he erected 2,000 [tenement] houses in the city of New York. That, according to the census methods of reckoning, means that he has sheltered 100,000 people. Yet, he is condemned by a prejudiced press and a public who would positively hound him into a State prison, because at a disaster, in which his own life was in jeopardy just as much as that of any other man, the life of one unfortunate was lost" (*New York Times* June 19, 1885, p. 8). These two ideas, that Buddensiek was guilty of depraved indifference towards the effect of his actions, and that he was acting in a manner similar to that of other developers and builders, do not necessarily contradict one another.

Another more subtle issue is that the majority of people in New York at that time lived in Old Law or pre-Old-Law tenements, and could see a direct link between this case and their own lives and safety. Despite some 40 years of public discussion of "the tenement problem," it was easier to vilify Buddensiek than to upend the entire system of housing for the city. The latter eventually happened, with the 1901 New Law and its successors, the modern building codes starting in 1916, and the implementation of zoning in 1916. In 1901, when Buddensiek died, an item in the *Times* stated The [62nd Street] case attracted considerable attention at the time, and was the direct cause of new and stringent building laws that have been enforced ever since" (*New York Times* December 25, 1901, p. 5).

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

By-passing the bye-laws: The 1905 Letchworth Cheap Cottages exhibition

A. Coste, S. Sadoux & S. O'Carroll
Université Grenoble Alpes, Grenoble, Switzerland

ABSTRACT: This paper offers an insight into the emergence, development and enforcement of building bye-laws in Britain in the late 19th and early 20th centuries. It shows how some organizations and designers sought to by-pass them and suggests that the Cheap Cottages exhibition held in 1905 in Letchworth reflects such an approach. It summarizes the complex context in which 19th-century building regulations emerged. The legal apparatus is presented as a background against which the cottage exhibition initiative can be explained and understood. The paper also highlights the crucial role of the press in promoting the view that regulations were too stringent and contributed to the rural housing crisis. It also shows that two parallel processes were underway: on the one hand, the development of public policy for health and housing, on the other hand practical experiments which sought to address the same issues, albeit in different ways.

1 INTRODUCTION

Studies of cottage exhibitions can focus on construction and design aspects. Yet, such an approach would ignore most of the originality and intelligence underlying the Cheap Cottage and Urban Housing and Rural Homestead exhibitions held in Letchworth Garden City in 1905 and 1907. This paper focuses on the first of these events.

The practical implementation of Ebenezer Howard's garden city utopia is a challenging subject for historians in the fields of construction, architecture and planning, but also for historians of health, politics or religion. The organization of the cottage exhibitions and competitions in early 20th century British new settlements raises a number of political, social, economic, legal and construction issues. These initiatives can be seen as building and architectural experiments within an urban experiment. They aimed to show that contemporary building regulations, which required the use of specific building materials, hampered designers' ability to innovate and reduce the cost of construction, and thus to provide affordable housing for the working classes in rural areas.

The quality of buildings designed and erected for the 1905 exhibition varies and is on occasions questionable. Yet, these buildings played a major role in promoting the first British garden city. They also reflect the wealth of technical innovations which emerged during that period. This contribution offers a multidisciplinary and critical insight into the emergence, development and enforcement of building bye-laws and shows how some organizations and designers sought to by-pass them. The paper suggests that the Cheap Cottages exhibition held in 1905 in Letchworth reflects such an approach. The success of the exhibitions is assessed in the light of the range of contemporary issues which designers sought to address.

The paper provides a summary of the complex context in which 19th-century building regulations emerged in Britain. The legal apparatus is presented as a background against which the cottage exhibition initiative can be explained and understood. The paper also highlights the crucial role of the press in promoting the view that regulations were too stringent, thereby contributing to the rural housing crisis. The architectural, technical and economic results are then summarized and assessed. Most importantly, the paper highlights the fact that two parallel processes were underway during this formative period: on the one hand, the development of public policy for health and housing, on the other hand practical experiments which sought to address the same issues, albeit in different ways.

2 A COMPLEX CONTEXT

2.1 *The emergence of building control: Addressing fire and health risks and jerry-building*

The origins of development control and building regulations in Britain have been abundantly documented (see for example Booth 2003; Ley 2000). Although some scholars have pointed out that the origins of building regulation in Britain can be traced to the Middle Ages (Cooke 2009), most scholars argue that it should be viewed as a consequence of the Great Fire of London in 1666, and as a legacy of Charles II's Act for the Rebuilding of the City of London dated 1667. This major piece of legislation banned thatched roofs and required all buildings to be built in uninflammable materials, namely in brick or stone.

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In addition, party walls were to be sufficiently thick for them to act as a fire barrier. Such provisions influenced later regulations, in particular those which emerged a few centuries on. The application of rules to the construction of new buildings became widespread from the second half of the 19th century. Although they can in many respects be considered as a continued response to fire risk, they also addressed other contemporary issues such as health hazards and the need to put a halt to jerry-building. Notwithstanding the importance of this latter issue, it will not be addressed within the scope of this paper.

A first milestone in the development of legislation was the Public Health Act 1848. It enabled the state to become the custodian of health conditions and standards. A number of *ad hoc* bodies were set up, most notably the General Board of Health which in turn set up local boards of health whose role was to deal with issues such as water supply, draining and sewerage or refuse disposal. The management and enforcement of such prerogatives was made possible by the appointment, at the local level, of various experts such as medical officers, surveyors and inspectors of nuisances (Brockington 1950; Wilson 1930). Public health legislation was of course a direct consequence of the cholera epidemic of the early 1830s and of a growing awareness that the health of the urban working class was to a great extent conditioned by their living conditions. Robert Slaney, Member of Parliament for the Borough of Shrewsbury, claimed that "in consequence of these vast changes in the social condition of the country, large masses of the population were suffering irreparable injury from the want of proper sanitary precautions" (Hansard HC Deb. 10 February 1848).

The work of Edwin Chadwick contributed to bringing to the fore the question of public health in a ground-breaking manner. The results of his enquiries were published in 1842 in a revolutionary report on the sanitary conditions of the labouring population of Great Britain (Chadwick 1842). The cholera epidemic that swept through Europe in the late 1840s prompted the government to take further action, which included the creation of the General Board of Health. Interestingly however, the work of this body was from an early stage seen to be hampered by vested interests, and regulations were perceived by some as an infringement of individual freedom (Rosen 1958). In the field of construction, building regulations were certainly seen by some as such an interference (*Country Life Illustrated* 1901). This debate famously led Viscount Morpeth to argue that it would "be a waste of words to attempt to prove that authority not only has a right, but that is its duty, to interfere" as regards health (Hansard HL Deb. 30 March 1847).

Despite debates related to the acceptability of such interference with individual freedom, the development of health regulations was pursued and the General Board of Health's prerogatives were at a later stage taken over by the Local Government Board which was founded by the Local Government Board Act 1871. A few years later, the Public Health Act 1875 set up urban and rural sanitary districts throughout the country and required that a local health authority and a medical officer be appointed in each of them, thereby generalizing the provisions of the earlier 1848 Public Health Act. This formative period can be seen as one during which the respective roles of the central and local governments were widely debated. The relationship between these two tiers of government caused much controversy. The experiments carried out in Letchworth as part of the Cheap Cottage Exhibition are in many ways an outcome of these debates. They reflect the complexity of defining building regulations at a national level, and the complexity of applying them to both urban and rural areas, where the context was, of course, very different (Barton 1901). This paper focuses on the building bye-laws that emerged as part of the legislative apparatus which accompanied the various Public Health Acts.

A bye-law has been defined as a regulation made by a local authority or corporation (Stevenson 2010). It is, therefore, a form of delegated legislation (Gooch & Williams 2015) and it is not uncommon for central government to provide draft bye-laws which can, in turn, used by local authorities as a canvas (Law 2018). According to Ley (2000), the emergence of building bye-laws in England can been understood as a process whereby powers were distributed between the local and central levels of government.

The Public Health Act 1875 was a landmark in policy-making. The Local Government Board, a central government body whose role was to supervise local administration, issued model bye-laws as of 1877 (Local Government Board 1877). That year, a circular issued in July encouraged local authorities to use them and draft their own bye-laws. This circular was sent to sanitary authority clerks by John Lambert, the then Permanent Secretary to the Local Government Board (Lambert 1877). In total, 94 model bye-laws were produced by the Local Government Board. These were intended to provide local authorities with a framework they could follow in order to produce their own bye-laws. Their adoption was compulsory in urban areas, but discretionary in rural ones. The topics covered were wide-ranging and included street width, pollution, building foundations, the relation between a room's surface and the size of windows. As an illustration, the Model bye-laws include a section "with respect to the structure of walls, foundations, roofs, and chimneys of new buildings for security stability and the protection of fires and for purposes of health". Here, it is clearly stated that "every person who shall erect a new building shall cause such building to be enclosed with walls constructed of good brick, stone, or other hard and incombustible materials, properly bonded and solidly put together (…)" (Local Government Board 1877). It is worth pointing out that, although these model bye-laws aimed to frame the design and construction of buildings and settlements, the content of the publication issued by the Local Government Board is text-based. The 1877 volume only features one drawing. Building regulation as public policy was thus arguably an administrative, rather than design-based field of action. Such an approach was at the time criticized by a range of observers, particularly by architects (Clark 1877). As we will show, the introduction of these model bye-laws and the extent to which they were suited to rural areas are crucial in understanding the rules set out for the 1905 Cheap Cottages exhibition in Letchworth.

2.2 *The rural housing problem and bye-laws*

Bye-laws emerged in a period of profound change. Of particular importance was the agricultural depression that Britain had been facing since 1871, due to various factors, including free trade and mechanization. The view that urban areas would provide a better future led many to leave rural areas and move to cities. One of the consequences of this trend was that landlords in rural areas were reluctant to invest in the maintenance of cottages for labourers and indeed to erect new ones (Horn 1984). In this context, rural housing became a pressing issue: retaining some workforce in the countryside was required to feed the nation. Various solution to the rural housing problem were put forward at the time.

One is found in the first report of Her Majesty's Commissioners for Inquiring into the Housing of the Working Classes: "Turning to the unquestioned causes which produce overcrowding and the generally lamentable condition of the homes of the labouring classes, the first which demands attention is the poverty of the inhabitants of the poorest quarters, or, in other words, the relation borne by the wages they receive to the rents they have to pay. This is not the place for a full discussion of the wage question. It will be sufficient to attempt to consider what are the usual incomes of the classes especially under investigation" (Royal Commission on Housing of the Working Classes 1889).

The second idea consisted in providing financial assistance to those in need. Zucconi (1985) has argued that one of the roles of the state was then seen to be the redistribution of revenue, and financial aid was one way to achieve this. State intervention could thus regulate the income-to-housing cost ratio. Many people and organizations then endorsed this view, including the Fabians and industrial philanthropists. Zucconi has shown that these debates occurred at a time when studies were carried out in England from 1890 to examine the evolution of the relation between salaries and the cost of construction. In similar vein, he points out that it is around this time that the first results of surveys focusing on household income were published in the *Cornhill Magazine* by Colmore and Layard.

The third idea to address the rural housing problem is what inspired John St Loe Strachey, the proprietor of two periodicals: the *Spectator* and the *County Gentleman.* In his autobiography, he explained: "I have always been, and still am, deeply concerned in the housing question. We cannot be a really civilised nation unless we can get good houses and cheap houses for the working class. Not being a philosopher, I had always supposed that the surest way of getting good and cheap houses was to find some improved system of construction" (St Loe Strachey 1922). According to Strachey, the reason for the difficulties posed by the question of rural housing for labourers is easy to identify and it is economic in nature: "Why are there so few cottages being built in the country, and why is no proper provision made for housing the rural labourers? The answer is quite simple. It costs more to build a cottage than the labourer can afford to pay in rent." (St Loe Strachey 1905) It is this view that prompted him to organize a competition for the construction of Cheap Cottages, which would be showcased as part of an exhibition. He put this idea forward in an article first published in the *County Gentleman* in October 1904 and later reproduced as part of a catalogue for the Letchworth Exhibition (Cheap Cottages Exhibition 1905).

3 CAMPAIGNING AGAINST THE BYE-LAWS

3.1 *A convergence of interests against bye-laws*

The Cheap Cottages exhibition can in many ways be seen as an illustration, and perhaps the climax, of the campaign. Whilst a number of contemporary stakeholders argued that bye-laws should simply be abolished, many rather argued that it is their blind application that should be stopped. A piece published in the *County Gentleman and Land & Water* in 1905 reveals that the complexities stemming from their elaboration and their enforcement were still causing vivid debate several decades after they first appeared. This specific article (*Home Counties* 1905a) quotes the example of a project by R. Macdonald Lucas, an architect, Fellow of the Royal Institute of British Architects and practitioner in Southampton, whose design was rejected by the South Stoneham District Council on the grounds that it did not comply with the bye-laws. Macdonald Lucas criticized local authorities who were seen as unable to provide for the use of new construction techniques including timber and concrete, the latter only being allowed for building foundations. Bye-laws were thus seen as defining methods of construction rather than defining required resistance and performance. This example illustrates the fact that striking a balance between the economy of construction and the need to tackle fire and health risks was complex.

Architects were campaigned against the bye-laws. One particularly active group was the Building Bye-Laws Reform Association, which held its first meeting in February 1903 (British Architect 1903). This organization aimed to "promote amendments to by-laws so that official control of private building shall not extend beyond the demand of public health and safety and thus to prevent encroachments on individual liberty". In 1904, a deputation of members of the Association visited the Local Government Board. Its members argued that bye-laws should not be abolished, rather, they should be better adapted to rural areas in which the context was very different from that of cities. As a result of such actions, the Local Government Board drafted new model bye-laws, which were gradually better adapted to the specific context of rural areas.

3.2 *The press as campaigner, Strachey as leader*

The campaign against bye-laws took place in a range of arenas and one of them was contemporary newspapers and periodicals. Numerous articles were published on the topic, both in newspapers and the nascent specialized press. John St Loe Strachey was arguably one of the main protagonists of this campaign. He argued that "if the agricultural problem and the problem of rural depopulation are ever to be solved they will be by the £150 cottage (…) if the matter is carefully studied it will be seen that we are not exaggerating in our contention that a £150 is what we want to improve our agriculture and to keep people on the land" (St Loe Strachey 1905).

From over a hundred years' distance, readers cannot help but remark J. St. Loe Strachey's optimism and faith in the ability of innovative housing solutions to provide answers to the complex and entrenched historical problems of the rural-urban shift, low agrarian wages and unsanitary living conditions for labourers and their families. This is an early example of the general belief in technical/technological solutions to the recurring crises of modern capitalism, and reflects in particular the formal and functional approach of planning to solving the urban-rural relationship.

Moreover, Strachey is equally vigorous in his defence of the health benefits of the rural over the urban environment in a subsequent passage, relating this issue to the need for a healthy fighting-force, rather than entirely for the concern for the loss of potential man-hours of labour and general health of the working population, which were central to the sanitary reforms inspired by the work of Edwin Chadwick (1842) and his research into the link between epidemics, contaminated water and urban overcrowding. The image of healthy rural activities is joined to the military motive typical of a period when the mounting perils of international conflict were keenly felt by anyone with an interest in politics and foreign relations: "It is clear that the decay in the national physique, which at present is causing so much anxiety to all thoughtful and patriotic men, is due to the decrease of our rural population. It is only in the country, as far as the mass of the population is concerned, that really healthy men and women are bred, yet yearly our population becomes more urban and less rural" (St Loe Strachey 1905).

This deceptively simple economic question, which could even be considered to be knowingly naïve, belies the complexity of conflicting social and economic forces which were fought out during the 19th century and which ultimately led to the domination of the urban over the rural, industry over agriculture, liberalism over protectionism, imported food over national production, and cheaper food for the urban poor over profit for land owners. Simply put, cottages had to be cheaper to build because agricultural wages were low, yet profit had to be made from both the labour and the housing of rural labourers. After a period of protectionism when imports were restricted through taxation, the fear of social unrest, due to high food prices, in the newly franchised urban working-class ultimately led to the dominance of liberal economic policy over landed aristocratic interests.

4 THE LETCHWORTH CHEAP COTTAGE EXHIBITION

4.1 *A competition and an exhibition as a proof of concept*

The Book of the Cheap Cottages Exhibition (Cheap Cottages Exhibition 1905), as the full title suggests, is a catalogue rich in detail: maps, plans, illustrations, advertisements and travel information were designed to inform and entice prospective visitors, while also including a complete section with detailed information about the different jury categories and entries to the competition. For a historian examining the importance of this event and its context this is already a rich variety of material, which can be usefully completed by the catalogue from the 1907 exhibition (First Garden City Limited 1907). Furthermore, the 1905 "Book" also includes several notable articles addressing the wider social and political context in which the exhibition took place, relating directly to the "housing problems" of the day, as identified by the organizing committee and esteemed patrons. The most remarkable, "In Search of a £150 Cottage" (St Loe Strachey 1905), reproduced expressly for the Exhibition catalogue, is significant in this light for several reasons. Firstly, as it was the initial publication of this article in *The County Gentleman* in October 1904 that sparked interest among readers for the subject of the economic and social difficulties caused by a shortage of affordable rural housing for agricultural labourers, simple farmers and rural land-owners. Secondly, John St. Loe Strachey, the author of the article in question, used this platform and his position as journalist, editor and proprietor, to give weight to the argument that innovative thinking, political reform and new ways of building would be needed to address what became known (and still is referred to) as the land or rural question.

Strachey had understood that there was no point in launching studies to come up with innovative cottage designs if these innovative construction methods were illegal in the light of contemporary bye-laws. The aim was therefore to find ways to change the laws, and more specifically bye-laws as applied in rural areas.

The main innovation Strachey relied on was arguably the use of the press in the campaign. In his autobiography, he claimed: "It is our intention to utilize the pages of The County Gentleman in order to help bring about a state of things under which it will not only be lawful to erect a £150 cottage, but also will be possible to discover plenty of firms ready and able to erect such a cottage" (St Loe Strachey 1905).

A contemporary source reveals that the Garden City Company contacted Strachey following the publication of the papers in the *County Gentleman*, and offered him land on which to build cottages on a site "(…) on which cottages would not be subject to unduly stringent building by-laws, and would not have to be destroyed when the Show was over" (Home Counties 1905b). This is far from insignificant. As previously mentioned, many observers and specialists claimed that bye-laws were necessary, but that their content should be tailored to the context in which they were to be enforced. The Letchworth Cheap Cottage exhibition took place in Letchworth Garden city, where bye-laws did apply, namely those drafted by the Hitchin Council (*Observer* 1905). Some of the architectural innovations showcased as part of the exhibition were arguably made possible by the local legal framework, namely a set of bye-laws that were not overly restrictive and which some referred to as lenient (*Country Life* 1906). It is this specific local context that explains why timber cottages were allowed to be erected for the exhibition (*Manchester Guardian* 1905).

4.2 *Architectural, technical and economic innovation*

The 1905 Cheap Cottages exhibition allowed builders to work with contractors. The maximum price of construction was set at £150 per cottage for detached cottages falling into Class 1, whilst pairs of five-roomed cottages (Class 2) were to be built for a maximum of £300 and Classes 3 and 4 should not exceed £35 per room. As Strachey had envisaged, cottages erected as part of this event were to become demonstrators which potential investors who visited the Garden City would have seen. The Cheap Cottages competition and exhibition focused on the cost of building material and on the cost of construction, and partly relied on the serial production of some components in order to reduce costs.

In a recent paper, McGuinness (2017) examined the provision of affordable housing for workers and the development of construction systems in a historical perspective. He argued that several means can allow to provide such affordable housing, including the intensive use of land and the efficient use of land, but also the use of innovative construction methods as well as cheaper, less-skilled labour. McGuiness points out that such methods could not be used in the context of early bye-laws, which were far too restrictive.

The competition organized in Letchworth in 1905 focused on reducing the cost of construction through innovative methods. The quality of cottages erected for the event was variable from an architectural point of view: it can in particular be argued that in many cases, architectural designs were not improved by progress in structural design. In most cases, contestants attempted to replace one material with another (for example concrete instead of brick) and made no attempt at using this process as an incentive to altering the architectural form and appearance of cottages. Thus, the winner of the prize for the "cement concrete" category, sponsored by the Associated Portland Cement Manufacturers, was built with moulded rather than poured cement. It is no different from contemporary and traditional British residential architecture and is far from innovative when compared to contemporary architectural innovations that were based on the use of this specific building material.

In similar vein, the winner of the second class, for a pair of cottages, boasts a steel frame which is in fact invisible and does not contribute to generating a specific architectural design. Only timber cottages have a design that is clearly related to the material with which they are built. It is worth noting that timber cottages were, as part of the competition, grouped in a specific category for which a special prize of £50 was offered. The competition rules specified that "a wooden cottage is considered to be one built of timber between the roof and the foundations" (County Gentleman and Land & Water Limited 1905).

4.3 *Strengths and weaknesses of the 1905 Cheap Cottages exhibition*

In terms of construction, a number of interesting designs can be identified, but overall, the architectural quality is questionable and can partly be seen as a result of the lack of rules. From an economic point of view, the outputs of the Cheap Cottages exhibition can be questioned, not least because all the costs of building were not taken into account. The cottage that won the £150 category was designed by architect Percy Houfton. It was built with bricks rather than concrete and the price did in fact not include the architect's and builders' fee, the cost of land, sewerage and fencing. It has also been pointed out that the bricks used for the cheap cottages built in Letchworth were actually provided below market prices (Swenarton 2003).

5 DISCUSSION AND CONCLUDING REMARKS

The study of the 1905 Letchworth Cheap Cottages exhibition and of the context in which it was organized sheds light on a range of various issues and raises a number of questions.

First, it is an incentive to think about the extent to which it is possible to reduce the cost of building whilst ensuring that reductions are not synonymous of impoverished architectural designs and qualities. This early 20th century experiment also shows that quality of construction does not necessarily equate to architectural quality and that an innovation in construction does not always entail an innovation in architectural design. As this paper established, many cottages erected for the competition did in fact follow dominant contemporary trends in residential design.

Second, an in-depth analysis of the competition outputs reveals that from an economic point of view, the event did not fully contribute to proving, as Strachey had hoped, that building costs be sufficiently reduce so as to allow to provide a solution to the rural housing question in an efficient way. The fact that some aspects of building were not costed in somewhat undermines premise.

Notwithstanding these limitations, it can be argued that the event held in Letchworth was a significant milestone in history – not only in the history of construction, but also in the history of public policy and urban planning. During this period, two simultaneous and interrelated processes were underway: building regulations were being developed and so was the administrative apparatus that allowed design and implementation. The emergence of bye-laws can be seen as a trial-and-error process, whereby principles and models were developed and enforced, criticized and gradually altered as a response not only to verbal campaigns, but also to practical experiments that sought to provide tangible proof that affordable housing for rural workers could indeed be built if the legislation was more suited to local contexts.

During the last few decades of the 19th century, construction was seen as sufficiently important that it crystallized the fears and hopes of a wide range of observers and stakeholders, including architects and builders of course, but also politicians, landlords, reformists and perhaps most importantly the press. In a sense, it was not only the construction of buildings that was at stake: the construction of a new society and the development of an adequate legal and administrative framework was at the heart of debates. The campaign against overly stringent bye-laws sheds light on the strengths and weaknesses of models – in this case, those drafted by the Local Government Board and on the risks of framing construction within a rigid set of rules. The campaign also highlights the role of demonstrator projects and prototypes as proofs of concepts. It shows their power not only as a means of persuasion, but also as physical objects that can be used to stimulate a debate between a range of actors, regardless of their political stance or profession. In other words, divergence in points of view as regards the role of construction in addressing the rural housing question meant that construction was both dividing public opinion and endorsing a federative role as an issue which a range of stakeholders could discuss.

The Cheap Cottage exhibition also show that whilst many contemporary observers were fiercely opposed to bye-laws and wished to abolish them, the true question was rather to find ways of providing a much-needed framework that would address the risks associated with buildings, not on the basis of a one-shoe-fits-all approach, but by taking into account the local context. Here, the notion of local building culture, as defined by Potié & Simonnet (1992), sheds light on why the application of urban bye-laws in rural areas arose much controversy: such regulations were an obstacle to the intelligent use of local materials and know-how.

In referring to a process whereby bye-laws were bypassed, we do not mean that proponents of this view sought to infringe them. Rather, we wish to highlight the fact that they took a side step and worked around them, as an automobile driver would do when he chooses to drive around a city, using a bypass, rather than through the urban area, where obstacles are numerous.

If anything, the debates related to the Letchworth Cheap Cottages exhibition show that it took place at a pivotal point of Britain's history – a point which can only be understood by simultaneously scrutinizing the construction of homes and the construction of public policy, and by focusing on the key role of experiments in this process.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Towards a social history of the Portuguese construction industry (1914–1918)

A.P. Pires
Universidade dos Açores, Ponta Delgada, Portugal

J. Mascarenhas-Mateus
Universidade de Lisboa, Lisbon, Portugal

ABSTRACT: This paper discusses the impact of the First World War on the daily life of different Portuguese classes of building craftsmen and labour organizations. During a transition period in building cultures, the war disrupted imports of coal, steel laminated products and Portland cement, and the supply of basic goods to the country's entire population. Strikes, sabotage and violent demonstrations against the war, including by construction worker trade unions, were interspersed with campaigns for better working conditions that began prior to the outbreak of war. *O Construtor*, the fortnightly newspaper of the Lisbon federation of construction workers, enables us to address the following research questions: how did this working class group fight for better living and working conditions? Did they question construction processes and workplace safety? How did these workers organize themselves for protests? The work concludes with an analysis of how the 1914–8 war influenced the construction industry in Portugal.

1 INTRODUCTION

The activities of the construction sector throughout the First Portuguese Republic (1910–26) were characterized by the coexistence of three construction cultures: stone and brick masonries, metallic structures and the emerging culture of reinforced concrete. This period thus coincides with the transition from predominantly manufacturing methods of building to the industrialised forms of production that define modern construction cultures. World War One influenced this process and thereby emphasised the particularities of working conditions in the Portuguese construction sector.

However, understanding the social evolution of construction workers between 1914 and 1918 first requires interrelating: the legislative context; the transformation of education, and the associative regimes of the key participant actors; and the system for supplying construction materials. Having set the context, we interpret the key debates that emerge from reading the fortnightly *O Construtor – Órgão e Propriedade das Associações dos Operários da Indústria da Construção Civil do Sul de Portugal, Colónias e Ilhas* (Figure 1), with its headquarters in Lisbon, founded in 1913 and subsequently shut down in 1927 under the Military Dictatorship (1926–33).

Despite the publication aiming to represent all civil construction workers associations in the Portuguese capital of Lisbon, its contents also extend to the main trade union initiatives in Oporto and the country's other main cities.


O Construtor
QUINZENARIO, ORGÃO E PROPRIEDADE
Redactor principal—José Lopes
Calçada do Combro, 38-A, 2.º
LISBOA
LISBOA
Federação Nacional dos Operarios da Industria
da Construção Civil de Portugal e Colonias

Figure 1. *O Construtor* newspaper header (n^{o}. 275, 1919).

This reading enables identification of the main problems faced by workers in this sector throughout the war period thereby contributing to the social history of construction in Portugal.

2 BUILDING CULTURES IN TRANSITION. THE PORTUGUESE CONTEXT

At the beginning of the Great War, important transformations were taking place in the daily life of the building sector in Portugal. Not only were the traditional stone and brick masonry ways of construction changing very swiftly with the introduction of

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Figure 2. *Empresa Industrial Portuguesa* advertisement featuring one of the bridges made by the company (Source: private collection).

mechanisation but it also impacted on the carpentry and ceramics processes involved. Rammed earth constructions were forbidden in the main cities, including the capital Lisbon in 1914 (*O Construtor* 1914, 68:4).

In the quarries, steam powered cranes and locomotives reduced the number of carriers, and helical wires replaced many labourers cutting stone from the quarry face. Furthermore, steam powered sawmills became commonplace in the quarries as the means to cut irregular lumps into slabs, thus reducing the number of men required to frame, saw and dress by hand the blocks of stone. Whirling disks for limestone and marble polishing superseded the labour-intensive manual flattening of surfaces, traditionally done by stone cutters. Their work reduced to bush hammering and chiselling, manually or pneumatically, the visible surfaces of stone blocks. In turn, Portland cement started to be used in natural stone imitations for façades and interiors, transforming the activity of former scagliola plaster-workers. Hoffman kilns produced both bricks and the new hydraulic mosaics made with Portland cement. In addition, mechanisation became ever more present during the execution of the works. Portable engines, steam concrete mixers, locomotives with carrying wagons and steam shovels reduced the need for labour on important public works sites.

With steam power, the new culture of iron and steel had arrived in Portugal, with the construction of the railway network beginning in the 1850s. While the majority of the metallic structures for bridges, viaducts, stations and storehouses were initially imported from the United Kingdom, France, Belgium and Germany, from the 1890s a few Portuguese companies, including *Companhia Aliança – Fundição de Massarelos* and *Fábrica das Antas* in Oporto or *Empreza Industrial Portugueza* in Lisbon (Figure 2) embarked on the production of major structures. Their production was incorporated into cast iron constructions such as the Ferreira Borges Market in Oporto (1885–8), the *Sala Portugal* of the Geography Society (1890–2) in Lisbon and the replacement of various steel bridges on the Leste railway line in the 1890s. Despite Portugal lacking iron and steel production, these were imported in the form of ingots, rebars and laminated sections. They were processed locally for the desired structures and therefore new metallurgical and metal-mechanic workers became an important class in the construction sector. Associated with this new construction culture, there was also a restricted number of importers who controlled the Portuguese market for iron laminates. Leading this group were *Empresa Geral de Construções*, Sommer & Cia., Orey Antunes & Cia and C. Mahony & Amaral.

Furthermore, the Portland cement and reinforced concrete culture had made its mark on the Portuguese daily reality. The application of Portland cement to concrete embankments for harbour works had become increasingly commonplace from the 1850s. Successive patent registrations, such as those by de Contancin in 1892 and Hennebique in 1896, were reflected in the construction of the Caramujo Factory in 1898, the first lattice construction in reinforced concrete built in Portugal. Hence, the first Portland cement factory opened in Alhandra in 1894, with a Hoffmann kiln and an annual production capacity of 6000 tonnes. The increase in demand for this product led to the opening of another factory in 1906, located in Rasca-Setúbal, with a capacity to produce 20,000 tonnes per year with two Candlot-Perpignani kilns in 1908 (Mascarenhas-Mateus & Castro 2018, 905–908). Contrary to the case of steel, imported Portland cement was distributed by small firms while the nationally produced Portland cement was supplied directly by the two producers. As regards reinforced concrete, since 1905, the company Moreira de Sá & Malevez was responsible for the largest number of reinforced concrete works completed using the Hennebique system: reservoirs, wine vats, road bridges, industrial pavilions, spas and maritime jetties. By 1909, more than 100 projects had been executed while more than 200 were progressing in 1913.

The two new building cultures underwent consolidation in the construction sector not only through specific legislation but also through the establishment of routes for teaching engineers and architects. In 1897, the regulations for planning, testing and monitoring metallic bridges were published, followed by the regulations for reinforced concrete applications in 1918, the first Portuguese standard on this building system. As regards its technical dissemination,

Figure 3. Labels of Portland cement brands commercialised in Portugal. Left, Alhandra cement (source: Orey & Antunes catalogue 1914). Right: a British cement brand (Portuguese patent / Invention patents 1914).

the many articles on recourse to reinforced concrete began as early as 1900 in magazine publications such as *Construcção Moderna* e *Arquitectura Portuguesa*. The first series of theoretical articles on structural calculations by Augusto Vieira da Silva, a military engineer, was published between 1914 and 1920 in the journals *Revista de Obras Públicas e Minas* and *Revista de Engenharia Militar*. Within the framework of teaching, the topic of Considered Experiences with Reinforced Concrete Structures was integrated into a module for civil engineers at the Polytechnic Academy of Oporto (*Academia Politécnica do Porto*) as early as 1898. Despite these initiatives, the training of architects at the two major Fine Arts schools of Lisbon and Oporto (*Escolas Superior de Belas Artes de Lisboa* and *Porto*) included for the first time a module on Mechanics and Strength of Materials only in 1911. An autonomous teaching module on reinforced concrete was only included in the curricula for engineers by Government Decree in 1915, which established the program in Reinforced Concrete at the Faculty of Engineering of Oporto. In 1918, it was the turn of the *Instituto Comercial e Industrial de Lisboa* to open such a course of study.

Concerning the distribution of building materials, the railway network allowed for the national distribution of all industrialised processed materials, such as hydraulic tiles, laminated steel profiles, standardized wood beams, bricks and tiles produced in the major factories located in Lisbon, Porto and Pampilhosa da Serra, on the intersection between the North and Beira Alta railway lines (Figure 3).

Despite all these changes, a great deal of the network of primary material sources (quarries, clay and sand pits, lime and ceramic kilns) remained intact all over the country.

In the 1914–8 period, irrespective of the processes and materials used in construction, the project tender and management systems were framed within two means of adjudication. For private construction projects, the project commissioner had free choice over adjudication and directly awarded the tender. State procurement procedures for public works contracts (item rate contracts) fell under the auspices of a law dating back to the monarchy (Ministerial Order 4 October 1897) with very few subsequent changes.

In terms of the system of organized work, the distribution of competences remained aligned with the activities established over time by the stonemasonry culture despite already partially reflecting the aforementioned new construction cultures. In addition to the project commissioner, the engineers and architects, immediately below in the hierarchy, came the site foremen and contractors. While the cement factories, lime kilns, the sand and clay quarries were overseen by foremen, the governmental works were managed by public works conductors (a category below engineers). Among craftsmen, the distinction stemmed from the category that incorporated both the technical capacity and the number of years spent training. The main categories in each profession were generally the same, staggered over rising levels of responsibility, recognition and authority: from servants, apprentices, journeymen to masters. The qualifications required for each of these levels derived from decisions taken by the association for each respective class. From our reading of *O Construtor*, we are able to identify the following different professional associations: diggers and lime kiln operators, quarry cart wagon drivers, stone cutters, marble polishers, mason servants and apprentices, stone and brick masons, paviours, plasterers, painters, mechanical fitters, metal workers, lathe turners, steel mill workers, carpenters, woodworkers, gas and water plumbers.

The first proposals for solidarity and social rights in Portugal can trace their origins to the end of the 19th century with protective legislation that included regulations over the duration of work, the employment of women and children and workplace safety to prevent accidents (Rodrigues 2013, 54). In 1864, the International Working Men's Association was founded with its activities continuing under the Second International as from 1889. The first legal diploma that established an effective juridical regime for compensation in the wake of workplace accidents came into effect on 24 July 1913. Until this legislation, compensation for workplace accidents would only happen when workers could demonstrate either the liability or the negligence of their employers thereby substantially reducing their rights to such compensation.

The juridical process surrounding social relationships in the workplace and the protection of workers assumed a higher profile following the outbreak of World War One, seeking to regulate for the rising social tensions that the civil construction sector personified among workers, employers and the state. Within this framework, regulations concerning workplace disasters were introduced, approved on 9 October 1914 and, already in 1919, specific legislation on compulsory social insurance for all professional activities.

Since the end of the 19th century, the masters and construction firm owners had been organized into two associations: Association of the Class of Civil Constructors, Master Builders of Lisbon (*Associação de Classe dos Construtores Civis, Mestres d'Obras de*

Lisboa) founded in 1890, and Association of Civil Construction Master Builders of Oporto (*Associação dos Mestres Construtores Civis do Porto*) set up in 1903. As was the case with their employers, workers were organized into two class-based federations from 1914: Federation of Civil Construction Industry Worker Associations of the South of Portugal, the Colonies and Islands (*Federação das Associações dos Operários da Indústria da Construção Civil do Sul de Portugal, Colónias e Ilhas*), and Federation of Civil Construction Worker Associations of the North (*Federação das Associações dos Operários da Construção Civil do Norte*). Both these organisations took an anarcho-syndicalist stance and were members of UON – National Workers Union (*União Operária Nacional*).

3 1914–1916: THE WAR, FROM AN ECHO TO DAILY REALITY

The Portuguese Republic had yet to celebrate its fourth anniversary when the heir to the Austro-Hungarian throne was assassinated in Sarajevo on 28 June 1914, triggering the First World War. Portugal was the only country to get involved in the conflict that maintained an undeclared neutral status between 1914 and 1916 while simultaneously engaging in war against Germany in Africa. In overall terms, Portugal had not proven able to embark on an industrial process and bring about economic and social modernisation, registering only extremely modest growth rates. In addition to internal divisions between monarchists and republicans, there were further splits within the core of republicanism that caused a lack of consensus as regards Portugal's intervention in the war. The Socialist Party, anarchist and trade union movements, which despite their lack of numerical support wielded significant social influence, expressed their opposition to any participation in the conflict right from the outset. This anti-war position was also the stance adopted by the Federation of Civil Construction Industrial Workers of the South of Portugal just a few weeks after the Sarajevo assassination despite the poor level of organisation both of the workers and their unions: "As we said war serves for no purpose because there is no utility in it whatever, launching workers against workers and almost, as if lunatics, deflowering women and children, practising the greatest of atrocities while the officers shout out brave soldiers, fight for your country, and they, blindly deluded, by these words continue with their deeds […]" (*O Construtor* 1914, 61:2).

A few days after the assassination of the heir to the Austrian throne in Sarajevo, a warning was issued over the difficult situation faced by stonemasons highlighting even their possible disappearance: "This is a phase in the history of this industry that we must go through due to the prejudicial arbitration of terrible professional education, for which industrialists and workers are to blame. The workers because they do not see or do not want to see any further than the primitive life of slaves and masters; working conditions and salary are matters of little or no concern (...) to the industrialists who show more direct interest in these concerns." (Ribeiro 1914a).

Unemployment was latent and transversal for a class broadly dependent on state public works projects. In the case of the stonemason class, the cutting of stones, the utilization of tile mosaics, the application of scagliola to building façades were some of the reasons set out by the aforementioned Federation to explain the increase in unemployment. In addition to these factors, there was also reinforced concrete, a material they declared needed to be "(...) with every possible determination, energetically repudiated to ensure its complete prohibition from the practice field of construction" (Ribeiro 1914b). For this debate, *O Construtor* turned to the tender for the construction of the Marquis of Pombal statue in Lisbon as the opportunity to defend traditional construction techniques in carved stone (Figure 4). Throughout 1914, and particularly in issue number 52, there is coverage of the reasons setting out why the monument should be constructed entirely in stonemasonry and finished in carved stone: this would employ many stonemasons, public money would not get spent on foreign cement, foreign iron, foreign workers and thus avoid "great difficulties and dangers".

This also referred to the newness of the other materials, speculating on their durability in comparison with stone: "There are those who affirm that reinforced concrete is perfectly solid even when nobody may precisely affirm any such thing because it is not even possible to make calculations as regards its duration; this in light of only modern experience as this has indeed only been known for some 40-something years, and even if it has not alternatively been roundly proven that stone (national, specialist) is the most resistant material for construction, and enough to highlight as an example of what I have just set out, analysis of the antiquity of certain buildings and monuments that date back long centuries, with some even displaying the impossibility of inquiring into their date of execution, such is their length of antiquity" (Ribeiro 1914b).

In fact, with the war, imports of Portland cement became far more restricted. This situation led to the total consumption of all the output of the Alhandra factory that *Companhia de Cimento Tejo* had brought onstream in 1913.

In 1914, the first additional Candlot-Perpignani kiln was installed in Alhandra, followed by another kiln of the same type in 1916-7. These two new kilns would enable the duplication of production. The war would also see Portugal, for the first time, export Portland cement to Belgium, Brazil and in lesser quantities to the Portuguese colonies on the African west coast (Oliveira 1999, 44–5). This derived from the relative independence prevailing in terms of raw materials: the lime and clays were national, with imported coal replaced by national coal mined in Cabo Mondego.

O Construtor

SEMANARIO, ORGÃO E PROPRIEDADE

Monumento ao Marquez de Pombal

Figure 4. The monument to the Marquis of Pombal. A late masonry building culture icon. *O Construtor* front page, 24 May 1914.

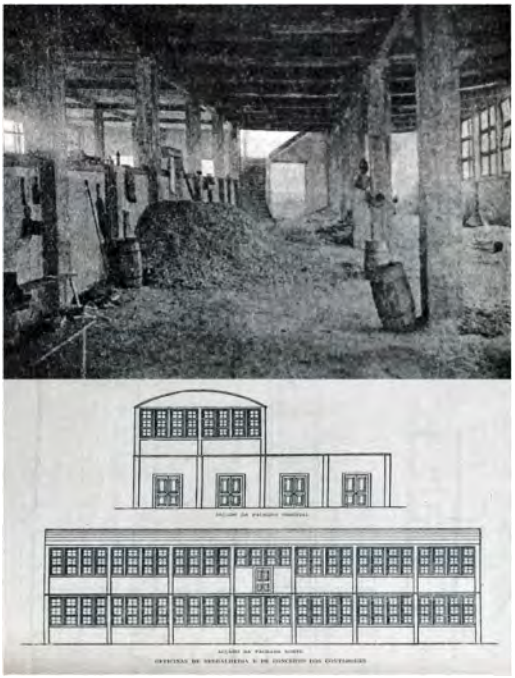

Figure 5. The Companhia de Águas de Lisboa workshop. Maximum surface 34.0 m × 19.6 m, 0.12 m thick slab, 0.20 m × 0.12 m beams. Reinforced concrete shell 0.6 m–0.10 m thick (*Revista de Obras Públicas e Minas* 1916, 559:96–108).

For such reasons, *Revista de Obras Públicas e Minas* and *Revista de Engenharia Militar* continued to present, in great detail, new and lofty constructions in reinforced concrete, as was the case with the new workshops for *Companhia das Água de Lisboa* – the Lisbon water supply company (Figure 5).

In parallel, the restrictions prevailing on the Portland cement industry deriving from external dependence on the national economic and financial sectors began generating a strong impact on the supply of staple food products to the population in general with the civil construction sector not immune to such effects: "Once again, Civil Construction is dealing with an enormous crisis. The Estoril works have already shut down partly because their managers, who were French, marched off to their country; there were over 300 workers who were left without duties. Various works that were planned for completion, some even with already signed contracts, have not gone forward due to the current situation. This all means that hundreds of persons have been thrown into poverty despite having no fault for this state of affairs." (*O Construtor* 1914, 64:2).

In addition to bread and cereals, sugar, potatoes and meat were among the first products to become scarce in the District of Lisbon due to the lack of transport and the limitations of Portuguese sources of production.

On 21 August 1914, Portuguese Prime Minister, Bernardino Machado, decreed the organization and dispatch of two mixed deployments – mountain guns, cavalry, infantry and machine-gunners – to Angola and Mozambique (Army Decree / *Ordem do Exército*, nº 19, I Series, 21 August 1914). Hence, both expeditions were organized under the auspices of the Ministry of the Colonies and not by the Ministry of War as the deployment did not derive from any declaration of war. However, and interestingly, there were clearly doubts about sending these expeditions to Africa expressed on the pages of the civil construction sector newspaper: "Yes, ten of our comrades are departing on the 10th, leaving behind in their homes their mothers who made such great sacrifices so that they would be of worth to their own, and when they needed them along comes the law and orders them to depart on an expedition that is to defend the estate owners who exploit the blacks, the bankers who rob at each and every moment ..." (*O Construtor* 1914, 65:1).

With the outbreak of war, the fragilities of a country so dependent on the exterior both in terms of raw materials (especially coal, steel and cereal) and their transport by foreign fleets (the national "merchant navy" did not undertake more than one-tenth of the cargo transport necessary for the national supply) only worsened (Pires 2011). In attempts to counteract this situation, the Federation of Civil Construction Industry Worker Associations of the South of Portugal proposed a commission comprising architects, engineers, site foremen and workers who would be responsible for "[...] indicating the most practical and effective means to combat these causes, and as well as proposing in the shortest possible period the appropriate measures, to offset the next crisis that is already looming.” (*O Construtor* 1914, 65:3). Various professional associations issued opinions that would set out the factors capable of overcoming the crisis that the sector was going through (*O Construtor* 1914, 70:2-3; 72:2; 73:2): – limiting the relocation to Lisbon of workers from other regions of the country; – regulating for an eight-hour working day; – campaigning against low wages; – reducing the lack of professionalism of some workers; – passing a law on public propriety; – accelerating the construction of affordable houses for the working class; – regulating the mechanisation of the construction industry; – eliminating the use of reinforced concrete in urban properties; – boosting public and private investment.

In September 1914, the headquarters of the Railway Trade Union hosted the unanimous approval of a motion that called for: (i) opening of public works; (ii) prohibition of tenant evictions due to the lack of rent payments throughout the period when the effects of the economic crisis persisted and (iii) compliance with the price table established for foodstuffs (*O Construtor* 1914, 70:3).

It was during the Great War that consumers emerged as a new pressure group in European society. From the food chain point of view, Lisbon experienced a chronic and endemic crisis as regards staple goods and from the outset that reflected in a shortage of both wheat and meat due to the inability of national output to meet the needs of the domestic market.

The combined effects of unemployment, the prevailing shortages of foodstuffs and spikes in prices created their own dynamics and triggered various breakdowns in public order in various districts around the country even prior to Portugal declaring war on Germany in March 1916. This provides the context for understanding the concerns expressed by Lisbon workers, for example, on the occasion of the commemorations for 1 May 1915, featuring, above all else, the determination with which they defended as an essential condition to bringing down the number of unemployed, the approval of legislation enacting an eight-hour working day (Minutes 1918: 730; *O Construtor* 1916, 146:1) (Figure 6).

Within this framework, any initiative designed to replace labour was perceived by the trade unions as robbing the working class who received their wages according to the number of hours of labour worked. There are various articles in *O Construtor* on this issue coming out against mechanisation, particularly in the cutting of stone and wood. In numbers 105, 106 and 109 of 1915, there was a long article signed by “a carpenter” who explained how mechanisation served only the owners of the machines and stripped away the work provided to the former woodcutters. According to the author, any worker who, in the name of progress, came out in support of mechanisation despite gaining no benefits was merely playing “the petty games of capital”.

Figure 6. First May celebration on the front page of the *O Construtor*, 1915.

4 1916–1918. PORTUGAL AND CONSTRUCTION WORKERS IN THE WAR

Despite the Portland cement industry having managed to partially adapt to the restrictions in place as regards raw materials, the commercialization of the cement produced by the Rasca factory, with its annual output reaching 30,000 tonnes following the construction of its third kiln, would suffer seriously from the effects of the war. On 27 June 1918, the factory was liquidated to make way for a new company, *Companhia Geral de Cal e Cimento SARL* (Oliveira 1999, 65–6). In effect, the drastic reduction in importing laminated and rebar iron drove a far lower rate of construction in reinforced concrete than that prevailing in the years preceding the war. Portland cement therefore was only gradually used for non-reinforced concrete structures on the few public hydraulic construction sites that remained open. Such is the case with the building of the Alcântara dock where the Civil Construction Workers Federation staged an important strike in 1915 against the terrible working conditions prevailing on the site (*O Construtor* 1915, 107, 108).

This situation also clearly emerges from the type of construction under discussion on the pages of engineering and architecture journals. Examples of reinforced concrete solutions were no longer subject to frequent publication in favour of constructions in traditional stonemasonry. The modernity of the iron and reinforced concrete cultures was only able to present a limited number of model constructions in these technical and commercial publicity publications.

All these trends would be further deepened in the year in which Portugal entered World War One. In January 1916, the UON central council for the first time advanced the idea of staging a general strike against the high cost of living in a short-term strategy. At the end of this month, a group including civil construction workers gathered in the Campo de Ourique neighbourhood in Lisbon and looted various establishments in the capital (*O Construtor* 1916, 140:1). The movement rapidly spread throughout the entire city and led to the explosion of bombs and exchanges of gunfire with the police and the *Guarda Nacional Republicana* (GNR) before the headquarters of the Federation of Civil Construction Industry Worker Associations of the South of Portugal was stormed and all those found within arrested (*O Construtor* 1916, 140:1).

During this period, the pages of *O Construtor* printed criticism of the involvement in the conflict and the sending of troops to Flanders: “Our silence would almost lead you to believe that we go along with those who created the current state of affairs; the war seems to wish to go on eternally and we should not continue in the same stagnation that we have retained thus far, leaving to prevail the wishes of those who have interests in the war continuing” (;opes 1916; Silva 1916).

In the months of April, May and June 1917, there were worker conferences held in Lisbon and Oporto. In both cities, it was possible to bring together 176 trade unions, four industrial federations, two syndicalist unions, various worker newspapers and diverse cooperatives. The agenda for these events involved discussing three theses: one about organizing workers; another about the cost of living; and the last about the position of worker organizations towards the terms for peace. As regards the thesis about the cost of living – the most discussed issue – the conclusions presented, alongside criticism of the prevailing economic regime, the uselessness of the measures thus far taken by the government to resolve the subsistence crisis and deemed them a reflection of the incapacity and impotence of government action (Pires 2018, 185).

Shortly afterwards, on 19 May, the Ministry of the Interior banned the staging of a rally by the Federation of Civil Construction Industry Worker Associations of the South of Portugal in Lisbon’s Eduardo VII park. On that same dawn, there began a wave of assaults, with the violence then spreading from the city centre out into the peripheral neighbourhoods. In an unprecedented movement (known as the “potato rebellion”), a total of 186 bakeries were looted between 13 and 20 May 1917.

On 20 May, the President of the Republic, Bernardino Machado declared a state of emergency and handed over command of the city of Lisbon to the military (Decree no. 3 150, Government Official Gazette, I Series, no. 80, 20 May 1917). The protests then spread to interior regions of the country. On 29 May, a law was signed confirming decree no. 3150 on the suspension of constitutional guarantees in the city of Lisbon and its adjoining councils (Law no. 696, Government Official Gazette, I Series, no. 84, 24 May 1917). Across the rest of the country, in Viana do Castelo, houses were ransacked and on 7 July, there began a strike by civil construction workers that took on a practically insurrectional character and continued for 11 days. Amongst the shooting and bombs, the strikers held out against the *Guarda Nacional Republicana* and the police. Hundreds were imprisoned but the outcome included a wage increase of 50%. Normality was established on 28 July (Decree no. 3608, Government Official Gazette, I Series, no. 124, 28 July 1917).

Table 1. Strikes organised by civil construction workers (1915–1918).

Date	Strike
13-09-1915	Strike by metal turners and plumbers against wage cuts.
17-10-1915	Civil construction workers stage a walkout.
12-03-1916	Strike by Lisbon civil construction workers as part of their campaign for an eight-hour working day.
05-04-1916	Strike by civil construction painters.
12-04-1916	Strike by civil construction workers.
16-06-1917	General strike launched by the União Operária Nacional.
07-07-1917	Strike by civil construction workers.
18-07-1917	End of the civil construction strike.
18-11-1918	General strike against the cost of living staged by the União Operária Nacional.

Source: Table drafted based on analysis of the daily press.

The development of events made clear the major difference that existed between the disturbances caused by the strikes of the summer of 1917 and the demands and actions that took place prior to the war.

On 6 September, a UON delegation was received by Prime Minister Afonso Costa. The meeting ended in the arrest of the worker representatives. On 12 September, UON brought an end to the campaigning movement (*Informação* 1917, 1). Irrespective, from across the entire country, and in almost dramatic fashion, reports continued to arrive in the Minister of the Interior’s office of outbreaks of violent discontent that described assaults on food transports along national highways, inspired by events in Russia. In addition, there was campaigning around the issue the Federation deemed was most responsible for placing the working class at a disadvantage: the construction tender regimes and the direct awarding of public works. These procurement processes were perceived as serving only to boost the wealth of the master constructors and construction company owners. A fairer alternative would be the “*comandita*” (limited partnership business) regime. This position encouraged workers to organize into small companies that would last only for the length of the tender under implementation. Competing on an equal basis with the owner class, they would be able to obtain "a regime of solidarity and equality" (*O Construtor* 1917, 219:2).

5 CONCLUSIONS

Throughout the First World War, Portugal had four presidents of the republic (the last, Sidónio Pais, was assassinated in December 1918) and eight prime ministers. From the date of Portugal's entry into the war, the construction cultures of modernity (those of steel and reinforced concrete) shrank to only a residual influence and remained on standby due to the consequences of the reductions in laminated steel and rebar imports. In response to these circumstances, the centuries-old stonemasonry culture would still predominate.

However, in the 1914–8 period, the construction sector, to a large extent already industrialized, emerged not only as an essential component of the national economy but also as a political and mobilized force that government decision-makers would always have to take into account. Clear evidence of this emerges with the successive and constant strikes by civil construction workers throughout this period of transition in construction cultures (Table 1). Difficulties of supply interwove with resistance strategies such as those put into practice by civil construction workers unquestionably compounded by the consequences of the failure of republicanism to bring about national administrative reorganization on a significant enough scale.

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Evolution of the Mexico City building code for tall buildings in the 20th century

P. Santa Ana & L. Santa Ana
Universidad Nacional Autónoma de México, Mexico City, Mexico

J. Baez G.
Baez Santa Ana Ingenieros Consultores, Mexico City, Mexico

ABSTRACT: The Mexico City building code is the product of many improvements made over the years due to tragedy and research. The current construction code is subject to stricter architecture and engineering requirements related to building and systems design due to groundwater extraction, flooding, land subsidence, and the earthquake risk with their potential effects on those components. The paper summarizes Mexico City's building code for tall buildings. Its purpose is to highlight the contributions made to the architectural, structural, geotechnical, and seismic regulations for tall buildings.

1 INTRODUCTION

Building codes provide a comprehensive set of minimum safety, energy, and health standards for designing and constructing new buildings. Tall buildings in Mexico City have remained smaller than in many other countries because of the region's hydraulic condition, soil, and seismic behavior. Over time, analysis of each of these topics has created a much stricter building code, with particular attention for tall buildings in order to prevent a higher level of damages after earthquakes or during their life cycles.

Even though most major cities have their own building codes, Mexico City's building code stands out as a model code. It is a recognized technical and architectural document for building design in the country. A brief description of this code's evolution during the 20th century is presented along with comments on the political, economic, and seismic effects.

This paper aims to analyze the evolution of Mexico's City building code considering the country and the city's political and economic aspects while focusing on the most critical technical and architectonic issues for vertical buildings: foundation and seismic behaviour, morphology, and architectural advances considering spaces and function.

2 1920 BUILDING CODE

The first Mexico City building code was passed in 1920; its purpose was to regulate urban growth, zoning, land subdivision, protect public health, and avoid foundation subsidence.

2.1 *Background 1900–1920*

President Porfirio Diaz came to power in 1876; he created a central government and turned the country to modern development. During his regime, Diaz built railroad tracks, increased exports, and attracted foreign investment, primarily from the United States.

At the time, tall buildings stood four levels high using masonry as a bearing structural system. Mexico City's soil is mainly formed by alluvial deposits covered by lacustrine clays (Auvinet & Juárez 2003), part of a closed basin that has been drained since the Aztecs (Alcocer & Williams 1996). The most common construction problem presented was subsidence settlement producing damage to the load bearing masonry walls.

Public buildings such as the main post office (five stories, built in 1902) or the National Theater (Bellas Artes Building with four levels 1904) were built, introducing American architecture and engineering. The New York firm Milliken Brothers provided the steel, cement, fire-proof, plumbing, and water supply systems; Engineer William H. Birkmire took part in the National Theater's structural design and in other tall public buildings built in the city centre. These engineers introduced skeleton steel buildings in the country, including American building materials, construction technology, and structural and plumbing systems design (Santa Ana 2020).

Mexico City has always been a site for water to collect; as the bottom of Lake Texcoco is located higher than the city, it constitutes a potential flood generator. To prevent flooding in Mexico City, as happened in 1888, engineer Roberto Gayol installed four drain pumps and presented a general city drainage system

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in 1891. This plan included constructing the Grand Canal, which transported pluvial and sewage waters outside the city and drained Texcoco's lake (Carrillo 1948).

Health education was a crucial priority under the Diaz government as it was linked to social renovation: a drinking water supply was provided to Mexico City centre. For this purpose, groundwater wells were pumped in the Toluca Valley and Ixtlahuaca-Atlacomulco aquifers; surface water from the Magdalena River was also used.

2.2 *Architecture & water supply and plumbing regulations*

Rain effects were considered as demanding a minimum roof slope of 1.5%, covered with stone or clay roof shingles and fitted with gutters; the lowest floor thickness should be 15 cm above the surrounding ground. Fire was another critical issue so buildings were to include a staircase built with fire-proof materials, a width footprint of 25 cm, a tread depth of 19 cm, and a width depending on the building's height.

Only bedrooms were attributed a minimum size, no less than 7.5 m^2, an open height of 2.50 m, and windows of 1 m^2. The maximum height for non-public buildings was 22 m, considering the street in front of its façade, and 12 m in width. Building appearance was fundamental and so the city authorities evaluated façade decorations before their approval.

Buildings were to have drinking water facilities, via a rooftop water tank with a capacity of 100 L per user per day and a plumbing system connected to the city's sewers.

2.3 *Foundation and structure regulations*

To avoid building settlements, builders were to follow requirements stipulating foundation soils free of manure, a concrete slab with a minimum 10 cm depth should be placed below bearing walls. Bearing soil capacity in Mexico City should be considered with a maximum value of 5 t/m^2 or lower; higher soil bearing capacities had to be demonstrated experimentally.

Because many tall buildings caused damage to adjacent small constructions because of subsidence effects, buildings with three stories or higher should use a cofferdam to enclose the building's ground.

Concrete was mainly used for foundations so the code established that concrete should be "good concrete," using clean gravel or crushed masonry with lime or cement.

The buildings' structural systems were bearing walls and the respective bearing wall width was to comply with the materials and gravitational loads that would ensure structural safety. Walls or columns should support beams, and they should be built in fire-proof materials. Beam materials could be steel or wood while avoiding water runoff to lower levels.

3 1942 BUILDING CODE

3.1 *Background 1920–1940*

Land subsidence induced by pumping deep wells increased as the city's population grew. The demand for services like drinking water accelerated just as the clay soil of this lake-bed kept compressing, and the city continued sinking. Engineer Roberto Gayol first reported on the subsidence phenomenon in Mexico City in 1925.

Foundations at that time were the most crucial issue for tall buildings so many studies were made. Professor Terzaghi was consulted for the woodpile foundation applied to the insurance building and the reinforced concrete floating foundation case used for the Lottery Building (Ortiz 1937).

Construction was paralyzed during the Mexican Revolution up until 1920. President Alvaro Obregón's government (1920–1924) stabilized the country, and national reconstruction started. From 1924 to 1928, the steel and cement industry flourished, and immigration from the countryside to cities occurred. Mexico City saw both its growth rate and land prices increase. The Mexican construction industry learned from the skyscrapers built in the United States, and tall buildings started being designed and constructed.

During the 1930s and 1940s, tall buildings were constructed in the city center; i.e., Insurance La National Building with 13 stories and 55 m in height began construction in 1930 and the National Lottery Building with 20 stories and 107 m in height was constructed in 1933. Both buildings used steel frame structures were produced in Mexico and with their structural design according to the 1927 American Steel Construction Manual.

Walls bearing systems were confined with vertical and horizontal reinforced concrete elements and tie-columns around the perimeter to control the wall cracking caused by differential settlements in soft soil.

Reinforced concrete was promoted as a construction material after 1925 with small buildings and houses first incorporating this material. Mexican engineers considered the American Concrete Institute Code ("1920 Standard Building Regulations for the Use of Reinforced Concrete") as their structural design guide (Santa Ana 2020).

Static wind analysis was considered for the structural design of tall Mexican buildings. The design method selected was published in the Structural Engineer's Handbook by the American engineer M. Smith Ketchum (1914), where static forces were calculated using a wind speed of 24 m/s. The National School of Engineers (Instituto de Ingeniería UNAM) was founded in 1935 and introduced the topic of seismic design and its effects on buildings. Seismic acceleration was obtained using the Sieberg-Cancani scale, and a static method design was considered for the structural design guide (Rabun 2000).

During this period, many earthquakes were felt in Mexico City. It was not until the 1941 earthquake with its epicentre at Colima that the new tall buildings suffered light structural damage. The 1942 code was the first modern code in Mexico that proposed structural design methods, load types, and seismic design.

3.2 *Architecture & water supply and plumbing regulations*

The main architectural topics assured that constructions were beautiful, functional, and safe. Buildings should be well exposed to light and well ventilated so their maximum height was 35 m considering a location adjacent to an avenue of 18 m width.

For a good room exposed to light and ventilation, buildings should include a ground floor-free area (patio on every level) with a surface of 3 m x 4 m for 10 m height buildings or 1/3 of its height in case buildings were taller. Bedrooms and offices should have doors and windows representing 1/8 of the room surface.

The risk of fire was an important issue, so buildings should have a staircase built with fire-proof materials, a width footprint of 25 cm, a tread depth of 18 cm, and a width of one meter for the last three levels, increasing by 0.20 m on any additional three levels. The main building entrance up to six stories should be 1.20 m in width and increase 10 cm per extra level.

For sanitary reasons, buildings were to install drinking water facilities through a rooftop water tank considering an extra water supply in case of fire. For plumbing systems, a 2% minimum slope and 45° elbows should be considered. A water supply of 150 L was the level set per inhabitant per day. Considering rain and street drainage, all rooms on the ground level needed to be 45 cm above street level.

3.3 *Foundation and structure regulations*

Three different foundation solutions were considered: shallow (footing or slab on grade), floating, and deep (pile). A shallow foundation could evaluate a soil bearing capacity from 5 t/m^2 to 3 t/m^2, depending on its consolidation level. For the lake-bed zone, pile foundations were to be considered, and for transition zones, a floating foundation was recommended.

Masonry footing could be considered for buildings up to 3 stories in height; above this height, concrete foundations were required. A stony soil layer could be found at a depth of 30 m in the lake-bed zone, so small, joined piles could be considered.

Values for permanent live loads were published for the first time in Mexican codes, i.e., housing was 150 kg/m^2, schools 200 kg/m^2, offices vary between 200 to 300 kg/m^2. Accidental live loads were also introduced for wind or seismic design

The building materials used in the city at that time and their strength capacity were considered: a) Volcanic stone was still regarded as a foundation building material, with a compression capacity of 10 to 20 kg/cm^2. Adobe was another construction material with compression stress of 4 kg/cm^2; b) concrete should be made with the minimum dosage: 50 kg of cement + 7 parts of gravel and sand + 31 L of water. Minimum compression stress was 150 kg/cm^2; c) cast iron still appears in this code with a compression stress of 15,700 kg/cm^2 and a tension stress of 210 kg/cm^2; d) steel produced in Mexico or imported should have tension and compression stresses equal to 1265 kg/cm^2.

Buildings were classified according to their occupancy level and importance degree in eight types: I) vital infrastructure buildings, i.e., fire stations, energy plants, etc. II) public buildings, such as theatres, schools; III) buildings with low people concentrations such as houses, hotels, offices.; IV) warehouses with high-cost machinery; V) buildings with a low occupation level like luxury residences; VI) housing for few people; VII) buildings where few people work or live; VIII) constructions that will not endanger people. This classification is used today worldwide for structural and seismic design, and with this code the first to introduce this concept (Fukuta 1991).

For design purposes, buildings were also classified by their construction material; a) steel rigid frames with masonry or concrete bearing walls; b) reinforced concrete frames with masonry or concrete bearing walls; c) bearing walls built with clay or concrete blocks, using wood trusses with a total height of 15 m; d) exterior masonry bearing walls and interior wood bearing walls with a height of 12 m; e) wood buildings of a maximum two levels in height; f) one-story adobe bearing walls. Structural design expressions were presented for the following structural systems: vaults, cables, chimneys, foundations, arches, brick domes, rigid frames, piles, and wells.

3.4 *Seismic regulations*

This code was the first to consider seismic design for buildings higher than 16 m or with a height greater than twice their width. Seismic acceleration (the shear coefficient) varies according to the building classification: 0.10g for type I, 0.05g for type II, 0.025g for type III to VI, 0.01g for type VII, and 0g for structures classified type VIII.

4 1957 EMERGENCY BUILDING CODE

4.1 *Background 1940–1957*

Between 1942 and 1957, many tall steel and reinforced concrete buildings underwent construction. In 1948, the first tall building with 140 m and 43 stories, the Latinoamericana Tower, began its construction in the city's center. This building was designed considering its overall weight for its foundations. Dr. Zeevaert considered long-term settlements and analyzed the structure using static and dynamic seismic analysis, with the first buildings designed explicitly for seismic design considering soil interaction.

Since 1946, many engineers studied the lake-bed zone applying soil mechanics studies. Essential contributions to the characterization of Mexico City soil were made by engineer Nabor Carrillo, who established the correlation between subsidence and piezometric drawdown (Auvinet 2010). Zeevaert started characterizing the Mexico City soils while designing the foundation for the Latinoamericana Tower.

The subsidence of Mexico City continues to cause foundation engineering problems as differential settlements affected buildings, especially when buildings constructed in concrete frames and walls started to displace the usage of steel frame buildings.

An earthquake with a Richter magnitude of 7.5 occurred on July 28, 1957. Its epicentre was located near Acapulco, on Guerrero coast, and severe damage occurred in Mexico City, specifically to tall buildings built on the lake-bed area. After this earthquake, emergency codes, including seismic effects, were enacted. As soil mechanics and seismic research developed in the country, the city codes became stricter.

4.2 *Foundation and structure regulations*

As a result of the soil mechanics studies made by different Mexican engineers, the urban area of Mexico City was divided into three geotechnical zones: a) the lake-bed with highly compressible soft soils; b) a transition zone where clayey layers of lacustrine origin alternate with sandy alluvial deposits; c) foothills with highly compressible strength.

Buildings types were reorganized and re-classified to assure structural safety: Group A included important infrastructure buildings and public buildings (Types I and II); Group B was almost every other type of structure, warehouses, buildings, and housing with low occupancy rates; and Group C buildings with a low risk of danger in case of collapse.

A classification considering the structural system due to its seismic behaviour was set out: a) class 1 were rigid concrete or steel frames infilled with shear walls; b) class 2 were fixed concrete or steel frames braced with diagonals or concrete walls and c) class 3 for load-bearing wall systems. All the rigid frames of a building were to withstand 50% of the seismic force without considering shear walls or bracing.

The structural design was included for each construction material; steel structures and reinforced concrete designs considered allowable stresses and proposed an alternative procedure that considered stress safety factors (design limits). Torsion effects due to seismic behaviour were also to be considered in structure design. Block or stone walls using mortar were allowed only for small buildings.

4.3 *Seismic regulations*

Most buildings damaged during the 1947 earthquake were tall so the code stated that every tall building below 45 m high should follow these emergency codes. If the building height was taller than 45 m, dynamic seismic analysis must be applied for its structural design.

This code was the first to introduce a linear distribution for static seismic analysis and limitations on relative horizontal building displacements, with 0.002 the maximum relative distortion value avoiding collision between buildings (Fukuta 1991). The seismic coefficients for seismic design were selected according to the building group and class type and the geotechnical zone of its respective location. Values were between 0.15g for structure group A class 1 over soft soil to 0.05g for group B class 1 buildings standing on foothills.

5 1966 BUILDING CODE

5.1 *Background 1957–1966*

Urban and industrial development took place on the city's marginal lowlands (Nezahualcoyotl City); these urban areas were developed to provide economically disadvantaged housing. These areas in the rainy season usually flooded. To avoid such floods, Lake Texcoco was progressively drained; this effect led to a hotter and drier local climate, dust storms, and soil salinization (Alcocer& Williams 1996).

Soil fractures started to be detected in Mexico City, causing damage to constructions and public services (Auvinet 2013). The accumulated settlement since 1900 of the city center totalled 6m. Many statistical analyses of the lake-bed zone properties and studies of the most common foundation solution behaviours over soft and hard soil were presented (Marsal & Mazari 1953). They also characterized the materials from the clayey deposits of this lake-bed zone due to their excellent compressibility.

Foundations over lake-bed soils were studied and new solutions proposed. Engineer González Flores patented control piles, which allows the building's settlement with control. New techniques were introduced to analyzed the properties of this soft soil in different zones of the city.

Young structural engineers who studied their master's and PhDs degrees in the United States returned during this period to Mexico; they founded the Engineer Institute of the National Autonomous University (Instituto de Ingeniería (II UNAM). The researchers of this Institute studied the most important fields: soil and foundation analysis, dynamic seismic behavior, and structural design methods. Their results were included in the 1966 code, for example the structural design method for reinforced concrete, which was similar to the ACI 318–63.

Probabilistic seismic hazard analysis and its results, a seismic hazard curve, were produced between 1960 and 1966 at the II UNAM. Allin Cornell, Luis Esteva, and Emilio Rosenblueth worked together and proposed seismic design levels applicable to any specific site. These engineers became pioneers and contributed to new ideas and seismic methods then adopted by codes worldwide (McGuire 2008).

With modern architecture, most buildings were built in reinforced concrete and rigid frames with concrete walls. Banobras Tower or the Tlatelolco buildings designed by architect Mario Pani provide examples of this kind of structure.

The architectural aspects became necessary as the building morphology and height played a critical seismic role; this also included minimum requirements for space length, height, ventilation and illumination.

5.2 *Architecture & water supply and plumbing regulations*

As heights of buildings increased, and to ensure adequate ventilation and illumination, their heights were limited to 1.75 times the width of the adjacent street or avenue. For light and ventilation, the free ground floor area decreased to a surface area of 2.5 m × 3 m for 8 m height buildings.

Constructions also increased their widths, and new architectural forms were considered, thus, buildings with a length of greater than 50 m or irregular shapes should be divided into separate structures using constructive joints to prevent seismic damage.

With an elevated population concentrated in the city, services such as water were essential but the supply per habitant was kept without any modification.

5.3 *Foundation and structure regulations*

According to its soil compressibility level, Mexico City was divided into two geotechnical zones: a) soil with high compressibility and b) with low compressibility. Additionally, every building should undertake its own soil mechanics study.

This set out three types of foundation solution: shallow with a minimum foundation depth of 50 cm (footings, slabs, inverted concrete shells), raft (floating), and piles (of end and friction types).

As engineers learned more about each structural system's seismic behaviour, these were classified into three types: i) rigid frame joints; ii) semi-rigid frame joints; iii) semi-rigid frames with limited capacity. The last two classes of the structural system were to be designed considering allowable stresses. Semi-rigid frame systems had to work with a bracing system. Structural design for every building must include live and dead loads; live loads were divided into permanent, accidental, and mean values.

Reinforced concrete and steel were the construction materials for tall buildings, and their structural design considered allowable stresses and limit state design. Small buildings continue with bearing wall systems with brick, concrete blocks, or wood, so they were designed considering allowable stresses. For non-conventional tall buildings, mixed sections (steel with reinforced concrete) were permitted.

For the first time in the city code, a static wind design was proposed, with a design wind of 85 km/h up to 25 m in height and 94 km/h for 50 m.

5.4 *Seismic regulations*

Following the city-wide emergency after the earthquake of 1947, buildings were divided into two groups according to their use and public capacity: a) public buildings with essential use in case of emergency; b) housing, offices, hotels, industry, etc.; c) isolated constructions that would not endanger lives in case of collapse.

The building classification made for the 1957 emergency code was completed. Establishments were classified according to their height and structural system. Type I. buildings of 7 m height or two stories with reinforced concrete or rigid steel frames that should be designed to resist 50% of the total seismic shear load without considering any contribution of walls and braces. Type II. wall bearing systems unable to withstand 50% of the seismic shear load of each element. Type III. elevated tanks or constructions with one column or one line of columns; this structural system needed designing according to allowable stresses.

Seismic coefficients were increased by 150%; for type I structures built over high compressibility soil, this was 0.06g and 0.04g for hard ground. Type II structures had a value of 0.08g for both kinds of subsoils, and the type III structure values were 0.15g and 0.10g for high and low compressibility soil respectively. Inter-story drifts were limited to 0.002 times the story height for type B, and 0.003 for type A over soft soil, and 0.004 on hard ground, and the separation between buildings must be 5 cm minimum or 0.006 times the building's height for constructions on soft soil or .004 on hard ground. These concepts were also later imported by different seismic codes such as the UBC code (Fukuta 1991).

According to the building's height or importance, three seismic design methods might be used: simplified static analysis for load-bearing wall structures, static lateral force analysis considering torsional effects, accidental eccentricity, and dynamic analysis.

6 1976 BUILDING CODE

6.1 *Background 1966–1976*

The urban area of Mexico City was divided into three main geotechnical zones, according to engineers Marsal and Mazari (2016). Floating foundations, friction, and control piles were reviewed as negative as friction produced undesirable structural effects.

Groundwater pumping from the thick aquifer system underneath the city slowed but did not stop; subsidence continued to attain levels of 8 m in the city centre in 1980. In 1976, subsidence slowed down with the construction of the second Tequixquiac Tunnel and Deep Drainage System (Alcocer & Williams 1996).

Tall buildings were designed and constructed using new structural seismic systems such as steel braced tubes and outrigger structures. The Pemex Executive Tower was an example of these latest buildings, 214 m in height (60 stories) constructed in Mexico City in 1972.

The design methods for foundations, reinforced concrete, masonry, wood and steel structures, seismic analysis, and wind analysis were published in a separate book so they could be modified frequently without affecting the legal and architectural topics included in the building code.

6.2 *Architecture & water supply and plumbing regulations*

The maximum building height was two times the adjacent avenue or street width.

Fire provisions for buildings with heights over 15 m required a fire extinguisher; in taller buildings, a water tank had to be included with a capacity of 5 liters per square meter. Buildings also needed a staircase in fireproof materials, and public corridors must be 1.50 m in width. Steel and wood structures always required appropriate fire protection.

Every building of more than five stories in height needed to be fitted with a water tank providing the capacity for two days of daily water demand.

6.3 *Foundation and structure regulations*

As a result of the long-term soil studies developed, the city was geotechnically divided into three zones: I. Foothills, with firm soil, to a maximum of 3 m depth. II. Transition, firm soil between 3 to 20 m depth. III. Soft ground, with firm soil below 20 m depth.

Three types of foundation solutions could be applied according to the soil characteristics: shallow (footings and slabs), raft (floating), and piles (of end and friction).

Reinforced concrete, steel, and composite structures were structurally designed using limit states (reduction and amplification factors).

Wind design included in its classification: type I buildings with low dynamic wind effects; type II slender buildings sensitive to short period of winds; type III chimneys and cylindric buildings and type IV structures with aerodynamic issues in their behaviour. The wind speed was equal to 110 km/h.

6.4 *Seismic regulations*

The classification of buildings according to importance and population remains as stipulated by the 1966 code, and the category of structural systems was precise; Type I buildings and warehouse designs with rigid frames with or without bracing systems, Type II tanks, Type III retaining walls and Type IV other constructions.

A seismic design spectrum was presented for the first time; this spectrum contained three zones: a linear ascending branch, a plateau, and a descending branch. The seismic coefficient is considered according to an elastic behaviour, and with the values of 0.16g, 0.20g, and 0.24g according to the geotechnical zones: foothills, transition, or soft soil.

Reduction of the seismic force due to ductility effects entered into consideration; two cases were published: 1. Rigid concrete or steel braced frames with the scope for plastic hinges at some joints until a failing mechanism is reached with a ductility factor of 6; 2. Concrete, wood, or steel frames without bracing but with concrete or masonry walls with a ductility factor of 2. Additionally, second-order and torsion effects were to be considered. These concepts were introduced in the Mexican code for the first time and accepted and used in other seismic codes, such as the National Building Code of Canada in 1970.

Three seismic design methods were kept: simplified static analysis for load-bearing wall structures, static lateral force analysis considering torsional effects and accidental eccentricity, and dynamic analysis. The seismic design was to analyze two horizontal orthogonal components and requiring the combination of these components.

Inter-story drifts were limited to 0.008 and 0.016 times for buildings where non-structural components may or may not suffer damages. Their values should be increased through including ductility. To avoid pounding effects, the separation between buildings was 5 cm minimum or 0.006, 0.007, and 0.008 times of the building's final height (I, II, or III zones).

7 1985 EMERGENCY CODE

7.1 *Background 1976–1985*

In September 1985, an 8.5 magnitude earthquake struck Mexico City. Over 800 buildings, mainly reinforced concrete systems constructed before 1960 collapsed. The lake-bed zone was most affected because of the resonance effect between the soil and buildings over six stories. Most masonry and reinforced concrete buildings were destroyed due to their lack of strength and ductility. Damage also occurred when two adjacent buildings collapsed after colliding while swaying or buildings with differential settlements and their floating foundations filled with water. Furthermore, multistorey buildings, founded on piles that were not long enough to sustain the firm stratum, slipped downwards.

Emergency codes were published to inspect affected buildings and reinforce them. Structural and seismic topics had to be applied for new buildings constructed over the transition and bed-lake zones.

7.2 *Structure and seismic regulations*

Tall buildings were used as offices so live loads for office buildings were increased: the permanent load was 140 kg/m2, and the accidental load 180 kg/m2. Concrete and steel state structural design limits continued but the reduction factors changed for the structural design of non-ductile columns.

Much structural damage occurred in buildings with flat slabs, caused by insufficient shear strength in the slab-to-column connection; to avoid this problem, the code included a flat concrete zone around the columns to increase the shear strength.

Buildings with differential settlements were then analyzed, reducing their strength capacity according to the damage suffered.

For the first time worldwide, it was observed that the ground possessed a dynamic period during earthquakes, changing the behaviour of different structural systems. According to this fact, the seismic coefficient increased to 0.27g and 0.40g for geotechnical zones II and III. The simplified method could only be applied for buildings under 8.5m height, and their seismic coefficients were increased (Fukuta 1991).

The ductility factors changed; the maximum value was four instead of six. This applied to concrete, wood, or steel frames, braced, and designed with a resistant capacity of 50% of the seismic force without considering bracing systems. Ductility factor 3 was for structural systems with flat slabs, steel frames with trusses, or shear walls linked to the load bearing frames; they were to be designed to resist 50% of the seismic force. Ductility factor 1.5 was for infilled bearing walls, and a factor of 1.0 applied to different material structural systems.

Small column sections were detected in many building failures and the code thus stipulated concrete columns with a ductility factor of four could not be less than 30 cm on any cross-section side, and their stirrups not separated by more than 20 cm.

8 1987 AND 1993 BUILDING CODE

8.1 *Background 1976–1985*

After the 1985 earthquake, architects and engineers found that asymmetrical buildings, triangular or T shapes, are more likely to collapse in significant earthquakes; also determined that leaving open spaces on lower floors with more structure on the floors above caused structural problems (soft stories). Other damage causing factors were: the lack of sufficient reinforcement in concrete columns, and buildings being placed too close to each other.

With the resonance effect between the lake-bed soil and buildings from five to twenty stories, these were subjected to lateral accelerations six times greater than ever before experienced in Mexico City; this affected the design of modern tall buildings over lake-bed seismic zones.

There was little damage in the foothill zone around the old lake-bed; residents over the hills felt a slow shaking. Engineers like Esteva and Rosenblueth believe that when the seismic waves reached the old lake-bed in the Valley of Mexico, the layers of gravel, sand, and clay produced a striking effect. They calculated some parts of the lake bed, because of its constituency, vibrated with a periodicity of two seconds.

With a population of 20 million people, water supply and sewerage have long been challenging tasks. While the Lerma and Cutzamala river basins with the city Valley aquifer continue to be the primary sources of water for the metropolitan area, subsidence will keep going, and fractures will continue appearing.

8.2 *Architecture & water supply and plumbing regulations*

During the 1985 earthquake, many of the collapsed buildings were those that had changed their architectural use during their lifetime, thus increasing their live loads. As a consequence, the code dictated that structures could not change their function when live loads increased unless a structural redesign took place. The maximum building height remained twice the width of the adjacent avenue or street.

Fire risk was classified into three categories, and high fire risk buildings were to deploy a water tank with a volume equal to 5 L/m^2 built and a minimum capacity of 20,000 L. Every building standing over five stories in height had to install a water tank with a capacity for two days of daily water demand; this tank was to be sited 2 m above the last fixture.

8.3 *Foundation, structure, and seismic regulations*

Buildings were classified into three groups: A) essential facilities that should remain operational and those with large occupation levels. B1) constructions spanning more than 6000 m^2 built or with more than 30m height in geotechnical zones I and II and buildings with a height lower than 15m in geotechnical zone III. B2) all other buildings. The amplification factor for structural design changed: permanent loads were increased by 1.4 for group A and 1.5 for group B.

The structural design should consider avoiding failure state limits and comply with service limit states. An ultimate strength design was proposed for concrete and steel structures. This established two concrete classes with the difference in their elasticity modulus and unit weights (grade 1 for Group A and B1 buildings). This reduced live loads for housing but with all other 1976 code live loads maintained.

The three geotechnical zones were revised and kept: I. Foothills, with firm soil found to a maximum 3 m depth. II. Transition, hard soil between 3 to 20 m depth. III. Soft ground, with firm soil below 20m depth. Seismic coefficients increased to the following values: 0.16g, 0.32g, and 0.40g for geotechnical zones I, II, and III. These values were subject to a factor of 1.5 for structures in group A.

Seismic effects depend on the regularity of a building; the following conditions needed satisfying to ascertain whether a building was regular: a) its shape should be symmetric in two orthogonal axes, including its masses and shear walls or columns; b) its height/minor length ratio does not exceed 2.5; c) its proportion between side lengths does not exceed 2.5; d) a rigid diaphragm floor system; e) openings in walls or slabs do not exceed 20% of the total area; f) the maximum difference between live loads of adjacent stories is 30%; g) the surface of adjacent floors can differ by 30%; h) static torsional eccentricity evaluated should not exceed 10% of one side. Interstorey drifts were reduced to 0.006 and 0.012 to satisfy the service conditions.

9 CONCLUSIONS

The geographic position of Mexico City, surrounded by lakes, with a lower level acting as a rainfall collector and with the exponential growth of population demanding water supply and sewage, all generated different problematics in the construction field, with tall buildings especially affected.

The Mexico City building code regulates the execution of public and private constructions with the development of the first codes (1920 and 1945) depending on technological advances imported from Europe and the United States. The 1966 and 1977 regulations contained Mexican researcher advances in soil mechanics, seismic engineering, and structural behavior (especially masonry and reinforced concrete structures) that then influenced and were recognized in the codes of other countries. The 1985 emergency norms and the 1987 code were published alongside new research results for building safe structural constructions and reinforcing existing buildings.

The Mexico City code keeps changing and introducing new results to obtain safer and sustainable buildings. Mexican regulations have contributed worldwide with new concepts and ideas, especially in the seismic, geotechnical, and structural fields. American, Canadian, Japanese, and New Zealand seismic and structural codes have adopted parameters such as building classifications and structural systems, lateral displacement limits, or higher seismic coefficients for soft soil sites. The building codes published after the 1985 earthquake demonstrated promising results as reflected in the 2017 earthquake with fewer collapsed and damaged buildings.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Monumentality in modern construction processes: An ideological exposure of totalitarian strategies

C. Breser
Leopold-Franzens-Universität Innsbruck, Innsbruck, Austria

ABSTRACT: The modernisation of architecture in Italy during the Fascist period between 1922 and 1943 was mainly driven by its monumentalisation to scale. In this article, the ideological impact of the regime on the architectural production will be examined through the Fascist regulatory mechanisms that led to a reshaping of normative conditions of construction processes. Regulatory mechanisms, such as the 'structural monumentalisation', were applied to expand organizations through which the regime could institutionalise its power in professional networks. An ideological conformity of politics and professionals was thus not only striven for in the standardisation of construction technologies through which the regime intended to influence the building industry. Interventions, such as the establishment of new professional organisations and codes, were used to reshape Italy's constructing conditions institutionally, that continued to influence the architectural production normatively even after the ideological change of power in 1943.

1 INTRODUCTION

1.1 *Monumentalisation as a normative mechanism*

The modernisation of architectural production in the first half of the 20th century will be examined in this article from the perspective of the collective-normative conditions set by the Fascist regime in Italy. It forms part of a broader investigation into planning-ethics within authoritarian regimes, which will further include the impact of relevant stake-holders as well as the interests of individual actors. The main issue of this contribution however considers the early interventions of the Fascist regime that led to a reshaping of the legal and institutional circumstances of architects and engineers with significant normative impacts on professional decision making.

In the Fascist regime in Italy, the assertion of its sovereignty as a state power initially took effect not only through ordinances and directives but also in parallel, by means of subtle regulatory mechanisms. Through such mechanisms, for example, the expansion of professional organisations, the Fascist regime was able to anchor novel conditions normatively in the long term in everyday cultural practices (Eco 2020, p. 22.). The phenomenon of monumentalisation, which can be observed above all in the overscaling of public buildings, is evaluated here from a 'substantial' as well as a 'structural' point of view. The industrial development of building materials and construction techniques at the beginning of the 20th century necessitated a series of regulations and standardisation. In the building industry, these applied mainly to the processes and safety standards in the production and processing of reinforced concrete. Substantially, therefore monumentality was perceived in the effects of the relatively new reinforced concrete and the associated overscaling of the buildings in design, as a 'demonstration of power'. Beyond this, however, the phenomenon of monumentalisation is here also observed as a structure-altering mechanism through which the Fascist regime sought to exaggerate ideological ideals in the organisations and institutions of architecture and thus also became an important factor in the 'institutionalisation of power' within the network between the architecture, politics, the building industry and building administration. Structural monumentalisation was thus used as an institutional reform engine to infiltrate organisations and institutions politically. This was achieved by expanding and implementing parallel structures (expansion of organisations), as well as by means of new differentiations through legislative criteria (segregation of actors) and the reduction of pluralistic ideological conceptions (manipulation of actors). An awareness of the effectiveness of Fascist regulative mechanisms on the modernisation of architectural production in Italy is of twofold importance: on the one hand, it clarifies the ideological strategies of authoritarian regimes, through which the conformity they seek between politics and architecture can be recognised. On the other hand, the effectiveness of institutional interventions shows that the influence they exert is not necessarily temporary but can last far beyond a change of ideological power and thus

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Figure 1. Research context (Author).

influence architectural production and its actors in the long term (Figure 1).

2 STATE REGULATORY MECHANISMS AND THEIR IMPACT ON THE MODERNISATION OF CONSTRUCTION PROCESSES

2.1 *Normative and institutional interventions between 1922 and 1929*

In an effort to modernise the state and its economy in order to compete more effectively with other nations, administrative reforms had already been introduced in Italy under the liberal governments between the First World War and the March on Rome of 1922 (Melis 1996, pp. 269–284). As in most other European nations, attention was initially focused on economic interests, especially regulation expanding industrial mass production, which required the modernisation of administration and at the same time a rationalisation of operational planning and construction processes. Many of these modern ’industrialised’ processes were already regulated by standardisation at the turn of the century. In Italy, this included the first construction standard for the execution of reinforced concrete works, which was regulated together with the standardised test procedure for hydraulic agglomerates and also the technical conditions for the supply of hydraulic binders via a ministerial decree of 10.01.1907 by the Ministry of Public Works, *Ministero dei lavori pubblici*. With the emergence of political ’mass movements’ (Arendt 1955, pp. 492ff) in the 1920s, regulations then became the object of political-ideological reforms aimed at reshaping society in terms of a totalitarian mass socialisation under Fascist auspices (Gentile 2003, p. 7). The authoritarian regimes of Europe asserted their ideology first in economic and technological arenas – before pervading other areas of society. Initially in Italy, however, this was done less through regulations and directives and more through the use of institutional regulatory mechanisms and opinion-forming normatives. In the expansion of professional organisations, through the implementation of parallel structures as well as corporate bodies, the ideologisation of society took place gradually, which led to a growing step-by-step conformity between politics and architecture.

The Fascist regime in Italy shares with other authoritarian regimes in Europe in the early 20th century, such as those in Germany, Spain or the USSR, their usage of modernisation of the processes of architectural production to influence the everyday practices of society. The Fascist regime in Italy retained control over central building projects and large-scale urban projects (Nicoloso 2008, p. XXVII). However, such a comparison also shows that different approaches were taken in dealing with the institutions of architecture (Galasso 1998, pp. 19–47). In Italy, during the establishment phase of the Fascist regime between 1922 and 1929, no homogeneous building policy in the sense of a clearly preferred formal language can initially be detected. In the case of public building projects, such as those for railway stations, there were initially no explicit guidelines from the regime on architectural style and typology (Albrecht 2017, pp. 136–137). As the case studies of railway station buildings in Brenner/Brennero (1925–1930), Bolzano/Bozen (1927–1928) and Trento/Trient (1933–1936) demonstrate, a development towards a specific building typology as well as a clearly recognisable architectural language of form was only gradually being worked out. The architect responsible, Angiolo Mazzoni, made a decisive contribution to this architectural development in his dual function as architect and functionary for the State Railways of the Ministry of Posts and Telegraphs, *Ministero delle Poste e Telegrafi*, which was restructured into the Ministry of Communications, *Ministero delle Comunicazioni*, in 1924. However, his operating parameters as an architect were influenced by those institutional mechanisms considered here in particular and subtly introduced by the Fascist regime. Similarly, he was also surrounded by different stakeholder groups from architecture, building administration and the building industry, whose institutional influence can be detected in different group-specific normative conditions and will be the subject of the following research. Initially, the architectural scene in Italy was not yet dominated by any of the various architectural movements, as was later apparent, for example, for the National Socialist regime in Germany in its preference for an exaggerated classicism in terms of scale, basically from its inception. The Fascist regime initially seemed to push a ”policy of aesthetic pluralism” (Stone 1998, p. 5), which also seemed to allow for the kind of heterogeneity that would do justice to the diverse architectural scene in Italy. This aesthetic pluralism, however, belies the fact that on the way to a totalitarian system of power, there were indeed clear objectives within this system (Mattioli & Steinacher 2008, p. 19). Semantic normatives emanating from the *Duce* himself and also from other influential personalities were gradually realised, as has been observed in parallel in the reform of administrations (Melis 1996, p. 294–324) as well as for legal and moral orders concerning civil rights (Pergher 2018, pp. 1–24). During the establishment phase, the Fascist regime operated mainly through structurally differentiating mechanisms. The regime's strategy was characterised by a step-by-step approach that, by setting external conditions, attempted to achieve long-term changes in design, technology and social processes (Mussolini 1927, p. 1); always, however, with the definite goal of a total 'transformation' of society by reversing previous collective-normative agreements. The establishment of new external conditions can be observed alongside the structure-changing mechanism of monumentalisation described here, which essentially took place in three steps: (1) the expansion of organisational structures, (2) the segregation of their actors and groupings, and (3) the manipulation of segregated actors in new groupings.

2.2 *Monumentalisation through structural expansions*

The expansion of national territory and Italy's associated colonisation policy illustrates how substantial overscaling went hand in hand with structural monumentalisation of organisations and the changing of legal principles. The policy of the Fascist regime in the northern provinces of *Alto Adige* and *Trentino*, which had been internally colonised since 1919, as well as in the African colonies of *Abyssinia* (today's Ethiopia and Eritrea), demonstrates that the territorial expansion did not only aim, as originally propagated by Ettore Tolomei (Tolomei 1938, p.23), at the strategic-military safeguarding of the northern state border or a necessary population expansion, but for the expansion of regulative normatives. The completely unrealistic settlement plans, which were characterised by strikingly inconsistent implementation, ostensibly served to stabilise the regime's power by attempting to legitimise new ideological conceptions and to reverse the legal and moral orders of the former liberal nation state in order to establish new civil rights. The settlement policy in the *Alto Adige* was thus part of a visionary propaganda for an ideal Fascist "super nation" (Pergher 2018, pp. 1–24), which was primarily aimed at establishing a new two-class society and the necessary adjustment of civil rights.

The penetration and appropriation of the general public administration by the Fascist regime in the period between 1923 and 1939 demonstrates similar procedures. Here, an expansion of the administrative structure was sought through the implementation of a bureaucratic 'parallel system' (Melis 1988; Salvati 2006, pp. 59–60) as well as (semi-)public corporations (Salvati 2020, pp. 28–41). Under the auspices of the 'rationalisation' or 'modernisation' of the state, however, this structural expansion was primarily aimed at restructuring the administration in terms of personnel and exerting political-ideological influence. The initial resistance from the political-liberal camp of the government under Francesco Saverio Nitti from 1919 to 1920, which initially remained partially influential, was finally met with a massive expansion of administrative structures, which ultimately also led to the undermining of liberal-democratic administrative structures (Conti 1986, p. 449). Under the increasing economic pressure caused by the world economic crisis and the Lateran Treaties of 1929, the regime succeeded in completely implementing the totalitarian practices it initially sought in the expansion of public administrations (Melis 1996, pp. 269–322; Salvati 2006, pp. 55–65).

The strategy of expanding organisations and institutions can also be observed in architecture, with the development of the organisation structure of the Chamber of Architects and Engineers of Rome, the *Ordine degli ingengieri degli architetti – provincia di Roma*. The *Ordine* was founded as early as 1886 as a municipal corporation in Rome and initially operated without a legal basis until it was reconstituted by law in 1923 (n.1395). The organisation structure, which basically still exists today, consisted of the 'Council for the Maintenance of the Register of Architects' (*Giunta dell'Albo*), the 'Directorate of the Union' (*Direttorio del Sindacato*), the 'Board of Directors of the Chamber' (*Consiglio Direttivo*) and the 'General Assembly of the Chamber' (*Assemblea*). With the aim of influence and appropriation by the Fascist regime, their organisation structure was expanded by placing a *Direttorio*, initially still working in parallel, alongside the *Giunta* founded in 1930, which was entrusted with the same tasks. From 1939 onwards, the management of the professional register was formally handed over to the *Direttorio*, which completely disempowered the *Giunta*. Item 1 of the minutes of the meeting in question accordingly announces a revision of the list of members and, in preparation for the following meeting, item 3 also decides on the measures to be taken regarding the treatment of members of the 'Jewish race'. The *Ordine* of Rome and its provinces kept its own register of architects until 1923 (ASOR 1939).

2.3 *Impact on professional organisations and professional codes in architecture*

The monumentalisation of organisational structures had an extensive effect on all sectors of the state, which architecture with its professional associations and education system could not escape. In this sector too, the implementation of parallel structures served to establish new regulatory differentiations that were intended to divide the mass of society into individual, more easily controlled groupings. Thus, 'aesthetic pluralism', and also the dissent resulting from it, were used to play the architects off against each other, as well as against the engineers; also known as the *Führerprinzip* (Arendt 1955, p. 639). The separation of architects from engineers, which had already become apparent beforehand, was thus intentionally used by the Fascist regime to distinguish them from other professional groups involved in architectural production. Separated professional associations thus enabled the

Fascist regime to exert influence more easily, whereby political-ideological interests could be infiltrated more deeply into the group-specific consciousness and thus manifest themselves more long-term in their practices (Berta 2008, pp. 34–48). Singular professional groups of engineers and architects are first of all ’ordered’ and attributed to different spheres of action. This is reflected in particular in the founding of various architecture faculties during the 1920s and 1930s.

The strongest means to be used was the implementation of a uniform professional code for architects and engineers, the *Tutela del titolo e dell’esercizio professionale degli Ingegneri e degli Architetti*, which was intended to protect their professional practice and to increase the quality of their services. As early as 1890, such a code had been demanded by all the universities existing at the time as well as by the delegates of the local associations of engineers and architects (Annali II.1890, pp. 65–66). However, the Fascist regime succeeded in implementing this demand in 1923, which can be interpreted to mean that from this time onwards the architects, and in particular their local professional associations became increasingly involved in the modernisation of the state, in the establishment of a new *Italianità* as well as in the associated new Fascist order and its expansionist policy (Fuller 2007, p. 94). The development of this professional code, the *Tutela*, and its repeated amendments of 1923, 1925, 1927 and 1938, as well as the legislative additions by other laws, such as the legal regulations for labour relations of 1923 and 1926, reveal two significant strategic interventions of the Fascist regime for exerting influence. On the one hand, it was possible to exert influence through Monumentalisation structurally, i.e. through the expansion of organisational structures and institutions of architecture especially by means of the centralisation of professional associations, which also included the implementation of the long demanded national professional code and its regulations. On the other hand, the regime was also able to exert influence through the unification of previously locally managed professional registers into a national *Albo professionale architetti*, as provided in the new professional code, by differentiating actors according to new criteria and legislative regulations, that finally became a professional code of conduct.

2.4 *Differentiations within professional codes as an act of segregation*

A nationally uniform professional register, the *Albo*, which was contained in the *Tutela* by the 1923 law (n.1395), brought together all professional registers that had been kept separately and locally until then, namely that of the municipality (*Albo municipale*), that of the ’Society of Italian Engineers and Architects’ (*Albo della Società*) and that of the Chamber (*Albo d’Ordine*). Four central institutions were significantly involved in the creation of the *Tutela* and its *Albo*: 1. The ’Society of Italian Engineers and Architects’ (*Società*) founded in Rome in 1885, 2. the ’Chamber of Engineers of Architects - of the Province of Rome’ (*Ordine*) founded in Rome in 1886 and reconstituted in 1923, 3. the ’National Association of Italian Engineers’ (Associazione ANII), founded in 1919 and reconstituted in 1922, as well as the ’Union of National Architects’ (*Sindacato*), founded in 1923, which was renamed to the ’Union of Fascist National Architects’ in 1932 and saw itself from the very beginning as a loyal actor of the Fascist regime. Together with the unification of a national *Albo professionale architetti*, there also started a debate about the specialisation of the education system, in terms of its technical or artistic orientation, and about its professional title. Initially, it was intended that only graduates of the *Scuole di applicazoine per ingegnieri* should be admitted to the *Albo professionale architetti*, as had previously been the case with the *Albo della Società*. In addition, it was proposed that the graduates of the *Scuole Superiori di Architettura* and the *Scuole di applicazione* were to receive the title *’architetto civile’* (’civil architect’) while those graduates of the *Istituti di Belle Arti*, receive the title *’architetto abilitato’* (’architect with teaching qualification’) which would have created a differentiation between them. The ensuing debate about different competencies and designations eventually led to a confrontation and a letter of complaint from the president of the Rome Architects’ Association, Marcello Piacentini, an architect who was subsequently influential within the Fascist regime. Piacentini complained to Giovanni Gentile and the *Commissione Centrale*, that such an intended decision would undermine the dignity of the graduates of the *Istituti di Belle Arti* (Berta 2008, p. 45; ACS 1923). In its final legal version, for a uniform protection of professional practice and title, an agreement was reached in the *Tutela* in Art. 12 that ”the titles of *ingegnere* and *architetto* were reserved exclusively to those who have obtained their diplomas from legally accredited higher education institutions, subject to the provision of Article 12” (n.1395 /1923). Article 12 then specifies that the title of *architetto* applies to those, who are registered in accordance with Articles 8, 9 and 10 or have the qualification to practise the profession of engineer (n.1395/1923). In this version both classifications were thus considered equivalent in the *Albo professionale architetti*. Already at this time, however, the relationship between architects and engineers can be described as significantly divided, a situation that increased in subsequent events.

The agreement on a nationally uniform professional code, the *Tutela*, and its uniform professional register, the *Albo*, enabled the Fascist regime not only to increase the recognition of architects as equal actors in an industrialised architectural production but also to simultaneously make new differentiations within stakeholders. A previously demanded distinction between a registered and a non-registered person in practicing certain activities was taken into account in Art 4 of the 1923 *Tutela* which determined that the public administration could only consider assessments of freelance engineers and architects who were registered in the *Albo* (n.1395/1923). After two years, however, through a Royal Decree (n.2537/1925) the awarding of expert's reports was also allowed for persons who were not registered in the *Albo*, under the conditions that a) the person was a scientific luminary in his field or a technician of singular fame, or b) the application of the technique was simple and did not require any special scientific preparation, if there were no registered experts in a particular place where the expertise or commission was needed (n.1395/1923). This development seems significant and it was of particular interest with regard to those areas of *Alto Adige* and *Trentino* newly acquired in 1919, since there was an increasing number of non-Italian-speaking experts who were not members of the Fascist party and who had also acquired their professional education elsewhere, such as in Munich or Vienna. However, the opening of the *Albo* to non-registered persons is particularly noteworthy because, with the amendment of the *Tutela* by the Royal Decree of 1925 (n.2537), compulsory membership of the *Albo* was simultaneously required in order to participate in public building projects (Estermann-Juchler 1982, p. 37). In addition, from 1925 onwards, an Italian state examination was required for all new registrants, which resulted in the restructuring of the educational systems, and via Royal Decree (n.2145) in 1927, the introduction of two separate professional registers, which now sealed the complete segregation of architects and engineers (Pfammatter 1990, p. 17). Another law of 1927 (n.1766), reforming the Council of Provincial Administration, and a Royal Decree of 1928 (n.332), the so-called *Giunta sindacale*, gave the regional syndicates the executive function of supervising their members with regard to the 'correct' practice of the profession. With these two amendments, the second step of the three authoritarian strategies started, through which an attempt was made to manipulate the members by reducing pluralistic ideological views. With the compulsory membership of all architects and engineers in the *Partito Nationale Faschista* (PNF), introduced in 1932, the directive influence of the Fascist regime expanded even further; henceforth, with a distinction only made between members and non-members (Ghirardo 1989, p. 62). In a step-by-step process, from a still quite liberal expansion of organisational structures to authoritarian penetration with the help of segregation and finally to totalitarian manipulation and appropriation of architecture, non-registered members and non-members of the political party became upstream sympathisers in the system who were able to establish a link between the political-ideological world of the regime and the subject-specific reality of experts (Arendt 1955, p. 639).

3 CONCLUSION

On the question of the regulatory mechanisms striven for by the Fascist regime, by establishing substantial and structural monumentalisation, an attempt was made to illustrate the close interconnections of architecture with industry and the economy as well as with building administration and politics. By examining regulatory and legislative changes in architectural organisations, it could be shown that the Fascist regime in Italy between 1922 and 1929 not only acted through decrees and directives but also used latent mechanisms that had a long-term structural effect on architectural production. With the expansion and simultaneous implementation of parallel organisational structures in already existing organisations as well as the segregation of their members through new legislative differentiations, the regime succeeded in exerting influence on architects and engineers; by following the overall aim of reducing political-ideological and also subject-specific-ideological perceptions and thereby completely transforming the architectural landscape. The centralisation of the professional associations played an important role in this, as did the previously demanded implementation of a nationally uniform professional code, which also initiated an indented separation of architects and engineers and finally became a professional code of conduct. This segregation had the effect of both a reorganisation of two different professional associations and a separation of the educational system, and in the long term thus also led to differentiated normative perceptions of design, technology and social processes. These differentiated normative perceptions continued to conduct and shape the understanding of modern Italian architecture, which leaves important questions about the responsibility and effectiveness of architecture in a political context unanswered due to their increasingly specialised subject-specific orientation.

Methodologically, a comparative approach was chosen. A three-level model, which is based on the approaches of Descriptive Planning Ethics to systemic reciprocal influences (Düchs 2011; Berr 2017; Müller 2017) distinguishes between (1) the interests of a state regulatory level, (2) group-specific interests of an institutional level and (3) those of an individual biographical level, which was largely unconsidered in this contribution – due to resources. From a pragmatic point of view, the topic dealt with was discussed primarily at the state regulatory level, because collective-normative conditions form the basic prerequisite for all actions of stakeholder groups as well as all individual actors. For this purpose, archival sources, law gazettes and professional journals were consulted, through which qualitative statements about changes by legal as well as institutional normatives could be made by means of discourse analysis. Thus, it has proven significant for research on the conditions of the modernisation of the architectural production within the Fascist regime in Italy to maintain a critical distance from one-sidedly political-ideological or also one-sidedly subject-specific-ideological approaches to architecture. Regulatory mechanisms such as structural monumentalisation through the expansion of organisational structures and institutions of architecture show, due to their long-term manifestation in the system, that ideologically conditioned interventions also methodologically require a critique of ideology. However, bringing together developments and effects of technical progress and social *Lebenswelten* (Habermas 1968, p. 118) is not only important for a unifying reappraisal of the technical and social-historical contexts but also with regard to the ecological, social and related technical challenges that are coming our way, which will ultimately require such an overall understanding of architecture.

4 PREVIEW

The collective-normative conditions on the part of the state apparatus, which are primarily considered in this contribution, serve the author as a basis for more detailed investigations of biographical networks, whose heterogeneity changed extensively in Italy within the 'penetration phase' of the Fascist regime between 1929 and 1938. Future research will focus on the differentiation of the regime's manipulative influences on stakeholder groups, the *Sindacato degli Architetti* and the *Sindacato degli Ingegneri*, that had been operating separately since 1927. In parallel, the segregated organisations and education systems of architects and engineers will also be dealt with as well as individual actors. The influence of the regulatory and institutional interventions of the Fascist regime will then be considered specifically in the architectural developments in the northern border regions of *Alto Adige* and *Trentino*. Using two case studies, the railway station buildings in Bolzano/Bozen and Trento/Trient, the respective planning processes will be analysed in detail with regard to their different normative criteria of influence of the stakeholder groups involved from architecture, building administration, building industry and politics. The focus here will be on institutional changes, which were caused by the interventions of the regime and also took effect through negotiations within the stakeholder groups themselves. Then, from the biographical perspective the architect of the two station buildings, Angiolo Mazzoni, and his individual interests will be analysed, his institutional involvement in the various stakeholder groups and his professional dual role as architect and state official.

Apart from the results in terms of content, the methodological approach applied here is understood as a diversified contribution to a methodology to be established: The methodologically proposed interdisciplinary linking of the new approach with social and technical paradigms is at the same time intended to specifically prevent any ideologically conditioned determinations that still exist, such as those detected above all in relativising the ideological part of architecture in a pretended coexistence of architecture and politics (Bodenschatz 2007, p. 10). In Italian research since the early 1980s, the modernisation efforts of the 1920s and 1930s in architecture are to a large extent reflected uncritically (Higgins 2018, p. 289–309), which from a historical point of view can be attributed to undifferentiated perspectives, as the focus is either on a purely aesthetic or a purely technical view, as well as on the detachment of modern architecture from its immediate social and political context. However, a reception of modern architecture that is completely decoupled from politics and ideology also led to "right-wing historical revisionism" and "semi-scientific" congresses and exhibitions in the 2000s (Mattioli & Steinacher 2009, p. 9). In the long run, such a methodology would thus counteract the increasingly observable indifference to ideologies in architecture, which has developed within a "post-ideological age" and a frameless, self-correcting liberal-democratic society (Münkler 2011, p. 146). The long-term goal should be to overcome the alienation of architecture from applied-ethical issues.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Bricks of wrath: (Re)building the *IJzertoren* memorial (1925–1930 and 1952–1965)

W. Bekers, R. De Meyer & E. De Kooning
Universiteit Gent, Ghent, Belgium

ABSTRACT: Between 1925 and 1929, the *IJzertoren* [Yser tower] memorial was built on the Yser river bank in the Belgian town Dixmude. Both war memorial and monument to Flanders' struggle for political emancipation, the tower became an increasingly charged and divisive symbol in interwar Belgium, and its construction was highly ideologized. This situation, exacerbated by the tower's associations with collaborationism in the next war, would ultimately lead to its intentional destruction in 1946 under suspicious circumstances. The subsequent questions, if, how and by whom the tower should be reconstructed, refueled these debates. Despite ambitious reconstruction plans, the memorial was eventually rebuilt between 1952 and 1965 as a slightly modified and upscaled replica of the old tower, an approach that deliberately rejected modern design references or construction methods. The lengthy construction process itself was operationalized in propaganda and iconography of the annual Flemish nationalist rallies that were staged on the building site.

1 INTRODUCTION

At 2:15 a.m. on 16 March 1946, the rural town of Dixmude was startled by the crackling noise from a heavy explosion on the banks of the Yser River, just west of the town center. In the early morning light, after the dust had settled, a crumbled pile of bricks and concrete (Figure 1) was all that remained of the once 52-meters tall *IJzertoren* [Yser tower], a peace memorial to Flemish soldiers fallen during the Great War, but at the same time a monument to Flanders' struggle for emancipation within the Belgian nation and a rally point of the Flemish nationalist movement. Its intentional destruction was the chronicle of a death foretold, after an earlier attempt on 16 June one year earlier. Although unsuccessful, this first assault nevertheless punched a 2 × 20 meter hole in the façade. Moreover, the integrity of the monument's concrete structure and foundations was severely compromised by the impact of the blast. A judicial and parliamentary inquiry until deep in 1951 was unable to bring the perpetrators to trial, let alone identify those responsible (s.n. 1952b). However, the professionalism of the attack (the explosive charges were placed in such a way that the tower collapsed vertically without doing further damage to adjacent property) was evident from the very start of the inquiry, hinting towards the involvement of the nearby stationed Belgian military demining service. In retrospect, sufficient evidence exists to credit Belgicist factions in the army with the responsibility, possibly in alliance with remnants of right-wing wartime resistance cells (De Wever 2008). Such insights are opposed to the widely propagated view in Flemish nationalist circles at the time, who recognized in the attack the hand of the Belgian state, wanting to break the backbone of the Flemish movement because of its collaborationist entanglement during the Second World War. A commemorative plaque on the preserved rubble of the tower thus states: "On March 16, 1946, this tower was dynamited and pulled down skillfully, efficiently, anonymously, but yet known." In the Flemish nationalist rhetoric, the war monument had become a victim of war, in its own right.

Figure 1. Ruins of the dynamited IJzertoren, 1946 (ADVN).

2 A DIVISIVE MONUMENT

To understand the impact of the IJzertoren's divisive symbolism, leading ultimately to the assaults of 1945–6 and to come to grips with the monument's

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multi-layered meanings and present-day connotations, we need to outline briefly how the monument's history is intertwined with the rise of this Flemish nationalism (Shelby 2014). The Flemish Movement developed from a late-19th-century cultural phenomenon into an active political and Catholic movement (the *Frontbeweging*) in the trenches of the First World War. Dixmude, at the easternmost edge of the Belgian sector of the Western Front, subsequently became the epicenter of the veneration of the perished, especially of those who had allegedly died as martyrs for the Flemish cause or had struggled for cultural emancipation against the French-speaking military elite. In this spirit, an annual pilgrimage to the graves of the Yser (*IJzerbedevaart*) was organized from 1920 onwards by a group of likeminded war veterans, whose core consisted of members of the aforementioned *Frontbeweging*. The following years saw an exponential growth of the number of participants, tens of thousands by 1930 (Figure 2), as well as an increasing tension between, on one hand, the commemorative anti-war message that the manifestations wanted to express, and, on the other hand, the political agenda of anti-Belgian and Catholic Flemish nationalism.

The story is well-documented (Seberechts 2003; Shelby 2014). The success of the annual pilgrimages necessitated the acquisition of a large private (as to escape control of the Belgian authorities) terrain, which was ultimately found on the banks of the Yser. The terrain overlooked the former front landscape and was in close proximity to the hard-fought Dixmude flour mills and Trench of Death, both important symbolic locations of Belgium's war loss and grief. Here, the *Heldenhuldezerken* [Heroes' tombstones] that had been placed from 1916 onwards on the war graves of Flemish soldiers without the consent of the Belgian authorities, could be collected and relocated. These stones were, in the early 1920s, replaced by official Belgian gravestones. The Belgian state had already started to reduce some of the wartime stones to gravel for military road construction, an event that was extensively exploited in Flemish nationalist propaganda.

A plan by the Province of West Flanders to erect a *Doodentoren* [Tower for the Dead], a monument to all Belgian victims on a nearby site, gave the impetus to the Yser pilgrimage committee's plans for its own privately sponsored monument to all Flemish soldiers, for which a design competition was held in July 1925. As the plans for the *Doodentoren* became more and more clear, the ambitions of the committee grew. Initially the committee conceived of a monument measuring a mere eight to ten meters in height. By the time of the competition however, a monument of 15 to 20 meters was envisioned. From 39 proposals, the jury selected the design by the young brothers Robert and Fritz Van Averbeke from Antwerp, both sons of the well-known liberal and Flemish-oriented Art Nouveau architect Emiel Van Averbeke. Their design, a monolithic bluestone stele topped with a cross, was inspired by the shape of the *Heldenhuldezerk*, which was an explicit requirement in the competition brief. The cross prominently featured the slogan of the Catholic Flemish Movement AVV-VVK, short for *Alles Voor Vlaanderen – Vlaanderen Voor Kristus* [All for Flanders – Flanders for Christ].

Figure 2. Building site of the first IJzertoren during the annual pilgrimage of 1929 (ADVN).

To compete with the threat of *Doodentoren* (later effectively sabotaged by members of the pilgrimage committee in the provincial council), the height of the IJzertoren design was raised at several intervals during 1925. By the time of tendering in 1927, contractors were asked to make an offer for three variants with a height of 30, 35 and 40 meters, whereas the foundation was calculated on 40 meters. This enlargement necessitated considerable modifications to the initial design, materiality and structural concept. To save weight on the pile foundations, the tower now became a hollow structure. This in turn allowed for the tower to become accessible, offering space for a small exhibition in its base as well as a panoramic view on the former front landscape from a terrace on the top. Since bluestone became too costly on this scale, other alternatives were proposed, such as simili-plastered brick and exposed concrete (as was the case in the Ossuaire of Douaumont, one of the committee's reference projects). The final choice for a brick-clad framework in reinforced concrete was accepted only reluctantly and on the condition that cost savings on material would allow for a tower that would reach its final height of 52 meters, as a testimony of the committee's architectural priorities: "Preferably no bricks, as they look so modest. […] But a fifty-meters tall tower will sound better and make a stronger impression over the centuries than a beautiful bluestone ten-meters tall monument" (ADVN Y714/2/6). The encapsulation of the concrete structure in the brickwork is unsurprising at a time when reinforced concrete as a material was still balancing between "mud" and "modern" (Forty 2012). With the exception of a few modernist diversions that explicitly used exposed concrete, postwar reconstruction in Flanders would generally tend towards a *vieux-neuf* approach in which, for instance, a reinforced concrete structure could be seamlessly integrated in a neo-Gothic building envelope. Nevertheless, the resulting image of the IJzertoren was that of a robust brick

Figure 3. The completed first IJzertoren, 1934 (ADVN).

tower, reminiscent of the sturdy medieval brick towers of the area, albeit in a modernist architectural language that seemed to be borrowed from the Amsterdam School, not unlike, for instance, Huib Hoste's brick *Belgenmonument* in Amersfoort (1917–8). In turn, the tower-like appearance that the IJzertoren had gradually adopted, was shared with other war monuments of the time, such as Jos Smolderen's 1923 International Memorial in Liège or Eduard Van Steenbergen's design for a "Monument Flanders for The Netherlands" from 1928 (s.n. 2020a).

After the design had taken its final shape, a technical board with committee members and engineers Jan De Bondt, Honoré Van der Ghote and Albert Mallebrancke was installed (ADVN Y714/2/6). The board relieved the Van Averbekes and was responsible for some rationalization in the design. They also took care of the study of the reinforced concrete and the day-to-day follow-up of the construction site, together with contractor De Tandt.

The pilgrimage committee, sensitive as ever to symbolism, decided to reuse the remaining *Heldenhuldezerken* in the construction of the tower base, a solution that also intended to save them from destruction. After the completion of construction in 1929 (the ceremony of the last stone having included the integration of remains of the crushed *Heldenhuldezerken* in the top of the tower) and its inauguration during the tenth pilgrimage of 1930 (which was disturbed by riots and an aircraft that dropped leaflets on the pilgrims who were labelled traitors), several new steps were undertaken to charge the tower with additional symbolic meanings. An underground crypt was added between the foundation walls of the tower base. It would hold the bodies of nine alleged martyrs of the Flemish cause, the so-called *IJzersymbolen* [Yser symbols], as well as other material relics that took up a central position in the Flemish nationalist reading of the war events, among them a sink stone from the village of Merkem, on which soldiers had written "Here our blood, when our right?" Between 1931 and 1934, the four tower buttresses were clad with monumental concrete bas-relief sculptures by the expressionist sculptor Karel Aubroeck, the winner of an additional competition (Figure 3). These statues represented, again, some of the *IJzersymbolen*.

During the Second World War, the IJzertoren was physically damaged: it was affected by the bombing of nearby bridges and, after being modified to accommodate the installation of machine guns, it was further struck by a British aerial bomb in May 1940. But most importantly it became morally compromised by the continuation, albeit in a reduced form, of the annual pilgrimages that now had become unabashed manifestations of collaboration, ever since right-wing groups within the committee had continued to gain influence over pacifist members during the late 1930s. In the climate of repression and political crisis that deeply divided Belgium immediately after the Second World War, the IJzertoren and its self-confident (but now compromised) rhetoric acted as a lightning rod for patriotic and unitarian sentiment, making it an easy target for acts of physical vandalism and destruction.

3 AN UNMODERN RECONSTRUCTION

Following the destruction of the tower and taking advantage of the immediate postwar bewilderment among the Flemish movement, attempts were made by the local municipality of Dixmude, as well as by the Belgian Government and associations of war veterans, to expropriate and nationalize the site of the memorial. Proposals to create a cemetery for allied soldiers or a monument to the heroes of both world wars were met with such fierce resistance in Flanders, that they were abolished (Seberechts 2003).

In the course of 1949, a monumental arch was erected from the rubble of the tower and the remnants of Aubroeck's statues. The arch was designed by artist Karel De Bondt together with his brother Jan, who had been a member of the technical advisory board in the construction of the IJzertoren. The so-called "Pax gate" reiterated the De Bondts' 1933 design strategy for a monument to the Van Raemdonck brothers and Aimé Fiévez (three prominent *IJzersymbolen*) near Ypres, which had been built from concrete fragments of a nearby German strongpoint (Decoodt 2020). After clearing the debris, the ruins of the IJzertoren were consolidated to create a new memorial ensemble with the restored crypt and the arch.

Amidst all these events, a new debate centered around the issue on what a rebuilt tower should look like. As early as 1948, the Belgian modernist architect Huib Hoste inquired with the committee about a possible survey of the site: “not only to let my thoughts …but also my pencil wander about the new tower,” a question he repeated in late 1951 (ADVN Y104/1). In the same letter Hoste expressed his criticism of the highly contested reconstruction proposal by Clement Van Himbeeck, professor in civil engineering at the Catholic University of Leuven and counselor of the pilgrimage committee. In Van Himbeeck’s vision, the new tower, 350 meters high and entirely made of reinforced concrete, would be crowned with a six-to-ten-story cross that could accommodate a museum, a congress center and a scientific institute. Vaguely reminiscent of Giacomo Mattè-Trucco’s Fiat factory in Lingotto, Turin (1914–22), and well ahead of Abraham Lipski’s Parking 58 in Brussels (1956–7), the entire tower was made accessible to motorcars and buses by means of a double helicoidal ramp, measuring 4857 meters in length and ending in a multi-storey car park (Figure 4). Turning points and lookout platforms were provided every five windings. Making use of an ascending working platform and slip forming techniques, Van Himbeeck calculated that the new tower would rise at a continuous speed of 20 centimeters per day.

Much against his will, Van Himbeeck’s ambitious plan was made public by the Flemish Catholic student association KVHV (*Katholiek Vlaams Hoogstudentenverbond*), instigating a fierce debate between advocates and opponents in academic, architectural and Flemish nationalist circles. In a 1952 booklet, the KVHV published details of the plan and bundled “ideological, technical, financial and aesthetical” arguments pro and contra, together with some of the opposing opinions as quoted by propagators of the Flemish movement (s.n. 1952a). Among the critics were Robert Van Averbeke, who compared the design to “an American tower building” and a “Tower of Babel”, and Karel Aubroeck who declared that “greatness, beauty and monumentality cannot be derived from size: those can harm and destroy beauty and proportions.” This vision was contested by those who saw the reconstruction as an opportunity to reaffirm Flanders’ resilience and self-confidence in the face of the injustice that had been its part in the immediate postwar years.

Interestingly, most objections against the Van Himbeeck plan were not so much directed against the technical or financial feasibility of the project, but rather against its radical modern stance and functionalist approach. Many of the critics were horrified by the prospect of a meaningless television mast of the likes that were popping up everywhere, such as Gustave Magnel’s proposed 635-meters tall television tower in Brussels. Furthermore, the plan’s embracing of the new postwar reality of car mobility and mass tourism constituted to many critics an impermissible profanizing of the IJzertoren’s initial intentions. Aubroeck, for instance, noted that “to him [i.e. Van Himbeeck], everything is just function, matter and engineering. […] It indeed remains some impressive engineering – but ever since the engineers have come with their tensioning force, ‘beauty’ is on the run and is nowhere to be found on the site” (ADVN Y56/1/1). Publisher Joris Lannoo adds: “Advise the designers of [this] tower to overlook the ground it’s standing on. […] If they would only realize what happened on that ground, they would think piously and devoutly of the heavily wounded and killed, rather than of a skyscraper.” His writing includes a 1917 aerial picture of the front landscape mutilated beyond recognition, on the back of which is written laconically: “Top left (on the location of the soap factory) is now the IJzertoren” (ADVN Y56/1/1).

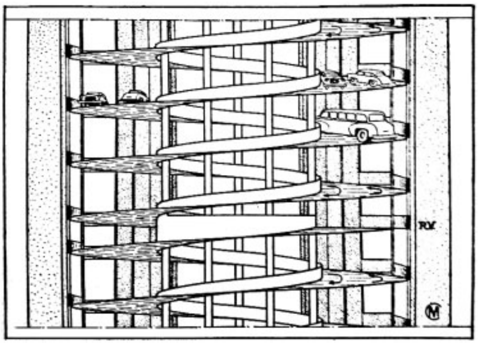

Figure 4. Proposal for a reconstructed IJzertoren by Clement Van Himbeeck, partial cross section (s.n. 1952a).

But the proposal’s materiality and construction method were also food for disapproval. Aubroeck, apart from warning about the extensive use of reinforced concrete, which he considered, judging from his own experience in monumental concrete sculptures, an inferior and unsustainable building material, also rejected the use of machine-produced bricks, as were widely used in the old tower “because of budgetary restrictions.” Noting that Flanders has been a land of tower builders since the Middle Ages, he dismissed industrial building processes and wanted the reconstructed *IJzertoren* to reconnect with this ancient craftsmanship and tradition. After summing up examples in the surrounding area of the “deeply rooted” medieval brick towers that, “like all great architecture, rely solely on their loadbearing and supportive capacities,” Aubroeck concluded: “May they build like our ancestors did; and may they rebuild it as it has been before” (ADVN Y56/1/1).

To put an end to all debates on the reconstruction, the pilgrimage committee, asked four architects (Robert Van Averbeke, Jan-Albert De Bondt, Jan Lauwers and the unfortunate Clement Van Himbeeck) to prepare a sketch for a new monument, 80 to 100 meters in height, and preserving the silhouette of the old tower (ADVN Y104/1). In its meeting of 9 February 1952, the committee, obviously choosing the path of least resistance, commissioned Van Averbeke to draw out the new plans (ADVN Y57/1/4). The reworked design was an upscaled replica of the old tower; only the proportions of the top cross and the tower base were modified (ADVN Y72/1/4).

Given the difficulties to collect the necessary funding for the construction through crowdfunding, a slow and phased building process was envisioned. Resorting under the regulations of war damage and reconstruction, the new memorial was subject to a partial financial compensation from the Belgian Government. The amount of compensation was fixed only in 1961, after a long discussion with the ministry of reconstruction as to the value of the destroyed tower; a debate that centered around the cost that might have been saved if the pile foundation of the old tower had been reused. The discussion was only settled after a technical report, again by Clement Van Himbeeck, on the impact of the 1946 blast on the pile foundation (ADVN Y73/3). In the end, the construction of the new tower, without its interior finishing and elevator, would last over 13 years. Work was interrupted and continued as the necessary funding was gathered, and the tower was not inaugurated until the pilgrimage of 1965.

This lengthy construction process had two immediate consequences. First, it allowed for earlier design decisions to be questioned again by the pilgrimage committee, resulting in numerous discussions and tensions between the committee, Van Averbeke, engineer Amaat Monthaye and contractor Lode Van Der Kinderen. This was most evident in the last and most difficult stage of the construction, leading up to the cross on top of the tower. In a letter to Van Averbeke from 20 February 1963, just prior to the start of the works on the upper floors, the committee expressed its dissatisfaction with the then current design: “It doesn’t have the tough and robust looks of the old tower. Still, much can be saved if we build the cross on top correctly” (ADVN Y74/2/1). The committee then asked to enlarge the proportions of the cross, and at the same time to reduce the concrete structure and all unnecessary floors in the upper part, so that a panoramic room with large windows could be integrated (initially, only a terrace was planned and the windows in the cross were to be integrated in the letters AVV-VVK). What followed was an endless stream of discussion with the contractor and a nauseating series of reworked designs for the upper part (Figure 5), that would only take its definitive shape with large cross-shaped panoramic windows in late November 1963, when work on the floor just below had already started (ADVN Y74/2/1).

Second, the slow construction forced contractor Van Der Kinderen to come up with creative solutions that would allow for long disruptions of the work, also in terms of cost efficiency and equipment on the building site. The private photo archive of foreman Karel Canfyn is a testimony to what measures were taken to achieve these goals, mostly by resorting to manual labor, craftsmanship and small-scale prefabrication on the building site itself. This attitude, unsuited for a mid-century high-rise tower, fitted surprisingly well in the pilgrimage committee’s rhetoric and complemented Karel Aubroeck’s earlier observations on the virtues of craftsmanship and vernacular construction.

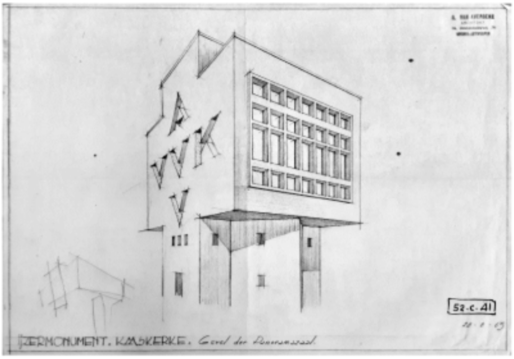

Figure 5. Intermediate design of the cross, 1963 (ADVN).

Figure 6. Prefabricated corner elements in place, ca. 1961 (Collection Karel Canfyn).

One example of this approach is the method that was developed to position the brickwork of the tower shaft, a rather complex process considering the tapered cross section of the tower combined with its polygonal floor plan. The devised solution was a series of V-shaped molds that represented the different angles in the outline of the ground plan. In this formwork, bricks were arranged in the desired bond and covered with a thin layer of concrete. Wooden slats in the joints provided perfect positioning of the bricks and prevented filling up the joints with concrete. Once these carefully labelled pinnacles had been placed in position on the floor under construction (Figure 6), the remaining gaps could then be filled in with brickwork and finished on the inside with a layer of cement plaster. Similar to the construction of the old tower, the whole then served as a lost formwork for the actual solid concrete walls (Workum 1934). The connection between brickwork and concrete was further assured by the inclusion of protruding flipped bricks, resulting in a truly hybrid construction of bricks and concrete. The tiny windows in the tower shaft were prefabricated as brick frames in a similar way. Another example of this approach is the contractor’s proposal for the cantilevering arms of the cross, positioned at an altitude of 69.50 meters above ground level (Figure 7). Whereas exten-

Figure 7. Trusses forming the arms of the cross; prefabricated brick-and-concrete slabs, ca. 1964 (Collection Karel Canfyn).

sive scaffolding and a working platform had been used in the construction of the first tower, the contractor now proposed to use preassembled steel trusses, to which brick-and concrete slabs were anchored. These trusses later served as reinforcement for the 150-centimeters high concrete beams that supported the entire cross.

The organic genesis of the rebuilt IJzertoren and the mutual interaction between its design and construction manifested itself in an unusual relationship between the commissioner, the architect and the contractor with a shared ideology as common denominator. A resolute and well-advised pilgrimage committee would not hesitate to intervene in issues that were traditionally reserved for architects and engineers; a contractor whose duties went beyond the mere execution of the plan, and an architect who saw himself confronted with a career-spanning project and a construction method that was to be retrofitted in a design nearly three decades old. Lightyears removed from Van Himbeeck's scheme, with its mechanized growth of 20 centimeters per day, the slow building process was entirely in the "fourteen hands that built the tower" (s.n.; s.d.). Many years later, in his twofold description of the construction method for the Zeebrugge Sea Trade Center project, Rem Koolhaas rephrased the challenge: "In the first case, sudden erection would become *spectacular*; in the second almost imperceptible progress a potential source of *suspense*: the workers would visibly age during the course of construction; children would become adults as the building stubbornly remained unfinished" (Koolhaas et al. 1998).

4 AN IDEOLOGIZED BUILDING SITE

An indirect consequence of the slow-going building process was the opportunity to tailor the planning of the building site to the pace of the annual pilgrimages. This allowed the committee to operationalize the construction site in its Flemish nationalist rhetoric and mold it into the iconography of the pilgrimages. This operationalization worked on different levels. Most obviously, the memorial (both in its original shape and its reconstruction) had been literally erected from symbolically charged materials. Be it the blood-stained earth that held the tower, or the reuse of the *Heldenhuldezerken* in the tower base, or the subsequent adorning with monumental statues or even the reuse of the debris in the arch: time after time the pilgrimage committee succeeded in charging built matter with additional layers of meaning.

Figure 8. Building site during the pilgrimage, 1958 (ADVN).

Hosting the martyrs' bodies and the relics of the *IJzersymbolen*, the tower "transubstantiated" through the Christian-inspired rites that took place during the annual pilgrimages.

Moreover, the building site played a crucial role as stage and pulpit during successive pilgrimages (see also Figures 2, 8), and the design of the second tower incorporated this need. Van Averbeke pointed out to the committee: "May I establish your attention to the four platforms that are located in front of every entrance […]: they offer the potential to place *Sprechgesänge* or choirs during festivities" (ADVN Y74/2/1). In other instances, the construction site presented itself as décor for choreographic performances or as a canvas for banners with political slogans (adopting the language of the contractor's and architect's prominent nameplates, see Figure 8).

Milestones in the construction process were photographed and published in the committee's communications or gave cause for organized press visits (Figure 9). This happened on significant occasions, such as the groundbreaking or the erection of the maypole upon finishing the top floor, although ceremonial events were also organized on numerous less obvious occasions, such as the geotechnical survey, the canalization of the terrain's drainage system, the driving of the first pile, the completion of the foundation slab, etc. Whenever possible, these ceremonies were matched with the timing of the annual pilgrimages, to become mass-attended and heavily mediatized events. On more than one occasion the contractor was urged to meet certain goals in the construction that could be integrated into the program of the pilgrimages. If this was not feasible, the committee did not hesitate to (re)stage certain events and integrate them in the pilgrimage, sometimes in a symbolic way.

Figure 9. The new tower near completion during the placement of the lettering, ca. 1964 (Collection Karel Canfyn).

The very "vocabulary of the construction site" was activated in the discourse of the pilgrimages. Building cranes, site equipment, scaffolding, scale models and reinforcement bars featured prominently throughout the visual culture of the pilgrimages and Flemish nationalism in general. The construction site of the monument became a familiar image in the iconography (and fundraising campaigns) of the committee, as had also been the case with the first IJzertoren that had appeared frequently in the propaganda films by Clemens De Landtsheer, the committee's secretary and owner of the film production company Flandria Film. Even fetching the building materials was celebrated, starting from the 1955 pilgrimage. This took place under the slogan "*Vlaanderen brengt stenen aan*" [Flanders offers stones] and culminated in a parade of trucks delivering bricks from all over Flanders. It was a clear signal that the reconstruction of the monument embodied the renewed aspirations of the postwar Flemish movement.

5 CONCLUSION

Whereas the historiography of the IJzertoren has been claimed almost exclusively by scholars of Flemish nationalism and by art historians focusing on the iconography of the tower's statues (;e Wever 2008; Seberechts 2003; Shelby 2014), it remains a blind spot in architectural and construction history. This is a remarkable feat, not in the least because the IJzertoren is the only architectural object currently included as such in the attainment targets of Flemish primary education: every 12-year-old is supposed to be familiar with the "acknowledged symbols of the Flemish Community (i.e. its holiday, weapon, anthem, flag and memorial)" (s.n. 2020b). Possibly, its divisive nature, as well as its political and ideological connotations, have prevented a closer inquiry, perhaps even today if we consider the monument's contested nomination for UNESCO heritage more recently (Van Alstein 2016). Yet, from an architectural and construction history perspective, the IJzertoren presents itself as a valid and layered case that raises several important questions. The memorial invites us to consider the mechanisms through which monuments, and their construction processes, contribute to the formation of national identities (Gillis 1994). In a most explicit way, the IJzertoren reminds us how these identities are not static and shift over time. The violent destruction of the first tower is proof of the monument's capacity to absorb ideological meaning and nationalist sentiment over time (Allais 2018). The reconstructed IJzertoren, "bigger and better," has burdened later generations and curators with questions on how to address these issues in a contemporary context, so different from the context in which it was created initially (Van Alstein 2016).

It is impossible to see the IJzertoren and its construction history detached from these connotations. On one hand, all actors in the construction process shared a similar ideological background, and often found one another through their resilient shared social networks. On the other hand, every step in the construction process, from the first pile to the last crowning brick, was to some extent ideologically exploited, or ideologically biased at least. Precisely this aspect constitutes, among other things, the richness of the case and suggests that construction history should not (or cannot) be neutral towards ideology.

However modern in its original shape and architectural language, the destruction of the IJzertoren in 1946 presented the pilgrimage committee with a dilemma. Its reverting to the original 1920's scheme, despite the availability of a highly charged modern alternative, does not seem to have been based on any kind of rational parameter, but rather on a revival of nationalist sentiments, resulting in a somewhat anachronistic design and an obsolete construction method that nevertheless perfectly matched the rhetoric of the pilgrimage committee. This implies that the interplay between the monument and its commemoration was not a one-way process: nationalist motives bestowed the bricks and concrete of the IJzertoren with ideology. In turn the very act of construction, destruction and reconstruction fueled nationalist rhetoric.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Alentejo Marbles in the construction of the Basilica of Our Lady of the Rosary of Fátima, Portugal

C.M. Soares & R.M. Rodrigues
Universidade de Lisboa, Lisbon, Portugal

C. Filipe
CECHAP – Centro de Estudos de Cultura, Artes e Património, Vila Viçosa, Portugal

N. Moreira
Universidade de Évora, Évora, Portugal

ABSTRACT: The ornamental stones used in the construction of the Basilica of Fátima (built between 1928 and 1954) are a carefully selected visible material that dominates both the architecture and the sculpture of the building. These rocks came from various locations and suppliers in Portugal. Using an interdisciplinary methodology that combines analysis of historical records with macroscopic analysis of the ornamental stones, it was possible to identify a great variety of stones from the regions of Pêro Pinheiro-Sintra and the Estremoz Anticline, as well as from Fátima quarries. In this paper, several varieties of white, pink, and dark marbles from the Estremoz Anticline in Alentejo that were used within the Basilica are identified. The criteria that were used in their selection for application in some of the most important parts of this building are discussed. The interdisciplinary methodological approach employed here may support decision-making for conservation and restoration work in the future.

1 INTRODUCTION

The city of Fátima is located in central Portugal, around 130 km north of Lisbon (Figure 1A). This town came to prominence in 1917, after the apparitions of the Virgin Mary to three shepherd children (Lúcia, Francisco and Jacinta) in Cova da Iria. The Chapel of the Apparitions was built there in 1919 to commemorate the event. That chapel would later be replaced by the imposing Shrine of Our Lady of the Rosary of Fátima (Figure 1B), which today is one of the most important international destinations for religious tourism. The Basilica of the Rosary and the adjoining colonnade (Figure 2) were constructed between 1928 and 1954. This monument has been selected for this case study, not only because it is one of the most important buildings in the Shrine of Fátima, but also because it is a paradigmatic example of the use of Estremoz Anticline marbles, from the Alentejo region, the southernmost region of Portugal. The Estremoz Anticline, located about 200 km from Fátima, is internationally recognised due to the quality of their marbles.

This study aims to improve the understanding of the use of marble from the Estremoz Anticline in the Basilica. As such, it also aims to contribute to knowledge about the history of the building through the study of the stone materials used in its construction, a factor that has received little attention in previous research (Duarte 2012; Fuente 1992). At the same time, it is intended to increase appreciation of this exceptional stone, which, in addition to its aesthetic quality, has a cultural history dating back more than 2000 years (cf. Fusco & Mañas 2006; Moreira et al. 2020; Mourinha & Moreira 2019). This stone has been used in monumental constructions both in Portugal and internationally, and has been recognised as a Global Heritage Stone Resource (Lopes & Martins 2015, 2018).

The methodology used in this study is based on the analysis of historical records and archival materials, mostly unpublished, and which are located in several archives, namely the *Arquivo do Santuário de Fátima* (Shrine of Fátima Archive, ASF). In situ macroscopic observation (by the naked eye) of the stone materials used in the building was also performed. As such, the interdisciplinary approach combines Earth Sciences with Art History, and is similar to the methodology used in other case studies (cf. Aires-Barros et al. 1998; Figueiredo et al. 2010; Malesani et al. 2003). It is important to establish the origin of the materials used in historic buildings by means of documentary record (cf. Bresc-Bautier 2012; Hervier & Julien 2010; Mallet 2016), just as it is important to characterise them through multi-analytical studies, whether with the aim of conserving monuments (cf. Debljović Ristić et al. 2019; Pereira & Marker 2016) or stimulating geotourism (cf. Châtelet 2016; Gambino et al. 2017; Lopes

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2016). In addition, it is imperative that the ornamental stones be identified and characterized, the suppliers and source locations be established, and also that the historical, political, artistic, and technical contexts that determined the choices of materials be fully studied. Questions such as these cannot be answered through technical, laboratory-based research alone.

With all of this in mind, this paper intends to map the Alentejo marbles used within the Basilica of the Rosary, to identify the suppliers and sources of materials, and to establish and discuss the criteria that were used in their selection. These factors were not neutral given the political context of the time in Portugal, the aesthetic standards that were established by the Catholic Church, and the financial autonomy of which the Shrine of Fátima benefitted.

2 THE CONSTRUCTION PERIOD (1928–54)

The Sanctuary of Fátima is a large architectural complex – constructed in stages between 1917 and 2007 – composed of the Chapel of the Apparitions, the Prayer Area, the Basilica of Our Lady of the Rosary, the Basilica of the Most Holy Trinity, the retreat houses of Our Lady of Mount Carmel and Our Lady of Sorrows, the Way of the Cross and Hungarian Calvary (Valinhos), and the Paul VI Pastoral Centre (Figure 1B). It reflects various aesthetic movements: Neo-Baroque in the Basilica of the Rosary (Figure 2), "Neoclassical" style of architecture of the *Estado Novo* (dictatorial regime in Portugal from 1933 to 74) in the esplanade and colonnade built in front of the Basilica of Rosary, and Post-Modernism in the Basilica of the Most Holy Trinity (Duarte 2012). Despite this stylistic diversity, there is no aesthetic conflict due to the homogeneous nature of the stone materials that are used (mainly of local provenance). The collaboration between both well-established and promising young artists and architects in the architectural complex is also worthy of mention, with Fátima becoming a privileged repository of religious art (painting, sculpture, stained glass and tile work).

The foundation stone of the Basilica of Our Lady of the Rosary was laid on 13 May 1928. The project had begun in 1921 (Duarte 2012, vol. I: 130–31), and the initial plans were drawn up by the Dutch architect, Gerardus Samuel Van Krieken (1864–1933), who had been resident in Portugal since 1889. He was commissioned by the Bishop of Leiria, D. José Alves Correia da Silva, who had a prominent role in the overall management of the project and in the aesthetic choices that were made (Duarte 2012, vol. I: 64). Van Krieken was neither Portuguese nor Catholic, but his skill and suitability were recognised both in his experience as a teacher at the Industrial School in Oporto, and as the chief technician on buildings for important families in that city who were linked to the Bishop of Leiria. There was a preference for a building that would display a "national style", and the Dutch architect gave form to this notion within a framework of traditional Portuguese religious architecture. By contrast, the Modernism that was adopted by the architect, Porfírio Pardal Monteiro, in his design of the first modern Portuguese church, Our Lady of the Rosary of Fátima in Lisbon (1934–38), was not considered to be a desirable model to follow (França 1982, 247–50). The Basilica was erected in a central position of the Shrine (Figure 1B), and its construction lasted for over two decades. After Van Krieken's death (1933), João Antunes (1897–1989) was appointed by the Bishop of Leiria to supervise the works, and he remained in this role until 1951. Antunes was the chief architect at Lisbon Municipal Council, and member of the jury for the Valmor prizes for architecture (Bairrada 1988). The suggest for him to replace Van Krieken came from Manuel do Carmo Góis, the parish priest of Barreira (Leiria); Antunes had family links to the parish. He was responsible for the design of a number of decorative works in Alentejo marbles, such as altars and pulpits.

Finally, in 1951, António Lino (1909–61) was appointed as the official architect of the Shrine of Fátima, presumably because Antunes was no longer able to continue in his role. The monumental, curved, stone colonnade that was erected between 1951 and 1954 is one of the most striking aspects of the Shrine to have been conceived during this period (Figures 1B and 2). The colonnade is located on the eastern side of the Shrine and it invokes, in simplified form, Bernini's construction in St Peter's Square (Vatican City). A broad staircase leads up to the colonnade, which is formed by a succession of arches. On the architrave, seventeen sculptures of saints are displayed. They were installed there from the 1950s to the 1980s. This construction was intended to link the hospitals (which today are used as retreat houses) to the Basilica. The colonnade confers an undoubtedly monumental aspect to the temple, located in the square of the Shrine that had meanwhile been reconstructed in accordance with plans drawn up by the architect Cottinelli Telmo (Fuente 1992, 70–72). The Catholic Church assumed full responsibility for the construction of the architectural complex of the Shrine, which benefitted from financial resources that originated national and international donations resulting from the extensive adherence to the Marian cult. These funds enabled the smooth completion of the works, as well as the selection of more costly features such as the use of choice stone materials without the problem of budgetary shortfall, as can be ascertained from an analysis of the archival documents.

3 THE ORNAMENTAL STONES IN THE MONUMENT: THE ALENTEJO MARBLES

Natural stone was the construction material of choice for some buildings up until the 20th century due to its durability and monumental nature, and also because of the ease with which it could be adapted to new technologies and construction processes (Candeias

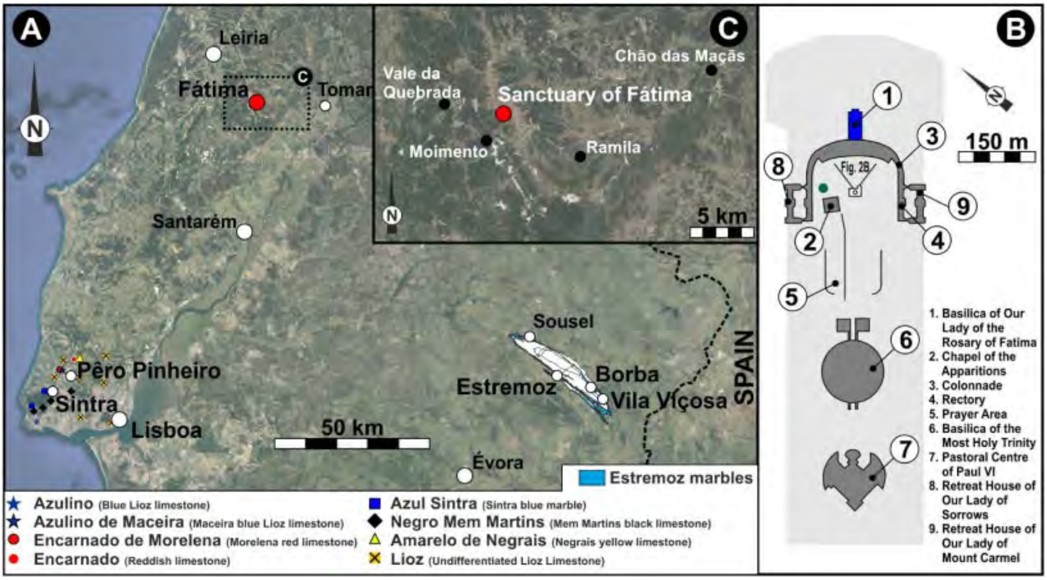

Figure 1. (A) Location of the Sanctuary of Fátima and the two main sources of ornamental stones (adapted from Figueiredo et al., 2010; Moreira & Lopes, 2019). (B) Simplified map of the Sanctuary of Fátima area, highlighting the Basilica of Our Lady of the Rosary of Fátima. (C) Approximate location of the local limestones quarries.

2014, 23). In the architecture of Fátima, and especially in the Neo-Baroque Basilica of the Rosary (Figure 2), the selection of the materials used would have been based on these kinds of considerations. Stone was used both as a cladding material for the buildings, and in the creation of solid decorative works.

For reasons of budget, time, and logistics, and due to the availability of primary and other materials, it was common to use local quarries at building sites. Indeed, the majority of stone used in the construction at Fátima came from the local area, and from the Limestone Massif of Estremadura. The Moimento Quarries (Figure 1C), which are no longer active, were located around 1 km from Cova da Iria, and were the property of Fátima Parish Council. These were the principal suppliers of the limestone that was used as a structural element of the building. One of these quarries, to the south of Fátima, came to be known as the “Shrine Quarry” (Carvalho 2001, 44, 49), and extraction at that location was discontinued in the 1950s after the inauguration of the Basilica of the Rosary (Pinto 2007, 361). Innumerable blocks of “hard and fine-grained stone”, both black and white in colour, were extracted from that site to be used as cladding for the main structure of the building. Furthermore, archival documents reveal that quarries of Loio, Ramila, Vale da Quebrada and Chão de Maçãs (Santarém) were occasionally used to supply stone from the 1930s onwards (Figure 1C).

In addition to the structural materials of the Basilica, other natural ornamental stones were used, with diverse sources and finishes (smooth, polished, shiny) to decorate, elevate, adorn, or highlight specific architectural elements, mainly within the Basilica. A significant proportion of these stones came from the Pêro Pinheiro-Sintra region (Lisbon surroundings) (Figure 1A), which is rich in carbonate rocks, sometimes showing contact metamorphism related to the emplacement of the Sintra Igneous Complex (cf. Kullberg et al. 2013). This process gives it a crystalline granoblas-

Figure 2. View of the Basilica of Our Lady of the Rosary from: (A) the colonnade and (B) the prayer area (note the image of the Immaculate Heart of Mary in the central part of the bell tower of basilica).

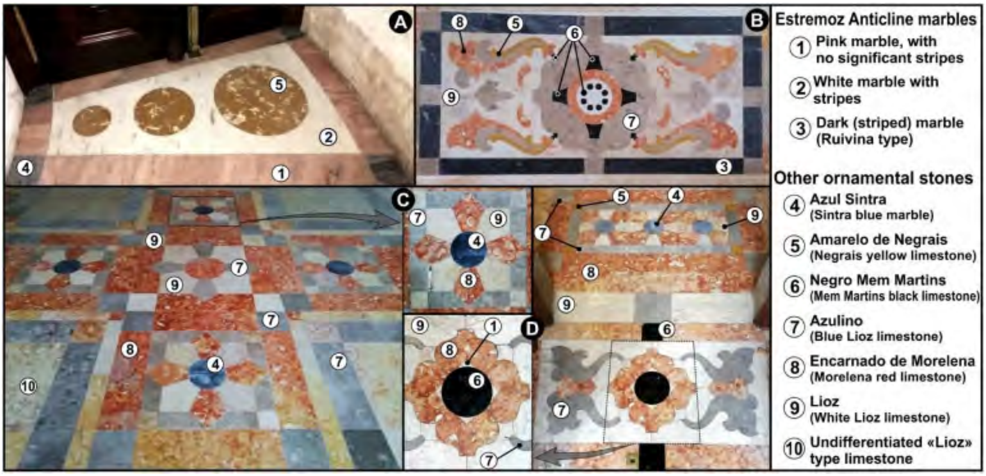

Figure 3. Ornamental stone pieces applied as flooring in the Basilica: (A) sacristy, at the lateral entrance of main altar; (B) staircase leading to the main altar (see location on Figure 4A) (C) main floor of the sacristy; (D) lateral entrance of Basilica.

tic texture, often referred to as "marble". Among these materials, the presence of various lithotypes can be noted, such as *Amarelo de Negrais* [Negrais Yellow], *Azulino de Maceira* [Maceira Blue Lioz], or *Lioz Azulino* [Lioz Blue], *Azul da Sintra* [Sintra Blue], *Encarnado de Morelena* (also *Encarnadão de Lameiras* or *Montelavar*) [Morelena Red]. The overwhelming majority of these stones were applied as flooring in the Basilica (Figure 3). In turn, the Alentejo marbles tended to be used in the sculptural elements, particularly in the main altar, the ten lateral altars, the four transept altars, the pulpits, and also, although more rarely, in the flooring (Figures 3 and 4).

The choice to make significant use of national ornamental stones from regions that were further away from the site of the Shrine would have created transportation difficulties and would also have increased the costs of the enterprise. However, in accordance with the historical records, and as mentioned above, these factors seem not to have had great influence and were easily overcome, even taking into account the economic impact of the Second World War, with which a large part of the work coincided chronologically.

3.1 *Brief characterization of the Estremoz Anticline Marbles*

The Estremoz Anticline is a geological structure, with NW-SE trend, extending for more than 40 km, crossing the Sousel, Estremoz, Borba and Vila Viçosa municipalities (Alentejo region, southernmost of Portugal; Figure 1A). This geological structure is a result of a set of geological processes associated with the Variscan Cycle during the Paleozoic times (541–252 Ma; Lopes & Martins 2015). These processes were responsible for formation of metamorphic rocks, among which marbles stand out for their importance and exploitation in the Estremoz, Borba and Vila Viçosa municipalities (the Marble Triangle). The extractive industry has been active there since, at least, the Roman Empire (Fusco & Mañas 2006; Maciel 1998; Moreira et al. 2020), throughout the Middle Ages, and into the present (cf. Mourinha & Moreira 2019; Quintas 2020), with hundreds of current and historical exploitation sites (cf. Carvalho et al. 2013). Estremoz Marbles, as they are generally known, are calcitic, medium to fine-grained, showing extreme mineralogical purity and excellent physical-mechanical properties. There are multiple chromatic types ranging from white to black, and including pink, beige and grey varieties, which are the result of slight variations in their geochemical and/or mineralogical composition (cf. Menningen et al. 2018; Moreira & Lopes 2019). It is possible to recognise marbles with high chromatic uniformity and marbles with abundant stripes, which allowed to create a diverse range of architectural patterns (Lopes & Martins 2015).

The Estremoz Anticline Marbles are a high-quality product, internationally recognised, presenting a high aesthetic relevance, and an irrefutably historical importance. This region is one of the main centres for the exploitation of ornamental stones at national scale (Carvalho et al.2013). Their intrinsic qualities enabled their use in several royal and noble buildings, both secular and religious (Lopes & Martins 2015; Mourinha & Moreira 2019).

3.2 *Suppliers and supplies*

The analysis of the documentation has shown that several chromatic varieties of marble were brought from the Marble Triangle (white, beige, light and dark pink, grey and black). All of them with obvious aesthetic beauty and their presence is a decisive contribution to the embellishment of the building: the particular nature of these rocks expands the range of colours and textures in the architecture. The documentary sources make reference to *Mármore de Estremoz* [Estremoz

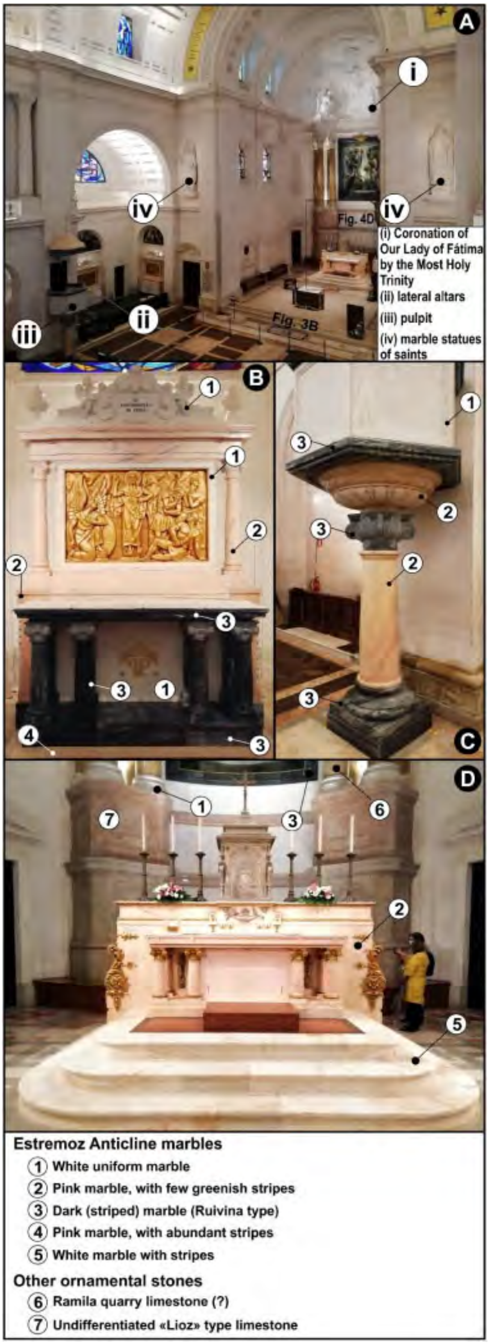

Figure 4. Use of Estremoz Anticline Marbles within the Basilica of Our Lady of the Rosary: (A) location of use; (B) Lateral Altars (example); (C) Pulpit; (D) Main Altar.

marble], *Mármore de Vila Viçosa* [Vila Viçosa marble], *Vila Viçosa claro* [Vila Viçosa light], *Branco de Extremoz* [Estremoz white], *Branco estatuário* [statuary white], *Rosa de Borba* [Borba pink], *Rosa de Extremoz* [Estremoz pink], *Rosado claro* [light pink], *Rosado escuro* [dark pink], *Escuro com veios claros* [dark with light stripes], *Preto de Bencatel* [Bencatel black], *Preto Preto* [Black Black], and *Extremoz Félix*.

The main suppliers were the stonemason and sculptor, Caetano José Godinho, and the company, *Mármores e Cantarias de Pêro-Pinheiro-Estremoz, Lda*. The archival documents refer to other suppliers too, some of which were used more for the supply of rocks from the Sintra region. Caetano José Godinho had a workshop in Portas de Santo António, Vila Elvira, Estremoz. He executed all types of marble work (cf. the newspaper *Brados do Alentejo*, 9 May 1937). At the suggestion of the architect, João Antunes, and through contact between the Bishop of Leiria and the Archbishop of Évora, this stonemason-sculptor was invited to work on the Basilica of the Rosary. His name was suggested to the archbishop in April 1945 by the priest of Estremoz, João d'Almeida Canejo, who testified that he was a "very able and decent person" (ASF_UI413-DS413.204). Caetano José Godinho was responsible for the supply of some of the most notable and significant sculpted pieces in the Basilica, which had been designed by the architect João Antunes (Duarte 2012, vol. I: 159, 193–4). These include: the main altar (1946–48), the altars in the ten side chapels (1948–49), the 4 altars in the transept (1950–51), the two pulpits (1951), and an image of Our Lady of Fátima (1953). From 1948, reference is made to the stonemason and sculptor, Francisco Dias Ramos from Vila Viçosa (Filipe 2015, 59; Matos & Quintas 2019, 96), who collaborated with Godinho on the side altars. This partnership would have been imposed in response to the urgency of completing the construction, which was repeatedly expressed by the Bishop of Leiria. The effects of the Second World War on the price of raw-materials and fuel, the cost of which was rising daily, was an argument that was deployed several times.

The company, *Mármores e Cantarias de Pêro-Pinheiro-Estremoz* had its headquarters in Pêro-Pinheiro and an office in Lisbon. It was one of the principal exporters of marble, and between 1947 and 53 this company supplied several stone blocks, as well as pieces for the columns, bases, four altars, fourteen crosses corresponding to the station of the cross (at the entrance, the main body of the church and the main altar), pieces for the flooring and for the vestry and throne of the main chapel, and for casements.

Some of the main suppliers of marble to the Basilica in Fátima would have been the following quarries, which were managed by the *Sociedade dos Mármores de Portugal* and the *Sociedade Luso-Belga* (Matos & Quintas 2019, 93): Herdade da Vigária or Barrinho (white statuary marble), or Pardais (black marble), both in Vila Viçosa; and Montes de Santo António (white and beige marbles) in Estremoz. In addition, the Borba quarry (Matriz da Borba) managed by *Mármores e Cantarias de Pêro-Pinheiro-Estremoz* (Matos & Quintas 2019, 93) was the source of the dark pink striped marble. All of these quarries were in full exploitation in the 1930s to 1950s, benefiting from the most recent technological developments in the extraction processes (Filipe 2015, 62–4; Matos & Quintas

2019, 94).Stone from the Alentejo was transported mainly by rail, from the stations in Estremoz and Vila Viçosa. Large tonnage rental trucks were also used. As an example, in July 1948, trucks were used to make the four return journeys necessary to transport the altar for the main chapel (ASF_UI2457). In contrast, ox-wagon continued to be used to supply stone from the quarries nearest to the building site. The selection of modes of transport depended essentially on the size of the pieces, their nature and delicacy of the stone and the resources that were available, and these factors are also reflected in the records of expenditure on packing and insurance. One example is the careful transportation of the angels intended for the main chapel, which were crafted by the Lisbon-based company, *Apolo Lda*. It was decided that transportation should be by car, and a "chauffeur … experienced in this type of load" was selected for the job.

3.3 *Mapping the use of marbles in the building*

The mapping of the use of marbles within the Basilica of the Rosary and colonnade is based on a two-way methodology: identification via documentary records and *in situ* macroscopic analysis, that is, through observation with the naked eye by an experienced geologist, seeking to confirm the documentary data.

Despite the abundance of rich documentary records, this method poses certain difficulties because of the terminology used at the time to classify stone. Common or traditional names or designations that have disappeared in the meantime, were often used. This is the case, for example, of "Black Black" or "Estremoz Félix", which may have been given the name of the businessman whose firm supplied it (probably Félix Ribeiro, an important industrialist of the time; Quintas 2020). This situation creates some obstacles to establishing the corresponding current, scientific, or commercial designations. Furthermore, there is an imprecise identification of some stones, such as the indiscriminate use of the term "marble", which requires careful evaluation to avoid gross errors; this situation has already been identified in the literature (cf. Pereira & Marker 2016). The scarcity or gaps of information in historical documents sometimes constraints *in situ* identification. The places where the materials have been used, the terminology used for parts of buildings, which are currently difficult to match, or the modifications of architectural spaces that resulted in changes of their features and in the suppression of some materials are the main constraints. As examples, one of the two sacristies of the Basilica was transformed into St Joseph chapel or the transept area, which was modified to receive the tombs of the three shepherd children.

Once the information contained in the archival documents had been systematically organised and analysed, it was possible to complete the knowledge about the ornamental stones used in the Sanctuary, focusing on the Estremoz Anticline Marbles, through macroscopic in situ analysis. This on-site observation made by a geology specialist, accompanied by an art historian, is essential. This interaction resulted in the correct identification of the use of each material within the building and the establishment of correspondence between historical and scientific designations for stone materials. This approach is valid not only for the Basilica of Fátima, but also for other monuments, as long as no gross errors are made in identifying the materials used in historic buildings.

Several varieties of marble from the Estremoz Anticline were therefore identified (Figures 3 and 4):

- White marbles of high level of chromatic uniformity in the main chapel (base and capitals of columns and piers, presumably the sculptural group of Our Lady Coronation; Figures 4A and 4D) and in the throne of the main altar (background and ceiling), in the crosses (galilee, nave and chapel), in the lateral altars (crowns, base, backgrounds and frames of bronze reliefs; Figure 4B) and pulpits (Figure 4C);
- White to beige marbles with stripes, used in the steps leading to the main altar platform and in some pieces of sacristy flooring, located next to the entrance to the main altar (Figures 3A and 4D);
- Dark pink marbles, with rare (greenish) stripes in the main altar (Figure 4D), the lateral altars (frontal pieces with columns that encase the bronze reliefs; Figure 4B), bases and pulpits (Figure 4C) and in small details in the flooring of the Basilica and sacristy, especially on the floor next to the doorways giving access to the sacristies (Figure 3A);
- Pale to dark pink marble with abundant stripes, in the socles "framing" of the lateral altars;
- Pale pink marble in the pulpits;
- Dark *Ruivina*, with abundant white to grey stripes on lateral altars (table, bases, columns, capitals; Figure 4B), on the throne of the main altar (frame; Figure 4D) and on the pulpits (Figure 4C);
- Dark *Ruivina*, with high level of chromatic uniformity on the throne of the main altar, the floors of the lateral altars, on the sacristy (old altar, removed and on deposit) and on the pulpits.

It is also possible that small pieces present in some of the flooring (Figures 3B and 3D) might correspond to varieties of dark *Ruivina* (termed *Preto do Félix* or *Preto de Bencatel* in the documentation). Due to the high chromatic uniformity, the general features and similar typology, those marbles seem to be *Negro Mem Martins* (Mem Martins Black limestone; cf. Figueiredo et al. 2010). However, in this specific case, macroscopic analysis was insufficient to dispel all doubt.

Furthermore, it was also possible to identify a dark-grey to bluish-grey marble (Figures 3C and 3D), but with some chromatic variation in shades of grey, equigranular, medium-grained and with a well-developed granoblastic texture used abundantly in the patterns on the flooring of the Basilica and the sacristy. Macroscopic analysis reveals clear dissimilarities between these marbles and similar typologies from the Estremoz Anticline, as well as other similar varieties, such as São Brissos-Trigaches marbles. Cross-referencing between existing documentary data and *in situ* observation seems to suggest that this marble corresponds to the variety described as *Azul Sintra* in the documentation. This denotes a typology of marbles resulting from the contact metamorphism of Upper Jurassic limestone from the São Pedro Formation (Sintra region; Kullberg et al. 2013).

As the documentary sources prove or suggest, sculpture (reliefs, statuary, and other important works of stonemasonry), would have been crafted in Estremoz Marble. Examples of the use of this stone are to be found in the statues of saints displayed in the interior of the Basilica (Figure 4A) and in the colonnade (Figure 2B), and, presumably, in the group of carvings in the dome of the main chapel, which represent the Coronation of Our Lady of Fátima by the Most Holy Trinity (by the sculptor, Maximiano Alves and carved from "top quality marble" by Apolo Lda, the company owned by the sculptor Anjos Teixeira Filho) (Figure 4A). By contrast, the image of the Immaculate Heart of Mary (Figure 2B), donated to the Shrine by the American sculptor, Thomas McGlyn (1906–77) and which has formed part of the external facade of the Basilica of the Rosary since May 1958, is made with marbles from Pietrasanta (Duarte 2012, vol. I, 266–7, vol. II, 177–8).

3.4 *Selection criteria*

It is important to reflect on some of the issues involved in the process of selection of stone materials used in the Basilica of the Rosary. Who had responsibility for the selection? What criteria were used to make these selections? Why were different stones used in identical types of pieces?

The use of prestigious, traditional, Portuguese materials was dominant in the period when the Shrine at Fátima was constructed: such materials were favoured in the public buildings constructed by the *Estado Novo* regime. The materiality of these buildings was marked by a solid and rectilinear structure, through which the dictatorial and nationalist regime sought to transmit a message of stability and power. At the same time, the development of the construction of Fátima took place in the mid-20th century, in a period when new materials such as reinforced concrete, which challenged architects' creativity, also came to be used in religious architecture (Cunha 2014). This was a private construction project in which the regime did not interfere directly; however, the choices made in relation to both the architectural direction and the materials selected were conservative, and demonstrated a reconciliation of the architect's taste with that of the entity which had commissioned the work (represented by the Bishop of Leiria).

Furthermore, the selection of materials for the construction of the Shrine of Fátima acquired clearly symbolic connotations: the "most solid and pure", "most perfect and most beautiful" stones were chosen "from all the provinces and corners of the Portuguese nation, which offers thus, in grateful and moving homage to the glorious Patron and Queen, the best of its land and production". These words from Canon Sebastião Martins dos Reis, one of the most prominent scholars of Fátima, are in relation to a project for the Chapel of the Apparitions that was never realised; nonetheless, they provide evidence of the careful selection of materials destined for the construction of the Shrine, and in particular, of the imposing presence of Estremoz Anticline Marbles in the sculpted elements that are imbued with a heightened symbolic-religious value, such as the altars, the pulpits, and the statues (Figure 4).

In practical terms, the choice of materials would have come down to the architect of the building, who was responsible for establishing harmony between symbolic-religious and aesthetic values. Various colour samples were sent to the shipyard that would have facilitated the selection by enabling the architect to simulate the chromatic effects – for example, the stonemason C. J. Godinho sent samples when he was working on the altar for the main chapel of the Basilica.

It is credible that factors relating to conservation would have informed the choices. Alentejo marbles were considered a highly resistant and long-lasting material. As can been seen in a 1938 advertisement for the Vila Viçosa-based firm, Solubema-Sociedade Luso-Belga de Mármores, marble was "non-porous and non-fibrous [material] that lasts for centuries without costly maintenance" (Matos & Quintas 2019, 108). Over the long term, these features would compensate for the initial, high level of investment.

4 CONCLUSION

An interdisciplinary approach to knowledge and sources enables a deeper understanding of buildings, and particularly of those with historical and artistic dimensions. In this sense, the materials which give these buildings structure and form assume crucial importance throughout the process, whether in technical, aesthetic, or symbolic terms. The use of marble from the Estremoz Anticline in the Basilica of the Rosary in Fátima must be considered to gain full understanding of its use when the fields of Civil Engineering and Architecture are placed in dialogue with those of Earth Sciences and Art History.

The results presented in the foregoing discussion, make it possible to identify, through archival and in situ macroscopic analysis, the ornamental stones used, the suppliers and details about what was supplied, as well as the various applications of these materials within the building. The presence of different types of marble from the Estremoz Anticline, which were used in prominent places within the Basilica, and often in sites with deep symbolic meaning such as the main altar, the sacristy, the side altars, and the pulpits was demonstrated. This use has much to do with the heightened aesthetic value of the marble, which allows for the possibility of colour combinations and, simultaneously, for highlighting specific symbolic elements. However, for now, other historic building located outside the region of the Alentejo that use so many marbles from that region have not been identified. This is one of the aspects that makes this case study unique.

The availability of information about the ornamental stones used in the Basilica enables a deeper and more comprehensive understanding of the building. At the same time, knowledge about the sources and types of materials used, the classification of the ornamental stones (colour tones, mineralogical composition, mechanical resistance, porosity, and so on), and their application, will support future decision-making for the purposes of conservation and restoration.

The existence of a systematically organised collection of documents supported the data gained through in situ observation and the identification of different types of marble pieces, enabling their differentiation and attributing the source of the materials used in the building. Such favourable conditions are not always in place, especially in relation to older historic monuments; in this case, the advantageous research context allowed us to forgo destructive analytical methodologies (e.g. elaboration of thin-sections and geochemical studies). These methodologies would only be applied in cases of lingering uncertainty.

This investigation, which presents a work methodology adaptable to other monuments, constitutes an initial approach to the broad study of the ornamental stones used in the Basilica of the Rosary in Fátima. It is important that this research continues, particularly in relation to the systematic and detailed mapping of the stones within the Basilica and the other buildings that comprise the monumental Shrine of Fátima, the "Altar of the World", as described by the Portuguese journalist and politician, João Ameal, in 1953.

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Tile vaults in the works of government institutions after the Spanish Civil War: A first approach

E. Redondo
Universidad Europea de Madrid, Madrid, Spain

F.J. Castilla
Universidad de Castilla-La Mancha, Ciudad Real, Spain

ABSTRACT: This work which aims to document the use of tile vaults in the construction of new and rebuilt villages after the Spanish Civil War is based on two main documentary sources: the journal *Reconstrucción*, specifically devoted to the work of the *Dirección General de Regiones Devastadas y Reparaciones*, and the archives of the *Instituto Nacional de Colonización*. The entire journal collection and a total of 254 projects from the archives have been reviewed, verifying the use of this construction system in 14% of the projects. A sample of the most representative typologies of buildings constructed with tile vaults is presented. The geographical distribution and relations between different projects were analyzed. As a first approach, we conclude this was a commonly used construction system, though not one homogeneously distributed across the country. The construction details and the actual preservation of these buildings deserves further investigation through documentary and on-site research.

1 INTRODUCTION

Although the Spanish Civil War had not ended, in January 1938 the *Dirección General de Regiones Devastadas y Reparaciones* (DGRD) was created by the first Franco government. Its aim was to rebuild homes and infrastructure damaged during the war, initially in the Nationalist area. In October 1939, a few months after the end of the war, the *Instituto Nacional de Colonización* (INC) was created, with a greater concern for the rural areas, and aimed at a complete reform of the Spanish agricultural system.

Their objectives were similar, not the same. The DGRD was responsible for rebuilding the towns and cities that were destroyed, totally or partially, during the Spanish Civil War. The choice of village to be rebuilt depended on the damage suffered in the war and was organized around the phrase "villages adopted by the Caudillo" when destruction was estimated to be greater than 75%. The term "partial adoption" was created later, when the damage was less or covered a specific area of the municipality; this occurred more frequently in cities or large towns. In 1941, the DGRD also took charge of the reconstruction of religious or Historical Heritage buildings, thus giving rise to the *Junta Nacional de Reconstrucción de Templos* (JNRT) which was more specifically responsible for this task.

In May 1941 there were already 148 villages listed as adopted (*Reconstrucción* nº. 12, 9) which were logically concentrated around the great battle fronts of the civil war: Madrid and its surroundings, the lower part of the Ebro valley, some mountainous areas in the North and specific areas in Extremadura and Andalusia (Figure 1). The number of "adopted villages" would continue to increase over the years, and by 1948 there were 228 (*Reconstrucción* nº. 87, 326).

In some cases, these villages were built on the same location, over the ruins (total or partial); in other cases, the old village was abandoned and a new one was built nearby. The reasons for the latter are varied, ranging from a desire to leave the ruin as an example of what should not happen again (as is the case of Belchite) to more practical reasons, such as the excessive cost of debris removal from their initial location in unhealthy areas or far from crops.

The DGRD was active from the end of the civil war (1939) until 1956. The journal *Reconstrucción* was its main propaganda mode, thus we have found in it some of the information included in this work.

With regards the INC, it was responsible for the repopulation of areas in Spain that were little exploited from an agricultural point of view. Its interventions included an architectural and urban planning project (the new town) with agricultural interventions, usually the creation of new irrigation systems in large water basins. It also included an important network of reservoirs built by the Franco government. The INC was active until 1971 and its work was more prolific between 1950 and 1965 (Flores Soto 2013, 119).

During this period of action, the INC created nearly 300 new villages, with non-homogeneus geographical distribution, since they were grouped around the great

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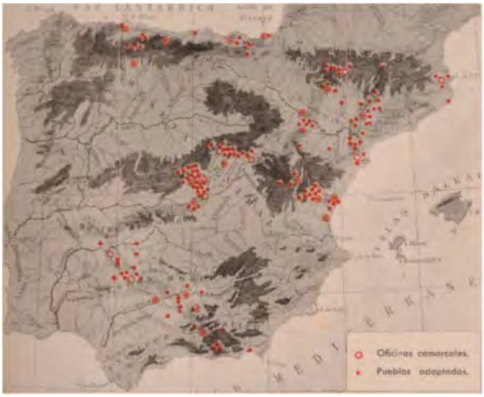

Figure 1. Map of Spain with the situation of the "adopted villages" by the DGRD in May 1941 (*Reconstrucción* nº. 12, 9).

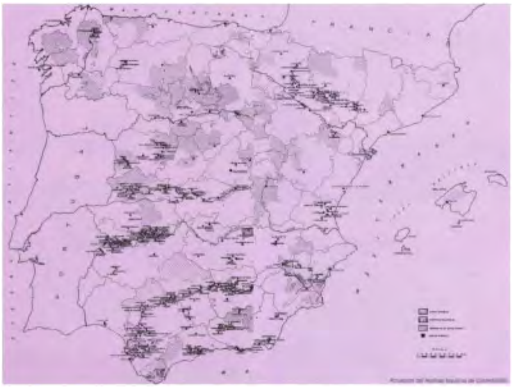

Figure 2. Map of Spain with the location of the villages built by the INC (Tamés Alarcon 1988, 5).

rivers of Spain, especially the Guadalquivir, Guadiana and Ebro (Figure 2). In fact, the numerous existing studies on these villages generally classify them by river basin and/or irrigation area.

2 THE CONSTRUCTION METHODS USED

The years of most intense work by both organisations coincided with the era of autarchy, when the Franco state, economically blocked by democratic countries, had to supply itself with its own resources, avoiding imports. This led to a major shortage of building materials, which affected the way these villages were constructed.

This general shortage of materials in Spain is mentioned in several issues of *Reconstrucción*, as well as the increase in the cost of transport, even between different areas or regions of the country. Antonio Cámara Niño, project director of the DGRD, wrote two relevant articles:

– "*Notas para el estudio de la arquitectura rural en España*" (*Reconstrucción* nº. 6, 3-12) published in November 1940, analyzes the different types of popular housing in Spain by geographical area and climate. The materials and construction methods used are presented as a starting point for those to be used in the reconstruction of villages: stone, wood, brick, rammed earth, lime, or mud bricks. Brick vaults are also recorded as commonly used in Extremadura and Catalonia.

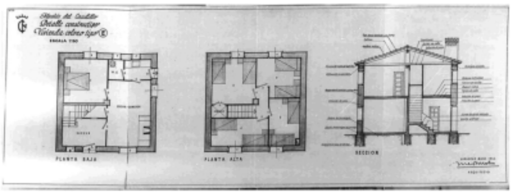

Figure 3. Project type of housing for a settler, with a wooden structure. This particular plan belongs to the documentation of the village of Alpeñes del Caudillo, although it appears in other locations as well. Source: INC archive. Architect: José Borobio Ojeda. 1953.

In 1941, the DGRD had already started several projects. The extensive article "*Construcción de la vivienda rural*", written again by Cámara Niño (*Reconstrucción* nº. 18, 19-40), emphasizes the use of local materials. Small brick or tile ovens and forges were created close to building sites. The article mentions different construction methods used for foundations, walls, lintels, slabs, and stairs in projects already built by the DGRD. Vertical structures were systematically load-bearing walls made of brick, masonry, rammed earth or mud bricks. The foundations were continuous footings, made of plain concrete, seeking as far as possible areas with good quality soils and avoiding expensive systems. Referring to the horizontal structure, the author describes timber as the most commonly used material, and concrete beams when the spans are longer. There are also numerous patents in which hollow ceramic blocks served as lost formwork for concrete beams and joists.

Timber was used for roof structures in simple sloping joists or small trusses if the span was bigger. In villages built in dry areas, such as Levante and Andalucia, the roofs were flat with a terrace, and could then be built like the lower floors.

Tile vaults were also an important part of the article which detailed the projects, where they had been used, before the publication of this issue of the journal.

These same methods can be seen in the project blueprints kept in the INC's archive. It can be deduced that it was common to work with "model projects" applied to several villages, especially for the settlers' homes, which were replicated in all successive interventions. As in *Reconstruccion*, structures with load-bearing walls (masonry, brick or rammed earth) and foundations under them can be found. For horizontal structures, the most common types were:

– Timber joists (logs) in floors and roofs. On the roofs, the joists were simply bent over. Above this, only a tile or wooden sheet is placed (Figure 3).

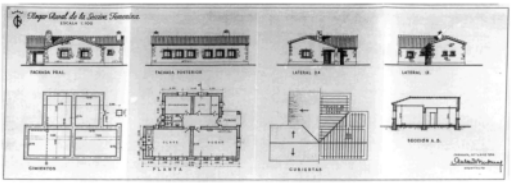

Figure 4. Model project for *Hogar Rural de la Sección Femenina*, with a structure of reinforced concrete-ceramic beams. This particular plan belongs to San Juan the Flumen village documentation, although it also appears in other locations. Source: INC archive. Architect: Antonio Barbany Bailo. 1956.

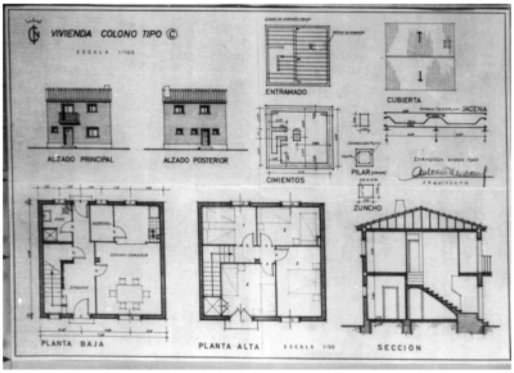

Figure 5. Project type of housing for a settler, with a reinforced concrete structure. This concrete plan belongs to the documentation of the village of Rada, although it appears in other locations as well. Source: INC archive. Architect: Eugenio Arraizo Vilella. 1954.

- Floors and roofs with reinforced concrete and ceramic joists. As in the case of wood, beams were placed horizontally in the slabs and sloped in the roofs, serving as a direct base for the roof tiles (Figure 4).
- Reinforced concrete structures: ribs of the floor, beams and even the interior columns. In this case, partition walls based on a flat slab usually support the roof (Figure 5).

3 USE OF TILE VAULTS IN THE INC VILLAGES

With reference to the use of tile vaults, it could be described as the perfect system to solve the problem of material shortages, as they only needed bricks, plaster and some tie rods. The blueprints from the INC archive that are digitized in the library of the *Ministerio de Agricultura* have been traced to find the frequency, location and exact time when the tile vault construction system was used for the construction of these towns. Of the original 281 interventions of the INC (according to the list published in Calzada Pérez 2008), 254 villages (some of them simple farmhouses or scattered houses) were studied. The projects, carried out between 1943 and 1970, were signed by an architect and some engineers: electrical, agricultural, etc. Most of the architects in charge worked in various towns, some were INC staff: Jesús Ayuso Tejerizo, Manuel Jiménez Varea or José Borobio Ojeda (DARA n^{o}. 8, 10); others were prestigious architects in Spain such as Alejandro de la Sota or José Antonio Corrales. José Luis Fernández del Amo is the architect most studied for his colonization village plans.

The studied villages are grouped by river basin:

- 22 villages in the Northwest basin (North and Duero)
- 72 villages in the Guadalquivir basin
- 29 villages in the Tajo basin
- 57 villages in the Guadiana basin
- 36 villages in the Ebro basin
- 38 villages in the Mediterranean basins (South and East)

In this piece of research, tile vaults were found in a total of 36 villages, corresponding to 14% of those studied. Most are located in the Guadiana basin and more specifically around Badajoz, where there are 19 villages in which this type of construction appears. Furthermore, in these villages they are used in a general way: in houses, public buildings and in the church. In the Ebro basin, they are found in eight villages, but with a more specific use (only in the church or in the civic centre). Around Guadalquivir we find six villages, in four of them (grouped around the river Guadalete, Cadiz) tile vaults are generally used in the housing programme and in the other two they are used only occasionally. In the remaining areas, they are seldom used: there are none in the Tajo area nor in the North, only one in the villages of the Duero basin and two in the Mediterranean zone.

As far as architects are concerned, we could not find a significant relationship with the use of vaults, except in one case. Alejandro de la Sota uses them in four of the five villages in which he worked. In several towns designed by Manuel Giménez Varea, Manuel Rosado Gonzalo or José Borobio Ojeda, we find tile vaults, but the three are staff architects at the INC, so they work in many other towns, also using other building systems.

Finally, considering dates, they appear between 1943 and 1964. The bulk of the buildings using vaults were constructed in the 1950s and 1960s, but these were also the years with the greatest number of buildings under construction.

3.1 *Tile vaults in the villages around Badajoz (Canal de Montijo and Canal de Lobón)*

Here we find the largest group of tile vaults, in villages that border the lower course of the Guadiana River and its network of canals. There are tile vaults in ten villages that are very close together: Guadajira, Balboa, Valdelacalzada, Guadiana del Caudillo, Pueblonuevo del Guadiana, Barbaño, Sagrajas, Novelda del Guadiana, La Alcazaba and Valdebótoa. In all these villages, they were used in general construction,

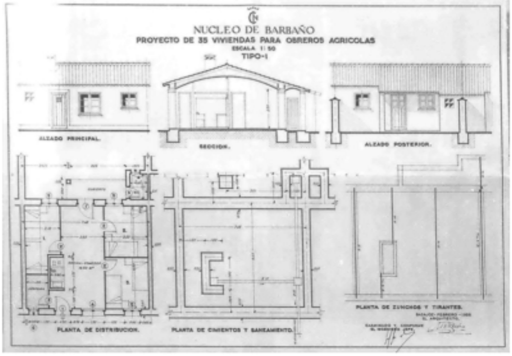

Figure 6. Type project for a single-storey farm worker's house, with tile vaults. This plan belongs to the documentation of the village of Barbaño, although it also appears in other villages in the area (Canal de Montijo/Canal de Lobón). Source: INC archive. Architect: Manuel González Rosado. 1953.

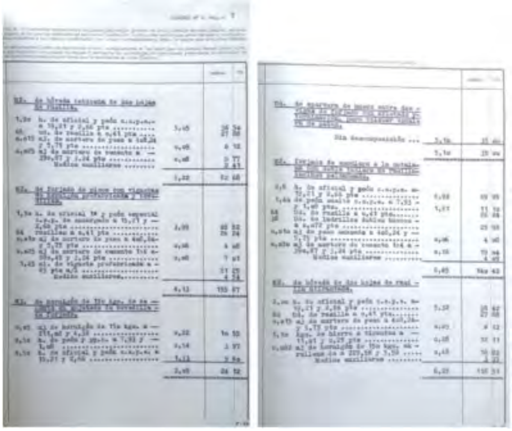

Figure 7. Project for the expansion of La Bazana (Badajoz), measurement and budget. Source: INC archive. Architect: Perfecto Gómez. 1959. Similar information can be found for other villages, like Barbaño.

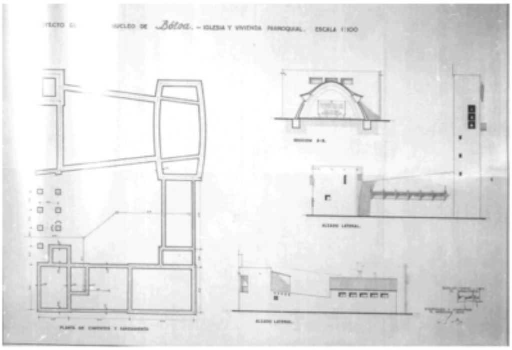

Figure 8. Project for a church in Valdebótoa (Badajoz) Source: INC archive. Architect: Miguel Herrero Urgel. 1957.

both for the housing of settlers and in the church and public buildings (town hall, civic centre, schools, etc.).

The most complete documentation can be found in the village of Barbaño, where various types of houses are listed (for settlers, workers, craftsmen, teachers, etc.) as well as the rectory, schools, agricultural buildings, and public buildings, all of which have floors and roofs constructed with tile vaults.

Some of these blueprints appear in the documentation of other villages, so they must have formed part of one of these "model projects" mentioned above, such as the housing for agricultural workers in Figure 6.

As can be seen, construction information is scarce. A tile vault construction can be deduced because of the very thin sheet seen in the section drawing. Neither the thickness nor the number of tile sheets is indicated. There is, however, a plan detailing the necessary tie rods. This occurs in a similar way in the rest of the "standard projects" of dwellings (Figures 3–6). The most likely reason for this is that the specialized knowledge of the masons required no further detailed information in the drafts.

More information about the construction system can be found in the measurement and budget for each project (Figure 7). It is the only project document in which we find a detailed description of the elements to be built. In them, we always find a description of tile vaults, with or without ties, used for the floor slabs and as a base for the staircases.

Finally, in Figure 8 we see a plan of the church of Vadebótoa, with a curious parabolic profile vault that is built directly from the foundation. Again, the use of the tile vault can be deduced due to the slenderness represented in the drawing and by the references to the use of this technique in the surrounding villages. In the plan, there is no reference to how it is built, although it probably does exist in written documents that have not yet been consulted for this village.

3.2 *Tile vaults in the villages of Guadalete Valley (Cádiz)*

The other group of villages where tile vaults are used for the housing programme is an area in the province of Cadiz around the river Guadalete, in the Guadalquivir basin. There are four small villages, very close to each other: El Torno, Torrecera, José Antonio (Majarromaque farmhouse) and San Isidro del Guadalete. Three of the projects were designed by the same architect (Manuel Lacasa and Suarez Inclán), while the village of El Torno was designed by Víctor D'Ors and José Subirana.

In the documentation of these villages, blueprints of simple single-storey settler houses are found, in which the roof is built with a tile vault. The slope of the roof also looks like a thin sheet of bricks, and few partitions must have been built to give unity and rigidity to the whole building set, see Figure 9.

We have consulted other documentation (reports, measurements, and budgets) of one of these villages

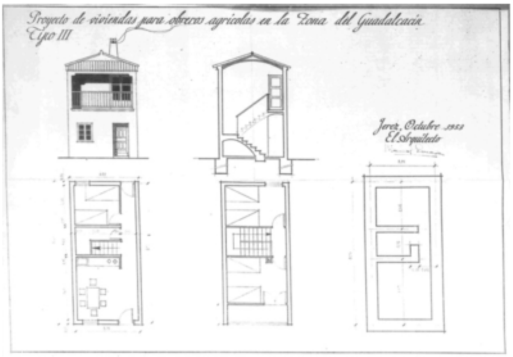

Figure 9. Project for settler housing in San Isidro del Guadalete. Plans identical or similar to this one are repeated in the documentation of Torrecera and José Antonio (Majarromaque), settlements by the same architect. Source: INC archive. Architect: Manuel Lacasa and Suarez-Inclán. 1953.

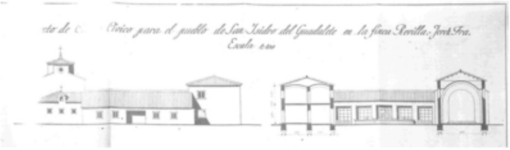

Figure 10. Project for a church and civic centre in San Isidro del Guadalete. Source: INC archive. Architect: Manuel Lacasa and Suarez-Inclán. 1957.

(San Isidro de Gualalete) and found that the intermediate floors, roofs and staircases are actually built with tile vaults. The header of the plan does not include the name of the town, only the area where it applies, reinforcing the idea of "model projects" for specific areas undertaken by the INC.

In these villages around Guadalete River, tile vaults are again used as a general construction system, not only for houses. We find drawings in which they appear in the construction of churches and civic centres (Figure 10).

3.3 *Tile vaults in the villages built by Alejandro de la Sota*

As mentioned above, Alejandro de la Sota was involved in the project with five villages: Gimenells (Lérida), La Bazana, Valuengo y Entrerríos (Badajoz) and Esquivel (Sevilla). Tile vaults were used in all but the first. This does not mean that it was the architect's decision, since three of the interventions are in Badajoz, where the use of vaults was common (although the villages of Alejandro de la Sota are somewhat distant from those mentioned in section 3.1). The fourth town, Esquivel, is in Sevilla, where no other tile vault construction was found.

In Entrerríos, typical drawings of dwellings, similar to those of Barbaño and Valdecalzada, were found (Figures 6–7), but the plans referring to the city council and the church are more interesting.

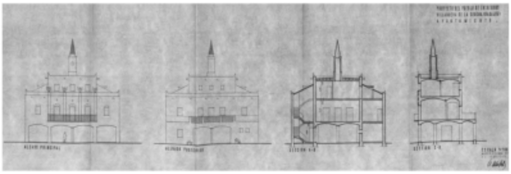

Figure 11. Project for the Entrerríos Town Hall (Badajoz). INC. Archive. Architect: Alejandro de la Sota. 1955 (Cabecera Soriano 2013, 334).

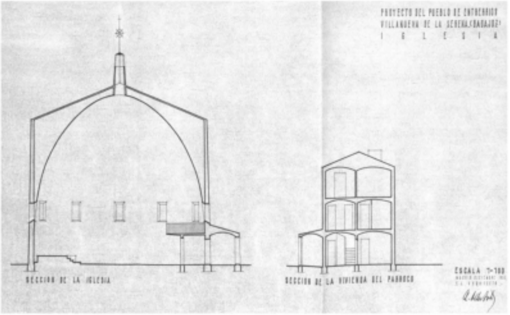

Figure 12. Project for the church of Entrerríos (Badajoz). Archives INC. Architect: Alejandro de la Sota. 1955 (Cabecera Soriano, 2013, 338).

The plans of the city council are striking because we can see a building of a greater magnitude, with three floors, built entirely with tile vaults (Figure 11).

As for the church, we find a parabolic section (Figure 12), similar to that of Valdebótoa. Again, construction information is scarce. Only the slenderness of the two layers drawn in the section and the certainty that tile vaults were used in other parts of the village (Figure 14), make us think that this is a tile vault construction. The vault could also be joined with the roof board by little partitions between them.

In Entrerríos church, a powerful circular drum made of exposed brick (Figure 13), is a very singular element in the village. It is located in the centre of the square and surrounded by arcaded streets that continue around the whole square. The roofs of these arcaded areas are also made of tile vaults.

This arcaded street is one of the few places where we can confirm that the construction method was really tile vaulted, because an image of its construction has been preserved (Figure 14).

In La Bazana and Valuengo, towns closely located in the south of the province of Badajoz, next to the Ardila River, we found documentation about similar types of houses to those of other towns of Badajoz (see Section 3.1). In Figure 15 we can see slightly more detailed drawings than in others.

In the central section, the radii of curvature are drawn to outline the vaults. It can be seen somewhat better that the structure is a set formed by a single-sheet tile vault, an upper board that serves as a base for the roof and partitions between both layers. The construction reports of these villages have been consulted in the

Figure 13. Church of Entrerríos (Badajoz) and surrounding arches. Architect: Alejandro de la Sota. 1955 (Cabecera Soriano 2013, 319).

Figure 14. Arcaded street surrounding Entrerríos Square: tile vaults, groined and very flat, following a common pattern in Extremaduran construction (Delgado Orusco 2013, 108).

Figure 15. Model project for a house in Valuengo-La Bazana. Source: INC file. Architect: Alejandro de la Sota. 1958.

INC archive, confirming that the construction system used tile vaults in floors, roofs and stairs.

In Esquivel, in the province of Seville, there is a preliminary project, drawn up by the architect Aníbal González in 1951. The final project was by Alejandro de la Sota in 1952 (Cabecera Soriano 2013, 265). In no town in this area, not even in the province of Seville, was any reference found to construction with tile vaults. Nor were there any in Aníbal González's initial draft. In Alejandro de la Sota's final project the church seems to have been built with concrete beams, while houses and city council are drawn with a flat slab. However, we find vaults in the school project (Figure 16). We cannot be sure that they are tile vaults due to the lack of detail in the plan, but it seems probable, given the similarity of the project with others in which we do know.

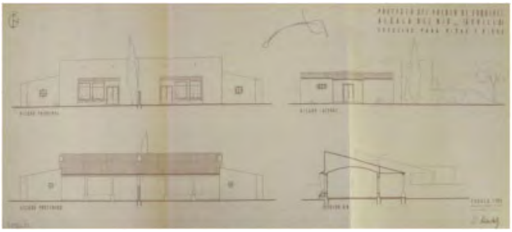

Figure 16. School project in Esquivel (Seville). Architect: Alejandro de la Sota. 1952 (Cabecera Soriano 2013, 281).

This project for Esquivel was earlier than those carried out by Alejandro de la Sota in Extremadura (Entrerríos 1955; Valuengo-La Bazana between 1954 and 1958) so it is worth asking if he had any previous knowledge of the work carried out. Was it a decision by Alejandro de la Sota? Did he know any previous work by the INC using this technique?

3.4 *A particular case: Pueblonuevo del Bullaque*

The Bullaque area is in the west of the province of Ciudad Real. Again, it is in the Guadiana basin, but very far from the Extremaduran villages above mentioned. The project was drafted by Manuel Jiménez Varea, one of the INC staff architects, who planned a total of 23 villages. He designed tile vaults only here and in two other villages (San Francisco and San Rafael de Olivenza, in the province of Badajoz). Pueblonuevo del Bullaque was built with a conventional system, with timber in roofs and floors. In the section of the church there are thin vaults that could be made of tiles. But the most interesting thing is the project of a variant of housing (not built), named in the blueprints as "Solution B" (Figures 17–18). In this solution, three types of housing for settlers, one for workers and agricultural dependencies, are drawn, all of them with a double vaulting construction in which the outer layer creates the roof and the inner one delimits the interior space of the dwelling.

They are single-layer vaults reinforced by brick arches at intermediate points of the roof (Rivero and Peris 2014). Between the two layers we can see the construction of partition walls that stiffen the whole structure.

3.5 *Other tile vaults in the INC works*

The previous sections describe the most interesting groups of villages with tile vaults, which have a clear link. However, several others have been found in the remaining 36 villages previously mentioned, in different situations or locations.

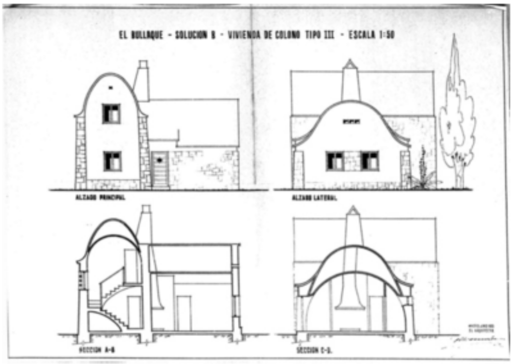

Figure 17. Type III settler housing. Pueblonuevo del Bullaque. Source: INC archive. Architect: Manuel Jiménez Varea. 1954.

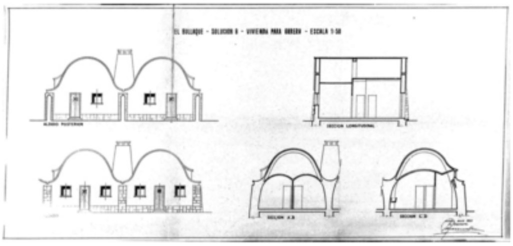

Figure 18. Worker housing. Pueblonuevo del Bullaque. These dwellings, smaller than in the case of the settlers, are grouped in rows with a counter-curve that unifies the roof. Source: INC file. Architect: Manuel Jiménez Varea. 1954.

- They are systematically used in staircases, even in areas (such as the Duero Basin and North area) where no reference to this form of construction for general structures can be found. In Figure 19 we see the plan of a dispersed housing intervention in the Terra Cha region, in Lugo. The construction system is formed by masonry walls and flat slabs, but in the section of the staircase we can see a vault, which most likely would be made of tiles.
- In several villages, where the main constructions (houses, public buildings) follow other methods, the arcaded areas that very often surround the main squares, (situated in front of the artisans' houses) are usually built with tile vaults, similar to that of Entrerríos. This is the case in Solana de Torralba and Vegas de Triana (both in Jaen), in Brovales (Badajoz), or in San Isidro del Albatera (Alicante) by the architect José Luis Fernández del Amo. Another interesting case is Sancho Abarca, built in 1954 by the architect Carlos Sobrini. The roof of the square is a very thin double curvature surface (Figure 20) built with a tile vault. Despite the lack of construction definition in the plan, we have consulted the construction reports, which confirm the use of this construction system.
- They are used with some frequency in the construction of churches, also in villages where the general construction system of the houses is different. This occurs especially in the villages of the Ebro basin: El Temple, San Jorge, Valfonda de Santa Ana, Sodeto; most of them under the direction of José Borobio Ojeda. Some of these churches follow the classical patterns, for example, in the church of El Temple with a ribbed vault. Others, such as the church of Sodeto (Figure 21) or the church of Valfonda de Santa Ana, with a parabolic

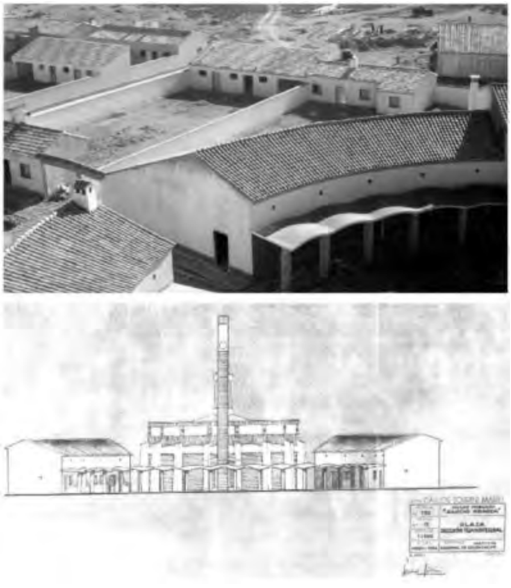

Figure 19. Porticoed area in the main square of Sancho Abarca. Above, image of the village under construction (Calzada Pérez 2008). Below, elevation of the square. Source: INC archive. Architect: Carlos Sobrini Marín. 1954.

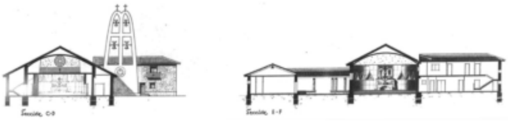

Figure 20. Plans of the church of Sodeto Source: INC archive. Architect: Santiago Lagunas Mayandía. 1956.

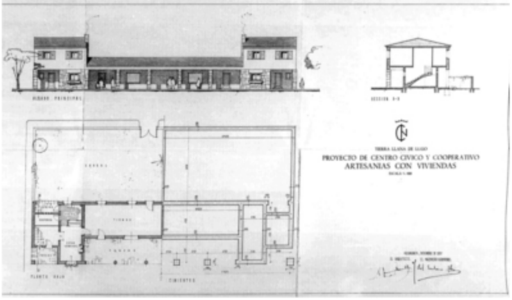

Figure 21. Civic centre and artisan houses in the Terra Cha region (Lugo). Source: INC archive. Architect: Santiago García Mesalles. 1958.

vault similar to that of Valdebótoa or Entrerríos, have a more modern architectural approach.

4 CONCLUSIONS

A frequent (although not habitual) use of tile vaults has been detected both in the villages planned by the INC and in the works of the DGRD. More documentation was located on the INC projects. We found tile vaults in 36 of the 254 villages studied. In 15 of them it was the general system for building the village, both the housing and the public buildings (church, civic centre, town hall). In the rest, they were used occasionally, in churches, in the arcades of the main square, or in staircases.

The greatest concentration of villages with tile vaults is in Extremadura, specifically around Badajoz. In a very small area, there are 14 villages with tile vaults, mostly used in general construction.

We did not find any relationship between the architects who designed the villages and the use of tile vaults, which, together with the above, makes us think that it was a decision linked to the building habits of the area. Architects who used partitioned vaults in the Guadiana basin did not use the same procedure in other areas. Alejandro de la Sota used tile vaults in much of his work, but this was mostly developed in the Guadiana area.

Neither is there a clear relationship between the year of construction and the use of tile vaults. Vaults are found between 1943 and 1964. However, this is the period in which the INC was most eager to build.

The construction information that appears in the plans is very scarce, most likely because the knowledge of masons and master builders using this method of construction was sufficient to enable them it to do the work without further explanation.

Information about the building system is more abundant and precise in construction reports, especially in budgets. In all the documents consulted to date (Barbaño, La Bazana, Montesodeto, San Isidro de Guadalete, Sancho Abarca, Valuengo and Brovales) there is clear evidence to show the use of tile vaults. The use of thin concrete shells could be another option associated with these drawings, but references in the literature to this type of construction are not clear enough.

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The metamorphoses of the EUR Water Tower, Rome, between autarchy and economic miracle (1940–59)

M.G. D'Amelio
Università degli Studi di Roma Tor Vergata, Rome, Italy

L. Grieco
Università degli Studi di Roma Tor Vergata, Rome, Italy
University of Kent, Canterbury, England

ABSTRACT: In a 1961 article, the engineer Roberto Colosimo Sr described his iconic water tower at EUR, Rome (1957–59, also known as 'the mushroom'), recalling a previous 1940 project, unexecuted due to the entry of Italy into World War II. This paper analyses the transition between the two towers as a sort of animal metamorphosis, largely conditioned by the different scientific and cultural contexts. The first design maximized the strength through form-resistant structures. Its image would have evoked late antique architecture, in which firmness was entrusted to mass and geometry. The continuous and bold structures of the first solution, conceived during the autarchy imposed by the Fascist government, became more discrete in the 1957 project. The second solution, built in reinforced concrete, transformed the massive buttress of the autarchic design in punctual supports, intertwined in a stellar arrangement of shelves, which showed the high technological level and creative genius of post-war Italian engineering. The paper refers to archival documents to jointly study the two projects, revealing the metamorphoses that took place between two projects conceived for the same place and by the same author, but within different political and economic conditions.

1 INTRODUCTION

On December 1st, 1942, Vittorio Cini, the general commissioner of the Ente Autonomo Esposizione Universale di Roma, resigned from his position. His decision marked the end of construction of the sumptuous international fair E42, established in 1936. In reality, the opportunity to fulfil the "Olympiad of Civilizations" had already vanished on June 10th, 1940, when Italy had entered the war.

Since 1937, E42 planning had required the development of many projects, which were coordinated by Marcello Piacentini in collaboration with the architecture department directed by Gaetano Minnucci. Such "urban visions" were mainly based on the cross scheme of the Roman *castrum* (Figure 1). The Via Imperiale – currently a trunk of Via Cristoforo Colombo – was the SW-NE oriented *cardo maximus*. The *decumanus maximus* crossed it connecting the two poles of the Palazzo dei Congressi and the Palazzo della Civiltà e del Lavoro. A pseudo-obelisk in reinforced concrete and Apuan marble dominated the Piazza Imperiale (today entitled to Guglielmo Marconi) at the perpendicular intersection of two axes. Of the approved 1939 scheme, only a dozen buildings were completed, remaining for a long time as monumental epiphanies in the 400-hectare-wide pentagonal area once destined to the Exposition.

Figure 1. E42, Servizio Architettura Parchi e Giardini, Ufficio Piano Regolatore, general plan of E42, mapping of waters (lake, fountains, pools, etc.) and green areas, 1940.

A later solution comprised significant changes both for the entrance square towards Rome, with the definition of the two exedras of the INA and INPS, and for

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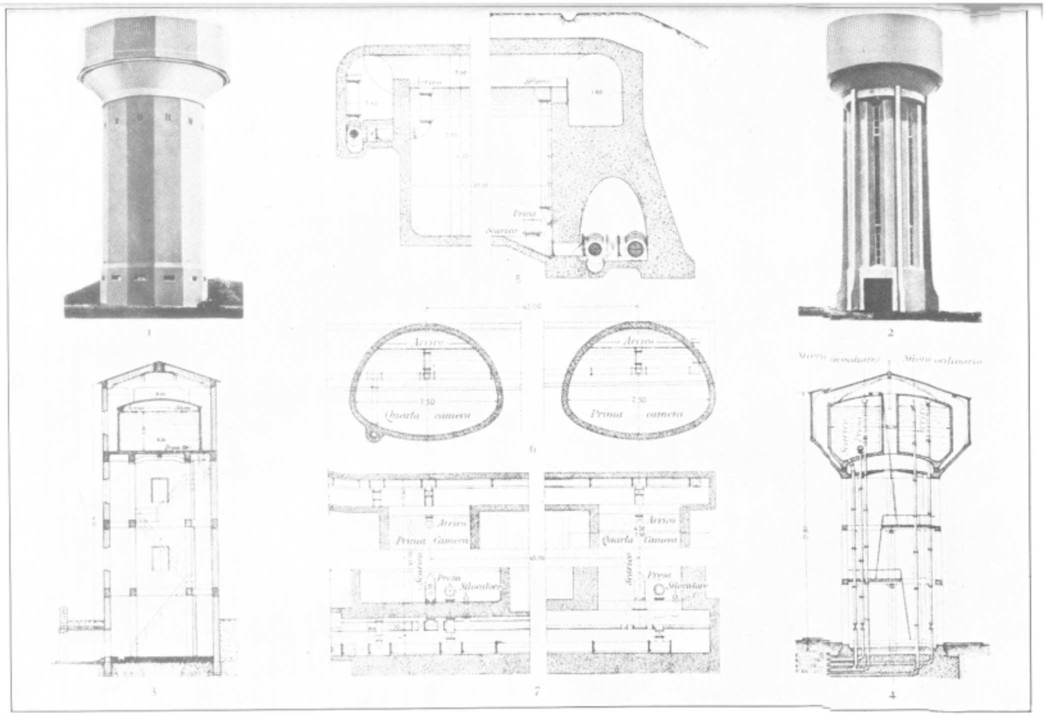

Figure 2. Roberto Colosimo Sr, table for the entry ‘Serbatio’ (Tank), in *Enciclopedia Italiana di Scienze, Lettere ed Arti*, vol. XXXI, Roma: Istituto della Enciclopedia Treccani, 1937, pp. 412–4.

the western area. Destined to a large artificial basin (the ‘Laghetto’) and to a waterfall garden, the latter area had to be marked by Adalberto Libera’s majestic parabolic arch and a Palace for Water and Light, both unexecuted.

The project of the lake and waterfall garden, as well as the other gardens and parks for the E42, was entrusted to Raffaele de Vico (1881-1969) and Roberto Colosimo Sr (1893-1986): the former a landscape designer, the latter a hydraulic engineer. Colosimo was even asked to design a water tower on the top of the hill towards the sea to feed the fountains and the several water outlets for irrigation or fire prevention.

Although crucial in the scenography and functionality of the entire exhibition area, they were not completed, and the works were limited to excavations and incomplete arrangements. Incidentally, Roberto Colosimo was one of the most successful hydraulic engineers of his age: university professor, he also authored many books, including those on the aqueducts of Lugo and Bertinoro, of Ravenna, of Ferentino and Alatri (Colosimo 1930, 1935, 1937). In the 1930s, he also wrote entries on “Condotta”, “Fognatura” and “Serbatoio” (conduct, sewage and tank) for the Treccani Encyclopedia (Colosimo 1931, 1932a, 1936, Figure 2).

In the 1950s, the EUR was planned to house facilities for the 1960 Olympic games. This required a new landscape design for the area, including a hydraulic system to be fed by a water reservoir. The definition of these elements was entrusted to the designer and the engineer who had already prepared the project for the E42: de Vico, for the gardens, and Colosimo senior, for the hydraulic system.

Colosimo designed a complex hydroelectric system, fed by a tunnel aqueduct which draws water from the sources of the Cecchignola and from the well of San Leone, with a flow rate of 400 l/s. The system comprises a network which passes under the EUR area with a flow rate between 120 to 300 l/sec. It was provided with lifting stations in the waterfall garden (completed in 1961) and in the artificial lake. The lake, one km long and 60 to 130 m wide, had a surface of 85,120 m^2, and a depth varying from 2 to 4 m, for a total of 220,000 m^3 of water. To grant continuous availability of water, the system was equipped with a series of tanks, with the function of hydraulic compensation or reserve. Among them, the project included a hanging tank. Its structure, already drawn up in 1940, was reformulated according to a new design and a different technology to be finally erected in 1957 (Figure 3).

2 THE WATER TOWERS OF EUR: A METAMORPHOSES

A text published in a 1961 issue of *L’Industria Italiana del Cemento* describes the iconic water tower of EUR, built between 1957 and 1959 and soon renamed by Romans as ‘il Fungo’ (the mushroom). In the arti-

Figure 3. Roberto Colosimo Sr with Aldo Capozza and Sergio Varisco, the Water Tower of Eur, Rome, 1957–59.

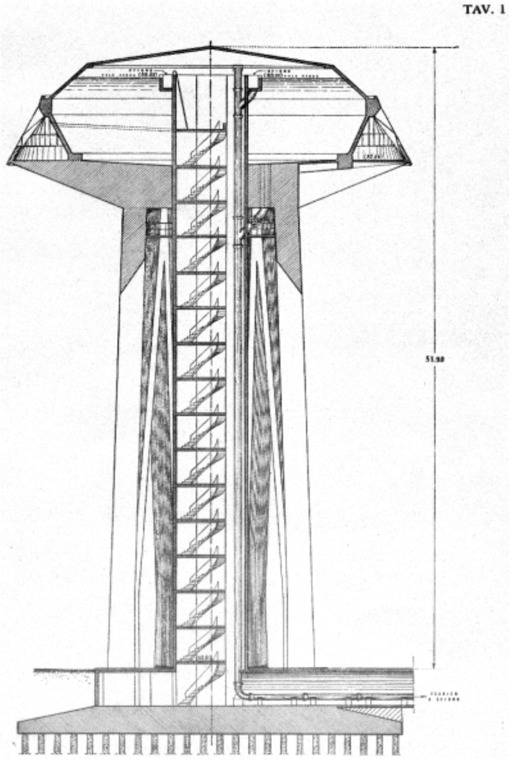

Figure 4. Roberto Colosimo Sr with Aldo Capozza and Sergio Varisco, section of the Water Tower of Eur, Rome, 1957–59.

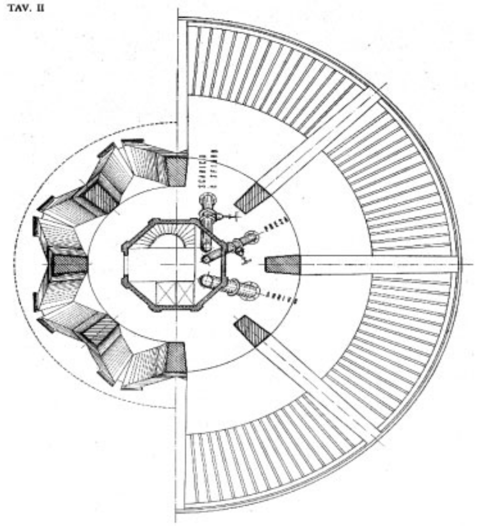

Figure 5. Roberto Colosimo Sr with Aldo Capozza and Sergio Varisco, plan of the Water Tower of Eur, Rome, 1957–59.

cle, Colosimo recalls the project he had presented in May 1940, which remained unbuilt for Italy's entry into World War II (Colosimo 1961). It is only a brief mention, since the essay is dedicated to the new 52-m-high water tower, designed after the war in collaboration with Aldo Capozza (EUR technical office) and Sergio Varisco (in charge of the architecture).

The tank, working as a piezoelectric tower, soon became one of the landmarks of the area, then crowded by the construction of office blocks and sport facilities. The tower presents an inventive structure, whose structural and formal instances are eloquently solved by a trestle-like frame in reinforced concrete (Figure 4). This concrete exoskeleton is made of eight pillars. At a height of six metres from the ground level, they split in a fork-like configuration, bending diagonally to the height of 34 m, where they join the contiguous trunks. They meet in a ring with eight large shelves supporting the upper tank (Figure 5).

The tank, covered by a segmented conical roof, was surrounded below by a hollow annulus with a triangular section. The exterior side of the triangle was perforated by un uninterrupted fenêtre-en-longueur to bring light into a space conceived as a belvedere-restaurant-bar (to be managed by the tenor, Mario Del Monaco).

The construction work conducted by the Vianini Company was as advanced as the tower design. The construction site was served by two antennas and a *blondin*, a machine created for construction sites with horizontal development which was modified to work along a vertical axis (Figure 6). The boldness of the structure, in which the geometry complicated the exact

Figure 6. Roberto Colosimo Sr with Aldo Capozza and Sergio Varisco, view of the EUR Water Tower, Rome, 1957-59 the construction site was served by two antennas and a *blondin*.

Figure 7. Raffaele de Vico and Rodolfo Stoelcker, structure of the water tank in via Eleniana, Rome, 1932, from G. di Castelnuovo, *Roma di Mussolini: primo decennale della rivoluzione fascista*, Roma: Azienda Editoriale Italiana, 1932, p. 131.

Figure 8. Raffaele de Vico and Rodolfo Stoelcker, facade of the water tank in via Eleniana, Rome.

determination of stress and bending, led Antonio Martinelli, consultant engineer for the Vianini Company, to adopt special measures, especially in the choice of materials. As testified by some photographs of the construction site, the tower was supported by a reinforcement in structural steel (Twisteel), while the castings used a high-strength R680 type cement.

The first solution presented by Colosimo in 1940 comprised an equally daring structure. While the built tower would make extensive use of steel, the first project envisaged a concrete construction completely devoid of steel reinforcement. In the report, the designer proudly described the project as fully in line with the metallurgical autarchy promoted in Italy in those years. The rejection of steel was made possible by resorting to structures that were only subjected to compressions, like the domes and vaults forming a system of radial buttresses around the tank. In the late 1930s, the regime propaganda had programmatically affected the resources strategical to military goals, both in terms of construction employment and material supply.

The material shortage for construction was mainly related to a propagandistic reason which did not reflect its effective economical convenience. Indeed, the shortfall due to the importation of steel was no more burdensome than that of wood, cement, or aluminium, which were instead promoted as “very Italian” materials. However, the restriction led to research and experiments on new construction methods. Many of them aimed at improving the resistance of structures with non-steel reinforcement, as well as structures built in weakly-reinforced and unreinforced concrete.

The refrain “better calculations and better construction” limited the use of steel in concrete to the point that the government assessed a ‘degree of self-sufficiency’ measuring the cost of structures, even weakly-reinforced ones, in foreign currency (cost in gold) (Capomolla 1994-95, 98). The limitation in using steel was a first step towards stricter autarchy in construction, which was confirmed by the blocking of private construction in 1939, enshrined by a decree law in 1940.

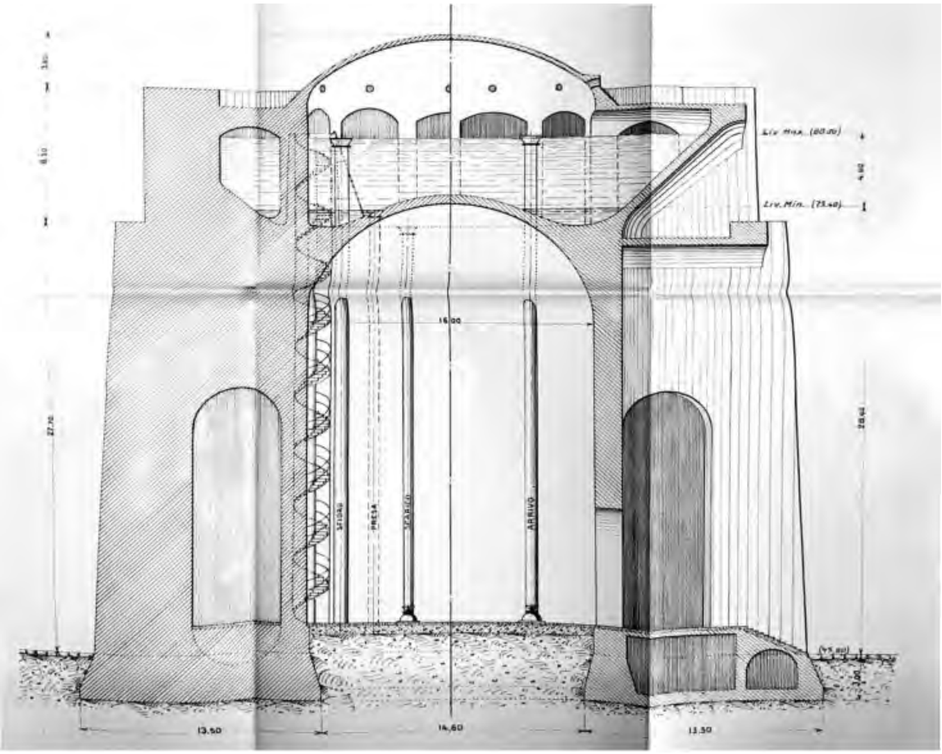

Figure 9. Roberto Colosimo, section of the autarchic water tank of E42, Rome, 1939–40, Archivio Studio Idrotecnico Colosimo, Roma.

Indeed, most of projects presented in the 1938 and 1939 issues of *L'Industria Italiana delle Costruzioni* deal with structural elements in fibre cement, cement without reinforcement, and cement with a reinforcement in steel wires, wood, or bamboo poles, indirectly confirming the creative effects of autharchy. Conversely, other structures designed for the E42 proclaimed the boldness of autarchy but covertly resorted to steel reinforcement.

It was the case of Libera's monumental arch, sponsored as a structure in concrete "without a kilogram of steel", to use the words of its designer (Capomolla 1994/1995, 105). Actually, Libera expected to erect the arch with a weakly-reinforced concrete structure. Nevertheless, calculations went beyond his predictions, prescribing a massive steel core, which would have eventually been coated in Avional D metal alloy. Similarly, Marconi's stele (1939–59) in the Piazza Imperiale, which was described as an unreinforced concrete structure, actually had a reinforced core to resist wind loads due to its 55 m height.

Unlike Libera's and Marconi's monuments, Colosimo's first project for the water reservoir of E42 envisaged a tank which, although subjected to variable loads, thermal oscillations and wind actions, was to be realised in unreinforced concrete.

Structural calculations confirmed the possibility of this solution, which was architecturally defined through exposed, hammered surfaces. The surface finishing rendered concrete as if it were stone, however artificial, suggesting an idea of technological and cultural self-sufficiency.

To understand Colosimo's innovative vision, one must consider that water towers and suspended tanks were usually realized in metallic or mixed technologies (metal and masonry). Reinforced concrete technology was adopted in their construction only in the 1920s,. For instance, in 1933, Raffaele de Vico was commissioned a 2000 m^3 tank to serve the Appio Latino, Tuscolano, Prenestino and Tiburtino districts in Rome (Figures 7, 8). The water system, fed by the Pia Antica Marcia aqueduct, was built between 1933 and 1934 by the company of Rodolfo Stoelcker. The reservoir comprised four, large cylindrical tanks in reinforced concrete, suspended at a height of 23 metres, each supported by five reinforced concrete pillars. Despite their fascinating structure, the four tanks were hidden behind a conventional urban facade in bricks and stone (Ciranna 2018).

Reinforced concrete tanks, like the mushroom-shaped tank described by Goldstein Bolocan in *L'industria Italiana del Cemento* of April 1936 were widespread in the 1930s (Bolocan 1936). On the contrary, the first tank designed by Colosimo for the E42, with a capacity of 2000 m^3, was a structure completely in concrete, as the metric estimate confirms. The project maximised the resistance by shape of the tower, increasing its load-bearing capacity with

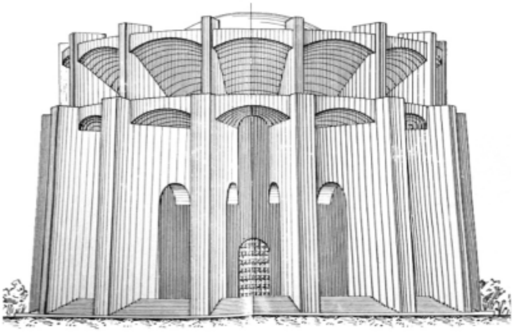

Figure 10. Roberto Colosimo, elevation of the autarchic water tank of E42, Rome, 1939–40. Archivio Studio Idrotecnico Colosimo, Rome.

the attribution of three-dimensional curvatures. The design tended to homogeneously exploit the material, distributing the stress along the entire resistant section. Resorting to curved surfaces minimised the bending stress. The geometry therefore reduced the dangers of tension stress in favour of plain compression, more suitable to the property of concrete, which is not resistant to tension when unreinforced. The proof was in the calculation attached to the project that defined the loads resulting from own weight, overload, hydrostatic thrust, and verified the stability of a buttress. The calculus was accompanied by the graphical procedure used to verify the maximum and minimum values of stress at the base of each pier (Figure 11).

Like a *peripteros*, the structure was elevated on a circular *crepidoma* with a 49-m diameter. The steps were interrupted by two rings of 14 solid piers, radially disposed around the *cella* housing the manoeuvring room, the pipes (for loading, unloading, and overflow) and the spiral staircase for maintenance.

The 20-m-wide *cella* was surmounted by a hemispherical dome, whose extrados, stiffened by a crown of radial vaults, constituted the bottom of the reservoir (Figure 9). The dome had a variable thickness, which increased from 0.50 m at its top towards the impost. It supported the weight of the reservoir above, transferring the load to the radial buttresses.

To simplify the geometry, the reservoir tank could be compared to a tumbler, whose perimeter was stiffened by 14 vaults, arranged radially, which transferred the loads to the piers below. The basin was encircled by vaults which had a trapezoidal plan and their longitudinal axis angled at 45° on the horizontal, according to a truncated conical surface. In the plan, the geometry could be schematised as a hypocycloid, a curve generated by the trace of a fixed point which follows the rotation of a smaller circumference inside a bigger one.

It was made of a concatenation of inverse curves which were internal to the footprint of the building (Figure 10). The inclination of the vaults and the radial geometry made the section change with height. This star-like geometry was intersected with ten vertical buttresses. Disposed radially to the tank, they marked the points of the star, in correspondence of which they were pierced by rounded arches. The front part of the buttresses was conceived as the piers of a thin (0.30 m) segmental dome, perforated by a series of oculi for ventilation and lighting.

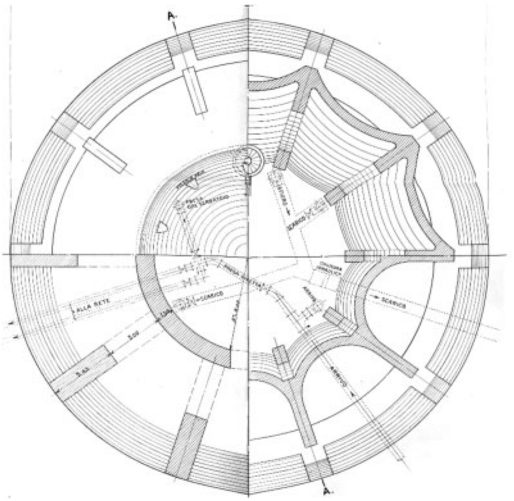

Figure 11. Roberto Colosimo, plan of the autarchic water tank of E42, Rome, 1939–40. From below, left, clockwise: ground floor (+2.10); roof, maximum level of water (+33.00), minimum level of water (+28.00). Archivio Studio Idrotecnico Colosimo, Rome.

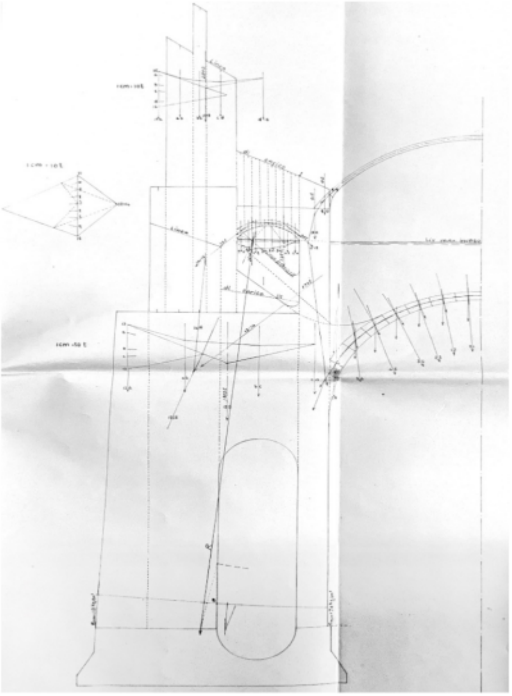

Figure 12. Roberto Colosimo, Cremona diagram for a buttress of the autarchic water tank of E42, Rome, 1939–40. Archivio Studio Idrotecnico Colosimo, Rome.

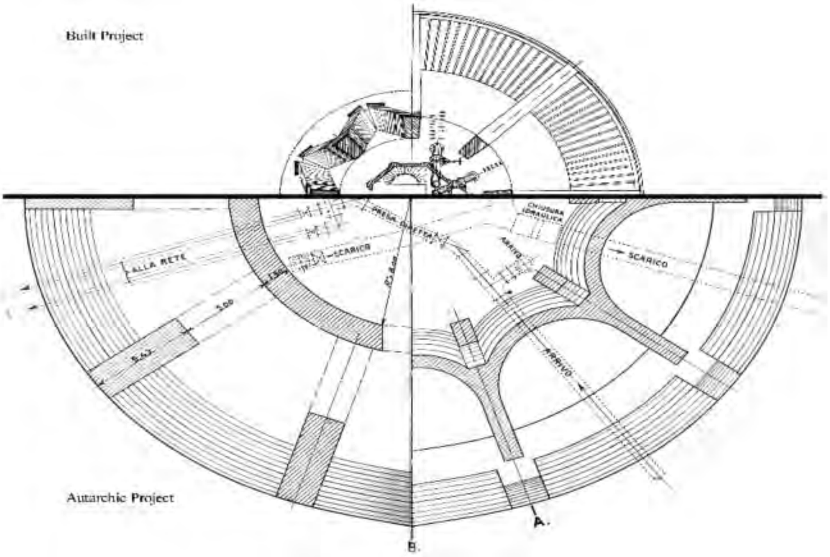

Figure 13. Comparison between the first project and the built tower. Archivio Studio Idrotecnico Colosimo, Rome.

The bases of the buttresses were instead connected and braced by a second ring system of vaults. These vaults had a trapezoid plan but horizontal generatrixes. Hence, we could say that the lower vaults (with the horizontal generatrixes) were conoidic barrel vaults, while those bordering the tank (with angled generatrices) were conic ones.

The buttresses differed between the lower and the upper parts, too. The upper ones, less stressed, were 1 m thick. Pushed towards the centre of about 2 m, they were perforated by round arches evoking the image of ancient cisterns. The lower buttresses were slightly splayed to the exterior with a thickness of 2 m. Reaching a height of 25 m, they were similarly perforated by round arches creating a circular *peribolos* around the cell.

Other details on the tank construction can be derived from the price analysis, the metric calculation and the work estimate attached to the project. According to them, the buttresses and the vaults had to be erected with unreinforced concrete. Indeed, the only metal recorded in the calculation was intended for the spiral staircase, the anchoring brackets, the pipes, and the ventilation grilles.

The concrete mix was designed according to a ratio of 300 kg of cement, 450 type, to 0.800 m3 of gravel and 0.400 m3 of sand. The documents do not specify the use of anti-shrinkage additives, which would have reduced the danger of cracks while hardening.

3 CONCLUSION

Comparing the sections of Colosimo's autarchic water tower with those of a typical reinforced concrete tower, the shapes of the tanks can highlight deep similarities. However, the autarchic solution in unreinforced concrete completely entrusted stability to a massive belt of buttresses, which can be easily opposed to the slim trestle-like supports of reinforced concrete towers. The bold structure, required to stiffen the tower, would communicate a certain image of *romanitas*. Indeed, its image would have evoked Late Antiquity architecture, those whose stability was entrusted to mass and geometry (Figure 12). However, the need to ensure a good safety margin made the concrete structure excessively oversized, bordering on historicistic rhetoric.

The reference to history would also be evident in the finishing of the surfaces, both internal and external. They would be hammered until reaching a visual uniformity erasing the signs of the formworks. The idea of hammering concrete, as if it were a stone, also reinforced the monolithic image of the structure. Differently, the *crepidoma* would be paved with travertine, to create a chromatic contrast with the concrete.

Unlike the E42 tower, the tower designed in reinforced concrete in 1960 has a detailed structure and an entirely different stylistic and iconographic direction. The two solutions, albeit developed in less than 20 years (1940 and 1957), reflect the rapid change in shapes, construction, and economic politics. Indeed, throughout the years, the project lost the linguistic and material constraints imposed by the regime's rhetoric.

Yet the study of the two projects proposed in this paper reveals a sort of metamorphosis, like that occurring to butterflies. The squat and powerful structures of the first solution, conceived when the use of steel in construction was expressly forbidden, are turned into slender and detailed supports in the 1957 project. Elegantly intertwined in a stellar arrangement of shelves, the structure of the water tower built at EUR display the technological level reached after the war by the Italian School of Engineering.

DEDICATION AND AKNOWLEDGEMENTS

This paper is dedicated to Giulio Regeni (1988-2016), PhD student at the University of Cambridge, killed in Cairo while he was researching independent labour unions in Egypt.

The authors owe a special thanks to Roberto Colosimo Jr and Raffaello Colosimo of the Colosimo Hydrotechnical Office for their kind provision of archival documents, and Fabio Colonnese for his suggestions.

The water tower analysed in the paper concerns a solution for 3,500 l of water. The project was accompanied by a further solution: a slightly smaller one with a capacity of 2,000 l, provided with only ten buttresses.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The constructive principles behind the materials and techniques used in state-subsidised housing buildings: The improvement plan (Porto)

L. Rocha & R.F. Póvoas
Universidade do Porto, Porto, Portugal

ABSTRACT: This paper analyses the construction process of state-subsidised multifamily housing buildings from the mid-twentieth century in Porto. The analysis focuses specifically on the scope of the 'Improvement Plan', including its subsequent extension, as a representative sample of the everyday building practices of this period. The research thus seeks to analyse the transformations introduced throughout this plan (over more than two decades), looking at them from both an engineering point of view, with the introduction of new materials and techniques, and an architectural point of view, with the development of new typologies and access systems. The relevance of this study lies mainly in the simultaneous analysis of these two disciplinary fields, allowing for an extensive reflection on the changing culture of construction, which was particularly significant in the period under review.

1 INTRODUCTION

Over the years, the population's quantitative and qualitative housing needs (Simões et al. 2015:15) have remained an urgent problem, especially when this question is associated with the disadvantaged classes and the large urban centres.

In Portugal, as in other countries, housing initiatives subsidised by the state and local authorities have been a significant factor in the construction of a considerable number of houses all across the country. In Porto, the first public initiatives in this area appeared at the end of the nineteenth century, resulting from philanthropic efforts that led to the transfer of municipal land for the purposes of housing construction (e.g. *Monte Pedral* neighbourhood). But the main initiatives really emerged during the First Republic (1910–1926), and, above all, under the "Estado Novo" dictatorial regime (1933–1974). Some of the most re-levant examples in Porto were *Affordable Houses* (1918), the *Affordable Houses Programme* (1933) or the *Houses for Poor Families Programme* (1945), among others. The State-subsidised housing programmes in this period (1910–1974) and their constructions were mapped by the research project 'Mapping Public Housing', which can be consulted via its database [https://mappingpublichousing.up.pt/en/].

This collection allows for a broad view of the quantity, quality and diversity of these achievements (Ramos et al. 2019).

This research paper analyses the specific case of the 'Improvement Plan', as one of the most striking public initiatives to be promoted in the city of Porto, due both to the significant number of new dwellings built in a limited period of time, and the essential urban expansion and territorial transformation that it entailed. The neighbourhoods built under this plan constitute a representative sample of the construction practices of that time and in this city, in relation to the housing promoted by the state. Based on this sample, and through analysis of the architectural and constructive features of these housing ensembles, this paper seeks to identify the principles underlying the construction of these buildings and to reflect on the relationship between the two disciplinary areas. This analysis also serves as support for the important recognition of the heritage legacy of these constructions.

This paper is also part of a broader ongoing research project that is currently looking into the formal (architectural) and functional (constructive) safeguarding and sustainability of the built heritage. The project proposes the analysis of specific cases to establish a relationship between measures for the protection of built heritage and the implementation of sustainability strategies.

1.1 *The Improvement Plan for the city of Porto*

The Improvement Plan for the city of Porto (Decree-Law No. 40.616, of 28 May 1956) was not only designed to offer support in resolving the growing housing problem, but also presented an opportunity for important urban development. The plan provided for the construction of 6,000 new dwellings by 1966 (within ten years) and the implementation of an extensive territorial reorganisation process that included the design of expansion areas and the consequent decongestion of the city centre, the demolition of unhealthy

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buildings and the development of new access infrastructures (DL No. 40.616:631). The construction of a surplus number of dwellings and the early completion of this programme (CMP 1966:5) showed the success of “the most extensive State-subsidised housing initiative ever undertaken in Porto” (Queirós 2016:41; Pereira 2016). These neighbourhoods were built by the House Building Division (*Repartição de Construção de Casas*) of the Porto Municipal Council, which included a wide range of technical experts, including architects, engineers and designers who were part of this department over the decades.

The Improvement Plan (1956-1966) led to the construction of 14 neighbourhoods and a significant number of new dwellings (6,072 in the first phase). The first neighbourhoods (*Bom Sucesso* and *Pio XII*) occupied excess land remaining from previous expropriations. The other neighbourhoods gradually appeared on land purchased or expropriated by the municipality, namely the neighbourhoods of *Carvalhido*, *Pasteleira*, *Outeiro*, *Agra do Amial*, *Carriçal*, *Fernão Magalhães*, *São Roque da Lameira*, *Fonte da Moura*, *Cerco*, *Regado*, *Campinas* and *Engenheiro Machado Vaz*. Some of these housing ensembles were further expanded, such as *Outeiro* and *Fonte da Moura*.

The distribution of the neighbourhoods on the outskirts of the city derived both from the urban growth plan and from the economy of means that resulted from obtaining more accessible land. The urbanisation and structuring of these settlements followed the provisions of the Regulatory Plan drawn up by Antão de Almeida Garrett in 1954 and the Porto Municipal Master Plan of 1962 (*s.n.* 1962). However, the neighbourhoods presented different dynamics in their urban structures and their relationship with the road infrastructure. While some examples were built within a single block (e.g. *Pio XII*) or integrated in several blocks (e.g. *São Roque da Lameira*), other neighbourhoods were located at road intersections (e.g. *Outeiro*) or next to a main road with secondary accesses to the interior of the ensembles (e.g. *Cerco* and *Pasteleira*) (Simões et al. 2015:20).

The extension of this plan (Decree-Law No. 47.443 of 30 December 1966) proposed the continuity of the previous objectives and an increase in the number of inhabitants rehoused from unhealthy neighbourhoods, through the construction of a further 3,000 dwellings within five years. In this context, in 1966, the municipality began the construction of 1,674 dwellings in the neighbourhoods of *São João de Deus* (*III* and *IV*), *Francos*, *Aldoar*, *Lordelo* (*do Ouro*) and *Monte da Bela* (*Corujeira*) (CMP 1966:27-29). The cost of this process exceeded the estimated budget and it took longer to complete than originally planned but nonetheless promoted the construction of 11 neighbourhoods and a further 3,500 new dwellings by the end of the 1970s (Queirós 2016:56). The remaining ensembles built in this period include *Falcão* (*I* and *II*), *Pinheiro Torres*, *Lagarteiro* (*I* and *II*), *Bom Pastor*, *Aleixo* and *Contumil* (*I* and *II*).

These housing ensembles followed the same distribution principles as in the first phase but were often located in areas closer to the city centre (Queirós 2016:41). The logic of their urban insertion tended, especially in the more recent cases, towards the establishment of neighbourhoods within blocks and the construction of secondary access roads (Simões et al. 2015:24). Another distinct and relevant issue is the growing concern that was displayed in relation to the treatment and hierarchisation of the public space (Simões et al. 2015:24).

This study follows the publication of Porto municipal council (CMP 1966) and the research presented by João Queirós (2015, 2016) and so considers the 11 neighbourhoods built up until the end of 1970 as part of the Improvement Plan extension. These neighbourhoods present a set of common features typical of this period and serve as the basis for this present architectural and constructive analysis.

2 ANALYSIS

The methodology used for analysing the case studies consisted of three main stages: data collection, systematisation and interpretation. The first part involved the collection of data relating to the original project, drawn from elements such as technical drawings (plans, cross sections, elevations, construction details), written documents (project briefs, specifications) and photographs taken during the construction period. This survey relied mainly on the information compiled in the ‘Mapping Public Housing’ research project database and on the elements provided by Domus Social E.M. and available in the archives of the Porto Municipal Council. The research was further complemented by the collection of relevant bibliographical references.

The second part consisted of the organisation and systematisation of the information collected, using tables and graphic materials. This phase presupposed an in-depth analysis of all the case studies, based on a series of topics relating to the two disciplinary areas. The third part corresponded to the interpretation and interrelation of the systematised data in order to be able to conduct a cohesive review of the different elements. This method allowed for comparative analysis between the architecture and the engineering involved in the project in order to reflect on the main principles underlying the construction of these buildings.

The following analysis is divided into two parts, corresponding to the different construction phases of the ‘Improvement Plan’. The two phases have different characteristics so this review examines the development of the construction process and seeks to arrive at a better understanding of the changes introduced over time. The topics of analysis cover the main characteristics of the two disciplinary areas. The general characterisation of the structural and constructive system was based on analysis of the respective components such as

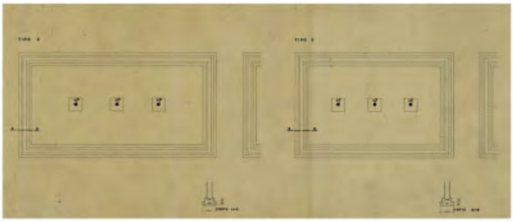

Figure 1. *Pasteleira*. Foundations plan. 1957 Calculations: A. Amendoeira dos Santos © Arquivo Municipal do Porto.

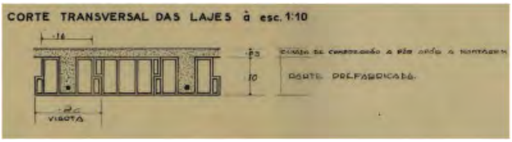

Figure 2. *Pasteleira*. Floor slab. 1957 Calculations: A. Amendoeira dos Santos © Arquivo Municipal do Porto.

Figure 3. *Pasteleira.* General view © Arquivo Municipal do Porto.

Figure 4. *Outeiro*. Rui Paixão, architect. Construction phase © Arquivo Municipal do Porto.

the foundations, floor slabs, pillars, beams, perimeter walls and roofs. In order to understand the architectural project that characterises the group of buildings and dwellings, it was also necessary to analyse the access systems, typologies, functional programme and language/materiality. The urban concept, essential for the understanding of the architecture, was discussed earlier in the introductory section.

2.1 *First phase: Experiences based on a standard project*

2.1.1 *Construction system*

The construction system that characterised the first phase involved the building of perimeter walls made of granite masonry (approximately 28cm thick), supported by continuous foundations (Figure 1), combined with concrete interior pillars built upon isolated foundations (Vale and Abrantes 2012). The structure of the floors consisted of lightweight reinforced concrete slabs (total thickness approximately 13cm). These elements also served as formwork for the concrete ribs of the slabs (Figure 2). The materials most commonly used as floor covering were wooden boards placed on battens and cement screed. The simple perimeter walls were plastered and painted.

The roofs, mostly made of ceramic tiles ("Aba e Canudo" or "Marselha") and without any sub-tiles, are supported on a wooden structure occasionally sustained by brick or stone masonry walls (e.g. *Pasteleira* (Figures 3 and 5) and *Outeiro* (Figure 4)).

The *Carvalhido* neighbourhood appears, in this context, as an exceptional example. This ensemble has a porticoed structure composed of beams and pillars (perimeter and interior) in reinforced concrete and supported by isolated foundations. The floor structure consists of a variation of the solution generally used in lightweight reinforced concrete slabs. The roof is made of a similar wooden structure but differs in its fibre cement coating.

2.1.2 *Architectural project*

The first phase of the Improvement Plan was marked by the frequent use of a standard design (DL 40.616: 632), which was reflected both in the design of the buildings and in the housing typologies. The buildings of four or five storeys (with the exception of those in the *Fonte da Moura II* neighbourhood, which only had three storeys) had vertical accesses and/or distribution galleries and followed a logic with a simi-lar configuration. The first cases (e.g. *Bom Sucesso* (Figure 6), *Pio XII*) present only access systems based on the use of a distribution gallery, a solution known as East-West (CMP 1966:17). The *Pasteleira* neighbourhood was the first ensemble to also include buildings with vertical accesses and entrances to two dwellings per floor – the so-called North-South solution (CMP 1966:17). This combined access system was to be found in a significant number of neighbourhoods (e.g. *Agra do Amial*, *Fernão de Magalhães* (Figure 7), among others). Still in this phase, the first cases appeared that displayed variants of this vertical access system, with entrances to three dwellings per floor (e.g. *Machado Vaz* (Figure 8), *Campinas*, *Outeiro II*).

There were four different housing typologies, corresponding to the number of rooms in each case. These

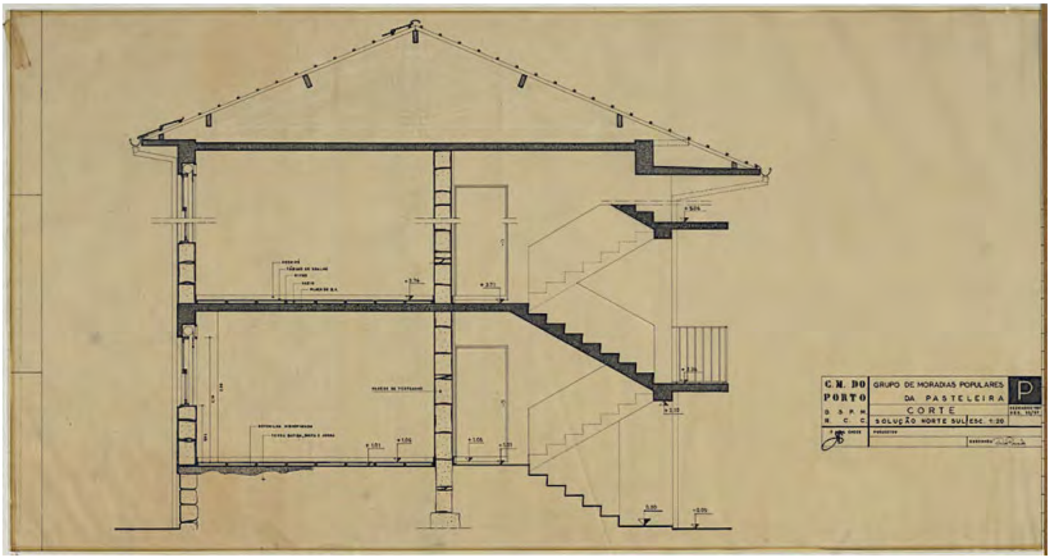

Figure 5. *Pasteleira*. Cross section. 1957 © Arquivo Municipal do Porto.

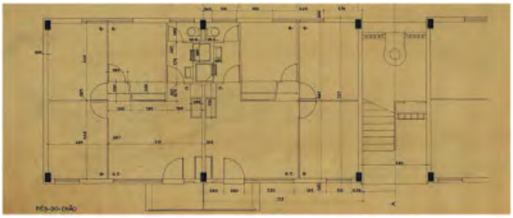

Figure 6. *Bom Sucesso*. Floor plan with distribution gallery. 1956. Almeida d'Eça © Arquivo Municipal do Porto.

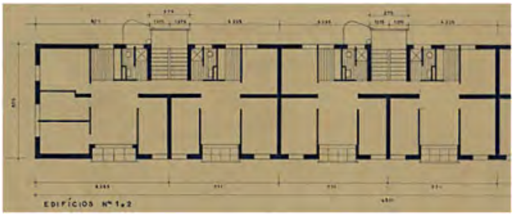

Figure 7. *Fernão de Magalhães*. Floor plan with vertical access. 1959. Rosmaninho et al. © Arquivo Municipal do Porto.

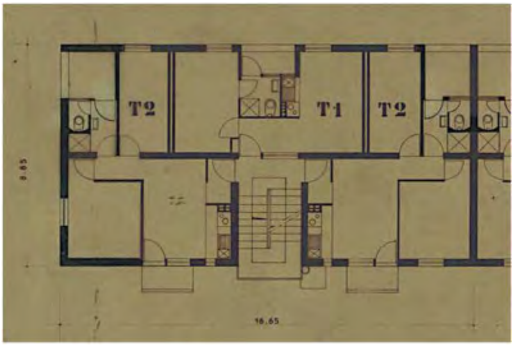

Figure 8. *Machado Vaz*. Floor plan with vertical access. 3 dwellings per floor. 1963. Vasco Mendes et al. © Arquivo Municipal do Porto.

ranged from one to four rooms, with the exception of the *Bom Sucesso* neighbourhood where only type 3 dwellings were constructed (with three rooms). What was most notable about the dwellings was the minimum dimensions of the spaces and the rationalisation of the layout. The living room formed the central area of the dwelling and served as an entrance area, living space and circulation area (providing access to the various compartments) and, in many cases, also included the kitchen. However, the kitchen gradually gained its own dimensions and autonomy, so that, in the more recent solutions, it appeared as an independent space. Each dwelling had a single service area, which often included both the bathroom equipment and a tank for washing the laundry.

The architectural language of the buildings followed the same logic, frequently involving usage of a granite masonry base – as a result of the construction system – and with the façades being coated with plaster (e.g. *Fonte da Moura I* (Figure 9)).

2.2 *Second phase: Turning point*

2.2.1 *Construction system*

The first neighbourhoods built in the second phase of the 'Improvement Plan' followed the same constructive principles as the first phase: a hybrid system consisting of a granite perimeter base and a reinforced concrete structure (pillars and beams), lightweight slabs and ceramic tile roofing supported by a wooden frame (e.g. *Francos* and *Aldoar*). However, this phase was, above all, characterised by an alteration in the

Figure 9. *Fonte da Moura I*. General view. Rui Paixão et al. © Arquivo Municipal do Porto.

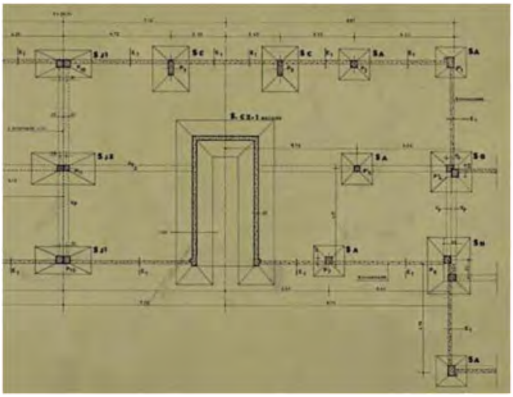

Figure 10. *Lagarteiro II*. Detail of the foundation plan. 1976. Calculation: Rui Paixão © Arquivo Municipal do Porto.

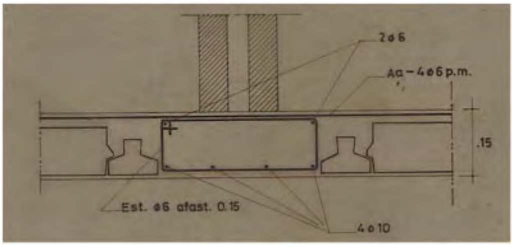

Figure 11. Lightweight concrete floor slab. “MAPREL” type detail © Arquivo Municipal do Porto.

architectural language, which was similarly reflected in changes in the construction process.

The structure of the buildings progressively adopted a porticoed system consisting of a grid of pillars (perimeter and interior) set on isolated foundations and reinforced concrete beams. This system was also often reinforced with resistant concrete cores or stone granite walls built on continuous foundations in the staircase area (e.g. *Lagarteiro II* (Figure 10)). The *Bom Pastor* neighbourhood was, exceptionally, supported on piles, given the clayey nature of the terrain.

The lightweight concrete floor slab of the “MAPREL” type (a prefabricated system widely used at the time) consists of pre-stressed ribs and lightweight blocks (e.g. *Monte da Bela*). These slabs also present a reinforced grid under double interior walls (Figure 11). The materials used for the interior floor coating continued to consist of wooden boards and cement screed.

The façades now used a double-walled system (Figure 12) without any intermediate insulation, with the inner wall being made of hollow bricks and the outer wall varying in its composition, although the most common solution was the use of solid ceramic brick (e.g. *Falcão I*). Other solutions included outer walls made of “LECA” concrete blocks (e.g. *Lagarteiro I*), fibre-cement panels (e.g. *Bom Pastor*) or stone masonry (e.g. *Falcão I*), with exposed concrete being used on both balconies and stairwells, or as floor slabs (e.g. *Monte da Bela*).

The roofs have a distinct structure consisting of prefabricated joists made of pre-stressed concrete, although they maintain the ceramic tile as their predominant covering material. Some cases also include fibre-cement panels on the roof with the same structure of prefabricated joists (e.g. *Aleixo* and *Contumil I*).

2.2.2 *Architectural project*

The second phase reflected a continuous process of experimentation in the design of buildings and dwellings. The blocks of three, four or five storeys reveal greater formal flexibility and a predominantly linear development (e.g. *Monte da Bela* (Figure 14)), resulting in extensive constructions characterised by the discontinuity of the façades and the variation in volume heights (between three and five storeys, except for the *Aleixo* neighbourhood, which includes 14-storey buildings). Another essential concern was with the context, as was made evident by the better adaptation of the buildings to their surrounding environment.

At this stage, there was a predominance of vertical accesses to two or three dwellings per floor. The solutions that involved the use of distribution galleries were progressively abandoned and were only identified in occasional cases such as the *Contumil I* neighbourhood.

The buildings displayed a range of housing typologies with one to five bedrooms: there were fewer one-bedroom dwellings, while the first dwellings with five bedrooms appear (e.g. *Lagarteiro II*). The compartments become more significant, and the distribution of the functional programme accompanied the experimentation that was characteristic of this phase. The living room continued to display the same central character, also including the main circulation area of the dwelling. However, the kitchen acquired greater autonomy and was often associated with a new laundry area. The entrance hall also gained greater importance and, in many cases, constituted a separate area from the other compartments (e.g. *Falcão I* (Figure 13)).

Although the first cases presented the same architectural language as the first phase (e.g. *Francos* and *Aldoar*), with a granite masonry base and plastered

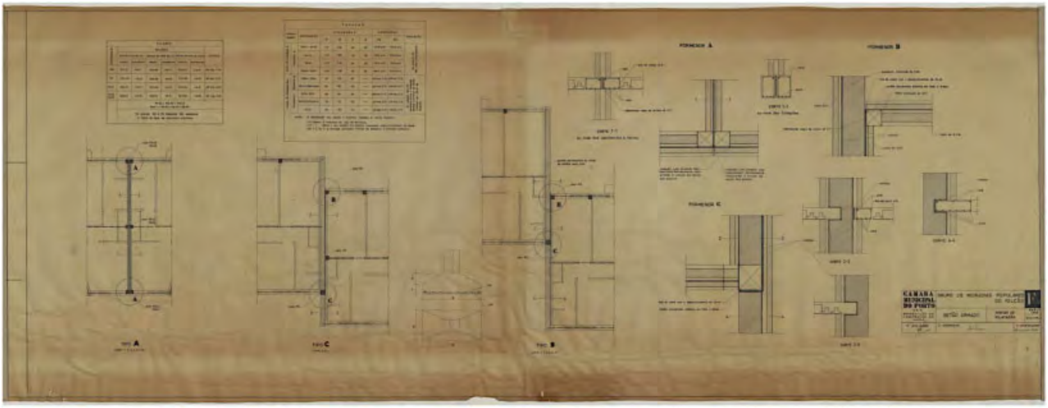

Figure 12. *Falcão I*. Details of the exterior walls © Arquivo Municipal do Porto.

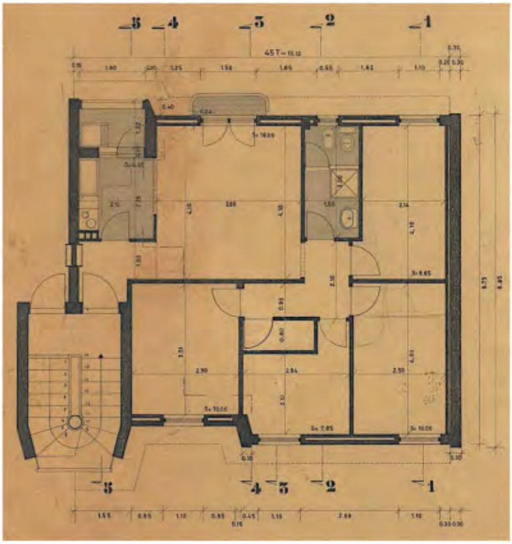

Figure 13. *Falcão I*. Housing typology (example). 1968. Rui Paixão © Arquivo Municipal do Port.

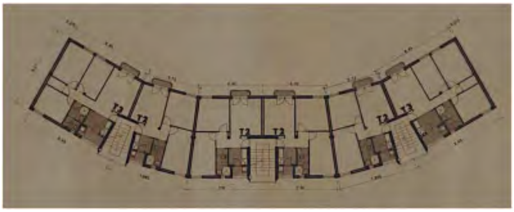

Figure 14. *Monte da Bela*. Floor plan 1966. Rui Paixão © Arquivo Municipal do Porto.

Figure 15. *Lagarteiro I*. General view. 1972. Domingos Faria © Arquivo Municipal do Porto.

exterior walls, the second phase was marked, above all, by the diversity of coating materials. In this phase, there was a prevalence in the use of ceramic brick (e.g. *Falcão I*, *Lagarteiro I* (Figure 15)). However, other materials were also used, such as fibre-cement (e.g. *Lagarteiro I* and *II*) and prefabricated concrete (e.g. *Bom Pastor*) or tiles (e.g. *Falcão II*). This trend was naturally associated with the development of the construction system.

This phase also revealed new models, such as the tower blocks of the *Aleixo* neighbourhood. This ensemble built between 1969 and 1976, but since demolished between 2011 and 2019, had five blocks of 14 storeys each and an innovative access system consisting of a vertical core with a staircase and lift and a distribution gallery arranged around a central atrium.

3 CONCLUSIONS

The residential complexes built under the 'Improvement Plan' (and its extension) serve as a representative sample of the multifamily housing subsidised by the state in mid-twentieth century Porto. They also sustain the study of the architectural and constructive transformations of that period. This analysis reveals some common principles and the development of different construction processes, involving two distinct phases and supported by important relationships and conditionings between the disciplinary areas of architecture and engineering.

3.1 *A. Standardisation and experimentation*

The architectural experimentation accompanied the development of the engineering and structural processes. In the first phase, the more rigid structure characterised by the use of perimeter masonry walls determined the use of an architecture supported by a standard design and a rationalisation in the design of buildings and dwellings. In the second phase, however, a more flexible construction system, consisting of a grid of pillars and beams, released the exterior walls from their predominantly structural function. This solution allowed for greater diversity in the volumetric composition of the buildings and in the distribution of their interior spaces, with significant changes in the external language of the ensembles, associated with a greater flexibility in the use of cladding materials.

3.2 *B. Housing comfort and/or economy of means*

The first phase in the construction of the 'Improvement Plan' revealed a constant economy of means, reflected in the use of local materials, such as granite, simple exterior walls and the standardised design and rational language of the ensemble.

The second phase brought a paradigm shift, resulting from the development of the constructive system and experimentation in terms of the architectural design. The main changes included the use of a double-wall system and the introduction of new materials, with a predominance of ceramic brick. While, on the one hand, these options suggested significant improvements in the comfort of the housing (even without the use of thermal insulation), on the other hand, they demonstrated an investment in materials with greater strength and durability and, consequently, resulted in a considerable reduction in maintenance costs.

3.3 *C. Form and function*

The further extension of the blocks, especially du-ring the second phase, highlights an essential constructive issue relating to the treatment of the expansion joints. These mandatory devices were taken into account by the architects right from the very beginning of the preliminary study, thereafter, being expressively incorporated into the design of the buildings.

The expansion joints are thus mentioned in the architectural projects and detailed in the technical drawings (e.g. *Falcão I*), with the indication of a standard insulation with black corkboard, waterproofing with bituminous plastic cord and Compriband-type sealing tape. In the design of buildings, these joints are frequently associated with the misalignment of the volumes so that this structural requirement was intrinsically related to the architectural language that characterised this phase.

As far as the relationship with the local constructive principles is concerned, mention should be made of the important impact of solutions previously adopted in other neighbourhoods, such as that was applied to the *CTT* in Pereiró (1956) or in the *Rainha Dona Leonor* housing complex in Lordelo do Ouro (phase 2, 1955), by the municipal architect Luís Almeida d'Eça, who was also responsible for some of the first ensembles of the 'Improvement Plan' (e.g. *Bom Sucesso* and *Carvalhido*). These housing complexes include common architectural principles, such as the system of access via a distribution gallery, and the rationalisation of the functional programme. The main difference is to be found in the staircases, which played an important role in the first cases (the *CTT* and the *Rainha Dona Leonor* housing complex), and which were located at the ends of the buildings, resulting in a major artistic expression. In terms of the construction system, these examples seem to present the same structure as the *Carvalhido* neighbourhood.

This study will later be complemented by an analysis of the architecture and construction of a significant sample of rental apartment buildings constructed in the same period in order to arrive at a broader and more in-depth understanding of the local culture of construction.

A general overview of these ensembles also calls for a reflection on this current and recent architectural heritage. Despite the economic and political constraints that marked this period of construction, with an impact on the architectural and construction patterns of these buildings, these various neighbourhoods display clear signs of formal and functional innovation. The buildings also show a great capacity for resilience and adaptability, which is reflected in their tolerance to successive interventions over time.

This research also contributes to a more distinct and in-depth knowledge of these structures and, in this way, promotes the development of better informed and more conscious future interventions in order to safeguard this housing heritage.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Construction of diplomatic embassies, post-independence New Delhi

B. Dandona
Sushant School of Art and Architecture, Gurugram, India

P. Sachdeva
Independent scholar, Delhi, India

ABSTRACT: The newly independent Republic of India was for many countries an especially important location to devel-op an international presence and contribute tangible manifestations of their design ideologies. Extraordinary buildings were designed, and construction techniques evolved for their completion, by several modernists such as Edward Durrell Stone, Hans Hofmann and Johannes Krahn. The construction processes and their difficulties are rarely highlighted, and the importance of these rarely recognized, either in India or internationally, apart from some identified by their respective countries as significant buildings. Our intent is to critically evaluate the significance of this important parcel of architecture by examining and analyzing the construction processes, understanding the influence and exchange of materials and technology, and to acknowledge the role of local consultants and contractors in the construction of these buildings. Lastly, to review their significance and contribution to future developments in India.

1 INTRODUCTION

India, post-independence, was looking for a style that would resonate with its newly found freedom from the British Empire and be a symbol for the whole nation. Under the first Prime Minister, Jawaharlal Nehru, the vision of Modern India was bolstered. Emphasis was laid on science and technology, and methods to support industries while catering for the newly migrated population. In line with his ideologies, Nehru encouraged modern designs under the Central Public Works Department, Government of India (CPWD). Le Corbusier was invited to plan and execute the city of Chandigarh, where Nehru desired to hold diplomatic exchanges of new India with the world.

1.1 *Planning of Chanakyapuri*

In 1950, an area of 900 acres lying behind the commander in chief's house (Rashtrapati Bhawan) was reserved for the Diplomatic Colony, with 450 acres for actual building construction. The land was divided into four-acre plots with the maximum allotment for embassies being 20 acres. Regulations and byelaws had to be followed as per the New Delhi Municipal Corporation building guidelines (Ministry of WHS, Protocol Branch, 1953). Amenities like site clearance levelling, electricity, water, roads, sewage, drainage and horticulture were to be provided while the actual building work was left for the foreign missions to undertake. Given the material shortages and strain on industries during this period, material provision was considered high priority to allow completion within a reasonable time.

1.2 *The Corbusier influence*

Chandigarh and Corbusier's work in concrete, precast panels, glass and metal had created a benchmark of modern design in India, especially for the foreign missions. Many either visited Chandigarh, given its proximity to Delhi or had been much aware of it, and been influenced by its architecture. Chandigarh's construction happened in parallel with the construction of many embassies.

1.3 *Search for Indian-ness*

The embassies' paramount function was to represent their national identity in India, but also to accommodate the culture and region of the foreign land. While some adopted traditional features pertaining to the micro-climate, others took inspiration in modernizing the heritage. Courtyards, screens, use of water features and local materials being the primary considerations.

2 EMBASSY DESIGN AND CONSTRUCTION

This paper investigates the pioneering embassies in New Delhi, for they laid the ground for others and perhaps faced the most difficulty and need for alternative methods of construction.

2.1 *The American Embassy, 1959*

Designed by Edward Durell Stone, representing modernist philosophy, the American Embassy buildings were the first to be constructed in Chanakyapuri,

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Delhi. The chancery is a two storey, large rectangular (appx. 122 m × 58 m) building perched on a podium with an equally large roof overhang. The rectangular building has a central water garden flanked by corridors for offices. The construction primarily comprises a Reinforced Cement Concrete (RCC) framed structure since India was already well versed with the material. Both brick and hollow concrete blocks were used to install walls.

The RCC and brick structure is covered with a variety of finishing materials. The base or podium is faced with slabs of Indian marble while the floor is marble border, terrazzo and sandstone. Italian marble had been under consideration, but the likelihood of a long delivery time made Stone decide on Makrana marble, an Indian variant (Weiss Manfredi Architects 2016, 62).

Large screens of terrazzo spanning from floor to roof were installed along all four façades. The screens made on site are prefabricated modular units (Weiss Manfredi Architects 2016, 117). Constructing the screens on site was a landmark, as all work would have been handcrafted given the lack of machinery. The embassy can be credited for transforming the traditional *jaali* into a modern form, widely adopted in establishing the modern architecture of the capital. The perforated screens were also used by Stone in his New York house and the chancery as an influence for the Kennedy Center.

In situ terrazzo wraps finished all surfaces of the building. This building may contain one of the largest applications of terrazzo of this scale and is not seen anywhere else in Delhi. Full length glass windows held in aluminum frames are installed at large openings behind the screen. The large overhang is supported on slender steel columns, originally with gold foil finish.

Chancery offices have practical and functional materials compared with those employed in public spaces. On both floors, the walls in the offices are plastered and painted with flush doors with outer louvre doors. The outer walls are fixed glass panels set in wood frames. Air conditioning units run along the floor but are enclosed in louvered wooden cabinetry. The east elevations of the water garden on both floors consist of decorative metal screens that allow light from the two-storey entryway (Weiss Manfredi Architects 2016, 54).

One can see the advances in technology and technique in this case. Air conditioning systems were uncommon, and their working and ducting was not used in other buildings, apart from a few palaces. The technique of using concrete ribs to accommodate air voids as insulation is certainly a wise technique to accommodate the climate. Perhaps inspiration for the embassy derived from the Taj, a Mughal magnificence clad entirely in white marble (Figure 1).

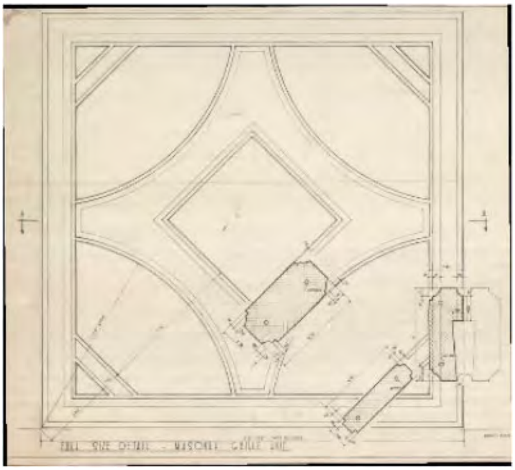

Figure 1. Initial Screen Module detail with reinforcement (Weiss Manfredi Architects 2016).

2.2 *The Embassy of the Federal Republic of Germany, 1956–62*

Located on main Shantipath, the German Embassy in New Delhi was the first new diplomatic mission building to be built by the young Federal Republic following the end of the Second World War and thus assumed special importance, symbolically underlining the country's reintegration into the Western community of values (Matussek et al. 2010, 17). The embassy complex was built based on plans prepared by Johannes Krahn and executed by their local architect Karl Malte von Heinz. The building represents simplicity and functional values adapted to local climatic conditions. The chancery along with a small residence is a long, compact rectangle (65 m × 16 m) with ground and four floors, facing Shantipath. The ground floor is partially open to accommodate a shaded car park. All upper floors are used for office spaces on both sides of a central corridor. When inaugurated, the construction of this building was an example of German innovation and craftsmanship.

The chancellery block is constructed by employing a RCC frame. While the exterior walls are installed using bricks, the interior partition walls use concrete blocks. The roof is unique compared with other embassies built earlier. It comprises two slabs (double) or butterfly roof, one flat slab connected to the beams and columns of the lower floors, topped with another inclined as a protective barrier to reduce the impact of heat on the main roof. The dramatic flying roof that seems to be full of energy and movement recalls the image of Le Corbusier's pilgrimage church in Ronchamp (Matussek et al. 2010, 31).

The climatic response is realized in the configuration of windows too, which are recessed from the main façade. In addition, the façade has been covered with louvres acting as sun shading devices for the two main façades (west and east). The louvres are made of steel sheet and steel pipe welded together and chemically polished and anodized in natural color. Louvres very clearly indicate inspiration from the Government Press building in Chandigarh which has a façade covered with concrete louvres and was built in 1953. The

German architects were clearly inspired by their visit to Chandigarh (Matussek et al. 2010, 32).

The north and south façades are clad with Makrana marble slabs, as is the ambassador's residence and other official apartments. The choice of materials was not only determined for aesthetic reasons but also for the fact that excessive monsoon rains and sandstorms have a lesser effect on marble than they do on other cladding materials (Matussek et al. 2010, 31).

Metal doors, windows and the use of glass are a reminder of Germany's progressive industrial potential. As in the chancery building, the aluminum rolling shutters confirm high mechanical achievement. The mechanical investment would have been a gamble as electricity supply was often hindered in the city and generators for such large-scale purposes sparsely produced.

Unlike the chancery, the ambassador's residence was built of brick (Matussek et al. 2010, 32). The appearance of the ambassador's residence is largely determined by comparatively small windows and balconies. The balcony parapet is geometrically cut to profile steel sheets. The residence's porch was probably the most imaginative and bold structure to be built in New Delhi (*The Indian Architect* 1959, 13) This expressive gesture contrasts with the otherwise calm and modest appearance of the complex. False ceilings with geometric patterns are installed in many rooms and carry the ducting above them. The use of glass blocks is noticeable in both the chancery and ambassador's house. Small circular glass blocks set in concrete walls have been used in the residence block next to the chancery. Skylights were another new feature of the building, particularly the acrylic dome as seen on the residence's overhang. Skylight profiles, roofs and structural members were rarely seen, coming from a strong colonial hold. However, in the subsequent decade, many experiments were made giving a modern feel to the city's architectural look.

The numerous drawings showing elevations, sections and details are proof that a good number of design decisions were taken while under construction (Matussek et al. 2010, 29) (Figure 2).

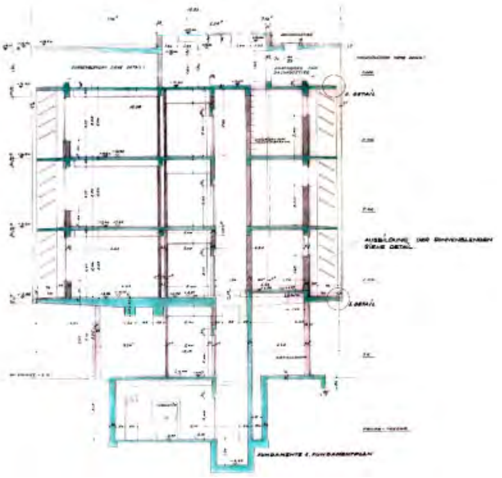

Figure 2. Section through the chancery. Note the double roof and deep-set windows with louvres (Matussek et al. 2010).

2.3 *Swedish Embassy, 1959*

The embassy was Sweden's first large-scale modern expression built by Jöran Curman and Sune Lindström, with assistance from the local architect masters, Sathe and Kothari. The Swedish Embassy is perhaps the simplest in the entire Chanakyapuri. In response to the climate, the architects selected simple construction techniques and functions for the basic design. This very humble piece of architecture is regarded an example of internationalism and migrational architecture (Hagströmer 2012, 171).

Planned around three sides of a courtyard, the single storey structure was a way to avoid complicated construction in India, which the Swedish felt was not too developed (*The Indian Architect* 1960, 14; *Arkitektur* 1961, 154). All the buildings are south facing with short east and west sides and protected by vegetation. Both south sides of the building are shaded by colonnaded corridors. The structure is constructed with RCC foundations and the framework with brick masonry infills. The brick columns supporting the corridors are also a part of the structural system. The exterior walls and roofs are heat-insulated, and windows airtight (*Arkitektur* 1961, 156). Concrete, asbestos sheets and prestressed beams form the roofing system. A flat roof or rain roof has been used to span the interior spaces which is topped with a separate ventilated sunroof. Brick has been used as cladding material for all façades and painted red/pink, adding to the simplicity and earthy character of the building. White painted bricks have been used in parapets in profiled patterns forming a unique feature of the building, moving away from ornamentation or elaborate façades. The brick patterns help break the scale and length of the building.

Doors, windows and built-in cabinets are made of Indian teak. The floors are terrazzo, Indian kota stone and, in some places, marble. Concrete screens have been strategically and carefully placed across openings for indirect sunlight. The interiors are filled with imported furniture, products, and fittings, harmoniously complementing the Indian material palette (*Statens Fastighetsverk* 2020).

2.4 *Embassy of Switzerland, 1963*

Designed by Hans Hofmann and implemented by Walter Rüegg, the building with the chancery and residence under a single roof was one of the most important architectural symbols of Swiss diplomacy to that time (Maurer 2018, 29). The embassy building is rectangular (80 m × 40 m), double storey, with two inner courtyards. The structural system has columns and concrete cross walls enveloped by an arcade, all in exposed concrete apart from the façades which are clad with precast concrete slabs. Modular brick was used for the foundations and other masonry work.

A slender but prominent flat roof projects out from the main building cantilevered beyond the façade by six meters, protecting the building from direct sunlight and the monsoon rains. The roof uses an imported prestressing technique, a Birkenmeier, Brandestini, Roš Vorspann system (BBRV) developed by Stahlton (Maurer 2018, 111). The Swiss Embassy was the first building in New Delhi to install a prestressing technique.

Apart from concrete, a large number of surfaces are clad with black marble. It was recorded that the slightly slaty and extremely hard black marble caused difficulties in workmanship. Special care, and consequently time, was needed to link the marble connections with the aluminum windows on the upper-storey terrace (Maurer 2018, 112). For the floor surfaces, various types of terrazzo, grey-green polished limestone slabs and marble have been laid, depending upon the purpose. The light green, slightly shaded ornamental modelled coats on the plastered walls, the white ceilings and the warm brown of the cabinet fronts and doors made of local processed teak give the rooms a light atmosphere (Maurer 2018, 113). The cantilevered roof slab makes a statement of its own and many future embassies adopted this feature.

3 FRONT END: LOCAL ARCHITECTS AND CONTRACTORS

In the 1920s, Delhi had one contractor who could build in RCC, but by the end of 1960s, just three decades later, the city directories listed people who were prestressing experts (Tappin 2003, 1933; Delhi Progressive Enterprises 1964, 204). The embassies provided a hands-on experience for the contractors who could learn and advise on imported techniques within the Indian context. Some are discussed below.

3.1 *Sardar Mohan Singh*

Sardar Mohan Singh was awarded the contract for the American Embassy in partnership with Tirath Ram Ahuja. However, the partnership dissolved soon after the completion of the main buildings (Deolalikar 2020). The duo was also responsible for the first modern hotel in Delhi, Ashoka, built during the same period, which led to an exchange of techniques and experts between the two projects. Sardar Mohan Singh, known as the furnishings king, started Oriental Building and Furnishings Pvt Ltd from a small workshop. During the Second World War, when American troops established a base in Delhi, Mohan Singh became familiar with many, ultimately being assigned numerous contracts by the Americans and British alike. This acquaintance took him on a tour of America in the year of independence and following this exposure, he came back with new ideas and visions (Arunam & Sheel 1950, 37).

Building materials, furniture and furnishings were also under the same contract for the embassy. Furniture was designed by Edward Wormley of Dunbar Furniture Company of Berne, Indiana, which Mohan Singh finished to a superior quality (Weiss Manfredi Architects 2016, 30). This was the first contract of its kind, entrusting all works to a single contractor (Hindustan *Times Weekly* 1959, 8).

Given his experience with both Americans and British, Mohan Singh was familiar with quality design and could offer suggestions to balance the architect's proposition with construction efficiency. For the embassy, he suggested switching from teak to aluminum window sashes for the chancery and staff housing, with slight alterations to the design of Stone's terrazzo grille blocks for the screens that simplified fabrication and repetition (Weiss Manfredi Architects 2016, 30).

Along with Mohan Singh, three American architects and three engineers were also on site as a support team given Stone's absence and sparse visits (Maurer 2018, 104). Adolf KN Waterval was the American project supervisor (*The Sunday Statesmen* 1959, 3). Also involved on a regular basis as a consultant was local architect KP Sharma, and engineer BS Puri who was the engineer for the hotel project as well (Weiss Manfredi Architects 2016, 30). S.G. Deolaliker who undertook the plumbing works was his companion for many future projects (Deolalikar 2020).

The completion of the American Embassy, as one of the most significant architectural contributions to the Diplomatic Enclave and Delhi, having a richer material palette than what the rest of Delhi could afford, can partly be credited to Mohan Singh bringing in a team of skilled technicians and workers. His experience with his first led him to successfully complete construction for many others, like the Pakistan and Australian High Commissions (*The Indian Architect* 1959, 4).

3.2 *Tirath Ram Ahuja*

Established in 1950, Tirath Ram Ahuja Pvt. Ltd, was engaged on numerous large-scale projects, including several banks together with architect masters, Sathe, Bhutta and Kothari (Maurer 2018, 108). Tirath Ram was commissioned for many embassies, including Polish and Singapore, the first being the Swiss Embassy. At the same time, Tirath Ram was involved in the construction of the India International Center designed by American architect Joseph Allen Stein, later commissioned for the Australian High Commission.

By the end of 1960, Tirath Ram was one of six shortlisted for the construction of the Swiss Embassy. This project was challenging especially as the building stands in exposed concrete with a large overhanging prestressed concrete roof. Kanvinde & Rai, architects and engineers, were brought on board as site supervisors and collaborators especially for planning and execution of the staff quarters. However, given the challenges and need for technical assistance to maneuver concrete for a good finish, engineer and architect Walter Brandli and Walter Ruegg were asked to be present in New Delhi to supervise along with an Indian site manager, DR (Maurer 2018, 111-36).

In addition, there was the challenge of fluctuating electricity and inconsistent labor. Site labor would change every day, throwing the contractors the challenge of briefing a new set of people each day, sometimes up to 200 workers some of whom were still children. This would not have been possible without the mediation of the Indian companies responsible (Maurer 2018, 111).

Concerning exposed concrete in Delhi's high temperature and hot air, the contractor had several times to take the decision to rough dress parts of pillars and recast them. In a particular instance, Tirath Ram's material spares from another project yielded good for the Swiss Embassy. To save wood given its cost and shortage, the tie beams were to be supported on lattice girders and, fortunately, Tirath Ram had about a thousand lattice girders. However, even Tirath Ram did not know how the girders were supposed to be used and the supervisor had to make sketches themselves, leading to a quicker and more fruitful process. (Maurer 2018, 140).

3.3 *Masters Sathe and Kothari*

Master Architects Sathe and Kothari were ordained local contractors for many embassies, including the Swedish, USSR and Norwegian. They contributed 30% of India's growth post-independence (Master and Associate, n.d). Apart from the embassies, they were engaged in various large-scale projects, including the Swedish mission's Bonow House in Delhi designed by the Swedish architect Gunnar Savas in collaboration with the Swedish engineering firm SENTAB. This collaboration perhaps started at the Swedish Embassy and continued to the Norwegian as well (International Co-operative Alliance – Asia & Pacific 2010, 72).

3.4 *Specialists – Swedish & German Embassy*

Unlike the Americans, the Swedish had multiple subcontractors with SENTAB as the general contractor. A different contractor for painting, flooring and plumbing was chosen. John Tinson & Company Pvt. Ltd undertook their sanitary works. They worked for the Norwegian, Japanese and UK High Commissions' residential blocks and servants' quarters also (*The Indian Architect* Adverts, 1959). Painting work fell under John Flemings and Company who were agents for Noble paints and took on the embassies of USSR and Norway. Both Sweden and Norway preferred plain painted façades. Flemings later worked on important institutional buildings in Delhi, while Modern Tiles and Marble were responsible for terrazzo works (*The Indian Architect* Adverts 1959, 2–6). The flooring for the German Embassy was assigned to terrazzo specialist, R. Lorenzoni and Company.

3.5 *Air conditioning: Voltas*

Air conditioning was an aspect which did not expand locally: only a few hotels like Ashoka and the Rashtrapathi Bhawan. Voltas, a partnership between TATA group and Volkart Brothers of Switzerland, took on the responsibility of installing Carrier air conditioning units (Maurer 2018, 42). Carrier, being American was brought to India by Voltas. Most diplomats felt the need to have air conditioners since the climate in Delhi was unknown, especially the harsh summers. Apart from the American Embassy, whose air conditioning was also under Mohan Singh's scope, Voltas completed installations for all the other embassies till 1968, perhaps being the only choice without importing machinery. The method of ducting, fabricating vents and grills, and housing them in a false ceiling were not familiar aspects of domestic architecture.

3.6 *Other noteworthy contractors*

There is conflict of information in published journals over general construction contracts for the German, Swedish and Russian Embassies. Both Harbans Singh and United Builders take credit. It must be noted that the construction of the German Embassy took six years (Matussek et al. 2010, 40). This could possibly explain the claims by the different contractors. In addition, SENTAB being a foreign engineering company perhaps would not have been able to execute orders themselves and would have hired a local subordinate.

4 TRENDS IN BUILDING MATERIALS AND CONSTRUCTION TECHNIQUE

Production of cement and steel started in India in 1915 while glass too was produced at Dehradun and Firozabad from 1916 (Indian Industrial Commission 1918, 299). Despite in-house set ups, towards 1947, there was a serious shortage of materials. Basic construction material was rationed and that available was at much higher cost. “Bricks are not available at even fifty per cent more than the normal prices” (Mehra 2013, 361). This shortage had carried well into the late 1950s when the government advised on efficient use of materials and launched initiatives to limit the use of cement suggesting it be switched with lime. Embassies, too, faced shortages and had to make informed choices as different materials were available at similar prices. In addition, materials had to be locked and secured to prevent theft. The Government of India, however, believed the home industries were sufficient to provide materials to the embassies, and any additional items required could be imported with all customs duties being paid, apart from fixtures and furnishings (Ministry of EA 1953). Steel either came from the TATA steel plants, TISCO and government undertaking SAIL, or Indian Iron and Steel Corporation, IISCO (Railways Works Branch 1957). Aluminum was also available locally, however mostly through an American company, ALCOA (Deolalikar 2020). Jindals started producing many aluminum sections by the end of the 60s, given their popularity in town, a material that almost all embassies chose during the 50s. Chandigarh too, perhaps, would have been an aid to the embassies apart from its architecture, as it attracted many industries to set up on the outskirts of Punjab.

Many diplomats feared the availability of electricity, generators and equipment in India which could hamper construction. Some were noted visiting each other's sites during construction to discuss the problems faced. But the availability of skilled labor made up for the lack of equipment, many parts being either handmade or hand finished (Maurer 2018, 101).

The material choice for the American Embassy, with fine terrazzo, Makrana marble, brass hardware, and gold filmed columns, made it expensive and exclusive. The steel columns provided by J.S. Fries Sohn, of Frankfurt, Germany, were gold filmed in Delhi. Material shortages impacted prices mostly. Instead of bronze grilles, the contractor offered gold finished cast aluminum, which Stone approved. For the steel columns intended to support the trellis at the staff quarters, a Bombay fabricator was selected, who suggested replacing wood with steel at no extra cost as there was a shortage of wood (Weiss Manfredi Architects 2016, 61-8). Anodizing technique was introduced by Mohan Singh and used for the embassy as well. A pre-plumb system was imported for plumbing, especially of the ambassador's residence which also used copper pipes in place of cast iron pipes, swaying away from the generic economic norms (Deolalikar 2020).

In terms of technical assistance, an Italian shell structure expert, Dr A. Carbone, was hired when the pool slab failed, and he suggested methods to cast another one with the help of pile foundations (Weiss Manfredi Architects 2016, 66). In a similar situation, on one of the visits of the Swiss architect in-charge, Walter Reugg, the freshly cast roof slab had sagged, which made Reugg call for prestressing experts and help from Switzerland (Maurer 2018, 111). Mirko Robin Ros from Stahlton Company was approached who sent Mr Ivano Dompieri on 21 June 1960 to introduce the BBRV system developed by them, making the Swiss Embassy the first in Delhi to use a prestressing technique (Maurer 2018, 111). The exchange could possibly have triggered a series of advancements beginning with prestressing cables being manufactured locally from 1961 (Indian Standards Institute 1961, 2). The Swiss had opted for simple materials and exposed concrete which turned into a challenge and approximately twice as expensive as in Switzerland. One of the field notes explained: "the air is extremely dry and the surface of the concrete turns white almost instantaneously if wet Jute sacks are not immediately laid over it and kept constantly damp. The problem of curing the concrete, and shrinkage in particular, is making things extremely difficult for us" (Maurer 2018, 111).

The German focus on precision and opting for mechanical fixture was evident, re-enforcing their identity through skilled and polished technical skills. The Swedish wanting a simple look called for "bricklayers from Rajasthan who camped on site with their families" (Hagströmer 1959, 171). The overall rhythm of the brick, profiled roof, and fixed concrete louvers represented a new method of achieving something simple and aesthetically pleasing. Electric and Mechanical installations were imported from Sweden as was all the furniture (*Statens fastighetsverk*). The color choice of the exposed brick further distinguishes it from the local bricks.

Figure 3. Indian team for the American Embassy, Sardar Mohan Singh seated in the center (Deolalikar 2020).

5 CONCLUSIONS

Construction of embassies in New Delhi contributed to shaping the future of construction in the city. It created new opportunities for architects, engineers, contractors and construction workers. Local and international collaborations enhanced knowledge about design and building techniques and materials which were implemented in the building of modern Delhi. Together the cluster of the Diplomatic Enclave exhibits the unique identity and approach of each building. Not only the know-how of methods, but the design choices of various nations, including fixtures and furniture, came in the form of a permanent exhibition in the city. The mention of contractors and technicians in the narrative of building construction in India is extremely rare. Furthermore, the lack of documentation about the parcel and contribution of the people associated with its development further reduces their significance in the city's growth. Only a few countries have registered their buildings as significant (Figure 3).

Acknowledging its value, the US Department of State placed the chancery on the Secretary of State's Register of Culturally Significant Property in 2004 along with 26 American diplomatic properties. The Swiss, in 2004/5, submitted an initial comprehensive redevelopment by the Federal Office for Building and Logistics (FLB) based on the assumption that the embassy building should be integrally preserved as an outstanding witness to modernism and not be hampered when new blocks were added, but no formal protection exists (Maurer 2018, 115).

Sadly, Indian laws do not protect heritage under 100 years old as the preservation of modern heritage is a recent phenomenon in India. These properties are also considered foreign land and therefore none of the embassies have been identified as historic landmarks under any Indian law. However, recognition of the Capitol Complex Chandigarh as a UNESCO World Heritage site represents a growing awareness towards the preservation of modern heritage giving hope for the Diplomatic Enclave.

6 NOTE

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The modernization of raw earth in Morocco: Past experiments and present

N. Rouizem
Université Paris 1 Panthéon-Sorbonne, Paris, France

ABSTRACT: Between 1962 and 1965, some 2750 mud-brick houses were built in Marrakech (Morocco) by a French engineer who modernized the material, the tools and the building site. He then realized 200 houses in Ouarzazate in collaboration with a Belgian architect. Through the analysis of the course of these operations, this article will show how a material can be the bearer of an ideology.

1 A HISTORICAL STUDY RESPONDING TO CONTEMPORARY ISSUES

The modernization of raw earth architecture sector dating back to the late 1970s, following environmental crisis, is well known across the world. But the period before the revival of this vernacular material has remained relatively unexplored. Many experiments in raw earth architecture have been carried out in developing countries, most often by Europeans, as a solution to the housing crisis.

In Morocco, the modernization of raw earth in architecture actually began in the early 1960s. Alain Masson, a French engineer and Director of Public Works in Marrakech, built 2750 economical dwellings in compressed earth blocks in 1962 in the Daoudiate district; he then built 200 rammed earth dwellings in Ouarzazate in 1967 in collaboration with Jean Hensens, a Belgian architect; followed by 400 dwellings in compressed earth blocks in 1969 in Berkane, in the north-east of Morocco (Figure 1). These three projects were inspired by local traditional techniques but modernizing the material, tools and construction methods.

However, these experiments have been little studied by researchers to date. As such, our study proposes to fill this gap. Our objective is to understand how ancient skills transmitted by local tradition have been reinvented by Europeans in a decolonized country. There is no publication that identifies the archives related to the history of the modernization of raw earth architecture in Morocco: this research identifies them. Through the exploration of new archives scattered between France, Morocco and Belgium, crossed with field work and interviews with actors in earthen architecture in the three countries, our research will have a transnational approach and an interdisciplinary research methodology. We will take a critical look at these projects in order to highlight examples and draw lessons which could be very useful in the current context of environmental crisis.

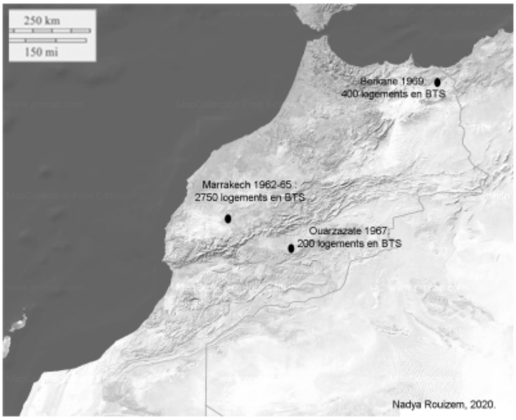

Figure 1. Situation map of the three case studies in Morocco.

This research highlights a period of Moroccan architecture rich in experimentation using an ecological building material: raw earth.

These operations have been marginalized, even though they favor experimentation and a site-specific approach, practices that are now being re-emphasized and revalorized.

2 TECHNICAL NORMALITY

The archives of these projects are scattered between France, Morocco and Belgium. In the documentation center of the Ministry of Housing in Rabat, there are several reports devoted to the Daoudiate project. We discovered several reports written by Alain Masson in the archives which precisely describe the stages of building with supporting photos and an emphasis on the rationalization of construction processes. Indeed, according to these reports, this was an industrial building project, which implies rationalization, serial

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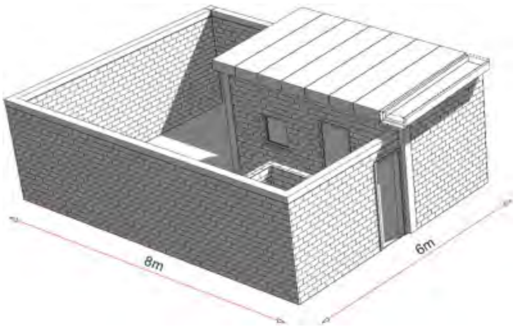

Figure 2. Three-dimensional view of Daoudiate housing (Rouizem 2019).

execution of prefabricated elements, and adaptation of the execution program.

In traditional raw earth brick construction, called adobe, the soil is usually mixed with vegetable matter then molded into a wooden frame and sun-dried. The compressed earth block (CEB), is a modernization of adobe. The soil is stabilized with cement and then compressed in a mechanical press.

The construction process chosen is itself very rational: it consists of a concrete column-and-beam structure; the foundations, the substructure and the ground slab are also made of ordinary unreinforced concrete. The walls are filled with cement-earth agglomerates, measuring 29 cm in length, 13.5 cm in thickness and 10 cm in height. These earth blocks are therefore not load-bearing; it is the concrete that performs this function, as we can see in Figure 2.

Several other items of equipment and construction elements are prefabricated in concrete: among them the tubs, the Turkish WC, the door and window frames, and the wall caps.

We can also see that the housing design in Daoudiate is very rational. The housing unit measures 6 × 8 m, multiplied identically to form a neighborhood with a layout of orthogonal streets, a layout very different from that of the traditional Moroccan city. The use of raw earth in the construction of Daoudiate is thus not associated with a traditional design of housing.

Therefore, in this construction site we notice that the earth is almost only a detail element integrated into modern constructive systems, and industrialization and prefabrication techniques imported from Europe.

This rationalization of the production of mud bricks seems to be an attempt to bring the earth material back into technical normality. And this "technical normality" therefore consists in using earth concrete as if it was cement concrete. The project was adopted by the authorities, given that the second tranche of 800 housing units started in 1963, and the operation was continued to build a total of 2748 housing units over five years, instead of the 1500 initially planned (Figure 3).

Figure 3. Photography of Daoudiate dwellings in 1965 (Alain Masson archival holdings, Archives of Morocco, Rabat).

3 ALAIN MASSON, SOCIAL ENGINEER

Let us now review the trajectory of Alain Masson, the designer of this project.

Masson arrived in Marrakech in 1961, at the age of 34, to head the Public Works District of several provinces in southern Morocco. This position represented a promotion for him, as he was given more responsibilities. In an autobiographical narrative, Masson tells of the freedom he enjoyed from his direct superiors, most of whom were European, as well as the trust placed in him by the Moroccan governor of the Province of Marrakech (Masson 1987).

The Daoudiate project was considered a success by Masson's superiors. It was visited by senior Moroccan officials, and by invited foreign personalities, such as André Malraux. The French engineer was, moreover, decorated with the Alaouite Ouissame by King Hassan II on 7 May 1965. Thanks to this, and to the success of the Daoudiate project, Masson was appointed in 1968 in Rabat to the Directorate of Urban Planning and Housing (DUH) which had just been attached to the Ministry of the Interior, to a position he held until 1973 when he left Morocco. During these five years in Rabat, Masson continued to work on the problem of economical housing in Morocco, proposing development plans in which housing would be built using natural materials for reasons of economy. Nevertheless, he regarded housing built with natural materials to be transitory because in the future a more efficient housing could be designed following the development of the country. Thus, for this engineer, building with raw earth met the economic imperatives of a developing country in the post-colonial period. It was, for him, a temporary solution adapted to the economic and social context of the country.

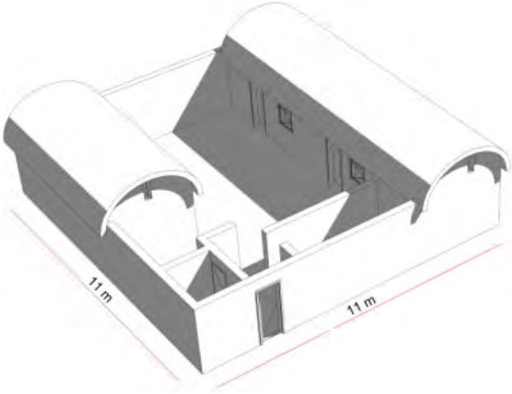

Figure 4. Three-dimensional view of BTS 67 (Rouizem 2019).

4 SPEED OF CONSTRUCTION

After the Daoudiate project, Alain Masson wanted to improve the technique and architecture through a new experiment in 200 economical earthen housing units in Ouarzazate. The two operations were called BTS 62 and BTS 67, respectively. For BTS 67, the housing design was larger, cheaper, and entirely made of earth. During an interview, Jean Dethier told us that it was Alain Masson who undertook this second experiment in cooperation with Jean Hensens. Dethier, a Belgian architect and cultural mediator, worked with Alain Masson and Jean Hensens in Morocco between 1965 and 1969. He has published numerous works on earthen architecture, which describe Moroccan experiments as technological successes.

According to Patrice Doat, French architect and co-founder of CRAterre (International Centre on Earthen Architecture), the constructive method is indeed that of an engineer since the formwork is concrete-inspired. However, Doat is critical of the thinness of the walls, 25 cm, insufficient to ensure thermal inertia in a hot climate like that of Ouarzazate (CRAterre 1979). Thus, the thermal properties of the raw earth were not taken into account in these operations.

Indeed, the technique used in this project is a modernization of rammed-earth, using a metal formwork that allows the construction of a house in 24 hours. A report highlights the reference to tradition in this constructive mode: “This process is directly inspired by Moroccan tradition, which it was sufficient to adapt to modern techniques” (Anonymous 1968).

Traditional rammed earth, called *pisé* in French, is a construction process that consists of pouring the soil between two wooden forms; the soil is then compacted with a tool, then the forms are moved horizontally to continue the construction of the wall.

The wooden formwork panels used in traditional rammed earth construction are replaced in BTS 67 by metal formwork that allows the construction of the exterior and interior walls, as well as the roof. The parts of this formwork are assembled by wedges; jacks allow the formwork of the vaults comprising the roof to be removed.

Compared to traditional construction, several other modifications were made. The roof is not flat, as in traditional housing, but is in the form of a low vault also made of stabilized earth (Figure 4). The wood used in the traditional habitat is, in fact, very expensive, and the vault allowed the roof to be made of earth, avoiding the use of concrete. However, cement was still used to stabilize the earth, and the dosage was increased for the roof.

A special method was used to optimize the speed of construction; the living rooms are adjoining, so they are shuttered together. Thus, each group of four rooms or two living rooms, as well as the adjoining walls, are boxed together in a single strip 1 or 0.75 m high. The earth concrete consisted of river soil combined with clay and cement in a mixer and then mechanically compacted using pneumatic rammers of the Pokorny type, or a Wacker vibratory rammer run on gasoline. This equipment was therefore much more sophisticated than the very rudimentary tools of the traditional Moroccan *pisoir* (rammer): a hoe, a basket, and a wooden *pisoir* (CRAterre 1979: 38).

The speed of construction was thus a key element of the building site. The assembly of the formwork was carried out in the morning, the filling with earth and the pneumatic compaction took the rest of the day, and the mold was dismantled the next day. Drying was done during the night thanks to the high temperatures and dry climate. Compared to the traditional process, once the metal formworks have been created, a considerable amount of time was saved. However, only the first eight houses were built with vaulted roofs. A high-ranking state official must have rejected this form and imposed the construction of a concrete flat roof for the remaining 192 houses.

5 5 THE DISOBEDIENCE OF THE ARCHITECT: JEAN HENSENS

For this second project, Masson collaborated with the Belgian architect, Jean Hensens, who designed the plans for the operation taking inspiration from the housing in the medina. Indeed, the centered typology of this housing is directly inspired by Moroccan traditional housing, according to Hensens, an architect who worked for 30 years in Morocco, and who wrote about and designed much of the vernacular habitat of this country. Coming from a working-class background, Jean Hensens had a left-wing ideology from an early age, and he tried to develop his theories and have them recognized by publishing in Moroccan magazines. It is notable that he was more interested in the construction process than in the project itself, his written works being much more abundant than his constructions.

Hensens left an important archive fund never exploited by researchers, preserved today at the University of Architecture of La Cambre in Brussels. The themes that emerge through the study of his work are related to his political and ethical interests, as well as to the defense of local cultures against their globalization. As for many activist architects, raw earth is for him more than a construction material; its use must take place within a true society-based project. The architect should serve only as a technician helping to develop local techniques that are modernized to better meet needs but not industrialized, thereby maintaining their social interest. This is also the vision of Yona Friedman, who considers that the architect has only an advisory role.

According to Patrice Doat, the architect's innovation can be disturbing when it calls society into question (Doat 2018): it is "the architect's disobedience", an expression taken from the book by the famous Italian architect Renzo Piano (Piano 2007). However, taking a present-day perspective on these designers allows us to elevate them from a status of refractory to that of avant-garde – or, as Jean Dethier writes, from the rank of marginal utopian to that of pioneer (Dethier et al. 2019).

6 APPROPRIATION OF THE MUD BRICK

As Edgerton writes, one must study not only innovation but also its adoption, or disappearance (Edgerton 1999). So what does the current state of buildings tell us about their use by their inhabitants?

Through survey, photography and drawing, the fieldwork of this research identified the various transformations of the dwellings, and the practices employed to maintain and develop the construction.

Regarding the current state of these two projects, the district built in the 1960s in Marrakech is still inhabited, even if it is unrecognizable due to the houses' increasing elevation. Indeed, most residents have added two or three floors above their homes, sometimes without demolishing the original house (Figure 5). Thus, the neighborhood has over time acquired an anonymous aspect similar to other economical housing estates in Morocco, a typology that characterizes the Moroccan peri-urban landscape, as studied by Daniel Pinson (Pinson 1989).

These interventions by the inhabitants are a spontaneous part of contemporary approaches that consider architecture not as a finished product but as a continuous process of co-construction of housing according to the evolution of needs and resources (Revedin 2017). As for the rammed earth dwellings of Ouarzazate, they were demolished and rebuilt in cement by the inhabitants.

The appropriation of the site by the inhabitants of Daoudiate has preserved it for more than half a century. On the other hand, in Ouarzazate, the project's architecture was rejected, which contributed to accelerating its destruction. However, we must add that the main reason for this rejection was that these houses were allocated to state employees who were able to buy the houses and demolish them to build two-story buildings as we can see in Figure 6.

Figure 5. Daoudiate in 2020 (photo: author).

Figure 6. BTS 67 in 2018, Ouarzazate (photo: author).

The transformation of housing by the inhabitants constitutes a know-how particularly well developed in traditional societies. The knowledge of these practices by architects would make it possible to better anticipate the transformations which a building can undergo, in order to better take into account the use of the building and integrate it into the design.

7 IMAGE AND USE OF RAW EARTH ARCHITECTURE

This research shows that during these projects built in the 1960s raw earth was not treated as a traditional material but was assimilated to concrete. The engineer's point of view is essential here because it considered the modernization of raw earth an argument for its appreciation and a condition for its acceptance. Hence, it seems that, from the engineer's perspective, raw earth embodied values of progress, representing another model of development adapted to a southern country in the post-colonial context.

Calling on foreign experts sometimes allows for greater efficiency, since a foreign actor is not subject to the same local pressures; this appeal greater freedom of action attracted the most competent professionals to the Maghreb and to the former colonies.

Successive designers in Morocco have used raw earth as a material of openness and experimentation, using the atypical qualities of this material as a lever for technical, architectural, and social innovation. This was possible thanks to a legacy that still survives today, that of the status of foreign architect in the country, admirer of the local vernacular architecture, a status which lent their approach legitimacy in the eyes of local authorities and international bodies.

The rejection by the authorities of the technical solution of the vault as roofing system for the dwellings shows that raw earth is better accepted when it is not identifiable as such in the appearance of the constructions. It seems, therefore, that trivializing raw earth as a construction material and ridding it of its militant dimension would be required for its use in contemporary projects.

Architecture can hide the construction material or enhance it, and the use of earth in a project can totally change perceptions of it. It is the architectural design that gives meaning to the use of a construction material. Architects can, therefore, give a different image to raw earth depending on the form and architectural quality of their project, but also in the implementation of the construction material. This shows the importance of the demonstrative value of architecture when awakening the interest of the range of actors involved in a project.

Finally, appropriation can be considered as a test of architecture; it is also part of the experiment.

By analyzing appropriation, we can anticipate the evolution of the building, apprehend its temporal dimension and integrate the evolutionary dimension of housing, which is in continual evolution.

The architectural object should be considered by architects not as a finished product but as subject to a continuous process of co-construction with its inhabitants that evolves according to their needs and resources. Residents' skills would also be a resource to integrate into a process of knowledge exchange between project managers and users. The construction site as a place of learning is an important concept worthy of development today and very suited to a building material such as raw earth.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The construction history of the N2 motorway: Networking on reinforced concrete in the Canton of Ticino

I. Giannetti
Università degli Studi di Roma "Tor Vergata", Rome, Italy

ABSTRACT: The N2 Chiasso–San Gottardo Motorway in Switzerland features the global use of reinforced concrete and is a symbol of the modernisation history of Canton of Ticino in the 20th century. This paper addresses the N2's construction history (1961–86), discussing how the networked relationships among the various actors involved in the project (institutions, engineers, builders, and regional planners) were embodied in the N2's conception, and shaped a shared technical culture of reinforced concrete design. The studies were conducted within the FSN project 'Architecture in Canton Ticino, 1945–1980' (www.ticino4580.ch), which was promoted by the Archivio del Moderno. The main archival sources were the National Roads Office in Bellinzona, the Renato Colombi (head of the National Roads Office), and the Rino Tami Archives at the Archivio del Moderno.

1 INTRODUCTION

The 300km of the Swiss N2 highway links the cities of Chiasso with Basel, crossing seven cantons. The construction of the Ticino Canton sector, which is more than 140km long, began in 1961 and was finished and inaugurated on October 23, 1986. Built over 25 years in segments made entirely of reinforced concrete, the highway is an extraordinarily unified work characterised by evident rigor and formal coordination among the structural works located along its route.

In 1961, the famous Italian critic Bruno Zevi (1918–2000), speaking about the Italian motorway *Autostrada del Sole*, attributed the realisation of an infrastructure that was non-uniform and inconsistent from an aesthetic point of view to a 'fragmentation of the works'. He complained about the involvement of 18 companies and 27 engineers in the construction of the various viaducts in the motorway's 84km Apennines section (Zevi 1961). In that same year, in Ticino, 25 engineering consultants and 25 construction firms (in addition to associations, committees, communities, consultants, and consortia) were involved in the construction of the first 10km of the N2 highway (Colombi 1961). Furthermore, along the entire route of the N2 and including its bridges, 78 structures were built between 1961 and 1968, and 115 between 1980 and 1986, 20 years after its initial construction. New structures incorporated technological advances that had occurred during that time.

It is clear that the N2's formal, structured design is due to a design strategy that differed from the centralised one called for by Zevi, an efficient 'coordination' already personified by the architect Rino Tami (1908–1994) (Maffioletti 2008; Navone 2017), who in 1963 was designated the N2's 'consultant on aesthetics'. This history of the project's construction focuses on that different design strategy, investigated through the observational lens of the network of actors involved.

In the following pages, the organisation of and methods used by the 'N2 network' are reconstructed with the general aim of highlighting the network's role in shaping a specific Ticinese culture in infrastructure design that has persisted in recent works (Navone 2017; Maffioletti 2018).

The analysis focuses on two levels, both conducted by material analysis of primary sources in the canton's archives, which are as yet poorly investigated: the National Roads Office (USTRA) Archives, Bellinzona; the Renato Colombi Archives, Archivio del Moderno, Balerna; and the Rino Tami Archives, Archivio del Moderno (AdM), Balerna.

At the 'macroscale' level, with regard to the canton's social and political framework, the network of actors involved and their respective roles in the design process have been reconstructed, beginning with the choices of politician Franco Zorzi (1923–1964) regarding ideation and promotion of the motorway project. At the 'microscale' level, the design effects of the network have been investigated by following Tami's actions through a single phase of the project.

Finally, by way of comparison, the specificities of the operational strategy developed in Ticino are discussed and compared to those used in the Italian case, which is considered a direct counterpart of the N2.

2 ZORZI'S STRATEGY

In the 1940s, it was decided to complete the main road network in Switzerland by adding two major transit

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routes, one from Sankt Margrethen to Geneva and one from Basel to Chiasso. In 1954, the Federal Council appointed a commission to develop this road network. The commission, which was responsible for defining the legal basis for and clarifying the financial aspects of the operation, remained in charge until 1958, when the commission published its first report. For Ticino, the proposal foresaw a predominantly two-lane road with no motorway tunnel through Saint Gothard. On April 5, 1959, the politician Franco Zorzi was elected councillor of the Department of Construction. Confident that infrastructure would play a crucial role in modernising the canton, he firmly opposed the federal programme, foreseeing the construction of a road that had four lanes and was complemented by the Gothard Tunnel. Following the March 8, 1960 'Federal Law on National Roads', the connecting roads of major importance and general interest for Switzerland were declared to be national roads and were divided into three classes. The Ticino section of the N2 national road was included in the first class, defining it typologically as a real motorway.

Two words, chosen by Zorzi, were key to the creation of a clear operational strategy for the N2 project: reinforced concrete and coordination.

2.1 *Reinforced concrete*

The choice for reinforced concrete was strictly linked to the canton's economic and productive development.

Inspired by the coeval improvement of the hydroelectric infrastructure, featured in large concrete dams from the early 1950s (Botter Balli 2003), the motorway construction would boost reinforced concrete supply demands and support the establishment of Canton cement production. In 1959, the project for a new cement factory in the Breggia Gorges, the SACEBA, was settled (Buzzi & Pronini Medici 2012). The factory, utilising the limestone resources of the valley, would ensure the supply of canton cement for infrastructural works. The construction of the factory began in 1961, and its activity started in 1963. In 1959, the Agglomerati di Cemento SA company, established in 1913, founded a new plant in Noranco for the upcoming N2 construction sites.

Within the same scope of fostering the canton building industry sector, the choice of reinforced concrete was accompanied by the preference for in-situ construction techniques that continued to be systematically applied in the N2 construction site from late 1979 onwards. For the other Swiss segments of the same motorway, prefabricated and industrialised systems were widely spread from the mid-1960s on, according to general European trends (Menn 1982).

2.2 *Coordination*

The choice for coordination was undertaken in accordance with the vision of infrastructure as a tool for modernising the territory, avoiding its aesthetical spoil (Zorzi 1959).

In 1959, Zorzi decided to set up an autonomous section of the Department of Construction that would coordinate the N2 project from its layout to construction on site. Thus, on May 5, 1959, one month after his election as head of the Department of Construction, he met with civil engineer Renato Colombi (1922–2015) (Colombi 1959), a graduate of the Federal Polytechnic. Colombi was employed in the hydroelectric sector of the company Blenio SA, and was an expert on large reinforced-concrete constructions. Zorzi explained to Colombi the intention to form a new team of technicians within the department that, under Colombi's leadership, would be entirely dedicated to the freeway project. This team constituted the 'National Roads Office', and was officially established on July 7 of that year (Colombi 1960). As the section's 'chief engineer', Colombi began recruiting technicians. On August 6, he met Zorzi with engineer Francesco Balli (1925–2015) (Colombi 1959), a graduate of the Federal Polytechnic who was also employed by Blenio SA, and a specialist in reinforced-concrete construction.

The National Roads Office began working unofficially on October 1, when Colombi's first collaborators settled in a small villa in Bellinzona (Grassi 1979). On October 7, examinations were held for drafters and to recruit eight civil engineering graduates of the Federal Polytechnic, who were employed by the office under private companies fees (Colombi 1960). The Office's activities officially began on January 1, 1960. The team numbered eight engineers, one technician, six draftsmen, and one secretary in charge of expropriation procedures. Despite its small staff, the Office was divided into three main services: 'design' (directed by Balli), 'geotechnical laboratory and materials testing' (entrusted to engineer Marco von Krannichfeldt), and 'administrative services' (directed by Renzo Sailer). In April, the 'works management' service was added, coordinated by engineer Glauco Nolli.

Beetween 1961 and 1963, three technical consultants were involved in supporting the Office tasks: the traffic engineer Jaques Richter (Sailer 1992), the geotecnis engineer Ezio Dal Vesco, and the architect Tami.

From its foundations, the Office represented the operational hub for the various actors in the project that ranged from the Federal Council (Swiss government) itself and the canton's municipalities, to engineering firms and contractors. The organisation of the different office section workflows that are reported in Figure 1 held a crucial role in structuring the network relationships between the involved actors.

The Federal Council established the annual loans, the general time planning, and the route layout. In accordance with the law of March 8, 1960, the office design section's first tasks involved design services for the route layout, which was proposed on a scale of 1:25000 by the Federal Council and was detailed in 'general plans' on a scale of 1:5000. During this phase, the office design section drew up the 'general plans' of the individual sections according to a list of priorities (Colombi 1960) and then shared them

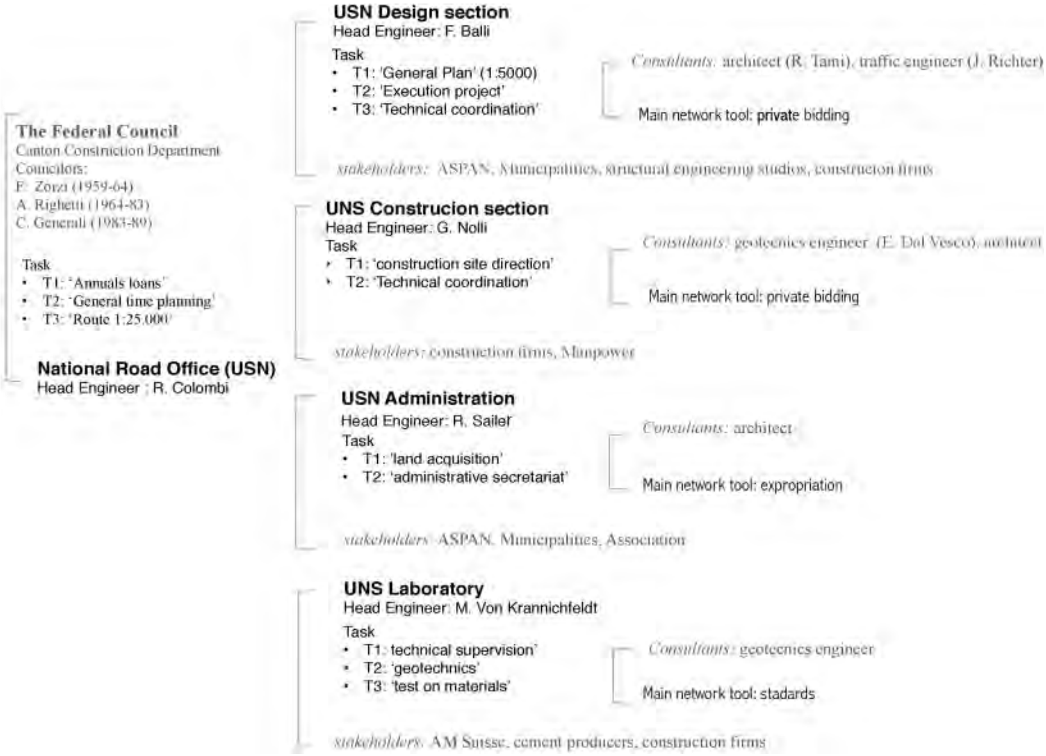

Figure 1. Diagram of the National Road Office workflow and its stakeholders.

Figure 2. Colombi explains the N2 design, 1966 (ETH-Bibliothek Zürich, Bildarchiv, picture by Josef Schmid, Com_L15-0896-0001-0001 / CC BY-SA 4.0).

with the municipal administrations so that they could be examined and commented on by the municipalities (Figure 2). After being modified, the plans were submitted, once, to the Federal Council for approval (Colombi 1961).

While the 'general plans' were under review by the municipal administrations, the design section was working on the final execution drawings of the sections for which the approval process had already been completed. Given the design section's limited staff, the network expanded during this phase to involve professional engineering firms that were already active in the Ticino region. As represented in Figure 2, between 1961 and 1968, while about 25% of the freeway was being built, the Office's staff increased from 14 in 1960 to 168 in 1968, and the number of consulting engineering firms involved in the execution phase increased from 3 in 1961 to 38 in 1968 (Colombi 1968).

2.3 *The operational tools: Private bidding*

At this stage, consistent with its general objective of 'coordination', the Office used an effective operational tool that was valid both in the design and tendering phases: private bidding competitions. In particular, extending the practice of private bidding competitions to the design execution strengthened the relationship between the Office and the other professionals involved, and enabled the Office to formally control the individual products in accordance with the overall vision for the motorway.

The first private bidding competition for design was announced on January 4, 1961, for the Melide viaduct. Analysis of the jury and its participants clarifies the operational aims of this tool. Five engineering firms (Hans Eichenberger, Gellera and Lombardi, Losinger and Cie, A. Casanova, and Conrad Zschokke), all Swiss and mostly from Ticino, were invited. Among the jury members were Zorzi himself, representing the Department of Construction; Balli and Colombi, representing the Office; Luigi Pini and Amedeo Marrazzi, representing Ticino's professional engineering firms; and architect Tami.

While the inclusion of professional firms on the jury ensured that the Ticino Canton's professional community was committed to the N2 project, Tami's inclusion was the key element in the public's perception of the motorway as a project that would enhance the region (Maffioletti 2008; Navone 2017). Indeed, Tami was already the director of the motorways section of (Swiss Association for Territorial Planning) ASPAN, of which Zorzi himself was president (Maffioletti 2008; Navone 2017). The jury's reports indicate that the projects were judged from two perspectives: 'construction' and 'aesthetics' (Figure 4). Although it was unusual for infrastructural designs, the aesthetics perspective called for the projects to be verified using photomontages explicitly requested by participants to enable them to check architectural aspects of the designed structure in relation to the landscapes in which they were being built.

Thus, in the Melide competition, Eichenberger's viaduct was awarded the contract because it was considered 'valuable' for its 'lightness and unity of rhythm of the structural elements' (Ufficio Strade Nazionali 1961). Even before the solution was presented, it had also been judged 'excellent' in terms of its construction concept.

Following the successful outcome of the Melide competition, a continuous dialogue was established between Tami and the Office, aimed at the 'harmonious' integration (Maffioletti 2008) of the new road with the canton's landscape. In 1963, when 'the freeway works entered the execution plan' (Colombi 1963), Tami was officially designated by the Council of State as an 'aesthetic consultant for the motorway works', a role he held until 1983.

Zorzi died in a tragic accident in 1964, when the motorway construction was at the very beginning. Both the defined structure of the Office and the organisation of its workflow, with Tami's institutionalised role, allowed the extension of Zorzi's strategy up to the completion of the motorway construction in 1986.

3 TAMI'S ROLE

From the very first construction sites, Tami charged his young collaborator, architect Aurelio Galfetti (1936-), to compile some 'albums of errors'. These albums used photographs and annotations to document the main formal errors made in the design of the various structures and their relationships to the landscape.

These errors were identified, classified, and transformed into a series of 'standard solutions' to be adopted moving forward. Tami elaborated these standard solutions in a series of dense drawings of 'standard bridge abutments' and 'standard overpasses'. In the early 1970s, the Office translated these drawings into a series of 'standard plans' (Ufficio Strade Nazionali 1974), which were execution drawings that included details of the reinforcements for various dimensional hypotheses. They described, for example, inclined walls featuring standard bridge abutments or profiles of the retaining walls to be used on the entire route.

Tami's accurate aesthetic coordination on the structures—explicitly translated into the Office's 'standard plans' after 10 years of work—were introduced in the project's three main phases, from the preliminary drawings to the execution drawings. They were used to train the various actors involved in the design process to ensure a shared practice.

3.1 *Coordination and corrections*

Aesthetic coordination had already been implemented in the 'general plans' drawn up by the Office as the basis for the private bidding regarding design.

During this phase, the dialogue between Tami and the 'design service' technicians focused, beginning with the first sites, on the road profiles. In this way, unique structural figures took shape, both for the substructure viaducts and the road overpasses. In accordance with the global use of reinforced concrete, the substructure viaducts conformed to the image of high-pier girder bridges featuring 'sliding and profile' decks (Figure 5), while the overpasses conformed to the image of 'overpasses with sliding decks and inclined piers' (Figure 6).

The coordination also extended to the control of the final projects that had been developed by engineering firms in the competition phase. By participating on the jury, Tami directly influenced the individual viaducts within the overall view of the sequence of structures. During this phase, Tami designed the special viaduct abutments, as 'inclined connections to the ground', and, to architecturally define the relationship between the viaducts and the tunnel entrances, elaborated the novel figure of the 'tunnel portal' (Tami 1984). Tunnel portals were designed, one by one, by Tami himself, featuring the whole route as a series of architectural artifacts overplayed to the road (Maffioletti 2008; Navone 2017).

During this phase of the project, the most interesting collective effects of this project strategy were suggested in the design of the standard structural bridge type—the high-pier viaduct with a continuous box-section beam—developed by the canton's engineering studios following Tami's indications. For example, the Bisio viaduct (1962–65) and Ruina viaduct (1977–84) projects indicated, on one hand, the continuation of Tami's 'coordination' and, on the other hand, the establishment of a specific competence acquired by Ticino engineering firms regarding this approach to the project.

The Bisio viaduct's design was developed by the Ticino engineering firm Bernardi-Gerosa for a 1962 competition. Five engineering firms (four of which were from Ticino) were invited to bid privately: Bernardi and Gerosa from Mendrisio, Marazzi and Pini from Lugano, Lombardi and Gellera from Locarno, Augusto and Alessandro Rima from Locarno (consortium with Elektrowatt) and Emil Schubiger from Zurich. In addition to Tami, the jury included Zorzi, Colombi, Balli, and engineers Hermann St'ssi, Edmond Rey, and Eichenberger. The Bernardi-Gerosa

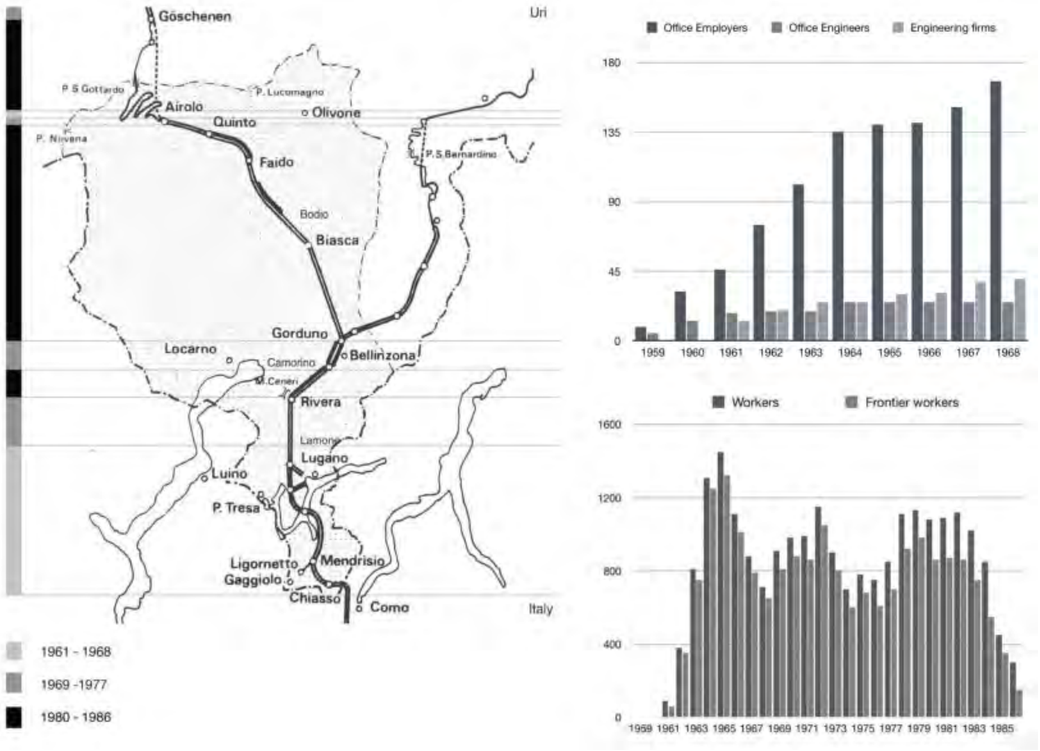

Figure 3. N2 construction periods; numbers of the Office employers and steakholders (1961–68); numbers of N2 workers (1961–85).

firm won the contract, thanks to its design of a viaduct that was considered of 'excellent formal appearance' (Giannetti 2020). After the competition, at Tami's suggestion, the viaduct's appearance was further improved by the addition of inclined abutments designed to connect the deck line geometrically with the terrain's slope.

In the execution phase, the invitation to focus attention on the viaduct's architectural lines was further reflected in the elegant solutions developed independently by Bernardi and Gerosa. The inclined sections of the deck's beam box and the strong overhang of the carriageway platform contributed to the elimination of the traditional structures that supported the freeway's twin roads. Furthermore, the head of the two-cantilevered carriageway was emphasised to create a 'light band', which contrasted with the 'corresponding shadow effect' created by the overhang. Finally, the design was completed by original commuter devices placed at the foots of the piers and between them and the deck. They were entirely made of reinforced concrete and featured the use of crossbar hinges.

The Ruina viaduct was built in the Biaschina gorges between 1976 and 1984, designed by the engineers Balmelli and Filippini. After a private bidding competition (Ré 1977) that involved five engineering firms from Ticino, Balmelli and Filippini's proposal won the second prize. Then, their bid was combined with Kessel and Blaser's, and thereby won preference in the execution phase. According to the jury's report, the competition was characterised by a variety of proposals, including those based 'on solutions that have been widely tested' and those characterised as 'new and original', confronting the jury with a 'real choice'. Kessel and Blaser's project, which presented a mixed solution in concrete and steel and was characterised by special Y-shaped supports, was judged the best in terms of aesthetics for 'the degree of lightness and transparency it offers as a whole'. Balmelli and Filippini's

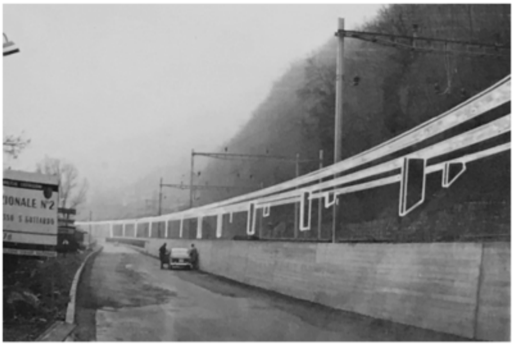

Figure 4. Photomontage for the viaduct study (Ufficio Strade Nazionali 1961).

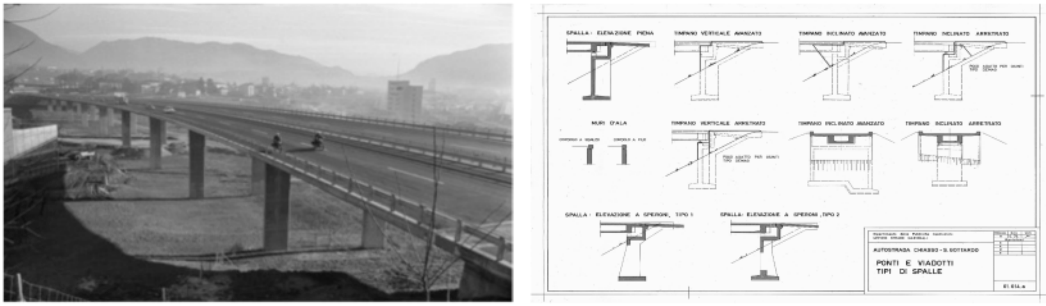

Figure 5. Picture of the Bisio viaducts and viaduct abutments ‘standard solutions’, execution drawings by the Office, 1974 (USTRA, Archive).

viaduct was also judged well for ‘aesthetics’ because it was ‘formally valid’ in accordance with ‘tradition’. In fact, the latter proposal’s deck ‘flowed harmoniously’, and the rhythm of its high, slender piers was described as ‘almost regular’. While its appearance conformed typologically to the vision developed by Tami in the 1960s, in terms of structural design, the viaduct presented a particularly innovative solution. According to the jury, ‘the parts’ sizes responded well to the forces’ flows’, and the viaduct differed from all other structures on the route because of the design of a unique box deck made of prestressed reinforced concrete that included both of the road’s pathways, thanks to two cantilevered side decks of 7.5 metres.

3.2 *On-site corrections*

Tami’s influence also extended to the construction phase, engaging in dialogue with the engineering firms, contractors, and more broadly, the Office’s two sections: design and construction sites.

During the first two phases, if the architect’s conception had affected the engineering project, stimulating those professionals to reflect on the overlap between Tami’s formal themes and the structural design, in the third phase, the architect’s influence extended to the construction site, directly involving the contractors and workers in the creation of tailored solutions. One example is the case of the Capolago viaduct, built in 1964 by the Zschokke Company. The project involved building a structure that had spans of 20 metres and slender rectangular piers on which rested, with transverse lintels, the longitudinal beams of a prestressed reinforced-concrete deck, completed with slabs cast in situ. The beams, with T or double T sections, were composed of two prefabricated elements, each 10 metres long, coupled on site with longitudinal prestressing cables, which provided both a productive and constructive advantage. However, the appearance did not comply with Tami’s ‘shaped’ and ‘profiled’ vision set out for the N2 viaducts. Therefore, during the execution phase, Tami corrected the viaduct by designing a new deck cross-section and shape for the connections between it and the piers. By inserting a continuous lateral ‘edging’ in the form of an inclined wall composed of small, prefabricated reinforced-concrete elements (Figure 7), Tami reconstructed the deck profile to create a continuous longitudinal band that inclined outward. While the viaduct was under construction, the execution drawings, developed between 1964 and 1965, called for the 495 prefabricated elements. They were one metre long and different through the valley from on the mountain, to be assembled on site into the new reinforced-concrete enclosure. In 1968, Zevi appreciatively noted ‘the profile of the prefabricated viaduct of Capolago’, which had been completed slightly more than a year before, for its ‘value of lightening the figurative weight of the roadside’ (Zevi 1968). He thereby culturally validated, in comparison with the much-criticised Italian project, the coordination strategy developed in Ticino.

4 ON THE N2 METHOD

As mentioned, the Italian project was the most direct reference, both productively and technologically, for the construction of the Ticino motorway and therefore is a useful point of comparison in the quest to fully understand the N2’s operational specificities. In Italy, a 1955 law enacted a freeway-development plan with a 10-year timeline. In addition to strengthening the pre-war freeway segments, the plan called for two new highways, the Adriatica and the Sole, which would connect Milan to Naples using 800km of new road. The higway was completed in only eight years, establishing itself as the most daring feat of the Italian ‘economic miracle’ years. In 1959, at the very beginning of the N2 project, the *Autosole* construction sites provided clear proof of the technological success of the reinforced concrete construction in the artisanal dimension of the construction site. In October 1959, Colombi, Balli, and some other engineers directly involved with the Office made a study trip to these construction sites in Italy (Colombi 1959). As they reported, the Italian strategy was based on subdividing the work into small segments and entrusting their completion, on a contract/competition basis, to various construction firms, while *Società Autostrade* supervised the bids (Iori & Poretti 2015). This subdividing strategy was considered effective to the Ticino productive and economic system and, thus, suitable to be successfully re-used.

Figure 6. Extract from the ‘album of errors’: study for the architectural details of the overpasses; picture of the Soresina over-pass designed by Tami and the engineer Ervino Kessel (AdM, Tami).

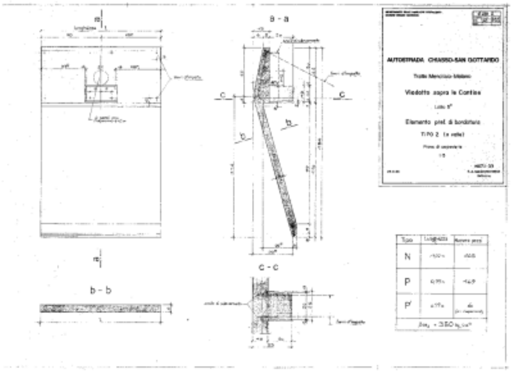

Figure 7. Capolago viaduct, detail of the “edging” elements, 1964 (USTRA, Archive).

Over 25 years, the construction involved more than 100 construction companies, many workers (2200 at peak), and more than 40 Swiss consulting engineers. Anyhow, the network- and coordination- strategies adopted in the two countries, differed by two crucial correlated aspects: the organization of the bids, and the role of the contractors. In Italy the bids were dedicated to the one phase of design and construction, while in Ticino were divided into two subsequent steps: the design bid, thus, introduced the possibility to formally coordinate the works. In this way, while in Italy, the contractors played a crucial role in the design of the works, establishing a direct relationship with designers, in Ticino the designers established relation with the ‘coordination team’, enhancing a network cultural ‘training’ on infrastructural design. Furthermore, while in Italy the execution phase was ‘governed’ by the contractors and designers, in Ticino, the Office held a solid directive role in this phase, allowing the coordinate design strategy to extend over the entire time-span of the project.

5 CONCLUSIONS: THE N2 LEGACY

This article discusses the working methods of the network of actors involved in the design and construction of the N2 motorway (1959–86). As a consequence of Zorzi’s strategic choices, the structure of the network of actors and their respective roles in the design process were analysed at the ‘macroscale’. The effects of the network’s working method embodied by the design and construction processes used for the N2 were analysed through the narrative of the individual works.

In conclusion, it is thus possible to report some findings of the N2 construction history through network-based analysis. First, the network-based analysis shed light on the direct effects of the choice of reinforced concrete as the only structural material used in the N2 on both the productive and economic system of the, and, more specifically, on the design approach. Regarding the productive and economic system, the reconstruction of the Zorzi strategy focused on the fundamental role of N2 planning in the development of canton cement production. Moreover, the related choice for the cast-in-situ solutions proved to be fundamental to enhance the artisanal nature of the construction site, taking advantage of the large numbers of non-skilled workers available (Figure 3). Regarding the N2 design approach, the global use of reinforced concrete allowed Tami’s formal coordination to be extended to the under-construction works.

Second, the network-based analysis highlights how the N2’s formal unity has been achieved through the Office’s operational strategy that, established by Zorzi, was pursued over the years, after his death in 1964, thanks to the crucial roles of Tami and Colombi. In addition to Zorzi’s choices in favour of cement and coordination, the Office ensured success by played a lead role in selecting the actors involved in the project and, above all, in their commitment over the years. In this way, a community of technicians that spoke a common design language was established, leading the N2 artifacts to effectively illustrate Tami’s best-known writings: *Problemi estetici dell’autostrada* (Tami 1969), and *L’autostrada come opera d’arte* (Tami 1984).

Third, the network-based analysis reveals the cultural training of the N2 constellation, conducted during the 25 years of the motorway construction, as the direct reference of the recent reinforced concrete infrastructural works of the canton (such as the Transjurane). These works, though the intervention of the architect, clearly integrate structural and construction functions with ‘artistic directives’ (Maffioletti 2018).

ACKNOWLEDGEMENTS

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Open session: Knowledge transfer

History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Leonardo da Vinci, centering construction and knowledge transfer

H. Schlimme
Technische Universität Berlin, Berlin, Germany

ABSTRACT: This paper discusses Leonardo da Vinci's drawings for centerings for vaults. Although the drawings are regularly mentioned in the literature, an in-depth analysis is still lacking. Taking the drawings *Codex Atlanticus*, f. 225r-a [609r] and Manuscrit B, ff. 19v and 67v as examples, the paper tries to figure out da Vinci's thinking behind the drawings and tries to collocate them between the theory of mechanics and the building and workshop practice of his time.

1 INTRODUCTION

1.1 *Topic*

The present paper deals with Leonardo da Vinci (1452–1519) and his interest in construction techniques. Da Vinci studied composite beams, roofs, arches, straight arches and centerings for vaults. But while this has been mentioned and dealt with regularly in the literature, it has rarely been the main focus of attention. This paper aims to shed more light on the topic. While composite beams, roofs, arches and straight arches will be discussed in a further publication by the author, the present paper aims to make a contribution to our understanding of da Vinci's centerings for vaults.

A well-known set of da Vinci's centering drawings is in the *Codex Atlanticus* (CA), Biblioteca Ambrosiana, Milan, ff. 225r-a [609r], 200a-r [537r], 283r-e [770v], 114v-b [316v], 259r-a [696r]. The CA group can be dated to da Vinci's stay in Rome from September 1513 to the end of 1516 (Pedretti 1972: 58, Pedretti 1962 limits the period of the centering drawings to 1513–1514). The drawings are most probably inspired by the centerings visible on the building site of St Peter's Basilica in Rome, which da Vinci could see from his apartment in the Belvedere Villa. Evidently the view of these constructions led him to make further studies: the dimensions of St Peter's in general fostered innovation in building construction. Two further drawings by da Vinci showing centerings are conserved in the Institut de France, Paris, Manuscrit B, ff. 19v and 67v (Ms. B).

1.2 *Bibliographic analysis*

The bibliography often mentions the centering drawings, but an in-depth analysis has thus far been lacking. Uccelli (1940a: 246–247) brings together all of da Vinci's statements on mechanics, encompassing structural mechanics, and thus virtually compiles da Vinci's "treatise on mechanics". He cites the comments da Vinci makes on Ms. B, f. 19v and on *Codex Atlanticus*, f. 225r-a [609r]. The transcription of the latter is not reproduced as a coherent text, but distributed between the main text and the footnotes. Uccelli does not provide an analysis of da Vinci's statements. In his contribution to the catalogue of the 1939 Milan exhibition on da Vinci, Uccelli (1940b) reproduces CA, ff. 225r-a [609r] and 200a-r [537r] and Ms B, f. 19v, but he does not discuss the centerings at all. For the drawings of Ms. B see the catalogue of Authier et al. (1960).

Pedretti (1962: 90 and note 24), mentions the whole group of centering drawings in the *Codex Atlanticus* and brings together all the hints for dating the drawings. Pedretti (1972: 58) mentions the centerings and links them to St Peter's but says that f. 114v-b [316v] could also be dated to da Vinci's Florentine *intermezzo* 1515 and linked to the Medici Stables alla Sapienza (Pedretti 1972: 114). In his monograph on *Leonardo architetto*, Pedretti discusses the centerings of the *Codex Atlanticus*, except f. 114v-b [316v]. The sketch of the statue of the sleeping Arianna in f. 283r-e [770v], which da Vinci was able to admire in the Cortile del Belvedere in the Vatican, makes probable a link between the centering sketches and the building site of St Peter's (Pedretti 2007: 238-245). In his discussion of the restored pages of the *Codex Atlanticus* Pedretti mentions the pages with the cantering drawings and remarks that there are notes by da Vinci on the mechanics of the arches; however, he does not discuss them (Pedretti 1978/1979 vol. 1: 154 and 249, vol. 2: 38-39, 77, 105). Frommel (2019: 208-209) discusses the centerings in *Codex Atlanticus* f. 200a-r [537r] and notes that the centerings seem to follow geometric rather than static principles as the load of the vault under construction weighs heavier at the crown so that the construction could be simplified at the impost.

Centerings in general have been more in focus in recent times. Döring-Williams and this author have contributed to the topic of centerings in relation to 17th-century domes and barrel vaults of Sant'Andrea della Valle, Sant'Agnese in Agone and St Peter's in

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Rome (Döring-Williams/Schlimme 2011; Schlimme 2011). Holzer made contributions to 17th- and 18th-century centerings – and more importantly deals with centerings which do not stand on the floor of the building but only begin at the impost of the vault under construction (Holzer 2010; Holzer 2013: 137–139).

1.3 *Approach and aim*

A seminar on da Vinci taught by this author during the summer term 2019 at the Technische Universität Berlin aimed to contribute to a deeper understanding of da Vinci's centering drawings and of all the other building construction issues he addresses. The students who dealt with centerings were Alina Möhrer (*Codex Atlanticus*, f. 225r-a [609r]) and Chenzhi Gong and Mustafa Nejem (Ms. B, f. 67v). The latter proposed to study those drawing together with Ms. B, f. 19v, which shows a similar construction. Simon Lindner, Tobias Patzek and Gabriel Sigler dealt with *Codex Atlanticus*, f. 200a-r [537r]. This drawing is however not part of the present paper, which instead concentrates on the former three drawings. The paper is partly based on the students' work which is duly acknowledged.

Starting from da Vinci's drawings, we tried in the seminar to retrace the underlying lines of thought and design processes. To do this we used virtual and physical 3D models, simulations and digital tools. Da Vinci developed a deep interest and often profound knowledge in various fields, among many others arithmetic, geometry, structural mechanics and artisan workshop and building site practices. Taking centering into the focus, the paper examines the extent to which da Vinci's thought dwells on a knowledge transfer between these fields of expertise and to what extent it was firmly anchored in the building practice of his time.

2 DA VINCI'S CENTERINGS FROM MS. B

2.1 *Ms. B, 19v and the capriata*

Da Vinci links his drawing Ms. B, f. 19v (Figure 1) to the question *Perchè ragione questo arco è forte?* (Why is this arch robust?). In his long comment about the drawing (see Uccelli 1940a: 247) da Vinci first describes the large triangle *gch* as a robust form. Its stability relies on the fact that it is difficult to tear the wooden beam *gh* apart. Da Vinci thus understands the beam as a tie beam. Because of the tie beam the beams *gc* and *ch* will not drop. The same is true for the triangle *gfh*. Furthermore, the triangle *bdf* and the beam *am* [and also *em*] cannot drop unless the vertical beam *cm* is torn apart, which is thus also identified as a tie beam. At this point at the latest it becomes clear that the construction is supported only at the edges *g* and *h* and not supported in the middle. Da Vinci concludes that, with all these supporting elements which cannot drop, the arch *g a b c d e h* is robust. The stability of the arch is the aim of the construction. Therefore, the drawing most likely shows a centering.

The stability of a triangle and the vertical tie beam are the key characteristics of a *capriata* roof construction, which was common in da Vinci's Florence (Valleriani 2006). The *capriata* is made of two rafters which are put against each other and which produce the roof form (Figure 2). Without help, the rafters just would slide down, so they are linked at their bottom ends with a long horizontal tie beam so that the construction does not produce horizontal thrust at the abutments. As the tie beam can be long, it may break under its own weight. Therefore, a vertical hanging post is suspended from the ridge and the tie beam attached to the hanging column. Normally this is achieved with a wrought iron strap. Struts leading diagonally upwards from the base of the hanging post are also characteristic of the *capriata* (not shown in Figure 2).

It seems quite extraordinary that da Vinci introduces principles from the *capriata* construction to centerings. Centerings at St Peter's would probably have commonly looked like those in Figure 3, with no horizontal tie beam at impost line and without a hanging post. Da Vinci seems to refer to the *capriata* on different occasions. He makes a 3D geometrical pattern of *capriate* in order to create a pyramidal roof (Ms. B, f. 15r). He uses the principle of the hanging column as a supporting position for bridge constructions (Ms. B, f. 23r) and he transforms a simple beam into a *capriata*-like composite one, which, while having the same overall shape, does not bear the load through bending but as a truss (Ms. B, f. 30v). He even transforms the *capriata* in a beam-bending machine. Thus, the *capriata* is a sort of *idée fixe* for da Vinci and therefore it is not surprising that he introduces it into centering construction, too. More on the topic of the application

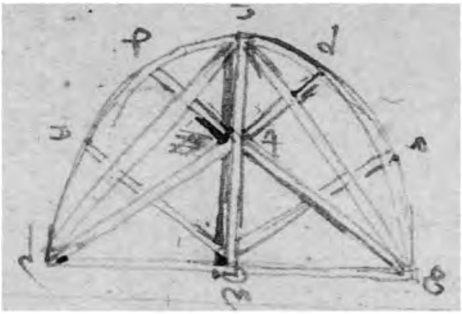

Figure 1. Leonardo da Vinci, stiffened arch probably for centering construction, Institut de France, Paris, Ms. B, f. 19v, detail (Photo © RMN-Grand Palais (Institut de France)).

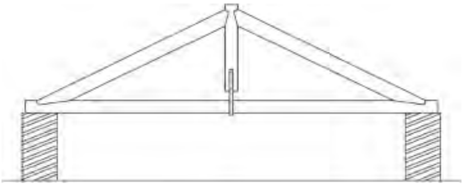

Figure 2. Schematic rendering of the *capriata* roof construction (drawing by Ho Kim).

of *capriate* in different contexts will be published in a forthcoming article by this author.

2.2 *Ms. B, f. 67v: beyond the capriata*

The *capriata* also seems to be the basis of the drawing Ms. B, f. 67v (Figure 4), which da Vinci himself calls a centering (*A[r]madura d'una volta*). One can see three *capriata*-like elements, each one with a vertical post, two inclined supports and a common horizontal tie beam (Figure 4 in black). While these elements have to be set up first, the other elements – except the further horizontal tie beam at half height – seem to be shorter and could have been thought to be placed in position one by one (hypothetical reconstruction in Figure 5).

In the end, a further arch is constituted, more pressed in relation to the upper arch, which accompanies the form of the vault under construction. In this case, da Vinci is thinking beyond the *capriata*. The proposed construction produces the form of the vault through a network of smaller elements which make up further loadbearing arches, but also a sort of stable network of short beams that distributes the vault's weight particularly well.

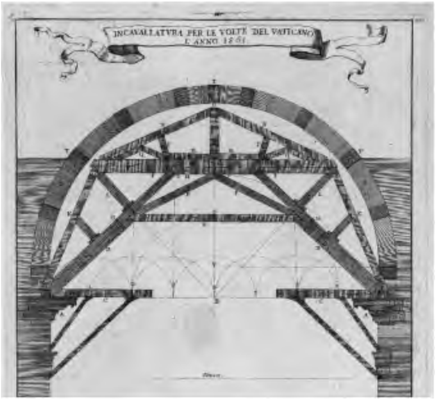

Figure 3. Centering for the barrel vaults in St Peter's in Rome, from Fontana 1694: 413 (© Bibliotheca Hertziana, Max Planck Institute for Art History, Rome).

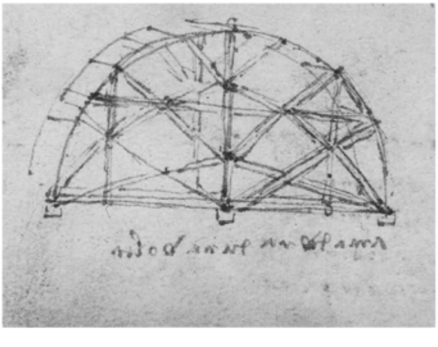

Figure 4. Leonardo da Vinci, centering and formwork, Institut de France, Paris, Ms. B, f. 67v, detail (Photo © RMN-Grand Pal-ais (Institut de France)).

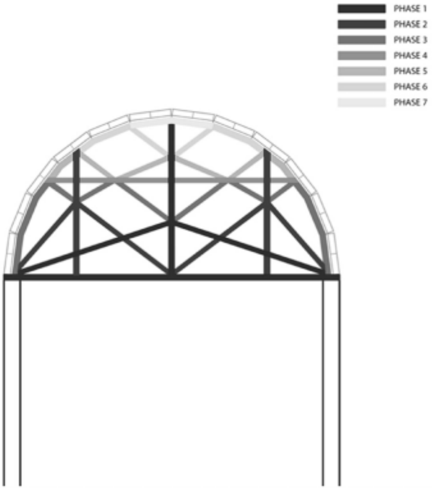

Figure 5. Hermann Schlimme, hypothetical reconstruction of Leonardo da Vinci's centering and formwork, Institut de France, Paris, Ms. B, f. 67v (drawing: Ho Kim).

3 CODEX ATLANTICUS F. 225R-A [609R]

3.1 *Centering and theory of the arch*

The centering drawings in *Codex Atlanticus*, f. 200a-r [537r] have a different character (Figure 6) to those in Ms. B. Those in the CA still show *capriata* elements but radial struts starting from the centre of the string of the bow dominate the construction. This centering construction based on radial struts or radius arms acquires a deeper meaning in the drawing *Codex Atlanticus*, f. 225r-a [609r], especially in the second centering drawing form the right in the upper row (Figure 7). There are still *capriata* elements even here, but da Vinci does not talk about them. The radial support arms are predominant. One of the students in the seminar, Alina Möhrer, chose the drawing *Codex Atlanticus*, f. 225r-a [609r], as her topic for the term paper and her choice proved to be hugely productive. Alina Möhrer will give an extensive account of her term paper in the catalogue publication of the exhibition *Léonard et l'architecture: Inventions, projets, techniques, au prisme de la modélisation* which is scheduled to take place at the Institut de France in Paris in April-June 2021. During supervision meetings, Alina Möhrer pointed out that da Vinci in his comment undertakes a theoretical discourse about arches and the present author and supervisor observed that the second centering drawing from the right in the upper row (Figure 7) is the only one which, beside the centering itself, also shows the arch divided in keystones on top of the centering. Thus, we both made the link between da Vinci's comment on f. 225r-a [609r] and what Kurrer (2003: 132–133) calls da Vinci's wedge-theory of the arch or better keystone theory of the arch, which is prominently visualized by da Vinci in the Madrid Manuscript I, f. 142v (redrawing in Figure 8).

3.2 *Da Vinci's keystone theory of the arch in Madrid Manuscript I, f. 142v*

The drawing Madrid Manuscript I, f. 142v had already been a topic in the classroom (Figure 8). Da Vinci's keystone theory has been analysed several times, e.g. by Mislin (1997: 277 and 280), who sees in it the beginnings of the decomposition of forces. The drawing describes the state of equilibrium of the keystones of a vault. Becchi (2004: 87-91 and 2017: 102-103) compares da Vinci's theory of the arch with later theories and differentiates it from the theories of Bernadino Baldi, for instance. Kurrer provides an extensive explanation: da Vinci starts from the arch as an addition of keystones, taking the construction process and the experience of the stonemason, who assembles the arch stone by stone, into account. Kurrer explains that da Vinci sees the arch/vault as a machine, which is composed of wedges (keystones), ropes and pulleys, with a kinematic understanding of statics based on the equilibrium of the five simple machines of Antiquity (lever, wedge, hoist, pulley, screw), which was founded by Aristotle (Kurrer 2003: 132–133). Through his friendship with the Milanese mathematician Luca Pacioli, da Vinci would have had knowledge of this.

Galluzzi confirms that da Vinci changed engineering because he linked theories with the practices of the building site. He further affirms: "Leonardo tries to achieve a complete geometrical analysis, concentrating on dynamic processes and the mechanical instruments with which to implement them. Leonardo applied this method to his architectural studies, where he introduced the laws of the 'elements of machines' (simple machines of antiquity) to quantify the lateral thrust of arches. He analysed buildings, their construction, ad their components as a 'machine' – not a static structure based on precise proportions but living organisms in dynamic equilibrium" (Galluzzi 1996/2001: 77–78).

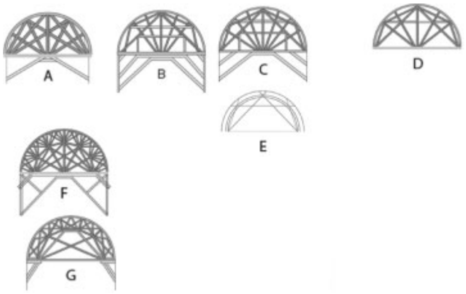

Figure 6. Simon Lindner, Tobias Patzek, Gabriel Sigler with amendments by Ho Kim, redrawing of the centerings of Leonardo da Vinci on Biblioteca Ambrosiana, Milan, *Codex Atlanticus*, f. 200a-r [537r].

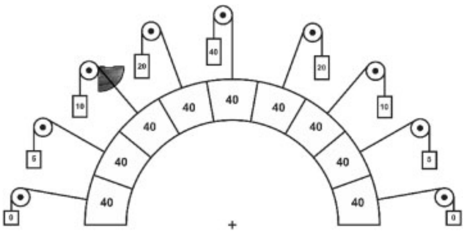

Figure 8. Leonardo da Vinci, keystone-theory of the arch, after Madrid Manuscript I, f. 142v (redrawing: Ho Kim).

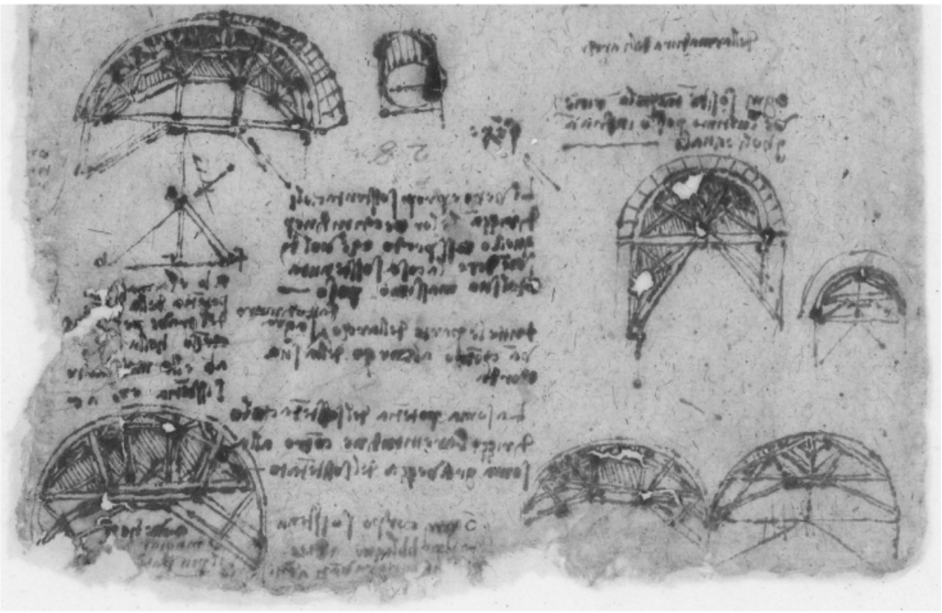

Figure 7. Leonardo da Vinci, centering constructions, Biblioteca Ambrosiana, Milan, *Codex Atlanticus*, f. 225r-a [609r], detail (© akg-images / Mondadori Portfolio / Veneranda Biblioteca Ambrosiana/Metis e Mida Informatica).

In his drawing (Figure 8) da Vinci divides the arch ideally into single keystones of the same size. In an ideal frictionless world, as long as the arch is still under construction each keystone slips down along the joint with the neighbouring keystone and falls down. In order to prevent this and to counteract the weight of the keystone, a counterweight is necessary which is applied through a rope conducted through a pulley. While the counterweight for the keystone at the ridge of the arch is as heavy as the key stone itself (“40”), the counterweight becomes lighter the more the keystone is positioned towards the impost of the arch. Da Vinci writes the numbers and that the keystone at the impost does not need any counterweight. Da Vinci signs “0” in his sketch (Figure 8).

3.3 *Italian transcription paragraph by paragraph by Augusto Marinoni*

In *Codex Atlanticus*, f. 225r-a [609r] (Figure 7) da Vinci gives a long comment, where the parallel between the keystone theory of the arch and the centering construction based on radial supporting arms becomes clear. The comment runs into three columns. This author refers to the diplomatic and critical transcription of Marinoni (1978: 223-224). In the following, Marinoni’s critical transcription is reproduced. The comments in brackets are Marinoni’s:

Figura con: a – b

a val *b*

Dell’armadura delli archi.

Ogni sostentaculo riceve l’ultiomo peso infra angoli equali.

Sempre …

Li veri e propi sostentacoli dirizzan la lor rettitudine per quello aspetto che vol discendere la cosa sostenuta col suo massimo peso. [explaining comment by Marinoni in an endnote on p. 224: È disposto colla sua lunghezza volta nella direzione lungo la quale si scarica il massimo peso].

Tutte le parte dell’arco fatto di muro s’aggravan contro al mezzo della sua corda.

La somma potenzia del sostentaculo dirizza la rettitudine contro alla somma gravezza del sostentato.

Ogni corpo sostenuto per obbliquo ha due …avanti a due …

Margine sinistro:

O …ti …r …

Figura di trave sostenuto, con: a – b c f

ab è la massima potenzia della fronte del trave nel suo discenso, e la linia *ab* è la massima resistenza e non *ac*.

Entro la figura:

Dov’è il maggior peso …il più potente sostentaculo.

3.4 *English translation paragraph by paragraph*

The translation into English including Marinoni’s comments in brackets was prepared by the author:

Figure with: a – b

a corresponds to *b*

About the centerings for arches.

Each support arm receives its definite load within equal angles.

Always:

The actual support arms use their straightness for the share that wants to lower the supported part, with its greatest weight. [explanatory comment by Marinoni in an endnote on p. 224: It is arranged with its length turned in the direction along which the maximum weight is discharged].

All parts of the arch made of masonry strain the middle of its tendon.

The excellent performance of the support arm directs its straightness against the great heaviness of the supported load

Every obliquely supported body has two ... in front of two

Left margin:

O …ti …r …[this line seems to have no connection to the discourse]

Figure of supported beam, with: a – b c f

a b is the maximum performance of the front of the beam in its descending and the line a b is the maximum resistance and not a c.

Within the figure:

Where the heavier load is, there …[shall be] the strongest support arm.

3.5 *Analysis*

The analysis of da Vinci’s short text was developed by Alina Möhrer and this author in supervision meetings. The text has the title “About the centerings for arches” and is evidently referring to the second centering drawing form the right in the upper row, which shows the arch divided in keystones on top of the centering (Figure 7). The text then goes on saying that “each support arm receives its definite load within equal angles”. This means that each radial arm supports an equally large piece of the arch, which is virtually divided into equal keystones, each one ideally held by a support arm; thus, supported and supporting structure are idealised geometrically. Then the text goes on with an “Always” and now da Vinci gets specific and says that “the actual support arms use their straightness for the share [of weight] that wants to lower the supported part, with its greatest weight”. Therefore, each radial support arm here takes a part of the weight of the keystones and exactly that obliquely active part of the weight which makes each keystone slip down along the joint with the neighbouring keystone. This is exactly the part of the weight of the keystone, which is held up by a rope and by the counterweight in the keystone theory of the arch (Figure 8).

Thus, with the centering da Vinci substitutes the counterweights with radial support arms. Da Vinci continues and says that “all parts of the arch made of masonry strain the middle of its tendon”, which means that through the radially arranged supporting arms the load is concentrated in the middle of the bottom/impost line of the arch. Da Vinci continues by repeating that “the excellent performance of the support arm directs its straightness against the great heaviness of the supported load" and says that "every obliquely supported body has two ... in front of two". This sentence is incomplete due to legibility issues, but confirms that da Vinci is talking about inclined supporting arms; about their supporting performance he makes a short remark, which we may call an *excursus*, saying that "a b is the maximum performance of the front of the beam in its descending and the line a b is the maximum resistance and not a c". This means that in this context the loadbearing capacity of the beam is best when it is inclined and not when it is disposed vertically, thus da Vinci affirms that axial loads are best – hence the radial disposition of the support arms. Da Vinci finally says that "where the heavier load is, there …[shall be] the strongest support arm". This strongly links back to the keystone theory of the arch, where the counterweights range from the maximum "40" at the crown of the arch to "0" at the impost. In the centering, too, the support arms are stronger when the weight is bigger. Da Vinci explains his keystone theory of the arch through the principles of the construction of centerings for barrel vaults. He replaces the counterweights holding up the single keystones through pulleys by the radial support arms. Here he links building site practice he could observe especially Rome, to theoretical approaches.

Do we have cross fertilization here? Most likely the answer is yes. On the one hand, da Vinci uses centering constructions to explain his keystone theory of the arch in an alternative way, which is better linked to the building site context. The other way round, the keystone theory of the arch animates and encourages him to propose an alternative type of the usual centering for barrel vaults (Figure 3). Da Vinci's alternative type with the radial support arms has to start much below the impost of the arch and is therefore uneconomical. Evidently, da Vinci is aware of this and proposes on the same f. 225r-a [609r] an alternative centering where the radial beams are shortened with a lifted horizontal beam (Figure 8, bottom left).

4 CONCLUSIONS

When da Vinci was engaged with building construction he documented and dwelt on craftsman knowledge of his time and transferred this knowledge – for instance, on principles and characteristics of the *capriata* – to very different fields. One of these is the centerings of vaults. Da Vinci's further uses of the *capriata* will be the subject of a forthcoming paper by this author. When da Vinci deals with centerings for vaults, he is concerned with a topic which is not just linked to the building site, but which is an integral part of it. As we have seen, da Vinci links the world of the building site to his keystone theory of the arch and explains the latter through the centering. On the other hand, he proposes an alternative centering construction. The connection between da Vinci's theoretical discourses in structural mechanics and building site practice has already been pointed out several times in the literature. The present paper has attempted to make a further contribution in this direction.

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The brick vaults of the Alfonsina Tower in Lorca Castle. Geometric aspects and possible sources

P. Natividad-Vivó, R. García-Baño, M. Salcedo-Galera & J. Calvo-López
Universidad Politécnica de Cartagena, Cartagena, Spain

ABSTRACT: This paper deals with an ensemble of brick vaults in the Alfonsina Tower built in Lorca Castle between the middle of the 13th and the beginning of the 15th centuries. These vaults are built using a system of brick slices arranged according to two different patterns or bonds, rhomboid and rectangular. The study analyses the geometry and constructive organization of the vaults and connects them to other similar ones which belong to Eastern and Byzantine architecture.

1 ON THE ALFONSINA TOWER

The construction of the keep of Lorca castle, known as Alfonsina Tower, was begun after Prince Alfonso, later King Alfonso X, conquered the city in 1244. It is in the central and highest part of the castle, and at that time it was a main point in the defensive line of the Murcia kingdom, held by the Castilians, against the Islamic kingdom of Granada.

The tower has a rectangular plan that measures approximately 22.4×19.6 meters and is almost 30 meters high. The perimeter walls, about four meters wide, are built in rubble masonry and reinforced with ashlar at the corners (Figure 1). The tower has three floors: the first two are lit by loopholes, while the third has four larger windows, one on each front (Figure 2). The only gate is located on the east façade and allows entry to the first floor. Next to this access we find the start of a staircase embedded in the perimeter walls that leads to the upper floors. Inside the tower is a large solid central nucleus with a rectangular plan measuring approximately 6.00×3.25 meters, which vertically crosses the building. It was built with large-gauge rubble masonry and has chamfered corners made with ashlar.

On each floor there are eight pointed arches resting on stone corbels embedded in the perimeter walls and in the nucleus. These arches are built with brick and divide the space of each floor into eight sections covered with vaults (Figure 3). All the vaults are executed with slices of brick that present two different orientations. On the one hand, there are some slices oriented according to the diagonals of the plan setting a constructive arrangement that we could call rhomboid bond. On the other hand, there are other slices parallel to the sides of the plan and that, by analogy to the previous arrangement, we could call rectangular bond. In addition to these vaults, there are others similar, although smaller, in the access of the tower and along the staircase.


Figure 1. Alfonsina Tower. Photography by P. Natividad Vivó.

Several hypotheses have been posed about the beginning and end of the construction of Alfonsina Tower. The first and probably best known is the theory of Espín Rael (1925) which is based on three documentary pieces of evidence. The first mentioned by this author appears in a document from the third division of Lorca, dated 1272, in which a stonemason named Domingo Aparicio is cited as the “master of the tower”. The second is included in *Anales de Aragón* by Jerónimo Zúrita, dating from 1300, where the Alfonsina Tower in Lorca Castle is mentioned. And the third bit of information appears in a royal provision by Juan II in 1412, which states that Pedro Yuste de Monzón is to receive a salary of two thousand maravedíes for “building and carving the castle and the Alfonsí Tower”. Espín Rael points out, starting from the first two documents, that the tower construction began in the second half of the 13th century and finished by the

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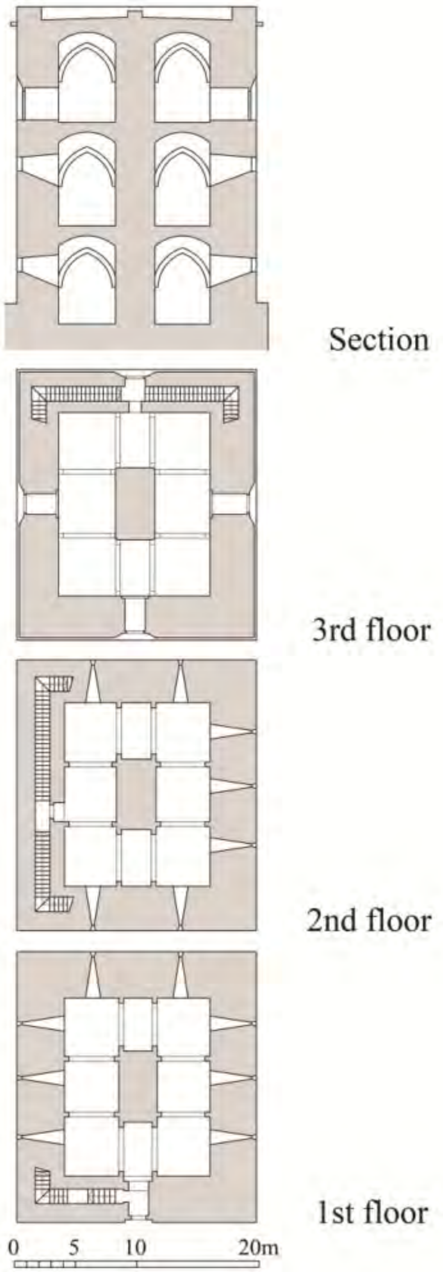


Figure 2. Section and floors of the Alfonsina Tower, based on the plans by M.J. Rodríguez Pérez, coordinating architect of Turespaña – Instituto de Turismo de España.

end of the century. Regarding the works of the 15th century mentioned in the third notice, Espín Rael considers that it refers to refurbishing works, specifically a thickening of the perimeter walls to adapt them to the new artillery systems that were spreading at this time.

Figure 3. Arches and vaults on the third floor of the Alfonsina Tower. Photography by J. Calvo López.

A second hypothesis has been suggested by Martínez Rodríguez (2003, 114–5). This author points out that the works on the Alfonsina Tower were paralyzed in 1300, when the city of Lorca was conquered by Jaime II of Aragón. However, at that time the tower would be practically finished, given that no sudden change is seen in its design; on the contrary, there is a remarkable formal and constructive continuity. Martínez Rodríguez thinks that the intervention of Pedro Yuste de Monzón at the beginning of the 15th century would have been to complete the tower top.

The third and last hypothesis to which we will refer is the one formulated by Muñoz Clares (2003, 13-23). He agrees with the previous two authors in that the Alfonsina Tower construction began in the second half of the 13th century. However, he posits that construction lasted throughout the 14th century, considering that the works must have been very expensive and were carried out at the same time as other defensive works in the castle and in the city. Muñoz Clares points out that Espín Rael's theory is not compatible with the location of the staircase embedded in the tower walls. He also supports the fact that the walls have a continuous and homogeneous appearance because all their stones were probably extracted from the same quarry, which is inside the castle itself (Pujante Martínez *et al.* 2009). In his opinion, the overall design of the tower was chosen in the second half of the 13th century and was closely followed until its completion in the early 15th century. However, some constructive and decorative variations that would not affect the general structure were incorporated during construction. These would include the change from the loopholes on the first and second floors to the larger windows on the third, or the change from the vaults with rhomboid bond on the first floor to the vaults with rhomboid and rectangular bonds on the second and third floors.

2 PHOTOGRAMMETRIC SURVEY

The main goal of this paper is to advance knowledge of the geometry and constructive organization of the brick vaults of the Alfonsina Tower. With this aim, we have carried out a rigorous photogrammetric survey of the vaults.

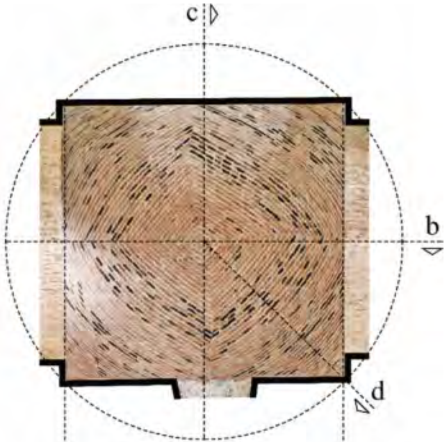
We took photographs in JPG format covering the entire intrados surface of the vaults. A Canon EOS 550D camera was used for the vaults of the first and second floors and a Nikon D5000 for the vaults of the third. In all cases, we provided a minimum overlap between images of 60%. After, we processed the photographs using Agisoft Metashape, an automated photogrammetry software. The workflow with this software was developed in the following two phases. Firstly, the photographs were aligned by detecting the tie points and estimating the camera locations, and then the dense point clouds were generated with millions of coloured points that precisely define the shape of the intrados surface of the vaults. Finally, the point clouds were exported in E57 format and loaded in Rhinoceros 3D, a three-dimensional modelling software. The final plans were drawn with this software. In particular, the point clouds were processed using a script programmed in Python by P. Natividad Vivó and were projected orthogonally to create the orthophotos with textures of the materials that we can see in the final plans.

The plans of four vaults are shown in this paper. One of the first floor with rhomboid bond (Figure 4), another of the second floor with rectangular bond (Figure 5) and two more of the third floor with rectangular and rhomboid bonds (Figures 6, 7). From here on we will identify these vaults with the references V1, V2, V3 and V4 respectively.

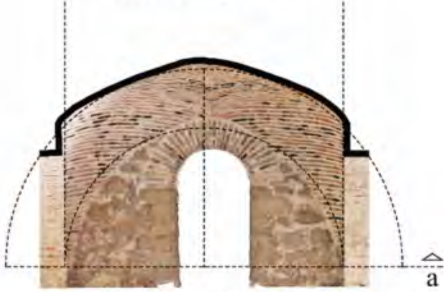
3 GEOMETRY OF THE VAULTS

There are several authors who have put forward their opinions on the geometry of the brick vaults of the Alfonsina Tower. For example, González Simancas (1905–07, 2: 347–51), in his manuscript (not published until 1997) "*Catálogo Monumental de España. Provincia de Murcia*", refers to these vaults as pavilion or cloister vaults, but he does not give more details. Martínez Rodríguez (2003, 102–4) and Muñoz Clares (2003, 19) also define them as pavilion vaults. Furthermore, they explain that the vaults with rhomboid bond are pavilion vaults formed by the intersection of two semi-cylinders with axes arranged along the diagonals of the plan (Figure 8a) and those with rectangular bond are conventional pavilion vaults formed by the intersection of two semi-cylinders with axes arranged parallel to the sides of the plan (Figure 8b). On the contrary, other authors such as Torres Balbás (1949, 344) and Pavón Maldonado (2010, 17) consider they are sail vaults (Figure 8c).

Before starting the geometric study, we should comment on the definition and scope of sail vaults. Sail



(a) Ceiling plan



(b) Vertical section


(c) Vertical section

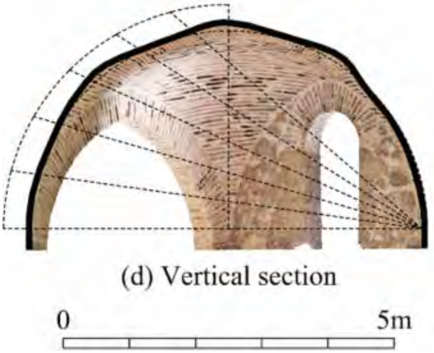
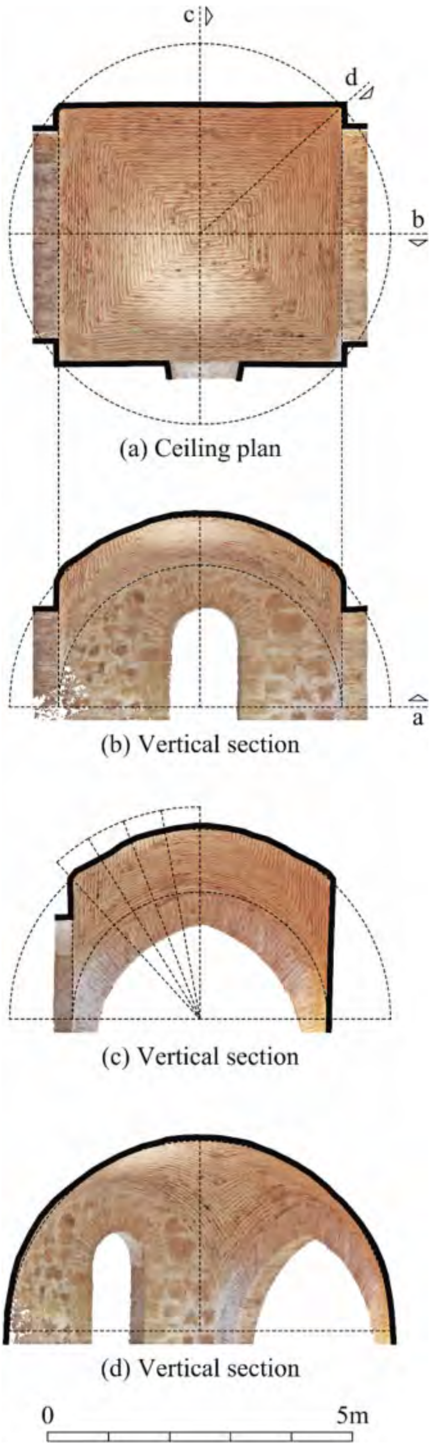

(d) Vertical section

Figure 4. Plans of the vault V1 with rhomboid bond on the first floor. Image by the authors.



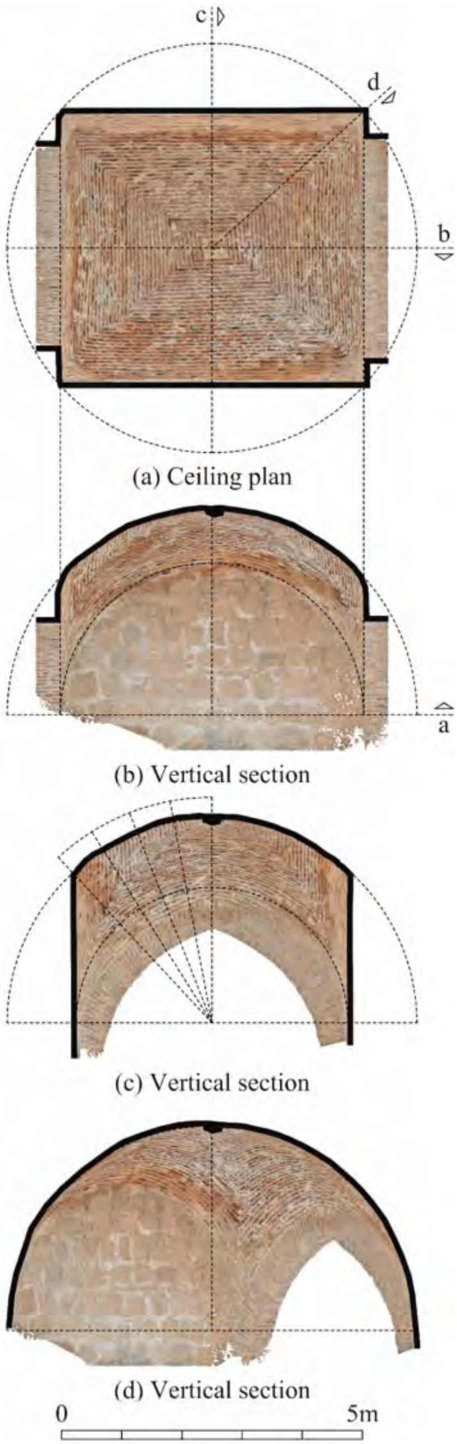
(a) Ceiling plan

(b) Vertical section

(c) Vertical section

(d) Vertical section

Figure 5. Plans of the vault V2 with rectangular bond on the second floor. Image by the authors.



(a) Ceiling plan

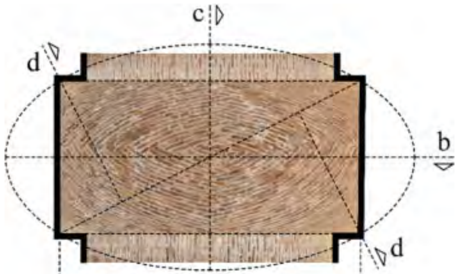
(b) Vertical section

(c) Vertical section

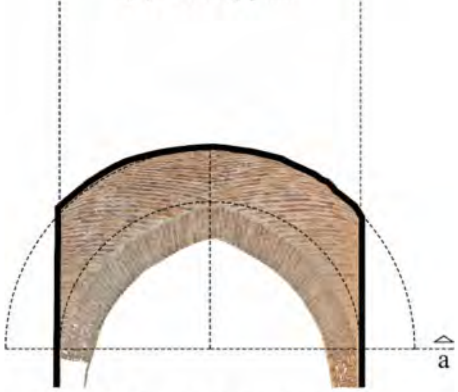
(d) Vertical section

Figure 6. Plans of the vault V3 with rectangular bond on the third floor. Image by the authors.

vaults traditionally have been defined as vaults which are obtained by cutting a hemisphere into four vertical planes, which results in a segmental dome resting on four spherical triangles called pendentives (Figure 8c). However, recent studies show that this definition is excessively rigid and ignores a wide range of formal

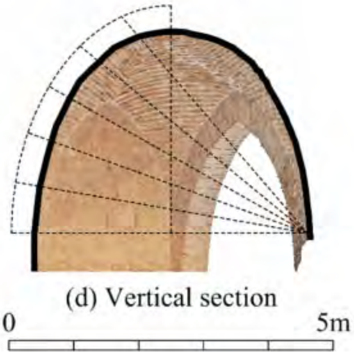


(a) Ceiling plan



(b) Vertical section

(c) Vertical section



(d) Vertical section

Figure 7. Plans of the vault V4 with rhomboid bond on the third floor. Image by the authors.

variants that appear when the standard sail vault modifies its plan or deforms its intrados surface adjusting to different contour conditions (López Mozo 2009, 317-50; Senent Domínguez 2016, 303-22; Natividad Vivó 2017, 1: 321-2). We also agree that the concept of sail vault should be wider, and thus we define it as the vault that covers a polygonal plan with a spherical or approximately spherical intrados surface.

We start by analyzing the geometry of vault V1 (Figure 4). This vault covers an almost square plan and has an irregular curved intrados surface with some bulges in its upper part. First, we compared vault V1 with a pavilion vault formed by the intersection of two semi-cylinders with axes arranged according to the diagonals of the plan and verified that there are significant deviations between the two. These deviations are mainly caused because the intrados surface of vault V1 is curved in all directions, while the pavilion vault is made up of half cylinders whose generatrixes are straight lines. Second, we compared vault V1 with a hemisphere (drawn in the plans with dashed lines) whose center is at the same height as the springers of the pendentives. We verified that both are quite close, although there are some deviations, especially in the bulges and the edges of the pendentives next to the pointed arches. However, the intrados surface of vault V1 is close enough to the spherical shape to be considered a sail vault.

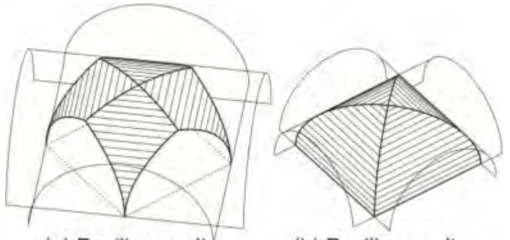
Vault V2 covers a rectangular plan and its intrados surface is close to a hemisphere whose center is located at the same height as the springers of the pendentives (Figure 5). There are areas of the intrados surface that deviate a little from the hemisphere, particularly the edges of the pendentives that are in contact with the pointed arches. However, the intrados surface of vault V2 is close enough to the spherical shape to be considered a sail vault. We analyzed vault V3 in the same way and reached the same conclusion: it is a sail vault (Figure 6).

Finally, we studied the special geometry of vault V4 (Figure 7). This vault covers a rectangular plan and has an intrados surface quite close to a semi ellipsoid whose center is located at the same height as the springers of the pendentives. A half ellipsoid is a surface like the hemisphere but whose planar sections are not semi-circular arches but semi elliptical ones. As in the previous cases, the intrados surface of this vault has some deviations, especially in the pendentives. Having said that, the deviation of its intrados surface from the semi ellipsoid is so small that it allows us to affirm that vault V4 is a formal variant of a sail vault.

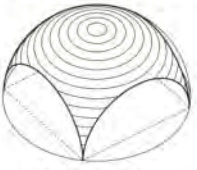
To summarize, the photogrammetric surveys carried out reveal that the intrados surface of vaults V1, V2 and V3 are close enough to the spherical shape to be considered sail vaults. Similarly, vault V4 is a formal variant of a sail vault in which the intrados surface is deformed until it acquires an ellipsoidal geometry.

4 CONSTRUCTION FEATURES

As previously mentioned, all the vaults of the Alfonsina Tower were built with brick slices according to two different configurations that we called rhomboid and



(a) Pavilion vault (b) Pavilion vault



(c) Sail vault

Figure 8. (a) Pavilion vault formed by intersection of two semi-cylinders with axes arranged along the diagonals of the plan. (b) Pavilion vault formed by intersection of two semi-cylinders with axes arranged parallel to the sides of the plan. (c) Sail vault formed by cutting a hemisphere by four vertical planes. Image by the authors.

rectangular bonds. The construction of brick vaults by slices is an alternative system to brick tile vaults, which places bricks aligned with vault surface. By contrast, in brick vaults by slices, bricks are arranged with their larger face vertical or slightly inclined, so that each new course forms a slice that rests on the anterior. The first slice must rest on a wall or an arch, while the following are progressively adhered to the preceding one by means of the mortar applied to their larger faces. It is an old Oriental construction system which presents the advantage of requiring little or no formwork (Choisy, 1876; 1883, 31-47; Van Beek, 1987; Sánchez Leal 2000; Almagro 2001, 152-4; Arce 2006, 201-5; Huerta 2009; Rabasa Díaz *et al.* 2020).

First, we consider vault V1 with rhomboid bond. If we look at the ceiling plan in Figure 4a, we see that the intrados surface is composed of four groups of slices oriented according to the diagonals of the plan. Combining the four groups, we can appreciate concentric rhomboid figures, which are precisely those that give their name to the bond. If we then observe the vertical section perpendicular to one diagonal of the plan in Figure 4d (detail in Figure 9), we see that the group of slices on the left seems to be defined by a fan of planes whose axis (seen as a point) is perpendicular to the diagonal and goes through the springer of the right pendentive. The group of slices on the right seems to be defined by a fan of planes as well, but in this case the axis goes through the springer of the left pendentive. If we check the vertical section perpendicular to the other diagonal of the plan, we can see that the other two groups of slices seem to be oriented in the same way. We repeated this analysis with vault V4 (Figures 7a, d) and we obtained the same conclusions. Therefore, our hypothesis is that vaults V1 and V4 with rhomboid bond were built by means of four groups of planar brick slices defined by fans of planes whose axes are perpendicular to the diagonals of the plan and pass through the springers of the opposite pendentives.

Figure 10a shows a drawing of our hypothesis on the rhomboid bond applied in a standard sail vault. In this vault, the construction would begin with the four pendentives, which would be built by brick slices following their corresponding orientation. Once the pendentives were completed, execution would continue with the upper slices of each group, which would match each other creating the rhomboid figures. The orientation of each group of slices would be controlled with a lath or rope with one end fixed at the springer of the opposite pendentive. Consequently, four laths or ropes would be necessary to control the whole construction.

Some authors have studied vaults with a similar constructive organization to that seen in vaults V1 and V4. Choisy (1876; 1883, 102-3), in his publications on Byzantine architecture, shows sail vaults built by brick slices with a rhomboid bond very similar to that of vaults V1 and V4. Although both bonds look the same, there is a significant difference: Choisy's vaults have conical trunk slices, while vaults V1 and V4 have planar slices. Similar others are the European sail vaults studied by Wendland (2007), which also have a rhomboid bond made of brick slices. However, these vaults present planar parallel slices and vaults V1 and V4 have, according to our hypothesis, planar radial slices. More vaults with similar constructive features, built in ashlar rather than brick, are the Armenian pendentives analyzed by López Mozo *et al.* (2013), whose courses have bed joints defined by convergent planes in some cases and parallel in others.

Next, we analyze vault V2 with rectangular bond. If we observe the ceiling plan in Figure 5a, we see that its intrados surface is composed of four groups of slices parallel to the sides of the plan. By combining the four groups, concentric rectangular figures appear, giving its name to this bond. If we then observe the vertical section perpendicular to one side of the plan in Figure 5c, we see that the slices on the left are shown as vertical lines on the intrados surface. Having said that, since the visible faces of the bricks are adjusted to the curvature of the intrados surface, our hypothesis is that the slices are defined by cones with axes perpendicular to the side of the plan whose vertexes are in the center of the hemispherical intrados surface. The group of slices on the right would also be defined by similar cones. If we observe the vertical section perpendicular to the other side of the plan in Figure 5b, we notice that the other two groups of slices would be oriented in the same way. We repeat this analysis with vault V3 (Figures 6a, c, b) and obtain the same conclusions. Therefore, our hypothesis is that vaults V2 and V3 with rectangular bond are built using brick slices defined by cone trunks whose axes are perpendicular to the sides of the plan and whose vertexes are located at the center of the intrados sphere of the vault.

Figure 10b shows a drawing of our hypothesis on the rectangular bond applied in a standard sail vault.

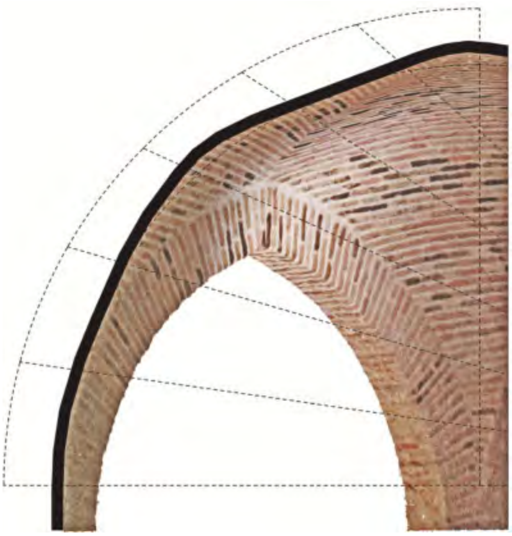


Figure 9. Detail of vault V1 from Figure 4d: group of brick slices defined by a fan of planes. Image by the authors.

In this vault, construction would begin with the slices attached to the walls and the pointed arches. The first slices would be placed with their corresponding orientation and the rest placed progressively over them. As the work developed, the slices of the different groups would match each other creating the rectangular figures of the bond. The orientation of the four groups of slices would be controlled with a single lath or rope fixed in the center of the vault.

In his publications, Choisy (1876; 1883, 100–1) included several sail vaults built by conical trunk brick slices with the same rectangular bond that we appreciate in vaults V2 and V3. In addition, we must point out that this arrangement is not exclusive of brick construction by slices, but also appears in a multitude of ashlar sail vaults (Natividad Vivó 2017, 1: 207–13).

5 POSSIBLE ORIENTAL INFLUENCES

For a long time, different authors observed Oriental influences in the Alfonsina Tower. For example, González Simancas (1905-7, 2: 347-51) thought that the masons and workers of the tower were *mudéjares*, that is, Muslims living among Christians, and remarks that the walls, the brick vaults, and the corbels of the arches were reminiscent of Arab architecture. Martínez Rodríguez (2003, 110-2) agrees with González Simancas and raises an interesting hypothesis about the Oriental origin of the central nucleus of the tower. According to this author, this unique element does not appear in any nearby building except the keep of the Concepción Castle in Cartagena, but can be seen in some Syrian fortifications such as the castles of Qal'at Nadjem or Saône. Martínez Rodríguez's hypothesis posits that the Alfonsina Tower and the one built in Cartagena were designed by the same master mason, who arrived at the port of Cartagena from the Middle East. This mason, with experience in building castles for the Crusaders, would have come looking for work in a new border territory between the kingdoms of Castile and Granada. Torres Balbás (1949, 344) observes influences of Islamic military architecture in the Alfonsina Tower and Pavón Maldonado (2010, 17) directly includes the brick vaults in an inventory of West Arab architecture, pointing out that their masonry system could be related to Byzantine and even Iranian vaults.

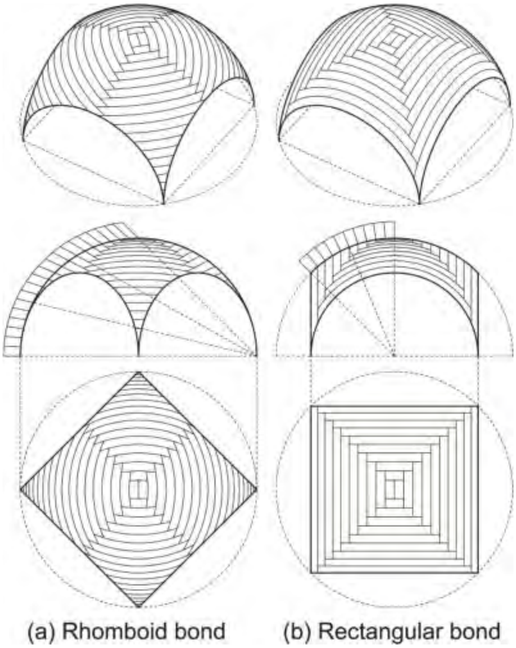


Figure 10. (a) Standard sail vault with rhomboid bond. (b) Standard sail vault with rectangular bond. Image by the authors.

We also notice Oriental influences in the vaults of the Alfonsina Tower. Not only at a formal level, but mainly at the constructive level. From a formal point of view, the photogrammetric surveys show us that the studied vaults are sail vaults, a type of vaulting widely used in Oriental architecture. From a constructive point of view, we verify that the vaults are executed with brick slices, an ancient constructive system of Oriental origin that allows construction with little or no formwork. Likewise, we find that the settings of the rhomboid and rectangular bonds have similar precedents in Byzantine sail vaults. All these aspects point to vaults related to Oriental and Byzantine architecture whose influences perhaps reached southern Spain through North Africa.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The art of building in New Spain: Knowledge dissemination and religious orders in the 16th century

R.A. Musiate & M. Forni
Politecnico di Milano, Milan, Italy

ABSTRACT: Some 16th century religious buildings provide evidence of the influence of European treatises on architecture in the New World. Many early Dominican monasteries in the central-southern regions of modern-day Mexico are part of the remarkable repertoire of this phenomenon. This paper provides in-depth analysis of the dissemination mechanisms of treatises on architecture in the ecclesiastical realm.

1 INTRODUCTION

1.1 *Architecture and printing*

The built heritage presents vast interactions of knowledge and know-how. In order to interpret it and learn more about it, we need to build a reliable set of hypotheses based on direct and indirect sources. The 16th century witnessed the exponential spread of technical literature as a result of developments in the printing process. Many titles on architecture and the art of building were published and broadly disseminated. Many titles were soon also exported to New Spain, the Spanish American territories that had recently been annexed by the Spanish Empire. Accordingly, we find many examples of early religious architecture in New Spain influenced by the treatises, such as Dominican architecture in territories where this order was actively spreading (the current Mexican States of Mexico, Morelos, Puebla and, in particular, Oaxaca). In this context, we see particular ways of dealing with the reproduction of typical forms of classical language (Figure 1). Many of these buildings serve as indirect evidence of these adaptations/adjustments to both local technical tradition and local building organization.

The technical literature as a whole is often considered among the references of these buildings, while its actual interaction and diffusion are rarely documented. It is important to investigate the selection of authors and treatises, the period of time and the areas in which they spread, the means of their circulation, and how they were used. The interaction of this technical literature with the cultures it reached can be seen through different types of mediation and interpolation, which indicate both the passive and active presence of this technical tradition. These aspects interact uniquely in the framework of this case study. In the highly complex cultural programme of Dominican preaching in the territories of New Spain, functional and symbolic spaces were configured by adopting formal references to classical models. These were transferred through the shapes and geometries that regulate technical procedures applied to a construction site which, in this case, was both traditional and extra-cultural.

1.2 *Books and education within the order of preachers*

The Order of Preachers has stood apart for its erudition and scholastic organization since the Middle Ages, which is why the library has always played an important role in the Order's operational scheme. The prelates had to equip Dominican monasteries (*conventos*) and study centres with as many books as the friars needed to be at the forefront of intellectual life. The largest number of books were undoubtedly those intended to provide religious and scientific knowledge; however, there was no lack of books on the mechanical arts, as we shall see.

Humbert of Romans (1200–1277) dedicated a chapter of his *Opera de vita regulari* to the profession of the *librariu* (librarian), whose expertise was measured not only by the efficient organization of Dominican libraries but also by their ability to expand the collections based on usefulness for the Order. The duties in a Dominican monastery were certainly not limited to the religious sphere. Indeed, the operational duties mentioned by Romans include the building superintendent.

It could, therefore, be expected that the order's obsession with collecting books would also extend to architecture, especially in a historical and territorial context where the construction of new monasteries was so essential.

The aim of this work is to outline the extent of architecture books within Dominican libraries in the 16th century and to ascertain if they were actually available to friars before and during the construction of monasteries in New Spain. The 16th century was a period of

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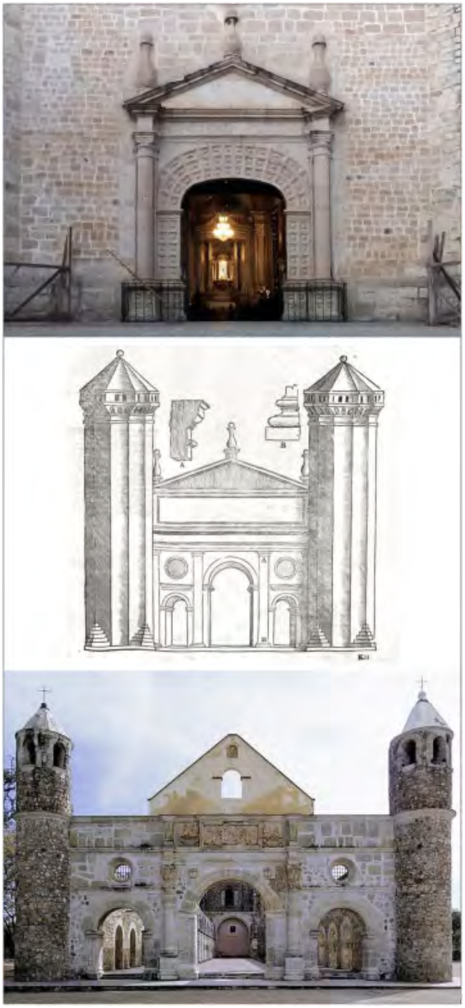

Figure 1. From top to bottom. Main doorway of the Dominican Monastery in Tlaxiaco (1550s). Prison of Orlando (Serlio 1540, LXXI). Three-aisled church façade at St. James the Greater's Dominican Monastery in Cuilapan (ca. 1555–9).

interesting experimentation and adaptation in a territory with conditions that at times differed considerably from the situation in Europe.

2 THE CIRCULATION OF BOOKS AND TREATISES ON ARCHITECTURE

2.1 *Methodological premise*

An exhaustive study of the diffusion of books in the ecclesiastical sphere has not yet been conducted for this territorial context. The available literature is disconnected and fragmentary.

The state of the art of importation of European books could be partially reconstructed through official documents stored in the *Archivo de Indias* in Seville. The *registros de ida* (outbound registers) contain the names of passengers travelling overseas along with a list of their goods. The records also present lists of goods shipments, some of which even contain book titles (post-1586). However, the loss of the pre-1586 registers (Kropfinger-von Kügelgen 1973, 6) means there is a lack of information about groups of travelling missionaries in the first half of that century, consequently preventing any direct tracing of the books they carried.

The study of book circulation in the ecclesiastical sphere requires more diversified historical sources, as we shall see. Monastery libraries and archives in both Spain and Mexico were partly dispersed following secularization laws introduced in the two countries in the latter half of the 19th century. For example, only a small part of the Library of Saint Dominic's Imperial Monastery in Mexico City, about 6,500 specimens, reached the National Library of Mexico in 1861 (Arroyo 1987, 61).

2.2 *Book exportation and commercial circulation*

The above-mentioned registers show the exportation of books relating to mathematics, geometry and architecture among other miscellaneous topics. This is correlated with the extensive spread of architectural treatises in 16th century Spain. In fact, the exports also included some Spanish editions of treatises, such as the Vitruvius works by Diego de Sagredo (1526) and Miguel de Urrea (1582), while Serlio's third and fourth books were edited three times by Francisco de Villalpando (1552, 1563, 1573), highlighting its particular success (Bustamante-Marías 2004, 245).

Many books that had recently been published reached New Spain in 1586. The documents mention three editions of Serlio, one of his fifth book (1566), a Latin translation of the first five books by Giovanni Carlo Saraceno (1569) and, finally, the famous Spanish translation by Francisco de Villalpando (1573, 3rd edition). There is also evidence of a Vitruvius Spanish edition by Miguel de Urrea (1582), as well as a Latin translation edited by Daniele Barbaro (1567). Leon Battista Alberti's treatise was recorded twice, one of which, we can guess from the Spanish title, was Francisco Lozano's edition (1582) (Torre 1940, 241). Vignola's treatise (1562) is found in many later expeditions, even in groups of ten, and, lastly, Juan de Arfe y Villafañe's treatise (1585) is reported in a register dated 1591 (Torre 1956, 5–6).

Commercial networks also helped to enhance the spread of the treatises. The document *Memoria de 40 caxas de libros* ... (Note concerning 40 boxes of books ...), dated 1584, lists the titles in a shipment addressed to the bookseller Diego Navarro Maldonado of Mexico City by the Spanish bookseller Benito Boyer (González 1914, 263–281). This long list records two copies of Euclidean geometry, one of which was the Castilian translation by Zamorano (1576), four of Alberti's treatise, four of Vitruvius' treatise, and two of Serlio's.

2.3 *Circulation in monastery libraries*

The creation of monastery libraries was a priority shared by all the mendicant orders after their arrival in the New World, especially in monasteries and centres of religious and secular education. The first monastery library in the New World (1540) was founded by the erudite Augustinian Friar Alonso de la Vera Cruz. In 1573, Vera Cruz also brought 60 boxes of books from Spain to establish Saint Paul's College Library in Mexico City. The presence of architecture books in this shipment cannot be ruled out (McAndrew 1965, 107).

Libraries have always played an essential role in the structure of the Dominican Order. Since the Middle Ages, the Order considered studying a vital activity, the point of convergence between preaching and the salvation of souls. Books were considered real weapons in the hands of Preachers, without which no friar could successfully carry out his duties (Cinelli 2016, 279). This view had not changed at all in the 16th century. The following ordinance of medieval origin was reported in one of the first Provincial Chapters held in Mexico, while discussing bookselling: "... as stated in our Constitutions, the aim of our Order is the salvation of souls through preaching and, to this end, whatever serves to propagate studies in favour of sacred science must be sought" (A.O.P. 1541, note 17).

Dominican friars, perhaps more than other religious orders, were keen to quickly establish their American libraries. An excerpt from a historical-biographical essay of the Order of Preachers in Mexico between 1526 and 1968 gives us an idea: "The Catholic Church and its Religious Orders, plus the clergy, are generally accused of ignorance and obscurantism. To counteract such baseless lies, it can be said that the Dominican friars began to establish libraries from 1550. Each boatload of friars, they said, was accompanied by boxes and boxes of books just published in Europe. They collected thousands of volumes …" (Orejel Amezcua & González Beascoechea 1970, 70).

Official documents dated between 1550 and 1570 illustrate intense, continuous activity to strengthen the Order's book collections. They record payments made to transport book loads to the port of Seville. The documents record at least 204 arrobas of books (approximately 2,500 kg), corresponding to a few thousand copies (Arroyo 1987, 60–61).

Many of these collections have been scattered or lost due to nineteenth-century secularization. Notes such as Arroyo's on the monastery library in Mexico City or reports on book-selling of entire monastery libraries at the price of paper (Regis 1936, 105) unveil a very disjointed picture.

3 BOOK TITLES AND COLLECTIONS

3.1 *Lists of 16th century architecture books*

We have compiled a list (Table 1) of European books published in the 15th and 16th centuries on topics regarding the art of building (early-modern architecture treatises) but also those containing images depicting architecture, which, as we shall see, may have represented an immediate reference to architectural and ornamental solutions. Castilian translations of some treatises were also listed, as they indicate the success and extensive diffusion of the volumes in Spain.

General works and compendia mentioning the art of building were also included. It must be said that many of these could be part of general training and, consequently, be more frequently available in libraries.

Writings on architecture-related subjects, such as the sciences in the *quadrivium*, were recurrent in the collections consulted. Since they do not relate to the central topic, these were not listed although they will be discussed as they seem to have been extensively present in the ecclesiastical sphere. In fact, these disciplines were part of the first cycle of studies at the University of Salamanca at the time, which included readings on Euclidean geometry and arithmetic. These topics may also have been part of the preliminary studies of novices in monasteries. These subjects must be considered useful foundations for architectural training, as was highlighted in the recommendations of the Academy of Mathematics in Madrid (1582). The academy, intended to train professionals serving the monarchy, strongly recommended knowledge of both the Vitruvius and Alberti treatises and of Euclidean geometry as the foundation for architectural studies (Ovando 2017, 37–59).

Citations of related subjects, such as geometry and arithmetic, are common in architectural treatises. This point needs a brief parenthesis to mention two seventeenth century Spanish architectural treatises cultivated in the ecclesiastical sphere to indicate the influence of these subjects.

In his *Arte y Uso de architectura* (1639, 1663), the Augustinian friar Lorenzo of San Nicolás (1593–1679) often mentions the works of Juan de Ortega (1480–1568) and Juan Pérez y Moya (1512–1596) on geometry and arithmetic. References to Euclidean geometry are innumerable and he dedicates a large part of his second volume to translating it into Castilian. Perhaps the handwritten treatises of the Carmelite Andrés de San Miguel (1577–1644) contain more diverse sources, given the miscellaneous themes (from hydraulic engineering to carpentry). In his writings, we find almost the same references regarding geometry as well as interesting drawings of geometric and architectural figures, with clear references to the Renaissance precepts of proportion and perspective (Báez 1969, 64–75).

Other writings influencing the friars' education could have been consulted through handwritten copies. It is widely known that manuscript copies and compendia may have remained an economic resource for mendicant orders to transmit useful knowledge. Indeed, handwritten copies subsisted along with printed books in libraries throughout the 16th century. We deem it useful to briefly mention the Spanish architect Rodrigo Gil de Hontañón. Considering his notable proximity

Table 1. Titles of printed editions available in the late 16th century with identified copies.

Author, exponent, or editor	Title	Year
		De re rustica
Gryphe/Pétit/Keyser (eds.)	*Libri de re rustica* (compendia of Cato, Varro, Collumella, and Palladius)*	1528–1549
Niccolò Angeli	*Libri De Re Rustica ... commentariis I. Pompo ... adnotationibus P. Beroaldi*	1521
Giorgio Merula	*Ennarrationes ... De Re Rustica ... Philippi Beroaldi ... Aldus de Dierum*	1541
Pietro Vettori	*Marci Catonis ac M. Teren. Varronis De re rustica libri*	1541
		Pliny
Blavis/Froben/Hirtzhorn/ Honorat/Prez/Vidali (eds.)	*Naturalis historiae libri XXXVII (various European editions)*	1491–1587
Hernán Núñez de Toledo	*Obseruationes in loca ... historiae naturalis C. Plinii ...*	1544
Jerónimo de Huerta	*Historia natural de Cayo Plinio Segundo*	1599
		Vitruvius
Sulpicio da Veroli	*De architectura*	1486
Giovanni Giocondo	*M. Vitruuius per Iocundum solito castigatior factus cum figuris ...*	1511
Cesare Cesariano	*Di Lucio Vitruvio Pollione de architectura ... traducti ... commentati ...*	1521
Diego de Sagredo	*Medidas del romano o Vitruvio ... añadidas muchas pieças y figuras ...*	1526
Walther Hermann Ryff	*M. Vitrvvii ... De architectura libri decem ... primium in Germania ...*	1543
Guillaume Philandrier	*M. Vitruuij Pollionis De Architectura libri decem ...*	1552
Daniele Barbaro	*I dieci libri dell'architettura di M. Vitruuio. Tradotti & commentati ...*	1556
Miguel de Urrea	*M. Vitruvio Pollion de architectura ... diez libros, traduzidos ...*	1582
Giovanni Antonio Rusconi	*Della architettura ... con ... figure ... secondo i precetti di Vitruuio ...*	1590
Vincent de Beauvais	*Speculum majus***	1473
		Alberti
Leon Battista Alberti	*De re aedificatoria*	1485
Eberhard Tappe	*De re aedificatoria libri decem Leonis Baptistae Alberti Florentini ...*	1541
Pietro Lauro	*I dieci libri de l'architettura…*	1546
Cosimo Bartoli	*L'architettura di Leon Battista Alberti tradotta in lingua Fiorentina ...*	1550
Francisco Lozano	*Los diez libros de architectura de Leon Baptista Alberto. Traduzidos ...*	1582
		Serlio
Sebastiano Serlio	*Il primo [-quinto] libro d'architettura ...*	1551
Francisco de Villalpando	*Tercero y quarto libro de architectura de Sebastian Serlio ... traducido ...*	1552
Sebastiano Serlio	*De architectura libri quinque ... Necnon extraordinarius ...*	1569
		Vignola
Jacopo Barozzi	*Vignola Regola delli cinque ordini d'architettura*	1562
Patricio de Caxesi	*Regla de las cinco ordenes de architectura de ... Vignola ... traduzido ...*	1593
		Mirabilia Romae
Andrea Palladio	*L'antichità di Roma*	1554
Bernardo Gamucci	*Le antichità della città di Roma*	1565
Fernando Salazar	*Mirabilia Romae: adonde se trata de las yglesias, reliquias ... Palladio ...*	1573
Vincenzo Scamozzi	*Discorsi sopra l'antichità di Roma*	1582
		Other treatises
Francesco M. Grapaldi	*Lexicon de partibus aedium*	1494
Pietro Cataneo	*I quattro primi libri di architettura*	1554
Pieiro Valeriano	*Hieroglyphica, sive de sacris Aegyptiorum ... libri LVIII*	1556
Daniele Barbaro	*La pratica della perspettiva ... Opera molto utile ... ad architetti*	1568
Andrea Palladio	*I quattro libri dell'architettura*	1570
Carlo Borromeo	*... lnstructionibus ecclesiasticae fabricae, & supellectilis suis locis ...*	1577
Juan de Arfe y Villafañe	*Varia commensuracion para la esculptura, y arquitectura*	1585
Juan de Herrera	*... diseños y estampas de la fábrica de San Lorenzo del Escorial ...*	1589
Cristóbal de Rojas	*Teorica y practica de fortificacion, conforme las medidas y defensas ...*	1598

**De re rustica* is a body of Latin literature on agronomy and rural architecture by Cato, Varro, Collumella and Palladius. This group of titles refers to humanistic editions, including translations and miscellaneous compendia.

***Speculum maius* was listed along with Vitruvius' other exponents. However, since it is an encyclopaedic work, its recurrent presence in collections is commented on separately in the conclusions.

to the Order of Preachers, we cannot entirely exclude his influence on the preparation of friars concerning architecture. The architect contributed to construction works for St. Stephen's Monastery in Salamanca between 1557 and 1572. His son also joined the Order in that monastery and later reached Chiapas, Mexico, where he died. However, Rodrigo's written work (ca. 1560–1577) remained unpublished for many centuries (Bustamante-Marías 1985, 217–218). Hence, to date, neither manuscript copies nor documents have been found in relation to Mexico and the survey for this study was limited to printed books.

3.2 *Inventories*

Old inventories would be the most suitable source for overcoming issues of dispersion. Though consultation of the archives in Spanish Dominican monasteries has been logistically complicated this past year, we were fortunately able to gather information about the Library of Saint Dominic's Imperial Monastery in Mexico City, the largest and most representative for Dominicans in New Spain.

The analysis conducted on this inventory yielded valuable information never published before. It shows an outstanding number of copies (2,460 titles and 5,293 books) and, most importantly, it enables its extent to be reconstructed a few decades before the dramatic consequences of the secularization laws. Books containing architectural references in this inventory include Pliny's Natural History, the medieval encyclopaedia *Speculum maius* by Vincenzo di Beauvais, *Hieroglyphica* by Pierio Valeriano, and a copy of *Mirabilia Romae* in Castilian. There are also titles on architecture-related subjects, such as Euclid's geometry and Juan Pérez de Moya's arithmetic.

3.3 *Identifying collections*

Our list of books was first compared with book collections present today in Spanish and Mexican Dominican Provinces (Biblioteca Histórica J.L. Espinel in the Salamanca and Historical Library of the Instituto Dominicano de Investigaciones Históricas in Querétaro). The results, however, were weak. In fact, 19th century secularization laws in both countries led to the Order's (remaining) expropriated bibliographic heritage being merged into university libraries or large public libraries. Accordingly, a further comparison was made with contemporary catalogues that would most likely contain part of the Order's collections (Table 2), verifying the source of the books through ex-libris, stamps, fire marks or handwritten notes.

The libraries analysed contain bibliographic heritage that belonged to Dominican monasteries and study centres of great influence for the Evangelization of New Spain. In the case of Spain, libraries in Salamanca, Valladolid and Seville were the most concerned about educating missionary friars at an early stage when the American foundations still depended on Spain. In the case of Mexico, study centres such as those in Mexico City, Puebla and Oaxaca gradually vindicated their importance as places of intense exchanges of knowledge. These centres trained and instructed the clergy about native languages and all other practical know-how useful for evangelizing the territory.

Table 2. Catalogues, inventory and book sources.

16th century architecture books preserved in libraries or listed in inventories

	Source		
Catalogue/inventory	Quantity	Preachers	Other orders
Spain			
USAL Lib., Salamanca	30	19	12
J.L. Espinel Lib., Salamanca	4	3	–
US Lib., Sevilla	23	–	12
Santa Cruz Lib., Valladolid	14	–	5
Mexico			
Old inventory, Mexico City	7	7	n/a
Palafoxiana Lib., Puebla	14	–	9
National Lib., Mexico City	21	1	6
Burgoa Lib., Oaxaca	4	–	4
INAH Nac. Lib., Mexico City	4	–	3
Lafragua Lib., Puebla	4	–	2
IDIH Lib., Querétaro	–	–	–
Total	125	30	53

The survey of the catalogues (Table 2) provides quantitative and qualitative data, focusing on the treatises available within the sphere of academic training of the Order of Preachers. We also indexed treatises that belonged to other religious orders. These may have been accessible to Dominicans given that the Order strongly encouraged academic exchange between religious orders (Arroyo 1987, 57).

4 RESULTS

4.1 *General books and architecture-related subjects*

There is a significant presence of encyclopaedia-type texts, such as Pliny's *Natural History* and Pierio Valeriano's *Hieroglyphica* in keeping with how they would have been useful to several areas of the friars' academic training given the breadth of topics covered in the texts. Many copies of Pliny's text have been found. Three copies in the nineteenth-century inventory of the Mexican monastery are worth noting; one is the late sixteenth century Spanish edition by Gerónimo Huerta. Valeriano was found practically everywhere; in fact, three copies relate to Dominican centres in Mexico City and Salamanca.

As mentioned above, architecture-related subjects are not the central object of this research, though we consider it important to report the recurring presence of Euclid and Juan Pérez y Moya and their presence in the inventory of Mexico City's monastery (Figure 2).

The medieval florilegium *Speculum Maius* by the erudite Dominican Vincent of Beauvais, which contains a chapter on proportions based on Vitruvius, is

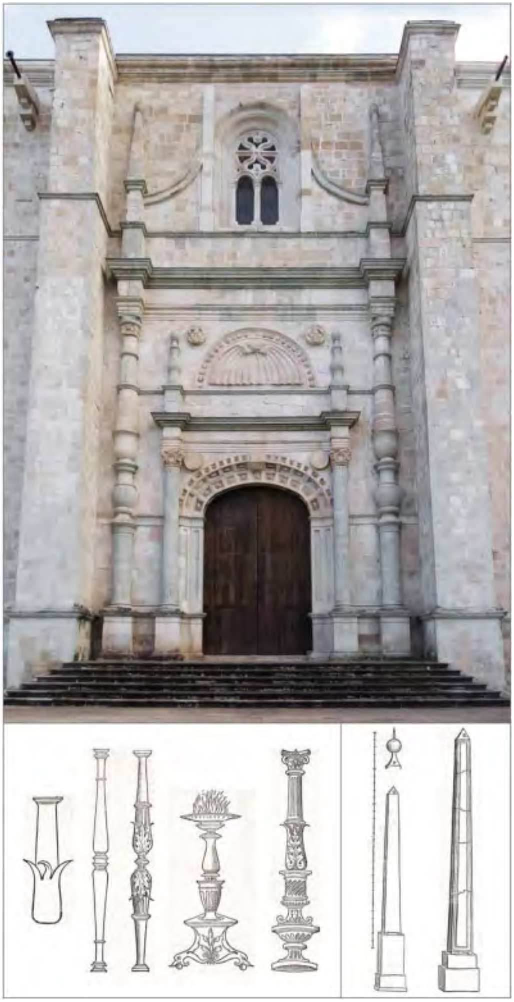

Figure 2. Top: Saint Dominic's Monastery in Yanhuitlán, church, north doorway (pre-1558). Left: Ornamental repertoire of columns, balusters and vases (Sagredo 1526, 33–36). Right: three obelisks from Rome with a scale (Serlio 1540, LXIII).

worth commenting on separately. We found a total of five copies in the ecclesiastical sphere, two of which were in Dominican monasteries: one in Saint Stephen's Monastery in Salamanca, and the other in Saint Dominic's Monastery in Mexico City.

4.2 *Early modern period*

The most frequent architectural texts are Vitruvius writings. We counted about 20 copies among incunabula, exponents, and translations, four of which were from the Dominican realm. Moreover, some Castilian editions of Vitruvian texts were found to have belonged to the realms of other orders. Two copies of Urrea's edition were found in ecclesiastical spheres of Mexico City and Puebla, while one copy of Sagredo belonged to the Jesuit college in Salamanca.

A lcuni altri Architetti hanno uoluto uſar maggior dilicatezza, & più ordinato compartimento, non dimeno, tutta tal'opere ha hauuto origine da l'opera Ruſtica, anchora che comunemente ſi dice, a punte di diamante.

Figure 3. Illustration of diamond rustication (Serlio 1537, LVIII). This ornament was broadly used in Oaxacan Dominican monasteries decorating doorways, arches and pedestals.

An equally numerous group consists of the Latin compendium on agronomy and rural architecture, *De re rustica*. Six copies of this title are linked to the bibliographic heritage of the old *colegios* (colleges) of the University of Salamanca, and one has the fire mark of Saint Dominic's Monastery in Mexico City.

De re rustica contains Vitruvius mentions and/or syntheses regarding the art of building within this text's characteristic practical framework. The compendium represented an important and valid reference for late medieval building traditions. Given that most mendicant monasteries were located in the rural hinterland of New Spain, not to mention that such complexes had to be mostly self-sufficient, we believe the compendium may have been broadly used by religious orders seeking to solve not only building issues, but many other aspects of monastery management such as material supplies, water procurement, other general livelihood issues or even land surveying (*agrimensura*) and settlement organization, tasks that we know Dominican friars saw to personally in similar contexts (Chávez 2014, 72–74).

Other editions of early modern architectural treatises were found less frequently. Of the seven copies of Serlio's writings that were retrieved, only two can be attributed to the old colleges of Salamanca, one of which is Villalpando's Castilian translation. This edition recurs fairly often in other collections; however, the copies do not present clear evidence of their origin through ex-libris or stamps (Figure 3).

4.3 *Mirabilia*

Lastly, another significantly recurrent group was that of the *Mirabilia Romae*. We believe this genre would have been useful to architects for both the descriptions of classical monuments, as in the case of Palladio (1544), and the illustrations, as with Gamucci (1565) and Scamozzi (1582). Of a total of ten books retrieved (including Castilian translations), four can be attributed to the Dominicans of Salamanca and Mexico City.

5 CONCLUSIONS

Texts dedicated to the art of building constitute an endowment that responds, as with other technical

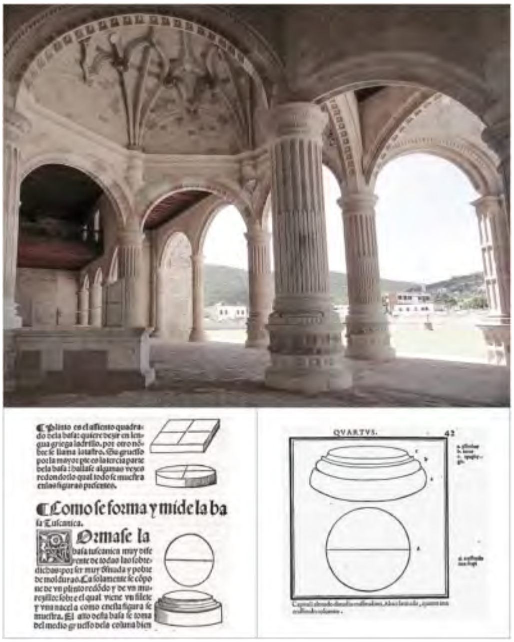

Figure 4. Top: Dominican Monastery of St. Peter and St. Paul in Teposcolula, open chapel (16th c.). Bottom: illustrations of cylindrical plinths in a clear perspective of Vitruvius exponents (Sagredo 1526, 43) (Giocondo 1511, 42).

knowledge, to a criterion of utility in the ecclesiastical realm. Given the shortage of architects, religious construction in 16th-century New Spain was mostly directed by the friars themselves, and it is impossible to ignore certain related aspects. We find clear evidence of good quality representations of the Late-Gothic building tradition and also the recurrent grafting of classical elements. As mentioned in the introduction, this contribution investigated the most recurrent authors and means of circulation and interaction of architecture treatises in our specific sphere. The illustrations presented throughout this article aim to briefly exemplify how references to the literature appear in the specific area of Dominican architecture. As mentioned, this kind of comparison between possible references and early buildings in New Spain has been a common indirect way to discuss the influence of the treatises as a whole in past decades.

In the monastery in Teposcolula, for example, Late Gothic vaults coexisted along with classical elements found in the literature such as diamond rustication (Figure 3) and cylindrical plinths. Unorthodox elements such as round abaci could either be a result of misreading, a mediaevalism or a technical-compositional solution to gracefully converge the irregular *bouquet* of arches into the columns (McAndrew 1965, p. 550–551) (Figure 4).

It seems that images represent a synthetic and immediate means of implementing this language, and often constitute obvious repertoires of references

Figure 5. Left: View of the Arch of Titus in *Mirabilia Romae* (Gamucci 1565, 41). Right: Peculiar monastery church doorway, Tlaxiaco (1550s).

(Manrique 1982). Images are used as a schematic outline and are commonly simplified with a certain degree of clumsiness. This is possibly due to a lack of familiarity with representation, fragmentary understanding of architectural language or even the disconnect between forms and technical processes on site. Misreading, for example, may have resulted in expressions such as Tlaxiaco's doorway (Figure 5).

As previously mentioned, the Order's Constitutions enlisted a figure specialized in construction: the building superintendent or *praefecti operum*. The Dominican monasteries can be considered choral works, the result of a system of knowledge shared by individuals at different levels (patrons, designers and project managers), not to mention the indispensable local workforce (masons, carpenters and officers). designation of this figure and his places of work can be found in the earliest Chapter proceedings of the New Spanish Dominican Province. Superintendents were most likely joined by other delegate figures before undertaking the construction of new monasteries in the hinterland. These movements certainly favoured training and exchange within the order, as well as the circulation of knowledge applicable to architecture.

The well-documented case of Saint John the Baptist Dominican Monastery in Coixtlahuaca (Oaxaca) is a good example of this type of cross-cultural construction. The local technical tradition of stonework was enriched with training provided by a Spanish master stonemason. More importantly, this religious or lay master instructed local masters to reproduce European models from either engravings or drawings (Vences 2000, 196–203).

The surest evidence of the use of treatises undoubtedly relates to references found in the buildings themselves. This study did not find a large number of architecture texts that could be directly attributed to the Dominicans. Despite the misfortune of secularization, the earlier inventory of the Mexican monastery already showed this trend. A possible explanation is supported by some studies on Dominican libraries. It is common knowledge that bibliographic collections were not stationary since library management was deeply based on utility. Duplicates or worn-out books, for example, could be sold to raise funds for new purchases, not to mention book exchanges between monasteries (Cinelli 2016, 288).

As the sixteenth century passed, the Order of Preachers became less concerned with the establishment of new monasteries and the number of available architects in New Spain gradually increased. Could these factors have made the consultation of architectural texts to a certain extent obsolete, contributing to their gradual dispersal?

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The roots of the 18th century turning point in earthquake-resistant building

C.F. Carocci & V. Macca
Università degli Studi di Catania, Catania, Italy

C. Tocci
Politecnico di Torino, Turin, Italy

ABSTRACT: The *gaiola pombalina* and the *casa baraccata* seem to be the turning point of a gradual improvement process that, in Italy, becomes clearly recognisable after the 1703 L'Aquila earthquake. The reconstruction following that event saw the introduction of a constructional system, based on wooden elements embedded in masonry works, quite distinct from the rigorous organization of the late 18th century systems but having seemingly comparable intents. Recent earthquakes in Italy have enabled the value of that early anti-seismic technique to be recognized. In this paper we describe this technique its comparison with the systems at the end of the century and attempt to trace them back to more ancient constructional techniques attested also in low seismicity areas In these areas they seem to refer to a general attempt to rationalize masonry building's procedures whose anti-seismic potential was gradually recognized during the Enlightenment, finally leading to the Portuguese and Bourbon systems.

1 INTRODUCTION

Codified in the 18th century for the reconstruction of the centres destroyed by the devastating earthquakes of Lisbon (1755) and southern Italy (1783), the *gaiola pombalina* and the *casa baraccata* represent the first formalization of expressly anti-seismic construction techniques. They were both based on the adoption of wooden elements interacting with masonry work aimed at strengthening the building's joints, thus showing quite a mature awareness of the inherent, as it were, seismic vulnerability of historical masonry constructions. The level of detail in terms of structural conception and technical expression (which is not surprising within the cultural context of the 18th century) suggests that their appearance cannot have been sudden but was a gradual evolutionary process in which construction traditions, already experimented with during the earthquakes, found their formal definition.

In the Italian context this process of intentional and systematic reflection (and action) becomes clearly recognizable during the reconstruction of the centres destroyed by the great earthquake of L'Aquila in 1703. Recent Italian earthquakes (L'Aquila, 2009 and central Italy, 2016), which affected the same areas struck by the 18th century's event, allowed a direct study of the main characteristics of that reconstruction technique which, even though far from the rigorous systematic approach adopted by the Bourbon and Portuguese Governments, aimed at the same purpose of ensuring the building behaved holistically and can, for this reason, be considered an explicitly anti-seismic technique.

The purpose of this paper is to consider the relationship between this rudimentary anti-seismic technique and the more mature expressions of the late 1700s, proposing some introductory reflections on the geographical spread of construction techniques comparable to those abovementioned. It will further consider the impact of these techniques on subsequent developments, and their use in low seismicity contexts, including of the period in which these techniques were practised.

2 FROM LATE TO EARLY 18TH CENTURY

2.1 *The Gaiola Pombalina and the Bourbon system*

The *gaiola pombalina* technique is based on the creation of an internal three-dimensional wooden structure which, systematically bonded to the external masonry walls, would exert a common action against earthquake loads. It could be argued that buildings using the *gaiola pombalina* system are based on the coexistence of different construction techniques: masonry reinforced with embedded timber braced frames for the ground floor and façade walls, and a wooden load-bearing braced frame for the internal structure of the above-ground levels. The internal timber frame – which is at the core of the construction process – is made of timber floors and vertical panels (the so-called *frontais*) connected to each other by classic woodwork joinery and iron ties. The *frontais* are made of a trussed frame of organized elements creating rigid shapes (diagonal and cross bracing) and

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Figure 1. L'Aquila, chiesa delle Anime Sante, three courses of wooden radiciamenti in the drum of the dome.

using different types of infill material. The latter is essentially independent of the timber structure which alone fulfils the entire building's structural function.

The Bourbon technique, adopted for reconstruction after the 1783 earthquake, is based on the prototype conceived by Giovanni Vivenzio, the physicist appointed by the Bourbon Government to study the earthquake's damage. Both contemporary theoretical studies and direct observation of the local buildings' responses to the earthquake formed the basis of the prototype's conception (Tobriner 1983). Timber braced frames were conceived to realize wall structures quite similar to the Portuguese *frontais* (in this respect, the latter's influence on the Bourbon model has still to be clarified); but otherwise, these vertical panels were used both for internal and external façade walls creating a uniform three-dimensional system which differs from the "specialized" Portuguese one. Moreover, the Italian prototype proposes, at least for "the great walls of public buildings" (Vivenzio 1783), the doubling of these panels, their mutual connection by means of wooden transverse elements and their placement on either side of a masonry wall made of squared stones bonded to each other with iron cramps.

It is not clear whether the timber frame's doubling was provided for ordinary buildings too. What is certain is that the scarcity of timber and the possibility of reusing rubble stones of the buildings damaged by the earthquake led the engineer Francesco La Vega (entrusted by the Bourbon Government with the reconstruction) to simplify Vivenzio's model through an increase of the masonry component and the settlement of a smaller quantity of wooden elements inside the wall's thickness. In La Vega's directions the timber frames are reduced to the vertical and horizontal elements while the diagonal ones are maintained for the internal partition walls only. Therefore, the *baraccato* system – as it became known from the 19th century – can be considered, partly in Vivenzio's first definition and definitely in the practical applications of the reconstruction, a pure masonry construction system within which wooden elements reinforce and connect the structural elements.

2.2 *The post 1703 L'Aquila technique*

The construction technique employed after the 1703 earthquake – which we want to compare with the late 1700's methods briefly described above – has been recognized thanks to the examination of buildings damaged by the earthquake which struck L'Aquila and the neighbouring areas in 2009 (Figure 1); confirmation and further observations on the areal extent of this technique have been deduced from the seismic sequence that occurred in central Italy between August 2016 and January 2017.

The *radiciamenti* are wooden logs embedded in masonry walls. Their role is to work in the building as real belts – to use a term referring to the similar, though more refined, Greek system known as *imantosis* (Figure 2). The features which distinguish the various practical applications of these devices (and which are usually strictly linked to the general construction quality of the building) refer both to the different level of finishing of the elements and their relationship with the masonry's assembly. In modest buildings it is possible to observe rough wooden elements whose mutual connection is entrusted to the sole timber, without the use of iron nails or ties (Figure 3); in more significant buildings the *radiciamenti* are made of dressed wood and are directly connected to the orthogonal wall by means of metal anchors

Figure 2. L'Aquila, chiesa di S. Giuseppe Artigiano, the metal anchors located in the corner walls connect the wooden 'radici- amenti'.

Figure 3. Villa S. Angelo (AQ), wooden *radiciamenti* placed in the thickness of corner walls.

(Figure 4). Their position is always dependent on that of doors and windows to ensure a continuous hooping system. It is not uncommon to find them associated with vaulted structures at the height of the haunch to counteract the horizontal thrusts.

The *impalettature* are elementary wooden devices that improve the support conditions of the roof structure. They provide an anchoring system that integrates the structural elements' interlocking aims of the technique.

With reference to the context of L'Aquila, trusses equipped with such devices working as constraints for the supporting walls are quite common (Figures 5–6). Similar devices were not seen in central Italy during analysis of the 2016 earthquake's damage. Their absence could be due to the recurring roof replacement practices undertaken in the wake of the Valnerina earthquake in 1979.

Although not the specific subject of the reflections here presented, it is worth noting that recent studies (Aloisio, Fragiacomo & D'Alò 2019) have highlighted further traits which might be included in this construction technique: timber frame walls made of vertical studs – both load-bearing and partition walls but mostly internal – were found and seem to suggest an even closer proximity to the mid-century codification.

Figure 4. L'Aquila, chiesa di S. Flaviano, metal anchors of façade 'radiciamenti'.

Figure 5. L'Aquila, wooden anchors of the roof trusses.

2.3 *Comparisons*

The overall structural concepts – and geographical proximity – suggest how the anti-seismic technique of L'Aquila has a closer correlation to the Bourbon system. As a matter of fact, both techniques appear to be essentially masonry techniques in which, as opposed to the Portuguese system, wooden elements work jointly with the masonry walls, and not as independent structures. This underlines the importance of masonry work's quality for the system's efficacy. However, these wooden elements only work in the presence of horizontal forces (regardless of thrusts against vaulted structures or earthquake activity).

Figure 6. Detail of a wooden anchor connecting the roof trusses to the external wall.

What mainly sets the techniques apart is that the early 18th century technique provides for a simpler – in a sense, more elementary – configuration of the wooden material which is, to our knowledge, limited to the creation of horizontal elements. That appears to relate to these techniques' different aims: the first, essentially a reconstruction technique, appears to be suitable both for the construction *ab imis* of new buildings and, more frequently, for restoring earthquake-damaged buildings by reusing the remaining structures (usually the lower floors) and connecting them to the new completion. The second, the Bourbon system is, instead, a prototype for new buildings whose construction solutions do not need to be adapted to pre-existing configurations.

The difference between the two construction techniques seems to be coherent with an evolutionary interpretation where the Bourbon system represents a mature and normalized variation of the earlier L'Aquila system. Its most relevant outcome lies not so much in the connection between the different elements' efficacy as in the walls' in-plane strength. Recent earthquake activity has revealed the technique to be rightly tailored for that area's seismic severity, although a better or, more precisely, different quality of the Bourbon system is unquestionable. It is indeed true that the *radiciamenti* of L'Aquila technique can work as orthostats increasing the walls' shear capacity, but this improvement is not comparable to the one obtained by the trussed frames of the *baraccato* system.

The global seismic response of these systems is also affected by other factors: the quality of the masonry works (discussed later) and constructional organisation. The early 18th century system, theoretically less effective, would reveal itself more ductile than the turn-of-the century one.With reference to this second aspect, it is worth noting that the Bourbon system's strictly prescriptive nature and complexity made its effectiveness heavily dependent on the accuracy of the construction process: a rough execution could be the cause of an entire system's impairment – the more damaging, the greater differentiation from the prototype's specifications. In fact, buildings where the presence of wooden frames were not associated with their appropriate connection were observed (Tobriner

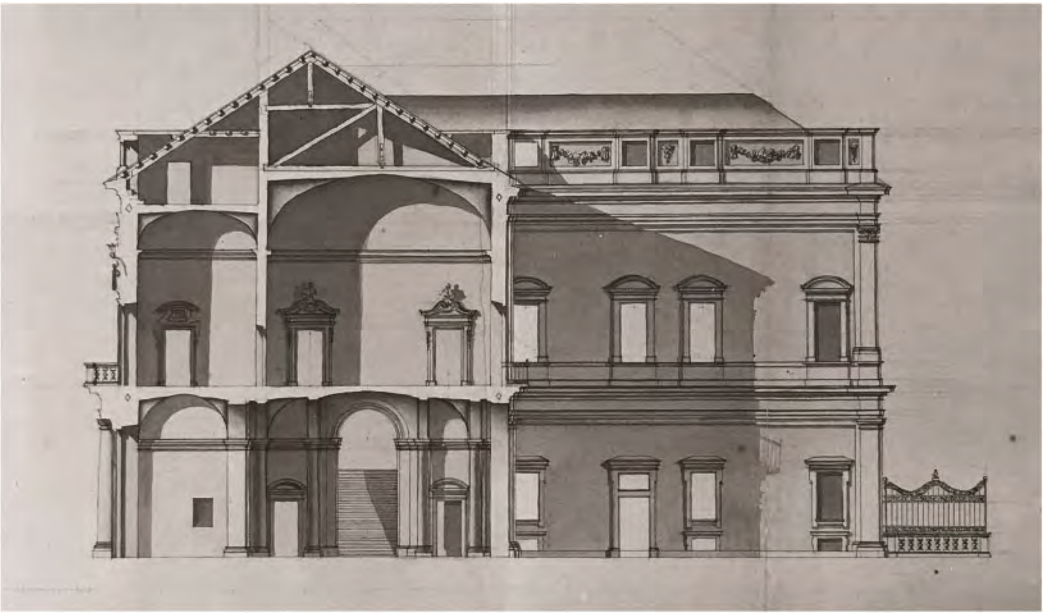

Figure 7. Transverse section of a palace (Palazzo Giriodi, Costigliole Saluzzo?) by B. Vittone's atelier (ca. 1740) showing a two-level order of *radiciamenti* (Musei Civici, Turin, coll. Vandone). Courtesy of E. Piccoli.

1983); Vivenzio himself had identified this kind of hidden danger warning that "the enormous complexities destroy the entire building's strength" (Vivenzio 1783).

L'Aquila technique, on the contrary, because of its uncoded character and its "essential" nature, appears to satisfy the performance aims in a more reliable way adapting the anti-seismic requirement to a consolidated local construction tradition: when some ineffectiveness of the technique has been surveyed, it was ascribable to subsequent transformations and not to some intrinsic fragilities of the system.

As regards the masonry work's quality which, together with that of the wooden elements, is essential for the anti-seismic efficacy of both systems, similar observations can be made with reference to different geographic areas, despite the differences in local construction techniques and the century which separates their development.

The introductory study carried out by Vivenzio in the wake of the 1783 earthquake had already noted the inadequacy of the typical building materials used until then: the *brest* or *bisari* (that is mud-and-straw bricks), rubble stones and poor-quality lime. The same criticalities had been later noted and confirmed – maybe with a more persuasive interpretation both based on the nature of the materials and their assembling – by the committee responsible for drawing up the standards in the wake of the 1908 earthquake which affected the same area (GGC 1909). Despite the suggestions provided by Vivenzio, some of which were integrated within the reconstruction regulation issued in 1784, and the cost savings which led Francesco La Vega to simplify the original prototype, those same materials belonging to the traditional construction technique were indiscriminately reintroduced during the reconstruction. These circumstances clearly undermined the buildings' seismic resistance ensured by the earlier use of timber frames and re-established the condition of fragility of the local construction technique which was, in fact, observed again in subsequent earthquakes (Tobriner 1983).

In a similar way, wooden bond elements (*radiciamenti* and *impalettature*) belonging to the early 18th century technique were defenceless against the 2009 and 2016 earthquakes when embedded in low quality masonry walls, which ruinously collapsed. But, at the same time, they turned out to be essential in raising the seismic capacity for those buildings where mastery of masonry construction had balanced the poor quality of local materials allowing the creation of state-of-the-art walls, which survived.

3 FROM HIGH TO LOW SEISMIC HAZARD AREAS

The 18th century construction technique which has been outlined in its essential traits could probably be considered an enhancement – promoted by a new "rational" awareness of the earthquake, not surprising in the favourable cultural climate of that period – of a technique already widely diffused, even in areas characterized by low seismic risk. In fact, construction systems conceived regardless of earthquake activity – but aimed at strictly connecting the entire building, not necessarily to counteract the vaulted structures' active thrusts – could have been recognized as anti-seismic devices once awareness of the earthquake's damage modes on historical buildings had been reached.

The practice of wooden elements to connect the entire building organism is attested in northern Italian regions, and specifically in the Lombard area, from the 16th and 17th centuries (Della Torre 1990).

Regarding this practice, it has been said that it exemplifies a gap between architectural theory and construction-site practice, the former being attested on an ideal of masonry buildings able to stand by themselves, without the "*stringhe*" (laces) condemned by Vignola, while the current technique has employed different materials' ligatures continuously since the Middle Ages. However, the issue is not so simple, and examples can be found (Villani 2009) in which the need for connections stronger than those based on simple masonry bonding is not only exploited by expert masons but also recognized by architects involved in practical as well as theoretical activity (Figure 7).

Whatever the case, this very ambiguity is significant. It shows the existence of an evolutionary process in which building traditions selected by trial-and-error in ordinary conditions were recognized, from a certain point onwards, as equally effective to resist earthquake activity.

Such a process seems to be echoed in the lexicon's evolution. The oldest terms used to define wooden reinforcing devices – "*chiave*" (key) or "*ligato*" (binder) – refer to single elements with basically a local nature. They are systematically replaced, in Venetian and Lombard sources of the 18th and late 18th century respectively (Concina 1988), with the far more expressive "*telaro*" (frame). From as early as the 17th century, the new term has a wider meaning and precisely indicates a skeletal wooden structure working together with the masonry organism and somewhat affecting its "global" structural behaviour.

In the same period the term is recorded in Piedmont. In the citadel of Alessandria, a huge construction site of the second half of the 18th century in the Kingdom of Sardinia, a *telaro* "to be formed both lengthwise and across with large red oak logs" (Piccoli et al. 2018) is embedded in the perimeter walls of the barracks and its technical features shows surprising similarities with the aforementioned Lombard cases.

Just think of how wooden elements are joined to each other by means of nailed metal strips (*grappe incavigliate*) for *radiciamenti* longer than the available wooden logs; or timber is replaced with metal bars (*lamoni*) in relation to the chimneys (Figure 8).

But what sets this Piedmont example apart from the Lombard cases cited in Della Torre (1990) are not so much the construction aspects as the general purpose of the system as a whole. Such a system indeed no

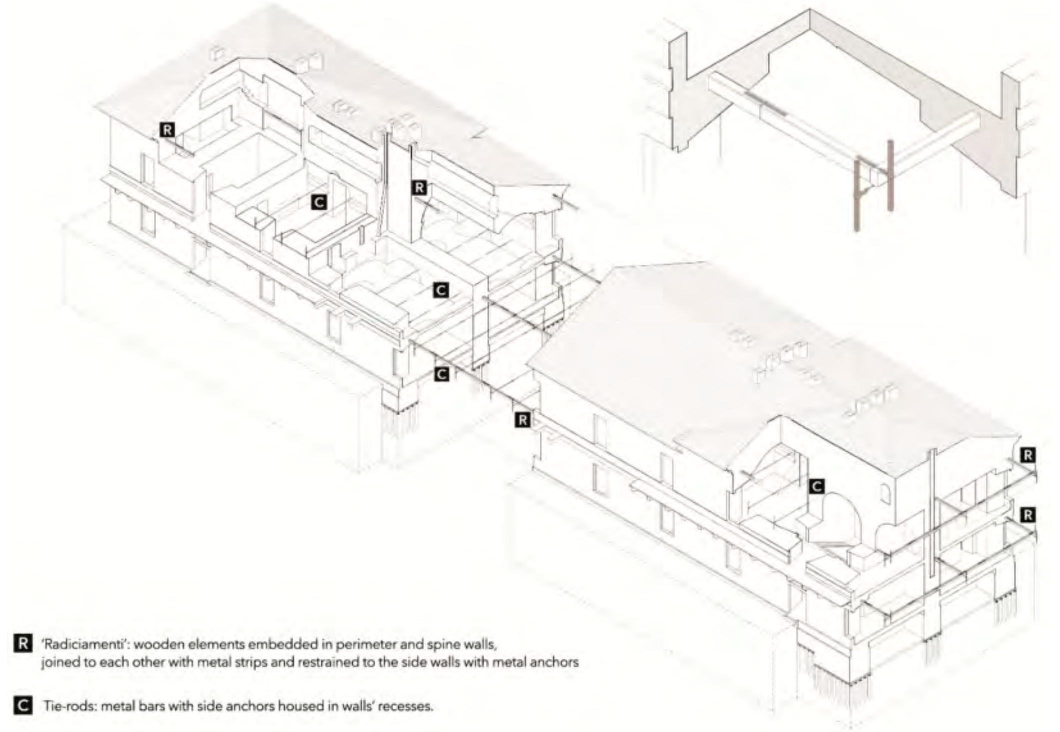

Figure 8. Citadel of Alessandria, the wooden *radiciamenti* and metal tie-rods as an overall connection system for San Tommaso barracks (1749-59). (Rossi 2019).

longer serves to counteract the thrust of the vaulted structures (for which a dense system of metal tie-rods had been designed) and represents, instead, the answer to a new problem, which is similar to the one we are discussing in this paper.

The Alessandria barracks had been designed to be "bomb-proof", a structure that needed to be impenetrable to cannonballs and stable against the actions induced by their impact. The first is obtained by increasing the thickness of the walls, the second by ensuring that all elements act as a whole, introducing more efficient constraints than those deriving from simple bonding (the *radiciamenti*, indeed).

The "bomb-proof" requirement invokes dynamic actions, which were explicitly taken into account by military engineers in an extraordinary mathematical discussion that took place late century (Piccoli & Tocci 2019). Just as dynamic was the result of the earthquake, whose effects in the early 18th century were evidently clear for those who rebuilt damaged areas in central Italy, even if they could not yet attempt any theoretical reflection (which started soon afterwards – Barbisan & Laner 1983). Similarly, the vibrations induced by carriages, which Rondelet had thought of, at the end of the same century, led to the introduction of nothing but metal *radiciamenti* (or *telari*) in order to increase the stability of buildings.

But at the dawn of the 19th century, in the high-risk seismic area of southern Italy, the *radiciamenti* technique had already turned into that extraordinary anti-seismic system that is the "*casa baraccata*". Outside of this exceptional context, and especially in low seismicity areas, the technique maintains its original configuration, only within a formulation by now mature and perfectly recognizable in its anti-seismic intent. It is in Piedmont that we can still find some interesting examples. In the early 1800s the technique of "*racinnements*" is used – together with a refined tie-rods' arrangement strictly cooperating with vaults and roof trusses – as a connection system for the Waldensian temple in Luserna San Giovanni, at the foot of the Cottian Alps (Ravera 2019). Just two years after the temple's completion, the same technique, using a smart metal transposition of the original tying wooden system, was proposed by the French architect Philippe Ghigliani to repair the damage caused by the earthquake which affected the valley of Pellice in April 1808.

This was not an isolated case, as evidenced by the widespread presence of metal *radiciamenti* in Turin buildings (Figures 9-10-11).

Already known in the 1700s – as we have seen with the Savoy military construction yards – at least for huge public buildings (where it is clearly recognizable due to the local habit of exposed brick facings) the presence of the *radiciamenti* seems to have no presence in residential constructions that constitute the backbone of the 19th century town expansion.

Figure 9. Turin, anchors of façade's metal *radiciamenti* emerging from recesses housed in the transverse wall.

Figure 10. Montalenghe (TO), metal anchor recessed in the masonry toothing revealing the presence of a metal tie-rod in the half-width of the back transverse wall.

The presence of the INA-casa specifications defined as *radiciamenti*, the reinforced concrete ring beams resting on load-bearing masonry walls and supporting the joist slabs with hollow tiles, in the 1900s provides evidence of the prevalence of a construction practice that, tackling the root of masonry building issues (which can be summarized in the inherent weakness of connections), had become the most effective response to earthquake activity, (Barelli 2020). Despite the material (timber, iron or reinforced concrete), it is evident that the function was (correctly) believed to be the same.

4 CONCLUSIONS

The evolutionary process outlined in this report – which from a set of uncodified construction practices (recognised in territorial contexts which differ in building technique and earthquake intensity and frequency) would lead to an expressly anti-seismic normative system – certainly deserve to be investigated in detail.

Figure 11. Turin, the closeness to the façade edge of the metal anchor reveals that the corresponding tie-rod is embedded in the orthogonal wall.

This process should, first, try to define more precisely the geographic scope and time frame within which it is possible to find the first (even if embryonic) appearance of what, with time, was to become an anti-seismic technique. For this purpose, the large existing literature (Langenbach 2007; Touliatos 2016) could be examined to highlight similar cases across different territorial contexts which reveal the connection between construction practices and awareness of the destructive potential of earthquakes.

The scepticism expressed more than 30 years ago by Emanuela Guidoboni is probably still justified today regarding the possibility of finding traces in "the great earthquakes of 1117, 1169, 1222, 1348 […] for considerations or dispositions dealing with measures against earthquakes' effects [or] subsequent devices incorporated into the practice of building techniques, which could be interpreted somehow as preventive measures for future damage" (Arrighetti 2015).

Nevertheless, the recent strong Italian earthquakes (L'Aquila 2009, Emilia 2012, central Italy 2016) unveiled a technique that indisputably contains "preventive measures for future damage" about which nothing of its real spread and anti-seismic efficacy was known until then. They further demonstrate how the same traces are just waiting to be systematically documented for seismic events immediately following those discussed which we linked with the great earthquakes of the early 1700s. In this respect post-earthquake restoration works could continue providing precious documentary evidence – as referred to here – supported by systematic interpretation of the data obtained.

At the same time, it seems inevitable that the approach adopted in this work, based on the gathering of information from single buildings, construction sites and experiences in accordance with the typical method of construction history, will continue at the expense of large syntheses of anthological collections.

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Continuous stucco and smalto flooring in the former Austrian Lombardy: Sources, techniques and communication

M. Forni
Politecnico di Milano, Milan, Italy

ABSTRACT: The revival of historic techniques that accompanied the rise of neoclassicism taste is seen in Milan with the choices of its refined aristocratic patrons. In their homes, which were veritable workshops of applied arts, continuous floors were documented. Based on ambiguous contemporary descriptions that identify a plurality of products, continuous floors can be traced as being part of the stucco or smalto categories. Among the workers who experimented in these techniques, Agostino Gerli and his brothers stand out as craftspeople and skilled communicators of their eclectic inventions and work. This knowledge applied to construction was still available in the 19th century as a specific Milanese tradition.

1 WORDS AND OBJECTS. THE LIMITATIONS OF TECHNICAL LITERATURE

Continuous flooring using aggregate mixes with various materials, techniques and degrees of fineness has been known since ancient times. Vitruvius’s *De architectura* (Gros 1997,VII,1) is the main reference in either the original text or through widespread epitomes: Marcus Cetius Faventinus (Cam 2001) and Rutilius Taurus Aemilianus Palladius (Di Lorenzo 2006, Liber VI Mensis Maius, XI) and other minor or fragmentary evidence, including indirect references, such as Isidore of Seville (Lindsay 1911, Lib. IX, X, 25). Similar evidence and variants appear by other authors of antiquity, such as Marcus Porcio Cato mentioning a clay pavement of pozzolana earth, impregnated with “amurca”, i.e., olive oil dregs, intended for rustic buildings or dwellings (Canali & Lelli 2000, *Habitationem delutare,* CXXXVII), or with the addition of cocciopesto (Canali & Lelli 2000, XXI. 7). The attention to continuous floors is handed down seamlessly in treatises starting from Leon Battista Alberti (Alberti 1550, III, XVI), Daniele Barbaro (Barbaro 1556, VII, I, 184), Pietro Cataneo (Cataneo 1567, II, XII, 67), Andrea Palladio (Palladio 1570, I, XXII), Giovanni Antonio. Rusconi (Rusconi 1590, 94), and Vincenzo Scamozzi (Scamozzi 1616, III, VI, 243). There are many consistent techniques based on materials, procedures, and uses. This amplifies the problems posed when interpreting the manuscript and printed sources’ technical vocabulary and require a wider correlation with other sources that are more useful for depicting a social and cultural framework.

The great mediator, Francesco Milizia, provided one of the most authoritative reinterpretations and noted the end of an active and passive “tradition” of these techniques. Knowledge transfer and interpolation recounted through the most widespread cornerstones showed an important change. This concerns the relationship between knowledge, technique and the market, and corresponds to contemporary ideas of taste.

“*Terrazzi* paving or *smalti* (enamels) (...) were used on floors by the ancients, who used to build them with great diligence, as Vitruvius taught us” (Milizia 1827, II, 272). Milizia faithfully outlines the procedure from the lime and brick dust-based composition to the final installation. To this authoritative tradition, the author added contemporary developments including the introduction of plaster and other ingredients into the mixture. This increased mechanical resistance and shine, besides creating endless possibilities of reproducing both marble and wood by replicating the most complex textures and colours.

Milizia described the preparation of the artificial material: “The coloured enamel is made up of one third of thin and dry cement, a third of marble dust and a third of sifted lime” (Milizia 1785, III, VI, 182). Once the layers were applied, they were beaten to compress the mass and ensure surface compactness. After drying the floor, it was polished with white wax. A variant included transferring a drawing by engraving, and creating grooves with a chisel, which could be filled with coloured enamels. The enamels were composed “of lime, sifted cement and coloured earth or powdered colours used by painters” (Milizia 1785, III, 182) in a ratio of one to three between the materials indicated. Milizia warned that the mixture’s consistency must be oily and not too liquid to allow compression and adhesion in the cavities. A good imitation of black marble could be achieved by using the dross from iron forging. The possibility of using marble or glazed ceramic

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fragments underscored the technique's similarity to commesso.

The features, performance and variety of these floors were similar to European productions in artificial stone (Holt 1730; Gargiani 2013, 30-34) or *pierre factice* (Pelouze 1829), which were widely disseminated in the technical literature from which Milizia extensively drew.

These techniques are re-proposed within the revivals that fed the European Neoclassical culture. In this scenario, imitation is often accompanied by research and experimentation using the nascent applied sciences to develop reproduction procedures. During this transfer of knowledge, the results of the change in mentality favouring the circulation, comparison and integration between historical, scientific and technical knowledge through interaction and recurring translation mechanisms become tangible. A critical review of sources, started as early as the 17th century by antiquarian scholarship, has now developed a renewed methodology. The philological and critical approach, exemplified for painting by the studies of Lessing (1774) and Raspe (1781), is integrated with the perspectives opened by Delaval (1777) and Sheldrake (1797) who make use of the analysis of physico-chemical components (Bordini 1991, 118–19). The techniques are observed, described and criticised not only with focus on performance, but also on alterations and deterioration of materials. The debate, which was opened by the conservation issues, compares, renews and firmly establishes the method, sometimes with controversial outcomes, different approaches and cognitive traditions in a renewed interpretation related to technological, historical and scientific observations. Artistic practices are not separated from these cultured elaborations and constitute their field of experimental verification.

The exchange that takes place in lesser-known technical fields about the introduction and experimentation of new organic materials presents evident analogies, in terms of development methods, with the process of re-interpreting encaustic painting. Research and experience relating to techniques for the reproduction of encaustic and continuous floors affect the same areas, drawing a precise cultural geography, and sometimes involving the same people. The Milanese Agostino Gerli's work can be read in the light of the described cultural coordinates as an example of osmosis between practices that define and qualify themselves in the exchange's many directions. Along with his two brothers, Gerli mastered artistic languages and technical specializations permeable to mutual interaction, in an applied arts workshop, where there was encaustic painting (Fig. 1) experiments, such as in Ferdinando Cusani's villa in Desio (Gerli 1785, 59).

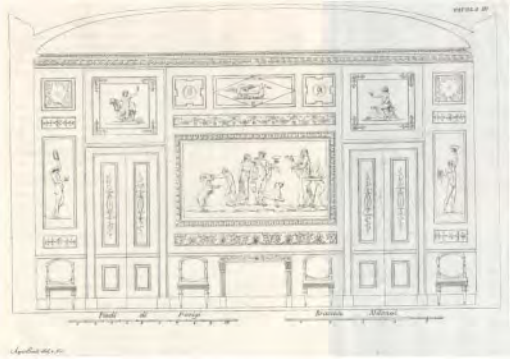

Figure 1. Engraving of encaustic painting for a bedroom of Villa Cusani in Desio (*Discorso sulla intonacatura de' muri ed all'antico modo di dipingere de' Greci e de' Romani*. Gerli 1785, pl. III).

2 THE OPUSCOLI SCELTI BY AGOSTINO GERLI (1785)

The Cusani, D'Adda, Moriggia, Barbiano di Belgiojoso, Andreani, Greppi, Anguissola, Monti Melzi, Serbelloni, Mellerio families represented the vast majority of clients that Agostino Gerli (1744-1817) received in Milan for the many applications of his innovative talent for taste in interior decoration and the production of luxury objects (Colle 1999, 150-55; Melani 2000). If he did not hold the boasted exclusivity of modernity, Gerli certainly knew how to offer this wealthy clientele complementary services and specializations, in an unstable area defined by the ephemeral needs of the fashion of the time. Sometimes he presents himself as an architect, but his training was unconventional from his start at Ercole Lelli's school in Bologna. Lelli was an anatomist, painter and modeller. Thanks to his patrons, Gerli consolidated relations with the Brera, Parma and Venice Academies of Fine Arts. It is unknown which contacts ensured his hosting of Honoré Guibert at the workshop in Paris in 1764 to carry out a *maître menuisier en bois* apprenticeship (Baccheschi 1990). Returning to Milan in 1769, he showed a chameleon-like talent, enhanced by the possibility of working in association with his brothers Carlo, who was a painter, and Carlo Giuseppe, an expert engineer or "mechanical artist".

Their *atelier* could offer diversified performances to satisfy the most varied requests, effectively nullifying the boundaries between the arts by using his operating method and its theoretical and empirical foundations. Gerli promoted his activity by skilfully using contemporary media (Fig. 2). Contacts with the editorial staff of two important contemporary periodicals, *Memorie enciclopediche romane* and *Antologia romana di Belle Arti*, gave him reasonable publicity and attracted the attention of Angelo Comolli in his bibliography of architecture (Comolli 1788, 273-274; 317-22).

Among his eclectic experiments, including a spectacular hot-air balloon ascent made with his brothers, Gerli's floor was one of the most successful types of continuous flooring. Its presumed inventor described it as free from defects found in other floors, and adaptable to different environments because it could be

OPUSCOLI

DI

AGOSTINO GERLI

PARMA

DALLA STAMPERIA REALE

MDCCLXXXV.

Figure 2. Frontispiece (Gerli 1785).

Figure 3. Detail (*Discorso intorno a una nuova maniera di fare i pavimenti*. Gerli 1785, 35).

superimposed on a pre-existing layer of any type and material except for wood.

The floor adapts, both in terms of colour and surface, to the characteristics of interior decoration, and thus becomes functional to the taste of the time, of which the inventor was an interpreter. This orientation looked for unity among languages in a variety of space components. It consisted "in an enamel [*smalto*] layer having the thickness of leather, which weighs very lightly on the underlying ceiling; it is as strong and resistant as a hard boulder, as it can be used to imitate marble and porphyry, and form any figurative ornament" (Gerli 1785, *Discorso intorno a una nuova maniera di fare pavimenti*, 43). Thinness, lightness, and mechanical resistance were evidence of exceptional performance, combined with the possibility of executing any design and of applying multiple colours on the surface (Fig. 3). The price of the enamel varied between eight and three *paoli* per *braccio quadrato*, but its low price did not apply only to production but also to maintenance, which was simple and, therefore, less expensive than treatments required for painted bricks used in France.

Marquis Giovanni Battista Moriggia was among the first to order a prototype for a building in Via Borgonuovo, which he had purchased in 1773 and entrusted its transformation to Giuseppe Piermarini. Gerli recalled its complex execution, which included a design "with compartments and several colours and figures, in Raphaelesque taste" (Gerli 1785, 44). Unfortunately, the client's premature death in 1783 prevented its completion. However, there is interesting evidence of the decision to replicate grotesque motifs also on the floor, a choice that spread to walls and vaults throughout Europe in those years, drawing on the neo-16th-century iconographies disseminated by engravings.

Gerli was careful not to reveal the formula of the technical process of his invention, justified by the need to preserve the marketing exclusivity in a highly competitive sector. The name chosen, *smalto*, referred to lexical uses attested to at least in Late Antiquity, which were already barbaric, and associated, even in a broader sense, with a protective barrier. The improved or innovative contribution introduced by the Milanese included an adhesion to the substrate and ease of installation. These features were associated with mastics used in construction, which permanently joined materials and reduced discontinuities in surface finishes – plasters and floors – in damp environments and as water repellents. They needed the highest degree of fast-setting properties in air and water, and water insolubility.

Media exposure helped to keep Agostino Gerli in the public eye. However, traces of his polytechnical creations and productions remained fragmentary even where he was historically recorded, such as the *maître ménuisier en bois* works. This study highlights his contribution to techniques related to *smalto* for floors, with applications documented in one of the most important noble residences in the city (Fig. 4), a place where a new taste in architecture was developed.

3 EXPERIMENTAL BUILDING SITES: THE RESIDENCES OF BARBIANO DI BELGIOJOSO

In Palazzo Belgiojoso in Milan, the floor and wall surfaces were set up with different formal results and finishing techniques suited to the room's use and tone. The works can be traced to the last decades of the 18th century. It was an environment comparable to a workshop where architects, artists and craftsmen worked together to ensure a renewal of language that could not be separated from the search for equally qualified material results (Forni 2020).

This programme was imposed by the client, Prince Alberico XII Barbiano di Belgiojoso, the first president of the Academy of Fine Arts in Milan and a

Figure 4. *Smalto* floor of a cabinet in Morando Attendolo Bolognini Palace in Milan.

cultured amateur of architecture, collector and bibliophile. Skilled workers of the time include the brothers Agostino and Giuseppe, who were involved in various assignments. This shows the move towards the hybridization of knowledge and practices that constitutes the innovative factor of their technical experiments.

Generic payments made to the artist for stuccoes in a personal room, and for carvings and floors between 1778 and 1787 have been confirmed (Bianchi 2017, 117 note 25). As for the floors, material traces can be found in 1816 in some rooms of the apartment on the second floor of the wing overlooking Piazza Belgiojoso. Here a "polished white and cendrée stucco" covered the bricks and matched the walls, which were decorated with floral paper on a white or sky-blue background (Forni 2020, 141). The soft colouring is adopted in contrasting variants for the floors of other rooms. The "enamel" features and qualities advertised in the *Opuscoli* in 1785 were reconfirmed everywhere: low thickness, adaptability to any underlying material and the possibility of creating a multicoloured surface.

The same properties can be noticed on the floor of a personal room in an apartment located in the wing facing the garden. Here the interior was renovated using a layer of stucco on top of the brick floor. Its colour recalled the lively paper tapestry with a green background and coloured flowers.

In the Prince of Belgiojoso's palace, Gerli's works were part of a repertoire of continuous flooring which exemplified countless variants. These were chosen according to the *convenance* that regulated the relationship between architecture and the interior decoration system.

These relations are expressed at the highest level of complexity in the client's project (Forni 2016) for the main reception hall, where the painter Martin Knoller was commissioned to fresco Alberico the Great's triumph. It was for this room that a payment was made in 1786 to Antonio Scotti "for having painted the ornaments of the new hall floor" (Bianchi 2017, note 41). This could have been when an experimental, fragile, continuous floor, decorated with painted ornaments, was tried. This proved to be a risky choice for the intended use, and subsequently had a short duration, since already by 1816 the original floor was replaced by a *terrazzo alla veneziana*.

Figure 5. Remains of *stucco* floor in the small chapel of Barbiano di Belgiojoso palace in Milan (1993, Private Collection, Milan).

Different specializations called into question other artists involved in the decoration of the chapel designed by Simone Cantoni (Fig. 5). The small room overlooking a bedroom had a "polished stucco" floor (Forni 2020, 146). To use an oxymoron, it was a modern, old-fashioned finish that guided us towards another direction of technical experimentation. The decoration of the tiny chapel was entrusted to Giocondo Albertolli who, in 1787, undertook to execute the interior in "glossy stucco to replicate marble" but did not provide details of the technical procedure used for the floor. This was described in later archive sources as "polished stucco", which allowed us to hypothesise that it was a coloured paste, applied with a spatula and polished with wax.

The terminology allowed us to include it among the countless variations of artificial stone that contemporary literary and archival sources referring to the Milanese building sites can define as "stucco" or "scagliola" in a complex semantic tangle that is hard to unravel. Based on the brief and ambiguous descriptions documented by archive sources, floors in the "stucco" category could have used a plurality of products. Their compositions, processing and installation methods and performance varied, against a similar final finish with a polished single- or multiple-coloured surface.

The Lodovico Barbiano di Belgiojoso Villa based on a Leopoldo Pollack design, was built ex novo shortly afterwards, between 1790 and 1793, and is in many ways "parallel" (Forni, 2014). The interiors, completed only on the ground floor, demonstrate the relationship between architecture, finishes, decoration and furnishings in a multiplicity of variations, each marked by a specific figure or character. The perceptive qualities, colour and shine of the surfaces represent the element of continuity between the villa's various rooms where "scagliola floors" or "squared scagliola" in two bedrooms and related cabinets were described in 1802 (Forni 2014, 62). In the eyes of contemporaries, much of the charm of this extremely modern architecture derived from the taste of the cosmopolitan client, the Austrian ambassador to London from 1769 to 1783 and a friend of King George III. Alberico's brother, a leading figure in London's cultural and social life, developed a profound knowledge of English living customs and taste. Here, since the first decades of the 18th century, the possibilities of using artificial stone had been the subject of lively discussion at the intersection between archaeology and science, and revitalised experimentation with traditional techniques. The infinite possibilities of reproducing precious materials using stucco represented a ductile tool for architects' imaginations applied to the ancient invention.

In the wide range of stucco applications, Isaac Ware (1756) focused on floors that he considered a modern and irreplaceable feature in its version made of plaster: "In elegant houses the floors of this nature are made of stucco, that is of plaster of Paris beaten and sifted and mixed with other ingredients. This may be coloured to any hue by the additional matter, and when well worked and laid makes a very beautiful floor, some of it looking like porphyry" (Fawcett 1998, 142).

The scagliola technique, in its Italian tradition (Massinelli 1997), attracted Robert Adam's attention during his trip to Italy. In this perspective, the meeting in 1756 in Florence between the architect and his colleague, Charles-Louis Clerisseau, with the collector and merchant, Ignazio Enrico Hugford, (Ingamells 1997) should be seen as an opportunity to compare notes. His brother, Enrico Abate di Vallombrosa, became famous for perfecting scagliola. Adam promoted the spread of scagliola throughout England as an alternative to the different types of stuccoes available (Gapper 1999; Gapper & Orton 2011). He suggested its use in the extraordinary anteroom floor of Syon House. Robert Adam particularly appreciated the ductile feature of this technique: "The scagliola is curious", he writes, "and could be made to answer different purposes; for instance, for columns resembling different marbles, for tables resembling mosaic work, and for most elegant floors for baths and low apartments, or for linings to any place damp, etc.; and likewise, for imitating different marbles in cabinet work, and such like things" (Fleming 1955, 106). The Adam brothers' speculations commenced with the commercial initiative of purchasing the Liardet patent for the production of an oil-based stucco. This resulted in a court case where they defended themselves claiming to have introduced their own variant by adding ox blood serum (Kelsall 1984, 118–23; Takenaka 2009, 112–19).

4 CONCLUSIONS

The material suggested by Gerli is clearly a mastic composed of fine grain aggregates to make it spreadable or applicable by brush in thin layers that could be smoothened, relatively elastic, and water-repellent. The exact composition is not yet determinable.

Although they differ in the formulations and proportions of the individual component groups, the materials and their joint and synergistic use almost always feature mastics. These were used in building sites between the 18th and early 19th centuries.

Experimentation started by Gerli found continuity in Milan in the marketing of cements available for the wide range of uses. The process patented by Giuseppe Giuriati, "experimental physics machinist", received an award in 1818 at the Lombard Institute of Science, Letters and Arts. His "cement" or "amalgam" lent itself to the creation of continuous floors and modular elements, waterproof fibre-reinforced roofing, water-repellent coatings of tanks, table tops and blackboards. Considered useful for hygiene reasons, this artificial material was proposed in 1818 for the remaking of floors in scientific classrooms and in the library of the University of Pavia. Giuseppe Marchesi, the architect in charge and professor of architecture, was in favour of its use, but his request for a discount on the estimate submitted was rejected by Giuriati, who withdrew from the tender (ASPv, Università - Rettorato, 22).

Formulations handed down by later sources used categories of components and surface finishes that ensured performance resembling the one described by Gerli. The formulae for mastics published by Giovanni Pegoretti in the variants always mention: an airborne carbonate binder (quicklime or slaked lime) added to a protein binder of animal origin, such as ox blood, silicatization or hydraulic or pseudo-hydraulic agents from pozzolanic reactions (such as cocciopesto, pozzolana, plant-based charcoal, Piacenza lime); marble dust and various traditional carbonate or siliceous aggregates; iron or steel slag filings; siccative and non-siccative oils, animal fats, plant-based or animal soaps (Pegoretti 1843, 227).

This "Milanese" tradition included the formula for "Stucco for bathtubs and bathroom floors" as experimented by engineer Gaetano Brey and published in his *Dizionario enciclopedico* (1843-52) (Brey 1844, 49-50). To confirm the continuity of interest, the formula was reproduced in several editions of a popular anthology (1867, 120–21; 1887, 183). The mixture was composed of a pound of ox blood, mixed to avoid clots, half a pound of "powdered slaked lime or calcium hydrate", half a pound of very fine marble dust, and three ounces of finely ground brick dust. They made stucco which consisted of a paste as soft as an ointment, which could be easily spread on the treated surface. The perfectly cleaned surface was prepared with a coat of hot ox blood using a brush. This was followed by the application of the stucco, which had to be carried out quickly to prevent it from settling. The first coat was more fluid to obtain better adhesion to the substrate, the second was denser to ensure a more compact and resistant finishing surface.

The directions pursued by technical innovation were confirmed in the most singular and dynamic variations even in the 19th century (Zhang et. al. 2018). Gaetano Brey's name came to be associated with a heterogeneous set of curiosities and eclectic experiments applied to pre-industrial building sites. The most famous outcome remained his improvement of the gas lighting system without a gasometer, introduced in Milan around 1830 (Del Curto & Landi 2008).

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Rebuilding after the earthquake: Earthquake-resistant construction techniques in Sicily in the 18th and 19th centuries

F. Scibilia
Università degli Studi di Catania, Catania, Italy

ABSTRACT: This essay attempts to offer a contribution on earthquake-resistant techniques employed in Sicily between the 18th and 19th centuries through a comparative study of construction practices after three earthquakes: that of 1726 in Palermo, that of 1818 in the Etna area, and that of 1823 in the northwestern part of the island. Research is based on a cross study of iconographic and bibliographic sources (manuscripts, printed works by coeval authors, and treatises), and new archival documents, which provide general views of damage to towns hit by earthquakes, as well as many expert analyses of individual architectures. An analysis of certain case studies and the systematic study of sources, integrated with inspection of the sites, will make it possible to analyse the technologies applied to consolidate and restore buildings. The paper also shows persistence and innovations, that contribute to outlining the development of an earthquake-resistant technical culture.

1 INTRODUCTION

Sicily is a notoriously seismic area, and earthquakes were – and are – a recurring aspect of its history, as documented by historic seismology.

Over the years, the answer to natural disasters has differed, depending on a range of factors: identity of places; extent of damage; availability of economic resources; materials and craftsmen; and the building techniques used. The cultural orientation of institutions, administrative management, and efficacy of legislative tools were also factors.

When exploring reconstruction of architectural heritage, earthquakes have represented an opportunity to get to know the buildings, as these assessments are almost always accompanied by surveys and experts' reports that evaluate damage and also often include reflections aimed at experimenting in the field of construction.

The reinterpretation of traditional construction practices by architects and workers, which has often accompanied post-earthquake reconstruction, has frequently been linked to an attempt to innovate techniques, materials and means of reinforcement from an anti-seismic perspective. These efforts also served to encourage regulatory bodies to draft rules, as well as technical regulations, as evidenced by the many reconstruction regulations that are issued after an earthquake occurs. The awareness that earthquakes can be repeated over time has, in fact, also led to steps being taken in the field of prevention, as well as developing strategies and techniques to mitigate the seismic vulnerability of buildings. This has given rise to the most recent technical and regulatory tools that call for architectural adaptations and improvements of a monumental and strategic nature.

We will try to verify if there have been any advances and forms of experience sharing among different periods, by comparing the construction practices adopted in the reconstructions after the earthquakes on 1 September 1726 in Palermo, 20 and 28 February 1818 in the Etna area, and 5 March 1823 in the northwest area of Sicily.

The research task has been undertaken by studying both bibliographical sources, - with particular reference to printed texts by contemporary authors and treatises – and iconographic and archival sources.

The analysis of this readily accessible documentation has made it possible to gain a deeper knowledge of the main types of damage and the consequent reinforcement and reconstruction interventions on buildings as related to the definition of anti-seismic design criteria.

2 POST-EARTHQUAKE INTERVENTIONS ON ARCHITECTURAL HERITAGE - BETWEEN TRADITION AND INNOVATION

When faced with the problem of how to deal with a building damaged by earthquakes, historically two paths have been taken: on the one hand, demolished pieces are repaired or reconstructed, revamping pre-existing traditional techniques, geometries and materials; on the other hand, an attempt is made to experiment and, consequently, innovate techniques (both materials and reinforcement elements) aimed at giving buildings greater resistance. This second path, explored here

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through the analysis of some case studies, has helped to define an evolution of building practices, based on verifying how effective certain solutions have been in the face of seismic events.

2.1 *Iron corbels, tie rods and hoops*

In 18th- and 19th-century Sicily, some attempts at seismic ’improvement’ were often associated with iron devices, such as the introduction of metal chains and hoops. These techniques were employed in order to absorb thrusts and provide more effective connection among resistant elements to prevent them from falling outside the floor. This material was also used for cantilevered elements (Scibilia 2020).

The criteria identified for suitable reconstruction involved the combination of stone with other materials, the first of which was specifically iron which had been identified as an essential instrument to confer solidity and resistance on buildings. Though more rarely, wood, which is highly appreciated due to its properties of elasticity and lightness, was also used (Scibilia & Campisi 2016).

In reconstruction after the 1726 quake, the iron chain and hoop technique was perfected considerably and systematically applied to a large number of buildings, both monumental and traditional, setting the benchmark for subsequent construction works in cities (Scibilia 2020).

Sources testify that a few days after the earth-quake, the Tribunale del Real Patrimonio, the supreme administrative body of the kingdom, issued a dispatch (10 September 1726) that provided instructions regarding emergency management and included requirements related to reconstruction, such as forbidding stone corbels in balconies and ordering balconies to be reconstructed using iron corbels and slate sheets (so-called ’balate’ or ’Genoa stone’). This provision was contrary to local traditions, according to which balconies were made using exposed stone corbels, stone balustrades acting as railing and sheets used as flooring; all of these were elements that, since the last quarter of the 16th century, had strongly characterised the façades of the city’s aristocratic palaces (Fatta 2002). This provision stemmed from the awareness that stone overhangs were fragile elements, and it can be considered as one of the first anti-seismic regulations in Sicily.

The adoption of metal chains and hoops became widespread in the reinforcement of vaults and domes, which, as it is well known, are characterised by a high degree of seismic vulnerability. In these elements, damage was suffered not only by the dome shell, which often presented deep cracks, but also by the underlying wall structures, the inadequacy of which was mostly caused by insufficient dimensioning. The most frequent intervention on domes involved inserting hoops surrounding the whole perimeter of the dome shell; whereas, in the arches, chains were positioned at the springer or at the reins.

Taking into account the documentary evidence found and inspections carried out on a series of buildings, it can be inferred that the chains and metal hoops belonged to different types: in the case of chains, a distinction was made regarding the presence of either single-bar elements or several bars put together in order to reach the desired length. Other differentiating criteria concerned the section (square or round) and the type of joint (Fatta 1993). Hoops, on the other hand, were made of circular or square (*quadralino*) section bars that had shaped ends or eyelets or, according the terminology of that time, *bocca di lupo,* i.e. having an end slot and connected with each other by means of the insertion of pins or sticks. Alternatively, hoops were characterised by flat iron reinforcements (*righetti o righettoni*).

Archive documentation has permitted further investigation of some monumental buildings in Palermo in which iron was widely used after the 1726 earthquake, as demonstrated by the cases of the Royal Palace, the Cathedral and the Church of SS. Salvatore.

In the Royal Palace, according to the report written by the engineer of the Royal Court, Giuseppe Mariani (8 October 1726), the introduction of a large number of iron chains located in different parts within the architectural complex was proposed; this included the Palatina Chapel where the dome was reinforced with metal hoops, for which the report written by Giuseppe Furceri, master builder of the Royal Court, specified the conformation of the elements and the connection system (National Archives of Palermo-ASPa, *Conservatoria*, b. 2452, fasc. 37, c. 1r).

Iron chains were also used for reinforcement work on the cathedral, designed by Giovanni Amico, who, in 1725, already held the prestigious position of engineer of the *Tribunale del Real Patrimonio* for the whole of Sicily. The intervention on the dome, described in four surveys drawn up once the works were completed (all of them dated 15 October 1729), provided for the construction of “different chains, *stanghetti*, *cugni*, *gaffe*, long pins, hoops and other things that were necessary for repairing the devastation caused by the earthquake” by the *ferraro,* Giovanni D’Angelo. These were placed on the roof, in the steeple behind the tribune, and in the chapels of Nostra Signora Libera Inferni and of San Francesco di Paola, in the north-west part of the church. Additional metal tie rods were employed when reconstructing the upper part of the bell tower where oak-wood chains were also inserted (ASPa, *Notai defunti*, Giuseppe Magliocco, vol. 5223, cc. 156r-157r).

Among the different buildings mentioned, the church of SS. Salvatore is particularly interesting due to the substantial use of iron in the reinforcement works. During the earthquake, the building suffered considerable damage in several parts, including the dome, which it was suggested should be demolished and then reconstructed. This recommendation, however, was rejected, given the fact that the intervention was expected to be more expensive than the insertion of iron hoops and tie rods, according to the

Figure 1. Palermo, Church of SS. Salvatore, detail of the connection system of the chain.

influential architects, Giacomo Amato and Gaetano Lazzara, who were asked for their opinion (ASPa, *Corporazioni religiose soppresse*, SS. Salvatore, vol. 843, cc. 116r-122v; Nobile 2004, 158; Scibilia 2015, 96-97). The works, which were carried out by *fabermurarius*, Simone Marvuglia, entailed the introduction of a large number of iron chains, consisting both of bars (*a braca*), and flat iron reinforcements (*a fascio*) for the hoops. The metal tie rods – the length and manner of preparation of which were specified – were placed at the arches limiting the main chapels and the choir, in the sacristy, at the corners, which were at risk due to the frequent lack of toothing in the intersection of walls, on the floor and in other, different parts of the building.

The chains were characterised either by single-bar tie rods (such as at the springer of the arches in the chapels) or by several square section bars that were put together. In the latter case, the end of one of the bars was made up of a simple eyelet while the end of the other one was characterised by a bifurcation; they were connected to each other by locking pins (Figure 1).

Such a system is the one that Jean Baptiste Rondelet, in his treatise, *Traité theorique et pratique de l'Art de Bâtir* (1802), would subsequently call a 'hinged' union, as exemplified by Figure 1 of table CXLVIII, contained in volume III, tome III, in which the adoption of iron reinforcements is shown.

In this type of connection, "the end of one of the bars forms a fork in which the end of the other bar is introduced. The three iron elements put together are perforated by a hole; through this hole, either a screw bolt or a key and some double wedges are passed" (Rondelet 1802, 59).

In the Church of SS. Salvatore, the iron hoops placed at the base of the dome along its perimeter are made up of round bars having slots at their ends so that the locking system can be inserted. Such a system consists of metal wedges, which pass through several chains and continue inside the stone buttresses (Figure 2).

The hooping system, placed at the springer of the small domes located at the main dome and at the tribune, is different; such hoops are made, in most cases, with flat iron bars connected to each other by means of pins.

Figure 2. Palermo, Church of SS. Salvatore, hoops placed at the base of the dome.

Even though the adoption of iron tie rods and hoops did not represent a novelty in the local context, as is demonstrated by their use before 1726, the earthquake constituted the perfect occasion to implement knowledge, to verify the choices that had been applied so far, to spotlight critical aspects and to take corrective measures.

The experience gained in the field of construction in this occasion was used after the 1818 and 1823 earthquakes, as indicated by express reference made to the measures and solutions tried out after 1726.

In relation to the quake that struck the Etna area between 20 and 28 February 1818, there are documented records of wall cross connection interventions by means of the insertion of iron chains, such as the ones foreseen in a private house in Catania by Antonino Battaglia, who indicated the placement of tie rods 'in a square', i.e. perpendicular to each other, and reinforcement of domed structures with metal hoops. This was done in the Church of San Michele Arcangelo in Catania, an intervention designed by Battaglia himself, and in the Church of San Giacomo in Aci Sanfilippo, where Salvatore Zahra Buda, head of the Catania Commission for Earthquakes, appointed by the Intendant of Catania, intervened (Lo Faro & Salemi 2009; Lo Faro, Mondello & Salemi 2018).

Iron chains were frequently used to reinforce bell towers, whose slender elements exposed them to greater seismic vulnerability. The use of metal tie rods is documented in the bell tower of the Basilica of San

Sebastiano in Acireale, where the structure was reinforced with a mesh of iron chains which was also used to reinforce the roof vault of the church at the central nave. A similar intervention was also carried out in the south bell tower of the Mother Church of the same city. This intervention, designed by engineer Giovanni Maddem, also included an increase in the resistant wall section (National Archives of Catania-ASCt, *Intendenza Borbonica*, b. 1159, cc. n.n.) which will be mentioned again further on.

As regards the 1823 earthquake, some reflections related to the use of iron can be traced back to Carlo Dolce, engineer of the Civil Engineer Corps and author of a text contemporary to the seismic event which contains considerations of a technical nature. Dolce approved the use of metal chains, which he considered necessary in order to make up for the "lack of tenacity and linkage in the different parts making up our buildings" (Dolce 1823, 35-36). However, he stressed the need to use them properly, both in relation to the positioning of the bars – to be carried out in such a way as to hold up the entire thickness of the masonry – and the adoption of a means to delay or prevent oxidation. In spite of the fact that the author did not specify such means, the methods used to counter iron oxidation were known and, in some cases, indicated by the writers of treatises. Some examples include the use of carbon black dissolved in linseed oil, as suggested by Francesco Milizia, or the method indicated in the subsequent treatise by Francesco Masciari Genoese, which recommended that "the iron used in walls should be previously coated with minimum on two occasions, or immersed in a cast lead bath…" (Masciari Genoese 1915).

Additional indications related to the use of metal elements were included in the "damage comparison charts" aimed at systematically identifying all the damaged buildings within each town; these "charts" constitute one of the most interesting documentary sources. In the "chart" corresponding to Monreale, which was drawn up after 13 March 1823 (ASPa, *Intendenza*, b. 7, cc. nn.), for example, it is possible to see that the most frequent reinforcement action consisted of the insertion of iron chains. The lengths, as well as the exact positioning and shape of the anchor plates – which always belonged to the Y-type (the so-called *a orecchie di lepre* or "hare ears") – of these chains were specified. Such a technique was adopted in Monreale for reinforcing not only several houses of private citizens, but also some monumental buildings such as the Monastery of the Benedictine Fathers, the Monastery of San Castrense, the Church of Monte di Pietà and the Archiepiscopal Seminary.

2.2 *Reed and plaster vaults and domes*

Among the innovations resulting from anti-seismic focused reflection on local construction criteria, we can mention the construction of reed and plaster vaults and domes, which were characterised by a self-supporting structure independent of the overlying wooden frame. The construction of these elements using light material was, in fact, a valid alternative to the consolidation of real vaults with iron hoops and tie rods, although the adoption of metal elements was also privileged in order to guarantee the preservation of the dome outside the building.

Figure 3. Rib vault in the church of St. Francis of Assisi in Palermo, revealed by the destruction caused by the 1943 bombings (Archive Soprintendenza per i Beni Culturali e Ambientali di Palermo. By courtesy of Assessorato regionale dei Beni Culturali e dell'Identità siciliana. Dipartimento regionale dei Beni Culturali e dell'Identità siciliana).

Although this technique had been adopted previously, for example, in Abruzzo after the 1703 earthquake (D'Antonio 2013, 99-109), in Sicily, one of the first documented cases of this construction system is the reconstruction of the dome of the Church of San Carlo alla Fieravecchia after the 1726 earthquake. On this occasion, the original dome shell, dating from the first half of the 17th century, made in freestone and covered by a Lombard-style lantern tower with an overlying small lantern, was demolished and rebuilt with a light structure that weighted considerably less than a real stone structure. The documentation proves the construction of a 'false' shell, a so-called rib vault (*a incannucciato*), consisting of a wooden supporting frame, made up of poplar ribs and large reeds (*cannoni*), placed on the intrados of the wooden deck to which it was nailed and covered with lime and plaster mortar (Nobile 2004, 158–159).

It was probably after the discussion that started in Palermo following the 1726 earthquake that Noto-born architect, Rosario Gagliardi, the undisputed protagonist of the long reconstruction season following the 1693 earthquake in Val di Noto, chose to adopt such a solution to reconstruct the roof vault of the Church of Santa Chiara in Noto (1735), designed and built with an oval vaulted structure crafted from wood, reeds and plaster.

A similar system was used by the same architect in the oval vault of the Church of San Michele Arcangelo in Sicicli (1750), as he was aware that this kind of structure was more effective in the event of an earthquake (Nobile 2012, 20).

Similar structures were adopted in the Etna area as certified and documented, among other cases, by the reconstruction of the reed and plaster vaults of the dormitory of the Benedictine Monastery in Catania, damaged by the 1818 earthquake (Lo Faro & Salemi 2009, 115).

On this occasion, a similar criterion was applied when reconstructing the *Loggia Giuratoria* in Acireale, where the vaults called *mazzacannate* (made of stone) were discontinued and replaced by false vaults (Municipal Historical Archive of Acireale, *Court of jurors*, Acts of Liberation, vol. 25).

Also, after the 1823 earthquake, a similar intervention was used to restore the Church of St. Francis of Assisi in Palermo (Scibilia 2016, 177–178). For this church, there is a report prepared by the court engineer, Giuseppe Patti, who was commissioned by the Chapter house of the convent to detect any instability and to suggest the appropriate “restoration” (Rotolo 1952, 159-60). For the 16th-century stone vaults, demolition and subsequent reconstruction were planned with ’false’ rib vaults both in the central nave and the side aisles, a system that, in addition to reducing the weight of the structure, also had economic advantages. The reconstruction with light vaults, actually carried out later (Figure 3), was also approved by court engineers, Luigi Speranza and Giuseppe Truglio, who, summoned by the convent fathers to give a second opinion, confirmed the validity of this solution.

The works on the church, carried out between 1824 and 1837 under the direction of several architects, involved building barrel and cross rib vaults matching, respectively, the central and side aisles, linking the foundation pillars, and their coating with *balatoni* (ashlars ‘palms’ measuring 2 x 2 x 1, where one palm is approx. 25.8 cm) from the Aspra quarries, turning the pointed arches of the main nave into round arches by means of lining with *pantofali* bricks (11 × 23 × 1.5 cm) and the reconstruction of the triumphal arch (Tinaglia 2005).

2.3 *Stone chains*

The search for alternative solutions for the reinforcement construction practice as a response to seismic events is evidenced, among other examples, by the original proposal developed to reinforce the Cathedral of Palermo by Amico, whom we mentioned above. One of the four reports written by the architect on the interventions carried out in the church – whose roof had been seriously damaged by the fall of the crenellations of the crowning – speaks of the adoption of “30 chains of ’Palazzo di Trapani’ stone made in a doubled dovetail by the masters of that city”, that is, stone “chains” shaped as a double dovetail (ASPa, *Notai defunti*, Giuseppe Magliocco, vol. 5223, cc. 158r-159r). The document does not specify the positioning of these elements, but their use is significant as an experimental intervention for the construction sites of the time. The hypothesis that this technique was foreign to the Palermo workers could be suggested by the choice of having these elements made by masters from Trapani, who would have resorted to the so-called “Palazzo di Trapani stone”.

It was after this experience that Amico himself proposed similar methods for the unrealised project of reinforcement of the dome of St Peter in the Vatican (1743), which at the time was severely dam-aged. This can be seen in the attached report where we read “of such chains I have full experience for having tested them wonderfully in the repair of the great ruins that occurred in the city of Palermo wrought by the earthquake of the year 1726”. The drawing, kept in the Vatican Library, shows four masonry ’turrets’ around the dome shell and stone chains with ’dovetail’ shaped ashlars to compensate for the damage; here, Amico extracts the details to give us a sufficiently clear idea of its conformation (Schlimme 2006, Piazza 2013).

The awareness of the anti-seismic effectiveness of stone chains is subsequently confirmed in other post-earthquake interventions. Gagliardi, whom we mentioned above, summoned Pozzallo in September 1744 to draw up an appraisal on the cracking of the 15th-century Cabrera Tower that was damaged by earthquakes. He proposed insertion of stone chains, to be installed together with iron bars, to reinforce it; it has been suggested that he was probably mindful of the Amico’s experience in Palermo after the 1726 earthquake (Nobile 2012, 22).

Use of this technique also following the 1818 earthquake is demonstrated by the report of engineer Fra Bonaventura da Sortino (2 May 1818), who was in charge of assessing the damage and the consequent restorations of the Church of Sant’Agata in Vizzini. To reinforce the vault, in which deep cracks had appeared, the use of “15 stone dovetails, three iron chains to join the bottom of the ‘Cappellone’ and another four on the sides of the nave” was proposed (ASCt, *Intendenza borbonica*, b. 4212, 1818-19, cc. nn).

2.4 *Supporting walls and pillars*

Another seismic improvement intervention was the construction of supporting walls and pillars, both at the foundation level and on walls above ground, which were aimed at increasing the resistant section of the solid walls, thus avoiding the demolition of considerable portions of the buildings. Walls could be reinforced either through the construction of continuous supporting walls leaning against the external faces or through discontinuous elements, such as pillars connected at the top by arches or architraves.

The construction of supporting walls after the earthquake of 1726 was documented in the convent of Santa Chiara in Palermo where linings in rough-hewn ashlars were made, both on the internal and external facing, in this case made integral with metal bars acting as cross connection (Campisi & Fatta 2009). This technique was mainly used in those cases in which the original masonry belonged to the so-called *pietra e tajo* type, i.e. made up of an internal core of incongruent material, characterised by broken stone, earth, straw and a little mortar, held by two faces made of roughly-hewn ashlar.

Works to reinforce walls were particularly widespread in the Etna area after the 1818 earthquake. From the documentation, it can be inferred that the effectiveness of the intervention was linked to properly toothing the new masonry to the existing one by means of ashlar blocks which were forcibly inserted by cutting the masonry.

A well-documented case is represented by the consolidation of the Mother Church of Acireale, where Maddem, whom we mentioned above, identified the insufficient dimensioning of the foundations as the main cause for the weak structures (ASCt, *Intendenza Borbonica*, b. 1159, cc. nn). The project considered a consolidation of both the north façade and the south bell tower, which was reinforced at the base with a scarp supporting wall of square basalt blocks (lava stone) called *cannarozzoni*, toothed to the pre-existing masonry (Figure 4).

A similar intervention was also planned for the church of San Giovanni Nepumoceno in Acireale, for which the same architect designed a reinforcement of the foundations with squared-stone supporting walls having a scarp section. This is documented in the report of 15 August 1820 on the restoration of the building (ASCt, Intendenza borbonica, b.1159, cc. nn.).

The use of a scarp profile was also deemed to be effective anti-seismic protection by Baldassare Spampinato, author of a text written at the time of the earthquake that contains observations on the vulnerability of buildings, on the materials used and, on the construction criteria prevailing at that time. The text reads, "If you want solid and lasting works, you have to start from the foundations. What is the form that best suits them? In my opinion, there is none better than the one commonly called scarp; this method must be maintained up to the top of the buildings, as we will say later. The advantage of such a form comes from a principle of mechanics, from which it is deduced that a body is more solid in proportion to the width of the base, on which it rests" (Spampinato 1818, 58).

The construction of supporting walls was also adopted by Antonino Battaglia for the building of the University of Catania, whose north, south and west fronts, after the 1818 earthquake, were evidently out of square. The intervention involved the construction of external faces of variable thickness (from 50 cm at the base to 26 cm at the top) on the three façades, toothed to the walls by means of large semi-square basalt blocks and having foundations 8 m deep (Dato & Magnano di San Lio 1999, 54–55).

Among the seismic improvement interventions adopted after 1818, it is also worth mentioning the use of buttresses (so-called *delfini*), both straight and scarp, as shown, for instance, in the Mother Churches of Zafferana and Tremestieri (Lo Faro & Sammartino 2019), Santa Maria della Catena (Figure 5) and San Giacomo in Acicatena and in the dormitories of the Monastery of SS. Trinità and the Reclusorio della Purità in Catania (Lo Faro, Mondello & Salemi 2018).

Figure 4. Scarp base with basalt *cannarozzoni* in the south bell tower of the Mother Church of Acireale (photo: L.P. Alfonso).

3 CONCLUSIONS

The comparative study of the construction techniques used after the three earthquakes examined, based on a systematic analysis of memorial sources and archive documentation, supplemented by on-site investigations on some monumental buildings, has highlighted some of the most widely adopted anti-seismic devices in Sicily between the 18th and 19th centuries, while offering a wider panorama of the technical culture of that time.

The study shows that the earthquake of 1726 represented a special chance to reflect on the anti-seismic validity of local construction techniques, and offered the opportunity to implement structural knowledge, to verify the construction choices applied so far, to highlight the critical issues and to make the necessary corrective measures.

The effectiveness of some choices made after the 1726 quake, which were considered to be 'experimental' at that time, entailed significant progress in knowledge, constituting a sure point of reference for the reconstruction works after the subsequent earthquakes that struck the island – in particular the 1818 and 1823 quakes – decreeing their application in both reinforcement interventions and buildings completely reconstructed.

Figure 5. Buttresses placed on the south side of the church of Santa Maria della Catena in Acicatena (photo: A. Lo Faro).

For the 1818 earthquake, there were no particular technical or regulatory innovations, as evidenced by the persistence of already-tested construction solutions. However, some post-earthquake management practices, similar to the current ones, emerged and were then replicated after the 1823 earthquake. As a matter of fact, the verification and monitoring of buildings, and the subsequent reconstruction works, were carried out in a thorough and rigorous manner, as can clearly be seen from the institution by the Intendant of Catania, the Duke of Sammartino, of Commissions for Earthquakes, which were located in the main urban centres of Catania, Bronte, Acireale and Adernò (today Adrano), each of them having competence over a territory. These bodies first carried out a systematic survey of the damaged buildings, leading to the formation of "Charts" that summarised the damage that occurred in each municipality. Each survey detailed the name of the owner, the location, a comprehensive description of the damages observed, the possible "temporary" precautions, i.e. the measures taken in a first emergency phase to avoid further damages, the necessary "shelters" and a first economic assessment of the interventions to be made. In addition, these commissions distributed the funds allocated by the government, approved the restoration project plans for the damaged buildings that each owner had to submit, and supervised the quality of the works carried out in each of the individual buildings (Iachello 2000; Mariotti & Ciuccarelli 2001).

The post-earthquake management system developed after the 1818 earthquake, reflected a renewed administrative system that, as of 1 January 1818, had abolished the island's century-old subdivision into the Mazara, Demone and Noto 'valleys', replacing it with the division into seven Intendencies (Palermo, Catania, Messina, Siracusa, Caltanissetta, Trapani and Agrigento). This system was substantially replicated after the events of 1823.

The cross-reading of these "Charts" and the large number of expert reports drawn up by the engineers and masters involved has provided an instrument of knowledge of the state of the buildings not only in relation to the damage, but also to the techniques used in the consolidation and reconstruction works. The reports have offered a sample of the solutions implemented, based on the adoption of recurrent construction practices, adapted to earthquake prevention criteria.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Education at the École centrale in Paris and its influence on the creation of modern iron construction

Tom F. Peters
Lehigh University, Bethlehem, USA

ABSTRACT: In 1829 a businessman and a group of French scientists and engineers established an engineering school to serve industry. Building on the French excellence in theoretical engineering they developed a pedagogy based on the concept of "vulgarization" that enabled engineers to function in both theory and practice equally well rather than simply learning how to apply predeveloped theory to practice. The method they used: a combination of intellectual communication, visual learning through drawing and tactile learning through workshop experience. The graduates of the program later helped develop the industrialized form of iron construction. They gained their initial professional experience in railway construction, the only field that used iron consistently as an industrially produced material in the first half of the 19th century. The school's pedagogy was successful and led to the industrialization of iron construction by the middle of the century. It also initiated changes in existing programs worldwide.

1 INTRODUCTION

How do we educate innovative engineers? What pedagogy will guarantee success? The École centrale des arts et manufactures in Paris provided an astonishingly successful answer in the first half of the 19th century. The school developed an innovative pedagogy and educated a number of civil and structural engineers, contractors and industrialists who, together with their spheres of influence, became prominent and innovative players in the development of our modern industrialized form of iron construction. They defined its system characteristics and self-assuredly proclaimed its aesthetic value.

The triggering issue for developing a successful pedagogy was the profound dissatisfaction of the engineering profession with the abstraction of the scientific approach to knowledge as it had developed in the course of the 17th and 18th centuries (Weiss 1982: 91–93) Although it was clear to engineers that the advantages of a scientific understanding of structural and material behavior were crucial to advancing the field of construction, it was equally evident that an interface between understanding and application was lacking. Science was too abstract and limiting a model for practical purposes because scientific thought excludes many minor – or from a scientific standpoint extraneous – factors that practitioners knew were important in order to achieve a successful result.

The content of a curriculum is only part of an educational process: it has to be communicated by an appropriate method based on an intellectual concept and backed by a school of thought. Weiss (1982) and Pfammatter (1997) wrote on the content of the curriculum, but no one has yet discussed the pedagogy and how the teachers interacted to make the program a success.

2 THE CONCEPT

Alphonse Lavallée, an investor in the early railway development and an influential group of liberal scientists and businessmen surrounding the short-lived journal *Le Globe*, recognized in the mid-1820s that industry was in urgent need of flexibly educated engineers who understood and could build on theory, and yet were also able to adapt to a rapidly changing industrial world.

France had recently lost the war, and these men recognized that Britain had enjoyed a serious advantage in industrial development that had contributed to its military might. While Britain's success rested on private initiative, it was equally clear that France enjoyed an advantage in the well-organized state support of science, especially through the École Polytechnique where eminent scientists specialized in developing the theory of engineering. The question was therefore how the French qualities could be applied to a liberal development in the service of industry.

The answer was a private school that bridged the boundary between analytical science and practical, industrial application. The first, a private school of higher education, was unheard of in France; and the second, the amalgamation of scientific research and engineering practice, had been prepared by Gaspard

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Monge in his approach to engineering education. He had developed his border-crossing approach from the end of the 18th century and had based the foundation of both the short-lived teacher's college, the École normale de l'an III (subsequently recreated by Napoleon in 1808 and later renamed the École normale supérieure), and especially the foundation of the École polytechnique on his ideas. However, Napoleon had subverted the new engineering school to become a military academy in 1804 and then, after the downfall of the empire, Laplace had directed it toward pure scientific research in 1816.

Scientific thought is quite distinct from technological thought. Scientists want to understand the world while technologists want to make functioning objects (Rankine 1856: 20). Not only are the goals of the two different, but even their languages. For instance, a scientist commonly uses the term "detail" to denote a minor and therefore hierarchically less important part of a problem, while a technologist always uses the same term to describe a small-scale problem, the solution to which can be as critical to the functioning of an entity as its major components. For a technologist, a "detail" is never "minor". Monge had avoided the distinction by relating all his abstract research to everyday practical problems.

Many of Monge's former students who concerned themselves with education, like Charles Dupin or Théodore Olivier, were inspired by this synthesis and they were unhappy with the turn toward pure science that the École polytechnique had taken under Laplace. The engineer Dupin complained of it in his eulogy of Monge in 1819 (Dupin 1819: 80–8; Pothier 1887: 26) and the mathematician Olivier strongly expressed his distain of the elitist attitudes of researchers who engaged in "pure science" to the detriment of practical engineering in the introduction to his treatise *Mémoires de géométrie descriptive* in 1851 (Sakarovitch 1988: 312ff).

They were not the only ones who were troubled by the inability of most theoreticians to make themselves not only understood by practitioners but available for their use. The general dissatisfaction of practitioners with theory had long bothered engineers from Bélidor in the 18th century to Navier in the 19th, and it was a dissatisfaction that Lavallée could build on.

Jean-Baptiste Dumas, an enthusiastic young chemist, inspired him through his brilliant lectures at the Conservatoire des Arts et Métiers (Colladon 1893: 187–191), and together they recruited the military engineer Philippe Benoit, the physicist Eugène Péclet and Olivier to their cause. Established scientists like Sainte-Preuve showed interest in their idea of a "Sorbonne industrielle", but only as a small program through the established university system (Pothier 1887: 23). This group was unwilling to agree to that. They had set their sights on the establishment of a comprehensive, independent and more flexible private school.

Through a former co-student of Dumas's in Geneva, Jean-Daniel Colladon, who had recently moved to Paris, they contacted the newly appointed liberal Minister of Education, Antoine de Vatimesnil, who was interested in all aspects of education. He agreed to support their novel idea of a private school against the established interests of the state schools. This was a daring political undertaking as the undergraduate École polytechnique, the École des ponts et chaussées and the Sorbonne were powerful institutions (Comberousse 1879: 33–34; Pothier 1887: 11, 33 and 59–60). What convinced the government was the idea to supplement the universities of the liberal arts (Beaux-Arts), the humanities (Sorbonne) and science (École polytechnique), with a university of the "industrial arts" (Lavallée & Dumas 1835: 3). Vatimesnil's tenure (and the whole reform-interested government) lasted only a year. But the short liberal interlude was enough of a window of opportunity for the group surrounding Lavallée, who wasted no time in founding the school.

In reaction to the missing translation between the two so different and yet interdependent professional modes of thought, science and technology, the École centrale's founders determined to find and develop a fruitful middle ground between practical empiricism and theoretical science in the service of industry. The method they decided on was "vulgarization".

The meaning of this French term in contrast to "innovation" lies somewhere between popularizing and enabling or applying. The key term is enabling (Langlois & Seignobos 1898: 271) rather than "applying". Vulgarization fulfills the intellectual function of pedagogical incorporation, not just the diffusion of knowledge, and it implies democratization and inter- or transdisciplinary cross-fertilization.

The two existing schools that educated engineers in France at the time could not fulfill this role. The École polytechnique had deviated from its original goal as defined by Monge and become a scientifically and research-oriented undergraduate school in the early decades of the 19th century. Its educational concept was based on innovation, while the more practice-focused graduate École des ponts et chaussées, still known today as an "école d'application" was based on the "application" of scientific knowledge to practice, and it exclusively educated engineers for the state at the time.

3 THE PROGRAMM AND THE TEACHERS

Lavallée was a gifted negotiator and organizer. He secured funding from his father-in-law, an expatriate French businessman in Louisiana, and formed the private school with his four partners: Dumas, Benoit, Péclet and Olivier. They also recruited Pierre-Charles Gourlier, a technically-minded architect from the state approval board, the Conseil des bâtiments civils, and Dumas's friend the experimental/theoretical physicist Colladon who had made the initial contact with the Minister of Education. These two men were intimately involved in the planning of the school alongside the five founders, but they were not counted as founders because they did not commit to long-term teaching as the agreement of association that the five founders had signed on 20 January 1829 stipulated. They left the group after only a few years, while one of the founding members, Benoit, left before the program even began.

The railway pioneer Eugène Flachat was also intimately involved in the project in its planning stages and a strong supporter of the concept of vulgarization (Malo 1873: 12) but he was fully engaged in his engineering practice and decided not to teach but rather to serve as a post-graduate employer of the graduates (Belhoste 2008: 60; Malo 1873: 52).

The founders hired Jean-Baptiste Belanger, a hydraulic engineer who was also a theoretician and former Monge student; the engineer and railway pioneer Auguste Perdonnet; and several others. They were quickly joined by Louis-Charles Mary, an engineer who had also studied under Monge. These men were all committed to the concept of vulgarization, crossing the boundary between theory and practice. They formed the core educators who produced a whole generation of innovators in iron construction, among whom William LeBaron Jenney and Gustave Eiffel would be the most prominent.

Through Flachat and Perdonnet, the railway industry played a critical role in the school's development and, although only 40% of the École centrale's graduates began their careers there (Belhoste 2004: 67), it formed an important element in the education of virtually all the iron constructors among them.

The reason for this is that railway construction was the only field in which iron was used as an industrialized material in the first half of the 19th century. All the other early iron structures that have been so thoroughly researched in the history of architecture and construction were experimental one-off structures that had been produced in small manufacturing establishments in a proto-industrial fashion, up to and even a little beyond the Crystal Palace of 1850.

Of the École centrale's teachers who exerted such an influence on the future of innovation in iron construction, it was Belanger who was able to bridge between theory and practice in mechanics, principally by systematizing statics for technical purposes by defining it as a special case in dynamics (personal communication from Karl-Eugen Kurrer 28/01/2019). His form of vulgarization consisted in linking every aspect of his theory to practical issues in the Monge tradition, which stood in contrast to the abstract approach adopted by his theoretical colleagues at the École polytechnique. His students considered him to be the true creator of engineering mechanics (Comberousse 1879: 95; Molinos & Pronnier 1857: vi).

Belanger was a practitioner as well as a theoretician and did not only live in the world of abstract analysis. In a committee with Olivier and Péclet he expanded how the curriculum communicated the concept of vulgarization beyond his own field by defining drawing and drafting as the language of the engineer in excruciating detail (Guillet 1929: 94; Pothier 1887: 168), thereby adding the visual aspect of learning into the curriculum and following Monge, who had considered descriptive geometry a visual "language" (Picon 2000: 27).

They went further than Monge however, and required the drawing teacher they hired, the architect Nicolas-Auguste Thumeloup, to teach drawing as a technical course, using buildings, structures and machinery as models rather than traditionally using the human body. Thumeloup was also obligated to coordinate and grade the students' work in all courses ranging from physiology, industrial chemistry, mechanics, general physics, railway and machine design to descriptive geometry, architecture and construction where one would expect visual communication. The whole program revolved around visual competence as the "language of the engineer" (Olivier). Eiffel is said to have bitterly complained of this stringent requirement in a letter to his mother.

Visual learning is complex. It is multileveled and non-linear. It enables adepts to combine information in new ways and at multiple scales through immediate and simultaneous visual analogy, unlike intellectual learning through lectures and reading that depends entirely on linear sequence and in which analogy can only be established through ratiocination after the fact. The effect of this concentration on visual learning was that the students developed a multileveled spatial ability and an intellectual flexibility in conception and design.

In the few early years in which Colladon taught the physics of energy that he defined as prime movers (steam engines), he supplemented the analytical and visual learning process with a third method: tactile learning through workshop experience as well as disassembling and analyzing actual engines that he caused to be delivered to his classroom.

This haptic learning contributed yet another level of understanding and experiencing to the students' education. The "feel" of a material, its weight, relative size, surface quality, heat conductivity and so forth all contribute to technical knowledge. Although he only taught for a very few years, the haptic tradition that Colladon initiated remained an important characteristic of the curriculum. This tri-partite, experiential form of teaching: intellectual, visual and tactile, distinguished the École centrale's curriculum from all other forms of engineering education that relied solely on the intellectual communication of subject matter.

All the teachers, and especially the two who had studied in Geneva (Dumas and Colladon) were influenced by the pedagogical teachings of Rousseau, and the railway pioneer Perdonnet had also studied under the pioneering pedagogue Pestalozzi in his youth. The influence of pedagogues and engineers educated in Switzerland on French engineering was substantial (for the influence of Swiss Protestant thought on engineering, see Peters 2015).

Pestalozzi stressed learning the ability to recognize the essence of a problem ("das Wesen einer Sache") through “Anschauung”, observation that leads to the creative act of “seeing”, which is the creative discovery of the unexpected that depends on analysis of what one observes and that lies beyond the individual limitations of perception. In religious terms “seers” are oracles; in science, art, technology or other activities like business they are creators. The degree of freedom from cultural limitation that a seer is able to attain defines the quality and the originality of that individual’s ability to see. This ability helped the students to cross back and forth freely between theory and practice and constituted an important component of the vulgarization approach developed by the school.

Although the first years were uncertain due to the fall of the government that removed the support of Vatimesnil and the Ministry of Education, requiring Lavallée to seek patronage from the Ministry of Agriculture and Commerce, compounded by the revolt of 1830 (“Les Trois Glorieuses”) with the abdication of Charles X and a cholera epidemic, the concept of the school’s educational system: tri-partite learning and education of the ability to see through vulgarization fulfilled a need, and the program matured quickly. One of its characteristic criteria was that all students, whatever major they chose in their second year, had to take all courses, including those that really concerned only the other majors. The difference lay only in the exercises: all students had to complete general exercises, while those who had chosen that particular major had additional, more detailed exercises to accomplish. This fostered the border-crossing character of the program and prepared the students to adapt to many different professional situations as well as preparing them to invent new ones.

4 INFLUENCING IRON CONSTRUCTION

As far as this applied to the new material iron, the instructors in machine construction, a field that developed the most of any in the early years, provided expertise in small-scale iron construction and metallurgy. Perdonnet provided the conflation of the small-, medium- and large-scale use of iron in locomotive design, track infrastructure and station hall construction, while Mary developed a consistent design method based on the concept that his teacher, Jean-Nicolas Louis Durand had created for the École polytechnique in the previous generation.

Mary translated Durand’s concept from an abstract method of formal manipulation into a construction and process-oriented approach that led to the modularization and industrialization of iron production and its use in system design and construction. To do this, Mary borrowed a great deal of visual material from Durand and others (Nègre 2011: 3–4), but far from merely plagiarizing it, he modified it to suit his purpose and amalgamated Durand’s step-by-step hierarchical development of formal design with two of his other former teachers’ concepts at the École des ponts et chaussées: Charles-François Mandar’s detail design course in architecture (construction as architecture) and Louis Bruyère’s technological approach to the use of materials as design parameters (construction as technology) (Picon 1988: 129, 1995). He shifted Durand’s focus from “composing” formal configurations of architectural elements, to “organizing” functional factors and unit structural members, and thereby subtly shifted the focus of the method from a resultant architectural form to the dynamic design process, and thus from “art” to “industry” (Mary 1862: 29–31 and 43–44).

Among the prominent graduates of this program, the most active in the development of modern iron construction were Camille Polonceau (grad. 1836) and Henri de Dion (grad. 1851) in the early period; and Eiffel (grad. 1855), Jenney (grad. 1856), Armand Moisant (grad. 1859) and Victor Contamin (grad. 1860) in the later phase. Eiffel became a design-build contractor and Moisant a consultant contractor, and many other graduates of those years entered the material manufacturing and construction industries.

Two others played important roles in the transitional phase from experimental iron construction to the industrialized form of construction around 1850–1860, a development that César Jolly, one of the largest and most experienced French contractors of the day, wrote about (Jolly & Joly 1863: 1–2).

The École central graduates who exemplified this transition were Alexis Barrault (grad. 1836) and Émile Baudet (grad. 1858). Both bridged between the technology of iron construction and the visual architectural aspect of the new material. Barrault clearly defined iron construction as an aesthetic statement in his development of the visibly exposed iron structure for the Paris Exhibition Hall of 1855 (Barrault & Bridel 1857: 2, cited by Belhoste 2004: 74 and 76), and Baudet, as partner in the contracting firm of Leturc et Baudet, assisted the architect Henri Labrouste’s transition from the structurally unclear and primarily decorative use of iron structure in the reading room at the Bibliothèque Sainte Geneviève in 1843–50 to the structural use and architectural expression of the material in the study room and the exposed stacks of the Bibliothèque nationale 1862–68.

Labrouste had innovatively designed this last building in Mary’s sense by organizing functions, materials and structure rather than by traditionally composing forms as was the norm in both the Beaux-Arts and Durand traditions (Neil Levine in Bélier et al. 2012: 172). Whether or not he had been influenced in this shift by the École centrale and its graduates is unknown.

From the outset, the École centrale had accepted foreign students into its innovative program. This was another break with established French tradition. As a result, the school’s influence was immediately international, and by mid-century, the success of the École centrale’s concept in establishing the connection between engineering and industry manifested in a spate of school foundations and shifts in focus of the already established engineering schools after mid-century, especially in the French- and German-speaking world.

The École des ponts et chaussées expanded its purview to welcome foreign students and include the civil aspect of the profession in 1851. New foundations were: the École spéciale de Lausanne in 1853, that eventually became the EPFL. It was founded by a group that included two graduates of the École centrale, Jules Marguet (grad. 1840) and Louis Rivier (grad. 1843). The Eidgenössische Polytechnikum in Zurich (the later ETH) followed Lausanne in 1854, and Munich's Polytechnische Hochschulein 1868.

Of the existing schools, the 1745 Collegium Carolinum became the Braunschweig Technische Universität in 1862; Karlsruhe's 1825 Polytechnische Schule morphed into the Polytechnische Hochschule in 1865; Dresden's 1828 Technische Bildungsanstalt was transformed into the Königlich-Sächsisches Polytechnikum in 1871; and Hanover's 1831 Höhere Gewerbeschule-Polytechnische Schule became the Königliche Technische Hochschule in 1879.

5 CONCLUSIONS

The novel form of engineering education pioneered at the École centrale in Paris was based on the pedagogical concept of learning to see by means of vulgarization, using intellectual, visual and haptic methods of learning across the full spectrum of subjects. It impacted the development of modern iron construction and the corresponding industries, helping to move the use of the new material from an experimental to an industrial phase. This shift critically influenced the creation of our modern infrastructure to an extent that remained unique in the history of construction. Its impact was similar to the analogous border-crossing educational system developed by Walter Gropius for the Bauhaus at the beginning of the 20th century in industrial and product design. Both of these systems fostered the creative ability to see, in the Pestalozzian sense, and led to a density of innovative activity that has rarely been seen since.

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Innovation and technology in the 19th-century Belgian window glass industry

V. Volkov
Universiteit Antwerpen, Antwerp, Belgium

ABSTRACT: This paper explores the development of the window glass industry in Belgium between the Belgian independence in 1830 and the outbreak of the First World War in 1914. This industry experienced a steady growth during this period, making Belgium one of the most important window glass manufacturers in the world. However, the nature of this growth is still not fully understood. In the existing literature, it is described as being based on traditional craft and lacking important innovations. This paper analyzes the development of new technologies in the Belgian window glass industry to argue that the industry was characterized by a unique combination of innovation and tradition. While Belgian glass workers were indeed very skillful, the entrepreneurs and engineers developed important innovations during this period. These innovations even became an export product in its own right, making the glass-producing region of Belgium into a true innovation hub.

1 INTRODUCTION

The development of the iron-and-glass architecture in the 19th century would have been impossible without the development of the associated industries of iron and glass production. The Crystal Palace, erected in London in 1851 to house the Great Exhibition, is both a fine example and a true symbol of this architecture of the industrial age. However, the glass that covered this magnificent structure was still produced by the means of the "traditional" manual process (Douglas & Frank 1972: 35). Indeed, mechanical production of window glass was not introduced on the industrial scale until after the First World War (Cable 2004). This presents us with an important question. In what way did window glass production change during the 19th century? Did it remain fully "traditional" or did important technological innovations take place?

This paper will take the Belgian window glass industry between Belgian independence in 1830 and the outbreak of the First World War in 1914 as a case study. Belgium makes a fine case study as it was one of the most important glass-producing countries in the world. The Belgian window glass industry grew spectacularly during this period. Production increased from 1.28 million m^2 in 1840 to 23.47 million m^2 in 1900. About 95% was exported (Chambon 1955: 198; Douxchamps 1951: 512; Engen 1989: 194).

Despite these achievements, this sector is generally characterized as very traditional and technologically conservative in Belgian historiography. This assumption is based on two arguments. Firstly, the usage of steam power was quite limited within the industry. Secondly, the manual skills and tacit knowledge of the workers (glassblowers) remained of paramount importance to the industry (Delaet 1986: 113–130).

However, the relation between "modern" industrial technology and "traditional" skills and tacit knowledge is far from dichotomous. The mechanization of manufacturing, whereby manual labor was replaced by steam-powered machines, was a long process. As is well known, mechanization first started in the textile industry (spinning and weaving) in the 18th century. Despite this, many industries remained "traditional" (based on manual labor) until the very end of the 19th century, such as many food industries, for instance (Samuel 1977). This does not necessarily imply a total lack of progress, however. As had been noted by Maxine Berg & Pat Hudson, intermediate forms integrating "old" and "new" elements were quite common. Often, it was precisely by combining old and new elements that various industries managed to succeed. Other types of innovation, such as new types of products (new "fashions" in consumer goods) or labor organization were important as well, but will not be explored further here (Berg & Hudson 1992). Rather, this paper will focus on the technological development in a specific industry, arguing that the mere usage of steam-powered machinery as a replacement of manual labor is not an adequate "one size fits it all" indicator of innovation in a given industry. Rather, the industry-specific production process needs to be assessed. The case of the window glass industry will contribute to our understanding of the process of technological innovation beyond simplistic dichotomies.

The development of the Belgian window glass industry took place within a relatively small industrial district formed by the surroundings of Charleroi

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and parts of the neighboring region of Centre. This kind of geographical clustering of industries can be seen as an example of an industrial district. It has often been suggested that such an environment is conductive to innovation, as various types of positive externalities occur there. Roughly, two types of externalities can be distinguished: “Jacobean externalities” (after Jane Jacobs, spillovers between different industries) and “Marshallian externalities” (after Alfred Marshall, development of knowledge specific for one industry) (Lane 2017: 36–38). While the Charleroi region was home to many industries, this paper will focus on the knowledge development within one specific industry, making use of Marshall’s theory. The theory of industrial districts was first developed by Alfred Marshall around 1920. It postulates that numerous small- and medium size enterprises clustered together can achieve effectiveness by sharing resources (economies of scale). Moreover, industrial districts form fertile ground for technological developments and innovations as much of the relevant knowledge is shared between various enterprises and individuals. This phenomenon was called the “industrial atmosphere” by Marshall (Popp 2001: 1–23).

This paper will explore how the Belgian window glass industry adapted and developed new technologies while retaining manual craftmanship as a key resource. It will survey both the adaptation of “general purpose technologies” such as steam power and electricity as well as the developments of industry-specific technologies like melting furnaces and annealing kilns.

While this paper focuses on the 1830–1914 period, a short note on the earlier period is appropriate here. Although the window glass became an important export product for Belgium only after 1830, the origins of this industry can be traced at least until the middle of the 18th century. Back then, various types of glassware were already being produced in the region of Charleroi of present-day Belgium. Around 1750, various owners of glass workshops recruited skilled glassblowers from Southern Germany and Alsace. These glassblowers brought the “secret” of the production of high-quality window glass with them to present-day Belgium (Lefèbvre 1938: 31).

This paper considers blown window glass only. The cast and polished “mirror glass” (plate glass), that could also be used as material for windows will not be considered as its production was quite different from the technological point of view and would merit a separate study. The production of basic chemical components for glass production is also not considered here. Important as it was, it was a result of the development of chemical industry, rather than of the glass industry in the strictest sense. Suffice it to say that the introduction of the artificial processes to produce soda by Leblanc around 1800 and Solvay shortly after 1860 was of great importance for the glass industry (Chopinet 2009; Lauriks et al. 2012).

In recent years and decades, the development of window glass technology has been studied by Chopinet (2009, 2012, 2019) and Cable (1999, 2002, 2013, 2020). However, these studies focus mostly on developments in England and France, and pay only limited (if any) attention to Belgium. Nonetheless, Belgium was an important center of technological innovation as well, as will be argued in this paper. An overview of the most important innovations in the Belgian window glass industry has been provided by Lauriks (2012a: 31–49, 2912b) recently. This paper will take the research a step further. By using “new” sources (both published and unpublished), it will explore how these innovations developed within the context of the glass-producing industrial region, whereby the knowledge seems to have been shared in a way that allowed innovations to develop through the interaction of various actors, such as entrepreneurs and engineers.

The paper is based on a wide range of both published and unpublished sources, such as permissions to establish factories, invention patents and publications in contemporary Belgian and foreign press.

2 STEAM POWER AND ELECTRICITY

Steam power and electricity are known to be the key technologies of the first and second industrial revolutions respectively. Therefore, the adaptation of these “general purpose technologies” by various industries is often regarded as a proxy of innovation and modernization in general. It is hence relevant to see how these technologies were adopted by the window glass industry.

The first steam engine in the window glass industry of Belgium was introduced in 1828 at the Mariemont glass factory (Stanier 1870). It remained the only steam engine in that industry until 1837 when the Frison factory also started to use one (ARA-Mons, chambre de commerce, dossier 343). By 1850, roughly one-third of all window glass factories possessed a steam engine (;*Journal de Charleroi* 7 July 1852; Poty & Delaet 1986: 72; Van Neck 1979: 575, 706). By 1896, all factories possessed at least one steam engine (Office du travail 1900–1902: vol. XV, cadre XIII, 30–31). By 1910, an average engine power per factory amounted to 46 hp. At the same time, at mirror glass factories, where more mechanical power was needed to polish the glass, the average power per factory was as high as 2295 hp, while in the mechanical engineering industry (machines and metal construction) it amounted to 12.5 hp per factory, and within the furniture industry mere 0.7 hp per factory (Office du travail 1913–1921: vol. VIII, 272, 267, 269).

Obviously, this mere quantitative data is insufficient to judge whether an industry was “modern” or “backward”. It is essential to look at the way the steam engines were used in order to arrive to a more balanced assessment. As various industries differed in their production processes, so the need to use steam power also differed.

In the window glass industry, the primary usage of stream engines was to mill and mix the primary materials. This usage is indicated in sources from the 1830s and 1840s (for example Statuts Société de Dampremy 1839: 343–347, AGR Mines n°. 776, dossier 1671 and n°. 778 dossier 582). In the second half of the 19th century, other usages started to emerge. For instance, steam engines were used to pump water or to drive ventilation equipment (AvCh, Etablissements, DA, BT 22, dossier n°. 698 and Etablissements JU, BT 110, dossier 3379).

From the late 1880s, factories started to use steam engines to produce electricity. The first usage of electricity was most probably for lighting (Établissements JU, BT 110, dossier 3379). By the First World War, electrical power was used for many other purposes, at least by the most progressive enterprises. For instance, the Piges window glass factory possessed nine electrical motors in 1916 that were used to action overhead cranes, to mill and mix primary materials and to saw wood for packaging. The usage of steam power was not reported anymore; the factory seems to have been fully electrified by then (MdV, Verrerie des Piges).

The use of electricity from the 1880s on, and the full electrification of at least some factories by 1914, indicates that the window glass industry was certainly then behind in adopting this new technology.

3 MELTING FURNACES

Melting furnaces are used to melt the primary material, such as silica (sand), flux (alkali) and stabilizer (lime) at temperatures of around 1200 to 1400 degrees Celsius. Coal was introduced as a fuel for glass melting furnaces in 1643 in present-day Belgium (Lefèbvre 1938: 22). The construction of melting furnaces did not change much until the 1860s. Furnaces contained large pots wherein primary materials were melted. Around 1860, an important innovation was developed in England by the Siemens brothers. It was a regenerative furnace that allowed for considerable fuel savings. The regenerative principle implied that the heat of the exhaust gas was used to preheat the fuel gas and air before burning. This process took place in the so-called regenerators; that is, heat exchangers constructed of refractory bricks. The fuel gas was produced in the gas producers, which transformed coal into gas by partial combustion with air. While the melting of glass still took place in individual pots, just like in old "traditional" furnaces, the Siemens regenerative furnace thus combined two important technological innovations: the usage of regenerators and gas producers (Cable 1999; Chopinet 2012 & 2019; *Fabrication et travail* 1907: 52–54). However, the adoption of this type of furnace and accompanying gas generators in Belgium took place rather slowly. In 1867, the Bennert & Bivort glass factory started to use this type of furnace. It took the factory years of experimentation to fully implement this type of furnace. By 1881 this firm, one of the most innovative in Belgium, possessed 18 melting furnaces, nine of which were of the new type (Drèze 1913: 446; MdV, Verreries Charleroi, 8914/161/57 and 8914/161/59, "Les verreries Bennert & Bivort"). But the real breakthrough came only with the tank furnace after 1880.

Unlike the older furnaces, which used pots to melt the primary materials, in tank furnaces the melting took place in a huge tank, allowing for a continuous production. As in the previous type of Siemens furnace, regenerators and gas producers were also used. Just like the regenerative furnace, the tank furnace was first invented in England by Siemens brothers. The first commercial tank furnace was installed at Pilkington factory in 1872. A lot of technical problems still remained, however. For instance, the wear of materials occurred at fast pace, so the lifespan of the first furnaces was limited to just a few months. Moreover, the first tank furnaces were used for the production of bottle glass (Cable 1999; Chopinet 2012, 2019).

The introduction of the tank furnace in Belgium was the merit of engineer Martin-André Oppermann. Originally from Germany, he had worked with William Siemens in England, where he had been introduced to furnace technology (*Revue belge des industries verrières* 1930). He settled in Charleroi in 1874 or shortly before, advertising himself as an "engineer and entrepreneur, specialist in Siemens furnaces for glass industry and metallurgy" in a local newspaper (*Journal de Charleroi* 9 February 1874). Between 1874 and 1875, he conducted experiments with tank furnaces at his own expense. His main achievement was the adaptation of the tank furnace for window glass production. Between 1876 and 1890, he worked as an engineer at the Jonet window glass factory, where the first large tank furnace for window glass production was installed under his supervision in 1877–1878 (Chambon 1969: 42–44; Drèze 1913: 450, *Journal de Charleroi* 29 February 1920; *Revue belge des industries verrières* 1930).

The Baudoux window glass factory, established in 1881, was the second to use tank furnaces in Belgium. Before starting his own factory, Eugène Baudoux had worked at the Jonet factory. We can assume that he learned the workings of a tank furnace there (Chambon 1969: 44). Together with his engineer Jean-Matthieu Pagnoul, Baudoux had made numerous improvements to the tank furnace construction. The greatest challenge in adapting the tank furnace for window-glass production, as opposed to the production of bottle glass, was a much greater depth of the glass bath required. This depth depended on the permeability of glass to the heat. This permeability depended on the glass composition, and hence on the sort of glass. For bottle glass, a bath depth of 30 to 40 cm was sufficient. For window glass, the depth required was 1.5 to 2 m, which implied tremendous technical difficulties. Baudoux and Pagnoul succeeded in resolving this problem. The construction of their first large tank furnace started in August 1884, and it was put in service around the new year of 1884/1885. It employed 36 glassblowers who gave it the nickname Leviathan. Encouraged by good results, Baudoux constructed a second tank furnace that was put into use in September

1885. (Damour 1896: 138–139; Linet 1888; *Moniteur industriel* 4 January 1885).

The final improvements to the tank furnace in Belgium were made by Emile Gobbe. Originally from France, he settled in Jumet near Charleroi in 1890. Here, he worked on further improvements to tank furnaces. With Pagnoul as a partner, he established a firm that came to play an important role on the world market for tank furnaces. Around 1896, there were two major players on this market: Siemens in England and Gobbe & Pagnoul in Belgium. Gobbe & Pagnoul dominated the world market, as, according to Damour in 1896, two-thirds of all tank furnaces in the world bore their signature. They were especially successful in the United States, where they delivered the majority of all tank furnaces. Gobbe & Pagnoul were a studio rather than a production company. The physical construction was executed by specialized contractors, who worked under the supervision of Gobbe & Pagnoul (Chambon 1969: 46; Damour 1896: 138–139). An advertisement published in a Belgian newspaper in 1895 lists various clients of Gobbe & Pagnoul in the United States, including, for instance, Chambers Glass Company (Kensington, Pennsylvania) and Thomas Wightman Glass Company (Pittsburg) (*La revanche des verriers* 15 May 1895).

Generally, the tank furnaces constructed by Gobbe were 25 m long and 3.5 m broad, while the depth of molten glass amounted to 2–2.2 m. The content reached 400 tons of glass (*La nature* 1896). Most tank furnaces in the Belgian window glass industry made use of Wilson gas producers, which added hot steam to the fuel gas in order to enrich it with hydrogen. Therefore, the use of large steam boilers became widespread together with tank furnaces (*Fabrication et travail* 1907: 52–53).

The introduction of tank furnaces in Belgian industry proceeded at a rapid pace in the second half of the 1880s and 1890s. By 1894, Belgian window glass factories used 32 tank furnaces in total. Only six pot furnaces remained in use at that time, and exclusively for the production of colored glass and other special sorts of glass requiring lesser quantities of glass melt (Engen 1989: 197). The introduction of the tank furnace profoundly affected the Belgian window glass industry in many ways. Because of the high cost of such an investment, the number of glass factories declined sharply from 42 in 1870 to 24 in 1911, while total production increased (*Journal de Charleroi* 21 February 1911). As the tank furnace allowed for a better (more regular) melting process compared to the pot furnace, the quality of glass also increased (Drèze 1913: 450). Moreover, it allowed for the elimination of potters' workshops, thus cutting on staff costs *(La nature* 1896).

The work of glassblowers changed as well. Collecting molten glass from the tank furnace was easier than from individual pots. This resulted in a lesser demand on the skillfulness of glassblowers, allowing a larger number of less skilled apprentices to be employed instead of fully-trained "senior" glassblowers. The huge discontent from the part of the glassblowers, who feared for their privileged professional and social position, erupted in violence on 25–26 March 1886 (as a part of a broader "social revolt") when they burned down both the Baudoux factory and its mansion (Baudoux himself managed to escape). This could not stop the rapid spread of new technology, however (Linet 1888; Poty & Delaet 1986: 78–85).

In all, the introduction of tank furnaces can be described as a truly revolutionary innovation. While the production process (glassblowing) remained manual, the industry could not be described as being "traditional" (craft-like) anymore. Apart from furnace itself, the adjacent equipment such as gas producers and large steam boilers transformed glass factories from relatively small workshops into large-scale industrial enterprises.

The development of the tank furnace was not an exclusively Belgian innovation, as it was pursued at the same time in other countries, most notably by Siemens (Cable 1999). However, after the initial introduction of this concept in Belgium, further improvement was in the main independently undertaken by various engineers and entrepreneurs within Belgium (Oppermann, Baudoux, Gobbe & Pangoul) in a successive, almost "relay race-like" way. This makes a fine example of technological development within an industrial district, where an "industrial atmosphere" allows for knowledge-sharing between various actors.

4 GLASSBLOWING

The second step in the production of any type of glassware after the melting of primary materials in melting furnaces is the shaping of glass mass into the required form. In the case of window glass, manual glassblowing remained the dominant technique until the First World War. Two methods to produce flat window glass were known from the Middle Ages: the crown glass method and the cylinder method (Cable 2004). As the crown glass method was not used in the 19th-century Belgium anymore, it will not be discussed further here. The "cylinder method", also known as "broad glass" in England, was a standard way to produce window glass in Belgium from around 1750 until the First World War. It was introduced by migrant glassblowers from Southern Germany and Alsace. In very basic terms, the method consisted of blowing a huge glass cylinder that was cut and flattened to achieve a sheet of flat glass. It may seem quite straightforward and uncomplicated a method, but the production of glass required exceptional skills. While glassblowing has developed mainly outside of craft guild organization, some aspects clearly recall guild-like conduct until the beginning of the 20th century. For a start, there was no formal vocational training. Learning was conducted on the workshop floor in informal way. Only sons or nephews of glassblowers were allowed to learn the craft. In a matter of fact, a "popular wisdom" even had it that only a person with "the right blood" could become a glassblower. Apprenticeship took up to seven years (Delaet 1986: 125–126; Poty & Delaet 1986: 125–154).

The tacit knowledge and craftsmanship of glassblowers were of extreme importance for the industry. Unfortunately, the content of this knowledge is largely unknown to us. For one, as the training had always remained informal, very little was ever recorded. Moreover, the famous assertion that "we can know more than we can tell" (Polanyi 1966) is very true is this case. Still, we possess indirect indications of the value of the glassblower's tacit knowledge. Wages are one of the best indicators in this respect. In 1846, glassblowers earned the highest wages of all Belgian industrial workers. An average day wage in glass factories was 2.58 francs, while in coal mines it was 2.07 and in linen just 0.80 francs (Olyslager 1947: 145–146). In 1846, the best glassblowers at the Mariemont glass factory earned 400 francs a month. Given that the average day wage in the Belgian industry amounted to 16 francs, we can conclude that at least some glassblowers used to earn tenfold the average wage (AGR Mines n^{o}. 778 dossier 1665). By 1891, glassblowers earned a day wage of 15 to 17.5 francs, while wool weavers, for example, had to be satisfied with a day wage of just three francs (Olyslager 1947: 146).

The glassblowers were very well aware of their exceptional position, too. For instance, in 1846 the glassblowers of the Mariemont factory resolutely refused to contribute to mutual aid together with other workers (AGR Mines n^{o}. 778 dossier 1665). Clearly, they regarded themselves as a special kind of workers, quite distinct from proletarians.

Yet this is not to say that they were totally conservative. Although the basic process remained unchanged, small improvements could prove surprisingly efficient. Between 1822 and 1867 various equipment pieces were developed that helped to support the glassblower's cane, thus allowing for a larger cylinder. These pieces of equipment are known as the *lanceman* (introduced in 1822–1823), *crochet d'ouvreau* (introduced in 1845) and *manique* (introduced in 1867) (;ngen 1989, 195; Lefèbvre 1938 52–54). A report on the state of the Belgian window glass industry published in the Official Journal of the French Republic in 1872 mentioned a kind of mobile support for the glassblower's cane that was mounted on a small rail cart. It is possible that various systems of supports for glassblower's cane were used in Belgium at that time. At any rate, according to contemporaries, these seemingly trivial innovations allowed for "great progress" in the window glass production, as they facilitated the production of larger sheets of window glass (*Journal officiel* 1872). Because of these improvements, the maximum size of glass plates evolved from 49 × 38 cm in 1820 to 130 × 86.5 cm in 1870 (Engen 1989: 195; Lefèbvre 1938: 52–54). Unfortunately, the origin of these "trivial" yet important innovations is unknown. It cannot be ruled out that they were imported from other countries. In any case, as was attested by the French report, the adaptation of these devices was perceived as an important advance in the Belgian window industry.

The quality of Belgian glass became recognized internationally. It was even quoted as "the best in the world" by a contemporary study (Lalière 1913: 17). The aforementioned French report described the Belgian window glass as being of distinguishing quality and superior to any other [foreign] product (*Journal officiel* 1872).

5 ANNEALING KILNS

Annealing kilns were used to flatten the glass and to cool it down. The annealing process consisted of two operations. Firstly, the cylinder had to be warmed up, cut open in the longitudinal direction and flattened to achieve a sheet of glass. Secondly, the sheets of glass needed to be cooled down in a gradual and controlled way. Otherwise, the glass could develop internal tensions and break due to a minor shock – or even spontaneously. The temperature in the annealing kiln was 600 °C.

Until around 1824, a primitive annealing kiln without moving parts was used. It consisted of two chambers. The glass cylinder was flattened in the first chamber. Afterwards, it was manually placed in another chamber. As soon as the second chamber had been filled, the whole furnace was cooled down. It was a discontinuous process. Much glass shattered along the way. Moreover, a lot of fuel was wasted as the kiln needed to be warmed up and cooled down time and again (Drèze 1913: 450–453; Pesch 1949: 12; Poty & Delaet 1986: 47–49).

The first attempts to improve the annealing kiln in Belgium in the period under consideration were undertaken shortly after 1830 by François Houtart-Cossé, director of the Mariemont glass factory. In a report he submitted to the Charleroi Chamber of Commerce (undated, presumably 1830s) he mentioned two of his own inventions that were meant to improve annealing kilns at his factory. These improvements were patented by him in 1830 and 1832. Unfortunately, these two patents have not been preserved in the archives, therefore we do not know exactly what their content was. It seems, however, that they concerned the use of "moving stones" and some way to use fuel more effectively. According to Houtart-Cossé's report, these improvements allowed for significant cost reductions, and were taken up by all other Belgian window glass factories within a short time (ARA-Mons, chambre de commerce, dossier 343).

The construction of the annealing kiln was hugely improved by two principles: the "turning stones" and the "annealing tunnel". The former was a kind of turntable that transported the glass mechanically from one chamber to another; the latter functioned as a kind of conveyor belt, thus enabling the gradual cooling of glass by transporting it from the source of heat, while the kiln worked continually.

The “turning stones” kiln was invented in France in 1825 or 1826 by a man named Aimé Hütter of the Rive-de-Gier glassworks. The annealing tunnel was introduced at the Chance factory in England in 1846 (Drèze 1913: 450–453; Pesch 1949: 12; Poty & Delaet 1986: 47–49). However, an analysis of Belgian invention patents reveals that both principles were known in Belgium already in the 1830s. As noted above, the “turning-stones” principle was probably introduced in Belgium in 1832 by Houtart-Cossé. Of particular interest are three invention patents, all dating from 1839. All of them incorporate both principles (turning stones and annealing tunnel), although they differ in some small details. The holders of the patents are Frison, Houtart-Cossé and De Dorlodot, all known window glass manufacturers in the Charleroi region at this time (AGR-2, inventions 878, 1133, 1408, 1428). It seems, therefore, that the annealing tunnel principle was introduced in Belgium earlier than in England.

The main disadvantage of invention patents as a source is that they tell us nothing of the factual implementation of the innovations. However, various considerations strongly suggest that these new types of annealing kilns were indeed put in practical use in Belgium in the 1830s and 1840s. First of all, the sheer number of patents for annealing kilns issued in 1830s and 1840s (more than a dozen) suggests a systematic innovating activity within industry, rather than isolated inventions that might never have had practical consequences. Moreover, all patentees were owners and managers of glass factories, people with practical knowledge of the industry and its requirements. Some held multiple patents for annealing kilns, whereby some minor improvements for previous patents on annealing kilns were protected (For example, inventions 845, 1133 and 1359 by Jules Frison). This suggests practical experimentation and usage of the kilns. Plans of glass factories accompanying requests to establish new or to modernize existing factories indicate the rate of introduction of these new kilns. Plans from the 1840s show elongated annealing kilns, which is a typical form for the annealing tunnel, as was the case at Denuite factory in 1846 (AGR, Mines, cartes et plans, AK3648) or Bennert & Bivort factory at the same year (AGR Mines, cartes et plans, AK3641). Meanwhile, plans from the 1830s show us “old-fashioned” annealing kilns without an annealing tunnel.

Therefore, we may conclude that innovative annealing kilns with annealing tunnel were first developed by the most innovative entrepreneurs (Frison, De Dorlodot, Houtart-Cossé) in the 1830s and introduced on broad scale by other entrepreneurs in the following decade.

Another major improvement of the annealing kiln was brought in by Désiré Biévez, an engineer at the Mariemont glass factory, in 1867 (Engen 1989: 195; Poty & Delaet 1986: 49). Due to a sophisticated system of “moving stones” that transported glass through the annealing tunnel, this kiln allowed the annealing time to be dramatically reduced from 7 to 8 hours to just 25 to 30 minutes (*Bulletin du musée de l’industrie* 1866 & 1870; Chevalier 1867: 81–82). The Biévez annealing kiln became a de facto international standard until at least the first decade of the 20th century. Or, as a Russian encyclopedia of Brockhaus-Yefron from 1901 put it, “The best annealing kilns, that are used everywhere, are designed by the Belgian Biévez of Haine St.-Pierre [Mariemont glass factory - V.V.]” (Petukhov 1901: 582).

6 DRIVERS OF INNOVATION

As has been mentioned above, the growth of Belgian window glass production was mostly driven by exports. The success of Belgian window glass on global market can be attributed to various factors. As already mentioned, the quality, which could be attributed to the skillfulness of Belgian glassblowers, was recognized internationally. Good access to primary materials and, especially, cheap fuel (coal) has been cited as a major advantage of the Belgian window glass industry, especially in the contemporary French publications (*Journal officiel* 1872).

Until the second half of the 19th century, the need to increase production was met by the increase in size of the melting pots. At the beginning of the 19th century, one pot contained 150 kg of glass, in 1860 it amounted to 600 kg and in 1875 as much as 1200 to 1800 kg. However, this had an unfortunate consequence for fuel consumption, as larger pots required more fuel in relation to the quantity of glass produced. While in 1840 some 260 kg of coal was needed to produce 10 m^2 of glass, in 1874 the same quantity of glass required 371 kg of coal (Drèze 1913: 442; Lefèbvre 1938: 51). Hence, the energy efficiency of glass melting declined as production increased.

The introduction of regenerative and tank furnaces helped to tackle this problem, as they allowed for the significant economy of fuel.

Moreover, the export orientation of the Belgian window glass industry implied permanent competition with manufacturers from other countries on the global market. In the given circumstances, being able to innovate was a must. Thus, in 1885, the *Moniteur industriel* (12 April) urged Belgian window glass manufacturers to adopt new furnaces as fast as possible in order to face competition from foreign competitors.

Other innovations, such as the development of new annealing kilns, could be attributed to the purposes of cost savings as well, since they allowed for the limitation of losses due to breakage, as well as a more efficient use of fuel.

All in all, we can conclude that innovative activity within the Belgian window glass industry was mostly driven by the ever-growing demand for Belgian glass on the global market, which can be attributed to the quality of Belgian glass and the advantage of accessible primary materials and fuel. This innovative activity was mostly focused on the improvement of the energy efficiency of the production process, as fuel consumption proved to be the major Achilles' heel of the industry.

7 CONCLUSION

The 19th-century Belgian window glass industry provides a great deal of evidence of innovative activity. The limited usage of steam power is not a reason to characterize that industry as "backward"; rather, it simply did not require that much mechanical energy. Due to the specific character of the industry, the effective usage of thermal energy was much more important. Therefore, most creative inventive activity was directed towards developing melting furnaces and annealing kilns. While many innovations had foreign sources, Belgian window glass manufacturers did much more than just passively import foreign technology. This can be described as a Belgian "tradition", if we remember that the window glass production was introduced in present-day Belgium by German glassblowers in the 18th century. The development of annealing kiln seems to be a Belgian development for the greatest part. While the most important innovations of melting furnaces originated abroad, they were further developed and commercialized in Belgium. It is interesting to note that innovation, while connected to certain individuals like Oppermann or Biévez, was firmly embedded in the context of an industrial district, with whole networks of entrepreneurs and engineers. The developing of melting furnace, for instance, was successively carried out by Oppermann, Baudoux and Gobbe. It does not seem to be a coincidence that Oppermann and Gobbe, who were both of foreign origin, decided to settle and develop their innovative activities in the glass-producing region of Belgium, where they could take advantage of collaboration with entrepreneurs and engineers who were active in the industry. The development of both annealing kilns as well as melting furnaces can be seen as an example of Marshallian externalities at work, whereby industry-specific knowledge was developed within an industrial district by various actors. This does not mean, however, that the traditional craftsmanship of glassblowers was of no importance anymore. Quite on the contrary, their tacit knowledge was crucial in securing the high quality of Belgian glass, which was essential for the success of the whole industry, and was held in high esteem. The window glass industry clearly had a hybrid character in which the "industrial" elements, such as modern furnaces, went hand in glove with "traditional" (manual glassblowing). Here we are reminded of Maxine Berg and Pat Hudson's thesis of the hybrid character of many industries during the Industrial Revolution.

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AGR-2: State Archives of Belgium, depot Joseph Cuvelier, Brussels Brevets d'inventions: n^{o}s 845, 878, 1133, 1359, 1408, 1428

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Compound brick vaults by slices in written sources

R. Marín-Sánchez & P. Navarro Camallonga
Universidad Politécnica de Valencia, Valencia, Spain

M. de Miguel Sánchez
Universidad de Alcalá, Alcalá de Henares, Spain

V. La Spina
Universidad Politécnica de Cartagena, Cartagena, Spain

ABSTRACT: The vaults called “par tranches” by Auguste Choisy are those built by laying the bricks with their bed in a vertical or slightly sloped position. The form and process of executing these vaults have been scarcely studied, partly because it is difficult to define the hidden elements of the masonry. Until the 19th century there were no primary sources explaining these ways of building, which depend more on the skill of the masons than on the abstract knowledge of the designer. This article compares the technical proposals of French and Spanish texts from the late 19th century addressing construction works in Byzantium and Extremadura (Spain). The genesis of the system (designed for barrel vaults) is explained according to each author. The subsequent evolution of different types of compound vaults is analysed with special attention to the groin vault since the others are based on its layout and construction strategies.

1 INTRODUCTION

The vaults that Auguste Choisy (1876, 1883) calls “par tranches” are those that are built by laying the bricks with their bed in a vertical position (aligned with the directrix of the arch), or slightly pitched. The brick is supported without the help of any formwork due to the adhesion of the mortar and the slight inclination given to the pieces when lime or clay is used as a binder. The alternative use of plaster allows greater freedom in the laying of the bricks, which can sometimes be even capricious.

The oldest examples of this solution, originally used for the construction of barrel vaults, have been located in the Middle East and Egypt as of the 13th century BC (Besenval 1984). The Eastern Roman Empire used this technique profusely and brilliantly to elaborate compound forms (groin vaults, sail vaults and domes) and disseminated it throughout the Mediterranean. It also spread throughout the Islamic world (Galdieri 1981). Examples abound in the Iberian Peninsula, some of them prior to the 10th century (Almagro et al. 2013; Araguas 2003: 84). Since the Modern Age, in an area of Extremadura, Spain known as La Raya, a characteristic type is very abundant, also extending through the Alentejo in Portugal to reach Lisbon and the south of Salamanca (Spain). In addition, it travelled to the New World, where in Mexico it continues to be used – and in a very imaginative way (Rabasa, in press).

In Extremadura today they are called *bóvedas a rosca*, but they are actually vaults by slices. The authors of the 19th century also called them pitched vaults or vaults by slices according to the layers (Albarrán 1855: 49; Ger & Lóbez 1869: 253). More recently, some researchers have referred to them as “byzantine brick laying” or “tangential” vaults (Araguas 2003: 84), or vaults “a bofetón” (Almagro 2013). A careful study of these *de rosca* vaults would likely show that they were a much more common solution than it might seem.

2 THE SOLUTION IN THE TECHNICAL TEXTS OF THE 19TH CENTURY

The real shape and the execution process of these vaults have been little studied, partly due to the difficulties in defining the precise arrangement of their bricks, which are usually plastered. Unlike the timbrel vaults, it seems that this variant was not incorporated into construction techniques texts until the 19th century.

The first written references to vaults by slices are found in 19th-century texts by several Extremaduran authors. In this region of southwestern Spain, the peak popularity of this variant began in the 18th century (Paredes [ca. 1883]: 2004). In 1855, a short article by Francisco Javier Boguerín was published in the magazine *Obras Públicas* encouraging civil engineers to use this option because it was economical. Boguerín pointed out that, although they were not reported in the treatises, the masons of Extremadura used this method with great ease. The manuscript describes the

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execution of barrel vaults in sparse detail, although its author claims to have seen “vaults of all kinds and openings built in this way” (Boguerín 1855:136). Later, the article was cited by Espinosa (1859) in his *Manual de Construcciones de Albañilería*, though he does not mention the author.

The text by Florencio Ger y Lóbez (1869, 1898, 1915), which also echoed Boguerín’s proposal, includes a greater number of variants. Ger y Lóbez explains and draws, for the first time and with greater precision, what he calls “shear vaults, without formwork” according to the traditional method of radial beds, down to the angle of slip and the link of their “cuts” or pitched slices (Ger & Lóbez 1869: Figs. 292–294).

In 1885, José Albarrán García-Marqués published another description of this technique in his article “Bóvedas de ladrillo que se ejecutan sin cimbra” (“Brick Vaults Executed without Formwork”). Relying on fairly precise drawings, he explains how to build barrel vaults, as well as the adaptation of this method for the formalization of “bóvedas cruzadas” and “bóvedas de pabellón”. In particular, he also lists several real examples that follow the method (Albarrán 1855: 89).

But beyond these precocious incursions, the studies of two authors from the last quarter of the 19th century stand out from the rest since they describe the design and construction strategies of these vaults in a more detailed way. The French engineer Auguste Choisy (1841–1909) first published a paper in 1876 and subsequently his full investigation in 1883 in the book *L’art de bâtir chez les byzantins* (*The Art of Building in Byzantium*), where he analyses the construction processes of the eastern part of the Roman Empire, dedicating six chapters to the execution of brick vaults by slices.

The Extremaduran architect Vicente Paredes (1840–1916), who trained at the Madrid Special School of Architecture, wrote a manuscript entitled “Construcción sin cimbra de las bóvedas de ladrillo con toda clase de morteros” (“Construction of Brick Vaults without Formwork with All Kinds of Mortars”) probably between 1883 and 1885 (Pizarro & Sánchez 2004: 14). In this book he details the technical design and the construction of Extremaduran vaults with bricks arranged by vertical or pitched slices.

Choisy’s explanations are precise and methodical while Paredes’s are more intuitive, although less didactic. The first arise from the analysis of a selection of real examples, which the author complements with the construction of a 3.40 m-span vault, with 22 × 11 × 5 cm bricks, to reinforce his hypotheses (Choisy 1876: 441). The latter are deduced from daily practice, although Paredes attempts to enrich them with some theoretical reflections of a geometric nature. However, both technicians describe systematic processes that allow the construction of a certain variety of vaults (groin vault, sail or star vaults) that are normally set as the composition or intersection of cylindrical fragments, whose execution is similar to that of a barrel vault.

The most elementary technical solutions in the form of a barrel vault in the texts by Choisy and Paredes have been studied by Rabasa et al. (2020). These authors suggest that Paredes may have known Choisy’s work because his proposals have points in common, despite Paredes’s proposal of an unprecedented configuration based on the definition of concave constructive cones for the formation of the slices of the vaults, which is the opposite of the convex cones proposed by the French author. As noted, Choisy bases his proposals on the study of Byzantine vaults while Paredes echoes the Extremaduran construction tradition (18th and 19th centuries). For this reason, it is reasonable to compare the technical proposals of these French and Spanish texts of the late 19th century.

This work analyses the design and construction strategies of the groin vaults defined by these five authors, based on the studies of Rabasa et al. (2020) for barrel vaults, and their adaptation to other variants of compound vaults, devoting especial attention to sail vaults (Figure 1).

3 TECHNICAL CONCEPTION OF THE SYSTEM

The vaults by slices arise from the necessity of building brick vaults without formwork in the absence of wood. It should be remembered that the formwork, in addition to serving as a support for the bricks while the lime mortar sets, permits control of the shape during the implementation process.

The absence of plaster as a binder forced many builders to look for assembly strategies and construction arrangements that would help to preserve the position of the pieces when the adherence of the lime or clay mortar was not sufficient. The bricks slide due to the action of the tangential component of their own weight. The force of friction, strengthened by the adherence of the mortar, opposes this sliding. Therefore, to increase the stability of the pieces during laying, it is advisable to use light bricks with wide beds in order to increase the contact surface and, therefore, the friction. Furthermore, it is necessary to take into consideration the possibility of laying the bricks with inclinations of less than 40^{o} to reduce the incidence of tangential force. This option can also be reinforced

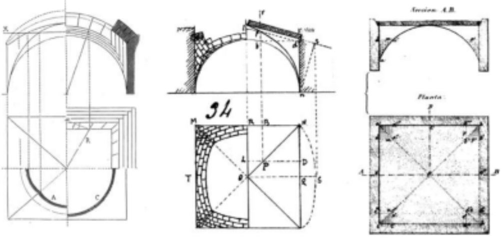


Figure 1. Tracing of the groin vaults in Choisy (1876: pl.21), Paredes (ca. 1883: pl.4) and Albarrán (1855: 86).

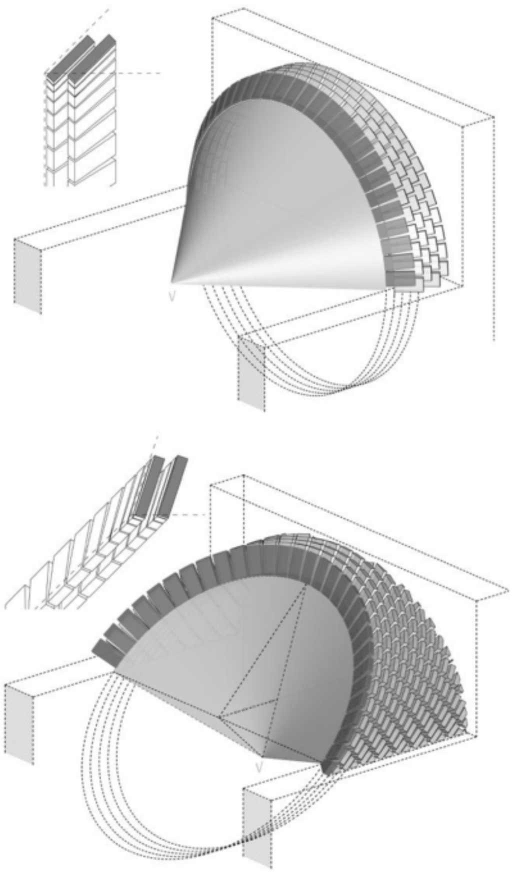


Figure 2. Above, convex cones vault (Choisy). Below, concave cone solution (Paredes).

by other additional means to improve the fastening, increasing friction and preventing parts from slipping, such as the formation of the pitched and conical beds so characteristic of vaults by slices.

Byzantine builders, for example, usually used large, thin bricks. According to Choisy, the smallest ones were 30 × 15 × 4 cm and to help their stability and prepare the correct seating plane of the next sheet, a thick layer of mortar, 4 to 5 cm thick, was laid on them just after their placement (Choisy 1883: 37). As will be seen later, this levelling layer is essential when the slices are inclined and conical. In Extremadura, Paredes (ca. 1883: 160) recommends using a small brick measuring 21 × 14 × 3.2 cm called a “trabuto” or “stool” because, when the vault is small, a larger size creates “too large openings for wedging in the back of the layers”. However, in one of his examples he uses a 28 × 14 × 2.4 cm brick, which is quite close to the size of the bed proposed by Choisy and the Roman “later pedales” (López & López 2015: 995), although the thicknesses of the Extremaduran bricks seem to tend to be smaller and, therefore, so is their weight.

Regarding the tilt of the pieces, Choisy (1883: 31–37) explains four possible arrangements used by the Byzantines to ensure the stability of the bricks during the execution of a barrel vault by slices. These are the result of formalizing the vault by adding vertical or inclined slices up to a maximum of 45^{o} and, optionally, arranging the beds of the bricks to the directrix of the cone or with a slight inclination of about 20^{o}. Arguably as compensation, the most favourable settings for the stability of the pieces are those that acquire more complex shapes. In addition, the option of inclining the pieces relative to their directrix plane forms frusto-conical slices with their axis in horizontal position (coinciding with the axis of the vault) or slightly inclined (with their axis tilted). This creates difficulties in controlling the shape that led Choisy to offer his own solutions based on the use of ropes and belts.

As mentioned above, according to Paredes, in Extremaduran vaults the brick layers form concave cones (from the operator’s working plane) and not convex ones, as described by Choisy in the Byzantine examples. In this case, the plane of the directrix is also inclined as in Choisy: the difference lies in the direction given to the inclination of the bricks with respect to the directrix plane (Figure 2). For Paredes, this peculiarity improves the resistance of the leaves and facilitates the implementation. The process has been explained by Rabasa et al. (2020: Fig. 17).

4 GROIN VAULTS

The groin vault has been treated in different depths by four of the five cited authors. Florencio Ger y Lóbez (1869: 255, 1898: 258, 1915: 202) describes these vaults as the result of the encounter between two-barrel vaults with their bricks arranged by inclined slices. Neither the graphics nor the text provide information on the exact arrangement of the slices. His recommendations are strictly constructive. In the 1869 edition, the author emphasizes the need to formalize both cylinders simultaneously, without the help of formwork, to ensure stability during execution and the formal control of the edges. For the definition of these edges, he briefly proposes the setting of diagonals using ropes and plumb or by the natural meeting between the brick slices of the two barrels, performing an ellipse in this case (Ger and Lóbez 1898: 258). During the laying of the bricks, they are mounted “one on top of the other”, compressing each other “by their edge” (Ger & Lóbez 1915: 202).

In his texts, the Frenchman Choisy (1876: 443, 1883: 49) makes a conceptual abstraction of various real cases of groin vaults on a square and rectangular plan that proves a more practical understanding of the type. As stated above, his explanations address the control of the form and the problems of implementation in an orderly and exhaustive manner, based on plan and elevation drawings that refer to the examples studied during his travels.

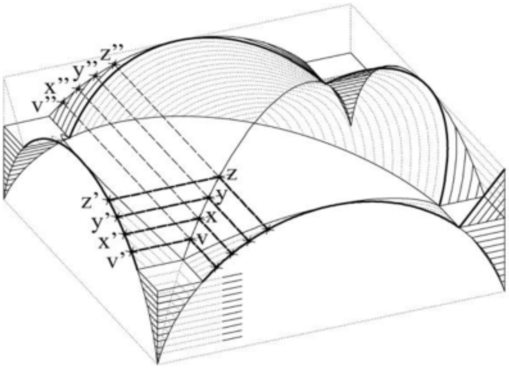
During his fieldwork, Choisy identified two design variants in Byzantine groined vaults, but only one constructive arrangement for the bricks. He begins his exposition by explaining that the principles applied to barrel vaults “immediately resolve the question of groin vaults”, understood as an intersection of two cylindrical surfaces formed by layers parallel to the perimeter arches (Choisy 1883: 49). In this case, its conception would be similar to that proposed by Ger and Lóbez, but with one caveat: in Byzantium the cylinders are formed by vertical frusto-conical slices and not by inclined flat courses (Choisy 1876: 444, pl. 21). He also points out that the underground vaults at Vatopedi, Athos and those of Zografos belong to this first group. But he immediately clarifies that those examples are, in fact, exceptional. According to the author – and this is his most important observation – the Byzantines preferably opted for another, much more interesting geometric construction method to form the groin vaults which facilitated the execution and produced less thrust. Moreover, it allowed the closure of rectangular plans and could be easily adapted to the construction of other compound vaults.

Something similar occurs in Paredes’s text (ca. 1883), whose dissertation is not as systematic as Choisy’s, perhaps because it is a rough draft, but offers some drawings that reveal great insight. The author states that this variant is one of the most important in construction due to its numerous applications, and his approach to these vaults is especially complex. Like Choisy, he first describes the groin vault as the meeting of two barrel vaults formed by cylinders of inclined slices with a frusto-conical section (Paredes ca. 1883: 130). But then, he offers various variants of increasing difficulty in which he progressively moves away from the initial constructive concept towards a purely formal typological classification of various compound vaults that only considers their edges and the shape of their panels.

Albarrán (1855: 85) pays little attention to the shape of the groin vaults, but offers interesting recommendations for the construction process of the solution by cylinders and some novelties on the formation of their springings. This author reports that the vault is initially built from the inside by four masons, one for each lunette, forming “curvilinear slices” (truncated cone courses), just like in barrel vaults. When the masons start to get in the way of each other, they continue the construction from the rear side.

Albarrán offers two enforcement procedures. For the first one, he uses two strings attached to the vertices of the opposite arches as a guide. The formation of the edges depends largely on the skill of the mason. For definition purposes it is supported by five plumb lines, four of them “close to the angles and on the diagonals” and a last one at their intersection. The plumb lines only determine the plane in which the cylinders are located, which is why he warns that “irregular edges are often seen that the mortars and plasters have to correct” (Albarrán 1855: 88).

Albarrán states that his second method had been inspired by the work of commander Don Carlos Vila, whom Ger y Lóbez also claims to follow when he sets out his constructive indications. According to



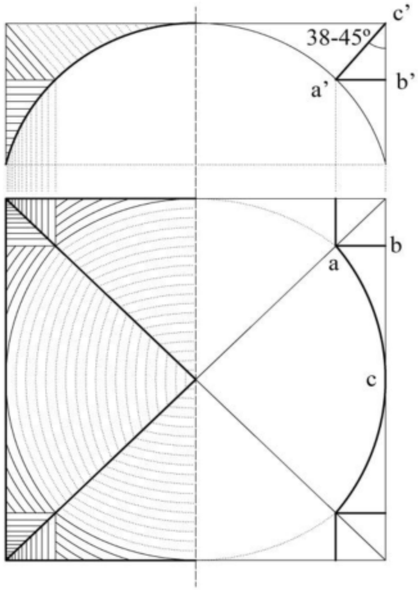


Figure 3. Trace of the Extremaduran groin vault according to Albarrán (1855: 86).

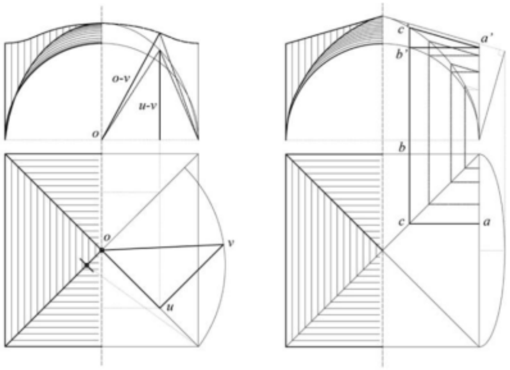


Figure 4. Trace of the Byzantine groin vault according to Choisy (1883: 55) and the Extremaduran pointed groin vault with “retumbo” proposed by Paredes (ca. 1883: plate 4).

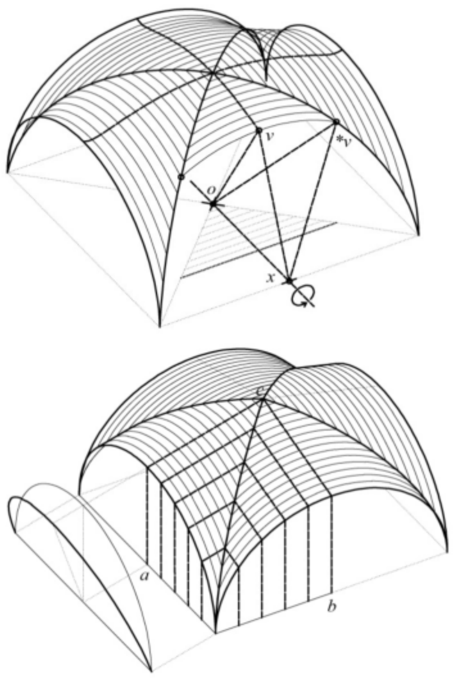


Figure 5. Comparison between the Byzantine groin vault (Choisy) and the Extremaduran pointed groin vault (Paredes).

Albarrán, this method makes it possible to make the edges "with bricklayers who had never built groin vaults as perfect as those performed by the most skilled masons". In this case, the four lateral arches are divided into the same number of parts, as if it were a subdivision into voussoirs. Each of these divisions is numbered and joined with its equivalent in the opposite arch by means of ropes (Figure 3). Thus, the intersections of these "tendeles" define in practice the points of control of the joins, since those lines match the generatrices of the cylinders. The greater the number of divisions of the arches, the greater the number of control points that will define them, and therefore, the more precise its definition will be (Albarrán 1855: 88).

5 FROM THE GROIN VAULT TO THE COMPOUND VAULT

According to Choisy, the Byzantines introduced an alternative design for the groin vaults to avoid the formation of elliptical curves at the diagonals and correct the height of the central point. This solution was suitable for both "elongated rectangular plans" and square ones and was generalized for the design of other variants of compound vaults.

The layout described by Choisy reverses the problem, giving the designer great freedom (Figures 4, 5). The diagonal arch is always an arc of circumference that sometimes has its centre under the line of imposts so as not to exceed the height of the perimeter arches. As a result, the four panels or lunettes of the vault always take the shape of a surface of revolution. The condition of a common centre of intersection for the axes of revolution of the four panels can also be breached. Optionally, those axes can be arranged at different heights. In addition, the control of the form during execution is simple and lies in two operations. The correct formation of the diagonal is controlled with a wooden ruler or a rope tied to its geometric centre; the same happens with the slices of the vaults. The latter are formed by circumferences of variable radius whose measures are obtained successively just by taking the rope to a point on the diagonal. Each measure defines the layout of the concurrent course at that point (Choisy 1883: 54–56). Logically, this graphic abstraction of the author is expected to suffer some deviations during the construction of the vault. Ger y Lobez's 1898 edition includes a proposal very similar to the previous one.

In this system, all the elements of the layout become independent of each other. A panel can be lowered; the next one can be lifted; the diagonal arch can be given the desired deflection and each lateral arch can assume the appropriate height. The resemblance of this layout to the Gothic ribbed vaults design is evident and highly advantageous because it allows the formation of different shapes, from cylinders to surfaces of revolution and even a perfect sphere (Choisy 1876: 444, pl. 21). Nevertheless, it sometimes also introduces some rather peculiar irregularities to the relief of the vaults. In the case of the groin vault, its edges are gradually lost in the upper part of the vault, which usually approximates a spherical shape. In addition, the curve of the cross section presents an inflection in the shape of a small counter-curve close to the perimeter arches or the walls that support the vault (Choisy 1883: 55).

The Byzantines sometimes chose to hide these defects and sometimes not. The author describes some techniques to correct them and also reports on the numerous licenses that these builders introduce to make the shapes of these vaults more flexible and adapt them to a wide variety of requirements. This also allows a more agile execution when it comes to covering secondary spaces – such as fortifications – where construction speed prevails and such irregularities of their vaults are less of a problem. Apparently, there are currently no graphic studies that support Choisy's hypotheses (Huerta 2009). The authors of this article are collaborating with a team of researchers to verify them.

Like Choisy, Paredes also addresses the execution of non-canonical groin vaults in chapter 2 of his manuscript. His proposal also affects the layout of the edges, although with a different strategy. He starts transforming the orthogonal cylinders by tilting their directrix. He then proposes other variants in which the vaults are made up of surfaces of revolution (toroids or ellipsoids). And, finally, he also shows the formation of pointed vaults and even starred vaults or compound by spherical sectors.

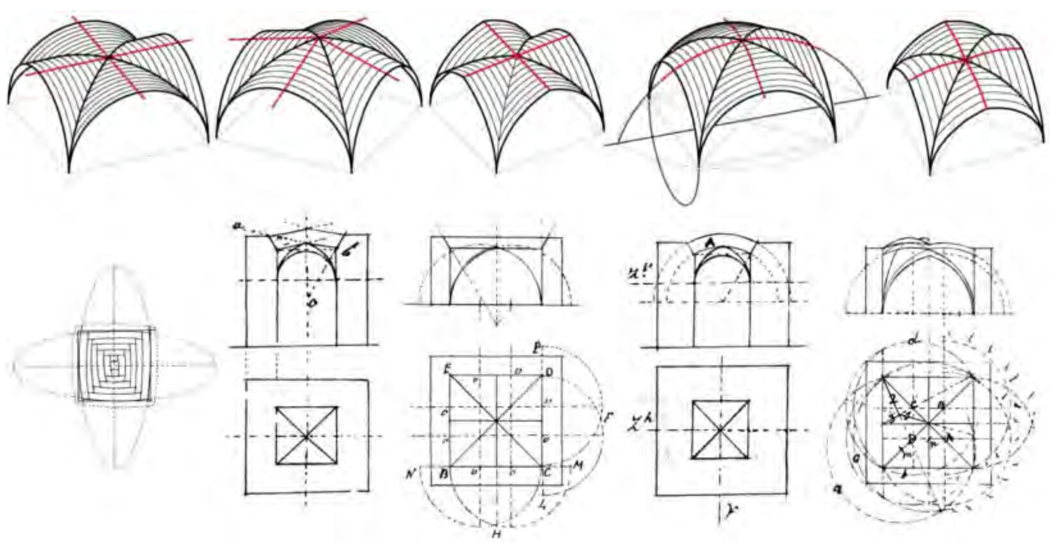


Figure 6. Variants of compound vaults according to Paredes (ca. 1883: plate 1, 2 & 3).

Paredes pays particular attention to the variant of inclined barrels on a square plan with semicircular arches because, according to him, this type has certain constructive and resistance advantages. He offers very specific instructions for controlling the shape during the construction process that can be adapted to other compound vaults such as the groin vault with spherical sectors, the star vault and the sail vault (Figure 6).

Paredes explains a practical way to raise the key during the execution process. For some authors, this "capialzado" (which is also known as an "arrepio", "resubido", "retumbo" or "empinamiento") is the raison d'être of the groin vaults without formwork and what the Roman vaults lack, transforming the cylindrical sections into the conical sections (López & López 2015: 996). The procedure consists of the laying of two ropes from the keys of the lateral arches and then raising the crossing point of both threads to a height of between 1/10 and 1/30 of the span, thus providing the barrels of the desired slope (Figures 4, 5). It also offers a practical method for defining some points of the diagonal ellipses in space, consisting of laying lines parallel to the directrix of the barrels and arranging a plumb line at its meeting point with the projection of the diagonal. Before that, he explains the geometric characteristics of the inclined slices, necessarily of an elliptical shape, that form the cylinders of these tilted vaults and also refers to the bricklaying to define those diagonal curves.

6 THE JOINS OF GROIN VAULTS IN EXTREMADURA

Paredes and Albarrán discuss this question in some depth. The first describes the aforementioned example of tilted barrels on a square ground plan, a method traditionally used in various countries. According to Paredes, in the springings of the vault the bricks must be "miter" cut so that they "form more perfection", at least until the vaults "interlock" (Figure 7). From that point, where the slices are forming an almost orthogonal angle, you can continue in the same way or choose to overlap some bricks with others, depending on whether the vault will be plastered. The author also proposes reducing the section of the vault in its upper part. In addition, he gives a brief overview of some particular cases, solving implementation problems such as the intersection of the vault with a non-orthogonal wall (Paredes ca. 1883: 154). The contributions of Albarrán (1855: 86 and 88) are much more interesting and closer to the actual construction in Extremadura. Albarán offers a solution for the formation of its joins dismissed in the previous texts and perhaps inspired by stonework. This consists of using an ordinary brickwork in several horizontal courses of bricks until the "slip angle" is reached; that is, until the bed planes of the bricks form angles of 38^{o} to 45^{o} with the horizontal. This option avoids the "miter" cuts proposed by Paredes for the springings (Figure 8). The issue has been analysed in a practical way by Wendland (2007).

A variant of the Albarrán proposal is widespread in Extremadura. Lowered vaults with this solution of the "pendentives" (or springings) supported by "dormido" and "spatillado" bricks are quite common. Thus, the courses are superimposed in a staggered manner along the entire edge up to the keystone, recalling the stonework of the ashlars of stone vaults. It seems that these vaults were built slowly, in sections, pausing for several days to allow the lime mortar to set before executing the next "pendentive" and its corresponding conical courses (López & López 2015: 997).

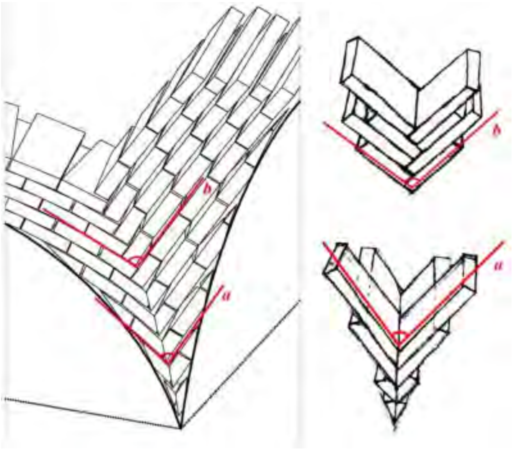


Figure 7. Explanation of the formation of the groins at the springings, according to Paredes (ca. 1883: plates 3 & 4).

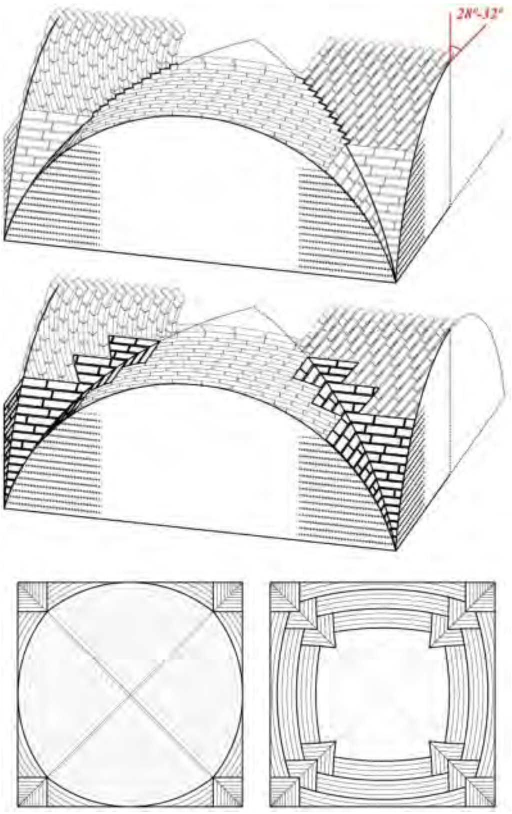


Figure 8. Scheme of the formation of the edges at the springings according to Albarrán (1855: 86) and in a real example of an Extremaduran vault.

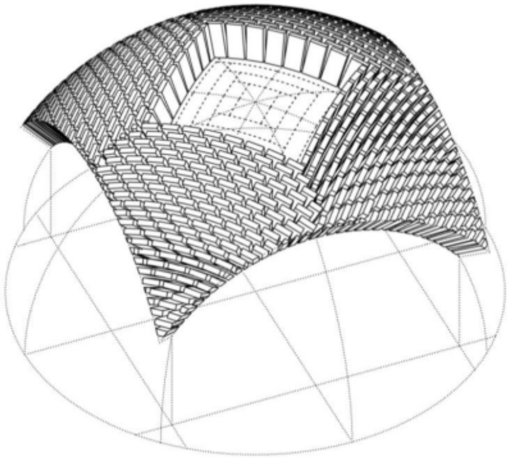


Figure 9. Formation of a sail vault by turned square courses. Thus, the joints between the slices occur at the quadrants.

These brickwork difficulties at the edges explain why many vaulted vaults both in Byzantium and in Spain have layers parallel to the planes of their diagonals. This way, the joints between vaults are produced on the quadrants, miter cut bricks are not necessary and the spans are shorter (Figure 9).

7 CONCLUSIONS

During the 19th century, several texts emerged in France and Spain that focused on the construction of vaults by slices, but it seems that they are not related to each other. The texts by Boguerín, Ger y Lóbez, Paredes and Albarrán are based on the authors' own professional experiences, while Choisy seems to support his hypotheses with visual analysis of some Byzantine vaults, although he claims that he carried out some practical experience to verify them.

The proposals do not show a direct connection. Extremadura seem to have developed independently, even while the texts undeniably share the Roman roots as a common origin. In his 1876 text, Choisy points out that, at that time, vaults by slices were being made in Mosul in the Byzantine manner, although the techniques differ in some aspects from those of Extremadura.

This article is limited to analysing and explaining the theoretical approaches offered by the manuscripts, without assessing their concordance with the preserved examples actually constructed, particularly in Spain. It is known that these types of texts sometimes provide a limited vision of the problem that only covers a few cases, usually the most elementary and descriptive of the technique. But this initial analysis is essential to any subsequent detailed study of surviving examples. In this new phase, the viability of these theories should be tested and other possible strategies not contemplated in the primary sources should be identified.

The authors are part of a team of researchers dedicated to the study of vaults by slices in the Iberian Peninsula and the eastern territories of the ancient Roman Empire. It is a complex task, because the most relevant data – such as the inclination of the bricks – can only be deduced from the visible surfaces of the vault (intrados and extrados). Therefore, some of the theories presented must be verified through the construction of scale models, with the support of the "experimental archaeology" that offers such good results in other analogous fields.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The first patents of prefabrication and the industrialization of reinforced concrete in Spain and Europe: 1886–1906

F. Domouso & A. Abásolo
Universidad Europea de Madrid, Madrid, Spain

ABSTRACT: This article explores the contribution of the European pioneers in prefabricated concrete proposals in Spain and is based on a deep analysis of unpublished patents of prefabricated reinforced concrete objects designed from 1886 to 1906. During these decades, an important catalogue of contributions was developed: from formwork or moulds intended for industrialization, to slabs and prefabricated structures. As a result, the patents for prefabricated systems and elements, which were mainly foreign in origin, provided the Spanish construction sector knowledge of complex manufacturing processes and ensured that technicians were tackling, from the very beginning, problems such as the continuity of prefabricated elements, their structural behaviour, and the layout of reinforcement bars. Prefabrication requires greater technology than the execution of in-situ reinforced concrete. This technology encouraged and boosted improvements to reinforced concrete construction in Spain. Thus, the patents for prefabricated systems and elements contributed new structural types and previously unknown techniques that had not been widely disseminated until then, such as prestressing. At the end, this contribution was fundamental to the development of construction in reinforced concrete in Europe and the future development of its applications. In this respect, we can highlight the figure of Bernardo de la Granda y Callejas, who patented the first Spanish system of pre-stressed concrete, which was possibly one of the first of its kind worldwide.

1 REINFORCED CONCRETE IN SPAIN, 1884–1906

Spain was two decades behind France and Germany in the introduction of reinforced concrete techniques. During the last years of the 19th century and the first five years of the 20th century, the business, construction, and theoretical foundations were laid in Spain that would allow the subsequent development of reinforced concrete, and in just six years, engineers and architects were building top-level structures in reinforced concrete. Construction techniques evolve and develop according to society's needs, and the need for reinforced concrete in Spain came two decades later than in France or Germany due to the country's historical, economic, and territorial circumstances: until the beginning of the 20th century, reinforced concrete construction in Spain was practically non-existent. Nevertheless, between 1900 and 1906, the country made up for lost time, catching up with the rest of Europe.

To explore this period in Spain, and the development of reinforced concrete impact, this investigation focused on this technology's first footprints by analysing its primary patents. In this regard, the raw material of this article is the critical examination of 11 patents designed by several European authors; selected among 114 original patent archives located, studied, and documented in the Spanish Patent and Trademark Office-Historical Archives (*Oficina Española de Patentes y Marcas O.E.P.M. Archivos históricos*) in Madrid from 2007 to 2014, some of which are images presented for the first time. In addition, two key ideas developed during this research: firstly, reinforced concrete patents played a vital role in this late development; secondly, the first patents registered for reinforced concrete in Spain made it possible to learn and develop construction processes from other countries with more experience in the use of the material.

To begin with the historical background, we have to highlight the French influence during the first years of the use of reinforced concrete in Spain. The *Revista de Obras Públicas,* a reference magazine in the dissemination of construction science in Spain at the end of the 19th century (and still published today), once again reported on the articles, works and experiences from France to the benefit of Spanish engineers. In 1884, the first patent for reinforced concrete was registered in Spain for the use of the French Monier patent.

Between 1884 and 1899, only minor works were carried out in Spain using the new material, such as the open water tank in Puigverd, Lérida (1893), built by the engineer, Francesc Macià, using Monier's patent (Figure 1). This water tank was the first structure in reinforced concrete on record in Spain, and it is still in use today.

During the last decades of the 19th century, the situation in Europe was very different (Figure 2). Constructions made with reinforced concrete – and

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Figure 1. Open water tank in Puigverd, Lérida. Design: Francesc Macià. 1893.

Figure 2. Factory roof, Paris. Design: Cottincin, 1900.

those based on Monier patents – had proliferated, and by 1890, advanced knowledge of the material, its structural behaviour and the building and construction techniques required were available.

In fact, new types of reinforced concrete construction would not be introduced in Spain until 1898, when structures with some degree of complexity began to be built.

Between 1898 and 1899, Eugenio Ribera built the slabs to be used for the new prison in Oviedo in reinforced concrete using the Hennebique system. The construction was preceded by a vast publicity campaign, well documented by the journal *Revista de Obras Públicas*.

In 1899, the first reinforced concrete building was built in Spain: the Viuda e Hijos de Ayala flour factory in Badajoz, another Ribera design using the Hennebique patent (Figure 3). Columns, beams, girders, and reinforced slabs gave shape to the first whole reinforced concrete structure built in Spain. In this regard, this complete application of the Hennebique system was patented in Spain in 1898.

Immediately after this, between September 1899 and May 1900, the flour mill, known as *La Ceres*, was built in Bilbao. It had a more complex geometric structure due to the shape of the plot, but its construction had similar complexity than the previous flour

Figure 3. The Viuda e Hijos de Ayala flour factory in Badajoz. 1899. Design: Ribera.

mill: a full, reinforced concrete structure following the Hennebique system, which was entrusted to the civil engineers, Ramón Grotta and Ga-briel Rebollo.

These structures are not representative of the construction sector in reinforced concrete in Spain in 1900, given that all the technology employed (both in designs and construction) were imported from France, but they were nevertheless the starting point for a boom in reinforced concrete in the country.

As of 1900, constructions in reinforced concrete began to be plentiful in Spain, and their structural types and design gradually became more complex, such as the Avilés Theatre in Asturias, completed in 1901, and designed by the engineer, Eugenio Ribera, and the architect, Manuel de Busto. This can be considered the starting point for this brief five-year period leading up to 1906 in which Spain caught up with the rest of Europe in terms of its reinforced concrete designs. This design paved the way for reinforced concrete in Spain, with building types a far cry from the usual industrial and civil engineering standard models; and it was the first structure for a civic building completely built in reinforced concrete.

The three most important names to introduce reinforced concrete in Spain were the engineers Eugenio Ribera, Juan Manuel de Zafra and François Hennebique.

José Eugenio Ribera (1864–1936) was born in Lisbon, and he was the son of the civil engineer, Pere Ribera i Griñó. He completed his own civil engineering degree in 1887. Even though he was a self-confessed non-conformist (he admitted that during his years as a student at the school on Turco Street, he studied little, and learned even less), Eugenio Ribera was the man who introduced reinforced concrete in Spain.

Following a visit to Geneva where he observed the construction of the arches of the Coulouvrenière Bridge and the slabs of the new post office building in Lausanne, both designed in reinforced concrete, he wrote that he was astonished by these kinds of buildings, which broke away from all the traditions to some extent old-fashioned, which are the base of the teaching in the schools.

In 1918, he started working as a professor at the Madrid *Escuela de Ingenieros de Caminos* (School of

Civil Engineering) where he taught structural design to, among others, Eduardo Torroja.

In the meantime, Hennebique took a personal interest in Ribera and the potential that he offered for introducing his methods in Spain, since Ribera was an engineer working for the state and an important figure in his own right before he had started to work with reinforced concrete.

In his capacity as a state engineer of public works in Asturias, Ribera sent preliminary designs to the Hennebique Paris offices so that they could examine these and propose solutions in reinforced concrete.

As a result, Ribera and Hennebique had a fruitful relationship between 1895 and 1899 that gave rise to modest but varied works. During this period, various new construction types in reinforced concrete were introduced to Spain: straight road bridges, reinforced concrete bridge decks, concrete slabs such as those used in the prison at Oviedo, Asturias, in 1898, and water tanks like the one in Llanes. Thus, Ribera was responsible for all these constructions as a state engineer but using the Hennebique system. In September 1899, Ribera was officially granted a concession by the Hennebique firm in Oviedo; he was also a member of the first editorial board of the journal, *Le Béton Armé*, the "body disseminating the authorised dealers of the Hennebique system".

Alongside Ribera, Juan Manuel de Zafra y Estevan was born in Huelva on 24 August 1869 and died in Madrid on 26 March 1923. His professional career was tied to the development of reinforced concrete from very early on.

His first work in reinforced concrete was the mining jetty in San Juan de Aznalfarache, built in 1904 for the Minas de Cala company, which mined the iron deposits in Huelva (Figure 4). Zafra was an engineer who underwent vast and rigorous scientific training, and he applied his solid knowledge of mechanics to create reinforced concrete structures.

Moreover, he joined the teaching staff at the Special School of the Corps of Civil Engineers, and he taught lessons in "Constructions in Reinforced Concrete and Ports and Maritime Signals", which was the first module in the subject "Constructions in Reinforced Concrete and Ports". Incidentally, this was the first university course in Spain in the discipline, which ran during the 1910–11 academic year.

Zafra revived energy principles applied to structural design theories and introduced them to Spain, publishing the first treatise on reinforced concrete analysis in the country in 1912, in which he applied theories of elastic strain to structural analysis. On this subject, he published, *Construcciones de hormigón armado* (Reinforced Concrete Constructions), in 1911, the first scientific treatise on reinforced concrete by a Spanish technician.

By 1906, construction in reinforced concrete in Spain had reached a similar level to the rest of Europe. This rapid development was made possible by the fundamental role of patents as follows:

Figure 4. First jetty built to serve the Cala mines, San Juan de Aznalfarache, Seville, 1904. Design: Zafra.

- In Spain, the main European systems of rein-forced concrete were patented during the period 1884–1902: this means the best technology and knowledge on reinforced concrete of the age reached Spain before large-scale, complex constructions had been undertaken.
- The exploitation of reinforced concrete patents gave rise to Spain's modern construction companies.
- Reinforced concrete patents offered substantial advantages to the construction sector: a selection of the patents registered in Spain during the period in question provided first-rate building know-how required for the quick development of reinforced concrete from 1901–06.

2 THE FIRST REINFORCED CONCRETE PATENTS IN SPAIN: 1884–1906

During the last decades of the 19th century, Spain attracted the interest of foreign technicians and companies that were leading the development of reinforced concrete.

In this regard, during the period 1884–1906, 114 reinforced concrete patents were registered in Spain:

- Number of foreign patents: 59 (51.8%).
- Number of Spanish patents: 55 (48.2%).
- Number of patents implemented: 48 (42.1%).
- Total number of foreign patents implemented: 29 of 48 (60.4%).
- Reinforced concrete systems: 32.
- Applications (reinforced concrete replacing another material): 63.
- Machines whose purpose was the manufacture of reinforced concrete applications or improvement of components: 9.
- Procedures or construction methods specific to reinforced concrete: 10.

Besides that, the origins and sequence of events in the implementation of the patents registered in Spain during the period 1884–1906 are as follows (Figure 5):

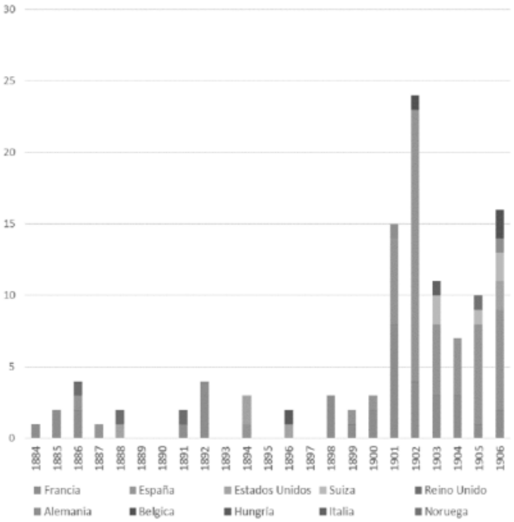

Figure 5. Ratio of the number of foreign patents registered in Spain by year and country of origin for the period 1884–1906.

Consequently, a statistical analysis of the patents confirms that reinforced concrete was an imported technique in Spain. During the period 1884–1900 (the years when reinforced concrete was introduced in Spain), around 82.7% of reinforced concrete patents registered in Spain were foreign patents.

In the period 1901–06, Spanish technicians and builders incorporated reinforced concrete technology into the construction sector. From 1902, more Spanish patents were registered than foreign ones: during this period, 41.2% of the reinforced concrete patents filed in Spain were foreign, compared to 82.7% in the previous period, 1884–1900.

In the end, the implementation of patents shows that the Spanish construction sector incorporated the most advanced technology that had been tested at the international level.

Of the 114 reinforced concrete patents registered in Spain between 1884 and 1906, 42.1% were put into practice. It is significant to note that 60.4% of the total number of patents filed in Spain were foreign. For this reason, we can consider that the introduction of a patent represents a real transfer of technical knowledge to the construction sector.

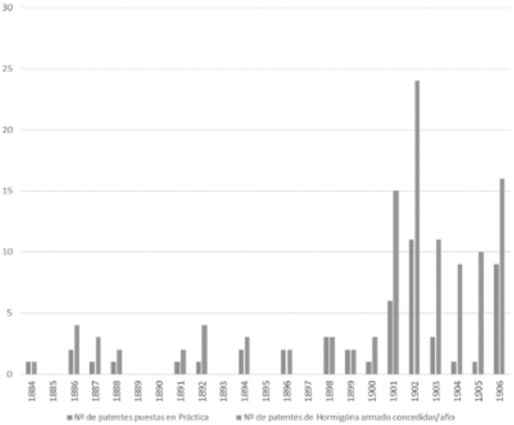

Figure 6. Reinforced concrete patents related to prefabrication and industrialization, filed in Spain in the period 1884–1906, by country.

3 PATENTS THAT HELPED TO DEVELOP PREFABRICATION AND INDUSTRIALIZATION IN REINFORCED CONCRETE

We will focus on the technology development of different patents designed by several authors. In other words, the goal in this part is to open the framework of potential cases, as we want to understand the fast and non-linear evolution of this technology – with its successes and failures – which developed in only two decades. The landmarks include, from our point of view, the work of Bernardo de la Granda y Callejas. In this regard, of the 114 patents studied in the Spanish Patent and Trademark Office (O.E.P.M.), we highlight 11 applications including: Hans Bayer, David Wilson, Joseph Monier, Paul Cottancin, François Hennebique, Paul Victor Parcy, Franz Visintini, Denis Isoard, Bernardo de Granda y Callejas, Oscar Lavanchy and Edmond Joseph Sacrez.

3.1 *Constructive analysis*

Patents providing relevant knowledge in the prefabrication and industrialization of reinforced concrete were filed at the beginning and end of the period studied. This suggests its relative importance for reinforced concrete in Spain, although patents for prefabrication and industrialization are relatively few (11 out of 114, representing only 9.6% of the total).

It would be expected that the concept of prefabrication and industrialization would take time to be reflected in the patents, as prefabrication implies greater industrialization and technology. However, in the first years of the period analysed, there were already proposals on how to work with reinforced concrete prefabrication.

The first patents focus on the replacement of traditional objects made of other materials, such as water tanks, pipes, or posts, with objects made of reinforced concrete, it is not until the end of the study period that the real innovations in prefabrication appear.

Besides, when analysing the origin of the patents, it is significant that, although they come from five countries (United Kingdom, France, Spain, Belgium, and Switzerland), most of them are from France (around 50%) (Figure 6).

One of the first patents selected (Wilson, 1886) is aimed at tube manufacturing, and it represents and

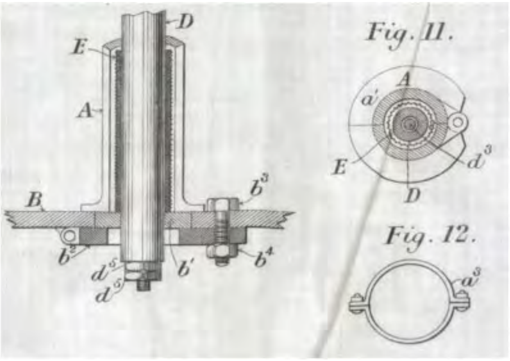

Figure 7. Wilson, Spanish patent number 5787, 1886.

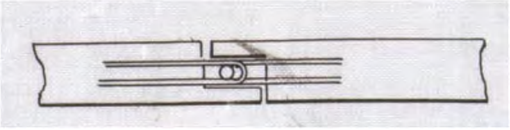

Figure 8. Cottancin, Spanish patent number 12301, plan detail, 1891.

describes a highly elaborated development of moulds and mould release systems (Figure 7).

The design is quite exhaustive and technical, following the best industrial descriptions of the time. The objective of the patent is not structural, but rather, its purpose is the replacement of steel pipes by others of reinforced concrete.

A different case is Cottancin's patent (1891), which is the first one aimed at solving constructive joints between parts. Certainly, it is one of the most important aspects to be solved in a concrete prefabricated system (Figure 8).

Apart from that, the first patent that we find with a clear structural character is a patent by Hennebique (1900). It is a prefabricated, reinforced concrete wall, designed to contain the land near the railway station platforms. The prefabricated wall incorporates a metal rail to prevent the concrete head from splitting due to the impact of the train carriages.

Hennebique, in contrast to Cottancin, does not define the joints between the walls, but designs a form that responds to the forces which the element should resist (Figure 9).

Nevertheless, the construction of this three-dimensional element, which requires a very complex formwork and a very laborious demoulding system, has not been considered in the design of the proposal. In addition, no assembly guide or gripper system was considered for lifting or handling the walls. The following year, in 1901, Parcy filed a patent for the construction of prefabricated slabs. He designed thin slabs of prefabricated concrete supported between metal beams (Figure 10). Unlike Hennebique, Parcy considered the joint between the slabs, which formed an open joint with the metal beams. The joint was concreted on site, giving continuity to the whole system.

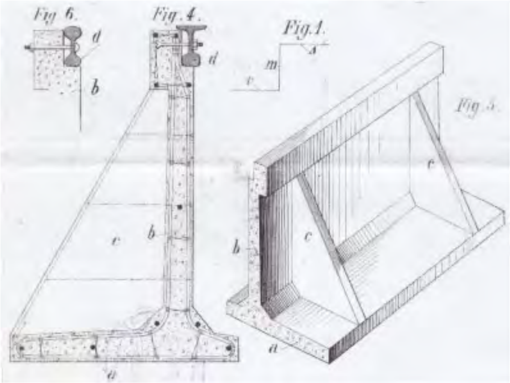

Figure 9. Hennebique, Spanish patent number 25990, 1900.

Figure 10. Parcy, Spanish patent number 28475, 1901.

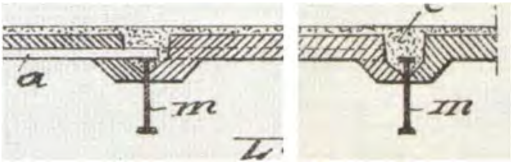

Figure 11. Parcy, Spanish patent number 28475, plan detail, 1901.

The joints between pieces are essential in a prefabricated system and Parcy detailed and drew them in a clear construction and assembly process (Figure 11), unlike to the steel reinforcement, which is not drawn, as it is supposed to be based on the calculation of the structure.

This patent therefore defines the constructive aspects of the system. These reinforced concrete pieces are designed to be stacked and transported without major problems. In 1903, an important patent was filed for prefabrication in reinforced concrete. It was a prefabricated concrete truss designed by Visintini, a Swiss architect. It had three variants: The Warren truss, the Pratt truss, and a double truss (Figure 12). The truss elements that are supposed to work in traction are reinforced, while those that are supposed to work in compression have no metal reinforcement.

Although from a conceptual point of view the approach is correct, this patent shows us that Visintini did not foresee the alternation of loads, nor the intermediate states of the forces generated during the assembly process. Other inconveniences include: Visintini did not consider something as important as the

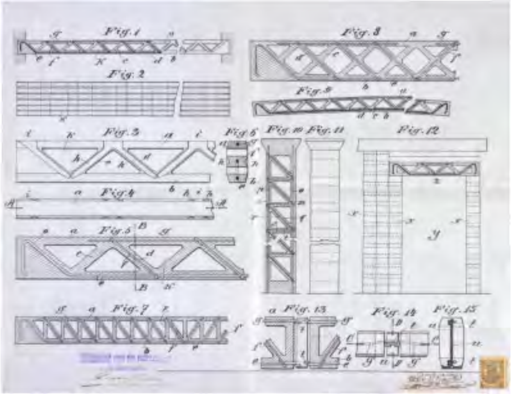

Figure 12. Visintini, Spanish patent number 31097, 1903.

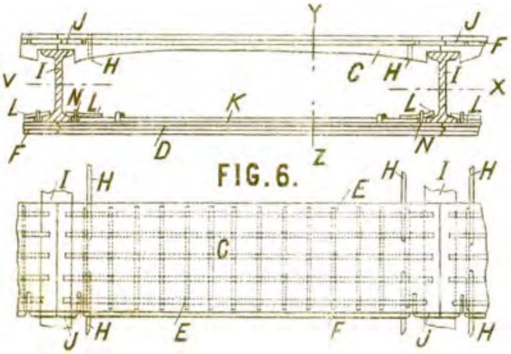

Figure 13. Isoard, Spanish patent number 31622, precast floor, 1903.

union of the trusses with other construction elements in this patent; and he did not take into account the joints in the supports either. In fact, he represents them as hyperstatic supports, instead of isostatic supports. However, what this patent details precisely is the shape of the concrete in the truss, although it does not consider the difficulty of the double-sided formwork required. Despite these drawbacks, his proposal for prefabricated trusses was an interesting milestone that would be further developed in subsequent years.

In the same year, 1903, Isoard filed a patent for a prefabricated concrete slab, of small thickness, supported by metal beams (Figure 13). The reinforcement of the pieces is defined as an isotropic steel mesh. This patent, although later than that of Parcy, does not deal with important aspects of prefabrication in reinforced concrete: continuity between the pieces once they have been placed, the mould system, etc.

Two years later, in 1905, Lavanchy, of Swiss origin, filed a patent for beams and prefabricated floors (Figure 14). Firstly, it is remarkable that it reflects on the need to enhance the roughness between concrete and steel, to ensure greater adhesion between the two materials and, therefore, greater durability. In this respect, the drawings show the reinforcement of the beams with precision.

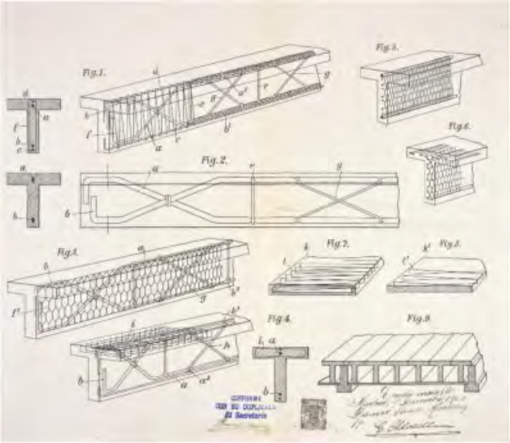

Figure 14. Lavanchy, Spanish patent number 37371, steel reinforcement arrangement, 1906.

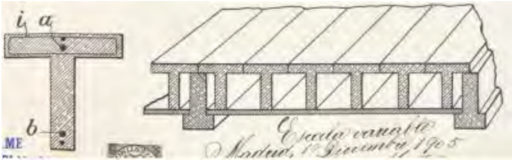

Figure 15. Lavanchy, Spanish patent number 37371, slab typology, 1906.

On the other hand, the reinforcement bars are not correctly positioned, but despite this, the geometric proposal of the piece is interesting. Additionally, this patent develops different proposals, including one that uses an isotropic steel mesh as the main reinforcement.

In this patent case, despite being later, it is less technically advanced than Parcy's, demonstrating ignorance of the structural behaviour, and it does not address the substantial problems of prefabrication. Despite this, it is valuable because it includes structural typologies that will later be commonly used in reinforced concrete prefabrication, such as slabs based on T-beams and inverted T-beams (Figure 15).

3.2 *The first two patents for pre-stressed concrete: 1904 and 1906*

Two patents were pioneering in the development of pre-stressed concrete: the patent of the Spanish civil engineer, Bernardo de Granda y Callejas (1904), and the patent of the Belgian engineer, Edmond Joseph Sacrez (1906).

The first patent was filed by Granda y Callejas, professor at the School of Civil Engineering of Madrid in Applied Mechanics in the first decade of the 20th century. He later taught Materials Resistance. He was the author of numerous teaching publications, notably his classic and constantly re-edited, *Materiales aglomerantes* (1904, Madrid). This publication will be the bedside reading of many civil engineers and architects

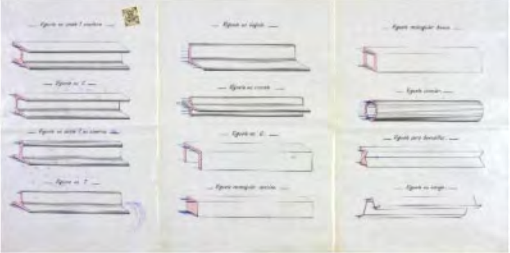

Figure 16. Granda y Callejas, Spanish patent number 33301, 1904.

Figure 17. Granda y Callejas, Spanish patent number 33301, definition of tensioning elements in beams and precast concrete slabs, 1904.

in Spain. In 1904, Granda y Callejas registered patent number 33301, entitled: “The procedure for preparing pieces for construction, moulded under pressure formed with paste mortar or hydraulic cement and reinforced with external metal reinforcements with or without cable-stayed” (Figures 16, 17). However, this patent was not implemented, probably because the proposal was too advanced for the early 1900s.

Although the patent lacks technical definition, the structural concept “pre-stressed concrete”, was a very relevant and advanced fact at the time, besides being an absolute novelty in 1904.

The second pre-stressed concrete patent filed in Spain – also not implemented – is the one by the Belgian engineer, Edmond Joseph Sacrez, which, in a simple way, introduces the concept of pre-stressing. It states textually in the report of the patent: “Straight, strong and numerous bars that are put in tension before concreting” (Figure 18).

Unlike Granda y Calleja’s patent, Sacrez shows that he has more advanced knowledge in the execution of this type of structure, indicating the need to have “an element that generates compression at both ends”.

Despite some limitation on the pre-stressed and post-tensioned concepts, Sacrez is considered one of the pioneers of pre-stressed concrete structures, together with Doehring and Koenen (Germany), Lund (Sweden) and Jackson and Steiner (USA).

3.3 *The first patent for composite slabs*

The 1906 patent of the German engineer, Hans Bayer, is an important contribution to the structural typology of collaborating slabs made of prefabricated beams.

It is the only patent of the 114 studied that proposes a system of “collaborative structure”. It was called “Roof of reinforced concrete” and was put into practice in Madrid in 1908. Geometrically, the design of the prefabricated beams is excellent. The in-situ concreting of the compression block provides the necessary continuity and rigidity to the slab to fulfil a structural function (Figure 15).

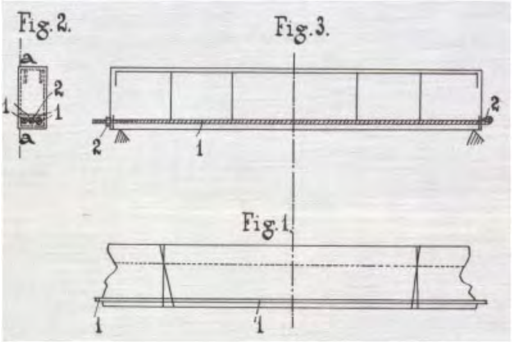

Figure 18. Sacrez, Spanish patent number 39541, 1906. Source: Spanish Patent and Trademark Office. Historical Archives.

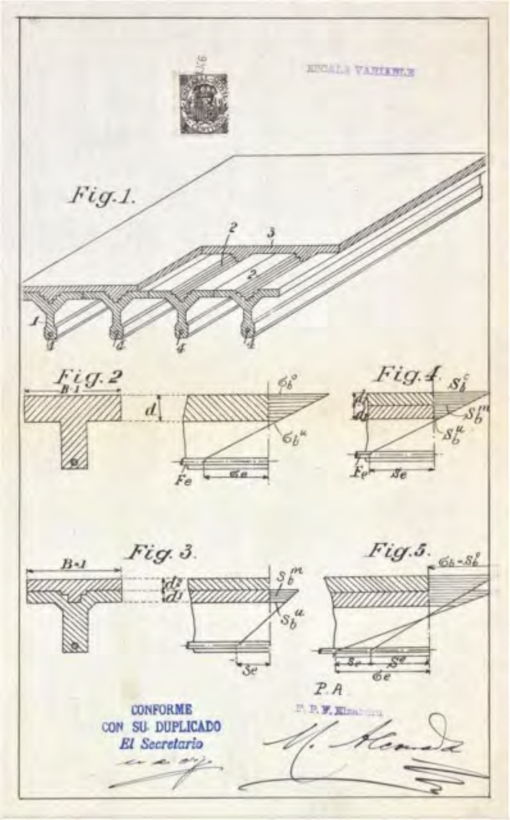

Figure 19. Bayer, Spanish patent number 38624, 1906.

From the point of view of structural behaviour, Bayer describes the advantages of this slab in a graphic and precise manner.

The graphic representation of the patent, in axonometric perspective, is outstanding. It explains the structural behaviour of the concrete executed on site next to the prefabricated beams, representing the distribution of the stresses between both elements. This solution introduces the novelty that the top layer of concrete collaborates with the compression head of the beam. In this way, the beam can be lighter than the self-supporting T-beam solution. The author graphically and mathematically demonstrates its structural advantages. In Spain, the application of this patent provided new knowledge of the reinforced concrete techniques and, above all, opened the way to the development of mixed typologies and composite slabs.

4 CONCLUSIONS

To summarise, the patents for prefabricated and industrialised reinforced concrete systems deposited in Spain in the period 1886–1906 were fundamental for the development and the modernization of the construction economic sector in Spain.

In our research, we have found that 50% of the patents related to reinforced concrete prefabrication were French. In the end, however, this was beneficial for Spain, as the transfer of technology and knowledge came from the most developed country in prefabrication in Europe at the beginning of the 20th century. This is to say that these patents contributed to the development of prefabrication and industrialization of reinforced concrete in Spain.

Besides this local development and thinking about constructive innovation in Western countries, we can also say that these patents provided new structural typologies, such as composed slabs and prestressing, an upcoming technique in reinforced concrete (Figure 19).

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Brick vaults by slices in Toledo

A. López-Mozo, M.A. Alonso-Rodríguez, R. Martín-Talaverano & L. Aliberti
Universidad Politécnica de Madrid, Madrid, Spain

ABSTRACT: This paper studies the existing cases of brick vaults by slices in Toledo (Spain). This forms part of a wider study of the Mediterranean cases of this type of vault, which does not require formwork, focused on finding similarities in their constructive configuration and tracing their dissemination. The methodology is based on data collection of the preserved remains by automated photogrammetry to generate three-dimensional models allowing the study of their formal and constructive configurations. Twenty-six vaults in nine buildings, out of a total sample of eleven, have been analyzed. All cases present a rectangular or irregular polygonal plan and most display rounded vaults that remain far from perfect spheres. The study of the constructive evidence leads us to consider that a cintrel might have not been used as a control tool in the construction process.

1 INTRODUCTION

Brick vaults by slices are built by placing the bed of each element vertically or slightly pitched. Each new slice is supported by the adhesion of mortar and brick and no formwork is needed. The earliest examples, made with adobe, are documented in the Middle East and Egypt in the thirteenth century B.C. The Eastern Roman Empire used this technique profusely and spread it throughout the Mediterranean basin, but it was also transferred throughout the Arab world as well. From Spain and Portugal, this tradition might have jumped to the New World with this method nowadays still in use in Mexico.

A fair number of examples of brick vaults by slices are known but they are not connected in the existing literature. This paper stems from a research project on the historical construction technique of brick vaults by slices, focused on analyzing the constructive configurations and material characteristics of the preserved vaults to identify links between the main foci and the role of the Iberian Peninsula in their dissemination.

This work analyses the existing cases identified in Toledo (Spain) to understand their constructive configurations. Such vaults have not hitherto been deeply studied. The analysis methodology is based on data collection of the preserved cases by automated photogrammetry to generate a three-dimensional model with the purpose of studying the formal and constructive configuration of each vault.

Within the global sample of 65 buildings with brick vaults by slices thus far collected on the Iberian Peninsula, 15 of them contain sail vaults. Toledo appears to be an important sail vault focus as 10 of those 15 cases are found there within a whole sample of 11 buildings in the city (Figure 1). Hence, this first addresses studying the contents on sail vaults in the written sources.

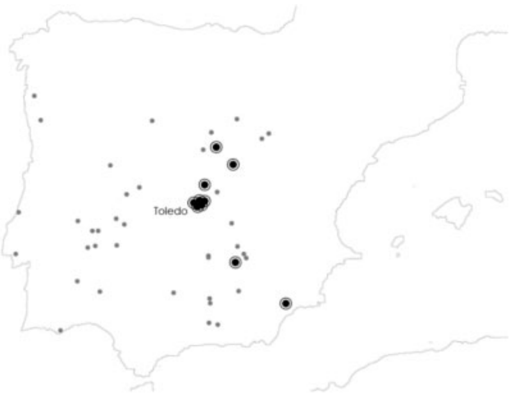

Figure 1. Brick vaults by slices on the Iberian Peninsula; sail vaults are highlighted (by the authors).

2 THE CONSTRUCTION OF SAIL BRICK VAULTS BY SLICES ACCORDING TO THE WRITTEN SOURCES

Texts on brick vaults by slices can be traced to the end of the 19th century when this tradition was still alive. Some describe the constructive configurations of sail brick vaults. Ger y Lóbez (1869) explains the construction of a vault "…similar to a groin vault, but rounded in their prominent angles, popularly called a carriage cover" (authors' translation). This is a vault made of pitched slices resting on each perimeter arch, combining groups of slices belonging to adjacent sides in order to solve the corners. In his new version in

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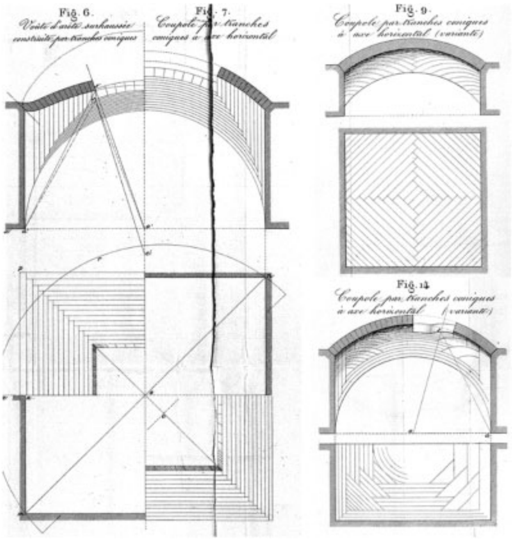

Figure 2. Choisy 1876, figs. 7, 9 and 14.

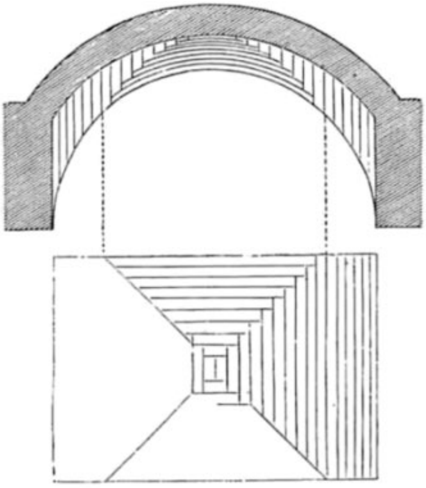

Fig. 119.

Figure 3. Choisy 1883, 101.

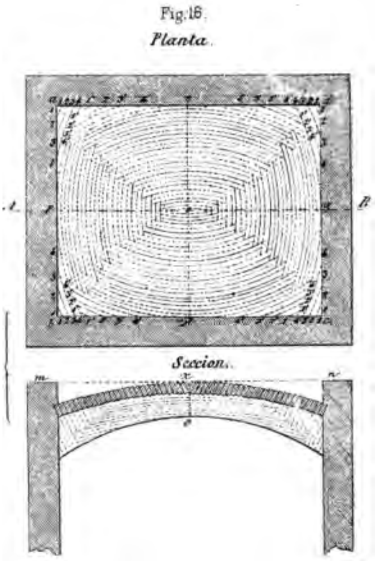

Figure 4. Albarrán 1885, 87.

1898, Ger y Lóbez also includes the description of the construction of a sail vault similar to that shown by Choisy (1876).

Choisy posits the sail vault by slices as a particular case of the Byzantine groin vault, comparing the constructive process of both cases in his Figure 7 (1876, 446). The author describes the use of a cintrel tensioned with a string fixed to a point on the revolution axis of the slices. This device would be carried along the axis to build the following slice. His 1883 book again describes these procedures and the close relationship between the construction of the Byzantine groin vault and the sail vault by slices.

Regarding their constructive arrangements, Choisy explains three cases: slices set in parallel to the perimeter, slices set in parallel to diagonal planes, and a mixture of both. He draws the three arrangements in Figures 7, 9 and 14 of his 1876 article and in his 1883 book (Figure 2). He also describes a rectangular layout solution with two lateral stripes leading to a central square, pointing out similar arrangements in Santa Irene (Constantinople) and in a warehouse in Zografos (Choisy 1883, 101) (Figure 3).

Albarrán was an engineer with wide experience in the construction of brick vaults by slices in Extremadura, a Spanish region with a long tradition in this constructive system. He explains the construction of a vault called “en rincón de claustro” (pavilion vault), drawing a rectangular plan vault with a segmental arc layout both in the longitudinal cross-section and in the perimeter arches (1885). Despite its rounded appearance, the vault is not spherical since the large and short perimeter arches hold the same central height. In addition, its longitudinal section through the highest point and its parallel perimeter arch do not display a concentric layout. The brick arrangement seems to be similar to that described by Ger and Lóbez: pitched slices (tracing a curved projection plan) resting on each perimeter arch, and alternating groups of slices from adjacent sides to solve the corners. Albarrán also explains a system to control the execution by using a ruler and strings tied to the “vertexes” of the arches (Figure 4).

3 BRICK VAULTS BY SLICES IN TOLEDO

The earliest Spanish brick vault by slices might be a rectangular plan sail vault in the Roman Villa of Carranque, near Toledo (ca. 450), already studied by this team (López-Mozo et al. in press). There are other cases in Toledo, which seem to approach the form

	TOTAL	Puerta del Vado	Mosque of Las Tornerias	Mosque of Cristo de la Luz (apse extension)	Puerta Antigua de Bisagra	Palacio de Galiana	Puerta del Sol	Puerta Nueva de Bisagra	Town Hall	Puerta de Valmardón
date		ca. 1100	ca. 1159-1190	ca. 1186	ca. 1200	ca. 1300-1400	ca. 1375-1399	ca. 1576	ca. 1576	
vaults	26	8	8	1	1	3	2	1	1	1
square plan	0									
rectangular plan	18	3	7	1		3	2		1	1
trapezoidal plan	8	5	1		1			1		
rounded vaults	24	8	8	1		3	2	1		1
photo										

Figure 5. Main features regarding the form of the surveyed vaults (by the authors).

of a sail vault: the city gate of Puerta del Vado ca. 1100 (Ruiz Taboada 2002, 59;79); the mosques of Las Tornerías ca. 1159–1190 (Porres 1983, 413–415) and Cristo de la Luz (apse extension) ca. 1186 (Calvo Capilla 1999, 301); the city gate of Puerta Antigua de Bisagra ca. 1200 (Fernández Valdés 2018, 74); the Palacio de Galiana in the 14th century (Jiménez Esteban 2012, 399); the city gates of Puerta del Sol ca. 1375–1399 (Pavón Maldonado 1990, 511) and Puerta Nueva de Bisagra ca. 1576 (Fernández Valdés 2018, 60) and the Town Hall, ca. 1576 (Díaz Fernández 1994, 31). There is another vault of this type at the city gate Puerta de Valmardón, which has not yet been reliably dated. Two more cases have been identified but not yet visited: a barrel vault in the basement of San Clemente Convent, prior to 1250 (Rodríguez Untoria 2011, 22), and a sail vault in the basement of a dwelling in Callejón Verde. This sample therefore consists of 11 buildings in the city of Toledo; ten of them feature vaults with the appearance of a sail vault and the other one has barrel vaults. Regarding the data collection of brick vaults by slices, an inspection of 46 and a survey of 26 have been carried out in nine buildings.

The number of new case studies that have emerged during the research indicates there might be many more that have not yet been identified, particularly taking into consideration that this reflects a very simple building technique, appropriate for domestic scales, and present in many buildings. The cases that have already been identified are addressed in this paper. The brick vault by slices at the lower level in the Puerta Antigua de Bisagra has been measured, while the brick vaults also present at the upper levels have not been visited thus far. In the Palacio de Galiana, where there are eight brick vaults by slices, the three examples in the central bay have been surveyed. The six vaults at the lower level in the Mezquita de las Tornerías have not been measured as they had undergone previous restoration. All the existing vaults in the remaining buildings have been surveyed.

3.1 *On the form of the vaults*

The plans of the 26 surveyed vaults show a quadrilateral layout, which seems to coincide with a rectangle in 18 cases and a trapezoid in the remainder while none aligns with a square plan. All of the vaults inspected seem to approximate the form of a sail vault, i.e., at first glance, they seem to be a sphere sectioned by vertical perimeter planes. However, two cases do not match this layout: the lower level vault in Puerta Antigua de Bisagra, with slightly prominent diagonals noticeable to the naked eye and surbased diagonal sections, and the vaults at the Town Hall, resting on oval arches (Figure 5). Only one of the identified vaults is a barrel vault, located in the basement of the Convent of San Clemente, which is one of the two buildings that could not be visited.

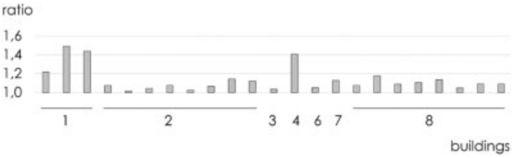

Figure 6. Table of ratios between the largest and the small-est diameter of the four meridian sections of each vault (1 Pa-lacio Galiana, 2 Puerta del Vado, 3 Mezquita Cristo de la Luz, 4 Puerta de Valmardón, 6 Puerta del Sol, 7 Puerta Nueva de Bisagra, 8 Mezquita de las Tornerías). By the authors.

Figure 7. View of the 3D models: on the left, the vault best fitting a sphere (Puerta del Vado); on the right, the vault worst fitting a sphere (Palacio de Galiana). By the authors.

In order to accurately determine the shape of the 26 surveyed vaults, contour lines at every five centimetres were first obtained: this has allowed for determining whether there are rounded surfaces or if prominent edges highlight the presence of a groin vault, as happens in Puerta Antigua de Bisagra. Hereafter, meridian

Figure 8. Plan and elevation of the 3D model of the vaults in Palacio de Galiana, with the layout of the perimeter arches overlapped in the dashed-line. By the authors.

sections approaching a circular layout were analyzed. Firstly, this firstly traced a circle adjusted to the measured points before then determining the ratio between the largest and the smallest diameter of the four meridian sections (two cross sections and two diagonal sections) for each vault. These calculations indicate the degree of deviation from a theoretical spherical surface, which would result in a ratio of 1. The vaults best fitting a sphere are the one at Puerta del Vado (with a ratio of 1.02), as well as the vault of the apse in Mezquita del Cristo de la Luz (with a ratio of 1.03). On the other hand, the most irregular vault (furthest from the theoretical sphere) is in Palacio de Galiana (with a ratio of 1.49) (Figure 6). With the naked eye or by viewing the 3D model, these "deviations" from a perfect sphere can hardly be appreciated (Figure 7). One might therefore deduce the intention of the builders as that of creating a shape with a rounded appearance rather than a perfect sphere.

The system seems quite versatile in order to achieve different ways of vaulting the same level. In Palacio de Galiana, for example, the plan of the three analyzed vaults is very similar but the volume differs greatly, with short perimeter arches of very different maximum heights (Figure 8).

3.2 *On the brick arrangements*

Regarding the spatial arrangement of the bricks, they seem to be aligned with the surface of the vault, without any steps in the intrados. Thus, it may be understood that they generally form conical slices with their apex in the centre of the vault, a basic control point by means of a cintrel. This arrangement by conical slices, described by Choisy (1876; 1883), is evident in two partially ruined vaults of this type in Toledo, which allow us to appreciate the arrangement of the bricks: the vault preserved in Carranque (ca. 450, Toledo province), and one of those included in the case studies here, in Puerta del Vado in the city of Toledo (ca. 1100) (Figure 9).

The resolution of a vault of this type, with a rounded form and slices running parallel to the perimeter, on a non-square floor plan, raises problems that require explicit solutions. If the plan is a rectangle or an irregular polygon, the coordination of the slices at the confluence of two adjacent sectors needs solving. As far as we know, there are four possibilities. One solution might be setting side stripes that define a central squared area (Figure 10, 1). A second solution may be arranging rectangular or polygonal courses and a rectangular "keystone", so that adjacent sectors

Figure 9. On the left, vault in the upper level of Puerta del Vado; on the right, vault preserved in the Roman Villa of Carranque. Photographs by the authors, 2020.

meet up at the corners following the bisectors (Figure 10, 2). A third solution might combine adjacent sectors by counterbalancing one-to-two or one-to-three courses to compensate for the difference (Figure 10, 3). And, finally, thicker joints may be applied to the small sectors (Figure 10, 4).

Not one of the 26 surveyed vaults features a square plan and are instead solved with diverse solutions. 13 cases show courses meeting one-to-two or one-to-three in adjacent sectors (Figure 11); eight vaults present the bisectors and rectangular "keystone" solution; seven cases place side stripes to leave a central square area that is easily solved, and one shows thicker joints in two of the sectors (Figure 12). In the three vaults measured at Palacio de Galiana, two constructive strategies were interwoven. They applied side stripes leaving a central square area and counterbalancing the courses of adjacent sectors. This solution for course compensation reaches one-to-three or one-to-four in some of the vaults in Mezquita de las Tornerías. Some buildings present three different systems. In Puerta del Vado, for instance, rectangular plan vaults are solved either with side stripes leaving a central square area or courses counterbalanced at the diagonal, and with the trapezoidal plan vaults solved by bisectors and rectangular "keystone".

With the intention of searching for evidence of the construction process, reflection has been made about any possible traces of recourse to a cintrel to control the position of bricks in circular slices, assuming construction without any formwork. For this purpose, the circles best fitting the courses have been adjusted and their centres determined. The use of a cintrel moving along the horizontal vault axis, would result in an alignment of these centres along that axis. This configuration, even ignoring vault deformation, might emerge from analysis of these built cases. However, only one example, the ribless vault in Puerta del Sol (ca. 1375–1399), reports an alignment of centres compatible with this hypothesis. The rest of the cases stray far from this configuration; with the two extreme cases depicted in Figure 13. In one vault, the position of the centers rises as they approach the centre, implying this is not a matter of deformation (Figure 13, centre). In the case of Mezquita de las Tornerías, some vaults might have been built using a cintrel, given the centres of the circular courses are approximately located following a horizontal alignment; however, other vaults in the same building do not feature the same configuration and would not have been built with any such kind of control tools. In the remaining buildings, to a greater or lesser degree, the layouts of the centres are far from any horizontal alignment so were also feasibly built without any device to control de execution of the slices.

4 CONCLUSION

Within the sample of 48 vaults that have hitherto been identified in Toledo, it must be underlined that 47 might be classified as rounded vaults, approaching a spherical form. 37 within those 47 cases appear to be sail vaults at least when seen with the naked eye. All the 26 surveyed vaults feature a rectangular or trapezoidal plan layout. It is therefore possible to think that this rounded formal solution, built by slices, was an option appreciated by masons when vaulting a non-square plan.

The general form of the vault seems to have been sought as an idea in a broad sense, which is then built according to a choice of coordinated arches and a way of building, possibly without any formwork or control by a cintrel. Regarding their non-canonical form, they seem to relate to the very free configuration that Albarrán (1885) would later propose for a vault of this type; with a rounded appearance and segmental circular arches on the perimeter and cross-sections but not forming a sphere. For all these reasons, it perhaps does not make sense to speak of "approximately sail" vaults but rather of "rounded vaults". The constructive configuration is quite versatile, given the scope for easily adapting the system to different plan conditions, perimeter arches or cross-sections.

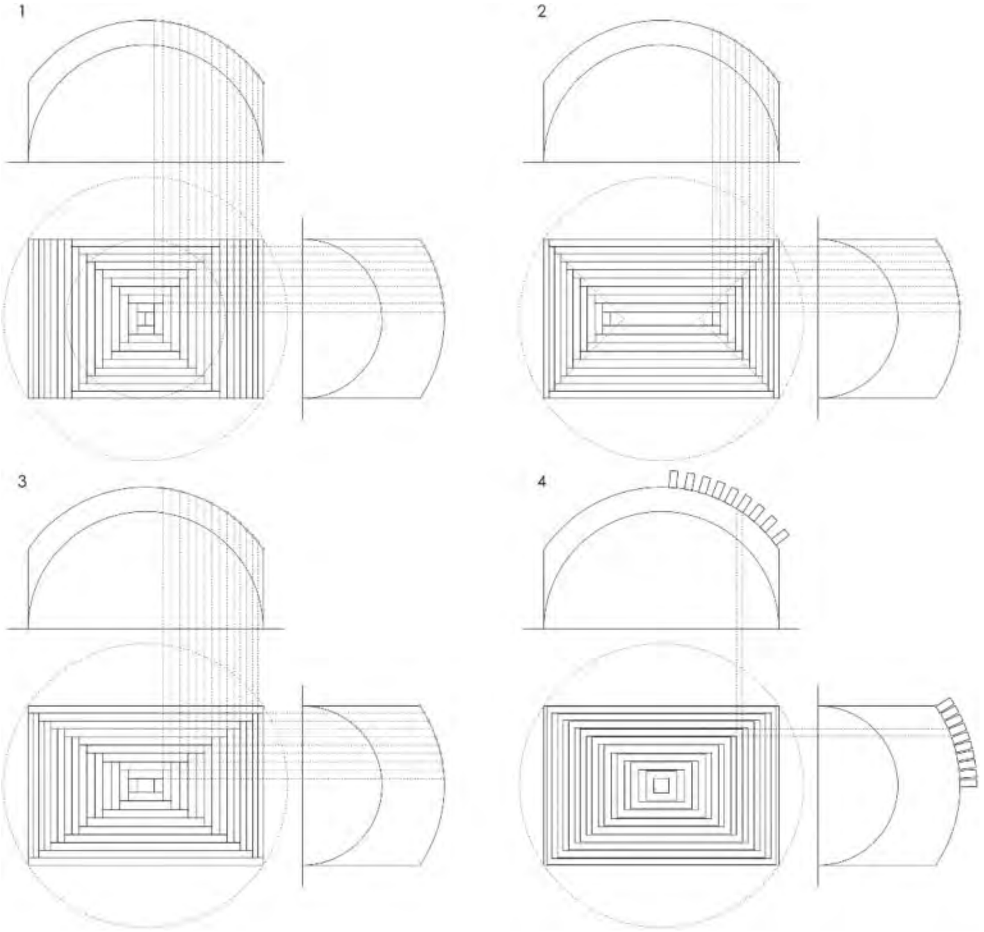

Figure 10. Different alternatives to solve a rectangular plan sail brick vault by slices. By the authors.

Figure 11. Courses counterbalancing adjacent sectors: on the left, Mezquita de las Tornerías; on the right, Palacio de Galiana. Photographs by the authors, 2020.

Regarding the constructive arrangement, our surveys in all cases report the bricks appearing to be aligned with the vault surfaces, with no steps in the intrados so that the slices follow a conical layout. This configuration emerges from the remains of a ruined vault in Puerta del Vado. The apparent courses are noticeably vertical, except for one vault in Palace of Galiana and another in Puerta del Vado. The form of those apparent courses matches a circular layout, except for the Town Hall's vaults, with oval courses

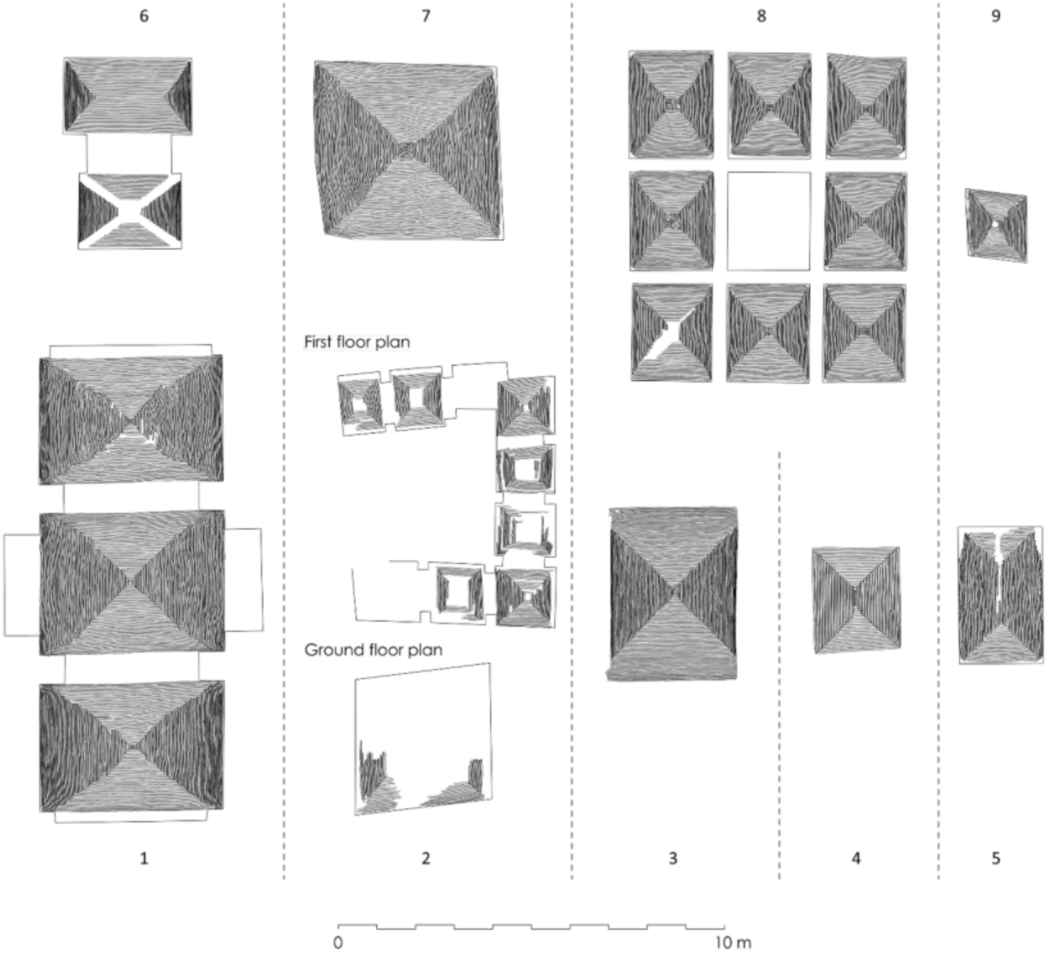

Figure 12. Plan of the surveyed vaults, at the same scale (1 Palacio Galiana, 2 Puerta del Vado, 3 Mezquita Cristo de la Luz, 4 Puerta de Valmardón, 5 Town Hall, 6 Puerta del Sol, 7 Puerta Nueva de Bisagra, 8 Mezquita de las Tornerías, 9 Puerta Antigua de Bisagra). By the authors.

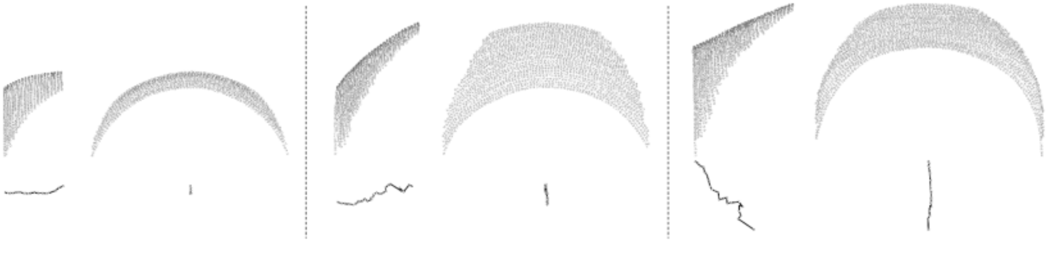

Figure 13. Extreme cases of course centre alignments: on the left, Puerta del Sol; on the centre and right, two vaults in Palacio de Galiana.

in two sectors. Most circular courses in the Toledo cases do not have their centres aligned according to a transversal or longitudinal axis of the vault so it is possible they were not built according to the cintrel procedure described by Choisy. These may perhaps represent evidence of a way of building not only without any formwork but also without a cintrel.

Diagonal brick slice arrangements, as described by Choisy, have not been found. However, there are several cases of slices with a curved plan projection as in the proposals by Ger and Lóbez (1867) and Albarrán (1885). The most frequent solution in the Toledo cases for a rectangular or trapezoidal plan layout involves the counterbalancing of courses as they meet at the diagonal. This solution appears in half of the analysed cases and was not included in the Byzantine solutions described by Choisy.

Hopefully, in the development of the aforementioned research project, assessing these vaults in Toledo within the whole group of Mediterranean cases will help the argumentation of possible relationships between the different foci, and thus generating a better understanding of the factors involved in their dissemination.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

"Dry and ready in half the time": Gypsum wallboard's uneasy history

T.W. Leslie
Iowa State University, Ames; Northwestern University, Evanston, USA

ABSTRACT: Few construction materials have become as ubiquitous as gypsum wallboard. Easily cut, shaped, and transported, its density and mineral nature make it an ideal solution to interior issues of fire separation, acoustic privacy, and durability. Meanwhile, the abundance of gypsum throughout the world and efficient manufacturing processes have made it affordable for virtually all building types. Yet, like many building materials of the last century, gypsum wallboard's history belies its commonplace usage today. It was among the 20th century's most disruptive technologies in terms of construction labor, threatening the livelihoods of tens of thousands of tradespeople and radically altering the pace and staffing of traditional interior jobs. Wallboard's introduction forced city building commissions to directly address the growing impact of industrialization on American construction in the postwar era and the simultaneous waning influence of labor unions. It was a signal moment in the industrialization of construction, altering expectations for interior finishes and detail while influencing the wholesale evolution of building codes from prescriptive models to performance standards. Gypsum wallboard also helped to spawn a new laboratory testing industry that, in turn, encouraged the further amplification of building science research and development throughout the last half of the 20th century. Wallboard's effects were particularly impactful in Chicago. This city saw some of its earliest applications, its major corporate producer's headquarters, and virulent fights over its application and impact on demography and the evolving balance of power among the city's labor and trade unions.

1 PLASTER – AN ENTRENCHED CRAFT

Wallboard's appearance threatened a 3500-year tradition of hand-based, artisanal plastering in Western building construction. Burning or calcining minerals such as lime or gypsum to reduce them to a dry powder that could then be re-hydrated into a solid mass of plaster was common in ancient Egypt. Gypsum had the great advantage of requiring less heat to become fully calcined than lime, and it became the basis for "plaster of Paris", a medieval advance that took hold in northern Europe. On the other hand, lime plaster formed the basis for *stucco duro*, a key material in Renaissance architecture. Plasterers could fine-tune either material by varying water ratios or adding animal hair or gelatin to adjust its workability and strength. Lime and gypsum plaster could be easily carved, colored, or molded while setting, leading to their use in moldings, sculpture, and fresco (Gapper 1999; Guedes 1979).

Plaster's most widespread use was as a wall coating. It served as a fire-resistant, sound-deadening, durable finish that was far less expensive than masonry, wood, or stone. It served as a journeyman material for interiors of all types and classes from medieval times forward. Plaster was usually applied by first constructing a *lath*, or network of light wood slats spaced $^1/_4$" to $^1/_2$" apart, enough space that workers could push through a thick first coat of plaster (the "scratch"). This coat formed "keys" bonded mechanically to the lath, ensuring the plaster's stability. Scratch coats were usually impregnated with fibers – either animal hair or grasses – to provide tensile strength as a defense against cracking. Plasterers would rough up the drying scratch coat, providing enough tooth to bond to a second, "brown" coat that provided a troweled, flat surface. They would then place the third or "white" coat atop this, often of lime instead of gypsum, designed to provide a more refined finish that could be painted or incised with ornament (Conklin 1954). When executed by skilled craftsmen, the results were velvet-like surfaces of great precision, seamless and smooth, that provided excellent substrates for paint or paper – or that could simply be left bare. Thick lime white coats made the material suitable for exterior finishes as well, while plaster's malleability while wet made it ideal for extruded shapes such as moldings (Cameron 1883). These delicate surfaces came with drawbacks that inspired attempts at improvement. As plaster had to be placed wet, it required extensive drying time, during which it would discharge its moisture into building interiors. The resulting overly humid environments frustrated other trades – particularly carpentry, where freshly placed wood was susceptible to humidity changes. Once dried, gypsum plaster was vulnerable to re-hydration, which weakened its chemical bonds and could cause walls or ceilings to break up and fall. Plaster's near-perfect surfaces were susceptible to cracking as building frames settled, as their mechanical

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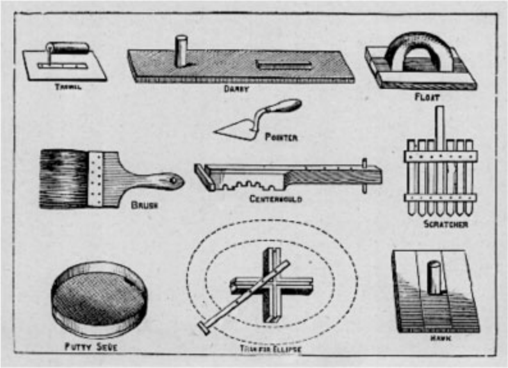

Figure 1. Plasterer's Tools, from *Cameron's Plastering Manual* (Cameron 1883). The tools here would have been familiar to a Roman or even Egyptian plasterer, reflecting the field's relative lack of innovation and continued reliance on skilled labor.

connection to building structures – whether frame or masonry – provided no flexibility. Plaster's need for skilled labor to create such finely crafted surfaces proved the most difficult, however, as other trades and materials became more efficient through industrialization in the 19th century (Figure 1).

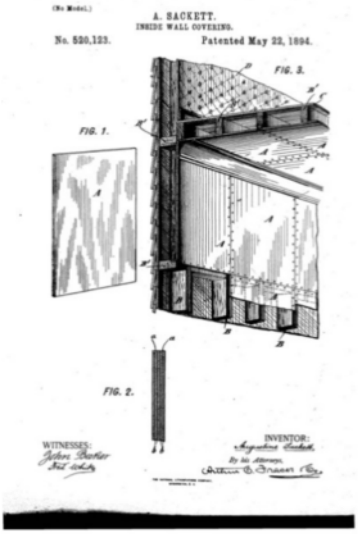

Figure 2. Patent for "Inside Wall Covering", A. Sackett, 22 May 1894.

2 DRY WALLS: EARLY DEVELOPMENT

In February 1892, *Scientific American* announced a new product, manufactured by a New York inventor named Augustine Sackett. "Sackett Board" eliminated many of wet plaster's drawbacks while meeting its high standards for finish and durability – equaling plaster's fire resistance but without "cracking or falling". Being of dry construction, however, it eliminated the moisture problem inherent to plaster construction. "Rooms finished with it can be occupied at once", the article claimed, and "as there is no moisture in the material, wood trim may be finished to it at once, without danger of being injured by twisting or swelling". Most notably, however, Sackett Board could be "applied by unskilled labor at any time of the year", eliminating the time and effort to construct lath and apply multiple wet coats ("Sackett's" 1892). Sackett, a Civil War naval engineer, filed a patent for Sackett Board in 1890, granted in 1894 for "boards or plates which may be used as a substitute for lath and plaster as a material for forming the inner walls of houses or rooms". (Sackett, 1894). Sackett's product used layers of plaster-impregnated paper to create a material "sufficiently stiff and rigid to form a firm wall surface, sufficiently strong to resist the effect of any ordinary blows or concussions to which it may be subjected; sufficiently soft to admit of nails being driven through it, and sufficiently tough and tenacious to prevent its cracking when in place on the wall". As importantly, his process produced sheets in sizes and thicknesses that balanced ease of transport and handling with the need to minimize joints. One laborer could handle a sheet or two and install it rapidly with simple hammers and nails, finishing it with a single, fine plaster coat over its surface. Sackett made no claims for fire or acoustic performance in his patent, but his advertising emphasized these qualities alongside the boards' ease of handling and placement. Sackett Board was one of many patented wall materials of the era, but it proved the best commercial balance of performance and assembly. Other boards made of vegetable fibers, such as Celotex, proved either more fragile or less fire-resistant. Competing products made out of cement proved to be heavier or difficult to affix because of their tougher composition.

Initially, Sackett Board served as a replacement for lath alone, replacing the labor-intensive carpentry of wood slats or even newer metal mesh sheets that provided a grippable plane into which workers could press first coats. As such, it remained a tool in the plasterer's arsenal of materials, replacing the typical thick scratch coat but leaving much of the skilled labor – the thinner brown and white coats – still to be done (*Western Architect* 1910). As long as it remained an adjunct to the plasterer's craft, Sackett Board proved popular with plasterers and their unions. It made for a quicker process and one that reduced their reliance on carpentry. But Sackett Board's position as an underlay for the plastering trade evolved with Chicago-based United States' Gypsum's purchase of Sackett's company in 1909. The company, a combination of three dozen manufacturers, was among the earliest to adopt vertical integration as a strategy, purchasing mines and manufacturing plants throughout North America to extract raw gypsum and convert it into building material. By 1917, it had re-christened Sackett Board as, first, "Adamant" board and then as "Sheetrock". Within a few years, the company marketed Sheetrock as more than mere lath – it was sold as a complete packaged wall material to contractors and homeowners alike,

Figure 3. General Houses "Steel House", 1933 Century of Progress Exhibition, Chicago. Interior showing Sheetrock partitions (Raley 1934).

as "The Fireproof Wallboard". "Its cost is low, and the cost of erecting it is low", its advertising pointed out. "There is no lath or lathing, no mixing of plaster, no plastering with Sheetrock" (Des Moines Register, 1922). This description reflected the material's evolving role. United States Gypsum refined Sackett's original formula, wrapping the gypsum-impregnated core with waterproof paper to toughen vulnerable edges and standardizing sizes to match residential ceiling heights. (United States Gypsum Co., n.d.) The company developed ancillary tapes and beads that allowed even unskilled homeowners to achieve good results from the boards alone – without the need for covering coats of plaster or, crucially, the expense of hiring skilled plasterers themselves (Figure 2).

Sheetrock's full potential was put on display when designers for Chicago's 1933 Century of Progress Exhibition pressed it into service for exhibition buildings and display homes. Alongside early air conditioning and fluorescent lighting installations, the Exhibition's structures featured over five million square feet of Sheetrock. The new material could be shaped to comparatively tight radii using no other tools than a plasterer's knife, proving particularly apt for the streamlined curves that defined the Exhibition's house style (Beach 1934). But the material's most telling application was in the contemporary houses on display, which showcased the state of residential technology. Chicago's Keck Brothers designed the best known of these, the so-called "House of Tomorrow," a twelve-sided glass prism that boasted of its "dry construction", which eliminated "wet" plaster walls in favor of Sheetrock partitions. Other, lesser-known exhibition houses also turned away from plasterers and other crafts in favor of industrialized building. Steel houses by Stran Steel-Irwin and General Houses used Sheetrock for their interior walls and the Keck Brothers' Crystal House, erected in the second year of the Fair in 1934, used a competing wallboard product by Celotex (Raley 1934) (Figure 3).

3 CHICAGO: LABOR, POLITICS, AND GYPSUM

By the Century of Progress, though, drywall and its competitors had already disrupted construction – particularly in Chicago. The city's plasterers were among Chicago's best-organized unions, leading a devastating strike that shut down building operations in 1897 and carefully limiting apprenticeships and membership to keep wages high. In 1925, work on an extension to the Palmer House halted when disputes between members of the local union and plasterers who had joined the rival bricklayers' union broke out, a precursor to strikes in 1926 over wages that shut down construction all over the city. In response, contractors in Chicago threatened to increase the use of "substitutes for plaster in construction" in the hopes that these would "lessen the effects of the walkouts" and, ultimately, "lead to a permanent decrease in the demand for plasterers". Celotex leaped on the announcement, pointing out that its sales had increased twenty-fold over the previous five years. But the city's building code at the time restricted wallboard to wood-frame residential construction. A clause required that all "plaster substitutes" be composed of 96 % plaster – a transparent giveaway to the plasterers but a standard soon met by Sheetrock and other competing gypsum-based wallboards. However, the code only permitted wallboard to substitute for wood lath; it still required two plaster coats as a finish for fire resistance. Plasterers and their union saw the threat. Chicago plasterer Byron Dalton authored a manual on *Practical Plastering* in 1937 in which he decried the "indifference and abuse" of those manufacturing "substitutes". These, he felt, were "the effect of poor work" and a decline in skills and standards in the plastering trade. Not once in his book did Dalton mention Sheetrock, even when discussing various laths. (Dalton & Carlson 1937).

Dalton would become a key figure in the fights over the gradual industrialization of construction in Chicago and its building code's modernization. He was a longstanding member of the International Union of Plasterers and the Chicago Building Trades Council and the Chicago Plastering Institute's founder. His Institute campaigned for higher wages but, more importantly, for continuing requirements that interior wall construction in the city be of plaster or masonry – and nothing else. Dalton's record was colorful. He was charged with beating a Berwyn homeowner who had employed a lapsed union plasterer in 1935 and later indicted on charges that he had strong-armed contractors into banning limestone from non-union quarries in Indiana. In the aftermath of WWII, with the city struggling to build housing for the Great Migration's second wave and the postwar demographic boom, Chicago sought to liberalize its building code, hoping that this would spur builders to meet growing demand. John O. Merrill, a housing expert who had joined Louis Skidmore and Nathaniel Owings to form Skidmore, Owings, and Merrill, was appointed head of a technical committee to advise on the city's code in 1946. He

Figure 4. Sheetrock panel being installed by a single, semi-skilled worker. From USG, Walls of Worth (U.S. Gypsum ca. 1937).

immediately decried the existing code's prescriptive material standards – in particular, that of hand-placed plaster. "If we are going to require a wall that can resist fire for half an hour", Merrill told the City Council, "why not say that instead of stating it in terms of materials?" Merrill's complaint was a succinct definition of a "performance-based" standard. This approach left the choice of material up to a builder or architect, placing the onus on them to show that whatever they had specified would meet a given set of requirements – in this case, a given amount of time that a wall would contain a fire. Such standards were the subject of an FHA campaign, but Dalton and other tradespeople – who saw their hold on the housing market slipping – put up fierce resistance. In the same meeting, Dalton raised the specter of house fires, getting Merrill to admit that the code-required layering of plaster would perform better than a Sheetrock substitute. Still, Merrill campaigned heavily for the alternative, noting that plaster's growing costs made it "unrealistic" to continue the requirement. Merrill's committee ultimately suggested performance standards, and it referenced the FHA's wartime standards as appropriately high and agile. While these recommendations were praised nationwide, the Tribune noted that such progress remained subject to the city council's notorious self-interests. "If the aldermen start messing around with all these details, and subject themselves to the sophistries of the innumerable special interests who want to continue to use the code to [swindle] the public and blackjack their competitors, the city will end up with a code that is little better than the present one" (Figure 4).

These special interests included manufacturers, who sought more liberal codes that would provide markets for new products, and tradespeople who argued for more conservative requirements that would require their skills. Larger political and demographic forces amplified these pressures. Many suburbs that began the 1940s as small towns ended them as well-populated cities in their own right. These municipalities suddenly needed more robust building codes, and most adopted the FHA's performance model. By the end of the decade, according to Park Forest developer Nathan Manilow, builders "found it easier to build effectively under suburban codes than under Chicago's outmoded regulations". The National Committee on Housing anticipated exactly this "interurban competition" in 1946, warning that "the movement of population away from central cities is certainly not decreased by this situation, and the tax and fiscal problems of the central city are greatly increased". Nearly three-quarters of new homes in the region were built outside of Chicago's city limits in 1949 (Figure 5).

Figure 5. Labor and Industry Demonstration House, Chicago, IL. 1949. (*Chicago Tribune* 1949).

Dalton and the Plasterers' Union managed to foul Chicago's approval process for nearly five years, frustrating progress with lurid but unfounded claims of Sheetrock's supposed vulnerabilities to fire. These claims, however, played into aldermen's fear of housing that was *too* inexpensive and thus attractive to the city's growing Black population. Plasterers and representatives of the city's outer neighborhoods formed an uneasy alliance, as aldermen saw prefabrication as a precursor for "affordable housing", a phrase that threatened suburban America with the specter of mixed-class, and thus mixed-race, neighborhoods. "A man with a good home doesn't want prefabs to be put up in his neighborhood", noted one suburban politician, explaining his objection to performance standards. Solid brick and plaster became material bulwarks in the city's race battles, a way of pricing out public housing in outer wards while offering the cover of fire safety to politicians and residents.

Allied against plasterers, bricklayers, and their racially-motivated allies on the city council were civic leaders desperate for a more liberal, development-friendly code and other unions who saw their employment hindered by retrograde prescriptive regulations. A demonstration home constructed on the city's north side in 1949 highlighted this divide. While it incorporated new technologies such as air conditioning, precast floor joists, and metal roof trusses, the home included walls of thickly-plastered metal lath – with no wood stud backup. All of these innovations reduced the amount of *carpentry* required while maintaining the *plasterers'* full employment and bringing new, unionized trades – sheet metal workers for the air conditioning's ductwork, for example – into the plasterers' camp. The code battle was also joined by a small but growing contingent of testing agencies – Underwriters' Laboratories in particular, who saw a tremendous market for their services in performance-based codes.

Chicago finally passed a performance-based code in December 1949 after compromises that required testing for interior finishes other than brick and plaster but permitted drywall assemblies in all residential and commercial construction, provided they passed flame tests. Underwriters led the way to establish protocols for testing. The city streamlined its approval process in 1956; UL, as it was re-christened, opened the world's largest testing laboratory in suburban Northbrook two years later. But drywall saw significant growing pains as contractors struggled to learn new techniques and to replace the craftsman-based model of plaster installation. Unskilled labor produced walls that were not plumb, and overly optimistic standards released by U.S. Gypsum for recommended thicknesses left initial installations short of the acoustic and durability standards that plastering had established. By 1956, U.S. Gypsum revised those standards, suggesting either a solid $^1/_2$ inch board for each side of a residential stud wall or, in areas where acoustics were a concern, two layers of 3/8" board. They developed new hardware for attaching drywall to wood or steel studs that provided a better mechanical connection and a whole family of tapes and finish compounds that produced better, more consistent finishes. That year, US builders completed an average home in six to eight weeks instead of the 12 to 15 typically required before WWII. Contractors attributed this reduction to drywall's quicker construction and the elimination of plaster's drying-out period. Material savings matched these reductions in time. Drywall produced far less waste, and walls constructed of drywall weighed less than fully plastered ones, reducing the load on walls and carrying structures.

4 CONCLUSIONS

A ten-week strike by Chicago lathers in 1951 helped encourage builders there to abandon plaster wholesale. The city's leading homebuilders' association urged its members to "investigate the merits of drywall construction and learn how to use it best". Meanwhile, the flame spread tests favored gypsum wallboard over plywood in wall surfaces. U.S. Gypsum funded testing programs that assured architects and builders of its applicability as Chicago and other municipalities updated their codes to performance standards. By 1955, U.S. Gypsum reported that it could barely keep pace with demand, despite opening new factories and operating their plants twenty-four hours a day. The company's stock price began to track the American housing market with almost exact precision, indicating the growing preference for its product over traditional plaster. Wallboard had the added advantages of providing shear strength to light framing, making it an ideal counterpart to increasingly delicate metal and timber stud framing standards. Plaster required far more robust substructures to hold its weight while wet and provided little of the drywall's racking resistance. Continued testing, performance in actual building fires, and developments to increase its moisture resistance and applicability in a wide array of environments contributed to its dominance. By 1985, more than 90% of all American residential construction used gypsum drywall, and the industry reported that it had produced over 20 billion square feet of the product that year.

Yet, the successes of drywall and U.S. Gypsum were not without consequences – notably the rapid decline of plastering as a trade and the associated impact on tens of thousands of skilled workers throughout North America. From a peak of more than 64,000 plasterers in the US in 1950, the trade dwindled to under 24,000 in 2010. In Chicago, the local plasterers' union was sued by federal anti-trust lawyers in 1956. In 1959 Dalton and the local union were sued by the national Employing Plasterers' Association, a contractors' group, on the grounds that Dalton had misspent funds on political contributions and gifts as well as on payments to city building inspectors who, in turn, harassed contractors using drywall or non-union labor. The union won both court battles, but they showed that plasterers had relied increasingly on political muscle to maintain their livelihoods. In one case, the union gave a Chicago alderman access to the union's insurance plan at no cost and stuccoed his house for free. Dalton and his union tried one last time to outlaw gypsum wallboard in Chicago in 1965, but by that point, the material had become ubiquitous and had proven itself in numerous building fires. Dalton died in 1969, and without his robust leadership, the Plastering Institute remained active but catered almost entirely to specialist construction. Carpenters took over the tasks of building and finishing interior partitions in most buildings throughout the US. The re-named USG saw continued corporate success, developing metal stud systems that reduced weight further and marketing dedicated screws and accessories that further streamlined partition construction. The company began an aggressive acquisitions campaign, buying rock wool and mining interests to control more of its supply chain. It built three new headquarters buildings in Chicago's Loop in succession – at 101 S. Wacker in 1961 and two blocks farther north, at 123 N. Wacker in 1986, and 125 S. Franklin in 1992 – evidence of its growing financial success and market dominance.

The corporatization of the interior partition wall in American construction was one of many similar narratives of commodified products and simplified assembly that replaced traditional trades. Often referred to as the replacement of "wet" construction by "dry", the real significance of this transition lay in the shift from specialized labor and craft to job sites populated by fewer, less-skilled workers and the migration of construction budgets from actual building fabric to systems. The percentage of cost associated with partitioning has plummeted compared to that spent on mechanical and electrical services. These changes have had salutary impacts for builders, suppliers, and developers, but they have also lessened the importance of trades and their unions in building construction. Drywall's ubiquity today – accounting for half a billion dollars of sales in 2016 – is reflected in the relative cleanliness of a commercial or residential project in its final, finishing phases, but also in the relatively small number of workers on-site and the nature of their tasks – assembly rather than craft, dust instead of plaster "mud".

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

A study of the history of concrete technology introduction in China

Q. Du & B. Qiu
Shanghai Jiao Tong University, Shanghai, China

ABSTRACT: Concrete technology was introduced to China in the late 19th century, and it deeply impacted Chinese construction patterns in the century that followed. This paper, based on Chinese publications in the first half of the 20th century, demonstrates the categories of knowledge and "importation" of concrete technology. It aims to clarify how this technology integrated into local engineering academia and industry and gradually influenced native construction in China, and it is expected to contribute to understanding the knowledge exchange between the East and West.

1 INTRODUCTION

Early concrete technology in China, tentatively from the late 19th century to 1949, is an area that is often neglected in the study of modern architectural history. Perhaps the reason for this is that concrete technology was a "Western Import", and it is difficult to find its roots in China, either in culture or in craft. However, concrete is a widespread and fundamental material in modern architecture, and early concrete technology is a transition between traditional crafts and modern construction systems. It is impossible to exclude concrete from modern Chinese architectural history. "Without the context of the history of technology, the history of architecture is inevitably fragmentary" (Wang 2016). It will be difficult to explain the modernization of Chinese architecture in the 20th century without studying the introduction and development of concrete technology in China.

The research of Chinese modern architectural technology can be categorized into three streams. The first is case-based: taking the early Bund complex in Shanghai or modern architectures in Guangzhou (Canton) as study objects (Leng 2017; Zhang & Yang 2017;. The second is literature research: examining the process of architectural modernity from journals, books, and newspapers (Liu & Jiang 2014; Qian et al. 2012; Zheng et al. 2019). The third is from the engineering perspective, especially in the architecture restoration domain: studying the early concrete component details and relating failure (Chun & Pan 2015).

It is impractical to construct a panorama of early Chinese concrete technology development in a few pages according to the scattered information and archives. Hence, this paper focuses on publications from 1900 to 1949, trying to profile an intellectual history and to provide a reference list for future researchers.

2 A PANORAMA OF CONCRETE CONSTRUCTION IN EARLY 20TH CENTURY CHINA

Concrete technology was introduced with the establishment of Treaty Ports in China. From late 19th to early 20th century, early concrete buildings were constructed in Guangzhou and Shanghai. Between 1881 and 1883, during the construction of the waterworks in Shanghai, the British engineer J.W. Hart used Portland cement for large-scale foundations of water towers (Zheng et al. 2019). The Club Concordia (1904) (Zheng et al. 2019), Sino-Russian Righteousness Victory Bank (1905) in Shanghai (Wu 2008), Arnhold & Karberg & Co. Building (1905) and the East Hall of Lingnan University (1905) (Peng 2008) were among the first reinforced concrete buildings in China.

The construction in concession territories led the changes in municipal regulations. For example, the reinforced concrete buildings were not mentioned in the 1906 regulations of Western-style building in Shanghai. In 1916, the Shanghai Municipal Council for International Settlement (SMC) issued the first rule of reinforced concrete – *Rule with Respect to Reinforced Concrete Building* (Tang 2006). The rule provided the specification of material selection, proportion and basic design method. This document was translated into Chinese and adopted by the Shanghai Public Works Department of Chinese territory in the following years. Nevertheless, this was only a specification of construction and not a systematic introduction of concrete technology.

3 IMPORTANT CHINESE BOOKS ON THE WESTERN INFLUENCE OF CONCRETE TECHNOLOGY

The "localisation" of concrete technology cannot be separated from the Chinese scholars' endeavours of

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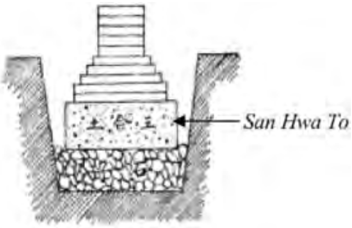


Figure 1. Drawing of *San Hwa To* foundation (Zhang 1910).

translating foreign publications into the Chinese language. The beginning of these activities coincided with the second phase of the "Western Studies", which happened from the late Qing Dynasty to the early Republic of China (c.a.1840–1919). In that era, Chinese young talents were sent to Europe, America and Japan, and the knowledge they acquired was disseminated through publications.

3.1 Jiànzhù Xīnfa (1910) Yingxu Zhang

Jiànzhù Xīnfǎ (《建筑新法》, literally *Neo-Methodology of Building*), compiled by Yingxu Zhang (张锳绪) and published in 1910, was the first Chinese publication to introduce the application of concrete to building construction. Most of the content and images in the book were cited from *An Encyclopaedia of Architecture* by the British architect Joseph Gwilt and Wyatt Papworth (Pan 2018).

Concrete was recognized as a new type of *San Hwa To* (三合土, literally *trinity combined clay*, refers to concrete) during that period. *San Hwa To* was a traditional material for making pavements and floors in buildings in China for centuries. Traditionally, the component of *San Hwa To* was a mixture of lime, clay and sand.

In *Jiànzhū Xīnfǎ*, *San Hwa To* was described as a material often used for building foundations (Figure 1).

San Hwa To, a mixture of gravels, river sand, and lime, or cement. To build a *San Hwa To* foundation, place a certain amount of gravel on the ground first, then spread river sand and lime or cement on the gravel. Mix these materials with water, pour the mixture into foundation pit, cast into a form and vibrate, and wait till set (Zhang 1910).

Cement, also called as *Yánghuī* (洋灰, literally *foreign podzol*), was a very expensive material in that era. It was commonly used with lime to reduce the cost of building.

Wall bricks are bonded with lime mortar or cement mortar. Dry lime mortar is normally a mixture of one volume of lime and two volumes of river sand. On the occasion where higher strength is required, a component of two volumes of lime and three volumes of sand is feasible. For the volume of water used, the weight of water is one-third of that of sand. Dry cement mortar consists of one volume of lime, three volumes of lime and six volumes of river sand. The weight of water is also one-third of that of sand …Once dry lime mortar is mixed with water, it will transform as hard as stone through the setting process of a certain period. If some cement is added into lime mortar, the substance will be particularly strong. The strength of lime mortar and that of cement mortar are remarkably different (Zhang 1910).

Throughout the entire book, there was no mentioning of using rebar together with concrete.

3.2 *Tiějīn Hùnníngtǔ (1925) Nangui Hua*

Tiějīn Hùnníngtǔ, (《铁筋混凝土》, literally *Ferro Armed Concrete*), was published in 1925 by Nangui Hua (华南圭). Hua was educated under the French engineering system. He studied at *École Spéciale des Travaux Publics, du bâtiment et de l'industrie* (ESTP Paris) from 1903 to 1910. He had served as the general engineer of Ministry of Transportation and Communications, Beijing-Hankou (Peking-Hankow) Railway, Peking-Mukden Railway (Peiping Liao-Ning Line) and the director of the Public Works Bureau of Peiping Special City (now Beijing) after returning to China. Considerable efforts were contributed by him to the Chinese education system in civil engineering. He was also employed as the dean of academic affairs at the Ministry of Communications Traffic Training Institute, the predecessor of Beijing Jiaotong University, where he established the Department of Civil Engineering. From 1930 to 1937, Hua served as the president of *Institut des Hautes Études Industrielles et Commerciales de Tientsin*, which was the predecessor of the Department of Architecture of Tianjin University (Hua 2009).

Tiějīn Hùnníngtǔ was compiled in 1925, but some of its contents appeared as early as 1917 in the fourth and fifth issues of *Journal of the Chinese Institution of Engineers* (《中华工程师学会会报》), with the title *Zhùzuò – Zhùwū Gōngchéng Zhī Tiějīn Hùnníngtǔ* (《著作——住屋工程之铁筋混凝土》, literally *Writings – Ferro Armed Concrete for Housing Works*). *Tiějīn Hùnníngtǔ* consists of four volumes: *Principes Généraux* (literally *General Principals*), *Formules Classiques* (literally *Classical Formulas*), *Formules Pratiques* (literally *Practical Formulas*), *Applications*. The title and keywords and titles of each section were auxiliary with French. In the part of *Principes Généraux,* concrete was defined as "a composite of cement, sand and stone". Compared with the definition of concrete in *Jiànzhù Xīnfa*, this definition specified that cement was a raw material of concrete. The author detailed a variety of reinforcement system, not only the well-known Hennebique systems, but also many of the less common forms, such as Matrai, Chaudy, and Degon (Figure 2). The other three volumes were all concerned with formulae, and each was essentially divided into tensile, pressure and flexural forces in turn.

The book is similar in form to a college textbook. It can be assumed that the source of this book was the knowledge that Hua acquired while studying

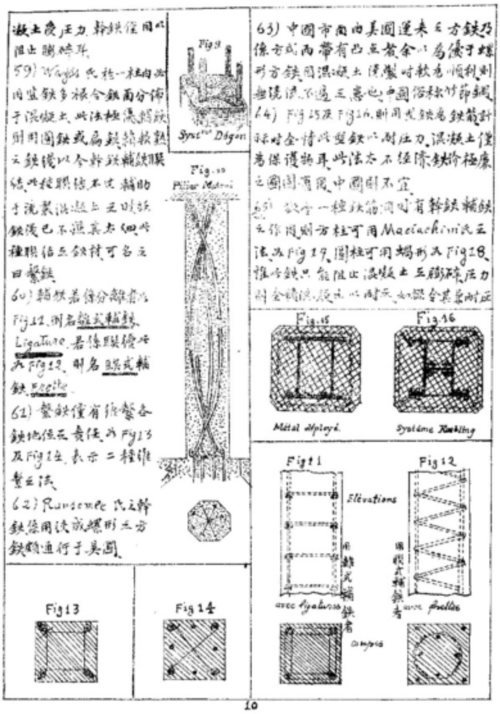


Figure 2. The drawing of reinforced concrete column in *Tiějīn Hùnníngtǔ* (Hua 1925).

abroad. He collated the theories to facilitate teaching in China. Besides *Tiějīn Hùnníngtǔ*, Hua also compiled a series of books entitled *Jiànzhù Cáiliào Zuōyào* (《建筑材料撮要》《房屋工, literally *Summary of Building Materials*), *Fángwū Gōngchéng* (程》, literally *Housing Engineering*) and more. All of these books were of great value for the study of early concrete technology.

3.3 *Concrete (1930) S. Feng*

In the 1930s, the number of publications increased. *Concrete* (《三和土》), published in 1930, was a part of *The Complete Library* (《万有文库》) series, edited by Y.W. Wong (王云五) and published by the Commercial Press in Shanghai. The content of *The Complete Library* was classified by 15 categories, ranging from agriculture to engineering and commerce. This series of books introduced Western achievements in natural and social sciences. It drove the production and innovation of modern knowledge in China (Zhu 2019).

Concrete was one of first collections in the series of Engineering. The author S. Feng (冯雄) was a famous Chinese hydrologist, writer and bibliophile. Besides *Concrete*, he contributed 10 books for the book series *The Complete Library*, including *Masonry* and *Mechanical Design, Irrigation, Surveying*. As no bibliography was provided in *Concrete,* it is not feasible to clarify the originality of the book. From the tables, formulas and citation of this book, it can be assumed that this book referred to the sources that originated in the United States of America.

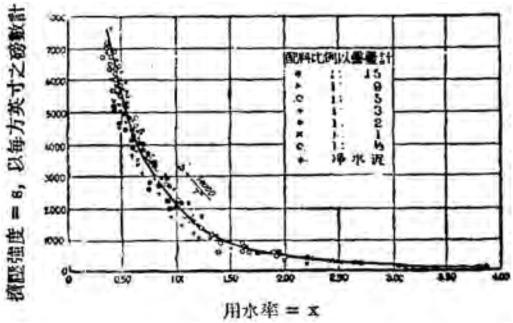


Figure 3. The relationship between the compressive strength of Concrete and water consumption, Figure 15 of *Concrete* (Feng 1930).

The focus of *Concrete* was on materials, including the mixing, transporting and depositing, and physical properties of concrete. The book briefly introduced reinforced concrete, cement products and concrete vessels. No complicated formula derivation or property calculation were mentioned in the book. Even in the chapter on reinforced concrete, it just briefly introduced neutral axis of beams and gave Kahn's Trussed Bar System as the only example. Thus, it is clear the book was aimed at education rather than professional demonstration. Moreover, the materials section of the book embodied the trend towards standardization of concrete techniques at that time, such as D.A. Abram's theory of "water-cement ratio" (Figure 3) and concrete proportioning curves. The specification developed by the American Society for Testing and Materials and the American Society of Civil Engineers were also mentioned.

3.4 *Gāngjīn Hùnníngtu Xué (1935) Fuling Zhao*

Gāngjīn Hùnníngtu Xué (《钢筋混凝土学》, literally *Science of Reinforced Concrete*), according to the author, "was referred to a code formulated by an American reinforced concrete association in 1928." By a series of comparison, it can be defined that the code referred to in the book was *JOINT CODE Building Regulations for Reinforced Concrete*. The code contained 1206 entries and was drafted jointly by the American Concrete Institute (ACI) and the Concrete Reinforcing Steel Institute (CRSI). In fact, Fuling Zhao (赵福灵) had already translated this code into a brief version called *Tiějīn San Hwa To Shèjì Jí Shīgōng Shuōmíng* (《铁筋三合土设计及施工说明》, literally *Design and Construction Instructions for Ferro Armed Concrete*) in 1930 and published as part of *The New Han-kou* (《新汉口:汉市市政公报》).

In *Gāngjīn Hùnníngtu Xué,* the *JOINT CODE* was attached at the end as an appendix. The principle of the book was categorized from a perception of building elements. The chapters ranged from reinforced concrete beams, columns, slabs, foundations, parapets, house construction to bridges. Compared with Hua's *Tiějīn Hùnníngtǔ*, this book was more practical, and contained more formula derivations and diagrams. Experiments used by American and German institutions, especially University of Illinois and the Massachusetts Institute of Technology, were frequently referred to in the book. The author had reviewed a wide range of concrete technology. For example, the development of concrete in Germany, Austria, Britain and United States of America was compared in order to explain specific properties of concrete, whereas the building codes of ACI, SMC and Hankow municipal government were evaluated to discuss the safety stress of concrete. It is clear that the book was not only a translation of foreign publications. The author explained his own understanding and experience of concrete technology and had developed his own derivation and contribution based on Western technological development.

3.5 *Jiànzhù Gòuzào Xué (1936) Ying Tang and Shoubao Wang*

Ying Tang (唐英) and Baoshou Wang (王寿宝)'s book *Jiànzhù Gòuzào Xué* (《建筑构造学》, literally *Science of Architectural Construction*), was one of the most repeatedly-reissued and influential books in the field of architecture. Although not a monograph on concrete technology, it frequently mentioned this subject in *Chapter 8 Gāngjīn Hùnníngtu Gōng* (《钢筋混凝土工》, literally *Reinforced Concrete Construction Work*) and *Mùké Daozhì Zhī Qiángyuán* (《木壳捣制之墙垣》, literally *Wall Built with Timber Cast and Jolt Ramming*) part of *Chapter 5 Qiánggōng* (《墙工》, literally *Wall Building Work*). This book embodied Germany's achievement in the field and its influence on Chinese engineers. The authors were educated in Germany, and two of the five references were related to the German publications on concrete technology – *Der Eisenbetonbau* (*Reinforced Concrete Construction*) by C. Kerten and *Der Eisenbeton* (*Reinforced Concrete*) by R. Saligaer.

3.6 *Shíyòng Gāngjīn Hùnníngtu Jiànzhùfa (1939) Zaishan Gu*

From Nangui Hua, the French influence continued. *Shíyòng Gāngjīn Hùnníngtu Jiànzhùfa* (《实用钢筋混凝土建筑法》, literally *Practical Construction Method of Reinforced Concrete*), was translated by Zaishan Gu (顾在埏) from the French scholar L. Malphotte's book *BETON ARME a la portee de tous* (*A Book on Reinforced Concrete for the Most Common Man*). The book was divided into four sections: construction methods, calculation methods, tables and general application formulas, and integrated design. The most extensive part of the book was the second section, on calculation methods. Stress properties, calculation and design were explained in this section, which ranged from reinforced concrete beams, columns, floors, water closets, water pipes, chimneys, walls, electric poles, to staircases. Each case is accompanied by a detailed calculation derivation.

3.7 *Hùnníngtu Gōngchéng Xué (1941) Kaiying Xiao*

Hùnníngtu Gòuzào Xué (《混凝土工程学》, literally *Practical Science of Concrete Engineering*), published in 1941, was a part of the *Shíyòng Tumu Gōngchéng Xué* (《实用土木工程学》, literally Practical Civil Engineering) series. According to the editor Zhen Wanghu (汪胡桢), a famous Chinese hydrologist:

> The source of this book series was a professional civil engineering series published by the American Technical Society, whose advantage was that it focused on practical applications and avoided abstruse theories. ... The series has long and important impact to the American academia. ... The latest 1938 edition, which contains seven large volumes, was adopted to compile …(Xiao 1941).

Based on this description and the publication records of the American Technical Society, it can be assumed that the series adopted to compile *Shíyòng Tumù Gōngchéng Xué* was the *Cyclopedia of Civil Engineering*. The *Cyclopedia* was first published in 1909 and had been reissued several times afterwards. The original authors of *Hùnníngtu Gōngchéng Xué* were Walter Loring Webb and Herbert Gibson, and the translator was Kaiying Xiao (萧开瀛). Xiao wrote in the translator's introduction:

> Our country was so backward in construction that all materials relied on import. However, reinforced concrete was an exception. Apart from some steel bars, the rest, such as cement, sand and gravel, had already been available in China. Compared with steel and timber, which material was completely imported, it is much worthy to adopt concrete structure. Therefore, it was urgent to promote the development of reinforced concrete engineering and to popularize the knowledge of reinforced concrete, in order to improve the construction in our country and avoid excessive spill over of profits (Xiao 1941).

This introduction clearly explained Xiao's motivation for translation. It also embodied local engineers' efforts to change the unsatisfactory situation of Chinese construction industry.

As the original title of *Hùnníngtu Gōngchéng Xué* had not been provided, and the series of *Cyclopedia of Civil Engineering* did not have an identical book to Xiao's translation, the original was identified by searching among the books co-authored by Webb and Gibson, and it was finally identified as *Concrete Design and Construction*. *Concrete Design and Construction* had been reissued several times, and Xiao's translation was quite faithful to the original, both in terms of text, figures and tables, compared with the first American edition published in 1931. He integrated several chapters into one and divided *Hùnníngtu Gòuzào Xué* into four parts, corresponding to materials, plain concrete construction and design, reinforced concrete design, and construction, attached with an English-Chinese glossary at the end.

4 CONTRIBUTION AND DERIVATION BY LOCAL ENGINEERS

4.1 *Shíyòng Gānggǔ Hùnníngtu Xué (1930) S.D. Dzü*

Shíyòng Gānggǔ Hùnníngtu Xué (《实用钢骨混凝土学》, literally *Practical Science of Reinforced Concrete*) was published in 1930. Its author S.D. Dzü (徐鑫堂) had no experience of overseas studies, but had a Western education background nevertheless. Dzü graduated from Hangchow University, a Protestant missionary university in Hangzhou (Hangchow) jointly founded by the Presbyterian Church of North America and the Presbyterian Church of South America. After graduation, he served as a draughtsman for Hangchow University and as head of the drawing and calculation unit of the building department (Lai 2006).

From this experience of Dzü, it can be assumed that *Shíyong Gānggǔ Hùnníngtu Xué* was both a compilation of the author's knowledge at Hangchow University and the accumulation of engineering practice. According to preface of this book, written by Cixin Xue (薛次莘):

The literature on this kind of (concrete) architecture was abundant in Europe and America, but few scholars in our country can contribute to it. ... Dzü had participated in a lot of architectural engineering projects, and his research was particularly profound in steel and concrete engineering. ... His book would not only be a milestone in Chinese academic history but also benefit architectural industry (Dzü 1930).

The book consisted of ten chapters, starting with a general introduction to reinforced concrete, followed by a description of reinforced concrete beams, slabs, foundations, materials, notes and notations, and calculation tables. Compared with *Tiějīn Hùnníngtǔ*, practical discussion was focused on rather than the mechanics of materials. Beams, slabs and columns were clearly explained in corresponding chapters, incorporating the method of tying reinforced concrete and mixing raw materials.

In the same year, Dzü also published *Gānggǔ Hùnníngtuliáng Biao Jí Gānghuán Biao* (《钢骨混凝土梁表及钢环表》, literally *Reinforced Concrete Beam Table and Stirrup Table*), explaining the calculation of rectangular beams, T beams and inverted T beams, reinforced concrete slabs, two-sided reinforced concrete beams, and rib beams. Such tables had never been mentioned in Chinese books before (Figure 4). Dzü's work embodied that reinforced concrete technology had been widely applied to and deeply integrated into local engineering practice.

Figure 4. The table of reinforced concrete beam (Dzü 1930).

4.2 *Zhōngguó Tǔmù Gōngchéngshī Shǒucè (1946) Zhen Wanghu, et al.*

Zhōngguó Tǔmù Gōngchéngshī Shǒucè (《中国土木工程师手册》, literally *Manual for Chinese Civil Engineers*) was a series of books edited by Zhen Wanghu in 1944. This series consisted of three books: *A. Jīběn Shoucè* (《Ａ基本手册》, literally *Basic Manual*), *B. Tumù Shoucè* (《Ｂ土木手册》, literally *Civil Engineering Manual*) and C. *Shuilì Shoucè* (《Ｃ水利手册》, literally *Hydraulic Engineering Manual*). Wanghu reviewed existing translated engineering publications in the preface and noted that:

Foreign project cases, construction codes, engineering materials, laws and labour costs were considerably different from those in China. Translation was required to be faithful to the original so that no adding or deleting any words to the original was allowed. This led reader focus to foreign countries (and dismissed this fact in China) …Therefore, a goal to compile a manual for civil engineers had been set in Spring R.O.C. 30 (1941). The manual would only refer to fundamental principles and common customs of the foreign country and the remaining parts would be selected from local materials (Wanghu et al. 1946).

This shows that local engineers had absorbed and rethought Western knowledge and had started to

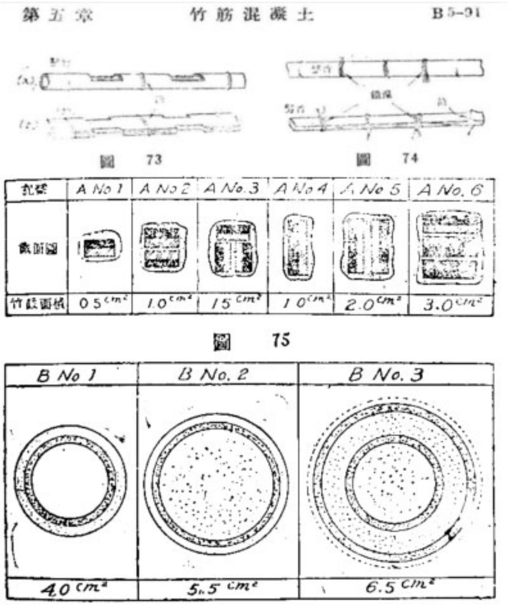


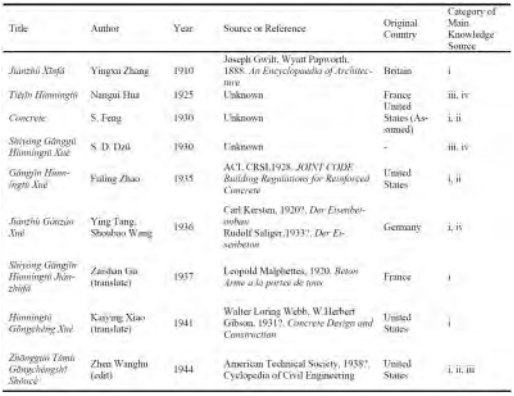
Figure 5. The illustration of Bamboo R.C. (Wanghu 1944).

develop and derivate new applications, while respecting local reality in that era.

The second book, *Tumù Shoucè*, consisted of 19 volumes, covering engineering materials, structural mechanics, roads, railways, houses, and even urban planning. Most parts mentioning concrete were in the fifth volume *Hùnníngtu* (《混凝土》, literally *Concrete*), whose author was the same as *Hùnníngtu Gōngchéng Xué*'s – Kaiying Xiao. The contents of this volume were classified into five chapters: simple concrete, steel-bar reinforced concrete, miscellaneous works, standards and bamboo reinforced concrete (Figure 5). Especially, this book paid special attention to bamboo-reinforced concrete, which can be considered a localised reinforced concrete in East Asia. The first experiment conducted on the properties of bamboo-reinforced concrete was undertaken by a Chinese overseas student Hou-Kun Chow (周厚坤) at Massachusetts Institute of Technology (Archila et al. 2018; Chow 1914). Bamboo-reinforced concrete was then introduced into China, and its first application to industry was no later than the construction of Sichuan-Hankou Railway in 1919 (Jin 1921). As bamboo is a characteristic building material in the East, its application to concrete as a substitute for steel-bar embodied the combination of Western technology with the Chinese local reality of having no steel.

5 CONCLUSION

From the late 19th to the mid-20th century, concrete technology was gradually introduced into China. Besides the construction practices of foreign engineers in the concession areas, which stimulated the enactment of building regulations on the reinforced concrete (e.g. the 1916 Western-style building regulations issued by SMC), the technology was also spread via publications. The historical publications covered in this paper can be classified into four categories by source (Figure 6):



Title	Author	Year	Source or Reference	Original Country	Category of Main Knowledge Source
Jiànzhù Xīnfǎ	Yingxu Zhang	1910	Joseph Gwilt, Wyatt Papworth, 1888. *An Encyclopaedia of Architecture*	Britain	i
Tiějīn Hùnníngtǔ	Nangui Hua	1925	Unknown	France	iii, iv
Concrete	S. Feng	1930	Unknown	United States (Assumed)	i, ii
Shíyòng Gānggǔ Hùnníngtǔ Xué	S. D. Dzü	1930	Unknown	-	iii, iv
Gāngjīn Hùnníngtǔ Xué	Fuling Zhao	1935	ACI, CRSI,1928. *JOINT CODE Building Regulations for Reinforced Concrete*	United States	i, ii
Jiànzhù Gòuzào Xué	Ying Tang, Shoubao Wang	1936	Carl Kersten, 1920?, *Der Eisenbetonbau* Rudolf Saliger,1933?, *Der Eisenbeton*	Germany	i, iv
Shíyòng Gāngjīn Hùnníngtǔ Jiànzhùfǎ	Zanshan Gu (translate)	1937	Leopold Malphettes, 1920. *Beton Arme a la portee de tous*	France	i
Hùnníngtǔ Gōngchéng Xué	Kaiying Xiao (translate)	1941	Walter Loring Webb, W.Herbert Gibson, 1931?, *Concrete Design and Construction*	United States	i
Zhōngguó Tǔmù Gōngchéngshī Shǒucè	Zhen Wanghu (edit)	1944	American Technical Society, 1938?, Cyclopedia of Civil Engineering	United States	i, ii, iii

Figure 6. Historical books related to concrete in the first half of 20th Century China.

i. Professional engineering publications;
ii. Building codes and specification;
iii. Engineering practice;
iv. Higher and/or vocational education.

From the view of source countries of origin, early Chinese concrete technology was influenced by many Western countries, including Britain, France, United States of America and Germany. Among these countries, the influence from the United States was the most significant.

From the view of chronicles, introduction and popularization of concrete technology peaked in the 1930s. Also in this decade, Chinese native engineers began their initial absorption and reflection, including the first Chinese monograph on reinforced concrete design written by S.D. Dzü, which included the knowledge from his earliest educational and then practical engineering experience, and the manual for Chinese civil engineers formulated by Zhen Wanghu et al, following a comprehensive translation of a series of foreign civil engineering books.

It can be concluded that the theoretical system of concrete technology had already been formulated in China by the mid-1940s. However, the complete localization of concrete technology was not completed until there was independent local steel production, realized after the establishment of People's Republic of China in 1949. However, the influence of European and American systems was far less than before, and the Soviet Union became the main source of the reinforced concrete technology. This can be proved by the translated publications since 1950. Thus, in cultural and technological terms, the year 1949 can be defined as the upper limit of early concrete technology in China.

To end, this paper is only a preliminary collation of a series of publications and has not involved analysis and inter-comparison of specific content. This will be implemented at a later stage of research.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Victor Horta and building construction. The written testimonies of the architect's teachings and library

D. Van de Vijver
Universiteit Utrecht, Utrecht, The Netherlands

ABSTRACT: The notes taken by Victor Horta's students for the construction courses he taught during his professorship (1892–1911) at the Polytechnic School of Brussels University (Brussels, Archives ULB) and the presence of building construction-related books in the architect's library (Sint-Gillis, Horta Museum, inventories, dated respectively 1931 and 1944), constitute two exceptional and unstudied written testimonies that shed light on the relationship between Horta (1861–1947) and building construction. Both source types furnish a wealth of detailed information that complement each other beautifully. Moreover, besides the individual and biographical level information, these sources provide a better understanding of the teaching subjects and practices of building construction and situate the Belgian construction culture in its broader international context.

1 INTRODUCTION

The Belgian architect Victor Horta (1861–1947) judged building construction as the core of architecture. The use of iron at the Maison du Peuple and the acoustics of the Salle du Boeuf at the Palais des Beaux-Arts prove this mastery.

This contribution approaches the subject of Victor Horta and building construction through the exceptional and unstudied written testimonies of (1) the notes taken by Horta's students in the construction courses taught during his professorship at the Polytechnic School of Brussels University (the actual ULB) from 1892 to 1911 (Brussels, Archives ULB [further ULB]) and (2) the presence of building construction-related books in the architect's library, dated respectively 1931 and 1944 (Sint-Gillis, Horta Museum, Papiers Jean et Renée Delhaye [hereafter HM]). These sources document Horta's relationship with construction science at two moments in his life: one at the turn of the century, which was the high point of his Art Nouveau oeuvre, and the other at the end of his career.

An in-depth analysis of these documents permits the author to articulate Horta's relationship to building construction within the local Brussels context (especially, the construction teaching tradition at the Polytechnic School of Brussels University, for example, that of his predecessor Jean-Ernest Hendrickx), within the national Belgian context (especially, the relationship with construction courses given at the other Belgian engineering universities of Ghent, Liège, and Leuven), and within the international context (especially, French construction manuals).

The proposal aims to contribute to a better understanding of the teaching subjects and practices of building construction at a major Belgian engineering institute and the construction culture in Belgian at the end of the 19th century and the beginning of the 20th century in a broader European context and through the lens of one of its major architects.

First, the paper will present Horta's course "Architecture civile" at the Polytechnic School at the Brussels University through detailing Horta's teaching career, its situation within the different courses at the engineering school, and an overview of the course's content. This will also analyse different aspects of its content (rational/irrational, construction and style, and personal accents of the teacher). Secondly, the paper dives into the construction books in Horta's private library. Finally, the author relates the content of the "Architecture civile" course notes to the architect's private book collection.

2 HORTA'S 'ARCHITECTURE CIVILE' COURSE AT THE BRUSSELS POLYTECHNIC SCHOOL AT THE ULB (1893–1911)

Horta's teaching career started in April 1892, when he joined with Mouris (?-?), "*chef de travaux graphiques*", as assistant of the professor of architecture and architectural history of engineering studies of the Polytechnic School (the Faculté des Sciences Appliquées) at the Université de Bruxelles. In the academic year 1892–1893, E. Mouris and Victor Horta taught as "chef. des travaux graphiques" the "travaux graphiques (épures)" of the Polytechnic School, Faculté des Sciences Appliquées; to the first and second year students of the degree "candidat-ingénieur"), the "travaux graphiques" of the third-, fourth-, and fifth year (that is, on the engineering degree) students in the

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disciplines of mining and "constructions civiles" and the fourth- and fifth-year students for the disciplines of "génie civil" and "arts et manufactures (section de mécanique, de chimie et d'architecture)" (ULB 1892, 14–23). After the unexpected death of Ernest-Jean Hendrickx (1844–1892), Horta succeeded the professor in October of the same year (Horta [Dulière, ed.] 1985, 317; HM III.1; Cools and Vandendaele 1984, 44 note 20; ULB, dossier 1P177 'Victor Horta: note by Ph. Steenebrugen 19 September 1947' and dossier H12 'Horta Victor'); he acquired the title of "professeur extraordinaire" in January 1897 (ULB, 1P177; Cools and Vandendaele 1984, 44 note 20; HM, III.3) and of "professeur ordinaire" in March 1902 (Horta [Dulière, ed.] 1985, 318; Cools and Vandendaele 1984, 44 note 20; ULB, 1P177; Goblet d'Alviella 1909). From the academic year 1893–1894 until his resignation in December 1911, Horta taught the following courses: the "dessins à main levée" in the first two years "candidat ingénieur" (E. De Ré en L. Govaerts, "chefs des travaux graphiques") and on the engineering course the disciplines of "génie civil" and "arts et manufactures". He further taught different classes to different engineering student profiles: 'Architecture civile' in the third and fourth year of the "grade d'ingénieur des constructions civiles"; the second part of the course of 'Technologie' in the fourth year of the "ingénieur des constructions civils", and 'Histoire de l'architecture' in the fifth year of the "ingénieur des constructions civils". The third-year mining engineering students received his course 'Architecture industrielle-architecture civile'. He taught architecture in the third and fourth year of the grades "d'ingénieur civil et d'ingénieur des arts et manufactures"; and, lastly, he taught 'Histoire de l'architecture (cours special à la section d'architecture)' in the fourth year (ULB 1893).

Two series of course notes document Horta's university course 'Architecture civile' in the third and fourth year of the "grade d'ingénieur des constructions civiles" (respectively by the engineering student Edouard Bogaert [1881–1946], ULB 2QQ961a-e, further Horta [Bogaert]a-e s.d.; and Henri Michel, ULB 2QQ110, further Horta [Michel] 1905–1906). They comprise notebooks of the type Université de Bruxelles, Cours: the right-hand page contains the written text, and the left-hand page contains the related drawings. The numbering of the drawings guarantees the relation with the text. This type of note (text versus images) long remained the norm, even when polycopyed handwritten (Keelhoff 1910) and polycopyed machine typewritten notes (Verly 1925) replaced their handwritten peers. The first series comprises 56+73+57+57+44 folios (2QQ961a-e); the (incomplete) second series counts on 49 and 46 written folios (2QQ110I-II). The pages remained unnumbered, and to refer to the pages, I foliated them virtually and refer to the pages with volume number, folio number, recto/verso.

Other course notes by Henri Michel eloquently communicate the content of the Polytechnic School's program besides Horta's 'Architecture civile'. Charles De Keyser (1870–?) was in charge of the course of 'Hydraulique'. Alphonse Huberti (1841–?) taught 'Topographie'. Lucien Anspach (1857–1915) was responsible for the courses of 'Graphostatique' and 'Stabilité des constructions', two specialized courses in mechanics intended for calculating structures. James Van Drunen's (1855–1932) 'Cours de construction du genie civil' (succeeded by Eugène François [1870–1957] and André Deckers) covered roads, canals, and bridges, and his 'Architecture industrielle' offered more precision for foundations and masonry structures.[2] These other courses allowed Horta's course 'Architecture civile' to remain descriptive and informative, as the calculus of structures was taken care of elsewhere in the curriculum. Only a limited number of formulae were present in this course, reduced even to rules of thumb, such as Rondelet's (graphic) formula for the necessary thickness of masonry walls (ULB 2QQ110II, 24v). Also, the presence of vectors (representing the resulting force) in drawings of gothic structures suggests an understanding of their statics, again without calculus (ULB 2QQ110II, 32v; other examples of graphic representation of 'pressure' by a vector: ibidem, 5v, 20v, 26v; ULB 2QQ961d, 7v).

The content of the course 'Architecture civile' contains three main parts (see Annex): materials (Part I); the application of the materials to construction (Part II) in foundations (II.1), masonry (II.2), "pan de bois" and "pan de fer" (II.3), carpentry and "menuiserie" (II.4); and, at last, composition (Part III) with a general introduction on principles (III.1), parts of buildings (III.2) and, most importantly, building typologies (III.3) as in housing ("maisons ouvrières" are extensively treated, "maisons bourgeoises", and "hôtels privés"), as well as much more briefly approaching hospitals, schools, "halles", markets, and prisons. The "palais de justice", praised by Horta as a building typology par excellence and representative of the contemporary age (Hennebicq, Horta and Van den borren 1898; Van de Vijver article in print), remained absent. The housing section is subdivided in social classes, related to the width of the building lot (under 6 meters, between 7 and 8 meters, or 9 meters or more). The stress is put on workmen's housing, for instance French and British collective worker housing solutions (ULB 2QQ961b, 22r), and on up-to-date technical aspects related to the modern topics of hygiene (on Horta and hygiene, see: Van de Vijver 2012), heating, plumbing, and sanitary engineering (III.3.a.1). An important subdivision within the housing typology is the presence of the extensive section on the "devis" (III.3.a.4).

The relation of typology (III) to the composition drawing course of the architect-engineering program is obvious. On the last pages, the students noted some composition exercises, such as a "Projet de Salle de réunion et de repos pour ouvriers d'une usine" (ULB 2QQ110, 54v), a "Petite gare de 3^{e} rang" (ibidem), and "Projet de salle de reunion public pourvant contenir 1000 à 1200 personnes" (ULB 2QQ961e, last page).

Comparing the student notes of Horta's course with student Charles Frerich's notes for Ernest Hendrickx's 'Architecture civile' course of 1892–1893 (2QQ298a-c) seems to confirm Horta's autobiographical note of 1921 in which Horta stated he inherited the architectural courses of his predecessor (Oostens-Wittamer 1980, 278, mentioned source coll. W.D., no 4635/4637, Victor Horta, Cours d'Anatomie, ms. Chap. sur l'anatomie, 1921, 5). For part I and II of the course for which documentation is available, the parallels are tight in the subdivision and the details of each course.

Moreover, Horta characterizes this course of Hendrickx quite vaguely as "probablement sur inspiration de Viollet-le-Duc" (ibidem). In his work, Horta's predecessor as professor of architecture at the Brussels Polytechnic School at Brussels University (ULB) from 1873 until August 30, 1892, Ernest-Jean Hendrickx (Hennaut 2000; ULB, dossier H12; L'Emulation [1892], col. 157–159; Journal des Etudiants de l'Université de Bruxelles [2 February 1892], no 35, 1 and [17 October 1892], no 42, 2), paid tribute to Viollet-le-Duc's theories, in a non-historicist manner. He is recognised as "un des meilleurs architectes de son temps, élève de V[iollet]-l[e]-D[uc]" (Horta [Dulière, ed.] 1985, 20), a typecasting that is confirmed by the Ecole Modèle at Boulevard du Hainaut (1875) (L'Emulation [1879], col. 82–84, pl. 40–43) and the precise characterization of the university-enlargement of the Brussels University complex, the former Palais Granvelle, rue des Sols, as "d'un remarquable sobriété constructive" (Horta [Dulière, ed.] 1985, 20; L'Emulation [1891], col. 190, pl. 29–43, [1892], col. 172, pl. 18–23 and [1893], col. 188, pl. 18–19). Hendrickx had been a pupil of Viollet-le-Duc in Paris, and the necrological notes on him in the Brussels University journal and L'Emulation recognized this influence and captured his approach in the words 'rational architecture'.

The 'rational/irrational' concept in Horta's course text, which was fundamental to the whole course, seems inherited from Hendrickx. Hendrickx's course notes start as follows: "L'architecture est un art rationnel qui n'est cependant pas dénué d'imagination […] Nous commencerons par l'examen des matériaux puis leur mise en œuvre rationnelle, et en même temps leurs formes rationnelles […]" (ULB 2QQ298a, 2r). Judgments that appear as 'rational' and 'irrational' (the first often related to the gothic, the last to the 'classic') refer implicitly to the French theoretician in the Bogaert manuscript. In the Michel manuscript, Horta refers explicitly to Eugène-Emmanuel Viollet-le-Duc (ULB 2QQ110) (for Horta and Viollet-le-Duc, see Van de Vijver's book in print.) There is archival evidence that Horta used plates of Viollet-le-Duc in his courses (probably the one for architectural history in the fourth year of the architecture section). Horta's correspondence in January 1900 with Emile Lévy (1861–1916) of the Librarie Centrale des Beaux-Arts in Paris delivers explicit proof on the importance of Viollet-le-Duc in Horta's other university courses. Interested in two Viollet-le-Duc drawings/prints for his teachings, Horta addressed the Paris editor Lévy to obtain the whole series. As the requested series apparently did not seem to exist, Horta asked Lévy to investigate the existence of comparable drawings and suggested looking for comparable drawings, made by the teachers of the Ecole des Beaux-Arts for the architecture or architectural history courses. Subsequently, Lévy sent the two Viollet-le-Duc prints as well as the catalogue of excellent "*clichés de projection*" furnished by the publishing house of Lucien Magne (1849–1916) (HM XV.L.5.3. Emile Lévy [Paris, 8 January 1900] to Horta with pencil notes of Horta's answers; HM XV.L.5.4. Lévy [Paris, 12 January 1900] to Horta).

The tension between construction and style in part II of the 'Architecture civile' course, treating both masonry structures as well as the "décoration des murs" with elements, such as columns, arcades, windows, and portals, had been present in Hendrickx's course. In these course note pages (IIα-IIγ), almost all architectural languages are encyclopaedically present: from Egypt, Greek, Roman, Byzantine, and gothic up to the Renaissance and the classic "all'antica" idiom. The accompanying drawings contain all-time classics in the century-long tradition of architectural publications, such as the bossage variations taken from Serlio (ULB 2QQ961e, 12v; cf. Serlio IV 1611, fol. 15), the entasis of columns following the colloid curve (ULB 2QQ961e, 16v; 2QQ110II, 43v; cf. Serlio IV 1611, fol. 4), and so forth. The judgment of these foreign historic elements was limited to the notions of either 'rational' or 'irrational'.

However, some elements of the course demonstrate that Horta added personal accents to the course. The most obvious example is the presence of Horta's House Tassel (the building permits dates from 5 August 1893, Horta [Dulière, ed.] 1985, 34 note 7) as a prototype for the "maisons bourgeoises" (ULB 2QQ961b, 49v) and the detailing of the "pan de fer" (ibid., 50v). "Pan de fer" was made more important than in Hendrickx's course and received a separate status in the "table des matières" (II.3). Metal also had a presence in the wood section as an alternative support for parquet structures (ULB 2QQ961a, 9v-12r).

In this course, the professor's personality was also felt in the multiple references to Alphonse Balat and Hendrik Beyaert—the two Belgian master architects with whom Horta did an internship—as well as Joseph Poelaert and Charles Garnier's opera building in Paris. These three architects and one building were also present in Horta's other writings. Note also the remark on regionalism (with reference to Beyaert) as a possible style of the future.

The course notes on materials and on applied techniques contain examples (such as for the application of natural stones) for specific local buildings (I.1). There was also an obligatory section on local building manuals related to the Brussels Military School (De Vos 1879; Demanet 1847) and the contemporary manual by the Officer Paul Combaz (1895–1905). Horta's construction course was adapted to local customs and materials and applied to Belgian building. Furthermore, this implies the reference to local regulations, such as the necessary surfaces of internal courtyards being dependent on the built surfaces in Brussels (ULB 2QQ961b, 19r) and the relation to the adjoining wall at the Avenue Palmerston and Avenue Brugmann (ibidem), or the insistence on country particularities in building practices, such as France (Germany and Austria) and Belgium (parts of Germany and the UK) differences of housing in apartments versus private houses (ULB 2QQ961b, 49r) or the Dutch and Belgium differences of counting the cost of buildings in m3 or m2 (III.3.a.4).

In its encyclopaedic character, from foundations (II.1) to specifications (III.3.a.4), the formulae of the course notes is close to basic practical architectural manuals 'in one volume', such as the 17th- and 18th-century manuals of Bullet (Bullet 1762; Van de Vijver 2019, no. 277).

3 CONSTRUCTION BOOKS IN HORTA'S PRIVATE LIBRARY

Two inventories (HM, Nomenclature des livres composant la bibliothèque de Mr. Horta [6 June 1931?]; HM, Volumes composant la bibliothèque de Monsieur le baron Horta. Victor 18 place Stéphanie à Ixelles-Bruxelles [July 1944]), the estate report (HM VI.8, books in Horta's estate, no 289–301), and the purchase list of works from Horta's library by Jean Delhaye (HM, *Livres ayant appartenu à Victor et Julia Horta provenant de la Fondation J. et R. Delhaye*) document Horta's possession of books in the last decades of his life (Van de Vijver 2019—with reconstruction of Horta's library content, section "VI. Constructie", no 277–320). The notes of the courses that Horta taught at the Polytechnic School and at the Antwerp and Brussels Ecole des Beaux-Arts were not present in these lists.

The majority of the approximately 500 titles are in French and were published in Paris and Brussels. The publication dates reflect Horta's course of life, with a clear centre of gravity between 1883 and 1923 and particularly between 1897 and 1914. The First World War period is captured by titles acquired during Horta's stay in America (with a view to the reconstruction of Belgium). German publications seem to have been acquired during travels and concentrate on two periods: 1910–1912 and 1920–1921.

The classification used for the reconstructed book collection (Van de Vijver 2019) builds on the documented arrangement in the shelving of Horta's library in 1931 and 1944 and the classification used in 1931 for a part of the collection. It aspires to grasp the uniqueness of the collection as clearly as possible. The manuscripts (section I) were separated. The notes in Horta's handwriting underline the importance in this collection of the French architectural theorist Eugène-Emmanuel Viollet-le-Duc (present with nine titles, no 186–194) and the field of geography represented by the monumental series of Élisee Reclus. The numerical strength, the clearly broader than average presence of non-native works, their rhetorical role in the inventories, and the remarkably broader chronological and geographic distribution of the editions on Japanese art (II), Egyptian antiquity, (III) and ancient Greek architecture (IV) justify their inclusion as independent sections. The sound conventional order of contents from 1931 further inspired the division of the professional works into the sections architecture (V), construction (VI), art (VII), and sciences (VIII). An additional section on literature (IX) relieves the altera section (X). The collection has the character of an active working library, which only exhibits an encyclopaedic desire in limited areas of focus (especially the specific fields of interest II–IV).

The absence of working documents for an architectural historicist practice based on the Louis styles or the Flemish Renaissance is already in line with Horta's oeuvre (and explains the lack of older Dutch and Italian publications compared to other libraries). The Belgian provenance and content of technical works and arts publications reflects the local working context and arts scene. All this is consistent with an interpretation of the library content as a professional portrait.

The 30-title section 'Construction' picked almost two-thirds of its titles from cabinet D, located in the middle, opposite the office, in 1933 ("Bibliothèque côté côté opposé au bureau, environment") and supplemented it with construction manuals from the other cabinets, including Jean-Baptiste Rondelet's *Traité théorique et pratique de l'art de bâtir* (1830, Van de Vijver 2019, no 278; further: 1830, no 278), both *Cours de construction* by Alexandre Demanet (1847, no 280) and N. De Vos (1879, no 282), Florent Fouarges' *Aide-mémoire du constructeur* (1887, no 286), and the 1906–1908 volumes of the construction magazine *Le béton armé* of Hennebique (1906–1908, no 307). In turn, this regrouping separated the construction manuals from other technical titles, such as those devoted to practical physics; think of the works of Héloïs Ollivier (1918–1921, no 326) and Jules Violle (1883–1892, no 323), both entitled *Cours de physique*. Other content-related choices expressed in the placement in library cabinet D were not retained in the regrouping in the 'Constructions' section (VI). Alfred de Champeaux's *Histoire de la peinture décorative* (1890, no 391) already stood next to Alexandre Souris' *Traité pratique de la peinture industrielle* (1901, no 300). The work on construction law, *La possession, la propriété, les servitudes* by Arthur De Vos (ca. 1900, no 216), was already integrated in the technical works as were the design of surface ornament ("vlakornament") by J. D. Ros (1905, no 396) and *De la décoration appliquée aux édifices* by Viollet-le-Duc (1893, no 194)—this time less obvious and as the titles already suggest. *Alliages du cuivre* by Jacobsen (s.d., no 319) was taken from a shelf on which one also found titles on applied geometry and physics. All in all, books from the construction section were usually placed together on the bookshelves. To these, one can add the historical technical works by Auguste Choisy (1841–1909, no 66, 95, 136, 154, 159) and Viollet-le-Duc (no 186–194). Horta also possessed the notes taken by engineer Charles Lefèbure on the course “Architecture industrielle” taught by Henri Deschamps in 1886–1887 at the *École spéciale des arts et manufactures et des mines* in Liège (no 3).

In accordance with the local character of building science—present also in Horta’s course ‘Architecture civile’—the section on technical works (section VI) shows an important number of Belgian publications: the basic works from the second half of the 19th century, such as the manuals already mentioned by Demanet (1847, no 280), De Vos (1879, no 282), and Paul Combaz (1895–1905, no 293), and the *Aide-mémoire du constructeur* by Fouarge (1887, no 286), to which Horta apparently added Poutrain and Gobert (1920, no 313) for the 20th century; local syntheses on zinc (1908, no 308) and electric lighting (1930, no 320); and short specialised studies, often overprinted from congress books or magazines, in a range of fields of interest, from metal work (1913, no 310), over woodworking (1904, no 302), convection (1901, no 301), and fire safety (1899, no 299) to industrial painting techniques (1901, no 300).

The works in the technical series, published under the direction of engineer Gustave Oslet from the late 1880s and 1890s, *Encyclopédie théorique et pratique des connaissances civiles et militaires (Publiée sous le patronage de la Réunion des officiers) Partie civile: cours de construction* (3: *Traité des fondations, mortiers, maçonneries*, no 287; 4.1: *Traité de charpente en bois*, no 288; 4.2: *Traité de charpente en fer*, no 296; 4.3: *Traité de serrurerie, quincaillerie et petite charpenterie en fer*, no 297; 6: *Traité de coupe des pierres (stéréotomie)*, no 289; and 7: *Traité d’architecture théorique et pratique*, no 295), nicely represent the collection’s chronological centre of gravity.

The reconstructed library content teaches little about the architect’s way of informing himself about the architectural present after the core period 1890–1914. Acoustics was a problem that continued to interest him in later years: Ilja-E. Katel’s *Les bruits dans les bâtiments* (1929, no 316), Hope Bagenal and Alex Wood’s *Planning for good acoustics* (1931, no 317), and Edward Glick Richardson’s *Introduction to acoustics of buildings* (1933, no 318). His acquisition of books on physics (no 326 and 328) seems also related to this theme.

4 PARALLEL OF HORTA’S COURSE ‘ARCHITECTURE CIVILE’ AND HIS LIBRARY BOOKS

The course notes combine elements of the ‘Cours de construction’ (especially Part I, Part II, and Part III.3.a.1) with those of the “Traité d’architecture” (course Part II$\alpha\beta\gamma$ and Part III). The first and second part of the student notes document the materials (Part I) used in Belgium and their applications in Belgian building construction (Part II). This is also important content material in the principal Belgian construction manuals—modelled after Rondelet’s *Traité théorique et pratique de l’art de bâtir* (1830, no 278) but more modest. Building materials are treated by Demanet (1847, volume I, 1^{st} part “Connaisssance des matériaux”), De Vos (1879, volume I, 1^{st} part “Connaissance des matériaux”), and Paul Combaz (1895–1905, 1^{st} part “Connaissance des matériaux”). Close parallels of Horta’s course can be found in the Paul Combaz manual: both sections on natural stones start with a chemical classification of stones (Combaz 1895, Ier volume-fascicule I, 15–17; ULB 2QQ961c1r). Building material monographs are among the favourite later acquired construction books.

The application of building materials in foundation, masonry, “pan de fer”, wood, and so forth find parallels in Demanet (1847, volume I, 2^{nd} part “Emploi des matériaux”, volume II, 4th part “Etablissement des fondations”), De Vos (1879, volume I, 4th and 5th part, “Exécution des maçonneries” and “Fondations”), and Combaz (1895–1905, 3^{rd} part “Exécution des travaux de construction suivant les règles de l’art [I. Terrassements; 2. Maçonnerie: fondations, maçonneries; 3. Charpente; 4. Rejointements, enduits, plafonnages; 5. Menuiseries; 6. Couvertures; 7. Serrurerie; 8. Marbrerie, poêlerie, fumisterie; 9. Peinture, dorure, vitrerie; 10. Papiers de tenture]”). The mentioned technical series, published under the direction of engineer Gustave Oslet, from the late 1880s and 1890s, *Encyclopédie théorique et pratique des connaissances civiles et militaires …*, document this application of building materials for different parts of buildings (See 3). Building services related to hygiene (ventilation, heating, plumbing, and sanitation) are also covered in the third volume of Cloquet’s *Traité d’architecture*. The section on specifications and prices finds its parallel in Pierre Bullet’s *Architecture pratique* (1762, no 277) and Onésime Masselin’s *Dictionnaire raisonné et formulaire du métré et de la verification des travaux de terrasse, maçonnerie et carrelage* (1875, no 281).

The sections dedicated to calculus in De Vos (1879, vol. I, 2nd and 3rd part “Résistance des matériaux” and “Stabilité des constructions”) and Combaz (2nd part “Résistance des matériaux”) have no parallel in Horta’s course but do parallel the student notes (of Henri Michel) for the courses by Louis Anspach. Belgian manuals that elaborate the calculus of structures with titles such as *Résistance des Matériaux* and *Stabilité des constructions*, for example those by Henri Deschamp, Hadelin Rabozée (1867–1951), Arthur Vierendeel (1852–1940) or later ones by Louis Baes (1883–1961) and Gustave Magnel (1889–1955) are lacking in Horta’s library (Van de Vijver 2003).

The ‘architectural treatise’ element of Horta’s ‘Architecture civile’ such as building elements (walls, portals, windows, arcades, and columns) and building typologies (housing, schools, etc.) finds a parallel in local manuals, as the course at the Special Schools of Ghent University by Louis Cloquet (1849–1920) reflected in his *Traité d'architecture. Eléments de l'architecture, types d'édifices–esthétique, composition et pratique de l'architecture* (1898–1901, no 197, tome V: "Esthétique, composition et décoration" [1901) and tome IV: "Habitations priées et collectives. Entrepôts, marchés et abattoirs. Bourses et banques. Ecoles, bibliothèques et musées. Hôtels-de-ville et mairies. Parlements et préfectures. Tribunaux et prisons. Hôpitaux et hospices. Gares, hôtels des postes. Théâtres, panoramas, casinos, cirques, manèges, tirs. Bains et lavoirs. Tombeaux et cimetières" [1900])—typecast by Horta as a "Guadet, mis à la 'page belge"' (Oostens-Wittamer 1980, p. 278).[3] Both Cloquet's and Julien Guadet's (1834–1908) course at the Paris Ecole des Beaux-Arts, published as *Eléments et théorie de l'architecture* (1901–1904, no 198), was judged by Horta as being founded on the architecture of the past: "s'appuyaient sur les architectures antérieures, dont ils montrent les beaux exemples pour en tirer en parenté de beaux exemples futurs" (Oostens-Wittamer 1980, p. 278). Monographs on building typologies as a section in Horta's library (no 200–215), related to the subjects of the course notes, one finds in Horta's library a monograph on workmen's housing written by the Belgian Conseil supérieure d'hygiène public (1877, no 202), monographies by Henri Baudin on schools (1907 and 1917, no 206 and 208) and on hospitals (1872, no 201).

Horta's "Architecture civile" course demonstrates a comparable orientation as the construction book section of his library: an emphasis on the qualitative not on the quantitative (i.e., no calculus).

The reconstructed library content teaches little about the architect's way of informing himself about the architectural present after the core period 1890–1914. Acoustics was a problem that continued to interest him in later years: Ilja-E. Katel's *Les bruits dans les bâtiments* (1929, no 316), Hope Bagenal and Alex Wood's *Planning for good acoustics* (1931, no 317), and Edward Glick Richardson's *Introduction to acoustics of buildings* (1933, no 318). His acquisition of books on physics (no 326 and 328) also seems related to this theme.

5 CONCLUSION

Content analysis of the student notes of the course 'Architecture civile' brings forth elements of the traditional construction manual (building materials, application of building materials, hygiene and building services, specifications, and prices) and the architectural treatise (composition and architectural typologies). The course shows the influence of Horta's predecessor, Jean-Ernest Hendrickx, in the general structure and in the 'rational' and 'irrational' judgments, derived from Hendrickx's teacher Eugène-Emmanuel Viollet-le-Duc. The characterisation of the course as descriptive (qualitative)—the calculus of structures is completely lacking—fits well the content of the construction books in Horta's library. The different genres of construction publications present in Horta's library show parallels with the content of Horta's course: local building manuals, an emphasis on locally applied building materials and their local application, monographs of building materials, some key architectural treatises, and monographs of building typologies.

The absence of calculus in the content of the course and the library helps to understand different construction (calculus) problems that occurred during his career (e.g. the foundation of the Maison du Peuple, metal constructions at Hôpital Brugmann).

The two discussed source types (course notes and library content) provide a wealth of detailed documentation that permit an in-depth analysis of a nature that is quite difficult to obtain by other means. Moreover, the course content and reconstructed library enable comparative research in their respective fields, which makes it possible to surmount the biographical sphere and raise the research to a comparative national and international level.

6 NOTES

1. December 1911, Horta resigned as professor of architecture because he disapproved of the design commissions for new university buildings not being confined to him but to Albert (1853–1920) and Alexis (1877–1962) Dumont (Cools & Vandendaele 1984, 44 note 19; Devriese 2005). On the contrary, his predecessor, Hendrickx, had been responsible for the reconversion of the Renaissance Granvelle Palace into the seat of Brussels University (Horta [Dulière, ed.] 1985, 318).

2. For the Polytechnic School and its teaching staff: ULB 1897, 109–111; Bartier 1959, 60–64; Goblet d'Alviella 1909, 113–120 and 268–277.

3. On Horta and Cloquet, see also Van de Vijver 2012.

7 ANNEX. TABLE OF CONTENT OF HORTA'S COURSE 'ARCHITECTURE CIVILE'

PREMIERE PARTIE. MATÉRIAUX

I.1. Matériaux pierreux naturels (c1r-17r)
I.2. Matériaux pierreux artificiels (c17r-33r)

- I.2.a. Matériaux de maçonnerie – Briques-tuyaux (c17r-25r)
- I.2.b. Matériaux de pavement: I.2.b.1. Carreaux en terre cuite, I.2.b.2. Carreaux en ciments. I.2.b.3. Carreaux en grès céramique, I.2.b.4. Carreaux en faïence (c25r-28r)
- I.2.c. Matériaux de couverture: I.1.2.c.1. Les tuiles plates, I.1.2.c.2. Tuiles creuses; I.1.2.c.3e Tuiles à double courbure; I.1.2.c.4. Tuiles à emboitement (c28r-33r)
- I.3. Matériaux ligneux: bois (c34r-38r)
- I.4. Matériaux métalliques: fer, fonte, acier, cuivre, laiton, bronze, plomb (c39r-44r)

I.[5 .] Matériaux divers secondaires: mortiers, stuc, bitumes-asphalte, verre, couleur (peinture à colle, peinture à l'huile, vernis), papier peint (c44r-54r)

DEUXIEME PARTIE. EMPLOI DES MATÉRIAUX À LA CONSTRUCTION

[II.1] Fondations (c55r-57r; d6r-23r)
[II.2] Maçonnerie d'élévation (d24r-57r) (Maçonneries homogènes, maçonneries mixtes, maçonneries en briques)
[II.3] Pans de bois et Pans de fer (e2r-8r)
[II.α] Décors des murs (e8r-15r)
[II.β] Des supports verticaux (e15r-34r)
[II.γ] Frontons, arcs, arcade, fenêtres, balcons (e34r-44r)
[II.4] Charpente et menuiserie (a1v-50r) Constructions en bois

[II.4.a] Assemblage de charpentes (a1v-5r)
[II.4.b] Les planchers (a5v-18r)
[II.4.c] Fenêtres (et portes) (a18v-34r)
[II.4d] Combles (a33v-45r)
[II.4e] Portes (a44v-50r)

TROISIEME PARTIE. COMPOSITION

[III.1] Principes généraux de composition (a50r-54r: commodité, solidité, beauté)
[III.2] Différents parties des édifices : Parties extérieures : portiques, porches ; Parties intérieures: Vestibules, escaliers, salles (a53v-56r; b2v-21r)

Cours, trottoirs ouverts, parcs et jardins (b20v-22r)

[III.3] [Typologies d'édifices]

[III.3.a] Habitations (b22v-65r)

[III.3.a.1] Habitations ouvrières (b22v-49r)
[III.3.a.2] Habitations bourgeoises (b49r-51r)
[III.3.a.3.] Habitations riches ou hôtels privés (b50v-52r)
[III.3.a.4.] Devis (b52r-65r)

[III.3.b] Ecuries (b65v-68r)
[III.3.c] Hôpitaux (b68r-71r)
[III.3.d] Ecoles (b70v-71r)
[III.3.e] Halles et marches (b71r-72r)
[III.3.f] Prisons (b72r-74r)

Foliation after Horta (Bogaert) s.d., ULB 2QQ961a-e Titles of Part I and II after Horta (Michel) 1905–1906), ULB 2QQ110I-II.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Who built the timber formwork for fair-faced reinforced concrete?

Meltem Çavdar
Technische Universität München, Munich, Germany

ABSTRACT: Fair-faced concrete structures from the middle of the 20th century, like the impressive brutalist buildings of the post-war period, are mostly considered the product of a totally industrialized process, planned in detail by engineers and realized accordingly by unskilled labor. However, the construction of the necessary formwork in timber was an accomplishment of carpentry craftsmanship well into the 1970s. Discussing the interconnected transfer of technology, knowledge and expertise, this paper examines the transmission of traditional skills in carpentry to timber formwork construction in the post-war period in Germany. Through analyzing longstanding technical manuals, this assesses the mostly unrecognized means of timber formwork constructions.

1 THEORETICAL BACKROUND

Reinforced concrete, as its name suggests, consists of concrete and iron inserts, which together form a composite in which these two materials act together in resisting forces. The role of timber formwork is not insignificant in this since the formwork must first be built before the later construction can be created. However, the formworks discussed in this paper are by nature temporary structures, which are discarded after stripping. This is why formwork has seldom been the subject of studies on historical concrete construction.

Until the early 20th century, concrete was mainly used in unreinforced rammed form. The formwork structures were of minor importance because the concrete mixture for the rammed concrete had an earth-moist consistency and was placed layer-by-layer in small portions before being rammed. The addition of iron inserts to the concrete created a major challenge for formwork construction. The amount of water in the concrete mix was increased to enhance the concrete flow through the inserts (Figure 2) and the molding of bigger volumes of concrete became possible. Formwork then needed to be accessible for pouring and vibrating the wet concrete. It also had to be very tight at the joints to prevent leakage. It needed to be strong, properly supported and braced or tied to maintain its position and shape both during and after the pouring of concrete, and finally, be convenient to strip without damage to the set concrete.

Before its gradual replacement by prefabricated formwork panel systems in the 1970s, formwork constructions for in-situ reinforced concrete were mostly of timber (Austin 1960;; Bächer 1971; Häberli 1966). When concrete is cast in a timber formwork, the wooden boards imprint their pattern onto the non-treated building surfaces. Any defects in the formwork are later visible on the finished surface. Therefore, high-quality exposed concrete surfaces have to be seen as the skilled product of formwork carpentry. The quality of the craftsmanship can still be observed in the non-treated formwork imprints on concrete surfaces, which started to be left uncovered in the post-war period in Germany in the 1960s and 1970s, particularly on the brutalist designs then in vogue. The use of exposed concrete in construction was not, however, only a design feature reflecting a change in the aesthetic trends in architecture but was related to the developments in concrete technology and formwork carpentry. This progress is largely a result of the involvement of carpenters in the timber formwork.

2 FIRST HALF OF THE 20TH CENTURY

The board-marked exposed appearance of the concrete surface was neither a topic of the early textbooks on concrete construction nor the first building standards for reinforced concrete. In 1907, the *Deutsche Ausschuß für Eisenbeton* (German Committee for Reinforced Concrete Construction) introduced *Bestimmungen für Ausführung von Konstruktionen aus Eisenbeton bei Hochbauten*, the first regulations on reinforced concrete buildings in Germany (Haberstroh 1908, 155). Formwork construction was included in these regulations in terms of resistance to the effects of ramming and durability on fresh concrete but not regarding the appearance of the concrete surfaces or formwork shells. As a design feature, at the beginning of the 20th century, concrete surfaces were often plastered or finished by stonemasons, which meant the quality of the pure concrete surfaces was of less importance. If the surfaces were plastered, the formwork boards could usually be used directly from the sawmill because the concrete acquired a rough surface to which the plaster adhered better (Emperger 1907, 122). If the

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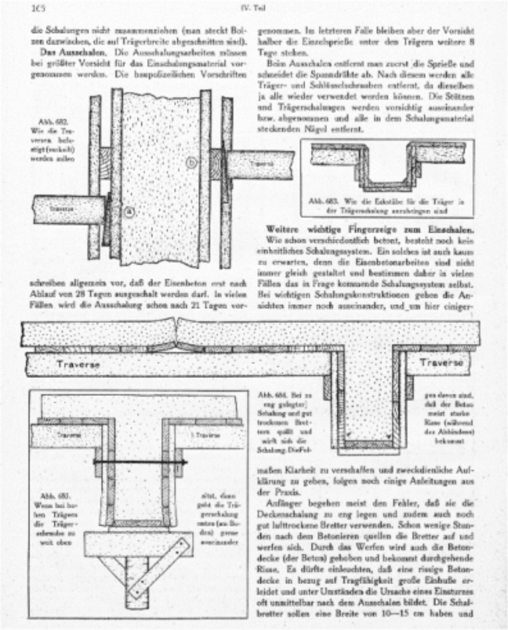
visible surfaces were not plastered but processed by stonemasonry techniques, the shuttering boards had to be planed on the side where they faced the concrete in order to reduce the work required for the subsequent smoothing of the concrete surfaces (Haberstroh 1908, 160). According to the regulations for reinforced concrete at that time, concrete was required to be poured in small portions while the load-bearing walls and pillars on one side of the formwork were gradually shuttered as the pouring progressed (Haberstroh 1908, 165). This method was very similar to rammed concrete; it ensured that the formwork was well-filled everywhere and that the iron inserts were completely embedded since the consistency of the concrete was earth moist as for rammed concrete. Construction of formwork for the full height of walls and pillars was not common at first but became possible by increasing the water ratio in the concrete mixture, allowing wet concrete to be poured from the top (Haberstroh 1908, 165). Constructing a timber formwork which was leakproof and resistant to the deformation which could result from pouring a large amount of wet concrete depended on specific carpentry skills. Initially, there were no trained concrete builders as such and therefore skilled carpenters were best suited to timber formwork construction; however, formworking was thought of as a subordinate skill and most master carpenters were opposed to concrete construction because of the potential threat it posed to the carpentry trade (Kress 1926, 145). Nevertheless, due to the increasing preeminence of concrete construction, growing numbers of carpenters began applying their skills to formwork construction. Indeed, one of the first reference guides specifically for timber formwork construction for reinforced concrete arose from the carpentry trade. In 1906, master carpenter Fritz Kress, an eminent author of technical textbooks for carpenters, founded the first private carpentry school of Germany, “Zifa-Kress” (*Zimmereifachschule Kress*) in Tübingen-Lustnau to train carpenters as foremen and to prepare them for the master carpenter examination of the trade chamber (Maushake 1978, 1). He dedicated a long chapter to formwork carpentry in the first edition of his seminal publication *Das Buch der Zimmerleute* in 1926 (Figure 1). Kress foresaw that reinforced concrete was a new and expanding trade—a combination of masonry and carpentry handcraft—and encouraged carpenters to work in the field of reinforced concrete rather than leave the work to the unskilled “woodworkers” (Kress 1926, 145). According to the school brochure of 1940, timber formwork subjects in his teaching program included the following: general information on reinforced concrete; formwork material; construction of formwork for the columns, beams, walls, straight and curved stairs, etc. according to various systems; setting up and stripping the formwork. The school complex consisted of a large teaching room with an adjoining machine and joinery workshop and a “framing floor” (*Reißboden*). The participants were introduced to the subject matter through lectures, which were followed by a general discussion. Following these introductory lectures, all students were asked to draw the related construction and produce a model of it, if necessary, on a 1:1 scale. Construction models, partly in 1:1, a large collection of photos, drawings and books were available for the course participants (Kress 1940b, 5).



165 IV. Teil

die Schalungen nicht zusammenziehen (man steckt Bolzen dazwischen, die auf Trägerbreite abgeschnitten sind).

Das Ausschalen. Die Ausschalungsarbeiten müssen bei größter Vorsicht für das Einschalungsmaterial vorgenommen werden. Die baupolizeilichen Vorschriften schreiben allgemein vor, daß der Eisenbeton erst nach Ablauf von 28 Tagen ausgeschalt werden darf. In vielen Fällen wird die Ausschalung schon nach 21 Tagen vorgenommen. Im letzteren Falle bleiben aber der Vorsicht halber die Einzelsprieße unter den Trägern weitere 8 Tage stehen.

Beim Ausschalen entfernt man zuerst die Sprieße und schneidet die Spanndrähte ab. Nach diesem werden alle Träger- und Schlüsselschrauben entfernt, da dieselben ja alle wieder verwendet werden können. Die Stützen und Trägerschalungen werden vorsichtig auseinander bzw. abgenommen und alle in dem Schalungsmaterial steckenden Nägel entfernt.

Weitere wichtige Fingerzeige zum Einschalen. Wie schon verschiedentlich betont, besteht noch kein einheitliches Schalungssystem. Ein solches ist auch kaum zu erwarten, denn die Eisenbetonarbeiten sind nicht immer gleich gestaltet und bestimmen daher in vielen Fällen das in Frage kommende Schalungssystem selbst. Bei wichtigen Schalungskonstruktionen gehen die Ansichten immer noch auseinander, und um hier einigermaßen Klarheit zu verschaffen und zweckdienliche Aufklärung zu geben, folgen noch einige Anleitungen aus der Praxis.

Anfänger begehen meist den Fehler, daß sie die Deckenschalung zu eng legen und zudem auch noch gut lufttrockene Bretter verwenden. Schon wenige Stunden nach dem Betonieren quellen die Bretter auf und werfen sich. Durch das Werfen wird auch die Betondecke (der Beton) gehoben und bekommt durchgehende Risse. Es dürfte einleuchten, daß eine rissige Betondecke in bezug auf Tragfähigkeit große Einbuße erleidet und unter Umständen die Ursache eines Einsturzes oft unmittelbar nach dem Ausschalen bildet. Die Schalbretter sollen eine Breite von 10—15 cm haben und

Abb. 682. Wie die Traversen befestigt (verkeilt) werden sollen

Abb. 683. Wie die Eckstäbe für die Träger in der Trägerschalung anzubringen sind

Abb. 684. Bei zu eng gelegter Schalung und gut trockenen Brettern quillt und wirft sich die Schalung. Die Folgen davon sind, daß der Beton meist starke Risse (während des Abbindens) bekommt

Abb. 685. Wenn bei hohen Trägern die Trägerschraube zu weit oben sitzt, dann geht die Trägerschalung unten (am Boden) gerne auseinander

Figure 1. Das Buch der Zimmerleute (Kress 1926, 165).

Besides carpenters, masons also worked on reinforced concrete structures, which they had been doing prior to this time. Founded in 1908, the *Deutsche Ausschuß für Technisches Schulwesen* (DATSCH) (German Committee for Technical Education), later renamed the *Reichsinstitut für Berufsausbildung in Handel und Gewerbe* (Imperial Institute for Vocational Training in Trade and Commerce), initially dealt with guidelines for the uniform and systematic training of engineers, and in the 1920s also provided training for skilled workers, developed courses and text books, defined job descriptions, fields of work, job titles, and teaching objectives (Zimmermann & Kirste 1998, 72). DATSCH included reinforced concrete and its formwork in their training manuals *Lehrgang für Maurer* (Training Course for Masons) and *Lehrgang für Zimmerer* (Training Course for Carpenters), both published in 1929. In the *Lehrgang für Maurer* there were explanations for the basics of the mixing of concrete and its usage in building construction with and without reinforcement as well as the necessary formwork constructions for these applications (Figure 2). On the other hand, in the *Lehrgang für Zimmerer* the only mention of concrete was in relation to the construction of the timber formworks for reinforced concrete buildings (Figure 3). Carpenters were better suited to producing complex and large timber formworks for reinforced concrete than masons, whereas masons were more familiar with cement mortar and its conventional rammed form.

The rapid growth of reinforced concrete construction during the 1930s in Germany outstripped the availability of skilled workers and the workers recruited from other technical branches were not numerous enough to meet this need (Reichsinstitut für Berufsausbildung in Handel und Gewerbe 1939, 1). Through the efforts of companies and industrial groups, apprentices for concrete construction had been trained in the workshops of master builders. Yet this kind of training only met providers' own needs and there was no formal education in concrete construction. Therefore, German concrete associations initiated the first concrete builder vocational construction site in Essen in 1927, and from then on, concrete builder training workshops were set up throughout Germany (Zimmermann & Kirste 1998, 26). The first training manual specifically for the education of concrete builders in Germany, *Lehrgang für Betonbauer,* was published in 1930 in the form of worksheets by DATSCH (Reichsinstitut für Berufsausbildung in Handel und Gewerbe 1939, 1). The worksheets consisted of detailed illustrations and accompanying short texts covering each necessary skill set for reinforced concrete. They gave practical information about formwork construction, the bending and laying of iron, as well as the basics of mixing and pouring of concrete. However, most space was given over to carpentry and timber formwork. Formwork was clearly considered the most significant part of concrete construction. Tellingly, the first two worksheets consisted of instructions for producing a timber ladder and a wooden work bench to help the learner acquire the skills and equipment needed for carpentry. The work sheets presented the basic construction elements, such as foundations, walls, columns, and ceilings, with step-by-step explanations, but did not cover the complicated situations which might arise in practice.

Concrete builder (*Betonbauer*) as a profession was first registered in the list of trades in Germany in 1936 (Bundesinstitut für Berufsbildung 2020). The concrete builder then typically underwent a 3-year apprenticeship and had to attend the vocational school and the training workshops set up and maintained by the reinforced concrete companies, and had to master all types of formwork and stripping, reinforcement, and concrete work (Figure 4) (Kupfer 1938, 13). It was not until 1938 that Carl Kupfer, a civil engineer, published *Der Betonbauer,* the first comprehensive training manual on concrete construction. The book series consists of four volumes, three of them entirely devoted to formwork construction. Kupfer's book follows the typological structure of the worksheets of the *Reichsinstitut für Berufsausbildung in Handel und Gewerbe* but gives more comprehensive technical details and solutions for more complicated problems. Simple graphics in the *Betonbauer* make it easy to understand the examples of formwork construction (Figure 5). The nails and wires and their

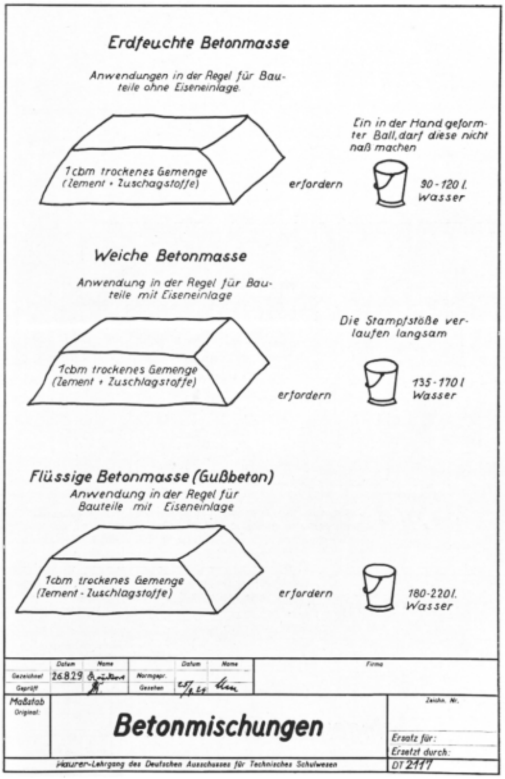


Figure 2. Concrete mixtures in the *Lehrgang für Maurer.* Earth-moist concrete mixture for the building components without iron inserts: 90–120L water for 1m^{3}sand, aggregates, and cement; soft concrete for the building components with iron inserts: 135–170L water for 1m^{3}sand, aggregates, and cement; cast concrete for the building components with iron inserts: 180–120L water for 1m^{3}sand, aggregates and cement (Deutscher Ausschuss für Technisches Schulwesen 1929a, 2117).

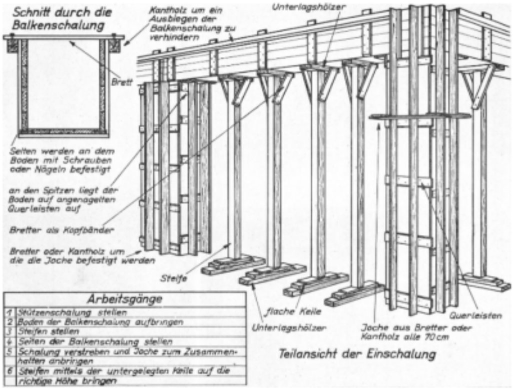


Figure 3. Formwork of beams supported by columns in the *Lehrgang für Zimmerer* (Deutscher Ausschuss für Technisches Schulwesen 1929b, 2351).

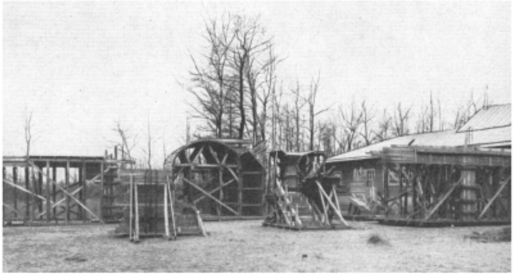


Figure 4. Formwork constructions from the final examination for apprentices at the vocational construction site in Hamburg (Kupfer 1938, 13).

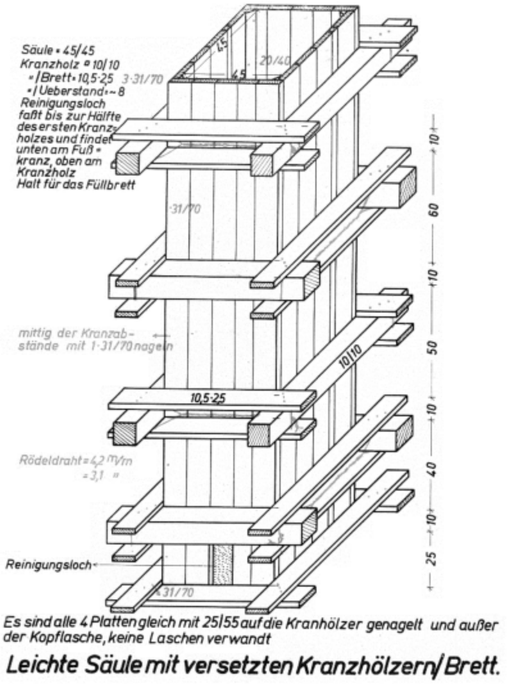


Figure 5. Drawing of the formwork for a column in the book *Betonbauer* (Kupfer 1938, 72).

explanations are presented in green in axonometric drawings to make them more visible. Nails and timbers are illustrated in each type of work with their specific dimensions. The nails used are 20/40, 25/50, 25/55, 28/60 and 31/70. The formwork shell and most of the other timber components are 10.5×2.5 and are referred to as "*nordische Schalungsbretter*" (northern formwork boards) (Kupfer 1938, 14). Kupfer gives an example of a column formwork braced with 10×10 boards and mentions that this is a formwork solution found in southern Germany (Figure 6). These kinds of local differences in detail and the hand tools required for formwork construction clearly show that formworking was a handcraft-based trade.

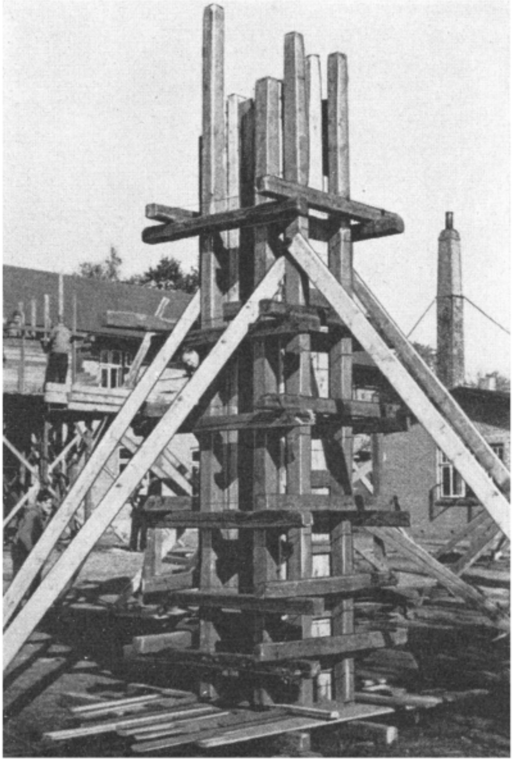


Figure 6. A solution that was never used in Northern Germany, according to Kupfer (Kupfer 1938, 73).

3 SECOND HALF OF THE 20TH CENTURY

At the end of the 1940s, formwork technology underwent rapid development; on the one hand, the shortage of wood and the very considerable increase in timber prices forced the rationalization of materials; on the other hand, because of the shortage of skilled workers, labor-saving procedures developed (Labutin 1957, 3). After reconstruction and the post-war economic recovery, there was a boom in major construction projects and reinforced concrete was the construction material of choice in the 1960s (Beton-Verlag 1977, 12). Innovations in the use of precast concrete accompanied the industrialization and rationalization of in-situ concrete building methods. One of the first such developments were adjustable supporting poles made of steel-tubes and formwork girders, allowing rapid opening and closing, which could be adapted in length within a certain range. They could therefore be used for shuttering different room heights and widths without the need to shorten or extend manually (Figure 7). Plywood boards, steel and plastic panels, steel clamps and anchors, fabricated shoring systems, climbing formwork, modular and tunnel formwork systems, and many other advanced technologies were presented systematically in the book *Schalung und Rüstung. Moderne Schaltechnik* (Böhm & Labutin 1957). Despite the efficiency of industrialized building methods and materials, in the post-war period, training publications on craftsmanship for concrete builders continued to be published. Content-wise, all these textbooks focused on formwork construction, thereby relying on older publications on carpentry. Meanwhile, formwork construction retained its prominence in the contemporary carpentry literature of the time. For example, carpenter foreman and lecturer Peter Gehl regularly wrote articles for the professional journal *Bauen mit Holz* explaining traditional methods of producing timber formwork constructions as well as giving information about the new tools for similar works (Gehl 1961) (Figures 8, 9). Master carpenter Fritz Kress elaborated on reinforced concrete and formwork carpentry in his various technical books from 1926 to 1954, with only minor changes (Kress 1926; 1930; 1937; 1940a; 1949; 1950; 1954). Finally, in 1959, he published his last book on the subject together with Kurt Haeberlen, *Schalungen im Betonbau*. This was a reference book for the then current state of formwork technologies, in which exposed concrete surfaces were considered as a means of expression in architecture, and considerable space was given to the impact of formwork on the surface.

Designing with exposed in-situ concrete required a thorough knowledge of the material and confident control of the execution techniques of the construction on-site. It was no coincidence that at the same time information about the different options for exposed concrete surfaces and the necessary formwork to create different surfaces started to appear in the textbooks. This was the period when the knowledge and experience required for the construction of the timber formworks fully developed. It now became possible to control the surface defects on the concrete and, as a result, board-marked exposed concrete surfaces became a feasible and available design feature. New, higher requirements for high-quality exposed concrete could only be achieved by selection and composition of the ingredients, by thorough mixing, and by careful placement of the concrete into the formwork; the most substantial part was the quality of the formwork craftmanship (Kress & Haeberlen 1959, 243).

In comparison to Germany, Britain did not have any apprenticeships for concrete builders to obtain an occupational qualification (Wall 2018, 97). Formwork carpentry became a specialized branch of the carpentry trade and employed a substantial percentage of carpenters and, as late as the mid-1960s, formwork construction still required skilled carpenters (Forty 2012, 225–235). Specialist companies employed dedicated formwork construction carpenters, who thus became experienced in the methods and details of this class of work (Wynn 1947, 1). At the same time, even though reinforced concrete developed its own craftsmanship in Germany, the number of concrete builders only partially met the demand of the building industry. In the middle of the 20th century, more skilled carpenters were employed in reinforced concrete construction than in timber construction or pure carpentry (Kress 1954, 160). There were also specialist carpentry companies focusing on formwork constructions in Germany, for example, *Firma Ing. Karl Richter Zimmerei-Holzbau* in Munich, which later took the name *Ing. Karl Richter GmbH & Co. Schalungsbau KG,* worked on the formwork construction of the St. Christoph church complex built in exposed concrete according to the plans of the architect Erhard Fischer (1930–2016) from 1968 to 1971 in Munich (Fischer 1969).

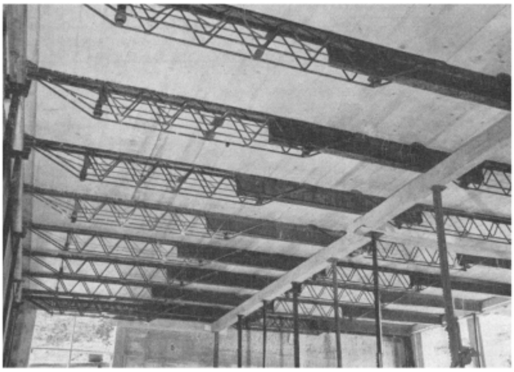
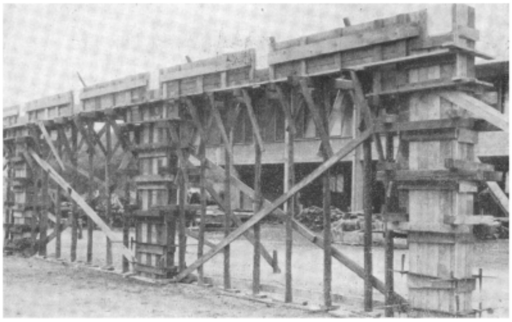


Figure 7. Room width is spanned by 4-part adjustable formwork girders supported by steel-tubes (Böhm & Labutin 1957, 67).



Figures 8 and 9. Timber studs and struts can be seen in the picture above. On the picture below the supports are made of steel tubes (Gehl 1961, 422–425).

German industrial standards (DIN) in the post-war period were far from representative of the state of

Figure 10. A formwork carpenter constructing a round staircase (Haeberlen & Kress 1959, 173).

knowledge in terms of the surface quality of concrete buildings. In DIN 4420 *Die Gerüstordnung* (Scaffold Regulations) in 1953, the terms formwork, formwork shell, formwork scaffolding, and falsework are defined in only a few sentences regarding their form-giving function on the surfaces, the bulk of the definition instead being devoted to the load-bearing function of the formwork (Deutsche Institut für Normung 1953). In the 1968 version of DIN 1045 *Beton- und Stahlbetonbau* (Concrete and reinforced concrete construction), apart from leak-tightness between single timber boards and the cleanliness of the inside of the formwork shell, there were no further requirements for the formwork that could influence the external appearance of the concrete surfaces (Deutsche Institut für Normung 1968). The effect of formwork on the appearance of the concrete surface was not comprehensively defined by building standards for concrete until 1980—with DIN 18 217 *Betonflächen und Schalungshaut* (Concrete surfaces and formwork shell)—when the knowledge and skills in formwork construction based on carpentry had already been lost and board formworks were gradually being replaced by prefabricated formworks. The notable lack of German building standards for formworking in an otherwise heavily regulated environment confirms the fact that formworking was a highly skilled handcraft with no use for industrial standards.

4 PLANNING AND EXECUTION PROCESS

The importance of the formwork planning phase is frequently mentioned in the earlier textbooks. However, they rarely make explicit what the extent of architects' and engineers' responsibilities as the providers of plans should be, nor how the ideal division of the different working phases was to be defined. By the beginning of the 20th century, a substantial portion of the total costs of a reinforced concrete building derived from the formwork costs. Thus, formwork constructions had to be planned in detail and computed by the engineer to avoid unnecessary costs, although in practice their arrangement was often left to the technicians carrying out the construction or a foreman or master carpenter on site (Emperger 1911, 161). The price difference

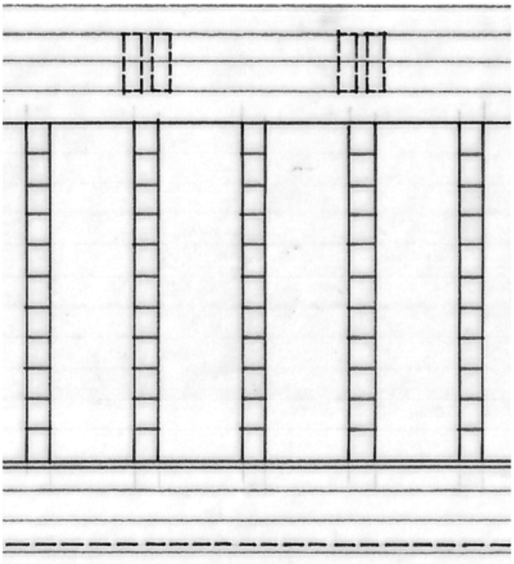


Figure 11. Design drawing of the pillars on the façade of the St. Christoph church in Munich (Drawing: Erhard Fischer 1969b).

Figure 12. Pillars on the façade of the St. Christoph church in Munich (Photo: Author 2020).

due to the complexity of the work for perfect fair-faced concrete was also not significantly lower than the costs for plastering or cladding, although potentially cheaper when the preliminary planning was correct (Künzel 1965, 11). The planning and the application process for timber formworks were different for each building project. Mostly, formwork carpenters held responsibility for the high demands of formwork tasks (Figure 10).

By the 1930s, a concrete builder could expect to receive only the outlines of the concrete core to be formed but not any detailed formwork drawing (Kupfer 1938, 45). Kress & Haeberlen mention that formwork plans rarely contain production details for the formwork. In most cases, it was entirely up to the formwork builder to decide how and with which materials to construct the formwork. In the drawings, the formwork builder could only find information about the finished concrete core after pouring and stripping. After that, the formwork builder would have produced his own hand drawings of each formwork component (Kress & Haeberlen 1959, 48).

As Christine Wall reports, during the construction of the Queen Elizabeth Hall in London, built in 1967, architect drawings did not include the production details of the formwork either. A draftsman produced the shop drawings together with constructors in a workshop on site. These drawings had to be approved by the architects and then passed on to the joiners' shop, where the actual formwork was built (Wall 2018, 99–101). This meant, despite its promising name, the formwork plan was in most cases little more than a basic layout from which the formwork carpenter had to make his own plan. The architect provided little more than elevation drawings to show how the board-marked concrete surface should appear. The drawings of Hardt-Waltherr Hämer (1922–2012) for the City Theater in Ingolstadt, built between 1960 and 1966, are a typical example of these types of drawings, representing the division and orientation of the formwork boards on the façade drawings (Hämer 19621, b). In a later example of elevation drawings showing the formwork imprints for the façade design of the St. Christoph church in Munich, Erhard Fischer designed all the formwork boards in horizontal order (Figure 11). However, formworks were not executed everywhere as he desired; for example, the pillars were cast using timber boards vertically because they were easier for the workers to produce on site (Figure 12) (Fischer 1969).

The engineer Walter Häberli stated that during the design phase, formwork dimensions were to be specified entirely by the designer in the plans and the calculation of intermediate dimensions were not supposed to be the responsibility of the foreman. Sufficient control dimensions in the plans facilitated the work, increased the plan overview, and prevented mistakes (Häberli 1966, 83). Häberli was the engineer of the St-Nicolas church in Hérémence in Switzerland, built between 1967 and 1971, and designed by the architect Walter Maria Förderer. With its very acute edges at the openings and higher and lower areas on the walls, the church was most certainly not an easy building in terms of formwork construction. In his drawings, Häberli presents the concrete core in detail on a scale of 1:20 to 1:2 and though he provides the dimensions on this drawing, there is nothing about the construction details of the formwork itself (Häberli 1968).

The architect Helmut Striffler had different experiences with the formwork builders from different regions in Germany. He assumed that the culture of timber formwork was related to the work of the shipwright. His foreman at the Trinitatiskirche project in Mannheim, built between 1956 and 1959, was a shipwright from Hamburg, and Striffler was quite satisfied with the quality of his work. However, he was not satisfied with the formwork quality of his Matthäuskirche in Pforzheim, built between 1950 and 1953, where he complained that the timber of the formwork had a "firewood-quality" (*Brennholz-Qualität).* He also mentioned that formwork culture came to Bavaria quite late. In his projects in Bavaria, he complained that he could not find a good formwork carpentry master and he therefore restricted builders from the planning activity, and drew very comprehensive and detailed formwork plans himself, including casting sections and the positions of the anchor holes (Vollmar 2015, 229).

5 CONCLUSION

Formwork construction has rarely been the subject of studies on concrete buildings, partly because formworks are temporary structures and no longer exist. However, the role of the carpentry craftsmanship in reinforced concrete construction, especially in achieving the quality of the board-marked exposed concrete surfaces, was enormous. The exposed concrete buildings from the mid-twentieth century are the productions of cross-disciplinary collaboration on site by masons, steel fixers but above all by carpenters. A high quality exposed concrete architectural surface represents the high level of craftsmanship in the formwork carpentry of that era. Surface sealing as well as the incorrect reconstructions of formwork during the maintenance and repair of the concrete surfaces erases the traces of craftsmanship and thus a significant part of their historic integrity.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Knowledge transfer in reinforced concrete bridges during the 1930s

E. Pelke
Hessen Mobil - Straßen- und Verkehrsmanagement, Wiesbaden, Germany

K.-E. Kurrer
University of Applied Sciences, Coburg, Germany

ABSTRACT: Beginning in the 1920s, reinforced concrete started to find its own design language for large bridges. This is seen in the building of long-span arch bridges, which reached its peak in the invention phase of reinforced concrete construction (1925–1950) and is characterized by the following:
– resolving the rectangular cross-section common in conventional masonry and concrete bridges;
– using better cements and separating creep and shrinkage;
– refining structural analysis through equilibrium based on the deformed system.
These features are demonstrated in examples of how journals contributed to knowledge transfer. This work is based on a thematic study of the main essays and short articles on theory, materials and projects in two journals that had a big impact in German-speaking countries: *Der Bauingenieur* and *Beton und Eisen*. The international significance of these specific themes was assessed by reviewing publications by the International Association for Bridge and Structural Engineering (IABSE).

1 UPHEAVAL IN GERMAN CIVIL AND STRUCTURAL ENGINEERING JOURNALS AFTER THE FIRST WORLD WAR

In 1901, the Viennese civil engineer Fritz von Emperger founded *Beton und Eisen*, the first engineering journal devoted exclusively to new forms of construction with reinforced concrete. The Berlin-based publisher Wilhelm Ernst & Sohn took over publication of the journal in 1905. Articles on theory, projects and standardization in this new form of construction appeared in *Beton und Eisen*, written by the pioneers of reinforced concrete, the second technical revolution in construction. During the first two decades of the 20th century, *Beton und Eisen* took knowledge transfer to a new level as empiricism and theory were firmly embedded in the practice of civil and structural engineering through materials research and testing plus theory of structures and strength of materials.

Another journal dedicated to reinforced concrete was founded by publisher Julius Springer in 1908: *Armierter Beton*. The editor of this monthly publication was Emil Probst, professor at Karlsruhe TU, and his agenda was similar to that of *Beton und Eisen*. Max Foerster, at that time professor at Dresden TU, joined the editorial staff in 1909. From then on, the editors attached greater importance to news from areas related to civil and structural engineering, too. In 1920 *Armierter Beton* became *Der Bauingenieur*, the publication medium of Germany’s steel and concrete associations, the Deutscher Eisenbau-Verband and the Deutscher Beton-Verein. Professors Probst, Foerster and Willy Gehler plus the directors of those associations, Hermann Fischmann and Wilhelm Petry, made up the editorial team (Burska-Erler & Jähring 2000: 531). Probst defined the sweeping aspirations of *Der Bauingenieur* in his editorial on the duties of civil and structural engineers (“Aufgaben des Bauingenieurs”, Probst 1920). In his view, among the most important duties in the civil and structural engineering profession was “collaborating in the expansion of materials-testing” as the “foundation for economic and safe construction” (Probst 1920: 1). Probst had therefore formulated one key item on the agenda of *Der Bauingenieur*. As an example, he highlighted the building of long-span bridges, “which had only become possible due to the progress in and expansion of engineering theory” (Probst 1920: 1). In this respect, one particular challenge facing engineers was the crossing of deep valleys, until then the domain of steel bridges. However, right at the start of the 20th century, steel bridges began to face competition in the shape of reinforced concrete arch bridges, which developed their own structural and constructional form, their own specific design language, during the invention phase of reinforced concrete construction (1925–1950). This historical process is described below using the example of knowledge transfer via the journals *Beton und Eisen* and *Der Bauingenieur*.

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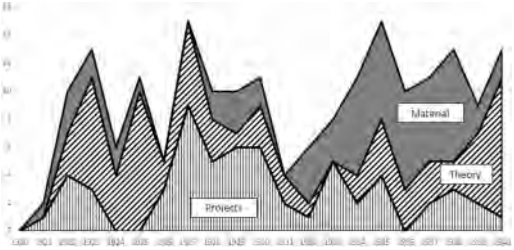

Figure 1. *Der Bauingenieur* 1920–1940; evaluation of the main essays on reinforced concrete arch bridges.

For example, a systematic study of the main essays on reinforced concrete arch bridges published in *Der Bauingenieur* between 1920 and 1940 reveals that, from the early 1920s, the structural analysis of the undeformed arch (first-order theory) and the deformed arch (second-order theory) played the greatest role. Five years later, however, the focus of the main essays had shifted to construction projects (Figure 1). Contrasting with this, in the 1930s many of the main essays dealt with the materials side of reinforced concrete, e.g. creep and shrinkage. By the late 1930s, consideration of these new findings from materials research led to a significant increase in the number of main essays investigating the structural analysis of reinforced concrete arches (Figure 1).

So, knowledge transfer in the construction of reinforced concrete arch bridges between 1920 and 1940 took place in several stages (see Figure 1):

- 1st stage (1923–1927): Dissemination of new findings and methods for the structural analysis of arch structures.
- 2nd stage (1927–1931): Application of the structural theory findings as methods for analysing and designing arch bridges.
- 3rd stage (1931–1940): Focus on materials.
- 4th stage (1936–1940): Formulation of structural analysis theories on a higher level, i.e. systematic consideration of creep, shrinkage and arch deformations (second-order theory).

Put into general terms, the knowledge transfer followed a recursive cycle: structural analysis theory (linear) – practice (design and construction) – materials research and testing – augmented structural analysis theory (non-linear).

Augmented structural analysis theory followed from practical design and construction, which sounded out the limits to reinforced concrete arch bridges and their design language. For example, with its span of 269 m (rise = 40 m), Sandö Bridge, a three-cell reinforced concrete arch over the River Ångerman (Sweden) which was opened to traffic on 16 July 1943, held the world record for the span of a reinforced concrete arch bridge for about 20 years (Neuffer, 1943). Therefore, Sandö Bridge marks the end of the great era of reinforced concrete arch bridges during the invention phase of reinforced concrete construction (1925–1950).

2 THE FORM OF STRUCTURAL CALCULATIONS FOR ARCHES

The successful use of reinforced concrete for building arch bridges right from the accumulation phase of reinforced concrete (1900–1925) is demonstrated by the Gmündertobel Bridge (Switzerland), completed in 1908. Emil Mörsch analysed the road bridge designed by him in 1904 as a fixed elastic arch according to first-order theory (equilibrium of undeformed system), a method he devised specifically for arch bridges and described in the *Schweizerische Bauzeitung* journal in 1906 (Kurrer 2018: 241).

Whereas the Gmündertobel Bridge had a rectangular cross-section that increased in size from crown to springings, Hermann Schürch resolved the cross-section of the arch structure for the Langwieser railway viaduct (Switzerland), completed in 1914, into a curved Vierendeel girder.

The building of reinforced concrete arch bridges with longer spans required significant progress in their structural analysis as well as materials research and testing. So, as arch cross-sections started to be resolved, arch deformation, buckling resistance and properties of materials became the key issues in research, development and knowledge transfer during the invention phase of reinforced concrete construction (1925–1950).

2.1 *The consideration of arch deformations (second-order theory)*

Josef Melan had quantified the influence of deformations when analysing steel suspension and arch bridges as early as 1888 (Kurrer 2018: 114). He was in favour of using first-order theory to analyse arch bridges because these “are generally much stiffer, i.e. are designed with a larger moment of inertia than suspension bridges” (Melan 1888: 100). Engineers also followed this recommendation when designing reinforced concrete arch bridges during the first two decades of the 20th century.

After 1900, Melan, Friedrich Engesser and Heinrich Müller-Breslau investigated elastic arch design according to second-order theory (Fritz 1934: 3). Nevertheless, more research was not undertaken until the construction of long-span arch bridges began in the 1930s. Bernhard Fritz brought together the various writings on elastic arch design according to second-order theory in 1934 (Fritz 1934). This was his response to the long-span, slender arch bridges that started to appear in the late 1920s. Whereas in suspension bridges the internal forces calculated according to second-order theory are lower than those according to first-order theory, this situation is reversed in arch bridges: “The relationships are totally different in arch bridges. Considering the influence of system deformations [second-order theory – the authors] increases the stresses here such that neglecting the deformations leads to more favourable stresses and, in reality, the structure has a lower factor of safety than the calculated one" (Fritz 1934: 1–2). Fritz formulated a method of calculation based on second-order theory for single-/two-/three-pin arches and fixed arches and compared the results with those from tests on models. He considered the strain stiffness of the arch as well as the bending stiffness. For arch bridges with long spans, Fritz recommended the fixed arch: "In the case of fixed, hinge-less arches, the unfavourable influence of the system deformations [second-order theory – the authors] can be completely eliminated by choosing a suitable form, something that is not always possible with pinned arches" (Fritz 1934: 140). Fritz provided methods for the form of the arch axis for all four arch types. As will be shown in the next section, the fixed arch was to become the dominant structural system for large reinforced concrete bridges during the 1930s. Fritz communicated the results of his dissertation to a wider public just one year later through an article in *Der Bauingenieur* (Fritz 1935) using the example of the three-pin arch.

2.2 *Dischinger's breakthrough*

Franz Dischinger was able to integrate the laws covering the creep and shrinkage of concrete as well as second-order theory into the structural analysis of reinforced concrete arch bridges through his essays in *Der Bauingenieur* (Dischinger 1937, 1939). In many respects these constitute a breakthrough in the evolution of reinforced concrete arch theory:

- Study of the buckling resistance of arches with any form and any course of moments of inertia; stability problem (second-order theory).
- Calculating the additional bending moments due to elastic deformation; stress problem (second-order theory).
- Determining the influence of creep and shrinkage (plastic deformation) on the internal forces according to first- and second-order theory.

Dischinger recognized the relationships between the internal forces in the arch calculated according to first- and second-order theory: using a polynomial approach, he was able to present the internal forces as algebraic equations – and not in the form of transcendental equations as Fritz had done (Fritz 1934). He thus developed a method of calculation that quickly produced understandable results.

Dischinger's method was based on the exact calculation of the buckled shapes and the buckling resistance, which enabled him to draw conclusions as to the way in which the arch axis had to be artificially deformed in order to achieve internal forces with a favourable course (Dischinger 1937: 517–520). That formed the basis for his theory of plastic deformation, which included the influence of the creep and shrinkage on the internal forces. So, with the help of research into the creep of concrete by W. H. Glanville, R. E. Davis, H. E. Davis and E. Freyssinet, he was able to prove that Hooke's law also applies to the creep range: "Whereas for concrete in the elastic range our calculations based on Hooke's law are only a rough approximation, it applies, conversely, very accurately for the plastic range" (Dischinger 1939: 54).

Dischinger concludes that arches with one hinge at the crown should be avoided because such structural systems lead to very high additional bending moments within the arch cross-section. On the other hand, the influence of creep on arches without a hinge at the crown (two-pin and fixed arches) "is sometimes even beneficial, particularly as the resistance to symmetrical buckling increases" (Dischinger 1937: 487).

In a summary of his work (Dischinger 1938: 18), Dischinger argues in favour of:

- the statically indeterminate arch;
- increasing the buckling resistance and reducing the self-weight by increasing the moments of inertia of the arch cross-section (e.g. box sections);
- increasing the permissible stresses; and
- striking the arch formwork as late as possible.

On the theory side, Dischinger's scientific studies rounded off the knowledge transfer in the building of reinforced concrete arch bridges during the 1930s. At the same time, his work laid the foundation for prestressed concrete theory on the material side.

3 THE FUNDAMENTAL WORK OF MATERIALS-TESTING INSTITUTES AND ITS TRANSFER INTO REINFORCED CONCRETE PRACTICE

Alfred Hawranek, professor at Brno TU in what was then a technically extremely advanced (and free) First Czechoslovak Republic, proposed five requirements for successful large reinforced concrete bridges at the 1936 IABSE Conference in Berlin (Hawranek 1936). One year later, he presented these to a German readership (Hawranek 1937):

1. improvements to the material properties, permissible stresses and cross-sectional form;
2. reducing the maximum stresses in arch bridges by way of a corrected arch axis (elastic theory);
3. more accurate calculations and deformation theories for arches (second-order theory);
4. the buckling resistance of arches;
5. knowledge and consideration of the shrinkage and plastic deformation of the arch.

Points 2 to 4 have already been dealt with in detail in section 2; points 1 und 5 will be dealt with below.

3.1 *Improvements to material properties, permissible stresses and cross-sectional form*

At the start of the 1920s, tamped concrete arches were reaching their technical and economic limits at spans of about 100 m. At an early date, after evaluating "long-span concrete and masonry bridges", Gesteschi recommended turning to reinforced concrete arch bridges to be able to compete with steel (Gesteschi 1922). His main proposals were to separate arch and deck, divide the arch cross-section into individual ribs or even multi-cell boxes and increase compressive strength by using reinforcement and better cements. Spangenberg developed the international comparison further (Spangenberg 1928) and validated Gesteschi's theses. At the same time, Emperger examined the cost-effectiveness of large reinforced concrete arch bridges compared with steel arches (Emperger 1928). However, it emerged that reinforced concrete did not offer any clear benefits. When it came to reinforcement, the Melan form of construction, i.e., the inclusion of rigid steel elements, continued to be the most popular method, followed by the embedment of cast iron with a high compressive strength, a technique developed by Emperger. In the discussion about cross-sections, he referred to the competition for the bridge over the Lech at Augsburg (Knab 1927): The approx. 83 m span three-pin arch with a rise/span ratio of 1:10 had a five-cell box cross-section that was superior to individual arched ribs or a rectangular cross-section.

In 1922, the French engineer de Tédesco introduced German readers to the possibilities offered by better cements (Tédesco 1922). The rapid-hardening high-alumina cement "Ciment Fondu" had been developed back in 1908 by the French chemist Bied and patented by the Lafarge company. This cement was made from a mixture of bauxite and limestone fused together in a specially developed electric furnace. Ciment Fondu enabled arch formwork to be struck sooner and increased the compressive strength substantially. Although Rüth wrote about further developments of the Portland cement "Dyckerhoff Doppel" having a similar quality due to "German leadership" (Rüth 1924), the translation of a lecture by the Danish engineer R. Christiani (Troche 1923) demonstrated the necessary transfer from other European countries. From 1922 to 1924, the main findings were often to be found under "Miscellaneous".

Nevertheless, the German building authorities remained cautious regarding higher permissible concrete compressive stresses for reinforced concrete. Those were determined by the 28-day cube compressive strength W_{b28} of specimens produced beforehand for the concrete mix to be used on site and depended on the type of cement. For example, for W_{b28} = 225 kg/cm^2, the 1932 German reinforced concrete specification (DAfEb 1932) specified a permissible concrete compressive strength of 75 kg/cm^2 for arches, and the 1933 "Calculation standard for concrete/masonry bridges" (Deutscher Normenausschuss 1933) increased the permissible compressive stress to $W_{b28}/3$ for those spans > 80 m, but not more than 90 kg/cm^2. For spans < 80 m, the permissible concrete compressive strength decreased to max. 50 kg/cm^2 provided $W_{b28} \geq 250$ kg/cm^2. This was far below the demands of the German reinforced concrete industry, which at the time of entering the market for large bridges called for permissible stresses of 120–150 kg/cm^2 and backed this up with measured cube compressive strengths of up to 500 kg/cm^2 (Nakonz 1933). To support these requests, numerous articles appeared in German journals (preferably under the heading of "Miscellaneous") which described how reinforced concrete was at a disadvantage compared with steel due to the unequal safety levels and the more positive treatment in other countries. For example, in Czechoslovakia, permissible compressive stresses of up to 160 kg/cm^2 were possible, provided the reinforced concrete contractor was properly qualified and good inspections could be ensured. At the IABSE Congress (Baravalle 1936), Baravalle was looking further, at possible maximum spans. With a moderate rise/span ratio of 1:2.5 and compressive stress of 150 kg/cm^2, he predicted a maximum span of 1000 m.

Reinforced concrete construction was still affected by poor quality control in the 1920s and, not unreasonably, the German building authorities remained cautious with respect to the wishes of the construction industry. Over the years 1923–1926, *Beton und Eisen* and *Der Bauingenieur* published many articles on accidents on building sites, concrete quality control, warranty claims as a result of poor construction and annual accident statistics. Development and application of testing methods was discussed. The adoption of the American flow table test (Graf 1926), which is still used today, must suffice here to demonstrate the knowledge transfer.

3.2 *Knowledge and consideration of the shrinkage and plastic deformation of the arch*

The fact that concrete shortens over time was quickly recognised by bridge engineers, and constructional means were employed for decades to counteract this phenomenon in the building of arch bridges. Suitable means of communication were needed to reflect and disseminate the knowledge that shrinkage is a function of time and creep a function of stress and time caused by the leakage of chemically bonded and unbonded water, and to describe the critical parameters. International networks fused together the strengths in materials, theory and practice, which differed internationally, to form a complete picture.

In 1955 Gaspar Kani, the prestressed concrete pioneer, wrote a brief outline of the technological evolution of creep and shrinkage (Kani 1955). Unnoticed by the European reinforced concrete community, William Kendrick Hatt, professor for civil and structural engineering and director of the materials-testing laboratory at Purdue University (USA), correctly interpreted the time-dependent deformation of concrete under load as early as 1907 (Hatt 1907), simultaneously with the failed tests of Koenen (Bach & Graf 1910). According to Kani, another eight American reports on the plastic behaviour of concrete were published between 1915 and 1919 (Freudenthal 1935) without anyone noticing the connection with Koenen's failure. In the second half of the 1920s, fundamental research was carried out by Faber (Faber 1932) and Glanville (Glanville 1930) in the UK and by the Davis brothers in the USA (Davis 1928; Davis & Davis 1931). Initial details and interpretations of the progress in Britain and America appeared in *Beton und Eisen* in 1930. Grünberger was the first (Grünberger 1930), reporting on Faber's observation that besides the known deformations due to temperature and shrinkage, attention should also be given to the less well-known "plastic yield". He was followed in 1932, again in *Beton und Eisen* (still under "Miscellaneous"), by Hoppe, who quoted the Danish journal *Ingenieren* (Hoppe 1932), and by an in-depth article by Josef Melan (Melan 1932), who acquainted readers with the work of Straub (Straub 1930).

Without really recognizing cause and effect, the shortening of concrete was mentioned at a very early date, as the discussion about Considière's findings in (Christophe 1902) shows. Just four years later, Schaechterle specified a shrinkage strain $\varepsilon_s = 0.00025$, corresponding to a temperature drop of -20 ° C, in his booklet (Schaechterle 1906), a figure that is still reasonable today. Numerous essays followed explaining this and its influence on the shortening of concrete. For instance, Hummel investigated the change in volume of concrete due to cement paste (Hummel 1924). Koenen reacted to this by saying that including joints and keeping concrete moist were more important than considering shrinkage strain in the calculations (Koenen 1924). Despite the findings from British and American research, the doyen of German materials-testing, Otto Graf, remained on the level of pure empiricism, merely provided information on working with concrete. Examples of that are (Graf 1922) on curing and (Graf 1928) on cement content. Not until 1934 did he acknowledge the leading role of British and American researchers (Graf 1934). Freudenthal summarized the status of that research in 1935 (Freudenthal 1935).

For the practising engineer, journals provided numerous shortening measurements from arch bridges already built, and considered other effects such as creep, abutment deformations and initial or secondary stresses. Consequently, in 1928 Schaechterle specified measures proven in practice for reducing or eliminating crack-inducing shrinkage stresses (Schaechterle 1928):

1. minimal addition of cement to reach the required strength;
2. preference for high-strength cement;
3. aggregates exhibiting little shrinkage;
4. the inclusion of reinforcement to avoid cracks induced by secondary stresses;
5. curing plus the inclusion of expansion and contraction joints;
6. shrinkage strain in reinforced concrete decreases: 0.00025 according to the Swiss standard;
7. avoiding interruptions to work on site by using the crown jacking method or temporary hinges with neutral axis offset for lowering (crown) and raising (springings) the line of thrust;
8. concreting in blocks/layers with contraction joints and/or concrete or masonry blocks or hinge elements for fixed arches and vaults.

When checking stability, generous temperature assumptions helped to allow for uncertain creep and shrinkage estimates. Those estimates varied between -10 and 40° C for reinforced concrete arch bridges already built, but mostly remained between -15 and 25° C. For example, in 1916 the Deutscher Ausschuss für Eisenbeton (German Reinforced Concrete Committee, DAfEb) specified a temp-erature difference of ±15° C and a drop in temperature of $-15°$ C for shrinkage. Not until 1936 did Freyssinet (Freyssinet 1936) supply a satisfactory explanation of shrinkage. His thermodynamic theory was communicated to the profession by Gehler (Gehler 1938). That marked the completion of knowledge transfer for creep and shrinkage.

The plastic properties of concrete ensure permanent deformations in reinforced concrete arches which depend on the magnitude and duration of the compressive stresses. Not only do they shorten the reinforced concrete arch, but also lead to the forces being transferred from the concrete to the steel within the composite material.

Emperger, on his 70th birthday, again raised the question of the reliability of the purely elastic calculation of the resistance of the cross-section via the modular ratio, i.e., the ratio of the elastic moduli of the steel reinforcement and the concrete, and at the same time appealed fervently for a discussion on this. He drew attention to his remarks made in *Beton und Eisen* in 1916 that the modular ratio increases with the compressive stress, something that Saliger confirmed in tests on reinforced concrete columns around a cast iron core in 1928 (Saliger 1928). The modular ratio discussion continued passionately, even descending to a personal level, in German journals with contributions from foreign professionals. The design of reinforced concrete columns according to failure load was first permitted by the German building authorities in 1932, but it was not until 1971 that this method was generally applied to the design of reinforced concrete cross-sections. Principles that still apply today for the design of loadbearing reinforced concrete members first appeared in 1936 as the outcome of Saliger's fruitful discussion (Saliger 1936, 1938).

W. A. Slater and I. Lyse (Lehigh University) and F. E. Richart and G. C. Staehle (Material Testing Laboratory, University of Illinois) succeeded in working out the behaviour of reinforced concrete columns subjected to permanent compressive loads. Long-term tests began in 1926, but even before they were completed, the key results had reached German engineers via *Der Bauingenieur* (Treiber 1931). Between 1931 and 1935, Doldt wrote several short articles on the progress of the tests in *Beton und Eisen* (Doldt 1931). In conclusion, Busch assessed the situation rather conservatively in the sense of the modular ratio approach for recognizing the load redistribution due to permanent loads (Busch 1935).

At the conference of the Deutsche Gesellschaft für Bauwesen (German Construction Association) on 30 January 1933, Nakonz, board member at Beton- und Monierbau AG., made an urgent appeal to adopt the findings of British and American researchers regarding plasticity and creep of concrete (Faber 1932, Nakonz 1933). Dischinger (Dischinger 1939) and Habel (Habel 1940) rounded off the intense discussions with the statement that permissible concrete compressive stresses should be limited to achieve sufficient buckling stability. Even though the National Socialists exerted their influence on the publishers of professional journals, the trans-formation in the material properties of concrete for building reinforced concrete arch bridges spans > 130 m still took place.

3.3 *Further impacts*

For reinforced concrete construction, arch bridges represented a “bridge technology” that enabled reinforced concrete to break into steel construction’s supreme discipline. By the mid-1930s, reports on reinforced concrete beam bridges began to dominate the journals. After the Second World War, prestressed concrete beam bridges were preferred for large bridges, enabling Dischinger’s research to be used to the full. Not until the late 1960s would Heinrich Trost set a milestone and replace Dischinger’s differential stress-strain relationship for concrete by simple algebraic equations based on rheological model concepts (Kurrer 2018: 620).

4 ERECTION OF LARGE REINFORCED CONCRETE ARCH BRIDGES TO MAINTAIN THRUST LINE AND INVERTED CATENARY

Between 1920 and 1940, *Beton und Eisen* published 66 main essays and 42 short articles on reinforced concrete arch bridge projects under “Miscellaneous”. *Der Bauingenieur* provided its readers with 33 main essays and 24 short articles on the same subject. A quick look at other German journals does not increase our knowledge any further. Whereas the main essays tended to concern domestic projects, the shorter articles ensured an exchange of information on international projects. Authors with knowledge of particular subjects and a good command of the languages involved were available to make sure that the journals kept pace with research; reports sometimes appeared as a literature review. The time lag between publication of original works and their appearance in German journals was generally one year.

The rather more passive knowledge transfer via journals dealing with particular forms of construction contrasts with the active participation within the international organisations that provided a structure for this transfer. The International Association for Bridge and Structural Engineering (IABSE), founded in Zurich in 1929 (Peters 2011), brought together the international community via its congresses, Congress Reports and annual scientific treaties. The congresses in Vienna (1928, prior to founding the association), Zurich (1932) and Berlin (1936) included sessions on the plastic behaviour of concrete, second-order theory and remarkable bridge-building projects. The proceedings, some of which were reproduced – at least frequently quoted – in German journals, provided vital ideas that shaped large reinforced concrete bridges.

The network arch bridges of Christiani-Nilsson mark the culmination of reinforced concrete arch bridges with a through deck. Most bridges of this type were built in France. Shallow reinforced concrete arches with hinges to control the flow of the forces remained a preferred form of construction in Germany (Gehler 1934 in favour, Boussiron 1936 against). To keep the spans acceptable, concrete hinges were needed at the abutments. Designs using rigid reinforcement (Melan or Ribera form of construction) and the fixed arch attributed to Eugène Freyssinet became popular internationally (Fischer 1922). The latter included jacks in a temporary crown hinge for dismantling the centering and eliminating all the elastoplastic deformations up to that point plus subsequent shrinkage effects. That hinge was grouted afterwards to turn the temporary single-pin arch into a fixed arch. The method was later refined for abutment deformations by fitting cast-in inserts or by applying the jacking forces eccentrically and providing temporary hinges at the abutments.

Calculation methods were mainly traditional. Jüngling mentions the pioneering work of Dischinger (Dischinger 1937) only as a special report to confirm the stability of the Teufelstal Bridge (Jüngling 1938). Only Victoria points to the use of modern methods of calculation to optimise the line of thrust and inverted catenary for the bridge over the Lužnice in Bechyne (now Czech Republic) (Victoria 1928).

Two basic methods were used for concreting:

1. casting the full depth of the cross-section in separate blocks;
2. casting in layers.

Contraction joints, sometimes also concrete or masonry blocks, were specified to eliminate creep and shrinkage (Paris 1928). Prestressing by way of adding weights was seldom used. Concreting operations started at the springings and crown, with the arch being closed on both sides at the quarter-points. Casting in layers developed as spans became longer and made use of box cross-sections and centering spanning between the springings. Concreting the base, sides and top of the box sections in separate rings while retaining the contraction joints meant that, from the second ring onwards, composite action relieved the load on such centering.

“The most difficult issue in the building of long spans was the solution for the centering and how to set it up”, was how the Paris-based engineer Boussiron summed up his experiences of theory, materials and site operations at the IABSE’s Berlin Congress (Boussiron 1936).

Traditional timber centering built off the ground was possible up to a span of about 130 m. Rationalization and reusability, e.g. centering moved sideways for the second arch of the Teufelstal Bridge (Jüngling 1938), exhausted the further development of this type of centering. A timber arch spanning between the springings established itself for longer spans. Composite action between the centering and the arch helped to ensure an economical trussed framework. Suspended platforms were added for assembly and diagonal guys for stability during construction.

Nilsson had already pointed out that clear spans exceeding 180 m would need steel centering (Nilsson 1933). Unfortunately, for the Sandö Bridge, this advice went unheard (Neuffer 1942).

Large bridges are built for political, economic and topographical reasons. Journals restricted themselves to providing information about projects, left the active exchange to the IABSE. However, this international transfer of knowledge came to a standstill as the fascists gained power across Europe.

5 CONCLUSIONS

Detailed evaluations of German journals have shown that their articles made a significant contribution to knowledge transfer and discussions in the three key themes of theory, materials and projects using the example of reinforced concrete arch bridges. The sharing of information was immediate and fast, and of high quality. Unlike today, different scientific approaches were discussed openly and passionately. The paper uses shrinkage and creep deformations to reveal the competitiveness of a proofread journal even in today’s digital world.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Architects, engineers, and two construction companies: Introducing reinforced concrete technology in South America (Brazil and Argentina)

M.L. Freitas
Universidade Federal de Pernambuco, Recife, Brazil

ABSTRACT: From the study of the practices of two companies working in South America in the 1930s, Christiani & Nielsen (Denmark) and GEOPÉ (Germany), this paper aims to understand the architectural practice whose premise is technique. The technique is reinforced concrete. Taking as starting point Smith-Miller's article of 1937 introducing South American architecture, we will focus on two buildings, the Jockey Club of Rio de Janeiro (Brazil), and the COMEGA, in Buenos Aires (Argentina). While the first example was marked by intense conflict between the architects who designed the buildings and the engineers of the Danish construction company, the second saw a rich dialogue between architects and engineers from GEOPÉ, a subsidiary of the German construction company. Using these scenarios, we seek to understand the role of foreign construction companies, and the relationship between architects and engineers, in the modernization of Brazilian and Argentine architecture.

1 MODERNIZING SOUTH AMERICAN ARCHITECTURE USING REINFORCED CONCRETE

"All parts of the concrete building are essentially structural" – words by the American architect Theodore Smith-Miller published in the *American Architect and Architecture*, New York, in January 1937. New connotations were thus attributed to the current architectural practice in South American countries, with emphasis on exemplary cases realized in Argentina and Uruguay (Smith-Miller 1937, 76).

This successful enterprise of the creation of new South American architecture – understood as the set of countries in the southern cone: Brazil, Uruguay, Argentina and Chile – was supported by the technical culture of reinforced concrete, constituted as a field consolidated by educational institutions and associations endowed with a discourse and exemplary works. Smith-Miller, in the article, points out the aspects that differentiate concrete construction in South America from North America, such as the establishment of autonomous practices, and above all the maximum exploitation of the potential of construction technology.

The rapid development of reinforced concrete constructions in America's southern cone was driven by a lack of steel for civil construction in non-belligerent countries during the First World War, 1914–1918. The European and USA steel industries had redirected most of their activities to arms production. In South America, the natural existence of all the raw materials for the composition of reinforced concrete, such as sand and limestone, as well as industrial production of Portland cement and laminated steel, already supplied the domestic markets.

The change, however, was attributed to the teaching of reinforced concrete theory in architecture schools and the dissemination of the ideals of new plasticity and design freedom by the premise that "no other construction system hides the function that concrete is running, as can happen in other types of construction" (Smith-Miller 1937, 76).

The form derived from constructive rationality was only possible when thinking about architecture in terms of its program and because of the physical laws that govern buildings. However, would the proposed project not cease to be architecture? Smith-Miller asked and found the answer in the dialogue between the work of the architect and that of the engineer, a cooperation capable of producing an efficient, economic and beautiful structure.

Such a relationship had already proven advantageous, since in 1937 the North American architect managed to identify five exemplary works, four of which were built in Montevideo and one in Buenos Aires, relating the following criteria: 1) the ideal structure consists of a column and beam, calculated to support the construction of walls anywhere in the floor area; 2) the thin section of the column and spatial flexibility; 3) openings in the floor slabs; 4) the adaptability and lightness of reinforced concrete, expressed in cantilevered buildings; 5) the reinforced concrete structure can be shaped in the conditions necessary

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to withstand an earthquake; and, 6) protection of the external walls from insolation by their covering by plastering (Smith-Miller 1937, 76). This set of essential characteristics make up the South American concrete construction.

According to Smith-Miller, the first manifestations of reinforced concrete in South American architecture were interpreted as mere reproductions of what was in vogue outside the country. After the introduction and full adaptation of the construction system, the new architectural practice was enhanced by the premise of constructive rationality. Among the protagonists of this undertaking, large construction companies occupy a unique place: such as the German based Wayss & Freytag, Philipp Holzmann & Cia./GEOPÉ and the Danish Christiani & Nielsen. The introduction of these companies into the South American context happened for different reasons, dependent on the construction company, but one aspect connects them: the role played by these companies as agents of modernization of the countries concerned.

The performance of some of these professionals has been addressed in other works, but a gap remains: the role of construction companies in the modernization of architecture. Based on the study of collections, such as that of the Danish construction company Christiani & Nielsen and of German construction companies operating in Argentina and Brazil, this article suggests that, in addition to those already described, when the threads link, one can find the origin of modern construction based on the principles of reinforced concrete.

2 THE GREAT CONSTRUCTION COMPANIES

Companhia Construtora em Cimento Armado played a crucial role at the 1922 Brazilian Independence Centennial International Exhibition. Architect and civil engineer Hyppolito Gustavo Pujol Junior did not contain his technical boldness and designed one of the most important pavilions of the event in terms of architectural value: the States Pavilion. The reinforced concrete structure of the States Pavilion is breathtaking and was built over the course of just five months by *Companhia Construtora em Cimento Armado*, a corporation founded on 16 January 1920 by Lambert Riedlinger, its director and president who graduated in Germany from a technical high school. The design of the elements was so narrow that its technical capacity still amazes us today, along with the speed of its construction. This is confirmed both from the perspective of Pujol Junior and of the construction company, which, despite being founded in 1920, had already been operating in civil construction since 1910 (Wayss & Freytag 1925, 51).

Construtora em Cimento Armado also built the *arco de boca do parque das diversões*, a reinforced concrete structure of thin and light design, for the Independence Centennial Exhibition, in addition to the States Pavilion. Using the same construction method, the company built, in 60 days, three scissors with a 16-meter span and two major 150-meter-wide galleries (*Revista Brasileira de Engenharia* 1922, 166).

Between 1920 and 1922, the company carried out important construction works, such as three hotels, all designed by French architect Joseph Gire: the Copacabana Palace Hotel and Casino (1917–23) and Hotel Glória (1920–1), both in Rio de Janeiro, and Hotel Esplanada, called Hotel São Paulo at the time, in São Paulo.

Construtora em Cimento Armado developed not only architectural and industrial projects, but also major hydroelectric structures and bridges, having its works featured in the *Revista Brasileira de Engenharia* magazine due to the “variety of its projects”:

“We have been interested in the works carried out by *Companhia Construtora em Cimento Armado*, and have been extremely delighted with how fast they develop from one day to the other; their speed of execution will certainly be worthy of applause. Professionals who, however, take their time to observe only for a minute any of the company’s ongoing construction works will certainly realize the reasons that allow for it to execute its works so fast: they can be summed up as the methodic distribution of workers and the rational employment of all sorts of techniques powered by steam or electricity, which result in greater productivity and reduced expenses” (*Revista Brasileira de Engenharia* 1922, 164).

And it goes on:

“We believe the technical orientation of the company may rival that of its best foreign counterparts, and today, during the construction works for the Independence Centennial Exhibition, its presence has been of great value for the rapid and fancy execution of magnificent works” (*Revista Brasileira de Engenharia* 1922: 164).

In view of the success of *Construtora de Cimento Armado*’s project, a substantial increase in the number of partners was observed in the minutes of the meeting held on 8 April 1922, including, among the new partners, names that would soon stand out in the development of the reinforced concrete technical culture in Brazil: “L. Riedlinger, José Pereira da Graça Couto, Frederico Bockel, José de Barros Ramalho Ortigão, J.M. Magalhães, J. Friese, E.H. Baumgart, Franz Kaindl, Gustavo Lyra da Silva” (DOU 1922 [8 Apr], 7000).

By the end of 1924, *Companhia Construtora em Cimento Armado* was taken over by *Wayss & Freytag A.G.*, which then founded *Companhia Construtora Nacional S.A. (Wayss & Freytag – L. Riedlinger)*. As of 1925, Riedlinger was legally prevented, for reasons we were unable to determine, from remaining as president of the company (DOU 1925 [18 Jan]) and died in late October that year.

In 1925, *Companhia Construtora Nacional* had the following ownership structure: Georg Grebin, Fritz Henning, Otto Meyer (representative of Wayss & Freytag A.G. – Frankfurt), Ernesto Schaene, H. Kronenberg, M. Hamers, Ernesto Blanz and Ludwig Blanz;

the director used to be appointed by the German parent company, and engineer Alfredo Schultz was the director until 1930. The company began to build mixed buildings – such as the one that included offices and a cinema at the Floriano Peixoto square (currently Cinelândia) some of which had their structural project attributed to Emílio Baumgart, in Rio de Janeiro and the Port of Niterói. In São Paulo, they built the new Sorocabana Initial Train Station (project by architect Christiano Stockler das Neves), and the water reservoir in the Moóca district; both works were stopped in 1928. At the meeting held that year, directors complained about the increased competition in the civil construction business (DOU 1928 [27 March]). Other companies were operating in the industry, particularly after 1927. At that time, *Philip Holzmann A.G.* opened a branch in Rio de Janeiro, under the name *Companhia Geral de Obras e Construções* (GEOBRA), *E. Kemnitz & Cia.,* whose chief engineer was Arnold Brune (1884–1964). After 1930, *Companhia Construtora Nacional* replaced its director, bringing engineer Jakob Baumann from Germany to the position, and in 1943, the company's German stock was nationalized by the federal government.

The 1922 exhibition featured not only the German construction company, but also *Christiani & Nielsen Engenheiros Construtores Limitada*, a branch of the Danish construction company that specialized in reinforced concrete. The latter built three international pavilions, one for its country of origin, according to the plan by architect Helwig Möller, another for Sweden, and the Holland Pavilion. On 8 February 1904, engineer F. Rudolf Christiani (1877–1960) and Royal Navy captain Aage Nielsen (1873–1945) established Christiani & Nielsen, a company that specialized in building projects using reinforced concrete. In Paris, Rudolf Christiani was an enthusiast not only of the system proposed by Hennebique, but also of the possibilities enabled by reinforced concrete, which could be a solution for any structural problem: "Concrete beams, slabs and columns reinforced with steel bars possessing almost unlimited potentialities. This presented a vast field for the imagination of the creative engineer" (Ostenfeld 1976, 242).

However, not even Christiani could foresee the company's size after 75 years of operation. The arrival of the Danish engineers in Brazil in 1917 coincided with the end of World War One and was determined by a contract with *The Pernambuco Paper Mills Ltd* to build its plant facilities in Jaboatão dos Guararapes, state of Pernambuco. The South American project opened new horizons for Christiani & Nielsen, which, until then, had not expanded beyond European borders: "The English branch was set up in 1913 and during World War I, offices in Oslo (1916) and Stockholm (1917). Then the company took the plunge with the office in Rio de Janeiro (1917) and Buenos Aires (1918)" (Ostenfeld 1976, 30).

The *Paper Mills Ltd* construction works presented new challenges for Christiani & Nielsen, both because it was a new country, in a distant continent, and because they had no knowledge of the technical, cultural and social local conditions. The engineers faced a number of issues: delay in receiving imported material, such as steel beams and "barrels of cement", and the non-existence of qualified labor. This meant the engineers had to train the workers on site to "make them understand technical drawings, prepare beam structures, make wooden boxes, dose and pour the concrete" (Amaral 1973, 3) in order to build the plant facility for Paper Mills, whose project comprised three buildings covered by reinforced concrete domes. Other materials, such as crushed stone, were precariously industrialized at the time. The buildings were built on the top of a hill, in an "L" shape. All buildings were simple and had no decoration, as industrial buildings usually are, with long, rectangular ground-floor plans, which allowed for Zenith lighting through windows placed on the domes or through skylights. In fact, they caused an impact in production at the time, when industrial buildings were usually built of bricks and covered by wooden truss roofs.

As Augusto Carlos de Vasconcelos, a civil engineer and construction historian, pointed out in *History of Reinforced Concrete in Brazil*: "The training of national specialists, provided by the German firm Wayss & Freytag would soon liquidate with the participation of foreign technicians in the project sector. There were exceptions naturally …" (Vasconcelos 1985, 48–9). This was what Lambert Riedlinger did, when associating with Brazilian descendants of Germans, such as Emílio Baumgart and, what he would do to Christiani & Nielsen when training the manpower for the construction of the paper Norwegian factory in Jaboatão dos Guararapes, at the state of Pernambuco, already in the first years of action.

These connections, however, have greater complexity when large construction companies specialized in the reinforced concrete construction system are included in this scenario. The entanglement of these relationships implies an articulated exchange between the European and American continents, as well as between American countries. Of German or Danish origin, these construction companies undertook works that modernized the landscape of the main cities in the countries we study: Buenos Aires (Argentina) and Rio de Janeiro (Brazil). To this end, we elected two companies: Christiani & Nielsen (Denmark) and GEOPÉ (Germany), to obtain an understanding of architecture as a technical premise resulting from the clash and interference between the architect and the engineer.

3 THE CONSTRUCTION STORY (ARCHITECTS, ENGINEERS & BUILDERS)

In 1926 the new Prado or Hipódromo or Jóquei Clube do Brasil was inaugurated, on the banks of the Rodrigo de Freitas lagoon. This act was the motivation for another controversy concerning the champion of the Brazilian neocolonial style: the doctor and patron José

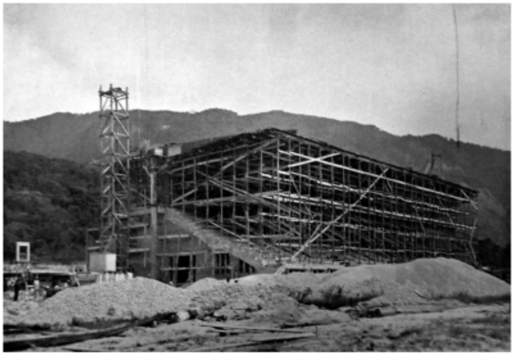

Figure 1. The grandstand under construction. Note the size of the structure used to support the assembly load of the awnings.

Marianno da Cunha Filho. Despite not being part of the struggle, Paulo Santos, a young architect and theorist, almost 40 years later, delivered his opinion on the set of controversial buildings:

"One could speak of independence between the structure and the walls, but independence not to let one perceive the proper function of each one – as in those years Le Corbusier already advocated – but rather to cover the structure as something that should not be displayed. The Prado do Jóquei Clube, with its bold reinforced concrete marquees set in the Luiz XVI stands, would make Frank Lloyd Wright in 1932 comment: 'it is the future anchored in the past"' (Santos 1956, 152).

There was also another controversy, the sanitation and beautification of Rodrigo de Freitas lagoon carried out by the then mayor of Rio de Janeiro, Carlos Sampaio. The work was to land and open an avenue 30 meters wide along the entire contour of the lagoon, landing the necessary parts with the garbage, which was normally dumped in Botafogo. The "sanitation" of the lagoon was carried out, according to the project of the sanitary engineer Francisco Saturnino de Brito, who routed all the rainwater into a canal bordering the Botanical Gardens and another in the Leblon neighborhood, to route the water into the sea, permanently changing the air from the pond water and keeping it healthy. The grounded part – layer of garbage, sand and stone – was donated to the members of the Jóquei Clube of Brazil, in 1921, by the district government (since the city of Rio de Janeiro was the capital of Brazil, and thus the Federal District), which did not anticipate some kind of building being put up in such a short time.

The two societies for horse turf – the Jockey Club and the Derby Club – were in the north, the Jockey where Maracanã Stadium is today, while the Derby remains in the same place. When they won the land in a privileged location in the south, they did not waste time. In 1922, a preliminary project carried out by Mr Mário Ribeiro, in collaboration with the designer Frederico Heime (of the Central Railway), was approved by Mayor Carlos Sampaio (Cunha Filho 1943, 105).

The plans were taken to the Heitor de Melo office, led by architects Archimedes Memória and Franscique Cuchet, who prepared the entire architectural project, consisting of:

A) Preliminary studies for choosing the preliminary project;
B) Water colored sketches in perspective;
c) definitive project, consisting of integral elevation of the façades; sections; polite; floor plans; plaster model;
D) technical study (calculation) of the reinforced cement work that served as the basis for the competition in which the firm Christiani & Nielsen was the winner;
E) elaboration of all the constructive and ornamental details;
F) original designs for interior decoration (furniture, tapestry, lighting, etc.)" (Cunha Filho 1943, 102).

With the project complete, competition was opened for the construction company, for which 15 construction companies presented themselves, among them Christiani & Nielsen, Companhia Construtora em Cimento Armado, Eduardo V. Pederneiras, E. Raja Gabaglia, E. Kemnitz & Cia, Gusmão, Dourado and Baldassini etc. Adjudication of the proposals was made separately for each building of the Prado complex, for example: partners' tribune, jockeys' tribune, special tribune, elevated passage, betting house and the deadline for beginning and concluding the works. On 8 March 1924, the members of the Jóquei Clube announced Christiane & Nielsen as the winner with the lowest cost and the shortest deadline, with the beginning of the work being announced as immediate: the other day and, with eight months of works. In the end, the work time was more than doubled:

"The works began in mid-1924 and ended in May 1926. Strictly speaking, driving the first stake from the jockeys' platform and removing the props from the partners' platform took 20 months" (Concreto 1938, 202).

There is clearly a separation, from the start of the design of the project, between the engineer and the architect. And this split stems from a problem in the formulation of the architectural project itself in which there was no concern with knowing the terrain, its characteristics, or the recent changes. At the time of the competition, the construction company relied on the technical study proposed by the Heitor de Melo office – at the time, the most important in Rio de Janeiro – based on its cost and time calculations. In May 1926, the engineers of Christiani & Nielsen, published an opinion on the construction of the new hippodrome of the Jockey Club reporting the problems raised:

"Indeed, anyone who passes through Rua Jardim Botânico and from there sees the beautiful tribunes of that meadow rising in his elegant Luiz XVI style does not assess the difficulties that were necessary to overcome in order to conveniently solve the various engineering problems that this execution raised" (Christiani & Nielsen 1936, 186).

He clarified:

“And to give the technical public an idea of these problems and the processes used to solve them, we decided to write the following lines. Of the technical difficulties, there is a single face that may surprise the public: we refer to the audacious constructions of the marquees: the small thickness in relation to the balance. Its construction presented serious difficulties, not only on the technical side, but still, and with even more reason, on the practical side, about the point of view of details and execution of structures like this in which the maximum balance reaches the value of 22, 4m and its own weight of 700 tons” (Christiani & Nielsen 1936, 186).

The problem simmered down to how to erect such a building on a newly grounded site. Christiani & Nielsen had experience in maritime works, in which the soil conditions presented difficulties similar to an area like Prado. One solution would therefore be to distribute the entire load over a large surface by means of foundation plates (surface foundations) or to reach the deep layers and massifs capable of supporting the loads by means of piles (deep foundations). To this end, a test was carried out, the bookmakers were built with surface foundations. It did not take long for the first signs of instability to appear:

“So, therefore, the technicians of the Jockey Club agreed with our proposals and entrusted us with the foundation of the tribunes on piles, with a fixed price and the obligations guaranteed by the contracted party. Determinations later made by the strict inspection of the Jockey Club came to fully crown the obligations and forecasts of the builders. There was not the slightest displacement in the fundamental structures” (Christiani & Nielsen 1936, 188).

These technicians of the Jockey Club were Mario de Azevedo Ribeiro and Lino Leal de Sá Pereira, inspectors of the work. The structural design projects were revised, and the work started in mid-1924. The same foundation system was applied to all buildings, with the largest piles 24 meters long: “The building thus forms a monolith attached by “pivoting” to the ground” (Christiani & Nielsen 1936, 193).

The popular tribune is 60m long and 23m wide, the ribbed canopy has 18m of swing and is 26m wide (Figure 1). The partners’ is 31m wide by 49m long. The sunroom has a 22.4m swing. And the jockeys’ is the smallest, it has only 9m of balance, its marquee. In addition to these, other technical data of the work was highlighted by the engineers of Christiani & Nielsen. The length of the piles driven for the foundation has a total of 8km, constituting a record in Brazil and South America.

The opening in July 1926 of the Hipódromo da Gávea – named from the neighborhood where the turf is located – drew the attention of the entire public, being announced in all newspapers. However, it is not known for certain when the controversy led by José Mariano Filho started and who began the idea of paying homage to engineer Mario de Azevedo Leão as the only author of the project, thus, eliminating the contribution of the artistic design by the architects Memória e Cuchet, and the structural design by the engineers at Christiani & Nielsen.

However, let us return to the contention of José Mariano Filho who mobilized almost all the authorities involved in the episode, including the former mayor Carlos Sampaio. The mayor responded to Mariano Filho’s provocation seven years later, attributing the confusion to a “misunderstanding” between the complex program of the racecourse, as a set of its parts, the benches. Sampaio considered, citing American architects who visited Rio de Janeiro, that the practice of the professions of the builder and the architect should be separated, the first being with the construction, and the second taking care of the artistic, without building (Sampaio 1928 apud; Cunha Filho 1943, 105).

José Mariano Filho apparently agreed with such ideas expressing no counterproposal, his concern was focused on defining who, in fact, the author of Prado do Jóquei was. According to Mariano Filho it should be the person who carried out the project, that is, “Give plastic (artistic) form to creative thinking (architectural idea). Bringing the plan and the needs of the respective program into line with the architecture. In a word: to project” (Cunha Filho 1943, 113).

Another entrant into the clash was the architect from São Paulo Christiano Stockler das Neves, who had the very peculiar title “De Re Aedificatoria” to the architect or engineer. At first, he agreed with the patron Mariano Filho that what impressed at Hipódromo da Gávea was not “Constructive utility”, but its architectural ensemble. Weaving a whole connection between the beauty of the architecture of the complex and the attention given to the place, because of art and not of the beauty of construction technique, was defended by the engineers of the Danish construction company:

“Without art, the new racecourse would go unnoticed like any difficult-to-build tunnel or any large span bridge, which would only interest technicians. Art is of interest to everyone because the feeling of beauty: innate in humanity” (Neves 1928, 21).

And it opposes once and for all the two professions of civil construction, the engineer and the architect:

“Evidently, the beauty of Gávea’s architectural ensemble is not in the invisible structure of reinforced concrete or in what is visibly presented – its well-built roof, justly appreciated. But the extraordinary projection of this huge slab impresses only by its constructive boldness. It has no beauty” (Neves 1928, 21).

Apparently, Neves would agree with Mariano Filho and Carlos Sampaio. The drawings are the graphic programs with which the architect conceives the building. For Neves, the controversy of the racetrack was beneficial for the profession as it demonstrated the architect’s work to the public, however, the engineer also had an important role, especially those trained in polytechnic schools such as São Paulo.

Architects, engineers, and builders had different roles and followed different paths in the design and construction of the Gávea Racecourse. Taking the words published about Prado, in the magazine

Concrete: “Classical structure at that time, used in Naples, Cannes etc. Associated reinforced concrete frames, showing a remarkable balance …” (Concrete 1938, 202) and considering that this chaotic scheme among engineers, architects and builders also seemed classic at that time, it turns to criticism. This was suggested by the architect Smith-Miller at the beginning of the article regarding the dissonances between constructive technology and architecture; it is clear there is no dialogue, not in the conditions imposed by the actors at stake.

4 DIALOGUE: COMEGA BUILDING

Contrary to what happened in Prado da Gávea, in Rio de Janeiro, Brazil, in the Argentine capital, Buenos Aires, the topic was discussed in other terms. We have seen another connection, one in which architecture results from the premise of constructive technology, the result of a dialogue between the architect, the engineer and the builder. German construction companies played an important role in the modernization of architecture carried out in Argentina.

Wayss & Freytag had built one of the first buildings of height in the Argentine capital already in 1910, with a reinforced concrete structure almost concurrent with the Plaza Hotel – with ten storeys – one of the most iconic examples of American culture using metallic structure, which allowed its construction in just six months, being inaugurated for the celebrations of the centenary of the May Revolution (1910). Three years later, the Galeria Güemes, a project by the architect Francisco Gianotti, was built by GEOPÉ (Phillip Holzmann & Cia), with 14 floors and an audacious mixed structure, which allowed the existence of the gallery at the level of Florida Street, under the building of offices. In 1921, the works of Pasaje Barolo, designed by the architect Mario Palanti, began, with 20 floors for offices and a gallery on the ground floor, in metallic structure. Located on Avenida de Mayo, it was also built by Wayss & Freytag, the summit of the tower is 100 meters from the ground. According to Liernur, Palanti was interested in the development of a monumental style, according to the new metropolitan dimensions and could solve the problem of colossal dimensions, and with that purpose he made use of vertical bay-windows, demarcated by powerful vertical pipes (Liernur & Aliata 2004, 145).

In the late 1920s, the way of designing skyscrapers changed. The building in height was beginning to be formulated as a landmark in the landscape, especially for the buildings along the façade of arrival in the city by the river of La Plata.

The impulse for the construction of this type of building occurred for two reasons, one, the incentive of the municipal government for promulgating a law and the other, for the redirection to the real estate market, a safer investment than investing in the stock market. It was at that moment that the Kavanagh was built, located on a site adjacent to Plaza San Martín, designed by architects Sánchez, Lagos and de la Torres, with 30 floors and 120 meters high.

In 1932, with the Kavanagh, construction began on the building of the Compañia Mercantil y Ganaderia, COMEGA, located on a corner of the avenues Além and Corrientes. Architectural design was by Alfred Joselevich and Enrique Douillet with consultancy from the architecture firm specializing in skyscrapers, Calvo, Jacob and Gimenez, and the structural design of engineer Alberto Stein. The construction company was GEOPÉ, which attributes to this building the title of “first skyscraper in Buenos Aires”:

“In Buenos Aires, we do not have the same advantage (as North America and Canada), which immediately increases the rate of audacity with which these works are viewed. For this reason, for many years, engineers did not dare to overcome a certain elevation in their works until in 1931 the COMEGA Society commissioned GEOPÉ to execute a commercial building located on the corner of Avenida Leandro N. Além and Corrientes, of monumental conception, as the elevation referred and in effect, with its 80 meters high above the level of the footpath, the first skyscraper in Buenos Aires is enshrined”.

The program was quite simple, aimed at offices, consisting of three basements, ground floor and 21 floors. Most of the plant was taken advantage of, using the available space as much as possible, creating an internal opening onto Leandro Avenue. In addition to lighting and ventilation, the services – elevators, stairs and bathrooms – were concentrated on the reverse side, which makes up the tower. On the top floor, a small balance was made on the gap.

In the construction photographs (Figure 2), the final architectural form can be seen, standing out from the form of reinforced concrete, the result of a dialogue between all those involved, despite the problems faced. In 1933, with the completion of the work, it could be said that Buenos Aires had a reinforced concrete architecture: elegant, beautiful, and efficient. Fruit of the dialogue between architect, engineer, and builders.

5 ARCHITECTURE, ENGINEERING AND CONSTRUCTION: DIALOGUES INCREASINGLY DIFFICULT TO REACH

The effort to trace these various connections and paths taken by the arrival of the large construction companies in Brazil and Argentina, allowed the creation of an overview of architecture and civil construction in South America, with a focus on two richer and more complex countries. It also made it possible to demonstrate the role of the great construction companies of German and Danish origin, Christiani & Nielsen, in developing the professional field of construction, composed by the engineer and the architect, and created another approach when placed alongside a third character – construction companies specialized in reinforced concrete.

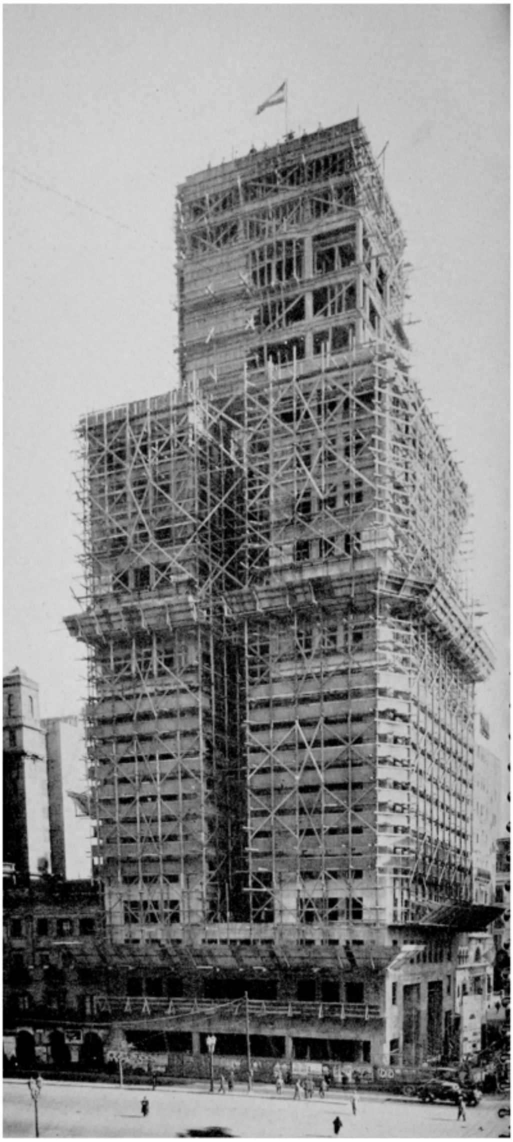

Figure 2. The COMEGA building under construction. (source: GEOPÉ 1938).

When analyzing the large construction companies together with the constitution and consolidation of the technical culture of reinforced concrete, against the background of the modernization processes of Brazil and Argentina, from around the turn of the 20th century, it was expected to have reached the objective to qualify this new architecture by the connections drawn between the construction companies, engineers and architects, through the works carried out in the 20s and 30s. This architecture is now read by the paradigm of the technical culture of reinforced concrete, which brings to the fore modernity, whose premise is constructive rationality, guided by the principles of economy, speed and efficiency in construction. This allows us to understand the modernization of architecture, overcoming the duality between modern and eclectic architecture, as well as the idea of style. Also, we tried to highlight the existence of cases such as that of the Jockey Club of Rio de Janeiro, where the opposite occurred, in which there was no dialogue between architects, engineers and builders, generating, in the end, an impasse between the three professional classes and an iconic work.

Despite the complexity and ambivalences of the field in question, the approach based on large construction companies specialized in the reinforced concrete construction system and in their technical culture answers questions paradigmatic to every architect, thinking beyond constructive and pragmatic technical issues. For these issues, coming to the fore during a period of war, it was necessary to highlight emotions and other important values related to the moment lived, rethinking some of the initial assumptions made.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Thermal standards, rationality and choices—To regulate or design thermal environments in Santiago de Chile

L. Epiney
Università della Svizzera Italiana, Mendrisio, Switzerland

ABSTRACT: Thermal standards shape the way cities are built and climatically experienced. By establishing clear boundaries between the interiors and exteriors of buildings, for instance, this *normalization* creates ever more homogeneous global thermal environments, with little care for local specificities. However, this does not appear to simply be a tension between local and global but rather what the place of experts is regarding the definition of norms. Taking Santiago de Chile as a case, I analyze the *deviations* from so-called objective, rationally defined codes, to those transformed by architectural, socio-cultural or historical contingencies. Case studies on modernist housing projects and the LEED certification scheme serve to reinforce this argument, nuancing the apparent *universality* of thermal standards. They then question the evolving role of the architect in design in general, and in city climates in particular. This is expected to return insights into navigating *between reason and experience* in thermal governance and climate control.

1 INTRODUCTION

This paper takes as its hypothesis how standards are not fixed but subject to *interpretation* over their existence. The question then approached is the consequences of the use of thermal standards. Standards can substitute un-formalized practices or building traditions, where formal ways might replace experience. My research relies firstly on documents I collected and observations I made during my fieldworks in Santiago de Chile in 2017 and 2018. The documents range from government-issued policies and plans, construction manuals, official guides on how to apply certain regulations, to more cultural records in the form of newspapers, advertisements, etc., as well as photographs I took. In addition, I assessed different neighborhoods and buildings through ethnography and microclimatic walking to obtain a sensory experience of their thermal characteristics.

2 BETWEEN REASON AND EXPERIENCE

With some simplification, “we’ll do as we’ve always done” is often the prevailing argument of the construction sector when faced by new challenges. In our case, energy performance and thermal comfort goals, which require innovation and change of governance in the current concern for more energy efficient buildings. Globally, this mostly takes place through the development and implementation of thermal standards and regulations, be they national or transnational. During the introduction of a new regulation, professionals will seek to align its contents with the practices of their field, trying to lessen additional costs and risks to the maximum. The building sector will try to make it compatible with the market’s capacity, construction feasibility or traditions as much as possible. For instance, in the second phase of establishing Thermal Regulations in Chile, bricklayers lobbied against it. In turn, academics will push for higher requirements or better heat resistance values, showing their simulation models or evoking international examples and best practices. In the middle, the decision- and policy-makers have to weigh the outcomes of each proposition, balancing scientific data with their application in the building industry.

This obviously represents a highly political process involving questions of legitimacy and power. Naturally, the foremost goal is the thermal comfort of users but a standard is not necessarily the technically most advanced outcome. It often emerges from an interplay of market interests as was the case for Santiago, where the studies on brick resistance for defining the standard were funded by the owner of the country’s biggest brick factory. The result is the “*SantiagoTe*”, the type of brick mainly used in Chilean construction today. The material characteristics were defined rationally yes, but with certain adaptations fulfilling the manufacturer’s technical capacities and financial strategy. It is also where labels such as LEED (“Leadership in Energy and Environmental Design”, a US-based standard and certification scheme) come to play a role, and adopted by foreign firms that

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aim to develop their projects somehow independently from these localized technical-political imbroglios. They established their role as "Standards organizations promise technical expertise without political entanglements" (Timmermans & Epstein, 2010, p. 80).

I perceive the "Thermal Regulation" incorporated into the General Construction Ordinance in 2000 (*Reglamentación Térmica*; *Art. 4.1.10 de la Ordenanza General de Urbanización y Construcciones* (OGUC)) as a shifting moment of change. This was the first regulation of its type in Latin America. Ninety per cent of the buildings in Santiago were built prior to 2000 (and some built afterwards also do not comply with the norm due to either a lack of control or resources) and so most dwellings are in brick masonry or concrete without insulation. Indeed, even now, with the regulation requirements being so low, you can attain them without using any insulation materials whatsoever. Furthermore, the scope of the standard, what kind of thermal environment it generates, results from the standard's definition. In Chile, applying a heat-degrees days scheme influences the strategy to attain minimum requirements. Moreover, by focusing primarily on the winter months, the national Thermal Regulation relies merely on specifying resistance values (U-values) for materials. Overheating issues are not addressed; an increasingly problematic issue as Santiago will only become hotter and drier in forthcoming decades.

Regulation aims at a fixed objective and can sometimes call for a change but this needs political will. This is the case for air pollution and the application of a new improved version of the Thermal Regulation in southern cities. Indeed, following studies of air quality in various cities across the country, some Atmospheric Decontamination Plans ("PDA" in Spanish) have been implemented. In these southern cities, such as Temuco or Osorno, houses are mostly heated by burning wood, often in bad-quality stoves, almost always in badly ventilated houses. The combination results in many health issues and pollution, which triggered the adoption of more severe regulation concerning insulation, alongside measures on car usage. This might be a step forward and we may thus question why this is not adopted nationally as Santiago also regularly suffers from air pollution. Again, as the thermal regulation only considers one situation (the cold/the winter), it here aims at a specific problem, particle matters, but fails to consider the urban climate as a whole, complex phenomenon. This illustrates the shortcomings of regulations to engage with climate control. Naturally, this also derives from political and economic reasons.

There is some progress in Chile following the "Standards of Sustainable Construction for Housing", a stricter standard encompassing various categories of sustainability in housing that will gradually become mandatory; but only gradually. It reflects the difficulties of convincing all the actors of its need, and is symptomatic of the political character of any standard. Indeed, to work, it has to recruit allies from every construction professional in power. As they all possess various agendas, this becomes a very complex process. It is worth noting how the impacts the regulation would have on real estate markets were not considered (Encinas 2015). Naturally, the foremost goal is the thermal comfort of users but a standard does not necessarily represent the technically most advanced outcome. Moreover, in defining the standard, only ideal cases (of orientation and location) were analysed. We would again note that the Thermal Regulation is based on certain fixed typologies that were selected in order to calculate the practical performance of the standard. They may be somewhat representative but still fail to encompass the reality of the urban fabric. Furthermore, this never considers other scales, such as the neighborhood. In the end, although the regulation embeds some directives on public spaces, it separates them from buildings. The two never interact in terms of what thermal environment might be achieved. We may criticise about the effects this will have on the design of urban spaces, perceived strictly as an *addition* of thermally isolated places. Nonetheless, an important aspect of the regulation's introduction is that it drew various actors called, from different backgrounds and fields, fostering national research on energy efficiency. In the end, the 'business-as-usual' model gets favoured to allow for a slower and easier transition.

I would now like to present and discuss the approach and overall framework that I apply for analysing the case studies. As stated previously, my main hypothesis is that regulations and standards are not "out there" waiting to be used but rather constantly manipulated and changed by different actors, endowing them values in the process. So, even though defined as purely rational, standards must not be categorized as merely technical-scientific artefacts as they are not independent of localized practices. Moreover, in the case of technical specifications or recommendations, the rules cannot be separated from the way they are applied at particular moments, in particular contexts. As any inquiry with architects would demonstrate, there are thousands of ways of designing and building the same standard, be it mandatory or voluntary. That is what case studies help trace and make visible. Having far more socio-cultural meaning than expected, what is the role of standards in shaping the built environment and its thermal aspects?

3 COLLECTIVE HOUSING & ITS THERMAL ENVIRONMENTS

The first Case Study concerns modernist housing production in Santiago on a district scale. I will concentrate on some of the collective housing projects inspired by the garden city. These dwellings were promoted by the state, selected through architectural competitions, and aimed at middle-class sectors of the population during the sixties: the *Unidades Vecinales*, or "neighborhood unit". The most well-known cases are the *UV Providencia* (1953–65), the *UV Portales* (1954–66), the *Villa Olímpica* (1960–64) but I am going to particularly refer to *Villa Frei* (1965–68). Adopting modernist ideas and standardized construction, they are all relevant case studies in analyzing standardization and institutionalization processes as well as shedding some light on the historical development of Santiago's mass housing thermal environments. Moreover, it is interesting here to look at architectural means of coping with urban climates and to acknowledge the existence of these urban models or typologies. Here, architects also take their own position in the creation of a good thermal environment. It is important to put them back in the centre of these issues as was the case in some of these modern complexes where architects used their knowledge of the place to design comfortable dwellings for the masses. In the end, technological and regulatory change are questioned. Can we bring higher standards to buildings *only* by improving products and norms?

These housing complexes emerge from the state institution called "*Caja de Habitación Popular*" ("Popular Housing Fund" set up in 1936). One of the Housing Fund's missions was to resolve the Chilean housing issues of the time, acting as a technical agency, and as such collecting ideas and knowledge, both locally and internationally. The "*Caja*" was open to experiments and new concepts in the development of housing solutions for the contemporary and the future city. It then very much sought to listen to the modern architectural and planning debates disseminated all over the world. All in all, it came up with a large variety of architectural solutions in terms of scale, urban layouts and domestic space configurations (Valenzuela 2008). Notably, this included gathering data on user needs, shifting away from the rather top-down approach of the modern movement. Nonetheless, it is important to acknowledge that the *Caja* received criticism over its capacity for tackling the housing deficit. One of its main adversaries was Luis Muñoz, Director of the Architecture Department in the Direction of Public Works. He very much defended a plan linked to the growth of cities and therefore taking economic development into account. He proposed a National Plan for Housing in 1936 (the same year the *Caja de Habitación* was founded). With the details beyond my scope here, his vision of solving the housing issue was rather pragmatic, fostering even more standardized, cost-controlled dwellings, partly using light construction materials. He also attacked the Popular Housing Fund for its independent status and felt it ran counter to his proposition of National Plans. In the end, with other Housing Institutions launched by Muñoz, the *Caja de Habitación Popular* was dissolved and a new entity emerged in 1953, the *Corporación de la Vivienda* ("Housing Corporation"), or CORVI. We now trace its role in the implementation of housing typologies during the 1960s and how it contributed to the mass housing dwelling conditions that I more thoroughly approach in the remaining sections.

What is of particular interest to my research is how the *Caja* started out creating standards for the minimum requirements of 'economic housing', be they from a technical, construction or urban point of view. The goal was to attain a hygienist model of a house and city (Bravo 1959). In around 1943, the house areas (36–100 m^2), their distances, heights, position and orientation to ensure good insolation and ventilation, as well as their interior layouts, were all defined. Moreover, the urban scale was also regulated with public spaces, density and the width of streets all quantified and controlled. It is interesting to address these modernist projects as a legacy of standardized typologies that need reassessing in relation to the current climatic conditions. I also want here to nuance the advantages or shortcomings of a *rule* (thermal regulation, housing policy) and a *model* (thermal features, housing typology) in their efficiency, and effects on thermal environment, past and present. If hygienist movements categorized houses into 'healthy' or 'unhealthy' ('unlivable' even, in the Chilean norm of 1943), there now came new categories to consider, such as "thermally comfortable", "energy-efficient" or "environmentally-fit".

To sum up, from the 1936 *Caja de Habitación Popular* to the 1953 *Corporación de la Vivienda* (CORVI), government backed housing production fostered the will to steadily evolve from amateurism to highly institutionalized practice. Interestingly, the institutional change that happened with the launching of CORVI provides one of the main reasons for its later success. Indeed, alongside its systemic incorporation into the governmental apparatus, and with the involvement of more architects and engineers in its organization, CORVI was able to enhance the architectural and constructive qualities of its projects. Housing production became more centralized and systematic, and also politically marked. It organized and developed prototypes in its architecture workshops, with the normalization of building systems as one of the pillars of its *Plan Habitacional* ("Habitat Plan"). Alongside the rationalization of the building sector, CORVI put a real emphasis on the role of the architect as the guarantor of the *habitability* of its projects. This conveyed how the state engaged the public responsibility of the architect (and engineer) for the good design of those "*Unidades Vecinales*". Adolfo Raposo sums this up as the "social ethos of political responsibilities" (Raposo 1999) inculcated by the period's governments.

While the CORVI developed this somewhat further, the *Caja de Habitación* paved the way for elaborating the collective space in the sense of defining what type of common spaces do people need, and how they will legally share them. This is clearly based on the form of housing but also on the rules guiding them. Hence, in the creation of modernist housing complexes, we have to understand the relationships between the *legislative* and the *morphological* in order to fully grasp how the model reacts to the rule, and vice versa. This is a factor in the type of thermal environment ultimately established as collective spaces depend on green areas, circulation as well as the transition between outside (the traditional public space) and inside (the flat or domestic realm). At the origins of the legal definition of collective, or common, space was the *Ley de Propiedad Horizontal* ("Law of Horizontal Property"), setting out the rights and duties of the tenants. Even while without actually defining their detailed morphology, this stipulates 'common spaces' as the spaces necessary for the "existence, security and maintenance of the building" (Chilean Government, Ministry of Justice, Law 6071). The spaces in question are listed as patios, gangways, lobbies, etcetera. Copropriety agreements then regulated how to treat these spaces in collective housing. In the end, the repetition of housing blocks alongside the "Law of Horizontal Property" allowed architects to free the land and design those common spaces, reinforcing the community aspect and its link with the urban (as well as providing green areas).

The first examples illustrating this kind of collective space as a continuation of the urban context into houses are found in the *Población Central de Leche* (1937), and the *Población HuemuI II* (1940–1943), also the first representatives of modern architecture in Chile. These typologies introduced the need to distribute several dwellings inside the same building as opposed to the traditional *conventillos* of workers, where "one door leads to one house", so to speak. Unintentionally or not, the Housing Fund solved this issue by providing a semi-public space between the house and the street. As Valenzuela puts it: "In a sense, the decades of *Caja* housing construction changed the image of home from that of an isolated room and facilities to a means of linking the domestic realm with its particular urban context" (Valenzuela 2008). The new residential design offers a buffer zone between the dwelling and city life. This is important to consider when reviewing these housing projects because, even if the reason was not environmentally obvious, it did engage an evolution in the transition from outside to inside, and the respective experience. Indeed, people would themselves quite rapidly appropriate those spaces (plazas, courtyards, passageways) participating in the process of building communities in a time of political and social turmoil. Nowadays, some of these spaces also appear climatically profitable.

The *Villa Presidente Frei* is an interesting housing complex because it encapsulates many typologies that are now spread all over the city of Santiago (and also Chile, actually). Indeed, the product of an architectural competition which saw thirty-six proposals, it would serve as a model for many other constructions by CORVI (Housing Corporation and later, the Ministry of Housing, MINVU). Additionally, it is a fine example of an urban microclimate within the city, with the creation of a good thermal environment based on architectural solutions rather than solely on the building's envelope (even if the latter might now understandably benefit from improvements). In 1964, the architects Osvaldo Larraín, Jaime Larraín and Diego Balmaceda, all graduates of Universidad Católica, won the competition. The brief contained the idea, much in vogue at the end of the 1950s, of the "neighborhood unit", theorized by the American planner Clarence Perry in the 1920s. This type of housing consists of an idealized number of inhabitants of ca. 7,500, living in community. Basics equipment for the development of a social life (such as playgrounds, crèches and shops) are located in the center. Perry goes on, in the "Regional Survey of New York and Environs" journal in 1929, to define the characteristics of the unit, including open and green spaces and ensuring all users enjoy them to the greatest possible extent.

In a first phase, the *Villa Frei* was planned in three sectors: a sector for the apartment buildings in blocks and towers, another for the civic and shopping center, a school, fire station and hospital, and the last for single-family houses. Linking these three sectors and their different volumes together was a park, functioning as the backbone for the whole housing complex. This established a good environment and community life that was considered successful (and still is according to by many inhabitants). Indeed, shared (green, when possible) spaces can often be seen as a plus in the creation of a comfortable environment around building groups. This is exemplified in testimonies by inhabitants of the *Villa Frei* expressing their appreciation for the open spaces of the complex. For instance, as compiled in the book "Ciudad Utópica, Villa Frei", by Rodrigo Gertosio Swanston: "To me, the *Villa* represents a space of togetherness that you do not experience a lot around Santiago, with green areas that allow a healthy and quiet life. This demonstrates that in those times such dwellings and spaces of quality and modernity could be created" (Gertosio Swanston 2016 with my translation and emphasis) or, more explicitly: "It is a lifestyle. It {*Villa Frei*} has a strong concept of neighborhood, with constructions of a good level and the presence of nature in the surroundings, creating a nice and pleasant environment. An oasis, a green lung for the city" (Gertosio Swanston 2016 with my translation and emphasis).

It is important to note here that many of the gardens were tended by the inhabitants themselves, getting together to organize, take care of, and upgrade green areas. Similarly, they would meet around their part of the housing complex to identify where open collective spaces might be improved in order to "make the *Villa* greener every day" (per a comment made by a neighbor in the newspaper "El Vecino", n.2, 1971). One thing to add as regards the collective space of these neighborhood units is that, at first, they did not have recourse to metal gates as was the case in other urban settlements (and how it in general is today across the city). The complex is thought to be designed for pedestrians but this does not nowadays always work as people want to arrive at their doors in their cars for reasons of both commodity and security. The first step of the project contains several typologies, consisting of blocks (4–5 floors), towers (10–15 floors) and single houses (1–2 floors), made of structures in concrete with brick partitioning walls.

The second stage came with the expansion of the housing complex in 1969, built with standardized models called *Bloques 1010/1020* ("Blocks 1010/1020"), developed by CORVI architects. This model is, once again, a simple concrete structure of slabs with bricks walls. These "Blocks" are one of most widespread economic housing typologies in Santiago (and the country, as previously stated). They are literally everywhere and represent the majority of the building stock. Since the late 1960s, this has been reproduced, with slight variations, all over Chile. They were developed as rational buildings to make the most efficient use of resources and materials. It is relevant to look at the way they were laid out in different parts of the city. As simple blocks, they might be located quite freely but we would remark how they often follow a north-south orientation, to optimize sunlight distribution for all flats (with four of two types on each floor). In the *Villa Frei*, they total the same amount as the simplex type. We may see how this typology is poorer architecturally as well as in terms of the inside and outside relationship. Moreover, in many cases, they lack surrounding green spaces, which contributes to a less comfortable environment overall. Nevertheless, they are good quality constructions that resisted the passing of time quite well, unlike later social housing. Thus, their conservation is under question. Moreover, they are constituted of rather generous flats in size, ranging between 47–55 m^2 for the 1010, and 66–75 m^2 for the 1020. Again, on the better side in comparison with what came afterwards (flats averaged 35 m^2 during the 1980s).

The purpose of this case study was not only to give an account of interesting housing forms as regards creating thermal environments and transitions between outside and inside but also to try tracing some comparisons. What could be learned today from looking back at those historical urban models? Indeed, we can see parallels between the *typical* dwellings in the blocks of the *Unidad Vecinal* and recent designs that rely on these typologies (once considered successful in terms of public space, social life and comfort). Moreover, I wanted to point out that housing went from an interesting solution (influenced by international modern ideas, yet developed by local architects with a care for the particular Chilean conditions) to a standardized model. This is even more the case in the following decades, the 1980/90s, with Chile embracing neoliberal policies that reduced housing production to property market mechanisms.

4 THE MARKET AND IMAGE OF THERMAL STANDARDS

The next case study I want to focus on here concerns voluntary standards, such as LEED ("Leadership in Environmental Design", a US-based green building certification scheme). Since the 1990s and the development of these labels and sustainable certification schemes (pioneered by the British method BREEAM from the BRE ("Building Research Establishment"), conceived in 1990 and that served as a basis for LEED and others, such as the French HQE ("Haute Qualité Environmentale") in 1996), we have witnessed the rise in the "green capitalist" approach towards sustainability in general, and energy efficiency in particular. This growth-oriented strategy did foster innovation and engage changes in the design and building apparatus. However, as Kipfer and Keil note, speaking about the privatization of urban development, "It is essentially market efficiency and service delivery that dominate the discussion here above concerns of ecological sustainability, democracy, or social justice" (Kipfer & Keil 2000). Indeed, these market-based systems function as a "set of principles" (Agyeman 2013) that do not take into consideration equity or local societal differences. When the environmental issues began to be apprehended globally at the end of the 1980s (with the famous "Brundtland report" published in 1987), sustainable development started to be seen as potentially compatible with economic drivers. This led, in the 2000s, to urban regeneration that integrated "green solutions" (green roofs, dense and compact planning, energy-efficient, high-performance buildings and reuse of existing infrastructure), and a close interconnection between the "sustainable city" and the "neoliberal city" (Krüger et al. 2019).

I conceive the "LEED Street" (actually, "*calle Apoquindo*") as a case study for the effect this certification scheme has had on the city climate on a smaller scale, the district, and the street. In the last section, I will also look at the buildings more thoroughly. I call it this because almost every building on the same street is LEED-certified, which is very much linked with the *image* the firms wish to convey. It is relevant in how this reflects a global trend in how the city has grown in recent decades and questions what prevails between efficiency and meaning. Also, it concerns the ways technical choices are in flux and makes us ask ourselves whether these are culture dependent or respond only to rational decision-making. This partly interrelates with the neoliberal path taken by the city in its expansion and land use since the dictatorship. These neoliberal policies were kept and even reinforced following the return to democracy in 1990 (Vergara-Perucich 2019). The city area in which "LEED Street" lies, in the north-east towards the Cordillera, has become the new CBD over the last 20 years or so, slowly replacing the historical district of the Santiago commune in the city center. The "LEED Street" is a site partly developed through foreign investment with international companies opening offices there because of its accessibility (the main road as well as a metro line run through it) and location in a rather green area of the city. Additionally, these transnational firms also seek access to spaces that suit their corporate needs and are adaptable to the same principles adopted elsewhere. Thus, the glass-façade building becomes the chosen typology to best respond to these demands. They represent the neoliberal city in the way they reflect the physical form of a free-market ideology, curtain walls now being part of a global aesthetic (Elkadi 2006) and a symbol of political power (Fierro 2003). It is important to set out the materiality at work in this place to later understand its consequences in recourse to LEED certification to assess the energy performance of these buildings.

Glass-facade buildings, one after the other, create some kind of similarities all along the way, heading eastwards towards the mountain range. They are arranged along a wide street where the asphalt surface gets pretty hot in the summer months between December and March. It is striking to see how these buildings seem cutoff from their immediate surroundings and well-protected behind their curtain walls. However, such a typology requires a vast number of active systems to compensate for the solar gain they receive most days in Santiago. We previously saw that the Thermal Regulation was developed according to the winter months and the use of glass makes little sense, especially when looking at the future climate of Santiago. Indeed, with ever more recurrent and extreme episodes of drought and heat waves, it might suffer regularly from the same issues facing cities of the North, thus those of a semi-arid desert climate. However, the area around "LEED Street" enjoys far more greener spaces than the rest of the city, which contributes to a nicer overall environment. Nevertheless, with private cars the principal mode of transportation, it is not such an enjoyable space for pedestrians, outside of parks. There are no exclusively office buildings but we can find some high-rise flats and condominiums for those who also work there.

If we now consider the kind of density present around "LEED Street", it verges on the low-density spectrum, even more so when going eastwards, uphill to the mountains. It is then quite a favorable urban climate in terms of the beneficial cooling effects from the vegetation in comparison with other, denser regions of the city, more heavily covered by asphalt and pavement. That may be true for between the buildings, in pockets of green (with some rather large, such as *Parque Titanium*, a four-hectare park at the foot of the three LEED-certified Titanium towers or the nearby golfclub). Closer to the buildings, another story emerges where the glass façade produces heat due to the sun's reflection. On that matter, it is relevant to note there have been some green façade projects, such as the "*Consorcio* building", already designed and built in 1993. This represents one strategy to mitigate the effects of overheating in office buildings but remains quite marginal in Santiago. It has, however, been applied on the tallest building in Latin America, the *Costanera Center* (with its construction completed in 2012) in which a 30,000 m2 green roof on the sixth floor should prevent excessive overheating of the different towers by thermal radiation.

The *Costanera Center* complex is a building on "LEED Street": This complex, the largest shopping mall in Latin America and constituted of two additional office towers, is located at the beginning of "LEED Street" (close to the river *Mapocho* and the aforementioned Titanium park). Alongside a high-performance curtain wall ensuring low radiant heat, as is the case in most such high-rise buildings, the indoor environment is controlled via an air conditioning system using water-cooled condensing units with heat recovery (using water from the canal). We here find that high-tech climate control systems were implemented to establish a solution now found worldwide, although benefiting from local technical support and service was also a key point for the building's owner, *Cencosud*. Indeed, and we can again discuss the term "local", with the firm responsible for the installation of this system being "Daikin Air Conditioning Chile, S.A", the Chilean branch of the well-known Japanese multinational HVAC manufacturing company. This is a recurrent aspect in the dissemination of standards such as LEED, their backing by these major corporations with accumulated experience in the field and leadership in terms of achieving certification requirements for lower costs. Actually, the development of the entire energy system was made by a team composed of Daikin Chile, Daikin Japan, the owner's own technical team, a consulting firm and a Santiago-based engineering office. That is quite an exchange of knowledge and practices among experts from different countries but that can work together by taking the LEED requirements and standards as their "common language". For the actual task of installation, as explained above, the tenants were responsible for connecting the pipes in their room to the central machinery provided by Daikin Japan. This means climate control (room temperature) is individualized and independent consumption recorded. Obviously, a building of this size has to react to different occupancy patterns and users.

International standards and certification schemes are generally conveyed by investors or private companies willing to implement them in their offices or housing projects. Their voluntary nature makes it clear that efforts to integrate them into designs must bring forth clear rewards and values. It is thus paramount for the firms adopting them to have access to qualified workers able to achieve their certification goals. This results in situations such as the development of the *Transoceánica* building in Vitacura, Santiago. The firm's headquarter, its energy concept was designed by an office in Germany, with the decision to aim for "LEED Gold" certification taken during the design process. To reach this objective and make sure the construction would follow the principles planned by the German engineering office, the contractor hired German workers, sending them to Chile for this purpose. Hence, in this example, we clearly see how the network of this building reaches far beyond its local context right from the beginning with its entire design and construction process outsourced to a foreign country. Clearly, this is also quite common nowadays in the globalized architectural practice. Nonetheless, it is revealing of how the voluntary certification scheme can sometimes work completely remotely to the site of its application.

Taking a step back and looking at which precise standards we are actually dealing with, I must remark that most of the buildings on "LEED Street" have followed the LEED 'BD+C: Core and Shell' standards (BD standing for Building Design, and C for Construction, setting it apart from the other versions: Interior Design and Construction, Operations and Maintenance, Homes, and Neighborhood Development). This certificate naturally focuses only on the structural, mechanical, electrical/plumbing, and fire protection systems of the building, without considering the tenant fit-out. Thus, it guarantees a clear division between the owner's and the tenant's responsibilities over the construction and installation of building components. However, there must necessarily be a possibility for the tenant to act in accordance with the requirements of the envisioned certificate credits. In terms of ventilation, for instance, if the project is designed to integrate a mechanical system, it must be provided by the team project or be ineligible for the credit. These kinds of rules try to minimize the potential gap between the design and the built product. In fact, the team project might conceive solutions that rely on certain well-defined elements that have to be implemented in order to attain the efficiency goals announced. As seen, these goals are assessed through the formulation of documents, stating the chosen strategies and demonstrating them. They can be based on diverse means, be they energy simulation or prescriptive compliance.

Again, if we look into the LEED guidelines, under the topic "Minimum energy performance", we encounter three options. First, the performance assessment is done in the form of whole-building energy simulation and must prove a betterment of 2% in comparison with the baseline building (an ideal case calculated on the base of ASHRAE standards, via simulation). The expected energy consumption of the building must therefore be determined. The second option is based on the ASHRAE "50% Advanced Energy Design Guide", that, after selecting the appropriate climate zone for projects outside the US, sets up standards for equipment efficiency (HVAC, water heating, ventilation, ducts, tampers, etc.). Option 3 is also based on complying with ASHRAE standards, in this case about air supply, temperature and speed. Thus, this choice between relying on simulation models or on ASHRAE standards has consequences on the type of spaces that are produced and experienced by the user. While this might seem like something quite insignificant and technical in nature, it can radically change the features of the building. Each of the three options have different scopes and methods around energy performance. This happens for every category, leaving substantial freedom of choice for designers to comply with the green certification. The same certification can be applied to two quite different buildings, and with distinct levels of efficiency. This tells us more about the somehow varied aspects of building design and construction in spite of being conceived under one certification scheme. Thus, it is then relevant to look beyond the categories and to search for just how their requirements were met.

5 CONCLUSION

The main argument of this research is that urban climates should be considered as design matters and not something completely remote, sometimes barely assessed or considered. In the modernist housing complexes we briefly reviewed, the idea of "neighborhood unit" did bestow some coherence on the grouping of building, and their implementation in the urban context. This happened to a point when some of these modern complexes are regarded as due to be conserved and preserved, and not only for aesthetic or "stylistic" reasons. Indeed, these urban settlements, even though often displaying the character of urban islands, represent important pieces in the built fabric of the city, made of consolidated communities and socio-cultural practices. The *Unidades Vecinales* could propose qualitative open spaces because they were based on the idea that those would be taken care of by the inhabitants through their common usage. In later social housing, from the 1980s onwards, the focus is generally on providing the building, not on its surroundings (as such is not affordable or profitable in any case).

Regarding the second case study, we may say this is the epitome of "LEED Street", where life happens inside buildings rather than on the street, in contrast with the rest of the city, usually bustling with people. Here, the private/public and inside/outside is sharper and with less threshold. Then, at the end of the street, more dispersed housing starts to take over from offices but still in a more or less clear withdrawal from the public space. The two scales of, on the one hand, the high-rise glass buildings and, on the other hand, low-rise dwellings are turning their back on each other. In a seemingly unaware fashion, they are developing themselves independently, creating this kind of fragmented environment without any continuity and compartmentalized thermal conditions. This is what happens all over "LEED Street", where buildings are repeated and treated as little worlds in themselves, relying on active climate control systems, without any great attention to pre-existing urban climates. "LEED Street" is composed of similar buildings in terms of program and construction. Then again, even though it has not directly to do with the application of the LEED standards system, but rather the economic principles tied up with the system, it is relevant to comprehending the typologies that express them. It is the purpose of such research, from an architectural (and multi-disciplinary) point of view, to assess the certified building as a socio-cultural and historical whole and as an urban phenomenon and not merely a "black box" cut off from the realities of the city.

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Wooden churches, managers and Fulbright scholars: Glued laminated timber in 1950's Norway

M. Rusak
Arkitektur- og designhøgskolen i Oslo, Oslo, Norway

ABSTRACT: The paper explores the introduction of glued laminated timber technology to the Norwegian construction market in the late 1950s. The paper concentrates on the activities of Norwegian construction conglomerate Moelven Brug, which in the 1950s brought back the production of laminated timber in Norway after 40 years of absence in the country. Building on the work of Norwegian glulam pioneer Guttorm Brekke (1885–1980) and on state-of-the-art academic research and industry know-how from the United States of America, Sweden, and Belgium, in the post-war period Moelven Brug quickly established itself as the market leader for laminated timber in Norway. By mapping these scholarly and professional exchanges, the paper traces the shifting ontological understanding of timber in Norway from a "natural" to a "scientific" material and its transformation into a complex assemblage of different substances subject to control and standardization through a series of variables and parametric values.

1 INTRODUCTION

1958 was the year of glulam in Europe. At the World Fair in Brussels in April, an exceptional number of pavilions featured structures in glued laminated timber (Devos & Floré 2009). The same year, Johannes Mageli, general manager of the Norwegian construction company Moelven Brug visited another "eye-opening" exhibition of building materials in Stockholm. There, upon examining products from Töreboda Träkonstruktioner, he realized that technology of lamination fitted like a "hand in a glove" with both the products and facilities of Moelven Brug (Mageli 1996). Laminated load-bearing elements complimented the already-developed prefabricated products and could be used in schools, gyms, storage and factory buildings. In fact, this Swedish factory whose production inspired Mageli was set up by a Norwegian civil engineer Guttorm Brekke some 40 years prior. By August 1958, a study group financed by Moelven visited several factories in Holland and Belgium to examine the production of engineered timber and to evaluate whether it would be possible to transfer this technology to Norway (Skogstad 2000). The group included Moelven's general manager, the head of local forest cooperative and two representatives from the Norwegian Institute of Wood Technology (NTI). These four individuals represented the main stakeholders in the laminated timber industry: material producers, research institutes, and foreign experts. The agency of all these actors was instrumental in re-establishing glued laminated timber technology in Norway.

This paper examines the network of academic, professional and industrial actors fostered by the Fulbright and European Recovery Plan programs between the United States of America and Norway in the 1950s. In particular, the paper considers how the introduction of this new material in Norway transformed local timber traditions, prompting a reconceptualization of timber from being a "natural" Norwegian material to a "scientific" one controlled through a series of variables. In addition, the paper considers the ways in which the import of the process of lamination was adapted by Moelven Brug to local conditions of labor, technical knowledge and supply of raw materials. The company became the main actor that advanced engineered timber on the Norwegian market, fostered the growth of new regulation bodies and crafted a unique marketing narrative bridging tradition and modernity that persists today.

2 THE OLD-NEW MATERIAL

Although gluing wood has been known for as long as people have used timber, the first contemporary use of lamination was recorded in 1893 in Basel, Switzerland (Johansen & Engan 2001). In 1904, a Weimar firm Otto Hetzer AG patented a glued compound beam and in 1907 a glued laminated arch (Hetzer 1907). Gluing together several layers of wood increased its structural resilience, forming a single roof member and accommodating spans up to 10 meters long. Technology of lamination overcame shortcomings of traditional construction methods, "showing that tradition is not always a blessing" (Brekke 1945). Over time, engineered timber proved more economic and efficient in terms of construction time in comparison with steel:

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it could accommodate large spans, while its structures were light and quick to assemble.

Otto Hetzer held licenses for laminated construction in Germany, Switzerland, and Denmark, but in the post-World War One period he nearly entirely abandoned the technology of gluing in favor of prefabricated connector-built trusses (Brekke 1945). This shift could be largely attributed to the fact that laminated technology made extensive use of a casein-based glue – a derivative of milk products – and with the post-war rationing of milk and complicated economic situation in Germany it was impossible to obtain the necessary amounts of raw ingredients (Brekke 1945; Rhude 1998). Since Norway and Sweden remained neutral throughout World War One, this situation allowed industrial producers to continue experimenting with lamination processes. In the absence of their own steel facilities and with shortages of rolled steel available on the market, glued laminated timber represented an attractive structural alternative.

In Norway, glued laminated timber was introduced by an engineer Guttorm Brekke who studied in Germany with Otto Hetzer and in 1916 at a cost of 60,000 NOK bought a patent for the use of laminated timber constructions in Norway, Sweden, "North Russia south to Vilna" and the United States of America (Brekke 1945). Overall, Brekke's patent rights were exercised only in Norway and Sweden between the years 1917 and 1925. The purchase of the license included a two-month course at the Hetzer AG factory in Weimar and a set of detailed technical instructions for all production aspects, besides the recipe of the glue (Brekke 1945). In 1918, Brekke established a laminated timber company Trækonstruktion A/S in Mysen, outside Oslo, with all equipment and facilities modelled after the Hetzer factory (Brekke 1945). For example, an assembly hall of 60 by 100 feet had plain wooden floors so that curves of glued laminated arches could be drawn on a one-to-one scale. In addition, the factory included large storage and wood conditioning facilities, a dry kiln, and a small steel workshop, along with hoists, monorails and mechanical equipment necessary for assembly. The technology transfer from Germany was so precise that Brekke obtained all equipment – from a special combined mixer and a grinder for manufacture of casein glue to "excellent" screw clamps – directly from Weimar (Brekke 1945).

Glulam elements produced by the company found broad application: from a pavilion for a Nordic-American exhibition in Tivoli in 1919, famous experimental "American" houses at the Norwegian Technical University in 1922 to railway stations in Oslo, Trondheim and Lillestrøm and a Norwegian pavilion at the world exhibition in Rio-de-Janeiro in 1922–3 (Bugge 1922). Among the most popular products were a truss design system adapted for churches, auditoriums and gyms and two- and three-hinged girders. In Norway, these systems found broad application in industrial facilities: for example, a storage building at Meraker Brug, a chemical factory at Sarpsborg and a zinc-rolling mill at Sannesund. In 1919, Brekke opened another company Fribärande Träkonstruktioner AB in Töreboda, Sweden that was the first in Sweden to implement fan-driven kilns that allowed for faster drying. The company worked closely with the expanding national railway agency SJ and delivered train stations and platform buildings including large halls for Stockholm, Malmö and Gothenburg (Figure 1). In addition to railway buildings, the factory produced sports and tennis halls – including the King's tennis hall – theaters, factory and storage facilities with just over 300 structures built in the first couple of years (Brekke 1945).

Figure 1. Fribärande Träkonstruktioner construction for Sundsvall station hall, Sweden.

However, casein glue was not entirely water-resistant and Brekke's glulam structures showed some signs of decay under prolonged exposure to damp and rain – an inherent quality of Scandinavian climate. Slow chemical hydrolysis during exposure to water, biological activity during too high humidity and temperature and mechanical stresses induced by shrinking and swelling caused deterioration of casein glue joints (Brekke 1945). The effectiveness of casein glue was hard to test or improve based on shared experiences, as most of the casein glue recipes remained a concealed business secret. In general, the glulam industry was at a disadvantage in Scandinavia, as the operating costs were high and the products "had not yet gained the confidence of the public" (Brekke 1945). With increased competition from concrete and steel producers that gradually returned to the market in the post-war period, many factories went out of business. With large operating debt and general liquidity problems, the first venture into laminated construction in Norway came to a halt. In 1925 it was decided to discontinue the production at Mysen, and when the factory burned down a year after, it was never rebuilt. Träkonstruktioner in Sweden with its established name and well-developed technology was sold, while Brekke decided to emigrate to the USA.

Although early history of the 20th century glued laminated constructions is well-studied in continental Europe, particularly in Belgium, Switzerland, and Germany, in Scandinavia this history still needs to be written (Devos & Floré 2009; Rinke 2015, 2019; Rinke

& Haddadi 2018, 2020). Virtually no works in Norwegian or Swedish historiography trace proliferation of this new building material. This research thus primarily draws on archival sources that have never been examined before, primarily Brekke's report (Brekke 1945). Guttorm Brekke emigrated to the USA in the late 1920s and worked for the National Bureau of Standards in Washington DC. In 1945, he was commissioned by the Norwegian Industrial Committee in New York to assess possibilities for re-introducing glued laminated timber to post-World War Two Norway (Amdam 2000). Comprising more than 700 pages featuring the early history of lamination, intricacies of Brekke's own venture and assessment of the most recent international research, this 1945 report is a unique first-hand historical account. Largely overlooked by architecture and construction historians, this report ought to provide the foundation in the historiography of engineered timber in Norway.

Guttorm Brekke was a key figure of a pioneering calibre, joining the present and the past: products from his Töreboda factory exhibited in Stockholm in 1958 inspired Mageli to try this technology at Moelven Brug. Brekke's report, in turn, contained valuable technical information, assessed the possibility for re-introducing this technology in Norway and was well known to technical professionals, advising Moelven on the intricacies of production.

3 AN AMERICAN REVIVAL

European in its origins, with advanced testing and research facilities in the USA, glued laminated timber was gradually transformed into a material perceived as "American" (Skjelmerud 1952). Imported to the USA with waves of inter-war European immigration, initially it was adapted to a limited extent before World War Two. Max S. Hanisch – a German émigré and another student of Otto Hetzer – was among the pioneers of glulam in the USA. In 1934, Hanisch founded Unit Structures Inc. and completed the first building from laminated wooden elements in the US – Peshtigo High School gymnasium (Fischetti & McNall 1995). Initially, innovative timber constructions were not approved by the Wisconsin Industrial Commission and Hanisch sought assistance from the USDA-Forest Products Laboratory (FPL) in Madison, Wisconsin. Although not familiar with the glulam elements before, FPL became the first institution to experiment with glued laminated timber in the USA. In 1934, a joint research program was started between the laminating plant of Unit Structures at the FPL (Rhude 1998).

While in Europe the main driver for lamination was shortage of other structural materials, in the United States the technology primarily took off as a way to utilize around 300 million acres of new forests. Research of the Forest Product Laboratory thus also aligned with the strategy of finding new markets for existing forest resources (FPL 1938). FPL studied mechanical properties of wood in tension, bending and compression, degrees of shear, toughness and rigidity (Brekke 1945). These stress tests provided accurate knowledge of timber performance, helped to avoid the "irrational" use of materials and defined the discrepancy between different wood species – a factor never accounted for before (FPL 1938). Most importantly, however, FPL enhanced and developed new resin glues that came from Europe and were used in the aircraft industry. New added catalysts made low-temperature setting resin glues possible to apply to thicker laminated elements, thus simplifying the lamination process and making structures more durable. The findings of the laboratory on new water-resistant glues were published "with typical American grandeur" and patented for the benefit of the people, in stark contrast to the "atmosphere of secrecy which has been customary in Europe" (Brekke 1945).

The laboratory experimented with new adhesives and technological details of the lamination process, recording results of these studies in exhausting tabulations of parameters and numerical values, graphs and force diagrams (Brekke 1945). Similarly to the way Michael Osman argues that concrete had been transformed from a material of "liquid stone" derived from natural components to a material of analytical control and managerial organization, it is possible to argue that laboratory experiments with new lamination processes transformed timber from a "natural" to a "scientific" material whose structural qualities and production process could be meticulously controlled and adjusted through a series of parametric variables (Osman 2012). Further, American research on synthetic resin adhesives, glue solvents and catalysts, fire retardants and chemical seasoning significantly improved the technological process of lamination and made engineered timber competitive with other post-war construction materials.

Knowledge exchange between Europe and the Unites States went both ways. As glued laminated timber was a novelty in the Unites States, American specialists visited European structures to study their structural qualities and performance. For example, in the summer of 1936, Mr T.R.C. Wilson, Senior Engineer of the FPL inspected around 50 glued laminated structures in Norway, Sweden, Denmark, Germany and Switzerland. In particular, Wilson visited one of the train platform cover structures built by Brekke in Trondheim in 1921, and later wrote that "[it] is in excellent condition as are structures in Sweden and Switzerland" (Brekke 1945). This served as proof that although European specialists were concerned with the waterproof qualities of the glue used for lamination, in fact these structures showed little signs of wear, "a proof which time only could provide" (Brekke 1945).

Thus, although European in its origins, the technology of lamination was significantly updated with state-of-the-art American research that challenged the role of timber as a "natural" material and enhanced it with non-traditional qualities, like resistance against fire, fungi and decay. While research on engineered timber was transferred to the USA with waves of European immigration, the technology was developed and returned to the continent with enhanced qualities, most importantly, waterproof resin adhesives.

4 INDUSTRIAL-ACADEMIC RESEARCH

In the years following World War Two Norwegian businesses fostered close academic and industrial ties with the USA, particularly through projects financed by the Technical Assistance and Productivity program (also known as the Marshall Plan). From singular actors to entire educational institutions, the latest research in construction technology and particularly glued laminated timber was transferred back to Norway. Norsk Treteknisk Insitittutt (NTI) – the Norwegian Institute of Wood Technology – was established in March 1949, largely following the example set by the Forest Products Laboratory.

To compensate for intellectual isolation during the Second World War the institute immediately ordered a substantial timber research library from the USA with generous financial support offered by Marshall Aid (Skogstad 2000). The institute's leader – engineer Halvor Skjelmerud – spent a year in the USA "educating himself about different aspects of wood technology and developing contacts," while NTI established a bilateral research collaboration with FPL (Skjelmerud 1952). Starting from 1955, many Fulbright scholars associated with NTI went to the USA, boosting the Norwegian-American knowledge exchange (Skogstad 2000). In 1957, FPL specialist Magnus L. Selbo – a key scholar in the field of lamination in the USA – came to NTI as part of a professional exchange program and authored a report on lamination of structural members together with Norwegian Ole Grønvold (FPL 1958). Engineer Hvamb went for a year's study in the US and came back with an impression that the laminated industry was the only one working at full capacity in the shrinking timber market, concluding that lamination harbored a lot of potential for Norway (Skjelmerud 1958). In turn, Brekke's report with its extensive technical research was well-known to the Institute's specialists.

In this way during the years after World War Two research on glued laminated timber made its way back to Norway both through the practice of individual actors – such as Brekke – and large scale international academic exchange, facilitated by Marshall aid. The Norwegian Institute of Wood Technology was the first body in the country to conduct comprehensive research on glulam, testing material properties of different timber species, water-resistant adhesives and drying technologies. Research findings were assembled in a vast technical library of reports, available for any private company to consult (Skogstad 2000). Managers of Moelven Brug – upon considering a venture into glued laminated timber – contacted NTI for consultation, and developed a close relationship with the Institute from the very beginning.

Halvor Skjelmerud – NTI's leader – was very enthusiastic about Moelven's venture and offered technical and information support. According to Skjelmerud, "it [was] not clear to [NTI] what the reservations about the introduction of [lamination technology] could be," as there were "no special Norwegian circumstances" that would hinder the development of this technology in Norway. However, "technical conservatism" of the Norwegian construction branch could be hard to overcome, warned Skjelmerud (Skjelmerud 1952). Two Institute representatives – Karl Mørkved and Eirik Raknes – were part of a Moelven study trip in 1958 that went abroad to study factories in Holland and Belgium that worked with laminated technology. Johannes Moe – a civil engineer from NTI who specialized in concrete constructions in the US – assisted Laminator with the research on the dimensioning for laminated constructions and, according to Mageli, provided "invaluable assistance in the problematic starting period" (Mageli 1996). The Institute's engineers, in fact, were instrumental in making Moelven laminated load-bearing structural members efficient and economic.

NTI was not the only research institution that Moelven developed close connections with. The company also sought advice from Hans Granum – a civil engineer, the head of the construction technology at the architecture department at NTH and the main specialist on modern timber structures in Norway. Granum suggested that laminated beams would be particularly suitable for typologies where the load-bearing constructions had to be visible and that aesthetics of laminated beams would be of a particular interest for architects (Granum 1958). Among the greatest advantages Granum identified "beautiful, concentrated form and significant height," concluding that laminated constructions would be particularly suitable in "more modern architecture where clear material effects and simple forms are sought after" (Granum 1958). In addition, he also pointed out that laminated beams could be used for agricultural barns with an overall market of about 1,5 million NOK – an important typology for the Norwegian economy that strove to modernize its agriculture. In this way upon seeking to implement the new technology of lamination, Moelven Brug fostered close industrial-academic ties with various institutions and research actors.

Besides seeking advice from academic researchers, Moelven managers were also interested in industrial experience with lamination: they studied technical processes at factories throughout Europe and the United States and fostered new business connections. However, not all experience could be applied to the Norwegian context: during visits to Nemaho facility in Holland, despite a seemingly amicable agreement with factory administration, Norwegian representatives only got a glimpse of raw material storage and some ready-made constructions without getting any specific information about the technology, equipment or production process (Mageli 1996). Swedish factories of Töreboda seemed old and technically outdated, as their equipment remained unchanged since the times of Brekke (Mageli 1996). Moelven American partners – Rilco products, the largest glulam producer in the USA – were supposed to supply Norwegian partners with technical data and calculations but this ambitious venture proved to be of little use (Mageli 1959). With its costly machinery, the technological process abroad had little application to Norwegian realities. While cutting-edge equipment could have been bought in the United States, Moelven Brug was short on cash, could not afford expensive equipment and thus had to engage in-house mechanical engineers to develop necessary machinery, like a new hydraulic press (Mageli 1996).

In this way although the lamination technology was perceived as one imported from abroad and despite extensive efforts to gather international industrial experience, in reality, little technical knowledge was transferred directly. Thus, "foreign" technology had to be adapted to available material and financial resources, local labor market and the conditions of the Norwegian building industry.

5 LOCAL APPLICATION

As Moelven established a subsidiary company Laminator A/S that specialized in load-bearing structures built with glued laminated timber, the production was strongly dependent on the local supply of raw materials. In the late 1950s, Hedmark and Oppland – two regions where the company was located – had the lowest timber prices in the country and the best-quality pine forest, making it easy for the company to access raw timber from a well-developed network of local sawmills at a low price (Vevstad 1994). The price difference for raw materials between Moelven's native municipality and other regions was so significant that it offset additional transportation costs required to deliver ready-made products to Oslo and its vicinity, fostering a close connection between the industry and its locality (Mageli 1958).

To ensure uninterrupted access to high-quality timber, Laminator was established as a shared enterprise with Ringsaker Almenning – a local forest cooperative that supplied all raw materials and pine elements used for lamination and had modern drying facilities. The lamination process in turn had to be adjusted to the physical properties of the local spruce and pine found in Ringsaker forests (Bovim & Sund 1977). In addition, Moelven's new factory had a formative effect on the local social fabric as it provided jobs for workers left unemployed by the increasing mechanization of Norwegian forestry and agriculture. As the process of lamination required a particular skill-set, the company considered the uneducated population an advantage, as new employees could be taught necessary skills quicker (Lindberget 1963). In this way, the technology of lamination was not just imported, but also adapted to the availability of local materials and labor.

"Laminated wood constructions from Moelven used for barns as well as churches" – opened one of the articles on Laminator products from 1960 (Ringsaker Blad 1960). And indeed, they were: load-bearing glulam beams had broad applications in typical Norwegian architecture of the everyday. The company delivered cheap, efficient and reliable structures that fulfilled their purpose at minimal cost. Laminator produced elements for schools, barns, churches, sports halls, storage buildings, hangars and airports – any typology that required large spans (Figure 2).

Figure 2. Moelven laminated timber advertisement.

Curiously, churches became one of the more peculiar buildings designed by the company. The first church in the country to be built with laminated timber was Jar Kirke in Bærum in 1959. The company delivered 23 straight 17-meter-long beams for the church's load-bearing roof constructions (Hamar Arveiderblad 1959). The following year, a chapel was built in Østfold, another church in Søre Ål in 1963, chapels in Ramsund and Borge in 1964 and a Storhamar church in 1971. By the 1970s, the company developed a typological solution for a modern Norwegian church that relied on laminated load-bearing constructions and walls built from large prefabricated elements (Sveen 1975). Moelven's prefabricated solution offered a possibility to obtain a representative structure at a low price.

Throughout the 1960s, Laminator was actively marketing the use of laminated timber in religious buildings, referring to the updated tradition of stave churches: "modern church architecture uses wood, which is both strong and decorative," while Laminator beams could be used for all structures "whenever the construction is visible" (Ringsaker Blad 1960). Exposed glulam beams offered a pragmatic but representative solution for an important element of Norwegian everyday life and drew parallels with the centuries-long tradition of wooden churches. Thus, Laminator elements provided an opportunity for new architectural expression, merging a traditional material with new technology, marketed particularly to architects and design professionals. For example, Norwegian famous architect Sverre Fehn used Moelven laminated timber beams in his famous Cathedral Museum of Hedmark (Domkirkeodden, Hamar 1988). The company extensively used the fact that Moelven beams made their way into signature architecture in their advertisements throughout the 1970s (Dalseg-Ervaco 1976).

In addition, "foreign" technology was ready to be domesticated for the local needs of the pragmatic welfare state. Many of Laminator's clients were large state and municipal actors, as the company worked on extending its connections within the state apparatus. Laminated timber beams were particularly suitable for sports halls, and became popular when provision of sports infrastructure became one of the priorities of Norwegian education. Rational and pragmatic, built with unusual shapes and the exposed materiality of wood, these sports halls soon became local landmarks. The first gym in laminated timber was finished in 1962 at Persbråten school with arches that spanned 40 meters (Hamar Arbeiderblad 1962). Another significant commission was Askerhallen – by then, the largest covered ice-stadium in the country with a ground plate of 105 by 51 meters, the fourth indoor ice-hockey rink ever built in Norway and the first in the Oslo area. Designed by a Fredrikstad architect Aksel Fronth, all timber elements were delivered by Laminator.

As with churches, Laminator developed a standardized typological solution and "Moelven-halls" were delivered all over the country – "from Karasjok in the north to Egersund in the south". They were fast to erect and cheap in comparison with facilities built using traditional methods. Typology of sports halls – similar to churches – combined utility and representation, while the use of laminated timber offered to bridge structural engineering and architectural work. In this way, by 1967 laminated timber became one of the most sought-after construction materials, while laminated timber structures became an increasingly common sight within representative buildings of everyday Norwegian life (Ringsaker Blad 1967). This development was likely a result of Moelven's successful marketing narrative that balanced claims of rationality of construction and expressive architectonic effects, efficiency and aesthetics, technology and tradition (Figure 3).

The story of updated tradition crafted for architects and design professionals culminated in the competition for the Lillehammer Olympics in 1994. After Moelven Brug won the commission and built three large Olympic stadiums in laminated wood, Moelven glulam products became intertwined with ideas of "contemporary Norwegian building style" that merged the wooden tradition and new technology. It was precisely this narrative recognized abroad that was key in Moelven receiving a commission for the new international Gardermoen airport in Oslo.

6 CONCLUSION

Re-introduction of glued laminated timber to the Norwegian construction market in the post-1945 period involved a wide range of actors: from industrial producers and academic researchers to foreign experts and marketing managers. A traditional Norwegian resource, timber was transformed from a "natural" material into a "scientific" one enhanced with new structural and material properties and strengthened by synthetic adhesives. Moelven Brug was a key actor in bringing the technology of glulam back to Norway, actively building academic and industrial connections locally and internationally. Although perceived as borrowed from abroad, international experience with lamination had to be adapted to Norwegian material and labor conditions. Incorporated into significant representative typologies, such as churches, glued laminated timber proved to be ambiguous in terms of the cultural interpretations attributed to it. Moelven managed to harness those interpretations to introduce structural timber into a wide variety of representative building structures across the country, making laminated timber synonymous with a "new Norwegian building style" (Karlsen 1999). An elusive bridge between tradition and modernity offered to a professional audience was a curious marketing by-product that fed into a myth of an industrialized timber tradition that flourishes until today.

As engineered timber was making its way to the Norwegian construction market, new regulation bodies overseeing the material quality and implementation had to be established. In 1962, Moelven Brug initiated a foundation of Lamineringsutvalg – a self-assessment organization of laminate producers, public officials and researchers with a goal to assure compliance within the new industry. This oversight body became international in 1965 as Limtre Norden gathered similar actors from Sweden, Denmark and Finland. By the late 1970s as Moelven grew into a large group of companies, Moelven Limtre – a new name for Laminator A/S – bought most competitors not just within Norway, but also Scandinavia (Mageli 1996). Among them was Fribärande Träkonstruktioner AB – a former Brekke company in Sweden and one whose products inspired Mageli to venture into laminated technology. In this way the historical loop was closed: today, Moelven Limtre positions itself as a direct descendant of Brekke's venture and retrospectively claims the design of all train station projects undertaken by Fribärande Träkonstruktioner (Brandt 2019). Moelven Brug was not just the main actor who brought laminated timber back to Norway, but also one who eventually completely shaped the market and defined implementation of this technology in the north.

This paper out to map the main actors involved in the establishment of the glued laminated industry

Figure 3. Moelven laminated timber advertisement.

in Norway, although its limited scope does not allow giving justice to all figures involved. While the 20th century history of lamination technology in Scandinavia remains to be written, this paper makes the first step toward uncovering this fascinating international exchange of ideas.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The SEAT Dining Hall in Barcelona (1956): Aeronautical construction applied to architecture

D. Resano
Universidad de Piura, Piura, Peru

C. Martín-Gómez
Universidad de Navarra, Pamplona, Spain

ABSTRACT: In 1957 a Spanish building finished two years earlier received the Reynolds Memorial Award. A jury consisting of Ludwig Mies van der Rohe or Willem Dudok highlights the use of aluminium in this building, choosing it from among 85 applicants from around the world. How was this possible in a country that still used mostly traditional construction techniques? José Ortiz Echaugüe, president of CASA aeronautics and SEAT automotive, provided the means for his son and architect César to lead a pioneering interdisciplinary collaboration between engineers and architects. To lighten the building, because of the low resistance of the terrain, aluminium construction technology was integrated into the architectural design. To provide thermal comfort, innovative solar radiation devices, and air conditioning services were developed based upon systems employed in airplanes and cars. We address this pioneering technology transfer process between aeronautics and architecture in the SEAT Dining Hall (1956).

1 INTRODUCTION

The SEAT Dining Hall (Barcelona, 1956) was the work of three young Spanish architects: Manuel Barbero Rebolledo, Rafael de la Joya Castro and César Ortiz-Echagüe Rubio.

This building was the winner of the Reynolds Memorial Award in 1957, chosen from among 85 other works presented from around the world. This prize recognized the quality of aluminium solutions integrated into the project. In the SEAT Dining Hall, the implementation of this material was due to the need to lighten the structure to avoid an expensive deep foundation system, given the low resistance of the terrain. But the use of aluminium went far beyond a mere technical solution, triggering a collaboration between engineers and architects that led to an innovative result.

The main objective of this paper is to deepen understanding of the process of technological transfer from the aeronautical construction industry to civil construction. For this, two fundamental sources of information are analyzed: the graphic and written documentation of the original project, located in the Historical Archive of the University of Navarra (Archivo Histórico ETSAUN, Universidad de Navarra), and references made to the building by its own authors and other historical studies. From these sources, a historical-critical discourse is built, focused on three fundamental points.

First, the close collaboration between the engineers of the CASA aeronautical company and the architects in charge of the project. This was possible because CASA was a subsidiary of the SEAT automobile company at the time.

Second, the innovative use of aluminium. Several components of the building were designed based on “pantal”, a Spanish commercial version of Duralumin, according to the UNE 38.3344 standard. These elements were: the structural trusses, adjustable slats for the façade and corrugated roofing sheets.

Third, the hygrothermal conditioning system of the building, also developed by CASA and SEAT engineers as if it were an aircraft’s ventilation system.

These three points have as a common factor the idea of constructing a building applying technology that at the time belonged to the aeronautical industry. In addition to studying the constructive and technical solutions of the building itself, we will briefly put them in the historical context of aluminium construction and air conditioning systems of that time. It is worth reviewing the technical contributions of this well-known Spanish building to the history of construction in the international forum of this congress.

2 THE BEGINNING OF COLLABORATION BETWEEN CASA’S ENGINEERS AND THE ARCHITECTS

José Ortiz-Echagüe (1886–1980) is the first key element to understand how the architects and engineers

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collaborated in this project. A pilot military engineer and Spanish photographer, he was also the founder and president of two relevant Spanish companies: the aeronautical CASA (Construcciones Aeronáuticas Sociedad Anónima, 1923) and the automobile firm SEAT (Sociedad Española de Automobiles de Turismo, 1950).

The second key element that gives meaning to this project is his son, the architect César Ortiz-Echagüe (1927-), who was commissioned by his father for the Dining Hall two years after graduating, when he was only 27. César had proved his worth as an architecture student by winning an award from the Academy of Fine Arts. He also had the experience of collaborating with the architect Miguel Fisac during his university studies, from 1949 to 1952. He had every hope of starting his career as an architect, so as soon as he graduated, he asked his father for work, who replied in the following terms:

> "'Look, you have just finished your studies, you know nothing; I have to manage the money from the banks and the National Institute of Industry, and I have to entrust the projects to prestigious architects who know what they're doing. In other words, find yourself a job, and in a few years, if you do something decent, then we'll see.' […] My father allowed me to use a small workplace which he wasn't using in the offices of Construcciones Aeronáuticas (CASA) and, by myself and rent-free, I started to draw and accept the orders he gave. […] Towards the end of 1954, he said: 'Look, we're going to build Dining Halls for the workers in Barcelona, in the factory which was already in full production. It's a small job, but anyway, it's a bit beyond you, so find yourself a couple of colleagues and let's see if you can do a pretty project and make it turn out well.' And so they gave me the project for the SEAT Dining Halls in the Free Trade Zone in Barcelona" (Ortiz-Echagüe 2000).

César took note of his father's advice and formed a team to undertake this project, surrounding himself not only with more experienced architects, but also taking advantage of the support of CASA engineers, with whom he shared the same office building. Thus, he contacted his brother-in-law, the architect Manuel Barbero Rebolledo, who, together with his partner Rafael de la Joya Castro, formed the group of three architects in charge of the design. Moreover, the team was completed with structural engineer R. Valle i H. Herrera (CASA) and facilities engineer Pedro Roca (SEAT) (Figure 1).

Figure 1. General view from the access. Archivo Histórico ETSAUN. (Historic Archive of the School of Architecture of the University of Navarre).

That is how César gathered an interdisciplinary team, which triggered the technology transfer from CASA's aircraft building experience to civil construction. This case of architectural design applied to an industrial building was similar to the Figini and Pollini relationship with the Olivetti factory in Italy. This interdisciplinary work for an industrial project such as SEAT Dining Hall resulted in one of the most cutting-edge examples of modern architecture in Spain, ultimately recognized as one of the most advanced in the use of aluminium worldwide.

The architectural design was led by César Ortiz-Echagüe, who explained how he suggested the original idea for their Dining Halls:

> "When we began to work together, I had already developed some sketches, accepted to become the final layout. […] The details of the project were developed in Ortiz-Echagüe's studio, located in the CASA building at 4 Rey Francisco Street, which meant that Barbero and De la Joya had to agree on sharing tasks. Thus, while the former worked hand-in-hand with Ortiz-Echagüe, the latter could not be so close, as he had to attend to the management of his studio, where he was carrying out important projects for the American military bases which were beginning to be installed in Spain."

The building consists of a group of five pavilions, connected externally by a canopy and internally by a corridor that articulates them with the kitchen area. This grouping intersperses pavilions and gardens, interconnected by glazed openings in the southeast orientation and closed through brick walls in the northwest. This comb-shaped layout breaks in one of its extremes to house the engineering canteen pavilion and the reception area, which are thus separated from the rest of the workers and open onto a private patio facing south. Typologically the scheme is clear, structurally too. A glance at the floor plan of the building is enough to appreciate the importance of modulation at 2.5m, which extends to the structure and interior distribution. César Ortiz-Echagüe justifies this organization as follows:

> "It was quite clear to me that we had to try to construct extremely transparent halls, with a garden surrounding them. The assembly line work in the automobile industry is boring and monotonous, so the initial idea was that, at least during the one hour when the workers were

> free at lunchtime, they would have a completely different environment, with flowers, water, and trees, because in this area, with Catalonia's good climate, it is easy to build beautiful gardens quickly. […] We drew up the project with five pavilions, three for workers, two for office staff, and another for the engineers; society was still somewhat class-conscious at that time. From the beginning, we aimed for very transparent buildings and thus a metallic structure" (Ortiz-Echagüe 2001).

Therefore, the architectural idea of transparency and lightness became one of the main objectives of the design. This thought led to the use of a metallic loadbearing structure. Although the usual at that time would have been employing steel, it ended up being aluminium-made. It was then a rare material in civil construction but typical in the transportation industry. Direct collaboration between architects and CASA aeronautical engineers (also responsible for the integration of the air conditioning system in the dining rooms) made it technically possible. But the ultimate reason to build with aluminium arose from the following issue:

> "We calculated the structure, and when the moment came to calculate the foundations, we had to accept the advice of the SEAT engineers who had participated in the construction of the whole factory, and they told us that, even for such lightweights, we would have to use piling in the foundations; we calculated the price, and it turned out that the foundations cost almost as much as the rest of the building. One day I was talking about this to my father, and he casually said: 'Why don't you try with aluminium (which CASA company used widely for aircraft manufacture); aluminium is ten times more expensive than steel, but maybe you can make up for that with what you save on foundations, and what is more, it is naturally very resistant to corrosion and would withstand extremely well the maritime climate where the factory is located'. […] Of course, we decided on aluminium: the fact that I was working in the same building as Construcciones Aeronáuticas (CASA) made it much easier to collaborate with the engineers. […] We drew up a project which was very work-intensive for us because there was nothing like this in Spain, and we could find nothing in the journals about construction in aluminium. We had to invent everything, and this was a great advantage because there was nothing conventional in the building, so every detail had to be studied, and this made the whole thing very interesting" (Ortiz-Echagüe 2001).

The previous quotation illustrates the attitude of architects and engineers when facing the design of a building and the process leading to the final result. The detailed definition of an-almost-modular and -almost-dry construction system, which was typical of the automobile and aeronautical industry, contributed to a swift raising of the building.

Figure 2. View from the interior of one hall towards the courtyard. Archivo Histórico ETSAUN.

A quote taken from the Spanish car market illustrates the technical situation in those years. Ricart was one of the great Spanish car body makers at the time, who designed the model Spider Serra in 1951 (Figure 2).

Asked about how such a high-class car could be built in Spain in the 1950s, he said: "We are a poor country that produces jewelry for rich countries …" (VVAA. *Industrial Design in Spain* 1998, 170).

Next, we explain the main points of the technology transfer from engineering to architecture in the SEAT Dining Hall, both from the side of construction and services.

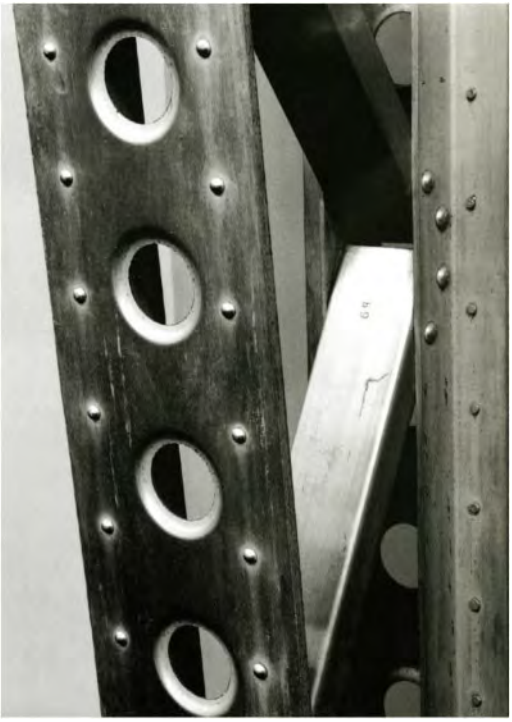

Figure 3. Detail of the main frame profiles and rivets. Archivo Histórico ETSAUN.

3 TECHNOLOGICAL TRANSFER FROM AERONAUTIC TO CIVIL CONSTRUCTION

Technology transfer from aerospace engineering to civil construction in the SEAT Dining Hall focused fundamentally on two main fields: first, the application of patents related to the material and the joining methods used in the construction of airplanes; second, the adaptation of some aircraft typical elements, such as the fuselage systems to the structure and the wings to solar protection elements. However, there were limitations to this transfer related to vertical enclosures and carpentry. Below, we develop these points.

3.1 *Material, profiles, and joints*

The three times lower density of aluminium compared to steel justified its use in the transport, automobile, and aeronautical industries, given the savings in fuel (Figure 3).

But its mechanical resistance three times lower meant a limitation for being used structurally. The Duralumin patent solved this inconvenience. Carried out by Alfred Wilm in 1910, it is an alloy heat-treated with magnesium and copper that increased the tensile strength of aluminium, achieving strength values close to those of steel (40–4KP/mm^2). This invention considerably improved the construction of airships in the first quarter of the 20th century. By 1936 airplanes were manufactured entirely in aluminium, a material that continues to be fundamental in aeronautical construction to this day. This patent was also essential to the development of civil construction with aluminium (Figure 4).

Figure 4. The flying boat or seaplane Dornier Do J Wal. From: Bundesarchiv, Bild 102-00857, ca. 1926.

Duralumin also improved corrosion resistance, which is why it was fundamental for seaplane manufacture. In 1926 CASA obtained a license to manufacture the Dornier Do J Wal seaplane, of which it produced 31 units at its factory in Cádiz. For its construction, they used a Spanish commercial version of “Duralumin” known as “Pantal”, as detailed in the UNE 38.3344 standard. CASA engineers proposed Pantal for the design of the SEAT Dining Hall. Besides, the profiles used to build this structure are the same that CASA used to design its airplanes, such as the Alcotán (C-201) and Halcón (C-202) models, which remained only in prototypes, and the already built twin-engine transport plane Azor (C-207).

3.2 *Structural and enclosure elements*

In addition to material and profiles, it was also necessary to develop the joining systems to withstand the stresses of the building. Aluminium can only be welded oxygen-free, due to its high oxidation. This process complicated and made welding assembly more expensive, so they opted for the same system used in aircraft construction, the rivet. Using pneumatic riveting machines, two flat elements were joined from one side very quickly, resulting in a non-reversible joint. There were alternative systems that allowed the reversibility of the joint, such as screws, but they were unnecessary since reversibility was not a requirement for a permanent structure (Figure 5).

The rivet was the best technical solution, and the architects explored its aesthetics, leaving the joints visible, just as in the joints between sheets of airplanes. Rivet employed as an aesthetical motif was one of the characteristic features of the structure, left exposed to the interior space of the Dining Hall. This decision valued the aesthetic of the construction technique. In a sense, it aligns with the trend of constructive sincerity as a design criterion, which was a motto since the beginning of modernity (Resano 2012). It also

Figure 5. Riveting in progress. Image: 1956, *Informes de la Construcción* 79, 139–45.

recalls what was explored years before by Otto Wagner in Vienna, who experimented with aluminium in the façade of the Die Zeit News Agency (1902) and developed a system for fixing the marble cladding of the Vienna Postal Box façade, where aluminium anchors are exposed (Rodríguez Cheda 2006).

Mainframes made by riveted Pantal structural elements are 12.8m span and connected with purlins every 5m. In a sense, the structure is a monocoque-type aircraft fuselage, with porticoed trusses forming perimetral framed ribs and the brick side walls functioning as a bulkhead.

The engineers aimed for the precision of the design of the structure. As was usual in the aeronautical industry, the plans were precise to the nearest millimeter and, significantly, a note emphasizing these tight tolerances appeared on all the detailed structural and construction drawings (Sepulcre 2004): "Important notes: 1) redesigning will be done with great precision, 2) the levels are all expressed in millimeters, 3) all measurements must have great accuracy."

In these plans, every detail drawing had high definition and clarity, just like the building projects for the North American bases in Spain, which were handled by the studio of Barbero and De la Joya at that time. All these demands implied a rigorous way of working, first in their studio and later on the building site, which was well beyond what was then usual in Spain. Such a high level of precision is usually unnecessary in the construction of a metal building, which can allow a tolerance of almost one centimeter, but demonstrates how precise the conception of the structure of the Dining Hall was. This systematic precision established modular construction as a rule and takes profit of riveted joints as a motive. As if it were an aircraft, the structure was designed and prefabricated in Madrid and later assembled on site in Barcelona.

Figure 6. SEAT Dining Hall. Roof over the entrance hall comprising corrugated aluminium supported by aluminium I-beams. Archivo Histórico ETSAUN.

The resulting weight of the structure was 41.2tm, which for the 4000m^2 of the building gives an average of 10.3Kg/m^2 (Figures 2, 4, 6). Thus, it was possible to distribute the weight through a surface foundation within the admissible pressure of the ground. A priori it might seem that building with aluminium to save on the foundation could be as much or more expensive than building traditionally and investing in a piling solution. And possibly this would have been without CASA know-how on aluminium. This collaboration between CASA's aeronautical engineers and the architect team was a turning point to undertake the construction with aluminum elements. This was groundbreaking for 1956 and would continue to be today (Figure 6).

In addition to the structure, other enclosure elements such as the corrugated roof sheets and the solar protection system were also aluminium made. The latter was necessary for building solar protection, reducing unwanted thermal loads in hot weather, and allowing heat supply in cold weather. This movable slat system is of some interest, insofar as the slats take advantage of the constructive systems of aircraft wings (Figure 7).

César Ortiz-Echagüe describes the considerations regarding sun protection in dining rooms as follows:

> "The aluminium-made brise soleils, aimed for protection against the sun, are interestingly designed for movement, according to aeronautical techniques and systems used in aircraft. […] If we had had money, we would have installed photoelectrical cells to change their orientation, but we couldn't go so far. But anyway, a simple button was enough to modify the slats according to their orientation, which were vertical on

Figure 7. Louvres on the south façade of the dining hall. Archivo Histórico ETSAUN.

Figure 8. Dining Hall view (2006). Photo. César Martín-Gómez.

> some façades and horizontal on others, and so, they pleasantly light the interior. There was one pavilion which faced north and did not need protection from the sun" (Ortiz-Echagüe 2001).

In a display of technological sophistication for the moment, these brise soleils (measuring 2.8 x 0.34m) rotated powered by the same engines that aircraft use to move their ailerons. These same brise soleils were later patented and marketed by CASA. As a result of this collaboration, the company created a small section of aluminium elements for construction. The placement of the mobile slats and the canopy is estimated to reduce the solar radiation that enters the dining rooms by 70%, allowing solar radiation access on the coldest days.

3.3 *Limitations on technology transfer*

At the time the Dining Hall was being built, there were already pioneering examples of buildings made entirely of aluminium: such as the Dymaxion house patented by Buckminster Fuller in 1941 and the Aluminium Centenary Pavilion, designed by Jean Prouvé and built in Paris in 1954 (Rodríguez Cheda 2006). However, the enclosure panels and carpentry were still systems that were to be developed industrially at that time, and they were considered unnecessary in the Dining Hall since by lightening the structure the resultant weight was enough (Resano 2012) (Figure 8).

Thus, brick enclosures and steel glazed frames are conventional construction systems. Until the late 1950s, the use of steel joinery was usual (Lever House 1952; Seagram 1958). It would be at the end of this decade when aluminium joinery began to develop.

Brick enclosures and steel joinery are weight systems compared to the aluminium structure. Nevertheless, there is no spatial or quality impairment. These traditional building systems are simply indicators of the state of technology at that time. In fact, for the architects, this material duality enriched the project: "Aluminium: lightness and modernity. Brick: enclosure and tradition" (Ortiz-Exchange et al. 1956).

4 INNOVATIONS IN VENTILATION AND AIR CONDITIONING SYSTEMS

At that time, in the words of the engineer José de Benito in 1954 (De Benito 1992), "in Spain, to be a heating technician, all you need is to know how to handle the *Roca* catalog and have a table or abacus to calculate pipes. Someone managed the *Aurrerá* catalog and even *Strebel, Ideal Classic,* or some other from a brand that did not come after 1936, but this was the exception. The cast-iron *Roca* boilers ranged from the famous single series zero and double zero boilers to the tremendous ones of the 7th series that could exceed one million kcal/h of nominal power. *Aurrerá* did not make them, neither so small nor so big, they were heavier and, by eye, or worse performance. I say 'by eye' because no one in the union ever thought of talking about performance."

Regarding urban facilities (De Benito 1992), "some services worked with superheated water, those from the […] 1930s and *Fasa* in Valladolid that M. Corcho installed in 1953 with a mixture preparation and superheated steam-water designed by Carrier-Paris. Towards the year 1956, the Labor Universities of Seville and Córdoba decided to install superheated water with boilers with 'internal natural circulation'. None of us initially had any idea what that was."

This technical panorama contextualizes the words that follow on the integration of the air conditioning installations of the SEAT Dining Hall in Barcelona (Figure 9).

CASA's engineers and SEAT's engineer Pedro Roca shared the responsibility for the facilities services system design. Aeronautic engineers had to adapt their work on airplanes (with reduced spaces, precise adjustments in calculations) to the scale of a building. The automobile engineer was responsible for transmitting the thermal needs of the dining rooms to the CASA engineers (Conversation with Mr César Ortiz-Echagüe. ETSAUN, Pamplona, 7 June 2007).

The backbone for the design of the services for the Dining Halls is an underground chamber which, on the one hand, joined the Dining Halls to the installations

Figure 9. The main impulsion line is carried out on the façade that receives the sunlight, and the return is on the opposite wall, through grilles located in the lower part. Photo. César Martín-Gómez.

Figure 10. Maqueta realizada por I. Isla, X. Leoz, I. Medina y D. Santamaría dentro de la asignatura de 'Diseño de Instalaciones' de la ETSAUN (curso 2007–2008). Phot. César Martín-Gómez.

of the main SEAT complex and, on the other, is the technical area which fed the pavilions above (Martín-Gómez & Resano 2015).

The kitchens of these dining rooms are somehow the most important internal part of the building program. They are necessary to prepare the food, but they stand out for their functional clarity and good service. That is the reason why they keep their same original layout until now (According to the SEAT maintenance technician, even some of the appliances used for cooking in 2006 are original).

Regarding thermal comfort, five air-handling (AHU) units located in the gallery provide air conditioning. Clean air comes to the AHUs from several air intakes in the gallery, and a direct outlet released stale air to the gardens (Martín-Gomez 2009).

Today, the return of the air remains through the original low grilles. Some additional impulsion grilles installation occurred due to façade duct deterioration because of partial loss of their air passage section, which was the result of aging of the materials that make up the ducts. (Thus, remnants of the original fiber insulation of the ducts appear in the micro nozzles) (Figure 10).

THE R.S.REYNOLDS
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For the outstanding contribution
in aesthetic and structural use
of aluminum in architecture

Por la más notable contribución
al uso estético y estructural del
aluminio en la arquitectura

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Figure 11. Reynolds Award Commemorative Plaque installed in the SEAT Dining Hall. Archivo Histórico ETSAUN.

5 CONCLUSIONS

Betting on aluminium to solve the structure dilemma of a building in a construction context is still dependent on traditional techniques, as was the case in Spain in the 1950s; it was a risky move. The international recognition the SEAT Dining Hall received at the 1957 Reynolds Prize confirms its success.

Related to the air conditioning installations, the imperfections observed in a more than half a century old installation should not cloud the advances it proposes. The air conditioning installations were a relatively new innovation for a building at that time and added greater complexity and richness to the constructive development of the Dining Hall.

To delve into the air conditioning systems and other technical details, we refer readers to our broader study published on this building (Martín-Gómez & Resano 2015) and other general studies about this building, cited in the bibliography. What distinguishes this text from the others mentioned above is that it focuses on the technology transfer process from engineering to architecture. As we have explained through the paper, this was a pioneering and exemplary case for the Spanish 50s, and it could also be so today (Figure 11).

The fruits of this collaboration between architects and aeronautical engineers were not because of theoretical reflections or abstract considerations on the technological progress of architecture. Undoubtedly, like other architectural milestones, it was the result of solving a practical need, oriented to achieve clear objectives by optimizing the available resources. That was the main reason for employing aluminium and innovating in air conditioning and ventilation systems.

Moreover, it is also necessary to stress the relevance of the José and César Ortiz exchange for the success of this venture. The first as a client, incentivizing and facilitating this innovative process. The second, as leader of the designing team, integrating all members and taking advantage of the technical difficulties to improve the architectural project. The client and architect's personal endeavor to trigger this transfer of technology is one of the main reasons why we have cited them through the text. We have considered that expressing their own firsthand words is relevant to understand the peculiarities of this process.

This building could not have been possible without the technical mastery of SEAT and CASA's workers, who precisely and finely executed the technical design and assembled the building. This research's main point was not the technological transfer in execution but at project design and conception phases. The essential role played by the workers could be a fascinating topic for further investigation.

Undoubtedly, the SEAT Dining Hall is an excellent historical milestone to exemplify a pioneering interdisciplinary work between architects and aeronautical and automotive engineers, all aiming to apply the avant-garde knowledge of their field to this project.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Open systems for open plans: Jean Prouvé's contribution to school building systems in the 1960s and 1970s

A. Leander Pöllinger
Eidgenössische Technische Hochschule Zurich, Zurich, Switzerland

ABSTRACT: The occasions when construction technology becomes a significant driver in efforts to reform schools are rare. In France, new examples of experimental school buildings started to appear in the 1960s. During this period, building systems were created that responded to the new demand for open plans. The proposed paper is part of a dissertation project on the experimental school buildings developed by Jean Prouvé from 1932 to 72, that analyses the lesser-known part of his œuvre from three main perspectives: Prouvé's methods of developing prefabricated building systems; pedagogical methods and their impact on architecture; and the developments of the French school construction program. The projects that are analyzed in this paper, the École Tabouret and École Elancourt, are part of the second half of Prouvé's œuvre that have not previously been studied. These projects question the classroom as the determining unit of the building and introduce team-teaching methods for varying group sizes. The quality of Prouvé's system lies in his ability to develop a coherent whole using elements based on specific pedagogical demands. The paper traces the origins of the construction elements of the Elancourt School and their contribution to this collaborative design process.

1 BUILDING COMPONENTS FOR OPEN PLANS

A shell system of simple steel tubes, IPE beams and specially designed nodes. Jean Prouvé's response to a request from two French educators in 1963 to design a new type of school building system seems simple, even banal, at first glance. Even more so, because the French designer had become known for his elaborate structural elements made of formed sheet metal with expressive tapered shapes. The explanation for this change can be found in the special demands for the structure of the school building – later called the Tabouret system – and its interaction with the other components of the system. However, the selection of these complementary components is not definitive. Their composition changes in the following years, parallel to the development of pedagogical concepts. Ten years later, Prouvé contributes to the creation of a new model school in Elancourt which documents the development of the previous years.

Both systems, the Tabouret and Elancourt systems, are highly specific responses to changing requirements in school construction, in particular the emergence of so-called open floor plans. This was the first time since the open-air school movement at the beginning of the 20th century, that a demand by progressive educators fundamentally influenced the constituent elements of a school building. While in countries such as the United States or Great Britain, open floor plans encouraged the establishment of open prefabrication in school construction, Prouvé continued to pursue the goal of creating closed systems. This approach allowed him to influence the spatial design of the buildings without formally acting as the architect of the projects.

In the following article, I introduce the École Tabouret system and its components in detail. Then I describe the subsequent stages leading up to the transformed system used for the École Elancourt.

2 THE TABOURET SYSTEM

The Tabouret system is Prouvé's first and only school system that is based on a specific demand by two pedagogues, Henri Charnay and Carmona, members of the National Pedagogical Institute (Institut Pédagogique National). They asked Prouvé to develop a building system that could accommodate a new type of secondary school. Spatial freedoms previously created for pre- and elementary schools were to be transferred to secondary schools and combined with the idea of "growing structures."

Prouvé and the two pedagogues collaborated on elaborating the spatial needs of these schools, their structural elements and the possible ensembles of their units. Raoul Pastrana, the architect who worked on the project in Prouvé's office, cites the basic spatial demands of the educators: an open plan, a minimum of support points, and, at the same time, the concordance of "pedagogical and architectural unity".

This last requirement is the starting point for Prouvé and Pastrana's proposal: a simple square base module representing a standard classroom, with a grid of 7.20

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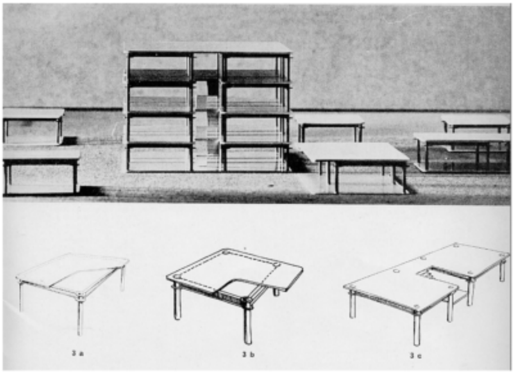

Figure 1. The Tabouret system: model and sketch.

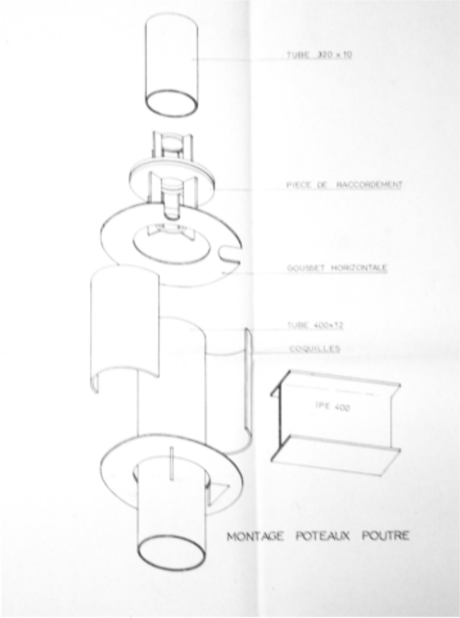

Figure 2. Tabouret system: elements forming a node.

meters and a distance between supports of 6.50 meters (Figure 1).

Only three years before, Prouvé had spoken out against the use of modules at the Tokyo Design Conference – and thus against the Metabolists present – citing a negative example from school construction in France: the 1.75-meter grid introduced by the French Ministry of Education in 1952.

In Prouvé's eyes this regulation contradicted the logic of standardization, which had to start from the material and not an abstract number. In 1956, Prouvé's examination of the grid led to the building system of the so-called Ecole Nomade. The system is based on the material behavior of a semi-finished product, the then newly introduced cross-laminated timber panels. Prouvé's insistence on the logic of the material is based on the conviction that a dynamic and rapidly evolving architecture cannot be based on industrial methods that do not yet exist (Prouvé 1960, p. 212). The reason for the apparent deviation from this principle, in the case of the Tabouret system, to Prouvé's – where dimensions, and not a building material, served as a starting point – can be found in a close examination of the components of its basic module.

2.1 *A shell module from semi-finished products*

All attempts to establish school building systems based on prefabrication are confronted with the challenge of geographically distanced building sites. While the problem was met at the level of pre- and elementary schools in France in 1956 with the introduction of the "*commandes groupées*" – the regional bundling of orders from different municipalities – the problem arose anew for secondary schools at the beginning of the 1960s.

In further specifying the system, Prouvé designed the shell system in such a way that only a minimum of prefabrication was necessary, and most of the assembly work was done on site. This was made possible by the use of semi-finished products, the steel tubes and IPE beams mentioned above which could be supplied by local manufacturers as linear elements in appropriate lengths. At first glance, Prouvé seems to return to principles of classical steel construction. However, by reducing the elements to one type of column, beam and node, he maximized the standardization of the system. With this reduction, the requirements for the individual elements increased.

According to Prouvé, this limitation to ready-available components made it impossible to use his typical columns with tapered shapes. And the cylindrical columns were the only available semi-finished products that could be used as box-girder columns. A box girder was advantageous because of the loads acting in two directions. Likewise, the IPE beams were selected according to static and economic criteria.

The system was designed so that the semi-finished products could be delivered directly to the construction site without having them processed by the construction company beforehand. To this end, the connection of the columns to the beams was planned in such a way that it would compensate for dimensional inaccuracies in the semi-finished products. The node designed by Prouvé for this purpose consists of three parts: the two plates are welded to the columns as half-collars (Figure 2); they reinforce the column at the point of support of the beams and compensate for dimensional inaccuracies of the column; and two circular plates, one of them with angle plates, support the forces of the beams. For the vertical connection of two supports, a connector is provided, with a recess for installations running in the supports.

2.2 *The design of the on-site construction process*

However, the development of a standardized shell module was not limited to the selection and development of suitable semi-finished products and node connections. On a technical level, the innovation of the Tabouret system lies in the meticulous design of the construction process and, in particular, of the welding operations on site. To weld on the collar plates, a so-called “*mannequin positionneur*”, a welding gauge was set up on the construction site. At this workstation, the position of the plates to be welded on could easily be determined. A motor was used to rotate the pipes for welding on the collar plates, so that the quality of the weld could be determined by the speed of rotation. This conception of the work process is reminiscent of that of the Ateliers Jean Prouvé – the company Prouvé ran from the 1930s until 1954. It is based on the use of “hand-tool-techniques” that are determined by the “relative movement between tool and workpiece, and thus the result of the technical action is directly determined by the human being” (Paulinyi 1989, p. 23). In the factory of the Ateliers, this allowed, for example, the production of a large number of different bent sheet metal elements with the same mechanical press brake. On the construction site of the Tabourets system, this interaction of men and machine brought the quality of the execution closer to that of the factory.

The simplification of the welding operations can be seen in another detail. The length of each weld was given by static requirements. In order to define this length, the upper circular plate was given semicircular recesses at the points where it rested on the IPE supports. By following this recess, the worker automatically established the correct length of the weld, without plans or measurements. At the same time, this allowed all welding to be done from above and in the area, greatly simplifying work on the job site.

2.3 *From ideal to built*

“The only reason for the existence of these schools, as they were conceived, is to allow an evolution of the current school building” (Prouvé 1964).

As a prefabricated system, the Tabouret system stands between two extremes: Systems with coordinated grids, in which interior partition walls – and thus the program – is integrated into the main structure, and systems with independent grids, in which the two structures are largely independent of each other (Rossmann 1969, p. 180). In the Tabouret system, Prouvé clearly separates the interior walls structurally from the main structure.

Still, the main structure retains a reference to the program. The basic shell module corresponds to the standard classroom and can be enclosed by matching partitions. Larger rooms, such as the dining room, are formed by combining several basic modules.

However, the system provides for deviation from the basic module. The slabs supported by the structure can project beyond its limits by a quarter of the width of the module, and the resulting space outside the four columns can be used, for example, as a corridor area or for sanitary facilities. Here, units deviate from similar ones, such as that of Louis Kahn’s Haus Adler or Helmut Spieker’s Marburg system, by introducing variable distances between two modules. Thus, in the Tabouret system, the ceiling and its constructive design take on greater importance. At the same time, it remains undefined in the early study.

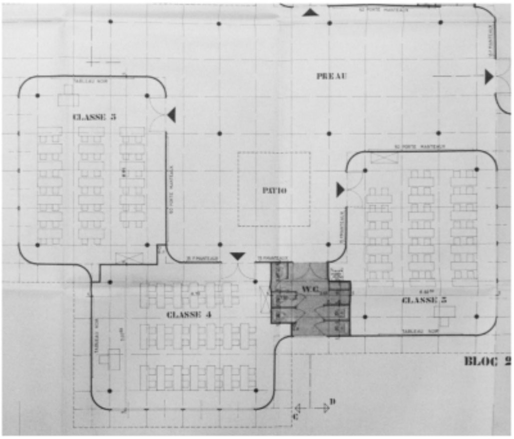

Figure 3. École Villagexpo: altered Tabouret system.

This condition is one reason why it becomes difficult for Prouvé to maintain the strict basic concept in the following three attempts to execute the Tabouret system. A first opportunity arose in 1964, when Prouvé, together with the architects Andrault and Parrat, participated in the planning of the Cité scolaire, a comprehensive school center in Orléans la Source. The question of the expandability of the system soon recedes into the background. Instead of the original module, a column-and-slab system is chosen, the so-called lift-slab construction. Similar to the Tabouret system, this system does not require scaffolding to build the structure. On the other hand, the lift slab construction makes later vertical expansion in the same system practically impossible, since all floor slabs are poured on site at ground level before being lifted to their final height. This first failed attempt to implement the Tabouret system documents how specifically the advantages of the system had been developed. If these advantages were not a determining factor in a project, the system could not succeed.

In parallel with the project in Orléans la Source, the same team worked on the design of an elementary school in the municipality of Saint-Michel-sur-Orge (Figure 3). The school was part of the first of a series of model housing developments, so called Villagexpos, designed as a horizontal alternative to the multi-story apartment buildings being built throughout France. (Bossé & Guennoc 2013) As the school was built in a newly constructed residential neighborhood, the growing Tabouret system responded to changing demographic needs. However, in revising the floor plan, the architects deviated from the original concept of the system. For example, the square shape of the classrooms was lost. This geometric decision represented a break from the classic directional

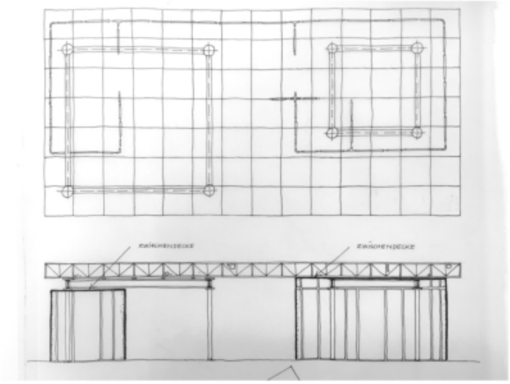

Figure 4. FU Berlin: structural concept developed by Prouvé and the architects.

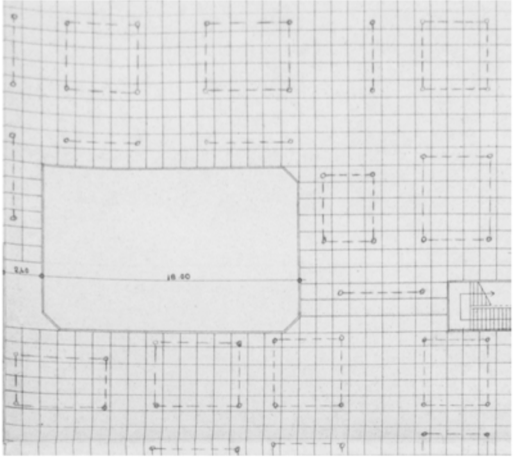

Figure 5. FU Berlin: System proposed by Prouvé and BessonLepeu.

rectangular classroom and its rigid seating. Mobile partitions were also not provided in the Villaexpo project, so that the classroom units remained fixed. This is all the more remarkable given that the two school buildings house a pre- and an elementary school. Examples of open floor plans were created for both types of schools long before the secondary schools for which the Tabouret system was intended.

Unlike the case of the Cité Scolaire d'Orléans la Source, the structural elements of the Tabouret system were retained in Villagexpo, but were significantly modified during further revision. The expansion of ancillary spaces and circulation areas led to deviations from the basic element of four connected columns: in the preschool, six columns are connected to form one element in one case. In the elementary school, nine columns are found in the circulation area, which were set in a common grid. Connecting the columns resulted in three new node types for one, three or four beams meeting the column.

Andrault and Parat's interpretation of the system strictly implemented the unity of space and structure. While their changes in the structure of the classrooms were minimal, special solutions had to be developed for the complex access area. This complicated the implementation of Prouvé's decisive considerations on the expandability of the system, which were based on the unity of the elements. The fact that the two extensions of the school, which followed shortly after completion of the first phase, were not executed in the same system points to the problematic nature of these changes.

2.4 *Transformation within the Free University Berlin*

Another opportunity to test the suitability of the Tabouret system was provided at the occasion of the competition for the new building of the Free University (FU) of Berlin, which was announced on 1 March 1963, in the middle of the study phase of École Tabouret. The architect's office, Candilis-Josic-Woods, engaged Jean Prouvé as consulting engineer for their competition entry. Together they designed a basic grid in which the various faculties are located as growing structures. No structural details are shown in the competition documents received. The dimensions of the proposed system refer to the program and are aligned with the Modulor system. Thus, instead of structural and technical design criteria, spatial and aesthetic criteria are the primary considerations. Only after the Team won the competition was the structural system described in greater detail in June 1964 during the execution planning. Three concept sheets for the supporting structure, drawn by the German architect, Manfred Schiedhelm, in consultation with Jean Prouvé in March, have been preserved (Figure 4). They show three main components of the proposed system: the Tabouret elements, a floor slab forming a three-dimensional truss, and a panel system for the facade and interior partitions. Prouvé participated in the tender together with the Besson-Lepeu company (Figure 5). In their proposal, the Tabouret system maintains the logic of the basic modules with four columns. However, their shape is no longer necessarily square which, at first glance, seems justified to accommodate the univerity's diverse uses. The architects' plans envisage a highly flexible system with partitions whose position can be shifted as the use changes. The connection between structure and enclosed space that existed in the schools, therefore, was no longer a criteria. Similarly designed American and English school building systems provided for wide-span support structures with regular column grids. In this case, the Tabouret system's claim to relate the structure to small spatial units was thus lost. Thus, partition walls crossed the beams of the Tabouret element several times instead of enclosing them as in the original design. The attempt, therefore, to transfer the principle of the basic module of the Tabouret system from the school building to the complex program of a university undermined its original strengths.

The small-scale nature of the design, as well as the requirement for expandability, nevertheless allowed Prouvé to stick to the Tabouret system. The logic of the arrangement of the individual tabouret elements was determined by the access axes and irregular inner courtyards. Therefore, there were no consistent axes for the position of the columns and thus a great variety of rectangular Tabouret elements existed.

Prouvé's offer was rejected due to excessive costs, despite a positive evaluation by the jury. The contract for the construction of the FU shell was awarded to the Germain company, Krupp-Druckenmüller, which proposed a system of steel columns, continuous steel girders and precast concrete slabs. The requirement for flexibility of use was finally translated into a generic system, with uniform spacing of columns.

2.5 *The roof and ceiling systems*

While the FU design demonstrates the limitation of Tabouret elements in the context of open floor plans, a different structural element proves its worth: the proposed ceiling system. The patent applied for in 1964 for the Tabouret system leaves open the ceiling system with which the supporting structure can be combined. Both the original study and the Villagexpo school called for thin, reinforced concrete slabs for the ceilings and roof. This allowed the spacing of half a module width between the previously mentioned two Tabouret elements. The architects of the FU project asked to increase this spacing to about one module width. In the tender documents for the structure of the building, Prouvé proposed a system using a space truss instead of reinforced concrete ceilings.

This system is divided into square modules with a side length of 1.20 meters. Prouvé patented a similar system in 1964. This patent for a new construction system for entire buildings was limited in its description to the slab (Les Techniques Jean Prouvé 1964). Matching columns, facade and partition elements could be added as desired. The slab consisted of square frame elements made of perforated sheet metal profiles and cross-shaped connecting elements made from steel. In this, Prouvé followed up on his ambitions, dating back to the 1930s, to make load-bearing components out of sheet steel.

While this system was never built, a similar one, called the Petroff system, became an important component of many of Prouvé's buildings in the 1960s. Engineer Léon Petroff was an employee of Jean Prouvé at C.I.M.T., the company Prouvé worked for, after he had left his own ateliers. The system he patented is one of many space frame systems of the time – Petroff was later involved in a patent dispute with the engineer, Stéphane du Chateau whose distinctive feature is the design of the nodes. Its arrangement makes it easy to connect the small modules to each other and to other components, such as façade elements or columns (Sulzer 2008, p. 229).

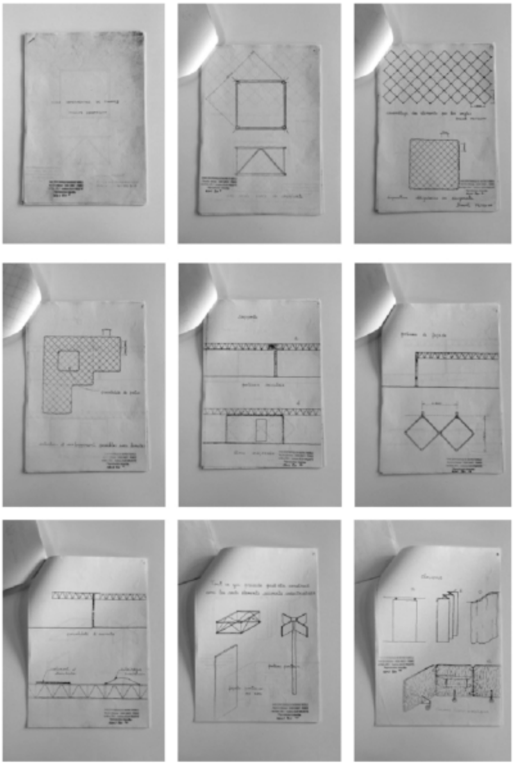

Figure 6. École Elancourt: catalog of the proposed components.

At the same time, like the other components made of semi-finished products, it is technically simple, so that it can be manufactured inexpensively in large quantities. Thus, it follows the line of the Tabouret elements.

With the experiments on prefabricated ceiling systems, a new field opened up. Subsequently, the Petroff system became the starting point for the design of new building systems. To this end, the components described in the 1964 patent as "flexible and varied configurations" – columns, partitions, façades – are each reassembled for different programs.

3 THE ECOLE ELANCOURT

At the beginning of the planning of the new school building project in Elancourt, Prouvé compiled a catalog of a number of basic components (Figure 6). The catalog included the Petroff system, steel columns and concrete cores, a façade system with vertical load-bearing profiles, and three proposals for movable partitions. In 1971, the architect Yves Merlin commissioned the design of a building system for the project. The school was part of the Ville nouvelle Saint-Quentin-en-Yveline and was planned through an experimental process led by a group of architects and educators – the Association pour l'Environnement Pédagogique (AEP). The AEP's goal was to involve future teachers in the planning of the school at an early stage. They were to help develop the ambitious program, which envisioned the extensive dissolution of the classroom structure and a turn to group teaching. In order to be able to implement the goal of open floor plans, the AEP relied on an open planning process. Prouvé's catalog provided a reliable basis for this at an early stage, allowing for the desired freedom to develop the program and the floor plan layout. The elements assembled in the catalog therefore had to be precisely coordinated.

3.1 *Facade panels and partitions*

In the 1960s, Prouvé used two types of facades: story-high facade panels and modular facade elements with vertical mullions. Both could be used as curtain walls for multi-story buildings or as load-bearing facades for pavilion buildings. Three variations of the second type were proposed for the curtain wall of the Tabouret system (Figure 7). While the three panel types (fixed glazing, sliding window or opaque element) were always the same, the variations provided three different mullions.

This variety points to the importance Prouvé attached to this element in the preceding years. The first type of mullion, a V-shaped steel profile with round vents, was first used in 1957 for the above mentioned École Nomade. A variation of the second type was used for the school in Villagexpo. Here, the aluminum clamps are made with the iconic T-profile that Prouvé developed in the 1950s. The third type, with posts of square cross-section, allows for easy connection of partitions.

While Prouvé had to forgo the load-bearing possibilities of the facades for the multi-story Tabouret system, this became an important feature in the Elancourt project. Three years earlier, Prouvé had shown the full potential of the Petroff system in a project for a residential building in Mainguerin. The low dead weight of the system allows the vertical loads, with small spans, to be largely transferred via the façade profiles. In Manguerin, the aluminum T-profiles were used for this purpose. While their shape was originally developed to support horizontal forces, especially wind loads, their cross-section was sufficient to transfer the vertical loads, as well. For larger spans, the Petroff roof is supported with steel columns or concrete cores, enclosing bathrooms. In the following variations of single-story systems with Petroff roofs, rectangular hollow sections are also used, which offer more possibilities for connecting other structural elements. In the case of the school in Elancourt, the partitions were attached to the façade profiles.

For the Elancourt, a specially designed ceiling element was added for the installation of the mobile partitions. The square gypsum fiber element was adapted to the dimensions of the Petroff truss. On its underside, there were grooves running in an X-shape along the edge, which, together with profiles bolted to the floor, held the partition elements in place. Alternatively, rails for folding walls could be installed in the same grooves.

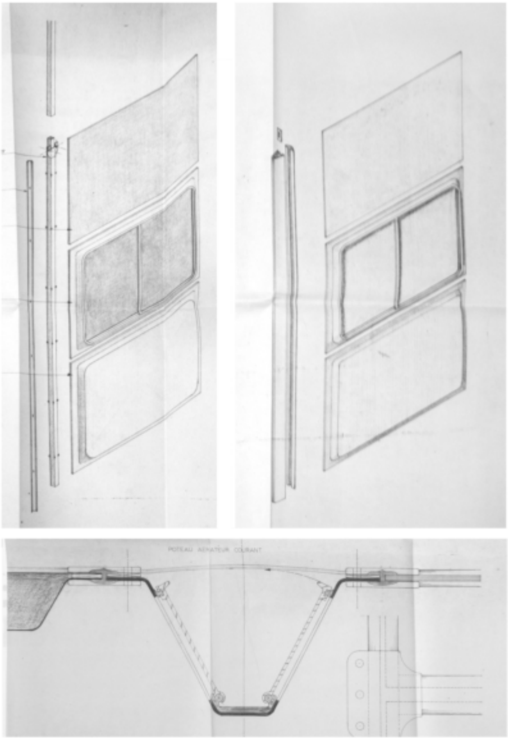

Figure 7. Three variations of panel types devloped by Prouvé.

The components of the system thus resulted in the following design specifications: the system was based on the square 1.20-meter grid given by the Petroff elements; from spans of about 9.60 meters, columns or concrete cores must support the roof, in addition to the facade posts; and partition walls could be connected to the facade every 2.40 meters.

In particular, the non-directional Petroff system allowed design freedom for projections and recesses of the building volume. Added atriums made it possible to create spaces with great depth, not only because of the lighting, but also because of their static function.

3.2 *Result of a participatory process*

The school building that was finally erected in Elancourt matched the original concept (Figure 8). The classrooms were open for different uses. Some of them could be combined into larger units, all of which received daylight through the fully glazed facades each of which had doors to the outside. Nevertheless, the school quickly came under criticism. The early hiring of teachers and the necessary preparatory work by them before the opening of the school, as recommended by the A.E.P., were not implemented. The proposed diverse furniture was also not purchased. While the teachers tried to realize the concept of open

Figure 8. École Elancourt under construction.

classes in the first year, the situation changed quickly and dramatically. A year later, with eight additional classes, the new teachers abandoned the original concept and reverted to teaching their classes separately. A 1974 report documented the paradoxical attempt to establish two traditional classes within the open space. It remains unclear to what extent the proposed folding walls, which could have been helpful in these situations, were implemented. As Andrew Saint noted in 1987, the American examples of schools with open floor plans did not immediately fail, primarily because the good financial situation of individual communities allowed the schools to be more generously sized than was possible in most European countries (Saint 1987, p. 211). Under the pressure of growing numbers of pupils, the concept quickly failed in Elancourt.

4 THE COMPLEXITY OF BUILDING A SCHOOL

The story of the Elancourt School is an example of why many educators provide little detail about the spatial conditions for implementing their methods. Material necessities take second place to people, and, on a material level, teaching materials seem to be more important than the space in which they are located. Witnesses to this attitude are the many small implementations of the *École modèrne* movement, most of which took place in rural schools under improvised conditions. Architectural articulation, however, has at least a supporting role in the broader implementation of educational goals. Prouvé's more than 100 school buildings executed between 1931 and 1974 are proof of an intensive preoccupation with this architectural program.

In fact, only a few of these projects fall into the phase described above, which is surprising at first glance, since the 1960s are considered the high period of prefabrication in French school construction.

At the same time, the many repetitive buildings, executed by large construction companies, were strongly criticized even during their period of creation. Prouvé's attempts to renew schools not only architecturally, structurally and constructively testify to his conviction that it would be possible to totally transform schools and thus "the atmosphere of the place where children spend their day and where their taste is formed" (Prouvé 1971, p. 135).

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The Cor-Ten steel structure of the Royal Belge (1970): New insights

V. Boone & A. Inglisa
Université Libre de Bruxelles, Brussels, Belgium

ABSTRACT: From its inauguration in 1970, the headquarters of the insurance company *Royale Belge* in south Brussels, by the architects Pierre Dufau and René Stapels, became a new icon for office buildings in Belgium, and noted for the introduction of Cor-Ten-steel to Europe. The building had an extremely short construction time of three years, which also influenced the choice of the materials and construction methods, the architects opting for prefabricated concrete and a steel structure. The cruciform steel superstructure of nine floors in Cor-Ten steel is the primary feature of the building. The construction reflects a clever combination of structure and façade: structure flows over in façade, and structure is used as façade. Fifty years after completion, the material needs special attention at reconversion of the site, and to reconsider heritage values on its pioneering use.

1 INTRODUCTION

1.1 *A pioneering project*

The insurance company La Royale Belge, one of the oldest and biggest in the country, decided in mid-1960 not to continue extending its existing Beaux-Arts-style headquarters in the center of Brussels. Instead, it opted to exchange the city center for the green outskirts of Brussels, and to build a new headquarters based on a calculated capacity of 2500 employees. La Royale Belge wanted to portray itself as a progressive company embracing modernity, as an employer recognizing new post-war social situations, and as a pater familias wanting the best for its then 1500 employees. Following the example of American companies that were setting up outside cities in greener areas, and following the Modern Movement's focus on air, sun and space for new housing, La Royale Belge intended to extend these principles to the modern workplace. The French architect Pierre Dufau and his Belgian partner René Stapels were hired for the prestigious project by the Board of Directors of La Royale Belge and its Building Committee in 1965. As per the example of the American companies, they designed a transparent building with an external bearing Cor-Ten steel structure laid out in a wide green park and surrounded by a lake (Figure 1).

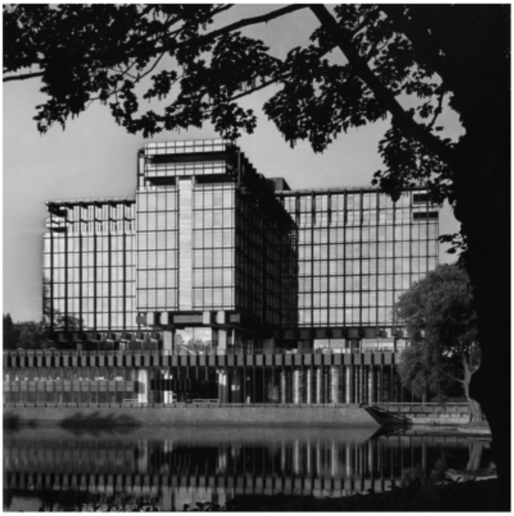
Figure 1. Lemaire, C. & Martin, G., Brochure Royale Belge 1970, 15.

The construction of La Royale Belge headquarters began on 4 April 1967 and lasted 36 months. In order to integrate the building into the landscape, the entire site was redesigned and recreated. For this purpose, the Woluwe stream was diverted and vaulted. One of the ponds was emptied, cleaned, and redesigned. To support the building, a base was planted in the artificial lake. In order to strengthen the soil, 1300 compacting piles were driven in to a depth of 20 meters. Foundations were finished by the end of 1968, and from 1969 the structure of the building grew quickly. Finishing materials and interiors were completed in 1970. 230,000m3 of earth was dug up, 49,000m3 of concrete poured, and 2582 tonnes of steel erected. An army of technicians and workers were guided by numerous engineers and one computer, as detailing and calculating continued during construction. On 1 June 1970, at eight o'clock in the morning, the staff of La Royale Belge moved into their

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new premises. The building was inaugurated on 25 June 1970.

1.2 *International context*

The building is a pioneering project in Europe and the first large-scale construction using weathering steel in Belgium. The John Deere headquarters in Moline, Illinois USA, designed by Eero Saarinen in 1957 and inaugurated in 1963, was widely publicised in Europe and stands as an example. Eero Saarinen applied Cor-Ten steel in architecture for the first time beyond its industrial use, in particular, to associate the company's products – agricultural machinery – with the architecture of its offices. Beyond an aesthetic desire or brand image, the durability of this steel, which does not require maintenance through the application of layers of paint, was highlighted, since it permitted the externalisation of the steel structure. This headquarters marked a new benchmark in corporate architecture, in which a company did not locate its corporate center in a city skyscraper, but rather sought out the suburbs and embedded it in a prestigious natural environment (Mozingo 2014). The insurance company referred to the building as an example of a modern workplace, as did the architects, for whom the green scenery and the use of Cor-Ten steel reflected a changing wind in architecture. Pierre Dufau and René Stapels wanted to go beyond the European context of late modern architecture, to choose new materials and detailing, while putting new programs such as offices on the agenda. Both architects went on architecture journeys to the USA to visit the newest buildings and be informed of the latest construction methods. Pierre Dufau met Gordon Bunshaft, collaborated with Max Abramowitz on the Rothschild Bank in Paris (1969), and undertook several corporate programs, especially banks, during the 1960s (Massire 2017). René Stapels was at that time portrayed as one of the leaders of the young generation of Belgian architects, and worked on the construction of the headquarters of the D'Ieteren car company in Brussels. However, it was later in his career that an abundance of tertiary building projects occurred, notably in association with André and Jean Polak (Inglisa 2017).

Other examples of the pioneering use of Cor-Ten steel in architecture in the USA include the *Daley Center* in Chicago by Jacques Brownson, inaugurated in 1965, and the head office tower of US Steel in Pittsburgh, designed by Harrison and Abramovitz in 1967. As patent holder, the company had a similar reason to use Cor-Ten steel as John Deere. The fascination of European architects for the rational organization of American offices, nurtured during numerous trips to the United States, meant that this material would be proposed in buildings in Europe from the second half of the 1960s. In 1968, Robert Anxionnat designed the offices of the printing works *Dernières Nouvelles de l'Alsace* in Strasbourg Koenigshoffen in Cor-Ten steel, and Marcel Lods used it the same year for the GEAI (Groupement d'Etudes Architecturales pour l'Industrialisation du Bâtiment) housing at the ZUP (priority urbanisation zone) of the Grand'Mare in Rouen. Other examples include the new offices of the Imperial Tobacco Group in Hartcliff, England, by SOM in association with Yorke, Rosenberg & Mardall in 1973, the University of Odense in Denmark in 1971 by Krohn & Hartvig Rasmussen, Knud Holscher and Svend Axelson, the Court of Justice of the European Community in Luxembourg, completed in 1973 and designed by Luxembourg architect Jean-Paul Conzemius and Belgian architects François Jamagne and Michel Vander Elst, and the headquarters of 3M in Cergy-Pontoise by Paul Depondt in 1978. Using patinable steel became more widespread during the 1970s, entering the field of art works for example, although it did not replace the widespread use in architecture of concrete or other steels.

1.3 *Constructing historical knowledge*

Few historical studies focus on this emerging period 1965–80 of the material in Europe. Besides the historiographic literature available on Eero Saarinen and the John Deere Center (Miller 1999), studies on the nascent architectural use of Cor-Ten steel remain absent. Some publications give an introduction and overview of the architectural possibilities of weathering steel, often initiated by the steel lobby, including some historic examples such as Royale Belge, 3M, or the Wills Tobacco headquarters (;outry 2016; Finnish Building Centre/Rautaruukki Oyj 2001; Hoeckman 2017). The need for more historic studies on the architectural use of weathering steel in the period 1965–80 is even more pressing if we scan the actual state of these pioneer buildings. The 3M building has recently been demolished, as have the offices of Dernières nouvelles d'Alsace. The Justice Court has been altered by a new lightweight façade, while Wills Tobacco Group has been transformed to high end residential use, albeit with preservation of the steel façade. But even when used in smaller buildings its future is precarious, as witnessed by the degradation of the GEAI residential blocs. The conversion of La Royale Belge headquarters into a hotel, coworking offices and a wellness-center, and the vacuum of knowledge on considering heritage values for this relatively young material and construction model, evokes the need to take a closer look at one of the most prestigious constructions of that period.

1.4 *The lack and abundance of source material*

The Pierre Dufau archives at the Archives d'Architecture du XXe siècle in Paris (IFA, Paris, fonds Dufau, 066 Ifa) is the most complete resource available in terms of architectural plans and correspondence. However, there are no as-built plans, no structural plans, and no correspondence on construction. Axa, who took over Royale Belge in 1999, did not have any archival strategy for the building, and contributed to the loss of much of the documentation of that time. Technical studies over the last 20 years on the building therefore worked on-site and from samples taken in situ. The most important knowledge gained from these studies concerned the two main elements of the façade: the aluminium window frames, by examining the detailing, and calculating performance and condition (Mangé et al. 2013); and the overall Cor-Ten steel structure, by determining the aging process of the rust and possible deterioration (Labo Soete 2004). The historical study ordered in 2013 concentrated on the pathology of the window glazing (Chapelle 2013), but no further detailed study has been undertaken about the pathology of the steel structure of the façade. Through extensive research with old employees of La Royale Belge, metamaterial has become available, such as detailed photographs of the building site. Other archival material has been acquired from the regional archives, the communal archives, the archive of René Stapels – partial and dispersed – and collaborators of René Stapels: Maïthé Paoli, Michel Benoît and Robert De Man. Besides collecting technical articles on the building, these archival documents do not contain extra information about the structure and the steel. The technical partners of the construction have also been investigated: the archives of the engineers Verdeyen & Moenaert, the contractor Nobels-Peelman, and the archives of Cockerill-Ougrée-Sambre (actually Arcelor). Technical plans of the concrete were still available from the archives of the engineers, but no other plans of the steel structure nor calculations have been found.

2 INTRODUCING NEW MATERIALS: DESIGN AND CONSTRUCTION

2.1 *Combining ideology and technical excellence*

Cor-Ten steel was introduced at several levels in the Royale Belge building: on a structural level, on the detailing with the glass framing, and on the decorative level. The Cor-Ten steel available at that time was the Cor-Ten A, patented by US Steel in 1933, with an alloy of Cu (0.30%), Cr (0.70%), Ni (0.20%), P (0.07%) and Si (0.50%) (Finnish Building Centre/Rautaruukki Oyj 2001, 6). The atmospheric corrosion resistance of Cor-Ten steel is the result of the highly impermeable oxide layer, formed through years of exposure under atmospheric conditions, which protects the base material from deterioration and avoids intensive maintenance (McGannon 1971). However, even after the patina has formed, the corrosion process will continue over time (Hoeckman 2017, 7) (Figure 2).

During the first years, rust formation will occur quickly and slow down significantly after ten years (Steelinfo, 5).

The choice of the steel material was above all ideological, to reference the John Deere Center both through architecture and as a corporate building. Nevertheless, the project owner's program prescribed the use of materials corresponding to the fivefold criteria of quality, economy, nobility, durability and ease of maintenance (Pierre Dufau, undated note, IFA, Paris, Pierre Dufau archives, 066 Ifa 1140/3). By using Cor-Ten steel the architects tended to fulfill these requirements. As a high-strength steel, its use resulted in an economy of material through smaller dimensions, and by the formation of the natural patina layer maintenance costs could be significantly reduced. It resulted in highly transparent floors, and, combined with the golden reflecting glazing, a homogenized appearance with the natural environment.

The steel became available in Belgium through the licence of US Steel delivered at Cockerill-Ougrée-Providence in 1967 (Figure 4) (Pasquasy 2017, 2:252).

As construction started in April of that year, it is clear that the material was not yet available on the Belgian market when the architects decided to work with Cor-Ten steel. The archival plans always note "acier

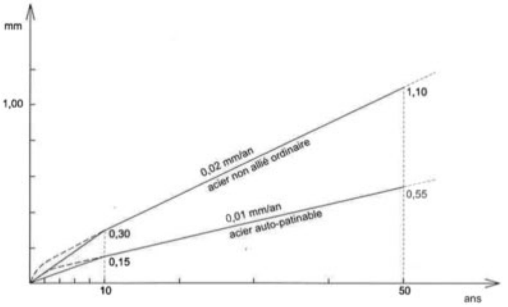

Figure 2. Patina evolution of Cor-Ten steel (Hoeckman 2017, 7) (Figure 3).

COR-TEN

Acier patinable à haute limite d'élasticité

Tôles laminées à froid et à chaud
Coils
Feuillards
Aciers marchands et profilés
Bardages, couvertures, etc...

ECOP M11/701

COCKERILL-OUGREE-PROVIDENCE
SERAING/BELGIQUE

Figure 3. Publicity for Cor-Ten steel by Cockerill-Ougrée-Sambre in *Environnement* 6 1970.

Figure 4. From the private archives of Benoît Berdoux, 1969.

patinable" without naming Cor-Ten, as the use of this patented alloy was not certain during the design of the project. The few Belgian projects using weathering steel before the introduction of Cor-Ten on the market were realized using Indadur weathering steel. Since Cor-Ten steel was available in France after 1965, through the steel company De Wendel (Boutry 2016), the architects probably knew its arrival would be imminent in Belgium, or that supply could come from France. Detailing was therefore highly experimental, as knowledge of use of Cor-Ten steel was practically limited to the John Deere Center in the USA and to buildings under construction in France. It is not known if the engineers Verdeyen & Moenaert, who calculated the structure from the second half of 1966, could rely on the US Steel technical manuals, which dedicated a chapter to high-strength, low-alloy steels (McGannon 1971).

The specialized technical press, including established national and international magazines such as *La Technique des Travaux, Detail, Acier-Stahl-Steel,* and *Bâtir* (;*âtir* 1973; *Detail* 1972; *La Technique des Travaux* 1971; Zaczek 1971;, publicized the building abundantly, focussing on the novelty of the material and the detailing of the steel structure, in combination with the newly developed glass, Stopray (Bertels et al. 2015).

2.2 *Bearing structure principles*

The Pierre Dufau archives contain plans for four preliminary projects, undertaken in October 1965: three of the versions show differently oriented bars, a fourth version a cross; the elevations of the latter are all composed of curtain walls. These documents do not contain annotations about the materials (IFA, Fonds Dufau, 066 IFA 048/4). However, with a rather discrete representation of the façade, the preliminary design is more akin to a "classic" type wall with an aluminium glazing structure. The project quickly evolves to its final appearance. The choice of externalizing the bearing structure of the façade and the use of Cor-Ten steel appeared by May 1966, giving the building its distinctive geometry and structure. Before starting the construction of the façade, the architects submitted the plans to Cockerill for agreement (Robert De Man, 11/08/20).

The building is composed of three distinct parts: a square concrete base of two floor levels, 80m by 80m, an intermediate floor, and a cruciform tower of nine floor levels. Each wing is 35m long and 18m wide, around a central concrete core that is 10m by 10m. The façade of the current plinth is characterized by the presence of suspended panes of single float glass of 7.36m (a system patented in 1965 by Glasbau Friedrich Hahn), alternated by double glass fins every 1.75m. The floor level between the base and the cruciform tower was originally designed by the architects as a diagonally working transition space, occupied by the canteen. This level has two façade processes. The façades of the canteen are almost entirely made of glass joinery, with a fixed, repeated aluminium frame module 2.3m wide and 3.6m high. Most of the façades consist of full height glazed windows, although some parts are filled in with ornamental concrete.

The façade of the cruciform tower is characterized by the Cor-Ten load-bearing steel structure visible from the outside. The main structure is supported by two double concrete beams over the whole length of the wing, supported by four concrete columns (per wing). The beams are crossed by 10 rectangular steel tubes 1.35m high. Their external part, on which the superstructure rests, is made of Cor-Ten steel, bolted at the nul moment zone on normal steel piercing the concrete beams. The external superstructure is made up of HEB300 column profiles with a centre distance of 3.50m, with the addition of two horizontal UPN300 profiles welded on both sides and crossing the façade inwards to form the beams of the floor slabs. The curtain wall structure (non-load-bearing) is marked by vertical UPN100 profiles made of Cor-Ten steel with a spacing of 1.75m. The glazing, with aluminium profiles, is attached to these UPN100 from the inside.

The steel structure of the building envelope was assembled on site from the outside in, and consisted of five stages. The first two stages concern the bearing structure: HEB and UPN in weathering steel and concrete floors and ringbeam; the next three stages are the assembling of the façade elements: weathering steel covering plates, outside aluminium window frames, and placing of the window glass and inside frame (IFA, Fonds Dufau, 066 Ifa 050/1).

Cor-Ten steel floor beams and bearing columns were welded in the workshop; all other parts were bolted together on site as well as some welding (*Environnement* 1970, 2134). Welding was done with copper, for the harmony of the color (*Bâtir* 1973, 6).

3 DETAILING

Studies on the detailing of the façade were undertaken by the architecture office of Pierre Dufau from May 1966 onwards. The drawing was essentially done by the main collaborators Jean-Pierre Dacbert and Jean-Pierre Girardot, who coordinated the project.

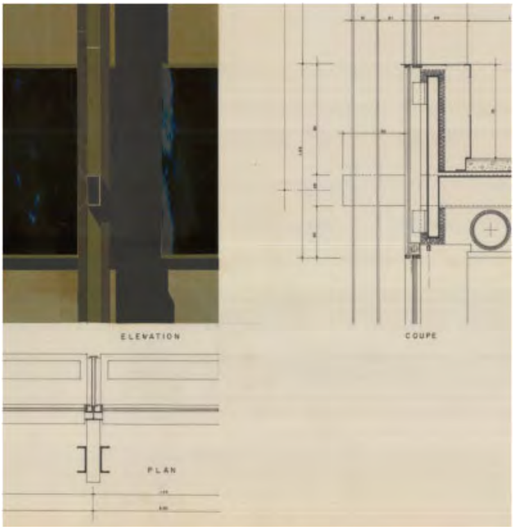

Figure 5. Detail of the facade drawn 12 May 1966 (IFA, Fonds Dufau, 066 Ifa 050/1).

The final characteristics of the façade structure as described above (bearing external columns crossed by bearing horizontal beams supporting the floors, and smaller horizontal beams supporting the façade) were already determined from May 1966 and studied through different versions.

3.1 *The floor knot of the external structure*

Three detailing options for the external bearing façade were studied in May 1966, and are almost the only detailed drawings that exist today. The first, dated 12 May 1966 and drawn by Girardot, shows external columns 240-profiles at 300mm distance of the glazing façade, with two lateral IPE200 bearing the concrete floors. The glass of curtain custom wall was supported by concrete ringbeams of 0.80m high; the weathering steel effect consisted of two thin plates covering the concrete. Another drawing was done simultaneously by Dacbert, which also shows the initial solution of the concrete floors with higher ringbeams of 1.10m, although here the bearing system was altered, with two external UPN210 columns and rectangular steel tubes of 250x100 supporting the floor in between (Figure 5).

A third alternative was studied the next week again by Dacbert, where the bearing columns are spread at 0.60m from the façade to include a rastering per floor – probably to resolve the practical problem of cleaning windows. This solution has strong similarities with the steel structure that would be adopted for the European Court of Justice in Luxembourg, designed by Conzemius, Van der Elst and Jamaigne during the same period. The hollow section was changed into an IPE240, the two disconnected UPN220 profiles are still in place, as is as the ringbeam, although its height is lowered to about 0.90m. Two months later decisions were taken on the appearance and structure of the façade, although still showing an under-dimensioned version that has not been checked with engineers. The choice of the bearing columns is a HEB profile, still drawn as a HEB240, the bearing floor beams are IPN240, and a connecting UPN240 is introduced for lateral stability. One year later, shortly after the start of construction, plans were checked with the engineers Verdeyen & Moenaert, and approved by Cockerill. The plan dated 29 July 1967, drawn by Girardot, still does not show the final solution, with the use of two UPN300 instead of IPN as bearing beams, to give the façade its “rigour and nervosity” (*Environnement* 1970, 213) and augmented sections to HEB300. The ringbeam, about 1.10m, is inversed, to limit the height above floor level to the strict minimum, and to take advantage of the ceiling void for hiding techniques. Nevertheless, the drawing leaves doubt about the use of the IPN300 for lateral stability; this profile is referred to on the plan, but not drawn (Figure 6).

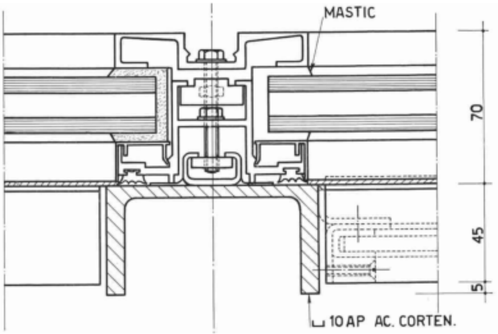

Figure 6. Detail of the façade of a current floor. *Environment* 6, June 1970, 214.

3.2 *The assembly of Cor-Ten steel with the window frame*

The external structure of HEB columns are conceived as bays of 3.50m each, which consist of two window bays in between. This aluminum framed wall is manufactured by the Belgian company Chamebel (Dethosse 1970, 50) containing heating at the sill, and attached by the glazing beads on a UPN100 profile of Cor-Ten steel, which for its part is assembled on the horizontal IPN beams. The window frames used for the construction were a newly-designed model with a technical cutting between the exterior part and the interior part (Figure 7).

Glass beads, as external elements, were detailed in Cor-Ten steel, and already welded in the workshop on the vertical UPN profile (Figures 5, 6). In the façade there are the fixed windows of the offices and, between them at the floor steel level, a closed spandrel consisting of two horizontal glazed strips separated by a strip covered with Cor-Ten steel. The window profiles are made of anodized aluminium but are not visible as they

Figure 7. UPN100 profiles with welded glass beads on the building site (from the private archives of Benoît Berdoux), 1969.

are hidden behind the UPN100 vertical profiles. The spandrel glass strips are made of clear laminated single glazing with the same gold coating as the vision glass. The profiles around the spandrel windows are made of thin, brown/bronze anodized aluminium profiles.

3.3 *Decorative panels of Cor-Ten steel*

All non-bearing finishing elements were designed in Cor-Ten steel. Most of the panels are 3mm thick folded Cor-Ten steel plates. At the bottom of the double height entrance level, the connection between the curtain wall and the ground and water level is made of a folded edge Cor-Ten steel plate.

At the higher edge of this level, forming the corner with the terrace, the façade is extended by a parapet set combined with thin, light, cantilevered light box elements every 1.75m. All elements – profile and sheet – are in Cor-Ten steel. The front of the light box is sealed with a transparent glass plate. The opaque vertical front strip between two light boxes is covered with the same Cor-Ten steel plate. Railings at ground floor level and at the top level of the cruciform tower are made of Cor-Ten steel elements.

4 THE COR-TEN STEEL STRUCTURE THROUGH TIME

4.1 *Cracked glazing*

Shortly after completing construction, a cracked glazing phenomenon started occurring. The thin Cor-Ten steel glazing beads welded on the UPN100 generated steel powder, worsened by the humid environment in which the building is located. This powder lodged against the glass and, as it accumulated, began to exert pressure on the glass, which cracked. As a result, all Cor-Ten steel glazing beads were replaced with aluminium profiles, following the standards of aluminium window frames.

Glass breakages were also noted due to another, major, problem with the tension that occurs in the façade. Window frames were fixed to the vertical UPN100 profiles and these profiles were bolted to the concrete spandrel, which caused the transfer of stresses to the glazing. Throughout the history of the building, a large number of glass breakages were noted and glazing repairs were frequently carried out, as can be seen today (Chapelle 2013). Problems of the same kind were detected at John Deere's headquarters in Moline. This building had already undergone major restoration work in 1981, replacing the *brise-soleil* elements consisting of a grating made of thin sheet metal fixed in a rigid frame by means of point welds, all in Cor-Ten.

4.2 *Current problems*

As it concerns the Cor-Ten steel elements, challenges to acquire new standards mainly need to be solved at two levels, structural and normative. Built before the oil crisis of 1973, the building no longer adheres to energy saving standards, nor does it fulfill the current standards in terms of evacuation, fire prevention, and fire safety, etc. First, at the level of the façades of the cruciform tower, thermal bridges are important in the UPN beams that pierce the façade from the outside steel structure to the inside concrete structure. Problems also occur when adopting new standards of the glass façade, especially at the connection with the UPN profiles.

On a normative level, problems are detected with the frame profiles, which do not meet current standards in terms of wind load within the façades at the ends of the cruciform tower, and with the balustrades which are not NBN compliant (Bovenbouw architectuur, Caruso St John architects, DDS+, Metzger & associes architectures 2020).

However, even if the Cor-Ten steel structure can overall be considered in good condition (Labo Soete 2004), some problems still occurred over time. Due to corrosion, the copper joints were dislocated and welding needed to be redone by means of a continuous sound link. The UPN100 profiles at the façades of the cruciform tower have allowed water infiltration at several places over the years. These are caused in part by faulty or missing sealing flaps. The sealing problem has been tackled by applying layers of liquid rubber and other stratagems that have proved unsuccessful (Bovenbouw architectuur, Caruso St John architects, DDS+, Metzger & associes architectures 2020). Smaller elements suffered from water stagnation, such as the light boxes at the higher corner of the base structure, and the finish of the Cor-Ten sheet steel panel at the bottom of the glass skirting shows perforation damage and swelling.

4.3 *A future-proof structure? Restoration vs replacement of Cor-Ten steel*

With the actual transformation and renovation of the building, questions arise over the heritage values of the building at large, and more specificly about the Cor-Ten steel structure. The pioneering architectural use of Cor-Ten steel in Europe is one of the elements that marks the importance of the building in the history of architecture, in general and for Belgium, especially if one considers the complex as one of the surviving examples of the use of the material combined with office typology in Europe. These historical considerations need to be taken into account when questionning the future life span: the aging of the structure, its compatibility with new norms for construction safety, ecology and occupation, and the aesthetics.

Various factors determine the speed of the formation of the oxidation layer on the Cor-Ten steel through time. Leftovers from the building site, such as scale, grease, chalk marks or cement water, as well as differences in temperature or rainwater drainage cause differences in the patina layer, both in terms of color and the progression of the layer thickness. For La Royale Belge, we can observe differences in color at the large bearing beams due to rainwater drainage, although these differences do not cause anomalies in the patina layer. Corrosion rate is estimated at 0.004mm/year (Labo Soete 2004). As seen above, deterioration is found on the steel plates of the light boxes, as well as on the bottom of the vertical UAP100 profiles on the ninth floor, due to water infiltration and stagnation. Problems continue with the 3mm steel plates, which have lost 1/30 of their dimension, and on damaged profiles. Although with normal patina continuity, problems will not occur for the thicker elements that remain intact.

Replacing elements generates several difficulties, on a structural as well as at an aesthetic level. Removing the Cor-Ten steel structural parts (such as the horizontal UPN300) for replacement, cleaning or new detailing would mean completely dismantling the building, as these elements carry the floors. Extracting the UPN100 profiles from the building envelope would be a delicate operation, whereby the aluminium frames would have to be uncoupled from the inside of the building and the vertical U-profile be removed from the outside and replaced by a temporary structure.

While the lightweight aluminium façade needs to be rethought to solve the tension problems, the aesthetics of today's Cor-Ten steel profiles needs to be taken into account. Sawing, welding or bolting would result in aesthetic changes and newly introduced pieces would not have the same patina as the existing 50-year-old elements. Chemical or fast ageing will create a layer of rust, though not comparable to real patina: rain creates marks on the artificial rust layer, and it does not resist shocks (Tim Meert (ArcelorMittal Europe) 25/11/2020)

Some parts of the building need to be brought up to current standards both in terms of safety and thermal insulation, which makes the debate on the original or replacement necessary. By working with original elements, the structural system needs to be rethought to solve the problems related to the tension of the façade in the current floors, which involves issues such as the possible loss of surface area – an extremely important consideration for the owners.

5 CONCLUSION

This article demonstrates that important work needs to be done to include the pioneering architectural use of Cor-Ten steel in construction history. These steel structures can be considered experimental, which contributes to the threat to this architecture, often misunderstood and considered obsolete. As it often concerns real estate products which are subject to other economic laws (30 years), stipulating heritage values requires a specific approach concerning building techniques, materials and restoration or re-use of them.

ACKNOWLEDGMENTS

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

The RBC building system—How to innovate between central planning and personal networks in the late GDR

E. Richter & K. Frommelt
Brandenburgische Technische Universität Cottbus-Senftenberg, Cottbus, Germany

ABSTRACT: This paper explores the conceptualisation and design of a prefabricated, concrete modular system within the building sector in the last decade of the former GDR. The system called *Riegellose Bauweise Cottbus* (RBC) originated from an academic group and promised a more versatile, time- and money-saving system for non-residential buildings. After the conception of the core principles between 1978 and 1983, the experimental work up to the erection of prototypes lasted for another six years. The development of the RBC was ultimately abandoned during the revolution of 1989–90. This paper reconstructs the development process and provides insight into the motivations and backgrounds of the developers. They faced serious resource constraints due to the state's centrally planned economy. Thus, the strategies dealing with the challenges are analysed and include interactions between industry, research, and education as well as between formal and informal networks.

1 INTRODUCTION

The year 1955 represented a pivotal point in the German Democratic Republic (GDR) building history that saw the whole centrally controlled building sector shift towards standardised and industrialised building. Throughout the 1960s, multiple solutions for building types were developed, each providing the complete design for a certain building task such as school, gymnasium, or residential building, for which only site-specific adjustments had to be added.

These building types relied heavily on modular and prefabricated elements. The trend of increasing differentiation of types was met by efforts to unify and harmonise the range of prefabricated systems. As a result of the GDR's Fifth Building Conference in April 1969, a unified system of building was established and introduced from 1970 onwards. Amongst the prefabricated concrete systems, there were two main structural types. Residential purposes were mainly served by wall-slab systems, such as the WBS70 system used 1972–90 (;ngler & Kuhrmann 2009, 17–8; Hannemann 1996, 82, 97–100). For non-residential uses, several skeletal systems, such as the SKBS75 and VGB, were used for sheds and multi-storey structures.

These systems were incompatible more often than not and relied on specific geometric grids. Skeletal systems generally used massive beams topped by pre-cast floor panels, producing considerable structural heights and resulting in a large unused volume of space, especially in buildings with little technical equipment.

The *Riegellose Bauweise Cottbus* (RBC) – literally "beamless construction system" – was intended to solve this structural problem. Its development began at the end of the 1970s at *Ingenieurhochschule Cottbus* (IHC), a rather young and small engineering college in Cottbus, under the direction of three main protagonists: Bernd Wagenbreth, Hans-Georg Vollmar, and Wolfgang Göttl. Although the innovation process was part of the regular top-down science and research system, it contradicted it at the same time with unconventional methods. This discrepancy mirrors the GDR-inherent conflict between the politically-based fixation on plans and the urgent need for necessary innovation (Förtsch 1998, 27–9).

The preliminary results of the authors' ongoing research are based on several sources. Interviews with Wagenbreth and Vollmar in the summer of 2020 provided information about careers, formal processes, and informal connections. Technical details, such as drawings, descriptions and calculations, were uncovered through the examination of unpublished research reports kept at the Brandenburgische Technische Universität (BTU) Library in Cottbus. Additionally, a dossier from the Bauakademie provides a 115-page research report, official letters as well as informal notes.

2 RBC – FLAT, FLEXIBLE, AND ECONOMIC

2.1 *Structural idea*

The basic idea behind the creation of the RBC was to provide a flexible "adapter" that many pre-existing modules could be plugged into (Figure 1). The base element was a square or rectangular column with a narrowed top that pierced through a correlating central opening of a "collar panel", a square element with

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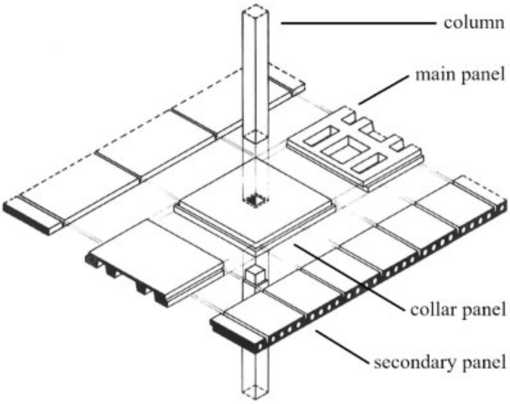

Figure 1. Isometric drawing of the basic system showing column, collar panel, coffered main panels and secondary panels of different widths (IHC 1987).

a 2.40 m edge length and 30 cm thickness. “Main panels”, which were the equivalent of conventional beams, spanned in one main orientation between the collar panels and rested on stepped consoles. With a thickness of 30 cm, they produced flush top and bottom surfaces, which were coffered regularly to create a 25% reduction in material and weight. “Secondary panels” spanned in the other structural orientation orthogonal to the main slabs. For this task, elements of the SKBS75 or WBS70 catalogues were to be applied, with various lengths, widths of 1.20 m or 2.40 m, and with thicknesses between 14 cm and 25 cm.

Formally, the RBC was divided into two separate systems, a skeletal floor system and a shed system with load-bearing walls. The two systems were technically compatible. Vertical façade elements could be added using specialised collar panels fitting different scenarios, such as half-sized edge panels, and quarter panels or three-quarter panels for convex or concave corners. Eventually, the catalogue, consisting of 210 elements, included columns of various lengths, collar panels, main panels of different sizes, and filler elements. Columns of different lengths allowed for the creation of nuanced floor heights throughout a building.

The use of different spans and the possibility to combine different span orientations accommodated a detailed differentiation of uses.

By reducing the structural mass, this structural solution addressed the notorious shortages of construction materials – especially steel – that the GDR industry suffered from. The system was designed to lower the economy’s dependence on imported goods, by creating interior elements and surfaces that should be fabricated “of silica-based raw materials from GDR origin”. To this end, a collection of divider walls and installation ducts made from fine grain high-performance concrete supplemented the RBC catalogue (IHC 1987, 9, 110–3).

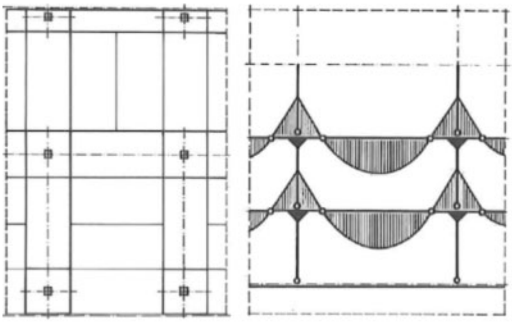

Figure 2. Simplified structural plan of the system with panels spanning in different directions. Sketch of the structural system with bending moments (Wagenbreth et al. 1983).

2.2 *Structural behaviour*

As opposed to a true flat slab, the RBC employed a hierarchical load-bearing system. In one direction, the main panels took on the role of beams. In the perpendicular direction, they were connected by secondary panels. Each of these members in itself represented a simple beam.

The connections between collar panels and columns were rigid. Both members were cast separately and connected on-site with the help of an adjusting console that was temporarily clamped around the vertical column. In this specific instance, the joint was only filled with grout without a connection of rebar. The collar panel rested on a flat metal bar running around the column’s top, helping to distribute peak stresses at this point.

The RBC interpreted the structural behaviour of a continuous hinged beam system. The cantilevering collar panels were connected to the main slabs through articulated consoles, creating a structure comparable to a Gerber system. In this way, the field moments could be reduced significantly.

The cantilever length of the collar panels – defining the zero position of the bending moments – had been determined in a way that created similar field and support moments.

This resulted in a stress pattern similar to that of a continuous beam while avoiding extensive welding and grouting at the consoles (Figure 2).

This basic system did not provide horizontal stability. For this purpose, staircase cores or shear walls had to be employed, which could be monolithic or consist of precast concrete panels from one of the available system catalogues. Double, or even quadruple, collar panels were produced to provide special RBC elements that could connect to more than one column, creating a frame sufficient to stabilise smaller structures.

3 INVENTION PHASE (C. 1978–83)

Economic Sciences distinguish phases of invention, innovation and diffusion of a new product or activity. This model also applies to the design processes of industrial products (Ertas & Jones 1996, 3). The RBC's "embryonic phase" between 1978 and 1983 can be associated with the invention phase that comprises the recognition of a need, the following conceptualisation phase and a first proof-of-concept.

3.1 *Academic work*

1978 could be designated as the initial year of the development of the RBC, when Bernd Wagenbreth began working at IHC. It was, like 11 other colleges, founded in 1969 to offer primarily academic training in the field of engineering. One of the colleges' aims was to strengthen the relationship between industry and higher education in order to use "science as a productive force" and to trigger the creation of urgently needed innovations (Schulz 2010, 168–9). The curriculum at this new type of college was shorter and more practice-orientated than at previously established universities, and was finished with a new type of degree (*Hochschulingenieur*). Civil engineering was only taught at two of these colleges: while Wismar offered three other subjects, Cottbus was dedicated solely to civil engineering, including a small military branch.

Already in the early 1970s, the engineering colleges intended to approximate university-level teaching, so studies with an extended duration were offered finishing with the degree, *Diplomingenieur*, comparable to the Master of Engineering (Buck-Bechler & Jahn 1991, 283). At the outset, the limited personnel had focused on intense instruction, and research projects became important only later.

Wagenbreth took a position comparable to that of an associate professor at the chair of "Building Systems and Structural Systems" that was created especially for him. Born in 1940, he had graduated with a PhD in civil engineering at TU Dresden and gone to work at the planning department of the Wohnungsbaukombinat (WBK) Cottbus, one of the state-owned housing construction companies. As head of the Department for Public Buildings, he supervised about 150 employees and established crucial contacts in the construction industry. At the same time, he taught at IHC as a lecturer and got acquainted with Heinz Präßler, the rector of the school. When Präßler finally convinced him to formally join the IHC team, Wagenbreth took several members of his team along with him, including the architect, Hans-Georg Vollmar, and the civil engineer, Wolfgang Göttl. All three of them needed to acquire further academic qualifications to secure future positions as full professors. They took these formal requirements as an opportunity to create a solution for a precast, flat-slab building system. This was an undertaking considered by all three to be of great relevance. A solution was not available in the GDR and imports of foreign systems, especially from the West, were limited and costly (Lauterbach 1988, 14). Since the building industry in the GDR was entirely focused on the production of assembly systems, any monolithic solution would have been unthinkable.

Within the joint research project that comprised Wagenbreth's postdoctoral qualification and the PhD theses for Vollmar and Göttl, they developed the basic concept of the RBC and defended the work in 1983. The results were published as a preliminary research report (Wagenbreth et al. 1983). Various patents were filed for the basic element configuration and technological solutions (e.g. Wagenbreth et al. 1984a).

The research report starts by examining the existing solutions in the GDR and concludes by asserting that only a new system could improve upon their economic feasibility and usage range. The associated patents refer to comparable flat-slab solutions that were analysed. For example, Dyckerhoff and Widmann had patented a system for a prefabricated mushroom floor, which had the disadvantages of bulky columns with integrated heads and non-rectangular floor panels (Dyckerhoff & Widmann 1962). Another solution created by Maurer (1969) employed a system using a column, a head panel, main panels and secondary panels placed on top of each other, creating a heavy and bulky stack that had to be smoothed over with an additional layer of concrete. A system proposed by Stilgenbauer et al. (1974) shared some similarities with the later RBC, while involving much more assembly effort owing to its use of screwed rebar connections for the columns and the necessary grouting of joints.

The task was to create a coherent, materially-efficient system of precast elements with little to no in-situ additions that could be easily assembled and combined with existing systems. The desired parameters of the RBC included floor heights of up to 4.80 m, spans of up to 9.60 m, floor loads (incl. dead weight) of up to 12 kN/m^2, and a total mass for single elements not exceeding 6.3 t (IHC 1985). As the goal was to reduce material usage significantly, steel usage was limited to 15.6 kg/m^2 gross surface area and concrete usage limited to 0.225 m^3/m^2 for multi-storey buildings (12.5 kg/m^2 and 0.155 m^3/m^2 for sheds). This would have meant a reduction in materials usage of 8 to 21 % compared to the available systems. Additionally, as the building volume was reduced by one third, the creators expected positive effects on maintenance.

3.2 *First prototypes*

To secure an opportunity for prototype testing, Wagenbreth used his connection to the VEB Spezialhochbau Berlin. This planning and construction company was affiliated with the Ministry for State Security, better known as the Stasi. This company had previously collaborated with him and his team to build a hospital reserved for members of the Secret Service shortly before Wagenbreth began working at the university. For the RBC, the VEB Spezialhochbau produced the formwork for the first columns and collar panels in their precast factory, which were subsequently erected on its premises in September 1982.

According to Wagenbreth, VEB Spezialhochbau later used the prefabricated elements for the urgent

Figure 3. RBC prototype at the Building Exhibition 1985 in Berlin (Klaus Völker, BTU, Photo Archive).

reconstruction of a small service building at the hunting lodge of General Secretary Erich Honecker. No detailed planning had been carried out for this simple structure. Ironically, Wagenbreth has never seen this first application, which probably no longer exists.

At the end of the invention phase, the structural principle, the modular system and a basic assortment of parts had been defined. Additionally, the creators had a grasp of the precast and installation process. The system's mechanisms for adaptability such as different spans, changing span directions and varying floor heights had been proven – but mostly theoretically.

4 INNOVATION PHASE (C. 1983–87)

Until 1982, the project was mainly driven by Wagenbreth's academic research group. During the subsequent "adolescent" innovation phase, the work was embedded in more institutionalised procedures that included the testing of preliminary designs that would later be converted into more elaborate designs

4.1 *Official bodies*

At this time, the building sector had evolved into a complex centralised network with the Ministry for Building at its centre setting the major directives. It managed the centrally controlled building companies as well as the Bauakademie (Building Academy). With its 16 institutes, the Bauakademie acted as the central facility for building-related research, covering topics from standardisation to preservation. The main directives concerning development, manufacturing and building capacities were determined by the central, five-year plan. The *State Plan for Science and Technology* supported projects of outstanding economic relevance by providing financial or material support (Sieber & Fritsche 2006, 23–27).

The Ministry for Building coordinated the first steps toward rolling out the RBC.Firstly, the project was supported through its inclusion into the *State Plan for Science and Technology* 1983–87. Secondly, the ministry proposed that the RBC should, in collaboration with construction companies, be applied to suitable projects in Berlin. Thirdly, the ministry also considered including the RBC into the assessment that compiled demands and available production capacities for industrial buildings for the period terminating in 1990. Finally, the Bauakademie was commissioned in 1985 to make an evaluation of the implementation of the RBC – under the condition that the required amount of steel would not exceed that of the existing systems. Not wanting to wait for the ministry's promotion and decision, the team took the initiative to promote the product. The group established an active communication strategy, which played a vital part in securing potential partners. In the middle of 1985, the IHC released a brochure outlining the characteristics and advantages of the RBC, presenting an element catalogue and describing its application in various scenarios (IHC 1985). At the building exhibition in June 1985 that accompanied the Eighth Building Conference in Berlin, a mock-up of one spatial cell containing four columns was exhibited, (Figure 3). Wagenbreth held a number of talks about the project. He presented the RBC in November 1985 in Leipzig at the MMM, a scientific-technological competition and forum for pupils and junior scientists.

4.2 *University resources*

As expectations for the project rose, the creators were under pressure to provide detailed designs, structural calculations, and manufacturing plans. Wagenbreth had moulded his department into a small project office with a staff of about 35, whose manpower and expertise could now be used to manage the amount of work required. This unique institution represented a hybrid of academic department, architectural bureau and commercial planning department, employing academic assistants, student assistants, and PhD students.

In the years between 1983 and 1987, at least 34 diploma theses and five doctoral theses produced by members of Wagenbreth's department addressed specific, clearly defined topics inside the RBC. These theses focused on the following topics:

- optimisation and iteration of the assortment, e.g. Rose 1987;
- optimisation of the production and assembly process, e.g. Weiske 1984;
- application of the basic structure to specific building typologies, e.g. Bartusch 1984;
- and investigations regarding the compatibility with other building systems, e.g. Rudolph 1985.

4.3 *Finalisation of the state plan project*

The number of persons involved is shown in the final report for the State Plan from September 1987 (IHC

Figure 4. The building site of the Berlin Postmuseum c. 1986 before the reconstruction of the façade, showing high exhibition floors with galleries and stabilising wall panels. (IHC 1987).

1987). It names 18 full staff members, not including the associated students. The team management included Wagenbreth as team leader, Vollmar responsible for architecture and design, and Göttl for statics and construction. Reimar Höppner joined as responsible for the assembly technology.

The report briefly describes the system's principles, while focusing mainly on numerous experimental buildings, already planned for implementation. Only two of these had been realised up to this moment. The team identified a range of usage scenarios and prepared at least two sample projects each, including the complete design and calculations. The proposals include a multi-storey laboratory building in Leipzig and a market hall in Berlin based on skeletal constructions, as well as two production buildings with staff rooms, which combined skeletal and wall-slab structures. As a pure hall, a youth club with a school canteen and a gymnasium in the small town of Triptis were designed. A study of an apartment block with a supermarket in the ground floor was designed to demonstrate the system's compatibility with the WBS70 system for residential buildings. This proposed configuration was designed to answer an urgent demand for effective ways to integrate shopping and leisure facilities into residential buildings in inner-city quarters.

4.4 *Experimental buildings*

The team was willing to get their proposals built and capable of managing the required planning in-house independent of a planning company. There were also resources to produce a part of the required precast elements in the college. As early as 1985–86, column heads and the critical connection between column and collar panel underwent a series of life-size tests in the Technikum, the school's experimental research facility. Technika had been established in the GDR as independently-staffed research laboratories within universities from the mid-1970s. There, theoretical, academic research projects could be developed into mass produced products, as the production and testing of prototypes and even small series was possible. This gave universities more independence from industry testing centres (Lauterbach 1988, 19–23).

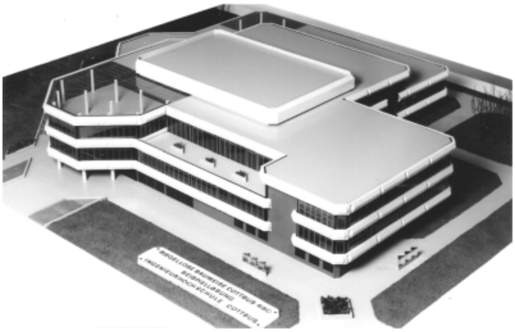

Figure 5. Model for the Congress Centre executed on the Sportforum Berlin, around 1987 (IHC 1987).

Wagenbreth and his team initiated the construction of the first experimental building in 1985. For and with the aforementioned VEB Spezialhochbau, they built a 5000 m^2 storage shed with load-bearing walls on the premises of the VEB.

For the second experimental building project, the reconstruction and expansion of the Postmuseum (the current Museum for Communication) in Berlin, the RBC offered a very suitable solution (Figure 4). The floor height of 5.60 m on the street side was determined by the building's (reconstructed) neo-renaissance façade. At the back of the wing, additional galleries were to be inserted to enlarge the exhibition space. Only the flat-slab system ensured an acceptable floor height of at least 2.50 m. Why exactly RBC was employed still remains unclear.

A publication states that the responsible planners learned about the RBC from a presentation given in late 1984 or early 1985. The fact that the assembly was carried out by a VEB Spezialhochbau team (in this case, the Magdeburg branch) indicates that this firm took on the role of facilitator. Now, the RBC had been used in a multi-storey building in a much more architecturally complex situation (Kothe 1986, 4; Niebergall 2000).

The construction of a congress centre for the Sportforum in Berlin built between 1986 and 1988 was, again, procured by VEB Spezialhochbau Berlin (Figure 5). This rather large structure combined a two-storey hall and other multi-storey parts and featured a terraced outline with tapered corners. The expansion of the assortment with elements for 45° angles, supplemented by fitting main and filler panels, allowed for changes of the structural direction and bends in the outer façade.

At that time, the institutions monitoring the development process, such as the Bauakademie, sought to evaluate the systems efficiency, but acquiring reliable data seemed to be a problem. Archival records on this contradict each other: In regard to the Postmuseum, some notes point out that the amount of steel used was many times higher than planned, while others report steel and concrete consumption similar to comparable constructions. In order to record the data systematically, a student of IHC evaluated the assembly of the Postmuseum's carcass in his diploma thesis (Kothe 1986). Once more, university manpower was used to improve the RBC and to adduce arguments responding to criticism. Notably, the ministry's handwritten notes show that Wagenbreth repeatedly failed to respond to letters and did not provide the demanded key figures. This nonconstructive working relationship was probably the result of differing approaches to work. While Wagenbreth preferred to make discoveries though experimentation, the official bodies were concentrated on the strict use of plans and indicators as main instruments in the decision about implementation.

5 PREPARING MARKET INTRODUCTION (C. 1987–90)

After having realized five buildings, the goal of Wagenbreth's team to show the advantages of the RBC came to fruition. Following the construction of the experimental gymnasium in Triptis, the partnering WBK in Gera, a major construction company in another GDR district, showed interest in including the project in their portfolio. This would have meant initiating the serial production of this system. In addition, a multilingual brochure was produced to support the marketing of the RBC as a flexible and economic solution. It was specifically designed for use in non-socialist countries, as costs of productions in the GDR were relatively low compared to those in the West. Furthermore, the GDR was dependent on exports, as they ensured payments in the form of Western currency. According to Wagenbreth, he was in promising negotiations with a partner in West Germany.

Meanwhile, the system's introduction to the GDR market was still pending, as the benchmark numbers seemed unrealistic to the official bodies. The executed projects each employed unique solutions. For example, the Postmuseum was an atypical project for the GDR building sector as its very dense urban setting provided only limited space for storage of the prefabricated components and complicated their assembly. The congress centre for the Sportforum was an unusually complex building task as well. Thus, information about the general performance of the RBC in standard buildings was difficult to provide. The existing numbers were not general enough for the persons in charge to determine the economic plans for the next five to ten years. Furthermore, aversion to risk was a general problem in the GDR economy (Lauterbach 1988, 14). In this specific case, VEB Betonleichtbaukombinat, a major company prefabricating elements for concrete skeletal structures, explicitly refused to expand their portfolio to accommodate a third production line.

Despite this unpromising situation by the end of the 1980s, the RBC was named as one of the building systems in the plan for industrial buildings for 1990–95 (Bauakademie 1989). Apparently, the introduction on the GDR market was still considered in the late 1980s. However, after the revolution and unification in 1989–90, the development and production of the RBC and other precast systems was terminated almost immediately due to various reasons, among them the radical change of the economic system. Some of the experimental buildings, though, do still exist and are in use.

6 EVALUATION OF THE PROCESSES

The development of the RBC was determined by individual circumstances. At the same time, it is an excellent example of the "modernisation dilemma" of the GDR economy. As early as the 1960s, science and technology were seen as vital means of modernisation (Förtsch 1997 p. 17, 32–3). To close the large gap between research and development on the one side and production on the other side, science was more closely linked to economic needs, for example by founding the engineering colleges like the one in Cottbus. Structures to support the transfer of research knowledge into practice were installed. The Technika, as institutions of knowledge transfer, represented the notable investments in this vein.

According to Förtsch, pre-modern media control and the high degree of institutionalisation within science policy stood in contradiction to this goal of efficiency. In addition, decisions were made according to a top-down approach, with the highest political authorities formulating the general objectives. These were defined in more concrete terms by the heads of ministries, research institutions, and industry. This second level created a "scientific oligopoly" as a result of its limited number of actors and lack of market pressure. Although they produced and diffused the knowledge and innovations the research institutions - R&D departments in the industry, academies, universities – took a subordinated position in the decisionmaking process (Förtsch 1997, 26–28).

Plans like the *State Plan for Science and Technology* or the *Research Plans* of the single institutions were the central communication instruments between the three levels; they were as rigid as the organisations and communication structures they passed through. Political-ideological norms dominated scientific and economic action, and criticism was hardly possible without "raising the question of power" – that means challenging the political system (Förtsch 1997, 27–28, 32–3).

The RBC provides an example of an individual practice-oriented academic research project, which certainly existed within the whole system, but could not shape innovation processes in general. The RBC's development process indicates how the protagonists dealt with this dilemma. Personal preconditions played an important role in this process - the professional lives of Wagenbreth, Vollmar, and Göttl did not follow a straight academic career. Wagenbreth spent almost ten years working at several companies, and established a growing number of personal contacts in the industry. At the same time, he was familiar with university processes, having received his doctorate at TU Dresden and taught at IHC. Göttl and Vollmar had gained many years of practical experience before joining the university. This gave them an awareness of the advantages and limitations of their building system that surely went beyond the benchmark numbers.

Furthermore, IHC Rector Präßler took the liberty to create a new department especially for Wagenbreth to recruit these experts. However, a formal process required for the justification of their appointments, was undertaken by their dissertation and postdoctoral qualification project. This kick-started the development of the RBC, and over the following years the small group worked more conventionally.

As experimental evidence had to be created, informal methods came into play once more in 1982. Without official backing, the developers had to create confidence in their projects through the presentation of successful prototypes. Allegedly, the Technikum at IHC could not assist in this matter at the time. The VEB Spezialhochbau could offer this unbureaucratically and took a risk of performing the required tests – none of the materials or labour cost has ever been officially accounted for.

The dissertation and postdoctoral qualification had been reviewed by three external experts who praised the highly innovative proposals. This benefitted the recognition of the RBC amongst other experts and made it harder for sceptics to ignore the project (*Gutachten* 1983). This might have contributed to the ministry's interest in including the project in the *State Plan*.

Although they were not tied to the industry, the developers were not on their own. They relied on the working conditions provided by the college, namely the manpower and the Technikum. The system's development greatly profited from the enduring personal support by Präßler, who backed the formation of the informal planning bureau. This made it possible for Wagenbreth and his team to refer to several successfully completed projects in 1987, when the *State Plan* had been concluded. On the other hand, the relationship with the Bauakademie's Institute for Industrial Building failed because both parties used completely different scales to evaluate efficiency. While the institute insisted on a numerical quantification, as required for rating and comparison schemes, Wagenbreth was unable to provide these, but referred instead to the experimental structures.

7 CONCLUSION

The RBC was an interesting technological solution and its development process matches well with the phase model of invention, innovation and market introduction typically attributed to industrial innovation cycles in economic sciences. Nevertheless, the small group of engineers partially subverted official plans and bureaucratic structures of the centrally stipulated research policies. They used, especially in the beginning, their informal network from the realms of academia and the building industry to implement their theoretical considerations into practical application and to prove success by experimental buildings and marketing. At the same time, the project was more and more integrated into the regular system of research funding with the advantage of financing and the disadvantage of supervision. Further systematic research shall provide insights, whether the RBC remains a unique example or in what respect other engineering developments correspond to the pattern.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

From form to words: Knowledge transfer vehicles in late-20th-century Portuguese modern architecture

R. Costa Agarez
Universidade de Évora, Évora, Portugal

ABSTRACT: Design and construction statements ("*memórias descritivas*") have been mandatory for every building permit application in Portugal since 1909. By the mid-20th century these bureaucratic documents had become essential means of expression for designers, architects, and non-architects, to convey arguments: functional and technical, but also their design philosophy and understanding of site and context, down to the proposal's zeitgeist, local traditions and particular circumstances. This paper draws on a selection of design statements written for works produced in Portugal between the 1950s and 1970s, interrogating their potential as fundamental knowledge transfer devices for designers to articulate, test and communicate their ideas as well as their take on new techniques and concepts. While these writings seldom contain comprehensive theoretical arguments, I suggest they nevertheless outline their authors' intellectual understanding of built environment creation processes, showing how (internationally) discussed ideas percolated into built artefacts and how their words complemented their form-creation process.

1 PREAMBLE

Design and construction statements, called "*memórias descritivas*" in Portuguese (*dévis* in French, *relazione* in Italian), have been mandatory with every building permit application in Portugal since 1909. By the mid-20th century these bureaucratic documents had become essential means of expression – alternative knowledge transfer vehicles, I posit – for building designers, architects, and non-architects, to convey arguments: functional and technical, but also their design philosophy and understanding of site and context, down to the proposal's zeitgeist, local traditions and particular circumstances. Such texts became more than mere formalities: they were opportunities for designers to translate concerns and intentions, put ideas into words, push the boundaries of their regulatory framework, defend their proposal from criticism or overcome resistance. Prompted by the design statement, agents on both sides of the bureaucratic counter exposed or hid their agenda, disputed or accepted impositions, opened new possibilities or insisted on preserving the status quo.

Often echoing pressing debates in the architectural scene – modernist vs conservative disputes, new understandings of tradition, the role of semiotics, the humanist turn, new postmodernist tenets – and technical innovations, designers' writings were submitted, assessed, and subsequently archived and forgotten. Not meant to be published, they constitute a source for architectural and construction histories that is not only unconventional (and uncommon elsewhere) but also complex, with their blurred public-private status. Yet they illustrate the built-environment culture of their authors, as well as that of bureaucrats, officials and politicians engaged in rule- and decision-making procedures and can be seen as an outlet for the (otherwise invisible) discourse of myriad agents who did not publish their reflections; furthermore, they can substantially complement the published output of better-known designers.

This paper draws on a selection of design statements written for works produced in Portugal between the 1950s and 1970s, from better-known pieces to more everyday initiatives, interrogating their potential as fundamental knowledge transfer devices for designers to articulate, test and communicate their ideas as well as their take on new techniques and concepts. While these writings seldom contain comprehensive theoretical arguments, I suggest they nevertheless outline the author's intellectual understanding of built environment creation processes, showing how (internationally) discussed ideas percolated into built artefacts and how their words complemented their form-creation process. They can be understood as vehicles for designers to participate in defining the built environment and in the broader, transdisciplinary conversations associated with this production.

2 NEW WORDS, OLD TRADITION

April 2014. A young Lisbon-based practice, Barbas Lopes Arquitetos, submits a planning application for "Torre da Cidade", a 17-storey tower in the city centre. With nearly 33,000sq.m., set on a delicate site, this was

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to become an important (neo-)modernist icon showcasing its authors' design philosophy. As with every other planning application in Portugal since 1909, for buildings big or small, the request is introduced with a *Memória Descritiva*: a design statement clarifying the functional, dimensional, technical and architectural features of the tower. This 28-page-long document has strictly legal-bureaucratic purposes; not meant for publication or dissemination, it is to be read by a small cohort of officials. Yet it opens with an epigraph quote from Saint Thomas Aquinas ("Now in matters of action the reason directs all things", from *Summa Theologiae*) and exposes the architects' firm functionalist beliefs – functions dictate form, this determined "spatial ordering" of the messy public realm – supported by the words of Mies van der Rohe ("The long road from the material through function to form has only one goal: to create order out of the unholy confusion of today", Palmer House Hilton speech, 21 October 1938). This tower, they state, belongs in a long lineage of similar private devices with a public expressive purpose: its well-defined identity reconciles "pragmatism [technical and financial] and aesthetic intent", to public and private advantage (Barbas & Lopes 2014).

This is a high-profile project, its designers particularly sophisticated – yet the level of intellectual investment in their design statement is not uncommon: more intensely since the 1950s, Portuguese architects invest this mandatory document with special capacities as a mode of written expression for their architectural thought. Why, I want to ask, has this been an important device – as a way for architects to rationalize their choices? To show awareness of on-going debates? To what extent was such form of expression integral to design processes, and how can it enhance our understanding of architecture's theory-through-practice approach?

3 BACKGROUND

Portuguese architects have traditionally used the *memória descritiva* to say something about the aesthetics of their proposal. There was no mention of project statements being required in 19th-century codes in Portugal, and when it first appeared in national law (1909) and in Lisbon bylaws (1913), the *memória* specified materials, construction techniques and structural calculus. No statute ever determined that design principles were to be justified in writing; but since regulations have long placed strong emphasis on the elevation's "decorum" and its role in valorizing public space (MOPCI 1864), it is not surprising that even the short application "requests" used before 1909 often referred to composition issues – and that, from the 1920s on, most *memórias* presented to Lisbon municipality included a paragraph on the "architectural stance" taken. With codes that clearly insisted on the aesthetic key, the need to argue for design choices may have been pre-emptively embedded in quotidian bureaucratic procedures: an unstated requirement for both applicants and officials (Agarez 2013).

Another important factor in making the *memória* an integral part of architects' daily practice was its adoption in architectural education. The new internship and CODA exam ("*Concurso para a Obtenção do Diploma de Arquitecto*") system introduced in 1936 for graduation in architecture from the Fine Arts schools in Porto and Lisbon kept existing requirements for a final justificatory *memória*, thereby reinforcing the need for architects-to-be to exercise their arguing skills alongside their design abilities. The *memórias* written for the CODA exam became transitional "real-life" exercises, since the projects submitted, developed by trainees in their internships, were for real commissions, being in fact closer to practice than to scholarly training (see also Moniz 2011, 67). This step was key in nurturing in architects-to-be a penchant – a taste? – for writing about design.

CODA texts offer valuable insight into the meaning of design statements in trainee architects' practice. Manuel Laginha (1919–85) began his CODA *memória* for a low-income-families housing scheme in Loulé (1947, built 1948–52; Figure 1) citing Josep Lluis Sert on the challenge such commissions posed in Brazil ("hard bones to chew"). Critiquing an aloof architectural education that disregarded reality and the hardship of concrete commissions ("students wander in a world of cost-less sketches"), he proceeded to defend the need for government programs to divert from single-family-unit initiatives, too onerous to significantly address the country's housing shortage, towards apartment-block schemes as acceptable compromises. Politically engaged and pushing for architectural renewal in post-war Portugal, as many of his generation, Laginha used his *memória* to stress his understanding of the designer's role in analyzing "the social meaning of the Home" at a time when segregated ghettos continued to be built for the working classes (Laginha 1947).

He briefly voiced his beliefs in architecture magazines in the late 1940s – in articles and works purporting a form of regionalist modernism that countered conservative, mainstream views (Agarez 2016) – before retreating to discreet civil service positions where he nonetheless continued to use bureaucracy and its media to express his convictions, architectural and social. To this end, Laginha employed not only his design statements written for private commissions but also his official assessments and internal correspondence exchanges within his Public Works department duties.

Eduardo Matos's CODA design statement for a single-family house in Francelos (1952) is another example of inflamed post-war political-architectural manifesto: its "foreword" (a section commonly dropped) put architecture "at the People's service, so that men, women and children be liberated from dwellings that are more tomb than shelter. Let us abolish styles and produce only modern architecture, to serve the Man that inhabits our world today. (…)

Figure 1. M. Laginha, arch. Low-income-families housing scheme ("Bairro de Casas para Famílias Pobres") in Loulé (1947, built 1948–52). © Ricardo Costa Agarez.

Let the works of Aalto, Corbusier, Lods, Mies, Neutra, Vlugt etc. serve as examples for simpletons [who lack] preparation and sincerity" (Matos 1952). A clear, recurrent line in *memórias descritivas* by architects-in-training emerges here: that of the designer's role as a social educator and an ameliorator of the lives of others.

The importance that the *memória* acquired as a probe in a trainee architect's toolkit is evident in the 1959 CODA essay written by Vítor Figueiredo (1929–2004) for a single-family house in Estoril, his first built work. This is a cathartic description of Figueiredo's design principles and education background, interspersed with references to client requirements' impact and to those of real-life building practice. He wrote:

"I woke up to architecture, I felt and began to love architecture [when] a language that had run its historical course was exhausted and ultimately, abandoned. [I accepted its failure] not because I simply found it outdated but because I saw the germination of sterility in formal purism, in the denial of all vaguely romantic expression [and] the concern with employing a language that had to be internationally valid to be contemporary. (…) rationalism appeared to me a betrayal to today's Man, the total Man, situated and concrete but also committed, the recipient of architecture. (…) rationalism could not help but betray a Man who is subjective, beyond the cubic metres of air one needs and square metres without which one dies. Metaphysical 'reality criteria' does not apply if Man is a dynamic totality, immersed in other dynamic totalities."

"To serve the real", the aspiring architect concluded, is "to adopt the courageous stance of the researcher: disquiet in accepting that each theme has its character, its problematics, its expression" (Figueiredo 1959).

Figueiredo's writings expressed his generation's discontent with modernism, in a particularly vocal, elaborate way. His realism was architectural (and internationally contextualized) and eminently social: "One has to know, properly know, seriously and profoundly, who one is designing homes for [since] Man is not only situated but also, especially, a being-under-project" (Figueiredo 1959; original emphasis). His "concrete humanism" countered "abstract idealism" and aprioristic solutions; it was grounded on a "criterion of experience", the only licit path for architectural practice (see also Maldonado 2020). Yet equally relevant were Figueiredo's comments on his design decisions and their consequences: throughout his career, the architect seems to have turned the *memória* into a written complement of his design process, and an indispensable work tool.

"I sensed some 'fragility' in deciding to merely encase horizontal planes between vertical ones; I accepted a certain exuberance, as humble silence would not be viable with an exuberant client and an amateur urban plan. Today, the work being finished I admit a neo-plastic stance to the plans and a bi-dimensionality that denies the volume (…) having refused to interlock the plans and placing all sense of volume in the balconies and roof slabs (…) but such 'fragility' stems from having found no valid alternative to those refusals that I chose to accept" (Figueiredo 1959).

Figueiredo's discourse is difficult to follow (and even more to translate) but its complexity conveys the architect's design rationale faithfully, often detailing his choices and their implications in a step-by-step account; importantly, this was not only the case with his writings for a degree examination (CODA) but also for works designed throughout his career, notably his projects for social housing schemes in the 1960s and 1970s.

4 WRITING SOCIAL HOUSING

In effect, design statements for public-sponsored low-budget housing schemes became, in the second half of the century, a privileged field of expression for architects, who saw the development of new funding models and scheme types (already claimed by Laginha) to address grave shortages in Lisbon and Porto, as opportunities to develop more "humanized" schemes; the *memórias* became an essential tool to stress their proposals' social-architectural strategies.

That same year (1959), Nuno Teotónio Pereira (1922–2016) – beginning a long and influential career – together with António Freitas (1925–2014) and Nuno Portas (b. 1934) submitted for planning permission the final design for an ensemble of blocks in Olivais-Norte, a new neighbourhood of Lisbon where experiments in social housing were being carried out by the municipality. In the 32-unit, eight-storey blocks, the architects introduced their vision of a sociability inducer: the tower was split into two parts to improve solar exposition of homes and, "with relative economy, treat landings as more than mere distribution mechanisms." Eight-storey blocks, they wrote, would not enable dwellers to "naturally" develop neighbourhood relationships outside, by the front door – but four apartments per floor were too little to ensure "a sufficiently free choice" of relationships (Pereira & Freitas 1959a). This led them to both encourage the use of the landing as a meeting and socializing place, and increase visual permeability between floors: generous spaces with sculpted concrete walls and flowerpots, open to the north and south, broke up the typically confined space for stair and lift access to the units.

Pereira and Freitas's detailed description of their innovative solutions for collective areas was extended to the homes: in the four-storey row houses, they took special care to specify how the relatively generous kitchen was devised to provide housewives, "whom we foresee, will nearly always perform these tasks [cooking, washing, ironing, sewing]", with "good working conditions". "This need for space, efficiency and domestic joy has a better chance to be fulfilled with the generous service balcony [which also serves] the children's bedroom, turning it into a hub of domestic interest, facilitating intimacy of mother and children, and extending outwards the wide array of dwelling-related situations." The balcony, "with its animation and communicative power, further reinforces the sociability among residents of this new neighbourhood" (Pereira & Freitas 1959b).

Figueiredo, Pereira and Freitas epitomize the committed architect who criticized post-war, "abstract" modernism and pushed for an acknowledgment of the values of use, dwellers' preference and community life; *memórias* were opportunities to reiterate their commitment and complete their designs with clarifying words.

Yet in the case of Figueiredo, the comprehensiveness and intensity of his *memórias* suggest a closer link between the writing and design aspects of his work. Former collaborators of the practice tell of the architect's "almost obsessive appropriation of each project", which translated into plastering the entire office with its drawings, "revealing the sediments in this appropriation process" (Spencer in Maldonado & Borges 2015). I would suggest that Figueiredo's design statements for social housing schemes, long and occasionally rhetorical, stem from the same immersive creation process: a rationalization of choices made, priorities defined, and results aimed at, working for these challenging, bare-minimum commissions. In other words, these texts act as final, after-the-fact, "clean-copy" accounts of intense immersion processes of architectural design.

The architect's 1960 proposal for a 324-unit scheme in Olivais-Sul, Lisbon (with Vasco Lobo), was submitted to planning with a *memória* that established his firm belief in what should be expected from the profession: "To dignify dwelling space is first and foremost the task of order-givers (more than stylists or form-testers) and increasingly demands consistent, updated attention (…). The new horizons opened by humanities hold urbanism and architecture responsible for the social fact of family life. They demand that dwelling be the instrument of a deep and sustained transformation of such life; that, beyond the poor places where one eats, cooks or sleeps, the home allows for communication or isolation, housework, meals, concentration, study, recreation, surveillance, reception and an indoors-outdoors relation."

With unit sizes and cost limited to the extreme, the architects chose (in their own words) to "severely sacrifice" the finishes and equipment of the homes to extract "maximum conditions of habitability" so that "each home would behave towards its occupants as a logical complex of interior spaces [and] even to create [compartments] that will respond to new fruition demands." Specifically: the type-unit layout offered a bathroom-laundry area that sought "to offer a breathing space" that average low-budget-housing standards would deny; the same principle applied to the bedroom corridor, with an "almost comfortable" size obtained by compressing other internal function areas. Simple, "elementary" materials and finishes, easily maintained, matched the spatial design solutions: apparent concrete elements, whitewashed render and simplified openings marked the effort made to "guarantee that minimum of architectural dignification which, we know, is everyone's intention."

The "dignification" of low-budget dwellings was a concern made apparent in Figueiredo's words: resorting to "superfluous" spaces and "luxurious" dimensions (for low-budget standards) to make up for the home's otherwise spartan features self-consciously justified repeated mentions in his *memórias* – a marked aspect of Figueiredo's work that has been recently discussed in detail (see Maldonado in ;aldonado 2020; Maldonado & Borges 2015). "It might be observed that this hall", he went on to write on the relatively generous three-bedroom-unit entry hall, "further impinges upon the area available for internal functions; we think it may represent a dimension and a sense of home that would be compromised by strict obeisance to existing area limits" (Figueiredo 1960; original emphasis).

This civic commitment to making social housing dignified, and Figueiredo's close written-drawn elaboration, are perhaps best exemplified in my last example here: a 317-unit, five-block ensemble in Chelas, Lisbon, known as the "Five Fingers" (for its open-hand-like plan), designed in 1973 with Eduardo Trigo de Sousa and Jorge Gil (Figure 2).

The scheme's peripheral, "special situation" in the area masterplan was, the designers explained in their *memória*, turned into an advantage: this would be not

Figure 2. V. Figueiredo, E. Trigo de Sousa and J. Gil, arch. Social housing scheme in Chelas, Lisboa (1973–4). © Ricardo Costa Agarez.

a "ghetto" but "a micro-complex that suffices itself spatially and visually", its striking form envisaging "the creation of a limit to the area" yet avoiding to "entirely break this edge-object apart from the rest of the area, keeping the extremity buildings parallel to the roads." The dramatic topography and the scheme's expressive presence in the new neighbourhood's skyline characterized the proposal: the architects felt "a long-standing, pressing need to consider as definitely outdated the neo-realist practice of matching lowest-budget housing schemes with miserabilist features", and to give "designed space – both built space [and] inter-building space – the dignity that allows architecture to be not only a response to a primary need but also a poetic dwelling proposition."

The fan-like disposition of the nine-storey-plus blocks, with interlinked access galleries, enabled the constructions to "regulate and definitely take possession of a plot of land that seemed to refuse to be owned. (…) a regulated form that disciplines topography and acquires an intentional expressiveness in the rapport between building and terrain."

Inside the type-unit, a "central space" taking up its full depth signalled "in a heartfelt way, the limiting presence of the enclosing façades. Concurrently, it improves the unit's habitability with a valuable, apparently superfluous space, with multiple uses (immediately de-congesting the available, crammed rooms). [I]n an organic ensemble where needs do not limit themselves but rather celebrate an endless game of exchangeable, playful, existential priorities, the dwelling becomes a cellular fragment of a Habitat that aims to be total" (Figueiredo 1973).

This was a home designed to be appropriated by residents, in the cadre of *existenz minimum* units, heavily bound by financial concerns – a condition which likely prompted Vítor Figueiredo to devote special attention to justify and elaborate on his team's proposal. They sought to have their design, and its economic implications, understood and accepted by the patron of the initiative (the municipality, in this case) in such a way that the inclusion of an extra, central space, "apparently superfluous", might be seen as reasonable.

Some important features stand out in this overview of design statements written by Portuguese architects in the second half of the 20th century. The *memória descritiva* reveals, to this day, some degree of posturing by its author: part manifesto, political, social and architectural, part a brief of the designer's intellectual ambitions; often mismatched with the cruel reality of practice and circumstance. These texts sometimes appear to convey in writing what Dana Cuff called the architect's "espoused theory", not always coincident with his or her "theory-in-use" (1991, 20).

In the cases discussed above, particularly in that of Victor Figueiredo, they seem to depict the filtering of the architect's theoretical framework through the act of designing for a specific commission, under concrete circumstances – a "theory-in-use" that is very much determined by practice and its constraints, using the *memórias* as written elaboration and communication devices. In other words: they constitute a platform of intellectual mediation, I posit, between the act of drawing and its intellectual and material conditions. Being required to elaborate on their proposal in writing, architects were led to expose their thought and decision process (at least partly), thereby coming to terms with it, especially where it might have raised concerns by side-stepping conventions and standard solutions. Through writing, architects were taken to reflect on such process, their architectural culture and the real circumstance of their lives; possibly – although only further research will determine this – their writing allowed them to revisit and revise their designs.

The *memórias descritivas* are, in these and many other cases, much more than mere legal requirements, buried in the archives of bureaucracy.

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History of Construction Cultures – Mascarenhas-Mateus & Paula Pires (eds)

Concerning the research "Material history of the built environment and the conservation project" (2008–2020), methodology and results

F. Graf
École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
Università della Svizzera Italiana, Mendrisio, Switzerland

G. Marino
Université Catholique de Louvain, Brussels, Belgium
École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

ABSTRACT: Recent successes in the reuse and rehabilitation of 20th century architecture have shown that design begins with the study of history. Study of the material history of built structures, together with historical and critical investigation, supported by diagnostic assessment of the object's state of preservation, are key instruments. This contribution intends to present over a decade's research in terms of both its methods and their results.

1 INTRODUCTION

Since its creation in 2007, the aims of the Laboratory of Techniques and Preservation of Modern Architecture (TSAM) at the École Polytechnique Fédérale de Lausanne have been to observe and analyse the transformation, whether silent or otherwise (Graf & Marino 2016a), of the built environment of the European city in the second half of the 20th century. This entails understanding, identifying, dissecting and mapping it, in short making legible the inexorable process of erosion, superimposition or disappearance of the buildings of which it consists. For this purpose, we have developed critical tools, such as the material history of the built environment (Graf 2014), namely the history of architects as a continuation of the work of the historian of architecture, the history of buildings, the archaeology of the project and much else. The rediscovery and reassessment of an architectural output that is too often stigmatised and too systematically disfigured has become common practice in recent years among architectural historians interested in the construction of buildings. But the distance between this accumulated knowledge and actual work on the material qualities of the objects of study remains too great. And yet it is the deep synergy between them through the conservation project that makes them among the most innovative critical and scholarly processes in the architecture of the 21st century.

Construction systems in the 20th century and their preservation are therefore one of TSAM's fields of study, and the material history of buildings provides it with essential knowledge. On the one hand, the history describes their background and materials; on the other hand, it contains the fundamental elements of the auto-reflexive relationship between buildings, the project of conservation and the new. It is therefore as much about providing a knowledge of materials, building sites and construction systems, together with the pathologies, forms of decay and failures that affect them, as it is about singling out and critically analysing interventions in them, whether with the aim of preserving, repairing or altering them.

2 MATERIALS, MEMORY, METHOD

The research method developed is the 'monographic study' of selected objects (buildings or complexes) chosen specifically for their relevance to the subject, the documentary part of which is developed in coherent ways. At the same time, the issues of conservation and preservation are identified and explored. The monographic studies therefore examine singular architectural works whose specifics are the subject of material and constructional analysis, supplemented by a detailed description of the conservation or restructuring, transformation or reuse projects that have affected them, on the basis of published or unpublished documentation (construction records, collection of information from designers, project managers, building contractors, etc.). The monographic studies focus on objects (buildings or complexes) emblematic of the material history of buildings in the 20th century and their remarkable diversity. This choice has been made on the basis of two fundamental criteria: firstly the historical, technical and architectural interest of the construction systems used; secondly, the existence or

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Figure 1. E. Fahrenkamp, Shell-Haus, Berlin, 1930–31 (photo G. Marino 2010).

imminence of a preferably significant conservation project. The design interest in the existing lies naturally in its quality but also in the conservation issues it raises.

The proposed research method was developed and tested at the TSAM, in particular with the development of experimental studies, such as that dealing with the Lignon housing development (Graf & Marino 2012), which firmly established the rules of applied and operational research in the field of preservation of the heritage. Part of this lengthy research took place within the framework of the project entitled “Critical Encyclopaedia for the Restoration and Reuse of 20th Century Architecture (2008–2012)”, funded by the Swiss Cooperation Project in Architecture of the Swiss University Conference (CUS), which promotes collaboration between Swiss schools of higher education. After this, it was continued within the framework of the Laboratory (2013–2019). It focused on three main themes: modern materials, in particular those used to build the lightweight façades of 20th-century architecture and the related conservation issues; construction systems and more specifically prefabricated and industrialised systems and their conservation and/or transformation; and, finally, the 20th-century technology of indoor comfort with the technological project that it entails for energy improvement (Figure 1).

All three are articulated around a fundamental issue (respect for material or iconic authenticity, improvement of energy performance, adaptability of forms of housing, etc.), closely bound up with the restoration and reuse project.

The conservation requirements of the project for the existing are the unifying thread of this research; the material history of the building is considered a privileged instrument in the definition of project strategies, procedures and appropriate technical and operational solutions.

These three major research themes were the subject of book publications: *Glass in 20th Century Architecture: Preservation and Restoration* (Graf & Albani 2011), *Understanding and Conserving Industrialised and Prefabricated Architecture* (Graf & Delemontey 2012), followed by *Histoire et sauvegarde de l’architecture industrialisée et préfabriquée au XX ème siècle* (Graf & Delemontey 2020), and finally *Building Environment and Interior Comfort. Understanding Issues and Developing Conservation Strategies* (Graf & Marino 2016b). The objective of this shaping of knowledge, challenging in terms of human investments and resources, was to create a powerful tool for researchers as well as stakeholders-actors in their choice of intervention strategies in the architecture of the 20th century, which has proved to be particularly fragile and is rapidly disappearing before our eyes.

2.1 *Glass in all its forms*

Research into glass as a construction material and system was probably the most urgent due to its very fragility, but above all because its main quality, transparency, suggests that its replacement will pass unnoticed, which is clearly not true. Yet, the beautiful nd extensive glazed surfaces of 20th century architecture are the first components to be systematically replaced, first for the sake of improved thermal insulation and then more recently for energy saving.

Given the variety and specifics of glass products from the beginning of the 20th century, a catalogue or inventory on the scale of Central Europe was ruled out. Instead a series of experts, both historians and architects, documented segments of significant technological and architectural culture. They presented a precise description of the use of glass in Secession Vienna by the pioneering Otto Wagner, Joseph Hoffmann or Adolf Loos, who drew on the considerable resources of the Bohemian glass industry. They also documented the “glass revolution” in Italy, when the country was isolated in productional autarky.

This led it to develop large-scale use of reinforced, laminated or tempered safety glass, such as Vetro Italiano di Sicurezza or Securit and Temperit, often under licence from Saint-Gobain, as well as diffusing and insulating glass like Thermolux. The shaping of glazed surfaces was recounted in the forms of curved glass transmitted by Biedermeier, that of the timber-framed Villa Neuhaus by Muthesius, for example, and the undulating volumes of modern buildings, the most emblematic being perhaps Emil Fahrenkamp’s Shell-Haus, both in Berlin. The transformations of glass blocks, bricks and pavers, which originated in the second half of the 19*th* century, were examined in their German version, such as the prismatic Luxfer blocks used by Hannes Meyer for the Bernau school, and their French version with the famous

Figure 2. L. Figini, G. Pollini, Officine Olivetti ICO, 1934–1957 (photo G. Marino 2014)

Nevada round-lens bricks. The latter were the object of immensely successful experiments in suspended form by Pierre Chareau at the Maison de Verre in Paris. These accounts and the knowledge arising from them were presented by the architects who restored the buildings, combining historical knowledge and project skills (Figure 2).

The lightweight façades and "glass houses" of the 1920s and 1930s were analysed in a second section, again with a particular concern for their material qualities and transformations. Most of these architectural works are buildings of high architectural and constructional quality, some classified as historical monuments or even UNESCO World Heritage Sites. There were two reasons for this choice. Advanced constructional elements and materials are one of the features in which modernity can be recognised. They include glass in all its states, and the restoration of modern monumental architecture, generally only in recent years, has been a subject of experimentation and debate which deserves to be documented for this reason. Prior to any intervention and to identify the original panes and frames, a case history and diagnosis of the buildings are essential, work which is not just technical but the basis of any intervention strategy (Figure 3).

Figure 3. J. de Mailly, J. Depussé, J. Prouvé, Tour Nobel, Paris-la Defense, 1963–1967 (Saint-Gobain archives, Blois).

Thus, only precious fragments remain of the polished plate glass chosen and installed by Walter Gropius in the main building of the Bauhaus since it was extensively damaged in wartime and careful renovation of the legendary curtain wall in 1976 had replaced the steel with aluminium. The last limited work on the building in 2006 reinterpreted the 1926 window frames as closely as possible, while ensuring improved energy saving. The glass façade of Sir Owen Williams' Daily Express Building in London was also reconstructed in 2006. That of the Van Nelle Factory in Rotterdam was carefully restored, which probably contributed to its Unesco classification. The Olivetti Central ICO Factory had its double façade restored on the exterior and renovated on the interior. The Clarté Building in Geneva has benefited from rigorous intervention, with the conservation of its Nevada bricks and reinforced glass still in a healthy state. All these detailed analyses advance our knowledge of the original materials as well of those that have replaced them, so combining two and sometimes more layers of construction history.

The third part, which deals with glazed surfaces since the 1960s, testifies to the technological breakthrough that was made not only with glass products, which become insulating, structural and durable – Thermopane, Polyglass, etc. – but also with synthetic plastic and elastic products and frames that have become true technological objects. Examples are the highly sophisticated window frames designed by Jean Prouvé for the Nobel Tower in Paris. All the same, they require maintenance and repair. Sometimes an accident requires emergency intervention, as happened with the damaged curtain-wall of the Pirelli skyscraper in Milan. It was dismantled piece by piece, restored and then reassembled in keeping with the standards of monumental restoration, a world first to be considered in relation to possible intervention strategies dealing with this type of component.

2.2 *Industrialising and prefabricating architecture*

Without systematically involving the whole of production, a permanent transformation of the act of building

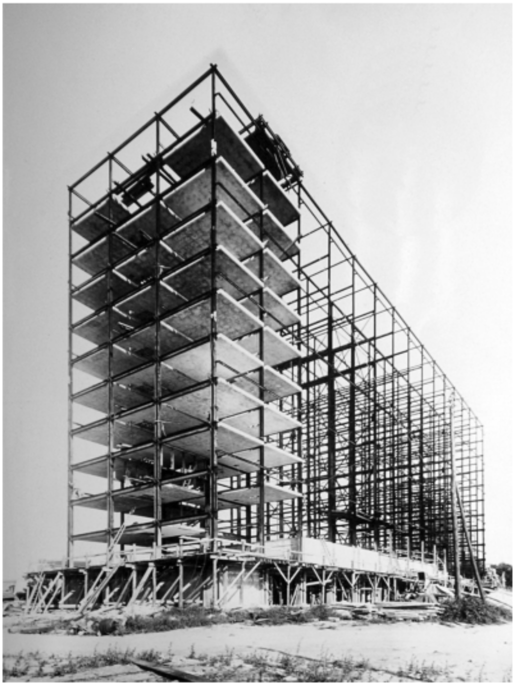

Figure 4. J.-L. Fayeton, Ensemble Porte de Lilas, Paris, 1953–1957 (Centre des archives contemporaines, Fontainebleau).

Figure 5. R. Lopez, M. Holley, Caisse d'allocations familiales, Paris, 1953–1959 (CAF Archives, Paris).

nevertheless took place in the 20th century, especially from the 1920s onward, with a rapid acceleration after World War II. It was necessary to establish an analytical vision and to identify the issues, to draw on the "industrial novel", to evoke the question of utopia and the relations between industrialisation and politics (Figure 4).

It was also necessary to understand the distant or fictional technological imagery and the reality on the ground, so different when they are French, British, Italian or German, although the construction systems, even the heaviest such as Camus panels, have spread across Europe to the East and even crossed the Atlantic to Cuba or Chile. To understand this permanent development, it is necessary to analyse the systems in series and in number, because they are the record of a fundamental structural transformation: the transition from the massive gravity structure to the resilient structure, the driving force behind the development of load-bearing structures in civil architecture from 1850 to 1970. This paradigmatic change that began in the 19*th* century, with the extensive use of iron as a strong material, would subsequently be consolidated with the successive innovations developed with reinforced concrete, which builders said would be the material par excellence of the 20*th* century. Concrete becoming common, though industrialisation and prefabrication, also called for machined materials, such as steel, aluminium, wood, or synthetic materials, especially plastics, and even eternal stone (Figure 5).

The choice of the objects of study was intended above all to represent the main industrial construction systems experimented with in the 20*th* century. Exhaustiveness being unattainable, it was a question of studying the principal construction techniques characteristic of the period studied in Central Europe, Switzerland and beyond. The objects of study were the various materials used for building structures and envelopes as well as their methods of installation (preassembly, mechanical assembly, fishplating, light prefabrication, heavy prefabrication, on-site prefabrication, factory prefabrication, open prefabrication, poured concrete, advanced traditional construction, experimental constuction, prestressing, mechanisation of quarries, pre-cut stone, etc.). Each case is associated with an operation which is also the subject of a conservation project, whatever the form it takes (heritage study, recommendations, maintenance, reclamation, upgrading, structural reinforcement, repair, recovery, restoration, renovation, conversion, restructuring, identical reconstruction, repurposing, replacement, deconstruction, redevelopment, roof lift, heritage protection, etc.). The combination of these two criteria reduced the range of possibilities but conversely considerably increased the richness of the analysis, which was thus conducted at the intersection between material history (materials, building site, construction systems) and the project as existing, the synergy of which undoubtedly constitutes the interest as well as the originality of the method used (Figure 6).

Figure 6. Addor & Julliard, L. Payot, Cité du Lignon, Geneva, 1963–1971 (Archives Addor & Julliard, Geneva).

Figure 7. Honegger frères, Cité Carl-Vogt, Geneva, 1960–1964 (photo C. Merlini 2010).

Here, we find celebrated enigmas, like Fuller's Dymaxion House, unique works intended to represent a series, like Jean Prouvé's Aluminium Pavilion or sophisticated principles of assembly, like those developed by Konrad Wachsmann for the General Panel System or the USAF Hangar (Figure 7).

Works studies include structures that adopted innovation as a paradigm, such as the CAF by Raymond Lopez and Michel Holley in Paris, and pioneering works of critical regionalism, such as the Mümliswil children's home by Hannes Meyer. Singular experiments also tested the constructional models of housing estates like QT8 in Milan and Torre Raineri in Naples, or the show homes at Northolt, a mass housing project; the domestic architecture of the *Trente Glorieuses*, from the Marseille Unité d'Habitation to the collective heritage of the Honegger brothers in Geneva; the experimental city blocks of Orléans; the apartment buildings at La Faisanderie in Fontainebleau; the sculptural concrete of the town of Flaine in the Alps; the large stone-built residential complex at Meudon-la-Forêt; the prefabrication of Park Hill in Sheffield and the Robin Hood Gardens.

Figure 8. M. Zanuso, Fabbrica Olivetti Argentina, Merlo, 1954–1961 (*L'Architettura, cronache e storia*, 3, 1982).

2.3 *Development of interior comfort*

Strategies for safeguarding glazed façades and industrialised and prefabricated architecture in the 20th century need to be developed and tested without delay in view of the pressures for alteration to which they are subject. But the future of devices of interior comfort is rarely considered, because it seemingly belongs to a technical world that lies outside architecture and its construction. Historians and architects often have limited expertise about these "machines". Reyner Banham is invariably evoked as still relevant whenever the issue is raised, proving both his fundamental role in this field of the history of construction and the dearth of subsequent studies that could be cited since he published his research (Figure 8).

This is incomprehensible given that environmental issues are at the centre of the design process for modern and contemporary architecture, on the one hand, while on the other hand they have now become essential; the imperatives of "sustainable development" being a welcome priority in architectural projects in the broad

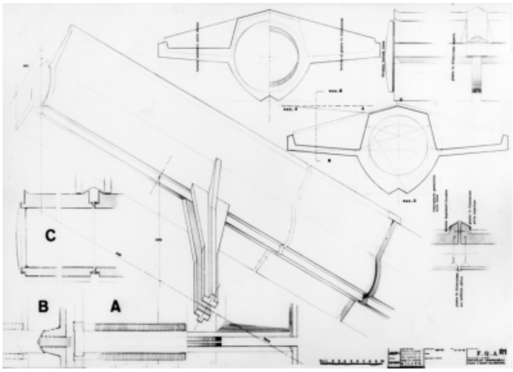

Figure 9. M. Zanuso, Fabbrica Olivetti Argentina, Merlo, 1954–1961 (Zanuso, M., 1977. La progettazione integrata per l'edilizia industrializzata. Turin: ITEC).

sense and more precisely for conservation. It is therefore necessary to reveal the structuring role of the devices of interior comfort to show how they were spatially, physically and aesthetically integrated into buildings to allow a coherent, open, transversal but largely unprecedented interpretation of the architectural output of the 20th century. And to do this we need the skills of the few historians and architects competent to deal with the place of technical systems in modern and contemporary architecture. This includes well-being and the aesthetics of comfort in the 19th and 20th centuries, the revolution in domestic life and interiors brought by technical systems, the position of the engineer-industrialist in the major stages of the development of air conditioning and the shortcomings of architect-designers, who were both fascinated and hostile. The research then explores pioneering or foundational achievements: the resounding failure of Le Corbusier and Pierre Jeanneret's attempt to apply the *respiration exacte* system to the Salvation Army's Cité de Refuge in Paris, the fine synergy between modernity and the tropical climate at the Ministry of Education and Public Health in Rio de Janeiro by Lucio Costa and his Brazilian colleagues, the importation into Banco de Bilbao (Madrid) of American air conditioning systens by a fascinated Javier Sainz de Oiza, and finally the superb control of the natural and artificial lighting of the living organism that is the Musée-Maison de la Culture in Le Havre by the lighting engineer André Salomon, working with a prestigious team of designers (Figure 9).

The premises of La Rinascente department store in Rome, built by Franco Albini and Franca Helg, were analysed comprehensively in a monographic study. Reyner Banham presented this masterpiece as an icon of environmental architecture and a remarkable demonstration of synergy between load-bearing structures and envelopes, air conditioning networks and artificial indoor and urban lighting.

The notion of comfort evolved in extremely significant ways throughout the 20th century and is today tipping dangerously towards "sustainability". Comfort and energy saving belong to two worlds that may be polar opposites, with the needs of human physiology pitted against the preservation of natural resources. The lightweight, transparent architecture of the 20*th* century, as we saw above, became the object of unjustified criticism and has been condemned for its poor performance, a judgment that completely overlooks the technical devices, not just present in the architectural design but actively participating in it. This means that they need to be treated as part of the heritage, while contributing to the preservation of the building they belong to by enabling it to attain its full potential (Figure 10).

Figure 10. G. Ponti, A. Fornaroli, A. Rosselli, P.L. Nervi, Grattacielo Pirelli, Milan, 1953–1959 (Edilizia Moderna, 71, 1960).

In this way a whole series of studies have been presented by the authors of conservation projects in high-quality but fragile architectural works with regard to an approach limited to the qualities of the envelope, which are preserved. It is a heritage in masonry like that of the Siedlung Halen by Atelier 5, the large Tscharnergut complex by Hans and Gret Reinhard or the University of the Arts by Henry Daxelhofer, all three in Bern. It also takes in metal building systems, those erected by the architects of the School of Solothurn claiming affiliation with Mies van der Rohe and the watchmaking precision mechanics of Jura, the main building of the OFSPO in Macolin by Max Schlup and the Kantonschule in Baden by Fritz Haller. Far from considering the constructional characteristics of this architecture as limitations, the architects in charge of the conservation project analyse Haller's implacable logic and his ability to take into account, even in his conception, the programmatic developments and the transformations they engender.

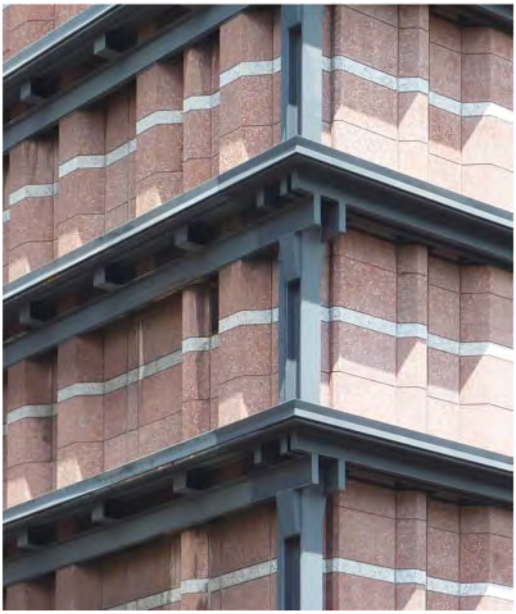

Figure 11. F. Albini, F. Helg, Edificio commerciale La Rinascente, Rome, 1957–1962 (photo G. Marino).

The issue of acoustic comfort was raised during this research but still needs to be developed. One project has been selected, the acoustic adaptation of the Tonhalle in St. Gallen. This brings out the specific method developed in the monographic studies. The original building was analysed in detail in the architecture of Gottfried Julius Kunkler and in the concrete structure by Robert Maillart to ensure its restoration and the acoustic improvement of the existing structure. This was achieved by installing a sound cloud designed with the acoustician Higini Arau-Puchades. It took the form of 120 vertical solid wood panels arranged above the stage with an alternating orthogonal geometry. The numerous constructional periods and types of projects studied cover more than a hundred years, forming a stratified history of construction.

3 CONCLUSION

The method thus established has made it possible to build up a reliable knowledge base that can be expanded and developed over time. The latest publication in the TSAM research book series (Graf & Delemontey 2020) demonstrates the open-ended structure of the research and its possible developments. In fact, this new volume completes the research by which international experts – architects, historians, researchers – have contributed to our knowledge and preservation of industrialised and prefabricated architecture and explored specific themes. The study could be extended to other themes or sub-themes. This research has established a highly articulated and largely original body of knowledge of 20th century building and its restoration (Figure 11).

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