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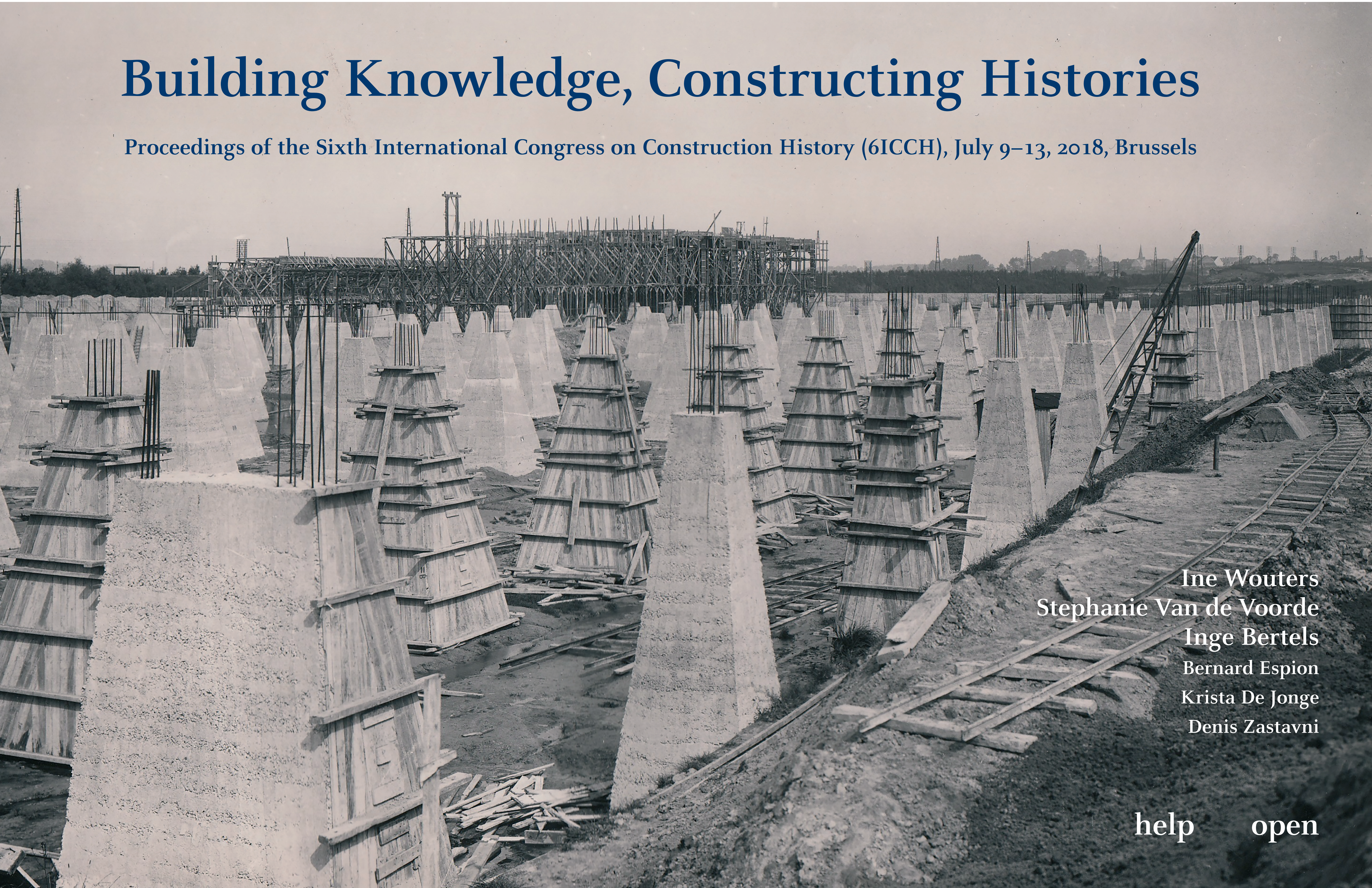

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Building Knowledge, Constructing Histories – Wouters, Van de Voorde, Bertels et al. (Eds)

Hangars built of concrete reinforced in various ways, 1908–21: Toward a majestic nave without ribbing

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ABSTRACT: At the beginning of the twentieth century and in the field of industrial construction a new scale of space emerged that stemmed from the advent of a new type of building: the hangar, intended to house airplanes, seaplanes and airships. With the need to cover ever larger spans without intermediate supports, engineers, entrepreneurs and even some architects set to work on the development of complex structural solutions. This paper outlines the evolution of hangars roofed with slender vaults built of concrete reinforced in various ways up until 1921. In an attempt to achieve the rapidity and economy of construction, the structural solutions focused on different ways of stiffening the vaults and would lead to the design of shells devoid of any reference to traditional forms that were destined to become the starting point for the generation of other exceptional types of roofing for public buildings and monuments.

Keywords: 1908–21, Hangars, Shells, Concrete

1 SLENDER VAULTS AND BUILDING TRADITIONS

The earliest applications of a kind of mixed structure of metal and concrete to the creation of slender vaults came in the second half of the nineteenth century in order to permit the rapid and inexpensive construction of fire-resistant and waterproof roofing for cisterns and tanks. This kind of roofing made an important contribution to the development of a system of construction that was adopted in industrial buildings, public buildings and monuments from the end of that century onward.

The slender vaulted roofs built between the end of the nineteenth century and the early years of the twentieth replicated traditional forms in both their configuration (domes, groin vaults, tunnel vaults) and the structural geometry of their components. The roofing was smooth or made up of cells and ribs. In smooth roofing, the concrete was reinforced with metal bars interlaced to form a regular mesh, in keeping with the structural tradition ushered in by the works of Joseph-Louis Lambot and Joseph Monier. This intertwining was to produce a first masterpiece during World War 1. It would continue to be used in the construction of vaulted roofing even after the development, in Germany, of a method of mathematical calculation that, accompanied by tests of tensile strength, would reveal different possibilities for the arrangement of the reinforcing bars than those of nineteenth-century derivation.

In vaults consisting of cells and ribs, the cells were made of concrete reinforced with metal bars interlaced in the same way as in smooth vaults, while the ribs were made out of different materials, such as reinforced brick and concrete, and combinations of them. The ribs ran along the lower or upper surface and their position was determined by a geometric arrangement or by the configuration of the roofing, at the points of intersection of the cells. The tie beams were connected with the ribs by means of vertical rods, forming a system comparable to that of the wooden or metal truss. In other cases, the vaulted roofing was made up of a metal framework with a regular pattern that produced areas enclosed by a metal mesh. Thus the framework and the mesh were embedded in a continuous layer of concrete. The size and configuration of the vaults became decisive factors in the use of stiffening like ribs or metal frameworks, at a time when the understanding of the behavior of reinforcing bars and the solving of mathematical calculations for vaulted roofing were not yet sufficiently well-defined to permit the use of bars as the only means of reinforcing roofing with large spans (Schöne 1999; Kurrer 2008, 547–54). At the same time, the role of such stiffening appeared crucial in the construction phase, as it could also function as centering for the building of the cells. For as long as they were constructed with this stiffening, whether visible or not, vaults would always be ribbed structures. It was only when, after about thirty years of experimentation and thanks to the mastery of mathematical calculation and tests of tensile strength by the science of construction, this stiffening was replaced by a particular arrangement of reinforcing bars designed to cope with static stresses that vaulted roofing could be defined as a "shell" in the sense the word is used in contemporary technology. The research into stiffening would also lead to another kind of solution in which the continuity of vaulted roofing with reinforcing bars interlaced in a uniform manner was shaped in such a way as to produce a form-resistant structure.

Industrial buildings saw the introduction of depressed vaults like those of the roofing of Monier's cisterns, without ornament or facing, combined with one another to produce spaces with no hierarchy. For reasons of a symbolic nature, vaults in public buildings were generally rounded, and joined together in such a way as to create a spatial hierarchy. It was in these buildings that concrete was faced with a variety of materials, decorated with pieces of glass or ceramic or made from a mix designed to make the material look like stone. Every detail of the vaults was studied to evoke Gothic, baroque or Oriental roofing, with the aim of representing one of the various building traditions, until they came to express the style that architects had been struggling to find since the nineteenth century. The particular nature of construction with concrete reinforced in various ways bestowed on this style an unprecedented character, that of the monolith, concealed in the structure of buildings of diverse and eclectic appearance.

In the field of industrial construction and against the background of the concept of monolith, a new scale of space emerged at the beginning of the twentieth century that surpassed even the monumental one of public buildings and stemmed from the advent of a new type of building: the hangar, intended to house airplanes, seaplanes and airships. With the need to cover ever larger spans without intermediate supports, engineers, entrepreneurs and even some architects set to work on the development of complex structural solutions. Oriented toward rapidity and economy of construction, these solutions focused on different ways of stiffening the vaults and would lead to the progressive disappearance of ribs and metal frameworks and the discovery of structures whose strength lay in their shape, producing shells devoid of any reference to traditional forms that were destined to become the starting point for the generation of other exceptional types of roofing for public buildings and monuments.

2 FRAMEWORK, RIBBING AND VAULTED ROOFING

Most of the early aircraft hangars had structures made of metal or wood and usually covered with tarpaulins, asbestos cement panels or wooden boards (Gargaro 1996; Polano 2016a, b). In the case of airship hangars, they tended to be given a parabolic profile, derived from a logical synthesis between the bulk of the dirigible, the optimal behavior of an arched structure and the technical conditions of the construction. The use of concrete reinforced in various ways was envisaged in the first ten years of the twentieth century in projects that were not realized, although its widest application in vaulted roofing coincided with the years of World War 1. The most innovative solutions for this kind of building were proposed mainly by French and Danish technicians, although, in the majority of cases, they would not be put into effect until after the end of the conflict.

In the conception of vaulted roofing for hangars, the dimensions of the buildings had a crucial role in determining the configuration of the structural systems. In the roofing of hangars designed up until sometime near the end of the war, the exceptional size of some hangars required the invention of composite structures, like the ones built of wood and metal, while hangars of smaller size tended to have vaults stiffened with arched ribs that ran along the outer or the lower surface, in line with the models widely used between the end of the nineteenth century and the beginning of the twentieth.

One of the earliest opportunities to test the potentialities of concrete reinforced in various ways for the construction of sheds with vaulted roofing was provided by the competition held in 1908 for a hangar for two airships of the Zeppelin company, measuring about 160   50 m, to be built at Friedrichshafen (Haenig 1910). A number of companies specializing in the structures built from concrete reinforced in various ways that were going to play a crucial role in the evolution and spread of shells, like Dyckerhoff & Widmann and A.-G. Wayss & Freytag, entered the competition. All the proposals in reinforced concrete envisaged a composite structural system, made up of a framework and various means of enclosing it that differed in their form and materials. The framework consisted of a succession of arches separated by gaps of between 2 and 12 m, stabilized by tie beams and braced crosswise by girders—in the case of the larger intervals, the arches were doubled. The arches had different profiles, ranging from the parabolic to the pointed to the composite, with three or five hinges, and were embedded directly in the ground, or were made up of lattice girders or Vierendeel trusses. The gaps, in the case of walls, were filled with bricks or reinforced concrete with windows, while in the other sectors the upper profile of the arches was flexed to configure flat or pitched roofing. If the upper surface was left curved, the roofing took the shape of a continuous vault or a sequence of cells interspersed with arches, built of concrete with metal reinforcing bars. This roofing was between 10 and 15 cm thick, protected in various ways by layers of insulation and waterproofing and fitted with openings for illumination and ventilation. (Fig. 1) The vaulted roofing, although contributing to the general stiffening of the structure, seems to have played a secondary static role and was designed so as not to increase the stresses on the framework. Emblematic in this sense was the choice of Hochund Tiefbau of Frankfurt am Main, H. Rek of Stuttgart and A.G. Wayss & Freytag of Neustadt to use a concrete made with pumice stone, with a thickness of 8 cm. Sometimes the persistence of traditional techniques of construction resulted in the choice of composite roofing, in bricks and concrete reinforced in various ways, like the vault of E. Züblin & Cie of Strasbourg. Bricks and concrete reinforced in various ways would continue to be used in the construction of vaulted roofing for hangars, as it is confirmed by the three depressed domes of the shed built between 1916 and 1918 by the Baugesellschaft Gebrüder Rank company at the military airport of Friedrichsfelde, in Berlin (Schmidt and Pichler 2004). A particular solution was the roofing submitted for the competition by Dyckerhoff & Widmann which, in order to obtain a light and perfectly insulated structure, envisaged enclosing the framework with a continuous sequence of prefabricated hollow reinforced concrete beams belonging to the system invented by the Swiss architect Hans Siegwart in 1900 (Siegwart 1900). This articulation into structure and light and prefabricated cladding would undergo an important evolution as a result of the research conducted by Henry Lossier (1878–1962), who from 1917 onward built hangars for aircraft with a structure of slender rods of reinforced concrete installed on site and enclosed by tiles made of *mortier riche armée* ("reinforced cement-rich mortar", Minard 1914). It was precisely the thinness of the framework's components that would induce Lossier to envisage, after the first experiments, a systematic prefabrication of the pieces. In the same way, the conception of a closure with cavities would also become the starting point, at the beginning of the 1920s, for the invention of new configurations for vaulted roofing.

When the hangars were of smaller size, the structural solutions envisaged a shift from frameworks closed in different ways to vaults stiffened with ribs. The configurations of the vaults and their combinations sometimes produced spaces evocative of those of historical buildings. In the circles of Anatole de Baudot (1834–1915) use was still made of the system of construction invented by Paul Cottancin (1865–1928) between the 1880s and 1890s, notwithstanding the repeated failures of his most important projects. Thus in Paul Voirin's 1911 design of a hangar, a succession of vaults grouped in two perpendicular bars that could rotate on tracks were set on pillars fitted with struts and stiffened by interlaced ribs in combinations inspired by those of De Baudot's Gothic revival church of Saint Jean de Montmartre. (Fig. 2).

In the search for technical configurations of vaults with ribbing a fundamental part was played by the experiments of Eugène Freyssinet (1879–1962) and the building firm he ran, Etablissements Limousin et Cie. While for factories and warehouses he continued to propose the model widely adopted in the first ten years of the twentieth century, that of tunnel vaults with a width of up to 30 m, set on pillars, with ribs, tie beams, king posts and an opening in the top, for airplane hangars he proposed, from 1913 onward, roofing that would pave the way in technical terms for the construction of his celebrated vaulted structures after the war (Freyssinet 1923a, 266). With the design for a hangar proposed to the Génie in Orléans, Freyssinet demonstrated the potential of the combination of several vaults to create a roofing with monumental characteristics, unusual in industrial and military constructions. Freyssinet's aim was to eliminate the forest of pillars of the supporting framework of the vaults. Hence he arranged a sequence of three tunnel vaults with springers embedded in the ground and spanned it with

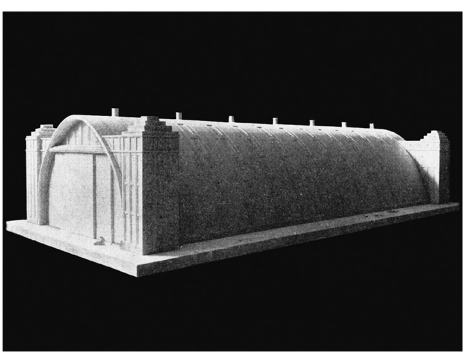

Figure 1. A.G. Alphons Custodis, competition design of airship hangar, 1908 (Haenig 1910, 147).

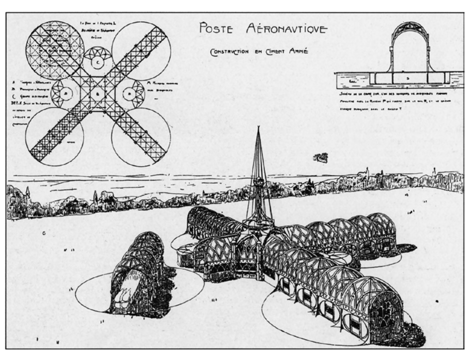

Figure 2. Paul Voirin, design of airship hangar, 1911 (Dumont 1992, 43).

another tunnel vault, obtaining four intermediate points of support. The space of the hangar ended up resembling that of traditional vaults, as they had been reinterpreted over the course of the nineteenth century.

The fact that Freyssinet was making rapid progress in his understanding of the potentialities of vaults with ribbing is evident from his construction of the hangars at Avord and Istres, between 1916 and 1917 (Espitallier 1925, 184–89). The vaults were embedded in the ground and had a dimension of 60 46 m, with ribs on the upper surface and tie beams. The presence of ribbing was necessary, according to Freyssinet, to reduce the time and cost of construction (Freyssinet 1923a, 266). In fact, although the configuration of the vaults still replicated the model developed in the first decade of the twentieth century, it was on the occasion of their construction that Freyssinet modified the stages in the process: first the vault was built by casting concrete in molds of a large size; then smaller formwork was assembled for the construction of ribs (these molds were removed 24 hours after the concrete was poured). The articulation of the vault into parts by the ribs was done for practical reasons and would not lead to an evolution in Freyssinet's vision toward smooth structures for vaults. However it is likely that it was experiences like the ones at Avord and Istres that indicated to Freyssinet the need to further articulate the vaults with ribs, for the moment limited to one stage of the construction.

3 VAULTS WITH ARRISES AND NO FRAMEWORK

In the second half of the 1910s, Christiani & Nielsen, Perret Frères, Freyssinet and Victor Auclair (1866–1928) proposed new configurations of roofing for hangars in concrete reinforced in various ways. At work in the process of evolution of the structure of the vault were, on the one hand, the progressive attainment of continuity and a monolithic character of the material, which would increasingly take the form of a continuous surface; and on the other, a constant effort to simplify systems of construction in order to save time and material. While this research led Perret Frères to invent completely new forms of vaulted roofing, it inspired Christiani & Nielsen, Freyssinet and Auclair to rework traditional types, resulting in the generation of spaces with a powerful expressive force.

In 1917 the Christiani & Nielsen company, founded in Copenhagen by the civil engineer Rudolf Christiani and Aage Nielsen, a captain in the Danish Royal Navy, built at Reval in the Russian Empire (now Tallinn, capital of Estonia) a seaplane hangar measuring 116 x 35 m, covered by three sail vaults set side by side and flanked by tunnel vaults. (Fig. 3)

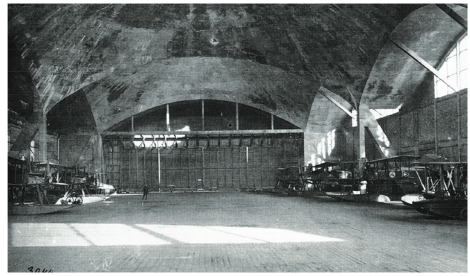

Figure 3. Christiani & Nielsen, seaplane hangar, Tallinn, 1917 (Namias 2012, 74).

The calculations for the construction of the vaults were based on the membrane theory (Mändel and Orro 2012; Mändel and Õiger 2016). Each pier was composed of a slender pillar and a massive inclined strut to bear the thrusts of the sail vaults. Each of the vaults had a large central oculus. Their thickness varied from 8 cm at the top to 12 cm at the level of the imposts. There was no ribbing on either the lower or the upper surface (only a ring around the oculus). The reinforcing bars were positioned in such a way as to create a uniform and continuous mesh like the ones used in the hulls of reinforced-concrete ships. The hangar became the ultimate expression of the potential of the metal mesh of nineteenth-century derivation. The definition of the hangar given in 1920 by Charles Newson in the pages of the British magazine *The Builder* as vaulted roofing built of "ferro-concrete" instead of "reinforced concrete" underlines the crucial role of that evenly distributed mesh with no stiffening along the lines of stress (Newson 1920, 133). In view of the imposing size and reduced thickness of the sail vaults of the hangar in Reval, the structure was compared to the basilica of Hagia Sophia in Istanbul (Newson 1920, 133).

None of the contemporary constructors of slender vaulted structures in concrete reinforced in various ways had set out to eliminate any visible arch in the intersections of the vaults in the way Christiani & Nielsen did. Having reduced those intersections to arrises without any framework, the company transformed the sail vaults into shells where the forces appeared to be distributed over the whole surface, without any visible thickening except at the point of contact of the vaults with the supports. The fact that the Danish constructors wanted to pursue a formal dematerialization of their structure is confirmed by the detail of the junction of the lateral tunnel vaults, which were connected by a narrow arris like the one marking the passage from one sail vault to another. The fact that those arrises concealed a thickening of the reinforced concrete did not modify the expressive force of Christiani & Nielsen's vaulted structure.

Vaults with arrises and no apparent framework were built around the same time by Freyssinet

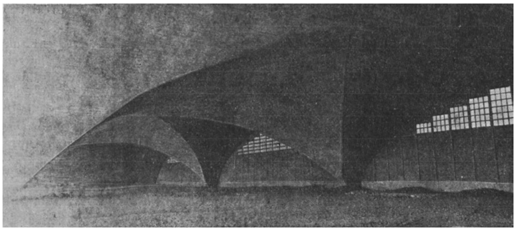

Figure 4. Eugène Freyssinet, hangar, Villacoublay, 1919–20 (Freyssinet 1923a, 267).

too, when he was commissioned to construct a hangar at Villacoublay, between 1919 and 1920. (Fig. 4) The shed measured 120 45 m and had three tunnel vaults embedded in the ground and traversed, in the central part, by another tunnel vault, along the lines of the project drawn up by Freyssinet at the beginning of the 1910s for the Génie in Orléans. Although the lower surface was smooth and continuous, like that of Christiani & Nielsen's vaults, Freyssinet stuck to the choice of ribbed solutions, with arched ribs positioned along the upper surface in accordance with the system tried out at Avord and Istres.

In the hangar built by Auclair in 1920 for the Chilean Air Force at Lo Espejo, near Santiago, the roofing took the form of three groin vaults with a diameter of 20 m each, with arrises and no apparent framework. In an early version of the design, in 1919, Auclair had planned to use three domes, of which the central one would have had a diameter of 40 m and the ones at the sides a diameter of 20 m. In the hangar the effect of lightness, present in both Christiani & Nielsen and Freyssinet's roofing, was cancelled out by the massive structure of arches and pillars on which the vaults rested.

4 PERRET FRÈRES' DOUBLY CURVED VAULTS

In their effort to design vaults of ever larger size and lower construction costs, Perret Frères came up with new configurations with a high degree of rigidity and strength. Their proposals were focused on the roofing of hangars for airplanes and airships and were made known in a patent filed in February 1920. Moreover, at the beginning of the second decade of the century, Auguste Perret (1874–1954), in collaboration with the engineer Louis Gellusseau (1883–1974), had embarked on research into different forms of slender vaults to be used as foundations of monumental buildings and the roofing of industrial buildings.

In the design of an airship hangar to be built at Bizerte, in Tunisia, for the Société de Navigation Aérienne, Perret proposed, between 1917 and 1920, sheds of different dimensions, materials and forms. Over the course of 1917 he designed a hangar with just one bay, consisting of a framework at the base inspired by the Vierendeel truss, on which was set a metal structure (Société Perret Frères 1917). In 1919 he reworked the solutions produced for the hangar in the 1908 competition and gave the structure the form of arches, while for the enclosure he resorted, in the case of the walls, to a framework with glazed infills, and in the arched sections to vaults (Société Perret Frères 1919a). In Perret's hangar the upper profile of the arches was kept parabolic, producing doubly curved vaults. The perspective drawing leads us to suppose that Perret had envisaged sectors of prefabricated vaults, jointed at the points where chains were strung between the arches.

In the solution with three bays, each spanning 45 m, designed in April 1919, Perret resorted to tunnel vaults to be constructed horizontally for the roofing of a framework made up pillars, arches and crossbeams, divided into sectors by expansion joints at the top of the arches (Société Perret Frères 1919b).

In another version of the hangar with three bays, the roofing was simplified and took the form of a closely packed transverse sequence of doubly curved vaults standing on pillars—there were three vaults in each bay (Société Perret Frères 1919c). The configuration of the uppermost part of the pillars served the needs of the static mechanism of the roofing and its construction (Société Perret Frères 1919d). The pillars were to have wide brackets to be used as imposts for the vaults, and as attachments for the tie beams. The vertical elements of closure consisted of square *claustra*, like the ones used in the cathedral at Oran. At the base of the vertical closures, where the arched buttresses were to be located, transverse vaults were introduced in accordance with the "cellular" arrangement. The whole hangar looked like a colossal Gothic cathedral built of reinforced concrete, foreshadowing the characteristics of the structure of Perret's churches roofed with vaults.

The discovery of the rigidity of doubly curved vaults led Perret to conceive, in 1920, a new design for a hangar with an even more daring structure (Société Perret Frères 1920a). This time the sequence of doubly curved vaults covered a single imposing bay with a width of 50 m and was set on an edge beam that ran right around the perimeter of the hangar to transfer the horizontal thrusts of the roofing onto struts. (Fig. 5) Long chains fitted with king posts bore part of the thrusts. Other transverse tunnel vaults were superimposed on two levels, between the arches, to contribute to the stability of the hangar. Although never realized, this design was to become the basic reference for the conception, together with the Boussiron company, of a hangar at the airport of Marignane (it was built between 1950 and 1952; the project was drawn up in 1947).

Perret's experimentation on the roofing of industrial buildings and hangar culminated in a patent filed in 1920 centering on the configuration, construction and use of singly or doubly curved structures (Société Perret Frères 1920b; Lambert 2016). In the patent, Perret also explained how to turn vaulted roofing into inexpensive horizontal structures to be used instead of traditional slabs. In the text of the patent we find justifications for the recourse to the form of the vault, which made it possible to simplify the process of construction, to reduce the scaffolding and formwork needed for reinforced-concrete slabs, to create an airspace for soundproofing and insulation and, not least, to obtain a lower surface of the structure free from ribbing and therefore able to produce particular formal and light effects. The exclusion of ribs on the lower surface did not however mean their complete elimination. The ribs were located on the upper surface instead and their presence signaled in any case. In fact Perret had no intention of obtaining the thin line of junction between the vaults discovered by Christiani & Nielsen, and while he removed the ribs from sight, he still left their flat strip visible between the vaults to reveal the presence of a decisive element of the structural system.

Perret explained the configuration and system of construction of the doubly curved vaults—*voûtes à double courbure* and *surfaces gauches* ("warped surfaces") is how he defined them. At the line of junction between *surfaces gauches*, reinforced-concrete ribs were set on the upper part of the vault. Steel and reinforced-concrete tie beams were positioned crosswise and lengthwise on the *surfaces gauches*. During construction support was provided by wooden centering resting, at the sides, on arched beams also made of wood and set on traditional scaffolding. The *surfaces gauches* were, as Perret stressed, non-deformable, light and exposed to few stresses. At the same time, the double curvature made the addition of any system for the discharge of water unnecessary and permitted expansion of the vaulted structures.

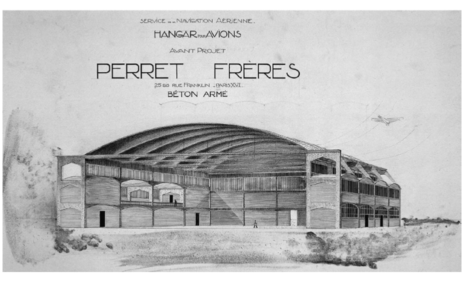

Figure 5. Société Perret Frères, design of a hangar, 1920 (Société Perret Frères, 1920a; ©Fonds Perret. SIAF/Cité de l'architecture et du patrimoine/Archives d'architecture du XXe siècle/Auguste Perret/UFSE/SAIF/2018).

5 HOURDIS AND PLISSEMENT: THE FORM OF THE STRUCTURE IN THE HANGARS AT ORLY

The extraordinary structure invented by Freyssinet for two airship hangars, which would make his work as an engineer an indispensable point of reference in the architectural debate of the early twentieth century, was the product of a particular creative process. This process tended at first to expand on a structural system that was already tested and made up of different parts, in order to increase the dimensions of the load-bearing ones, then to hollow them out to make them lighter and finally to model all the parts differently so as to turn them into a unitary organism in which no trace of its initial composite structure remained. In this process, which was achieved through the discovery of a pleated shell, Freyssinet succeeded in identifying the full plastic potential of reinforced concrete and giving that material a form that had never been seen before. Freyssinet adapted his own language to the new structure, seeking to bring out the characteristics of its form.

The process that led to Freyssinet's discovery began in 1921, when the French undersecretary of state for air announced a national competition for the construction at Villeneuve-Orly airport of two hangars for airships measuring 300 90 m and 60 m in height with five internal gangways, to be completed by the end of 1923—the competition and construction were supervised by the Services du Génie Militaire. The winner was the project submitted by the Etablissements Limousin et C[ie] for two buildings in the form of a *voûte monolithique en ciment armé* ("monolithic reinforced-concrete vault"), standing directly on the ground (Freyssinet 1923a, 265).

After building sheds for aircraft in the form of vaults with ribs on the upper surface, Freyssinet came up with a new conception of the hangar. Studies of materials, of construction techniques, their costs and their applications and of maintenance determined the configuration of the project (Freyssinet 1923b, 294).

Freyssinet put aside the system he had experimented with in the second half of the 1910s. In fact the imposing proportions of the hangar required by the competition would have entailed an increase in the dimensions of the ribs to the point where they would have had to be made hollow to lighten their weight, with consequent effects on costs and the difficulty of execution. Nor did Freyssinet find the recourse to a framework roofed with tiles like the one invented by Lossier convincing, as he did not trust the durability of the connections between the pieces of a structure exposed to the winds and severe weather conditions of the plain of Orly.

Hence for the structure of the great vault of the hangar at Orly, Freyssinet utilized a composite system similar to the ones proposed in the 1908 competition and that he had used to construct a glass factory at Montluçon between 1915 and 1917. He imagined colossal hollow arches with a rectangular section, interspersed by a system of closure and transverse stiffening, which would also provide bracing against the wind, made up of vaults and tie beams. The fundamental insight, in this phase of the design, was the decision to use arches with a parabolic profile that would not be solid like the ones he had built for the bridge at Villeneuve-sur-Lot, but hollow to economize on material. It was those hollow arches, and not so much the vaults, that constituted the prelude to the transformation of the hangar's structure into an articulated and continuous surface. Thanks to the section of the hollow ribs and the vaults, obtained empirically by enlarging a structure he had already tried out, Freyssinet discovered the potential of the form when he started to consider its neutral axis. It was at this point that he decided to modify the whole structural system, which was no longer conceived as a juxtaposition of parts (hollow arches and vaults with tie beams), but as a continual sequence of a material, reinforced concrete, to be located as far as possible from the neutral axis. According to his reconstruction of the process of design, Freyssinet here proposed a series of hollow arches placed side by side to create a hollow structure with continuous surfaces.

At this point in the creative process, Freyssinet came up with a terminology that allowed him to explain the special nature of his structural form. By using the word *hourdis* ("hollow block"), the technical term for a block with cavities and tongues for the construction of ribs, his intent was to stress the crucial passage in the invention, when Freyssinet abandoned the succession of parts—arches and vaults—in favor of a continuous system. It is no accident that his *hourdis* was *sans aucune nervure* ("without any ribbing"), as he made clear (Freyssinet 1923a, 269). The term *plissement* ("pleating"), introduced to explain what his *hourdis* would become when the cavities were eliminated, illustrates with what might even be called poetic precision the final state of the structure, which derived its equilibrium and its bracing simply from its form. Even the reinforcing bars had a secondary static role, Freyssinet pointed out, and had a section of between 7 and 10 mm. Although the configuration of the pleated *hourdis* had been designed to eliminate all ribbing, its section was still modified at the arrises. It was in these sectors that the thickness of the structure rose from the 8–9 cm envisaged for the *hourdis* to 20 cm. In addition, tie beams with a square section (14 x 14 cm) and six reinforcements with a thickness of 10 mm were added on the upper surface, every 10 m.

The configuration of the pleated *hourdis* would not have been possible without taking the questions of the construction of this form into consideration. At all stages of the design prior to the final version, the large size of the hangar had induced Freyssinet to envisage the use of hollow structures. The transformation of the *hourdis* into pleating was the outcome of the metamorphosis of a system in order to make it easy to construct. When Freyssinet opened up the *hourdis* to eliminate the cavities and entered the world of the pleated form, he modeled the folds so that they could be made with the minimum waste of material. It is precisely in the design of the formwork, intended to make it easy to remove, and in the resistance to lateral pressures that we should look for the reason for the inclinations given by Freyssinet to the faces of the pleating. "It is a perfect form from the viewpoint of the simplicity of its execution" (Freyssinet 1923a, 269).

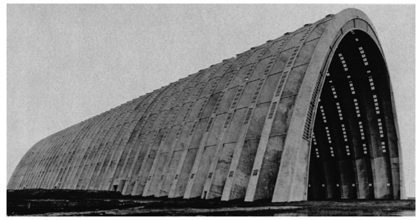

Figure 6. Eugène Freyssinet, airship hangar, Orly, 1921–23 (Fernandez Ordoñez 1979, 331).

And it was Freyssinet himself who made a comparison between his pleated *hourdis* and a kind of section in use in the metal structural work, the one devised by Charles Ferdinand Zorès (Zorès 1853; Freyssinet 1923a, 269). The reference to metal framework in connection with his structure can only be seen as the attainment of a goal in the creation of reinforced-concrete forms that could vie with the lightness, thinness, elegance and strength of nineteenth-century metal structures. Freyssinet was conscious of the fact that the hangars at Orly were going to represent for reinforced concrete what the Eiffel Tower had been for iron. (Fig. 6).

"Although no artistic concerns have affected our decisions, owing to the purely industrial nature of the buildings at Orly, their architectural aspect is generally appreciated", explained Freyssinet. "The effect achieved is the consequence of measures of a purely technical character, but so rational and simple that they are immediately understood and thus satisfy the eye, even though it is a severe judge of forms to which it is not accustomed" (Freyssinet 1923c, 319).

6 CONCLUSIONS

Christiani & Nielsen and Freyssinet's hangars represent two important chapters in the history of shells, one the ultimate consequence of an established tradition of construction of nineteenth-century origin, and the other the result of the discovery of structures whose strength came from their form. But the evolution of vaulted roofing in concrete reinforced in various ways over the course of the 1920s and 1930s would not follow the line indicated by the hangars at Reval and Orly. Only in the 1940s and 1950s the potentialities of the evenly distributed metal mesh tried out by Christiani & Nielsen and the pleating discovered by Freyssinet would generate a whole catalogue of forms of shells, of which the principal constructors, from Pier Luigi Nervi (1891–1979) to Félix Candela (1910–97), would propose an extensive series of versions. The technical evolution of the shells that had the greatest success during the 1920s and 1930s was instead the one based on mathematical calculation accompanied by tests of tensile strength. Emblematic in this sense was the work of the Dyckerhoff & Widmann company and its engineers Franz Dischinger (1887–1953) and Ulrich Finsterwalder (1897–1988). After first using metal framework embedded in the concrete and ribbing for the construction of vaulted roofing, Dyckerhoff & Widmann company came up with a particular arrangement of the metal reinforcing bars, generating shells of varied shapes.

REFERENCES

Dumont, Marie-Jeanne. 1992. "La pietra filosofale: Anatole de Baudot e i razionalisti francesi." *Rassegna* XIV, no. 49, March: 37–43.

Espitallier, Georges. 1925. *Cours de béton armé*. Paris: Ecole Spéciale des Travaux Publics.

Fernandez Ordoñez, José A. 1979. *Eugène Freyssinet*. Barcelona: 2C.

Freyssinet, Eugène. 1923a. "Hangars à dirigeables en ciment armé." *Le génie civil* XLIII, no. 2145, September 22: 265–73.

Freyssinet, Eugène. 1923b. "Hangars à dirigeables en ciment armé." *Le génie civil* XLIII, no. 2146, September 29: 291–97.

Freyssinet, Eugène. 1923c. "Hangars à dirigeables en ciment armé." *Le génie civil* XLIII, no. 2147, October 6: 313–19.

Gargaro, Martina. 1996. "Un tetto per la nave dell'aria." *Rassegna* XVIII, no. 67: 61–71.

Haenig, Alfred. 1910. Luftschiffhallen-Bau. *Sammlung moderner Luftschiffhallen-Konstruktionen mit statistischen Berechnungen*. Rostock i. M.: C. J. E. Volckmann Nachfolger.

Kurrer, Karl-Eugen. 2008. *The History of the Theory of Structures: From Arches Analysis to Computational Mechanics*, Berlin: Ernst & Sohn.

Lambert, Guy. 2016. "Préfabrication et standardisation chez Perret dans les années 1920. Performance de l'outillage et circulation des savoir-faire." In *Les temps de la construction. Processus, acteurs, matériaux*, edited by François Fleury et al., 849–60. Paris: Picard.

Mändel, Maris and Karl Õiger. 2016. "Conservation of Tallinn seaplane hangars." *Proceedings of the Institution of Civil Engineers—Engineering History and Heritage* 169, no. 1: 3–10.

Mändel, Maris and Oliver Orro. 2012. "The marvellous reinforced concrete shells of Tallinn seaplane hangars in the context of early concrete architecture in Estonia." *Construction History*, no. 27: 65–85.

Minard, Paul-Charles. Tuiles en ciment armé. FR Patent 467,643, filed January 23, and issued April 2, 1914.

Namias, Olivier. 2012. "Musée Maritime d'Estonie, Tallinn." *D'Architectures*, no. 212, October: 72–75.

Newson, Charles. 1920. "An example of Modern Dome Construction." *The Builder* CXVIII, no. 4017, January 30: 132–36.

Polano, Sergio. 2016a. "Atlante degli hangar per dirigibili 2016 - parte prima." *Casabella*, no. 867, November: 3–19.

Polano, Sergio. 2016b. "Gli ultimi nidi delle aeronavi. Atlante degli hangar per dirigibili 2016 - parte seconda." *Casabella*, no. 868, December: 3–17.

Schmidt, Hartwig, and Gerhard Pichler. 2004. "Die Flugzeughallen des ehemaligen Militärflughafens Berlin-Friedrichsfelde." *Beton—und Stahlbetonbau* 99, no. 8: 682–92.

Schöne, Lutz. 1999. "Kuppelschale und Rippenkuppel—Zur Entwicklung von zwei frühen Eisenbeton-Konstruktionsarten." In *Zur Geschichte des stahlbetonbaus Die Anfänge in Deutschland 1850 bis 1910*, edited by Hartwig Schmidt: 66–74. Berlin: Ernst und Sohn.

Siegwart, Hans. Deckenkonstruktionsbalken. CH Patent 19,425, issued March 7, 1900.

Société Perret Frères. Société de Navigation Aérienne. 1917. Objet PERAU-066, Dossier 535 AP 66/3. Doc. CNAM-20–06–0021. Fonds Perret, Auguste et Perret frères, Institut Français d'Architecture, Paris.

Société Perret Frères. Hangar à dirigeable. 1919a. Objet PERAU-070, Dossier 535 AP 70/1. Doc. CNAM-20–06–0033. Fonds Perret, Auguste et Perret frères, Institut Français d'Architecture, Paris.

Société Perret Frères. Hangar pour 3 dirigeables. 1919b. Objet PERAU-070, Dossier 535 AP 70/1. Doc. CNAM-20-06-0034. Fonds Perret, Auguste et Perret frères, Institut Français d'Architecture, Paris.

Société Perret Frères. Hangar pour grands dirigeables rigides. 1919c. Objet PERAU-070, Dossier 535 AP 70/1. Doc. CNAM-20-06-0031. Fonds Perret, Auguste et Perret frères, Institut Français d'Architecture, Paris.

Société Perret Frères. 1919d. Objet PERAU-070, Dossier 535 AP 70/1. Doc. CNAM-20-06-0032. Fonds Perret, Auguste et Perret frères, Institut Français d'Architecture, Paris.

Société Perret Frères. Hangar pour avions. Avant Projet. 1920a. Objet PERAU-079, Dossier 535 AP 79/1. Doc. CNAM-20-06-0043 A. Fonds Perret, Auguste et Perret frères, Institut Français d'Architecture, Paris.

Société Perret Frères. Perfectionnements apportés à l'établissement des planchers et des toitures en ciment armé. FR Patent 510,802, filed February 27, and issued December 11, 1920b.

Zorès, Ch. Ferdinand. 1853. *Recueil de fers spéciaux, des expériences faites sur leur résistance et de leurs divers applications dans les constructions*. Paris: Chez l'Auteur.