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Pioneering hypar thin shell concrete roofs in the 1930s

The paper explores the conditions of emergence and first applications of thin hypar concrete shells. They appeared in France in the 1930s in the context of building hangars for aircraft and roofs for workshops at air or naval bases. Two French engineers were mainly involved in the development of this form: BERNARD LAFFAILLE, who began designing conoid shells in 1927 but actually never got the opportunity to build concrete hypars, and FERNAND AIMOND, who established the membrane theory of the hypar in 1932 and applied it to design and construct several HP roofs in 1934–1939. The paper describes these forgotten structures and recalls the influence of AIMOND's contributions from the mid-1930s on the subsequent widespread adoption of the hypar.

Anfänge der dünnen Hyparschalen aus Beton in den 1930er-Jahren

Dieser Beitrag beschäftigt sich mit den Bedingungen der Entstehung und den ersten Anwendungen von dünnen Hyparschalen (HP-Schalen) aus Beton. Diese ergaben sich in den 1930er-Jahren in Frankreich im Zusammenhang mit der Errichtung von Flugzeughangars und Werkstattdächern für Flugplätze und Flottenstützpunkte. Es waren zwei französische Ingenieure, die hauptsächlich an der Entwicklung dieser neuen Bauart beteiligt waren: BERNARD LAFFAILLE, der 1927 mit dem Entwurf von Konoidschalen begann, jedoch nie die Gelegenheit hatte, Hyparschalen aus Beton zu bauen, und FERNAND AIMOND, der 1932 die Membrantheorie der Hyparschalen etabliert hat und diese auch in den Jahren 1934-1939 für den Entwurf und die Errichtung zahlreicher HP-Schalendächer angewendet hat. Im Beitrag werden diese heute teilweise in Vergessenheit geratenen Konstruktionen beschrieben und daran erinnert, welchen Einfluss AIMOND seit Mitte der 1930er-Jahre auf die anschließende verbreitete Anwendung von Hyparschalen hatte.

1 Introduction

A thin concrete shell in the shape of a hyperbolic paraboloid (HP or hypar) is a form of space covering which enjoyed great popularity in the 1950s, notably as a result of the numerous works, with considerable diversity of form, of Mexican engineer and architect FÉLIX CANDELA (1910–1997) [1, 2]. The purpose of this article is to shed light on the origins of this form. Already when the use of this type of structure was at its height, SIEGEL observed: "Who deserves the credit for designing the first HP? It is impossible to say. As so often when uncertainty prevails, the discovery was probably made at the same time by several people working independently" [3].

The first structures, however, were unquestionably French and were built in the 1930s as part of studies at the Air Ministry, for facilities (hangars, workshops, etc.) at air bases and airfields. Starting from the time of the First World War, the usual type of concrete hangar for aircraft developed in France was the short barrel vault-type "tunnel" hangar, stiffened externally with ribs, internally with trusses or by corrugation. In the late 1920s, it became necessary to envisage other types of hangar to cope with the increase in the size of aircraft and the new requirements for the operation of air navigation. In 1928, the famous engineer ALBERT CAQUOT (1881–1976) became the first executive director of the newly created Air Ministry [4]. He held this post until 1934. He set up the specifications for a new type of double-canopy hangar, called the "Caquot" hangar. Only three hangars of this type were constructed: at Lyon-Bron (1931–1932), at Orléans-Bricy (1933) and at Fréjus (1933–1934). The Lyon-Bron hangar was demolished in 2012 [5]; the hangars at Bricy and Fréjus are still partly standing today.

2 BERNARD LAFFAILLE and the experimental canopy at Dreux

It is in this context that the name of the engineer BERNARD LAFFAILLE (1900–1955) appears as a possible pioneer of the HP. Unusually in the field of construction, a significant part of the archives of this engineer have been preserved, as Collection 206 at the French Institute of Architecture (IFA, Paris). An inventory of the archives was prepared by NICOLAS NOGUE [6, 7].

LAFFAILLE, a 1923 graduate of the École Centrale de Paris, was a precursor of the technique of thin shell concrete roofs and a pioneer in the use of conoid-form thin shells, of which he produced many examples between 1927 and 1932 as technical director of the 4Cs company ("Construction de Charpentes et Couvertures en Ciment") [7, 8]. Around 1933, he became an independent consulting structural engineer. In his projects, he aimed

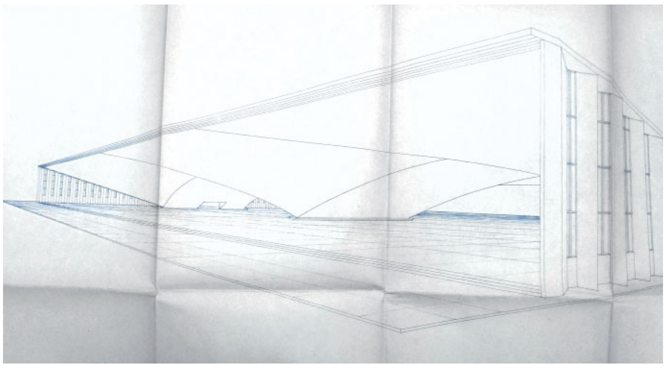

Fig. 1 Project for a Caquot type hangar with conoid shells (Fonds Laffaille. SIAF/Cité de l'architecture et du patrimoine/Archives d'architecture du XXe siècle)
Projekt für einen Hangar nach Caquot mit Konoidschalen (Fonds Laffaille. SIAF/Cité de l'architecture et du patrimoine/Archives d'architecture du XXe siècle)

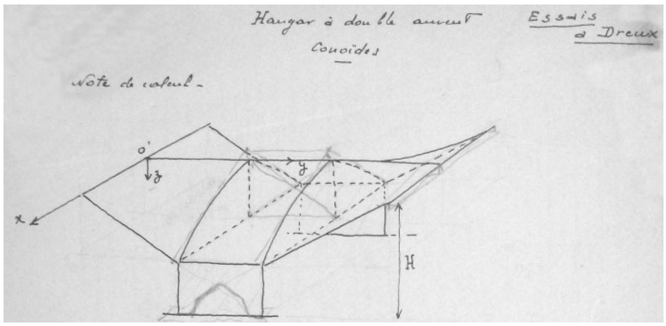

Fig. 2 Drawing of the double canopy at Dreux with conoid shells (Fonds Laffaille. SIAF/Cité de l'architecture et du patrimoine/Archives d'architecture du XXe siècle)
Zeichnung der doppelten Überdachung in Dreux mit Konoidschalen (Fonds Laffaille. SIAF/Cité de l'architecture et du patrimoine/Archives d'architecture du XXe siècle)

to propose an original and elegant roofing solution in thin shell concrete for the aircraft hangars programme with "Caquot"-type canopies. The use of conoid shells to produce a double canopy is clearly the object of Patent No. 726,846, which he filed in January 1931. IFA file 206-59/2 contains several projects studied by Laffaille in 1932 for double-canopy hangars with an overhang of 25 m (Figure 1). In the absence of any reference for his model of computation, he experimented in his project with a 1/2 scale model canopy built at Dreux in 1933 by the Rouzaud company. This test structure, which was used for many measurements, was an assembly of four thin shells, 5 cm thick, with an overhang of 12.5 m. It was mentioned by Laffaille in an article in 1934 [9], and results of calculations and measurements, together with several photographs, were published in his important report of 1935 [10] describing his realisations of roofs using conoids. It is interesting to note that Laffaille does not go into a discussion of the measurements as compared with the theoretical results.

Until now, this structure had been considered to be the very first roof composed of thin HP-shaped shells. However, that was an error, as consultation of IFA files 206-140/6 and 206-186/7 clearly shows that Laffaille designed and produced the thin shells of this canopy at Dreux not as HPs, but as conoids. It is true that his conoids are geometrically close to HPs, and HPs are a special class of conoids when the directrix curve is reduced to a straight line. This is clear from the figures in Patent No. 763,842 filed by Laffaille on 31 January 1933 as a supplement to his patent of 1931. However, his "Figure 2" (Figure 2) and photographs and comments published in [10] show unambiguously that the thin shells of the canopy at Dreux are bordered at their embedment by a curve. It should be noted that in neither of his two articles [9, 10] does Laffaille say explicitly that the thin shells at Dreux are HPs, but he knowingly introduced and maintained the confusion: he did this first in [9], written in response to [11], by emphasising that the thin shells of the Dreux canopy fall within a class of surfaces, defined in his patent, which contains the HP. But even more flagrantly, the drawing which he gives of the canopy at Dreux in "Figure 26" [10] represents a set of HPs with straight sides which does not correspond to what was built.

Judging from the plans kept at the IFA, the "Caquot" hangars conceived of by Laffaille on the model of Dreux (Figure 1) would have been exceptional structures, of rare elegance. It is therefore a matter of regret that they were never built.

3 The works of Fernand Aimond

Nogue, who sees HPs in the canopy at Dreux, has launched and attempts to justify the hypothesis that Laffaille was halted in his attempts to construct roofs for aircraft hangars or workshops with thin concrete shells in the 1930s due to the bias and interests of Fernand Aimond, Director of Studies in the Air Bases Department at the Air Ministry from 1932 [7, 8, 12]. Fernand Aimond (1902–1984), a graduate from Polytechnique and the École des Ponts et Chaussées (ENPC, Paris) in 1923, and also holder of a doctoral degree, joined the Air Ministry in 1929. In our opinion, he should be considered the true "father" of the HP, from the point of view of both its theoretical study and its first practical realisations and their posterity. This paternity, although attested to by one of his collaborators at the time [13], seems to have been completely obscured or even denied subsequently.

Consultation of documents in Collections 29649 and 29905 deposited at the École Nationale des Ponts et Chaussées, which seem to have been little utilised so far, shows that, starting in 1932, Aimond had studied in detail the potential of the HP for the construction of thin shell roofs. In particular, as early as November 1932 he had imagined the classic HP arrangements which he only published in 1936 [14] and which were subsequently re-

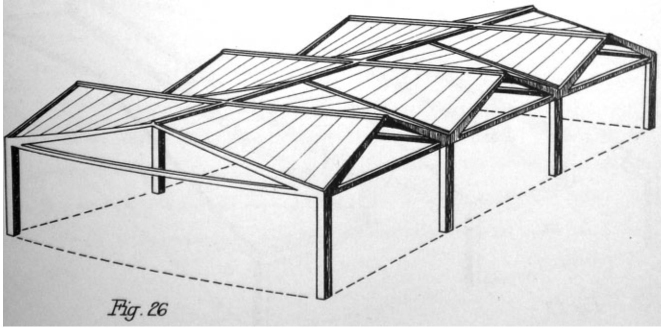

Fig. 3 Project for a workshop with gable type hypars (© École nationale des Ponts et Chaussées, Fonds 29649)
Projekt für eine Werkstatt mit giebeldachartigen Hyparschalen (© École nationale des Ponts et Chaussées, Fonds 29649)

produced repeatedly by different authors. For example, Figure 3 represents an HP arrangement from file ENPC/29649/10307 dated 14 November 1932.

An initial theoretical article which AIMOND published on this subject in "*Le Génie Civil*" in 1933 [11] met with a response in the same journal, albeit more than a year later, from LAFFAILLE [9] who, while attempting to claim the priority of the invention of the HP with his patent on conoids from 1931, no doubt understood that his hopes of constructing canopy hangars based on his model at Dreux (the testing of which took place during 1933–1934) were seriously compromised by AIMOND's work and prominent position in the Ministry. Indeed, in the years that followed, it seems that LAFFAILLE no longer worked with thin concrete shells. For his part, AIMOND studied several HP structures, which were realised in the years 1933–1939.

The year 1936 represented FERNAND AIMOND's apogee as a theorist and designer of HPs:

– He gave a series of lectures on the subject at the École des Ponts et Chaussées in which he presented all his projects, completed and under investigation;
– He published a voluminous study [14] detailing the structural calculation of HPs according to what is conventionally known as the "membrane" theory. His study is famous for its Figures 7–10, describing four conventional provisions for HP arrangement, including the gable type ([14] p. 9, Figure 9) and the umbrella type ([14] p. 9, Figure 10). The rest of the paper is very mathematical and unnecessarily obscure ([1], p. 239): it is not from reading this that one will understand the basic structural operation of the HP, which, through its simplicity and its optimal nature, would appeal to many engineers;
– He published the description and many photos of his HPs in a special issue of the influential journal "*Science et Industrie*" devoted to French aviation [15, 16]. Several illustrations of his works were also published in the widely read journal "*L'Architecture d'Aujourd'hui*" [17].

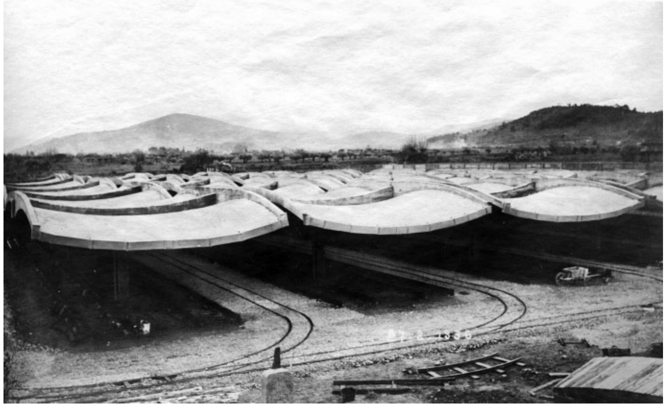

Fig. 4 Shelters for hydrogen bottles at Cuers-Pierrefeu (© École nationale des Ponts et Chaussées, Fonds 29905)
Schutzdach für Wasserstoffflaschen in Cuers-Pierrefeu (© École nationale des Ponts et Chaussées, Fonds 29905)

The roofs composed of thin HP shells segments which were designed by AIMOND and which were constructed are, in chronological order:

– Shelters for hydrogen bottles at the Cuers-Pierrefeu airship base (1933–1936)

30 HPs, saddle-type, 12 m × 7 m, thickness t = 3 cm, each resting on a pillar [15, 17] (Figure 4).

– Workshops for the School of Naval Mechanics at Rochefort (1936)

56 HPs in an "umbrella", 14.6 m × 13.7 m, thickness t = 4 to 5 cm, each resting on a pillar [15, 18] (Figure 5). They replaced an audacious roof composed of very large conoid shells designed by LAFFAILLE and built in 1932–1933 but which reportedly performed badly [7, 8], perhaps due to problems with the foundations. NOGUE [7, 8]

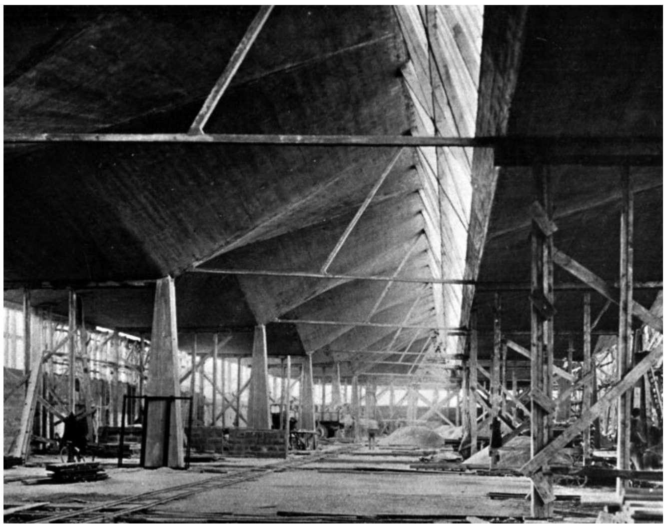

Fig. 5 Workshops for the School of Naval Mechanics at Rochefort (© École nationale des Ponts et Chaussées, Fonds 29905)
Werkstätten für die Schule der Flottenstation in Rochefort (© École nationale des Ponts et Chaussées, Fonds 29905)

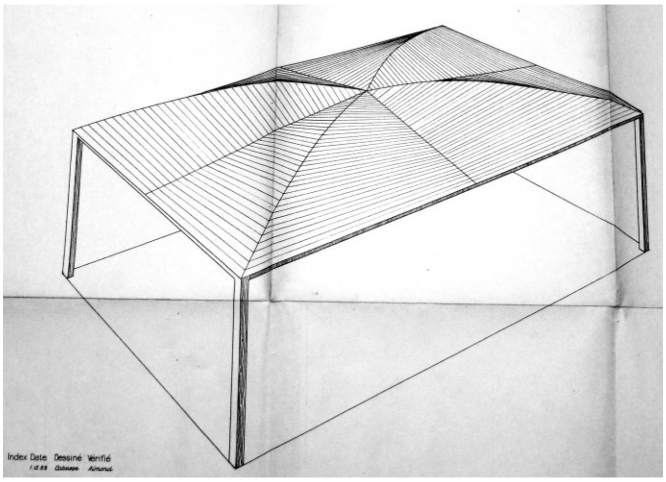

Fig. 6 Octopartite vault with HP segments (© École nationale des Ponts et Chaussées, Fonds 29649)
Achtteiliges Gewölbe mit HP-Segmenten (© École nationale des Ponts et Chaussées, Fonds 29649)

gives arguments aiming at attributing at least some co-authorship to LAFFAILLE in the early stage of the design of these hypars.

As early as 1933, AIMOND was studying a roof unit in the shape of a "priest's beret" composed of 8 HP segments (Figure 6). Using the vocabulary of vaults, one could also call this an "octopartite" shell or a "cross-ribbed" shell. This unit is used repeatedly by AIMOND in several applications. It was even the subject of experimental model studies [19].

– Garages at Saint-Mandrier (1935) and Lanvéoc-Poumic (1936)

These are garages in three "cross-ribbed" units (Figure 6). Each unit, with dimensions 15 m × 15 m and thickness t = 5 cm, is supported at its four corners by posts. The garage at the Saint-Mandrier naval air base (Figure 7) near Toulon is documented by [13, 17] and especially [20] and was still standing in 2014. The construction in 1936 of a similar garage at Lanvéoc-Poumic near Brest is attested to by a photo in IFA file 206-181/3.

– Workshops for arming of torpedoes at Berre (1936–1937)

These workshops (Figure 8) are mentioned in [13, 17]. This is also an application of octopartite shells in HP segments. The sheds are covered by ten units with dimensions 8 m × 10.5 m and thickness t = 3 to 4 cm. The main building is covered by two units 10.5 m × 10.5 m and thickness t = 3 to 4 cm.

– Hangars for aircraft at Limoges-Feytiat (1935–1936)

The hangar at Limoges-Feytiat (Figure 9) is documented by [12, 15, 16, 17] and especially [21]. This has a roof composed of 16 HPs with dimensions 10.25 m × 12 m and

Fig. 7 Garages at Saint-Mandrier (Fonds Laffaille. SIAF/Cité de l'architecture et du patrimoine/Archives d'architecture du XXe siècle)
Garage in at Saint-Mandrier (Fonds Laffaille. SIAF/Cité de l'architecture et du patrimoine/Archives d'architecture du XXe siècle)

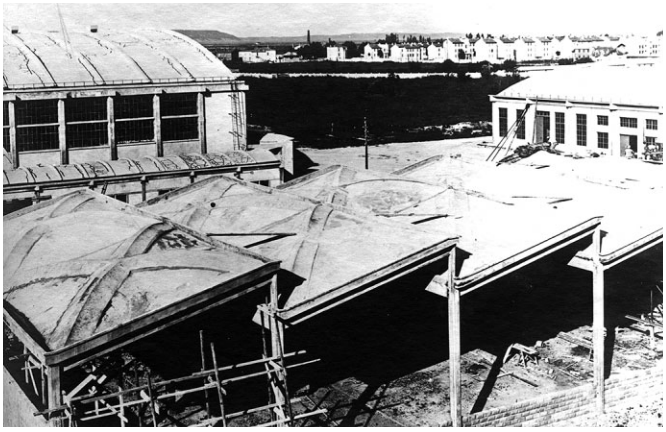

Fig. 8 Workshops for arming of torpedoes at Berre (© École nationale des Ponts et Chaussées, Fonds 29905)
Werkstätten zur Bewaffnung von Torpedos in Berre (© École nationale des Ponts et Chaussées, Fonds 29905)

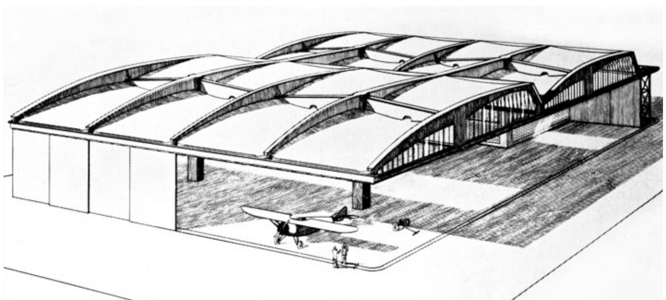

Fig. 9 Hangars for aircraft at Limoges-Feytiat (© École nationale des Ponts et Chaussées, Fonds 29905)
Flugzeughangars in Limoges-Feytiat (© École nationale des Ponts et Chaussées, Fonds 29905)

thickness t = 5 cm, supported by four offset columns, covering a total area of 53.5 m by 41 m. Demolished. A plan dated 1933 preserved in ENPC Collection 29649 indicates a similar project for Toulouse-Francazals airfield. HAHN [13] reported that a similar hangar was built at Le Havre.

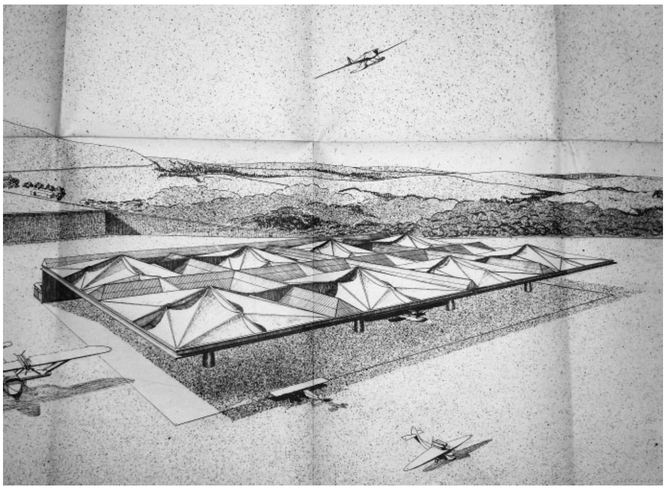

Fig. 10 Project, dated June 1934, for hangar for aircraft at Lanvéoc-Poulmic (© École nationale des Ponts et Chaussées, Fonds 29649)
Projekt, datiert mit Juni 1934, für einen Flugzeughangar in Lanvéoc-Poulmic (© École nationale des Ponts et Chaussées, Fonds 29649)

– Hangars for aircraft at Lanvéoc-Poulmic (1934–1937) and Châteaudun (1937–1939)

The hangar at Lanvéoc-Poulmic (Figure 10) is the first of three such hangars built. Several photographs of this hangar have been published [13, 16, 17, 18]. The other two were built at Châteaudun [13, 18]; one of them is still standing [22]. These structures are complex and of an impressive size: each hangar is made with a roof produced by the juxtaposition of 8 large umbrellas with dimensions 36 m × 36 m, each formed from many HP shell segments of thickness t = 5 cm (Figure 11). The total area covered by one hangar is 171.5 m by 88.5 m.

– Seaplane assembly hall at Saint-Mandrier (1936–?)

This is the most extensive application of self-supporting octopartite shells. The hall at Saint-Mandrier is composed

Fig. 11 Hangars for aircraft under construction at Lanvéoc-Poulmic (Fonds Laffaille. SIAF/Cité de l'architecture et du patrimoine/Archives d'architecture du XXe siècle)
Bauphase eines Flugzeughangars in Lanvéoc-Poulmic (Fonds Laffaille. SIAF/Cité de l'architecture et du patrimoine/Archives d'architecture du XXe siècle)

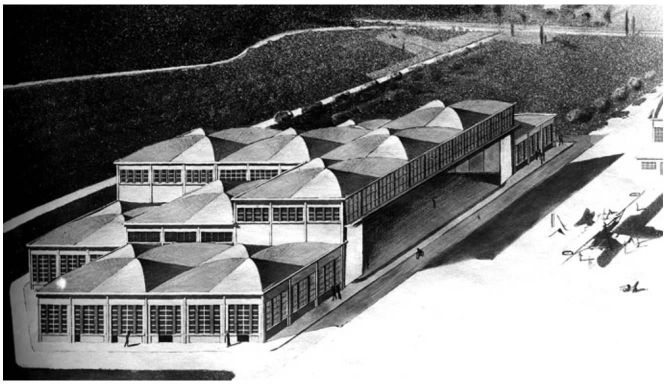

Fig. 12 Seaplane assembly hall at Saint-Mandrier (© École nationale des Ponts et Chaussées, Fonds 29905)
Montagehalle für Wasserflugzeuge in Saint-Mandrier (© École nationale des Ponts et Chaussées, Fonds 29905)

of 13 identical units (Figure 12) [15]. The dimensions of a unit are 20 m × 20 m and the thickness t of the HP segments is 3 to 4 cm. It was still standing in 2014. NOGUE [7, 8] has identified a similar construction built at Lanvéoc-Poulmic and called it the "Hagia Sophia" type.

4 Assessments of the work of FERNAND AIMOND

Examination of the projects built by AIMOND leads to some observations. His roofs are generally created by the repetition of a greater or smaller number of identical HP-based elements. Behind this there is obviously an idea of constructional economy. However, their architectural expression is poor and their structural readability is complex: one is struck by the contrast between the thinness of the HP shells and the heaviness of some edge beams. The reason for this must be seen in the fact that the design of these structures is dogmatically dictated by the membrane structural model of the HP developed by AIMOND, which is a – "statically admissible" – simplified theory which only satisfies the equilibrium equations without concern for strain compatibility. It is not without interest to quote here two very critical opinions of EUGÈNE FREYSSINET (1879–1962), one of them expressed at a very early stage:

"It is not always easy to achieve agreement between the deformation of the vaults and the deformation of the elements at the edge. In a vault there is compression, and in an element at the edge there is traction. For example, in hyperbolic paraboloids, one is obliged to support these paraboloids on an element which can be a vault and where there are extremely large forces. It is quite difficult to reconcile these deformations, and I think it is here that the reason can be found for some setbacks encountered in structures of this kind." (Discussion of [23], p. 51)

"I have never understood anything of Mr AIMOND's parabolism, and I am going to tell you why; he is a good friend, and I have often talked with him; building structures in which the compressive stress is equal to zero everywhere may be an objective, but then you have to transmit loads by shears. He supported these on structures which were submitted to 150 kg[/cm^2]; I didn't understand any more: he had cracks and said they were due to settlement of the soil." (Discussion of [24] p. 1020)

Although AIMOND's HP realisations – the innovative and original nature of which should be noted – were not passed on to posterity with the rank of major structures, it is important to emphasise the profound influence of AIMOND's writings and particularly of his study [14]. As MOREYRA GARLOCK and BILLINGTON recount ([2] p. 56): "A long article by the French engineer F. AIMOND was CANDELA's introduction to the hyperbolic paraboloid, commonly referred to as hypar", which is also attested to by CANDELA himself in several of his publications and by FABER ([1] p. 30). In 1955, CANDELA ([25] p. 403) reinterpreted the four basic HP arrangements which, as we have seen, AIMOND had imagined as early as 1932 and published in 1936 [14], adding, very usefully, the forces – tension or compression – induced by the HP shell segments into the edge beams. And it is CANDELA's drawings that are popular in the literature [26, 27], rather than AIMOND's originals – which, however, have recently been reproduced by ADDIS ([28] p. 497) and KURRER ([29] p. 553).

5 The birth of a legend

The first to identify LAFFAILLE as the inventor of the HP seems to have been his collaborator RENÉ SARGER (1917–1988) who wrote in ([30] p. 16): "As early as 1933, he constructed two experimental buildings in Dreux ... The second, in reinforced concrete, was the first realisation of a hyperbolic paraboloid." In this article ([30] p. 17), SARGER provides a schematic representation of the canopy at Dreux with HP rather than conoid shells, probably inspired by the one published by LAFFAILLE in 1935 ([10] p. 312). This figure, which does not represent the reality of Dreux, was reproduced in ([31] p. 15; [8] p. 153; [28] p. 497) and in other publications. We have seen, above, how this should be regarded.

It is more than likely that confusion over the paternity of the HP was also fuelled by the first synthetic study on the architecture of thin shells [31], published in 1962 by the influential architectural critic JÜRGEN JOEDICKE (1925–2015). That study remains indispensable and is always cited (e.g. [8], p. 149).

The first observation to make is that JOEDICKE does not mention any of the roofs built by AIMOND, although these are well illustrated in the literature, whereas he reproduces the HP arrangements published by AIMOND in 1936.

Then he reproduces SARGER's illustration supposedly depicting the canopy at Dreux and follows SARGER in designating Dreux as the prototype of HPs.

Finally, but without citing his sources, he describes three structures built in Italy by the engineer GIORGIO BARONI in 1937–1940 as the first HPs: "GIORGIO BARONI in Milan built the first shell in hyperbolic paraboloid form in 1934 (*sic*) and the first 'umbrella' arch in 1938 (*sic*) ([31], p. 11)." JOEDICKE's source was most probably an unsigned article, which has received little critical attention, concerning BARONI's HPs ([32], pp. 150–152), reproduced *in extenso* by FREI OTTO ([33], pp. 29–30). The little information that is known about GIORGIO BARONI comes from GRECO and IORI [34]. On 23 November 1936, BARONI filed a patent in Italy (No. 346696) for an HP-based reinforced concrete roof, and the illustration for the patent is a gable-type application very similar to Figure 9 in ([14]). The first realisation of this model was the theatre for the Vanzetti steel foundry in Milan in 1937 (a cover of 600 m^2), followed by the series for the Alfa Romeo workshops in Milan in 1937, which followed the layout of Figure 3. BARONI also used the "umbrella" arrangement in 1940 for shops in Tresigallo near Ferrare. BARONI's roofs display much greater architectural expressiveness than those built by AIMOND. However, there can be no doubt that, when filing his patent in 1936 and constructing his buildings in 1937 and 1940, Baroni was very probably familiar with the publications of AIMOND or those relating to HP which had already been published previously in France, such as those of ISSENMANN PILARSKI [35, 36, 37].

6 Conclusion

For the body of his work, very fruitful and original, BERNARD LAFFAILLE could most probably qualify for the title of "*structural artist*" that BILLINGTON reserves for certain engineers, including CANDELA. However, it would be wrong, as has often been done, to see in him the father of the HP on account of his canopy at Dreux in 1933; it has been established that he designed it using conoids and not HPs, but also that, as early as 1934, he himself contributed to casting doubt on this issue – which became the basis for a legend that this article was intended to demystify.

Until proof to the contrary is found in the form of a better candidate, the title of first pioneer of the HP in concrete in the 1930s belongs to FERNAND AIMOND for the projects that he constructed which are listed here, for the formulation of the theoretical structural membrane model, and for his influence both on BARONI in Italy in the late 1930s and on CANDELA in Mexico in the 1950s. However, it would be difficult to see in him a "*structural artist*": judging by the projects he built, one can even legitimately wonder whether his brilliant qualities as a theoretician did not sometimes simply obscure his practical judgement as an engineer...

Bibliography

[1] FABER, C.: *Candela: The Shell Builder*. New York: Reinhold, 1963.

[2] MOREYRA GARLOCK, M. E.; BILLINGTON, D. P.: *Félix Candela: Engineer, Builder, Structural Artist*. New Haven: Yale University Press, 2008.

[3] SIEGEL, C.: *Strukturformen der modernen Architektur*. München: Callwey, 1960.

[4] KERISEL, J.: *Albert Caquot 1881–1976. Savant, soldat et bâtisseur*. Paris: Presses de l'ENPC, 2001.

[5] LABEEUW, G.: *Hangar "Caquot". Histoire du premier hangar avions à "double auvent" réalisé en France*. Paris: Mémoire de l'Aviation Civile, DGAC et Anciens Aérodromes, 2012.

[6] NOGUE, N.: *Bernard Laffaille, Ingénieur (1900-1955)*. Colonnes 18 (2002) May, pp. 16-46.

[7] NOGUE, N.: *Bernard Laffaille (1900–1955), Ingénieur. De l'entreprise au bureau d'études: mode d'exercice et pensée technique*. Université Paris I – Panthéon-Sorbonne: Doctoral thesis, 2002.

[8] NOGUE, N.: L*es surfaces gauches minces. Une aventure constructive des années trente*. Les cahiers de la recherche architecturale et urbaine. 2–3 (1999) November, pp. 149–166.

[9] LAFFAILLE, B.: *Les voiles minces en forme de paraboloïde hyperbolique*. Le Génie Civil 104 (1934) N°18, pp. 409–410.

[10] LAFFAILLE, B.: *Mémoire sur l'étude générales (sic) de surfaces gauches minces*. IABSE Proceedings 3 (1935), pp. 295–332.

[11] AIMOND, F.: *Les voiles minces en forme de paraboloïde hyperbolique*. Le Génie Civil 102 (1933) N°8, pp. 179–181.

[12] NOGUE, N.: BERNARD LAFFAILLE, *de la coque à l'univers plié*. AMC Le Moniteur Architecture (1998) February.

[13] HAHN, L.: *Voiles de toiture en paraboloïde hyperbolique*. Bulletin of the International Association for Shell Structures 6 (1960).

[14] AIMOND, F.: *Etude statique des voiles minces en paraboloïde hyperbolique travaillant sans flexion*. IABSE Proceedings 4 (1936), pp. 1–112.

[15] AIMOND, F.: *La construction des bâtiments techniques de l'aviation*. L'Aviation Française. Paris: Science et Industrie, 1936, pp. 249–254.

[16] AIMOND, F.: *L'évolution de la construction des hangars d'aviation*. L'Aviation Française. Paris: Science et Industrie, 1936, pp. 255–264.

[17] *Voûtes minces autoportantes en béton armé*. L'Architecture d'Aujourd'hui (1936) November, pp. 28–51.

[18] DIGNE, R.: *La construction des hangars d'aviation*. La Technique Moderne 31 (1939) N°2, pp. 75–92.

[19] AUCLAIR, J.: *Les voiles couvrants et portants*. Recherches et Inventions 265 (1936) December, pp. 380–397.

[20] HAHN, L.: *Application des voiles minces en paraboloïde hyperbolique à la construction d'un garage en béton armé.* Travaux 53 (1937) May, pp. 207–215.

[21] HAHN, L.: *Aéroport de Limoges-Feytiat. Hangar en béton armé*. Travaux 46 (1936) October, pp. 458–469.

[22] LABEEUW, G.: *Le hangar "Poulmic" de la base aérienne 279 de Châteaudun*. Anciens Aérodromes 35 (2013) January, pp. 2-5.

[23] CHAULET, M.: *Voûtes autoportantes en béton armé*. Annales de l'ITBTP 1 (1936) N°3, pp. 43–54.

[24] JEAN-BLOCH, T.: *La salle des sports de Mulhouse*. Annales de l'ITBTP 11 (1958) September N°129, pp. 999–1020.

[25] CANDELA, F.: *Structural Applications of Hyperbolic Paraboloidical Shells*. Journal of the American Concrete Institute 51 (1955) January, pp. 397–415.

[26] GALANTAY, E. Y.: *Les voiles minces et la couverture autoportante*. L'Architecture d'Aujourd'hui 64 (1956) March, pp. 28–41.

[27] BELES, A. A.; SOARE, M.: *Das elliptische und hyperbolische Paraboloid im Bauwesen*. Berlin: VEB Verlag für Bauwesen, 1971.

[28] ADDIS, B.: *Building: 3000 Years of Design, Engineering and Construction*. London: Phaidon, 2007.

[29] KURRER, K. E.: *The History of the Theory of Structures*. Berlin: Ernst & Sohn, 2008.

[30] SARGER, R.: *L'œuvre de Bernard Laffaille*. L'Architecture d'Aujourd'hui 64 (1956) March, pp. 16–19.

[31] JOEDICKE, J.: *Schalenbau. Konstruktion und Gestaltung*. Stuttgart: Karl-Krämer-Verlag, 1962.

[32] *Umbrella building*. Architectural Forum (1953) January, pp. 150–152.

[33] OTTO, F.: *Das Hängende Dach*. Berlin: Ullstein, 1954.

[34] GRECO, C.; IORI, T.: *Sperimentazioni autarchiche in Italia per le coperture di grande luce: i casi di Engenio Miozzi et Giorgio Baroni. Curare il moderno. I modi della tecnologia*. Venezia: Marsilio, 2002, pp. 101–112.

[35] ISSENMANN PILARSKI, L.: *Calcul des voiles minces en béton armé*. Paris: Dunod, 1935.

[36] ISSENMANN PILARSKI, L.: *Le voile mince, matériau moderne*. Travaux 39 (1936) March, pp. 135–138.

[37] ISSENMANN PILARSKI, L.: *Le paraboloïde hyperbolique*. Travaux 40 (1936) April, pp. 177–181.

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