Thin concrete shells by Eugène Freyssinet

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ABSTRACT: Between 1914 and 1928, Eugène Freyssinet, working with the Limousin Company, designed and built numerous reinforced concrete roofs, some of which may be considered as significant structures in the early history of thin concrete shells. Basically, Freyssinet pioneered two types of innovative thin concrete shells: the large span “short” barrel vault that he mainly used for covering “tunnel” aircraft hangars, but also the Reims Market Hall, and the northern light shed with “long” and “short” conoids. Nearly every new construction was for Freyssinet an occasion to invent, and often patent, a new construction technique. Surprisingly, many of these structures built more than 90 years ago are still standing today. Most of them are not well known, and have not received the proper recognition they deserve. Some reasons for this omission in the history of thin concrete shells are discussed in the paper.

1 INTRODUCTION

Eugène Freyssinet (1879-1962) is internationally known as the engineer who “invented” prestressed concrete, notably by submitting on October 2, 1928 the French patent 680.547 that states correctly the sound principles that are to be relied upon to keep long-term prestrressing effects in concrete. Most biographies written on Freyssinet, and especially the last ones, published under the auspices of the Association Eugène Freyssinet (2004, 2014), concentrate nearly exclusively on the story of the discovery and development of prestressed concrete up to his last designs in 1962. They rely mostly on the account given by Freyssinet himself (Freyssinet 1954). There is however one biography that differs from all others, which is well documented and which covers the whole professional life of Freyssinet: this biography, written by José A. Fernández Ordóñez (1933-2000), was published in French and in English in 1979 and fortunately reprinted - in French only - in 2012 with annotations by P. Chemetov and a slightly different and enriched iconography than in the 1st edition.

The professional career of Freyssinet spans 57 years in three periods. From 1905 to 1914, he served as Ingénieur des Ponts et Chaussés working for the State, and became rapidly a brilliant designer of daring and innovating long-span bridges in reinforced concrete. From 1914 to 1928, he was co-manager with Claude Limousin (1880-1853) and technical director of the construction company that shall be called here “Limousin” for simplicity. Then, from early 1929, he ventured into the pioneering development of prestressed concrete. This last period is the best known, but lies outside the period that shall be considered in this paper. From the second period, only the world famous and record span structures like the Orly airship hangars (1921-1923) and the Plougastel Bridge (1924-1930) are most often highlighted. But during the 15 years that the 2nd period lasted, the Limousin Company built according to designs by Freyssinet and under his direction an incredibly large number of aircraft hangars and roofs structures in concrete for industrial halls or workshops. Some of these structures are innovating and landmark contributions to the early history of thin concrete shells.

The present contribution endeavours to modestly supplement the monumental work of Fernández Ordóñez with some elements which were not at his disposal or which became available recently. The Orly airship hangars, which can hardly be considered as thin shell structures, shall not be considered here. Neither shall be the numerous barrel vaults with moderate span (15-20m) and with ties built by Limousin and Freyssinet to roof industrial halls: even if Freyssinet did speed up and improve the economy of the construction of such vaulted roofs, he was not the inventor of such kind of structures which had appeared even before 1910.
Freyssinet declares that he first got interested in the design of concrete aircraft hangars with barrel vaults for a project in 1913 that was, however, not carried out (Freyssinet 1923, 266). But two years later, during the winter 1915-1916, he built a series of 8 military aircraft hangars at Avord (Cher) of a type that shall become standard: the “tunnel” type. Structurally, these were “short” thin concrete barrel vaults, with 46m opening (span) and 60m in length. The thrust of the vault was directly absorbed into the foundations. No information has been found regarding the depth of the shell, but it can be estimated to be of the order of 6cm. With these hangars, Freyssinet built for the first time thin vaults stiffened by ribs externally disposed at the extrados of the vault: “this detail, at first sight of small importance, had a profound influence on the development of this kind of structure because it simplifies considerably the construction and lowers its cost. Indeed, by disposing the ribs at the extrados, the formwork is reduced to a simple smooth surface that can be constructed by a low qualified workforce and that allows a fast centring by large panels without demolition of the moulds. The ribs are concreted after the vault with a small auxiliary formwork that can be removed 24 hours after setting and can be reused many times.” (Freyssinet 1923, 266). See also (Freyssinet 1936a). And Freyssinet added later: “In 1913, I have invented the vaults with ribs disposed at their extrados, and in 1916 the slip formwork. If I had submitted patents for these [inventions], I would have become a billionaire. It is indeed common knowledge that only stupid patents make the fortune of their authors.” (Freyssinet 1954). The external ribs were placed every 3.91m apart (Labbeuw 2013). Most of the Avord hangars were destroyed in 1944. However, after more than 100 years, one original hangar is still standing in excellent condition, testifying of the remarkable design and the care given to the concreting operations by Freyssinet (Labbeuw 2013. Labbeuw 2016).

Following the success of the construction of the Avord hangars, Limousin and Freyssinet built a series of 31 similar hangars for the Army at Istres (Bouches-du Rhône) in 1917-1918 (Freyssinet 1923, 266). The only difference is a shorter length: 42m instead of 60m. All were destroyed in 1944.

In 1919, Limousin and Freyssinet built an extraordinary aircraft hangar at Villacoublay (Yvelines) (Fig. 1): its origin lies already in the 1913 unrealized project and evolves also from the experience gained with the construction of the tunnel hangars at Avord and Istres. The basic structural shape is the groin vault: “The hangar consists of three parallel barrel vaults, with 40m opening and 45m in length, intersected perpendicularly by a third [sic; in fact a fourth] barrel vault from the apex of the first barrel to the apex of the third barrel. The whole construction spans a free space 120m x 45m. This structure is characterised by a total lack of any reinforcing rib on the interior, which allowed the use of a very simple formwork. All the reinforcements – stiffening ribs, extra thicknesses along the arisres – were exterior.” (Freyssinet 1923, 266). The thickness of the vault varies between 7 and 9cm.

This remarkable concrete hangar, which was destroyed in 1944, has been completely overlooked in the literature, and only very few pictures of it have been published by (Freyssinet 1923, 266. Biron 1934, 44. Fernández Ordóñez 1979, 300; Fernández Ordóñez 2012, 262). Labbeuw has reproduced an interesting aerial view from 1926 that underlines the plan of this groin-vaulted hangar (Labbeuw 2013).

Figure 1. Groin vault aircraft hangar at Villacoublay (Biron 1934, 44)

Generally speaking, Freyssinet published very few indications on the assumptions and formulas he used to design his structures. For this particular and complex thin concrete shell construction, it is interesting to quote a much later citation by Freyssinet: “My structural analysis for this vault did not exceeded two pages, and was characterized by no computations at all. They only referred to a simple drawing showing a possible flow for the forces in the vault, along with the extremely low resulting stresses.” (Freyssinet 1958). In modern terms, and conscious of the anachronism implied, we could say that Freyssinet looked only after the satisfaction of equilibrium of forces and intuitively designed by simply relying on the lower bound (statical) theorem of the theory of plasticity!

The simple solution devised by Freyssinet at Avord and Istres for spans up to 46m could no longer be applied for larger openings because it would have implied to increase significantly the depth of the exterior stiffening ribs. Freyssinet invented then – and this times submitted patents - other means to increase the stiffness and carrying
capacity of thin barrel vaults under unsymmetrical loading for further hangars with larger opening.

Capitalising on the experience of the construction of the Orly airships hangars, the Limousin Company won the competition to build two aircraft hangars with 55m span and 50m length at Villacoublay in 1924 (Gotteland 1925). The vaults are here quite shallow, with their ends placed at 12m above ground level and tied together by ties placed every 6.56m. But the cross section of the vault, acting like an arch, is now corrugated (trapezoidal thin walled cross section) to provide the necessary stiffness to the arched vault. The thickness of the walls was only 4 to 6cm. Once again, Freyssinet used a moveable formwork which, in this case, allowed to concrete four “waves” of the vault at the same time. This design and construction process is fully described in the French patent 560.526 submitted by Limousin on December 29, 1922.

The stiffening method that Freyssinet had experimented with the hangars at Villacoublay was only economical with rather thin walls that proved to be difficult to cast on site (Dantin 1927). For two hangars to be built in 1925 at Le Palyvestre near Hyères (Alpes Maritimes), Limousin and Freyssinet won the contract by submitting a different design. The opening is again 55m but the length is now 60m. Externally, the surface of the vault looks like the Avord and Istres shells with small ribs at the extrados. But the span is now 25% larger. The shell, 6cm thick and smooth at the intrados, is supported on columns and walls at 15m above ground. The thin shell itself is supported every 5m by a truss in reinforced concrete, and the bottom chord of the truss acts as tie for the vault. The top chord of the truss follows the intrados of the vault (semi-circular). In order to avoid to design the diagonal elements of the truss against buckling, Freyssinet applied a pre-loading of the diagonals by giving a slight polygonal shape to the tie and tensioning its reinforcement before casting its surrounding concrete (Dantin 1927, Digne 1939, 80). The diagonals remained therefore theoretically in tension under any loading combination. This construction process is described in the French patent 584.163 submitted by Limousin on July 29, 1924. At the time of their construction, these hangars were the largest in the world (Dantin 1927) and they are still in use today. Limousin built three pairs of similar hangars at Berre (Bouches-du-Rhône) from 1929 onwards; one pair is still standing today and partially reused.

This paper concentrates on the innovating thin concrete shells built by Freyssinet with Limousin: its purpose is not to give the evolution of the barrel vault concrete aircraft hangars built in France before 1940. This would imply to analyse contributions by other contractors like, e.g., Simon Boussiron (1873-1958) and other engineers like Henri Lossier (1878-1962) and Bernard Laffaille (1900-1955). The work of Laffaille has been thoroughly researched by (Nogue 2002).

3 THE REIMS CENTRAL MARKET HALL

The Reims Central Market Hall - or Halles du Boulingrin - has been built by the Limousin Company between 1927 and 1929 with the architect Emile Maigrot who had begun to work on this project in 1922. But neither the publications from the time of the construction (Forestier 1928. Forestier 1929), nor the extensive studies published recently on the occasion of their rehabilitation (Charlot and Truillet 2012. Chatillon 2016) allow to distinguish individually the contributions by the architect (Maigrot) and by the engineer (Freyssinet) in the design of the large thin concrete shell vault that spans this large market hall covering a free surface 38.86m by 79.85m. The vault clearly belongs to the structural type of the “short” barrel type like the vaults built at Avord and Istres (even with a shorter opening), with a minimum thickness of 6cm, smooth inside and externally reinforced with stiffening ribs. The main difference with the aircraft hangars is the profile of the vault: at Reims, the profile of the vault is parabolic, with a rise of 19.45m for a span of 38.86m, and the profile follows the funicular of the dead loads (Forestier 1929, 90). The vaults at Avord and Istres were much more shallow with a rise of only 11m for a span of 46m (Labbeu 2013). The formwork and center at Reims were therefore probably more costly, and the vault more complex and delicate to cast. The Reims market hall was closed in 1988 and listed as heritage building in 1990. The Halles have been re-opened after a rehabilitation campaign that lasted from 2010 to 2012.

4 NORTHERN LIGHT SHEDS - CONOIDS

On November 29, 1927, the Limousin Company submitted the French patent 644.726 for protecting the design and construction of northern light sheds with conoidal thin concrete shells. A conoid is a ruled surface obtained by translating a straightline generatrix along two curved directrices - “top” and “bottom” - which are the long edges of the shell. The “bottom” directrix is sometimes a straight line. The patent states “that the shape of the top and bottom edges, and of any profile of the shell between them, shall coincide with the funicular of the self weight”. Northern light sheds in reinforced concrete had existed since a long time, and Limousin had submitted previously patents for other kinds of such structures. But the novelty with this patent was the use of thin conoidal shells.
The plate of drawings from the patent reproduces, probably with very little difference, the sheds constructed by Limousin for repair workshops of the State Railways at Bagneux (in fact at Chatillon, Hauts-de-Seine), probably in 1927 (Fernández Ordóñez 2012, 299). (Fig. 2) Some spectacular pictures of these sheds have been published (Giedion 1929. Badovici 1931), but unfortunately no plan drawings. Giedion praised these sheds for the exceptional lighting quality, far superior to the lighting that could be obtained by previous types of northern light sheds. They still exist today and serve as maintenance workshops for the high-speed trains of the “Atlantique” railway line (Technicentre Atlantique SNCF Entretien TGV). These conoidal shells typically belong to the “long” type, with a span of about 12-15m being twice their length (6-8m). The thin shells are stiffened externally by two ribs at their extrados.

The Limousin Company built in 1932-1933 very similar sheds as maintenance workshops for the Parisian metropolitan railway at Fontenay-sous-Bois (Val de Marne). They are better documented (Fauconnier 1933. Fauconnier 1934): the workshops consisted in two series of sheds with 28 and 74 conoidal thin concrete shells respectively. The span of the conoidal shell is here 17.5m for a length of 8m. The thickness of the concrete shell is only 5cm, and the shells were stiffened by a single rib at the extrados. The papers by Fauconnier (1933, 1934) report the results of a full-scale load testing up to failure of a conoidal shell unit set up for validating the design method used by the Limousin Company (and probably by Freyssinet, although he had already left the company at that time): for the design, the shell was modelled as a series of arches “sliced” into the shell parallel to the directrix and assumed to behave independently one from the other. These arches were then verified for equilibrium for permanent and variable loading. These workshops with their conoidal shells are still (partly) existing and used by the RATP today.

At about the time of the construction of the Bagneux-Chatillon repair shops did Limousin and Freyssinet built in 1928 large span northern light sheds with conoids for the Compagnie Nationale des Radiateurs (CNR, later Ideal Standard) factory at Dammarie-les-Lys (near Melun, Seine et Marne). (Fig. 3) A detailed drawing and nice pictures of these sheds have been published by (Badovici, 1931). The conoids are now of the “short” type, with a span of 50m for a length of 6m. The long edges of this short segment of conoid are supported by slender trusses. These sheds still exist today but seem to be left unused and are potentially at risk to be scrapped. Slightly later (1929-1930), Limousin built for the same company CNR workshops for another factory at Aulnay-sous-Bois (Seine-Saint-Denis). These workshops consist also of northern light sheds with “short” conoids resting on trusses along their long edges. The span is here reduced to 35m (Furio 2006), and not increased to 60m as reported, probably erroneously, by (Fernández Ordóñez 2012, 299). These sheds still exist today and have been reconverted for a different use.

For the sake of completeness, mention should be made that Bernard Laffaille also began building northern lights sheds with (long and short) conoidal thin concrete shells from 1927 onwards (Nogue 1999. Nogue 2002). In the 1930s, this type of workshops became – in France - rapidly designed by other engineers (e.g. by Henri Lossié for a garage in Pantin in 1933) and built by other contractors (e.g. by Dumez for a railway shop at Rennes in 1935).
5 CANOPIES AT AUSTERLITZ STATION

The parcels dispatch railway station (Messageries) at Austerlitz Station (Paris), built by Limousin between 1927 and 1929, is probably the last major construction entirely designed by Freyssinet before he left the Company. This station consists of three parallel naves, 310m in length, covered by “short” barrel vaults with longitudinal openings for admitting light. Although the central nave is covered by a barrel with an honourable span of 24.7m, these classic barrels were not innovative at that time. Much more interesting for the history of early thin shells is the series of 30 canopies built, on one side of the station, to protect the platform used for loading of the lorries. (Fig. 4) Each canopy, independent from the others, is a 5cm thick cylindrical concrete shell, 8.5m in length, and with 10.18m opening (corresponding with the distance between the main columns of the whole construction). These very thin and light vaults are firstly supported along the façade of the main construction with hinges. At about two thirds of their length, a stiffening rib is concreted at their extrados. Two inclined stays in reinforced concrete link the extremities of the stiffening rib to the façade of the construction and support the shell. The extremities of the stiffening rib are linked by a (polygonal) tie under the vault: the tie and the rib form a stiffening diaphragm that prevents the distorsion of the thin shell. But Freyssinet considered also the question of the de-centering of the vault: this is why he knew that the tie had to be tensioned (made stiff) before the decentering of the shell. As for the hangars at Le Palyestre, he devised to pre-load (prestress) the tie. This idea is fully described in the French patent 670.525 submitted by Limousin and Freyssinet on June 22, 1928. This patent is the last one submitted by the Limousin Company on behalf (in the name) of Freyssinet before the famous patent on prestressed concrete submitted by Freyssinet in his own name with Jean Séailles in October 1928.

The Messageries of the Austerlitz Station have been used by the SNCF till 2006, and saved from destruction by an international call for reuse projects launched in 2007. They have been protected by being registered to some form of heritage lists in 2012. A new owner assigned them a highly visible new function, and renovation and refurbishment works took place between 2014 and 2017, notably by the Company that now bears the name of Freyssinet and which evolves from the STUP Company set up by Freyssinet in 1942 to promote the applications of prestressed concrete. The Messageries are called today “Halle Freyssinet” or simply “Station F”, as a tribute to their designer.
CONCLUSION - RECOGNITION OF THE THIN CONCRETE SHELLS DESIGNED AND BUILT BY FREYSSINET

As we have seen, Freyssinet played a pioneering role in the development of two structural forms of thin concrete shells: the “short” barrel vault with large opening (45m and more) and the conoid used for northern light sheds. What strikes us with Freyssinet is that the structure always results from an overall optimisation in order to reach the lowest cost by using the materials at their best and inventing new construction techniques in order to re-use a large number of times the same formwork and center, and with a particular attention paid to the quality of the cast-in-place concrete, which probably explains the very high durability of all the structures discussed here. Some of these constructions (Le Palyvestre hangars, Austerlitz canopies, and others not mentioned here because they fall outside the field of thin shells) gave Freyssinet the opportunity to mature his ideas on pre-loading of structures and helped him to pave the way to the invention of prestressed concrete.

Some may argue that Freyssinet only designed thin shells with “zero Gaussian curvature”, and which had to be stiffened either by ribs or auxiliary structures. But the contrast between the thinness of concrete shells and their supports is present in all categories of thin concrete shells: some may find that the stiffening ribs or trusses used by Freyssinet detract the visual appearance of his shells, but these elements are structurally necessary as are the ties and stiffening diaphragms in Zeiss-Dywidag long barrel vaults, the edge beams in hypar shells and the ring tie belt in domes. It is the architectural integration of the equilibrating and stiffening elements that gives the attractive-to-the-eye appearance to the whole structure. But there is no doubt that the thin shells built by Freyssinet were truly “thin shells” as they were designed as pure membranes, with uniform distribution of stresses in the concrete across the thickness of the shell.

Freyssinet always considered himself as a pure craftsman and engineer, designing utilitarian and optimised structures with no interest at all for other considerations. But he conceived that some people recognised in some of his constructions true œuvres d’art (Freyssinet 1936b). This recognition seems however to have lacked for the shells considered here in the writings of the most influential critics in the field.

Giedion, who however praised the sheds at Bagneux for their exceptional lighting qualities (Giedion 1929), mention just incidentally Freyssinet for these sheds in his book Space, Time and
Architecture in a voluminous chapter dedicated to Robert Maillart (Giedion 1956, 461-462). As Fernández Ordóñez already noticed (Fernández Ordóñez 2012, 111), it is quite astonishing that Giedion prefers to pinpoint as (nearly) single example of thin concrete shell in his whole book the Cement Hall designed by Maillart for the Swiss National Exhibition in 1939. This thin shell by Maillart, the only one he designed, may be pleasing to the eye but could hardly be considered as an optimised membrane thin shell.

In the first monograph dedicated to thin concrete shell architecture, Joedicke does not give much more consideration to the pioneering shells by Freyssinet: without giving any due reference or comments, he simply reproduces a view of the interior of the Bagneux sheds, and another of the Reims Market Hall (Joedicke 1963, 14). Reproducing a view of the inner space of these shells, rather than a view of the structures from outside, is probably significant.

We could also estimate that Billington, who coined the term “structural artist” with his book The Tower and the Bridge (Billington 1985), remains quite distant about the contributions of Freyssinet to the early history of thin concrete shells. Billington has read Fernández Ordóñez, but seems to have essentially followed the opinion of Giedion regarding Freyssinet, since he just mentions the sheds at Bagneux in his book. Chapter 11 of the book by Billington titled “The directing idea of Eugène Freyssinet”, is mainly devoted to Freyssinet as inventor of prestressed concrete. Fortunately, Billington concludes his chapter by opening the discussion: “It would be wrong, however, to conclude a chapter on Freyssinet on a negative note…. Freyssinet was a great structural artist whose life and works should and will be studied historically and criticized sympathetically in much greater detail than heretofore.”

It is quite certain that the recognition of the reinforced concrete structures built by Freyssinet in the period 1914-1928, besides the landmark structures (Orly, Plougastel, …), suffer from a lack of archives, a very limited description for many of them even in French literature of the time, and a lack of promotion of his own works by Freyssinet himself for this period. The production of Freyssinet as designer and builder of thin concrete shells before 1930, of which many are still standing, remains largely unrecognised. Their history, which is not well documented, has been shadowed by the emphasis given to prestressed concrete in the historiography of Eugène Freyssinet. The recognition was not helped by the judgement, which was either poorly informed or partisan, of some of the more influential architectural critics and historians of the history of thin concrete shells. It is only recently, with the actions taken in favour of the protection and rehabilitation of the Reims Market Hall and the Messageries at the Austerlitz Station that this part of the œuvre by Freyssinet has begun to be fully appreciated. But much remains to be done, especially for the aircraft hangars and the industrial structures.

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8 REFERENCES


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