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Inhalt

Eugène Freyssinet: “I was born a builder”

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1 Introduction

Eugène Freyssinet (Figure 1) was a real engineer and a builder in the full sense of the word. He said at one time: *“Je suis né constructeur. Imposer à la matière des formes nées de mon imagination est pour moi à la fois un besoin impérieux et une source de joies inépuisables“* [1].[1]

In his work, there was never conflict between construction and design. He solved both questions at the same time in such an original way that the solutions were both economic and competitive even though they were innovative. Many of the processes that he invented for a particular work were then used universally in many other works [2].

He assumed a construction project with absolute freedom from the design to the construction. He always took full technical and economic responsibility for the whole project. He participated from the drawings of the preliminary designs to the more manual work at the job site, including the organisation, payments to the workers, the safety of the construction, calculations, materials or external actions. He never wanted to design works for others to build or build other’s designs.

Figure 1 Eugène Freyssinet in 1954[2]

He was one of those persons that emerge once in a while and who are capable to fully understand all the construction as a whole, and thus can develop fully new techniques and materials. Like the historic engineers, he approached the works in a thorough way, taking into account all aspects, from design to construction, planning and costs. He also approached his work in an ethic way without looking for notoriety or social prestige. He, in fact, was not a social person and concentrated all his life on his work.

He developed new construction methods and invented the necessary auxiliary machinery, like for example in the Bridge of Plougastel, world span record, in 1928 with foundation shell that would be the inspiration of other brilliant engineer Coyne to develop his impressive double curvature dams, also record for the time [3]–[5]. He also developed a large wood formwork for the arches of Plougastel that could be reused for each of the 3 spans of the bridge. The formwork was made of very thin layers of wood of only 4 cm thickness, only tied with nails, and pretensioned with hundreds of steel wires. He developed also an 800 m cable car with autonomous driving. He also used for the first time the incremental launching cantilevers that he mastered later in the Marne Bridges. He used from the beginning the removal of the formwork with the use of flat jacks that he industrialised. He used the method of shifting the formworks for his bridges and for the shell used in industrial buildings and that had the highest expression in the Hangars of Orly.

1 *In English: I was born a builder. It was for me both an overriding need and also an endless source of joy imposing upon the crude material those shapes and forms which sprang from my own imagination.*

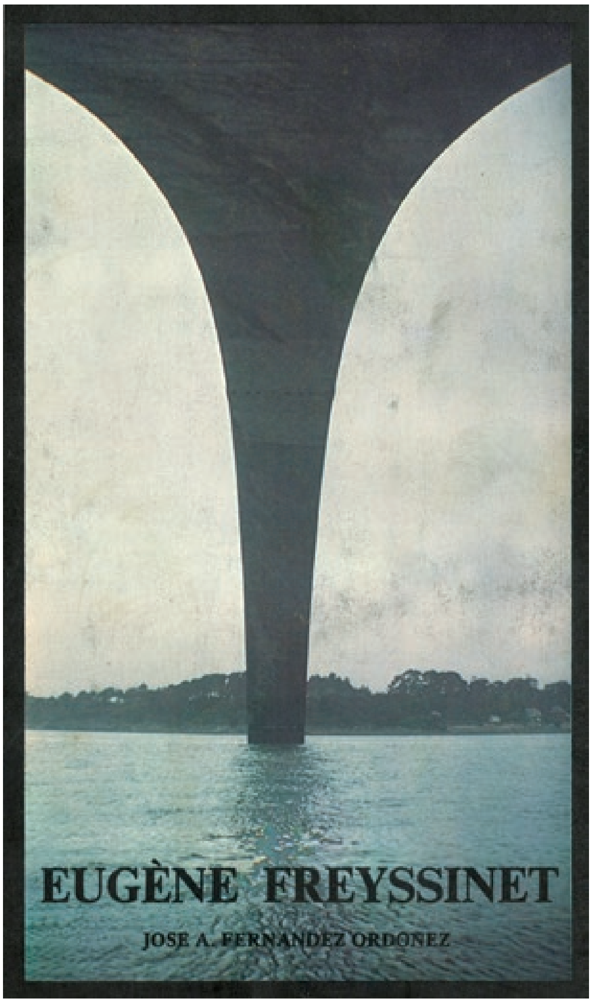
2 *Except figures 1–3, all pictures were taken from [2]. Figures 1 and 2 are from Archive JAFO (Jose Antonio Fernández Ordóñez), the photo in figure 3 was taken by Carlos Fernández Ordóñez.*

On concrete, he realised already in 1910 that the modulus of elasticity was not constant as the regulations imposed at the time, and he made a research to prove it while he was building the Bridge of Plougastel in 1928. He also used concretes with a strength higher than was normal at the time because he needed them for his very industrialised construction processes. He used in many works concrete strengths of 500 kg/cm² as soon as 1914 and he achieved 1.000 kg/cm² in the precast factory of Montarguis from 1928 when developing precast concrete posts. He realised that to achieve a high strength concrete he had to limit the use of water and to build with flowable concrete he needed some help for compaction. Then he invented vibration in 1917 to be able to use these flowable concretes in places of very complicated reinforcement.

On prestressing he realised in 1903 for the first time the possibility to create previous tensions, in 1910 he used it for the test arch in the Veurdre Bridge. In 1928 he presented a patent for prestressing but more than this he built a factory and he invented all the necessary machinery and steel and concrete technology to make it possible. Only in 1934 he could apply it to the sinking Marne Maritime Station, and then the rest of the world realised that this technology was an idea that could be used in everyday construction.

He was married to Mme Freyssinet, an elegant and beautiful woman that dedicated all her life to support him. They did not have any children and Freyssinet said at the end of his life that only the full support from his wife and that he did not have any children allowed him to dedicate all his fortune to the dream of creating prestressing. It almost led him to bankruptcy and disaster, but when he had the opportunity he demonstrated to everyone else the benefits of his ideas.

Eugène Freyssinet was a very focused man in what really interested him, and who did not pay any attention to conversations that were out of his interest. He did not really have close friends but colleagues whom he appreciated in his personal way. It is through his wife that we can reach his personality and how he approached life [2]. He was a very active man who was interested in life. When he approached any scientific problem he needed clarity in the solutions disregarding any-



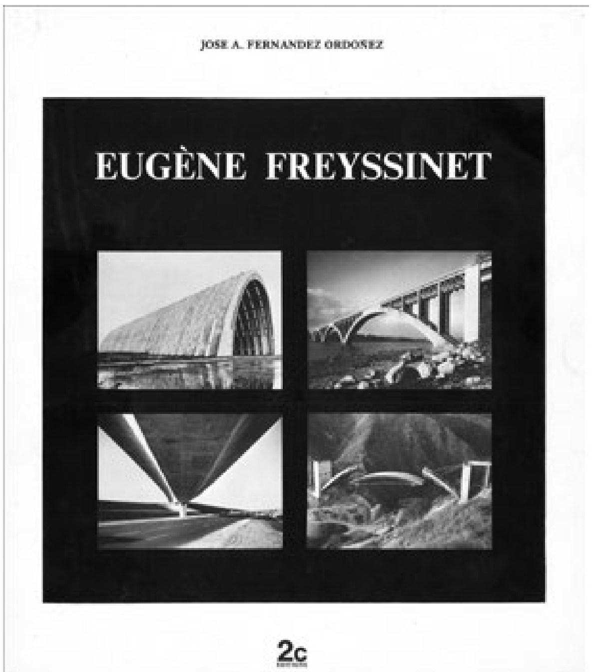


Figure 2 Eugène Freyssinet's books in Spanish and in English-French by José Antonio Fernández Ordóñez

thing that could be intangible or not straight forward. He liked mostly art and philosophy of the East and collected Chinese, Japanese or Indian art. He did not participate in any of the art or philosophical problems of his time. Modern art was undiscovered for him.

He could have worked and carried out his work under any administrative or political system. He did not understand the war even though he lived through two world wars. He thought they were just decisions of mad men. He was not interested in money. He spent all he earned in the successful years great reinforced concrete works from 1914 to 1928 in his art and in his research for prestressing, to the limit that he was almost bankrupt. He was very strict and self-confident. When he believed strongly in an argument for anyone that did not agree with him wether he was an idiot, someone that could not understand or someone that had business of his own interest.

He was an expert in all parts of construction, from design, through construction and material science to organisation of the work site, developing all necessary auxiliary machinery that he needed and taking the economic responsibility too. He was an incredible brave man that took absolute risks, as he said: *“At least three times in my life I showed how I could audaciously take the greatest risks”* [1], [6].

He liked the countryside and always preferred to go fishing or to spend an afternoon in the mountains to develop his social life, to visit offices or to go to formal receptions.

The information presented in this paper comes mostly from the book that my father, Jose Antonio Fernández Ordóñez, wrote about Freyssinet [2] and from the many papers given by Freyssinet’s friends and wife just after his death in 1962 [7] (Figure 2).

My father was able to write this book because another Spanish engineer of the time of Freyssinet, Francisco Fernandez Conde, was Freyssinet’s friend and also the father of Jose Antonio. Francisco Fernandez Conde brought Freyssinet’s prestressing patents to Spain to create in 1942 the first prestressing elements in Spain [8]–[10]. The works for the book started already just after Freyssinet’s death and in 1965 he did a trip to visit all his works in France and to talk to many of his collaborators, friends and his widow. All of them commented very important professional and personal information and also shared many documents about him. Mme Freyssinet even then dedicated all her efforts to support the memory of the work of her husband. If by chance some more years would have passed before starting this book, all this detailed professional and personal information would have been lost and many of Freyssinet’s personal achievements would have been forgotten (Figure 3).

Figure 3 Mme Freyssinet and Jose Antonio Fernandez Ordoñez in 1965

2 The early years

Eugène Freyssinet was born in Objat, a small town close to Limoges, in 1879. He always felt proud to come from a small town. He was introverted and a rebel even as a child. The family moved to Paris when he was six where he had bigger education opportunities. He always wanted to go back to the countryside where he had as friends craftsmen of all kinds, from carpenters to masons. He learnt there most of the crafts related to construction and industry, and thus began to understand and respect their crafts and their persons. He would apply many of the knowledge that he learnt when he had the chance in his construction works.

He was a brilliant student and this allowed him to study at the Polytechnique in Paris. There he did not match with the rigid scientific procedures that they followed. Later he said: *“They cushioned themselves with comforting equations, fully confident that the higher their degree of complexity the more likely they were to produce the desired solu-*

tion" [6]. He later used mathematics only strictly when he would need them. Freyssinet only used one rule, the rule of three *"but this rule of three was a very special one which took everything into account. It was really the outcome of distilling a great store of knowledge and also of extraordinary perceptiveness"* [11].

Rabut was his professor at the Polytechnique and probably was the person who most influenced him. He would stress the importance of combining experimentation and practical experience. In his lectures on how to read engineering construction he always made a point of differentiating between results based on theory and especially theory with incomplete supporting data, and those based on trial and error [12].

In Rabut's lectures Freyssinet could understand the qualities and defects of reinforced concrete and also learn to feel the sense of what were the stresses in the structures. It's in the crossing of these two ideas, in these lectures, that was the seed of what later would be his obsession with prestressing [1]. It is this time when he saw in 1903 the impressive cantilevers built by Rabut in the Rue du Rome in Paris, with 7.50 metres span, that widened the trenches to allow more railway lines at the Station of Saint-Lazare. To achieve this he stressed some bars to compensate the deformation and that he later acknowledged that was the first idea that came to his mind in stressing reinforcement [13] (Figure 4).

Freyssinet commented in several moments that the qualities that a person should have were the sense of vocation, personal hard work and a boundless and unreserved love of the task undertaken [6]. Everything else in an engineering work he believed to be simple and a matter of common sense [14].

He believed that to be a good engineer one should have just three qualities [15]:

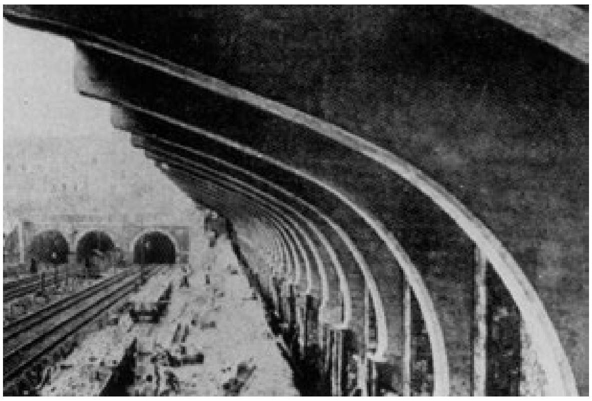


Figure 4 Cantilevers built by Rabut in Rue du Rome in Paris with stressed bars

1. To understand and apply the rule of three,
2. Be fully convinced that he will never get to heaven by tearing his hair out,
3. Understand that to get a hat onto its hook, there is no point in trying to put it too high on top, too low underneath or too much at either side.

3 First engineering works

Just after leaving the Polytechnique, Freyssinet took charge of the services at Moulins, Vichy and Lapalisse in 1905. As rural services engineer he would be asked mainly to build bridges for local towns. The official costs of the bridges were very high and most towns could not afford it and had to wait for a subsidy of the state. Then the leadership and entrepreneurship of Freyssinet came with some ideas. He would offer the majors a bridge 4.5 m wide, instead of the 2.5 m wide that was supplied officially for a cost of 25% of the official cost and without having to wait for the subsidy. All he asked was to change the official design that imposed large piers and foundations for other with longer spans with a new construction method.

He had complete freedom but also assumed full responsibility for the design and did not wait for official approval of the plans. He became very popular among the majors as he supplied bridges at an unbeatable cost and time [16]. Some of the bridges were small reinforced concrete straight frames (Figure 5) and other were longer spans arches (Figure 6) where he started to test some ideas that he would use in the Veurdre Bridges. When looking at the design of these bridges one can realise the strict dimensions, the love on the details and care for the relation with the environment.

4 Reinforced concrete

After the successful construction of the bridges in the countryside, he took another very brave decision. He proposed to build three large bridges for the cost of just one. They were the Veurdre, the Boutiron and the Châtel-de-Neuvre Bridges. He explained this incredible adventure many years later [1], [6]. He did himself the design of very slender arch structures that were completely out of the normal use then. He designed arches with two slabs, one for the roadway and one for the arch. As steel was very expensive he reduced steel to the minimum of 30 kg/m³. The arch was always in compression.

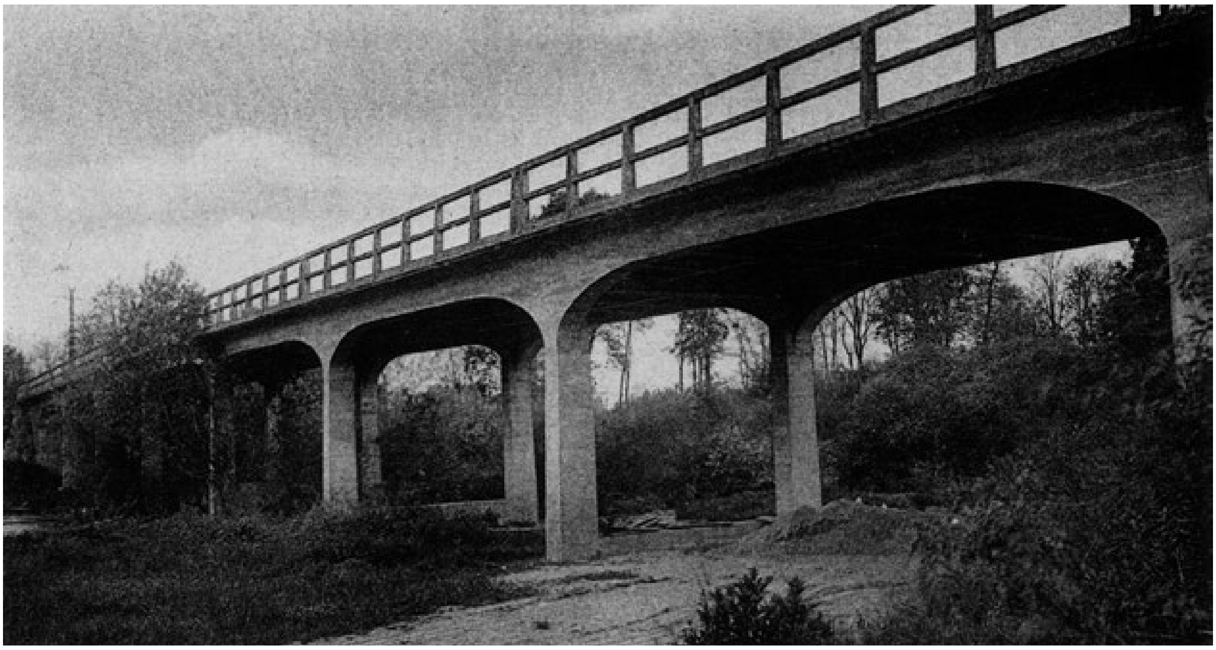


Figure 5 Bridge at Dampierre-sur-Besbre

Figure 6 Bridge at Prairéal-sur-Bresbe

He was given the confidence to do the work. Mercier allowed the funds and he had to do everything else, from gathering the team to looking for the materials or the auxiliary means. It was a one-man entrepreneurship. It was 1907 and he was just 28 years old.

He also found a big problem when taking the structures and the materials to the limit. At that time the national regulations form 1906 stated the modulus of elasticity of concrete was linear. They totally ignored the variations in relation to the strength and the time of application. There were twenty laboratory tests made by Mesnager that stated this [17]. As his own experience contradicted these tests and due that he refused to discuss the tests, Freyssinet had to go to talk to the labour of the laboratory to finally understand that they stopped the tests when they had the linear relationship, not to damage the machinery.

This is a very good example of how pure science and real engineering works have to develop the work together to find valuable solutions. This is also a good example of how sometimes when taking the materials and the structures to the limit a real engineer has to go to the last detail to really

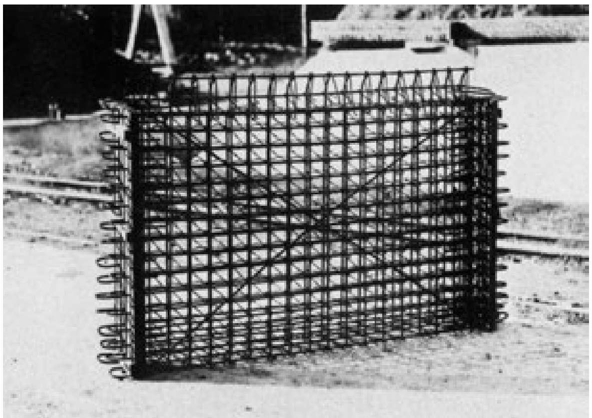


Figure 7 Hinge reinforcement of Veurdre Bridge

leap forward and this is only done by very special persons. The war delayed the publication of these conclusions from 1912 to 1926.

He realised that it was advisable to do a test arch to see how it would work under high loads and very low reinforcement. It was a 50 m span arch that for a test is a really impressive size [17]. There was no budget for such a big test. In any case he managed to do the test arch which gave him very valuable information about the behaviour of the structure, the removal from the arch of the scaffolding and the behaviour of the concrete. He also designed a prestressed tie for the arch with 8 mm wires which was a real prestressed structure designed in 1907 and built already in 1908. He even had to design he hydraulic machines to operate the jacks for the tensioning of the cables and the removal of the scaffolding (Figure 7 and Figure 27). He used the highest quality concrete that he could do at the time. He used 450 to 500 kg/m³ of cement to reach 400 kg/cm² of strength at 3 months. He placed the concrete with vibration by hand applied to the moulds. He even went to the detail to define the mixers that had to be used.

When building the Veurdre Bridge he also used industrialisation to some parts of the bridge. The abutment hinges blocks were prefabricated and were heavily reinforced to avoid brittleness (Figure 8). He also intended to do the arch in prefabricated elements but it was impossible at the time. He could achieve it later when he built the Marne Bridges. He left the hinges at the centre of the arch to use the hydraulic jacks that he invented to separate the arch from the scaffolding.

The construction of the Veurdre Bridge was an incredible adventure. First there was a flood in the winter of 1909/1910 that almost destroyed the centre of the town. There was a gathering of people warned by local newspapers that the bridge would collapse. Fortunately the bridge stood without further problems. The decentring was done with the help of the hydraulic jack without any further problem. The bridge was aligned vertically with the handrails. When Freyssinet came back to the bridge after some time he clearly saw the deformations of the arch in the handrails. The deformations were high and growing with time. The bridge was in danger of collapsing. As the positions for the jacks were still open he took some workers and in one night elevated the bridge back to a safe position. This problem and its solution conclusively demonstrated him that the modulus of elasticity had clearly reduced.

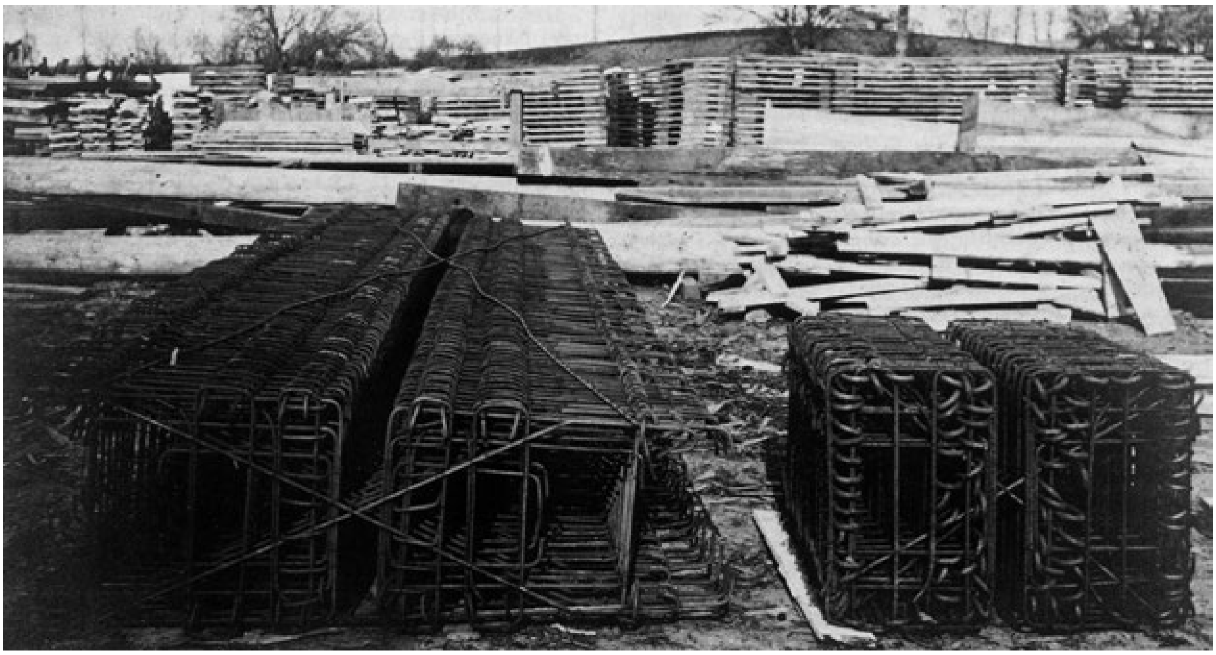


Figure 8 Boutiron Bridge, hinge reinforcement

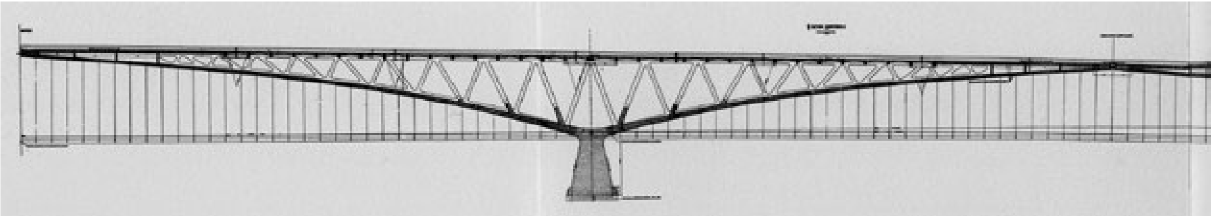


Figure 9 Veurdre Bridge, elevation

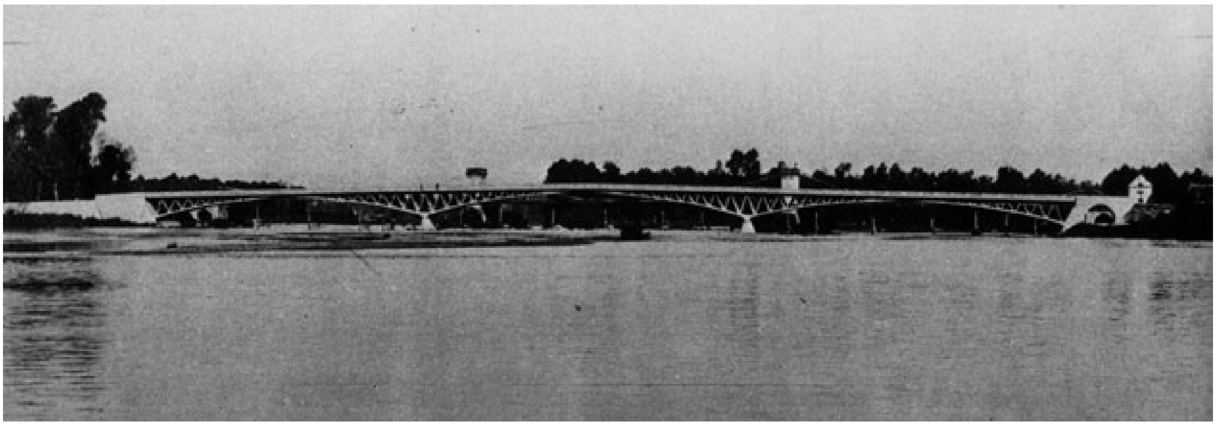


Figure 10 Le Veurdre Bridge

After the Veurdre (Figure 9 and Figure 10) came Boutiron (Figure 11), and Châtel-de-Neuve Bridges which were very successful and did not give any of the troubles that Freyssinet had to solve in Veurdre. He would say later *"It was a source of great pleasure to me to be able to go back and see my bridge from time to time. From 1907 to 1911 Le Veurdre had been constantly on my mind. I have always loved it more than any other of my bridges and of all the bridges destroyed in the war it is the one whose loss distressed me most"* [17].

He also wrote about the feeling when he finished a bridge: *"Je ne sais s'il existe une joie plus grisante que celle du constructeur qui, étudiant sans complaisance son œuvre terminée, ne lui découvre aucun défaut. Quelle récompense à ses efforts. Il est Dieu au septième jour"*[2] [17].

The conclusion of these bridges was the end of a phase of Freyssinet's professional career. With the solution of these problems he received the Caméré price in 1908, one of the most renowned prices for engineering in France, and he became a well known engineer. He then established a close relationship with Claude Limousin, who could see the great value of this very young engineer. He first took the construction company "Mercier, Limousin et Cie, Procédés Freyssinet", that later came to be named "Limousin et Cie, Procédés Freyssinet". Until 1928 he then dedicated his work to develop new solutions without other economic or administrative problems, but took over completely on the design and organisation of the constructions. At this point a new part of the personal and professional life of Eugène Freyssinet started.

Freyssinet was married in 1916 when he was 37 to a younger woman of 21, Jeanne Martin-Cheu-

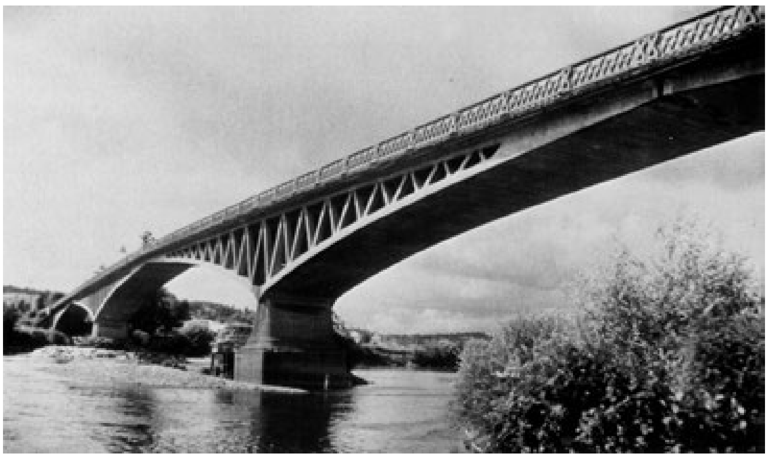


Figure 11 Boutiron Bridge

[3] *In English: Nothing can be more intoxicating than the joy experienced by the builder who, when he looks dispassionately at the finished piece of work, can find nothing wrong with it. What a reward for his labours. It is like being God on the seventh day.*

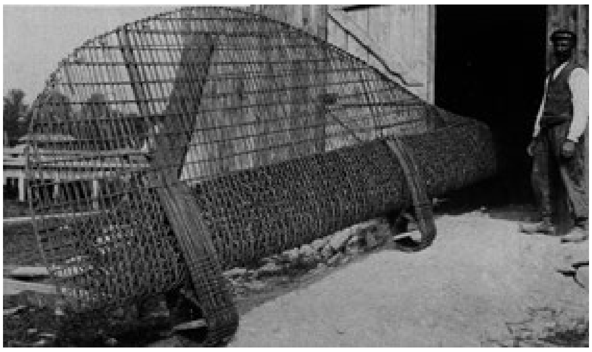


Figure 12 Reinforcement of a rudder for a reinforced concrete boat

Figure 13 Nave of the Aciéries de Caen

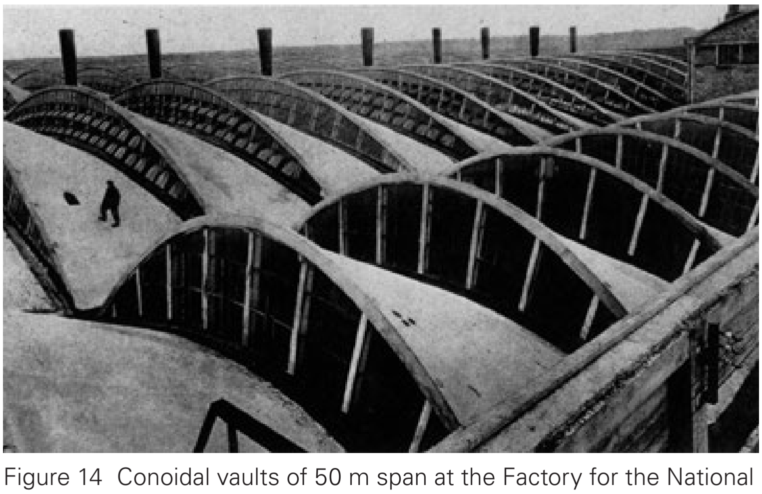


Figure 14 Conoidal vaults of 50 m span at the Factory for the National Radiator Company, 1928

tin, from now Mme Freyssinet. She made his passion and his happiness hers and this allowed him to dedicate his complete efforts to his passion of being a builder. She felt totally involved in his work and went with him everywhere, listening to explanations he would give after long sessions. He confided in her as his only real friend and as she herself said, she would have laid down her life if it could have made her husband's dreams into reality [2].

The first part of this new aspect of his life he dedicated to master the use of reinforced concrete. He developed solutions for industrial buildings, for water tanks, for silos, even for walkways using reinforced concrete. Due to the lack of the material and the high cost of steel, many elements were then made of concrete, like boats [18] or even railways carriages for guns [16] (Figure 12).

Freyssinet started to build with Limousin a large number of industrial buildings. He developed for these buildings new solutions like floors for large loads of about 2.000 kg/cm² in reinforced concrete, solutions for large spans and the possibility to have movable cranes, or even roofs built with shell solutions. He created architectural spaces even without noticing it himself. Only later when architects reviewed some of the spaces he created at this time they realised the similarities with other large traditional buildings in basilica style.

The example that stands out is the building for the Aciéries de Caen with a nave of 25 m wide, 25 m height and 80 m length, Figure 13. Later in 1936 he would write in Architecture d'aujourd'hui [19]: *"I think that Marcel Magne was the first to draw attention to one of my creations when he published specially some photographs of the foundry hall at the Caen steelworks. This hall has some fairly unexpected forms which are consequence of my having done my best to adapt a building to the requirements of an industrial process which requires heavy and complex machinery."* This is another example of how a good and detailed design works, taking into account all aspects of the requirements and the construction many times brings out also beautiful solutions.

Creating new solutions for these industrial buildings he also used concrete shells at the very early times when these solutions were under development. He started using shell solutions already in 1915 at the Verrieres du Centre, a glassworks company and used multiple solutions of shells until the end of 1920s. He built folded vaults, cylindrical vaults, and also conoidal vaults to a span of 60 m in the factory at Aulnay-sous-Bois (Figure 14).

In one of his works on shells he designed the tie to be prestressed in the Hangar of Palyvestre in Toulon in 1926. He used, for a 55 m span, a tie that was connected to the triangulated truss. He introduced the forces with the help of jacks in the nodes of the truss. The use of this prestressing was necessary to reach longer spans [20] (Figure 15).

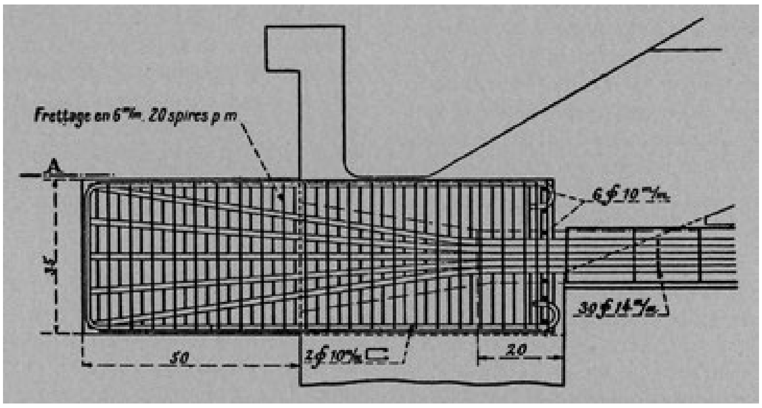


Figure 15 Prestressed tie at the hangars d'avions de Palyvestre, Toulon

It is important to note that most of the shells developed by Freyssinet were designed and built before the great evolution of shell construction, with great engineers like, among others, Maillart, Nervi, Torroja, or Dischinger at the end of 1920s and from 1930s. Freyssinet followed his works on shells with two exceptional works for railway stations. He designed and built the vaults for the Austerlitz Station in Paris in 1928. He built three parallel vaults with large openings, the side ones smaller and at a different level, and he added also a vaulted canopy (Figure 16 and Figure 17).


Figure 16 Vaults at the Gare d'Austerlitz, central vaults

The most important shell that Freyssinet built was the Hangars at Orly, built between 1921 and 1923. They were unfortunately destroyed in the Second World War. Albert Laprade later commented that Freyssinet told him that his success was due to a dreadful mistake made by the Société Limousin when the contract was awarded. It seemed that the operation would be a ruin when he thought of the idea of a single centring that would move sideways [21]. This principle was used by Saint-Bénezet when he built the Bridge of Avignon.


Figure 17 Vaults at the Gare d'Austerlitz, canopies

The novelty of Orly was that the concentration during the design was primarily done for the ease of construction [22]. Once again it was expressed the genius of a

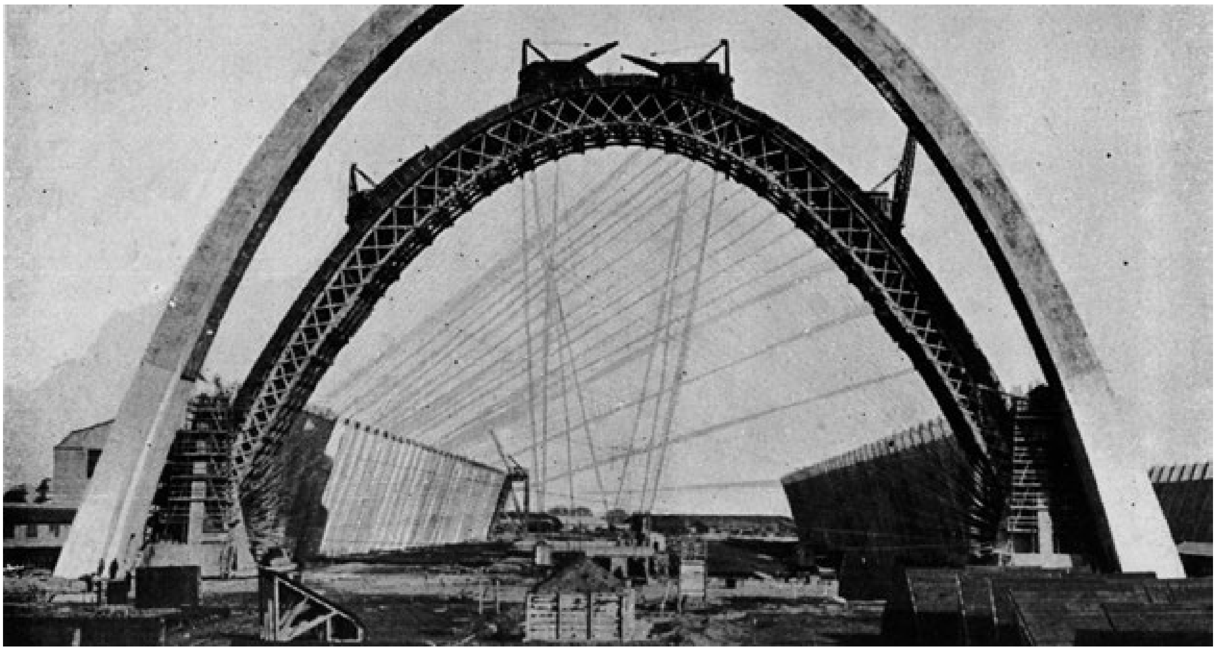


Figure 18 Orly Hangars during construction

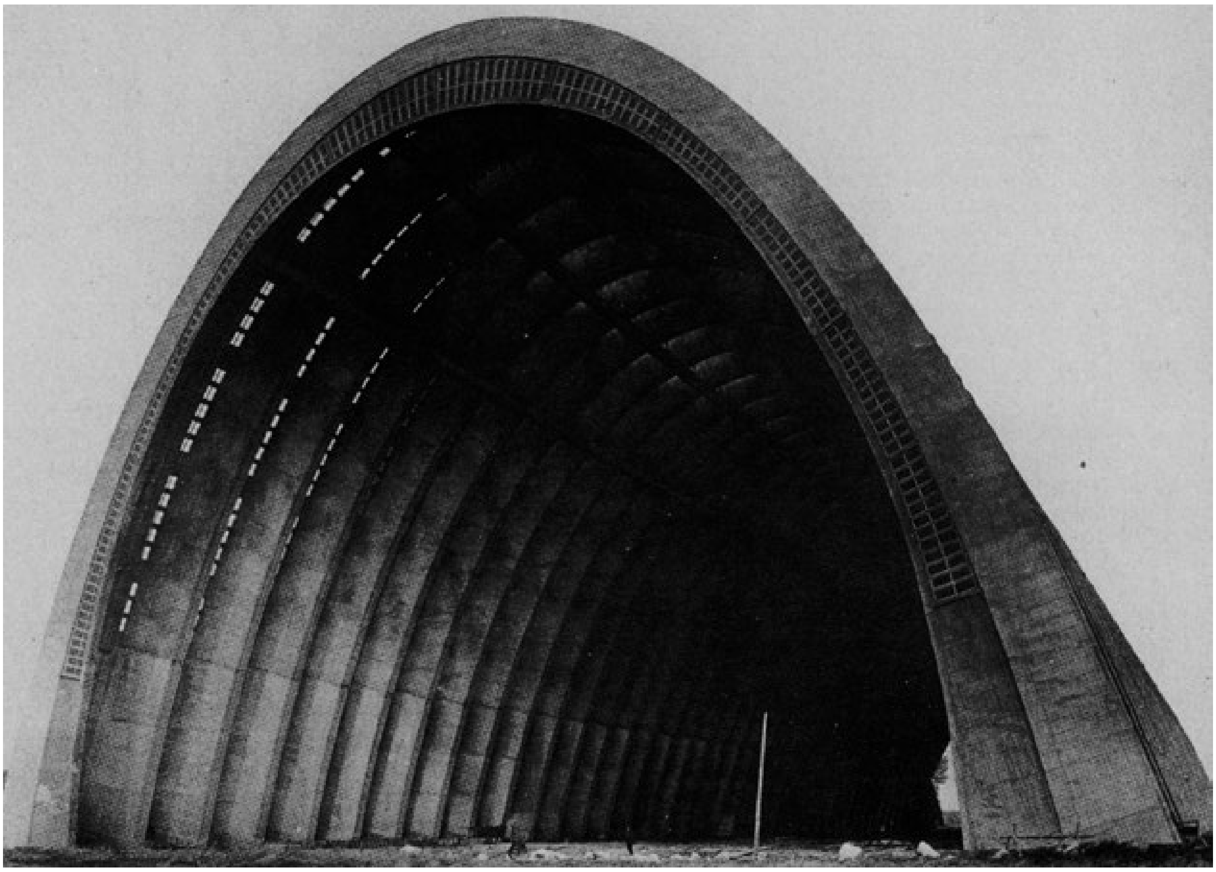


Figure 19 Orly Hangars finished

man that combined design, planning and construction methods. Only in this way it was possible to create such an incredible structure with so many novelties in the design and construction. He did not take special care for the aesthetics of the design, but he achieved one of the most impressive spaces and buildings ever built, as was written by anyone that could enter the building like Urban Cassan or Jaques Fougerolle. He left a question on this aspect, still today unanswered: *"How can an emotional response of this nature, essentially moral in outlook, arise from using mechanical means to achieve entirely utilitarian ends?"* [22].

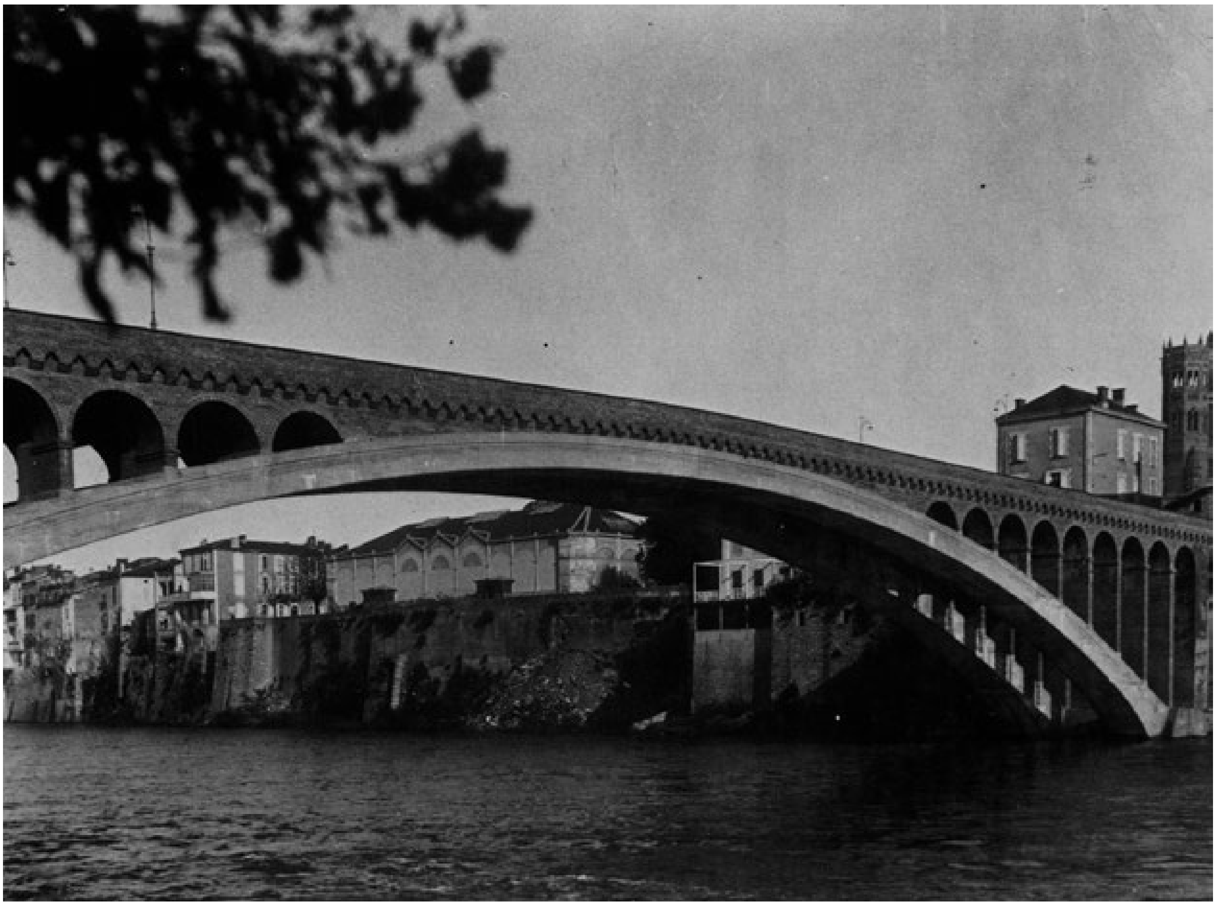


Figure 20 Villeneuve-sur-Lot Bridge finished

The twin hangars had 88 m span, 55 m height and 300 m length. They were designed as a double curvature folded vault (it was formed by 40 folds of 7.5 m width), built in reinforced concrete with a thickness of only 8 cm and thus many times more slender than the shell of an egg (Figure 18). He used the best concrete that he could prepare at the time with 350 kg of cement and 1.000 kg of gravel and natural sand. It was vibrated by means of repeated shocks to the moulds. He used wooden moulds strengthened with steel trusses. The movement of the moulds had to adapt the concrete pouring process and therefore they had to be industrialises for easy movement. They managed to complete a full cycle in one week (Figure 19).

The Hangars at Orly were world record and highly innovative at the time in many ways like the quantity of concrete for the volume of the building, speed in construction, the use of quick hardening concretes and the use of new mix designs.

Besides the work in buildings Freyssinet also continued during this period his work in bridges. He built some special bridges like the Villeneuve-sur-Lot Bridge, the Candelier Bridge, the St. Pierre-de-Vauvray Bridge and the Plougastel Bridge.

One of the most important bridges in this period is the Villeneuve-sur-Lot Bridge, built between 1914 and 1919. It was a world record arch in concrete with a single span of 100 m with a rise of 13 m, built with twin concrete arches, brick layered concrete spandrel piles and precast concrete slabs and in situ concrete for the deck (Figure 20).

Shortly later, in 1923 he built the St. Pierre-de-Vauvray Bridge that was world record for a concrete bridge with a span of 131.5 m, and the Candelier Bridge was also the longest span, with 64 m, for railway bridges.

St. Pierre-de-Vauvray Bridge (Figure 21) was another type of concrete arch. It had a suspension deck under the concrete arch. Even the transverse beams were designed as concrete trusses. The suspension ties were steel bars covered by concrete. The bridge was destroyed during the Second World War.

The Candelier Bridge (Figure 22) was another design of an arch bridge, in this case for very high loads for railways. It was started in 1914 and finished in 1921. The twin arches depth increased closer to the abutments from 0.50 m to 1.35 m. Freyssinet reached very high compressive stress-

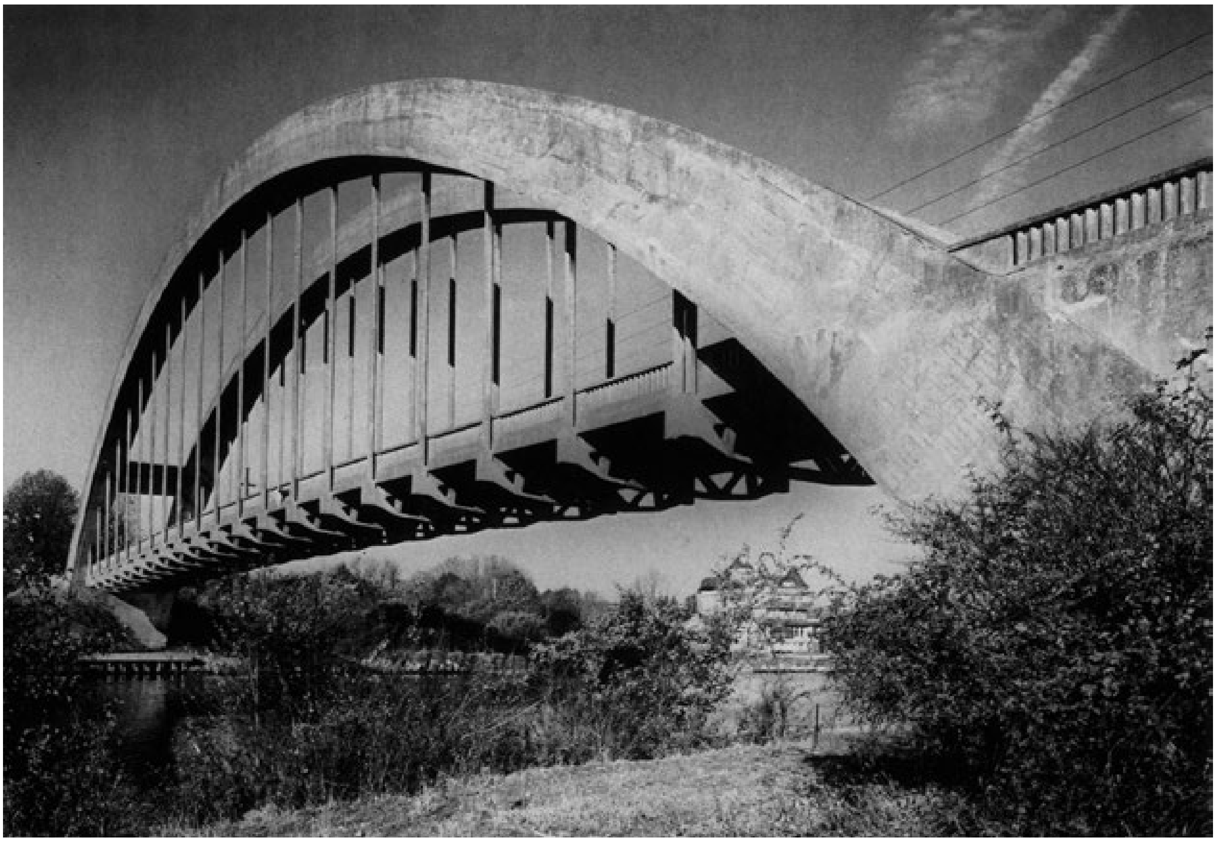


Figure 21 St. Pierre-de-Vauvray Bridge

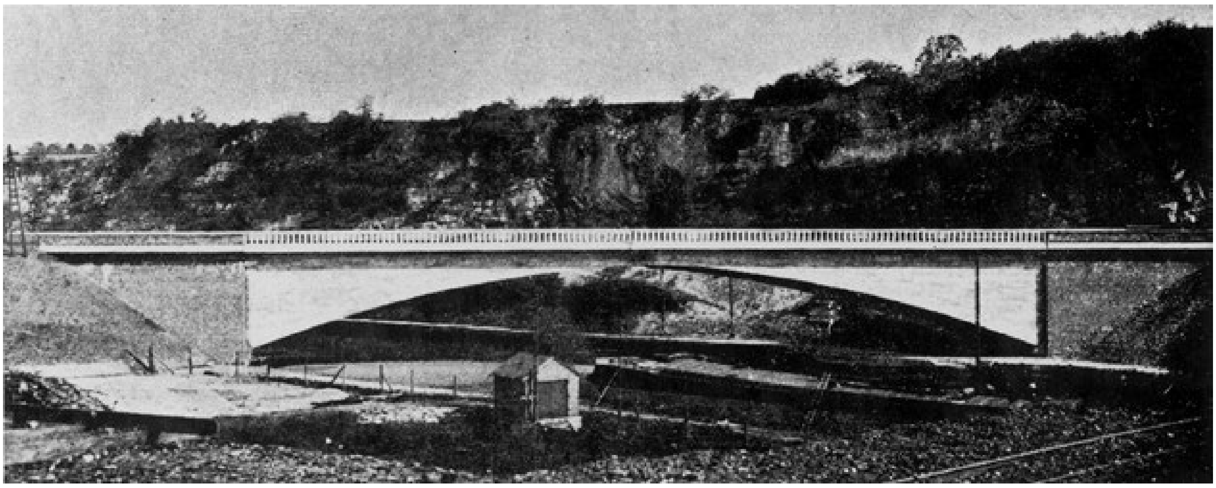


Figure 22 The Candelier Bridge

es, as far as 164 kg/cm² at the hinges which forced him to use very good concrete for the time. The use of steel was reduced by half, what the directive of 1906 then also considered very restrictive [23].

Freyssinet then started in 1924 one of his greatest works – the Plougastel Bridge (or the Albert Loupe Bridge as is the official name) on the Elorn Estuary, very near Brest (Figure 23). It is his most outstanding achievement in reinforced concrete bridges. It was built for both road and railway traffic. It was a world record of span of 188 m, between axis of the piles, that followed the also world record spans of Villeneuve-Sur-Lot Bridge with 100 m span and the St. Pierre-de-Vauvray Bridge with 131.5 m [24]–[26]. At that moment everyone thought that to achieve these spans was impossible. Freyssinet not only demonstrated that the span was possible but also used some revolutionary construction methods. Freyssinet considered that *"Plougastel arches were perfectly classical"* and constituted *"a simple continuation of the tradition of bridges in dressed stone adapted to the requirements of modern activities"* [26].

The price tendered by Limousin for the bridge was very low compared to any other similar bridge at the time. There is where the genius of Freyssinet brought innovative constructions methods that were very innovative at the time and that were so simple that were after Freyssinet's time used regularly. He reached every small detail in the whole work, from the design to the definition of the auxiliary methods or the definition and fabrication of the concrete. Seailles said that his methods *"always seem audacious when compared with his predecessors but are simple, logical and elegant when considered by themselves"* [27].

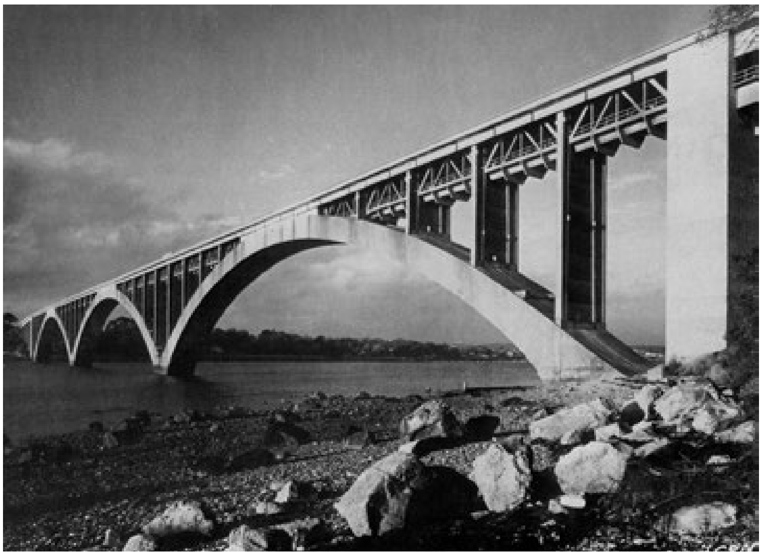


Figure 23 Plougastel Bridge

Among the construction methods used the most important were the design and construction of a cable transporter, with a total span of 800 m that Freyssinet used in all the construction. It was even controlled by an independent driver and not from the ground as they were normal then. He also built the foundations with two floatable cofferdam caissons. The foundations were designed as shells and there his colleague Coyne, who was the general manager at the job, had all the necessary experience to use these shells to the construction of dams in which he became the best designer in the world. The springing of the arches were built with a technology of an incremental symmetrical construction what is a clear start of what has been later widely used for the construction of bridges. To control the deflections in this first stage due to self-weight and the centring he used tensioned ties that he stressed using screw jacks. He used this technology of imposed deformations already in the test arch in the Veurdre, at the Palyvestre Hangars and in the canopies of Austerlitz (Figure 24).

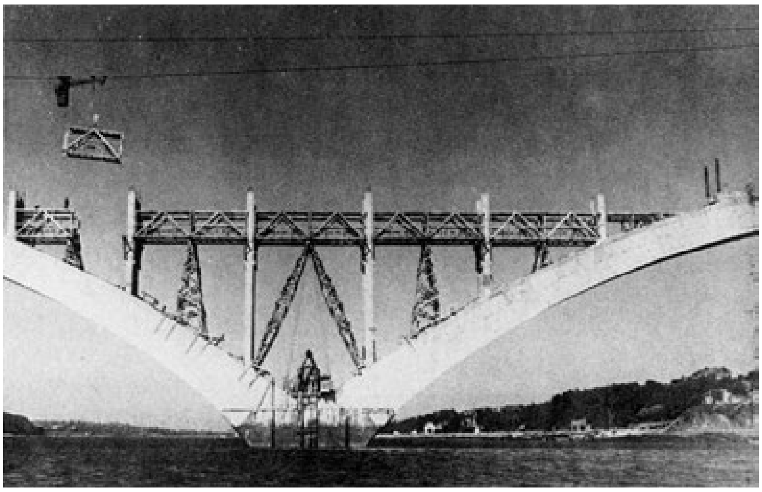


Figure 24 Springing of the arches and cable car

Figure 25 Centring of the Plougastel Bridge floating for the next arch

Even more impressive was the design and construction of the floating movable centring that he used for the construction of the three arches (Figure 25). It was a wood and steel arch of a span of 170 m with wood planks nailed together and with tension ties that allowed to adjust the deflections if needed. The adjustment of the centring was made using jacks that stressed and shortened the cables of the ties. Even for the reconstruction of an arch after the Second World War, after 20 years of the construction, no better method could be found.

The steel in the arch was merely 23 kg/m³. The design compressive stresses were 32 kg/cm² for

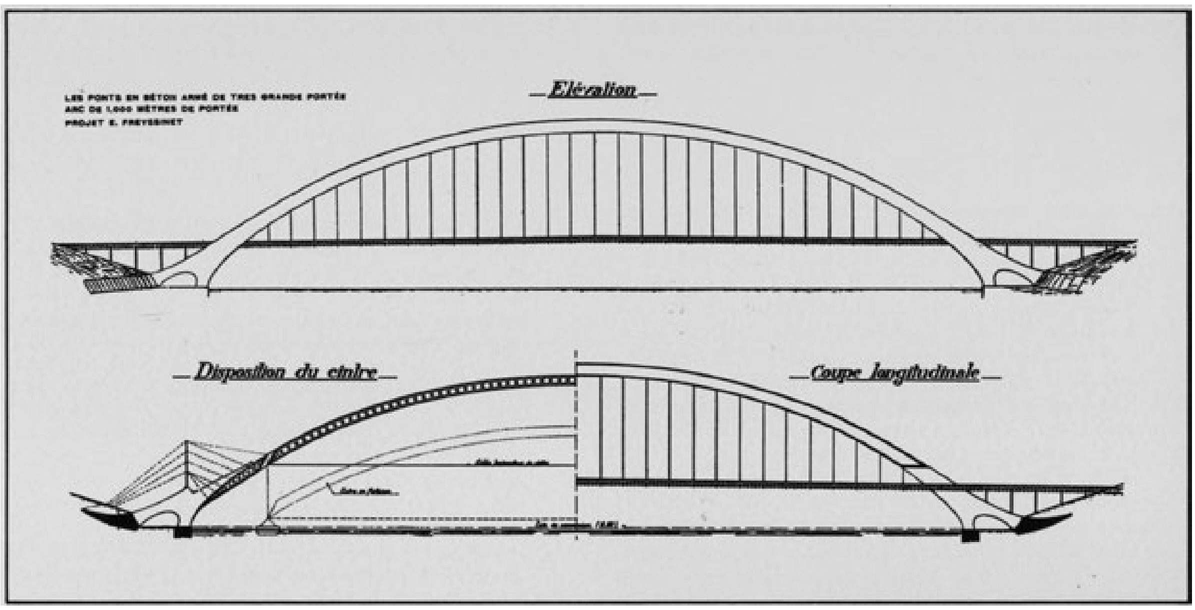


Figure 26 Design from Freyssinet for a 1.000 m arch

self-weight, 10 kg/cm² for slab weight, 20 kg cm² for imposed loads and 13 kg/cm² for shrinkage and temperature, which gave a maximum of 75 kg/cm².

During the construction of the Plougastel Bridge Freyssinet did very detailed tests to confirm his ideas on the deformation of concrete under load which he published later and was the start of the acknowledgment of these effects. These investigations were a key factor for the industrial development of prestressed concrete that he did in the following years [28]–[30] (Figure 28).

Both Coyne and Freyssinet thought that, after the construction of Plougastel Bridge, it would be clearly possible to build a reinforced concrete arch of 400 m span and even they did a conceptual design of a bridge with an arch of 1.000 m span. Freyssinet thought that this was possible without a further development of the technology as they had done at the time. Unfortunately, he never had the possibility to build this structure (Figure 26).

5 Prestressed concrete

When the technical and industrial limitations that held back the first ideas about prestressed concrete were solved, a new breakthrough in construction was quickly developed. While this breakthrough brought in-depth change to construction as a whole, it absolutely revolutionised concrete construction. Until that time, concrete had been an inert, passive material whose scant tensile strength inevitably induced cracking, the source of its ready deterioration.

Thanks to prestressing, concrete became an active, high compressive strength, isotropic product. This new, fine and highly durable material led in turn to the development of high strength steels and concrete with high early age compressive strength.

The idea of external compression is integrated in the history of construction. Even the arch can be considered a form of prestressing made by the gravity and the form of the structure.

The application of prestressing to concrete was not an easy task as engineers did not realise the importance of the special considerations that needed to

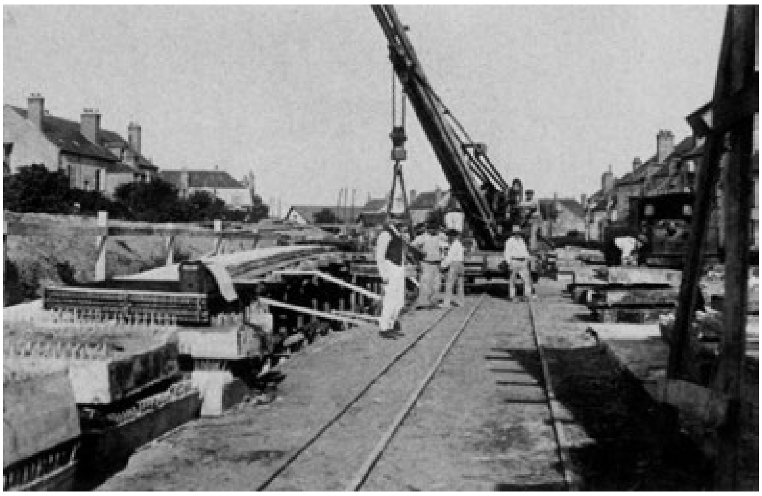


Figure 27 Test arch of the Veurdre Bridge

be done for concrete as are the rheological effects and also the importance to develop high strength steel that could solve the problem.

Freyssinet made a prestressed tie for his test arch for his Pont du Veurdre (Figure 27) in 1908 in which he prestressed high elastic 8 mm wires anchored in wedges in pairs to achieve a total force of 2.500 tonnes to a stress of 70 kg/mm² and introducing to the concrete a compression of 150 kg/cm². Magnel also used the idea of anchoring wires in pairs in his later developments of prestressing [16].

Many years after the application of prestressing these tests they were the base of the discussion for the invention of prestressing [31], [32]. After those years every book or publication on prestressing had a description based on the country where the authors belonged more than the scientific information of the research [33], [34].

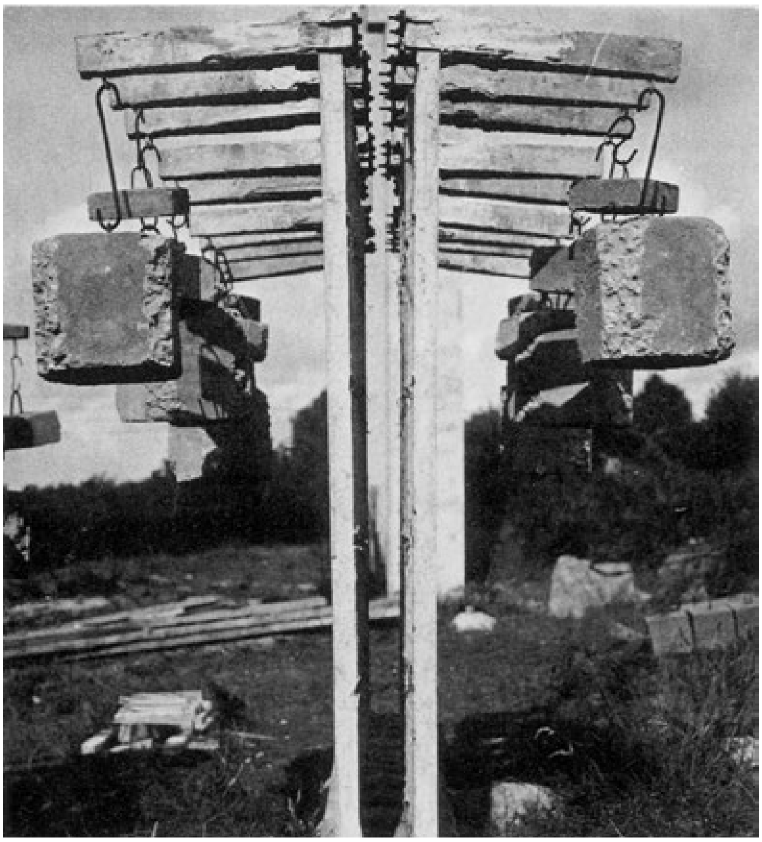


Figure 28 Freyssinet concrete tests at the Plougastel yard, 1928

Eugène Freyssinet, in an unpublished manuscript, wrote: *"One day it suddenly dawned on me that although I could not force concrete to adapt to steel strain without breaking, I could pre-impose concrete strain on steel. All it would take would be to impose higher total tensile stress on all of the reinforcement as a whole so that even if it adapted to any further concrete strain, it would still be permanently compressed"* [2].

The idea of prestressing first came to Freyssinet in 1903 when he visited the cantilevers built by Rabut in Paris. Since this date he kept this idea in mind and applied it partially in his works and helped him to solve all the technological problems that lead to the success in the application of prestressing to actual works. He used it in the test arch at the Veurdre Bridge in 1908 (Figure 27), and realised the importance of the technique and the relations between the high strength steel and and the deformation of the concrete. Later with Limousin they patented vibration of concrete in 1917 [35].

For 25 years he investigated the problems arising from slow deformation of cements and concrete under compression. He studied stresses, creep, the reversability of tension, the effect of grading and compaction. He also investigated the effects of temperature, humidity and moisture on shrinkage, the influence of time for all, the lack of consistency in the modulus of elasticity, the properties of the networks of voids which exit between the hydrates, the process of crystallisation, the mechanics of curing and setting, thermal deformations, shear deformations, and all the variable parameters that influence the first hours for concrete hardening.

Freyssinet published all his investigations in a series of publications that may be interesting for the researchers [6], [26], [28], [35]–[47]. He never wrote a book with all his discoveries but he applied them in his works. He discovered in 1910 the phenomena of creep and deformation under load in the Veurdre Bridge [48], and in 1926 the variation over time of Young's modulus as a fuction of its strength and the load. Guyon said that it was Freyssinet who brought light definitely to the phenomenon of creep deformation and formulated its laws after his experiments in Plougastel (Figure 28) [49]. He performed some very detailded tests when he built the Bridge of Plougastel in 1928. Later he refuted in 1930 the theory by Mesnager that concrete had a constant modulus of elasticity.

On 2nd October 1928, at the age of 50, Freyssinet took a serious personal decision. He decided to put at risk all he had achieved and dedicate all his efforts to the development of prestressed con-

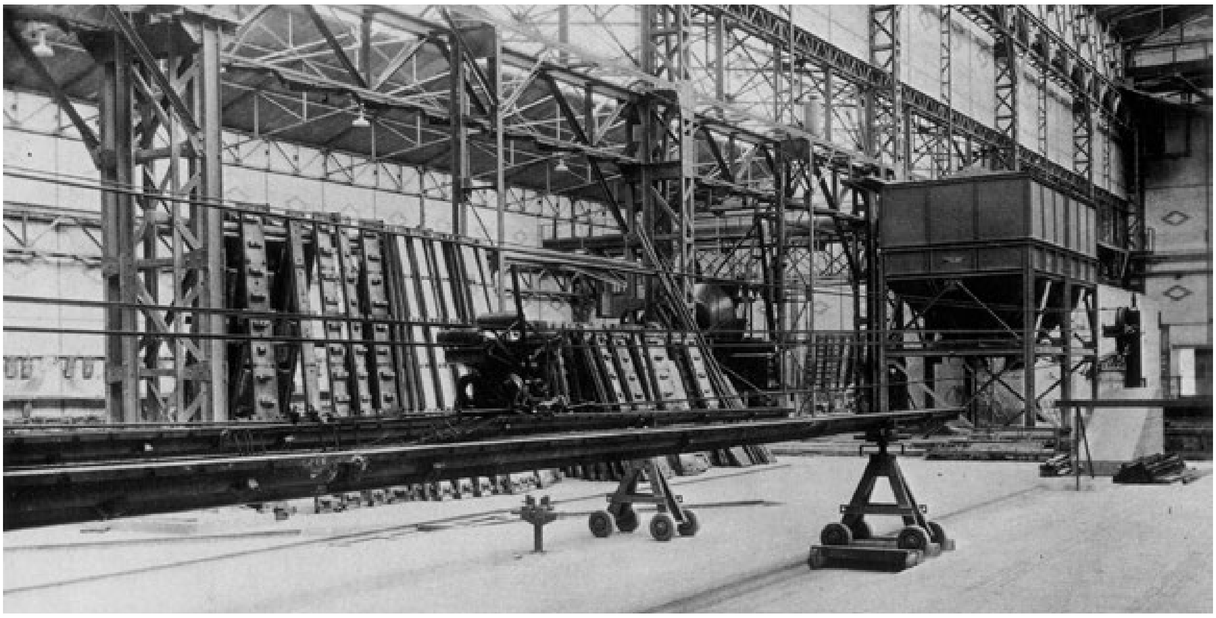


Figure 29 Precast prestressed factory for posts at Montarguis

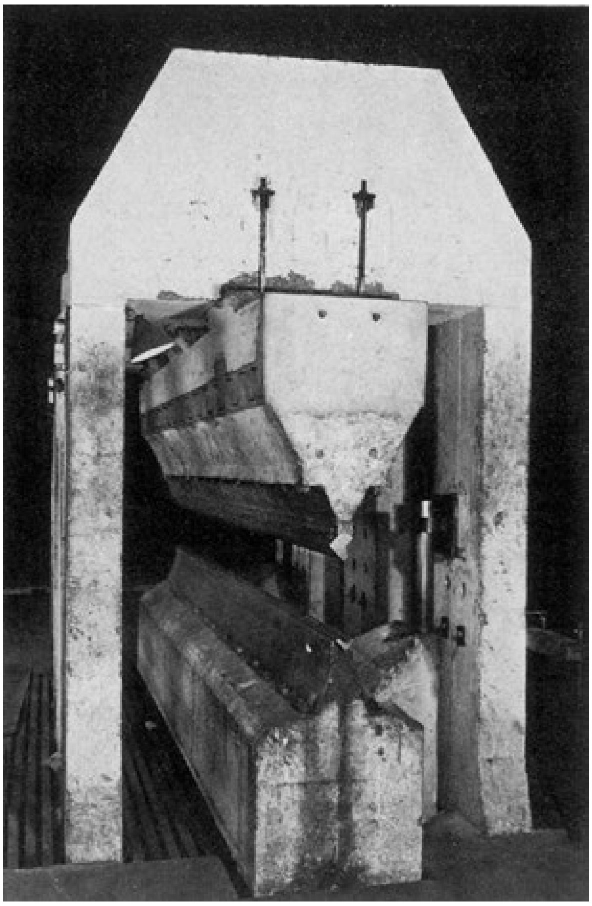


Figure 30 Prestressing press at Montarguis

crete. His former partner Limousin with whom he had achieved great success in reinforced concrete, did not believe in the challenge and they decided to split, so he was on his own. He and his good friend Séailles submitted a patent application in Paris (later granted under No. 680 547) [50] which contained a very precise and lengthy description of the theory of permanent pre-compression of concrete or other materials, and all the possible ways to attain it in a real-life construction or industrial environment. The die was cast. Starting absolutely from scratch, Freyssinet was to create the entire corpus of prestressing technology [51]. He founded a factory to produce precast elements with prestressed concrete at Montarguis, where he produced technically satisfactory prestressed poles (Figure 29). This process challenged even Freyssinet's immense inventive creativity. He had to come up with solutions to all the details involved in the mass production of prestressed concrete elements in place today in even the smallest factory.

He defined the exact placement of the strands, which is vital to prestressed elements, for misplacement can cause irreparable initial deformation; he designed the structure of the moulds, balancing their anchorages by varying the lever arms; he ensured the absolute accuracy of each prestressed wire with jacks and counterweights; and he devised versatile moulds whose lengths could be varied at will for de-stressing by placing anchors at the base and the top. He also developed a prestressed press for more than 1.800 tonnes. He even invented a machine capable of cold drawing the wires up to ten per cent which enabled him to reach an elastic limit of 90 kg/mm² instead of the more conventional 40 kg/mm² used then (Figure 30).

All prestressing was done by bond, his first invention for this technique and that was used by other designers later until the development of the cone anchorages. This meant that at the early stages of prestressing all elements had to be precast. In this

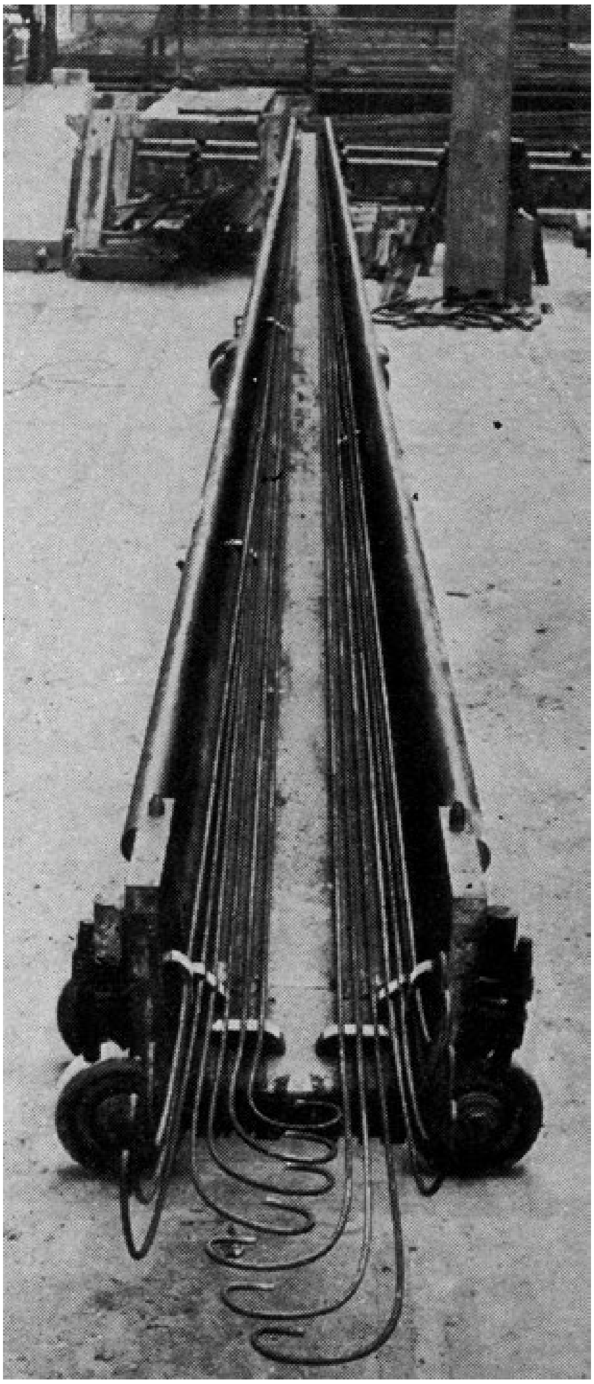


Figure 31 Anchor for precast elements at Montarguis

Figure 32 Precast prestressed posts

factory he developed many types of anchorages, some by bond and others with additional variants like: reinforcing loops (Figure 31); non-cylindrical wires; the torsion of one or more non-circular wires; the creation of protuberances in the wires and. He also developed the prestressing of tubes, using the deformation of blocks with external cables like the one he used later in Le Havre. Many of these ideas were later also patented by other researchers and some are still used even today. Freyssinet concluded that the higher the quality of the concrete the better the anchorage.

Freyssinet's concrete constituted a giant step forward in prefabrication. It's very high quality has even today yet to be matched in industrial prestressed concrete manufacturing (Figure 32). He used a special method that consisted essentially of casting the concrete in a matter of only a few seconds and then subjecting it to vigorous vibration (before and after its placement in the mould). The concrete was batched with excess water to ensure satisfactory casting and setting in the moulds, despite the large number of wires that had to be fitted into very small spaces. The excess water was then expelled by the high pressure exerted by an inner, prestressed, water-inflatable plastic mould. He achieved maximum concrete strengths of 1.000 kg/cm² and 500 kg/cm² at 16–48 hours (Figure 33).

From the technical point of view the project was a great success but from the commercial point of view it was a complete failure. In the factory, they developed elements to such high standards that there was no real need for them. They produced 16 m long poles at a rate of two per hour. The posts were ready for test the next day [6]. The economic crisis at those times lead to a total commercial disaster and steady losses. He was ruined and exhausted physically and mentally. In any case he thought that his achievements were far more relevant that those on previous years. During those years no other relevant construction was made using prestressing. The world was awaiting for a positive signal of confidence to start using this technique.

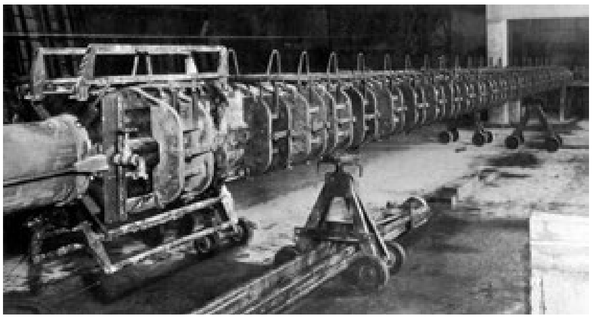


Figure 33 Flexible moulds to produce posts

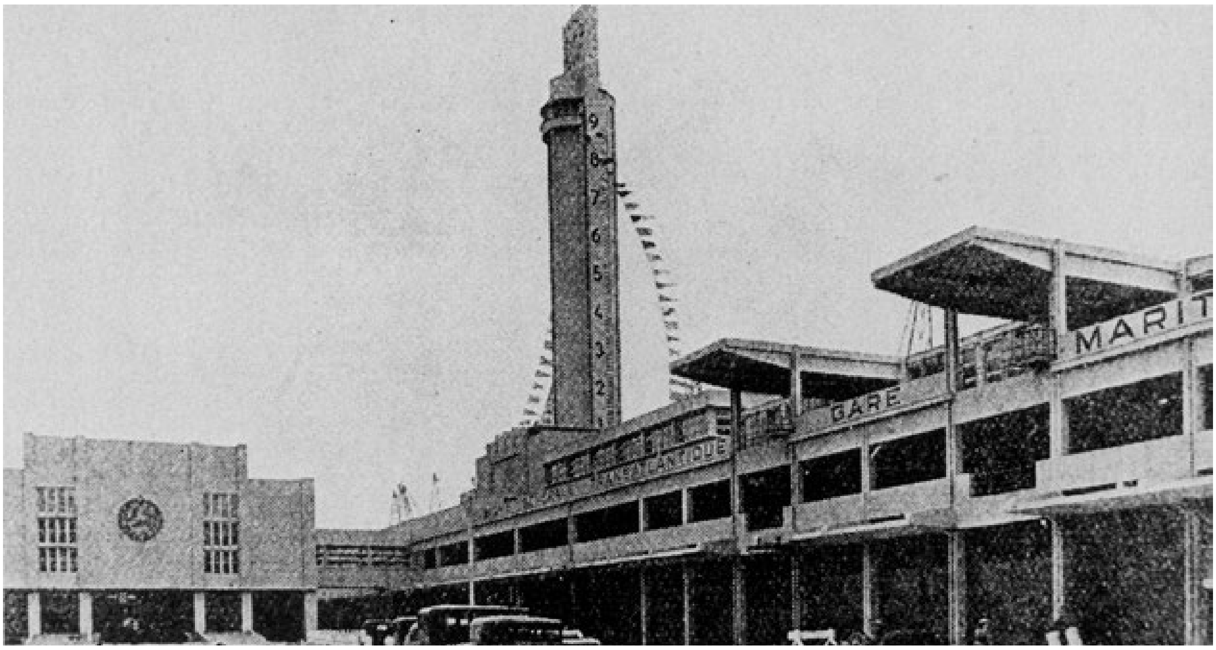


Figure 34 Maritime Station at Le Havre

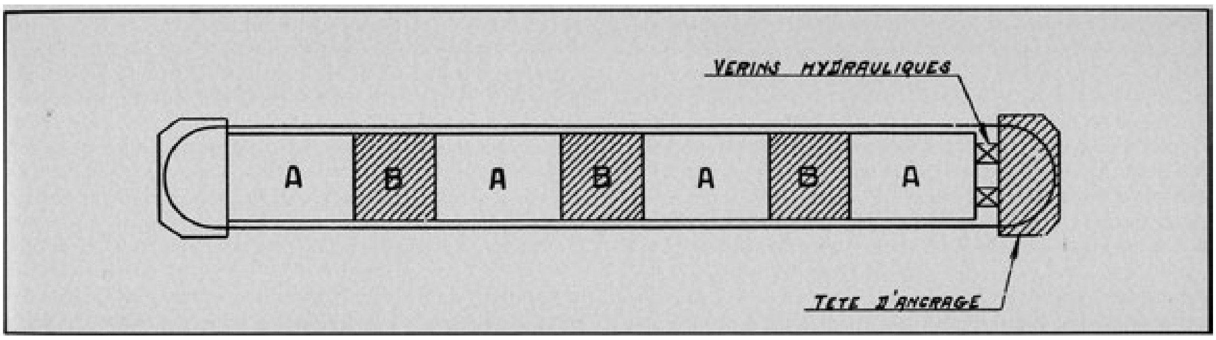


Figure 35 Idea to save the Maritime Station of Le Havre (drawing by Freyssinet in 1934)

Figure 36 Anchor blocks at the Maritime Station of Le Havre, solution for rehabilitation by Freyssinet in 1934

Freyssinet identified the primary cause to be the improvisation inherent in the world of construction, in which contractors never even consider engaging in long-term, in-depth research or studies. Rather, priority is given to immediate performance, unlike the practice in large industries, where the decision to mass produce a given model is adopted after many years of tests, research and verification. But six months later he developed a system to save the Maritime Station at Le Havre (Figure 34) that would give prestressing the confidence to be used by anyone in the world. At that time, the Le Havre Maritime Station was sinking into the Seine at a steady rate and with no possibility of rehabilitation. He proposed an innovative solution based on his technique of prestressing. The opportunity was given by the architect Urban Cassan. Part of the structure was sinking at a rate of 25 mm a month and the differential deformations were so important that a collapse was imminent. The building was finished in the summer of 1933. No one in the technical

Figure 37 Detail of holes for the piles at the Maritime Station of Le Havre, solution for rehabilitation by Freyssinet in 1934

Figure 38 Precast prestressed pipes for the Oued-Fodda project

community could find an answer to this problem. Freyssinet had the opportunity to propose a solution because there was no alternative possible and he let the Maritime Station and his own fate at a single stake [52].

The solution consisted of forming from the old foundations with some new concrete footings new elements of great length that were prestressed by means of external ties to the slabs with the help of hydraulic jacks and two anchorages of concrete at the end of the element. The cables turned at the end of the end blocks (Figure 35). The jacks developed a force of 1.000 tonnes in some cases. The link between the old and new concretes was only assured by the compression force of the prestressing. Through precast sockets in the beams large hollow cylindrical precast piles were driven and later filled with concrete (Figure 36).

They were then prestressed against the blocks with a force of 320 tonnes. The piles were produced in a similar way, even with steam curing, like the precast prestressed poles in Montarguis. At the end of 1934 with only part of the piles driven, the building had stopped to sink and the success was confirmed. Freyssinet had closed the vicious circle of innovators in which they find themselves trapped where any innovation is gambling with grave responsibilities and precedents and the example of a previous job is always demanded [6] (Figure 37).

From this moment Freyssinet could give the instructions on how to develop prestressing by any firm in the world. At this point an entrepreneur, Edme Campenon, saw the works and proposed him to continue as partners so they could develop this technique in the future [2].

Lebelle later related that Freyssinet presented this achievement in 1936 at the Berlin Congress of Bridges with more than 1200 participants among them more than 600 German engineers [2]. He also talked there about the possibility to create 100 m span beams for bridges and to prestress the elements in all directions to create an isotropic material and of working with concretes of strengths of 800 kg/cm².

Among the most relevant new developments at this time was the first prototype of a concrete prestressed pipe to be used in Oued-Fodda in Algeria (Figure 38) between 1935 and 1939. They used a compression of the concrete under placement and an external movable mould to produce the prestressing. Pipes under licence of Freyssinet were also produced in Germany after 1939 [53].

Also in the same hydraulic work, in 1936, Freyssinet built the first prestressed bridge in history across

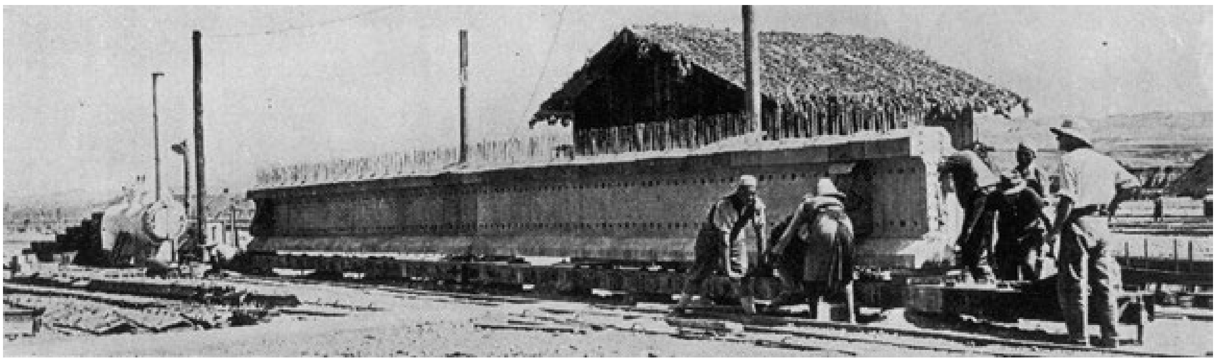


Figure 39 Precast prestressed beams for the Portes de Fer Bridge

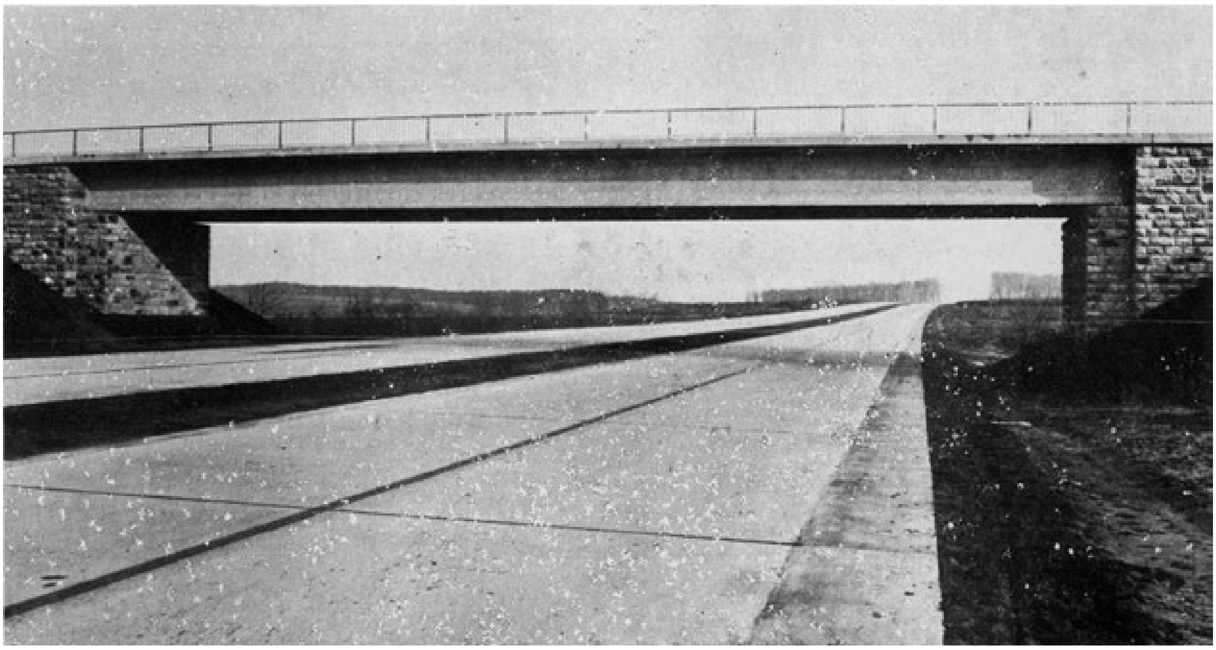


Figure 40 Oelde Bridge made with prestressed beams using Freyssinet's developments

Portes de Fer Dam, with a span of 19.0 m and a width of 4.60 m. Concrete was poured to form the bottom flanges of the beams after the longitudinal reinforcement had been prestressed against the mould. The vertical struts or ties were then prestressed before the webs and the top flange were cast. All the preliminary stress was always borne by the moulds. The concrete was *"vibrated, compressed and heated to accelerate the hardening"* [54] as in all Freyssinet's projects (Figure 39).

In 1933, in Germany, Mautner, then director of Wayss und Freytag, friend of Freyssinet, prepared some tests of a bridge under his instructions and drawings. It was a 1/3 model bridge of a 60 m beam in Frankfurt and other in Dresden in 1937. The beams were produced from 1938 in Stuttgart. The models were very important as they were studied in detail by Mörsch who published the results and wrote a book in 1943 on prestressed concrete, the first in German [55]. The first of the bridges built with these results was the Oelde Bridge in 1938 over a highway. It was a precast prestressed beam bridge with the slab in reinforced concrete, just as Freyssinet did then, with prestressing anchored in the moulds. The abutments were also prestressed (Figure 40).

In 1939 Freyssinet invented a lightweight and powerful prestressing jack and the anchorage cones that worked as friction connections [56], [57] (Figure 41). With the jack and the anchorage he developed a new way of using prestressing and made possible all the future developments that came

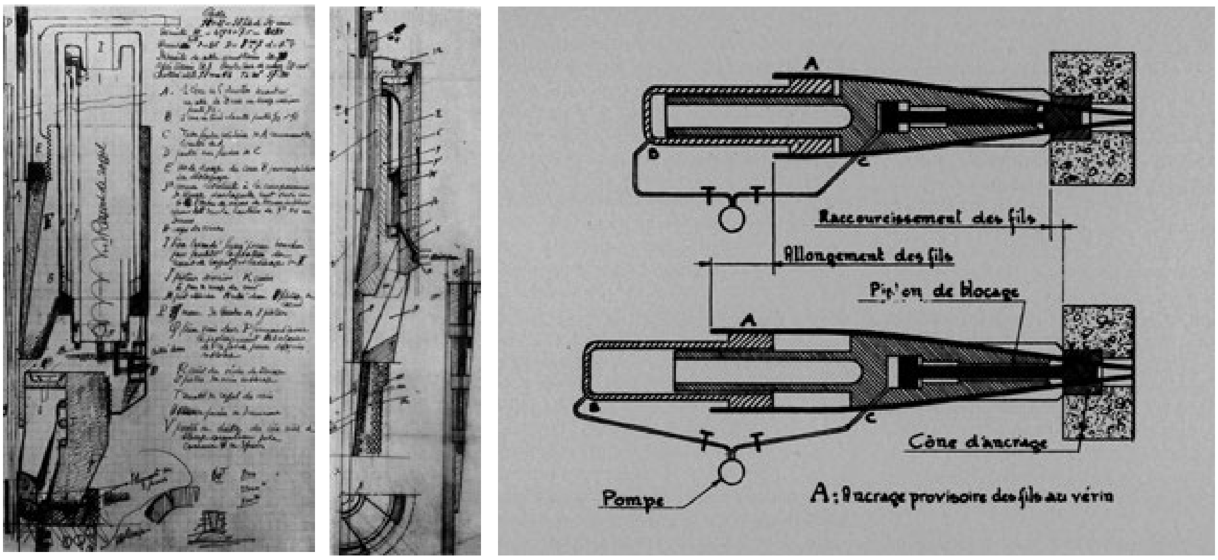


Figure 41 Schematic drawings of Freyssinet post-tensioning jack


Figure 42 Luzancy Bridge, completed

after and that allowed different and more complex construction systems. He considered it his great achievement after he had the idea to develop prestressing. This is the method that would make prestressing universal. It was a simple male cone of mortar and a female cone in steel-bound concrete.

One of the masterpieces built by Freyssinet in the decade of 1940 was the Luzancy Bridge (Figure 42). It was designed in 1939 and built during the periods 1940/41 and 1944–1946. It had to suffer from the problems of the Second World War. It is a 55 m span and 8 m width bridge, built with precast elements (Figure 43) connected with dry mortar and later prestressed in three directions (Figure 44). It was going to be the symbol of the new era of prestressed construction. It has only a depth of 1.22 m for 55 m span. It was built with integral prefabrication technique that is also the starting point of the later very popular segmental bridges. Each girder is formed of 22 sections and also the intermediate slabs, paving flags, and balustrades are precast – In total 1,016 precast elements. For Freyssinet it was a perfect structure that was elastic in every direction. The erection of the bridge (Figure 45) also demonstrated great ingenuity by means of cranes and cables without any temporary support [58], [59].

That first bridge would be the precursor to the very complex, large span, precast, structurally continuous bridges built today. Initially, all beams were verified by load tests run at the plant to determine whether the experimental deflection was consistent with the design value. The later development in the design and construction of segmental bridges has proven that this technology has been very successful since then all around the world.


Figure 43 Luzancy Bridge, precast segments


Figure 44 Luzancy Bridge, prestressing jack

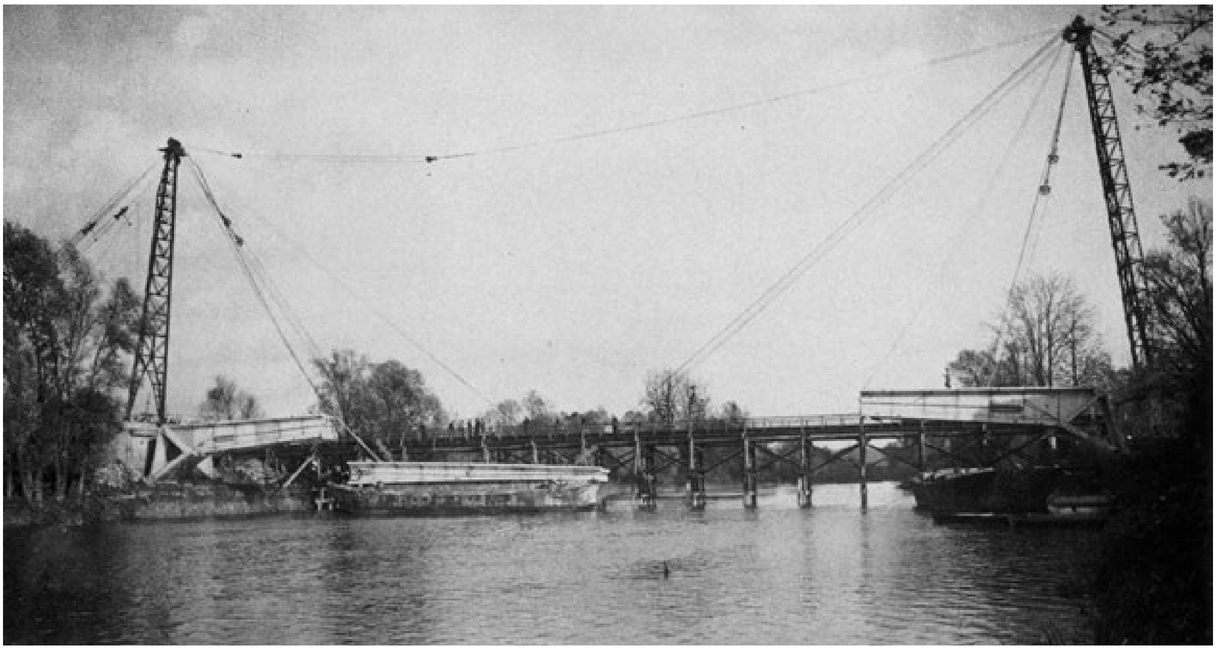


Figure 45 Luzancy Bridge, erection

6 Last works

After the landmark bridge of Luzancy, on Campenon's initiative, it was created S.T.U.P. (*Société Technique pour l'Utilisation de la Précontrainte*) in 1943 specially dedicated to the development of prestressing. Later in 1949 more than 500 engineers met at the Association Scientifique de la Précontrainte to discuss this new technology.

Some years after, a new association was created to serve as a place to look forward in the developing of prestressing. It was founded of the International Federation for Prestressing FIP in 1952 at an international meeting held in Cambridge. This foundation came after the decision that is was made by the *Association Scientifique e la Précontrainte* in 1950. The persons and countries represented in this international meeting were *Rinaldi* for Italy, *Bruggeling* for The Netherlands, *Gooding* for England and *Fernandez Conde* for Spain [60]. This meeting meant the success of the works developed for more than the two previous years by a small number of eminent technicians, professors and researchers lead by *Freyssinet* from France and *Magnel* from Belgium. In the inaugural session were present: *E. Bornemann* (Germany), *G. Magnel* (Belgium and South Africa), *W. l. Jonson* (Denmark), *E. Torroja* (Spain), *L. Goff* (USA), *B. Kelopuu* (Finland), *Y. Guyon* and *J. Prempain* (France), *J. Hartmann* (The Netherlands), *P. Gooding* (UK), *F. Levi* (Italy) and *U. Bjuggren* (Sweden).

The first FIP presidents were:

- Eugène Freyssinet 1952–1958,
- Eduardo Torroja 1958–1961,
- Yves Guyon 1961–1966,
- Franco Levi 1966–1970.

The FIP merged later with the CEB (*Comité Européen du Béton* – in English: European Committee for Concrete) in 1998 to create the *fib*, the International Federation for Structural Concrete that

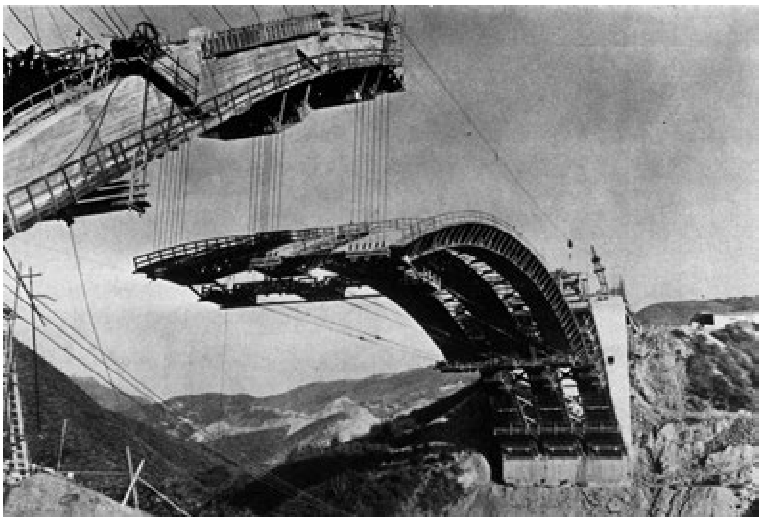


Figure 46 Viaduct at La Guaira Highway, centring

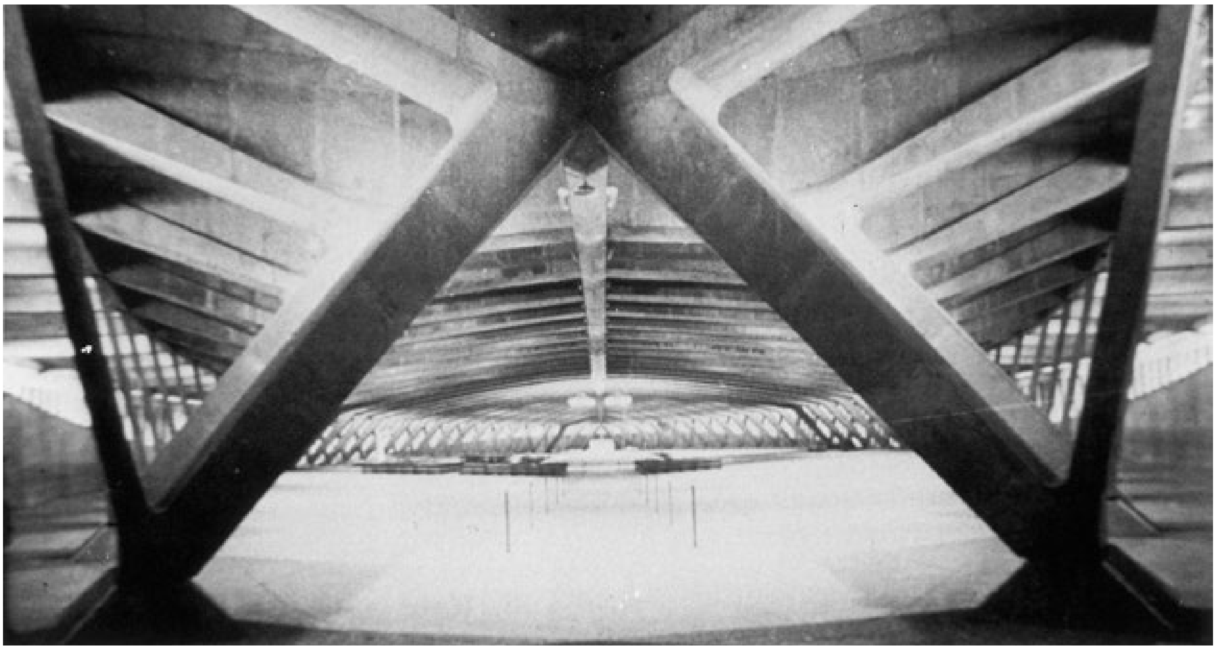


Figure 47 Basilica at Lourdes

continues the work today in creating and disseminating knowledge in structural concrete.

Freyssinet kept on with multiple projects, including a series of bridges similar to Luzancy, water reservoirs, and many other structures [61]. Among the most important ones were the design of three viaducts in Caracas for the La Guaira Highway for which he developed the construction method with a new light centring supported in cantilevers [62], [63] (Figure 46). He also worked in the new building at the Basilica of Lourdes with the architect Vago [64] (Figure 47).

In 1958 he built in collaboration with Baillard a very beautiful bridge at the Autoroute du Sud from Paris to Orly (Figure 48). It is a three-span bridge with a continuous box girder with variable curvature in two directions. This bridge also created a new design tendency for overpasses for highways [65].

At the age of 80 Freyssinet also designed of the Saint Michel Bridge over the Garonne in Toulouse (Figure 49). The bridge was opened in 1962 just a few months before Freyssinet's death. Even at that age Freyssinet could create a fresh design that would be the model for many future bridges. He used V-shaped piers that carried a variable depth continuous girder. He had used the idea of the triangular shape for the Luzancy Bridge and he brought it to a next level [66], [67].

Freyssinet died on 8th of June 1962, just two days after he received a congratulatory telegram from the attendees of the 4th FIP congress in Naples. A higher passion inspired his genius [68]. He was one of the most complete engineers of the 20th century and one of the greatest builders in history [2].

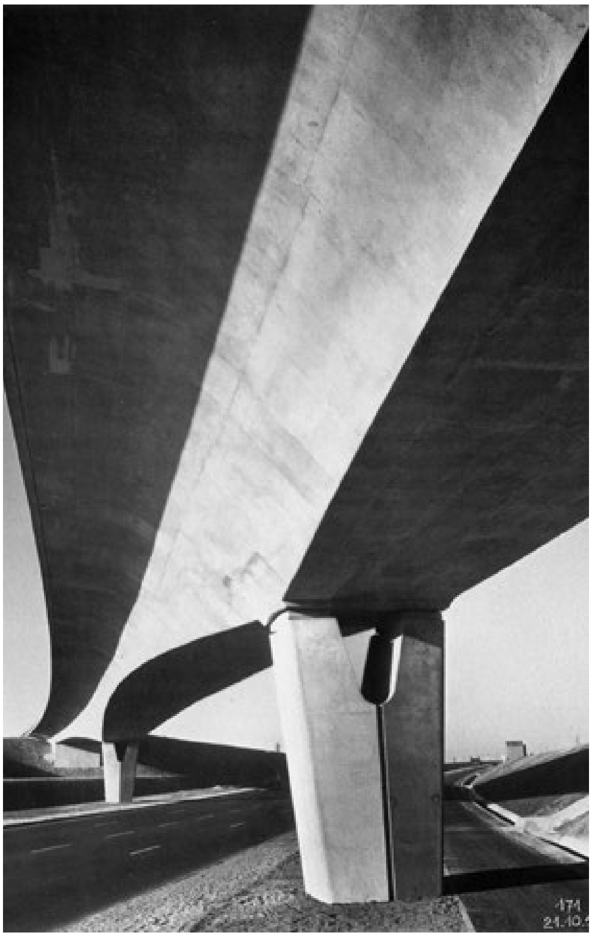


Figure 48 Orly Bridge

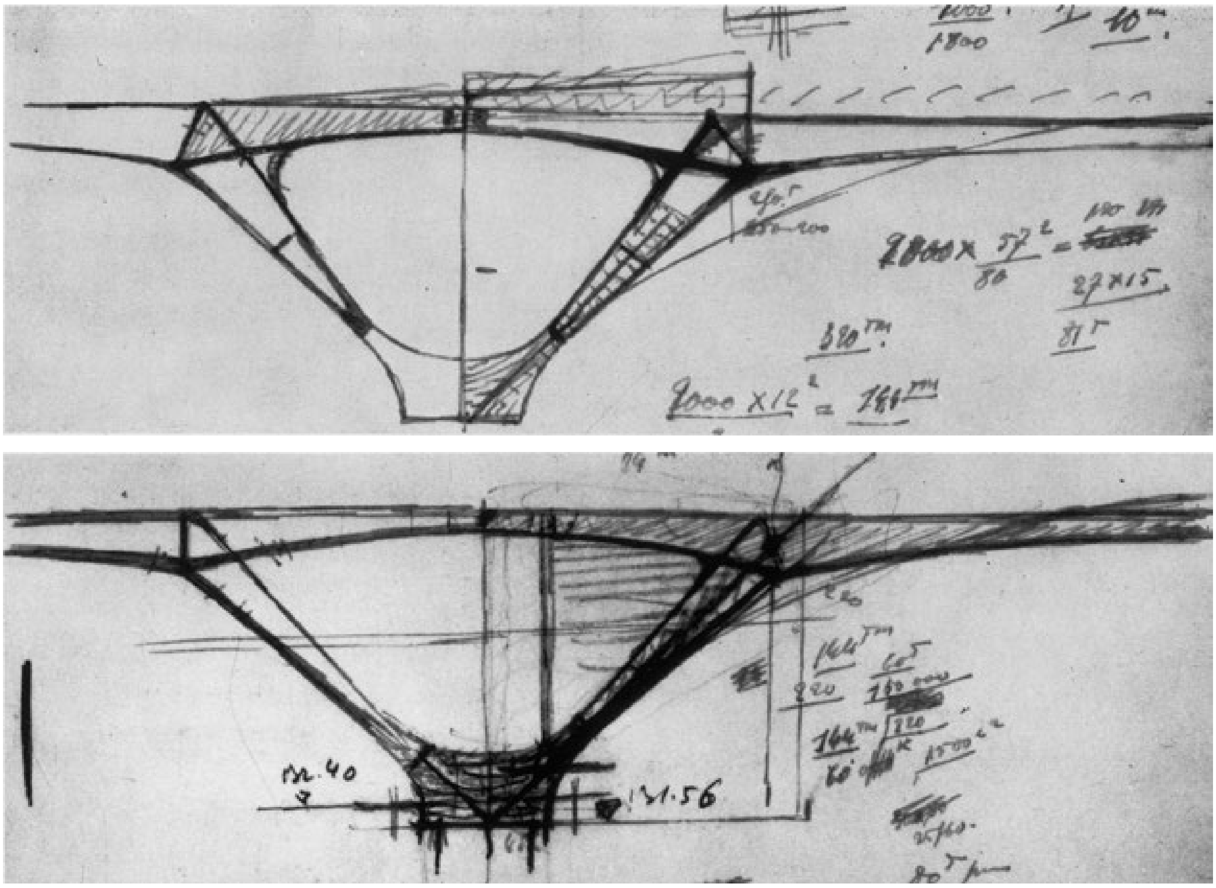


Figure 49 Saint Michel Bridge in Toulouse, sketches by Freyssinet

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