

EUGENE FREYSSINET – THE ORIGINS OF PRESTRESSED CONCRETE**Pierre Xercavins, Daniel Demarthe, and Ken Shushkewich****ABSTRACT**

It is well known that Eugène Freyssinet was the inventor of prestressed concrete. However, it is not as well known that he was a skilled craftsman and prolific bridge builder, and this is what prepared him to invent prestressed concrete. Upon graduation in 1905, Freyssinet built a number of concrete arch bridges each of which successively broke his own world record for span length. This enabled him to develop an appreciation for creep and shrinkage of concrete (a phenomenon the authorities obstinately denied the existence of). This encouraged him to develop high quality concrete and high strength steel that were necessary for the invention of prestressed concrete in 1928. His spectacular rescue of the Le Havre Maritime Station in 1934 was the first practical application of his prestressing devices and instantly earned him a worldwide reputation. His work with the contractor Campenon Bernard starting in 1934 allowed the proliferation of Freyssinet technology for prestressing and construction around the world. One of the more profound contributions of Freyssinet is precast segmental construction, which started with his structures of the Luzancy Bridge lineage in the 1940s, and to this day allows concrete bridges to remain competitive with steel bridges. This paper describes the journey taken to create this “entirely new material” that led to a “revolution in the art of building”.

Keywords: Arch Bridge, Anchorage Device, Bridges, Cast-in-Place Concrete, Centering, Confined Concrete, Construction, Creep, Decentering, External Prestressing, Falsework, Flat Jack, Formwork, History, Invention, Patent, Post-Tensioning, Precast Concrete, Prestressed Concrete, Prestressing, Pretensioning, Reinforced Concrete, Segmental Bridge, Shrinkage, Time-Dependent Deformation, World Record Bridges.

INTRODUCTION

It has been just over 100 years when Eugène Freyssinet (Figure 1) started his career in 1905 with the responsibility of “Ingénieur des Ponts et Chaussées” [“engineer in charge of the construction and the maintenance of public bridges and roads”] in Moulins. His first structures were small bridges that looked like masonry arch bridges, but where concrete replaced the stonework. He moved on to larger and larger concrete arch bridges each of which broke his own world record for span length (Table 1).

The construction of these bridges gave him an appreciation for the time-dependant behavior of concrete (creep and shrinkage), a phenomenon that the administrative authorities obstinately denied the existence of, and the official laboratories neglected or refused to measure over sufficiently long periods of time.

In 1928, after having acquired an appreciation for high quality concrete as well as high strength steel, he filed his first patent for prestressed concrete [pre-tension and bonded wires] (this is the birth of prestressing). This patent included everything that governs the prestressing field with bonded wires. Its huge scope was less spectacular than his subsequent patent in 1939 for the invention of the concrete anchorage [parallel wire system of cables, tensioned by special jacks, and locked-off by anchor cones] (this is the birth of post-tensioning).

It was Freyssinet’s spectacular rescue of the Le Havre Maritime Station in 1934, where “imminent collapse seemed to be inevitable”, that earned him an immediate worldwide reputation, and allowed him through his collaboration with Edme Campenon of the contractor Campenon Bernard to develop “prestressed concrete” as an “entirely new material” distinct from “reinforced concrete”. His vision was that prestressing allowed concrete to become a quasi-elastic material similar to steel for the anticipated service life of the structure.

In 1934, Edme Campenon offered Eugène Freyssinet “the chance to experiment, apply, and develop his invention of prestressing and his ideas on concrete construction, on the entire range of sites of the Campenon Bernard group”. This decision allowed the proliferation of Freyssinet technology around the world.

The vast achievements and prolific career of Eugène Freyssinet¹⁻⁴ are divided into five stages in this paper:

- (1) World record span length arch bridges (1905 – 1928),
- (2) Invention of prestressed concrete (1929 – 1933),
- (3) Rescue of the Le Havre Maritime Station (1934),
- (4) Proliferation of Freyssinet technology around the world (1934 – 1962), and
- (5) Invention of precast segmental construction (1941 –).

The story of Eugène Freyssinet is not well known, because he was intensely modest and private, and did not write about his work. Even late in his life he stated, “I believe that the creation of a new type of reservoir or lock is of more importance than a few pages in a book.” The purpose of this paper is thus to describe the journey that Freyssinet took to create this “entirely new material” that he then used to lead a “revolution in the art of building”.

WORLD RECORD SPAN LENGTH ARCH BRIDGES

Eugène Freyssinet often stated “I was born a builder”. There are two influences in his background that helped him achieve this status, and allowed him to successfully build some of the most audacious bridges (for his time), in addition to being the acknowledged inventor of “prestressed concrete” (pre-tensioning, flat jacks, post-tensioning).

The first influence is his youth in the countryside near Objat where he was born in 1879. He loved mechanical things and working alongside the villagers in anything that involved using his hands. In his words, “My friends were the craftsmen, the cabinet makers, the joiners and carpenters, the blacksmiths and weavers of the surrounding area.” He adds “Thanks to them, by the age of twenty I was a highly competent craftsman able to solve any problems that cropped up with the mill or the farm and quite capable of using my own hands on the job.”

The second influence is his experience starting in 1902 at l’Ecole Nationale des Ponts et Chaussées, one of the top Civil Engineering schools in France. At this school, he had lectures from three eminent engineers: Résal for the course on metals, Séjourné for concrete building, and Rabut who was the first ever lecturer on reinforced concrete in France. Rabut undoubtedly had the greatest influence on his career, stressing the importance of experimentation and practical experience.

It was with this background that Eugène Freyssinet started his career in 1905 in Moulins. He built numerous bridges in the region. The Praireal-sur-Besbre Bridge built in 1907, a three-hinged arch having a span length of 85ft (26m), was the first bridge in the world to have the formwork of the arch removed by creating forces using jacks at the crown hinge. Freyssinet positioned jacks in the key of the arch, applied horizontal thrust so that the two halves of the arch moved away from each other, and lifted the arch off the centering. The compression produced in the arch offset the shrinkage caused by the setting and hardening of the concrete.

One of the fortunate events in the life and career of Eugène Freyssinet was his close association with like-minded contractors [(Francois Mercier (1907-1914), Claude Limousin (1914-1928), and Edme Campenon (1934-1962)].

The long-term relationship between Eugène Freyssinet and Francois Mercier of the contractor Mercier Limousin is related in a somewhat amusing story. As Freyssinet explains, “Our friendship started with an argument”. Apparently, Mercier stormed into Freyssinet’s office expecting approval for some projects of which Freyssinet had just taken control. Mercier thundered that the projects were in conformance with the specifications; Freyssinet countered that they were in conformance, but they could be better – in his words, “more convenient for the clients and less expensive for you”. Two hours of working together were enough to make them good friends. During their period together, Freyssinet designed and built concrete arch bridges, which successively broke his own world record for span length (Table 1). They are the Veudre Bridge (Figure 2), Villeneuve-sur-Lot Bridge (Figure 3), Saint-Pierre-du-Vauvray Bridge, and Plougastel Bridge (Figure 4).

Veurdre Bridge (238 ft span) (1911-1912)

There is also an interesting story of how Freyssinet and Mercier agreed that Freyssinet would design and construct three arch bridges (Veurdre Bridge, Boutiron Bridge, and Chatel-de-Neuvre Bridge) with a budget of 630,000 francs, which had been allocated for the Veurdre Bridge alone (Figure 2). Freyssinet had prepared an alternative design to the standard stonemasonry bridge that was to replace the Boutiron suspension bridge over the Allier River. He had in his office a model of his proposed design for a flattened three span arch bridge having a central span of 238ft (72.5m) and a rise of 16ft (5m) that gave it a span to depth ratio of 15! When Mercier came in he said “that looks like a fine project” to which Freyssinet responded “indeed, but there is no chance of building it because first and foremost there is no money available and anyway, what sort of officialdom is likely to be bold enough to approve it?” Mercier then said “and suppose you were given the necessary funds, would you feel like building it?” to which Freyssinet responded “Of course, but within the public sector. There can be no question of private tenders.”

What happened next in the words of Freyssinet is, “Mercier took a sheet of paper from my desk and drew up an agreement for building a bridge over the Allier at Le Veurdre where the Council was about to authorize spending 630,000 francs. I was also interested in the Boutiron bridge and his friend, Regnier, the deputy, was interested in yet another bridge at Chatel-de-Neuvre. If the result of a preliminary test proved satisfactory they could be built for 210,000 francs each (a third of the sum envisaged for Le Veurdre), the amounts to be paid all at once. The bridges to be built according to a blueprint (mine) following a plan for which Mercier would assume total responsibility. If the tests turned out unsatisfactory he promised to reconstruct the defective bridges along the lines of the stonemasonry project which had been drawn up for Le Veurdre. The next day the General Council accepted this sumptuous present: two large bridges over the Allier. A fortnight later I received an official notification that I was to be paid by the Authorities for overseeing the construction of these bridges which I had designed and which I was to build. The plan never had to pass an inspection committee. Mercier went to Portugal. He had opened an account for me with unlimited credit, payable by him, but gave me no men, nor tools, nor any advice. No builder has ever enjoyed so much freedom; I was the head man and took neither orders nor advice.”

The main problem during construction of the Veurdre Bridge (Figure 2) was the decentering of the large vaults that were subjected to creep and shrinkage. This was achieved by using thrusts created directly following the procedure first used on the Praireal-sur-Besbre Bridge.

The initial bliss after construction was complete was soon followed by dreadful agony as disconcerting deformations (due to creep and shrinkage) started appearing, first slowly and then progressively more rapidly until there was no possible outcome imaginable other than collapse. According to Freyssinet, “It was evening when I reached Moulins and I got on my bicycle and went to Le Veurdre to wake up Biguet and three reliable men. Between the five of us we replaced the decentering jacks, and as soon as there was enough light to use the levels and the staffs, we began to raise all three vaults at once. Le Veurdre Bridge regained its shape and was cured of the disease which had been about to finish it off. It behaved perfectly until 1940; it was destroyed in the war.”

On future bridges, Freyssinet eliminated the crown hinge, and continued studying “the problem of deferred deformation in concrete which seemed to me to be the only possible obstacle to making initial stress constantly on my mind into something permanent.”

Villeneuve-sur-Lot Bridge (315 ft span) (1914-1920)

The Villeneuve-sur-Lot Bridge (Figure 3) on the Lot River consists of a plain concrete arch having a span of 315ft (96m), a world record at the time. Building started in 1914 but was stopped due to the war. In order not to leave the formwork up, the concreting was done by non-mobilized personnel. The bridge was completed after the war in 1920.

The most interesting aspect of the bridge from the construction viewpoint was the use of decentering jacks. This allowed Freyssinet to use them not only for striking the formwork, but also for correcting stresses created by deformation of the arch due to creep and shrinkage, so that it was possible to carry out this procedure at any time during the lifetime of the bridge.

Today, the bridge remains as natural in its urban setting as it did when it was first built. The spectacular aerial view shows this beautiful bridge spanning across the entire river along with an older masonry multi-span bridge. The bridge has reddish exposed brick arcades that hide the spandrels resting on the arch, and let the bridge blend in well with the buildings in town.

Eugène Freyssinet was able to make high strength concrete using cements locally available. He designed structures remaining in compression everywhere under live load. There is no doubt that this technical approach, derived progressively, generated the idea of prestressing.

Saint-Pierre-du-Vauvray Bridge (430 ft span) (1922-1923)

The Saint-Pierre-du-Vauvray Bridge crosses the Seine River with a single span of 430ft (131m), a world record at the time. Until then the largest concrete arch bridges had been the Langwies Viaduct in Switzerland with a span of 323ft (98.5m); the Risorgimento Bridge over the Tiber with a span of 328ft (100m); the Minneapolis Viaduct over the Mississippi in the United States with a span of 400ft (122m) was still being built.

Plougastel Bridge (3 spans @ 610 ft) (1925-1930)

The Plougastel Bridge (Figure 4) on the Elorn River near the City of Brest, close to its harbour, consists of three reinforced concrete arches each having a span of 610ft (186m), a world record at the time. The reinforced concrete trussed double deck accommodates a roadway on the upper deck and a railway on the lower deck (the railway over the bridge was never completed).

For this construction, Eugène Freyssinet took advantage of the tides to bring on floating barges an enormous wood truss, which was used for the successive construction of the three arches. The truss was built on the riverbank, launched at high tide with the aid of two barges, and installed for the construction of the first arch. After completion, the truss was then lowered and floated into position for construction of the second arch, and then the third arch.

INVENTION OF PRESTRESSED CONCRETE

In 1928, Eugène Freyssinet patented the first of his three inventions for applying compression to concrete. The first was a process of applying compression by “pre-tension and bonded wires,” which facilitated the manufacture of precast elements (this is the birth of prestressing). His other two methods for applying compression to concrete were his 1938 invention of the flat jack and his 1939 invention of the concrete anchorage [parallel wire system of cables, tensioned by special jacks, and locked off by anchor cones] (this is the birth of post-tensioning). As stated in reference 3, “these three inventions were the fruit of tenacious and solitary research into the practical means of compressing concrete.”

Prestressed Concrete Patent (1928) [pre-tensioning]

According to Freyssinet, “It was in 1903 that I first had the idea of consolidating concrete by prestressing. It took me twenty-five years of laboratory tests and much profound thought to discover the difficulties involved and a way of overcoming them. Finally in 1928, I decided that in order to realize my idea I would devote all my efforts and all the money that I had earned in fifteen years during which I had worked for a Public Works company.”

On the 2nd of October 1928, Eugène Freyssinet and Jean Séailles applied for a patent concerning a “fabrication process for reinforced concrete elements”, a process adapted to the manufacture of precast beams, pipes, sleepers, poles, etc. This patent was registered under the number 680,547. The patent was issued on the 22nd of January 1930, and published on the 1st of May 1930. Freyssinet and Séailles described with absolute precision, the theory of permanent precompression in concretes or other materials, and their overall potential. The word “prestressing” is not used in the text, although all the methods used in the precast prestressed industry (pre-tensioning) are addressed by it.

At the time of the 1928 patent, the scientific community did not believe in prestressing. Thus, Freyssinet had to go out alone in the world to demonstrate the merits and possibilities of prestressing. “I decided to risk all I possessed in the way of fortune, reputation, and energy to transform the idea of prestressing into an industrial reality,” he reflected.

Eugène Freyssinet thus became an industrialist and began producing electricity poles at the Forclum plant at Montargis (Figure 5). The result was a complete technical success, as he had perfected the industrial precasting of prestressed concrete elements, but a commercial failure (because of the worldwide Depression of 1929).

Freyssinet had perfected the grinding fineness of cement, improved on his previous invention for mechanical vibration of concrete, invented steam curing to accelerate the rate of concrete hardening and rate of production, and perfected the industrial precasting process for precast concrete elements. However, in five years he had lost the entire fortune he had accumulated during the previous part of his career. He regretted nothing, stating: “For the first time in my life I had had the opportunity to concentrate my thoughts on a single problem, with no other preoccupations. Thanks to this, over a period of five years of the hardest labor which any man could set himself, I had obtained technical results which I considered far more important than all those which I had achieved between 1905 and 1928.”

Freyssinet placed more value on his work on the invention and development of prestressing than on all his other accomplishments with world record span length arch bridges!

The strength used by Freyssinet in the 1930's was 4000 to 5000 psi (28 to 34 MPa) for the concrete and 190,000 to 200,000 psi (1310 to 1380 MPa) for the prestressing steel.

Flat Jack Patent (1938)

Eugène Freyssinet next invented the flat jack in 1936 for compressing the raft of the Portes de Fer dam in Algeria, and then immediately after that at a much grander scale for raising the height of the Beni Badhel dam in Algeria by 23ft (7m) to bring it up to 220ft (67m).

On the 1st of August 1938, Eugène Freyssinet applied for a patent entitled “combination of jacks and their application in construction, especially in reinforced concrete constructions”. This patent was validated on the 21st of August 1939.

The flat jack (Figure 6) is made of two stamped steel sheets connected by welding. By hydraulically introducing a fluid under pressure, the flat jack is inflated and can develop considerable force. It is a remarkable device for its power, lightness, and low cost. The fluid can be oil, resin, grout, cement, or other ingredients. The flat jack can be used to vary the compressive forces applied with time to allow for adjustment of structures. The flat jack has been used on a great many projects around the world, including the Montreal Velodrome described in this paper.

Concrete Anchorage Patent (1939) [post-tensioning]

According to Freyssinet, “At the beginning of the war, in September 1939, I made the most decisive progress since 1928 in the methods of cable tensioning by creating systems making it possible to anchor a group of wires under tension, by means of self locking-off inside the cones”. He added “I consider this to be the greatest development I have achieved with regard to applications of the prestressing concept, since the idea first came to mind.” The whole of his accumulated experience lies behind this deceptively simple looking invention.

On the 26th of August 1939, Eugène Freyssinet applied for a patent concerning “tensioned cable anchorage system for prestressed concrete construction”. This patent was registered under the number 926,505. The patent was issued on the 21st of April 1947 (because of the war), and published on the 3rd of October 1947.

The system (Figure 7) consists of 12 - 5mm diameter parallel steel wires locked or anchored in a concrete anchorage cone by a tensioning jack. The steel wires were threaded through the anchorage consisting of a reinforced concrete block having a central conical hole (female cone) and a central fluted conical block (male cone). The steel wires were tensioned simultaneously with the aid of a jack and locked-off by the male cone inside the female cone while under tension. The wires transmitted their tension to the structure via the anchorage.

This invention allowed tensioning to be achieved by resting on the concrete directly. The prestressing cable could be long or short, rectilinear or curvilinear, and positioned inside or outside the structure (external prestressing as well as internal prestressing). The force in the

prestressing cable could be adjusted during construction. This system gave the engineer a wide liberty in the position and intensity of prestress that he/she wished to develop, and has been used in the construction of most large structures since that date.

The original 5mm wires were progressively replaced by 7mm wires, then 8mm wires, and then by seven-wire strands at the end of the fifties. The concrete anchorage of 1939 (capacity 22tons [20mt]) was replaced by a steel anchorage in 1960 (capacity 165tons [150mt]). Individual “wedges” for each strand in the steel anchorage came into existence in 1965 (capacity 220tons [200mt]).

RESCUE OF THE LE HAVRE MARITIME STATION

The Maritime Station in Le Havre, completed in 1933 for the ocean liner Normandie, was sinking 1in (25mm) per month into a deep layer of clay, and according to Freyssinet “Imminent collapse seemed to be inevitable. I proposed a solution which, despite its boldness, was adopted without argument as it consisted in the only possible hope of avoiding disaster.”

The strengthening of this building in 1934 is considered to be the first use of prestressing devices. Freyssinet designed an integrated system: (1) he first strengthened the foundations to make them as monolithic as possible by the use of external prestressing cables and jacks at their extremities, and (2) he then increased the bearing capacity of the foundations by adding piles that were driven in segments until they reached sufficient resisting layers of soil.

The Freyssinet solution consisted of adding new footings between the existing footings to make the entire unit a monolithic prestressed horizontal element. The unit was prestressed with parallel wires turned around two reinforced concrete end anchorages. One anchorage was displaced by hydraulic jacks having a force of up to 1100tons (1000mt). The link between the old and new concrete was assured by the general compression of the whole. The moveable anchorage was fixed by concreting the free space and the jacks were removed. The wires forming the cables were concreted to protect them from corrosion. The “old” units supported columns above while the “new” units had formed sockets to drive piles through.

The second part of the Freyssinet solution was to install 700 piles, 82 to 98ft (25 to 30m) long that extended to sound layers of soil. The piles were cast inside the building in 6.6ft (2m) sections, and were assembled by prestressing and driven into the ground using special jacks designed by Freyssinet. Vibration, compression, and steam curing of the concrete were all used to improve the rate of casting and quality of concrete. The piles were then prestressed against the footing by means of hydraulic jacks having a vertical prestressing force of 352tons (320mt). The settlement immediately ceased as soon as the first piles were installed.

The result was both spectacular and convincing, and at once earned Freyssinet a worldwide reputation. This created the opportunity for a meeting between Eugène Freyssinet and Edme Campenon, and started the collaboration between the two in 1934 on the entire range of construction projects of the Campenon Bernard group, a collaboration that finally was destined to ensure the development of prestressing.

PROLIFERATION OF FREYSSINET TECHNOLOGY AROUND THE WORLD

With success at Le Havre, the contractor Edme Campenon offered Eugène Freyssinet “the chance to experiment, apply, and develop his invention of prestressing and his ideas on concrete construction, on the entire range of sites of the Campenon Bernard group”. Later in 1943, Edme Campenon created a special division STUP (Societe Technique pour l’Utilisation de la Précontrainte) [Technical Company for the Use of Prestressing] for the “development, protection, and implementation of the techniques of which M. Freyssinet is the inventor”.

In 1961, STUP created a design company, Europe Etudes, so as not to restrict development of prestressing techniques to the sole use of the original inventor and developer, Campenon Bernard. In 1976, STUP changed its name to Freyssinet International / STUP, which soon after became known as Freyssinet International. The group, at that time, included a prestressing supplier, which was a disseminator of technical information around the world (Freyssinet Company), a contractor (Campenon Bernard), and a designer (Europe Etudes).

INVENTION OF PRECAST SEGMENTAL CONSTRUCTION

Luzancy Bridge (1941-1946)

The Luzancy Bridge (Figure 8) over the Marne River (started in 1941 and completed in 1946 after the war), was the first of a new generation of precast segmental bridges designed and constructed by Eugène Freyssinet. It has a span of 180ft (55m), a world record at the time (Table 1), and was built to replace an old suspension bridge. It is very light in appearance and has a remarkable span to depth ratio of 45!

The bridge is a 26ft (8m) wide portal frame comprised of three box girders that were precast in segments (Figure 9), prefabricated and assembled on site in several sections (Figure 10). The bridge was prestressed longitudinally and transversely with 12 – 5mm diameter tendons, and vertically with 5mm pre-tensioning wires that were stressed prior to concreting. It was erected (Figure 11) by launching equipment consisting of masts and stay cables (one of the most imaginative systems ever used for the assembly of prefabricated bridge elements). Note that the middle box girder shown being erected is 128ft (39m) long and weighs 99tons (90mt). Flat jacks located in the bottom flange at the ends of the bridge allowed for adjustment to compensate for the effects of creep and shrinkage. All three of Freyssinet’s inventions for prestressing (pre-tensioning, flat jacks, and post-tensioning) were used here.

On this bridge, a thin layer of dry concrete (mortar) was inserted between two segments and compacted (match-cast epoxy-coated joints would be introduced about twenty years later).

The bridge has numerous innovative features. (1) It was the first bridge built using precast segments. This allowed better quality control of the concrete. (2) It was the first bridge to have triaxial compression. This allowed for exceptional concrete strength. (3) It was the first bridge to be erected without falsework or temporary supports between the piers. This provided a very economical construction method while allowing boat traffic to proceed.

The Luzancy Bridge was recently visited over sixty years after completion in October 2007. The bridge is in pristine condition (Figure 12). The concrete of the precast segments is of excellent quality. The abutment bearings were rejaacked using flat jacks and then shimmed with concrete blocks to accommodate creep for up to 30 years after completion.

The great success of the Luzancy Bridge allowed Eugène Freyssinet and Campenon Bernard under the supervision of Jean Chaudesaigues to build five similar bridges having spans of 243ft (74m) on the Marne River between 1947 and 1951. These five bridges were the Ussy, Annet, Tribardou, Changis, and Esbly bridges. All precast segments were made at a central plant near Esbly. They were assembled in sections using temporary prestressing, transported to the site by barge, installed by the mast and stay cable system, and completed with the addition of permanent post-tensioning. All six bridges are very light in appearance.

The Underground Basilica at Lourdes takes its inspiration from the Esbly Bridge of the Luzancy lineage. The structure was conceived by Eugène Freyssinet in only fifteen minutes, designed by Jean Chaudesaigues, and constructed by Campenon Bernard from 1956 to 1958. It consists of only 29 portal frames and can accommodate 20,000 people.

“Prestressed concrete bridges made up of prefabricated elements can be given the most diverse shapes and sizes and all types of structures can be achieved. Any erection system for a steel framed bridge can be adapted for the erection of a prestressed concrete bridge” he said.

Choisy-le-Roi Bridge (1962-1964)

Jean Muller, a close collaborator and eminent disciple of Eugène Freyssinet, pioneered match-cast technology in the early sixties with the Choisy-le-Roi Bridge (Figure 13) over the Seine River in France. On this bridge, he used for the first time, precast segmental box girder technology with match-cast epoxy-coated joints. (The previously cast segment was used as the end form for the next segment, in order to obtain perfect contact between adjacent segments and to get directly the final profile of the deck.) This bridge has three continuous spans of 123ft-180ft-123ft (37.5m-55m-37.5m), with a total width of 93ft (28.4m) that was divided into two parallel single cell box girder bridges. A total of 148 precast segments were fabricated using the long-line casting method. Typical segments weighed 22tons (20mt). The bridge was erected in balanced cantilever using a floating crane.

Bear River Bridge (1971-1972)

The Bear River Bridge (Figure 14) near Digby, Nova Scotia in Canada was the first precast segmental box girder bridge built in North America using the match-cast method with epoxy-coated joints. This curved bridge is 1998ft (609m) long with six interior spans of 265ft (80.8m) and two exterior spans of 204ft (62.1m). The bridge is 39.5ft (12.0m) wide. The 145 segments were cast in a plant located near the bridge site using two short-line casting cells each producing one segment per day. The short-line method was compulsory due to the variable geometrical complexity of the horizontal alignment, vertical profile, and superelevation, and the result was perfect. The segments weighed a maximum of 90tons (82mt), and were placed by a 200ton (180mt) mobile crane on land or on a barge over water.

The bridge was designed by A. D. Margison and constructed by Beaver Marine Ltd. with construction engineering assistance provided to the Contractor by Europe Etudes under the leadership of Pierre Xercavins and Daniel Demarthe.

This was followed by many structures in Canada by Europe Etudes / Preconsult Canada Ltd., (Islington Avenue Bridge, Credit River Bridge, Mullet Creek Bridge, Elora Gorge Bridge, and Twelve Mile Creek Bridges in Ontario), and in the United States where Figg and Muller first together and then separately have widely developed this method.

Montreal Velodrome (1973-1976)

The Montreal Velodrome for the 1976 Olympic Games (Figure 15) pays tribute to Eugène Freyssinet because it incorporates so many of his prestressing and construction techniques. This very flat airy vault of prestressed concrete is supported at four abutments only, and is inscribed in a rectangle of 564ft by 426ft (172m by 130m). The covered area without intermediate supports is 172,000ft² (16,000m²).

The main structural elements are six arches which spread away from the Z abutment, and meet again in pairs on either side of the W, X, and Y abutments. Two secondary arches connect the X abutment to the W and Y abutments. The arches are comprised of 142 precast segments that are built using the match-cast method with epoxy-coated joints, and erected on temporary falsework.

A network of 63 double Y-shaped beams span between the arches. The structural system is completed with cast-in-place concrete slabs joining the arches to the four abutments. Arched translucent acrylic panels span between the double Y-beams to cover the roof, and a curtain wall rises from the ground to the arch to enclose the building.

The general behavior of the structure was found to be somewhere between that of a number of arches and a double curvature shell. The transverse double Y-beams ensure the stability of the arches, and create a transverse hidden arch that reduces the loads on the X abutments.

One of the most interesting phases of construction was the decentering (the transfer of loads from the falsework to the permanent supports at the abutments). By placing flat jacks at the four abutments and jacking an amount equal to the calculated reactions, the roof slowly rose until the entire weight of the structure was taken by the four abutments only. A total of 226 flat jacks each with a capacity of 1100tons (1000mt) were used for the decentering.

Forces in the range of 24,200tons (22,000mt) had to be achieved by the flat jacks at the Z-abutment [hence 22 flat jack locations] in order to develop the stroke of 2in (50mm) necessary to lift the structure off the falsework [hence 3 flat jacks deep or a total of 66 flat jacks]. Giant safety wedges followed up the opening of the flat jacks in order to avoid any sudden lowering under possible hydraulic leakage, and to facilitate the filling of the jacks with grout after the jacking was completed. Once the loads were transferred to the abutments, the falsework was removed giving a magnificent clear span of 564ft (172m) between the abutments.

The velodrome was designed by Trudeau, Gascon, and Lalancette with technical assistance provided by Europe Etudes under the leadership of Pierre Xercavins and Daniel Demarthe.

CONCLUSION

Freyssinet repeatedly stated, “I was born a builder”. Indeed, he became totally immersed in the building of his structures, “becoming simultaneously engineer, contractor, carpenter, form worker, steel worker, cement specialist”. In the words of Jean Montagnon³ “If Eugène Freyssinet had been a musician, he would have been a composer, an instrument maker, an instrumentalist, and a conductor.”

Freyssinet also stated repeatedly that he had invented an “entirely new material” which led to “a revolution in the art of building”. Table 2 gives the chronology of the vast achievements and prolific career of Eugène Freyssinet. He continued to design and build until his death. Included in his latter structures are the three arch bridges of the Caracas Viaduct from 1951 to 1953, the Underground Basilica at Lourdes from 1956 to 1958, the Number 10 Bridge at Orly from 1957 to 1959, and the Saint-Michel Bridge at Toulouse from 1959 to 1962.

Freyssinet spent his last years studying a crossing of the English Channel with a series of 2000ft (612m) prestressed concrete arch spans. To keep the weight of these spans within acceptable limits, he proposed a concrete member that is completely confined by permanent biaxial transverse compression. This allows the concrete to resist stresses many times greater than normal. He called this new material “pre-confined concrete”. The permanent biaxial transverse compression is achieved by confining a circular cross section in a continuous spiral of pre-tensioning during casting or in a high-strength steel pipe. Although his invention of prestressed concrete, and also precast segmental construction, have caught on and are well known around the world, his invention of “pre-confined concrete” still remains to be realized.

Eugène Freyssinet has been proclaimed¹ “one of the most complete engineers of the 20th century and one of the greatest builders in history.”

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ABOUT THE AUTHORS

Pierre Xercavins graduated from the Ecole Polytechnique in Paris, and joined STUP in 1950. As a colleague of Eugène Freyssinet, he was soon involved in large projects, and was appointed Technical Manager of Europe Etudes. Mr. Xercavins has participated in the design of many bridges both nationally and internationally, as well as various buildings and sports complexes, most notably the Montreal Olympic Complex in Canada, without forgetting the Ekofisk, Frigg, and Ninian offshore platforms. He established his own design office, PX Consultants, in 1977 which became PX-DAM Consultants in 2000. Mr. Xercavins has been awarded the Medal of the Fédération Internationale de la Précontrainte (FIP) in 1970 and the Albert Caquot Prize in 1991.

Daniel Demarthe graduated from the Ecole Centrale in Paris (ECP), and joined Europe Etudes in 1966. As a colleague of Pierre Xercavins, he helped introduce precast segmental construction to North America in 1971-1972 with the Bear River Bridge. Mr. Demarthe then was one of the engineers in charge of the design of the Montreal Olympic Complex. He assisted in the design of a number of early segmental bridges (including Islington Avenue, Credit River, and Twelve Mile Creek) before returning to Europe Etudes in France at the end of the 1970s. He has designed the Hotel La Fayette and the Gennevilliers Bridge in Paris.

Ken Shushkewich graduated from the University of California at Berkeley with a MS degree in 1975. As a colleague of Daniel Demarthe, he started working with a subsidiary of Europe Etudes (Preconsult Canada Ltd.) in 1976 on the design and construction of some of the earliest segmental bridges in North America. He has worked with T Y Lin International and Jean Muller International before starting his own design firm, KSI Bridge Engineers, in 2001.



Pierre Xercavins (center), Daniel Demarthe (right), and Ken Shushkewich (left)
in Paris on October 17, 2007

Table 1 – World Record Span Length Bridges by Eugène Freyssinet

bridge	date	span	type
Veudre Bridge	1911-1912	216 ft - 238 ft - 216 ft 66 m - 72.5 m - 66 m L / 15	concrete arch
Villeneuve-sur-Lot Bridge	1914-1920	315 ft 96 m	concrete arch
Saint-Pierre-du-Vauvray Bridge	1922-1923	430 ft 131 m	concrete arch
Plougastel Bridge	1925-1930	3 @ 610 ft 3 @ 186 m	concrete arch
Luzancy Bridge	1941-1946	180 ft 55 m L / 45	precast/prestressed concrete segmental

Table 2 - Chronology of the Life and Career of Eugène Freyssinet

date	event
1879	born in Objat, Correze, France
1905	graduates from l'Ecole Nationale des Ponts et Chaussées
1905-1914	engineer in the Roads and Bridges Department in Moulins, France
1914-1928	technical manager and partner for the contractor Mercier Limousin et Compagnie which later becomes Societe Limousin et Compagnie
1907	designs Praireal-sur-Besbre bridge (85 ft arch)
1907-1914	designs three concrete arch bridges at the cost of one masonry arch bridge for Francois Mercier (Veudre, Boutiron, and Chatel-de-Neuvre bridges) (238 ft arch)
1914-1920	designs Villeneuve-sur-Lot bridge (315 ft arch)
1922-1923	designs Saint-Pierre-du-Vauvray bridge (430 ft arch)
1925-1930	designs Plougastel bridge (3 arches at 610 ft)
1928	submits patent application for prestressing by pre-tensioning
1929-1933	industrialist sets off alone manufacturing prestressed concrete poles at Forclum (technical success but economic failure due to Depression)
1934	saves Maritime Station of Le Havre - encounter with Edme Campenon starts long and fruitful collaboration with contractor Campenon Bernard
1938	invention of flat jack
1939	invention of prestressing by post-tensioning using a parallel wire system of cables, tensioned by special jacks, and locked off by reinforced concrete anchorage cones
1943	creation of STUP (Societe Technique pour l'Utilisation de la Précontrainte) for the "development, protection, and implementation of the new techniques of which M. Freyssinet is the inventor"
1941-1946	designs Luzancy bridge (180 ft span) and five other similar bridges (243 ft span)
1947-1951	invention of bridge construction using precast segments and erection methods for bridge construction without centering or temporary supports between piers
1951-1953	designs 3 bridges of Caracas Viaduct (3 separate arches built with same formwork)
1956-1958	designs Underground Basilica at Lourdes
1957-1959	designs Number 10 bridge at Orly
1959-1962	designs Saint-Michel bridge at Toulouse
1961	creation of design firm Europe Etudes to be separate from Campenon Bernard
1962	deceased at age 82 in Saint Martin Vesubie, Martime Alps, France



Figure 1 - Eugène Freyssinet



Figure 2 - Veudre Bridge (238 ft span) (1911-1912)



Figure 3 - Villeneuve-sur-Lot Bridge (315 ft span) (1914-1920)

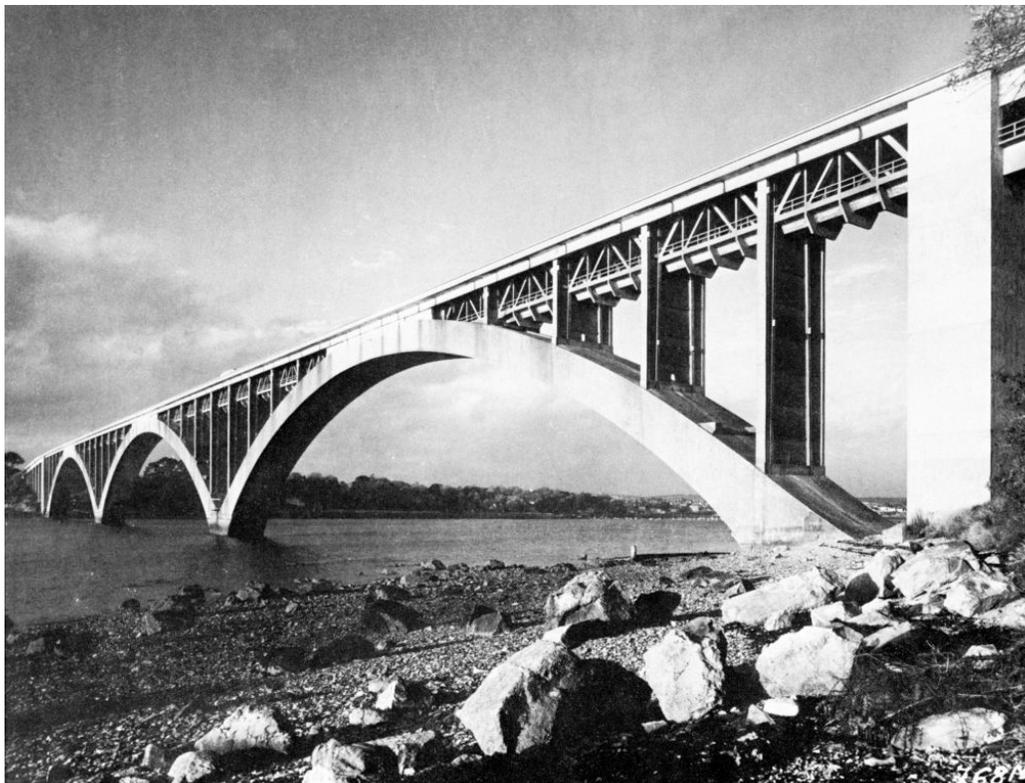


Figure 4 - Plougastel Bridge (3 spans @ 610 ft) (1925-1930)



Figure 5 - Forclum electricity poles

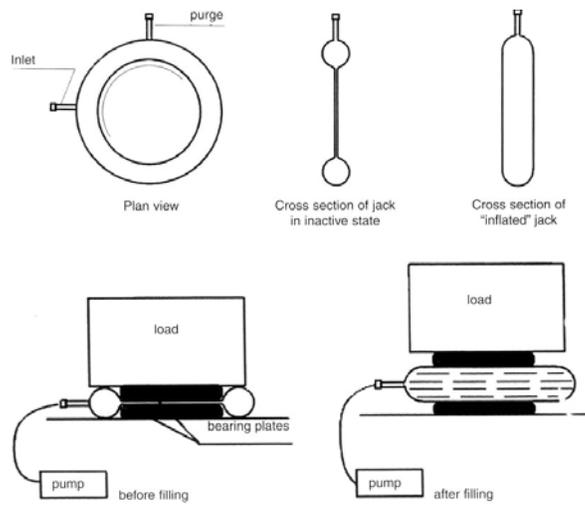


Figure 6 - Flat jack schematic

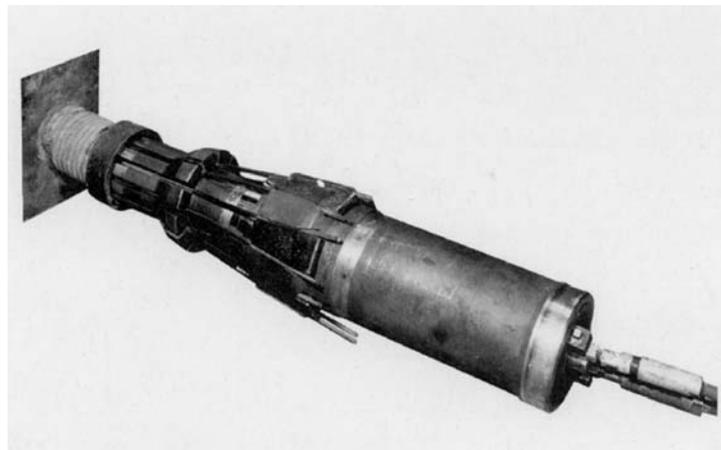


Figure 7 - Concrete anchorage cone and tensing jack

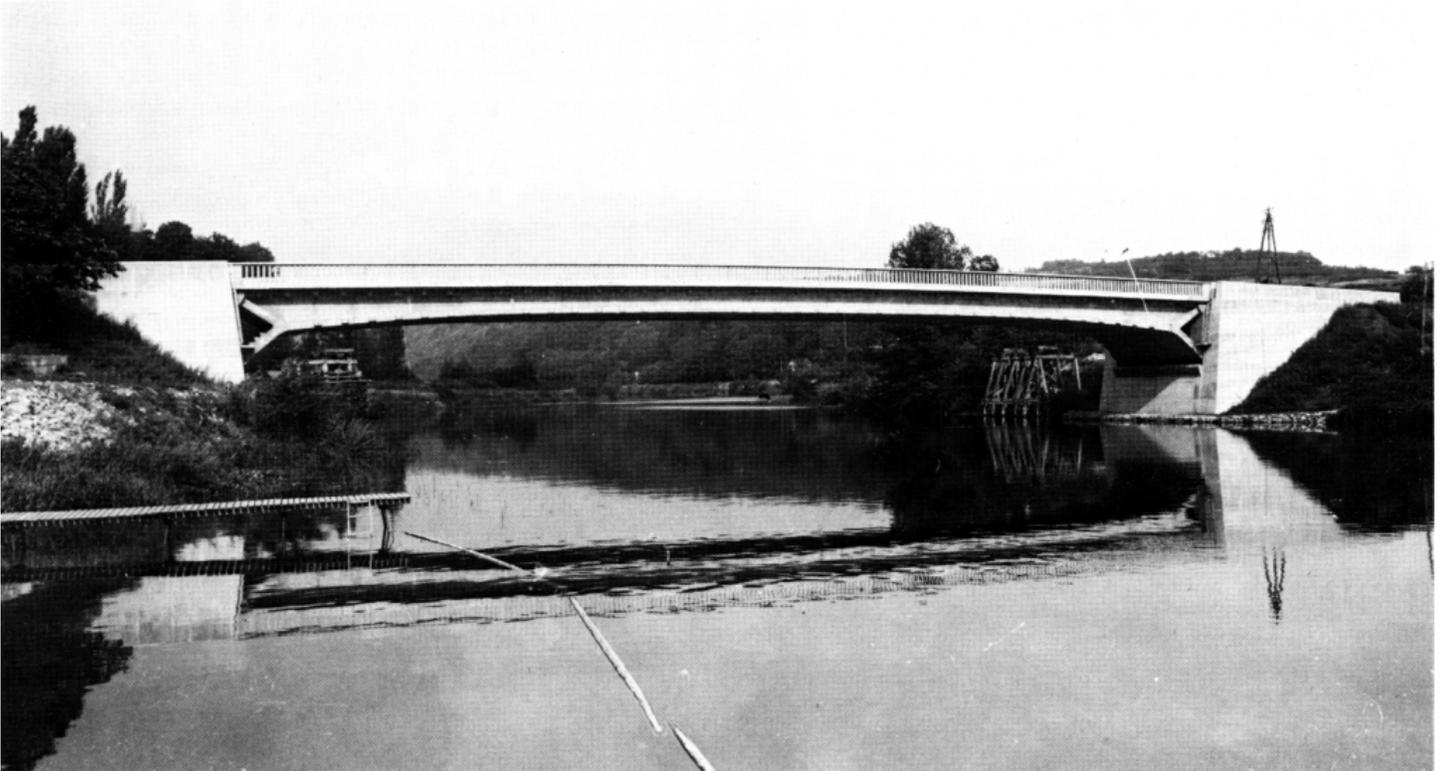


Figure 8 - Luzancy Bridge (180 ft span) (1941-1946)
(first precast segmental bridge)



Figure 9 - Luzancy Bridge segment casting



Figure 10 - Luzancy Bridge segment assembly



Figure 11 - Luzancy Bridge segment erection



Figure 12 - Luzancy Bridge in 2007

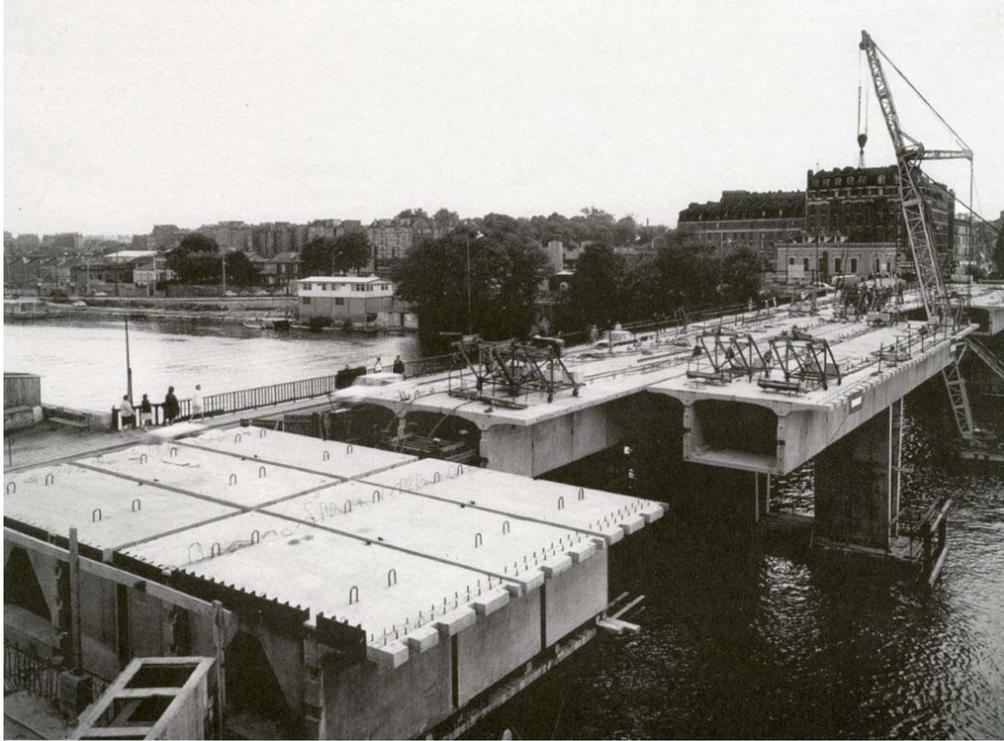
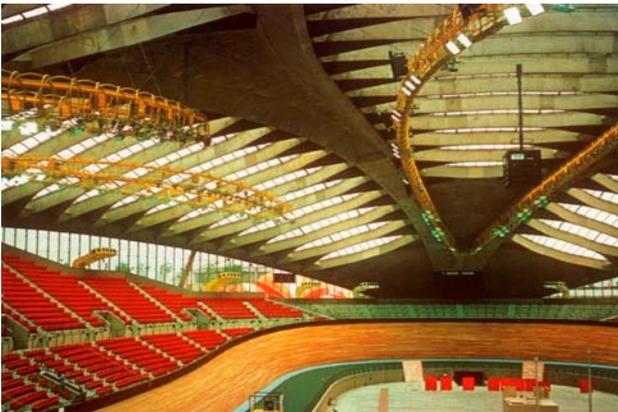


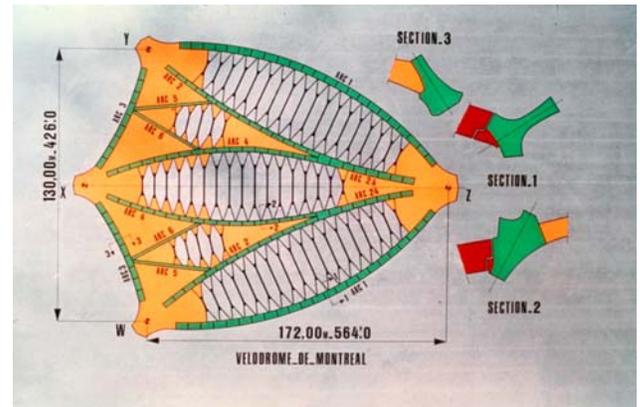
Figure 13 - Choisy-le-Roi Bridge (1962-1964)
(first precast segmental "match-cast" bridge)



Figure 14 - Bear River Bridge (1971-1972)
(first precast segmental "match-cast" bridge in North America)



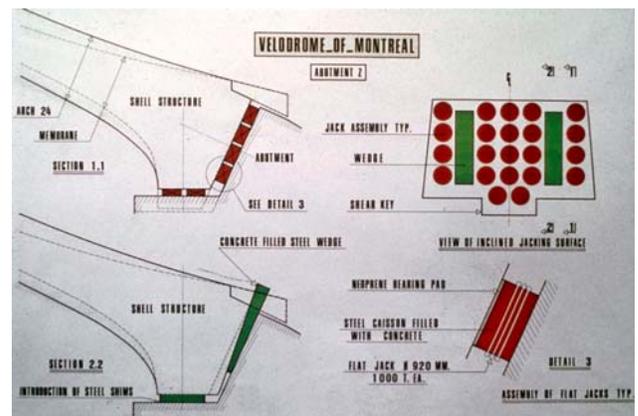
completed structure



structure layout



structure during construction



flat jack schematic at abutment Z



flat jack layout at abutment Z



decentered structure (564 ft span)

Figure 15 - Montreal Velodrome (1973-1976)