

From invention to production: the introduction of prestressed concrete

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ABSTRACT: How do new production methods resulting from inventions develop into practical applications? This case describes the innovation process for prestressed concrete in Denmark from 1939–52. This was achieved through new materials, new production machinery, changed calculation methods, new approval systems of the authorities, and new organizational frameworks around planning. Knowledge was dispersed mainly from Germany and France, and secondarily from Belgium and Sweden. Danish research played no major role. However, there was a lively exchange of experience among engineers. Dr. Techn. Christen Ostenfeld played a special role; he became acquainted with the French developer of prestressed concrete, Eugène Freyssinet. In 1941, Ostenfeld got Freyssinet to design a major bridge. It was not realized, but it resulted in licenses on Freyssinet's patents coming to Denmark. Ostenfeld's consulting and engineering firm (today known as COWI) grew in parallel with the use of prestressed concrete, including the construction of silos around Europe.

KEYWORDS: Pre-stressed concrete 1928-80, Innovation process, Denmark, Bridges, Large Scale Structures, Standards

1 INTRODUCTION

How do new production methods from inventions develop into practical applications? The historical writing often focuses on the inventor's role, but in order for a new idea to be used in practice, many other people and institutions must contribute.

The innovation process is not simple. For the introduction of electricity, 'major technical systems' are not only a technical solution but also the organization of a process (Hughes 1983). One can see the development in four phases: innovation, dissemination, development with constant improvements, and the momentum phase, in which technology is an integral part.

To see how this happens, this case shows how prestressed concrete went from a promising idea to practical use. Today we see the product everywhere, whether as big spikes in sports halls, factories, and bridges, or in poles and other items that need special strength.

The course of prestressed concrete is described in Denmark. The small, northern European country makes it easy to review the process so that the most important details are included in the description.

2 WHAT IS PRESTRESSED CONCRETE?

Prestressed concrete is a concrete structure with steel reinforcement that is applied to an extension. This reduces cracks in the concrete and reduces stress.

When I started this article, I thought that the design was invented by the French engineer Eugène Freyssinet, as indicated in several sources (Xercavins, Demarthe og Shushkewich 2010, Shushkewich 2013, Engelstoft 2014, Nasser 2008, Huggins 1981 and Hewson 2003). However, many others have also worked with prestressed constructions. The first use occurred in the construction of wooden bridges in the United States, with subsequent patents in 1830 (Sanabra-Loewe and Capellà-Llovera 2014). Later, the method was used with granite blocks in France in the 1860s. One of the first patents for prestressed concrete was taken in the United States, where in 1886 P. H. Jackson patented concrete contracted by rods and fixed with nuts. Two years later, German C. F. W. Döhring took out a patent on his system. Threads are stretched in a row, after which concrete is cast around the threads. When the concrete hardens, the threads are held inside the concrete. In Danish, the system is named after the threads: "strengbeton" (pretensioned concrete) (Troyano 2003, 192-194 and Sanabra-

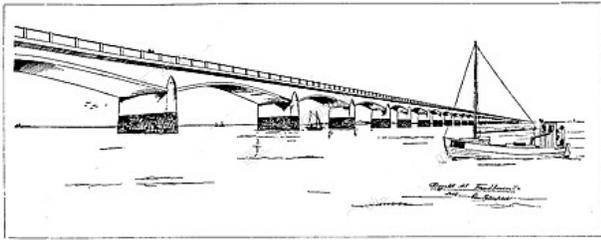


Figure 1. The bridge Fanø-Esbjerg projectet by Eugène Freyssinet 1941; drawing Chr. Ostenfeld (*Ingeniøren* 15 February 1958)

Loewe 2016. All patents are mentioned in Sanabra-Loewe and Capellà-Liovera 2014). Czech engineer E. Hoyer developed a similar method with quite thin threads of 2-4 mm.

However, it took a few years before the principle was ripe for commercial exploitation. One particular problem needed to be solved: when the cement was cured, it contracted and much of the tension in the steel wire was lost and the structure lost its strength. A solution came from French engineer François Chaudy in 1894 (Gasparini 2006), followed by other people's suggestions and patents. The most well-known is Eugène Freyssinet, who filed a patent application in 1928 and later one in 1939 on tension with internal cables (Espion 2013 and Ordóñez and Chemetov 1978).

The key element in the post-tensioned concrete was the anchors. The method had certain limitations that were improved upon by Belgian G. Magnel (Espion et al. 2015). Since then, there have been a number of new anchors, several of which can be regarded as a circumvention of patents, while others are actual improved constructions. In 1948, the Swiss BBRV was introduced, and in 1951 the Belgian Franki-Smet and the German Dywidag created a German system based on fastening nuts on a thick rod. (Provost and Del Fomo 2013).

3 THE FIRST PRESTRESSED CONSTRUCTIONS

Theories are one thing; practical applicability is another. There is no consensus as to when the first bi-ased constructions were built. Some authors go far back in history, like with the ancient Egyptian ships built over 1,500 years ago. It is stated that the 1928 bridge over the Saale in Germany, by German Karl Dischinger, was among the first with external tension. He continued the bridge over the Aue in 1936 in Germany. Unfortunately, the concrete crept so much that the tension gradually disappeared. This brought the development of concrete to a standstill until better methods were developed that included new types of steel (Menn 2012, 28-30). In 1934, Wayss & Freytag designed a bridge in Frankfurt according to Freyssinet's principles (Espion 2013).

Freyssinet first started the production of prestressed concrete, but in 1934 he was close to bankruptcy. However, a project in the Le Havre harbour showed that the system was useful. Now the road was seriously paved for a breakthrough on what in Denmark came to be called 'cable concrete' after the use of cables. Freyssinet was also lucky with construction after he started with a few small bridges on a 55 m long bridge over the Marne, completed in 1945.

In 1937, a company was established in England with a license from Freyssinet, but only when the German Jew Karl Mautner escaped to England with experimental results from France and Germany were the activities initiated. In 1942, prestressed concrete was introduced to reinforce mine galleries and in the production of railway sleepers as there was no wood and where ordinary reinforced sleepers would not work. The first production run of sleepers lasted only 10 days, but when Mautner took over the construction, sleepers were produced that last today. In addition, a few road bridges were produced. In the post-war period of a record-breaking lack of materials, prestressed concrete could save up to 75% of the steel and this is why bridges could be built so shortly after the war (Burgoyne, 2005).

In Belgium, Magnel completed his first bridge, the Rue du Miroir, in 1944 (Espion et al. 2017), and a textile factory in 1947-1948 with the largest area of 35,000 m². He not only became important in Europe, but also in the United States, where he designed the Walnut County Philadelphia Bridge, completed in 1950 (Taerwe 2013 and Scott 2004). It became a model for the many road bridges in the next year's construction of American highways (Frame and Mitchell 2014, Zollman 1981a, Zollman 1981b and Zollman 1981 c). However, a bridge made of prefabricated elements had been opened the year before in Madison County, which was subsequently clustered by post-tension (Podolny 1979 and Zollman 1981b) and a bridge for pedestrians build in 1943 (Gasparini 2009).

4 KNOWLEDGE TO DENMARK

Freyssinet prepared a proposal for a bridge to Fanø in Denmark in 1941 (Fig. 1). The work was carried out in collaboration with Chr. Ostenfeld, who wanted to quickly solve the task, and therefore encouraged Freyssinet to help (Ostenfeld 1975, 118-120).

Freyssinet was not good at communicating his ideas to other designers. In contrast, Belgian Magnel was not only a great theorist, but also a dazzling narrator and writer (Dinges 2009, IIV) who had great influence in Denmark. Magnel visited Denmark in 1948, where he held lectures. The following year he was again in Denmark. He also published a book in French in 1948, which was soon translated into English.



Figure 2. Hedehus-Teglværket became the first prestressed concrete factory in 1948 (Byhistorisk Samling og Arkiv i Høje-Taastrup Kommune).

Knowledge of pre-stressed concrete from articles in scientific journals was prematurely supplemented by more organized knowledge dissemination. The first international congress was held in Paris in 1949 by the Association Scientifique de la Précontrainte. There were 250 Frenchmen and approximately 200 foreigners, of which Denmark provided the largest Scandinavian participation with approximately 12 participants. The association became a precursor of the International Federation for Structural Concrete, formed in 1952.

Books on prestressed concrete were published by Eugène Freyssin's "Une Revolution dans les Techniques du Béton" in 1936, one of the first in the industry. This was followed by an Irish/English book in 1941-1942. At home, however, there was a German book in 1943 by Emil Mörsch, *Spannbetonträger*, which was very important (Sanabra-Loewe and Capellà-Llovera 2014). The first Nordic textbook on prestressed concrete was published in Sweden in 1952 edited by A. Wärnfeldt (Møller-Sørensen 1955).

The Marshall Plan also included pre-stressed concrete. A three-month study trip for a smaller delegation made it possible to see American relations. The majority of the visits were about ordinary concrete, but the participants were also given the opportunity to learn from the few American experiences with bridge construction with bias. In 1955, money was again granted to the Danish Engineer Association for studies on prestressed concrete.

5 KNOWLEDGE SPREAD IN DENMARK

5.1 Books

The professor of design at the Technical University of Denmark, Axel Efsen, had a very reserved position to the use of prestressed concrete. He was in 1944 asked to edit an article of Freyssinet for publication in a magazine. He did not want to do it, but instead wrote an introduction to the article, taking all reservations for the theories from the French. He wrote that anyone can "extract his impression of the often very imaginative text, which in many respects cannot even be termed as bold extrapolation based on our present knowledge and ability. The lecture thus has the character of a prophecy, which in many ways breaks with all the well-known ideas of reinforced concrete" (translated from Efsen, 1944).

When Efsen published his first edition of "Elementær jernbeton" (Elementary Reinforced Concrete) in 1948 he had still a restrained enthusiasm for prestressed concrete. "The possibility of tensioning the iron, however, we must say, with our present knowledge, to be limited to very special cases". Only production via pretensioned concrete after the Hoyer system got a bigger presentation; in the book was Freyssinet's name not mentioned at all (Efsen 1948, 25, 117-119).

When the Danish Engineering Association published a three-piece work on concrete in 1950, the books naturally contained a much more extensive mention of prestressed concrete (Johansen and Møller-Sørensen 1950, 205-217).



Figure 3. Cement silos under construction 1951, Copenhagen Harbour (Copenhagen Museum).

5.2 Meetings and courses

The first time the Danish engineers seriously discovered that prestressed concrete existed was at a lecture in the Engineering Association in the spring of 1939, where the head of the concrete industry information office, Dr. Techn E. V. Meyer, in front of a well-stocked hall, talked about the latest experiences in the iron concrete area in which bias was mentioned as having an "increasing use". The method was pretensioned concrete, since post-tension was not really introduced in Denmark.

At a major event in 1941 in the Danish Society for Building Statistics, the latest technology of concrete technology was presented to Denmark's engineers. Chr. Ostenfeld presented constructions with prestressed reinforcement. He primarily based this on Freyssinet's book from 1936. In addition, the results of German experiments with the Freyssinet method were mentioned (Johansen 1942, 98-120).

Ostenfeld concluded that the designs were so new that one could not yet predict the direction in which the development would go. He thought that one had to wait and see how the build bridges performed in practice.

In a 1942 course on modern concrete techniques, Chr. Ostenfeld mentioned "the latest French and German methods for prestressing reinforcement". In 1943, Chr. Ostenfeld gave a lecture in Aarhus in the Engineering Association about prestressed iron concrete. His starting point was again the theories that had appeared in E. Freyssinet's book in 1936. It was a profitable meeting, as the "interesting and lively lectures greeted with great applause."

In 1946, building engineers were given the opportunity to hear a lecture about prestressing; the subject caught on, for the subsequent discussion was characterized as "lively". Ostenfeld continued with his enlightening business. Thus, in 1948 he held a lecture at the Danish Society for Building Statistics, which was later published in two articles. By the late 1940s, most

engineers in construction were aware of the new construction method, and the influx was great for courses and meetings about the method. Thus, a smaller exhibition was held in front of the Danish Technological Institute in 1950, where all active companies exhibited their products. In 1951 the interest was so great in South Jutland that 100 people were gathered when Chr. Ostenfeld reviewed the practical application of prestressed concrete.

5.3 Guides and standards

In 1947, the Danish Engineering Association set up a committee to develop a standard for concrete. The committee discussed the matter and, as the members could not agree, the committee agreed with at least giving guidance to create a uniform practice regarding the design and execution of pretensioned concrete (Dansk Ingeniørforening 1951).

In 1949, when the Danish Standardization Council had to publish their standards for concrete and iron concrete constructions, there was not much experience with prestressed concrete to build on (Dansk Ingeniørforening 1949). The standard replaced a previous norm from 1930/43, where pre-stressed concrete was included, but only with a few remarks. There was a clue that "the overall design should have normal safety against fracture" together with the requirement that the reinforced cross section could be expected to remain planted by deformation. One was still very careful in drafting the new standard, and merely demanded that the prestressed concrete complied with the requirements for ordinary reinforced concrete.

However, the norms could not stand alone, for ambiguities with the many new concepts and issues required explanation and elaboration. Therefore, comments were made on the standards: where the standards filled 32 pages, the comments were up to 132 pages (Meyer and Moe 1950).

5.4 Calculations

From a lecture in the United States at about the same time Magnel was in Denmark, he told some students: "I will make you engineers in less than two years, so you can design and analyze structures as accurately as possible as quickly as possible. You should not be mathematicians who need six months to solve a problem based on assumptions ... which is still wrong. At that time the construction will be constructed by some other" (Zollman 1981a).

Ostenfeld gave further characteristics of another of the area's theorists, Freyssinet, in a book about French engineers. He claimed Freyssinet very often burdened himself with enormous responsibility - technically and economically. In his projects, "almost every time he has gone beyond the existing field of experience, which can be dangerous for normal engineering missions!" But he was guided by his ingenious ability to

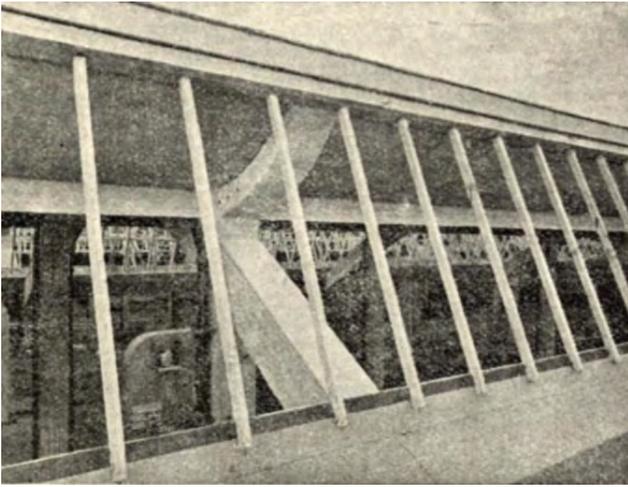


Figure 4. Prestressed concrete pins at a shed roof (*Ingeniøren* 1950-01-10).

construct with a craftsman-like sound judgment (Ostenfeld 1975, 100-105).

The previously mentioned bridge to Fanø was not built, which Ostenfeld considered positively, and "might be said to be happy". At that time, the performance was very radical, and when local authorities were to be convinced, the technology of the prestressed concrete was hardly adequately clarified either technically or economically (Ostenfeld 1975, 118-120).

Chr. Ostenfeld generally praised the Swedish textbook "Preloaded Concrete", but he was also critical of the Swedish, very German-inspired, attitude, which he found made the problem too complicated. Contrary to DIF's guidance on the calculation of pretensioned concrete, the German rules had become "impractically complex".

Similarly, other countries' standards for iron concrete were so detailed they had, to some extent, been a serious homage to development, seen from the "eyes of the experienced constructor". Thus, the German practice had become less flexible and applicable to the different tasks than the French and Swiss practice. However, one should remember that construction tends to be very inflexible, as there is a high risk in an area where the costs are very high. At the same time, decisions about the choice of methods are often taken by people other than the engineering engineers.

5.5 New materials

A prerequisite for prestressed concrete is a high quality of cement and steel. While especially German companies supplied steel for prestressing stood Danish cement factories behind the delivery of cement.

The Danish cement factories helped to reverse this trend by developing special quick-hardening cement. A special fast-hardening cement, Super Rapid Cement, was developed in 1946 and seriously marketed from 1948. Although it had its greatest prevalence

during winter construction, thereby expanding the active construction period of the year, it was also a prerequisite for the use of prestressed concrete. It was an advantage of the short curing time of prestressed concrete, whereby the strands of string concrete could be fastened fast. The product was characterized in particular by a high degree of fineness, which was measured by surface area per gram. While ordinary Portland cement had a surface area of 2,000-2,500 cm²/g, Rapid Cement was approximately 3,500 cm²/g (Jacobsen, 1949). While it took 28 days to get ordinary Portland cement hardened, it took Super Rapid Cement of the same strength only 7 days to harden. However, there were certain problems because England and the United States had two different standards for measurement (Norest, 1950). In addition, the price was about twice that of normal cement.

Abroad, fast-curing cement was similarly developed, but this was most often based on alumina cement based on bauxite, which had some negative structural properties which meant that the cement could not work with Portland cement.

6 CHRISTIAN OSTENFELD

Christen Ostenfeld (Fig. 5) was almost born to become an engineer and work with reinforced concrete. His father, Asger Ostenfeld, was a professor at the Technical University of Denmark, specializing in bridge building (Gimsing and Ostenfeld 2012).

Christen Ostenfeld graduated from the Technical University of Denmark and went abroad after graduating in 1924. He thus gained a very close connection

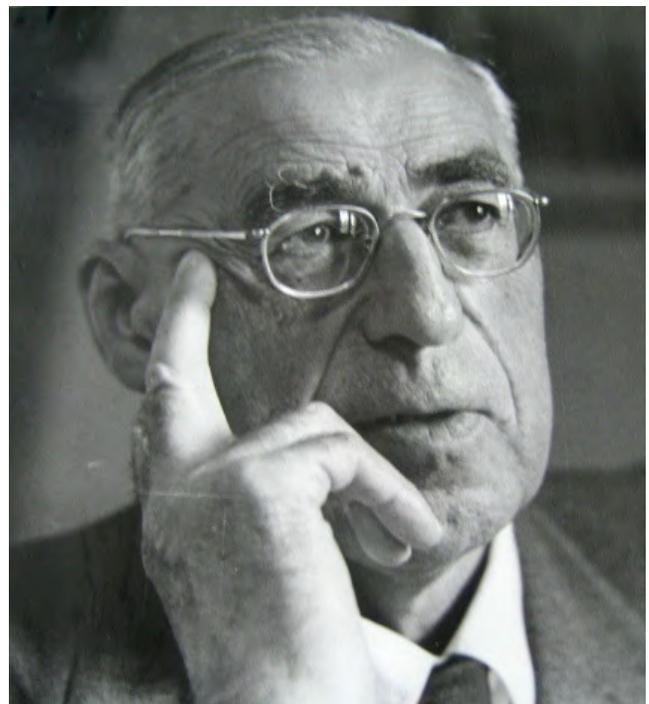


Figure 5. Dr. Techn. Christen Ostenfeld (1900-76) (Story, COWI).



Figure 6. Construction of the first prestressed steel-brick roof, Pakhus 47 (Warehouse 47) in Copenhagen, 1948 (Copenhagen Museum).

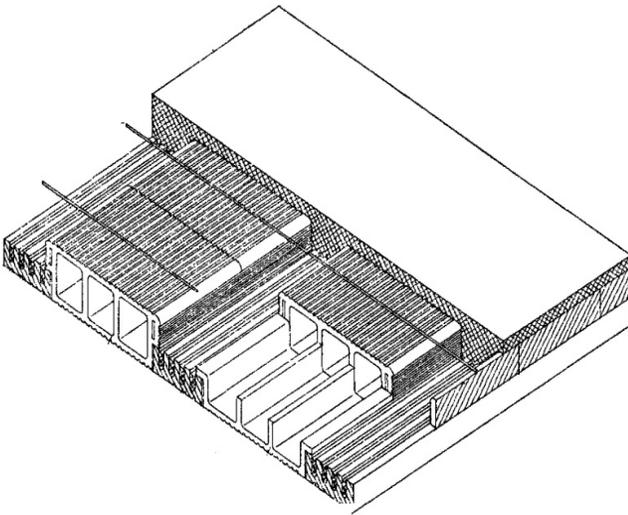


Figure 7. Prestressed brick elements block deck (Arkitekten 1949, 141-144)

with European engineers, especially the French speaking world, living for six years in Switzerland and France in 1924-30. In Switzerland he got further studies and employment at EMPA, and joined the French engineering company S. Geleff and the French branch of the Danish contractor Christiani and Nielsen A/S.

After returning home he became a Dr. Techn. He wanted to work with in engineering profession in practice and established his own engineering company in 1930. In 1946, Wriberg Jønson joined as a partner in the company, called "Chr. Ostenfeld & W. Jønson". In 1972, he resigned from the company, which at the same time received a change of name to COWI after the initial letters of the original founders.

During the war he was one of the country's central resisters as entrusted with the position of treasurer in "The Danish Council for Freedom", and after the liberation, Ostenfeld chose to bet on prestressed con-

crete. He sent an engineer to the French engineering office S.T.U.P. led by Freyssinet. The engineer came home with drawings, which were further developed and adapted to the Danish climate with frost and thaw. Ostenfeld continued working on the methods, in particular the construction of silos for liquids and granules. In 1948 he invented the post-tensioned thin wall concrete silo through resisting the hoop tension in the wall by circular horizontal post-tensioning of the walls to avoid cracks. The first project was a container of one thousand m³ of fuel oil. Later came silos for sugar and cement (Fig. 3). He re-exported the post-tension technology to France for large volume sugar silos.

7 THE FIRST CONSTRUCTIONS

The first prestressed concrete in Denmark was pre-tensioned concrete, which came to Denmark relatively late. As early as in 1938, the Swedish company Betongindustri gained knowledge from Germany about the new production method and after having entered into an agreement with the inventor Ewald Hoyer about the patent for Sweden, production began in 1939. A new company was established for the production, called Strängbeton after a modified translation of the German name for Stahlseitenbeton (Redlund, 2009).

In Denmark, the first production started around 1947 with steel tile planks, and soon the factory manufactured smaller items such as posts, foundation piles, beams and window gaskets (Fig. 4).

The planks were 6-8 m long, where a number of small brick blocks were clamped together by brick pretensioned planks. Subsequently, cement could be cast on the aggregate.

The method originated from Switzerland and was manufactured at Hedehus-Teglværket, which became the second factory in the world with this system (Fig. 2). The products were sold by Skandinavisk Spændbeton. The shelves were used for roofs (floor separations). Principal approval for this was given by building authorities in Copenhagen in 1947 (Fig. 6). The first major use was in the roof structure of 'Warehouse 47' in Copenhagen Freeport 1948-49. The roof was approximately 100 m long and 33 m wide and built of a steel tile tire deck, with an overall height of 18 cm. (Fig. 7). The building was designed by Ostenfeld and Jønsson and built by Jensen & Schumacher.

The first smaller bridges were built according to Freyssinet's method. All bridges were calculated by Ostenfeld and Jønsson. The tribune at the Esbjerg Stadium was assembled by cable concrete according to Freyssinet's method. The bias of the beams was carried out on the ground by pressing and pumping. One of the first major constructions was two bridges to expand a permanent road bridge in 1949.

8 CONCLUSION

The innovation process was not as pure as the theory of technical systems. The invention and innovation phase occurred with scattered inventions in many parts of the world, and it was only after many scattered experiments that prestressed concrete was introduced into Denmark.

Chr. Ostenfeld had a major role in this development. He was the predominant messenger for the method in Denmark, and his own company became a leading company in the Nordic region. If he had not put forth these efforts in the resistance movement in Denmark, the country might have made an earlier and greater impression in the area of prestressed concrete.

In about 1954 the knowledge and manufacturing facilities were in place with development of new materials (high-strength steel, new concrete formulas), the development of new production machinery, changed calculation methods, new approval systems of the authorities, new organizational frameworks around production, and new business agreements and planning.

The fourth phase of the momentum approached.

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