

WHY DID MODERN POST-TENSIONED FLOORS FLOURISH IN THE US AND NOT IN EUROPE –A MATTER OF TRADITION?

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INTRODUCTION

Unlike in Europe, prestressed concrete with post-tensioned reinforcement came to be a standard technique in building construction in the US. Kenneth Bondy has been the only one who has made a significant contribution to clarify why this occurred, by writing about his insights on the origins of post-tensioned floors in the United States. His vision is completed here with new data and put into context. Moreover, the American and European situations are compared in an attempt to explain why things developed so differently on each side of the Atlantic.

WHAT DOES ‘TECHNOLOGY TRADITION’ MEAN IN THIS STUDY?

The construction industry tends to be one of the least flexible, and the market for structure construction is one of the more resistant areas to technological change. Among the reasons for that are: the risk involved in the construction of structures, the high cost of buildings, and the fact that the prescriber (architect, engineer) uses a very different logic to make decisions than that used by other involved agents, such as the contractor, the developer or the final user.

We normally use the term ‘tradition’ to mean a custom kept for generations. Its origins are rarely known or questioned, but it is kept regardless. In this work, the word ‘technology tradition’, or simply ‘tradition’, means a technology which at a certain moment achieved a strong position¹ in one market segment and was able to keep it for a time, remaining almost unquestioned during that period. The features of such a ‘tradition’ are described next, but are not scientifically proven. The concept must be understood as a conjecture, which may show its validity only by its utility to explain the lack of flexibility of the market of structural systems in the construction industry.

The strong position of a ‘technology tradition’ typically originates when a strong technological shift occurs, which is when the new technology appears under the shape of several equivalent variant technologies. Each variant will fight the others to obtain a segment of the market, which is being shaken up and offers important positioning opportunities. In the struggle, each of the variants may or may not succeed in gaining a part of the total market.

As described by Trout, the *order* in which each of the variants appears in a certain market and the initial expansion speed are the most critical factors determining the size of the market for each variant. The first variant will have the largest effect: the first will hit the strongest. The more time the second takes to appear, the more difficult time it will have gaining market share. However, as there are only slight objective differences between competitors, factors other than initial speed may have an influence on the final market segmentation. These may include: the support of skilled pioneering engineers and/or determined capital investors; good advertising (which is not easy in this industry); and the ability to survive the initial struggle long enough for the technology to become a real 'tradition'.

After a time, say one or two decades, the market segmentation has been set and it remains almost constant. Once this status quo is achieved, it is reinforced by several factors, including: advertising, industry associations, scientific or technical publications, and academia which altogether establish links between a technology and its applications. This status quo or tradition will remain until a new technology arrives that will again disrupt the market.

Notice that because the order of appearance is very important, the idea of a technology tradition is tightly linked to the history of a particular local market. Thus, the validity of the idea would explain why some variants of a technology are well rooted in certain geographies but not in others.

THE FOUR MAIN VARIANTS OF PRESTRESSED CONCRETE

Prestressing is simply the introduction of loads to a structure to improve its performance. In the case of concrete structures, using reinforcement as the prestressing agent is the cheapest method, as reinforcement is already needed in any concrete structural element.

There are two main variants of the use of reinforcement to prestress concrete:

[1] *Prestressed concrete with prestressed reinforcement*: Concrete is poured on top of reinforcement wires kept under strong tension. Once the concrete has hardened, the tension of the steel is released so that prestress force is transferred to the concrete.

This technique is typically used for precasts produced in precasting plants

[2] *Prestressed concrete with post-tensioned reinforcement*: Concrete is poured to form a structural element. After concrete hardening, the reinforcement is strongly tensioned² and anchored at the ends of the concrete element to transfer the prestress force to the concrete element.

This second variant is often referred to as 'post-tensioned'.

As the prestressing force acts upon hardened concrete, the force may also have the function to ram together several elements cast separately. Therefore, post-tensioning can be divided into three main variant techniques:

[2a] Post-tensioned on a sole cast-in-situ concrete element

[2b] Post-tensioned on elements precast away from the job

[2c] Post-tensioned on elements precast at the job

TO WHAT EXTENT VARIANTS ARE EQUIVALENT

From the point of view of structural efficiency, there are reasons why post-tensioned structures are far more efficient than prestressed precasts, and much more efficient than reinforced concrete structures. However, each square foot of post-tensioned floor is currently more expensive than either of the other two technologies. This makes it *a priori* not evident to see which of the technologies to use. That is why we may say that those are, to a certain extent, equivalent technologies.

Other factors influence the structural floor choice, such as the depth of the floor, the weight of the floor, the speed of construction, the span between bearings, etc. That is why, depending on the relative importance a certain market gives to each of the involved factors, one technology or another may be more prevalent in a particular market. The primacy of one factor over another may very well be influenced by the same factors which shape a technology tradition.

ORIGINS OF MODERN PRESTRESSED CONCRETE USE IN FRANCE

It has been argued that the advent of modern prestressed concrete is closely related to the ability to predict the total amount of prestress force loss,³ which is complex as it is due to many interacting factors.

The most difficult part of this breakthrough effort was achieved by the French civil engineer Eugène Freyssinet through a series of studies performed from 1907 to 1929.⁴ In 1928, he applied for his patent for prestressed concrete with prestressed reinforcement [variant 1], and in 1939 for his patent for prestressed concrete with post-tensioned reinforcement [variant 2].

Soon after his patents were filed and during the rest of his career, Freyssinet successfully used three of the four variants described above [1, 2a, 2b] and went to considerable effort to disseminate the knowledge and broaden the usage of his advances.

HOW MODERN PRESTRESSED CONCRETE ARRIVED THE US

Freyssinet's inventions greatly disrupted the structure construction situation in both Europe and in the US, even though on the American continent Freyssinet was a virtual unknown. His inventions took root in the US after the end of World War II thanks to the influence of the Belgian Gustav Magnel. He designed and built the Walnut Bridge in Philadelphia in 1948-49, which left a fabulous footprint in the mind of American engineers.^{5,6} It must be highlighted that with this bridge, Magnel was the first to put into practice the fourth of the main prestressed concrete techniques mentioned above: Post-tensioned on segments precast at the job [2c]. It typically consists of precasting large elements lying on the ground and then lifting them into their final position.

HOW DID POST-TENSIONED FLOORS FLOURISH IN THE US: BONDY'S TESTIMONY AND ITS CONTEXT

Unlike in Europe, in the US prestressed concrete with post-tensioned reinforcement became a standard technique in building construction. How this occurred has been outlined by Kenneth Bondy, who was a direct witness to this technical evolution.^{7,8}

Below is a chronology of the main events he described, each preceded by (-). To ease contextualization, several facts have been added, each preceded by (+).

(+) *1929-30*: The French H. Sauvage patents what can be considered the antecedent of modern lift-slab.⁹ All concrete floor slabs of a building are poured at the ground floor, piled in a stack, and then moved to their definitive level using telescopic columns.

(+) *1944*: The Frenchman B. Laffaille patents a new lift-slab system in France.¹⁰ This is where slabs are elevated using a "lifting apparatus" which has a sort of rack with a backstop mechanism.¹¹ In the US, Laffaille patented only the "lifting apparatus".

(+) *1948*: The two first modern US lift-slab patents, almost simultaneously, were licensed to a group of companies owned by the Texan tycoon Thomas B. Slick. One of the patents, developed by P. N. Youtz,¹² (Fig. 1), was clearly influenced by Laffaille's patent. The other patented technique, developed by Slick,¹³ was less evidently also influenced by the French.

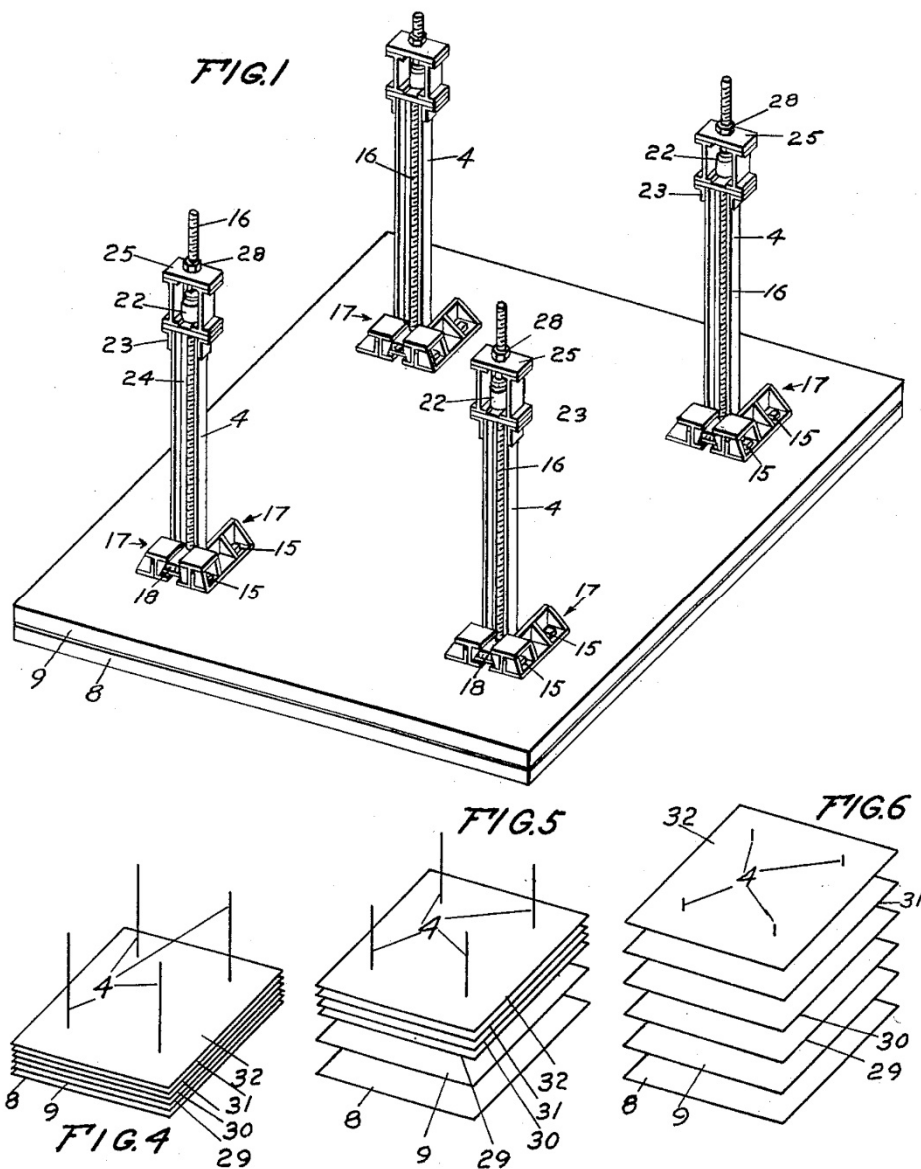


Figure 1. Drawings of patent for lift-slab system applied for by Youtz in 1948.

US 700346, US Patent Office

(-) *Mid 1950s*: According to Bondy, the lift-slab method was used for the first time in the US. Concrete slabs were typically solid and very shallow, with only mild steel reinforcement (no prestressing). The slenderness of slabs, necessary to reduce their weight, led to excessive deflection issues. Moreover, slabs tended to stick to each other during the lifting process.¹⁴

(-) *Mid to late 1950s*: Modern post-tensioning was used for the first time in building construction in lift-slab buildings. This allowed the use of shallow slabs while avoiding both excessive deflection and the problem of stuck slabs. These post-tensioned slabs typically used

a Swiss anchorage system developed by BBRV, which was called the “button-headed tendon”.

Because lift-slab companies obtained good results controlling deflection in slender slabs, other companies not affiliated to the lift-slab method decided to purchase licenses to install BBRV anchorages. Lift-slab companies then used defensive tactics to prevent tendon-installing companies (called ‘post-tensioning companies’ by Bondy) to enter bids for jobs where lift-slab was used.¹⁵

(-) 1962: Edward K. Rice¹⁶ established the company Atlas Prestressing and applied for the first patent for a post-tensioning anchorage for an unbonded monostrand tendon, which included conic wedges to anchor the strand (Fig. 2). This sort of anchorage enabled an easier and faster installation of tendons, which soon made BBRV anchorage totally obsolete. Nonetheless, lift-slab companies stayed defensive and never abandoned the “button-headed tendon”.

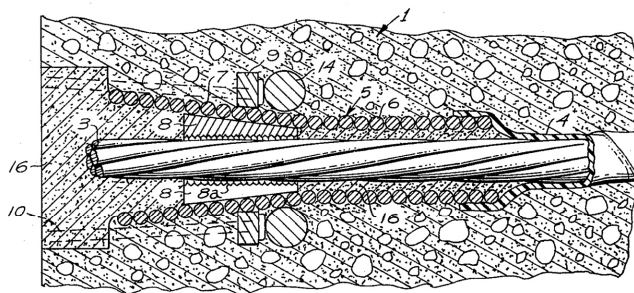


FIG. 2

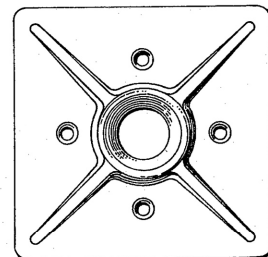


FIG. 10

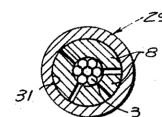


Figure 2. Drawings of the patent for the monostrand anchorage system applied for by Rice in 1962. US 3293811, US Patent Office

(-) 1963: T. Y. Lin published the “load balancing method”, which made it much easier to design post-tensioned slabs.¹⁷

(-)1960s: Atlas Prestressing forges alliances to outcompete the lift-slab companies in erection speed. The key alliance was made with companies using flying forms, a sort of form that was very fast to put in place and to remove.

(-) *Late 1960s*: Post-tensioning companies wiped lift-slab companies out of the market, thanks to the alliance of cast in place post-tensioning and flying forms, and thanks to the fact that lift-slab companies never adopted Rice's new anchorage. According to Bondy, the last was the fatal mistake that killed lift-slab.¹⁸

As a result, post-tensioned floors were no more made out of precast elements precast on the job [2c]. Post-tensioning was then exclusively performed upon slabs cast in place [2a].

ADDITIONS TO BONDY'S INSIGHT

Bondy's first-person testimony is hardly questionable. However, now that some decades have passed, a more general perspective may possibly help identify some things that were difficult to see at the time. That is why this work humbly attempts to suggest some additions to his insights. This is done by describing three factors that may have had an influence on the birth of modern American post-tensioned floors:

- (a) The first American post-tensioning 'tradition' in building construction
- (b) The similarity between the Walnut Bridge and lift-slab construction logic
- (c) Possible British roots of American modern post-tensioned floors

FIRST AMERICAN TRADITION (a)

- *1872-1888*: Peter H. Jackson developed several patents for post-tensioned floors^{19,20,21} made of stone, brick or concrete, mainly for building construction. Jackson thought his invention was particularly interesting because of its fireproof properties, as he stated in his first patent on the matter in 1872. This reasoning was not too original, as fireproofing was one of the main advantages attributed to reinforced concrete structures versus steel or timber structures. Jackson designed by intuition, as he had no formal engineering education, so his post-tensioning designs were not able to control losses, as he could not have even suspected the complexity of that phenomenon. As a result, his designs must be considered rather rudimentary when compared to modern post-tensioning. This led him to abandon his defence of post-tensioned concrete floors against solutions made of reinforced concrete,²² which were very well backed by highly qualified engineers, such as Ransome and his colleagues at the Technical Society of the Pacific Coast.²³ However, Jackson's rudimentary post-tensioned floors had a certain importance at the time, as those were present for decades in a very widespread construction manual written by Frank E. Kidder. While reinforced concrete ended

up being an almost all-purpose structural material, Kidder still credited Jackson's post-tensioned systems as particularly suitable for fireproof structures.^{24,25}

- 1890-1894: Thomas A. Lee followed in the footsteps of Jackson, and obtained his own patent for 'fire-proof' post-tensioned floors.²⁶ As in Jackson's 1872 patent, Lee mentions that blocks may be made of natural stone, artificial stone or brick. However, his drawings clearly show that Lee mainly thought of void ceramic bricks (Fig. 3). To exploit his inventions, he soon founded the Lee Fire Proof Construction Co., which specialized in post-tensioned floors made of blocks rammed together by prestress force [2b]. Lee's systems were soon included in Kidder's book.

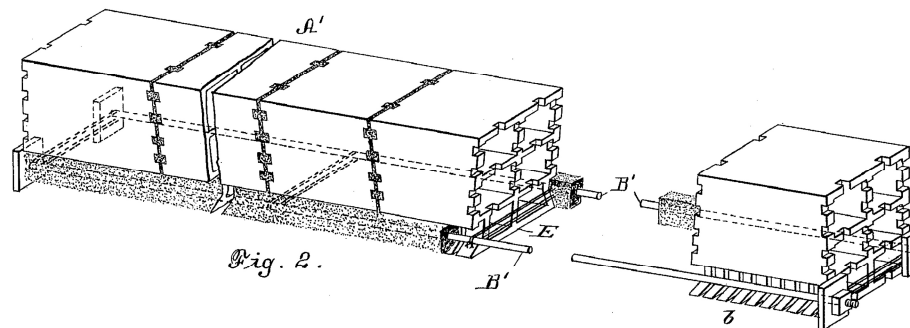


Figure 3. Drawings of the patent for a post-tensioned fire-proof floor, applied for by Lee in 1892. US 461028, US Patent Office

- 1940s to 1960s: Jackson's and Lee's rudimentary post-tensioned floors, along with several similar Scandinavian inventions of the first decades of the twentieth century, were the basis of an entire industry, known as Dox Plank (Fig. 4), which was flourishing across the US in the 1940s and 1950s. In the 1950s there were 25 production plants in 15 States. There was an industrial association, the Dox Plank Manufacturers Association, and their design was regulated by the ACI code. This phenomenon has been well described by Dolhon.²⁷ Most of the systems included in the association shared the basic features found in Jackson's 1872 original patent: a) very primitive prestress techniques and materials; and b) precast concrete or tile blocks rammed together the prestress force. During the 1960s most of this industry was replaced by modern prestressed concrete technology imported from Europe.

Most Dox Plank plants were in the west and mid-west of the US, but there was also one plant in Pharr, Texas, the state where modern post-tensioned technique was used for the first time in building construction. In all, it is not dismissible that the footprint of a 90 year "tradition"

of fireproof post-tensioned floors influenced American engineers in the 1950s and 1960s to use modern post-tensioned floors.

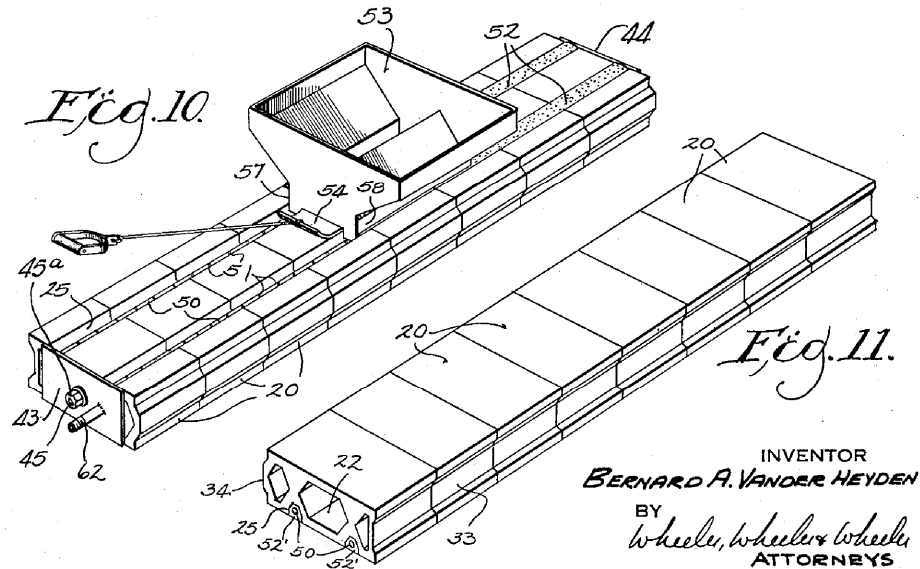


Figure 4. Drawings of a patent for post-tensioned floor made of lightweight concrete blocks applied for by B. A. -Doc- Vander Hayden in 1944. This system, known as Doc's Planks or Dox Plank, became the basis of an entire industry.

US 2696729, US Patent Office

THE WALNUT BRIDGE AND LIFT-SLAB BUILDINGS (b)

In the 1950s, Dox Plank was reaching the peak of its usage, while the lift-slab industry was just starting. At the same time, the modern prestressed technique had just landed in the US with the Walnut Built in 1948-49 and it was about to completely transform the industry. The erecting logic of this bridge was very similar to that of lift-slab: large elements precast on the job and then lifted and placed into their final position. The only difference was that the Walnut Bridge included post-tensioning [2c].

For the lift-slab industry, where problems with deflection were a main concern, post-tensioning in slabs to improve their performance could have been an attempt to address such problems. This approach may have been inspired by the example of the famous bridge, known to any well-informed engineer at the time, if we think both construction logics were not too far.

POSSIBLE BRITISH ROOTS FOR THE SECOND AMERICAN TRADITION (c)

When reviewing British patents of the 1940s and 1950s on post-tensioning, it has been found that they were quite early and original compared to the American equivalents, to the point that an influence of the former on the latter cannot be totally dismissed.

The following chronology includes some outstanding examples:

- 1942: P. W. Abeles and K. W. Mautner, both exiled from German-speaking countries during World War II, patented each one of the UK systems to erect modern post-tensioned floors for building construction by ramming together precast concrete elements [2b]. Abeles' proposals were quite abstract and general,²⁸ but Mautner's were much more specific.²⁹ This makes the latter more realistic, which could be a reason to credit Mautner with being the first to design a modern post-tensioned floor. This patent proposed the use of very thin tendons with very small anchorages. It all it looks very similar to use of monostrands and anchorages patented by Rice in the US 20 years later.

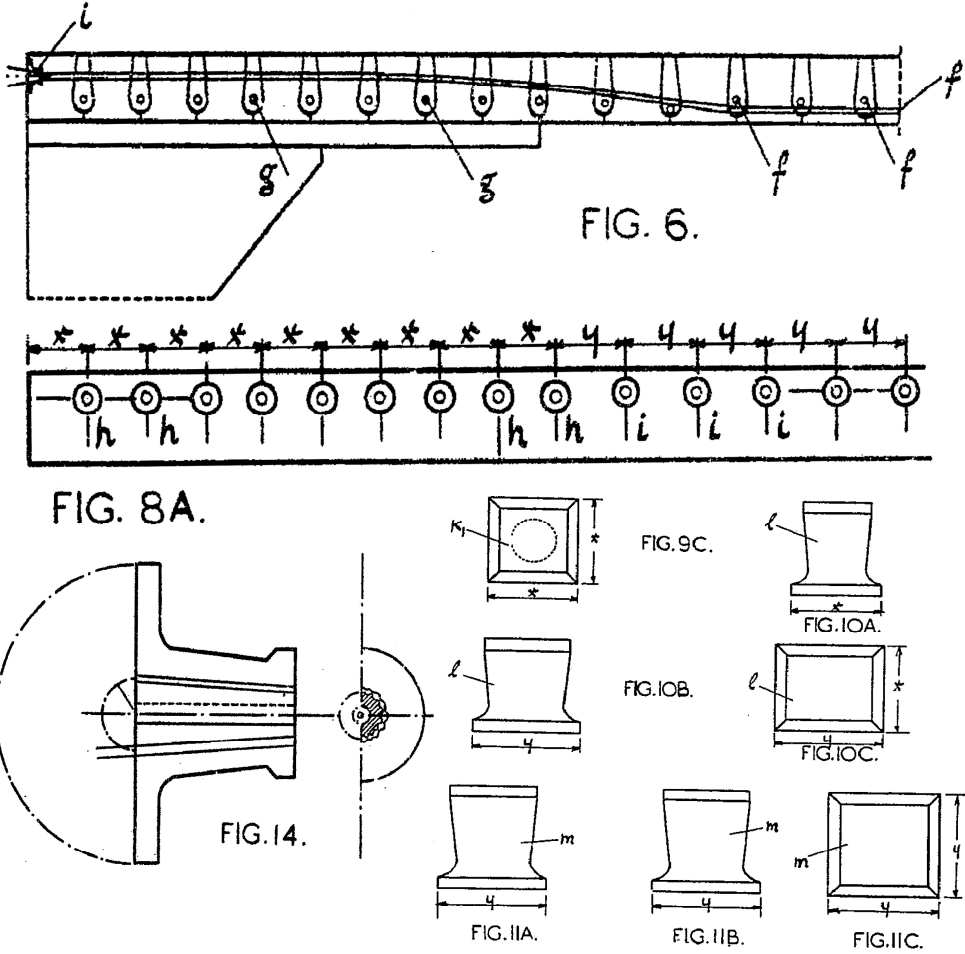


Figure 5. Drawings of the patent for the first modern post-tensioned floor system applied for by Mautner in 1942. GB 556570, UK Intellectual Property Office

1952: American Curzon Dobell, working for the contractor erecting the Walnut Bridge, the Preload Company of NY, applied for a patent for post-tensioned precast floors,³⁰ citing Mautner's patent as a reference. Two years before that, in the ACI journal, he had published a paper establishing the most important patents and references for prestressed concrete.³¹ His being involved in the Walnut Bridge construction and his paper in the ACI would make of him a quite influential person in this industry at the time. This could possibly mean that American industry may not have been alien to Mautner's idea to post-tension structural floors.

1953: British Udalls Prestressed Concrete Ltd. applied for the patent for an anchorage system for post-tensioning known as Gifford-Udall anchorage,³² which would be one of the most used in the US in the following decades. This anchorage was well known among the most skilled American engineers of the period, probably including some who worked for lift-slab companies.

1954: Udalls Prestressed applied for the patent for a system of post-tensioned slab-on-the-ground. The slab was lifted from the ground with jacks, just after post-tensioning it, to avoid problems associated with soil-slab friction (Fig. 6).³³ This technique was extremely similar to that used in lift-slab buildings and could have been an inspiration for American lift-slab engineers to solve their issue of slabs sticking together during the lifting operation. Notice that Bondy wrote that the lift-slab industry started to post-tension slabs by the end of the 1950s. By that time American lift-slab engineers who knew of Gifford-Udall anchorages might have also heard about other Udall Prestressed products, such as post-tensioned slabs-on-the-ground.

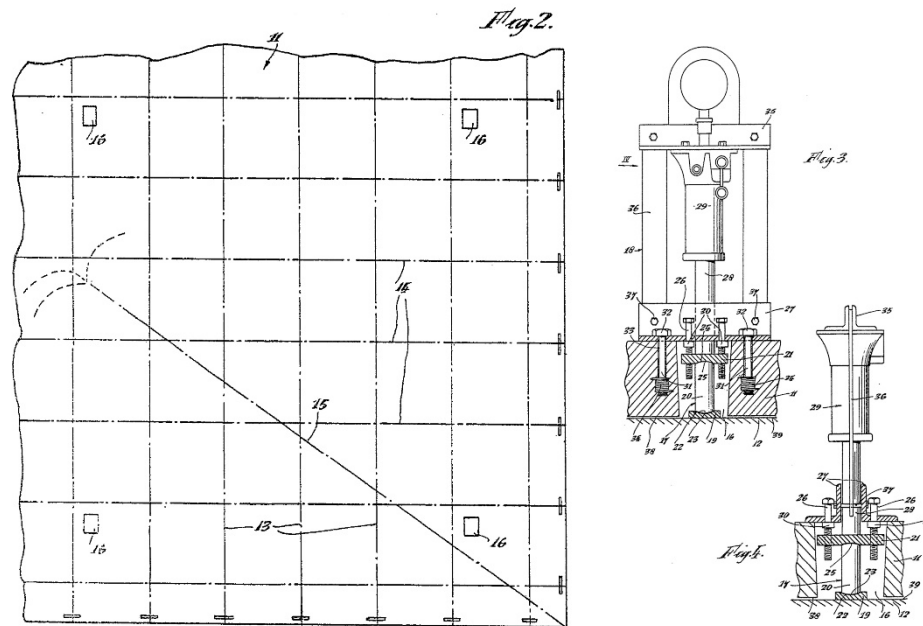


Figure 6. Drawings of patent for post-tensioned slab-on-ground applied by Udalls Prestressed Concrete Ltd. in 1954. GB 773890, UK Intellectual Property Office

- 1958: Karl H. Middendorf, working for the Texan Prescon Corporation, applied for a patent for the construction of waffle post-tensioned floors, good both for slabs cast in place and for slabs for the lift-slab method.³⁴ Patents similar to this one were used by lift-slab companies to protect their technology. Two features of this patent are particularly interesting. On the one hand, the anchorage system used is that of the Swiss of BBRV –which coincides with Bondy’s depiction of the state of the art at the time.³⁵ On the other hand, the patent cites as a reference Mautner’s patent of 1942. Therefore, lift-slab companies already knew about their British predecessor.

THE SECOND AMERICAN TRADITION OF POST-TENSIONED FLOORS

Viewing all the above topics under the perspective of the idea of ‘technology tradition’, we may summarize the whole using the following approach.

The four variants of modern prestressed concrete arrived the US at the same time, and each had to fight the others to gain a place in the market. While all four variants found application in civil engineering, in building construction they did not have quite the same fortune.

Prestressed concrete with prestressed reinforcement [1] soon became very popular, as in Europe, because it was cheap, fast and easy-to-use. Via lift-slab, post-tensioned also entered the building construction industry under the variant [2c] and soon after post-tensioned cast in situ slabs were also used [2a]. So, less than 15 years after the Walnut Bridge, modern

prestressed concrete was already used in building construction under three of its four main variants. However, due to the lift-slab companies' lack of strategic vision, they failed to predict the importance of the new generation of anchorages, and finally succumbed, reducing the living variants to two [1 and 2a].

Thus the foundations of the second tradition of post-tensioned floors for building construction in the US were built, which last to this day.

WHAT HAPPENED IN EUROPE?

A number of reasons can be found to explain why post-tensioned floors did not take root in Europe after World War II, but the most critical factor was how the war determined the way Freyssinet's inventions spread across the continent. The patents of his two main inventions [1, 2] were granted 17 years apart from each other, which is a long time in terms of 'technology tradition'. However, the most influential factor was the war that occurred during the time between these two patent publications. His first invention, modern prestressed precast [1] appeared in 1930, in the inter-war period,³⁶ and expanded very fast. It was probably considered war technology and was pushed to massive production levels by the Germans and the British.³⁷ During the war, the patents of the German E. Hoyer -to a considerable extent copied from Freyssinet³⁸ - virtually invaded Europe in parallel with German expansion.^{39,40}

Freyssinet had filed his post-tensioning patent [2] in 1939, but this technology only made it to the market in large scale after the war, and only in the field of civil engineering.⁴¹ By the time this occurred, all concrete precasts (prestressed or not) had already taken a very strong position in the market as a cheap and easy-to-use technique that was able to solve most of the massive and urgent needs of building construction. At that time, the expertise in prestressed concrete design was almost exclusively in the hands of civil engineers devoted to infrastructure and of industrial engineers devoted to precasting production. Those experts were busy reconstructing the continent, and had little time and incentive to innovate. Technologies proven effective during the war were simply used over and over. Civil Engineering was the exception, as Freyssinet bet and pushed hard his whole life for his ideas to succeed. He used post-tensioning in audacious bridges and other important infrastructures, and he soon succeeded in demonstrating that his proposals made sense and were cost efficient.⁴²

Another very important factor which prevented post-tensioning from entering the European building construction market was the lack of capital devoted to research as there was a lack of

funds due to the war. This is evident when we see that European and American inventors in the 1940s and 1950s had a similar number of productive patents related to post-tensioned floors, but in Europe they were not able to raise capital to invest in their ideas. The same could be said of lift-slab technology. Modern lift-slab was invented in France and was soon applied to post-tensioning in the UK, but none of these inventions were properly backed by venture capital. This lack of investment and engineering endeavour finally led to a situation where Europeans could not take advantage of key American inventions related to post-tensioned floors for buildings, such as monostrand tendons and anchorages or the balanced load design method.

Indeed, it can be said that, as a whole, World War II was the source of the technology tradition of prestressed concrete in Europe.

CONCLUSION

The order of events, i.e. the history of the technology, might have had a very strong role in determining why post-tensioned floors flourished in US in the 1950s and are still commonly used today, and why this technique has never had similar strength in European building construction.

If we look at the history of prestressed concrete as a ‘technology tradition’ as described above, two answers are found.

On the one hand, the spread of the two main variations of modern prestressed concrete in Europe was interrupted by the war, while just after the war all variations of prestressed concrete appeared in the US.

On the other hand, the stagnation present in post-war Europe made it difficult to innovate, while innovation was very much a part of the dynamic U.S. economy.

The market distribution resulting from these first critical decades of modern prestressing concrete created a solid basis for a ‘technology tradition’ that was very different on each side of the Atlantic and which will be very hard to alter unless a new technology is able to disrupt the status quo.

CONTACT DETAILS

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NOTES AND REFERENCES

- ¹ J. Trout, ‘Positioning is a Game People Play in Today’s me-too Market Place’, *Industrial Marketing*, vol.54, no.6, June 1969, pp.51-55
- ² A proper arrangement of the reinforcement must allow its free tensioning without leading to tensions onto surrounding concrete due to reinforcement-concrete bonding. A number of solutions exist to enable this.
- ³ M. Sanabra-Loewe & J. Capellà-Llobera, ‘The Four Ages of Early Prestressed Concrete Structures’, *PCI Journal*, vol.59, no.4, Fall 2014, pp.93-121
- ⁴ J. A. Fernández Ordóñez, *Eugène Freyssinet*, Barcelona: Xarait, 1978
- ⁵ G. D. Nasser, ‘The Legacy of the Walnut Lane Memorial Bridge’, *Structure Magazine*, October 2008, pp.27-31
- ⁶ D. P. Billington, ‘Historical Perspective on Prestressed Concrete’, *PCI Journal*, vol.49, no.1, January-February 2004, pp.14-30
- ⁷ S.C. McCraven, ‘Post-Tensioned Concrete: Five Decades of American Building Construction, An interview with Kenneth B. Bondy’, *Concrete Construction*, December 2001, pp.1-6
- ⁸ K. Bondy, ‘Post-Tensioned Concrete Buildings. Past and Future. An Insider’s View’, *PTI Journal*, December 2006, pp.91-100
- ⁹ H. Sauvage, ‘Ossature pour bâtiments et édifices de toute nature et système d’érection de ces bâtiments’, French Patent 684089, filed 2 February, 1929, and issued 20 June, 1930
- ¹⁰ B. Laffaille, ‘Procédé perfectionné de mise en œuvre des matériaux de construction’, French Patent 909771, filed 24 October, 1944, and issued 17 May, 1946
- ¹¹ B. Laffaille, ‘Appareil de levage’, French Patent 912526, filed 24 October, 1944, and issued 12 August, 1946
- ¹² P. N. Youtz, ‘Slab lifting apparatus’, US Patent 2686420, filed 30 November, 1948, and issued 17 August, 1954
- ¹³ T. B. Slick, ‘Apparatus for erecting a building’, US Patent 2715013, filed 26 July, 1948, and issued 9 August, 1955
- ¹⁴ Bondy, Post-Tensioned (Note 8)
- ¹⁵ McCraven, Post-Tensioned (Note 7)
- ¹⁶ E. K. Rice, ‘Anchorage for concrete stressing tendons’, US Patent 3293811, filed 1 June, 1965, and issued 27 December, 1966
- ¹⁷ T. Y. Lin, ‘Load Balancing Method for Design and Analysis of Prestressed Concrete Structures’, *Journal of the American Concrete Institute*, vol.60, num.6, June 1963, pp.719-742
- ¹⁸ McCraven, Post-Tensioned (Note 7)
- ¹⁹ P. H. Jackson, ‘Improvement in girders’, US Patent 126396, issued 7 May, 1872
- ²⁰ P. H. Jackson, ‘Building or bridge construction’, US Patent 366839, filed 7 January, 1886, and issued 19 July, 1887
- ²¹ P. H. Jackson, ‘Construction of artificial-stone or concrete pavements’, US Patent 375999, filed 27 October, 1886, and issued 3 January, 1888
- ²² Sanabra-Loewe & Capellà-Llovera, Four Ages (Note 3)
- ²³ S. E. Wermiel, ‘California Concrete, 1876-1906: Jackson, Percy, and the Beginnings of Reinforced Concrete Construction in the United States’ in *Proceedings of the Third*

International Congress on Construction History, Cottbus, 2009, Cottbus: Brandenburg University of Technology, 2009

²⁴ *ibid.*

²⁵ F. E. Kidder, *The Architect's and Builder's Pocket-book (12th edition)*, New York: John Wiley & Sons, 1895

²⁶ T. A. Lee, 'Artificial fire-proof joist for floors or roofs', US Patent 461028, filed 20 December, 1890, and issued 13 October, 1891

²⁷ A. M. Dolhon, 'Performance Evaluation of Dox Plank', in M. Ettorney, (Ed.), *AEI 2008: Building Integration Solutions*, Denver 2008, Denver: ASCE Publications, 2008

²⁸ P. W. Abeles, 'An Improved Manufacture of Structures from Reinforced Materials', UK Patent 556572, filed 3 March, 1942, and issued 11 October, 1943

²⁹ The Pre-Stressed Concrete Company Ltd. & K. Mautner, 'Improvements in and relating to Flat Slabs or Slabs Spanning in Two Directions with Precast Elements in Pre-stressed Concrete', UK Patent 556570, filed 28 August, 1942, and issued 11 October, 1943

³⁰ C. Dobell, 'Method of erecting prestressed floor sections', US Patent 2776471, filed 9 January 1952, and issued 8 January 1957

³¹ C. Dobell, 'Patents and Codes Relating to Prestressed Concrete', *Journal of the American Concrete Institute*, vol.46, num.5, May 1950, pp.713-722

³² Udalls Prestressed Concrete Ltd., 'Improvements in or relating to Means for Tensioning Rods and the like', UK Patent 746033, filed 24 February, 1954, and issued 7 March, 1956

³³ Udalls Prestressed Concrete Ltd., 'An Improved Method of Pre-Stressing Reinforced Concrete of Large Area, and Apparatus for Carrying Out Said Method', UK Patent 773890, filed 17 August, 1955, and issued 1 May, 1957

³⁴ K. H. Middendorf, 'Concrete building construction', US Patent 3152421, filed 17 November, 1958, and issued, 13 October, 1964

³⁵ McCraven, Post-Tensioned (Note 7)

³⁶ E. Freyssinet & J. Seailles, 'Procédé de fabrication de pièces en béton armé', French Patent 680547, filed 2 October, 1928, and issued 1 May, 1930

³⁷ J. Grote & B. Marrey, *Freyssinet, la précontrainte et l'Europe. Der spannbeton und Europa. Prestressing and Europe. 1930-1945*, Paris : Éditions du Linteau, 2000

³⁸ Fernández Ordóñez, Freyssinet (Note 4)

³⁹ E. Hoyer, 'Procédé pour faire du béton armé', French Patent 837141, filed 26 April, 1938, issued 2 February, 1939

⁴⁰ E. Hoyer, 'Einrichtung zur gleichzeitigen Herstellung einer größeren Zahl langer Betonkörper mit vorgespannter Bewehrung', German Patent 711506, filed 24 May, 1938, and issued 2 October, 1941

⁴¹ E. Freyssinet, 'Système d'ancrage de câbles sous tension destinés à la réalisation de constructions en béton précontraint', French Patent 926505, filed 26 August, 1939, and issued 3 October, 1947

⁴² Fernández Ordóñez, Freyssinet (Note 4)