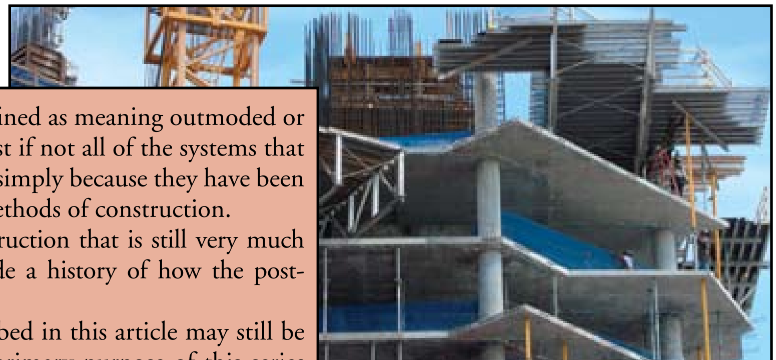
Antiquated Structural Systems Series

Part 7

By D. Matthew Stuart, P.E., S.E., F. ASCE, SECB



Courtesy of Larry Krauser, General Technologies Inc.

For this series of articles, "antiquated" has been defined as meaning outmoded or discarded for reasons of age. In reality, however, most if not all of the systems that have been and will be discussed are no longer in use simply because they have been replaced by more innovative or more economical methods of construction.

However, this article deals with a method of construction that is still very much in use today. Therefore, this installment will provide a history of how the post-tensioning industry developed in the United States.

The historic, original construction practices described in this article may still be encountered in existing structures. Therefore, the primary purpose of this series of articles will be fulfilled, which is to compile and disseminate a resource of information to enable structural engineers to share their knowledge of existing structural systems that may no longer be in use but are capable of being adapted or reanalyzed for safe reuse in the marketplace of today and the future.

Post-Tensioned Concrete Construction

In the 1950s, post-tensioned concrete was introduced into the United States from Europe, primarily as a part of the lift-slab construction industry. However, the first post-tensioned structure constructed in the U.S. was the Walnut Lane Bridge in Philadelphia, between 1949 and 1950. This structure consisted of precast girders that were post-tensioned using the Magnel system developed in Belgium; i.e., the tendons were stressed after the concrete was cast, as opposed to pretensioning in which the tendons are stressed between abutments or within self-stressing forms before the concrete is cast. From these beginnings, this system of "prestressing" both cast-in-place and precast concrete structures and members continues to this day.

Lift-Slab Construction

Originally, the lift-slab industry used conventional reinforcing in the framed slabs that were first stack-cast on the ground and then lifted into position via hydraulic jacks located at the tops of the building columns. Typical slab spans and depths ranged from 25 to 30 feet and from 10 to 12 inches, respectively. However, because of these span lengths and the related excessive dead load deflections, as well as the stresses associated with the stripping process, cracking of the slabs was very common.

In order to correct these inherent deficiencies, the industry turned to the available European BBRV (button-headed) post-tensioning system (*Figure 1*). This system of post-tensioning allowed the reduction of slab thicknesses to as little as 8 inches, along with a reduction in the amount of total reinforcing steel in the concrete section because the tendons were made of higher strength material than conventional reinforcement.

Button-Headed Tendons

The button-headed system involved the use of parallel, ¼-inch-diameter, 240-ksi, cold-drawn wires, each with an approximate tensile capacity of 7 kips. The wires were combined together, generally in groups of seven, to form tendons. To anchor the tendons at each end, the wires were threaded through holes in a steel bearing plate and then an externally threaded, circular stressing washer. A "button" was then cold-formed on the end of each wire via impact of a hammer on the end of the tendon. The buttons prevented the wires from passing back through the holes in the circular washer and, as a consequence, allowed them to become anchored during and after the field tensioning operation. The tendon assemblies were then coated with mastic for corrosion protection and wrapped in heavy wax paper to prevent the tendon from bonding to the concrete. The above process was completed in a pre-assembly shop prior to shipment to the construction site.

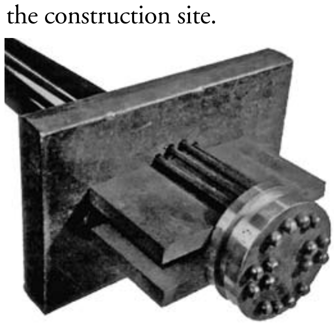


Figure 1. Reprinted with the permission of the Post-Tensioning Institute from Ken Bondy, "Post-Tensioned Concrete in Buildings, Past and Future - An Insider's View," PTI Journal, December 2006, pp. 91-100.

Once the tendons were at the job site, the assemblies were placed in the forms, the concrete was cast, and the wires were stressed once the concrete achieved a minimum strength. The stressing process was performed with a hydraulic jack, which was attached to the threaded washer. A steel shim was inserted between the bearing plate and the washer to prevent the circular anchorage from retracting back against the bearing plate. As the shim plate was prefabricated, the length of the plate parallel to the tendon had to match exactly the calculated elongation. This system of anchoring the tendon was inherently flawed because if the actual elongation did not match the length of the shim plate, field corrections had to be made.

A second problem associated with the button-headed system was the fact that the stressing washer and shim plate had to be external to the concrete in order to facilitate the stressing operation. This resulted in placing this portion of the anchor assembly either outboard of the concrete or within a formed stressing pocket. In either case, it was necessary to cast a continuous pour strip or fill in the pockets after the stressing operation was completed.

Another problem presented by the button-headed system was the need to use bulky couplers when intermediate stressing of the tendons was necessary. Intermediate stressing procedures were required any time a continuous framed slab was longer than approximately 160 feet. This was because the frictional restraint of the wires during the tensioning operation limited the practical stressing lengths of the tendons to approximately 80 feet. By stressing the tendons at each end anchorage, a maximum of 160 feet could be tensioned without having to introduce an intermediate stressing point coupler. The couplers usually consisted of large, high-strength, externally threaded steel studs that were screwed into an internally threaded hole in the stressing washer.

Formed-in-Place Construction

At the same time that lift-slab construction was being advanced, separate companies specializing in post-tensioned, formed-in-place construction began competing for the same projects. However, it was not until alliances were made between the post-tensioning companies and the emerging flying form industry that formed-in-place, post-tensioned construction really began to become competitive with lift-slab construction. By the 1960s, formed-in-place, post-tensioned construction had eclipsed lift-slab construction as the predominant method of constructing multistory, cast-in-place concrete buildings.

Post-Tensioned Strand

The use of spirally woven, seven-wire strand as post-tensioned tendons was introduced into cast-in-place, post-tensioned construction from the precast/prestressed concrete industry in the early 1960s. By the end of the same decade, the post-tensioning strand system had replaced the button-headed tendon system. Up until the early 1970s, unbonded, mono-strand tendons were installed greased and spirally wrapped with two layers of heavy kraft paper. By 1975, plastic sheathing was exclusively used for greased, unbonded strand.

The use of strand was identified because of the ability of the tendons to be secured with wedge anchors, which eliminated the primary disadvantage of the button-headed system – the lack of flexibility of the steel anchor shims. The first wedge anchor for use in the post-tensioned industry was patented by Edward K. Rice of Atlas Prestressing Corporation (*Figure 2*). The wedge anchor was constructed with a tapered, high-strength wire coil with no bearing plate. The plate shown in *Figure 2* was only provided to secure the anchor to the inside face of edge form. This method of installation also eliminated the other disadvantage of the button-headed system – the need for a continuous pour strip or infilled stressing pockets.

The wedge anchor assembly was installed with a small, two-piece, round rubber grommet that was positioned between the anchorage and the inside face of the edge form. The grommet allowed the anchorage to be recessed a few inches in from the edge form, which created a round hole in which the nose of the tensioning jack could be inserted. The grommet also filled in the space between the coil and the strand, preventing cement paste from entering the assembly during concrete placement. After tensioning was completed

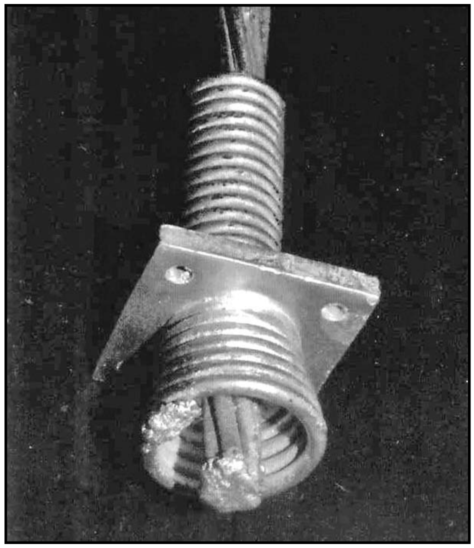


Figure 2. Reprinted with the permission of the Post-Tensioning Institute from Ken Bondy, "Post-Tensioned Concrete in Buildings, Past and Future – An Insider's View," PTI Journal, December 2006, pp. 91-100.

and any excess strand was removed beyond the outboard end of the anchorage, the remaining hole was filled with grout for a flush finish with the edge of the slab.

The seven-wire strand system was also more conducive to intermediate stressing locations, eliminating the final disadvantage of the button-headed system. With a strand, the cable could be placed as a continuous tendon with a wedge anchor assembly simply slid down the length of the strand to the intermediate stressing point.

The anchorage force associated with the coil wedge assembly was transferred to the concrete by direct tension resistance to the lateral forces generated by the wedges on the

> "…when ACI 318-77 was published, banded tendon distribution in two-way slab construction was recognized by the Code."

inside of the coil. As a result, localized failure of the concrete, particularly with lightweight mixes, was common. This inherent deficiency of the coil anchor resulted in the development of a ductile iron anchorage plate in the mid-1960s. The ductile iron assembly consisted of a flat bearing plate combined with a center, open, tapered barrel ring where the wedges were secured. The current end anchorage plates in use today are very similar to these original bearing assemblies.

Methods of Analysis

Because of the indeterminate nature of a continuous, cast-in-place concrete beam or slab and the secondary effects induced by draped post-tension tendon uplift forces at the structural supports, the analysis of post-tensioned structures was originally difficult. The analysis of cast-in-place, post-tensioned structures became much easier, however, after a simplified method of analysis called "load balancing" was presented by T.Y. Lin in a 1963 *ACI Journal* paper.

The load balancing method of analysis basically involved idealizing the vertical forces applied to a structure from the draped tendons as a series of upward uniform loads on the member. The load balancing method allowed structures to be accurately analyzed using standard structural engineering methods such as moment distribution. This greatly simplified the process of post-tensioned design, making it as easy as designing a conventionally reinforced structure, thereby helping to increase the popularity of post-tensioned construction from the late 1960s into the 1970s.

Two-Way Construction Methods

Originally post-tensioned, two-way slab framing systems were constructed with column and middle strips, similar to those used in conventionally reinforced two-way slabs. However, because the continuous two-way tendons had to be placed in a draped parabolic profile – near the top of the slab at the column lines, and near the bottom of the slab at midspan – the cables had to be placed in a basket weave pattern. This required that the tendons be numbered and installed in a specific sequence. This was difficult, particularly for structures with irregularly spaced column grids.

To avoid the complexities of a basket weave tendon installation, an alternate method of construction was conceived by T.Y. Lin & Associates and Atlas Prestressing Corporation for the infamous Watergate building located in Washington, D.C. in the late 1960s. The system involved banding the tendons – grouping the strands together within a narrow strip – in one direction along the column line grid, while the tendons in the other direction were spaced uniformly above the banded tendons. The banded method of construction resulted in considerable labor savings over the basket weave system, and has become the predominant method for placing post-tensioning tendons in two-way slabs ever since.

The structural adequacy and performance of the banded tendon layout was confirmed through a number of laboratory tests at the University of Texas, Austin in the early 1970s. In addition, the performance of the banded method of construction has also been proven through the continued serviceability of the many buildings that have been erected to date with this method of construction.

Building Codes and Industry Organization

Up through the ACI 318-71 Code, cast-in-place, post-tensioning design was essentially ignored, even though precast/prestressed members were addressed. However, when ACI 318-77 was published, banded tendon distribution in two-way slab construction was recognized by the Code. This improvement came about primarily through the formation and involvement of the Post Tensioning Institute (PTI), which was established in 1976.

Common Problems

The two biggest problems faced by the post-tensioning industry have been restraint cracking and corrosion, with the latter being the most pervasive. Solutions to restraint cracking were discovered fairly soon as the industry learned how to develop construction details to avoid the problem. Addressing corrosion did not start to occur until the PTI developed improved specifications in the mid 1970s.

Concrete volume change occurs in both non-prestressed and post-tensioned structures. Axial post-tensioning compression forces tend to close the restraint cracking associated with concrete volume change within the span of the member. However, the compression forces also result in significant axial shortening of the concrete member at the ends. Therefore, any restraint that is provided at the ends of the member – e.g., at walls or columns – can and does result in significant cracking in the post-tensioned member or the restraining structural support. Solutions to this problem include the development of slip joints and pour strips.

The early unbonded tendon coatings (grease) and sheathings were very inadequate for protecting the cables from corrosion, particularly in harmful environments such as parking garages, where the use of deicing materials created caustic conditions for both the concrete and the internal reinforcement. The actual extent of the problem did not reveal itself until about 10 or 15 years after the earliest post-tensioned concrete structures were constructed. The problem was corrected after the PTI developed specifications that became enforceable through certification programs created by the organization. The improvements established through the PTI specifications included sheathings, coatings and encapsulation systems for use in aggressively corrosive environments.

Conclusion

The post-tensioning industry is likely to continue to thrive worldwide for both building and bridge construction. Further advancements within the industry should continue to enhance the design and construction of post-tensioned structures. In fact, the author anticipates that, sometime in the future, an advanced chemical sheathing will be developed for mono-strand construction that will allow for conventional unbonded installation and tensioning, yet subsequently create a long-term bonded condition in the absence of internal ducts or grouting.▪

D. Matthew Stuart, P.E., S.E., F. ASCE, SECB is licensed in 20 states. Matt currently works as a Senior Project Manager at the main office of CMX located in New Jersey, and also serves as Adjunct Professor for the Masters of Structural Engineering Program at Lehigh University, Bethlehem, PA. Mr. Stuart may be contacted at ***mstuart@CMXEngineering.com***.

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