An interview with Kenneth B. Bondy

Beginning in the 1950s as a European import, post-tensioned concrete has changed the face of American building construction. Starting from lift slabs with button-headed wires and evolving into flying forms and cast-in-place slabs post-tensioned with strand tendons, post-tensioning has become a common technique in American construction.

Ken Bondy began his engineering career in 1963 with the pioneering California firm of T.Y. Lin & Associates. He has been a part of the post-tensioned concrete industry since its inception in American buildings. In the following interview, CONCRETE CONSTRUCTION's senior editor S.C. McCraven asks him for insight into how and why post-tensioned concrete has become such a dominant force in American construction.

When was post-tensioned concrete first seen in this country?

The first use was on the Walnut Lane Bridge in Philadelphia in 1949. The bridge had precast girders post-tensioned with the European Magnel system. The first post-tensioning in U.S. building construction was in the mid- to late 1950s in buildings using the lift-slab construction method.

How were lift slabs constructed?

Originally in lift-slab buildings the concrete floor slabs were reinforced with mild steel. The slabs were precast on the ground in a stack and then lifted individually into position using hydraulic jacks at the tops of the columns. While this was an inherently efficient process, there were two problems. First, the slabs tended to stick together as they were lifted, their weight causing them to crack as they were pulled apart. Second, since spans of 28 to 30 feet were common and the slabs were 10 to 12 inches thick, deflection was a serious problem. Midspan deflections of 2 to 3 inches and partition cracking were common in early lift-slab construction.

Did post-tensioning solve deflection problems?

Engineers with lift-slab companies were aware that post-tensioning the slabs could control deflections and reduce slab thickness. The problem was that the only post-tensioning systems available at the time were in Europe. So the lift-slab companies went to Europe and obtained licenses to market the Swiss "BBRV," or "button-headed tendon" system, the only available system with any possible application in building construction with unbonded tendons. Once the lifting companies started post-tensioning their slabs, the deflection problems virtually disappeared. Other companies not affiliated with the lift-slab method saw the advantages of post-tensioning and also obtained licenses to market the button-headed tendon system in cast-in-place

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buildings. These companies included Prescon, Ryerson, American Stress Wire, Conesco, and a few others.

What's a "button-headed tendon" system? How was it installed?

A button-headed tendon has parallel, 1/4-inch-diameter cold-drawn wires, each with about a 7-kip (7000-pound) effective force, generally six or seven wires per tendon. To secure the wires at each end, they were passed through round holes in a rectangular steel bearing plate and a circular stressing washer, usually externally threaded. Then a "button" was formed on each end of the wire by dynamic impact—basically hammering the steel end of the tendon. The buttons, too big to pass back through the holes, could then be anchored against the stressing washer. A mastic coating was applied to the wires for corrosion protection, and they were wrapped in heavy waxed paper to prevent bond with the concrete. All of this was done in the shop, and then these tendon assemblies were transported to the job. Tendon assemblies were installed into the forms, and the concrete was placed. When the concrete reached a minimum strength, the tendons were stressed to the required tension and elongation with a hydraulic jack attached to the threaded stressing washer. A steel shim exactly as long as the calculated elongation then was inserted between the bearing plate and the stressing washer to hold the elongation and stress in the wires. There was no room for error—the length of the wires and shims had to be exactly predetermined.

Exact length was required? Sounds like a construction nightmare. Didn't this create problems onsite?

There were actually two major problems with the button-headed tendons. First, of course, was the problem with

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Left: Flying form being hoisted into place. Above: Flying form panels cantilevering out of multistory building, ready for flying to floor above.

exact length. Any deviation between the tendon length and the length between edge forms required either a new tendon or moving the edge forms before pouring the concrete. Second, because the shims and the stressing washer ended up on the outside edges of the constructed slab, they had to be covered with a second concrete pour. This was done by either recessing the anchor inside the finished slab edge in a "stressing pocket" that was filled with concrete later, or by casting a continuous pour strip at the slab edge to cover the anchors.

Other than solving slab deflection problems, how did post-tensioning help the contractor?

That and reducing slab thickness. Since post-tensioning makes much more efficient use of a concrete cross section, 8- or 9-inch slabs could be used instead of the 12-inch-thick floor slabs that had been required for nonprestressed slabs. Thinner slabs meant savings in material, time, and labor for the contractor. Because prestressing steel has higher strength than mild steel, post-tensioned slabs could be built with less than half the weight of steel required in rebar slabs. This resulted in much more space for plumbing and other utilities, and easier jobs for plumbers, electricians, and any other trade installing their materials in the slabs. Post-tensioning soon had a major impact on suspended slab construction in all types of commercial buildings.

I've heard that the lift-slab companies were able to shut out other PT contractors. How did that happen?

The lift-slab guys were very clever. They bought the European button head licenses and packaged the tendons into their bids for lift-slab construction. By bidding a total "package," including both the lifting and the tendons, independent post-tensioning companies like my firm, Atlas Prestressing Corp. of Los Angeles, were shut out of the competition for these jobs. A tendon price by itself was meaningless to the general contractor bidding a lift-slab job because there was nothing with which to compare it. By packaging the lifting and the tendon price together, lifting companies tried to protect themselves from competition on either. But the result was that this encouraged aggressive post-tensioning firms to develop and submit alternate bids for cast-in-place floors, competing directly with the lift-slab method. This was not easy, however, since conventional stick-formed multistory buildings generally were not competitive with lift-slab buildings.

How did the post-tensioning companies finally beat out the lift-slab contractors?

Atlas Prestressing responded by forming an alliance with the emerging flying form industry. We worked with several concrete forming companies around the country who were developing large-panel flying form systems, and we jointly promoted the use of cast-in-place post-tensioned buildings using flying forms. This allowed us to compete directly with the lift-slab method, where we otherwise could not sell our tendons. It turned out that post-tensioned cast-in-place slabs formed with large-panel flying form systems were highly competitive with lift slab buildings, and by the late 1960s they be-

Above: Banded post-tensioned slab in a below-grade parking structure for a medical office building. Right: Looking down at banded slab construction, this photo illustrates the column reinforcing, the electrical conduit in the slab, and the pour strip between the slab and the wall to mitigate shortening and permit below-grade tendon stressing.

came the preferred method for multistory slab buildings. I firmly believe that if the early lift-slab companies had not been so shortsighted and had encouraged competition and joint promotion from the independent post-tensioning firms, lift-slab construction would be a significant factor in today's medium-rise building market.

What eventually happened to the button-headed tendon system?

It was replaced by tendons using seven-wire prestressing strand and wedge anchors. Atlas introduced the strand system to the American market. Ed Rice, who founded Atlas in 1962, was also the president of T.Y. Lin & Associates. Rice became familiar with strand systems through Lin's involvement as a consultant to precast/prestressed concrete firms. Rice was the first to recognize the advantage of strand systems for building with post-tensioning, and he invented and patented the first anchorage for use in an unbonded strand post-tensioning system. Shortly after founding the company, Rice sold Atlas to Hal Long, who was its president until 1977. Long and Atlas engineer Dick Martter developed and greatly improved the Atlas strand anchorage. The strand system was much more economical than the button-headed tendon system and eliminated all of its major construction drawbacks, like exact length and stressing pockets. After 5 or 6 years of fierce competition with the button-headed tendon firms, Atlas won the battle of the marketplace. By the late 1960s the button-headed tendon was extinct, and virtually all post-tensioned tendons sold in America for building construction were strand tendons.

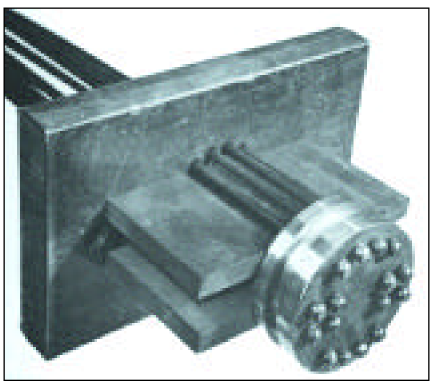
Isn't post-tensioning design difficult and tedious?

Yes, without the benefit of computers, that would be an understatement! Most post-tensioned beams and slabs in building construction are what we structural engineers call "indeterminate"—that is, they have continuous multiple spans and require special techniques for analysis. Prior to 1963, analysis techniques for indeterminate prestressed members were tedious, highly mathematical, and non-intuitive.

T.Y. Lin solved this problem for the design engineer. In 1963, in the *ACI Journal*, he published a revolutionary paper on the analysis of indeterminate prestressed concrete members using a method he called "load balancing." Lin demonstrated how during design the tendons could be thought of as being replaced by the loads they exert on the concrete member. Once this was done, the structure could be designed like any other nonprestressed structure. Using load balancing, post-tensioned structures could be analyzed fully and accurately using any standard structural engineering technique, such as moment distribution. The introduction of the load-balancing method made the design of indeterminate post-tensioned concrete members about as easy for the practicing engineer as the design of nonprestressed members.

So it was a simplified design method that revolutionized the PT industry?

Yes. Post-tensioned concrete construction grew exponentially as a result of this new simplified tool for design. In my opinion, the simplified structural engineering method for design of post-tensioned concrete buildings was the major reason for the explosive growth of post-tensioning in the late 1960s and 1970s. At that time a number of firms made their reputations specializing in PT design and construction. To bring simplified design to the practicing en-



Above: Detail of a button-headed tendon anchoring system, illustrating the stressing end, nongrouted. Right: A very complicated banded slab with irregular column spacing, interior pockets for stressing added tendons, and a confused ironworker.

gineer, Atlas ran seminars that trained thousands.

Didn't building codes address design problems?

No. ACI 318-71 virtually ignored post-tensioning design, mainly addressing determinate pretensioned members. I was appointed to ACI Committee 318 in 1973 largely to help develop code requirements for post-tensioned concrete. ACI 318-77 was much improved, recognizing banded tendon distribution for two-way slabs. ACI codes have continued to improve with respect to post-tensioning design with more PT expertise on ACI committees.

Were there similar advances in construction methods?

Yes, particularly in two-way slab construction. In the old days, tendons in two-way slab systems were laid out with some in the "column strips" and some in the "middle strips," similar to rebar in nonprestressed two-way slabs. Since the tendons in the two perpendicular directions were draped in a curved profile—high at the column lines, low at midspans—and since the tendons were continuous from one end of the slab to the other, the tendons had to be woven just like a basket, starting with the single tendon that was below all other tendons and proceeding to the single tendon that was above all other tendons—what was called the "basket weave" system. Detailers would figure out the tendon sequence for each slab. Each tendon had to be numbered and installed in sequence, and if a mistake was made, the tendon had to be pulled out and re-threaded through the in-place tendons. This, as you can imagine, was a tedious and labor-intensive procedure.

How was two-way slab construction simplified?

The basket weave system of placing tendons was replaced by the banded tendon distribution. The banded tendon distribution was first used in the late 1960s in the famous Watergate apartments in Washington, D.C. In this system, all of the tendons running in one direction are grouped together in a narrow "band" 3 to 4 feet wide over the columns, and the tendons in the perpendicular direction are spaced uniformly. In this way, all band tendons are placed first, and all uniform tendons are placed next. There are only two sequence numbers. This is a blessing for the ironworker, as banding eliminated sequencing and weaving. Design engineers also benefit from the banded tendon distribution. In two-way slabs with irregular and complex column layouts, it makes the visualization of load paths much easier, helping to ensure that all slab loads are transferred to columns. Laboratory tests and hundreds of millions of square feet of successful slab installations have verified the structural functionality of the banded tendon distribution.

How did the post-tensioning industry gain muscle in the construction community?

Improvements in the ACI code helped, but the post-tensioning industry did not have a unified voice until the formation of the Post Tensioning Institute in 1976. With PTI, contractors and engineers now have a single source of information, a forum to discuss problems and solutions specific to this method of concrete construction.

What were the biggest problems you have faced with post-tensioning?

Two come to mind: restraint to shortening and tendon corrosion. We quickly learned that the mechanics of slab shortening are different in post-tensioned slabs than in rebar slabs. We had to learn how to design post-tensioned slabs with levels of cracking no greater than those normally found and accepted in rebar slabs. This was accomplished largely by means of joinery details between the post-tensioned members and the attached walls and columns. But tendon corrosion has been the biggest problem faced by the industry. When the earliest post-tensioned buildings were about 15 years old, corrosion problems started to surface, and we realized that some tendon sheathings and coatings could not adequately resist corrosion in the most aggressive environments, such as where de-icing salts are applied to slab surfaces. Tendon material specifications developed by PTI, starting in the mid-1970s, have largely solved the corrosion problems with improvements in sheathing, coatings, and, in the most aggressive environments, complete encapsulation of the tendons.

What do you see in the future for post-tensioned slab construction?

I see two areas of great potential growth. One is in strengthening existing buildings. The use of externally applied post-tensioned tendons is an extremely effective way of increasing the load-carrying capacity of buildings with all types of framing and materials, even wood, and I anticipate continued growth in this area. The second is in tall buildings, say 20 stories and higher, where historically most framing has been structural steel. Concrete offers substantial cost and performance benefits in these tall buildings, and I think owners will be looking more to concrete in the future. I was involved in the design and construction of a 32-story post-tensioned concrete building in Burbank, Calif. in the late 1980s where the use of concrete saved more than $15 per square foot when compared with structural steel framing. Incidentally, that building was very close to the epicenter of the 1994 Northridge earthquake and survived with no damage. Post-tensioned concrete also offers significant performance benefits in tall buildings, particularly in the areas of fire resistance, sound transmission, and floor stiffness. Post-tensioning the floors and frames of tall concrete buildings will minimize their weight, and combined with the use of high-strength concrete, will make them feasible. ■