POST-TENSIONED CONCRETE IN BUILDINGS PAST AND FUTURE

AN INSIDER'S VIEW

KEN BONDY

It was the fall of 1963. I was 23 years old. I had completed the course work for my Master of Science degree in Civil Engineering at UCLA, and I was almost finished with my thesis. I was barely surviving on my meager teaching assistant salary. All things considered, it was time to…get a job.

I was living at the time in the San Fernando Valley, north of the UCLA campus. I grew up in that part of Los Angeles, and I hoped that my first professional job could be in that area. So out came the Yellow Pages. I sent a brief résumé to all of the structural engineering firms in the Valley, and I got about ten responses. I had interviews at all of those ten firms, and soon had offers from five of them. All of the firms were offering about the same salaries and benefits, so I had little objectively with which to make a decision. But there was something unique and unusually appealing about one of the firms. I felt a good connection with the engineering supervisor who interviewed me. His name was Ray Itaya, and the firm's name was T.Y. Lin & Associates.

Many of the crossroads in our lives are passed without our knowing that they are being passed, without sensing that the path we choose will change everything to follow. Seemingly inconsequential decisions and events make profound changes, and yet often we do not realize their significance at the time. When I accepted the job at T.Y. Lin & Associates in 1963 I did not know that they were the pioneering U.S. firm in a new field, prestressed concrete, that T.Y. himself was, or was about to become, the most respected individual in the history of prestressed concrete in this country, and that the decision to go to work for this firm would change my life forever.

EXCITING TIMES

Those were heady times in the history of post-tensioned concrete. It had been used in building construction for only a few years starting in the mid to late 1950s, primarily in lift-slab buildings and a few parking structures. Prestressed concrete had just appeared, for the first time, in the 1963 edition of the ACI Building Code. I was entering the field at its leading edge. In the 5 decades to follow, my career as a specialist in the design and construction of post-tensioned concrete spanned every major landmark in the field. I didn't know it at the time, but it was the best professional decision I ever made. I am semi-retired now, but my son Dirk carries on the tradition as a specialist in the structural design of post-tensioned concrete buildings, so my decision to join the T.Y. Lin firm has now influenced two generations.

THANKS TO LIFT SLABS!

The U.S. post-tensioning industry owes its existence to lift-slab construction. The first lift-slab buildings were built in this country in the mid 1950s using non-prestressed slabs. Problems were encountered during lifting in these early slabs because of their weight, and large deflections developed after construction due to flexural creep. Post-tensioning was being widely used in European bridges at that time, and the first post-tensioned bridges had been built in the U.S. and were functioning well. Post-tensioning offered a potential solution to the problem of weight and deflection in lifted slabs in buildings. The problem was that all of the existing post-tensioning systems available were in Europe, and most of those systems were heavy bonded multi-strand systems not suitable for slab construction. One of the European systems, however, held some promise for use unbonded in thin slabs. That was the BBRV or "button-headed" tendon system. This system consisted of parallel-lay ¼" diameter high-strength (240 ksi) wires which passed through a steel bearing plate and an externally threaded stressing washer, with "buttons" cold-formed by impact on the ends of the wires. The buttons were anchored against the outside face of the stressing washer, which attached to

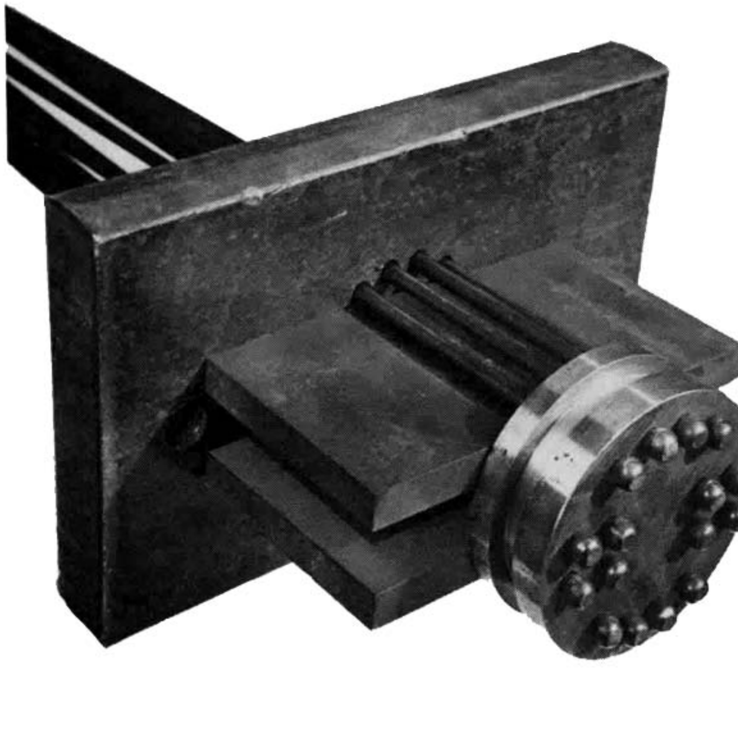

Fig. 1 – Button-Headed (BBRV) Anchorage

a hydraulic ram which elongated the wires and applied the stress. The prestress force was held by steel shims inserted between the stressing washer and the bearing plate. The button-headed anchorage is shown in Fig. 1:

To address the problems of weight and deflection, each of the early lift-slab companies went to Europe and returned with a license to fabricate and use an unbonded BBRV tendon system. Some "independent" companies (not involved in lift-slab construction) also obtained BBRV licenses and began to engage in the general marketing of post-tensioned buildings, those included Prescon, Ryerson, American Stress-Wire, and a few others.

Post-tensioning slabs in lift-slab buildings reduced their weight by about 30%, making lifting easier, and solved the deflection problems. For a short time the lift-slab industry thrived and many quality lift-slab buildings were built. However, while solving some problems, the button-headed tendon system created others. First, since both dead-end and stressing-end anchorages were attached in the factory, button-headed tendons had to be fabricated to a precise length between slab edge forms, with very little tolerance. If the as-delivered tendon length was shorter or longer than the length between edge forms, either the tendon had to be replaced with another one of the correct "exact" length, or the edge forms had to be moved.

Next, button-headed tendons required some type of stressing pocket at their stressing-end to cover the shims and stressing washer which protruded out from the bearing plate. Some contractors used a continuous edge strip to cover the anchorages; others preferred a "saw-tooth" arrangement with a pocket at each anchorage. But in both cases a second concrete pour was required to fill the pockets or the continuous edge strip.

Finally, button-headed tendons required bulky and expensive couplers when intermediate stressing was required. The coupler was usually provided in the form of a large high-strength steel stud, externally threaded, that screwed into an internally threaded hole in the stressing washer. Tendon friction in wire tendons at that time limited stressing lengths to about 80 feet from one end and twice that, or about 160 feet from two ends. Any building longer than 160 feet in either direction therefore required an intermediate construction joint, intermediate tendon stressing, and expensive couplers. Most buildings required such a joint.

THE FIRST STRAND POST-TENSIONING SYSTEM

The first strand post-tensioning system used in the U.S. was developed in the early 1960s by Edward K. Rice, the president of T. Y. Lin & Associates. The T. Y. Lin firm did consulting work for many precast concrete plants, and of course they all used seven-wire strand for prestressing steel, anchored at the bulkheads with various types of wedge anchors. T. Y. Lin & Associates had begun designing buildings with some post-tensioned members, and Ed was keenly aware of the construction problems with the button-headed tendons on those projects. Through his familiarity with the use of strand in precast/prestressed concrete members, he also recognized that the use of a strand system with wedge anchorages would solve all of the problems inherent in the button-headed system. Responsive to all of this Ed designed and patented the first wedge anchorage for use with seven-wire strand in post-tensioned applications. He formed a separate company to market the strand system. That company was called Atlas Prestressing Corp. Ed sold Atlas to Harold D. Long, a young engineer working for T. Y. Lin & Associates at the time, and Hal became its first chief executive. Atlas was based in Van Nuys, California. Through my design work at T. Y. Lin & Associates I became enthralled with post-tensioned concrete as a structural system, and familiar with Atlas as a company. I joined Atlas in 1965, after about three years with T. Y. Lin & Associates.

Atlas, under Hal Long's leadership, introduced the strand post-tensioning system to the U.S. construction market in 1962. Although competition with the button-headed tendon firms was fierce, Atlas met with much success because the strand system eliminated all of the construction problems inherent in the BBRV tendons. The strand system did not require exact length; the strand could be cut a few feet longer than the finished slab length; and the excess strand was simply trimmed off after stressing. The strand anchorages did not require formed stressing pockets or edge strips. A small two-piece round rubber "grommet", positioned between the anchorage and the finished edge form, recessed the anchorage a few inches back inside the slab from the edge. When the grommet was removed after concrete placement, it formed a round hole into which the jack nosepiece was placed when the strand was stressed. A portion of the grommet also filled up the space inside the anchorage, preventing ingress of cement paste from the back of the anchorage during concrete placement. After stressing and cutting off the excess strand just inside the finished face of the concrete, the small hole was simply filled with grout and finished flush with the slab edge. Stressing at intermediate construction joints was easy, the strand was cut to the full length of the slab and an intermediate anchorage was simply slid onto the strand and stressed at the intermediate construction joint using open-throated stressing jacks. The remaining length of tendon was then rolled out into the next pour.

That is not to say that the first strand system was completely problem-free. The first strand-wedge anchorage consisted of a coil of high-strength wire with a tapered shape to receive the wedges. It is shown in Fig. 2:

Fig. 2 – Coil Anchorage

There was no bearing plate used with this anchorage, the small steel plate shown was used only to attach the anchorage to the forms with nails passing through the nail-holes. The prestressing force was transferred to the concrete not by bearing but by the direct tensile resistance of the concrete to the lateral forces generated by the wedges on the inside surface of the coil. This required significant concrete tensile strength in the anchorage zone. Many concrete breakouts occurred when coil anchorages were stressed. These breakouts were particularly prevalent in lightweight concrete, which was widely used in California in the 1960s. It became obvious to Hal Long that the coil anchorage had to be replaced with a bearing type anchorage. Dick Martter, an extremely talented mechanical engineer and one of the first Atlas employees, stepped up to the plate and, with help from Hal, developed the first ductile iron casting. It went into service for the first time in 1965, the year I joined Atlas. The use of ductile iron, a casting material with ductile properties, permitted a bearing plate surface to be combined with the "barrel" ring containing the tapered hole housing the wedges in a single casting piece. The development of the ductile iron casting was a huge event in the history of post-tensioned building construction, and ductile iron castings similar to the original design by Martter continue to be used as the industry standard today.

THE BATTLE BETWEEN STRAND SYSTEMS AND BUTTON-HEADED WIRE SYSTEMS

Contractors quickly recognized the advantages of the strand system, and with a philosophy of good service and dissemination of structural design information to practicing structural engineers, Atlas grew rapidly. However competition from the established button-headed tendon firms was vicious. It was Atlas versus everybody else, and after a fierce five to six-year struggle, Atlas eventually won the battle of the marketplace by the late 1960s, and all of the surviving button-headed tendon firms switched to strand systems. Button-headed tendons became extinct in the U.S. construction industry and virtually all post-tensioning in building construction has been with strand tendons with wedge anchorages since 1970. In a ten-year period from the mid 1960's to the mid 1970s Atlas grew from the smallest to the largest of the U.S. post-tensioning firms with division offices throughout the country and an operation in western Europe based in Amsterdam.

WHAT HAPPENED TO LIFT-SLABS?

The concept of lift-slab buildings was a good one. It eliminated concrete forming, a major component of concrete building cost, and had many other inherent advantages. The cost of the specialized equipment could be amortized over many buildings. However the lift-slab companies, in my opinion, made a fatal marketing mistake which forever affected their penetration into the construction market. They combined the cost of the lifting with the cost of the tendons into one bid price which was provided to the general contractors on each new building project. This meant that independent post-tensioning companies could not bid on lifted projects. The lifting companies would not expose the tendon price, and therefore a tendon bid submitted by an independent post-tensioning company was meaningless because there was nothing with which to compare it. This had short-term advantages for the lifting companies; it allowed them to shield their tendon prices from competition from other tendon firms. But the practice had serious long-term consequences for the lifting industry, and eventually resulted in the downfall of what could have been a major construction industry.

Since independent tendon companies were excluded from bidding on lift-slab projects, our company, Atlas Prestressing Corp. decided to form alliances with the emerging flying form industry and provide a bid to the generals for a completely cast-in-place building. Joint promotion between Atlas, flying form companies, and progressive concrete contractors allowed direct competition with lifted buildings. The use of cast-in-place post-tensioned buildings using large-panel flying form systems was highly competitive with lifted buildings (particularly with their inflated tendon prices), and by the late 1960s cast-in-place buildings became preferred to lifted buildings, and lift-slab construction largely faded into obscurity.

I believe that if the lift-slab companies had encouraged competition from independent tendon companies, instead of trying to exclude them, lift-slab construction, with all its inherent advantages, would be a significant factor in today's medium-rise building market.

LANDMARKS IN POST-TENSIONED BUILDINGS

Looking back over my long career as a specialist in post-tensioned concrete, I would cite the following as the most significant developments affecting the growth and use of post-tensioned concrete in U.S. building construction:

- The introduction of the strand/wedge system to replace the button-headed tendon system
- The development of the ductile iron casting for single-strand unbonded tendons
- The introduction of the "load-balancing" method for the design and analysis of post-tensioned concrete members
- The introduction of the "banded" tendon system for two-way post-tensioned slab systems
- The formation of the Post-Tensioning Institute

The first two landmark events, the introduction of the strand system and the development of the ductile iron casting, have been discussed above. Following is a brief discussion of the others:

LOAD BALANCING

Perhaps the most important single event in the history of post-tensioned concrete building construction was the introduction of a simplified method for the design and analysis of complex, indeterminate post-tensioned concrete members called "load balancing". This was done in a paper written by T. Y. Lin himself, published in 1963 in an ACI Journal paper. It involved mentally removing the tendon from the concrete member, and replacing it with all of the forces that tendon exerts on the concrete. T. Y. didn't invent the load balancing method, but he did more than any other individual to explain it and disseminate information about its use. The concept was brilliant, easy to understand, and greatly reduced the mathematical drudgery involved in other design and analysis methods. It made the design of post-tensioned concrete members as easy for the practicing engineer as the design of non-prestressed concrete members. This design simplicity encouraged structural engineers to select post-tensioned concrete as the preferred framing method.

BANDED TENDONS

Two-way post-tensioned slabs have been a popular type of framing in concrete building construction. When this type of framing started to be commonly used, tendons in two-way slabs were installed in each of two orthogonal directions with some located in the "column strip", an imaginary area centered on the column lines and extending one-quarter of the bay width on either side of the column. The remaining tendons were installed in the "middle strip", the area located between the column strips. Since the tendons were "draped" in a curved vertical profile (generally parabolic), high at the column lines and low at midspans, each individual tendon would typically have some perpendicular tendons above it, and some below it, as shown in Fig. 3. This tendon arrangement was generically known as a "basket-weave" system.

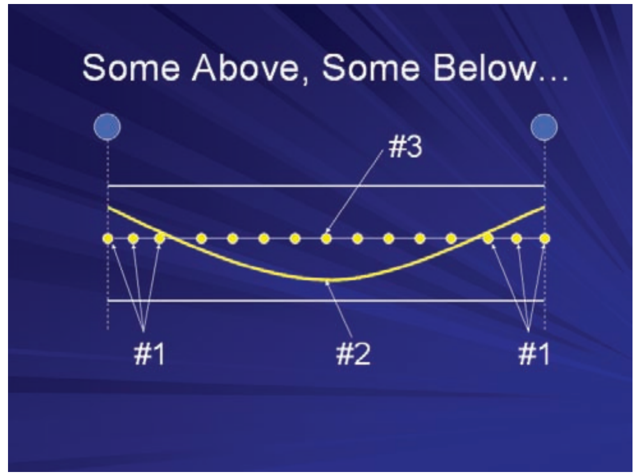

Fig. 3 – Basket-Weave Tendon Profiles

In order to install such a system of woven tendons, the tendon detailer had to locate and identify the single tendon which was below all other perpendicular tendons. That tendon, or group of tendons, was identified on the placing drawings as tendon sequence #1. Next the detailer found the tendon in the other direction which was below all other perpendicular tendons, with the exception, of course, of tendon sequence #1. That tendon, or group of tendons, was identified as tendon sequence #2. All tendons in the slab were identified in this manner with a sequence number. Each tendon had to be installed with the precise sequence number, or a bird's nest of tendons would result and the tendons could not be chaired at the proper heights. Often slabs would have 30 to 40 sequence numbers. An example of a sequenced "basket-weave" two way slab (in this case a foundation mat) is shown in Fig. 4:

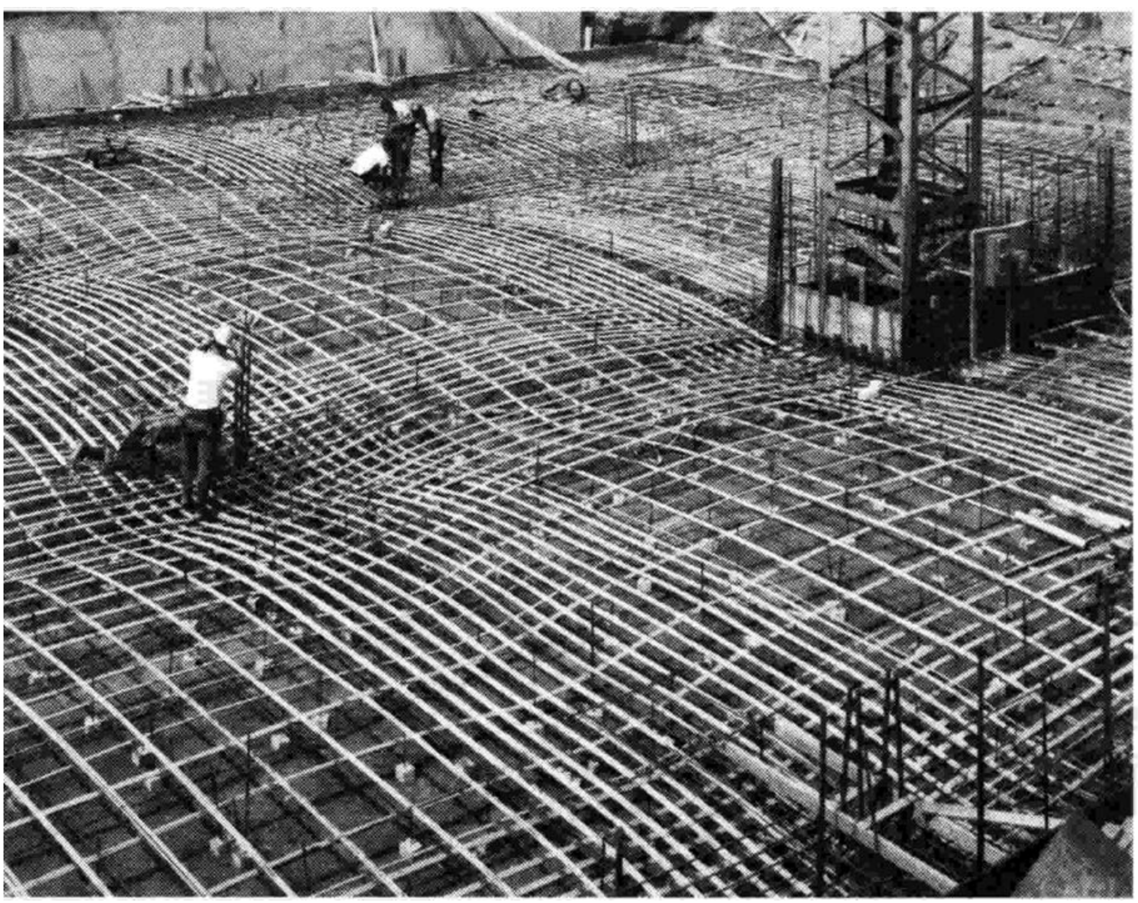

Fig. 4 -- Two-Way Foundation Mat with Basket-Weave System

Fig. 5 – The Watergate

In 1968 the most famous post-tensioned building in history was built. Its primary fame was not because it was post-tensioned, but because of what eventually happened in it. It was the Watergate Apartments in Washington, D. C. Yes, the very same one you are thinking of. Watergate is also famous for another reason, it was the first building ever built using a two-way post-tensioned slab with a new and innovative tendon distribution which came to be known as the "banded" tendon distribution.

In the architectural design of the Watergate building, the floor plan was curved and columns were located randomly in areas which substantially hid them, including walls, duct spaces, closets, etc. The resulting column layout did not line up in either direction. No column was spaced any farther than about 22 feet from any other column; however the concepts of gridlines, column strips, and middle strips were meaningless. The structural designers of the slabs (a joint effort of T. Y. Lin & Associates and Atlas Prestressing Corp.) were perplexed because, using conventional two-way slab techniques, there was no obvious path for slab loads to columns. Someone in the team suggested connecting columns in one axis of the building with imaginary straight lines between individual columns, and thinking of those lines as a series of beams, or hard points. A "band" of tendons could be run along that line connecting columns in one direction, then in the other direction tendons could be spaced uniformly over bands. With this concept, the load path became obvious, and the forces and profiles for both the band tendons and the uniform tendons could be easily calculated.

This tendon layout, with all of the post-tensioning tendons in one direction located in a narrow band over columns, and tendons distributed uniformly with no regard for imaginary column strips and middle strips, had never been done before. However the Watergate design team saw no alternative and the design and construction proceeded with the unique tendon layout. The performance of the slabs appeared to be good, and the tendon installer reported a significant savings in tendon placing costs when compared to the conventional "basket-weave" system. The primary labor savings resulted from the elimination of tendon sequencing. In this new banded layout, all of the band tendons were placed first, then all of the uniform tendons. Ironworkers did not have to place individual series of tendons, alternating in each direction, according to a complex sequence.

Fig. 6 – Typical Banded Tendon Layout

Since the Watergate Apartment building, built almost forty years ago, the banded tendon layout has become the standard method for placing tendons in two-way post-tensioned slabs. The adequacy of the banded tendon layout has been confirmed by the functional performance of hundreds of millions of square feet in service, and numerous laboratory tests, starting with a landmark testing program at the University of Texas at Austin in the early 1970s, supervised by the legendary professor and researcher Dr. Ned H. Burns.

Fig. 7 – Four-Panel Test at the University of Texas at Austin

FORMATION OF THE POST-TENSIONING INSTITUTE

Engineers, contractors, and material fabricators in the post-tensioning industry recognized early that they needed an industry organization to represent their interests and to disseminate design and construction information relative to this specialized field. From the late 1960s through the mid 1970s the post-tensioning industry was represented as a group within the Prestressed Concrete Institute (PCI), now the Precast/Prestressed Concrete Institute. However as the industry grew, it became apparent that a separate organization, dedicated solely to post-tensioned concrete design and construction, was needed.

Pursuant to this, the Post-Tensioning Institute (PTI) was formed as an independent organization in 1976. Now thirty years old, PTI provides all those with an interest in post-tensioned concrete a single unified voice and source of design and construction information. Since its founding PTI has been guided by three extremely talented Executive Directors, Cliff Freyermuth, Gerry McGuire, and its current Executive Director, Ted Neff.

PTI has matured and grown as the industry has grown. PTI now publishes a Journal with informative articles about post-tensioning design and construction issues, and holds well-attended annual Engineering Conferences. In many cases PTI documents and committee reports establish the standard of care for design and construction of post-tensioned concrete structures. PTI is now recognized internationally as the premiere source of information about post-tensioned structures worldwide.

PROBLEMS

Restraint to concrete volume change (shortening) was the first big pervasive problem faced by the industry. The mechanics of volume change, and the restraint to that volume change, is different in post-tensioned concrete members than in non-prestressed members. In non-prestressed concrete beams and slabs restraint to shortening provided by connected elements (walls and columns) results in many closely and uniformly spaced cracks throughout the length of the member. The ends of a non-prestressed member tend to stay in their original positions, and the total shortening is simply the sum of the crack widths along its length. Because of this, shears and moments induced into restraining connected elements are relatively small.

In post-tensioned concrete members, however, the effect of the axial prestress force tends to close most of the restraint-to-shortening cracks which would otherwise form between the ends of the member. Unlike non-prestressed members, the total volume change along the length of the post-tensioned concrete member is reflected in significant movement inwards at the ends. This induces large shears and moments into the connected walls and columns. These shears and moments can result in large and unsightly cracks in the post-tensioned member, and in the walls and columns themselves.

Engineers had to learn how to design post-tensioned concrete floor systems with levels of cracking normally accepted in non-prestressed floor systems. This was accomplished over the years largely with the use of joinery details (slip joints and pour strips) and the use of properly located and sized non-prestressed reinforcement. Mitigation of restraint-to-shortening effects in the design of post-tensioned buildings has become as large a part of the design process as the selection of the forces and profiles themselves.

But without doubt the biggest problem ever faced by the industry was tendon corrosion. The early unbonded tendon sheathings and coatings (grease) were inadequate for aggressive environments, such as those where de-icing salts are applied to exposed concrete surfaces. Serious corrosion problems began to be apparent in such buildings within about 10 years of service. Most were repairable, and several companies thrived by specializing in corrosion-related repairs.

Improved material specifications developed and enforced by PTI through certification and informational programs have largely solved these corrosion problems. These include improvements in the quality and performance of sheathing material, coatings, and the development of a complete tendon encapsulation system for use in the most severe environments.

THE FUTURE

Aside from a normal increase in growth and penetration into existing markets I see two significant areas of future potential growth in the use of post-tensioning, strengthening of existing buildings with externally applied post-tensioned tendons, and tall buildings.

The use of externally applied post-tensioning tendons (EPT) to strengthen and repair existing buildings is extremely effective. This technique has been used in the past to strengthen all types of members and all types of materials, wood, structural steel, and concrete, both prestressed and non-prestressed. In some cases the use of EPT has made the difference between saving or demolishing an existing building.

In most cases, the use of EPT in an existing building involves the construction of a "king-post" truss under or alongside an existing member. Holes are drilled through existing members, beams, columns or walls, and the tendons are anchored against the outboard surfaces of these members. The basic details of this truss system are shown in Fig. 8.

The king-post, or "saddle", is normally a vertical structural steel tube located in the most beneficial position on the member strengthened. The lower (tension) chord of the truss is the stressed tendon. The upper (compression) chord is the existing structure itself. The tendons pass under the tube and when they are stressed they exert a large, beneficial upward force on the member at the desired location. The use of high-strength prestressing steel for the tension chord allows the application of large beneficial forces on the structure with minimum structural depth. The forces applied to the strengthened member are shown in Figure 9:

With increased awareness of the restoration of existing buildings the use of EPT should increase substantially in future years. A finished EPT application for a two-way non-prestressed slab, where the upward load is applied in the center of the bay, is shown below. In this case fireproofing is provided by plaster applied over self-furring metal lath on the tendons and the kingpost (Fig. 10).

Perhaps the largest potential future growth for post-tensioned concrete is in the area of tall buildings, buildings taller than about 20 stories. Decision makers in building construction are beginning to realize the advantages of post-tensioned concrete framing in tall buildings. The use of post-tensioned concrete in the floor systems of these buildings reduces their weight by up to 30%, and the use of high-strength concrete in the columns of tall concrete buildings makes their sizes reasonable. Other advantages include:

- COST
  - o Existing tall post-tensioned concrete buildings have demonstrated dramatic cost savings when compared with all other types of structural framing.
  - o A major factor in the cost savings is the fact that the exterior concrete frame beams and columns can be exposed and used as a part of the architectural façade of the building. This can save up to 25% of the cost of the exterior "curtain wall" façade.
- SOUND AND VIBRATION
  - o The inherent stiffness of concrete buildings offers advantages for the comfort of its occupants.

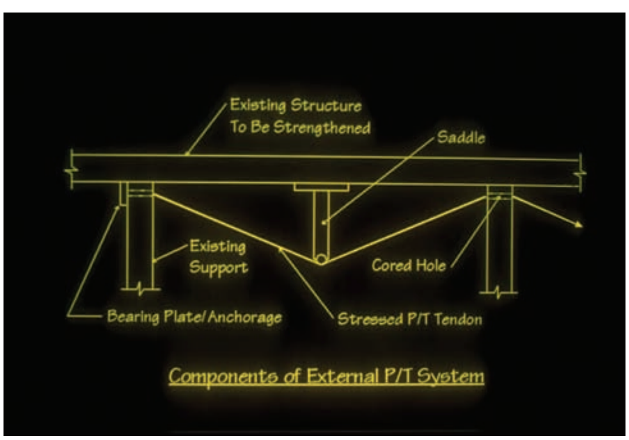

Fig. 8 – Strengthening with External Post-Tensioning (EPT)

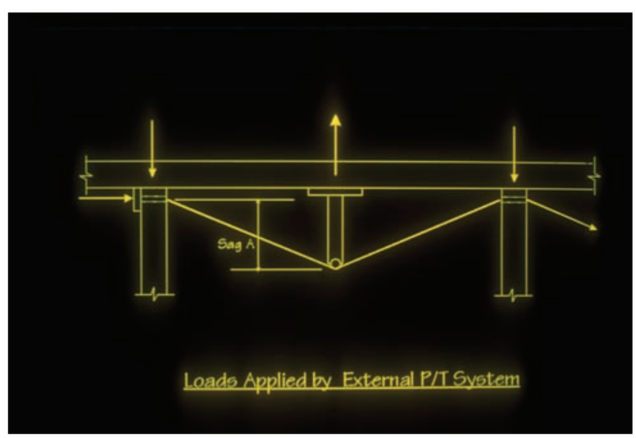

Fig. 9 – EPT Loads

Fig. 10 – Two-Way Slab with Upward Load Applied at Mid-Panel

- FIRE AND BLAST RESISTANCE
  - o Exposing the exterior beams and columns eliminates the “gap” between floors of structural steel buildings which can and has permitted the transmission of fire vertically from floor to floor.
  - o Fire resistance in concrete beams and columns is provided by the concrete itself rather than less durable spray-on fireproofing systems.
  - o The redundancy and structural continuity of cast-in-place buildings offers significant advantages in resisting catastrophic loadings.

The building in Fig. 11 is a 32-story post-tensioned concrete building built in Burbank, California in the late 1980s. At the time of construction, it was the tallest concrete building ever built in the highest seismic zone (UBC Zone 4). I was involved in the design and construction of this building. Initial construction cost showed a dramatic savings of over $15/square foot when compared to structural steel. Only a few miles from the epicenter, it performed very well in the 1994 Northridge earthquake.

Fig. 11 -- 3900 Alameda, Burbank, California

SUMMARY

My career in post-tensioned concrete has been rewarding in every way. It was technically challenging, always exciting, and it brought me into contact with some of the most interesting and talented people in the construction industry. I never tired of working in the field of post-tensioned concrete. Every day was fun. Some days were more frustrating than others, but it was always fun. Now, in PTI's 30th anniversary year, I have tried to look both backward and forward on this dynamic industry, and present a brief history of the industry as I saw it, and what may lie in the future. For me, it was a great ride.

*Post-Tensioning Legend **Ken Bondy** has been intimately involved with the post-tensioning industry in North America from its infancy in the early 1960's. Ken has regularly taught senior undergraduate course in prestressed concrete design at University of California. He has authored a number of papers in the area of post-tensioned concrete; he has also presented at numerous conferences and spoken at seminars around the country. Ken has been involved with the ACI Standard Building Code Committee since the early seventies and has been influential in rewriting and updating all of the building code provisions dealing with prestressed concrete.*

Mr. Bondy has been a charter officer and director of the Post-Tensioning Institute since its inception in 1976. He is a Fellow of ACI and a lifetime member of the Post-Tensioning Institute. Ken was recognized by the Post-Tensioning Institute as a "Legend of Post-Tensioning" in 2005.

Ken is highly regarded and respected by his peers in the industry. From his long association with post-tensioning, Ken has a developed unique perspective of the development of the post-tensioned industry in North America. This article provides a summary of the major landmarks that have led to the success of the post-tensioned building industry in North America.