Breathing New Life into a Post-Tensioned Parking Structure

By David A. VanOcker, PE

Repairing a distressed 35-year-old, post-tensioned parking structure is a challenging proposition. Unbonded post-tension (P/T) reinforcing systems add a level of complexity to any repair program, especially when encountering an early vintage P/T system that is generally incompatible with current post-tension system hardware and technology. This project encompassed a 5-year effort to diagnose, assess, and implement a phased restoration program that replaced approximately 1/4 of the tendon anchors in the this vital transportation facility for a major university, giving the owner another 20 to 25 years of extended operational service life.

The parking garage is a five-story, open parking structure that was built in the mid 1960s (refer to Fig. 1). The garage's split-level deck configuration employs one-way slab and beam construction with unbonded P/T reinforcing to accommodate 425 cars (Fig. 2). Expansion joint (EJ) separations completely isolate the P/T decks from the conventionally reinforced end ramps.

Need for Repair

In the summer of 1996, during a waterproofing and EJ seal replacement project, it was discovered that the P/T slab anchorages were failing. The anchorages occur in the short cantilevered slab regions abutting the expansion joint separations. Prolonged exposure to moisture from leaking EJ seals had lead to advanced levels of corrosion and partial failures of the button-headed tendon anchors.

Fig 1: Exterior view of garage looking northwest

The first significant task was to rationally and accurately assess the structural integrity of the P/T reinforcing system, given that the anchors were concealed within visibly deteriorated concrete. Unbonded P/T tendons are under considerable tensile loads maintained by the end anchorages. Significant compressive stress is exerted on the concrete in the anchorage zones, thus these regions are very sensitive to any deterioration, given the propensity of the system to exhibit rather dramatic and dangerous behavior when a tendon experiences a sudden release of energy. Deteriorating P/T reinforcing systems exhibit failures in various ways, ranging from ruptured tendons protruding from the slabs at high or low points, to crushed concrete at anchor pockets, to anchor hardware being rapidly projected out of the concrete. Partial tendon failures occur, with individual wires breaking within a seven-wire strand, producing no outward signs that a failure has occurred.

Early vintage P/T systems employed paper wrapping of greased wire strand, intended to prevent bond to the concrete and permit elongation during tendon stressing. The paper and grease were not intended to protect the bare steel cables from moisture and chlorides. Structurally, when an unbonded tendon fails, the resulting loss in load-carrying capacity extends the full length of the tendon, in this case, over a distance of almost 200 ft (61 m), or seven slab bays. The load-carrying capacity of a structural element can be severely reduced when unbonded P/T tendons fail.

Preliminary probes done on the roof level during the 1996 EJ seal replacement work revealed an extensive amount of corrosion in the P/T anchors. While only a single noticeable tendon anchor rupture had occurred, individual wires were found to have failed in many instances, as evidenced by a differential shortening of certain wires (Fig. 3). The initial visual examinations of tendon anchors were not completely conclusive, given that many of the wires couldn't be directly inspected. The initial assessment relied heavily on judging the visible concrete deterioration in the anchor regions on a comparative basis, using what was observed at the roof level, and extrapolating this information to visible concrete conditions on lower floor levels. While this method potentially had a wide margin of error, sufficient concerns over the structural integrity of the P/T deck slabs were warranted.

Evaluation Program

A comprehensive evaluation program began in the fall of 1996 with extensive surveys, material sampling and probing, destructive and non-destructive field and laboratory testing, along with engineering analysis. Surveys consisted of chain-dragging to detect delaminations. Careful visual examination concentrated on locations of tendon high and low points, but initial results failed to detect many outward visible signs of tendon distress or failures in slab regions beyond the cantilevered ends. Subsequent probing was performed to access tendons at random locations along the overall span lengths in an effort to inspect the paper wrapping, and wires. Samples of concrete and tendon reinforcing were removed for laboratory analysis.

Record files of the original structural design drawings were reviewed; however, the P/T shop fabrication and installation drawings could not be located. Pachometer surveys, combined with further localized probing, provided a rational basis for subsequent engineering analysis of the original design. The garage had been designed in accordance with the 1963 edition of ACI 318 Code. We also analyzed the structure based on provisions of the 1995 edition of the Code. Additional references included ACI Committee Report 423.3R-96, "Recommendations for Concrete Members Prestressed with Unbonded Tendons," and the Post-Tensioning Institute's "Design of Post-Tensioned Slabs Using Unbonded Tendons." A newer reference has been published by ACI Committee 423, "Corrosion and Repair of Unbonded Single Strand Tendons (ACI 423.4R-98)"; however, this reference was unavailable in 1996. The evaluation sought to understand the condition of the garage and rationally establish the remaining structural capacity. It further sought to assess the feasibility of successfully performing repairs. Many unsuccessful attempts to repair deteriorated P/T systems have been documented (Nehil, T.E. 1991 and 1992, "Rehabilitating Parking Structures With Corrosion Damaged Button-Headed Post-Tensioning Tendons," Parts I & II, *Concrete International*, V. 13, No. 10, Oct. and V. 14, No. 3, Mar.).

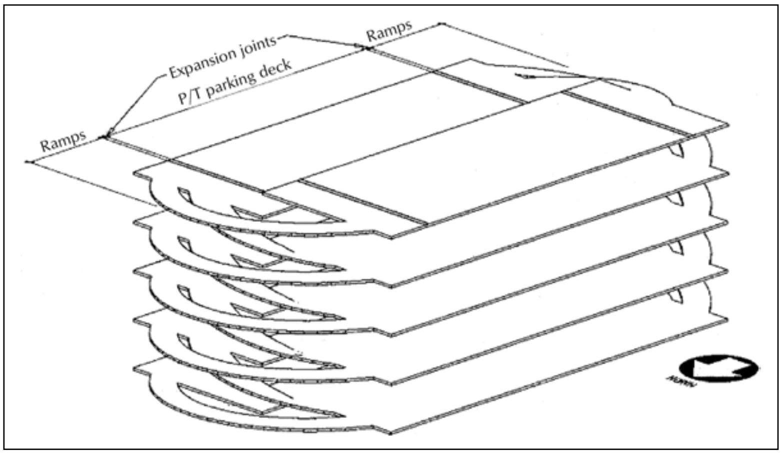

Fig. 2: Isometric of garage structure

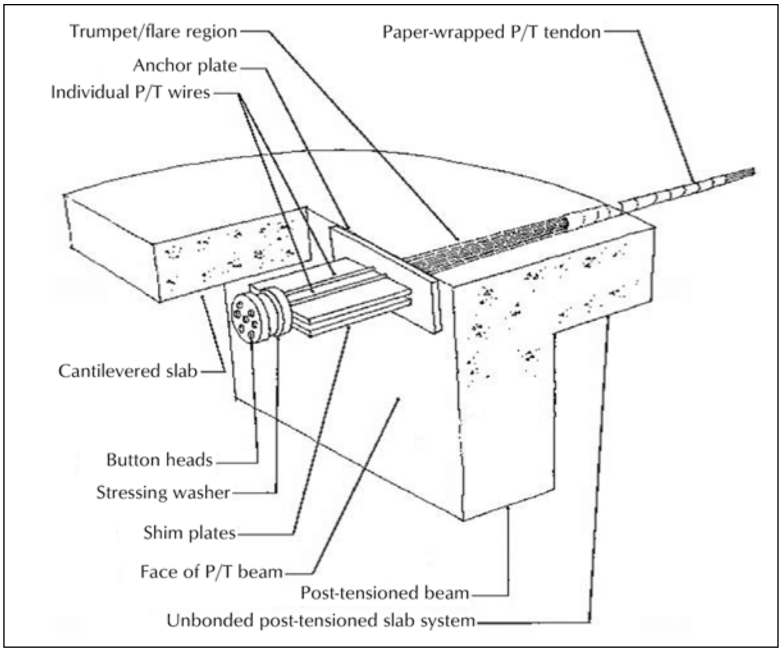

Fig. 3: Isometric of button-headed tendon anchorage

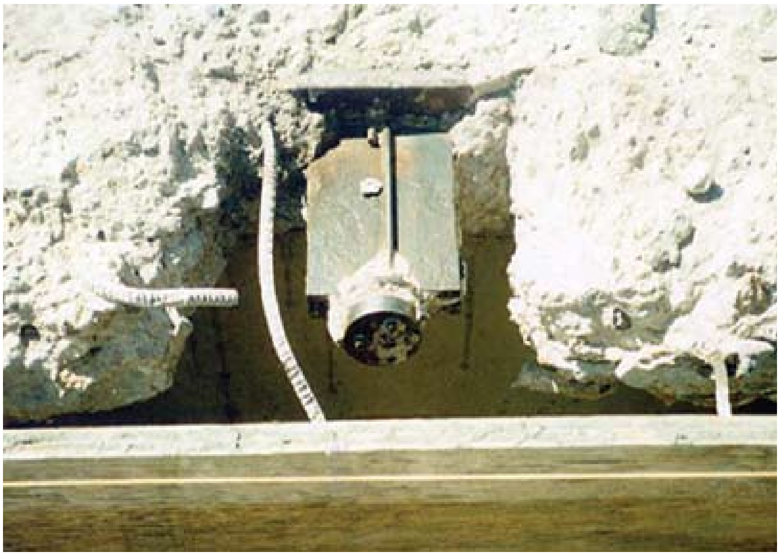

Fig. 4: View of exposed button-headed tendon anchor. Note failed wire on top side of spacer/shim plates

Test results indicated that the concrete was very durable in all of the slab regions except the cantilevered EJ ends. Compressive strengths averaged 5500 psi (38 MPa); chloride contents in the main parking deck regions were low (between 0.05 to 0.08 lb/yd^3 [0.03 to 0.05 kg/m^3], compared to recognized corrosion threshold levels of 1.0 to 2.0 lb/yd^3 [0.6 to 1.2 kg/m^3]). While air contents were lower than desirable (~2-1/2% versus standard of 6%), no freezing-and-thawing damage was present in any slab areas. Tests on steel P/T tendons established the grade and confirmed that the cables were 240 ksi (1.650 MPa) ultimate tensile strength.

Surveys generally established that a relatively small amount of concrete deterioration (delamination, spalling) occurred in the main deck slab spans, rather than in the immediate area of the expansion joints. Corrosion of mild steel reinforcing due to insufficient cover was confirmed to be the cause of these isolated areas of deterioration. Exploratory probing further confirmed that deterioration had not progressed lower in these regions to the level of the underlying P/T tendons. The main regions of repair would focus on the concrete encasing the tendon anchors along the expansion joints. This is the most vulnerable region for an unbonded P/T system, where the bare tendon wire and anchorage hardware have essentially no protection from moisture other than the concrete itself.

Complexities of Evaluating P/T Tendon Anchors

The visual inspection of a button-headed anchor assembly by itself is inconclusive, since you can only see the outer surfaces of approximately half the wires. More importantly, this level of inspection is possible only after careful removal of concrete to expose the anchors, an operation that can be rather dangerous, even when no deterioration is present. During the evaluation, a complete anchor assembly was removed and disassembled, revealing that corrosion was occurring on the wires between the shim/spacer plates, surfaces that could not be physically inspected. High-strength wire used to manufacture P/T tendons is subject to localized pitting, thus significant amounts of cross-sectional loss can occur in a very small region and beneath the surface of the wire.

Attempts to correlate visible concrete deterioration with corrosion damage to embedded tendon anchors is a very inaccurate way to diagnose the potential damage within a P/T system. Despite the above uncertainties, complexities, and reservations, a preliminary guesstimate was developed as to the number of failed (and intact, remaining) tendons on each floor level and preliminarily reached a general conclusion that the structural integrity of the parking level decks was sufficient to continue operational use.

At this stage considerable unknowns remained, so a comparative study looked at options of repair versus replacement of the garage. Major considerations included the risks and predictability of repairing the P/T system. The repair program was estimated to cost in excess of $1.0 million and take 3 to 4 years, performing work only in summer months. Replacing the facility was estimated to be approximately $6.0 million and would take 2 years to perform. Other significant considerations included the life expectancy of the repaired P/T system and the risk of unexpected cost increases once a repair program was committed to. A high degree of confidence was placed in the fact that P/T deterioration was localized at the end regions and that once anchors were replaced, enhancements to protect the vulnerable anchor regions could provide as much as a 20-year service life. The garage was a good candidate for repair. The client agreed to proceed with the repair program.

Engineering Analysis

The original design of the P/T slab system proved to be conservative, employing more mild steel reinforcing than necessary by code. Combining this with an analysis based on current code criteria, we provided a baseline of increased load-carrying capacity—and safety factor—then determined capacity reductions in certain slab regions to account for tendon failures. It was important to establish reliable load capacities across the deck slabs, not only to confirm the decision to permit continued usage, but to establish shoring criteria for the implementation of repairs.

Tendon deterioration had been found to be most widespread at the roof (5th floor) level and 4th floor level, tapering off on lower floor levels. Feasible repair sequences were analyzed in consideration of the need to perform repairs only during summer months and to maintain parking as much as possible during these periods. From a shoring perspective, the preferred approach was to commence repairs on the lower floors and proceed upward. This would provide additional assurance by placing shoring loads only on deck levels that had been repaired and that had their load capacity fully restored. This was in conflict, however, with the desire to repair the most extensively damaged floors first; the floors where the greatest reduction in load-carrying capacity existed.

The final order of repair performance addressed the 4th level first, followed by the 5th level, then Levels 3 and 2. A critical factor was to balance the sequencing of tendon replacement—the number of

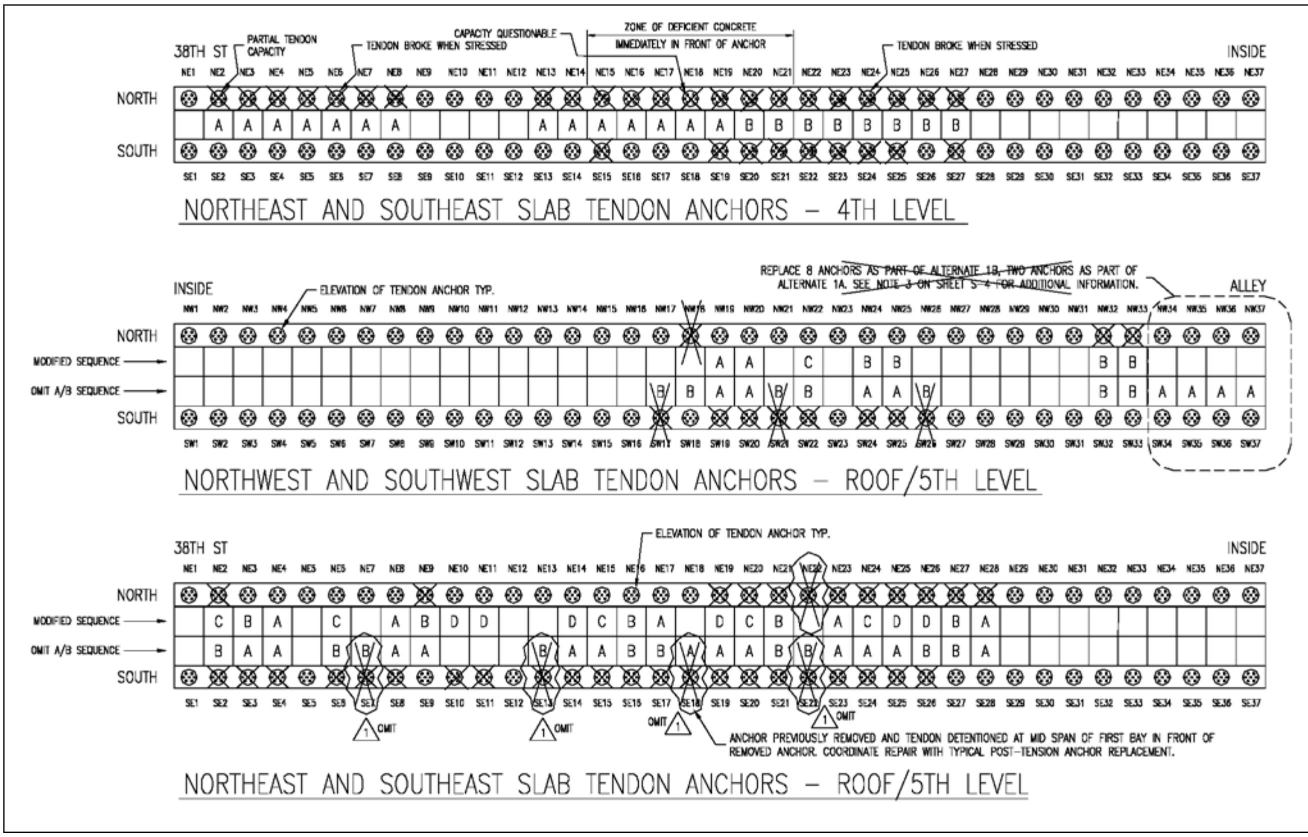

Fig. 5: Typical tendon sequencing diagram. Note that 4th floor had fewer sequences, but higher number of tendons per sequence; 5th floor sequence was modified after anchor inspection

tendons that could be cut, spliced, and restressed in a single stage—within the compressed summer schedule. The more conservative approach that minimized shoring loads required a 24-week schedule for the 4th floor work. The summer schedule dictated an aggressive 12- to 14-week construction period, thus we developed shoring and criteria and tendon replacement sequences to minimize the number of cycles.

Bid documents established an exact number and location of tendons to be replaced along with a recommended sequence (Fig. 5). Repairs began with careful removal of the concrete encasing the anchors. Physical inspection of the button-headed tendon anchors then confirmed the final number and sequence of replacement. Shoring was installed at the same time that anchor inspection was occurring, to permit the initial round of anchor replacement to occur within 2 weeks of starting on-site work. A 5- to 7-day cycle was established for each sequence, beginning with tendon cutting, then completion of concrete excavation inboard of the EJ line, where splicing and stressing would occur. Concrete placement occurred in two stages, with the initial placement encasing the new anchors. Fast-setting mixtures were used so that the tendons could be restressed in 2 to 3 days.

While stressing typically took less than a day, a 24-hour waiting period was required to perform a final lift-off test prior to filling in the stressing pockets. The extra day for lift-off testing was continually questioned, but it was observed that shortening of the paper-wrapped tendons had continued in some cases even 12 hours after initial cutting. While a construction joint occurred in the center of the deck, it had not been used as an intermediate stressing point, thus the original P/T system employed continuous tendons that were stressed from both ends. Many tendons required anchor replacement only at one end, so restressing could occur from two ends only where both ends were replaced. Even in these instances where both anchors were replaced, the contractor decided to restress from one end only. Everyone agreed to stay with the extra day added to each cycle for lift-off testing, rather than risk a tendon failure during restressing.

The first major summer phase proved to be a great success, accomplishing replacement of 1/3 of the 4th floor tendon anchors (48 anchors) in 14 weeks. Sequences involved as many as eight adjacent anchors per sequence, in an average 5- to 7-day cycle. No tendon failures occurred during restressing, even though the tendons were restressed to full load capacity. The confidence level improved significantly that the P/T system in the balance of the garage could be successfully repaired.

Fig. 6: Typical splice arrangement between single button-headed tendon and two monostrand tendons. Photo depicts arrangement at non-stressing end

Fig. 7: Tendon splice arrangement with multiple adjacent tendons. Note splice transition block between single B/H tendon and two monostrand tendons, as well as dogbone stressing anchors

More Technical Complexities

Replacing the button-headed tendon anchors required marrying modern P/T technology with 1960's technology. Button-headed cables employ the same 7-wire twisted arrangement as monostrand cables, but button-headed cable wires are larger than the wire used for the commercially available 1/2 in. (1.3 cm) ϕ and 5/8 in. (1.6 cm) ϕ sheathed tendons. Despite the higher strength of monostrand cables (270 ksi [1860 MPa]), a difference in capacity still results, unless two monostrand tendons are spliced to a single button-headed tendon. Through design phase consultation with some of the specialty repair contractors qualified to perform P/T work, it was decided to develop bid specifications with the option of replacing the button-headed anchors in kind, or to use 2-1/2 in. (1.3 cm) ϕ monostrand tendons for each button-headed tendon splice.

The technology used by the successful contractor involved a unique splice block that employed wedges to anchor the button-headed tendon wires individually, while also accommodating two single strand anchors with standard wedges (Fig. 6 and 7). This arrangement proved very successful, despite the number of small wedges that needed to be set very carefully. In only one case did tendon slippage occur during restressing, requiring excavation, disassembly, and resetting of the splice assembly.

When the garage was built, the stressing of the P/T decks occurred prior to construction of the ramps, thus now that the ramps were in place, no access was available for stressing rams (jacks). Removal of concrete along the adjacent ramp girder was not an option. The solution was to remove additional concrete inboard of the anchor locations to serve as stressing pockets. Anchor replacement involved installing new monostrand anchors first, in line with the remaining adjacent button-headed anchors. A consideration in positioning the stressing pocket within the first slab span was to locate it so the new stressing hardware was in the middle to lower third of the slab thickness, for increased protection from moisture ingress.

Concrete strength gain is critical to timing restressing operations. Sequences for anchor replacement involved splicing as many as eight adjacent anchors simultaneously to as few as a single anchor. The contractors relied on batch mix concrete for larger placements and site mixed concrete in other instances. In each case, the desire was to achieve 3500 psi (24 MPa) compressive strength in 2 to 3 days, to maintain the overall cycle. Unfortunately, in one instance, an anchor burst while stressing was occurring. This required controlled removal of concrete and detensioning, followed by replacement, but the event did not effect the schedule. An important lesson was realized that even with proprietary, premixed, high strength materials, the rate of strength gain can easily be impacted if not mixed carefully.

A common unknown when performing P/T repairs is that tendons can have corrosion-related damage at several points along their length. This occurs as tendons are exposed to moisture that penetrates the slabs and, in turn, the tendon sheathing, then travels to low points along the tendon drape profiles, where it causes concentrated corrosion to occur. Tendons commonly have multiple low points along their lengths, thus a splice repair at the point of failure might only reveal another weakened point when restressing occurs. This can lead to the costly circumstance of performing several consecutive splice repairs to a single tendon. Fortunately, this was a rare occurrence in this garage repair program.

Cost estimating and scheduling are always significant challenges when establishing a repair program budget for a deteriorating P/T structure. The number of failed tendons is difficult to predict accurately and contingencies are needed for the inevitable additional anchor replacements that are discovered during construction. What is reasonable contingency though? We had met with three specialty P/T repair contractors during the evaluation and preconstruction planning stages to get their input on project complexities and factors that drive costs. Suggested unit prices for anchor replacement varied by a factor of two or more, from $2,500 to $5,000 per tendon.

Previously-published references of as low as $1,000 per tendon (reference *Concrete International* articles cited earlier in article) seemed optimistically low by comparison sake. In actuality, final unit costs experienced by the contractors during the various phases or repairs did vary by this extent due to shoring complexities where large numbers of adjacent tendons needed to be replaced. Lower unit costs were achieved in the last phase, where two floor levels were repaired simultaneously, since the number of sequences remained the same, but replacements were more spread out over the deck levels. The short summer schedules added cost premiums, given the small margins for error in the replacement cycles.

Successful Repair

Lot 14 was at a crucial point on the life-cycle deterioration curve, where if tendon degradation had been permitted to continue, substantial loss of slab capacity and integrity would have occurred in 5 to 10 years, requiring shoring to remain safe and operational. The expense differential between repair and replacement would have narrowed considerably, perhaps eliminating the feasibility of repair.

Key factors in the successful restoration of this vital transportation asset were realizing the magnitude of the problem before it was too late, the high quality and extra integrity that went into the original garage design and construction, and the ICRI contractor groups who contributed their specialty P/T repair expertise and creativity enabling the implementation of the repairs. A recent inspection performed almost 4 years after completion of repairs reveals excellent performance of the P/T replacements, along with the protective seals and coatings.

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University of Pennsylvania Parking Structure

Owner
University of Pennsylvania
Philadelphia, Pennsylvania

Project Engineer/Manager
CVM Facilities Renewal

Repair Contractors
Quinn Construction
Newport Contractors
Masonry Preservation Group
VStructural (P/T)