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STRESSING THE QUALITY OF UNBONDED POST-TENSIONED SINGLE-STRAND SYSTEM INSTALLATIONS

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INTRODUCTION

Since the introduction of post-tensioned (PT) systems to the United States in the 1950s and the first viable systems for commercial building floor framing in the 1960s, the system components, code requirements, and installation practices have evolved considerably. The use of PT reinforcing systems in concrete construction has continued to grow since the 1960s and is now one of the most common and economical systems used for multi-story buildings and parking structures. However, the most significant problem still facing the industry is the protection to limit corrosion of the ferrous metal PT system components.

For ferrous metals to corrode, oxygen and moisture are typically all that is required. Chlorides and other deleterious chemicals, although not essential, will accelerate the electrochemical corrosion process. The annular spaces between the seven-wire strand and the split-tube, push-through, and heat-sealed sheathing systems used in the 1960s through the 1980s allowed moisture that penetrated the sheathing to collect and become trapped with oxygen at the level of the strand, leading to conditions favorable for the onset of corrosion.

Indications of corrosion problems in unbonded PT systems used in commercial building and parking deck construction first surfaced in North America in the late 1970s and early 1980s. The age of the affected buildings and parking structures typically ranged from 15 to 25 years. According to the ACI 423.4R (1998), post-tensioned structures designed and built prior to the adoption of the 1989 edition of ACI 318, "Building Code Requirements for Reinforced Concrete," are more prone to corrosion of the PT system. As awareness of these problems grew, the following were identified as contributing factors to the corrosion of these systems:

- Poor storage and installation practices allowing either direct moisture entry or damage to sheathing that would allow moisture entry
- Unprotected strand at stressing or live anchorages
  - Ungrouted or poorly grouted stressing pockets
  - Grout shrinkage
  - Strand tails with deficient grout cover
- Unsheathed strand inboard of stressing pockets and at intermediate stressing anchors
- Cracks in concrete exposed to moisture (balconies, plazas, parking decks, and so on)
- Unsealed or deficient construction at expansion joints

In addition to moisture ingress, material problems with the grouts used to fill the stressing pockets were also identified on some projects. These included the use of nondurable grouts and unsuitable grout additives, such as chloride-laden fine aggregate or beach sand. In later years, corrosion problems with anchorages in direct contact with soil were also reported. Widespread use of unbonded single-strand PT in slab-on-ground construction, combined with poor protection of the stressing anchorages from moisture ingress, resulted in numerous strand failures.

Many preventative measures have been taken by the industry since the 1960s in an attempt to protect PT systems and improve the performance criteria for sheathing, PT coating, and anchorage materials. PTI plant, installer, and inspector certification programs have continued to stress the importance of quality control in the fabrication of PT system components and field placement of these systems. PTI and ACI publications provide further guidelines regarding the system selection, placement, and stressing. In 2002, the industry elected to require the use of encapsulated PT systems for corrosive environments.

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In December 2011, Addendum No. 3 to PTI M10.2-00 specified that tendons in all applications governed by ACI 318 shall be encapsulated—not just those in corrosive environments. No significant changes to the ACI and PTI documents regarding corrosion protection of unbonded single strands have been made since 2011. With all these modifications to the building codes and a greater emphasis on plant, installer, and inspector certification by PTI, has the industry addressed some of the past serviceability concerns and placed sufficient emphasis on a quality installation? Several case studies of existing PT systems and the long-term performance of these systems follow.

CASE STUDIES

In the case studies presented in the following, the design, installation, and inspection problems observed in unbonded single-strand PT systems exposed to both normal and aggressive environments will be reviewed. The case studies are limited to projects designed and constructed after the implementation of ACI 318-02, and all designs described in the following required the installation of encapsulated PT systems based on the project specifications.

Case Study 1—Northwest Florida Multi-Story Condominium

The six-story beachfront condominium tower located in Florida was completed in 2005. The floor system consisted of a PT flat slab, with exposed and cantilevered balcony slabs on all four elevations of the building. Three years following the completion of the building, corrosion staining and balcony coating delaminations were observed by the unit owners. At the interface of the cantilevered slab and perimeter columns, a 3/4 in. (19 mm) slab turndown was specified by the engineer-of-record. At this location, the concrete cover over the embedded conventional and PT reinforcement was measured to be as shallow as 1/4 in. (6 mm) (Fig. 1). The structural and architectural drawings specified a minimum 1 in. (25 mm) concrete cover on all embedded reinforcement at the balconies and a sloped concrete top surface down toward the balcony edge. In addition, the PT design and shop drawings specified the tendon high points at the perimeter columns. Combining all the specified information and neglecting construction tolerances, it was determined that all of these requirements could not have been met, and only a maximum concrete cover of 1/2 in. (13 mm) could have been achieved given the specified tendon placement (Fig. 2).

Fig. 1—Exposed reinforcing at balcony and corner column.

Case Study 2—East Coast Florida Multi-Story Condominium

The beachfront 11-story condominium tower is located in Florida and contains a single-story parking deck on the bottom floor. Portions of the parking deck roof also contain balconies and plaza areas. The elevated floors of the plaza and tower consist of PT flat slabs using an encapsulated PT system. Following the occupancy of the tower in 2003, the condominium association retained various experts to complete a due diligence survey before the developer turned the property over to the association.

Based partly on the installation practices observed at an adjacent tower under construction, part of the due diligence survey also included a limited condition survey of the PT stressing anchorages located below the leaking plaza expansion and construction joints.

Four stressing anchors were exposed in three locations. At the first location, two stressing anchors were exposed and were observed to be missing encapsulation caps. At the second and third locations, the encapsulation caps were present but were not properly seated on the anchor because the strand tail had not been cut to the appropriate length. In addition, one of the caps did not have an O-ring seal

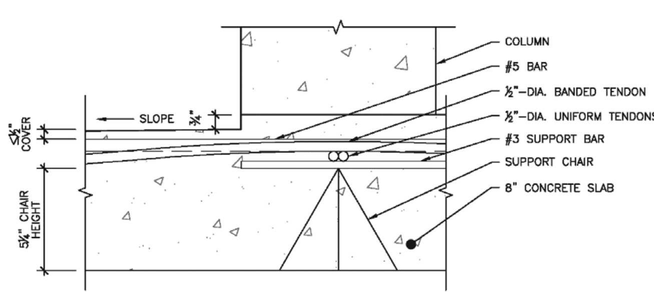

Fig. 2—As-specified reinforcing layout at balcony slab turndown.

between the anchor body and cap. Another encapsulation cap contained an O-ring that exhibited extensive cracking, which would have prohibited a watertight seal (Fig. 3). At the last location, the encapsulation cap was placed sideways in the stressing pocket, and a void was found behind the encapsulation cap (Fig. 4). Based on these conditions, additional stressing anchorages were exposed at random locations on the elevated floor slabs, and similar conditions were observed. In addition, moisture and minor surface corrosion on the strand tails and anchors were observed at some of the exposed stressing anchorages. These installation defects essentially changed the originally specified encapsulated PT system required in a corrosive environment to a standard system typically used in a protected environment.

Various repair alternatives were proposed to the association and the developer, including the removal of all the grout from the stressing anchorages, replacing and properly installing the encapsulation caps, and removing the surface corrosion. In addition, repairs to the plaza waterproofing and expansion joints were recommended. However, as part of the settlement negotiations, the developer only repaired the waterproofing and expansion joints, and applied an elastomeric coating on the exterior of the building. In addition to continued maintenance of these elements and coating, the condominium association was ultimately left with a non-encapsulated and less-protected PT system.

Case Study 3—Northwest Florida Condominium Parking Structure

One of two two-story parking structures constructed between 2004 and 2006 and consisting of elevated PT flat slabs with an encapsulated PT system contained exposed concrete patches on the undersides of the elevated slabs and exhibited strand blowouts (Fig. 5 and 6). Based on these conditions, the association became concerned about potential future strand and concrete failures, the as-built versus as-designed load capacity of the elevated slabs of the parking structure, and whether the long-term service life of the parking structure had been impacted by the as-built conditions. The available third-party inspector's field reports listed some issues with the PT strand drapes and vertical alignment, cut sheathing, and other minor placement issues, but stated that these were all corrected during the original construction.

However, a recent PT strand blowout showed deficient original vertical and horizontal strand alignment (Fig. 6). Similar conditions were also observed at the overhead concrete patches. After completing a ground-penetrating radar (GPR) survey of the elevated slabs and verifying these readings with exploratory openings, significant deviations from allowable construction tolerances were noted. Throughout the elevated PT slab, the uniformly distributed strands were observed to follow the drape of the banded strands along the column strips instead of the specified parabolic drape (Fig. 7). Furthermore, the hori-

Fig. 3—Close-up of end cap O-ring with cracks.

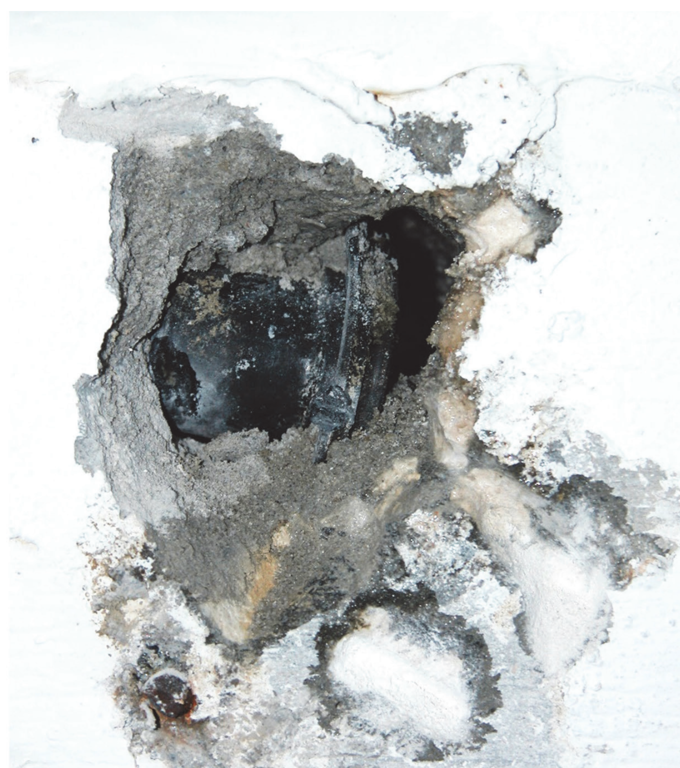

Fig. 4—Deficient encapsulation cap installation with void visible behind encapsulation cap.

Fig. 5—Typical overhead patches aligned with uniform strands in parking structure.

Fig. 6—Strand blowout with deficient horizontal and vertical PT strand alignment.

zontal sweep in the uniform strands exceeded industry standard tolerances (Fig. 8). At locations with overhead concrete repairs, existing strand sheathing repairs were exposed for visual inspection and were observed with incomplete sheathing repairs.

Along the slab edges, some of the stressing pockets exhibited moisture leakage and staining (Fig. 9). After removing the grout, the encapsulation caps were observed to not be properly seated within the anchor barrel. The exposed strand tails were measured to be too long to allow for these encapsulation caps to be seated. In addition to moisture in the stressing anchor barrel, emulsified PT coating was found in the encapsulation caps (Fig. 10).

Based on the field investigation and structural analyses completed using the as-built conditions, the elevated slabs were determined to have sufficient load capacity to carry the code-specified demands. However, the widespread excessive horizontal sweep of the uniform strands was not within industry standards and presented a potential safety concern in the form of potential future concrete blowouts. The strands with deficient horizontal sweep were recommended to be realigned to reduce the potential for such blowouts. However, based on bids from repair contractors and the magnitude of the necessary demolition required to realign the existing PT strands, it was determined that the removal and replacement of the elevated slab would be more economical.

Case Study 4—Georgia Parking Structure

As part of a regular maintenance program, a visual survey of a seven-story parking structure in Atlanta, GA, was completed. The parking structure was constructed in 2005. The PT-reinforced, flat plate elevated concrete slabs were observed to contain a few slab areas with deficient concrete cover over the PT strands at the column strips (Fig. 11). In addition, on every elevated level and on all elevations of the parking structure, the ends of the encapsulation caps for the encapsulated PT strands were exposed or efflorescence emanating from the stressing pockets was noted (Fig. 12 and 13). The proper seating of the encapsulation caps within the stressing anchor barrel could not be achieved because the strand tails were not cut sufficiently during the original installation. However, after removing the grout at the stressing pockets exhibiting efflorescence, no moisture within the stressing anchor assembly was noted. Instead, moisture appeared to have entered the top cold joint between the grout and formed pocket, carried with it some salts within the concrete, exited the bottom of the stressing pocket, and deposited the salts on the slab edge. To repair the deficient conditions and extend the service life of the parking structure and PT system, the existing PT strands along the column strips with deficient cover were realigned to achieve sufficient clear cover. Along the slab edges, the grout from each stressing pocket was removed, the exposed strand tails and stressing anchors were inspected and cleaned, the strand tails were cut to proper length, new encapsulation caps were installed, and the grout was replaced.

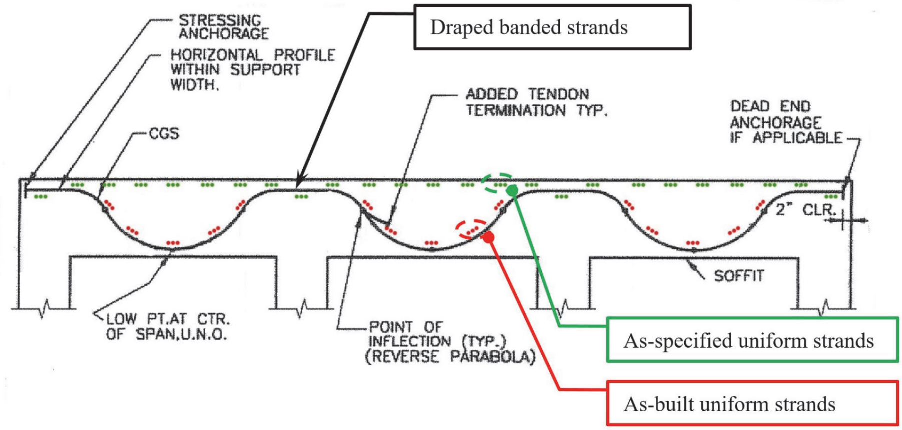

Fig. 7—Uniform tendon vertical alignment (red dots) following banded tendon profile. Green dots indicate specified uniform tendon placement.

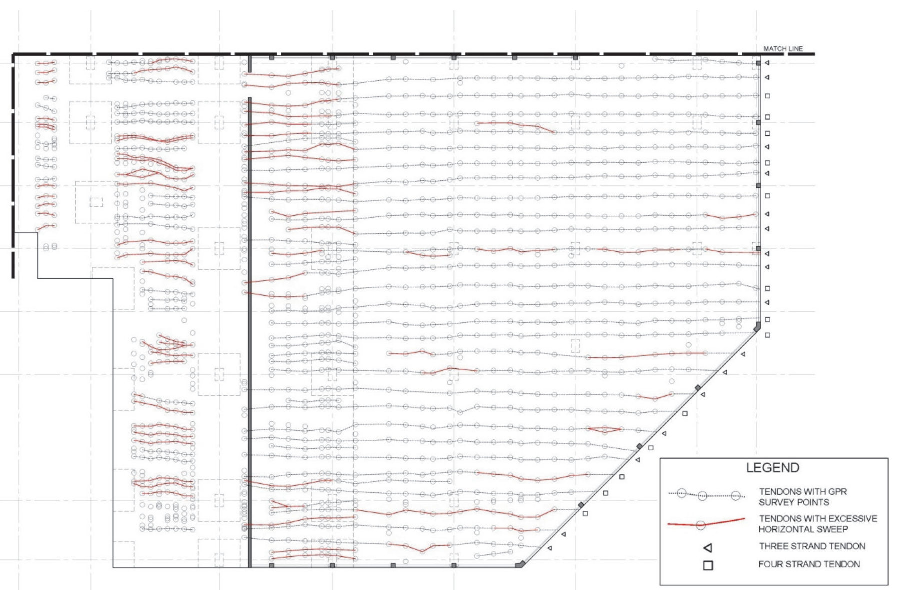

Fig. 8—Plan view of uniform PT strand horizontal misalignment based on GPR scans and exploratory openings. Red lines indicate tendons with excessive horizontal sweep.

Fig. 9—Moisture emanating from grout pockets along elevated slab edge.

Case Study 5—Alaska Multi-Story Building

During the construction of a multi-story building in Alaska, limited field inspections to review the steel and PT placement in the elevated slabs were performed. Multiple damaged sleeves at the stressing anchors were noted, and upon closer inspection, moisture was observed in the sleeves and on the bearing surface of the anchors (Fig. 14). After further evaluation, moisture ingress was also noted at other anchor locations exhibiting no obvious sleeve damage. It was determined that the sleeves did not provide a proper seal to prevent moisture ingress between the sheathing and the sleeve. Using water-sensitive and pH paper, moisture was identified in many of the sleeves on site (Fig. 15). These conditions were not limited to the installed tendons but were also identified in tendons stored on site. Metal strapping used to bundle strand delivered to the site was found to have damaged some sleeves on the fixed anchors (Fig. 16 and 17). Although the tendons were fabricated in a PTI certified plant, sleeves were found to not provide a proper seal to the sheathing and allowed for moisture ingress.

Fig. 10—Strand tail too long, encapsulation cap not seated, and emulsified PT coating.

Fig. 13—Grout shrinkage at grout pockets with efflorescence emanating from grout pocket.

Fig. 11—Exposed PT sheathing and PT coating stains at top of slab.

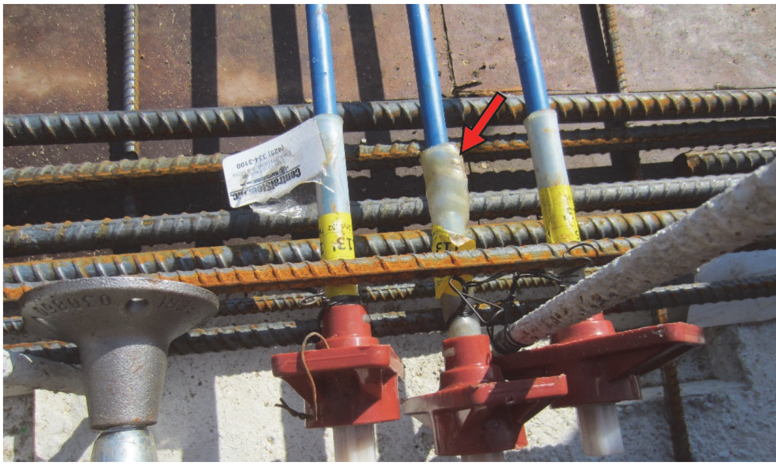

Fig. 14—Damaged PT sleeve prior to concrete placement.

Fig. 12—Exposed encapsulation caps and voids in grout at stressing pocket.

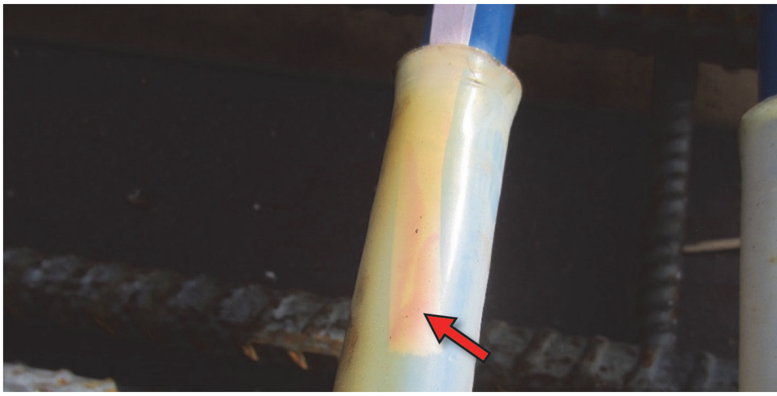

Fig. 15—Discolored moisture-sensitive paper indicating moisture in sleeve and poor seal between sleeve and sheathing.

Fig. 16—Typical on-site storage with metal strapping.

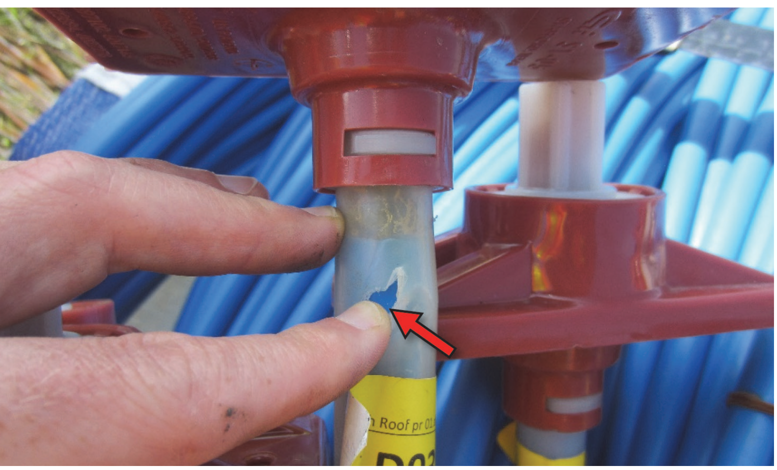

Fig. 17—Damaged PT sleeve prior to concrete placement.

Case Study 6—South Florida Hotel

During routine maintenance of a 54-story South Florida hotel constructed in approximately 2008, the repair contractor identified hollow-sounding stucco along balcony slab edges. After removing the stucco from the slab edge, debonded grout in the PT stressing pockets was exposed. In addition, the encapsulation caps of the stressing anchors were noted to not have been properly seated in the anchor barrel (Fig. 18). At several locations, the exposed wedges also exhibited offsets ranging from 1/8 to 1/2 in. (3 to 13 mm) (Fig. 19), while at others, unstressed strands with no visible wedge offsets were identified. Based on these conditions, limited pluck testing of randomly selected strands was completed, resulting in identification of additional partially stressed strands. However, the partially stressed strands did not correlate with the stressing end anchors exhibiting offset wedges. These conditions resulted in unplanned PT repairs and concerns about the original PT system installation and inspection. The available field inspection records did not identify any known issues with the original PT system installation.

Fig. 18—Deficient strand tail length preventing proper seating of encapsulation caps.

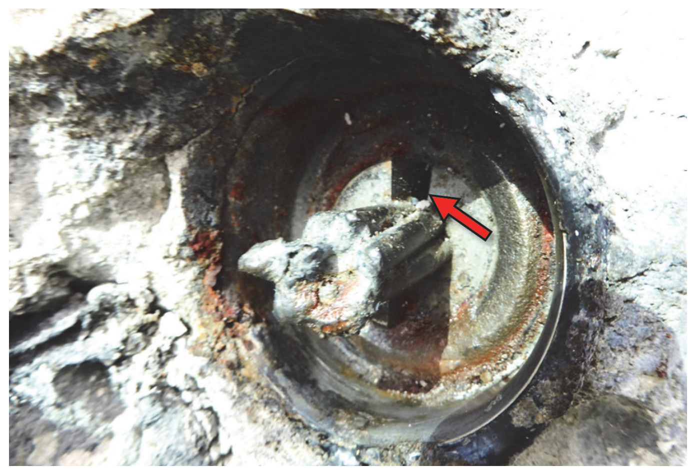

Fig. 19—Offset wedges at stressing anchor.

Case Study 7—South Florida Multi-Story Condominiums

The property consists of two 26-story condominium towers constructed between 2005 and 2007. In accordance with Florida law, a threshold inspector was retained for the project and completed regular field inspections during construction. In 2012, the condominium association retained a local consultant to complete a due diligence survey of the property, and hundreds of construction deficiencies were identified by the consultant. Based on their survey, a Florida Statute 558 construction defect claim was filed, and a more detailed evaluation of the claimed construction defects was completed. Similar to one of the aforementioned case studies, defects in the stucco installation were identified along the balcony slab edges, and after the removal of the hollow sounding stucco, defects in the grout used to fill the stressing pockets and the PT system were uncovered. These defects included voids and partially filled stressing pockets, improperly installed encapsulation caps, encapsulation caps with emulsified PT coating, mismatching of encapsulation caps with anchors, and strand tails that were not cut to proper length (Fig. 20 and 21). At the stressing anchors where the encapsulation caps contained emulsified PT coating, only limited surface corrosion on the strand tails was noted, and moisture within the anchor barrel was typically not visible. Therefore, the emulsified PT coating appeared to be the result of improperly stored encapsulation caps and moisture entering the encapsulation caps prior to their installation. Three types of encapsulation caps were identified on the project, and some of these did not appear to match the stressing anchor. This resulted in the encapsulation caps being improperly seated in the anchor barrel and not providing an encapsulated PT system. Because the threshold inspections were limited to observing conventional and PT reinforcing placement and the stressing of the PT strands, the deficient strand tail length, encapsulation cap installations, and grout placement were not identified in the field during construction. These deficiencies have resulted in significant remedial work and litigation.

CONCLUSIONS

Although significant improvements have been made in the fabrication, installation, and design of PT systems since the 1960s and the vast majority of PT systems perform as designed, similar problems to those identified back in 1998 in the ACI 423.4R document still continue to occur. Further emphasis to stress the proper detailing, care in handling, on-site storage, proper installation, and inspection of these systems will be needed to continue to increase the service life of structures and reduce future maintenance costs for building owners. The most significant problems continue to exist in areas considered to be corrosive environments, such as beachfront properties, parking structures, balconies, planters, and plazas. As demonstrated in the case studies outlined previously, the lack of attention to details such as concrete cover and constructability often result in less-than-desirable corrosion protection in both normal (protected) and aggressive exposure conditions. Many of these types of problems could be avoided through proper communications between the design team and contractor, and the use of qualified laborers and inspectors.

Although the PTI certification programs for installers and inspectors have improved installation quality, further improvements are needed. The requirements for certified personnel, installers, and inspectors should be enforced for all projects without exceptions. Further training and diligence by the design and construction community will be required to improve the quality and service life of PT structures. Simplifying the installation and further improving the durability of PT accessories may limit potential installation defects. In addition, the industry should consider requirements for the inspection and documentation of cut tendon tails and encapsulation cap installations prior to patching stressing pockets. By stressing these key areas during the design and construction phase of any project, the quality and service life of the PT systems and overall structure could be improved.

Fig. 20—Poor-quality grout with voids at stressing pockets.

Fig. 21—Encapsulation cap not properly seated in anchor barrel bonded to grout plug.

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