A STITCH IN TIME SAVES NINE: A PT REPAIR CASE STUDY

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INTRODUCTION

In the spring of 2015, a condominium association in Chicago, IL, reported that a piece of concrete had fallen from the ceiling of a parking garage and broken the rear window of a vehicle parked on the second level. The concrete fragment had dislodged from the slab soffit when a post-tensioning (PT) tendon erupted through the bottom of the concrete slab. Using selective tendon extraction, investigation openings, and nondestructive evaluation techniques, it was determined that incidental tendon damage that occurred as part of previous concrete repairs had compromised sections of the PT system. The findings of the investigation identified unmitigated and inadequately addressed tendon damage that had occurred incidentally to previous concrete repairs, and the impact of that damage on the long-term performance of the PT system. Based on the investigation, repairs were designed to replace sections of deteriorated tendon and reduce the likelihood of future failures.

DESCRIPTION OF STRUCTURE

The enclosed, nine-level parking garage is located at the base of a 40-story residential tower that was constructed around 1981. The garage is approximately "L"-shaped in plan, with the north and south bays offset by half a story from each other (Fig. 1). The garage structure typically consisted of a flat-plate two-way reinforced 7.5 in. (190 mm) thick PT slab. A section of the North Bay of the garage was located within the footprint of the residential tower and this portion was reinforced as a one-way PT slab. The one-way and two-way reinforced portions of the structure were separated by an expansion joint. The two-way system was banded, with the banded groups of tendons oriented in the east-west direction along the column lines and the distributed tendons oriented in the north-south direction. A general conceptual layout of the PT system is shown in Fig. 2.

Consistent with the 1980s construction, the slab PT system consisted of unbonded seven-wire steel strand coated with grease and enclosed in heat-sealed plastic sheathing. A typical cross section of this style of sheathing is shown in Fig. 3. The PT tendons were not encapsulated, so the sheathing stopped at the end anchors and the end anchors lacked protective sheathing and grease-filled caps. Conventional reinforcing bars were generally provided only in the negative-moment regions of the slab around the columns and as needed to support the PT tendons at the required elevation within the slab. The conventional reinforcement was not epoxy-coated or otherwise corrosion-resistant.

Prior to the unexpected PT tendon eruption in the spring of 2015, the garage had been considered by the owners to be in good condition. Some top-surface concrete repairs had been performed to address delamination and spalling, reportedly caused by corrosion of the conventional reinforcement around the columns. Miscellaneous cracks in the floor slab had been either filled with epoxy or routed and sealed, and a penetrating silane sealer had been applied to the top surface of the floors to reduce water and chloride ingress.

PT FAILURE

In the spring of 2015, one tendon in a banded group of 16 tendons erupted from the underside of the Level 4 floor slab (Fig. 4). A visual survey of the garage identified two additional locations of prior tendon eruption, also on the underside of the Level 4 floor slab. One of these older eruptions occurred at the west end of the garage along the same line of banded tendons; the other occurred near the south edge of the floor between the two ramps. The locations of these eruptions are shown in Fig. 2.

To determine the cause of the tendon failures, inspection openings were performed with the assistance of a repair contractor. The intent of the openings was twofold: 1) identify the cause of the eruption so that appropriate

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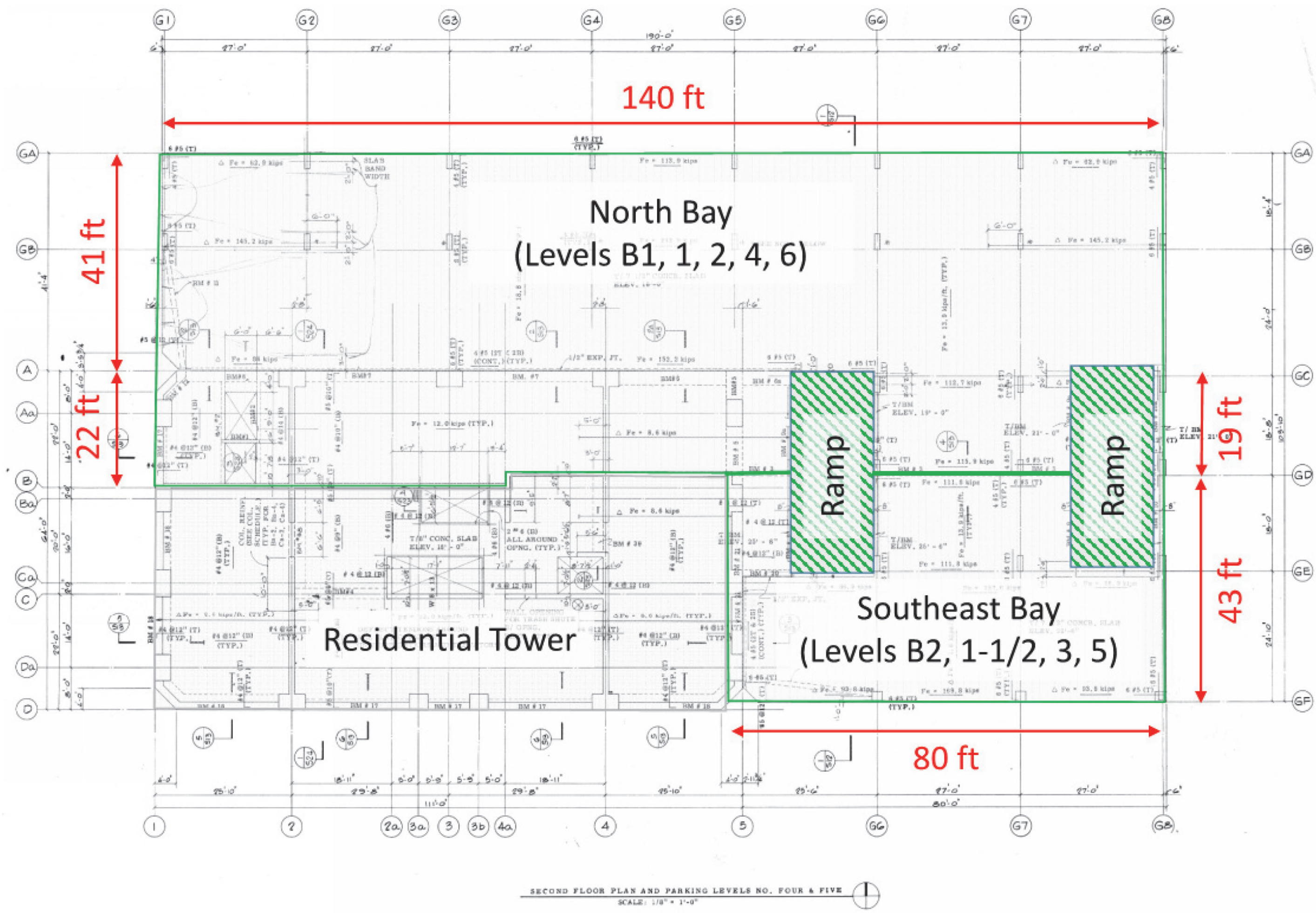

Fig. 1—Plan view of garage (north oriented up).

repairs could be implemented; and 2) evaluate the condition of other tendons in the banded group to estimate the remaining capacity of the floor slab. Ground-penetrating radar (GPR) equipment was used to supplement the investigation openings, allowing for confirmation of the tendon location and profile within the slab, and to determine the approximate concrete cover over the tendons.

Four inspection openings were made along the banded group of tendons that exhibited multiple eruptions (Fig. 5). The locations were selected to obtain information on the condition of the failed tendons at the break and along their length away from the break location, and to determine if the other tendons in the banded group were still under tension. The investigation was also intended to help identify conditions that may influence repairs, such as evidence of moisture contamination, portions of strand with corrosion, or instances of physical damage. The openings were therefore made at locations more likely to reveal these conditions, as follows:

- Cracks—Cracks in the structural slab may allow moisture to reach the PT tendons. If the sheathing is not fully sealed, the moisture may enter the tendon and promote corrosion of the strand.
- Delaminations and spalls—Delaminations may be caused by corrosion of conventional reinforcement, but may also be caused by corrosion of PT tendons or stresses released from tendon failure. PT tendons exposed at concrete spalls are subject to physical damage. Damage may be limited to tearing or abrasion of the sheathing, but this will allow water ingress, leading to corrosion of the strand. Damage could also be more severe, including section loss of the strand.
- Old repairs—Tendons may have been damaged or removed in old repair locations. In structures with a history of repairs to the PT system, repairs may also contain splicing or anchoring hardware.
- End anchors—In non-encapsulated systems, end anchors can be a source of moisture intrusion into

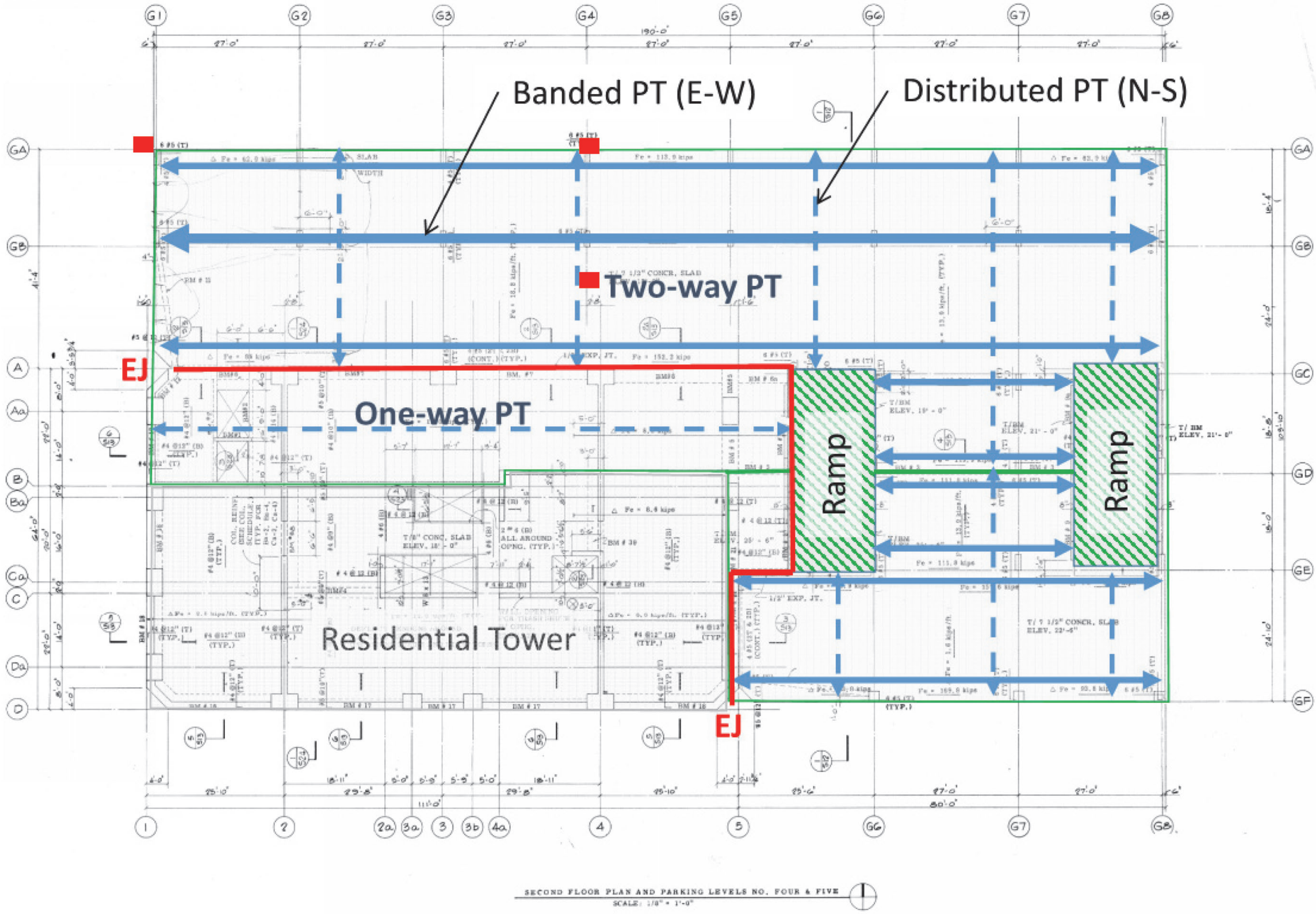

Fig. 2—PT layout of typical floor. Banded groups of tendons shown with solid lines and direction of distributed tendons indicated by dashed lines. Locations of tendon eruptions indicated by red boxes.

the tendon. Corrosion can develop on the wedges or on the strand in and around the wedges. Moisture can also travel through the sheathing and collect at the first low point from the anchor.

- Construction and expansion joints—End anchors and intermediate anchors may be susceptible to moisture ingress.

In addition to making openings at these potential locations of distress, exposing the tendons at the low points in the tendon profile near points of moisture ingress may help identify areas where water collects and may result in corrosion-related deterioration.

Inspection Opening No. 1 and 4 were made at the two eruption points. Inspection Opening No. 2 was made at an existing concrete repair at a column near the west end of

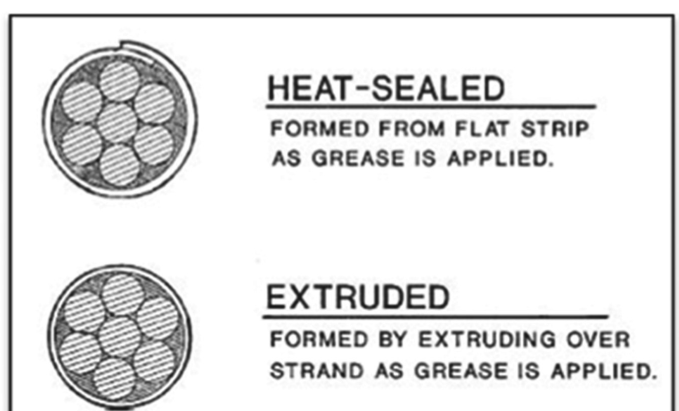

Fig. 3—Heat-sealed sheathing (courtesy of PTI).

the garage, and Inspection Opening No. 3 was made at the fracture location for a broken tendon. At each opening, the plastic sheathing was cut to inspect the condition of the grease and steel strand, and a screwdriver penetration test (Fig. 6) was performed to evaluate if the tendon was holding force. The screwdriver penetration test consisted of attempting to drive a flathead screwdriver between individual wires of an exposed strand. If the screwdriver can penetrate between the wires, it is likely that the tendon is no longer fully tensioned. However, the test can return false positive results that the tendon may be holding tension if the tendon has significant corrosion that can interfere with separation of the wires or sufficiently bind the tendon to restrict movement.

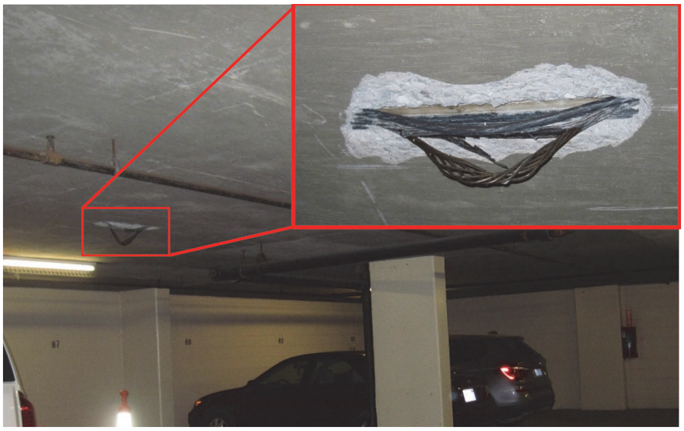

Fig. 4—Tendon eruption from underside of Level 4 slab.

A summary of the findings at each of the openings is as follows:

- Opening No. 1—Located at tendon eruption location at west end of garage, on the underside of the slab (Fig. 7). Four tendons were exposed, and three of them were noted to be detensioned. Two of these tendons had splayed wires ("bird-caged") and exhibited light surface corrosion evenly on all surfaces of the

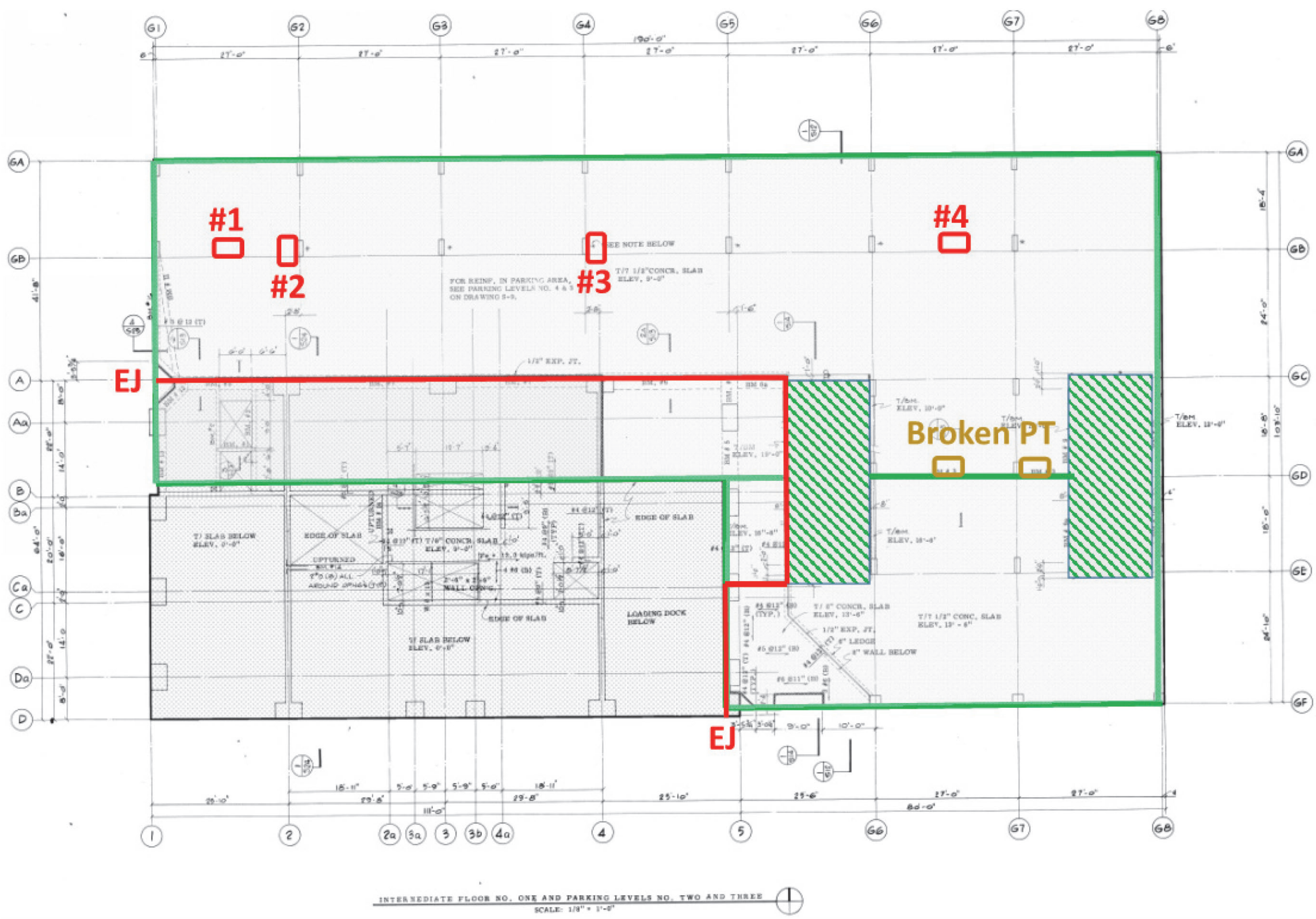

Fig. 5—Locations of inspection openings.

wires, indicating that the tendons had been exposed to atmospheric moisture for some time; after cutting the sheathing on the third loose strand, black corrosion by-product was visible in the grease. None of the exposed tendons had section loss or pitting on the exposed wire surfaces. The tendon that was still holding tension appeared to be in good condition.

The three detensioned tendons were cut to allow them to be gripped by a hydraulic ram. Two of the tendons pulled out of their end anchors at the west edge of the floor slab, while the third remained secure at its anchor. One tendon was removed to inspect the end that had pulled out of the anchor. As shown in Fig. 8, it had very light surface corrosion and no visible pitting or section loss. The tendon was extracted from the slab east of the inspection opening to determine the location of the fracture. At the first low point, moderate surface corrosion, section loss, and pitting was found on the strand (Fig. 9). The point of failure was found to be approximately 80 ft to the east of the opening, at an existing concrete repair location. The broken end of the tendon exhibited heavy corrosion and full section loss (Fig. 10). Importantly, the condition of the tendon between the first low point and the failure was good, with no signs of corrosion on the steel.

- Opening No. 2—Located at the first high point of the tendon drape, on the top surface of the slab and at the first interior column from the west slab edge. The opening was made through an existing concrete repair. Eight tendons were exposed in the east-west banded group, and two additional tendons were exposed oriented in the north-south direction (Fig. 11).

  All the east-west tendons were found to be in good condition, with no evidence of moisture contamination or corrosion. Four of the eight tendons were found to no longer be holding any tension, consistent with Opening No. 1. The sheathing on all the east-west tendons had been damaged by chipping as part of previous concrete removal, and light surface corrosion was visible on the exposed steel.

  The sheathing of two of the north-south tendons were found to have been damaged by the saw-cutting operation along the perimeter of the prior concrete repair, and no evidence of attempted sheathing restoration was noted. Both tendons were heavily corroded, as shown in Fig. 12, with at least one wire completely corroded through on one of the tendons. The screwdriver penetration test failed to separate the wires in the tendons, but based on the exposed tendon condition, this was likely due to the significant corrosion buildup and was judged to be a false positive.

- Opening No. 3—Located at the failure point identified by extracting one tendon from the first inspection opening. This opening is located on the top surface of the slab at a previous concrete repair. Four tendons were exposed. The three tendons that were found to be loose were all fractured at this point. The strands had retracted in the sheathing, away from the fracture point, so that the steel was not visible at this opening.

Fig. 6—Screwdriver penetration test.

(a) Overall view of Inspection Opening No. 1.

(b) Close-up view of birdcaged tendon.

Fig. 7—Inspection Opening No. 1.

The empty sheathings still contained corrosion by-product from the strands.

- Opening No. 4—Located at the tendon eruption location near the center of the garage, on the underside of the slab, in the area shown in Fig. 4. Four tendons were exposed. Two of them were visibly sagging out of the opening and were not holding tension; one was found to not be holding tension by using the screwdriver penetration test; and one was found to be tensioned.

Fig. 8—Tendon pulled out of end anchor.

Fig. 9—Pitting and section loss from corrosion at low point of tendon profile.

Fig. 10—Heavy corrosion on strand at location of fracture.

Fig. 11—Inspection Opening No. 2.

All four tendons appeared to be in good condition, with no signs of corrosion or moisture contamination on the strand or in the grease. The three loose tendons were cut using a grinder, and the east end anchorages were tested in a similar manner as at Opening No. 1. All the tendons were determined to still be secure at the anchorages.

An additional inspection was made at the two failed slab PT tendons that erupted near the south edge of Level 4 (Fig. 13). The tendons were exposed on the top surface of the slab at a column, where they had been placed too high during the original construction and had no concrete cover (Fig. 14). The heat-sealed seam in the sheathing separated, allowing moisture to enter the sheathing. The strand was heavily corroded, as seen in Fig. 15, and both tendons were fractured due to section loss.

The conclusion of the inspection openings was that failure of the tendons was caused by damage that had occurred as a result of the previous concrete repair efforts. Although the repairs were not intended to affect the tendons, damaged and unrepaired sheathing left the tendon susceptible to moisture ingress. As the concrete repair material shrunk over time, water was able to enter the slab around the perimeter of the repair concrete material and through cracks in the patched area, and migrate down into the tendon through the damaged sheathing. This promoted corrosion of the strand within the repair area. The moisture was also able to travel through the annular space within the sheathing to collect at nearby low points in the tendon profile, promoting additional corrosion of the strand at those locations. At locations where the PT was undisturbed by prior repair activities, very limited deterioration or distress was found that required repair. Only a couple of localized areas were identified where the tendons were misplaced during the original construction and left exposed and subject to moisture ingress and damage.

STRUCTURAL EVALUATION

A limited structural analysis was performed to estimate the reduced load-carrying capacity of the slab in the region of the east-west banded tendons where half of the tendons at inspection openings were found to be no longer holding force. The equivalent frame method was used to calculate load demands in the direction of the east-west banded tendons. Under the ultimate load condition specified by the applicable building code (50 lb/ft^2 [2.4 kPa] garage live load), the structure was estimated to be overstressed by approximately 20%. The slab was also evaluated for a lighter loading condition (35 lb/ft^2 [1.7 kPa] live load) that is more consistent with the actual day-to-day use (cars parked only in the striped stalls with no valet parking). It was determined that the existing capacity of the slab was adequate to support this reduced load without considering contributions from the tendons oriented in the north-south direction. Because no cracking, excessive deflection, or other signs of distress were present, the building continued use of the slab until repairs could be completed. However, periodic engineering inspections were recommended to continue to monitor the floor structure. If any sign of distress were to develop, no parking would be allowed on the affected portion of the floor.

REPAIRS ON LEVEL 4

A repair program was implemented on Level 4. Along the banded group of tendons, repairs were implemented by splicing in new sections of tendon to replace damaged areas and restressing the tendons at a point near the center of the garage. Damaged or deteriorated portions of the tendon were extracted from the slab, leaving the existing plastic sheathing intact, and new seven-wire strand threaded into the existing sheathing and spliced onto the existing strand that remained. Where the tendons pulled out of their end anchorage at the west end of the slab, a portion of the brick veneer on the façade was temporarily removed to allow access to the end anchors and to reseat the new tendon with new wedges in the existing anchor casting. Once the repairs at the anchorages were complete, the end anchors were cleaned and waterproofed, and the veneer repaired. Of the 16 tendons located in the subject banded group, half of them were found to have been deteriorated or damaged from previous concrete repair efforts and required repair. In addition to restoration of the PT system, any unsound concrete was repaired, and a traffic-bearing waterproofing membrane was installed to provide further protection.

Because the PT damage corresponded with past concrete repairs, all existing concrete repairs were removed on the top surface of Level 4 to allow inspection and repair (if determined to be needed) of the PT tendons. Additional deteriorated tendons and damaged tendons were identified through this process, including tendons where multiple wires had been severed from saw cutting and chipping. Ineffective sheathing repairs were also found, including coating the damaged portion of the sheathing with liquid polymer and wrapping the sheathing with duct tape. The liquid polymer failed to bridge gaps in the sheathing and therefore did not restore the sheathing to a watertight condition. The duct tape backing was found to be absorptive, and not only did not prevent moisture from accessing the strand but it also held water and accelerated strand corrosion.

Once the Level 4 repairs were complete, 2300 ft (701 m) of new seven-wire strand had been installed, including

Fig. 12—Close-up view of damaged north-south tendons where sheathing was saw-cut during past concrete repairs. Line of saw-cut shown in red.

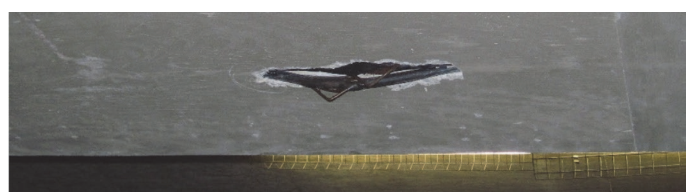

Fig. 13—Eruption from underside of slab near south edge of Level 4.

Fig. 14—Tendon exposed on top surface of slab due to initial construction defect.

Fig. 15—Close-up view of deterioration where heat-sealed seam split on sheathing exposed on top surface of floor slab.

23 tendon splice repairs and 16 new end anchors; 25 end anchors were reused with new wedges; 800 ft^2 of partial- and full-depth concrete repair was performed on the slab; and approximately 13,000 ft^2 (1200 m^2) of waterproofing membrane was installed.

CONCLUSIONS

Sudden PT tendon failures were caused by incidental damage associated with previous concrete repair efforts. The repair procedures had damaged the tendons and no measures were implemented to restore them to a watertight condition, allowing moisture ingress and localized corrosion of the tendons. The eventual tendon failures were sudden and resulted in property damage, and the potential for additional failures and eruptions to occur without warning was an unacceptable risk to the building owner. Investigation openings were used to conclusively identify the cause of the failure and design appropriate repairs.

The damage and resulting costly repair project that developed from failing to address minor damage to the PT system as part of maintenance repairs could have been mostly avoided. Proactive restoration of damaged sheathing and waterproofing measures to protect concrete repairs would have significantly slowed or stopped moisture ingress and corrosion. Repair professionals should always be cognizant of the PT system in a structure, even if repairs are not intended to affect the system. Even though there may be some short-term cost savings in ignoring minor damage to the PT system, the long-term costs can be very significant.

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