DISPELLING THE MYTH ABOUT UNBONDED POST-TENSIONED BUILDINGS

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INTRODUCTION

Since its introduction to North America in the 1950s, it is estimated that over 5 billion ft^2 (450 million m^2) of unbonded post-tensioned (PT) concrete building slabs have been constructed in the United States and Canada (Bondy 2012). As with all types of building systems, PT structures deteriorate over time, sometimes resulting in tendon corrosion and failure. There have been several cases where deteriorated PT buildings could not be sold, and even cases where relatively newer buildings were evacuated and subsequently demolished as a result of structural concerns (Tsong 2010). These cases have created a perception in the real estate industry that PT structures are unpredictable, costly to maintain, and difficult to sell. But aside from the extreme cases, how frequently do PT tendons actually fail and what are the typical causes of failure? This paper presents the key findings from two studies that analyzed the number and likely causes of tendon failures in PT structures.

BACKGROUND ON POST-TENSIONING

Deterioration of unbonded PT structures

The main cause of post-tensioning tendon deterioration is the presence of moisture, which over time can cause tendons to corrode and eventually break. Unlike conventionally reinforced concrete, contaminants such as salt are not required to cause tendon corrosion, although they will increase corrosion rates. There are several ways in which moisture typically enters a PT system:

- Entering the sheathing prior to or during construction (that is, strands are left unprotected at the plant, during shipping, or on a construction site during precipitation);
- Penetrating through cracks, expansion joints, or leaking cladding systems and into unprotected portions of the PT system during the building's service life;
- Condensation on cold surfaces such as glass or window frames, leaking into poorly protected tendon ends; and
- Entering the system during repairs (that is, through the use of hydrodemolition or exposed PT components that are subjected to precipitation).

Other causes of PT tendon failure include:

- Mechanical damage—Physical damage to the tendons caused by cutting, drilling, or coring into a concrete member (that is, severing tendons while coring for new drains or installing bolts for new roof anchors);
- Anchor slippage—Strand slippage from the anchors, which can occur naturally over time if the tendon was not anchored securely during construction; and
- Understressing—Tendons not stressed to the levels specified by the design documents may be considered to be failed if the reduced stress results in the slab not meeting loading requirements prescribed by applicable Codes.

EVOLUTION OF UNBONDED POST-TENSIONING:

While the principles behind post-tensioning have remained the same since its introduction to North America in the 1950s, the technology has evolved significantly to improve durability. The most common unbonded post-tensioning types are described in Table 1 (Kelly 2001).

Each of these PT types had varying degrees of protection for its steel components, but durability issues generally arose in early PT systems because moisture was able to enter the systems at the following locations:

- Poorly protected anchorages;
- Gaps between the end of sheathing and the anchorages; and

- Along the tendon, where the sheathing integrity is compromised.

As time progressed, these durability issues were identified and corrected, leading to technological advancements and the evolution of the durable modern post-tensioning technology. The newest form of PT technology is the extruded encapsulated system, which became widely used starting in the early 1990s. This system addresses the issues listed previously by encapsulating the entire tendon in plastic, including its anchors, from end to end.

THE STUDY—HOW OFTEN ARE TENDONS ACTUALLY BREAKING AND WHAT IS THE CAUSE?

A two-part study was undertaken to analyze tendon failure rates and causes in PT structures. The first part of the study involved analyzing acoustic monitoring records from 26 unbonded PT structures. Acoustic monitoring data was provided by Pure Technologies, a Calgary, AB, Canada-based company which provides monitoring services for buildings with PT tendons. This monitoring technology involves fitting structures with a grid of accelerometers that record vibrations triggered by a rupturing tendon or individual wires. The event location can then be triangulated based on the time of arrival of the vibrations at each sensor. Following a wire break notification, physical testing to confirm the breakage is typically undertaken to confirm the breakage occurrence and location (although not performed as part of this study). In addition to allowing broken tendons/wires to be identified, this technology provides information on tendon failure rates. Structures were monitored for a minimum of 3 years, although the majority of the structures (20 out of 26) were monitored for at least 12 years and include 14 high-rise structures and 12 parking structures with a total combined floor area of approximately 4.5 million ft^2 (420,000 m^2).

The second part of the study involved examining loose tendons that were removed from seven structures during repairs to determine the likely cause(s) of failure. Halsall Associates (a WSP aquisition) reviewed a total of 246 interior roof slab and parking garage strands.

BREAKAGE RATES

In Part 1 of the study, analysis of acoustic monitoring records indicated annual average wire breakage rates, based on structure type (it should be noted that acoustic monitoring records the failure of single wires; each tendon is comprised of six wires helically wound around a straight seventh wire) (Fig. 1).

Table 1—Descriptions and characteristics of post-tensioning technologies from 1950 to present day

PT type	Typical period of common use	Description	Characteristics
Paper-wrapped	1950s to early 1970s	Coated strand wrapped in kraft paper	• Poorly protected anchors • Paper wrap provides minimal protection from moisture and salt
Push-through or stuffed	1970s	Coated strand pushed through a preformed plastic sheath	• Poorly protected anchors • Oversized plastic sheath can form a conduit for moisture to penetrate and travel along tendon length • Deterioration typically found at anchors or low points in the tendons
Heat-sealed or cigarette-wrapped	1970s	Flat plastic strip folded around a coated strand and heat-sealed to itself	• Loose plastic sheath with longitudinal seam—moisture can penetrate the seam • Deterioration typically found at anchors or low points in the strands
Extruded	Late 1970s to present	Coated strand encapsulated in hot molten plastic (cooled and shrunk-fit around the strand)	• Tight plastic sheath—minimizes moisture travel • Unprotected anchors • Deterioration typically found at anchors
Extruded encapsulated	Early 1990's to present	Extruded strands with encapsulated anchors	• Tight plastic sheath • Protected anchors

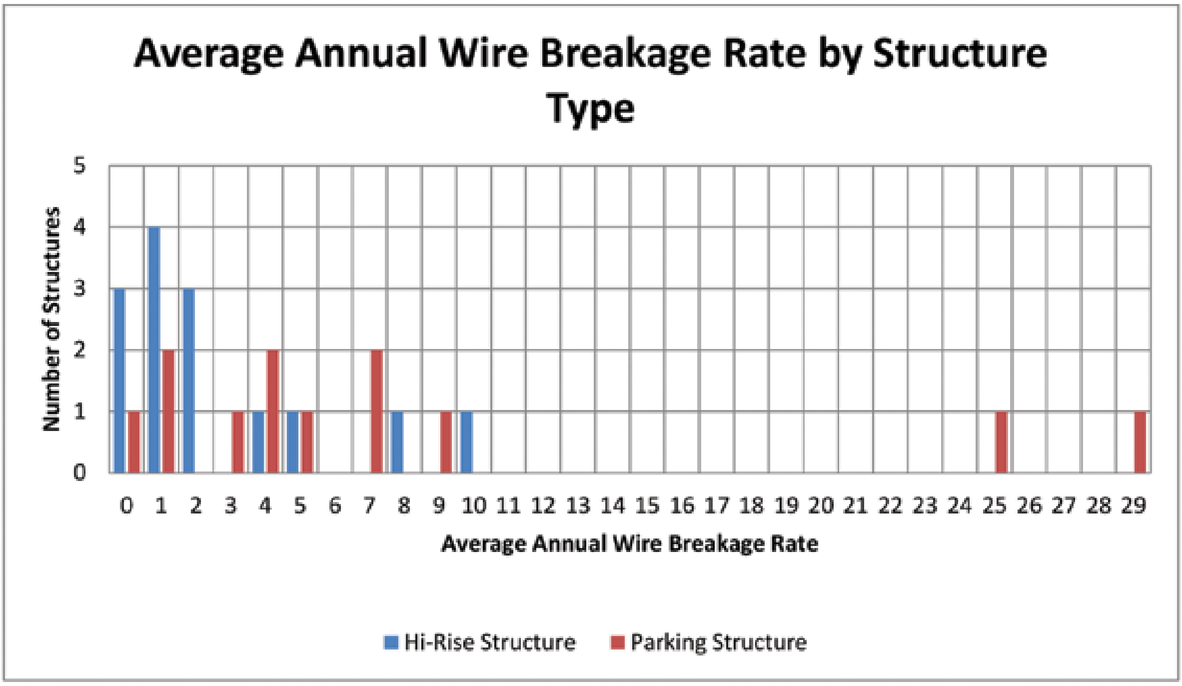

Fig. 1—Average annual wire breakage rate for acoustically monitored structures included in the study of 26 unbonded PT structures.

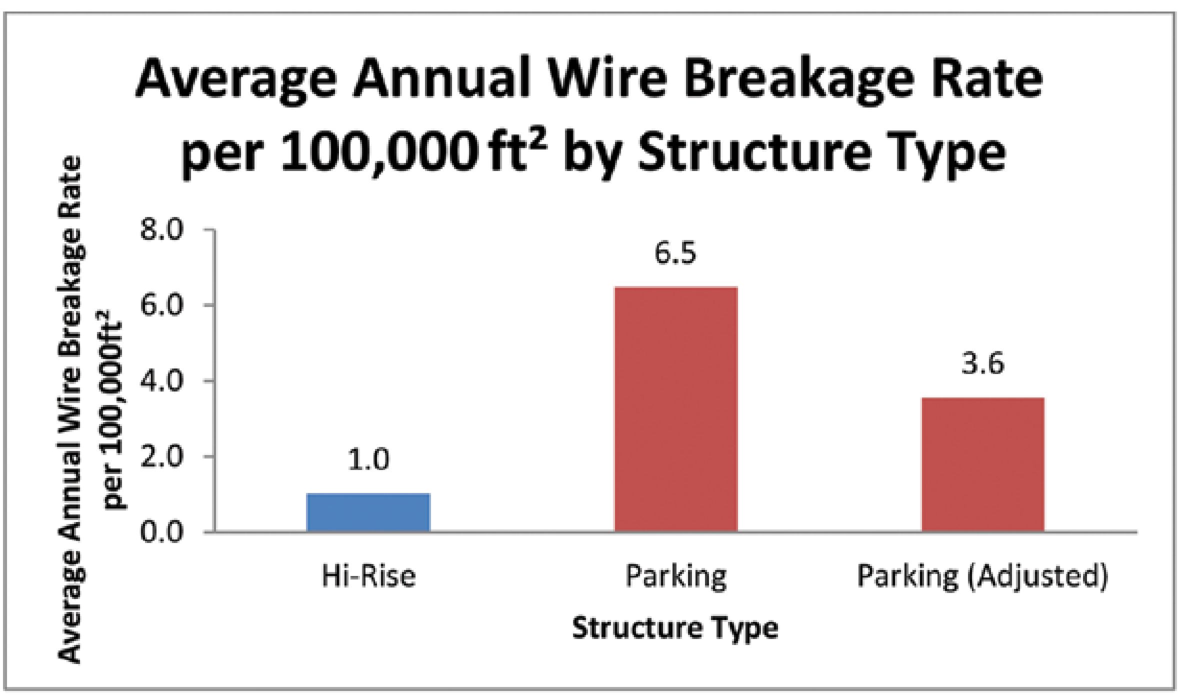

Fig. 2—Average annual wire breakage rate per 100,000 ft² (9290 m²) of acoustically monitored structures included in the study. The "Parking (Adjusted)" rate excludes the two structures averaging 25 and 29 breaks/year, shown in Figure 1.

It typically takes more than two individual wire breaks before the stress in the remaining wires exceeds the ultimate strength of the tendon and the tendon ruptures. With the exception of two parking structure anomalies, the remaining 24 structures had an average annual wire breakage rate of 3.6 breaks per year and all the structures averaged 10 or fewer broken wires per year. It is important to note that the wire breaks were reported but have not all been verified by field testing, and that acoustic monitoring systems are typically installed on structures with known durability problems; thus, the breakage rates in Fig. 1 are likely higher than would be expected in the general PT building stock.

Figure 2 presents the data normalized to account for building area.

The breakage rates presented previously are certainly manageable, particularly because a strand is comprised of seven wires—that is, several wires typically need to fail before the strand fully releases. The amount of capital that should be allocated annually for post-tensioning repairs will depend on the condition of the tendons, tendon length, predicted rate of failure, tendon access conditions, and location-specific construction costs. If structural analysis shows that failed tendon repairs can be deferred until a later date, economies of scale can be achieved through repairing additional tendon quantities during a single repair project.

CAUSES OF TENDON FAILURES

In the second part of the study, the suspected causes of failure of 246 tendons were evaluated. Tendons were divided into "interior" and "exterior," reflecting the exposure conditions. Interior tendons exist in controlled environments—often finished office spaces which are sheltered from the exterior elements, other than potentially at the slab edges (that is, if the building enclosure is not weathertight). Exterior tendons experience more direct contact with aggressive environmental conditions, such as parking garage slabs and roof slabs that are exposed to deicing salts and precipitation.

Tendon failure mechanisms were evaluated by visual site examination of broken strands that had been removed from slabs during repairs. Factors reviewed to determine the suspected reason for breakage included the following:

- The existence, location, and extent of corrosion, which indicates the current and/or past presence of moisture;
- The presence of post-construction slab penetrations (drains, pipes, and so on) aligned with tendon breakage locations, which indicates mechanical damage due to concrete coring; and
- Evidence of scraping at the strand ends, which results from slippage of the strand relative to the anchor.

Table 2—Exposure conditions and suspected causes of failure

Exposure conditions	Suspected cause of failure	Rationale
Interior	Moisture during service	• Tendon moisture/corrosion found at an end span of an enclosed structure was typically deemed to be from service due to cable end exposure to moisture at the slab edges, particularly if further investigation identified water penetration through the cladding at the tendon location.
	Moisture during construction	• Tendon moisture/corrosion found at an interior span of an enclosed structure was deemed to be from the time of construction due to the unlikelihood of moisture penetrating at an interior span during the tendon's service life.
Exterior	Moisture during service	• Tendon moisture/corrosion found at an end span was typically deemed to be from service, especially if cable end was exposed to below-grade conditions • If cracks in concrete or breach in waterproofing membrane aligned with moisture/corrosion, the source of failure is the result of in-service conditions or previous repair of such items.
	Moisture during construction	• Interior span showing evidence of moisture/corrosion with no evidence of concrete cracking or breach in waterproofing membrane.

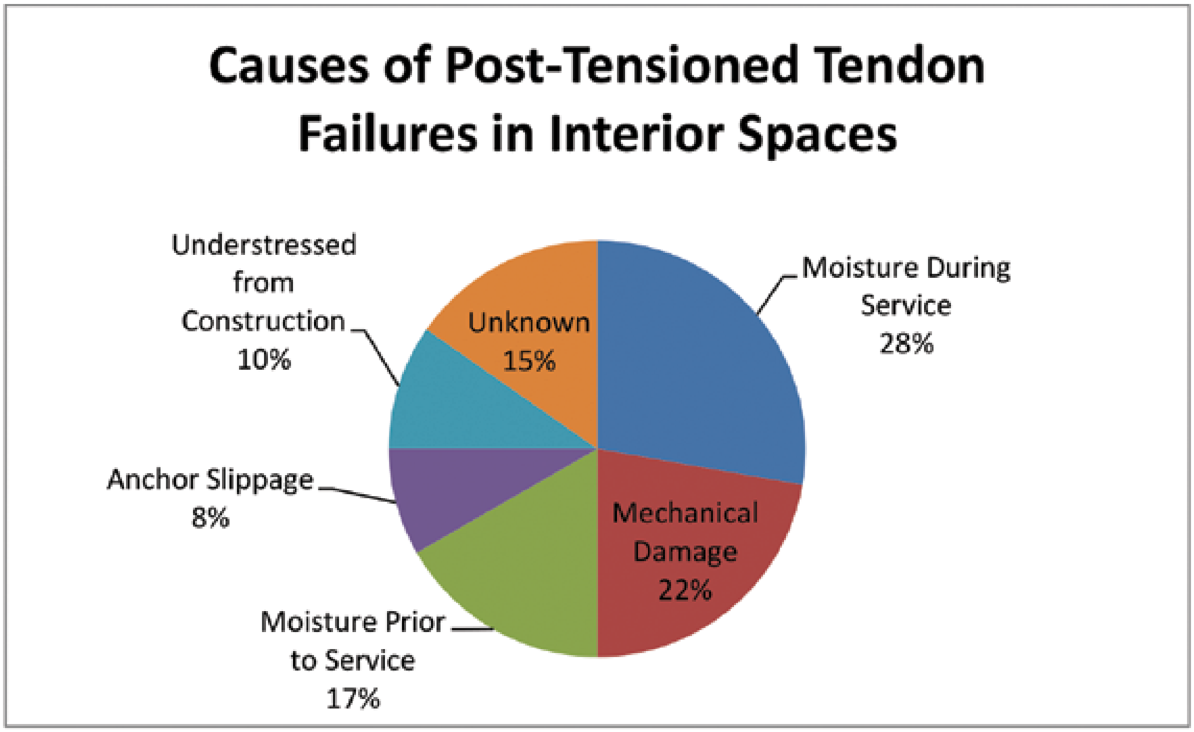

Fig. 3—Causes of tendon failures in interior spaces, based on evaluation of 72 tendon failures.

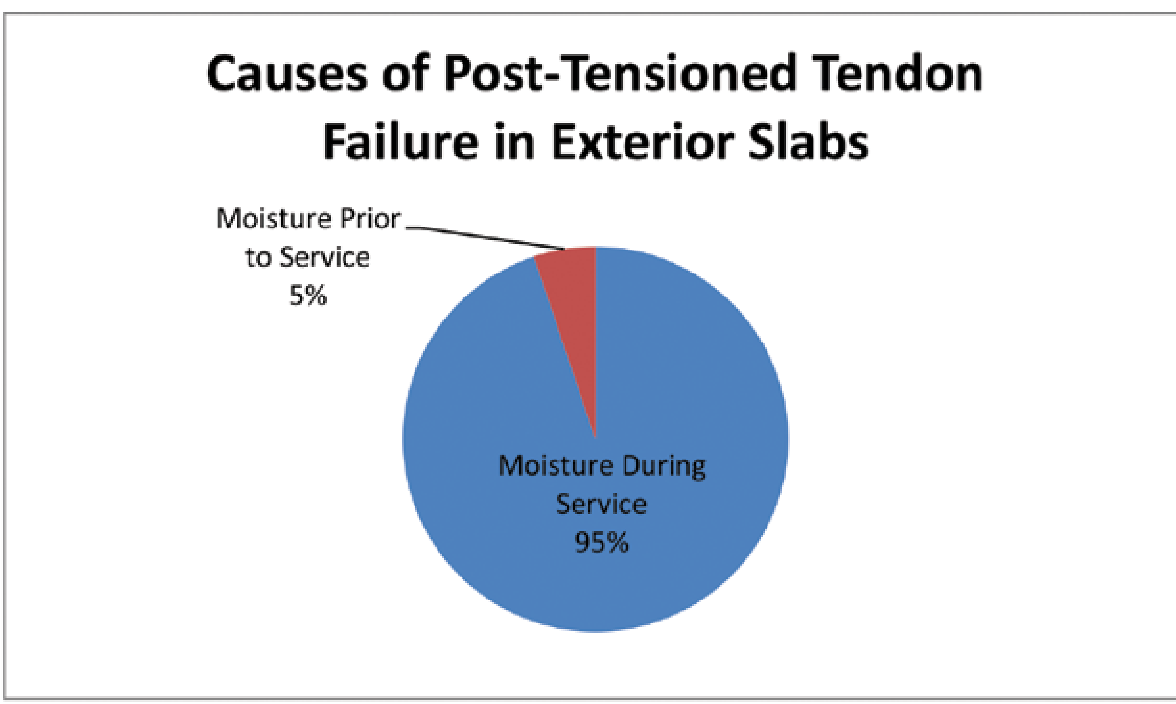

Fig. 4—Causes of tendon failures in exterior spaces (parking garages and building roof slabs), based on evaluation of 174 tendon failures.

In the event of corrosion-related failure, engineering judgment was used to assess whether the moisture penetration occurred during the service life of the strand or if it was present from the time of construction. Refer to Table 2 for assessment rationale.

Figure 3 illustrates that approximately 50% of PT tendon failures within interior slabs are the result of either moisture entering the system during the structure's service life or mechanical damage. Both failure mechanisms occur during the service life of the structure and can typically be managed through rational decision-making and the implementation of preventative maintenance. The source of moisture ingress in interior PT slabs is typically the slab edges, as they may be exposed to exterior moisture (that is, rain and snow) if the building enclosure's water control layer is not performing adequately. Regular inspection and maintenance of the building enclosure will help maintain a watertight condition, and will mitigate tendon failure due to moisture penetration at the slab edge. Mechanical damage to post-tensioning tendons generally results from careless coring or drilling through a concrete slab (and subsequently through post-tensioning tendons). A small investment in structural scanning services prior to creating any openings in a slab will significantly reduce the risk of damaging tendons and the associated repair costs.

Exterior slabs are exposed to more aggressive environments than interior slabs. The direct exposure to heavy precipitation (building and parking garage roof slabs) and salt/water runoff from cars (parking garage slabs) greatly increases the likelihood of PT tendons getting wet during the service life of these structures, as shown in Fig. 4 (95% of tendon failures in exterior slabs are the result of moisture entering the system during the structure's service life). Frequent points of moisture ingress include cracks and construction joints in the concrete slab and at slab edges. To protect the strands from moisture penetration, a proactive approach should be taken. This may be accomplished through slab and expansion joint waterproofing with periodic maintenance.

CLOSURE

The study demonstrated that tendon failures are relatively low in existing PT buildings, despite the study's focus on high-risk structures. This low failure rate would be associated with relatively low capital investment repair options, and as such, the analysis of acoustic monitoring records has shown that the stigma associated with PT buildings is generally unwarranted.

Causes of failure in over 200 tendons were evaluated, with the results indicating that the majority of tendon failures are due to factors occurring during the service life of the structure, which can be mitigated through preventative maintenance. Through the implementation of a sound capital planning strategy, regular monitoring, a diligent maintenance program, and thorough record-keeping, unbonded PT structures can be managed effectively and affordably while preserving real estate asset value.

REFERENCES

Bondy, K., 2012, "Post-Tensioned Concrete in Buildings—a Half-Century Overview," PTI Convention Proceedings, Nashville, TN, May 2012.

Kelly, G. S., 2001, "A Short History of Unbonded Post-Tensioning Specifications," *Concrete Repair Bulletin*, V. 14, No. 4, July-August, pp. 10-13.

Tsong, N. A., 2010, "Local News: The Seattle Times," The Seattle Times, http://seattletimes.com/html/localnews/2011585964_apartments12m.html. (last accessed Feb. 27, 2014)

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