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Corrosion-Induced Major Tendon Failures in Post-Tension (PT) Concrete Bridges

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INTRODUCTION

There are two types of PT tendons—bonded or unbonded—depending on the timing of installing the duct, tensioning the strands, and filling the duct with grout. Injected filler materials afford additional corrosion protection by providing physical barriers to water and air, i.e., oxygen and carbon dioxide. Cementitious grout can also be beneficial, providing a high-pH environment to form a protective, passive film (an invisible oxide film) on the steel surface. However, if the passive film is compromised by aggressive anions such as chloride ions and sulfate ions, and carbonation of the surrounding grout occurs (i.e., the pH falls below 9), prestressed steel can corrode.(1)

All the observed PT tendon corrosion problems were linked to water or moist environments and grout voids, although other issues sometimes were factors.(2) Water can enter from external sources or can form internally through the grout bleeding phenomenon. Grout voids can be formed due to poor-quality grouting, e.g., operations and from bleed water that eventually evaporates or absorbs into the hardened grout. Once corrosion starts, many factors control the rate of corrosion: oxygen availability, moisture content, the grout's electrical resistance, the degree of carbonation, ion concentrations, and grout segregation that leads to bleeding and variable water-cement ratios.

A collective protection system provided by concrete cover, ducts, and grout is the primary defense against any service environment. For grouted external tendons, prestressed steel is always buried in a grout and duct system. For grouted internal tendons, prestressed steel is buried in a grout, duct, and concrete system that makes ongoing corrosion difficult to detect before it is too late. Deployment of nondestructive evaluation technologies to assess tendon conditions presents a challenge at some critical locations—anchorage zones, diaphragms, and deviation blocks—where a heavily reinforced steel network is enclosed in massive concrete. When inspection is necessary, the semi-invasive method of drilling small holes for borescope inspection occurs but only for special situations and only at selected locations due to the destructiveness of the process and its high costs.

This document summarizes the reported cases of corrosion-induced tendon failures in the United States and foreign countries in chronological order and the lessons learned from these tendon failures. The basis for this document is information from chapter 3 of a Federal Highway Administration (FHWA) report (FHWA-HRT-22-090). Additional information is available in the full report.(2) This report also presents information about a failure case that occurred in 2020.

MAJOR TENDON FAILURES IN THE UNITED STATES

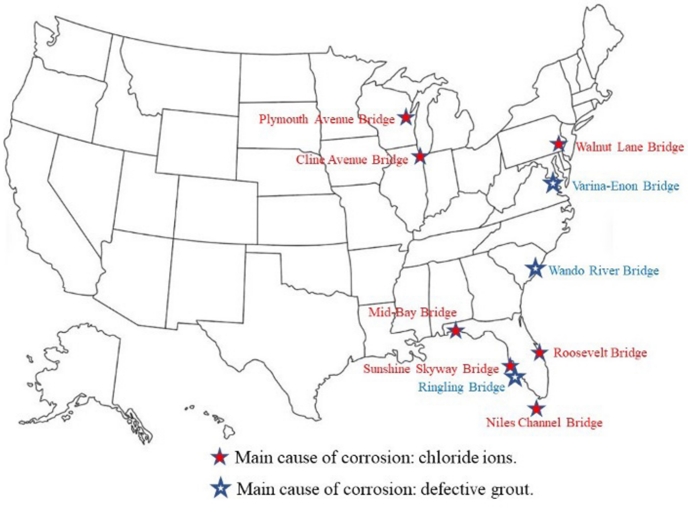
Between 1990 and 2020, 6 States—Pennsylvania, Florida, Virginia, Minnesota, Indiana, and South Carolina—experienced tendon failures in a total of 10 major PT bridges. Figure 1 shows the approximate locations of the affected bridges and their main causes. Also, table 1 summarizes the bridge characteristics and key corrosion-related information.

The following information briefly discusses tendon failures for each bridge in table 1.

Walnut Lane Bridge in Pennsylvania (1990)

The Walnut Lane Bridge in Philadelphia, PA, the first precast, prestressed concrete bridge in the United States was constructed between 1949 and 1950 and opened to traffic in late 1950. It had three spans, and each span consisted of thirteen 79-inch- (2-m-) tall PT I girders. A conventional grout injected into the ducts protected the prestressed wires from corrosion. The bridge was replaced in 1990 after nearly 40 yr of service due to improper tendon grouting and other detail deficiencies.(3)

Figure 1. Illustration. Bridge locations on the U.S. map, modified by the authors.



Source: Original map: © lesniewski/AdobeStock.com. Modified by FHWA (see Acknowledgments section).

Table 1. Summary of tendon failures reported in the United States (1990–2020).

Bridge Name (ID)	Year Opened	Failure Year (Failure Age)	Tendon Type	Location of Failure	Cause of Failure	Remedial Action
Walnut Lane Bridge, PA	1950	1990 (40)	Four rectangular internal ducts containing 62 0.276-inch (7-mm) wires in each girder	Multiple ducts	Improper grouting and detail deficiencies	Demolished
Niles Channel Bridge, FL (900117)	1983	1999 (16)	6 external tendons in each span; each tendon contains 19 0.6 inch (15-mm) 7 wire strands	Anchorage zone at leaking expansion joints	Leaked chloride bearing water into a void formed behind an anchor head	Tendon replacement
Mid-Bay Bridge, FL (570091)	1993	2000 (7) 2018 (25)	6 external tendons in each span; each tendon contains 19 0.6 inch (15-mm) 7-wire strands	Anchorage zone 2 severely corroded tendons in one span	A void formed behind an anchor head Corrosion by leaking water	11 of 846 tendons replaced 8 tendons replaced
Sunshine Skyway Bridge, FL (150189)	1987	2000 (13)	12, 17, and 18 0.5 inch (12.7-mm) 7-wire strands in a 3-inch (75-mm) primary tendon	A vertical tendon in a northbound column	11 of 17 strands fractured and many other tendons corroded due to leaking water through poorly sealed joints, presence of voids, and duct cracking	Many deficiencies in the 76 high-level approach columns were repaired, and the deteriorated north column was rehabilitated by adding mild reinforcing dowel bars into the support footings and filling the core of the hollow pier with concrete poured from the deck

Table 1. Summary of tendon failures reported in the United States (1990–2020). (Continued)

Bridge Name (ID)	Year Opened	Failure Year (Failure Age)	Tendon Type	Location of Failure	Cause of Failure	Remedial Action
Varina-Enon Bridge, VA (00000000 0010007)	1990	2007 (17) 2017 (27)	19 0.6 inch diameter (15.2-m-diameter) 7-wire strands in a 4-inch (100-mm) plastic duct); a total of 480 external tendons and 360 PT bars	A tendon near an anchorage zone Near a parapet in main span	Repaired grout Weak grout	2 tendons replaced Tendon replacement and acoustic emission monitoring since October 2020
Cline Avenue Bridge, IN (033029)	1983	2009 (26)	A total of 1,063 tendons	Widespread corrosion problems	Water seeped through deck cracks	Demolished
Plymouth Avenue Bridge, MN (27611)	1983	2010 (27)	19 0.5 inch diameter (12.7 mm diameter) 7-wire strands in a 3.5 inch (89-mm) metal duct	Internal tendons in the bottom slab	Chloride-bearing water from the deck corroded the bottom slab through the misaligned drainage pipe inside the box girders	Major repairs, including installation of extra external tendons
Ringling Causeway Bridge, FL (170176)	2003	2011 (8) 2011 (8)	A total of 132 external tendons; 22 0.6-inch (15.2 mm) 7-wire strands in a 4-inch diameter (100-mm-diameter) plastic duct.	Upper horizon portion of a sloped tendon At an upper deviator	Segregated grout	17 tendons replaced
Wando River Bridge, SC (0000000 00008235)	1989	2016 (27) 2018 (29)	A total of 696 internal and external tendons, including 240 external tendons in the approach span units and 60 external tendons in the main span units; Each tendon has 19 0.6-inch (15.2-mm) 7 wire strands	M-1 South tendon in WB structure M-5 tendon in WB structure (near the first failed tendon)	Grout void filled with recharging water; possibly carbonation	Tendon replacement and extra external tendons added
Roosevelt Bridge, FL (SB 890151; NB 890152)	1997	2020 (23)	Details are not available	Failed tendons found in the first span of SB structure	Chloride-bearing water seeped through segment joints and ducts; elevated the chloride concentration ranging from 12.5 to 25 pcy (7.4 to 14.8 kg/m3) in grout samples and 30 pcy (17.8 kg/m3) in concrete	Major repairs done including deck waterproofing

Niles Channel Bridge in Florida (1999)

The Niles Channel Bridge is a 4,557-ft-long (1,389-m-long) precast box girder concrete bridge with a deck width of 38.5 ft (11.7 m) that connects Summerland Key and Ramrod Key. The bridge was built in 1983 using a low-level, span-by-span method (the fourth bridge constructed with this method in Florida). The bridge has 6 grouted external PT tendons in each span, and each tendon contains 19 0.6-inch (15.2-mm) 7-wire strands filled with neat cement grout.

In 1999, bridge inspectors discovered that one of 234 external tendons had failed after 16 yr in service due to intensive corrosion in a grout void formed by bleed water. Figure 2 shows some of the damaged strands still attached to the anchor head associated with the failed tendon.(4,5)

This incident was regarded the first PT tendon failure caused by corrosion in the United States. The void location was behind an anchor head at an expansion joint diaphragm. Recharging water contaminated with airborne chloride in the void was responsible for the corrosion. Inspectors speculated that the water leaked through the expansion joints and ran down the inner faces of the segment diaphragms onto the anchorage in question.

Mid-Bay Bridge in Florida (2000)(4-7)

The Mid-Bay Bridge is a 19,265-ft-long (5,982-m-long), precast segmental concrete box girder bridge spanning the Choctawhatchee Bay between Destin and Niceville, FL. Like the Niles Channel Bridge, the Mid-Bay Bridge construction method was span-by-span and used neat cement grout. Each of its spans has 6 tendons, and each tendon has 19 0.6-inch (15.2-mm), 7 wire strands in 4-inch (100-mm) polyethylene (PE) ducts. The bridge opened to traffic in 1993.

In August 2000, a routine inspection revealed that a failed tendon had separated from an expansion joint diaphragm due to severe corrosion in the anchorage zone. The strong bond between the grouted steel pipe and the failed tendon section pulled the steel pipe from the expansion joint diaphragm during the tendon rupture (figure 3).

The failure pattern resembled the failed tendon observed in the Niles Channel Bridge. This incident was regarded as the second PT tendon failure by corrosion in the United States.

Figure 2. Photo. Failed tendon in the Niles Channel Bridge (main cause: chloride).(4,5)

© 2002 Florida Department of Transportation (FDOT).

Figure 3. Photo. Failed tendon in the Mid-Bay Bridge (main cause: chloride).(4)

© 2002 FDOT.

A second deteriorated tendon discovered in another span was ruptured but was severely damaged. The PE duct was cracked, and 11 strands were fractured in the free length of the tendon. Speculation was that the penetration of moisture and air through the cracked ducts appeared to initiate corrosion. The measured chloride concentrations in the grout samples were very low (0.150 lb/yd^3 (89 parts per million (ppm)) to 0.259 lb/yd^3 (154 ppm)) to play a role in the corrosion process.

These corrosion problems prompted the Florida Department of Transportation (FDOT) to launch emergency inspections, including visual crack inspections, vibration testing, the sounding of all ducts, and borescope inspections of all 1,728 anchorages. Inspectors subjected each PT tendon to magnetic flux leakage (MFL) testing to locate significant section losses nondestructively. The MFL testing located potential corrosion problems and wire fractures in two tendons. At the end of the inspections, inspectors replaced 11 severely corroded tendons of 846 tendons, and regrouted anchor voids using the vacuum grouting (VG) method.

Hartt and Venugopalan carried out a field investigation on the Mid-Bay Bridge's failed tendon and other tendons.(6) Although the duct cracking problem was the primary focus of Hartt and Venugopalan's investigation, some of their findings were related to segregated grout, which contributed to severe corrosion of the PT tendons. Specifically, they observed a white powdery deposit, a sign of grout segregation, along a void channel on a tendon and speculated that the channel was formed by air and bleed water during the grout segregation process. The quantity of white powdery deposit was directly proportional to the cross-sectional area of the void channel. The two investigators observed the channels and a white powdery deposit mostly in the top half of the tendon, but, in some cases, the channels and deposits also extended along the underside of individual strands or several closely grouped strands. White chalky grout was also found in an 8-ft-long (2.4-m-long) section of a tendon. However, the grout in the lower half of the tendon was typically dark gray, well consolidated, and showed no signs of segregation.

The investigators concluded that grout segregation occurred along the tendon in the presence of excess bleed water. Eventually, evaporation or reabsorption of bleed water into the grout resulted in a void at the exit anchorage area. The Hartt and Venugopalan investigation is credited with reporting the first domestic case of grout segregation-related problems, which were limited to isolated areas with no significant physical deficiencies.

The grout in two tendons revealed high pH values except within a thin top layer (16 mil (0.4 mm)). The white powdery deposit at the top of a tendon had a pH in the range of 8 ± 1 before cleaning with a wire brush. The lowest pH was 6. After cleaning, the pH increased to 12 ± 1. At the bottom, the 0.25-inch-thick (6.4-mm-thick) grout was carbonated with a pH of 8 ± 1. Investigators found the broken wires in this layer. The deeper grout, which exhibited a dark gray color, had a pH of 12 ± 1.

The investigators noted that the bleed water could be corrosive when it was carbonated and that adding an expansive admixture reduced its pH. Moreover, the carbonated grout (i.e., pH 8 ± 1) severely corroded four wires in the presence of oxygen and moisture. They also speculated that strand corrosion within grout voids and carbonated grout would reinitiate during periods of high humidity and that strand corrosion would also reinitiate in condensed water that previously was absorbed into the grout during occasional temperature drops below the dew point.

Also, investigators also noted that grout segregation occurred along the tendon in the presence of excessive bleed water; the bleed channels and a white powdery deposit were observed mostly in the top half of the tendon; evaporation or reabsorption of bleed water into the grout resulted in a void at the anchorage zone; and moisture and air penetrated the cracked ducts, resulting in depassivation and corrosion of the strands.

Eventually, grout carbonation, segregated grout, and excessive bleed water were collectively responsible for rapid tendon corrosion in the presence of oxygen, carbon dioxide, and moisture, irrespective of chloride concentration.

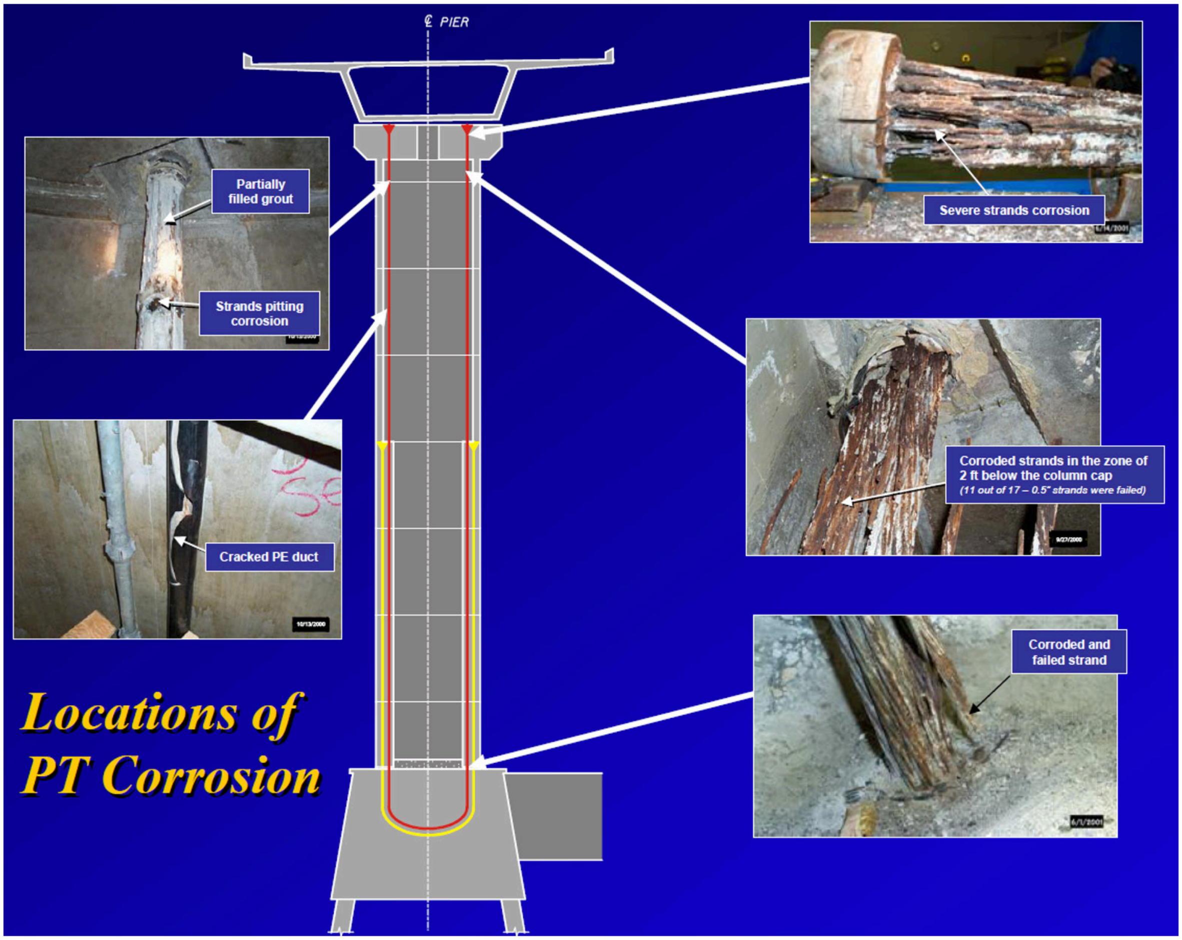
In 2018, a biennial bridge inspection discovered recurring corrosion problems on seven tendons in the Mid-Bay Bridge. A follow-up investigation in 2019 revealed that two corroded tendons were close to each other in the same span, a situation that forced FDOT to close the bridge for 8 d whether the 2000 investigations failed to detect ongoing corrosion problems or if new corrosion had started post inspection. Going forward, FDOT planned to conduct condition assessments of all tendons using a hammer-sounding method every 6 mo.

Sunshine Skyway Bridge in Florida (2000)(8,9,10)

The Sunshine Skyway Bridge is a 29,040-ft-long (8,851-m-long), precast segmental box girder bridge across Tampa Bay in Florida. The bridge was constructed using the span-by-span method and opened to traffic in 1987. The high-level approaches are supported by nearly elliptical, hollow precast segment columns with a mix of internal and external tendons. The vertical tendons holding the column segments together are bonded internally within the thick wall region and run externally along the upper inner walls. The 3 tendons are composed of 12, 17, and 18 0.5-inch-diameter (12.7-mm-diameter) strands housed in a 3-inch primary duct. This bridge uses a neat cement grout. The upper ends of these tendons are anchored in the cap and form a u-loop configuration in the footing. In the thick wall region, the 3-inch-diameter (76-mm-diameter) primary duct is inside a 5-inch-diameter (127-mm-diameter) corrugated PE secondary duct cast inside a precast segment wall. The bridge opened for traffic in 1987.

During a special inspection of the bridge in September 2000, inspectors discovered severe corrosion in a tendon housed in a northbound column: 11 of 17 0.5-inch (12.7-mm) strands were fractured at 2 ft (0.6 m) below a column cap. As a result, inspectors performed further inspections on all the other high-level approach columns (including comprehensive destructive testing on about 10 percent of the columns), the superstructure, and the cable anchorage of the main span. Figure 4 shows the locations of corrosion problems and illustrates construction of the precast segmental columns.

Figure 4. Schematic and photos. Column structure and locations of tendon corrosion (main cause: chloride).



Varina-Enon Bridge in Virginia (2007)[(11-15)]

The Varina-Enon Bridge, the only cable-stayed bridge in Virginia, opened to traffic in 1990 and carries Interstate 295 over the James River between the counties of Chesterfield and Henrico. The bridge is 4,680 ft (1,426 m) in length and consists of two parallel approach structures (southbound and northbound bridges) and a single structure on the cable-stayed main span. It has a total of 480 grouted external tendons and 360 PT bars. Each box has eight external tendons, and each tendon has 19 0.6-inch (15.2-mm) strands encased in a 4-inch, high-density polyethylene (HDPE) duct. The bridge opened to traffic in 1990.

In 2001, field inspectors found grout voids in many tendons, but the strands did not appear corroded. At that time, they also estimated that grout bleeding was approximately 4 percent in properly batched grout (water-cement ratio <0.42). This estimation meant that two 3-ft-long (0.9-m-long) voids at the high points adjacent to the anchor plates could be formed in a typical 150-ft-long draped tendon. Field inspections also found three issues. First, tendons were not appropriately sealed at metal straps used to connect a HDPE duct to steel pipe at diaphragms and bulkheads. Second, the seals on some vent tubes were incorrect. Third, previously holes had been drilled randomly in the HDPE ducts to check for voids. However, inspectors considered inadequate corrosion protection was limited to an isolated area. Following the discovery of the voids, the Virginia DOT (VDOT) carried out vacuum regrouting in 2003–2004 to fill the grout voids in 55 percent of the tendons.

In May 2007, a routine inspection discovered one failed tendon in the southbound bridge. Even though the tendon was regrouted in 2004, it still failed due to corrosion at the bridge age of 17 yr. Figure 5 shows the failed tendon: a short section attached to the diaphragm (figure 5-A) and the opposite section to the ruptured section fell onto a deviation block (figure 5-B).

Figure 5. Photos. Failed tendon in Varina-Enon Bridge (main cause: defective grout).

A. Section attached to the diaphragm.

B. Opposite section on a deviation block.

Source: FHWA.

Corrosion also damaged another tendon due to ponding water near a clogged drain hole in the bottom slab of a box girder. Both tendons were replaced in 2007. In late 2007, MFL testing conducted on approximately 17 mi (27 km) of external tendons (approximately 3,200 sections) identified a severely corroded tendon.

Additional inspections were conducted after removing 2-ft-long duct sections from the selected 20 tendons. The inspection discovered incomplete regrouting and broken wires in two tendons in the northbound bridge. After opening the selected tendon sections, inspectors also found large longitudinal grout voids between the 3 and 9 clock orientation (tendon top is 12). Some strands were partially exposed without any recognizable corrosion. However, well-hydrated grout filled the bottom portions of the strands. The top section of the exposed grout appeared porous, weak, and covered with white powdery grout. The defective grout condition indicated that grout segregation occurred during grouting.

Laboratory analysis revealed that all grout samples taken from the failed tendon had less than 0.003 percent acid-soluble (total) chloride by weight of cement, which was well below the corrosion threshold. On the other hand, the repair grout contained an elevated level of sulfate ions. Based on the analyst's findings, VDOT concluded that excessive sulfate in the repair grout might be responsible for such a rapid corrosion failure.

The original gray grout was an unsanded neat paste of ordinary portland cement and water. The estimated water-cement ratio was from 0.45 to 0.55 or greater (possibly greater than 0.65). Where the grout was medium to dark gray, the water-cement ratio was low. Where the grout was soft and pale gray, the water-cement ratio was high. Some settled dark cement lumps along the bottom end of the HDPE duct suggested that the grout had high water content and experienced bleeding before setting.

The repair grout material was found in the portion of the tendon next to the zone of strand failure (trailed off within a 4-ft (1.2-m) section of the failed area). It appeared to have been placed in the tendon after the original gray grout. The tendon in question had a 20-mil- (0.51-mm-) thick layer of sanded gypsum grout at the top surface. The repair grout contained minor amounts of a soft and whitish paste consisting of abundant cement paste, moderate amounts of clear siliceous sand, and minor amounts of small non-entrained air voids. The pH values of the samples were somewhat lower than that of normally hardened grout. The total sulfur (SO3) content of the white grout samples ranged from about 29 to 32 percent, which was substantially higher than expected for the portland cement-only grout. Additional free calcium sulfate, likely in the form of gypsum, was present as the major binder component.

In 2017, a transverse tendon also failed because of corrosion near the parapet in the main span. A follow-up investigation assessed the condition of transverse tendons in two cable-stayed spans (98 tendons per span) using the impact echo technique and inspection holes, visual inspections of over 20 tendons confirmed that many locations were fully grouted but contained weak grout. Vertical tendon inspections of the superstructure and substructure in 72 locations found 43 voids and 24 tendons (16 at the top of the pier anchors and 8 in the box anchors) exhibited significant corrosion.

As part of the corrosion mitigation effort, in 2015 VDOT injected four tendons with an impregnated type of corrosion inhibitor. Also, an acoustic emission monitoring system was recently installed on the bridge as the most economical technology for detecting real-time wire breaks and making decisions concerning tendon replacement. The system monitors some longitudinal external tendons, transverse internal tendons, the cable stays, the piers, and the towers. In operation since October 2020, the system has had no wire breaks reported as of April 2021.

Cline Avenue Bridge in Indiana (2009)(16,17)

The Cline Avenue Bridge is a 6,600-ft-long (2,012-m-long), cast-in-place concrete box girder bridge over the Indiana Harbor and Ship Canal in Indiana. It opened to traffic in 1983. A routine inspection identified significant longitudinal and transverse cracking in the bridge deck and more cracking in the webs and diaphragms. Indiana Department of Transportation (INDOT) was concerned enough about the condition of the PT tendons to conduct a field investigation in 2003.

Of 1,063 total tendons in the bridge, inspectors used drilling and borescope on 277 tendons (26 percent). Inspectors found a total of 33 voids at high points. Eight of them exposed the strands, but none was corroded. After the borescope inspection, INDOT filled the voids using the VG method. The investigators concluded that most of the PT system functioned with little corrosion (no section loss). The exception was at a few couplers, where significant duct voids resulted in some cross section losses.

However, a later year routine inspection revealed significant corrosion of PT tendons and reinforcing steel bars caused by water seeping through cracks in the bridge deck. INDOT determined that the level of corrosion compromised structural integrity beyond viable repairs. Consequently, the bridge permanently closed in November 2009 after 26 yr of service.

Plymouth Avenue Bridge in Minnesota (2010)(5,18,19)

The Plymouth Avenue Bridge is the first cast-in-place segmental box girder PT bridge constructed in Minnesota and opened in 1983. It consists of two parallel twin concrete box girders with varying depths of 10 to 13 ft (3 to 4 m) and carries Plymouth Avenue over the Mississippi River on the north side of Minneapolis, MN. This bridge has a total length of 943 ft (287 m) with a deck width of 75.5 ft (23 m) for four lanes of traffic and two pedestrian sidewalks. Among five spans, span numbers 1, 2, 4, and 5 were cast in place on falsework, MnDOT constructed the 260-ft (79-m) main span (span 3) using form travelers in unidirectional, cast-in-place cantilever construction. Each internal tendon contains 19 0.5-inch-diameter (12.7-m-diameter) 7-wire strands in a 3.5-inch (89-mm) metal duct.

During an annual inspection in 2010, inspectors observed slab cracking and rust stains in the box girders. A follow-up inspection revealed significant cracking, rust stains, and corrosion of internal continuity tendons buried in the bottom slab under the delaminated concrete. Figure 6 shows the damaged bottom slab.

Figure 6. Photos. Plymouth Avenue Bridge's severely damaged bottom slab (main cause: chloride).(5)

A. Interior condition.

B. Exterior condition.

© 2012 MnDOT.

The bridge was closed for nearly 1 yr to carry out detailed inspections, subsequent repairs, and the installation of five additional external tendons in each box girder to strengthen the bridge. Each new tendon contains 12 0.6-inch (15.2-mm) strands. The new tendons were installed through new concrete deviation blocks attached to the bottom slab and anchored in the concrete blisters (anchor blocks) newly formed at the girder ends.

The 2010 investigation also determined that the chloride-bearing water from the deck that leaked through the misaligned drainage pipe sections inside the box girders and deicing salts accumulated in the bottom slab triggered corrosion of the internal tendons and adjacent reinforcing steel.

The bottom slab had large, patched areas over the base concrete. Delaminating the patches allowed direct ingress of moisture, chloride, and oxygen to the tendons and structural reinforcing bars. Investigators observed that the totally corroded metal duct and grout and corrosion products mingled with severely corroded strands such that individual wires could not be distinguished. Nearby concrete contained a high level of acid-soluble chloride concentration (nearly 0.8 percent by weight of grout) at 0.8 inches (20 mm) deep.

The investigation included spot checks at high points of the tendon ducts in the box girder webs and other areas of interest, i.e., areas with moisture present on the web surface. Investigators also observed a good quality grout without moisture. The grout contained 0.075 percent acid-soluble chloride concentration by weight of grout, which explained its corrosion-free condition. The conclusion was that the web tendons were in good condition and appeared fully grouted with a normal (nonsegregated) grout. Although the grout used in the Plymouth Avenue Bridge would likely be neat cement grout (i.e., a nonthixotropic), the overall quality of the grout was considered very good.

Ringling Causeway Bridge in Florida (2011)(20,21,22)

The Ringling Causeway Bridge is a 3,094-ft-long (943-m-long), 106-ft-wide (32-m-wide) precast segmental box girder bridge spanning Sarasota Bay and the Intracoastal Waterway of the Gulf of Mexico in Florida. Completed in 2003, the bridge consists of 11 spans supported by 4 fixed and 5 expansion piers plus 2 abutments. The box girders have a three-cell configuration with a variable depth from 8.85 to 16.4 ft (2.7 to 5.0 m) held by internal and external tendons. Half of the span between piers consists of 12 12-ft-long (3.7-m-long) precast segments. This bridge is the first constructed with segmental duct couplers and prepackaged non-bleed/thixotropic grout in Florida. Each of the external tendons contains 22 0.6-inch (15.2-mm) 7-wire strands in a 4-inch-diameter (100-mm-diameter) HDPE duct.

Figure 7 shows corrosion failure of an external tendon was discovered in January 2011, and another external tendon failed in July 2011 after less than 8 yr of service. The figure shows the as-discovered condition when the failed tendon fell to the girder floor. The inset image shows the complete separation of entire strands due to severe corrosion.

Figure 7. Photos. Ringling Causeway Bridge's first failed tendon (main cause: defective grout).(21)

© 2011 FDOT.

These tendon failures were the first incident involving a prepackaged grout product in the United States, originally thought to be a solution to grout-related problems.

The first tendon failure occurred in the upper horizontal portion of a sloped tendon section adjacent to an upper deviator. This tendon exhibited severe corrosion mostly concentrated on the strands in the upper portion of the failed tendon. Except for the heavily corroded strands, the failure mode of the remaining strands appeared ductile, as evidenced by necking signs at the ruptured ends of the wires. The corroded-in-two wire tips suggested that the failed tendon must have been exposed to a very corrosive environment for some time. Also observed was corrosion in the upper portion of the galvanized steel pipe in the upper deviator. Although there is no initial photograph of the pipe's condition, two distinctive rust lines on the interior wall indicated that there likely was water or watery grout up to the rusty watermarks for an unknown duration after grouting.

The strands in the upper horizontal region of the tendon were not fully embedded in grout, and the cross section in some locations appeared more than half empty. The grout filled into the bottom was well consolidated and hardened with a thin white chalky layer at the grout and void interface. Cementitious residues on the upper part of the strands suggested that the tendon might have been initially filled to that level.

The grout in other sections filled the duct, but strands were partially exposed in the voids. Tight confinement of the strands against the HDPE duct wall appeared to create some voids. Most voids in the sloped tendon sections were still associated with a continuous longitudinal groove (bleed channel) at the 12 clock orientation. An upward movement of liquid and gases and subsequent severe grout segregation in a plastic state might have contributed to forming the large voids, segregated grout, and imprints of bubbles. As a result, the grout was moist and soft throughout. Unlike brittle and easily breakable grout found in the upper horizontal region, the segregated grout in this region remained claylike. It changed its color from dark gray to white upon drying in laboratory air.

Also in 2011, the second failed tendon occurred at the west face of an upper deviator. Severe corrosion damage was not as localized as it was in the first failed tendon. Instead, corrosion and strand fracture were observed at several locations within a 20-ft (6.1-m) section. The remaining strands showed a ductile fracture with necking. Severe corrosion of the strands within the galvanized steel pipe in the upper deviator was also observed.

Also observed throughout the region of corrosion failure was segregated soft/wet grout. At the low point anchorage zone, a large amount of segregated grout was also observed wherein severe corrosion of the anchor head and strands occurred.

While the hardened grout adhered to the anchor head's upper and lower areas, severe corrosion was observed in the middle area between them. A lack of adhered grout there suggested that the area was initially occupied by a mixture of air and bleed water before corrosion took place in the absence of protective grout.

Unlike the first failed tendon, large voids were not present in the second failed tendon. Instead, highly segregated, poor-quality grout material filled significant portions of the tendon. Some tendon segments had minor void spaces caused by a closely packed strand bundle against adequate grout flow in the HDPE duct. Also, investigators observed stratification of the black layer and signs of gas venting at the grout's top surface. There were significant amounts of soft and wet grout adjacent to both sides of the upper deviator, where investigators first saw the duct separation. The segregated grout had a strong odor resembling ammonia. Stratification of silica fume particles and intermixing of the white chalky grout were also observed. The sedimentation did not directly cause grout segregation and stratification as evidenced by different forms of segregated grout interspersed within the cross-section. Severe corrosion typically occurred in the wet plastic grout area.

After the second tendon failure occurred, field investigations occurred on all 132 external draped tendons. The scope of the investigations included understanding why and how such rapid tendon failures occurred; characterizing the grout's consistency; locating segregated grout, voided areas, and corroded strands; and repairing or replacing the affected tendons.

Segregated grout characteristics were the clay-like consistency of soft and wet (moisture content 50–80 percent), a sedimented black layer with silica fume, and a white chalky (moisture content 20–50 percent) appearance. During inspections of other tendons, soft and wet grout was present at numerous locations and sometimes present in large regions. Other characteristics included high corrosion rate (CR), high pH, high sulfate concentration, other soluble ionic contents, and no significant chloride concentration. In addition to different material properties, the segregated grout and normally hardened grout exhibited different colors. For instance, the segregated grout tended to have a white or light gray color contrasted with the normally hardened grout's dark gray color.

Even though it was not clearly understood how the segregation process of the identical prepackaged grout product could produce such distinctively different grout textures and material properties, the observed corrosion problems were mainly associated with segregated grout.

Wando River Bridge in South Carolina (2016)[23-27]

The Interstate 526 Wando River Bridge (formerly the James B. Edwards Bridge), completed in 1989, connects Mount Pleasant and Daniel Island over the Wando River in Charleston, SC. It is the only segmental box girder bridge in the State and was constructed using a span-by-span method for the two approach units and a balanced cantilever method for the main span. The bridge has two 7,900-ft-long (2,408-m-long) parallel structures carrying eastbound and westbound traffic. Each structure consists of 51 precast, segmental PT box girder spans and contains 696 longitudinal internal and external tendons, including 240 external tendons in the approach span units and 60 external tendons in the main span units. Each tendon has 19 0.6-inch (15.2-mm) 7-wire strands. The bridge also has 84 additional tendons composed of segments of concrete foundation.

Discovered in September 2016, the first external tendon failed when the M 1-South tendon loosened in the main span of the westbound structure. However, the bridge had other issues since its completion in 1989; since 2010, the bridge underwent several indepth inspections. A routine biennial inspection in May 2010 and a subsequent walk-through in August 2010 noted many deficiencies related to inadequate corrosion protection of the PT tendons. Following the cursory walk-through inspection in 2010, a comprehensive field investigation occurred in 2011. The following information summarizes the key findings.

The 2011 investigation inspected various locations on 31 tendons. The primary inspection used the visual inspection method with the help of a borescope on the external tendons. Even though there were grout voids, no strands were visible inside the voids. Also, there was a significant amount of corrosion products, presumably from a metal duct.

Water droplets observed in the anchorage area indicated that water was responsible for the active corrosion of that area. Most of the locations selected for investigation exhibited white-colored deposit material at pour-backs, unsealed holes in PE ducts, and duct connections adjacent to deviator blocks and diaphragms. In some cases, inspectors observed active water leakage. The main composition of the white-colored material was calcium carbonate, which accumulated after water that had infiltrated the PT system evaporated. One confirmed water source was an open grout vent tube in a diaphragm that extended up to the deck. There might be more locations where the grout vent tubes were partially filled or filled with poor-quality grout.

Other factors conducive to corrosion included incomplete grouting; extensive grout carbonation; and defective grout exhibiting excessive porosity, cracks, and absorption. Galvanic coupling of the tendons and dissimilar metals in the anchorage zone may also have increased corrosion.

A laboratory investigation inspected 6 strand sections retrieved from the failed tendon and 10 5-ft tendon sections from a span far away from the failure location. A visual evaluation of the grout revealed that, for the full lengths of all the tendon sections, the exposed grout was typically gray to dark gray with a good, hard consistency, except for segments of horizontal bands that contained porous, loose grout or white, chalky grout. These bands were indications that grout segregation occurred during construction.

Based on the investigation findings, investigators concluded that the unusual occurrence of two factors in an isolated area contributed to corrosion: poor quality grout void and exposure to recharged water (or moist air). These unfavorable conditions led to severe strand corrosion and, eventually, to tendon rupture. Nearby strands encased in poor-quality grout also experienced corrosion damages, even without chloride. Strands completely encased in good quality grout showed no corrosion.

Investigators discovered another failed tendon (M-5) in the westbound structure near the first failed tendon during a weekly routine walk-through inspection in May 2018. This tendon failure led to an emergency closure of the westbound structure for nearly 3 w. Examination of the fractured strands revealed 107 wires (80.5 percent) ruptured by corrosion and the remaining 26 wires (19.5 percent) ruptured by overstressing in the presence of reduced cross-sectional areas. During the replacement of the damaged tendon, workers added two extra external tendons to increase structural redundancy.

Roosevelt Bridge in Florida (2020)[28]

The latest corrosion problem was in the internal PT tendons on the Roosevelt Bridge crossing the St. Lucie River in Stuart, FL, in 2020 after approximately 23 yr of service. This concrete bridge construction used the precast segmental box girder technique consisting of 2 separate structures carrying 3-lanes southbound and 3-lanes northbound on Highway 1 (US–1). The northbound structure is 4,566 ft (1,392 m) long, and the southbound structure is 4,487 ft (1,368 m) long. Both structures have a deck width of 61 ft (19 m) and a maximum clearance above the water of 65 ft (19.8 m). Surrounding the strands in the internal PT tendons are cementitious grout and galvanized metal ducts. The failed tendons were in the southbound structure's span number 1.

Laboratory analysis of the grout samples revealed samples contaminated with excessive chloride concentrations ranging from 12.5 to 25.0 pounds per cubic yard (lb/y^3), 7.4 to 14.8 kilogram per cubic meter (kg/m^3) of the sample weight. Furthermore, the concrete's chloride content obtained in the vicinity of the failed tendons was around 30 pcy (17.8 kg/m^3). The grout samples contained low levels of sulfate ions (<96 parts per million (ppm)).

Field investigations confirmed that water containing chloride ions penetrated through some of the segment joints and metal ducts and evaporated in time. As a result, the chloride ions accumulated in the affected grout or concrete over time. Sealing the bridge deck with an overlay to reduce the water recharge on the bottom slab tendons is complete. Nonetheless, the conclusion was that the existing chloride-contaminated grout and water or moisture trapped in the PT system could lead to severe corrosion and possible failure of additional tendons in the future.

TENDON FAILURES IN FOREIGN COUNTRIES

European countries started experiencing PT tendon corrosion problems earlier than the United States. Some Asian countries also reported corrosion-induced tendon failures. The following paragraphs present notable failure cases observed in Europe and Asia.

In the United Kingdom, the Bickton Meadows Footbridge, a precast segmental bridge, collapsed in 1967 due to the corrosion of prestressing steel. In 1985, a single-span segmental bridge, the Ynys-y-Gwas Bridge, also suddenly collapsed due to the corrosion of internal tendons. In Belgium, the Melle Bridge collapsed in 1992 due to hidden corrosion damage on the prestressing steel.(29-33)

In France, several bridges also experienced tendon failures:(34)

- A prestressed concrete bridge built in 1986 over the Durance River experienced a tendon failure near an anchorage in 1994.
- The Saint-Cloud Viaduct over the Seine River that opened to traffic in 1974 suffered from one tendon failure at the lowest point between two deviators in 1998.
- The Riviere d'Abord Bridge that opened to traffic in 1991 experienced one external tendon failure at an anchor zone in the upper part of a pier segment in 2001.

In Italy, at least three PT bridges experiencing serious corrosion problems or structural failure were reported:(35,36,37)

- External tendons in an unidentified bridge failed less than 2 yr after construction due to a whitish unhardened paste exhibiting high pH.
- One span of the Petrulla Viaduct in Sicily built in the mid-80s collapsed due to a lack of grout in the internal tendons and improperly sealed grout vent tubes.
- One ramp of La Reale Viaduct collapsed in 2017 due to a lack of sufficient grout protection at the collapsed joint.

In South Korea during routine walk-through inspections, bridge inspectors of the Seoul Metropolitan Facility Management Corporation discovered failed external tendons due to corrosion in two precast segmental box girder PT bridges:(38)

- Cheong-Rung Creek Bridge, opened to traffic in 1999, lost one external tendon due to chloride-bearing water seeping through an opened air vent from the deck.
- Seo-Ho Bridge, opened to traffic in 1997, experienced tendon failures of two external tendons mainly due to the segregated grout.

In Hong Kong, the Highway Department staff discovered a ruptured external tendon on the Shenzhen Bay Bridge in February 2019.(39) It is a 6-lane bridge connecting Lau Fau Shan, Hong Kong, and Shekou in Shenzhen, China, and opened to traffic in 2007. Investigators concluded that three factors that occurred during the grouting operation contributed to the failure of the tendon: the segregation of grout due to excessive water in the duct, low pumping pressure, and the partial blockage of the grout vent tube at the failed anchor head that formed an air pocket behind the anchor head.

LESSONS LEARNED

Constructing a durable PT bridge and maintaining it throughout its service life can be achieved if every step during the construction and maintenance is performed correctly. If stringent requirements to ensure satisfactory performance are not met in any of the critical steps, corrosion can develop in localized areas containing deficiencies and eventually compromise the durability of the entire bridge. In many instances, corrosion-induced tendon failures and near-failure conditions have led to serious consequences, including temporary closures of the affected bridges during emergency repairs or tendon replacements.

Even though grout voids and exposed strands were reasonably common in the hardened grout, the probability of severe corrosion in the PT tendons has been relatively low. However, when an aggressive environment—chloride ions, sulfate ions, and grout carbonation—initiates intensive corrosion in local areas within a tendon, strand fracture can occur after a relatively short period, and, subsequently, the whole tendon can fail between 2 and 30 yr of service.

As the PT bridges get older, more durability problems will surface, and corrosion of PT tendons will likely continue to be a primary cause. Accordingly, the introduction of improved quality control and quality assurance practices to materials and construction processes would be desirable for building more durable PT bridges.

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The original map is the copyright property of lesniewski/AdobeStock and can be accessed from https://stock.adobe.com. The map overlays show the names of 10 major bridges that experienced tendon failures. Red and blue stars mark the approximate location of each bridge. Red stars signify the cause of the failure was chloride ions; blue stars signify the cause of the failure was defective grout.

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