Corrosion Evaluation of Bonded Post Tensioning

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Abstract

Corrosion of bonded post-tensioning (PT) can proceed with no externally visible signs of concrete deterioration until significant section-loss has occurred, which can seriously affect the structural capacity of the element. PT corrosion is typically caused by grouting defects, such as voids and soft grout. Grouting defects cannot be detected through normal bridge inspection methods like visual or tactile inspection methods because the PT strands are encased within plastic or metal ducts and are often embedded within slabs or walls. VCS has effectively used non-destructive testing methods such as ground penetrating radar (GPR) and impact echo/pulse velocity (IE/PV) testing to locate grouting defects in both internal and external PT tendons as well as PT moisture testing to determine if the if the tendons are exposed to a corrosive environment. This paper discusses the testing performed on bridges with bonded PT using three case studies. In addition, it includes a discussion of effective preservation techniques that are used on bonded PT to mitigate the defects.

Introduction

Throughout the world, voids and soft grout problems have been found within bonded post-tension (PT) ducts due to improper/ineffective grouting during construction. Despite the natural alkalinity of the grout these grouting defects often create environments that are favorable to the corrosion of the high-strength steel strands within the ducts. FHWA Publication No. FHWA-HRT-24-148[1] discusses failures of bonded PT tendons that have occurred in the US bridges up to 2020. Although each bridge had its own cause of tendon failure, they can all be attributed to either grouting defects that occurred during construction or chloride-contaminated water that had leaked from the deck.

The major challenge with the condition assessment of PT tendons is that PT grout defects cannot be identified through standard bridge inspection methods like visual and sounding inspection. PT tendons are encased within metal or plastic ducts and are embedded within the concrete which makes typical tactile and visual inspections ineffective in detecting and assessing PT defects or deterioration. As a result, issues in the grouting are often unidentified until advanced deterioration has occurred.

Most commonly, specialized PT inspections are initiated when there is observed concrete deterioration that points to potential PT issues. These concrete issues are cracks that follow the PT tendon profile and concrete spalling in the vicinity of the tendons. Excessive deflections in PT cantilevered slabs and, in extreme cases, visibly failed tendons can also trigger PT inspections. This is reactive approach that aims to address existing issues. PT inspections can also be carried out using a proactive approach to give the owner peace of mind that they structure does not have any grouting defects that put the PT at risk for corrosion or to allow them to address the issues before the damage has occurred.

Evaluation Methods

The objective of the evaluation phase is to assess the PT to determine if there are any issues regarding corrosion or grout defects that would affect the durability of the bridges. The evaluations include using non-destructive testing (NDT) methods, borescope inspections, and larger window openings to fully understand the condition of the PT and the presence of any grout defects or deterioration of the PT strands. The evaluation phase documents the location and size of the defects.

The NDT methods typically used by VCS include ground penetrating radar (GPR) for internal tendons, impact echo/pulse velocity testing (IE/PV) for internal and external tendons, and moisture testing, which can also be used on internal and external tendons. GPR is an electromagnetic testing method that is used to locate the PT onsite. GPR is a quick and effective way of identifying the location and depth of metal objects within reinforced concrete. The GPR emits an electromagnetic signal that is transmitted through the concrete cross-section. The wave transmission and reflection strength are dependent on the contrast in electrical properties of the materials being investigated such as dielectric constant and conductivity. Embedded metals typically produce strong reflections in concrete and are typically easily detected because they are highly conductive in comparison to concrete. The GPR operator needs to distinguish between the PT tendons and rebar, which is done by looking at the position/depth and profile of the tendons (Figure 1). Once an internal tendon is located, its profile is marked on the concrete surface for IE/PV testing.

IE/PV is used to effectively determine the presence of grouting defects, like voids and soft grout, in the PT tendons. Figure 2 shows the IE and PV data collection principle and illustrates using IE for locating grouting defects in internal tendons. IE measures the resonant frequency of an induced stress wave over the PT tendon. If the PT duct is voided or has a change in material properties due to soft grout, the path of the wave increases, lowering the resonant frequency. PV measures the velocity of the compressional and shear wave as it passes between the array of sensors and can be used to confirm the presence of grouting defects. In a fully grouted duct, the waves will pass through the duct, and their velocity will not be affected. A partially grouted duct or a duct with soft or incompetent grout will affect the wave's travel time between the sensors. Figure 3 and Figure 4 show typical examples of PV and IE data collected on fully grouted and voided ducts.

This testing can also be performed on external tendons (Figure 5). Here a transmitter placed on one side of the duct sends an ultrasonic PV signal to a sensor placed on the opposite side. As with the internal tendons, the measured distance between the transmitter and receiver is compared to the actual diameter of the duct. A measured diameter greater than actual indicates the presence of potential grouting defects.

The strength of the IE/PV technique is that it allows the condition of the PT grout to be evaluated non-destructively. With internal tendons, the embedment in the concrete web makes identifying issues without IE/PV extremely difficult. IE/PV provides rapid and effective means by which a trained technician can assess the condition of these very difficult but important structural components.

It should be noted that IE/PV testing cannot differentiate between different types of grouting defects. Lens voids and rind voids that do not expose the PT strands are generally considered benign from the durability perspective as they do not significantly increase the risk for PT corrosion. However, voids that expose the strands and soft grout create a corrosive environment and result in increased risk of PT corrosion. Another limitation of the IE/PV testing is that it cannot be used in the thickened sections like diaphragms and anchorages, which make the signal response difficult to interpret. To compensate for these shortcomings, IE/PV testing is typically coupled with borescope inspection, which is a minimally invasive testing method.

Borescope inspection locations are selected based on the IE/PV results predominantly at locations of grouting defects, although a few openings are also typically made in the fully grouted areas for verification. The first step is to drill a hole in the cover concrete to the duct exterior. Then hand tools are used to open the duct to allow access to the interior. Once the duct is opened, if there is a void, a borescope is used to visually inspect the condition of the void. The borescope can take photos and record video during the inspection to document corrosion of the strands and duct, broken strands, water, and other defects. If grout is present in the borescope opening, the technician probes the grout with a screwdriver to determine the presence of soft grout.

Similar to borescope inspection, moisture testing is a minimally destructive testing method that can be used on both internal and external PT systems. This test method measures the temperature and the relative humidity of the air present inside the duct, which can then be related to corrosion risk. In this test method, inlet and exhaust ports are installed along the tendon, and the inlet port is connected to a flow meter and a supply of compressed dry gas (Figure 7). As the dry gas is pushed into the tendon, it forces the air inside the duct through the exhaust port. The exhaust port is connected to another flow meter and a moisture meter that records the temperature and relative humidity of the air. The results are then plotted on a chart that relates these parameters to corrosion risk (Figure 8).

Large window openings can also be made to evaluate the grout materials. In addition to improper grouting, the chemical composition of the grout itself can have a significant effect on the service life of PT tendons. Things such as chloride and sulfate contamination can lead to advanced PT deterioration. To determine if any chloride contamination exists and to assess the potential risk for corrosion activity of the prestressing steel, grout samples are collected from the carefully conducted openings of the PT duct. The chloride content of the grout is assessed per ASTM C1152[2] *Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete.* In addition, petrographic examination can be conducted in accordance with ASTM C856[3] *Standard Practice for Petrographic Examination of Hardened Concrete.* The petrographic analysis can define the general and volumetric proportions of the grout mixture used in the original construction and identify if there are any chemical deterioration processes.

Case Studies

Case Study 1: Minnesota Bridges

VCS performed PT testing on 1 pedestrian and 2 vehicular bridges in Minnesota, USA. These bridges were constructed between 1996 and 1998. All three bridges utilize PT tendons in the concrete box girder webs. The pedestrian bridge has a single cell box girder with a total of 2 tendons in each span (Figure 9), and vehicular bridges have a four-cell box girder with a total of 15 tendons per span (Figure 10). The PT inspection was initiated due cracks observed in the girders that followed the PT tendon profile (Figure 11). The aim of this investigation is to locate PT grouting defects and determine their extent.

On this project, VCS performed GPR scanning to locate the tendons, IE/PV testing, borescope inspection and chloride testing of the grout. A targeted testing approach was used on this project. Testing was performed on 4.5 m of all the tendons from the anchorage locations and in both directions from the piers as the high points of the drape in deviated tendons are at the highest risk for grouting defects.

In the pedestrian bridge, voids and soft grout were identified in 1 tendon. No soft grout was identified in the vehicular bridges, but voids exposing the strands were found in both bridges with the largest void measuring 14.5 m. Overall, grouting defects were identified in 14% of the 1,319 m tested tendon length. Despite the presence of the voids, strands were generally in good condition with corrosion ranging from surface to moderate corrosion (Figure 13).

Large window openings were made for grout sampling (Figure 14). A value of 0.2% chloride by mass of cement is typically used as the corrosion initiation threshold for grout. This is based on a grout comprised of only portland cement and a water/cement ratio of 0.5. Chloride concentration testing performed in accordance with ASTM C1152[2] showed that chloride concentration in all the grout samples was well below the threshold and even below the 0.08% by mass of cement, which is the ACI 222[4] limit for prestressed (pretensioned or post-tensioned) construction.

Case Study 2: Ontario Bridge

This bridge was constructed in 1985 and utilizes 4 different types of bonded PT in the concrete box girders: longitudinal and transverse PT in the top flange, vertical PT in the webs, and longitudinal PT in the bottom flange. Here the owner used a proactive inspection approach to verify the condition of PT and ensure continued successful operation of the structure.

Due to the large number of tendons present in tis bridge, VCS selected representative tendons for testing focusing on the deviated sections which are at the highest risk for corrosion. The testing included GPR scanning to locate the tendons, IE/PV testing, borescope inspection and chloride testing of the grout. The IE/PV indicated the presence of grouting defects in 6% of the total tested tendon length. As expected, the grouting defects were generally located toward the high points of the tendon drape. While no true voids were identified during borescope inspection, the presence of soft grout was confirmed in 1% of the tested tendon length. The presence of corrosion at these locations was observed on the ducts, vertical PT bars, and strands. However, corrosion was limited to surface corrosion with no notable section loss. Chloride concentration of the grout was determined to be below the new construction limit and below corrosion initiation threshold.

Case Study 3: Post-Tensioned Pier Caps in Rhode Island

A number of bridges in Rhode Island utilize bonded PT in the pier caps. Concrete cracking at the ends of the pier caps raised concerns about possible PT issues, which initiated the PT inspection. The pier cap dimensions were too large to perform IE/PV testing. Instead, pour backs were removed at each end of the pier caps for visual inspection of the anchorages, grout ports were examined with a borescope, moisture testing was performed on the tendons, and grout samples were collected from the grout ports for chloride concentration testing.

Missing grout caps and voids inside grout caps were observed on several tendons (Figure 15). At voided locations, corrosion of the anchor plates and stand tails was observed. Although majority of the grout ports were full, borescope inspection showed that 6% of all the ports had lens voids that did not expose the strands, while 13% were voids that exposed the strands putting them at risk for corrosion. Figure 16 shows borescope images from some of the voided tendons showing corrosion of the strands. Moisture testing results showed that all the tendons were either in the “dry/wet” or “wet” classification, which puts them at a moderate and high risk for corrosion, respectively (Figure 17). Grout chloride concentration testing showed that only 1 sample was above the corrosion initiation threshold. An exposed grout port that was not enclosed by the pour back was observed at that location, most like allowing chloride-contaminated water leaking from the deck to enter the tendon (Figure 18).

Rehabilitation/Corrosion Mitigation Options

Once the presence of grouting defects is identified, several methods are available to mitigate corrosion of the tendons.

Regrouting

Voids should be regrouted with a cementitious grout to encase the steel strands and to prevent corrosion activity. The high alkalinity of a cementitious grout provides a protective environment in which a passive oxide layer forms on the surface of the steel protecting it from corrosion. However, care has be taken to ensure that the new grout is electrochemically and thermally compatible with the grout that is already installed in the tendons. Differences in the chemical composition, such as cement type, presence of supplementary cementitious materials (SCMs), various admixtures, etc., and resistivity can lead to accelerated corrosion of the steel that crosses the interface between the original and new grout.

PT Drying

Moisture content along the tendon has a significant impact on the risk and rate of strand corrosion. By reducing the moisture content, corrosion can be slowed or stopped. To accomplish the drying, inlet and exhaust ports are installed in each tendon, and dry air is passed through the tendon length. This dry air picks up the moisture and carries it out of the tendon. This process is continued until the tendons are at a low moisture level and are considered dry. This process often is the precursor to PT impregnation with a corrosion inhibitor when free moisture is present along the tendons. It is important that locations, where moisture could re-enter the tendons during or after drying are properly sealed. If the drying is performed and moisture re-enters the ducts, then the process will not be effective over the long term.

Corrosion Inhibitor PT Impregnation

The PT impregnation with a corrosion inhibitor is a rehabilitation method that is highly effective at mitigating the corrosion of PT tendons. Defects in PT tendons due to soft grout or voids can result in severe corrosion damage to the strands. The impregnation process coats the steel reinforcement and impregnates the surrounding grout thus protecting the strands from corrosion. The corrosion inhibitor used in the impregnation process is a specially developed low-viscosity material that travels along the interstitial spaces between the wires in a tendon and coats the steel strands (Figure 19). Due to the difficulty in accessing the full length of a PT tendon, the corrosion inhibitor can be applied either from the anchorage or from any point along the tendon length (Figure 20 and Figure 21). Very little pressure is required to push the corrosion inhibitor through the tendon since its primary transportation mechanism is the capillary effect along the strand. Occasionally vacuum is used to assist or control movement of the corrosion inhibitor. This method can be implemented on individual tendons or simultaneously on multiple tendons as necessary. The material creates a film on the strand's surface, protecting the steel from moisture and deleterious ions thus protecting the strands from corrosion activity (Figure 22).

Conclusions

Bonded PT tendons are susceptible to the presence of grouting defects, particularly in older structures. PT grouting defects cannot be identified through standard bridge inspection methods like visual and sounding inspection as PT strands are encased in the ducts and in the case of internal PT also located inside concrete members. Unless a proactive PT inspection approach is used, grouting defects may not be identified until advanced deterioration has occurred.

Despite the challenges with PT evaluation, several non-destructive and destructive testing methods are available that can identify the type, location and extent of grouting defects. Once the defects are identified, various rehabilitation methods are available to mitigate the presence of grouting defects and mitigate corrosion of the PT strands.

Figure 1. GPR Scanning to Locate PT Tendons

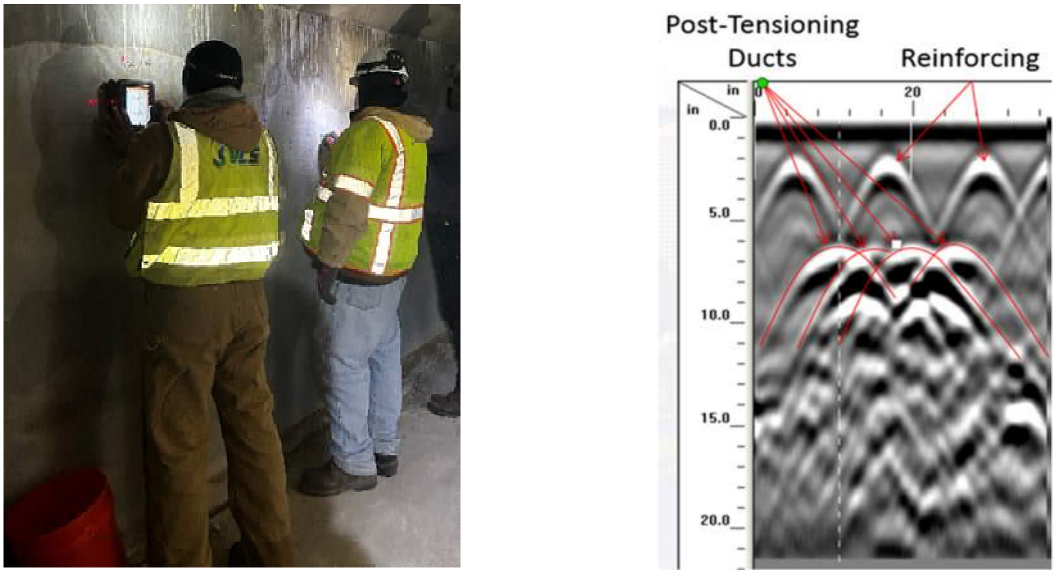


Figure 2. IE/PV Testing

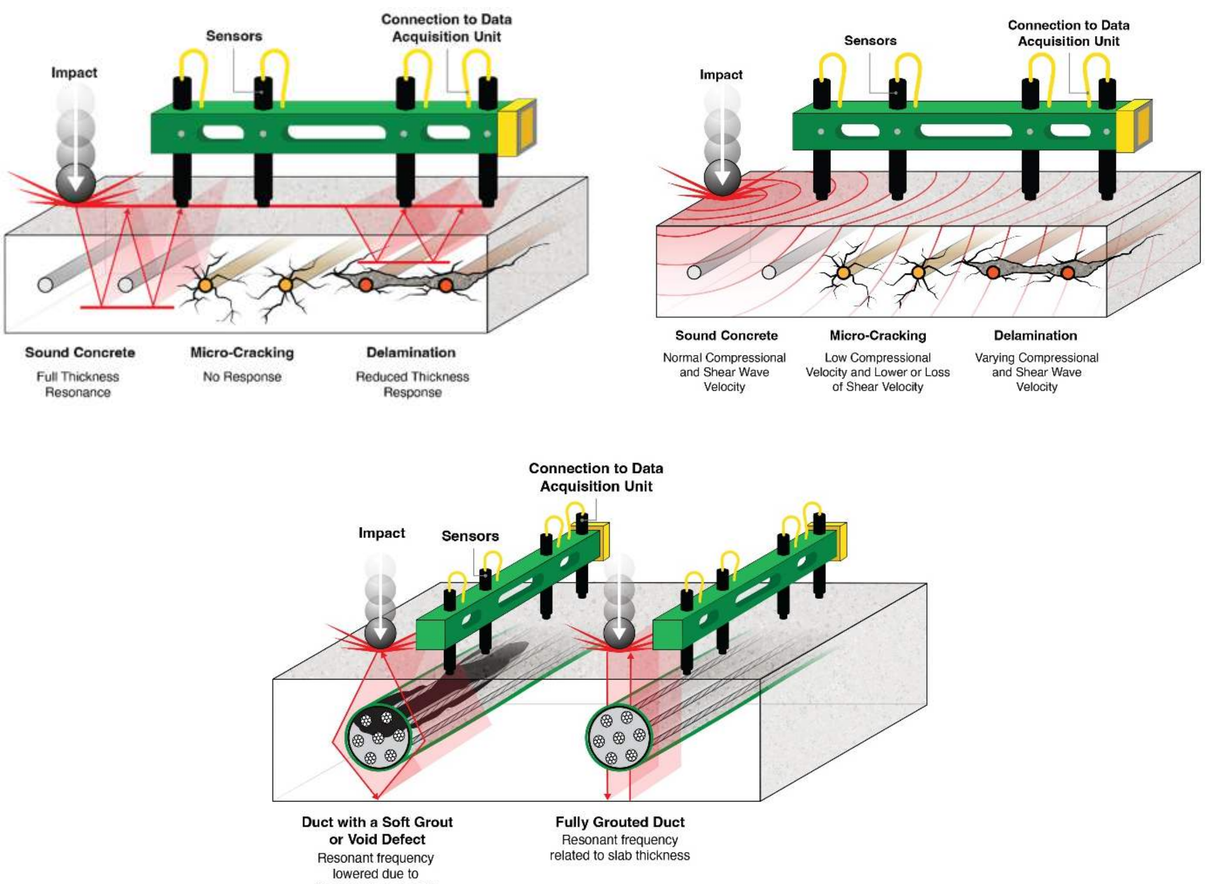


Figure 3. Typical Scan Results from Post-Tension Ducts that are Fully Grouted

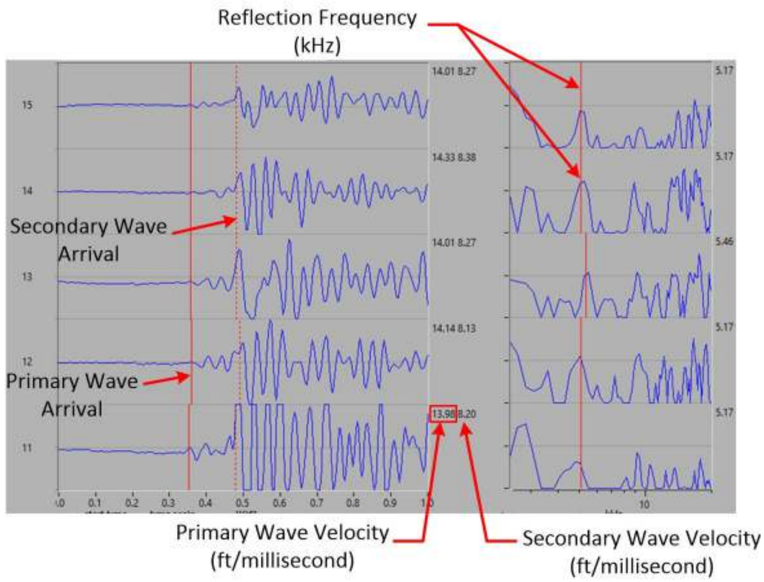


Figure 4. Typical Scan Results from Post-Tension Ducts that Have Suspected Defects

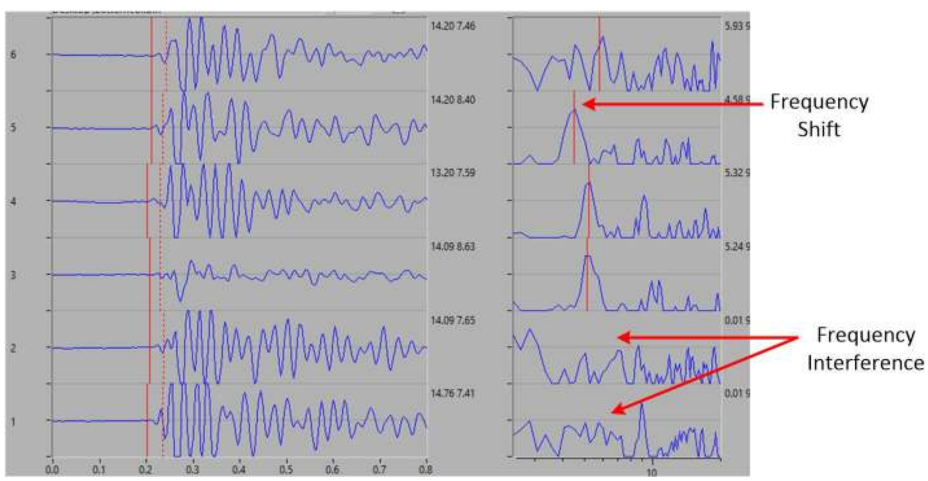


Figure 5. Testing of External Tendons

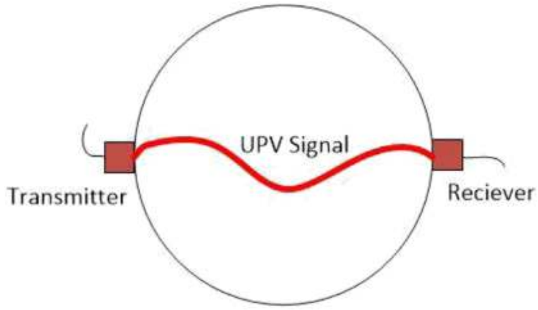


Figure 6. Borescope Inspection

Figure 7. PT Moisture Testing

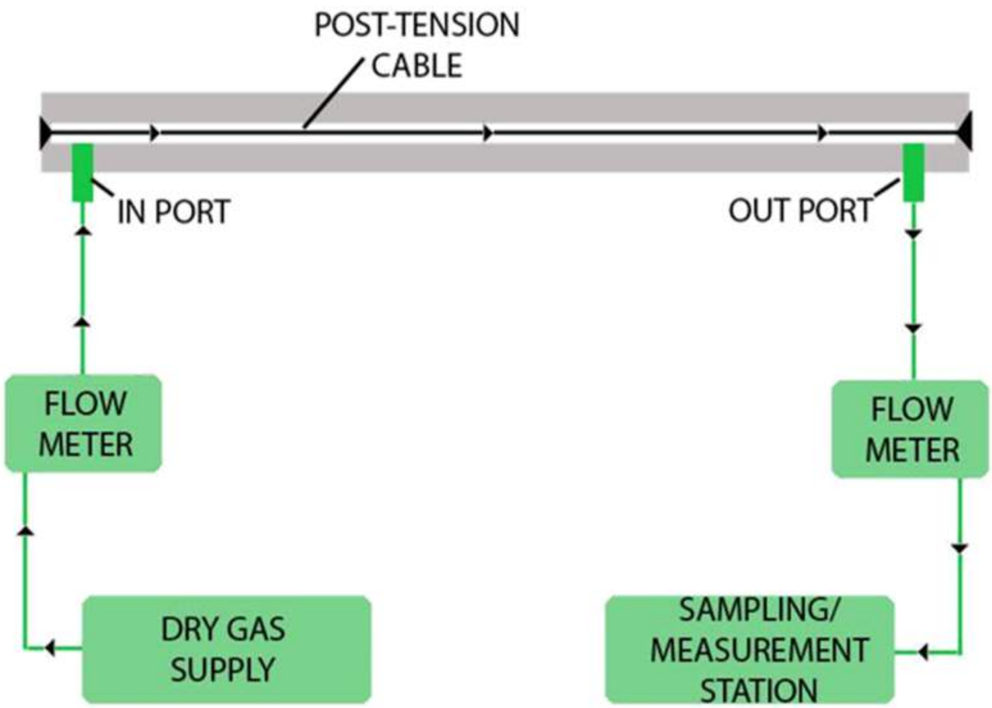
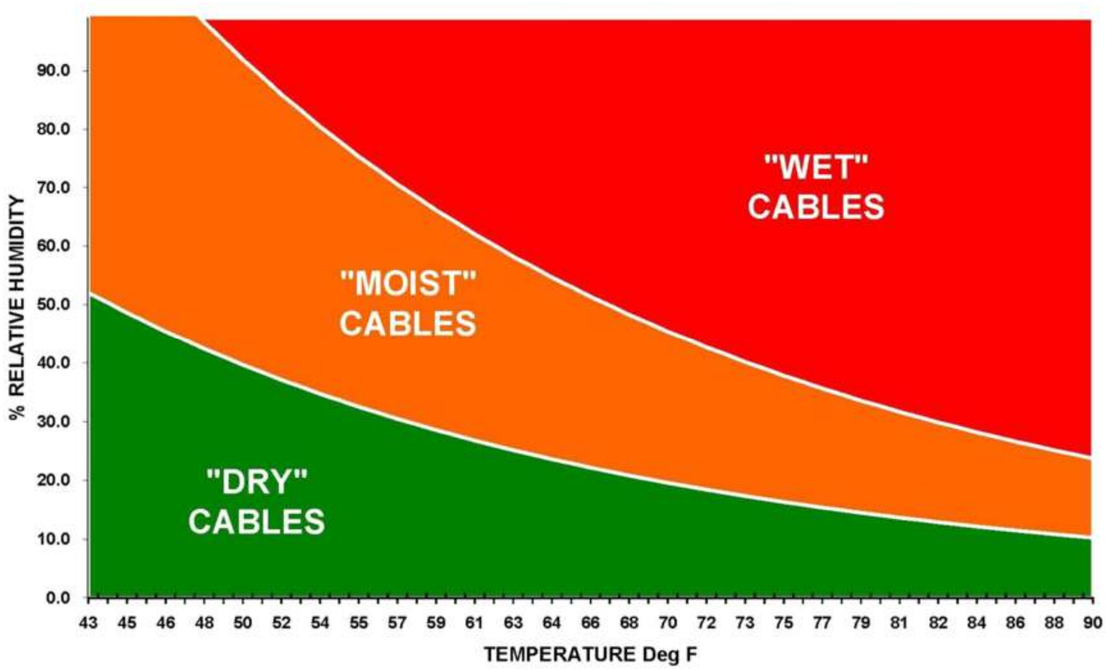


Figure 8. PT Moisture Testing Plot



<u>Risk of Corrosion</u>

- "Wet" – High
- "Moist" aka "dry/wet" – Medium
- "Dry" – Low

Figure 9. Elevation and Cross-Section View of the Girder for Pedestrian Bridge in Minnesota

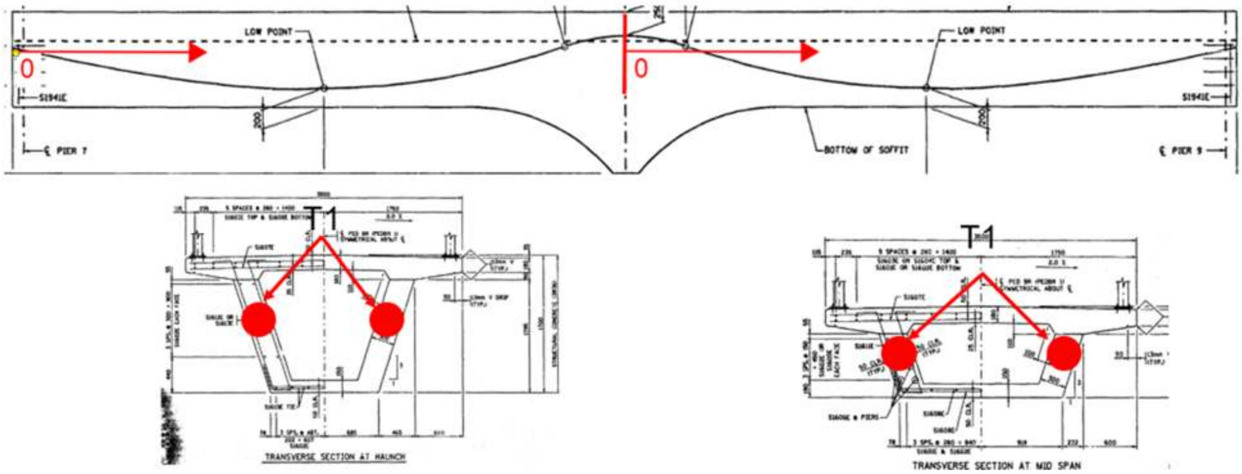


Figure 10. Elevation and Cross-Section View of the Girder for Vehicular Bridges in Minnesota

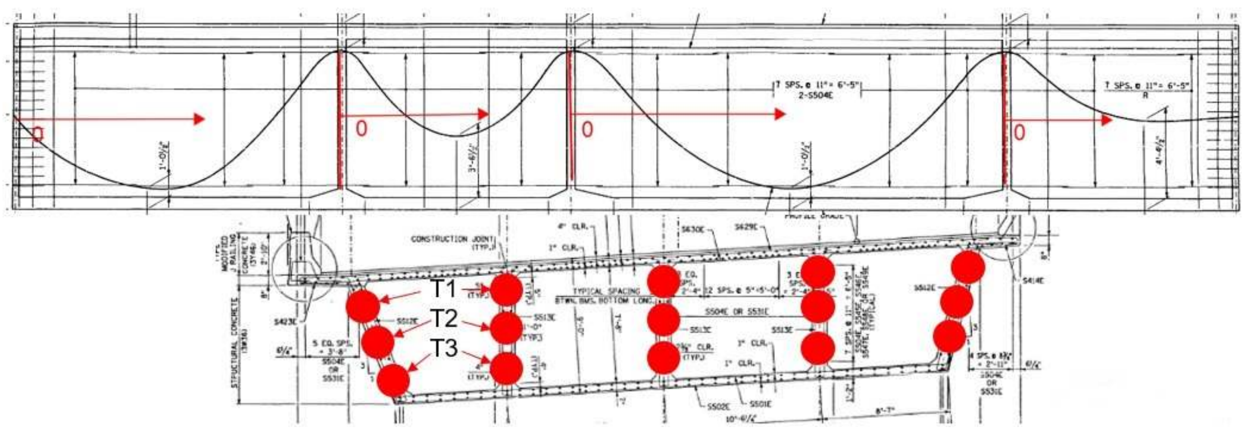


Figure 11. Cracking Following the PT Tendon Profile above a Void, Minnesota Bridges

Figure 12. Typical IE/PV Testing Results, Vehicular Bridge in Minnesota

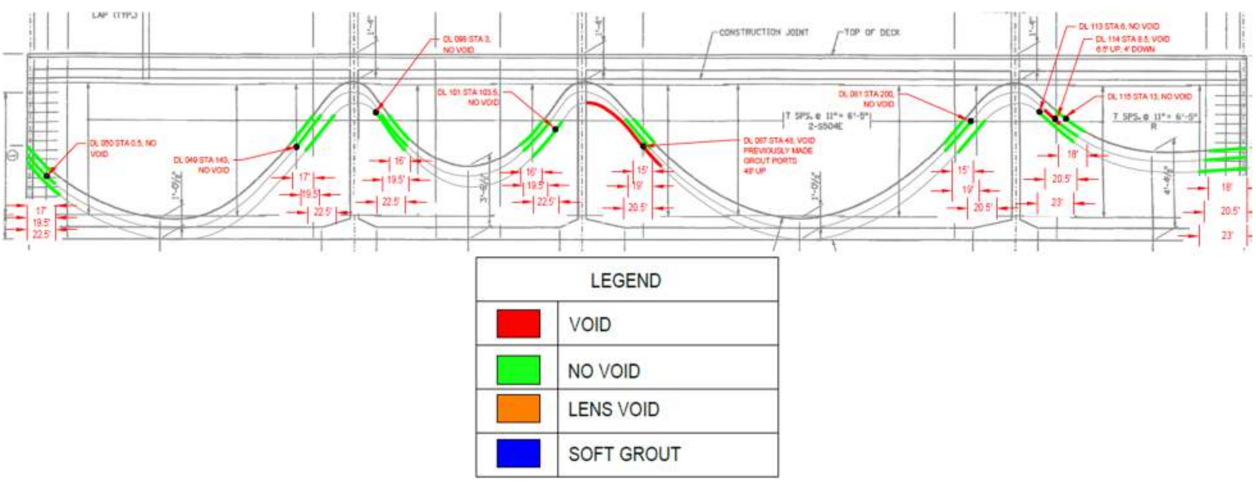


Figure 13. Typical Borescope Photos from the Minnesota Bridges

Figure 14. Typical Window opening for Grout Sampling, Minnesota Bridges

Figure 15. Missing Grout Caps and Voids inside Grout Caps

Figure 16. Borescope Images of Voided Tendons in the Pier Caps

Figure 17. PT Moisture Testing Results for the Pier Caps

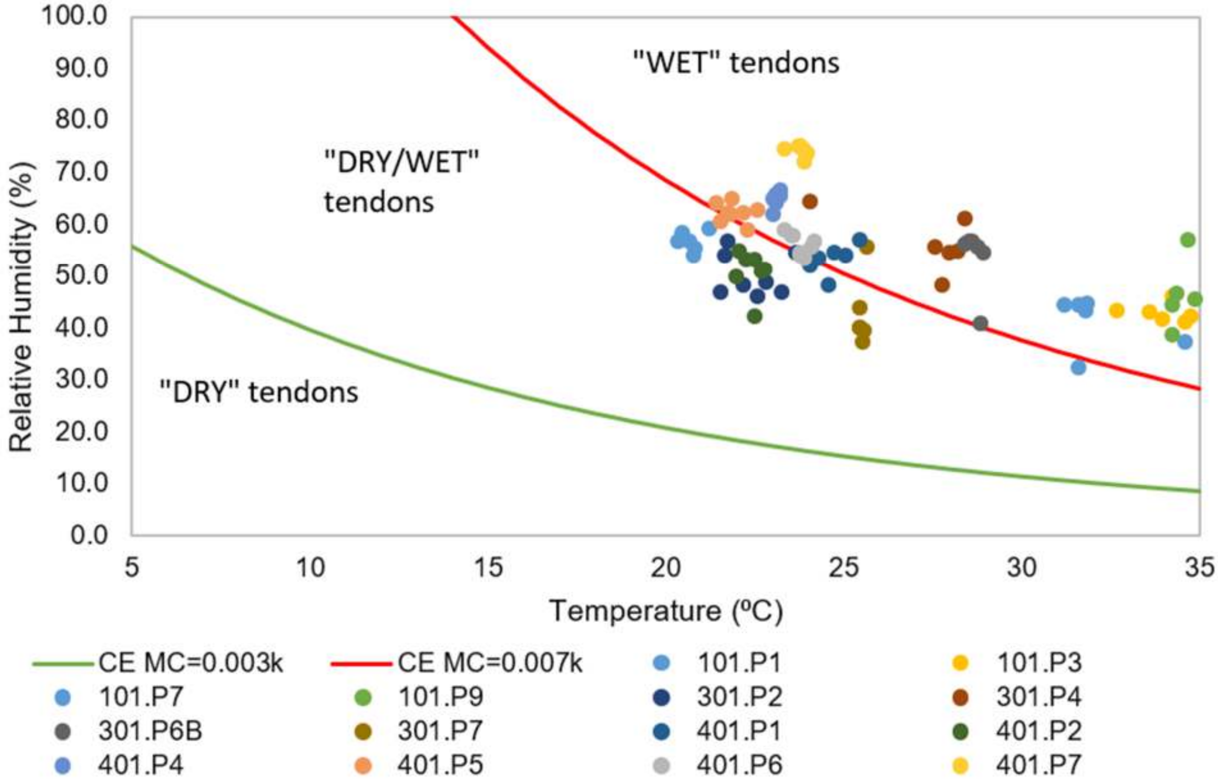


Figure 18. Exposed Grout Port in One of the Pier Caps

Figure 19. Illustration of the Interstitial Spaces inside a PT Strand

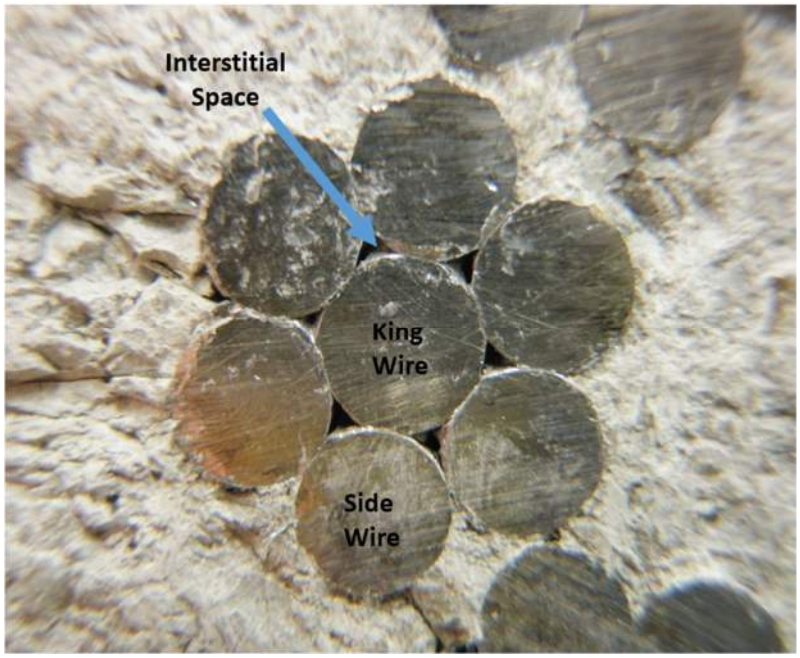


Figure 20. PT Impregnation through the Anchorage

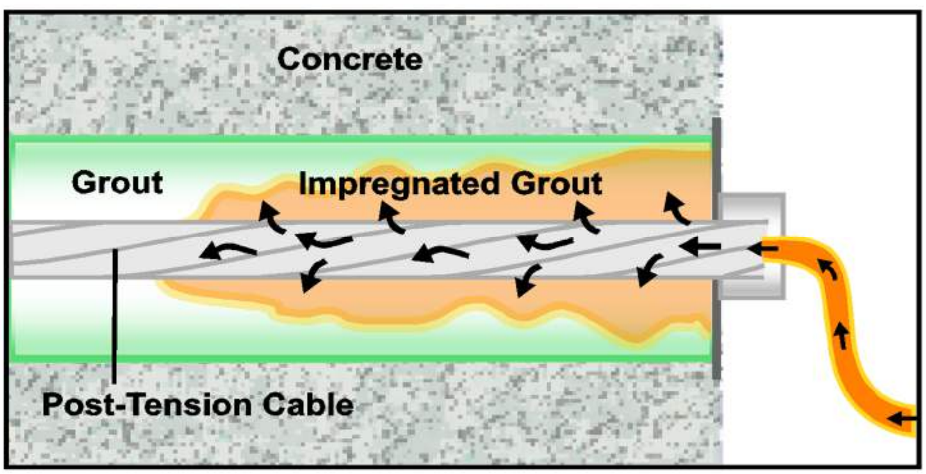


Figure 21. PT Impregnation along the Tendon Length

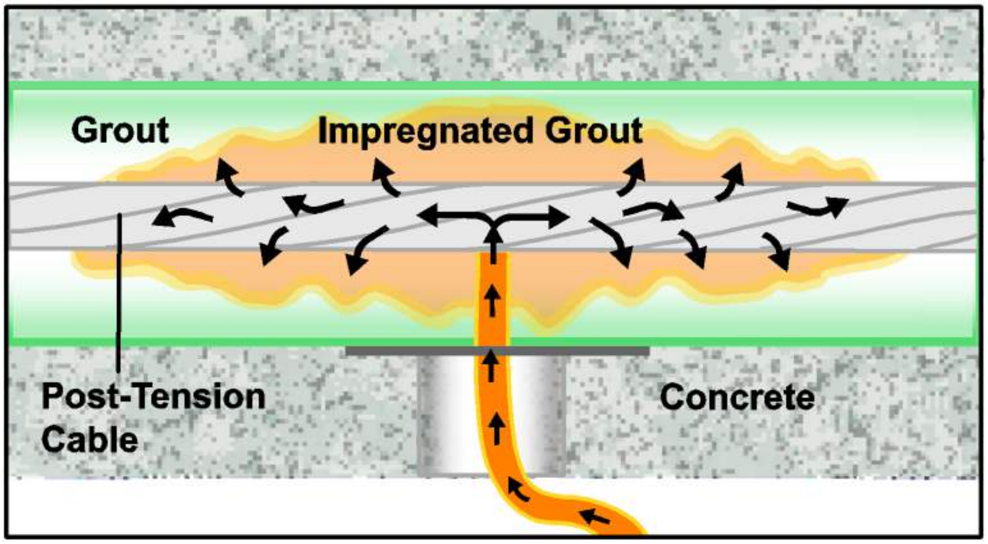
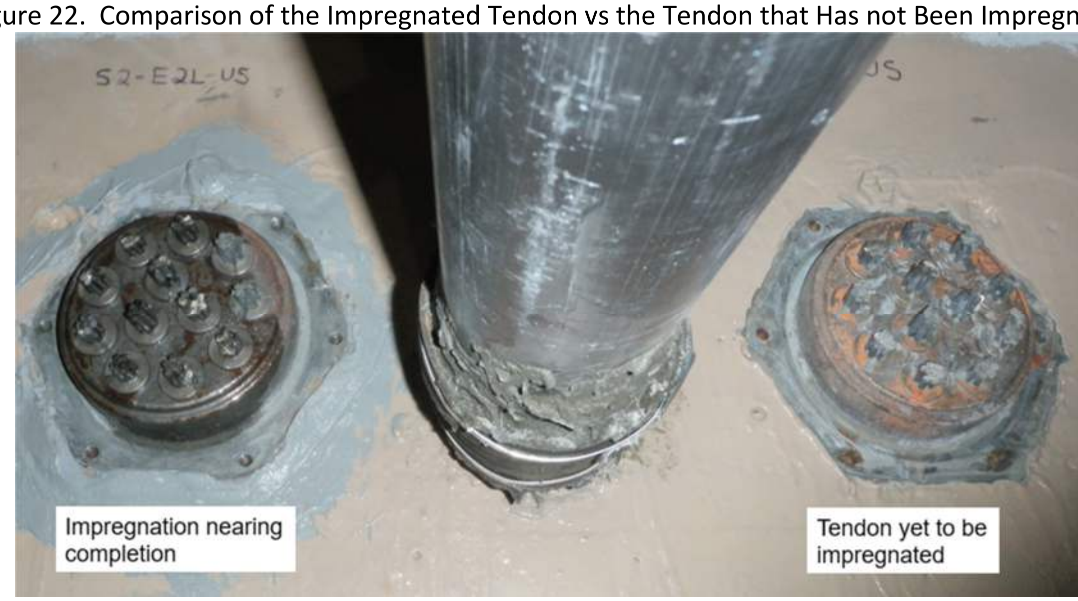


Figure 22. Comparison of the Impregnated Tendon vs the Tendon that Has not Been Impregnated



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[2]ASTM C1152/C1152M-20 "Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete." ASTM International. (2020)

[3]ASTM C856/C856M-20 "Standard Practice for Petrographic Examination of Hardened Concrete." ASTM International. (2020)

[4]ACI PRC-222-19 "Corrosion of Metals in Concrete." American Concrete Institute. (2019)