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POST-TENSIONING INVESTIGATION AND CORROSION MITIGATION IN VOIDED SLAB BRIDGES

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Abstract: Post-tensioned voided-slab concrete bridges have been used extensively since 1960s for continuous bridges spanning between 30-40m. They are an aesthetic alternative to I-girder and box-girder bridges because they are slender and have a smooth soffit. Their shallow depth and high torsional rigidity make them ideal for skewed and straight highway bridges with isolated supports and for interchanges where several curved roadways cross at different elevations. Many of these bridges have aged and some of them have even visible tendon corrosion such as concrete spalling and strand break due to improper grouting, voids and water/moisture ingress.

INTRODUCTION

This paper will first discuss the causes of post-tensioning corrosion, then introduce some non-destructive testing and destructive testing to evaluate the conditions of the tendons. Furthermore, Corrosion mitigation techniques including Galvanic corrosion, PTI impregnation and cable drying are introduced to mitigate the strand corrosion inside the tendon sheath. Finally two case studies are discussed from the evaluation to corrosion mitigation.

CAUSES OF POST-TENSIONING CORROSION

Steel is refined from iron ore (iron oxide) which is the natural form of iron. Great energy is used to convert iron ore into iron and steel, in the process heat energy in the blast furnace remove oxygen and leaves elemental iron. High-carbon steel wire rod is cold drawn into prestressing wires, and then 7 wires were twisted into one prestressing strands; more energy is stored in the strands in this process. Prestressing strands are more susceptible to corrosion than mild steel rebars (Figure 1) (Liao and Miyasato, 2018).

There are many factors resulting in corrosion:

- Poor/Soft grout (Figure 2)
- Voids due to incomplete grout and leaks
- Voids due to bleeding and segregation (Figure 3)
- Interstitial space between strands and between wires
- High water cement ratio

- Moisture/water in the tendons
- Oxygen from voids in the tendons, unsealed vent and inspection holes)
- Chloride content
- Sulfate content
- Relative concentration of chloride and sulfate content in localized areas, such as top of the grout next to the voids.
- Dissimilar grouts due to repairs/re-grouting
- Dissimilar metals, anchor-ductile cast iron, wedge plate- forged steel, strand-high strength steel
- Dead-end anchor corrosion, such as bulb anchor and looped anchors.

Figure 1: Prestressing Strands More Susceptible to Corrosion than Black Steel Regular Reinforcement - Strand Corrosion due to Poor Grout

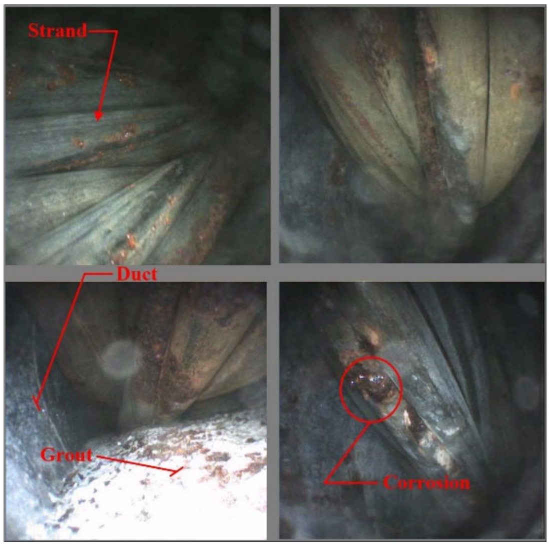
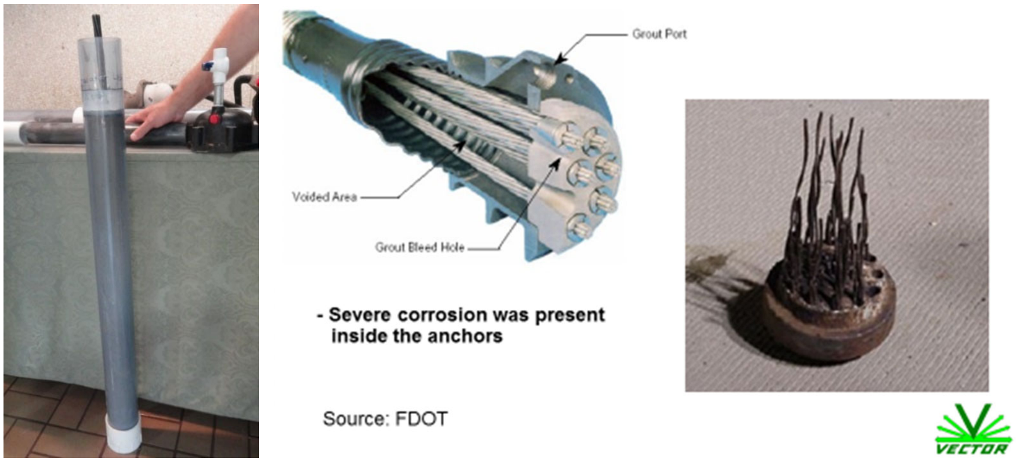


Figure 2: Strand Corrosion in Voided Ducts especially at Poor Grout Surface.



- Severe corrosion was present inside the anchors

Source: FDOT

Figure 3: Duct Void Created At High Points Of Tendon Profile Such As Just Below Anchorage Or Negative Moment Area Due to Wicking Action Of The Bleeding Water Along the Interstitial Space Between Wires And Between Strands.

INVESTIGATING GROUTED PT-STRANDS

There are several testing methods that can be used for investigating grouted PT strands, such as:

- Visual Inspection of the concrete surface along the Tendons to see whether there are cracks and spalling on the concrete surface along the tendons.
- Visual Inspection of PT-Strands is best done by installing opening test pits through the duct to expose strands.
- Locating PT-Strands can be done by using GPR.
- Grout Void Detection can be done with Ultra Sonic Impact Echo technologies.
- PT Corrosion Potential Evaluation by moisture testing can be done by testing the moisture content of air within the ducts (See Figure 4).
- Chloride Analysis of PT grout samples.
- Chemical and pH (Carbonation) testing of grout samples.
- PT tendon breaks can be detected by the Magnetic Flux Method

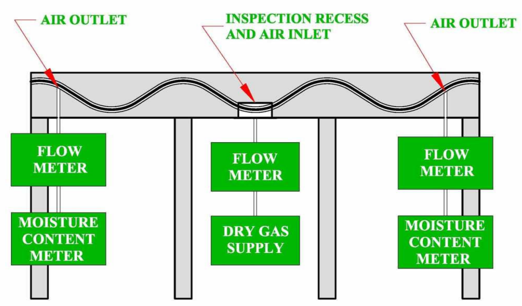


Figure 4: PT Corrosion Potential Evaluation by Testing Water/Moisture in Tendon Ducts

Table 1. PT Corrosion potentials.

Probability of Corrosion	Moisture Content	Wet or Dry
Low	<0.003kg/kg	dry
Moderate	0.003 to 0.007 kg/kg	wet/dry
High	>0.007kg/kg	wet

GALVANIC PROTECTION FOR POST-TENSIONING STRANDS

In a galvanic anode system, the current is generated by the potential difference between the zinc anode (-1100mV) and the steel reinforcement (typically at 350 to 500mV for corroding steel). There is no monitoring required to keep the sacrificial anodes working. The working potential is low and therefore safe for prestressed concrete, unlike impressed current cathodic protection system having higher voltage which may cause hydrogen embrittlement to the prestressing steel. Galvanic anodes embedded in many structures in or before 2001 have been working well so far, including Watergate Complex Parking Garage in Washington DC, Iowa 192 Viaduct prestressed girders in Council Bluffs, Iowa, USA, and Concordia bridge Prestressed Girders in Winnipeg, Manitoba, Canada. In 2012, after dissimilar grout accelerated corrosion was reported, galvanic anodes have been used in many tendons repair projects (Figure 5).

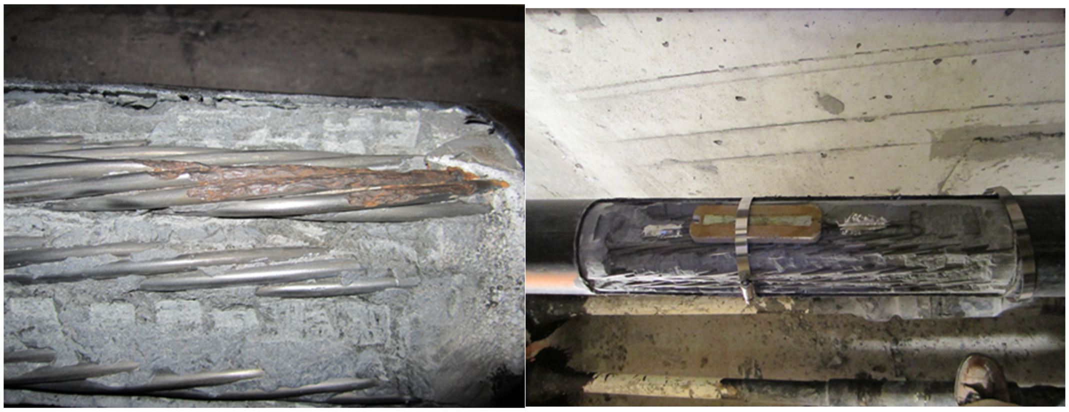


Figure 5: Galvanic Anode Installed to Mitigate Corrosion After Dissimilar Grout Accelerated Corrosion Discovered

Activated Arc Sprayed Zinc (ASZ+) can be used to control on-going corrosion in the areas where the concrete is sound but contaminated with chlorides or where the corrosion potentials are high (Liao & Ball, 2008). With this process, a thin layer of zinc is applied to the clean concrete surface in a few passes after the repairs have been completed. The anode is electrically connected to the embedded reinforcing steel and the humectant activator solution is applied to the zinc anode surface.

This method is practical and effective in mitigating steel corrosion in areas where concrete removal is not desirable, such as post-tensioned members and precast prestressed girders (Figure 6).

Figure 6: Galvanic Anode Installed to The Girder Ends to Mitigate Strand Corrosion

CABLE DRYING TO REMOVE WATER/MOISTURE FROM GROUT

Since the water/moisture is one of the fundamental components of a corrosion cell, once the cable is determined to be ‘wet’, it should be dried to arrest corrosion.

Cable drying process uses the same CPE system in that ultra-dry air is blown through the cables but in this case for an extended period of time. The extended drying period is required to allow moist air (and bulk water as well) to be removed from the grout voids, between the wires of the cable, and from grout. This process may take 4 to 8 weeks, and is determined by taking CPE measurement, before, during and after the drying is complete (Figure 7). The moisture levels are monitored throughout the whole process. When the moisture is well below the specified dryness criteria, the drying system is turned off for a period of time and CPE tests are performed to confirm the dryness criteria is met.

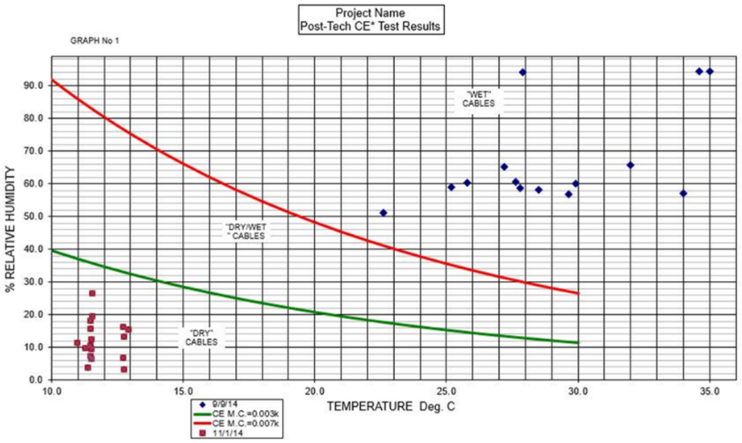
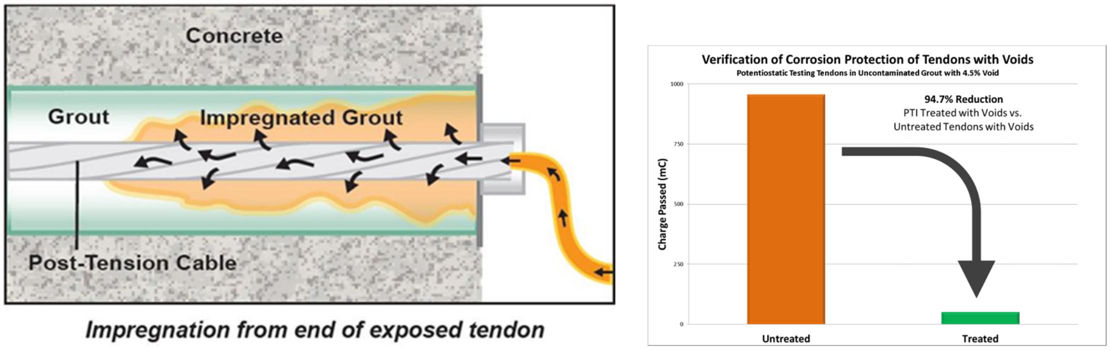


Figure 7: Water/Moisture From Wet Cables Purged and Corrosion Mitigated

PT Cable Impregnation

PT Cable Impregnation utilizes the naturally occurring interstitial spaces between the wires and between strands to deliver specially formulated corrosion inhibiting materials to impregnate the grout or concrete. The purposes of the materials are to a) fill the voids in the grout, between wires and between strands, b) create a corrosion resistance film on the exposed wire surfaces, c) impregnate or waterproof the grout. The end results are to reduce corrosion or prevent the initiation of corrosion activity.



Impregnation from end of exposed tendon

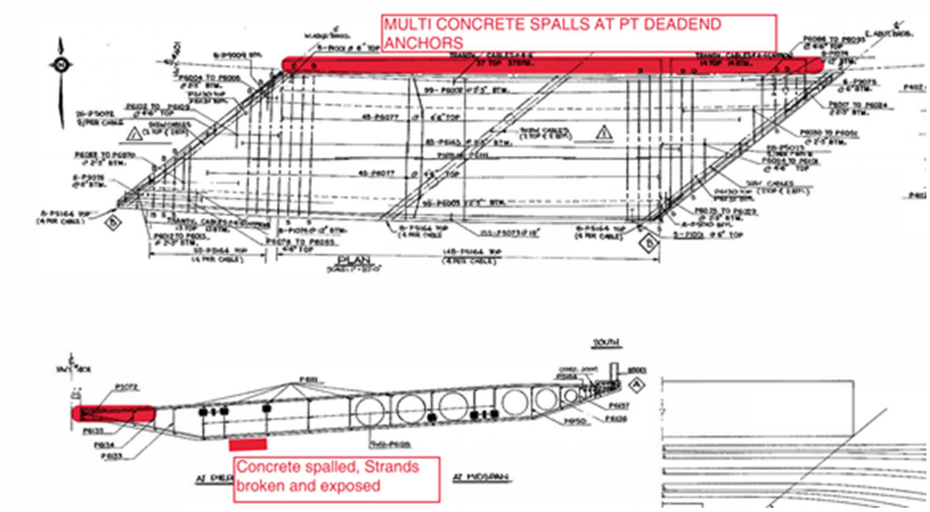
Figure 8: PT Tendons Impregnated To Increase Corrosion Resistance

The system utilizes the interstitial spaces between the wires of each strand in a multi-strand tendon to deliver (transfer) a unique corrosion inhibiting, impregnation material along the length of the cable (Figure 8). The impregnation material seeps between the wires of the strands to impregnate the surrounding grout or concrete. The impregnation material is designed to form a corrosion-resistant film on any exposed steel surfaces such as steel strands which are exposed in grout voids, and to make the grout more corrosion and moisture resistant (Whitmore, Lasa and Liao, 2015).

Laboratory confirmation was completed on tendon specimens provided by FDOT and grouted “lollipop” samples. The tendon specimens provided to Vector were sections of external tendons which had been removed from the Ringling Bridge in Sarasota, FL. Lolipop samples comprised a single strand section which was centrally grouted in a cylindrical block of prepackaged PT grout. Laboratory testing confirmed the ability of the impregnation material to travel along the length of the specimen, to soak into the grout surrounding the strands and to pass from strand to strand across the cross-section of a grouted tendon. Accelerated laboratory testing also confirmed the ability of the impregnation process to reduce corrosion by over 90%.

CASE STUDY – HIGHWAY 401 EB EXPRESS HIGHWAY 2 OVERPASS

The bridge structure was built in early 1970s and are comprised of 2 spans. The bridge is post-tensioned voided slab bridge, 240' long 44' wide and sloped at 6% toward WB Express. The north side of the bridge is in a more corrosive environment due to water pooling and roadside splash from both EB and WB. The concrete near the north pier column has spalled and exposed one transverse tendon (Figure 9, Figure 10).



MULTI CONCRETE SPALLS AT PT DEADEND ANCHORS

Concrete spalled, Strands broken and exposed

Figure 9: Dead End Anchor Corrosion, Strand Corrosion and Spalls at Lower Areas of the Soffit

Figure 10: Dead End Anchor Corrosion, Strand Corrosion and Spalls at Lower Areas of the Bridge.

Investigation of the Post-tensioning systems included:

- Visual Inspection and Penetration test for the exposed tendons. All 4 strands in the transverse tendons are broken. The rebar below the tendon appeared in good condition, see Figure 11 and12.

The north edge which is lower and has dead end transverse anchors has multiple spalls and patches.

- Locate tendons with ground penetrating radar
- Excavate concrete to expose the tendons
- Perform visual inspection for the exposed PT tendons
- Collect PT grout samples for lab tests
- Perform visual inspection and half-cell corrosion potential survey at the transverse dead end anchorage area.
- Conducted half Cell potential measurements
- Perform air testing for three tendons, which revealed that each tendon has the air communications between different locations.
- Laboratory testing of duct grout for Chloride ion content

Figure 11: All 4 Strands Broken at Lower North Corer of the Soffit.

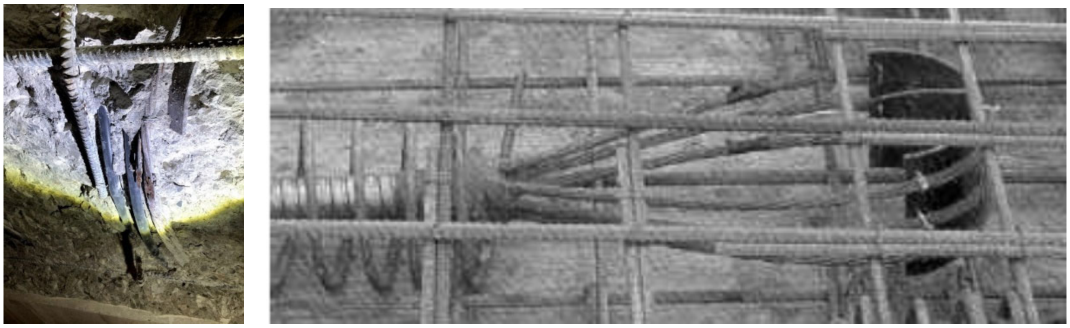


Figure 12: Looped Deadend Anchor Corrosion

Using copper coper sulfate reference electrode, half-cell corrosion potentials in the repair areas ranged from -141 to -236mV, which was low compared to the threshold of -350mV. However the original concrete at the slab edge had the corrosion potentials ranging from -370mV to -403mV (Figure 13), which exceeded the threshold of -350mV, indicating more than 95% of probability of active corrosion. It was consistent with the high chloride content at the slab edge.

Figure 13: Corrosion Potentials Measured at patch and adjacent concrete. High corrosion potential in adjacent concrete and Lower in patch can form a macro cell to accelerate corrosion in adjacent concrete.

The total of 17 test pits were excavated to inspect the strands, which revealed that

- Duct: 7/17 are in good condition, and that 10/17 have surface corrosion
- Grout: 11/17 good, 6/17 white and chalky
- Strands: 7/17 good, 4/17 surface corrosion, 6/17 active corrosion

Grout samples were taken from the tendon with exposed strands, chloride analysis was performed to determine the residual water-soluble chloride content in the post-tension grout in accordance with AASHTO T260-94. The chloride ion content in percent by weight of grout was measured using the ‘Revised SHRP Chloride Analysis Procedure’. A chloride threshold limit of 0.20% by mass of cement, in accordance with ACI 222R-01, was used for the analysis of the chloride ion test results. For cement water grouts with w/c = 0.45 and approximately 6 percent air content, the mass of cement is approximately 69% of the total batch mass. Once free water is removed by drying the grout prior to crushing to powder, the grout is approximately 80% to 85% cement by mass. So, the equivalent chloride ion content sufficient to initiate corrosion of 0.2% by mass of cement is actually 0.8 x 0.002 or 0.16% by mass of grout. Chloride ion content below this level is considered below the threshold for chloride induced corrosion of the steel tendon in alkaline noncarbonated structures. If the chloride levels climb above this threshold, the steel tendon may lose its passive layer and could initiate corrosion activity.
The test results showed:

- The grout samples in pits 1, 2 and 3 had 0.008%, 0.007% and 0.008% of chloride by mass of the grout respectively, which were significantly lower than the acceptable 0.16%.
- The grout samples in the spall had 0.322% (north, close to dead end anchor) and 0.058% (south) of chloride by mass of the grout respectively. The chloride might have penetrated into the tendon from the dead end.
- The concrete dust sample taken from the dead anchor location had the chloride content 0.319%, which was significantly higher than the 0.16% acceptable level.

Corrosion mitigation by Activated Arc Sprayed Zinc anodes is applied to north slab edge where the area is low and corrosive, and where the corroding deadend anchors are located (Figure 14).

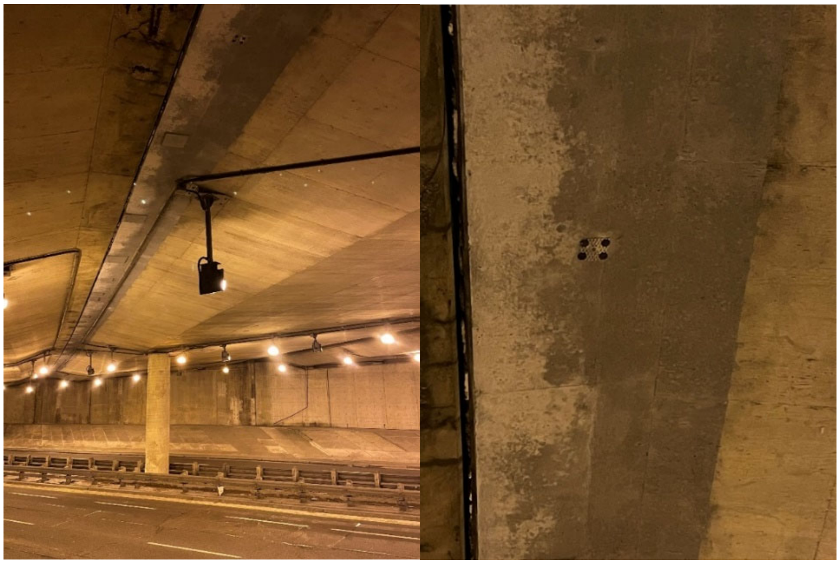


Figure 14: Activated Arc Sprayed Zinc anodes applied to the north soffit and connected to the steel

CASE STUDY – HIGHWAY 401 EB EXPRESS PORT UNION RD UNDERPASS

The bridge structures at Port Union Road over Highway 401 were built in early 1970s and are comprised of 4 spans and have dual carriageways. The two exposed tendons are transverse tendons and located adjacent to the north bound north abutment. The NB transverse tendon dead end anchors over highway 401 WB collector lanes were also exposed and inspected.

Similar investigation results were found in this Structure, and Similar corrosion protection strategies were employed to arrest the corrosion (Figure 15 &16). Distributed galvanic anodes were proposed for the patch repair to protect the tendons and the rebars, and PTI Impregnation was proposed for the transverse tendons as well.

Figure 15: Dead End Anchor Corrosion, Strand Corrosion and Spalls

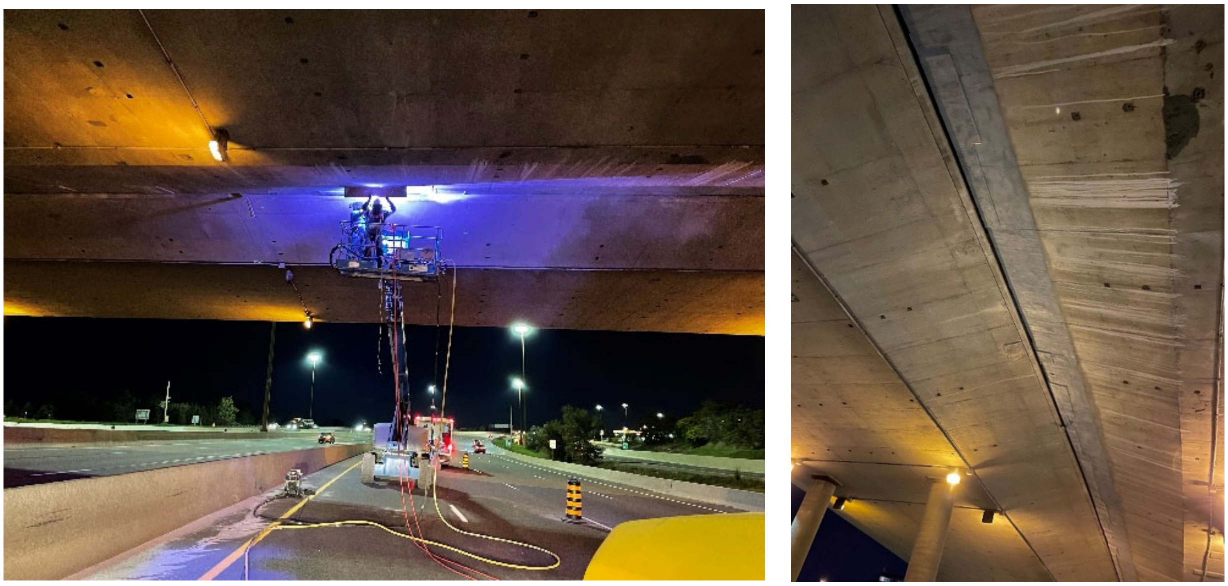


Figure 16: Activated Arc Sprayed Zinc anodes applied to the north soffit and connected to the steel

CONCLUSIONS

Since post-tensioning tendons are encased in ducts, some investigation and corrosion mitigation techniques that are applicable to reinforced concrete are not suitable for post-tensioning. In addition to the conventional reinforced concrete condition assessment techniques, grout void detection by ultra sonic impact echo testing, tendon moisture testing and cable break detection can be used to assess post-tensioning. PT cable impregnation technology is developed for post-tensioning corrosion mitigation and proven to be effective.

Acknowledgements

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