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TARGETED CORROSION PROTECTION FOR BRIDGE STRUCTURES

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Abstract: A cost effective method that mitigates against rebar corrosion in an existing chloride contaminated bridge deck has been the research and bridge management objective of many asset owners, including the Ministry of Transportation of Ontario. Bridge structures do not corrode uniformly and some components may be subject to more chloride attacks than others and fail first. When rehabilitating existing bridges, targeted corrosion protection can be used to address localised corrosion, such as areas with high chloride contents or high corrosion potentials, and macro cell corrosion where new concrete is joined to existing chloride contaminated concrete in locations such as deck widening, conversion to semi-integral abutment and link slabs over piers; such targeted corrosion protection can be implemented using distributed galvanic anode. Therefore, a targeted corrosion protection strategy can be more appropriate and cost-effective in many bridge deck rehabilitation situations. This paper will first discuss rebar corrosion in a bridge deck, then introduce the distributed galvanic anode system and the review of monitoring data from some MTO applications, and finally present the targeted corrosion protection strategy and some case studies. Case studies include linked slab conversion, rigid frame, semi-integral abutment conversion, abutments and piers.

1 CORROSION OF REINFORCED CONCRETE BRIDGES

Corrosion of reinforcing steel is recognized as the major cause of the deterioration of reinforced concrete structures. Exposure to de-icing salts, seawater and chloride-containing set accelerators, play a significant role in reinforcing steel corrosion (Figure 1). When the chloride content at the rebar level exceeds the threshold for initiation of corrosion, the passivation protective film on the rebar surface is destroyed and a corrosion cell can form either on the same piece of rebar with anodic and cathodic sites adjacent to each other, or a macro-cell between two different layers of reinforcement. Long-term exposure to carbon dioxide is also cited as a contributor to the corrosion of steel in concrete as well. Figure 2 illustrates both the local corrosion cell on the top rebar and the macro-cell between the top and bottom rebars. Table 1 shows the probability of corrosion according to ASTM C876 in relation to the half-cell readings. According to MTO's experience and the result of a literature survey, the chloride threshold for initiation of corrosion ranges from 0.025% to 0.075% by mass of concrete; MTO has adopted 0.05% as the chloride threshold above which chloride contaminated but otherwise sound concrete shall be removed by corrosion potential criteria.

2 LOCALISED CORROSION IN BRIDGE STRUCTURES

Prior to deciding what rehabilitation treatment is appropriate, a condition survey that includes corrosion potential survey (ASTM C876-15, 2015) and chloride testing of cores taken at representative locations shall be conducted to reveal the distribution of corrosion activities. While abutments and other components directly subjected to salt splashing may have global corrosion, waterproofed bridge decks typically have more localised corrosion in areas such as along barrier walls, curbs and expansion joints, where corrosion potentials and chloride contents are usually higher due to premature failure of the waterproofing (Figure 3). There could also be macro cell effect where new concrete is joined to existing chloride contaminated concrete in locations such as deck widening, barrier wall replacement, conversion to semi-integral abutment and link slabs over piers.

Figure 1. Pier Corrosion Due to Chloride from Leaking Joints and Roadside Splash

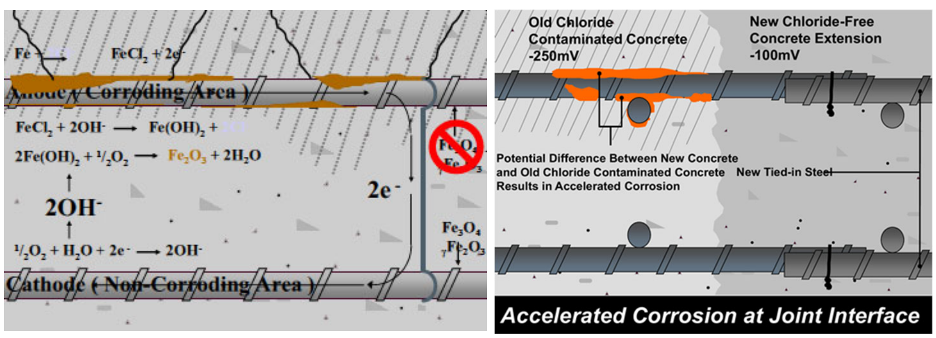

Figure 2. Corrosion Cell in Reinforced Concrete, Accelerated Corrosion at Construction Joints

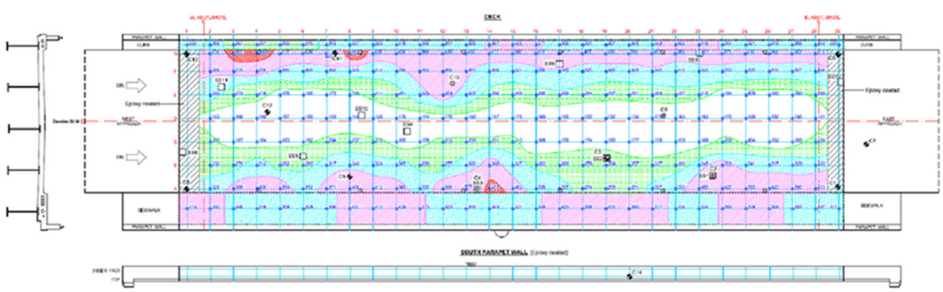

Figure 3: Typical Bridge Deck Corrosion Potential Map

Table 1 Corrosion Potentials

Reading (Cu/CuSO4 Half-cell)	Corrosion Condition
>-200 mV	Low (<5% probability of corrosion)
-200 to -350 mV	Uncertain (50% probability of corrosion)
<-350 mV	High (>95% probability of corrosion)

Figure 2 shows a construction joint where some old concrete is removed and new concrete is cast onto the remaining concrete, such as through slab repair, deck widening or barrier wall replacement. Typically the old concrete with high corrosion potentials or high chloride content is removed, the remaining chloride contaminated concrete may have a corrosion potential of -250mV, which is in the uncertain range. The new concrete typically has a low corrosion potential, for example -100mV. The difference in corrosion potentials between these two concrete areas will make the remaining concrete an anode, which will corrode to protect the cathode - the steel in new concrete. This will lead to the premature failure of the older concrete at the construction joint if no proper protection is put in place. Piles in soils typically have more severe corrosion at grade level and marine piles have more aggressive corrosion at tidal/splash zone (Figure 4)

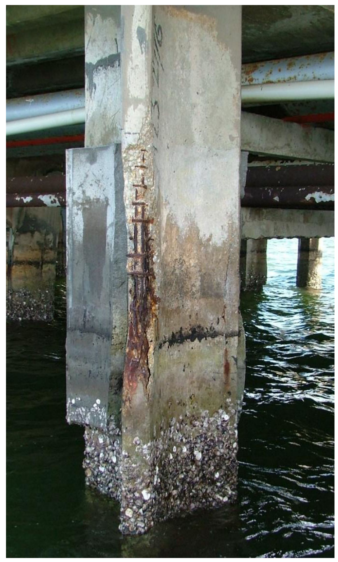

Figure 4: Localised Corrosion at Tidal/Splash Zone of Marine Piles

One option is to apply cathodic protection to prevent and control localised corrosion in high corrosion risk areas. Cathodic protection system has been shown to be effective in mitigating corrosion damage and reducing the rate of the delamination per year to 0.04% from the average 1% per year for unprotected structures (Gulis, Lai & Tharmabala 1997)

3 EMBEDDED GALVANIC ANODE FOR CORROSION PREVENTION

Since corrosion of steel reinforcement is an electro-chemical process, it can be mitigated by electro-chemical means such as cathodic protection. While impressed current cathodic protection system is typically used to provide general corrosion protection over the entire deck surface, galvanic cathodic protection system can be used in targeted areas where there is elevated risk due to higher content of chloride. Embedded galvanic anodes (Figure 6) have been used for patch repairs to address patch-accelerated corrosion (Figure 5) since late 1990s.

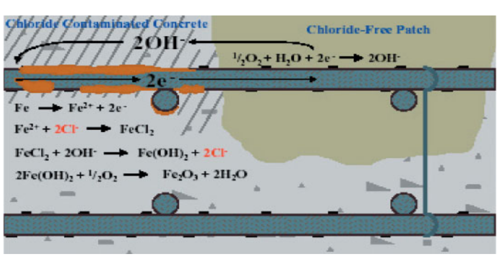

Figure 5. Patch Accelerated Corrosion Cell

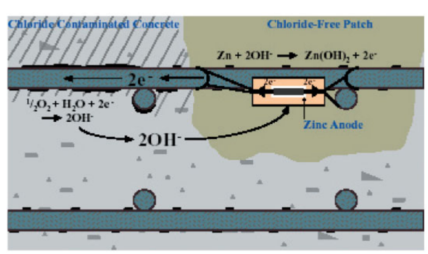

Figure 6. Patch Containing discrete Galvanic Anodes

The anode was produced from zinc metal encased in a specially formulated porous cementitious mortar saturated in a highly alkaline environment. Such an environment maintaining a constantly high pH, which is corrosive to the zinc and protective to the steel, was shown to sustain the zinc in an active condition producing soluble zinc corrosion products that do not stifle the corrosion process of the metal.
The first monitored application of the embedded anodes was completed at the Leicester Bridge, UK, in 1999. As verification for the performance of the anodes in actual structures, a total of 12 commercial anodes were installed in an otherwise conventional patch repair on spalled and cracked areas of a beam section of the bridge. The performance of these anodes was monitored with time. Each monitored anode generated up to 400-600μA of current during hot periods and less than 100μA during cold spells. The mean current density ranged between 0.6 mA/m^2 and 3.0 mA/m^2 with an overall mean of around 1.4 mA/m^2, generally within the suggested range for cathodic prevention. According to these results, a range between 24 years and 37 years service life can be achieved for 60g zinc mass. This is confirmed by the assessing the removed anodes from the repair, which lost about 25 to 30% of the zinc metal and were still active. Corrosion Prevention strategy can be used in various applications including structural extension or widening, new construction and patch repairs (Lai, Langendeon, & Liao 2018).

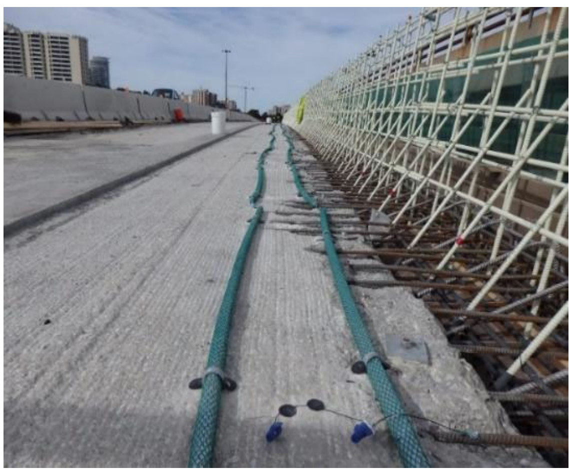

Figure 7. Distributed Anodes installed at the edge of existing deck for the parapet wall replacement to prevent corrosion from initiating, Toronto, Canada

Figure 8. Highway 622, Atikokan, Discrete anodes for patch repairs

4 DRILLED-IN FUSION ANODES FOR CORROSION CONTROL/CATHODIC PROTECTION

Anodes can be installed in drilled holes in the following applications.

- Sound concrete with high corrosion potentials and high chloride concentration, in which delamination and spalling are expected as results of the corrosion (Figure 9).
- Chloride contaminated prestressed concrete where concrete removal is not desired

Fusion anode is a two-stage anode system, combining the performance of an impressed current electrochemical treatment (Stage 1) with the long-term maintenance-free capabilities of an alkali-activated galvanic anode (Stage 2). As illustrated below, this modular corrosion protection system provides two stage corrosion protection. During the first stage, this system utilizes a self-powered impressed current cathodic protection anodes to perform an electro-chemical treatment to halt corrosion and passivate the steel. These two stage anodes then automatically switch over to provide maintenance free galvanic anodes to maintain the steel passivity for the life of the system. This switch occurs automatically without the need for external monitoring or human intervention. Each anode includes both the impressed current cathodic protection and galvanic protection components and is connected to steel using a single wire (Whitmore, Liao, Simpson & Sergi 2019) .

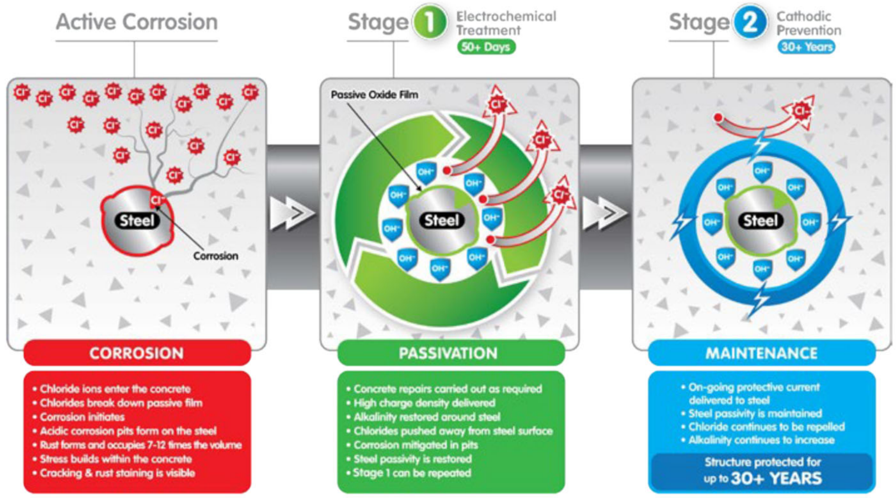

Figure 9. Illustration of Fusion Anodes
Corroded steel is protected by a two-stage corrosion protection system. Stage 1 passivates the steel, produces a shield of hydroxyl ions and repels chlorides. Stage 2 maintains the steel in passive condition

5 CASE STUDIES OF TARGETED CORROSION PROTECTION IN BRIDGE DECKS

5.1 Case Study 1 Highway 140 CNR Underpass, Welland, ON

The bridge was built in 1969. The condition survey performed in 2017 indicated that the corrected chloride content at rebar level was above the chloride threshold level of 0.025% in all tested cores except two cores. Overall, the results indicated that chloride contamination has extended to the upper rebar level in the entire area of deck with corrosion potentials more negative than -0.35 V. The expansion joint areas had extremely high corrosion potentials (Figure 10)

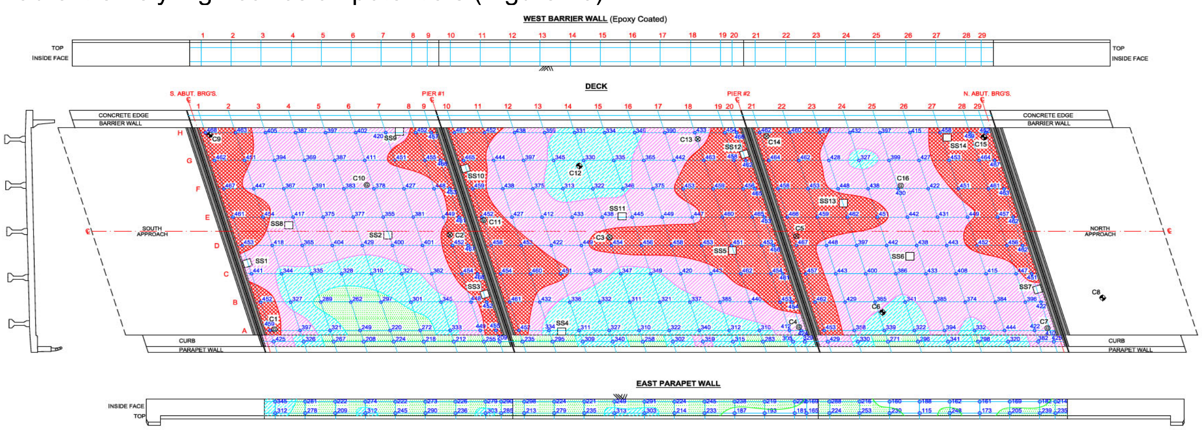

Figure 10: Corrosion Potential Map of Highway 140 CNR Underpass

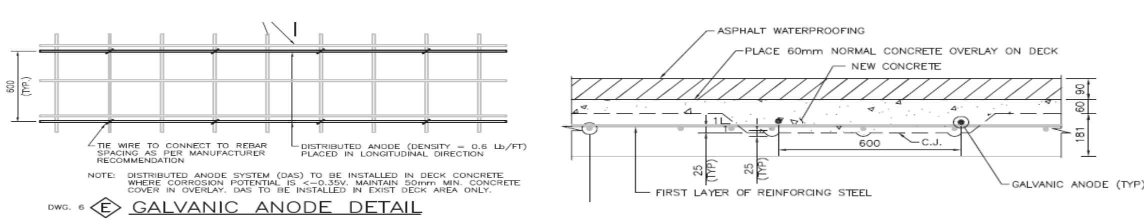

Figure 11 Targeted Corrosion Protection Plan and Section

The rehabilitation strategy was to remove the expansion joints and make it a link-slab. DAS anodes were incorporated at the construction joints between the new and existing concrete to control the accelerated joint corrosion.

Figure 12 Targeted Corrosion Protection for Link-Slab, Highway 140 CNR Underpass

5.2 Case Study 2 Highway 401 King St Overpass, Cambridge, Ontario

Highway 401 King St Overpass is a two-span rigid frame structure. The deck ends and deck over the pier (C18, C22, C26, C28, C28 in the following table) have higher chloride content at steel level than the threshold of 0.025% by weight of concrete, and the half cell corrosion potentials in these areas exceed -0.35V. Compared to other areas, chloride levels and half cell corrosion potentials are significantly higher likely due to the premature failure of the waterproofing membrane, thus have experienced significant corrosion. Since the main rebar is in the negative moment region, which happens to be located in the highly corrosive area. Cathodic protection is recommended to arrest the corrosion. Since the negative moment steel at the abutment goes deep into the abutment, anodes are recommended to be installed in drilled holes to protect the main curved bars in the end faces.

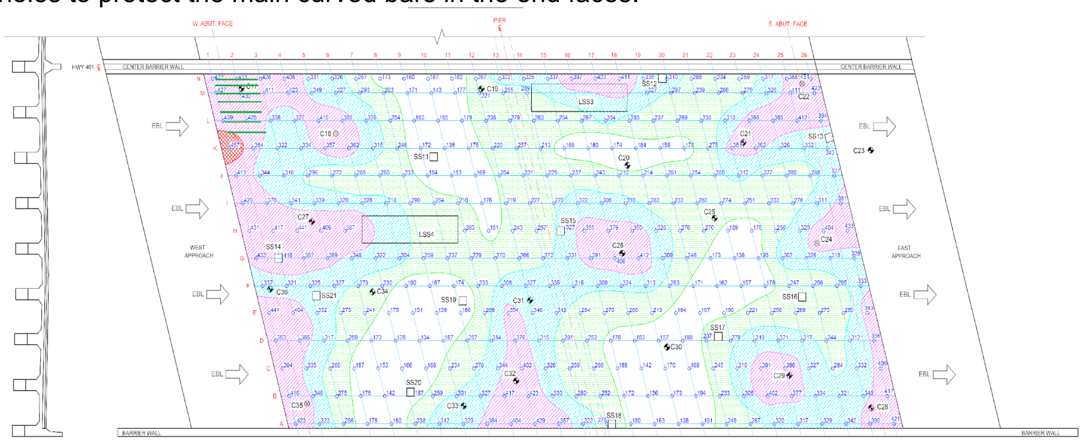

Figure 13: Corrosion Potential Map of Highway 401 King St Overpass

Table 1 Corrosion Potentials

Core No.	C18	C19	C20	C22	C26	C28	C32	C36
Corrected Chloride Content (%)*	0.026	0.021	0.013	0.026	0.042	0.041	0.028	0.008
Corrosion Potential (V)	-0.379	-0.221	-0.179	-0.408	-0.406	-0.409	-0.414	-0.337

* Background chloride ion content was estimated to be 0.015% for parent concrete and 0.017% for overlay.

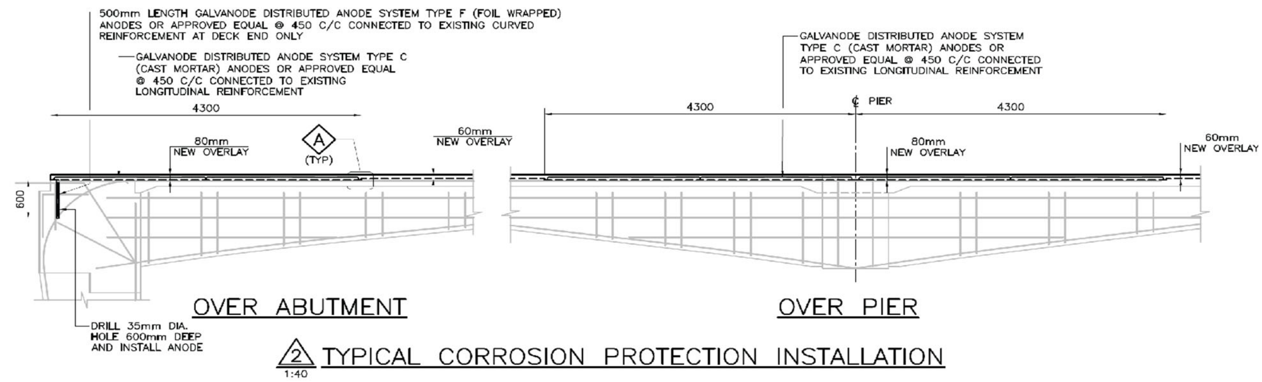

Figure 14: Repair Elevation of Highway 401 King St Overpass

The pier columns and abutments have also experienced severe corrosion from the roadside splash. The main rebars and ties in the pier columns have significant section loss due to corrosion. CFRP wrapping was recommended to strengthen the columns. Both ACI 440 and CSA 806 specify that CFRP shall be applied to sound concrete surface, if the substrates have on-going corrosion, the deteriorating mechanisms shall be stabilised prior to applying CFRP system, cracks greater than 0.25mm in width shall be repaired. To satisfy these requirements, galvanic anodes are introduced to the columns to control the ongoing corrosion. Concrete slots are made vertically on the columns and anodes are embedded in the slots.

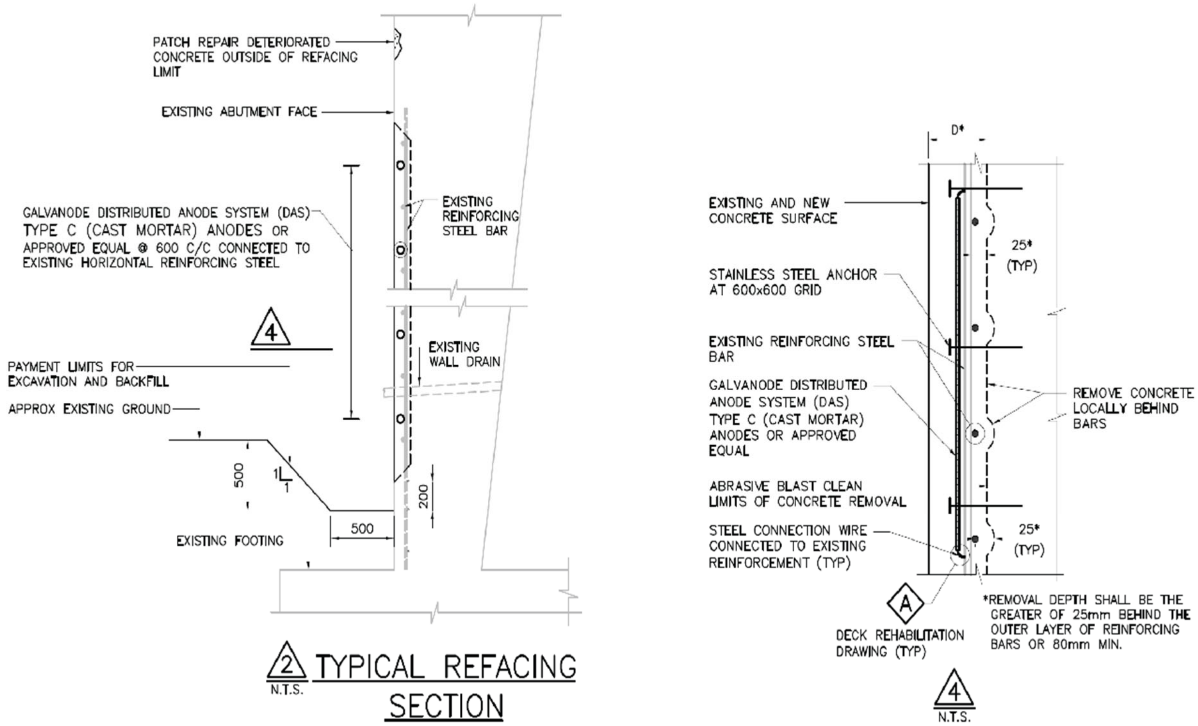

Figure 15: Galvanic Protection in the Refacing of Highway 401 King St Overpass

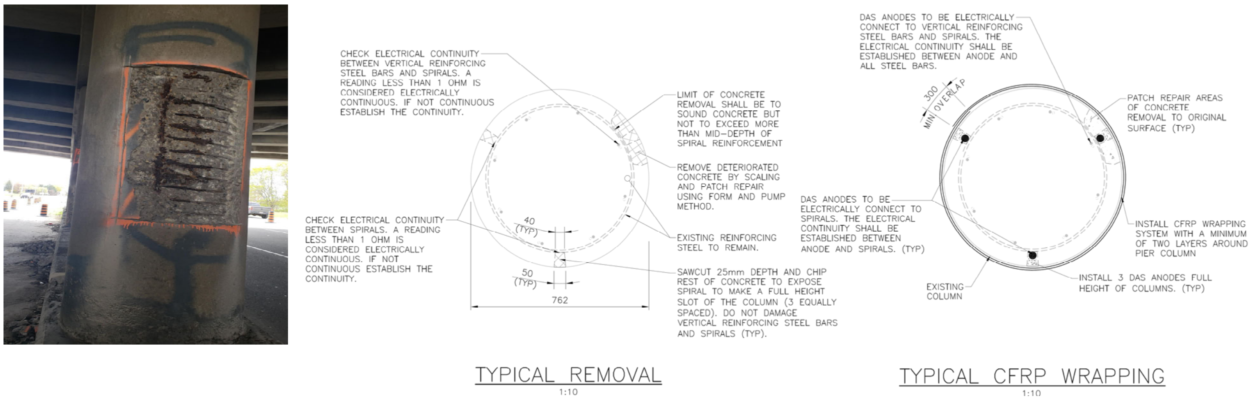

Figure 16: Pier Column Corrosion, Corrosion Protection and CFRP Strengthening for the Pier Columns

5.3 Case Study 3: Highway 404 Highway 7 Overpass, Ontario

The bridge, constructed in 1977, is a reinforced concrete slab on prestressed precast CPCI girders, overlain with an asphalt wearing surface and carries six (6) lanes of Highway 404 southbound traffic. The deck consists of eighteen (18) prestressed precast CPCI girders. The overall length of the bridge is 32.61 m. The roadway width is 35.28 m. The structure has a north-south orientation, and concrete barrier walls on the east and west sides. The deck was widened in 1996 by adding 7 and 2 girders on the east and west sides of the existing structure respectively.

The north and south abutments have 26% and 51.3% of the areas with corrosion potentials more negative than -0.35V while the chloride level is relatively low at 0.009% at rebar level compared to the threshold of 0.025% by weight of concrete. Overall, the abutments are in good shape except the high corrosion potential. Therefore concrete refacing is not recommended and the galvanic anodes in drilled holes are installed to provide 25+ years of corrosion protection.

Table 3: Concrete Conditions of Highway 404 Highway 7 Overpass Abutments

	Total area, m2	Previous patches, m2	Spall, m2	Delamination, m2	Cracks, m
North Abutment	225	2	0	1.9	41
South Abutment	230	0	1.5	2.5	23

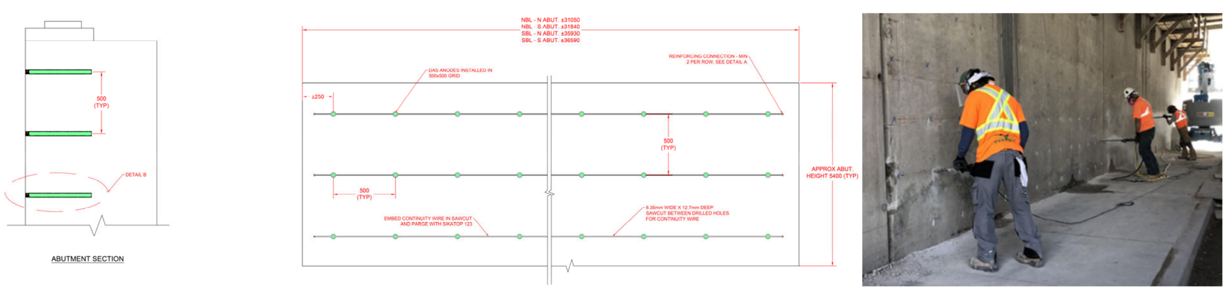

Figure 17: Drilled-in Corrosion Protection for the Abutments

The 11% of the bridge deck areas have more negative than -0.35V corrosion potentials and the chloride content levels were all below the threshold of 0.025%, which appeared in good conditions at the time of conditions surveys. However, when asphalts and waterproofing were removed during construction, the rebars at the west side of the NBL bridge deck (constructed in 1997) had insufficient concrete cover and significant section loss, where the slab thickness was only 150mm. The thickness of the slab increases from 150mm to 320mm from west to east. Cathodic protection was recommended, Fusion anodes were installed in chipped pockets to control the on-going corrosion where the slab was 150mm to 225mm. Where the slab is thicker than 225mm, Fusion anodes can be installed in drilled holes.

Figure 21: Low Concrete Cover and Rebar Corrosion after Asphalt and Waterproofing Removal

Figure 22: Chipping Pockets in Low Cover Area and Drilling holes for Anodes

6 DESIGN AND CONSTRUCTION CONSIDERATIONS

Design engineers should consider the following points during design stage:

(1) In the case of concrete removal by corrosion potential criteria, supplementary cathodic protection system may not be necessary since most of the chloride contaminated concrete would have been removed. However this sometimes can lead to excessive removal of sound concrete.

(2) In the case of a patch repair and concrete removal by delamination, it can be more economical and provide longer protection to install the galvanic anode to deal with the ring effect, either discrete anodes or distributed anodes can be installed to mitigate the corrosion depending on the service life required and the patch configuration. Discrete anodes can be better fit for smaller patches.

(3) The contract shall specify where the DAS anodes shall be installed and clarify whether patch repair areas are included.

(4) In thin slabs where drilling holes to accommodate anodes is not practical or where overlay is not desirable, anodes can be installed in chipped pockets, which shall be saw-cut, chipped and patched.

During construction, contractors should pay attention to the following items:
(1) DAS is not permitted to get soaked in standing water in which anode activator will leak and would render the system less effective. However, pre-wetting the existing concrete surface before overlay is needed prior to placement of new concrete. Thus, the control or monitoring plan should be in place to prevent the anodes from getting soaked from rain and concrete wetting water: anodes are typically installed within 24 hours prior to concrete placement, no standing water is allowed in the repair area, and use mortar cast anodes if moisture/water is a great concern while do not allow the mortar cast anodes to soak in water greater than 20' prior to concrete placement.
(2) Anode units shall be tied down to concrete substrate to prevent dislocation and floating during placing of concrete overlay. Electrical continuity between rebars, and between rebars and anodes should be established and verified.

7 CONCLUSIONS

Galvanic anode system can provide effective corrosion control to black steel in chloride contaminated concrete; it can be applied over the entire surface of the bridge component, or only in selected areas for targeted protection. Due to the high cost of the treatment, targeted protection in selected areas would often be a more cost-effective alternative. Compared with impressed current cathodic protection system, it has greater flexibility in applications and does not require long term maintenance. Galvanic system and two-staged system can be designed to protect bridge structures for 30 years or longer.

The Cathodic Protection has been used in many applications in Ontario, Canada:
(1) Cathodic Protection shall be used when corrosion potential is more negative than -0.35 volts over more than 30% of the deck area and average chloride content exceeds 0.05%. That is, when the corrosion potentials are high but concrete is otherwise sound, cathodic protection could be used to reduce the potentials and may be more cost effective than removing the concrete.
(2) Cathodic Protection should be considered as an option when areas of delamination and spalls are less than 10% of deck area, and area of corrosion potential more negative than -0.35 volts exceeds 30% of deck area.

Acknowledgements

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