Corrosion Mitigation Strategies for Durable Bridge Infrastructure

Randel J Sitepu
Business Development Manager – Western Canada
Vector Corrosion Technologies
Winnipeg, MB
randels@vector-corrosion.com

Paper prepared for the session ST Transportation Structures
2026 Transportation Association of Canada (TAC) Conference & Exhibition
Winnipeg, Manitoba

Acknowledgements

Ruby Kwan, Eng, PEng, PMP (Stantec)
Sarah Soprovich M.Eng., P.Eng (Stantec)
Damir Muhurdarevic, P.Eng., (City of Winnipeg)

Abstract

Reinforced concrete bridge infrastructure is highly susceptible to corrosion due to exposure to chlorides, moisture, and environmental conditions that accelerate the deterioration of embedded reinforcing steel. This paper presents an overview of the fundamental corrosion mechanisms, including chloride ingress and carbonation, and examines their impact on structural performance. The limitations of conventional repair methods, particularly patch accelerated corrosion (halo effect), are highlighted to emphasize the need for more effective solutions.

Modern corrosion mitigation strategies are explored, including targeted approaches using embedded galvanic anodes and global protection systems such as distributed anode systems and zinc metallizing.

This paper indicates the importance of integrating repair and corrosion control measures through a service-life-driven design approach. By combining targeted and global protection systems, infrastructure owners can significantly extend service life.

Introduction

Bridge infrastructure is routinely exposed to aggressive environments, including de-icing salts, marine chlorides, moisture, and temperature fluctuations, all of which accelerate the corrosion of embedded reinforcing steel. These conditions contribute to the breakdown of the protective passive layer surrounding the steel, initiating corrosion and leading to cracking, delamination, and spalling of the concrete. Traditional repair methods, such as localized patching, often address only the visible damage

and fail to mitigate the underlying electrochemical processes driving corrosion. As a result, deterioration frequently recurs, necessitating the implementation of advanced corrosion mitigation strategies that actively control corrosion activity and extend the service life of the structure.

Corrosion Mechanisms

Corrosion in reinforced concrete is an electrochemical process that occurs when four essential elements are present: an anode (site of metal oxidation), a cathode (site of reduction), a metallic pathway (reinforcing steel), and an electrolyte (the pore solution within the concrete). When these conditions are met, an electrochemical cell is established, allowing current to flow and corrosion to proceed. Figure 1 provides an illustration of an active corrosion cell.

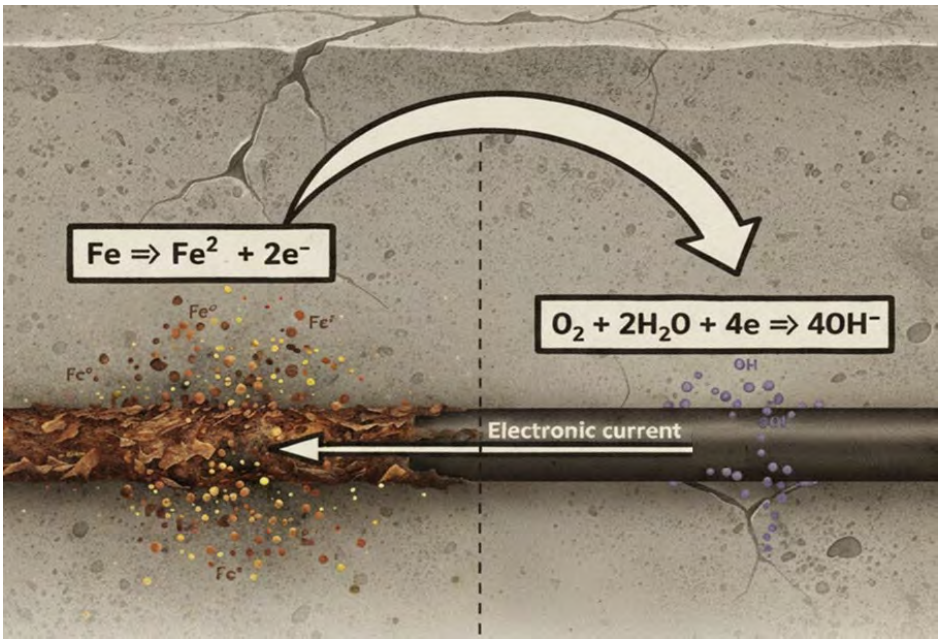


Figure 1- Active Corrosion Cell

Under normal conditions, reinforcing steel is protected by a passive oxide layer formed due to the highly alkaline environment of concrete (typically pH ~12.5–13.5). This passive layer significantly reduces the rate of corrosion. However, this protection can be compromised primarily through two mechanisms: chloride ingress and carbonation.

Chloride-induced corrosion occurs when chloride ions, typically from de-icing salts or marine exposure, penetrate the concrete cover and reach the reinforcing steel. Once a critical chloride threshold is exceeded at the steel surface, the passive layer breaks down locally, initiating corrosion.

Carbonation-induced corrosion occurs when carbon dioxide from the atmosphere diffuses into the concrete and reacts with calcium hydroxide to form calcium carbonate. This reaction reduces the pH of the concrete, eventually destabilizing the passive layer surrounding the reinforcing steel.

Environmental and material factors significantly influence the rate and extent of corrosion. These include concrete permeability, moisture availability, oxygen access, temperature, and the presence of cracks. For example, cyclic wetting and drying conditions can accelerate chloride transport and corrosion rates, while cracks can provide direct pathways for aggressive agents to reach the reinforcing steel.

Patch Accelerated Corrosion (Halo Effect)

Patch accelerated corrosion commonly referred to as the halo effect is a well-documented phenomenon in reinforced concrete repair where localized patching unintentionally accelerates corrosion in adjacent, unrepaired areas. While patch repairs restore damaged concrete and remove actively corroding steel within the repair zone, they often create an electrochemical imbalance between the newly repaired area and the surrounding chloride-contaminated concrete. Figure 2 provides an illustration of the halo effect in concrete.

During a typical patch repair, deteriorated concrete is removed and replaced with fresh repair material that is generally low in chlorides, highly alkaline, and relatively resistive. This restores the passive condition of the reinforcing steel within the patch. However, the adjacent concrete often still contains elevated chloride concentrations and active corrosion sites. As a result, a corrosion cell system is established, where:

1. The repaired area acts as a cathode (protected, low corrosion activity)
2. The surrounding contaminated concrete acts as an anode (active corrosion)

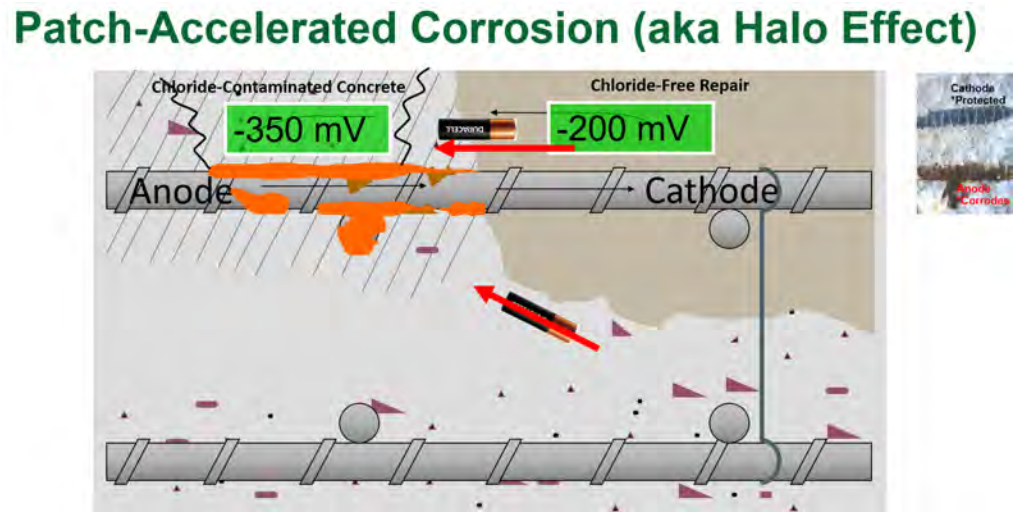


Figure 2- Halo Effect

The issue is particularly pronounced in bridge structures exposed to de-icing salts or marine environments, where chloride contamination is widespread. In high de-icing salt regions, elevated chloride loading often leads to aggressive halo effect deterioration around girder-end repairs and deck

patches, while in coastal environments, persistent moisture and marine exposure promote ongoing corrosion activity, resulting in more gradual but widespread deterioration. Figure 3 illustrates typical halo effect profiles observed at various repair interfaces across bridge elements.



Figure 3- Halo effect on Bridges

Corrosion Mitigation Options – SHRP-2 R19A Framework

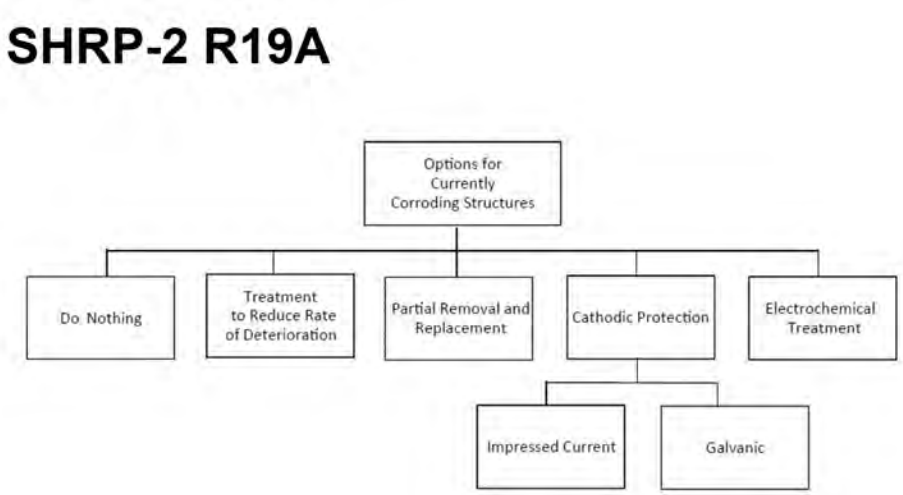


Figure 4- SHRP-2 R19A Framework

Figure 4 represents the SHRP-2 R19A (Service Life Design for Bridges) framework provides a structured approach for evaluating and selecting corrosion mitigation strategies for reinforced concrete structures. Rather than relying solely on conventional repair methods, R19A emphasizes a performance-based, service-life-driven decision process that considers environmental exposure, deterioration mechanisms, and long-term durability requirements.

Corrosion Management Strategies

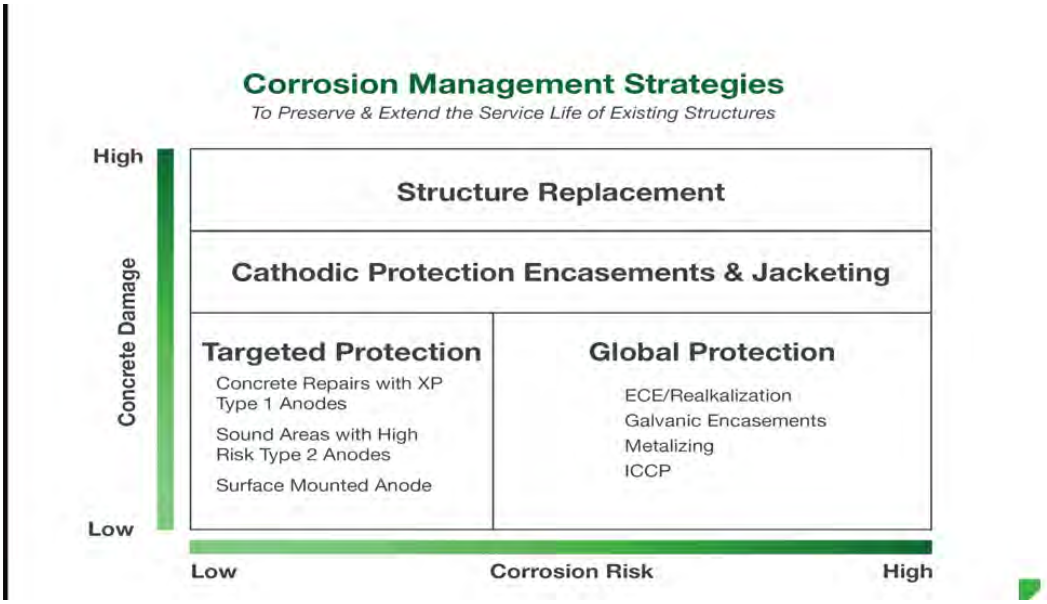


Figure 5 - Strategy Framework

Effective corrosion management requires aligning mitigation strategies with both the level of concrete damage and the overall corrosion risk. As illustrated in the framework (Figure 5), strategies range from localized interventions to full structural replacement, depending on severity and desired service life. Focusing on targeted and global protection strategies, each approach presents distinct advantages and limitations. The appropriate system should be selected based on project-specific design criteria, exposure conditions, and required service life.

Targeted Protection (Localized Strategy)

Targeted protection focuses on specific high-risk areas to deliver effective corrosion control while maintaining cost efficiency. It is typically applied in localized zones such as patch repairs using embedded galvanic anodes, as well as critical details like girder ends, joints, and bearing seats where corrosion activity is most severe. In some cases, targeted strategies are also extended to sound concrete with elevated corrosion risk using discrete or distributed galvanic anodes. This approach allows for focused intervention at vulnerable locations, improving repair performance and durability without the need for full-structure protection systems.

Galvanic Anodes – Review

Galvanic anodes are sacrificial corrosion protection systems used in reinforced concrete to control corrosion of embedded steel. Typically composed of zinc (or zinc alloys), they are electrically connected to the reinforcing steel and embedded within or applied to the concrete to provide passive cathodic protection.

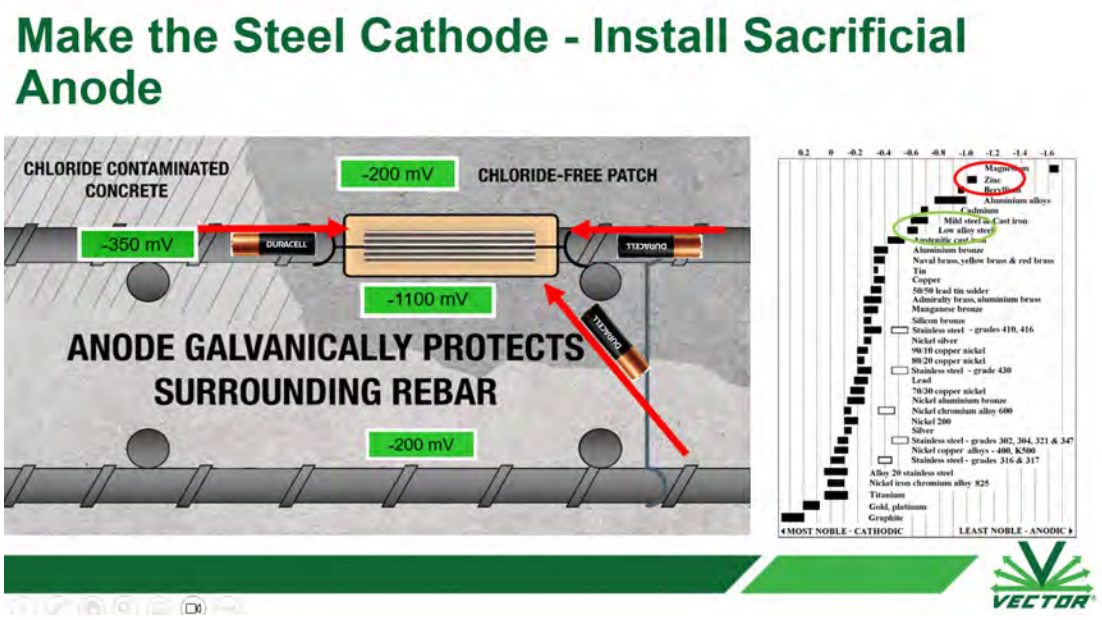


Figure 6- Disimilar Metals and Anodes

Galvanic anodes operate on the principle of electrochemical potential difference, where the anode material (in this case zinc) is more active than steel and will preferentially corrode, generating a small protective current.

This current polarizes the reinforcing steel, reduces corrosion activity, and helps maintain or restore its passive condition. These systems do not require an external power source, as they rely on the natural potential difference between dissimilar metals, forming what is known as a galvanic couple.
When zinc and steel are electrically connected in the presence of an electrolyte, such as the concrete pore solution, a natural voltage is established due to their positions in the galvanic series.
Figure 6 provides a depiction of the anodes embedded in the concrete.

Global Protection (System-Level Strategy)

Global protection systems are implemented when corrosion is widespread or systemic across a structure, requiring uniform, large-area corrosion control rather than localized repairs. These strategies address the underlying electrochemical processes driving deterioration and are designed to reduce the need for repeated maintenance.
Common approaches include galvanic encasements and distributed anode systems, which utilize multiple zinc-based sacrificial anodes installed across the structure or incorporated into encasements to deliver a continuous protective current to the reinforcing steel.
Metallizing (zinc coatings) is another widely used method, where a layer of zinc is applied to the concrete surface, acting as a distributed sacrificial anode that provides consistent corrosion protection over large areas. Both systems convert the reinforcing steel into a cathodic state, suppressing corrosion activity and extending service life.
Global protection systems can achieve 20–30+ years of performance and are often integrated with conventional concrete repairs to provide a comprehensive, long-term durability solution.

Case Studies Targeted Mitigation Strategies

Targeted mitigation strategies focus on localized corrosion control at high-risk or deteriorated areas rather than the entire structure. These approaches are typically integrated with conventional repairs to address both physical damage and underlying electrochemical activity, improving the durability of repairs.

Case Study 1: Granville Bridge South Ramp Rehabilitation with embedded anodes - (Vancouver, BC)

The Granville Bridge South Ramp Rehabilitation is a City of Vancouver project, with Stantec providing structural engineering support, focused on extending the service life of the south approach ramps. Originally built in 1954, the structure has experienced deterioration from chloride ingress, joint leakage, and sustained moisture exposure, resulting in corrosion of reinforcing steel, cracking, and spalling. Original drawings can be seen on Figure 7 below

The rehabilitation includes joint and bearing replacement, concrete repairs, and localized strengthening, with construction phased to maintain traffic flow. Typical anode design placement can be seen on both Figure 8 and 9 below.

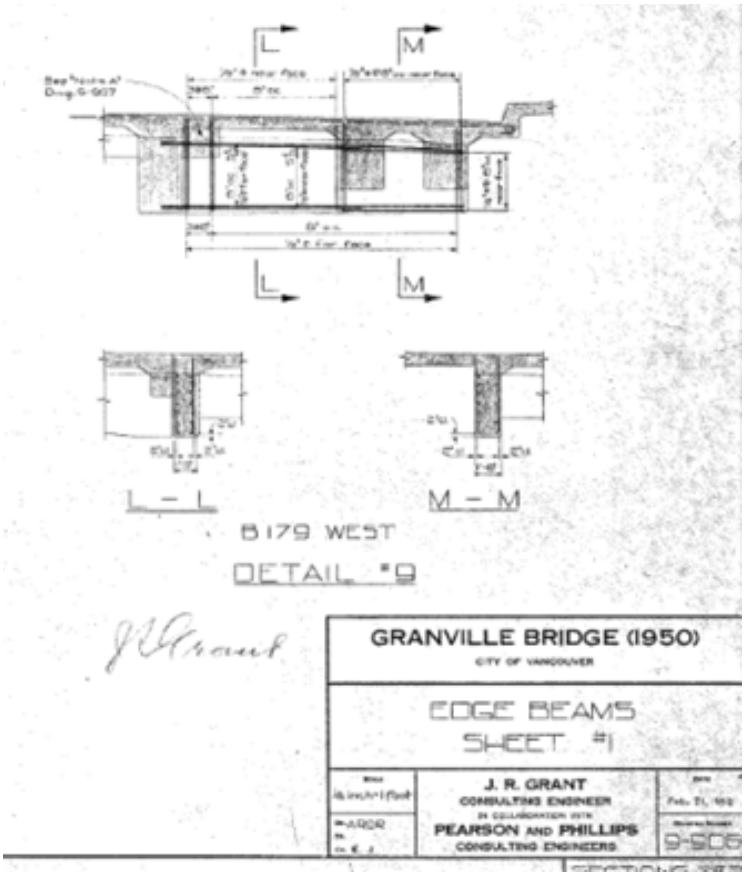


Figure 7-Original Drawings

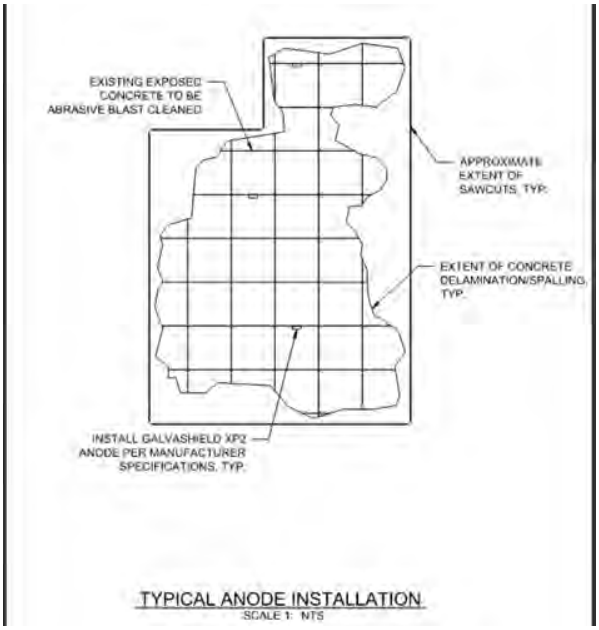


Figure 8- Typical Anode Install



Figure 9-Anodes installed at Site

Case Study 2: Horseshoe Bay Elevated Holding Area – *Localized Repairs with Galvanic Anodes*

The Horseshoe Bay Ferry Terminal in West Vancouver has undergone ongoing infrastructure renewal due to aging components and exposure to a highly aggressive marine environment. The elevated holding area, including the transfer deck and associated structural elements, experienced deterioration primarily driven by chloride exposure from marine saltwater spray, constant moisture with wetting drying cycles, and localized leakage and drainage issues. These conditions led to reinforcing steel corrosion, resulting in cracking, delamination, and concrete spalling typical of coastal infrastructure. As part of the life-extension program, repairs included removal of deteriorated concrete, steel rehabilitation. To enhance durability beyond conventional patch repairs, embedded galvanic anodes were incorporated into the repair strategy. Typical anode design and placement can be seen on Figure 11. Figures 11 and 12 represent actual site anode installs.

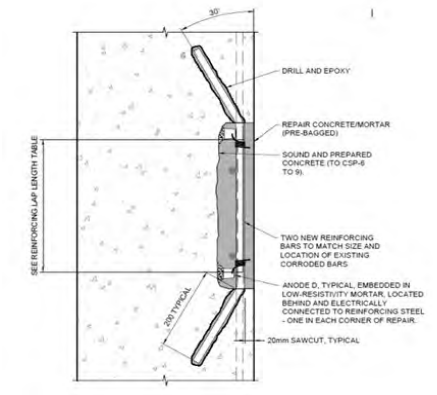


Figure 10- Typical Anode Install and Placement



Figure 11- Anodes on Column

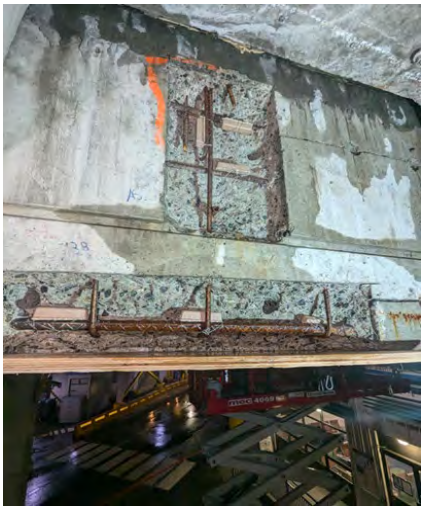


Figure 12-Anode on Beams

Use of Galvanic Anodes in Patch Repairs

Galvanic anodes are commonly incorporated into concrete patch repairs to mitigate patch accelerated corrosion (halo effect) and extend repair service life for these projects above. These anodes are embedded within the repair material and electrically connected to the reinforcing steel, providing localized cathodic protection by preferentially corroding in place of the steel.

Galvanic anodes are installed along the perimeter of patch repairs, typically near the interface between new and existing concrete where corrosion risk is highest. This placement helps counteract the electrochemical imbalance created by the repair, ensuring that adjacent chloride-contaminated concrete does not become anodic and accelerate corrosion.

Case Studies Global Mitigation Strategies

Global mitigation strategies are used when corrosion is widespread or systemic, rather than localized. These approaches aim to control corrosion across the entire structure, addressing the root electrochemical processes instead of isolated damage.

Case Study 3: Empress Bridge, Winnipeg, MB. Global protection with distributed anode system in overlay repairs

The Empress Street Overpass Rehabilitation was part of a broader City of Winnipeg infrastructure renewal program focused on upgrading a key regional transportation corridor between Portage Avenue and St. Matthews Avenue. As a major truck route and urban arterial, maintaining long-term durability and traffic continuity was critical.

The rehabilitation was driven by aging infrastructure and exposure to harsh prairie conditions, including heavy and repeated application of de-icing salts, freeze–thaw cycles leading to cracking and moisture ingress, and chloride penetration at deck surfaces, joints, and girder ends.

These factors resulted in high chloride concentrations and aggressive, localized corrosion. To address this, the corrosion mitigation design incorporated a global repair approach using a distributed galvanic anode system (Figure 13) integrated into a concrete overlay. In this configuration, the overlay functions both as a durability upgrade and as a host medium for the anode system, providing uniform, large-area corrosion protection for the bridge deck.



Figure 13- Distributed Anode system install

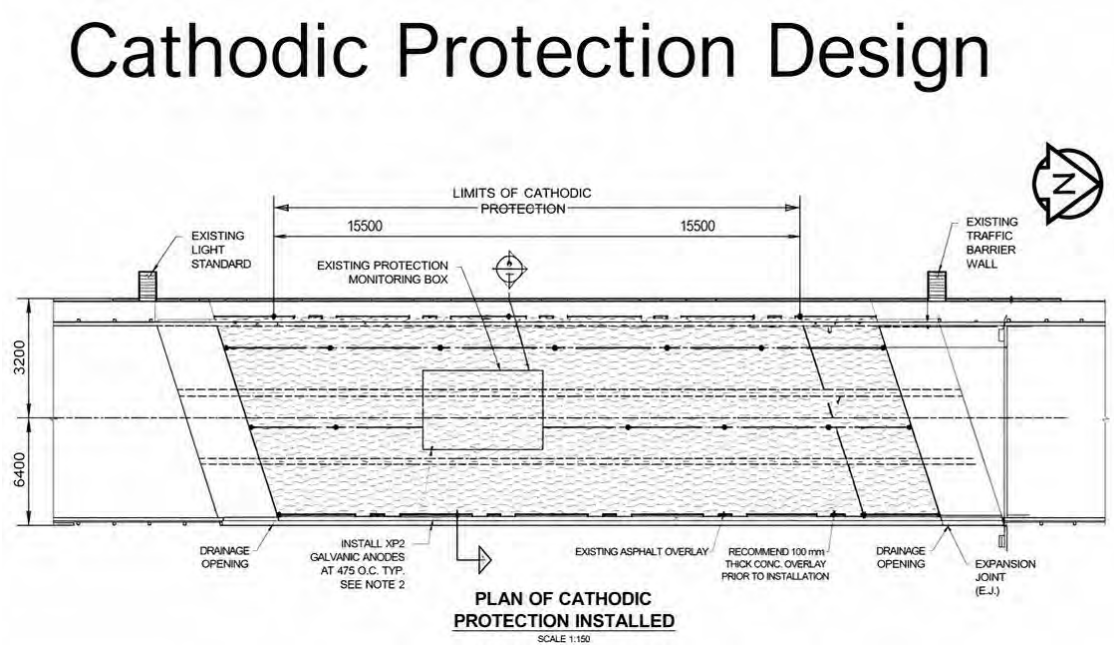


Figure 14- Anode Drawings and Design

A distributed galvanic anode system integrated into a bridge deck overlay transforms a conventional overlay into a corrosion protection system**.** By combining physical rehabilitation with cathodic protection will provide the structure a durable, long-term solution for chloride-exposed bridge decks. Actual detail of the plan and design can be seen on Figure 14 above.

Case Study 4: St Vital, Winnipeg, MB. Combined Targeted and Global Protection system.

The St. Vital Bridge rehabilitation is driven largely by corrosion-related deterioration typical of Winnipeg's harsh environment. Prolonged exposure to de-icing salts, freeze–thaw cycles, and moisture ingress has resulted in elevated chloride levels within the concrete, leading to passivation of reinforcing steel and active corrosion

For this project a combination of targeted and global protection approach was required. Utilizing both protection systems allows engineers and designers to deliver focused protection where needed and uniform control elsewhere, resulting in more reliable service life extension and optimized lifecycle costs. Figure 15 provides the site configuration of all the anodes to be installed.

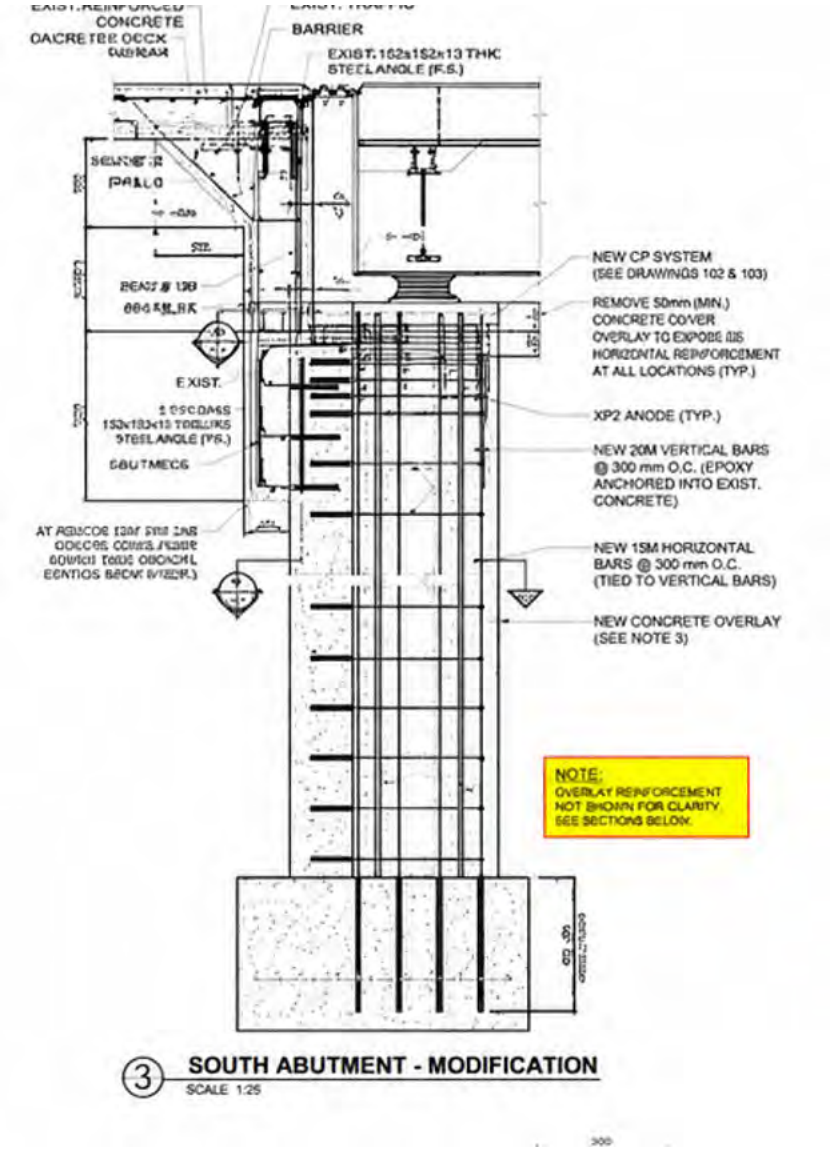


Figure 15-Anode Configuration

System Proposed and Composition

1) Galvanic Embedded Anodes – Targeted Repair System

Targeted repairs incorporated embedded galvanic anodes (Figure 16) at the interface between new and existing concrete to mitigate corrosion at these critical transition zones. This approach ensures localized cathodic protection where chloride-contaminated concrete remains adjacent to repair areas, reducing the risk of patch accelerated corrosion and improving long-term repair durability.



Figure 16- Galvanic Anodes installed at site

2) *Distributed Anode system: Global Protection System*

At the abutments, a distributed galvanic anode system was implemented to provide global corrosion protection across the entire element (figure 17 and figure 18). Unlike localized patch solutions, this approach targets widespread chloride contamination and ongoing corrosion risk typical of abutments exposed to roadway runoff, de-icing salts, and moisture accumulation.



Figure 17-Distributed Anodes on Abutments



Figure 18-Placement of Distributed Anodes

3) ***Metalizing: Global Protection system***

Zinc metallizing (Figure 19) was applied to the bridge piers as a surface-applied galvanic system to provide uniform, large-area corrosion protection in areas exposed to continuous moisture and chlorides. Piers are particularly susceptible to deterioration due to splash, runoff, and wet–dry cycling, which sustain electrochemical activity and lead to widespread corrosion rather than isolated damage.

In this system, a layer of thermally sprayed zinc is applied to the prepared concrete surface and electrically connected to the reinforcing steel. The zinc acts as a sacrificial anode, preferentially corroding and generating protective current that shifts the reinforcing steel into a cathodic state, thereby suppressing corrosion. A sealer is typically applied to control zinc consumption and enhance durability.

This approach is well suited for pier applications as it provides consistent activation in moisture-rich environments, requires no external power, and delivers long-term, low-maintenance protection. When combined with conventional concrete repairs, zinc metallizing provides global corrosion control, extending service life and reducing the need for future localized repairs



Figure 19-Metalizing application on site

Conclusion

Modern corrosion mitigation strategies are essential for maintaining durable and reliable bridge infrastructure in increasingly aggressive service environments. As demonstrated, corrosion is the primary driver of deterioration in reinforced concrete structures, and conventional repair approaches alone are often insufficient to achieve long-term performance. Without addressing the underlying electrochemical mechanisms, repairs are susceptible to premature failure, leading to repeated interventions and increased lifecycle costs.

The integration of targeted and global corrosion mitigation strategies including embedded galvanic anodes, distributed systems. These systems not only address existing damage but also actively control ongoing corrosion, significantly improving the durability of repairs and extending structural service life.

Case studies from environments such as Vancouver and Winnipeg highlight the importance of tailoring solutions to site-specific exposure conditions. Whether dealing with marine-driven moisture and chlorides or heavy de-icing salt exposure and freeze–thaw cycles, successful corrosion management depends on selecting and combining appropriate mitigation strategies based on risk, condition, and performance requirements.

Acknowledgements

The author would like to thank the Stantec teams in Vancouver and Winnipeg for their support and for permitting the use of project insights and technical details presented in this paper. Appreciation is also extended to the City of Winnipeg for their collaboration and commitment to advancing durable, service-life-driven infrastructure solutions.