Lessons in Galvanic Cathodic Protection Technology from Soldier Field and the Franklin Avenue Bridge

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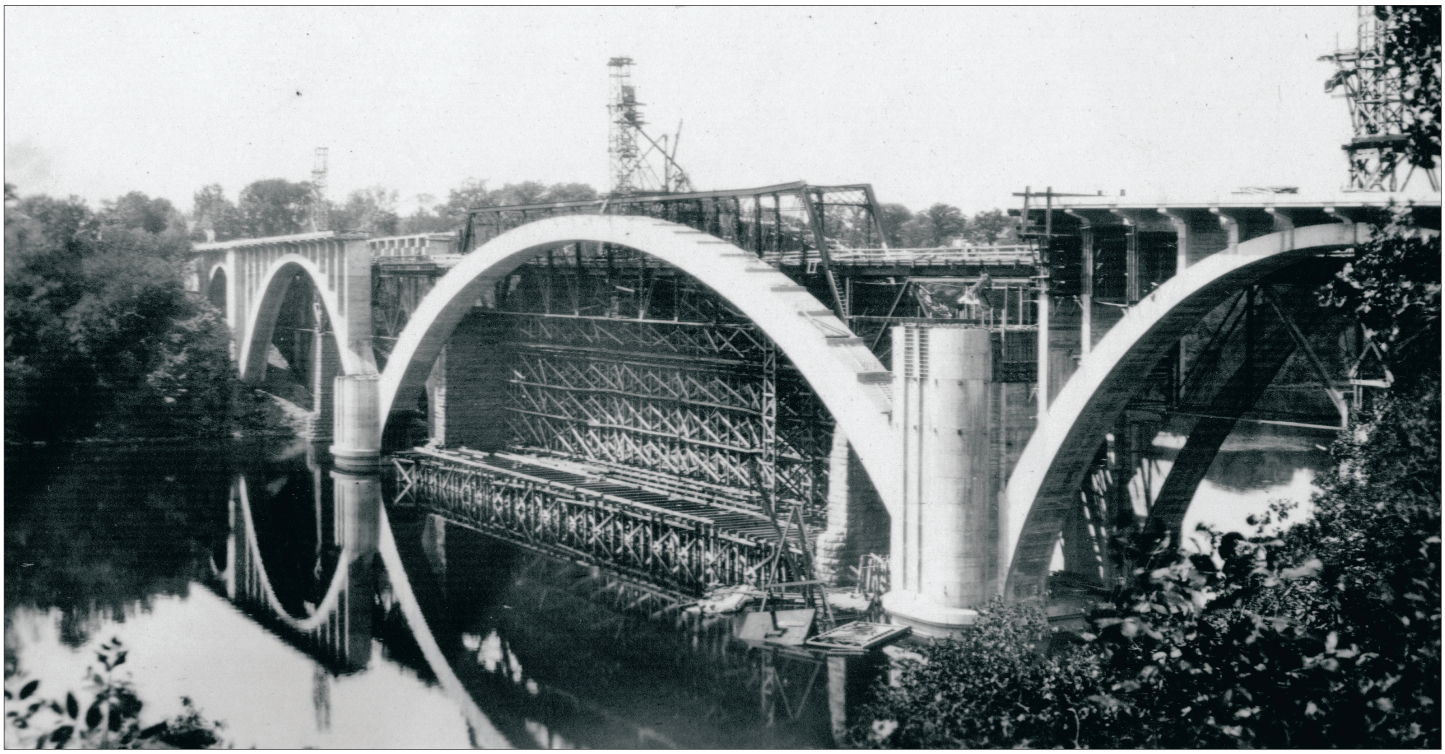

Fig. 1. Franklin Avenue Bridge, Minneapolis, Minnesota, during construction in 1922. This bridge has been recently rehabilitated. Image courtesy of Hennepin County Library.

Design of galvanic cathodic protection systems requires proper consideration of five key design factors, which are particularly relevant for historic structures.

Deterioration of older reinforced concrete structures is commonly caused by one or more of four mechanisms: chloride- or carbonation-induced corrosion of embedded steel, freeze-thaw deterioration of non-air-entrained concrete, and deterioration of the concrete matrix due to deleterious internal chemical reactions. These deterioration mechanisms must be addressed in order to achieve successful rehabilitations (Fig. 1).

Steel reinforcement in concrete is normally protected from corrosion by a thin oxide film (also known as a passive film) that develops around the bars as a result of the highly alkaline concrete pore solution that results from portland cement hydration reactions. As long as this passive film remains, corrosion is impeded. Chloride-induced corrosion can be initiated when chloride ions, in the presence of moisture and oxygen, accumulate to a sufficient concentration and then destroy the passive film around the reinforcing bars. Chloride ions can originate from external sources, such as deicing salts or seawater, or internal

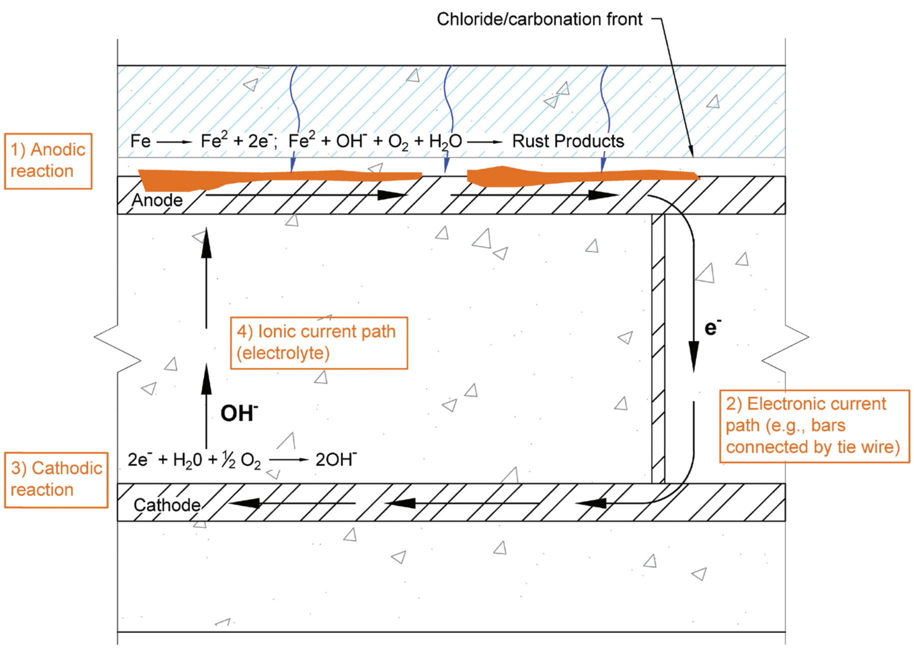

Fig. 2. Example of typical corrosion cell in reinforced concrete. All figures by Wiss, Janney, Elstner Associates, Inc., unless otherwise noted.

Fig. 3, opposite. Soldier Field, Chicago, Illinois, west grandstand and colonnade during construction in 1924. Image courtesy of the Chicago Park District.

sources, such as chloride-contaminated aggregates or chloride-containing admixtures. Carbonation-induced corrosion can be initiated when the carbonation front in the concrete reaches the level of the reinforcement. Carbonation is a natural process that occurs when carbon dioxide in the air penetrates the concrete and reacts with the cement paste, lowering its pH from as high as 13 in its uncarbonated state down to as low as 8.5, breaking down the passive film.

Freeze-thaw deterioration occurs in non-air-entrained concrete when the concrete is critically saturated with water and subjected to repeated freezing and thawing cycles. The damage first manifests in internal microcracking, progresses to paste deterioration or map-cracking visible on the surface, and culminates in disintegration of the concrete from the surface inward. Modern air entrainment avoids this damage mechanism by providing voids in the concrete into which internal water can expand when it freezes. Concrete deterioration can also be caused by deleterious chemical reactions such as alkali-silica reaction (ASR) and delayed ettringite formation (DEF). Further information on all of these mechanisms can be found elsewhere.[1]

In concrete deterioration caused by corrosion of embedded steel (either chloride- or carbonation-induced), the corrosion process is an electrochemical reaction that breaks down the steel to more chemically stable iron-oxide compounds (also known as rust). For this reaction to occur, a corrosion cell must be formed; it consists of an anode (location of oxidation reaction where electrons are lost) and a cathode (location of reduction reaction where electrons are gained) (Fig. 2). The anode and cathode are connected by an ionic current path (ions passing through an electrolyte such as moist concrete) and an electronic current path (electrons passing through a metallic conductor). The corrosion reaction results in rust at the anode that occupies a greater volume than the steel consumed, creating expansive pressures and eventually concrete distress in the form of cracking, delaminating, and spalling of the concrete surface.

Cathodic Protection Basics

Cathodic protection (CP) is one of several technologies used to prolong the life of historic concrete structures that are prone to damage from corrosion of embedded steel (i.e., CP does not address deterioration caused by mechanisms other than corrosion).

Used in the 1800s to protect ships by attaching billets of zinc to ferrous hulls, CP was first used for reinforced concrete structures in the 1970s. In short, CP involves making the reinforcing steel the cathode of a corrosion cell by supplying an alternative anode. There are two basic types of CP: galvanic CP (also known as sacrificial CP) and impressed current CP (ICCP).

Galvanic CP is a passive system in which a galvanic anode, typically zinc in various shapes and sizes, is embedded in or attached to the concrete and electrically connected to the steel. Because the zinc is electrochemically more active than the steel, the zinc becomes the anode and corrodes preferentially to the reinforcement, which becomes the cathode and is polarized, reducing the rate of corrosion. A galvanic CP system is usually relatively inexpensive to install and requires little to no maintenance. The anode is consumed and eventually exhausted, at which time it must be replaced to provide continued protection. Service life (i.e., the length of time that protection is provided) depends on many factors, including the size of the anode and severity of the corrosion environment, but typically ranges, in a well-designed system, from 7 to 20 years.

ICCP is based on an active system in which the anodes, powered by a DC power source, introduce an electrical current that promotes cathodic reactions at the surface of embedded steel. Use of a DC power supply may allow for higher currents and greater control. An inert anode that is not sacrificed over time is typically utilized. ICCP systems are generally more expensive to install and require more maintenance. Service life depends on many variables but can exceed 25 years.[2] Hybrid CP systems, which have been introduced recently, function as an impressed current system for a relatively short period of time (typically a few months) then revert to a galvanic system for the remainder of their service life.

This paper focuses on galvanic systems, the type of system used in the case studies presented, and, in the authors' experience, the more commonly used system for historic structures. The intent is to provide an overview of galvanic CP design in order to make information accessible to people who are not corrosion engineers. More detailed treatment on the subject can be found in corrosion engineering textbooks and National Association of Corrosion Engineers publications.[3]

Soldier Field

Soldier Field was constructed between 1922 and 1926 in Chicago, Illinois (Fig. 3). The stadium was listed on the National Register of Historic Places in 1984 and designated a National Historic Landmark from 1987 to 2006. Original elements of the structure that remain include the concourses at the stadium perimeter and the east and west colonnades.[4]

Overhead concrete in the concourses includes large transfer girders and secondary framing for the promenades and colonnades above. The coffered ceilings of the colonnades consist of an orthogonal grid of heavily reinforced concrete beams that support a thin, lightly reinforced concrete slab (Fig. 4). The formwork for the ceilings of the colonnade was lined with a 2- to 3-inch-thick architectural face mix that resembles granite, with structural concrete backup cast integrally behind.

Over the years, the concrete in the concourses and the ceilings of the colonnades has required annual inspections and frequent repairs to address distress from the corrosion of embedded reinforcement. In the colonnade ceilings, sampling and testing showed that corrosion was due principally to chlorides present in the architectural face mix. Calcium chloride had apparently been added as an accelerator to the face mix to aid in the two-layer placement method. In the concourses, sampling and testing showed that corrosion was due principally to carbonation of the concrete.[5]

Cathodic protection trials. In 2001, when adaptive reuse and rehabilitation of the stadium were being contemplated, the authors' firm was engaged to study means to prolong the life of the historic concrete elements (the firm was not involved in the adaptive-reuse design). Trials of five corrosion-mitigation systems were installed, including three galvanic CP systems: discrete zinc anodes, arc-sprayed zinc anodes, and zinc-hydrogel sheet anodes. The other methods were re-alkalization (an electrochemical treatment to address carbonization-induced corrosion) and surface-applied migrating corrosion inhibitors (a spray-applied penetrating liquid intended to mitigate corrosion).[6] This paper focuses on the discrete galvanic CP system installed in the coffered ceilings of the colonnades consisting of equally spaced, cylindrically shaped anodes embedded in holes that were cored from the attic into the top of the colonnade beams and electrically connected to the reinforcement. Anodes were installed at two spacings: 22 inches and 32 inches (Figs. 4 and 6).

Performance evaluation. After installation, the corrosion-mitigation systems were monitored for six months. Monitoring consisted of measurements of corrosion potential (using copper-sulfate reference electrodes), corrosion rate (using surface-contact linear polarization instruments and embedded corrosion-rate probes), and cathodic protection current (by direct measurement through a shunt resistor). Initial test results indicated good performance of the galvanic anodes in the colonnade ceilings, with sufficient protection current for the reinforcement (Fig. 5). Based on the initial measurements, it was predicted that the anodes would be consumed in 9 to 15 years, depending on actual environmental exposure conditions.

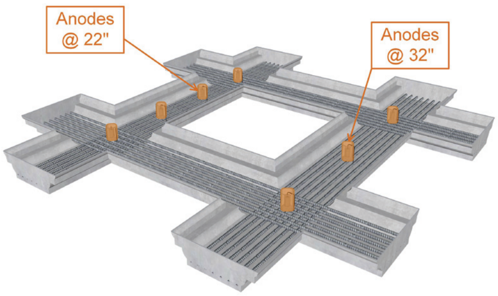

Fig. 4. Soldier Field, cut-away isometric view of coffered ceiling of colonnade, showing reinforcement and galvanic anodes (highlighted in orange).

Due to budgetary constraints, the owner elected not to install the anode system throughout the colonnade ceilings, but the trial installations were left in place. Each year, since that time, the historic concrete surfaces at Soldier Field have been inspected close-up. Corrosion-induced delaminations and spalls have continued to develop at a slow rate, and potentially loose material has been removed annually.

In 2014 the authors' firm performed follow-up testing to examine how the corrosion-mitigation trials were performing after 13 years of service. Evaluation of the galvanic anode system in the colonnade ceilings involved measurements of corrosion (half-cell) potential, measurements of cathodic protection current, and extraction of select anodes to observe the amount of zinc consumption and to measure the resistivity of the materials along the current distribution path.

As shown in Figure 5, the cathodic protection current in 2014 was found to be effectively zero, meaning no current was flowing from the anodes to protect the reinforcement. The current was expected to be only modestly less than that measured at the end of the monitoring in 2001, unless the zinc in the anodes had been fully consumed. Depolarization testing, an electrical technique used to assess CP systems by disconnecting the anodes and measuring the shift in the electric potential, was performed to assess the function and throwing distance (zone of influence) of the anodes based on a reference cell placed on the surface. No discernable depolarization potential shift was observed, which was consistent with the observed lack of current flow.

To assess the situation, three of the anodes and the surrounding embedding mortar were extracted by coring from the attic side. The embedding mortar was removed using an acid dissolution process, and the anodes were inspected and weighed. The extracted anodes showed only surficial zinc oxide and essentially no consumption of zinc compared to unused identical anodes.

Laboratory resistivity testing was performed on both the embedding mortar and the original concrete surrounding the embedding mortar in the core samples. Resistivity measures the degree to which a material conducts electrical current, which is needed along the ionic current path in a corrosion-cell or CP system (Figs. 2 and 6). Low resistivity indicates that the material readily allows current flow, while high resistivity indicates impeded current flow. High resistivity values may result where the concrete is dry and if the concrete is dense and impermeable (such as from very low water-to-cement ratios or in silica fume mixes). The significance of embedding-mortar resistivity on galvanic anode effectiveness was not widely known in 2001 and thus was not adequately considered in the design. Manufacturers of galvanic anodes now recommend that materials have resistivity of less than 15,000 to 50,000 ohm-cm, depending on the supplier, to support the function of the anodes.

Resistivity of the embedding mortar used at Soldier Field measured across the sample with an AC resistance meter was found to be very high (3,810,000 ohm-cm) under dry in situ conditions. When the mortar was saturated in the laboratory, the resistivity (51,000 ohm-cm) just exceeded the upper limit on resistivity permitted by anode manufacturers. Resistivity of the original concrete surrounding the embedding mortar was also high when dry (1,520,000 ohm-cm), though within the recommended limit when saturated in the laboratory (12,700 ohm-cm).

Considering these results, the poor long-term performance of this galvanic CP installation was attributed to the following:

- Wet or dry, the embedding mortar used in this installation was far too resistive to allow adequate current to flow along the ionic current path.
- When the surrounding concrete in the ionic current path was dry, as in the subject installation where moisture reaches only the bottom surface of the ceiling from ambient humidity and occasional condensation, the concrete was likely to be too resistive to allow adequate current flow.
- The high chloride concentration in this assembly is in the architectural face mix and not in the backup concrete. As such, chloride ions, which can reduce resistivity and enhance current flow, were not present along the ionic current path behind the reinforcing bars.

The good performance of the anodes for the first six months of monitoring is believed to be attributable to the moisture introduced into the system by the mixing water in the embedding mortar and the water used in the coring to install the anodes. The added water likely permeated the concrete temporarily and then took some time to dissipate, so that the initial resistivity of the moistened materials along the ionic current path was low enough to allow protection current to flow. However, once the added moisture dissipated and the materials along the ionic current path dried out, the dry materials no longer allowed current to flow.

Franklin Avenue Bridge

The Franklin Avenue Bridge over the Mississippi River in Minneapolis, Minnesota, is a five-span open-spandrel concrete arch bridge built between 1919 and 1923 (Fig. 1). At the time of its construction, it had the longest concrete arch span in the world at 400 feet. The arch ribs were constructed using the Melan system patented in 1892 by Joseph Melan, an Austrian bridge engineer. Steel trusses fabricated from riveted steel angles were erected between massive concrete piers; the arch-rib concrete was then cast in place around the trusses.

In 1970 the bridge deck, cap beams, and spandrel columns were removed and replaced as part of a major rehabilitation effort to address advanced deterioration. Localized concrete repairs were also performed on the arch ribs, piers, and abutments. The bridge was listed in the National Register of Historic Places in 1978.

The authors' firm was retained in 2007 to perform a condition assessment and a study of rehabilitation alternatives for the bridge. Follow-up inspections and rehabilitation design began in 2013, and rehabilitation construction took place from 2015 to 2017. Complete information about the condition assessment, rehabilitation design, and construction are available elsewhere.[7] This paper focuses on the rehabilitation of the arch ribs using targeted galvanic cathodic protection.

The assessments and materials testing identified widespread deterioration in the original concrete caused primarily by chloride-induced corrosion of the reinforcing steel, as well as freeze-thaw deterioration (cracking and eventual disintegration of concrete due to freeze-thaw cycling of saturated, non-air-entrained concrete). In the arches, the most prevalent damage was corrosion-induced cracking and spalling along the arch corners where deicing salts used on the deck had penetrated (Fig. 7). Freeze-thaw damage was also present below leaking deck expansion joints and in the spring-line zones where long-term moisture exposure was most severe.

Customized concrete-repair details were developed for the arch-rib corners, as illustrated in Figure 8, including removal beyond deteriorated regions, cleaning and coating of the embedded steel, anchorage into the substrate concrete, and crack-control reinforcement within the repair.

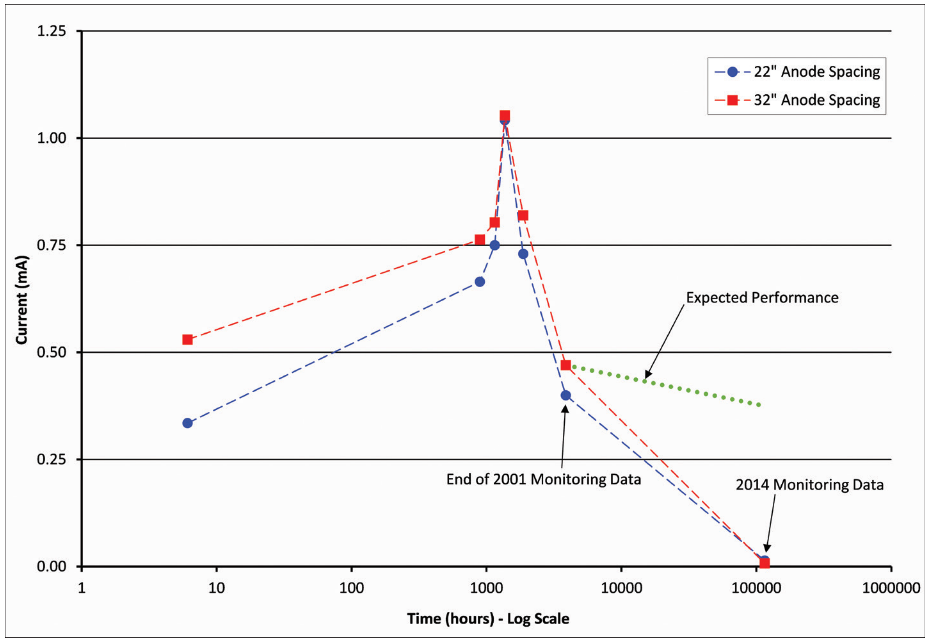

Fig. 5. Instantaneous protection currents generated by embedded anodes as measured in 2001 and 2014, showing high initial currents but near-zero current when tested 13 years after installation.

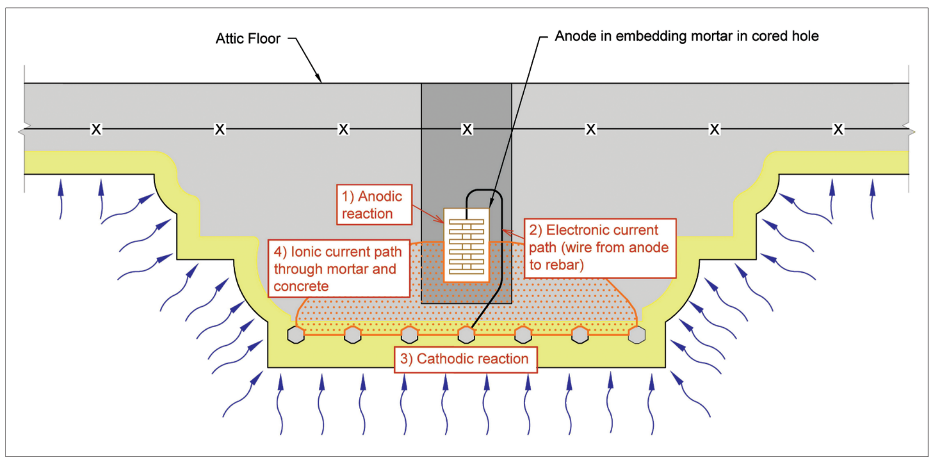

Fig. 6. Schematic illustration of problems with the anode performance. High-resistivity embedding mortar (dark gray) and dry zone of original concrete (orange, dotted shading) interrupt current flow. Chlorides (yellow shading) and moisture source (blue arrows) are remote from ionic current path.

Installation of galvanic cathodic protection.

Between the arch-rib corner repairs, where chloride contamination was likely but cracking had not yet begun, galvanic cathodic protection was installed to prolong the service life until the next repairs would be needed in approximately 15 to 25 years. The cathodic protection consisted of continuous rod-shaped zinc anodes placed in saw-cut grooves and electrically connected to the Melan truss angles with wires at intermittent locations (Fig. 8). Slots for the anodes were located to be least visible from the ground, minimizing

Fig. 7. Franklin Avenue Bridge, example of chloride-induced corrosion spalling along the arch-rib corner, 2012.

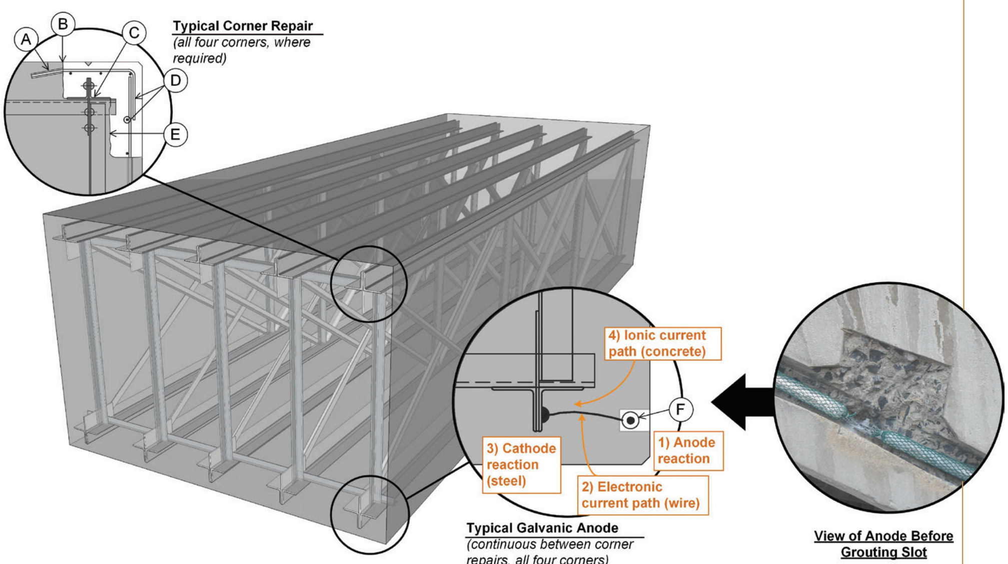

Fig. 8. Schematic drawing of typical arch-rib corner repairs, showing adhesive-grouted dowels for anchorage (A); saw cuts at perimeter (B); clean and coat existing steel (C); crack-control reinforcement (D); properly prepared concrete substrate (E); and continuous zinc anodes in slots between concrete repairs, with wire connections to Melan angles (F).

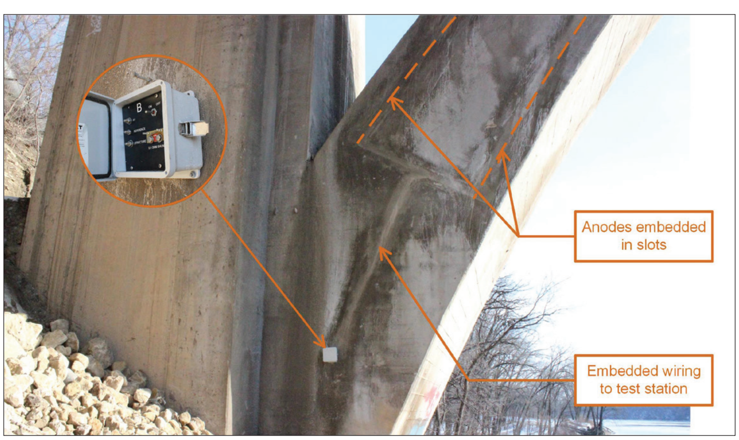

Fig. 9. Franklin Avenue Bridge, example of built-in monitoring station (before surface of concrete was cleaned and coated), 2017.

aesthetic impact. The anodes were sized to provide sufficient current density and were embedded in a pre-packaged low-resistivity mortar containing lithium hydroxide with a manufacturer-reported resistivity of 5,000 ohm-cm that filled the slots.

In this design, current flow along the ionic current path was promoted by the availability of moisture, presence of chloride ions, low-resistivity embedding mortar, and low-resistivity original concrete (when moist). Two permanent built-in monitoring stations were included in the cathodic protection installation, one at each end of the bridge (Fig. 9).

Performance evaluation. System commissioning using the monitoring stations was performed soon after installation, and system monitoring has been ongoing since that time. Each monitoring station included an embedded reference cell and current shunt to support depolarization testing and CP current. The reference cells were within 6 inches of the reinforcing steel, near the midpoint of the instrumented section. The monitoring consisted of routine measurements of the protection current and system depolarization, typically performed monthly at each monitoring station.

The protection-current density provides a general sense of the cathodic protection system effectiveness, while the anode consumption rate is dependent on the total protection current. Figure 10 shows the performance data that has been measured over the past two years. The measured protection currents fluctuate with temperature changes, as expected, since corrosion rates decrease with decreasing temperatures and can become almost dormant in very low temperatures. Based on an average measured current of approximately 40 mA and the surface area of the protected truss angles, the current density was 3.8 mA/m^2.

Depolarization is measured by temporarily interrupting the protective current (i.e., disconnecting the anode and the reinforcing steel) and monitoring the reinforcement's decay in polarization over time. Numerically, depolarization is the voltage difference between the final depolarized potential (typically after at least four hours) and the potential measured immediately when the system is turned off. According to the National Association of Corrosion Engineers (NACE SP0216-2016), depolarization values of 100 mV or greater indicate that cathodic protection is being achieved. The monitoring stations have registered polarization values greater than the 100 mV throughout the monitoring period, indicating good system performance over more than two years.

Lessons Learned: Key Design Factors for Galvanic CP Systems

The Soldier Field example emphasizes the need to provide a sufficient and complete path of protection current in a galvanic CP system. The protection path can be different depending on the geometry of each installation; for each case, the protection path should be identified and all of the materials along the path evaluated to ensure they will effectively conduct the protection current. Materials should be low resistivity and should be exposed to a sufficient and lasting moisture source. In the Franklin Avenue Bridge example, these factors were addressed, and testing is showing good performance.

Based on these two examples and the fundamental corrosion principles discussed above, five key design factors need to be considered to achieve long-term corrosion protection of historic concrete structures using galvanic CP. These factors are as follows:

- technical and economical merits of cathodic protection
- impacts on the historic resource
- sufficient source of protection current in a galvanic CP system
- complete path of protection current in a galvanic CP system
- performance specifications and field verification.

The authors suggest that these five general factors be used as a step-by-step guide to navigate the process of whether galvanic CP is an appropriate solution to mitigate concrete deterioration in an individual situation, and, if so, how it can be implemented effectively.

1. Technical and economic merits of cathodic protection. The technical and economic merits of cathodic protection should be assessed in the context of the individual structure, beginning with a thorough condition assessment and materials-testing program to identify the cause or causes, extent, and severity of any deterioration present. Targeted sampling and testing of the concrete are essential to understand the nature and cause of the deterioration in each individual structure. Without an understanding of the deterioration mechanisms, repairs may become unnecessarily extensive and expensive if they attempt to address deterioration mechanisms that are not relevant, or the repairs may be ineffective if they fail to address the root causes of the deterioration. Cathodic protection addresses only corrosion-induced deterioration; hence, if the primary cause of deterioration is not corrosion (such as freeze-thaw deterioration), then cathodic protection is not a technically appropriate solution.

From an economic standpoint, the costs and benefits associated with repairs that include a cathodic protection system should be weighed against those associated with conventional concrete repairs without cathodic protection. Various types and extents of galvanic and impressed current cathodic protection should be considered. Alternatives should be compared using realistic service-life predictions and life-cycle cost analyses. Since factors such as condition, access, local contractor expertise, and targeted service life may vary widely between structures, each structure should be evaluated separately.

2. Impacts on the historic resource. If cathodic protection is determined to be a viable option, a paramount consideration is whether it can be achieved with minimal impact to the historic character of the structure. For such consideration, the *Secretary of the Interior's Standards* and the National Park Service's *Preservation Brief 15* are critical resources.[8] Key questions to ask regarding impact on the historic resource include:

- Do the repairs retain (rather than replace) the original historic fabric?
- Is the appearance of the original structure altered unacceptably by the repairs?
- Are the repairs reversible?
- Is the repair a proven technology?

3. Sufficient source of protection current in a galvanic CP system. To design a galvanic CP system suitable for the project context and goals, the anode material (normally zinc) and geometry must first be selected in order to provide a sufficient source of protection current to the steel that is to be protected. Anode selection should consider material, shape, surface area, and mass of the anode. In general, a greater mass, electrical activity, and surface area of zinc are needed to achieve both a longer service life and a higher degree of protection to the steel. The types of zinc anodes commercially available for use in concrete vary widely. Various anode types include puck-shaped anodes, cylindrical anodes (like the ones used at Soldier Field), rod-type anodes (like the ones used at Franklin Avenue Bridge), and surface-applied anodes (like those used elsewhere at Soldier Field).[9]

In order for the anodes to generate current, the conditions at the anode must also be suitable to promote anode corrosion. Various strategies, including potting the anode in a high pH mortar or chloride-rich mortar, have been implemented by anode manufacturers to encourage the corrosion reaction. This corrosion process also requires moisture at the anode site.

4. Complete path of protection current in a galvanic CP system. Next, and the most important lesson learned through the case studies described herein, a complete and long-lasting current path must be provided for the CP system to be effective. As discussed above, completing the corrosion cell (and thus supporting the function of the galvanic anode) requires ionic current to pass through the concrete between anode and steel. The resistance to ionic current flow is increased with greater

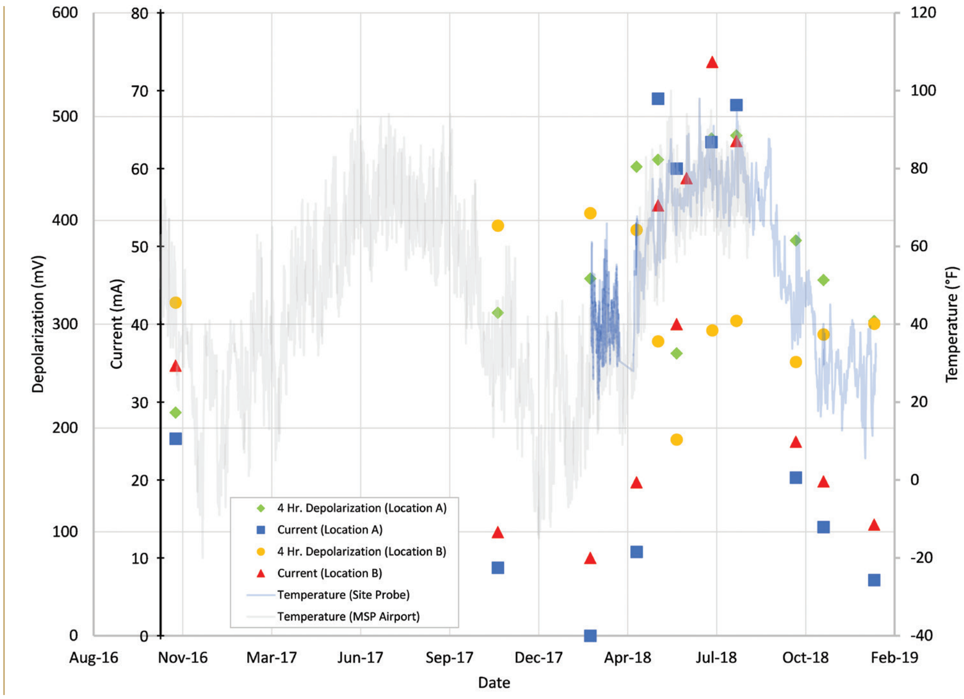

Fig. 10. Franklin Avenue Bridge, protection current and depolarization monitoring data, showing depolarization values greater than 100 mV over the testing period and variation in current with temperature.

distance and greater resistivity of the concrete. Therefore, to support ionic current flow, the anodes must be in relatively close proximity to the reinforcement that needs protection; the ionic current path must not include high-resistivity materials that will impede the current (see recommendations above for resistivity limits); and an adequate and lasting source of moisture must be present. Galvanic CP systems may be less successful in environments where moisture exposure is limited, such as concrete in climate-controlled, interior environments. One should also consider where chloride ions may be present in the system since their presence will reduce resistivity locally and enhance ionic current flow.

For example, the galvanic CP system installed in the colonnades at Soldier Field was not effective in the long term for the following reasons:

- Highly resistive embedding mortar and original concrete were present along the ionic current path.
- There was a lack of sufficient and lasting moisture along the current path.
- Chlorides were present in the system, but not along the current path.

In contrast, the CP system installed in the arch ribs of the Franklin Avenue Bridge has been shown to be effective for the following reasons:

- The embedding mortar and original concrete along the ionic current path have low resistivity.
- There is an ample and lasting source of moisture throughout the current path.
- Chlorides may be present along the current path.

In addition to the ionic current path, an electronic current path must connect all steel to be protected to the anode, and the connections between the anode and the protected steel must be durable. A qualified corrosion professional should evaluate both the ionic and electronic current path for each potential application of galvanic CP. Proper consideration of the current distribution path is particularly important for historic structures where it may be desirable to place anodes in unusual locations and orientations to hide them from public view and to protect historic fabric.

5. Performance specifications and field verification. If cathodic protection is pursued, it is critical that the performance requirements be thoroughly defined in the project specifications and that the installation details be described carefully on the plans. It is also critical that the installation include provisions for initial system commissioning and ongoing monitoring to verify the intended performance. The authors recommend built-in monitoring stations that can be used to measure protection current and depolarization for a period of at least three years. For the installation at Soldier Field, the six-month period of monitoring was not sufficiently long to detect that the performance was not as intended.

Conclusion

To design an effective galvanic cathodic protection system, one must understand corrosion fundamentals and the condition of each individual structure. Claims of product manufacturers should be verified by independent review and testing by qualified designers. The design of galvanic CP systems should carefully consider all five key design factors described above. In the authors' experience, the two design factors that are most often neglected in practice are the provision of a complete current-distribution path and sufficient field-performance verification testing. These often-neglected factors can be particularly relevant in applications for historic structures where anodes are often placed in unusual orientations and where built-in test stations are not installed in order to minimize visual impact and retain historic fabric.

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Notes

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