# CORROSION MITIGATION OF PRECAST CONCRETE PARKING GARAGES

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The use of precast concrete for constructing parking garages is very common and widespread throughout North America and is often the material of choice for architects, engineers, developers, and owners looking for a fast-track construction schedule, speed of construction, economy, and low initial cost. Fabricated under controlled conditions in a precast concrete plant, precast concrete elements are shipped fully formed to the construction site, where they are assembled. According to the Precast/Prestressed Concrete Institute (PCI),[1] because elements are cast and cured under factory-controlled conditions, precast concrete tends to exhibit better consistency, higher quality, and greater long-term durability than concrete fabricated on-site.

Unfortunately, precast concrete structures (Fig. 1) can be susceptible to premature corrosion-related deterioration, resulting in higher maintenance costs. In this article, we will present ways to mitigate corrosion, minimize maintenance, and extend service to existing and new precast concrete parking garages.

*Fig. 1: Typical precast parking garage*

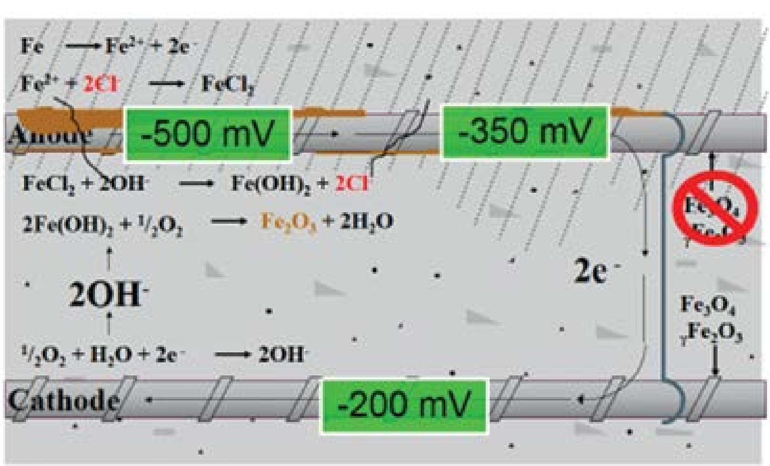


*Fig. 2: Reinforcing steel corrosion cell in concrete*

## CORROSION FUNDAMENTALS

The corrosion of reinforcing steel in concrete is an electrochemical process that can be influenced by chloride-ion content, pH level, concrete permeability, and availability of moisture to conduct ions within the concrete. Five elements are required to complete the corrosion cell: an anode, a cathode, an ionic path (electrolyte), a metallic path between the anode and cathode, and the availability of oxygen. This process requires an anode (or area of oxidation) and a cathode (or area of reduction). In the case of concrete reinforcement, the anodes and cathodes are elements of steel reinforcing bars, welded-wire reinforcement, or prestressing steel.

The anodic site becomes the site of visible oxidation (corrosion) and the cathode is the location of the reduction reaction, which is driven by the activity at the anode (Fig. 2). The mV potentials are shown to demonstrate the force driving the corrosion cell. The metallic path can be provided by the embedded prestressing stands and/or the mild steel reinforcing. The ionic path is provided by the concrete matrix with sufficient moisture for conductivity and oxygen, generally available from the atmosphere due to the permeability of concrete and the diffusion of gases.

Due to the high alkalinity (normally 12 to 13 pH) of the concrete pore water solution, a thin, dense, passivating oxide layer is formed and maintained on the surface of the embedded steel, thus protecting it from corrosion activity. If this passive film is destroyed by the intrusion of aggressive elements or a reduction in the alkalinity of the concrete, the reinforcement will no longer be in a passive, non-corroding state.

For corrosion to be initiated on the reinforcement, it is necessary for this protective film to break down. This may occur as a result of one or a combination of the causes listed as follows:

- Ingress of sufficient chloride ions into the concrete matrix to initiate corrosion. The chloride contamination may come from the use of deicing salts, exposure to a marine environment, or through the use of chloride-containing concrete admixtures; or
- Carbonation, the reaction of CO and $CO_2$ in the air with available alkali in the concrete will gradually cause the pH of the concrete to decrease. Once the pH drops below 9.5, the passivating oxide film will start to break down.

Chloride-induced corrosion is the most common. Once the chloride concentration at the depth of the reinforcing steel exceeds threshold levels, the passive oxide film will begin to degrade and corrosion may be initiated. The threshold of corrosion or the amount of chloride ions needed to initiate corrosion of steel is increased as the pH of the surrounding concrete increases. The corrosion threshold is usually around 1.2 to 1.6 $lb/yd^3$ (0.7 to 0.95 $kg/m^3$) of chloride or 300 to 400 parts per million (ppm) of concrete. Once the corrosion process begins, the way to slow or stop it is to apply direct electric current to the reinforcing steel to reverse the electrochemical process—a procedure known as cathodic protection.

In the presence of water and dissolved chlorides (as from deicing salts), reinforcing steel corrodes, leading to internal distress within the concrete matrix. As it corrodes, reinforcing steel can expand up to six times or more its original size. Because it is embedded in concrete, the corroding reinforcement can release the expansive pressure in only one way: by cracking, delaminating, and spalling the concrete. Typically, cracks begin as fissures at the site of corrosion. Eventually, a spall results, exposing the reinforcing steel to yet more moisture and corrosive chemicals in a self-propagating cycle of deterioration.

## PRECAST MEMBERS

Precast concrete garages are usually made up of a system of conventionally reinforced precast concrete columns and prestressed concrete slabs, beams, and girders. Conventional reinforcement consisting of embedded steel bars or wires is generally reserved for columns, load-bearing walls, and other members that undergo compressive stresses. Flexural members, however, including precast horizontal slabs (such as hollow core and double tees), are typically reinforced with high-strength steel strands that are prestressed and are the primary load-carrying reinforcement, and conventional reinforcement usually consisting of stirrups for crack control. The steel strands are tensioned before the concrete is cast and cured. Once the prestressed concrete members are installed on-site, the internal stresses applied by the strands work to counteract gravity and service loads, resulting in lighter-weight members that can span longer distances than their conventionally reinforced counterparts. Most prestressed members are single-span, which means their embedded strands are located in the bottom compression zone and not at the top of the members, and therefore not as susceptible to chloride contamination. The only reinforcement located near the top of the precast members are the welded flange-to-flange connections along the joints.

The floor slab system that comprises the parking surface is most commonly constructed with double tees, consisting of two joists or stems and horizontal deck having cantilevered flanges. Single-tee, triple-tee, and quad-tee members have been used as well, although less frequently. Placed side-by-side, the horizontal flanges create a large slab or deck that acts as the parking surface of the garage (Fig. 3). Embedded steel plates in the cantilevered flanges are welded to those of adjacent members, creating a unified structural system. When these connections are properly configured, the parking surface also acts as a diaphragm to resist lateral loads applied to the garage through wind or seismic forces.

Tees can be pre-topped or topped with cast-in-place concrete in the field. Field-cast concrete topping slabs should have the control joints tooled into the plastic concrete, not saw-cut after casting. The joints in the concrete topping slab need to line up with the tee flange joints below and have the proper

*Fig. 3: Precast double-tee deck*

*Fig. 4: Tee flange joint failure*

*Fig. 5: Corrosion of tee flange connector*

*Fig. 6: Double-tee stems and inverted T-beam haunch*

*Fig. 7: Inverted T-beam and column corbel*

cross section and depth. To prevent moisture intrusion, the control joints should be filled with flexible sealant (Fig. 3 and 4). Pre-topped tees, because they are less susceptible to improper location and construction of joints due to being cast at the precast plant, can offer a higher level of quality to resist the elements at joints.

## CORROSION-RELATED DAMAGE

Reinforcing steel corrosion and resultant concrete deterioration can weaken structural members due to loss of effective concrete cross section, loss of reinforcement cross section, and connection damage or failure. The most serious type of corrosion damage occurs adjacent to joints and is related to water leakage due to joint leakage and failure (Fig. 4). As a result, the portion of precast members adjacent to joints and steel connections between precast concrete flanges (Fig. 5) are most susceptible to water leakage, corrosion, and to prematurely deteriorate and be in need of repair.

Flange-to-flange steel connections are the most numerous of connections in a precast parking garage and occur at joints along the length of tees. Recently, it has become common to use stainless steel plates, and while some issues have been raised, should have the potential for significantly reducing corrosion-related concrete damage and connection failures at these locations. Yet other sections of precast members, such as the ends of tee stems, inverted T-beam haunches, and column corbels remain highly susceptible to corrosion-related damage due to moisture infiltration.

The threshold level for the initiation of corrosion in reinforcing steel is approximately 300 to 400 ppm of chloride ion in the concrete, so the objective is to keep the concentration well below that level. Double tees have their primary strand reinforcement located in the stems, well below the deck surface, but unfortunately the strand ends are exposed at the ends of the tee stem directly below the deck joints (Fig. 6). Consequently, chloride penetration due to joint leakage often presents a problem for this reinforcement and potentially for corrosion-related damage to the ends of the tee stems.

For the most part, because tees are manufactured in a precast plant and the primary strand reinforcement is located near the bottom of stems, these structural members should generally have a long service life. That is, except at joints. Joint failure is perhaps the most significant repair and maintenance issue in precast concrete parking structures.

Because joint sealants have a limited life and require the most maintenance, the ends of tee stems, beam haunches, and column corbels are the most common locations where premature corrosion-related damage occurs that can significantly shortened service life (Fig. 6 and 7).

## GALVANIC PROTECTION

An effective way to achieve long-term corrosion protection of existing chloride contaminated structures, or to provide extended service life to target locations on new precast members, is to use galvanic protection systems. Refer to ICRI Technical Guideline No. 510.1 for further information on galvanic protection and other corrosion mitigation techniques.[2] Galvanic protection is achieved when two dissimilar metals are connected. The metal with the higher potential for corrosion (generally a zinc-based system in concrete applications) will corrode in preference to the more noble metal. As the sacrificial metal corrodes, it generates electrical current to protect the reinforcing steel.

With this type of cathodic protection system, the galvanic protection system voltage is fixed and the amount of current generated is a function of the surrounding environment. Galvanic anodes will generate higher current output when the environment is more corrosive or conductive—for example, where there is higher chloride concentrations, and where current output exhibits a daily and seasonal variation based on moisture and temperature changes.

Galvanic protection systems are safer than impressed current systems because the driving voltage for the system is fixed and the potential for hydrogen generation and the risk of embrittlement of high-strength strands is greatly reduced. Galvanic protection systems are low-maintenance, do not require an external power supply, and are compatible with prestressed and post-tensioned steel. Galvanic protection systems are used for two types of applications: distributed systems for global corrosion protection and discrete anodes for localized protection. Discrete embedded galvanic anodes, in particular, have been used to protect chloride-contaminated prestressed beams exposed to leaking joints or poor drainage.

Different types of galvanic protection systems are available to use when protecting precast members as follows:

- Discrete galvanic anodes—as defined in ACI RAP Bulletin 8,[3] there are two types of discrete galvanic anodes available. Type 1 anodes are embedded within the repair area (Fig. 8). Type 2 anodes are placed in core holes drilled into sound concrete (Fig. 9).
- Surface-applied galvanic metalizing systems—these zinc sheet systems come in rolls (Fig. 10) and are used for both distributed and localized protection of elements, members, and structures. While thermally applied metalizing systems can, and are also used to, protect precast members, adhered systems may be more appropriate for protecting localized sections of members.

Fig. 8: Discrete galvanic Type 1 anode installation

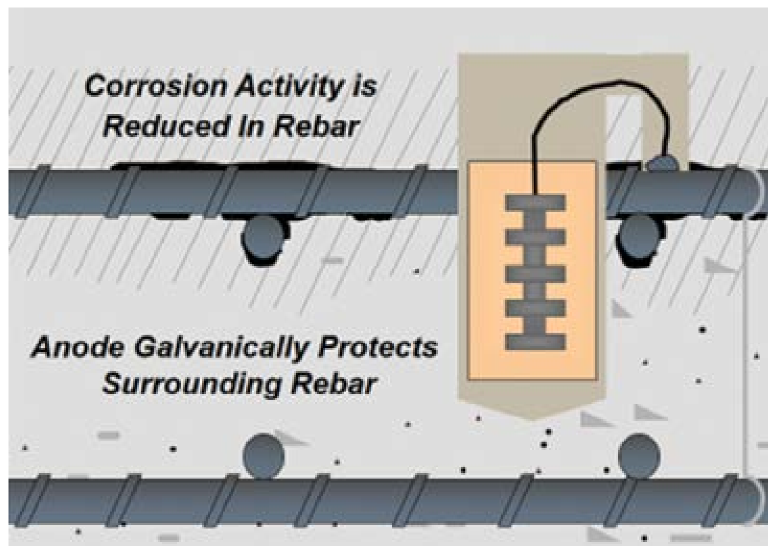


Fig. 9: Discrete galvanic Type 2 anode

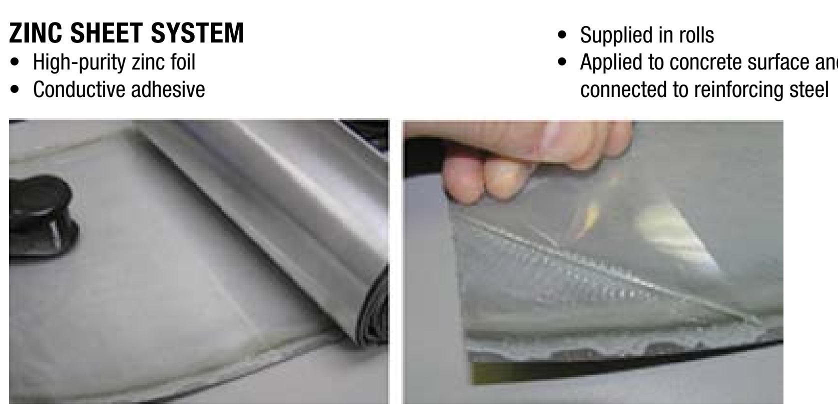


Fig. 10: Surface-applied galvanic metalizing system

## LEVELS OF CORROSION PROTECTION

There are three basic levels of active (electrochemical) corrosion protection available. These are generally referred to as:

- Corrosion prevention;
- Corrosion control; and
- Cathodic protection.

All levels are essentially similar in that a protective current is provided to prevent or reduce the corrosion activity of the reinforcing steel. They differ in terms of the intensity of the protective current and suitability for a given range of applications.

## CORROSION PREVENTION

Corrosion prevention is defined by the National Association of Corrosion Engineers (NACE) as "Preventing corrosion from initiating even though the concrete may be sufficiently contaminated with chlorides to favor corrosion."[4]

In the course of rehabilitation projects, there are many situations where concrete contaminated with chloride ions and subsequent concrete damage is localized. In other areas, also chloride contaminated, corrosion has not yet initiated and subsequently concrete damage has not yet occurred. In this situation, when localized repairs are undertaken, it may be necessary to further extend the repair area to remove additional sound concrete around all corroding reinforcement and continuing the removal until clean steel is reached. Undertaking repair work in this way removes much of the concrete from around currently corroding areas. However, chloride-contaminated concrete will still remain in contact with the reinforcement outside the repair areas. If not addressed, the reinforcement in these areas will eventually become anodic and will begin to corrode.

The approach of corrosion protection is usually not practical because it makes estimating the extent of localized repairs needed uncertain (for example, removing damaged concrete can be fairly well determined by sounding the concrete or by performing a delamination survey, but to require a contractor to continue removing sound concrete until no evidence of corrosion by-product is observed, is open-ended). Alternatively, half-cell potential testing could be performed by the contractor (prior to placing repair material) around the excavated repair areas to determine the probability of existing corrosion activity and to help determine if the repair area needs to be extended. However, this is not a common practice and leaves the extent of localized repairs needed uncertain.

Because less current is provided, smaller and/or greater spacing of galvanic anodes is required to provide corrosion prevention (to prevent new corrosion from initiating), than for corrosion control (overcoming ongoing corrosion), and designing for corrosion control may be slightly more costly. Nonetheless, the extra cost of designing the galvanic corrosion protection system for a higher level of protection or corrosion control is likely to be considerably less costly than additional concrete removal costs in enlarging the repair areas. Therefore, it is usually more conservative, practical, and cost-effective to design the galvanic protection system based on corrosion control rather than corrosion prevention, and is the recommended approach. The exception is when using galvanic protection in new construction, which will be discussed later.

## CORROSION CONTROL

Corrosion control is defined by NACE as "Providing a significant reduction in the corrosion rate of actively corroding steel in concrete."[4]

Corrosion control can result in an increased service life of the rehabilitated targeted sections of precast members at a relatively low incremental cost. This is how galvanic corrosion protection or mitigation is most often used.

Corrosion control may or may not completely stop ongoing corrosion, but the reduction in corrosion activity will significantly extend the service life of existing corroding structures. In corrosion control applications, the conditions for corrosion (such as chloride contamination) already exist and corrosion may have already initiated in some areas, although have not progressed to the point of concrete damage. The applied current necessary to address corrosion activity (after corrosion initiation) is higher than the current required for corrosion prevention. Therefore, either larger and/or closer spaced galvanic anodes will be required to provide corrosion control.

For either corrosion prevention or corrosion control, the current density required decreases over time as the beneficial effects of chemical reactions at the cathode build up the level of alkalinity at the steel, and the concentration of corrosive ions such as chloride at the steel interface decreases over time, which means the consumption of the anodes also slows down.

It's not usually practical to determine whether corrosion prevention or corrosion control is needed, especially because determination could be uncertain and may vary throughout members. As a result, designing for corrosion control is usually recommended. Because doing so can be conservative, if a lesser level of protection is all that is required, then a higher level of protection and longer service life will be the result. Alternatively, designing for corrosion prevention when all or part of the member may require corrosion control could result in inadequate protection and shorter anode life and protection.

### CATHODIC PROTECTION

Cathodic protection (CP) is an electrochemical method of suppressing corrosion to essentially zero. CP systems operate by electrically forcing the steel into a more cathodic (non-corroding) state. While this can be achieved with galvanic protection, it cannot be ensured because galvanic systems are not adjustable. Therefore, when designing galvanic systems, corrosion prevention or control is usually assumed.

## CORROSION MITIGATION OF EXISTING PRECAST MEMBERS

In general, precast concrete members are very durable, especially when joints are well-maintained and water infiltration is controlled, preventing chloride contamination of adjacent precast elements, such as tee stem ends, inverted T-beam haunches, and column corbels supporting beams. Unfortunately, joints are often not maintained or do not properly function to prevent leakage. As a result, it is very common that localized repairs are needed at these locations. Because these precast elements are chloride-contaminated, localized repairs alone will not likely provide long-term repairs. Some type of corrosion protection is also required. The following galvanic corrosion mitigation options can be used for extending service life to tee flange connections, tee stem ends, beam haunches, and column corbels that have been chloride-contaminated and exhibit corrosion-related damage. To protect these elements, various galvanic anode types can be used as follows:

- Tee flange connections—Because of their location directly within the joint, these connectors are the most susceptible to damage and represent the most common type of precast repair. Type 1 discrete galvanic anodes are most commonly used in protecting flange connectors that are damaged and being repaired (Fig. 11). To protect both the damaged connectors and other corroding connections that will likely be damaged in the near future along a joint, a surface-adhered galvanic strip (Fig. 10 and 12) can be installed on both sides of the joints.

*Fig. 11: Discrete galvanic Type 1 anode protecting flange connector*

*Fig. 12: Zinc sheet protecting damaged and undamaged flange connections*

- Tee stem ends—Either Type 2 discrete galvanic anodes can be embedded into the stems (Fig. 9 and 13) or a surface-applied galvanic metalizing system (Fig. 10 and 12) can be used to mitigate corrosion and extend the life of repairs to these elements. Because of lack of space, it can be difficult to install Type 1 discrete anodes; however, thinner elongated Type 1 anodes are available.
- Inverted T-beam haunches—As with tee stem ends, because of the lack of space to install Type 1 discrete galvanic anodes, Type 2 discrete galvanic anodes are typically installed between strands (Fig. 9 and 14). Alternatively, surface-applied galvanic zinc sheets (Fig. 10 and 12) can be placed in strips on the sides of haunches and on the undersides of inverted T-beams.
- Column corbels—due to the small size of these elements, primarily Type 1 discrete galvanic anodes in repair areas and/or Type 2 discrete anodes in contaminated sound concrete are usually used to mitigate corrosion.

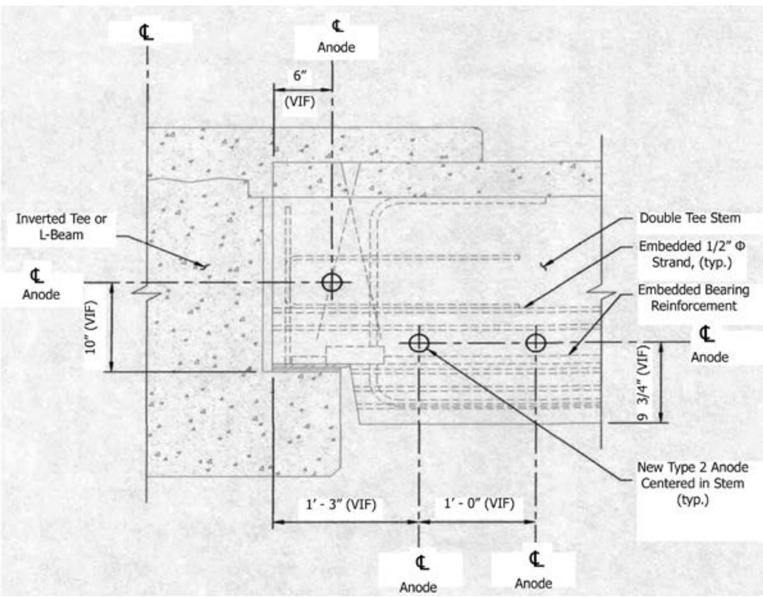

*Fig. 13: Discrete galvanic Type 2 anodes protect T-stem end*

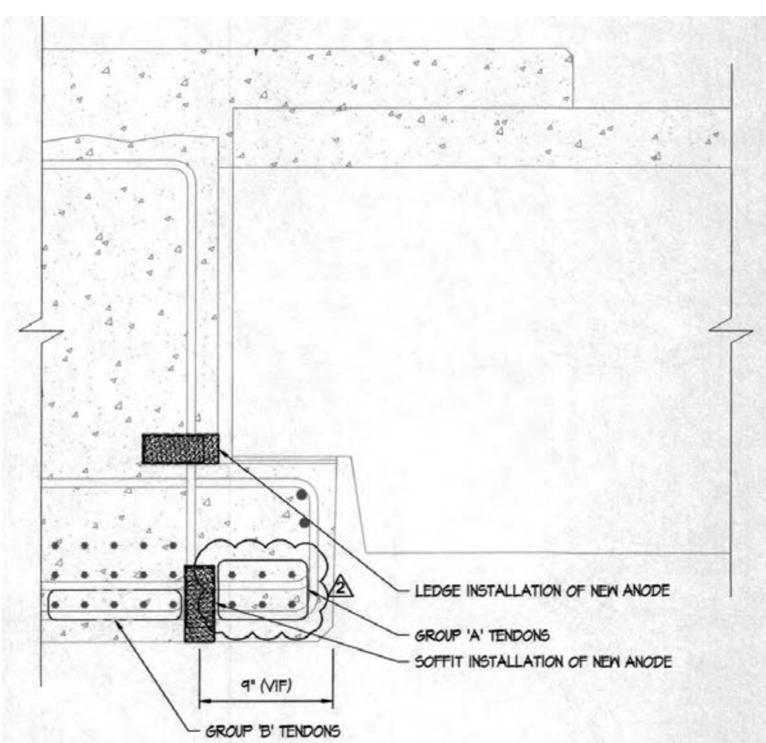

*Fig. 14: Discrete galvanic Type 2 anodes provide corrosion protection at inverted T-beam haunch*

When using any type of cathodic protection system, including galvanic protection, on existing precast concrete members, establishing electrical continuity between strands and mild reinforcement to be protected is essential. There are various methods for doing this, such as saw-cutting a continuity channel, which is later grouted in, to expose the reinforcing steel and make an electrical wire connection.

## TARGETED CORROSION PROTECTION IN NEW CONSTRUCTION

In new precast construction, because there is a high probability of water leakage at joints leading to contamination of adjacent elements and premature corrosion damage of tee flange connectors, tee stem ends, inverted T-beam haunches, and column corbels supporting beams, it would be beneficial to extend the service life and delay repairs at these locations. While steps can be and are being done to address this issue, such as improving deck drainage, better joint detailing and construction, better maintenance, and improved sealants, it is still likely that premature repairs at and adjacent to joints, and at vulnerable elements, will still be required in the future.

Galvanic corrosion protection is a cost-effective way to extend service life by 10 or more years to these most susceptible locations. The industry is already using stainless steel flange connectors, which should provide additional service life. Yet, options for protecting and extending service life to tee stem ends, haunches, and corbels are still not being effectively provided. Additional concrete cover adds weight and could increase member depth or element size. Using epoxy-coated or stainless steel mild reinforcement and strands may not be cost-effective and you would not want to mix these materials with uncoated mild reinforcement, which can result in accelerated corrosion issues. Alternatively, targeting these key locations (for example, tee stem ends, haunches, and corbels) and embedding Type 1 discrete anodes in them during the manufacturing process at the plant is easy to do and would add minimal cost to these members.

Using galvanic corrosion protection in new precast construction has several benefits and advantages. For example, installing the anodes in the plant is much easier and less costly than placing them in the field after damage has occurred. As discussed earlier, because the anodes are being placed in uncontaminated concrete where corrosion has not yet initiated, it is possible to design for corrosion prevention rather than corrosion control, resulting in smaller and greater spacing of the anodes (fewer of them). In addition, the anodes are forcing the steel to act as a cathode, which produces hydroxyl ions in the concrete surrounding the steel reinforcement. Because the threshold for initiating corrosion is directly related to the ratio of chloride ions to hydroxyl ions, the threshold for corrosion or the concentration level of chlorides needed to initiate corrosion is increased. Therefore, when exposed to chloride contamination, the future initiation of corrosion will be further delayed.

In tee stem ends and corbels, a couple of Type 1 discrete anodes should suffice to protect these elements. While along the length of beam haunches, Type 1 discrete anodes could be installed, it may be better and more practical to install galvanic strip anodes (Fig. 15), and like the Type 1 anodes, have wires at each end to tie to the reinforcing steel. Using galvanic corrosion protection, which means that all of the mild or strand reinforcement to be protected in the haunch must have electrical continuity, would be easy to ensure and establish in the plant prior to placing concrete in the precast member.

*Fig. 15: Galvanic strip anode installation within reinforcing cage*

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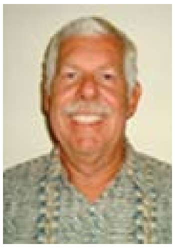

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