

# *Using Cathodic Protection to Control Corrosion of Masonry Clad Steel Framed Buildings*

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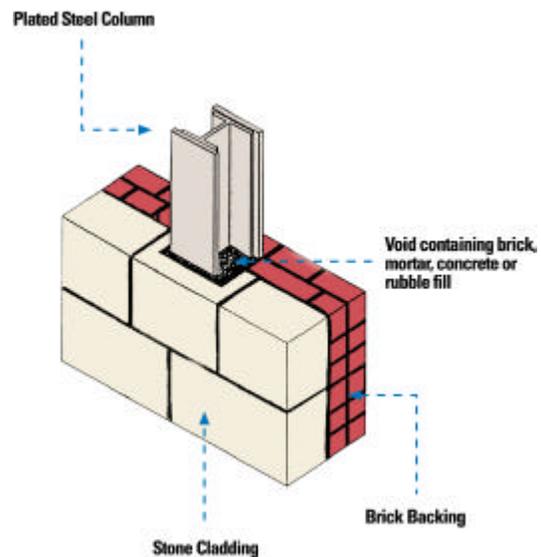
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## **Introduction**

In the period between the late 19<sup>th</sup> Century and early 20<sup>th</sup> Century, our nations' infrastructure exploded with the use of steel framed building construction. Thick wall, load bearing masonry buildings, which had been used successfully throughout the world for thousands of years, gave way to taller masonry clad steel framed structures. The steel framed buildings constructed during this time period are considered "transitional" and represent a period of change between structural masonry and the modern curtain wall designs of today. This type of building construction was very popular throughout the East Coast of the U.S. and many of the major industrial cities of the Midwest. Today, they represent a large portion of the U.S. building stock and form a backbone for many of the historic building districts in the cities across this country.

In early steel framed construction, the relatively thick external cladding was notched to fit around the structural steel and the void filled with a low grade cementitious mortar, which often contained brick and rubble fill (see **Figure 1**). This type of construction enabled moisture to collect within the masonry and mortar fill, which is in contact with the steel surface. Architects and engineers originally thought the mortar used to construct the wall systems would provide some degree of corrosion protection to the steel members due to the natural high alkalinity of the cement. In alkaline environments, steel surfaces will remain passive due to the formation of a protective oxide film, which provides some degree of

corrosion protection. However, due to the porous nature of the mortar and the inconsistent fill around the steel members, the protective oxide film is lost over time, resulting in corrosion of the steel framing and other embedded metals.



**Figure 1. Masonry clad steel-framed construction.**

## **Corrosion Problem**

The most common mechanism of failure in traditional masonry cladding systems is corrosion of metals that support these systems. This includes corrosion of small section lateral anchors, steel shelf angles and the steel frame of the building on which the cladding is suspended.<sup>1</sup> Relatively low levels of corrosion can result in significant deterioration of stone or masonry façades due to volumetric expansion of the corroding steel. Expansion of these corrosion products

can be 7-12 times the original volume of the consumed steel. Corrosion can lead to tremendous stresses on the surrounding mortar, stone and masonry, resulting in cracking, spalling and jacking away of large stone blocks. Corrosion damage not only destroys the integrity of these buildings, but also could pose a serious public hazard and liability issue for the owner.

The corrosion process that takes place in masonry clad steel frame buildings is electrochemical in nature, very similar to a battery. Corrosion will result in the flow of electrons between anodic and cathodic sites on the steel surface. Most metals are thermodynamically unstable and will revert back to their original energy state, or in the case of steel the stable condition of iron ore. For corrosion to occur four basic elements are required:

- Anode – site where corrosion occurs and current flows from.
- Cathode – site where no corrosion occurs and current flows to.
- Electrolyte – a medium capable of conducting electric current by ionic current flow (i.e., soil, water or mortar).
- Metallic Path – connection between the anode and cathode, which allows current return and completes the circuit.

For corrosion reactions to take place it is essential that both oxygen and moisture are present. In the absence of either, corrosion will not occur. Unfortunately, oxygen is always present and the levels of moisture required to support corrosion are relatively low. It is generally found that moisture content of 2% by weight of the masonry or mortar in contact with the steel will support significant corrosion.<sup>2</sup> The corrosion rate is therefore a function of the availability of oxygen and moisture, the type of environment, and the variability of the environment.

There are two major types of corrosion that can affect masonry clad steel frame buildings:

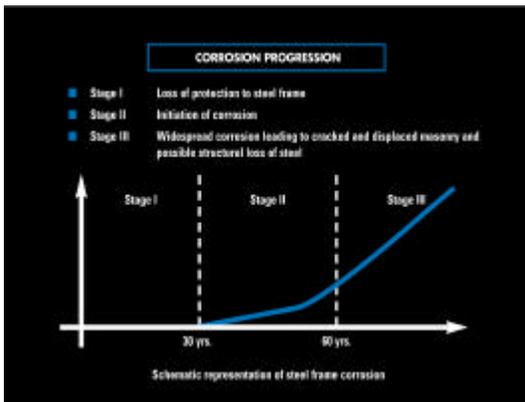
Uniform Corrosion – uniform attack appears as an even layer of rust on the steel surface. This is the most common form of corrosion that is found in perimeter steel of masonry clad steel framed buildings. Uniform corrosion is generally due to electrochemical reactions, which occur from the presence of oxygen and moisture. Under certain conditions the water or moisture that is in contact with the steel, may have extremely low values of pH due to acidic pollutants from rainfall (acid rain). In fact acid rain pH surveys have shown that acid precipitation at a pH of 2 is not uncommon, especially during the initial period of snow or rain.<sup>3</sup> Carbonation, another contributor to corrosion, is a process by which carbon dioxide enters into the masonry and reacts with the steel. Carbon dioxide combines with the pore water in the mortar to form carbonic acid, which reduces the pH of the mortar to approximately 8 or 9. At these levels the protective oxide film is no longer stable and with adequate supply of oxygen and moisture corrosion will start. The penetration of masonry by carbonation is a slow process, the rate of which is determined by the porosity and permeability of the mortar.

Pitting Corrosion – pitting corrosion, which is a localized form of attack, can lead to significant loss of steel section. Although this form of corrosion is uncommon in masonry clad steel-framed buildings; it can be found in coastal buildings where air born salts have penetrated through the porous cladding to the steel surface. The roll of the chloride ion in inducing corrosion of steel in concrete is well documented. If chlorides are present in sufficient quantity, they disrupt the passive film and subject the steel members to corrosion even when the steel is encased in good quality mortar or concrete. Field experience and research has shown that on existing structures subjected to chloride ions,

a threshold concentration of about 0.026% (by weight of concrete or mortar) is sufficient to break down the passive film and subject the steel to corrosion.<sup>4</sup>

Corrosion problems associated with masonry clad steel framed buildings have become increasingly evident during the past two decades. The rate of corrosion is initially governed by the resistivity of the stone or mortar in contact with the steel. This situation however changes as the corrosion process continues and a layer of corrosion product develops on the steel surface. Since ferrous oxide or rust, with sufficient moisture content, has a significantly lower resistivity than that of the surrounding masonry, the rate of corrosion can be expected to accelerate as rust forms on the steel surface. This process is further exasperated as moisture continues to penetrate through the porous cladding and mortar joints, and through the damaged or degraded drainage systems and roofing.

The progression of corrosion to a point where distress occurs in the external masonry is a slow process and is normally measured in terms of decades. For masonry clad steel framed buildings this progression has been characterized by a 3-stage model as shown in **Figure 2.**<sup>5</sup>



**Figure 2. 3-Stage model of steel frame corrosion.**

Stage I is identified as the initial phase where the protective oxide film on the steel surface is lost as a result of moisture ingress and possibly carbonation. Stage II can be considered an active phase where the corrosion process is initiated and layers of rust develop on the steel surface. The latter phase, or Stage III, is the stage at which widespread corrosion occurs leading to significant volumetric expansion of the corrosion products, cracking and displacement of the masonry, and possible loss of steel section. It is at this latter stage (i.e., the time frame after 60 years) that many of the early masonry clad steel-framed buildings are presently in. Of course, the length of time to widespread corrosion and subsequent deterioration can vary from one location to the next and on any one structure.

## Cathodic Protection

Traditional methods of repair for masonry clad steel framed buildings, which consist of removing the masonry, treating the steel with a protective coating or paint, providing new mortar encasement and installing new masonry can be both an expensive and impractical option. Cathodic protection (CP), a corrosion control method that has been used for decades on buried steel pipelines, tanks, ship hulls and bridges, is now developing as a strategic repair option for masonry clad steel framed buildings. In 1991 the first CP system for stone clad steel framing was installed by Taywoods Engineering on the entrance colonnade of Dublin's 1910 College of Science, now the Irish Prime Minister's residence.<sup>6</sup> In 1995, English Heritage applied cathodic protection to corroded ferrous cramps of the Inigo Jones gateway, which stands in the parkland surrounding Chiswick House in London, England.<sup>7</sup> Now this same technology is being applied to steel-framed structures in the United Kingdom and North America.

There are many ways to slow down the corrosion process, however cathodic protection is the only method that has proven to stop corrosion, regardless of the moisture, oxygen and chloride content in the mortar or concrete. CP systems can not reverse damage caused by corrosion, but can effectively retard further corrosion to such a level that the problems associated with corrosion induced damage are minimized.

Cathodic protection can be defined as the reduction or elimination of corrosion by making the metal a cathode through the application of a low voltage direct current. CP is feasible for masonry clad steel-framed buildings by virtue of the mortar and masonry in contact with the steel, which acts as an electrolyte for current to flow. CP can offer many benefits over traditional methods of repair including: cost savings through increased life cycle, minimal disruption to the occupants, long term corrosion control, and architectural/conservation benefits.

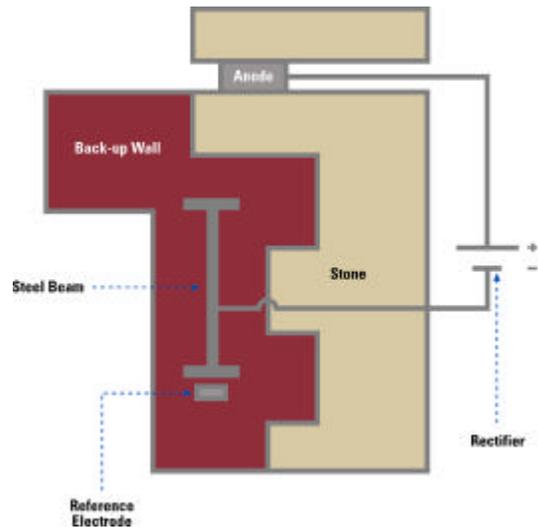
### CP System Types

There are two types of CP systems: galvanic or sacrificial systems, and impressed current cathodic protection (ICCP) systems.

Galvanic systems operate on the principle of dissimilar metal corrosion and the relative position of different metals in the galvanic series of potential. Zinc and various alloys of aluminum are examples of galvanic anodes. When connected directly to the steel, the zinc or aluminum will sacrifice itself and slowly corrode in favor of the steel.

ICCP systems, on the other hand, involve the application of a low voltage direct current from an inert anode material to the steel surface by means of an external power supply, or rectifier. Catalyzed titanium ribbon mesh and mixed metal oxide (MMO) titanium rods are examples of inert ICCP anodes. Due to the requirement of long anode life, system voltage, and current distribution

to the structural steel surface, ICCP is the preferred system for cathodic protection of masonry clad steel framed buildings. A schematic of an ICCP system using catalyzed titanium anode ribbon mesh installed in a mortar joint is shown in **Figure 3**.



**Figure 3. Schematic of impressed current cathodic protection system.**

An ICCP system for steel framed buildings may consist of the following basic components:

- DC power supply (distributed rectifier system).
- Inert anode material, such as catalyzed titanium ribbon mesh or titanium rods.
- Electrical continuity bonding of steel components.
- DC wiring between the anode, steel and rectifier.
- Monitoring probes, such as embedded reference electrodes.
- Remote monitoring and control system.

### Feasibility of CP

There are several important factors, which must be assessed before considering CP as a viable option for masonry clad steel-framed building. These include:

- Continuity of the steel frame, anchors and other embedded metallic items.
- Contact between the steel frame and mortar (affect that voids have on protection levels).
- Current distribution, which is controlled by anode spacing, mortar and stone resistivity.
- Position of anodes (joint details and steel framing design).
- System installation details and how the aesthetics of the structure are affected.

Many of these items can be assessed during a pilot installation (mock-up). The pilot installation is usually installed on a representative portion of the structure. The pilot installation allows the engineer to determine the current density required for cathodic protection, current distribution patterns to the steel surface, anode spacing, continuity bonding procedures and the type of system most appropriate both from a construction standpoint and an aesthetics standpoint. The system is usually powered with a portable test rectifier. Current distribution and protection levels on the steel surface are evaluated using embedded reference electrodes. The evaluation period for a pilot installation can be as short as 1-2 weeks.

### **Electrical Continuity**

Ensuring electrical continuity of the steel frame, angles, anchors, reinforcing and other embedded metallic items is an essential element in the application of cathodic protection. Failure to ensure electrical continuity will not only prevent current from being received on steel that is discontinuous but may lead to corrosion interference of the discontinuous items.

A thorough understanding of the common design details and the historic methods of building construction are essential for continuity assessment. A preliminary

analysis of continuity between the embedded items can be made during the pilot installation. Standard test methods consist of DC resistance and DC millivolt drop techniques. A stable reading of less than 1 ohm (after reversing the polarity of the test leads) or a potential difference less than 1 mV are indicative values that electrical continuity exists between metallic components embedded in concrete or mortar. Change in potential of the steel item through the application of cathodic protection current, as measured using an embedded or portable reference electrode, is another way of assessing electrical continuity.

The cathodic protection engineer should also be familiar with the methods of repair that are proposed and where stainless steel dowels and anchors are to be used in the repair and stabilization of damaged stone and other façade materials. If discontinuous metallic items are proposed, consideration should be given to their interaction with the CP system. Bonding procedures may consist of simple welding, mechanical connections or bonding of small, insulated copper wires using conductive epoxy.

### **Electrolyte**

Cathodic protection of masonry clad steel framed buildings is feasible because direct current can pass through the mortar fill, which is in contact with the steel frame. The masonry and mortar fill is therefore considered an electrolyte for protective current to flow. Although details often exist of the steel and masonry layout, knowledge of the mortar connection is not always possible. It is rare that embedded metal items in these cladding systems are completely embedded in mortar. More often, the mortar fill often contains large voids and in certain cases the mortar is completely absent. Knowledge of the in-fill consistency can be obtained through bore scope analysis. The quality, type and application of mortar fill between the steel and external façade varies

greatly both between buildings and within a single building. However, despite this variability, mortar in-fills were generally composed of a wet mix containing varying quantities of cement, sand and brick rubble.

Knowledge of the historic building construction methods is essential when analyzing in-fill areas with respect to voids. Voids may be large openings (i.e., >25 mm) where corrosion is minimal and no protection is required, or in certain situations corrosion may be significant in the void and grouting is required to ensure protection. Voids may also be small openings (i.e., <10 mm) in which corrosion has occurred but grouting is not required, since corrosion products tend to fill the small voids and act as an electrolyte for protective current. If the void area contains water, cathodic protection current will conduct across this area.

Porosity of the cladding material and mortar has a great effect on the resistivity of the electrolyte. Resistivity, the inverse of conductivity, is the electrical resistance of a substance commonly measured in ohm-centimeter (ohm-cm). The lower the resistivity of the mortar in contact with the steel, the higher the corrosion rate. Most cementitious materials with resistivities less than 10,000 ohm-cm can show moderate to high corrosion rates and in fact rust becomes extremely conductive when moisture content exceeds 3% by weight.

Most masonry materials have much higher resistivities that exceed 100,000 ohm-cm when moisture content falls below 2% by weight. However, the fallacy that cladding is impermeable to moisture has allowed significant damage to occur on these structures. In fact some cladding materials, particularly sandstones and limestones, can act as sponges in absorbing rainwater. Although higher porosity materials may be expected to allow rapid ingress of water, lower porosity materials such as marble, terracotta and glazed brick will trap water

allowing contact with the steel frame. The more common cladding materials can be ranked for porosity as shown in Table I.

Cladding Material	Porosity (%)
Limestone	17-23
Sandstone	10-24
Brick	2-10
Marble	< 5
Terracotta	~ 1
Glazed Brick	depends on glazing quality

**Table 1. Porosity of different cladding materials.**

### Anode Selection

The anode is one of the most critical components for a cathodic protection system. It is used to distribute protective current to the steel embedded in masonry and provides locations for anodic reactions to take place in lieu of the steel. By using relatively inert anode materials, such as catalyzed titanium, anode consumption is minimized. One of the main benefits of catalyzed titanium is that its life expectancy can be determined through accelerated life testing. N.A.C.E. Standard TM0294-94, "Testing of Embeddable Anodes for Use in Cathodic Protection of Atmospherically Exposed Steel-Reinforced Concrete" gives procedures for accelerated life testing of these anodes. Based on test results using this method, it has been found that the life of catalyzed titanium anodes can readily exceed 75 years.

The Federal Highway Administration (FHWA) has conducted extensive testing with catalyzed titanium anode mesh for cathodic protection of reinforcing steel in concrete bridge decks. To provide the maximum life expectancy for this anode, the FHWA recommend a maximum limit of 110 mA/m<sup>2</sup> (10 mA/ft<sup>2</sup>) for current density at the anode/concrete interface.

Titanium ribbon mesh anodes are particularly suited for installation in the fine mortar joints of stone cladding material. Ribbon mesh anodes are available in 12.7-mm (0.5") and 19-mm (0.75") widths. Ribbon anodes are generally installed using standard masonry pointing techniques and are recessed as deeply as possible in the joint where resistivities are lowest (see **Figure 4**). Care should be taken to ensure that the ribbon mesh is fully encapsulated by the cementitious mortar. Particular advantages of the ribbon mesh installation include:

- Non-destructive method of installation.
- Ribbon can easily be installed in mortar joints using standard pointing techniques at the time of repair.
- Ribbon anodes are usually installed parallel to the steel beams and columns.
- Ribbon anode is not visible. Completed installation restores integrity and aesthetics and to the building.



**Figure 4. Titanium Ribbon Mesh installation in mortar joint.**

Discrete titanium anodes are manufactured using mixed metal oxide (MMO) rods and catalyzed titanium ribbon mesh in various lengths and widths to suit the design requirements for the structure. They can be installed from the exterior of the building or the interior if access is permissible. Anodes are usually inserted in drilled or cored holes and backfilled with a high alkaline grout. Discrete titanium anodes are primarily used

where maximum current penetration is required to the steel frame. **Figure 5** shows a discrete titanium anode installation for the protection of steel shelf angles in a terracotta cornice.



**Figure 5. Discrete titanium anode installation in terra cotta cornice.**

Current densities for cathodic protection of steel embedded in carbonated concrete have been reported to be 10 mA/m<sup>2</sup> (1.0 mA/ft<sup>2</sup>) or less.<sup>8</sup> These levels are somewhat lower than those for chloride contaminated concrete. However, the main consideration in designing a cathodic protection for masonry clad steel-framed buildings is to provide sufficient current to protect the steel beneath the façade, so that the outward expansion of corrosion products is greatly reduced or eliminated. Current distribution from the anode to these critical areas of steel surface is therefore an important consideration in the design of a cathodic protection system.

## Instrumentation

Reference electrodes are used to evaluate cathodic protection levels. They may be small portable devices or permanently embedded probes in the masonry structure. Reference electrodes are installed at critical locations to evaluate system performance where effective corrosion control is critical. The most commonly used embedded reference electrodes for concrete structures

are silver/silver chloride (Ag/AgCl). Pseudo reference electrodes, such as MMO titanium rods or graphite probes, are used for short term differential measurements (i.e., depolarization tests) but are not used to measure absolute values because of a tendency for potentials to drift as environmental conditions change. However, pseudo reference electrodes have significant life expectancy versus Ag/AgCl. Reference electrodes should have a separate ground connection to the steel frame so that a potential can be obtained. To help facilitate testing of the system, the reference electrode lead and ground wires should terminate at a junction box or inside the rectifier enclosure.

### Power Supply & Monitoring

A rectifier is used to convert alternating current (AC) to direct current (DC). A rectifier works on the same principle as an AC adapter for a computer or a battery charger. In an ICCP system, the rectifier provides the power (i.e. low voltage direct current) and controls the amount of power to each anode zone. Usually for masonry clad steel framed buildings, the cathodic system is divided into a series of isolated anode zones. For instance a beam or column line on the face of a building may be a single zone.

Rectifiers are available in many types and operating outputs (i.e., constant current, constant voltage, and potential control). In general ICCP systems for masonry clad steel-framed buildings should operate on a constant current basis, so the voltage can vary to suit the changes in resistivity of the masonry and mortar materials. The process of cathodic protection for masonry clad steel frame structures surprisingly takes little power. Experience has shown that maximum voltage limits for rectifiers on masonry clad steel framed buildings is 20-30 Volts DC.

Distributed rectifier systems, which consist of a master control unit and small local rectifier units (LRUs) are best suited for

larger building installations. This technology not only minimizes DC wiring, but also allows for the complete remote monitoring and control of the system via a telephone line, modem and PC. To ensure continued operation of the system, the rectifier is usually monitored on a quarterly basis.

### Life Expectancy

The life of an ICCP system will depend on the performance of individual items installed within the building. With the exception of the anodes and reference electrodes embedded in the structure, all component parts can be maintained and replaced as required.

As stated earlier, the operational life of a catalyzed titanium anode is in excess of 75 years. However, the electronics associated with the power supplies and remote monitoring system are expected to have a life in excess of 20 years. With appropriate repair and maintenance of the electronic circuitry, this could readily exceed 30 years. The estimated life of the various major components for an ICCP system is shown in Table II.

System Component	Estimated Life (yrs.)
Power supply (rectifier) and remote monitoring system	20 years +
Catalyzed titanium ribbon mesh or discrete titanium anodes at 110 mA/m <sup>2</sup> design current density	75 years +
Ag/AgCl reference electrodes	up to 20 years
Pseudo reference electrodes (MMO titanium or graphite)	50 years+
Wiring	20 years+

**Table II – Estimated Life Expectancy of Cathodic Protection System Components.**

## Summary

Corrosion problems associated with late 19<sup>th</sup> Century and early 20<sup>th</sup> Century masonry clad steel framed buildings have become increasingly evident during the past two decades. Corrosion induced damage not only destroys the integrity of these buildings, but also could pose a serious public hazard and liability issue for the owner. Since the first installation on steel framing in 1991 in Ireland, CP systems have provided an increasing track record of use in the United Kingdom and North America. Impressed current cathodic protection has proven to be an effective method of corrosion prevention on bridges, pipelines, and other metallic structures and is now developing as a strategic option for engineers, architects and owners. CP can offer many benefits over

conventional methods of repair including: cost savings through increased life cycle, long term corrosion control, minimal disruption to building occupants and architectural/conservation benefits. With cathodic protection hydroxyl ions are produced at the steel surface, allowing the mortar in-fill to revert back to an alkaline state. This process allows the reformation of the protective oxide film on the surface of the steel. Providing the system is correctly installed and properly maintained the system will provide corrosion prevention for the lifetime of a structure. It is important to realize that CP systems can not reverse damage caused by corrosion, but can effectively retard further corrosion to such a level that the problems associated with corrosion induced damage are minimized.

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