CATHODIC PROTECTION

OF

MASONRY-CLAD, STEEL-FRAMED BUILDING IN SAN FRANCISCO

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ABSTRACT

Corrosion problems associated with late 19th Century and early 20th Century masonry-clad, steel-framed buildings have become increasingly evident during the past two decades. Corrosion induced damage not only destroys the structural integrity of these buildings, but also could pose a serious public hazard and liability issue for the owner. Corrosion control for masonry-clad, steel-framed buildings is gaining increasing importance. This is due to the mandate in today's society to preserve aging historical structures, building safety issues, as well as the economic considerations for repair or replacement. Cathodic protection is an accepted technique for prevention of corrosion. The aim of this paper is to provide a case history of how cathodic protection was applied to preserve a historic masonry-clad, steel-framed building in San Francisco, CA. The application of cathodic protection substantially reduced the cost of the building repair, facilitated completion of the repair on time, and more importantly, for the owner, the work was invisible to the untrained eye.

Keywords: cathodic protection, corrosion control, historic buildings, repair, masonry-clad, steel-frame

INTRODUCTION

In the period between the late 19th Century and early 20th 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 U.S. and especially in San Francisco in the 1920's. 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 naturally 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.

Corrosion Problem. The most common mechanism of failure in traditional masonry cladding systems is the corrosion of metals that support these systems. This includes corrosion of small section lateral anchors, steel shelf angles and the structural steel frame of the building on which the cladding is suspended.[1] Relatively low levels of corrosion can result in significant deterioration of stone or masonry facades 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-framed 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 electronic 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.[2] 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-framed 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.[3] 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 begin. 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 borne salts have penetrated through the porous cladding to the steel surface. The role 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.[4]

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.[5]

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 in Ireland. Since then, this same technology is being applied to many historic steel-framed structures in the United Kingdom and North America, including San Francisco.

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 cannot 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. 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. Provided the system is correctly installed and properly maintained the system will provide corrosion prevention for the lifetime of a structure.

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.

An ICCP system for masonry-clad, 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 framing and rectifier.
- Monitoring probes, such as embedded reference electrodes.
- Remote monitoring and control system.

BACKGROUND

This building considered for cathodic protection in San Francisco was built in the 1920's, following the typical design and detail used in high-rise construction even though it is only a five-story building. A view of the south wall of the building is shown in Figure 4. The design and detailing used in high-rise buildings (concrete floor) was chosen as the superior design than the typical design used in low rise buildings (wood floors). As such, this is a unique example of repair technique used on a smaller scale but appropriate and scalable to much larger buildings.

The building's construction is classic high rise construction which required more restrictive fire rating than would have been required under the then San Francisco Building Code. The skeleton of the building is a complete structural steel frame using rolled I-beam shapes with riveted connections. The steel frame is designed to carry all gravity (dead + live) loads. The floors are reinforced concrete slabs spanning between the steel beams. The concrete encases the steel beams to provide fire protection. This wrapping of the steel beams also occurs on all perimeter steel beams. The exterior walls are 13-inches thick brick masonry. The brick sits 9-inches on the concrete encased beams and cantilevers 4-inches beyond the beam. This allows for a brick veneer on the face of the concrete encased beams to give a continuous brick elevation. The brick wall also wraps around the exterior columns for fire protection on the inside and weather protection on the outside. None of the steel was protected with paints.

The building underwent normal repairs in the 1990's to address water intrusion. This included re-pointing of the deteriorated mortar joints and painting/caulking. This started on the western elevation. During this work it was noted that the south-west corner had extensive vertical cracks on the south and west face corresponding to the steel column behind. Additional investigation showed this situation to be present on the south east corner, single and double cracks in the middle column brick faces (between the end columns) and the horizontal brick veneer cracks at the floor/steel beam locations. The two corner locations were addressed first due to the extensive nature of the cracks, the location adjoining sidewalks and, more importantly, the discontinuity of the corner with cracking on two faces causing a stability problem. In addition, the repair of the two columns would provide in-situ data on the repair of the nine other columns. The corner columns were repaired by removing the brick, cleaning rust off the steel, repairing the steel columns, coating the steel, and reinstalling the brick exterior veneer. In one of the columns the corrosion had created holes approximately 3-inches in diameter in the column flange. The south elevation was then investigated further and it was determined that the middle columns could be repaired using similar technique refined during the repair of the end columns. The biggest challenge was salvaging old brick to blend with new brick to match the color and shine of the existing brick wall.

The major problem of the south wall was the repair of the floor beams. Investigation showed that these beams had minor corrosion that had not compromised their structural integrity and capacity. The areas of corrosion, though, were encapsulated in the concrete fire-proofing. Removing the concrete in the areas of rust was very problematic due to the brick wall sitting on the beam/concrete and thus increasing the repair cost. Since it was determined that the steel beams were still adequate to carry loads and the cost to remove the concrete, clean the steel and patch the concrete was so expensive (the cost estimate to repair the beams substantially exceeded the cost to repair the columns), it was decided to leave the rust on the steel beam in place and provide cathodic protection to prevent further corrosion. The south exterior wall was repointed and a siloxene coating was applied to help repel water.

This work was done in conjunction with the repair of the nine middle columns. The work was successfully coordinated between the contractor doing the brick work and the cathodic protection contractor/consultant. In addition, it was successfully permitted through the San Francisco Building Department and completed on time. The work is now one year old and, to date, the south façade has performed exactly as expected. More importantly, for the client, the work is invisible to the untrained eye.

CORROSION CONTROL

Corrosion Investigation

An investigation was undertaken to conduct field and laboratory tests to establish the corrosion mechanism(s) that had adversely affected the integrity of the external structural steel members associated with the San Francisco building. Tests included visual inspection of the brick façade for cracking, buckling and spalling; visual inspection of the structural steel columns, beams, and associated concrete at accessible locations. Tests were also conducted to determine carbonation (pH) and chloride content of mortar/concrete, and corrosion potential of steel. The results of the testing led to the following conclusions.

The structural steel beams, columns and beam-to-column connections had experienced serious corrosion. The oxidation (corrosion) product varied in thickness up to 0.75". The structural integrity of the fire escapes mounted on the steel beams was also a concern, considering the corrosion on the beams and columns. In the case of the structural steel columns, the observed corrosion on the external portion of the column had occurred in the absence of any bonded concrete. The corrosion was determined to be atmospheric. It appeared that rainwater entered the building exterior and traveled along the columns and beams. In the case of the structural steel beams, the corrosion occurred in the presence of concrete in the web and at locations without concrete on the top of the beam.

At 3 locations the exterior bricks were removed exposing the beam or the beam and column connection for inspection. One such location is shown in Figure 5, which revealed the severe corrosion and cross section loss. An air gap was noted between the brick façade and the structural steel. The concrete in the beam web was cracked due to tensile forces caused by the corrosion product. At numerous locations along the beams, the brick facade had been deformed outward. In many cases the mortar joints were cracked. It was believed that the condition was caused by the expansion of the concrete in the web of the beam, again, caused by tensile forces exerted by corrosion products. If an air gap did not exist between the brick façade and structural steel, more damage to the brick façade would have occurred.

pH testing in the field and laboratory confirmed that carbonation of the concrete in the web of the beam as well as the mortar joints had occurred. Electrical potential testing along each beam in the vicinity of the fire escapes confirmed that the steel beam was actively corroding throughout the sections tested. Because the structural steel columns were not encapsulated in concrete, there was no conductive electrolyte. As a result, cathodic protection could not be considered for the columns. Hence a coating system was recommended to prevent any further oxidation of the columns. A water seal was also recommended to prevent any water entering a column from traveling along the associated beams. Since the external portion of the structural beams was encapsulated in concrete, a cathodic protection system was recommended as the most cost-effective method to prevent further corrosion of beams.

Cathodic Protection

<u>Feasibility of CP</u>. There are several important factors, which must be assessed before considering CP as a viable option for masonry-clad, steel-framed buildings. These include:

- Electrical continuity of the steel frame, anchors and other embedded metallic items.
- Contact between the steel frame and mortar (effect 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.

These items were assessed during a pilot installation (mock-up) on the building. The pilot installation was performed on a representative portion of the steel beams. The pilot installation allowed the determination of 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 was powered with a portable test rectifier. Current distribution and protection levels on the steel surface were evaluated using embedded and portable reference electrodes. The pilot installation and testing indicated that cathodic protection could be effectively used for protecting the top portion of the steel beams where corrosion control was needed.

<u>Electrical Continuity</u>. 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 methods of building construction are essential for continuity assessment

A preliminary analysis of electrical continuity between the embedded items was 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 values that indicate electrical continuity exists between metallic components embedded in concrete or mortar. Change in potential of the steel structure through the application of cathodic protection current, as measured using an embedded or portable reference electrode, is another way of assessing electrical continuity.

Continuity tests conducted at the building indicated that the riveted beam-to-column connections did not provide adequate electrical continuity across the connections due to the presence of thick corrosion products at those locations. Hence all beam-to-column connections and column-to-column splices were welded to ensure electrical continuity.

<u>Electrolyte</u>. 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, or by direct inspection as in this case. 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 are 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.

In the case of the building in San Francisco, air gaps of up to 1 inch were noted between the brick façade and the concrete on the steel beam. Hence, cement grout was used to make contact to the concrete on the steel beam and encapsulate the anode. One row of bricks was removed near the beams for installation of the anode and grout. Subsequently, the bricks were replaced.

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 recommends a maximum limit of 110 mA/m^2 (10 mA/ft^2) for current density at the anode/concrete interface.

Titanium ribbon mesh anodes are particularly suited for installation in the fine mortar joints of stone or brick cladding material. Ribbon mesh anodes are available in 12.7-mm (0.5 inch) and 19-mm (0.75 inch) 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. 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 to the building.

Current densities (based on concrete surface area) for cathodic protection of steel embedded in carbonated concrete have been reported to be 10 mA/m^2 (1.0 mA/ft^2) or less.[8] These levels are somewhat lower than those for chloride contaminated concrete. However, the main consideration in designing a cathodic protection system 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.

For the San Francisco building, the bigger 0.75 inch wide titanium ribbon mesh anode was selected to ensure adequate current capacity, based on the pilot installation test. Each beam was provided with one anode ribbon extending for the full length of the beam.

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) or copper/copper sulfate ($Cu/CuSO_4$). Pseudo reference electrodes, such as mixed metal oxide (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 significantly longer life expectancy versus Ag/AgCl or $Cu/CuSO_4$. 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 protection 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). The process of cathodic protection for masonry-clad, steel-framed structures surprisingly takes little power. Experience has shown that maximum voltage limits for rectifiers on masonry-clad, steel-framed buildings is 20-40 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 I.

CP System Design and Installation. Based on the results from the feasibility study and the pilot installation discussed above, a CP system was designed for corrosion control of the structural beams of the building in San Francisco. The CP system was divided into four distinct Zones A, B, C & D. Each CP Zone consisted of titanium mesh ribbon anodes installed in the mortar joint of the brick facade, near the concrete-encased steel beams on the 4^{th}, 5^{th}, and 6th floors of the building. One monitoring probe (titanium rod with MMO coating) was also installed on each floor of each CP Zone for testing purposes. The anodes and monitoring probes were grouted using a non-shrink cement grout. All the cables for anodes, monitoring probes, structure and test connections for each CP Zone were routed to junction boxes in the utility room within the building, to facilitate future monitoring. Each CP zone was powered by a rectifier with maximum output capacity of 40 volts, 5 amps.

The CP system installation was conducted in conjunction with other repair work at the building. One row of bricks was removed near the top of the beams for installation and grouting of the anode ribbon. The bricks were then replaced such that the anodes, monitoring probes, and cables were not visible. Figure 6 shows a cross-section schematic of the anode installation while Figure 7 shows the actual installation of the anode ribbon at the building.

Post-Installation Test Results. The CP energization test was conducted after allowing a minimum of one month to cure the grout. The test was conducted by powering the anodes using the rectifiers, and then measuring the potential shifts of the steel beams using the permanent monitoring probes installed. Potential shifts were also measured using a portable copper/copper sulfate reference electrode placed at the mortar joints on the surface of the wall, where accessible from the fire escapes in CP Zones B & C. The current output was adjusted to obtain the optimum CP levels. The rectifier output voltage and current were documented. The individual anode currents were also documented using the shunts provided in the anode junction box.

Before application of current the "Static" (baseline) potentials of the steel beams were measured using the monitoring probe terminals at the junction box and a portable copper/copper sulfate reference electrode placed on the surface of the wall near the beams. The current "On" potentials were measured with the CP current applied, and the current "Off" potentials were measured with the CP current momentarily interrupted. The potentials were measured using a high-impedance digital voltmeter. The difference between "Off" and "Static" potential is referred to as polarization shift. It is the net protective effect on the steel due to the application of cathodic protection current. Polarization was documented after 30 minutes and 18 days of CP.

The criterion for CP of steel in concrete/mortar is a minimum of 100 mV of cathodic polarization (formation or decay), as established by National Association of Corrosion Engineers (NACE) International Standard RP0290-2000, Section 2.3.1. The potentials measured both after 30 minutes and 18 days of CP system activation considerably exceeded the minimum required polarization shift of 100 mV, indicative of adequate corrosion control. The initial rectifier current required to obtain this polarization ranged from 88 to 128 mA for the four CP zones, with corresponding anode current densities ranging from 95 to 135 mA/m^2 (8.8 to 12.5 mA/ft^2).

After one year of cathodic protection system operation, another survey was conducted to ensure that adequate corrosion control was being achieved. The tests included documenting the rectifier outputs and measurement of current "On" and current "Off" potentials. Subsequently, the CP systems were deactivated and the potential decay (depolarization) was documented at ½ hour, 2 hour, and 4 hour intervals.

Figure 8 shows the average depolarization measured using a portable copper/copper sulfate reference electrode placed at the mortar joints on the surface of the wall where accessible from the fire escapes in CP Zones B & C. The potential decay considerably exceeded the minimum required depolarization shift of 100 mV within the 4-hour period, indicative of adequate corrosion control. The average depolarization shifts after the 4-hour period were 434 mV and 512 mV for Zones B and C, respectively. The rectifier current required (after one year of operation) to obtain this depolarization ranged from 25 to 54 mA for the four CP zones, with corresponding anode current densities ranging from 23 to 82 mA/m^2 (2.1 to 7.6 mA/ft^2). This indicates a significant reduction in the current required for adequate cathodic protection compared to the initial current requirement.

SUMMARY

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/preservation benefits. It is important to realize that CP systems cannot 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.

This paper provides a case history of a historic building in San Francisco, where CP was effectively applied for corrosion control for masonry-clad, steel-frames. The application of cathodic protection substantially reduced the cost of the building repair, facilitated the completion of repair on time, and more importantly, for the owner, the work was invisible to the untrained eye. Tests conducted after one year of operation indicate that the cathodic protection system is operating properly and the potential measurements meet the NACE International criteria for cathodic protection.

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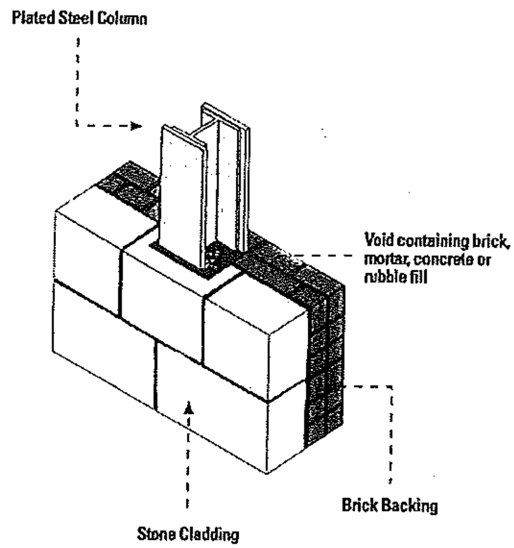

FIGURE 1 - Masonry-clad, steel-framed construction.

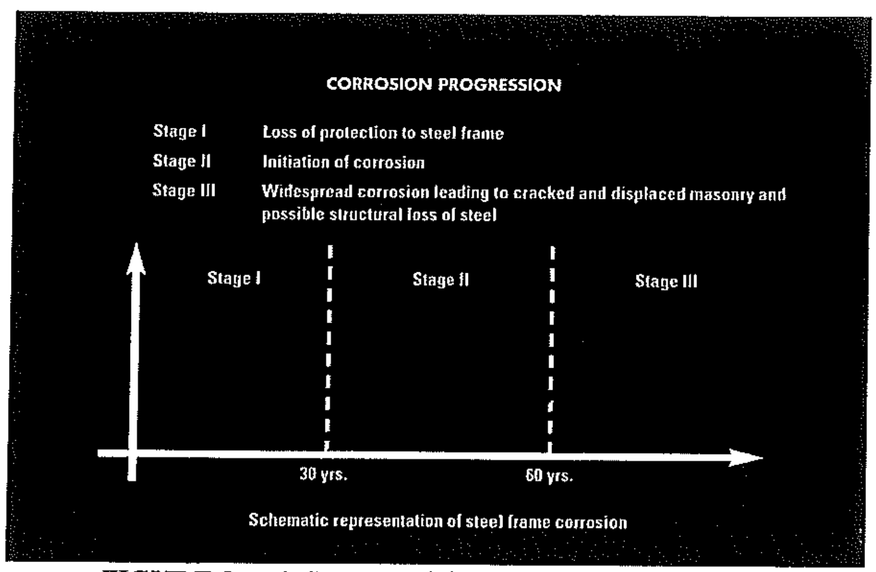

FIGURE 2 - 3-Stage model of steel-frame corrosion.

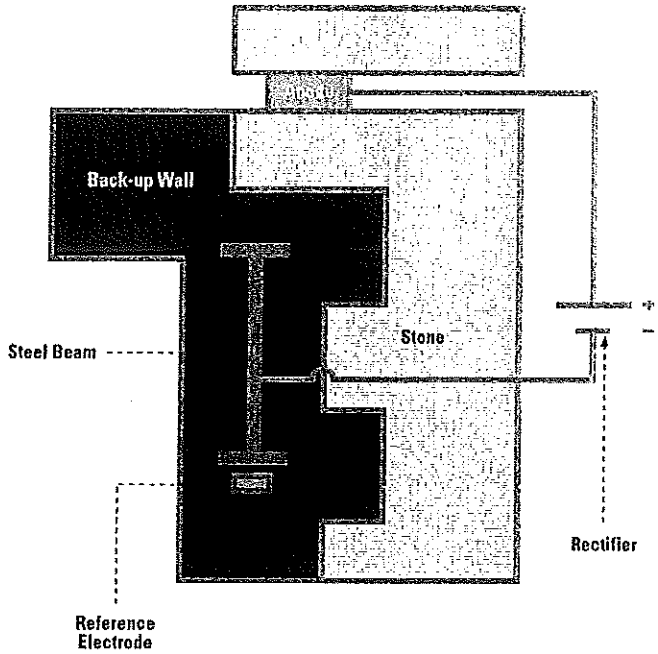

FIGURE 3 - Schematic of impressed current cathodic protection system.

FIGURE 4 - View of south wall of the building in San Francisco.

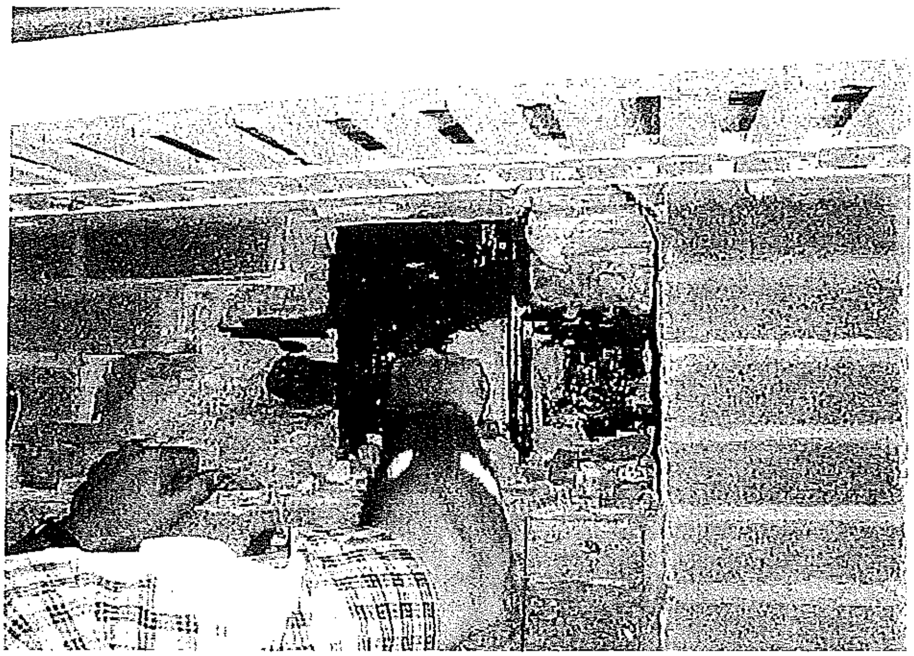

FIGURE 5 - Corrosion observed on steel beam and column after removal of brick facade and concrete on beam.

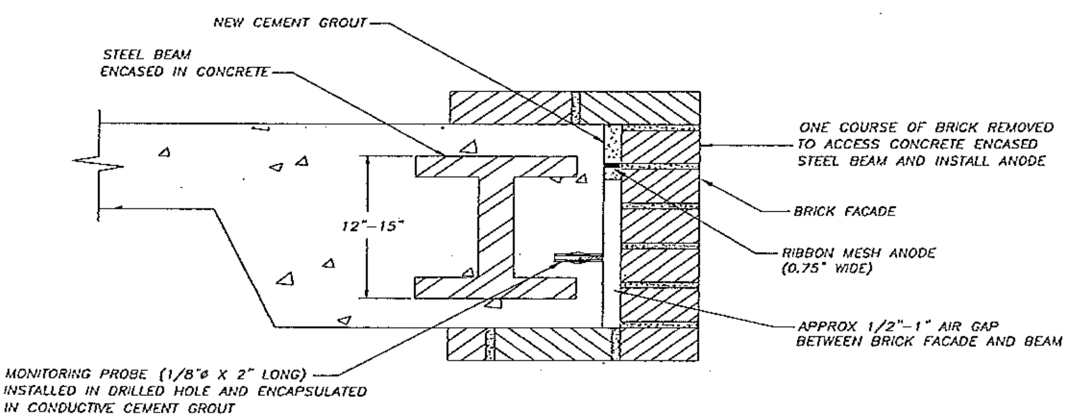

FIGURE 6 - Titanium ribbon mesh installation schematic.

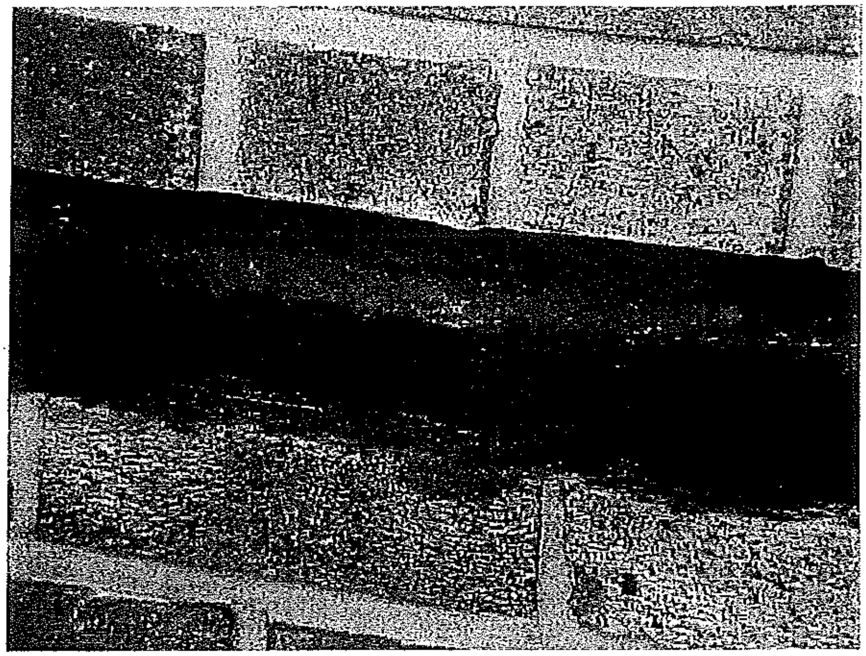

FIGURE 7 - Titanium ribbon mesh installation in mortar joint.

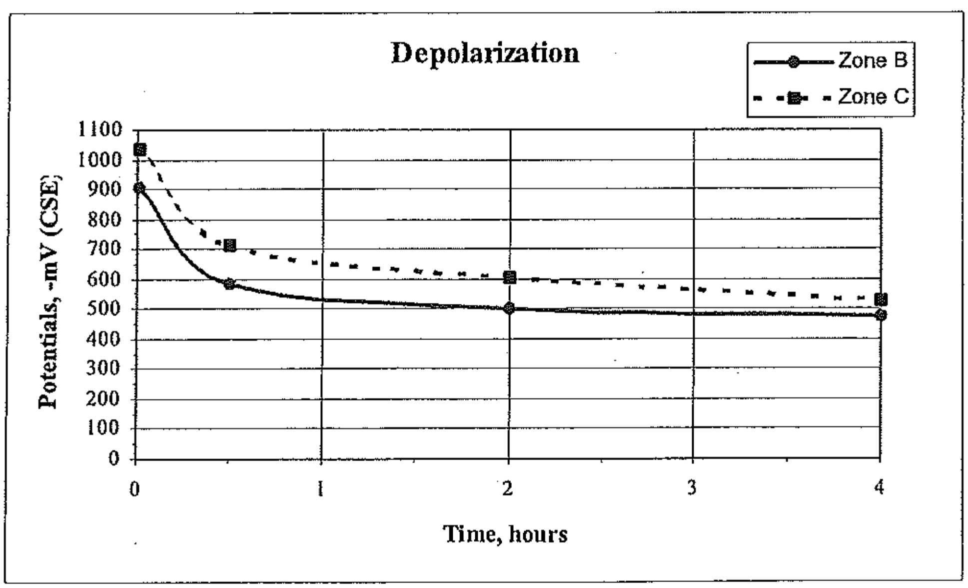

FIGURE 8 - Depolarization test after 1 year of CP operation.

TABLE 1
ESTIMATED LIFE EXPECTANCY OF CATHODIC PROTECTION SYSTEM COMPONENTS

System Components	**Estimated Life (yrs.)**
Power supply (rectifier) and remote monitoring system	20 years +
Catalyzed titanium ribbon mesh or discrete titanium anodes at 110 mA/m^2 (10 mA/ft^2) 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+