Cathodic Protection Solutions for Steel-Framed Heritage Buildings

By Paul Lambert

The form of steel-frame building construction, initially employed in Chicago and subsequently used in most major western cities in the first two decades of the 20th century, has resulted in serious consequences with respect to serviceability, safety, and aesthetics. Most notably, the identification of "Regent Street Disease" in the United Kingdom in the late 1970s first highlighted the problems of steel-framed corrosion. Many of the grand, high profile, and often protected structures in the centers of many cities have been affected (Atkins, Lambert, and Coull 2002).

While the "modern" problem of steel-frame corrosion dates back less than 25 years, the problem was originally encountered and recognized nearly 60 years ago. As stated by the Building Research Board in London: "One interesting case of corrosion in a steel-framed building was investigated in collaboration with the Chemical Research Laboratory. Extensive corrosion of the steelwork had caused cracking of the external walls. The photograph (reproduced in Fig. 1) shows a layer of rust up to half an inch thick on a truss member. The frame was encased in brickwork bedded in a black clinker mortar, clad with either glazed brickwork or Portland stone. It was concluded that the corrosion of the steelwork was due primarily to deficiencies in design which had allowed water to gain access to the steel, aggravated perhaps by the use of a clinker mortar, by the presence of soluble salts in the brickwork, and by inadequate painting of the steel." (Department of Scientific and Industrial Research 1947).

Fig. 1: Early 20th century steel frame showing corrosion, as reported in 1947

The problems observed form part of a pattern of decay that has only recently been formally recognized and one that is expected to become more apparent over the next decade. It is a direct consequence of the age and nature of construction.

Cathodic protection, originally developed by Humphry Davy in the 1820s while President of the Royal Society, and later employed widely on buried and submerged structures, was first considered for reinforced concrete in the late 1950s. It became a serious commercial solution after the development of improved anode systems in the early 1980s. The transfer to steel-framed buildings was somewhat slower and it was not until 1997 that the first sizeable structure was protected by such a system (Fig. 2) (Evans 1997).

Corrosion of Steel

In the presence of moisture and oxygen, steel rusts. The rate and nature of the process depends on alloy composition, environmental factors, design, and the nature of additional protection; but on average, 1 ton of steel is lost every 90 s in the UK as a direct consequence of corrosion.

In its simplest form, the corrosion process can be represented by two dissimilar metals in an aqueous electrolyte, joined to allow electrons to pass from anode to cathode. In reality, when a metal corrodes, anodic and cathodic areas can be formed on a single surface in contact with the aggressive aqueous environment. As a result, corrosion can occur at a large number of sites over the surface of the metal. Dissolved metal ions react with hydroxyl ions to form corrosion products (Lambert 2001).

The relative humidity (RH) of an environment has a profound effect on the rate of corrosion of steel. There is a critical level of RH below which corrosion does not occur, and often secondary and tertiary levels above the level of RH that the corrosion rate increases significantly. In the case of steel, corrosion commences at a slow rate at approximately 60% RH, the rate increases at 75 to 80% RH and again at 90%. Contamination of the environment, however, has a tendency to reduce the RH at which corrosion is initiated (for example, the presence of salts) (Vernon 1935).

Controlling the RH of encased steel and reinforced concrete can provide effective means of controlling reinforcement corrosion, particularly where the removal or exclusion of excess moisture also removes or prevents the ingress of potentially aggressive species of corrosion.

As most of the moisture and other mobile species that influence durability must cross the boundary between substrate and atmosphere, the application of coatings and surface treatments can be highly effective at limiting or preventing degradation subject to aesthetic and heritage considerations (Lambert 1997).

Steel frame corrosion

A pattern of corrosion-induced damage is now being widely observed in steel-framed structures, typically constructed pre-1930s (Jones *et al.* 1999). The mechanism of the damage can be summarized as follows and is illustrated in Fig. 3:

- The steel frame needs to be protected from its natural tendency to corrode (that is, returned to a more stable condition, through an electrochemical reaction in the presence of moisture and oxygen). At the time of construction, protection typically consisted of little more than a cement wash or thin bituminous coating followed by partial encasement in concrete or mortar. While concrete encapsulation can provide excellent long-term protection to steel as both a physical and chemical barrier, the original coating would not be sufficient to prevent corrosion in the presence of sustained high levels of moisture; and
- The gradual breakdown of joints, pointing, and flashing increasingly allows water ingress. As expansive corrosion products are formed, brick or stone cladding can be displaced, further opening up joints and cracks and permitting greater access to water. Thus, the rate of degradation will tend to accelerate. Thermal movements that aggravate the opening of joints will also lead to an acceleration of the damage, as typically observed on the weather-exposed corners of such buildings.

The rate at which the damage to the cladding occurs is governed by a number of factors:

- The time at which corrosion initiates—largely dependent upon location, aspect, and level of previous maintenance;
- The rate at which corrosion progresses—largely dependent upon availability to moisture and oxygen; and
- The intimacy of the contact between the corroding steel and the cladding—gaps between steel and cladding can accommodate extensive corrosion with no visible damage.

Where the steel is surrounded by a gap, the risk of displacing the masonry cladding is greatly reduced, although the likelihood of suffering significant loss of section is much higher, particularly in the upper levels of buildings where exposure conditions are generally more severe.

Fig. 2: Gloucester Road Underground Station, London


Fig. 3: Examples of steel-frame corrosion

Repair Options

A number of remediation options are applicable to treat the range of conditions observed on steel-framed structures suffering from varying degrees of corrosion-related damage, most notably the four approaches outlined in Table 1.

While all such approaches to repair are valid and employed as appropriate, cathodic protection may be seen to have particular advantages with respect to the preservation of historically significant structures, combining both long life and minimum disruption to the original structure.

Cathodic Protection

Although the beneficial effects of cathodic protection have been recognized since the middle of the 18th Century, it is only during the second half of this century that the technique has been seriously employed, predominantly in the protection of pipelines, ships, and oilfield structures. More recently, the technology has been refined and applied for the protection of structural steel, particularly that embedded in concrete, but equally well for other steel elements encased in mortar, plaster, or masonry. The systems employed for steel-framed buildings have been developed from the extensive experience gained in the cathodic protection of reinforced concrete (Chess 1998).

Corrosion of steel, being an electrochemical process, results in the formation of anodic and cathodic sites on the surface of the steel. Under typical atmospheric conditions metal is dissolved at the anodic sites while the cathodic areas remain unaffected. By applying a small, externally generated, current to the steel, it is possible to make all the steel cathodic and, therefore, non-corroding.

The externally applied current can either be produced by a material that will corrode preferentially to the steel—a "sacrificial" anode such as zinc, or provided by a low-voltage DC source via an effectively inert material to provide an impressed current to the steel.

Impressed current systems are driven by the application of a direct current through an inert or effectively inert anode. The potential of the reinforcement is depressed by increasing the applied current, which is generally supplied using a transformer/rectifier to provide a direct current supply. Ideally, the potential should be depressed to a level where corrosion is not thermodynamically possible, but any reduction in potential will lead to a reduction in corrosion rate.

Cathodic protection can be applied to any structure where the steel is in continuous contact with concrete or mortar encasement, the pore solution of which acts as an electrolyte. If the steel is not in continuous contact, then local anodic and cathodic sites may be developed under the influence of the impressed current, leading to stray current corrosion. Where electrical discontinuity is found or suspected, bonding or connection by cable can be provided to ensure electrical continuity throughout.

Hydroxyl ions are produced at the cathode (that is, reinforcement), which increases the alkalinity. There is a slight possibility that this increase in alkalinity may initiate alkali-aggregate reaction in susceptible aggregates, although this effect has not been reported in any protected structures.

Hydrogen gas may be produced at the cathode if the potential is sufficient for electrolysis of water (electrolyte) to occur. The steel/concrete potential must therefore be carefully monitored. Hydrogen

Table 1. Repair Options for Steel Frame Corrosion

Remediation option	Description	Considerations
Do nothing/monitor	Carry out minimum repairs and monitor the continuing degradation until further action is required. This may involve the use of embedded corrosion sensors	Such an approach is appropriate for those areas that have the potential for corrosion but are presently not actively corroding
Conventional repair	Repair areas where steelwork has suffered significant loss of section and areas where expansive corrosion has resulted in significant disruption to the adjacent building fabric	Reconstruction is the most effective long-term solution but is disruptive and expensive and hence should be restricted to localized areas that are considered essential
Corrosion inhibitor	Inhibitors, usually based on amino alcohols, can be applied to exposed surfaces, injected, buried as emitters, or fogged into voids to control corrosion of the steelwork	Corrosion monitoring is recommended to ascertain the effectiveness of the inhibitor and reapplication would be anticipated at 5- to 10-year intervals
Cathodic protection	Steelwork is protected from corrosion by the application of a small current at low voltage. The current is provided by anodes inserted into the mortar infill between the cladding and the steel frame or between joints in the masonry	On-going monitoring and adjustments are required. Time of first maintenance is determined by the life of the anodes that should provide a minimum of 25 years of service

evolution can cause embrittlement of highly stressed steel. For this reason, prestressed or post-tensioned reinforced concrete structures are generally not protected by cathodic protection in the UK, although cathodic protection of prestressed structures is undertaken in Italy.

Impressed current cathodic protection systems require regular monitoring because the current requirements for the system may vary as a result of many factors including variations in resistivity of the concrete due to variations in moisture content, and changes in the environment around the reinforcement as a result of the applied current.

Cathodic protection systems must be carefully designed and many different factors must be taken into account, such as the aggressiveness of the environment, the area of steel to be protected, the resistivity of the surrounding material, the positioning of any external metallic objects that could be affected by the system, and the type of anode employed.

Design

Conventional cathodic protection design is based on calculating the area of steel to be protected and selecting an appropriate current density. A suitable anode system can then be selected based on various site considerations such as access, environment, and the required current demand.

Cathodic protection design for steel frame buildings has a different emphasis with the primary concern being disruption to the façade of the structure. Anode systems are selected based on these criteria. Achieving adequate current distribution is the next important consideration. Due to the variable nature of the fill material surrounding the steelwork. This is often best established by carrying out a pilot installation over a small section of the building, typically including a length of beam and column.

In addition to allowing the anode type and spacing to be optimized, a pilot installation provides the opportunity to establish the aesthetic impact of the installation. This proves particularly beneficial where the structure is subject to statutory local or national government approval prior to installation by allowing relevant organizations to inspect a sample of the work and observe the method of installation.

Selection of anode systems

There are two basic systems that are in use for cathodic protection installations of this type: discrete anodes based on titanium oxide ceramic or titanium and expanded titanium ribbon anodes. Where titanium metal is employed, the surface must be coated with a mixture of metal oxides to prevent the titanium from anodizing.

The discrete anodes are typically much smaller than those used in reinforced concrete to minimize the aesthetic influence of the installation and to enable a more even current distribution. The ribbon anodes have been employed for many years in cathodic protection systems for reinforced concrete either in combination with other materials or on their own. (Atkins and Davies 2001)

The majority of cathodic protection systems installed on steel-framed buildings to date have been based on discrete anodes. This is due to the ease of installation and adaptability of such a system. Ribbon anodes, however, do provide a suitable option if it is possible to gain access to continuous strips of mortar. For example, if there is an appropriate void within the building that provides a direct access to the infill, or if large lengths of the frame are being exposed and refilled with mortar during the repair process, ribbon anodes can be used.

Installation

The installation process for both systems is relatively straightforward and does not necessarily require the use of a specialist repair contractor. If the system is to be installed from the exterior of the structure, the bulk of the work involves cutting fine chases for cabling and drilling small diameter holes for the anodes and monitoring probes. To achieve the required aesthetic finish, the chases and holes are usually back filled with a material appropriate for the cathodic protection system to 0.2 in. (5 mm) of the finished surface level. The final pointing may then be undertaken using a

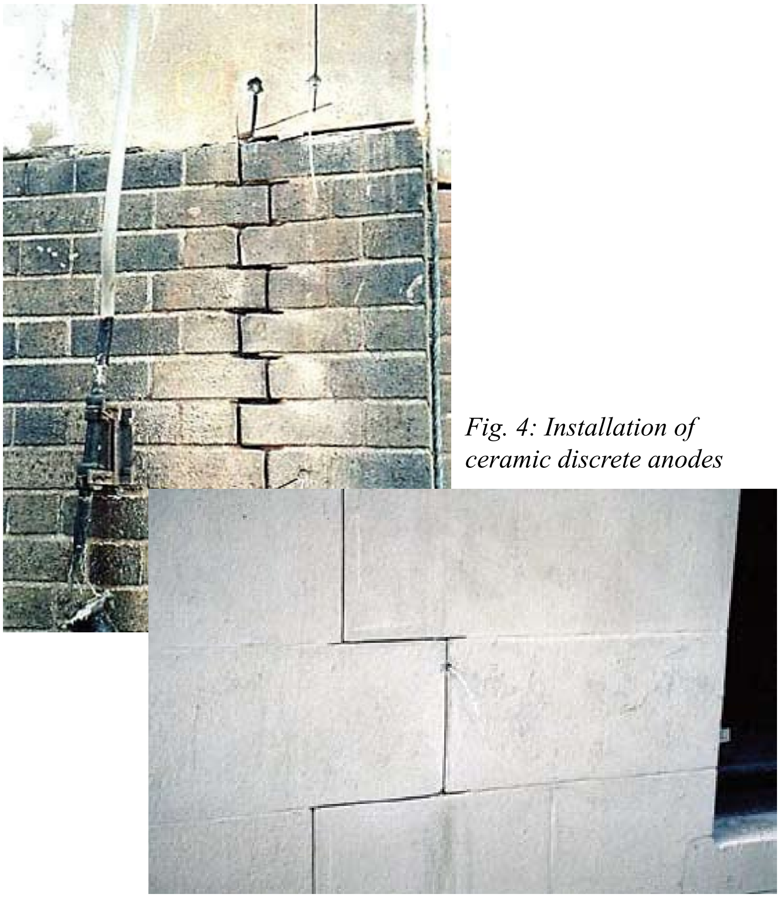

Fig. 4: Installation of ceramic discrete anodes

specialist color-matched material to achieve the desired aesthetic finish.

Power, monitoring, and control

System monitoring is important with all forms of cathodic protection and this is equally true for steel frame applications. Fortunately, improvements in data handling, manipulation, and transmission mean that effective monitoring can be performed relatively easily, even with large and complex installations.

The development of smaller, more integrated power monitoring and control systems has played a vital role in extending cathodic protection solutions to building structures by employing many of the latest developments in digital technology and Internet-based communications.

Particular considerations for steel-framed structures include limiting the amount of power and monitoring enclosures and the extent of cabling. In both cases, the order of magnitude reductions has been possible, allowing installation to proceed without disrupting the operation of the building or altering the outward appearance.

Protection criteria

There are a number of protection criteria available in international standards for cathodic protection. These are generally based on empirical experience, for example, 100 mV decay in 24 h (British Standards Institution 2000), or theoretical considerations that can be based on inappropriate assumptions, for example, a potential of –600 mV versus standard hydrogen electrode (Pourbaix 1974). For the purposes of steel-framed buildings, the former is more appropriate, although there is little formal guidance on the suitability of this or other criteria.

Stray current

The issue of stray current corrosion in cathodic protection systems is often a concern. In reinforced concrete systems for example, bars are rarely welded together, so electrically discontinuous steel can often be encountered. If this is not remedied, the isolated reinforcement can be subject to stray current corrosion where the cathodic protection system drives current through the discontinuous steel, leading to accelerated corrosion where the current is discharging. Typically, for reinforced concrete systems, continuity between reinforcement bars is investigated during the installation phase to ensure all the reinforcement is electrically continuous.

For steel-framed structures, electrical continuity between structural members is rarely a problem because the structural connections are typically bolted or riveted. However, there are a number of items, such as metal window frames or drainage downspouts, that are invariably electrically discontinuous; these must be considered during the site phase of the works. If the items are grounded, as would be expected for any electrical installation, for example, lighting brackets, the grounding system prevents stray current effects.

On historic structures, the grounding requirements may not be in accordance with present standards and so the possible effects of this must be assessed and appropriate remedial actions undertaken. Typically, this involves either electrical isolation from the surrounding material (possibly by replacing fixings with a resin-anchored type or by bonding the discontinuous items into the system), or employing monitoring during commissioning and carry out remedial isolation or bonding if required.

Development of Design Guidance

To properly quantify many of the factors associated with the design, installation and long-term operation of impressed current cathodic protection systems for steel framed structures, a 4-year research project has recently commenced at Sheffield Hallam University in the UK funded by the Royal Society with support by Mott MacDonald.

One of the major problems in understanding the mechanisms of cathodic protection in steel-framed construction is the relatively complex geometry of the system under consideration. No formal information exists with respect to current throw onto typical steel sections, yet this is fundamental to the design of the systems.

Initial studies are being carried out on a range of steel and anode geometries employing a sandbox to represent the surrounding masonry. This technique has been employed to study the throw of current from ground-beds to pipeline sections but is not believed to have been previously used in this context. This technique also allows the risk and magnitude of stray current effects on discontinuous metallic components, for example, cramps and wall-ties, to be formally evaluated for the first time.

The suitability of zinc-based sacrificial systems is also to be assessed for specific applications where an impressed system is considered overly complex or otherwise inappropriate.

In conjunction with the laboratory work, a detailed numerical model is being developed to assist in the design of optimized CP systems for steel framed structures. This is also allowing appropriate operating criteria to be established where previously it has been necessary to employ the criteria developed for submerged and buried steel or reinforced concrete.

From this study, it will be possible to generate proper, well-founded guidance on the design and operation of cathodic protection systems for such sensitive and important applications.

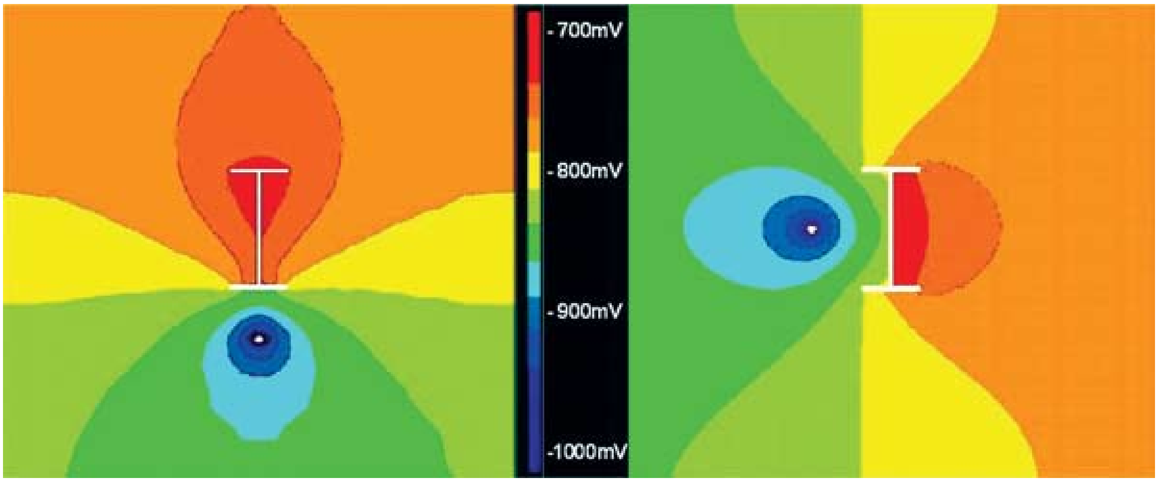

Fig. 5: Modeled current distribution of intersection stanchion and sandbox test

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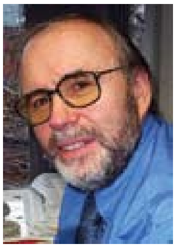

***Paul Lambert**, BSc, PhD, CEng, FIMMM, FICorr, is Technical Director of Materials & Corrosion Engineering at Mott MacDonald in Manchester, United Kingdom. Half his time is funded by the Royal Society to pursue the development of improved understanding and practices in the treatment of corrosion in steel-framed structures as a visiting professor at Sheffield Hallam University. His first degree was in materials engineering and he later studied for a PhD in the corrosion and passivation of steel in concrete. After 2 years working in the National Center of Tribology, he joined Mott MacDonald in 1989, initially to work on the site phase of the Channel Tunnel. He is a Royal Society Industry Fellow; a UK Chartered Engineer; a Fellow of the Institute of Materials, Mining, and Minerals; and the Institute of Corrosion, as well as holding a NACE Corrosion Specialist Certificate for 10 years.*