Cathodic Protection Of Steel Framed Heritage Structures

CP Atkins¹ P Lambert² ZL Coull¹

¹ Connell Mott MacDonald Material & Corrosion Engineering Altrincham UK
² Mott MacDonald Visiting Fellow School of Environment & Development Sheffield UK

Summary: The corrosion of early 20th century steel-framed structures is resulting in serious damage to the integrity and appearance of many historically important structures. Conventional repair technologies are expensive and disruptive and can result in sensitive buildings becoming little more than modern reproductions. Furthermore, traditional repair methods do not necessarily provide a sufficient extension of life.

Historically cathodic protection may be seen as the first engineered solution to the problems of ferrous alloy corrosion. Recent improvement in anode design and control and monitoring hardware have made the technique available for use with steel framed structures in a manner that is acceptable both commercially and from a conservation viewpoint.

This paper discusses the practicalities of steel frame cathodic protection and the general approaches available to achieving it. It will also cover the current research to establish more precisely many of the design and operational characteristics of the technique.

Keywords: Steel framed, heritage, corrosion, cathodic protection.

1 INTRODUCTION

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 1970's first highlighted the problems of steel-framed corrosion. Many of the grand, high profile, and often-protected structures, in the centres of many cities have been affected (Gibbs 2001).

While the 'modern' problem of steel frame corrosion dates back less than 25 years, the problem was originally encountered and recognised over 50 years ago, quote:

"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 Figure 1) shows a layer of rust up to half an inch thick on a truss member. The frame was generally 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).

The problems observed form part of a pattern of decay that has only recently been formally recognised 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 Humphrey Davy and later employed widely on buried and submerged structures, was first considered for reinforced concrete in the late 1950's. It became a serious commercial solution after the development of improved anode systems in the early 1980's. 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 (Figure 2) (Evans 1997).

2 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 nature of additional protection but on average one tonne of steel is lost every 90 seconds 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 of an environment has a profound effect on the rate of corrosion of steel. There is a critical level of relative humidity below which corrosion does not occur and often secondary and tertiary levels above 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 75-80% RH and again at 90%. Contamination of the environment has a tendency to reduce the relative humidity at which corrosion is initiated (e.g. the presence of salts) (Vernon 1935).

Controlling the relative humidity of encased steel and reinforced concrete can provide an 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. 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).
2.1 Steel frame corrosion

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

- The steel frame needs to be protected from its natural tendency to corrode (i.e. return to a more stable condition, rust, through an electrochemical reaction in the presence of moisture and oxygen).

  At the time of construction the 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.

- The gradual breakdown of joints, pointing and flashing increasingly allow 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.

- 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.

Figure 3. Examples of steel-frame corrosion.

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. In fact the location and severity of damage on a particular building can often be seen to follow a particular pattern, as illustrated in Figure 4.
2.2 Area A: Upper levels, including penthouse.
Damage is often most severe in this location, aggravated by degraded or inadequate roof coverings and rainwater goods. The top levels of such buildings are often both elaborately decorated and grossly under-maintained with the consequence that the risk of displaced and falling masonry can be very high. Considerable removal and reinstatement of damaged material can be required in such areas.

2.3 Area B: Middle levels.
The mid-band of steel-framed buildings often display only moderate levels of corrosion. Left untreated, the corrosion will eventually progress to the stage where disruption of the masonry cladding occurs.

2.4 Area C: Ground level.
In general, the ground levels have little or no serious damage. Not only are such areas often more sheltered but are also subject to the highest levels of continual maintenance with problems quickly and easily identified and repaired. The masonry at ground level is also often heavier with a superior quality of construction and this no doubt also contributes to the reduced risk of damage.

2.5 Area D: Basement.
The level of damage associated with basements can often be quite high. This may be due to a number of factors including inadequate tanking leading to groundwater ingress and the proximity to de-iced pavements and roadways. The damage associated with the leakage of rainwater and other drainage pipes is also often focussed on the basement level.

2.6 Area E: Exposed face or corner.
Not all cracks in steel-framed buildings are initiated by corrosion, though most encourage its progression. Thermal movements can cause the progressive jacking open of joints allowing corrosion to initiate and proceed. The facade facing the sun and exposed to the prevailing wind-blown rain will suffer preferentially. Corners, irrespective of orientation, will generally suffer more than mid-facade. Where the corners of building have suffered thermal crack and associated corrosion, considerable traditional repair may be required.

Awareness of such a damage pattern can be valuable when developing the inspection of steel-framed buildings and in particular, helping to target any intrusive investigation of such structures. The pattern described above is largely based on UK experience and therefore generally relates to structures of less than 10 stories exposed to a temperate environment.

Figure 4. Typical Pattern of Damage Distribution
Table 1. Repair Options for Steel Frame Corrosion

<table>
<thead>
<tr>
<th>Remediation Option</th>
<th>Description</th>
<th>Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do nothing /monitor.</td>
<td>Carry out minimum repairs and monitor the continuing degradation until further action is required. This may involve the use of embedded corrosion sensors.</td>
<td>Such an approach is appropriate for those areas that have the potential for corrosion but are presently not actively corroding, e.g. Areas C or D in Figure 4.</td>
</tr>
<tr>
<td>Conventional repair.</td>
<td>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.</td>
<td>Reconstruction is the most effective long-term solution but is disruptive and expensive and hence should be restricted to localised areas that are considered essential. Typically appropriate for Area A.</td>
</tr>
<tr>
<td>Corrosion inhibitor.</td>
<td>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.</td>
<td>Corrosion monitoring is recommended to ascertain effectiveness of the inhibitor and reapplication would be anticipated at 5-10 year intervals. Most appropriate for Area C.</td>
</tr>
<tr>
<td>Cathodic protection.</td>
<td>Steelwork is protected from corrosion by the application of a small current at low voltage.</td>
<td>On-going monitoring and adjustment is required. Time to first maintenance is determined by the life of the anodes that should provide a minimum of 25 years service. Appropriate for areas B, C and D.</td>
</tr>
</tbody>
</table>

Changes in building height, environment and local methods of construction are known to influence this basic pattern and must be taken into consideration when carrying out inspections and developing repair solutions.

3 REPAIR OPTIONS
A number of remediation options are applicable to treat the range of conditions observed on steel-framed structures suffering from vary degrees of corrosion-related damage, most notably they include 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.

4 CATHODIC PROTECTION
Although the beneficial effects of cathodic protection have been recognised since the middle of the eighteenth 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 from the mains 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 continuous 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 (i.e. reinforcement) which increase 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 evolution can cause embrittlement of highly stressed steel and for this reason prestressed or post-tensioned reinforced concrete structures are generally not protected by cathodic protection in the UK, although cathodic protection of pre-stressed structures is undertaken in Italy.

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

Cathodic protection systems must be carefully designed and account must be taken of many different factors 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 which could be affected by the system and the type of anode employed.

4.1 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 optimised, 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 organisations to inspect a sample of the work and observe the method of installation.

4.2 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 anodising.

The discrete anodes are typically much smaller than those used in reinforced concrete to minimise 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 in their own right. (Atkins & 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. However ribbon anodes 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 such direct access to the infill, or if large lengths of the frame are being exposed and refilled with mortar during the repair process.
4.3 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.

In order to achieve the required aesthetic finish the chases and holes are usually back filled with a material appropriate for the cathodic protection system to 5mm of the finished surface level. The final pointing may then be undertaken using a specialist colour matched material to achieve the desired aesthetic finish.

![Figure 5. Installation of ceramic discrete anodes.](image)

4.4 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 and more integrated power, monitoring and control systems have 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 size of power and monitoring enclosures and the extent of cabling. In both cases, order of magnitude reductions have been possible, allowing installation to proceed without disrupting the operation of the building or altering the outwards appearance.

4.5 Protection criteria
There are a number of protection criteria available in international standards for Cathodic Protection. These are generally based on empirical experience, e.g. 100mV decay in 24 hours (British Standards Institution, 2000), or theoretical considerations that can be based on inappropriate assumptions e.g. a potential of –600mV vs. 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.

4.6 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 and 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, since 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 connected to earth, as would be expected for any electrical installation, e.g. lighting brackets, the earthing system prevents stray current effects.

On historic structures the earthing 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. Alternatively, it may be sufficient to employ monitoring during commissioning and carry out remedial isolation or bonding if required.

5 DEVELOPMENT OF DESIGN GUIDANCE

In order 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 three year research project has recently commenced at Sheffield Hallam University in the UK.

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 previous 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, e.g. cramps and wall-ties, to be formally evaluated for the first time.

On completion of the sandbox work, a number of geometries will be selected for further testing with mortar and brick encasement. From field experience it is estimated that such specimens would not need to be more than 1 to 1.5 m in length to facilitate manufacture and manipulation within the laboratory environment. 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 parallel with the laboratory work, a study of existing installations is programmed to be carried out and discussions or questionnaires organised with the various bodies associated with the repair and preservation of such structures. It is hoped that it will be possible to communicate with overseas bodies elsewhere in the world where the problem of steel frame corrosion is also a concern but no cathodic protection installations have yet been carried out.

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

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7 REFERENCES


