Cathodic protection of historic steel framed buildings

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Abstract

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 large scale removal of original material for replacement with modern alternatives. Depending upon the causes of the deterioration, such traditional repair methodologies may not provide a satisfactory extension of service life.

Cathodic protection, dating back to 1824, represents the first engineered solution to the problems of ferrous alloy corrosion. Developments in anode design and control/monitoring hardware have made the technique applicable to steel framed structures in a manner that is proving acceptable both commercially and from a conservation viewpoint.

This paper discusses the practicalities of steel frame cathodic protection and the general approaches available for its application. It will also briefly discuss current research to properly establish 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 was initially employed in Chicago and subsequently used in most major western cities in the first two decades of the 20th century. This type of construction has resulted in serious consequences with respect to serviceability, safety and aesthetics.

The identification of "Regent Street Disease" in the United Kingdom in the late 1970's highlighted the problems of steel-framed corrosion [1]. The problems observed form part of a pattern of decay that has only recently been formally recognised. It is expected to become more apparent over the next decade and require considerable expenditure in building maintenance.

Cathodic protection, originally developed by Humphry Davy [2] became a serious commercial solution for the protection of steel encased in mortar 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 a purpose-designed impressed current system employing discrete anodes installed from the interior of the building [3].

2 Corrosion of steel

In the presence of moisture and oxygen, steel and other simple ferrous alloys undergo corrosion resulting in a loss of metal and the formation of expansive corrosion products commonly referred to as rust. The rate and nature of the process depends on alloy composition, environmental factors, design and the presence of additional protection. 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 with an associated loss of metal from the anodic areas. In reality, when a metal corrodes, anodic and cathodic areas can be formed on a single surface in contact with the aggressive aqueous environment. This is shown in Figure 1. 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 [4].

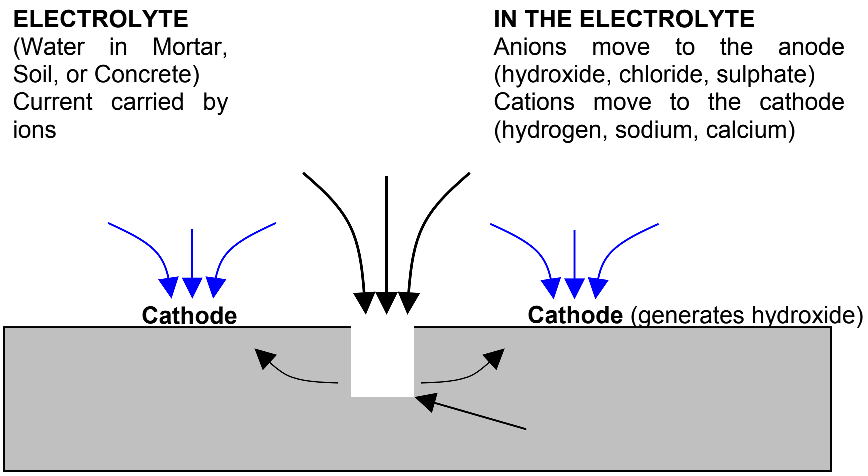

Figure 1: The corrosion process.

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 when 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, such as the presence of salts, has a tendency to reduce the relative humidity at which corrosion initiates [5].

Controlling the relative humidity of encased steel can provide an effective means of controlling corrosion. 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 [6].

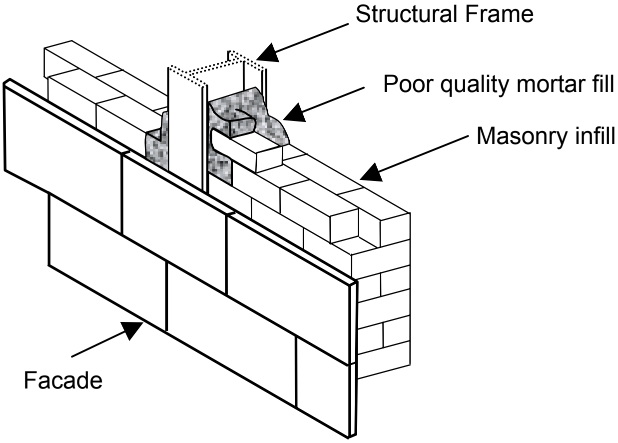

Figure 2: Typical construction detail.

3 Steel frame corrosion

The typical form of construction is shown in Figure 2. A pattern of corrosion-induced damage is now being widely observed in steel-framed structures, typically constructed pre-1930's [7]. The mechanism of the damage can be summarised as follows:

- The steel frame needs to be protected from its natural tendency to corrode (i.e. return to a more stable condition through an electrochemical reaction in the presence of moisture and oxygen). At the time of construction the protection would have typically consisted of 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 allows water ingress. As expansive corrosion products are formed, brick or stone cladding can be cracked or displaced, further opening up joints and cracks and permitting greater access to water (see Figures 3 & 4). 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 amount of damage to the cladding that 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: Corrosion of steel frame.

Figure 4: Cracking of cladding due to 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. This is particularly true in the upper levels of buildings where exposure conditions are generally more severe. The location and severity of damage on a particular building can often be seen to follow a particular pattern, as illustrated in Figure 4.

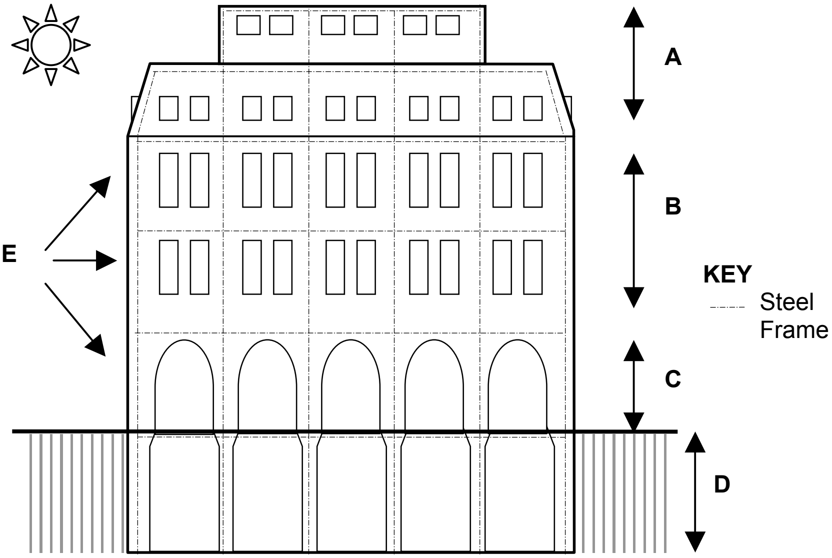

Figure 5: Typical distribution of corrosion damage.

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.

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.

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.

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 waterproofing 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.

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. 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.

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 embedded in concrete and extended to 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 [8].

As discussed previously corrosion of steel 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. This leads 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 which increases the alkalinity. This reduces the tendency to corrode. 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 but this is unlikely to be a problem with iron and early steel framed structures.

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.

4.1 Design

Conventional cathodic protection design is based on calculating the area of steel to be protected and an appropriate current density for protection. 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 limiting disruption to the façade of the structure. 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 trial or pilot installation over a small section of the building, typically including a length of beam and stanchion.

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. It allows 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 in use for cathodic protection installations of this type, discrete anodes based on titanium oxide ceramic or titanium and expanded titanium ribbon anodes. The discrete anodes are typically small (e.g. 10mm diameter 100mm long) to minimise the influence of the installation. The use of a significant number of small anodes also enables a more even current distribution.

Where titanium metal is employed, the surface must be coated with a mixture of metal oxides to prevent the titanium forming a coating and no longer working as an anode. Ribbon anodes have been employed for many years in cathodic protection systems for reinforced concrete [9].

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.

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. These employ 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 [10], or theoretical considerations that can be based on inappropriate assumptions, for example, a potential of –600mV against a Standard Hydrogen Electrode [11]. 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. If electrically isolated areas of steel exist they 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 continuity is investigated during the installation phase to ensure all the steel is electrically continuous.

For the bulk of the frame 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 may be electrically discontinuous which must be considered during the site phase of the works. Additionally in filler joist floors the joists can simply be rested on the flanges of beams. This leads to a poor electrical contact and so electrically discontinuous steel can be encountered. 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 four year research project supported by the Royal Society and Mott MacDonald is presently underway 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 distribution onto typical steel sections yet this is fundamental to the design of the systems.

Initial studies have been 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. From this study it has been possible to work towards the development of guidance on the design and operation of cathodic protection systems and to produce accurate numerical models to assist in optimising the design and operation of such systems [12].

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