Practical Aspects of Cathodic Protection for the Conservation of Iron and Steel in Heritage Buildings

David Farrell and Kevin Davies
Rowan Technologies Ltd, 216 Church Road, Urmston, Manchester M41 9DX, Tel: 0161-748-3644, Email: mail@rowantechnologies.co.uk

ABSTRACT

Since the earliest times, iron cramps and dowels were often built into traditional masonry structures to secure stones which might otherwise be prone to movement or displacement, for example copings, parapets, cornices, mullions and also larger structures such as porticos and arches. They were also widely used in ashlar walls, usually consisting of a thin facing of finely dressed and narrow jointed stonework with a core or backing of rubble or brick. Cramps would be incorporated to tie the facing back to the core and dowels were embedded in the facing itself to help maintain its structural integrity. Wrought and cast irons were also used in many other areas of building construction.

In the 19th and early 20th centuries, the advent of steel framed building construction methods allowed masonry-clad steel-framed structures to be erected. This form of construction drastically reduced the construction time and allowed taller buildings to be constructed with obvious cost benefits. Unfortunately, along with the benefits came new pitfalls. One of these being the spontaneous inclination for steel and iron to corrode and revert back to their natural state.

Corrosion of iron fittings and steel framing is now becoming an increasing problem within our heritage building stock. Although the rate of corrosion is relatively low, in the long term it can result in the fracture of stones and facings and sometimes loss of structural integrity of the structure. Architects have, in the past, attempted to remove as much as possible of the original iron fittings and replace them with more corrosion resistant materials. As a result, significant parts of the original structure were lost forever. The policy now followed in the UK for heritage buildings is that of ‘minimum intervention’ with the intention of retaining as much of the original structure as possible. For steel-framed buildings, replacement with stainless steel is not an option due to the high cost of the material and the difficulty of replacing it.

Cathodic protection, the application of a small negative charge to the iron or steel, is being used increasingly to control corrosion of embedded iron and steel fittings and steel framework in stone and masonry clad buildings. This paper provides an insight into cathodic protection techniques and illustrates how it can be used to conserve embedded iron and steel components in heritage buildings and provide long-term protection to steel-framed buildings.

INTRODUCTION

In the 18th and 19th centuries, dowels and cramps were usually made from wrought iron, which is susceptible to corrosion when exposed to air and moisture. The situation may be exacerbated if sedimentary stones, such as Portland or Bath, are used in the construction. These frequently contain chloride and/or sulphate salts which result in the depassivation of the iron surface and an acceleration of corrosion. Corrosion rates are also significantly higher where iron is in direct contact with damp stone compared to exposure to air.

For major construction work during this period, involving the use of large stones such as porticos, arches and columns, the larger cramps (typically up to 1 metre in length and 50mm thick) are often surrounded by lead. Molten lead was poured into the gaps around the cramps to secure the iron fittings in place at the time of construction. Lead corrodes at a very low rate in this environment and, if it completely surrounds the cramp, then the iron should be protected from corrosion. However, this is rarely the case and corrosion occurs on the non-leaded surfaces. The corrosion progresses along the lead/iron interface and eventually expansion forces cause the lead to delaminate from the iron surface.

In ashlar masonry, the smaller cramps are not normally protected by lead and it is common to find vertical joints not filled with mortar to their full depth. When the shallow bead of mortar at the surface decays or cracks, water is able to penetrate freely. The narrowness of the joints makes effective re-pointing very difficult, so water penetration continues, causing the embedded cramps to corrode.

For both cases, the expanding rust eventually exerts such pressure on the stone that the stone cracks or spalls. The volume ratio between iron and rust can be as high as 1:7. The conventional remedy involves major surgery to remove the cramps, to replace them with non-corroding phosphor bronze or stainless steel and then to repair the wounded stonework.

Some of the 19th and 20th century masonry-clad buildings, which incorporate steel- frames, are also liable to corrosion. In a like-for-like situation, steel corrodes at a far higher rate than wrought iron. Again, conventional treatments can be highly invasive involving large-scale opening up to expose and treat affected components. Cathodic protection offers an alternative approach to the treatment of rusting iron fittings and steelwork buried in masonry and stone.

CATHODIC PROTECTION TECHNIQUES

Cathodic Protection (or CP) is not a new process: in 1824 Sir Humphrey Davy presented a series of papers to the Royal Society describing how CP could be used to prevent the corrosion of copper sheathing in the wooden hulls of British naval vessels. Since then it has been applied to many other areas, including marine applications and for the preservation of buried underground structures such as pipelines and tanks [1]. CP technology has, over the past 20 years, been applied to concrete to protect steel reinforcement from corrosion and, more recently, it has also been applied to iron and steel embedded in brick, masonry and stone in heritage buildings [2,3,4].

Theoretical Principles

Corrosion is an electrochemical reaction involving both anodic and cathodic sites on an iron or steel surface. At the anodic site corrosion occurs as iron gives up electrons and forms soluble iron salts ($Fe \rightarrow Fe^{2+} + 2e^-$). At the adjacent cathodic site the electrons released by the corrosion process combine with water and oxygen to form hydroxyl ions ($1/2\ O_2 + H_2O + 2e^- \rightarrow 2OH^-$). Both these partial reactions have to proceed at the same rate otherwise a build-up of electrons would occur and this would suppress the anodic process. In CP systems the metal to be protected is supplied with electrons from an external source and the entire metal surface is thereby forced to act as a cathode (hence the term 'cathodic protection'), so controlling further corrosion.

When CP is used to protect embedded iron and structural steel, small DC currents are supplied to the metal via the building material. This constant stream of electrons (which move in the opposite direction to the conventional current flow) satisfies the cathodic reaction and suppresses the anodic (corrosion) reaction.

CP may be achieved by two somewhat different techniques, although the principles described above hold true for both. These are sacrificial anode cathodic protection and impressed current cathodic protection.

Sacrificial Anode Cathodic Protection (SACP)

SACP systems use sacrificial anodes (made of zinc, aluminium, magnesium or alloys of these) which corrode preferentially to the metalwork. These are placed in close proximity to the corroding metalwork and are electrically connected to it. As the sacrificial anode corrodes it generates a current that passes through the building material to provide protection to the embedded metalwork, Figure 1. The current is conducted ionically though the building material by means of pore water contained within it.

The main restriction in using an SACP system is that these anode materials have only a small natural 'driving' potential (i.e. the force which drives the electrons through the CP circuit - typically less than 1.5V), when coupled to the embedded metalwork, and this is further reduced by having to overcome the ionic resistance encountered in the building material. For this reason, the distance between the sacrificial anode and the embedded metalwork is normally restricted to a few metres. Another restriction is that the anodes are consumed and will need replacing at some stage in the future. These anodes (normally buried in the ground) are capable of protecting small metal components, such as embedded iron cramps and tie rods, set into walls, floors or roofs of buildings.

Impressed Current Cathodic Protection (ICCP)

ICCP systems require an external power supply, normally mains powered transformer rectifiers, to provide the DC current to the iron or steel to be protected. These systems use non-corroding anodes, located close to the metalwork, to provide part of the current pathway, Figure 1. ICCP systems are generally more complex than the SACP systems but, with their much higher driving voltage, they are suitable for providing current to much larger areas of embedded iron and steel, such as ‘I’ beams, columns and supports and where the stone or masonry has inherently higher electrical resistance.

As the ICCP system forces the metal to become cathodic, and therefore protected, the other side of the CP circuit (the current emitter) becomes anodic and therefore more ‘corrosive’. Materials for these current emitters (or ‘anodes’) therefore have to be highly resistant to corrosion. A variety of commercial anodes are available for use with ICCP systems: Carbon-loaded coatings can be used over short periods although their life is normally restricted to 10 to 15 years. For extended use, embedded titanium anodes, coated with precious metals or conductive ceramic coatings, are normally used.

Conductive coating systems are either based on thermally sprayed zinc or conductive paint. The organic-based conductive paint is generally water-based and loaded with graphite to provide a current pathway. Conductive, cementitious, surface-applied overlays are also available and these normally contain carbon fibres and/or graphite in sufficient quantities to provide a continuous conductive pathway for current. The resulting coating is lightweight and has mechanical and thermal properties similar to that of concrete. However, coatings and overlays are not normally used on heritage structures due to aesthetic constraints.

For titanium-based anodes: titanium on its own is unsuitable as it readily oxidises in air and especially when acting as an anode: it builds up an electrically resistive barrier. Platinum, or a conductive ceramic mixed metal oxide (MMO) coating is therefore applied to substrates to give a low resistance layer to emit the current. Platinum is expensive but the MMO coatings (typically containing mixtures of iridium, ruthenium, titanium and tantalum oxides) are cheaper and these coated anodes are now available as mesh, ribbon or wire. These are suitable for supplying high currents (up to $110mA/m^2$) and have a reported lifetime in excess of 75 years. Mesh is typically used to provide protection to large areas of reinforcement in concrete, whereas ribbon and wire may be used in the joints between stones and bricks to provide protection to horizontal and vertical iron and steel members.

Stand-alone (or ‘discrete’) anodes, comprising MMO coated titanium rods, are also available. These are also suitable for supplying large currents ($800mA/m^2$) and have an estimated life of 300 years. These are often more expensive than the surface mounted MMO coated anodes. The discrete anodes may be linked together using titanium wire and are commonly used where deeply embedded metalwork is to be protected or where surface-mounted systems are inappropriate. The discrete anodes are placed in pre-drilled holes on either side of the embedded metalwork using either a carbon loaded backfill or cementicious grout to fix them in. The titanium connection wires are hidden in the joints and repointed.

The design of a CP system should also take into account many other factors including:

- The surface area of iron or steel to be protected
- The resistivity of the masonry or stonework
- The distance and uniformity of the anodes to the embedded metalwork
- The service lifetime of the CP system

- The aesthetics of the building

APPLICATIONS OF CATHODIC PROTECTION

Four different applications are presented here to illustrate where CP has been used to suppress corrosion on historic buildings.

Whitchurch Almshouses – Corroding Cramps (SACP)

An SACP system was installed in 1999 to protect rusting cramps in the stone façade of four Grade II listed almshouses in Whitchurch, Shropshire, Figure 2. This was the first known application of its kind in the UK. The stones formed an interlocking frontage with iron cramps fitted between adjacent blocks. Water ingress beneath the eaves and window sills had permeated into the stonework joints and had allowed the iron cramps to corrode. The expanding corrosion products had introduced internal stresses into the stonework which had resulted in cracking and spalling to some of the stones.

Conservation policy favours the 'minimum intervention' principle, whereby any repairs should preserve the historically important features of the architecture. For this structure, a novel repair technique using SACP was adopted. Damaged stones, located on the outer edges of the façade, were replaced with new stones fitted with stainless steel cramps. For the remaining, as yet undamaged stones, an SACP system was installed to control further corrosion of the iron cramps.

To provide the cathodic protection, six 2.3kg magnesium anodes were buried in the pavement in front of the cottages and these were connected directly through to the cramps in a 'ring circuit' arrangement. Electrical connections were made to the cramps using a 'keyhole surgery' technique to minimise damage to the stones; the titanium connection wires were sunk into the mortar joints and the current from the sacrificial anodes was conducted through the stone façade thus completing the CP's electrical circuit. This allowed the cramps to be polarised from an external source and thus protected from further corrosion.

Dodington House – Corroding Cramps (ICCP)

The portico of this large country house (circa 1840s) had suffered significant damage from water ingress, corrosion of the embedded cramps and spalling of the large blocks of Bath stone, Figure 3. In late 2003, many of the damaged stones were replaced and stainless steel cramps used to secure the new blocks together. The remaining cramps (in excess of 100) were protected using an ICCP system. The large cramps (around 50mm square and up to 1.5m in length) were buried deep in the stonework (typically 120 to 250mm) and surrounded by lead. The lead surrounds were incomplete and the exposed iron had corroded, Figure 4. The corrosion face had progressed down the lead/iron interface and had forced the lead off the surface, resulting in the entire cramps now being subject to corrosion.

Due to the large area of embedded iron to be protected, the height of the cramps from the ground and the influence of the incomplete lead surrounds (which require a significantly increased current requirement) SACP was not considered suitable in this situation and an ICCP system was used.

Keyhole surgery was used to locate and make electrical connections to each cramp and these were daisy-chained to form the negative (cathodic) side of the circuit. The wires were sunk into the mortar joints, Figure 5. A mixed metal oxide (MMO) coated titanium ribbon (12mm wide) was also embedded into the mortar joints, prior to re-pointing, to provide the anodic side of the circuit, Figure 5. To enable the protection levels to the iron cramps to be monitored and controlled, reference electrodes were also installed within the stonework. These measure the effect of the electrical currents from the CP system on the embedded iron fittings.

The CP's instrumentation cabinet, containing the transformer rectifiers, was located within the servant's quarters above the portico. The cabinet also contained measurement circuits that allow true 'instant off' potentials (the potential of the polarised iron when the current supply has been removed) to be displayed; these measurements are used to assess the performance of the CP system.

<u>Sherborne Abbey – Iron Reinforcements to the Tower Fan Vault (ICCP)</u>

Sherborne Abbey boasts the earliest fan vault to be built in England (circa 1425). The tower vault had been subject to subsidence over the centuries and the Victorians had introduced a wrought iron reinforcement system covering the bottom and top faces of the ribs around 1840. Moisture ingress from the north and south walls had caused the iron reinforcement to corrode, Figure 6. This ultimately led to spalling of some of the stones resulting in the tower being cordoned off in 2000.

Consideration was given to replacing the wrought iron with stainless steel reinforcement but this was considered to be too disruptive and expensive. Besides, the wrought iron itself is of historic importance and its replacement would have been against the principles of 'minimum intervention'. Instead, an ICCP system was specified to provide protection to the iron reinforcements.

The reinforcements were riveted together and therefore electrically continuous and only a single DC negative connection was required. An MMO coated titanium 'web' was fixed onto the top surface of the tower vault using a specialised mortar, thus minimising any interference to the historic fabric, Figure 7. The CP current was subsequently passed through the mortar and stone to provide protection to those iron surfaces in contact with the stone.

<u>Royal West of England Academy – Steel Framing to the Pediment (ICCP)</u>

This 1858 building, situated in Bristol, was refurbished extensively in 2001, Figure 8. The pediment, dating from 1913, was constructed of clinker concrete with a render finish and used 'I' beams within the central construction to provide support. Clinker, from power stations, contains significant quantities of chlorides and these, in combination with water ingress through the render, resulted in corrosion of the steel beams and cracking of the concrete.

The front of the pediment contained various statuary cast into the stone and this important façade would have been seriously damaged if the steel had had to be replaced. It was therefore decided to use a cathodic protection system to control the corrosion of the embedded steel beams. An ICCP system was chosen due to the large area of steel to be protected.

The steel beams had been bolted together and only a single connection was required to complete the DC negative (cathodic) side of the CP circuit. As the steel was buried deeply in the clinker concrete it was decided to use MMO coated titanium discrete rod anodes; these 300mm long anodes allow the current to be delivered deep within the construction. They were installed in 12mm diameter holes at 300mm centres on either side of the beams and used a carbon-loaded backfill to conduct the current into the concrete. The discrete anodes were interconnected using a titanium wire. Note – the anodic side of the circuit is subject to extreme corrosion conditions when the CP system is operational and all embedded materials must be highly resistant to corrosion.

LIFETIME OF CATHODIC PROTECTION SYSTEMS

SACP systems, using sacrificial anodes, have a variable life depending upon the type and weight of anode used. Magnesium gives the highest driving potential at around 1.5V but its useful life is normally limited to around 8 to 12 years due to self-corrosion of the metal. Zinc may also be used to give a life in excess of 30 years but this has a lower driving potential at around 0.75V. However, zinc is a very efficient sacrificial anode and doesn't normally suffer from self-corrosion. Its useful life is therefore directly dependent upon the weight of zinc employed. If the current requirement is known, then Faraday's laws may be used to calculate the useful life of the anodes. However, SACP systems may only be effective where the embedded iron or steel is in close proximity to the buried anodes. Further research is currently in progress at Rowan Technologies to increase the applications where SACP may be employed successfully.

ICCP systems are different in that their components are not consumed by the operation of the CP system, but it is necessary to restrict oxidation of the anode. The transformer rectifier and other electronics may be expected to have a lifetime of between 20 to 40 years after which they can easily be replaced. The external wiring may also suffer long-term decay and may also need replacement after 40 to 60 years. However, the embedded anodes and internal wiring within the masonry and stonework are not easily replaced and should therefore be selected to give a maximum service life.

Low cost anode coatings, such as carbon loaded paints and conductive concrete, may be used, but this frequently results in 'false economy' for heritage buildings which are expected to have endless life. MMO coated titanium anodes are reported to have lifetimes in excess of 75 years and any embedded wiring on the anodic (positive) side of the circuit should use titanium wire. The DC negative wiring, which connects to the iron or steel, is effectively under cathodic protection and should not therefore suffer deterioration. Embedded reference electrodes, used to monitor the performance of the CP system, have a reported life of around 20 years although some have been known to fail within 5 years. Surface mounted reference electrodes may be substituted in their place. These may be fixed to the outer masonry or stonework to assess the performance of the system and then removed.

BENEFITS FROM USING CATHODIC PROTECTION

One of CP's principle advantages is that it provides corrosion control without changing the immediate physical environment; there may still be now, or in the future, damp stone, masonry or concrete adjacent to the metal which would previously have allowed corrosion to continue. Cathodic protection provides the electrochemical conditions to control this corrosion process.

Using cathodic protection there is no need to gain full access to the structure by removing the surrounding material and the existing or historic structure can remain largely intact. All that is required is to install the necessary anodes and cables that form the internal part of the system. If an SACP system is used, then the anodes are buried in the ground at the foot of the structure and only DC negative cables are required to connect to the embedded iron or steelwork. Usually, these can be installed in such a way as to have little or no impact on the structure's appearance.

For the Whitchurch almshouses, the use of CP removed the need to dismantle the stone façade and remove the expanded corroded cramps, a project with uncertain consequences. At Dodington House, some of the large stones in the portico had suffered significant damage from the expanding cramps and these were subsequently replaced. However, most of the cramps and stones had suffered only a minimal amount of damage or were currently undamaged and the application of CP should minimise any further damage in the future.

The Victorian iron reinforcement encountered on the tower fan vault at Sherborne Abbey was a special case, as the iron itself was of historic value and required preservation. Even if this had not been the case, the work involved in dismantling it and supporting this historically important fan vault whilst replacing with stainless steel reinforcement would have been immense. The application of CP was totally non-intrusive as the anode web was laid on the top surface of the vault resulting in no invasion of the original stonework.

The work at the Royal West of England Academy illustrates how CP may be used to protect steel-framing in buildings; in this case using discrete anodes. The cost of installing CP was many times less than the cost to dismantle and rebuild the pediment, which would have resulted in the loss of much of the statuary. Installation of a simple CP system to protect iron cramps in, for example, a church tower within the UK may cost as little as £2,000. This cost will increase depending upon the size of the installation.

CONCLUSIONS

Cathodic protection, in one of its two forms, has now become a useful tool for conservators to control one of nature's most forceful degradation mechanisms, that of corrosion of embedded metallic components. The application of cathodic protection can be achieved by allowing a more reactive metal to corrode preferentially in place of the important metallic components, or by the application of an induced current from an external power source.

With the correct and sensible approach, cathodic protection can be used to oppose the natural degradation of the historic components without detriment to the overall aesthetics of the structure.

The application of cathodic protection to historic structures is now becoming widely accepted and the list of projects where it has been used is increasing as the process is fully reversible and is in accord with modern day conservation principles.

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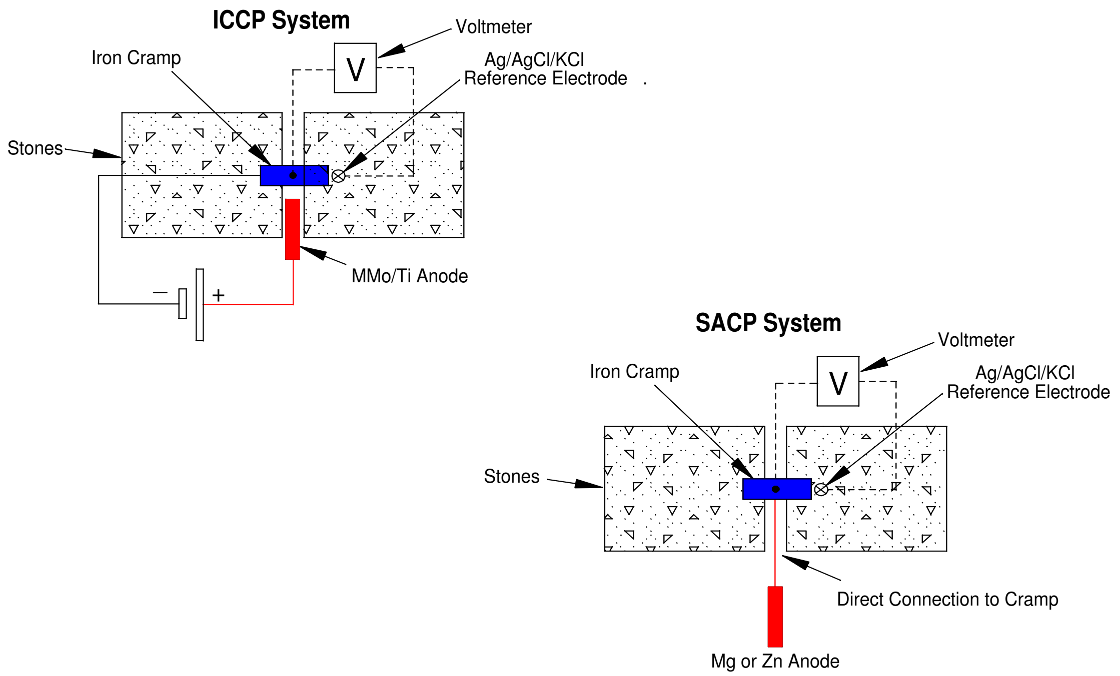

Figure 1: Schematic of SACP and ICCP Systems

Figure 2: View of the Almshouses—showing typical damage from the cramps

Figure 3: View of the Restored Portico at Dodington House –
showing the damage that had occurred to the original stonework

Figure 4: View of a Leaded Cramp—showing incomplete lead coating

Figure 5: Dodington House: Daisy Chaining the Iron Cramps and Insertion of the MMO Coated Titanium Anode Mesh

Figure 6: Sherborne Abbey—View of the Fan Vault showing Damage to the Stonework caused by Corrosion of the Iron Reinforcements

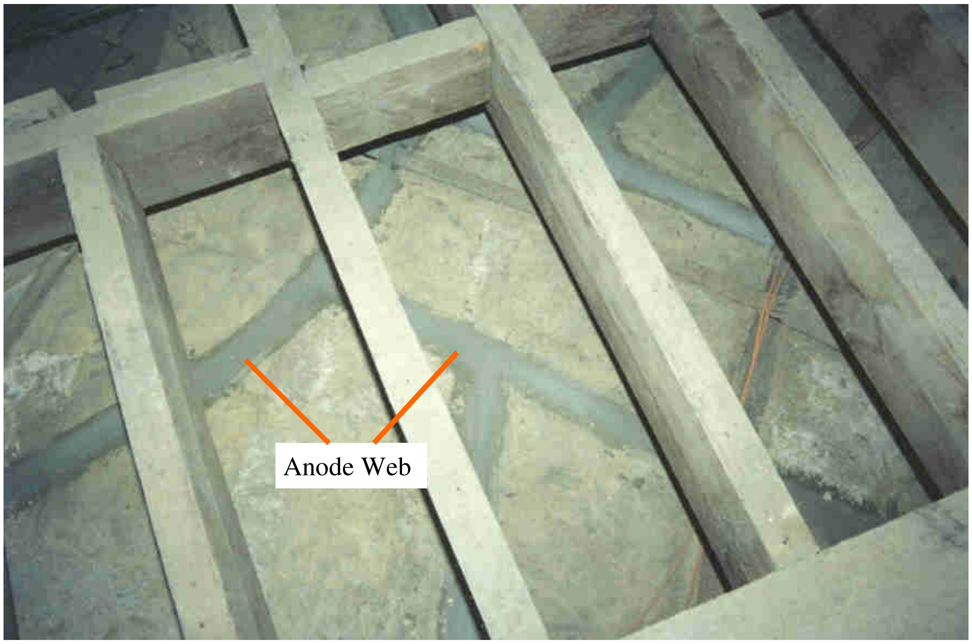

Figure 7: Sherborne Abbey—showing the web anode laid on top of the vault

Figure 8: Royal West of England Academy - showing damage to the back of the pediment