Construction Materials

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ice | proceedings

Proceedings of the Institution of Civil Engineers

http://dx.doi.org/10.1680/jcoma.16.00024
Paper 1600024
Received 16/05/2016 Accepted 11/10/2016
Keywords: concrete structures/corrosion

Hybrid anode concrete corrosion protection – independent study

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This study was the first of its kind to investigate the long-term performance of hybrid anode systems in reinforced concrete as part of a holistic approach to corrosion risk assessment. An independent appraisal of the site performance of hybrid anode corrosion protection systems (UK invention disclosed in Patent GB2426008B) was conducted on six bridge structures in 2014. The aim of the study was to investigate the effectiveness of current design approaches in meeting the residual service life when the anodes are operating in the galvanic phase. This was achieved by analysing data on the general condition of the structures, studying the ongoing performance of the installed hybrid anodes and assessing the overall corrosion risk. It was found that the six structures were generally in good condition, with low associated corrosion risk in areas protected by the hybrid anode systems. This is a positive finding for the wider implementation of hybrid anode systems as an alternative corrosion management technique. The reinforcement in the protected areas remained predominately in a passive condition, with calculated corrosion rates below the ISO 12696:2012 recommended threshold of 2 mA/m^2. Recommendations regarding design are provided in order to improve the redundancy, functionality and robustness of hybrid anode systems.

1. Introduction

1.1 Hybrid corrosion protection technology

Cathodic protection (CP) of reinforced-concrete structures is a well-established method of preventing the initiation of, and arresting ongoing, corrosion. Impressed current CP (ICCP) systems pass a protective current to the steel reinforcement without sacrificing the installed anode and have been used on concrete structures for more than 30 years (Christodoulou *et al.*, 2013a; Stratfull, 1957, 1974). Galvanic technology, in contrast, has been available for around 200 years and is based on the principle of a more active metal being sacrificed in order to create a cathode at the reinforcing steel (Davy, 1824).

The hybrid corrosion protection system is a discrete zinc anode system that is installed into pre-drilled cavities within reinforced concrete (Figure 1). It is a relatively new development in CP, as it combines both an impressed and galvanic system to arrest ongoing corrosion and prevent future initiation. The hybrid anodes are manufactured using 18 mm zinc cylinders, ranging from 42 to 220 mm long, with an integrated titanium connector wire. A coating is applied to the surface of the anode in order to keep the anode active throughout its design life. Initially, the system is connected to a temporary, constant 9 V DC power supply, typically for a period of at least 1 week, depending on the type of reinforcement (e.g. mild steel or prestressed), to deliver a charge to the reinforcing steel (Christodoulou and Kilgour, 2013; Christodoulou *et al.*, 2013b; Glass *et al.*, 2008, 2012; Holmes *et al.*, 2011a). This initial impressed treatment phase re-passivates the reinforcement by means of generating a reservoir of alkali at the steel – concrete interface and is achieved by passing a minimum of 50 kC of charge per metre squared of steel surface area (Christodoulou and Kilgour, 2013; Glass and Buenfeld, 1995; Glass *et al.*, 2004, 2007; Polder *et al.*, 2011). The hybrid anode is then disconnected from the temporary DC power supply and connected directly to the steel reinforcement, creating a galvanic cell, similar to a battery. This latter treatment phase continues for the remainder of the anodes' working life and provides a relatively low current to the steel reinforcement to maintain steel passivity (Christodoulou *et al.*, 2014; Dodds *et al.*, 2014; Glass *et al.*, 2012; Holmes *et al.*, 2011b, 2013).

The hybrid anode system is installed at a spacing dependent on the steel density (per m^2 of concrete), and the individual anodes are connected in series with insulated titanium wire.

Figure 1. Installation of hybrid anode system to typical reinforced-concrete pier (CPT, 2014)

Different sizes of anode are available and are named based on the expected charge output during the anode's life (e.g. D350 and D500 anodes relate to an output of 350 and 500 kC, respectively). The size of anode is chosen based on the design life required, average current density and steel density within the concrete structure.

The hybrid technology offers the same advantages as a galvanic system, in that little or no maintenance is required throughout its design life cycle, and no permanent power supply needs to be installed as part of the works, while also possessing the corrosion arrest power traditionally associated with a full ICCP system (Christodoulou and Kilgour, 2013; Christodoulou *et al.*, 2013b; Glass *et al.*, 2008, 2012). The system designs are based on an allowance for an additional impressed treatment phase (i.e. an additional 50 kC/m^2 of steel surface area to be implemented at a later stage in the structure's life if any corrosion activity is detected through monitoring), which does not impact on the remaining design life.

Hybrid anodes are usually designed to provide a residual service life of 30–50 years based on an expected current demand from the surrounding reinforcing steel in a structure, similar to that of galvanic technology (Christodoulou *et al.*, 2016). ISO 12696:2012 (BSI, 2012) acknowledges that hybrid and galvanic anodes may not necessarily meet the performance criteria set out in the standard (BSI, 2012). These are recognised as the empirical criteria (i.e. not theoretically derived) of the accepted performance of ICCP systems. Hybrid anodes' current tends to fluctuate with the changing risk of corrosion initiation, commonly referred to as 'responsive behaviour' (Holmes *et al.*, 2011b). This has resulted in some reservations within industry as to the accuracy of the designs to meet the residual service life when the anodes are operating within the galvanic phase. Instead of assessing performance against absolute values, ISO 12696:2012 (BSI, 2012) acknowledges that a holistic approach to the overall condition and corrosion risk assessment of the structure may be adopted for hybrid and galvanic anodes.

1.2 Performance evaluation

The performance criteria for CP systems require a positive depolarisation shift of steel potential by 100 mV over a period of 24 h or a depolarisation > 150 mV over an extended period of time. This potential shift has been empirically developed over time and later adopted within the ISO standard as an absolute value. Research into the behaviour of galvanic and hybrid systems has shown that the 100 mV potential shift is not always achieved in benign environments and when the risk of corrosion has been reduced by the anode system itself (Christodoulou *et al.*, 2013b; Glass *et al.*, 2012; Holmes *et al.*, 2013). It is for this reason that ISO 12696:2012 (BSI, 2012) allows the use of alternative criteria to assess CP systems, such as corrosion rates, with values < 2 mA/m^2 indicating passive steel (BSI, 2012). The corrosion rate can be determined from an established mathematical model, the Butler–Volmer equation, using the applied current (i_{appl}), the potential shift (ΔE) and predicted values for the anodic and cathodic Tafel slopes (β_a and β_c) (Equation 1). A corrosion rate of this magnitude (2 mA/m^2) equates to a steel section loss of ~1 mm over 500 years, which is a particularly stringent value for a reinforced-concrete structure that has a service life of 50–100 years. Christodoulou *et al.* (2010) found that the 2 mA/m^2 threshold is associated with benign environmental conditions and steel passivity when assessing the performance of impressed current CP systems. A falling trend in corrosion rate combined with a rising trend in open circuit steel potential is also a sign that steel passivity is being achieved (BSI, 2012)

1. $$i_{corr} = \frac{i_{appl}}{(\exp(2{\cdot}3\Delta E/\beta_c) - \exp(-(2{\cdot}3\Delta E/\beta_a))}$$

1.3 Aim of the study

The aim of this study was to determine the effectiveness of hybrid anode systems in providing sufficient protection against the initiation of corrosion and also to view the performance of the oldest hybrid anode installations in order to examine their long-term performance using a holistic condition and corrosion risk assessment as described by ISO 12696:2012 (BSI, 2012).

To achieve this, six bridge structures on which hybrid corrosion protection systems were installed around the UK between 2006 and 2013, in varying locations and climatic conditions, were examined, including the following

(*a*) Laverock Hall, Newcastle, Tyne and Wear
(*b*) Whiteadder, Berwick, Northumberland
(*c*) Storth Lane, South Normanton, Derbyshire
(*d*) Kyle of Tongue, Achuvoldrach, Highland
(*e*) M69 Junction 2, Huncote, Leicestershire
(*f*) Paston Interchange, Peterborough, Cambridgeshire.

This study assesses data obtained from hybrid anode systems installed on real-life structures throughout the UK; therefore the authors acknowledge that some variability may occur in the parameters presented. In some cases, the as-built information was not available for the bridge structure or the installed hybrid CP system. The amount of data collected and the type of testing that could be conducted were largely dependent on the original installation arrangements. Some sites also had difficult access restrictions, which unfortunately limited the amount of data that could be obtained for analysis.

2. Structures and installation

The hybrid anode system was installed on six reinforced-concrete bridge structures between 2006 and 2013 (Figure 2). An overview of each structure is detailed below.

System (a): Laverock Hall, Newcastle (2006) – Laverock Hall overbridge was constructed in two halves for the northbound and southbound carriageways. The two 43 m bridges form part of the A189, carrying traffic over the A1061 (Figure 2(a)). Two reinforced-concrete abutments are located at each end of the structure. Prior to repair works in March 2006, the bridge exhibited areas of substantial spalling and delamination to the piers, due to chloride ingress from leaking of the deck joints. Concrete repairs were undertaken to areas of significant corrosion damage, with D500 anodes installed in the reinforced-concrete abutments and piers, based on a design life of 30 years where significant levels of chloride content were measured. This was the world's first application of hybrid corrosion protection technology. Data logging equipment was installed to allow remote monitoring of the structure. The reinforced-concrete abutments and piers received an additional waterproofing coating.

System (b): Whiteadder, Berwick (2007) – This 90 m long bridge forms part of the B6461 carrying traffic over the Whiteadder Water at Canty, near Paxton (Figure 2(b)). It opened in 1973 and is constructed from four steel girders supported on bearings directly above reinforced-concrete piers. Prior to the repair works, the bridge exhibited areas of substantial spalling and delamination to the piers, due to chloride ingress from leaking of the deck joints. D500 anodes were installed across the entire face of the four reinforced-concrete piers to achieve a design life of 30 years. The piers also received additional protection in the form of a waterproof coating. Data logging equipment was installed on the bridge to allow remote monitoring of the structure (Glass *et al*., 2012).

System (c): Storth Lane, South Normanton (2007) – The bridge carries the A38 dual carriageway over Storth Lane in Derbyshire (Figure 2(c)). The single-span structure is constructed from simply supported prestressed beams spanning the two reinforced-concrete abutments. D500 anodes were installed along a single row in both bridge abutments, ~400 mm below the bearing shelf, to prevent further corrosion

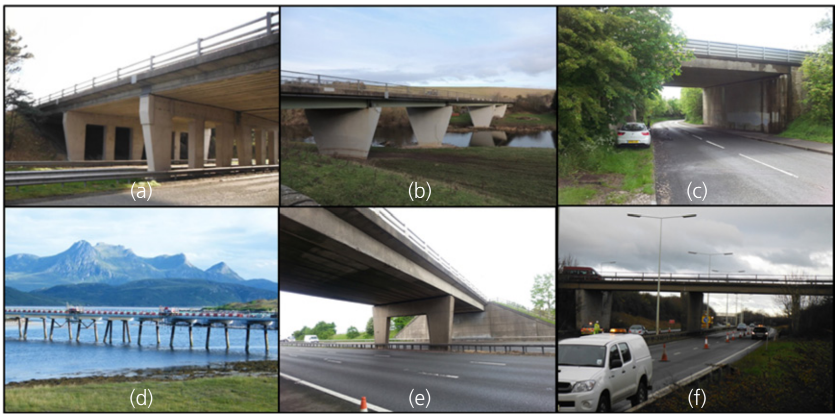

Figure 2. Bridge structures with installed hybrid anode systems: (a) Laverock Hall, (b) Whiteadder, (c) Storth Lane, (d) Kyle of Tongue, (e) M69 Junction 2, (f) Paston Interchange

damage from the leaking bridge joints and to achieve a design life of 25 years. No major repair works were conducted on this bridge. Remote monitoring is not available at this site and readings have to be taken from the monitoring enclosure.

System (d): Kyle of Tongue, Achuvoldrach (2011) – The 183 m long bridge forms part of a causeway carrying the A838 over the Kyle of Tongue estuary on the north coast of Scotland (Figure 2(d)). The bridge was fully refurbished following reports of high chloride concentrations due to the exposure to a marine environment and de-icing salts used on the bridge deck during the winter months. D175 anodes were installed in localised repair areas and it was the first time the technology was implemented in prestressed concrete beams with a design life of 30 years. On this particular occasion, the design required the steel potentials to be maintained more positive than −900 mV, during the energisation process, to prevent hydrogen embrittlement of the prestressed strands. Remote monitoring was installed due to the site location. A detailed review of the hybrid system at Kyle of Tongue has been conducted previously by Christodoulou *et al.* (2013b).

System (e): M69 Junction 2, Huncote (2012) – The two bridge structures at Junction 2 and the bridge north of Huncote village are situated on the M69 motorway in Leicestershire (Figure 2(e)). The three structures consist of simply supported prestressed beams spanning the north and south abutments with an intermediate pier and supporting columns. Concrete repairs and hybrid anode installation were carried out to three abutments along the westbound carriageway (one for each structure) following inspection reports that identified corrosion activity and significant chloride levels. D750 anodes were installed in a single row along the length of all three abutments 200 mm below the bearing shelf to achieve a design life of 25 years. The anodes are separated into two individual zones per abutment and wired back to a centrally mounted junction box. Remote monitoring is not available at this site and readings have to be taken from the monitoring enclosure.

System (f): Paston Interchange, Peterborough (2013) – The two 41 m long bridges of the A47 Paston Interchange both support a dual carriageway roundabout above the A15, located at Junction 20 (Figure 2(f)). The four-span bridge consists of 27 simply supported prestressed beams spanning three reinforced-concrete crosshead beams and supporting columns. D350 hybrid anodes were installed on the outer piers of both bridge structures, on both the traffic and verge faces, to prevent further corrosion damage following concrete repairs. The system was designed to achieve a 25-year design life. Remote monitoring is not available at this site and readings have to be taken from the monitoring enclosure.

3. Methodology

A desk study was initially conducted including a review of previous principal inspection reports, existing monitoring data and as-built drawings, where available. Each structure was visually inspected to determine the condition of the reinforced-concrete structures and to confirm details of both the structure and the installed hybrid anode system.

Steel potential readings were recorded before and after a 24 h depolarisation period, where possible. Corrosion rates were subsequently calculated by means of the polarisation resistance method to determine the effectiveness of the hybrid systems in preventing the initiation of corrosion. The Butler–Volmer equation (Equation 1) is an established method of calculating corrosion rates from depolarisation data and has previously been used to report on the performance of CP systems (Christodoulou *et al.*, 2013b; Glass *et al.*, 2008; Hassanein *et al.*, 2002; Holmes *et al.*, 2011a, 2013). The equation uses the recorded depolarisation shift and local applied current density, in an area of known steel density, to provide an indication of overall corrosion current density (e.g. corrosion rate), which is an indication of the condition of the reinforcement. The anodic (β_a) and cathodic (β_c) Tafel slopes were set at 120 mV (Holmes *et al.*, 2013).

The corrosion rate for each of the structures was assessed against the criteria for CP systems as laid out in ISO 12696:2012 (BSI, 2012), whereby a corrosion rate of <2 mA/m^2 indicates passive steel conditions. Where possible, the change in corrosion rates was also assessed against the trend of open circuit steel potential (BSI, 2012; Glass *et al.*, 2012).

4. Analysis

Overall, the six structures were found to be in good condition following refurbishment works with minor site-specific defects as summarised in Table 1.

As the hybrid systems were installed at different times between 2006 and 2013, the extent of record monitoring data varies. The calculated corrosion rates and subsequent corrosion risk assessments are summarised for each structure below.

System (a): The corrosion rate for the pier beam has generally remained significantly below the 2 mA/m^2 recommended value for passive steel (Figure 3). On two occasions, a higher corrosion rate was measured for the pier column; however, this has since reduced back below the threshold value, showing that the anode has responded to the risk of corrosion initiation.

The two occasions where the corrosion rate increased above the 2 mA/m^2 threshold does not necessarily indicate a

Bridge structure	Inspection date	Notes
(a) Laverock Hall	March 2014	No visible defects were noted to the reinforced-concrete piers. Water staining was observed at high level indicating that the bridge joints are still leaking
(b) Whiteadder	March 2014	No visible defects were noted to the reinforced-concrete piers. Water and rust staining observed on the piers from the primary steel girders due to water ingress through the deck joints
(c) Storth Lane	May 2014	Significantly more water ingress was observed on the south abutment compared with the north abutment. No defects were noted within the area of influence of the hybrid CP system
(d) Kyle of Tongue	February 2013	No signs of corrosion were found. Repairs to prestressed beams were generally in good condition with no evidence of delamination or spalling. No faults were identified with the hybrid CP system (Glass *et al*., 2008; Holmes *et al*., 2011a)
(e) M69 Junction 2	May 2014	No signs of corrosion were found. Small amounts of water ingress were observed from the carriageway above across all three abutments. No defects were noted within the area of influence of the hybrid CP system
(f) Paston Interchange	January 2014	No signs of corrosion were found. No defects were noted within the area of influence of the hybrid CP system. Water ingress was observed from the carriageway above

Table 1. Inspection summary

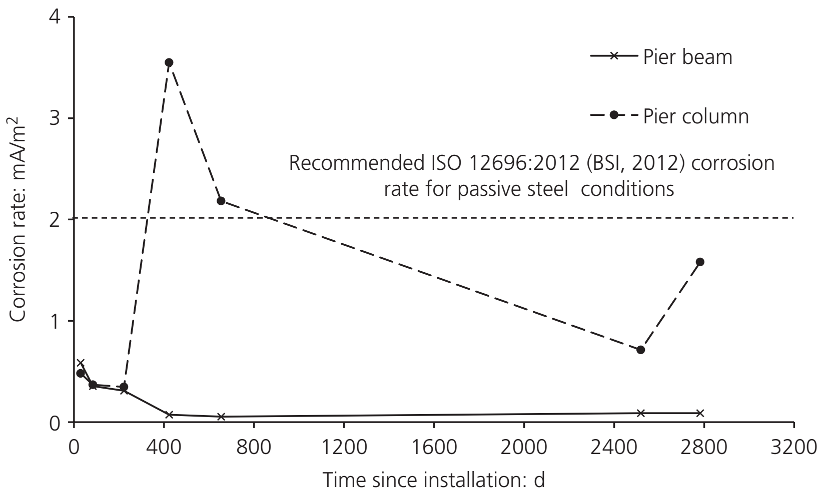

Figure 3. Laverock Hall, evolution of corrosion rate with time

non-compliant system. The corrosion rate calculated at these two occasions equates to a reinforcing steel section loss of ~3·5 and 2·2 mm, respectively, over a period of 1000 years, which is considered to be structurally negligible.

Furthermore, a review of the steel 'on' potential values indicates that generally they have increased over time, which suggests overall steel passivity (Figure 4).

The sudden changes in the 'on' potential readings observed at ~750, 1700 and 2550 d (identified in Figure 4) can be associated with changes in the environmental conditions due to wetting of the piers from the carriageway above. In these instances, the hybrid anodes have responded effectively by providing a higher current to overcome the increased risk of corrosion (Holmes *et al*., 2011b). The general trend of increasing steel potential with time, combined with the relatively low equivalent section losses and visual inspection details, suggests that this structure has a low risk of corrosion initiation.

System (b): The value of the corrosion rate for the upper anode zone has remained below the threshold value of

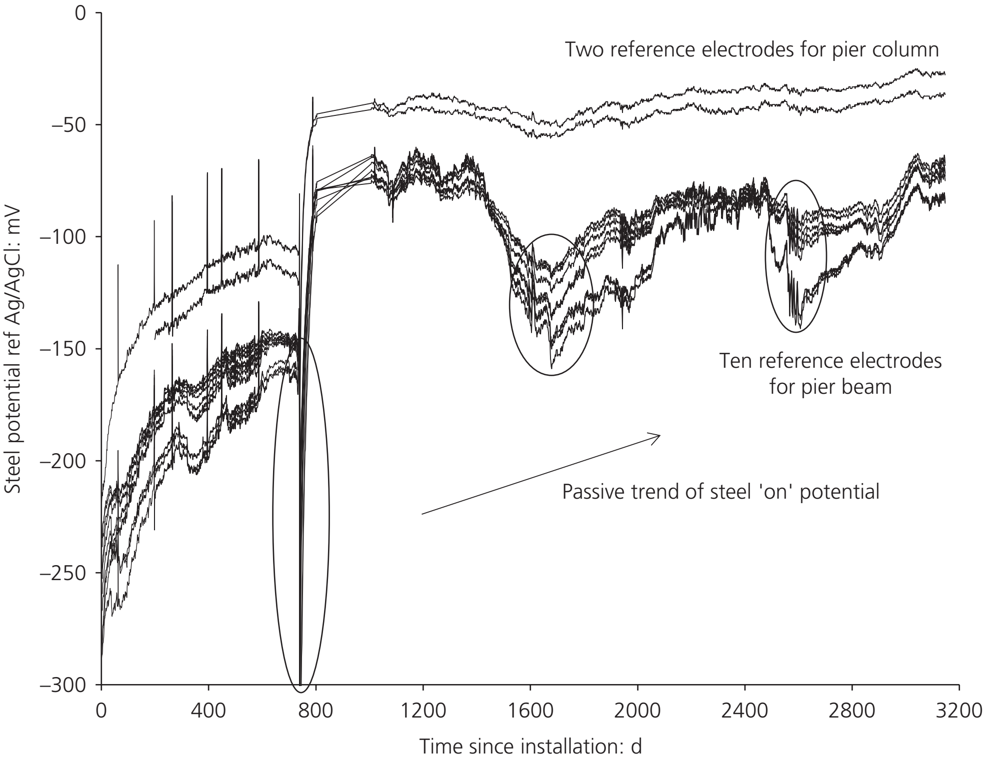

Figure 4. Laverock Hall, evolution of steel potential over time

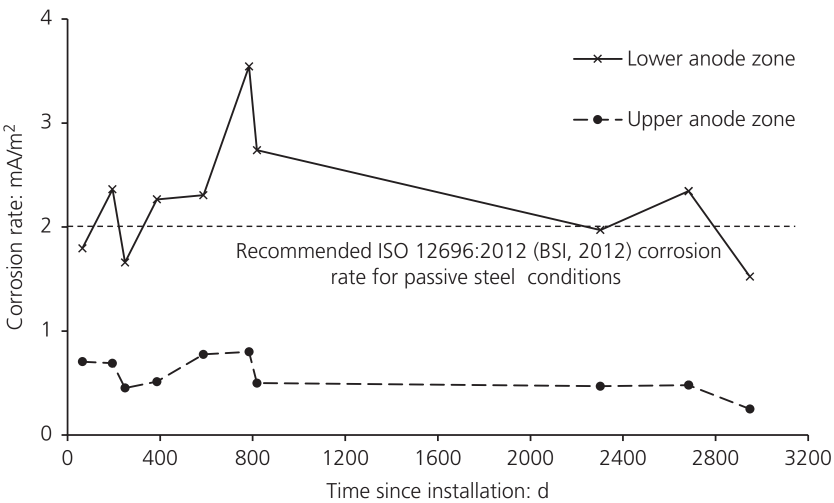

Figure 5. Whiteadder, evolution of corrosion rate with time

2 mA/m^2 since the installation of the hybrid system in 2007, indicating that the steel has remained passive. In contrast, the values for the lower anode zone have fluctuated with time (Figure 5).

The corrosion rate for the lower anode zone has largely remained above the recommended threshold, although it is acknowledged that there are only a handful of available readings. The maximum corrosion rate calculated since installation

Date	08 April 2009	12 May 2009	04 June 2013	20 June 2014	12 March 2015
Upper monitoring zone current: mA	0·36	0·30	0·18	0·18	0·08
Lower monitoring zone current: mA	2·24	1·95	1·25	0·92	0·48

Table 2. Whiteadder, development of monitoring zone currents from background monitoring data

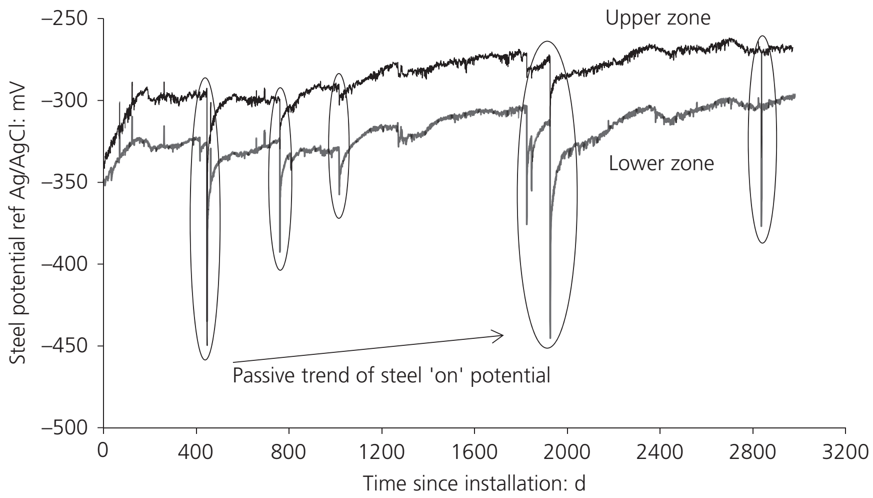

Figure 6. Whiteadder, evolution of steel potential over time

is 3·5 mA/m^2, which equates to a reinforcing steel section loss of ~3·5 mm over a period of 1000 years, which is again considered to be negligible when compared with a 120-year design life of a bridge structure.

The monitoring data also show that the current afforded by the anodes (four per monitoring zone) is higher for the lower anode zone (Table 2), which is most likely due to water ingress from the adjacent river. The current in the upper zone is significantly lower throughout, which suggests that the concrete is much more dry. The current for both the upper and lower anode zone is decreasing with time, which suggests that the steel reinforcement is gradually becoming more passive. The lower zone current has decreased at a more substantial rate, as the possibility of corrosion initiation is reduced in that area. The passivity of the steel reinforcement for both zones is confirmed by the fact that the 'on' potential of the steel has been increasing towards more positive values for all monitored areas (Figure 6).

Similar to system (a), the sudden changes in 'on' potential readings observed at regular intervals (identified in Figure 6) are attributed to flooding of the river. In these instances, the hybrid anodes have responded effectively by providing a much higher current to overcome the increased risk of corrosion (Holmes *et al*., 2011b). Based on the magnitude of the calculated corrosion rate and the equivalent reinforcing steel section loss, and the passive trend of both the measured output currents and steel 'on' potentials, it is anticipated that the structure has a low risk of corrosion initiation.

System (c): Long-term monitoring data are not available for this structure as no remote monitoring equipment was installed at the bridge. The corrosion rate was calculated from a site visit on 23 May 2015, which indicated passive steel conditions for all four of the monitoring zones in the north abutment (Table 3). The 'monitoring zone current (mA)' refers to the current distributed by the four anodes in the monitoring zone, and the 'anode driving voltage (mV)' refers to the potential difference between the anode and the steel when the system is switched off. This information helps to determine whether the anode system has been installed correctly and is still functional.

The system at Storth Lane had achieved the recommended criteria for passive steel conditions on the date of that inspection. Also, no visual defects were observed in the area of influence of the hybrid anode zone during the inspection.

Monitoring zone	1	2	3	4
Instant 'off' potential: mV	−442	−344	−466	−472
Monitoring zone current: mA	0·22	0·03	0·53	0·30
Anode driving voltage: mV	223	381	272	191
'Off' potential (1 h): mV	−436	−343	−450	−468
Total depolarisation: mV	6	1	16	4
Cathodic current density: mA/m^2	0·22	0·03	0·53	0·30
Corrosion rate: mA/m^2	0·95	0·78	0·85	1·95

Table 3. Storth Lane, calculated corrosion rates

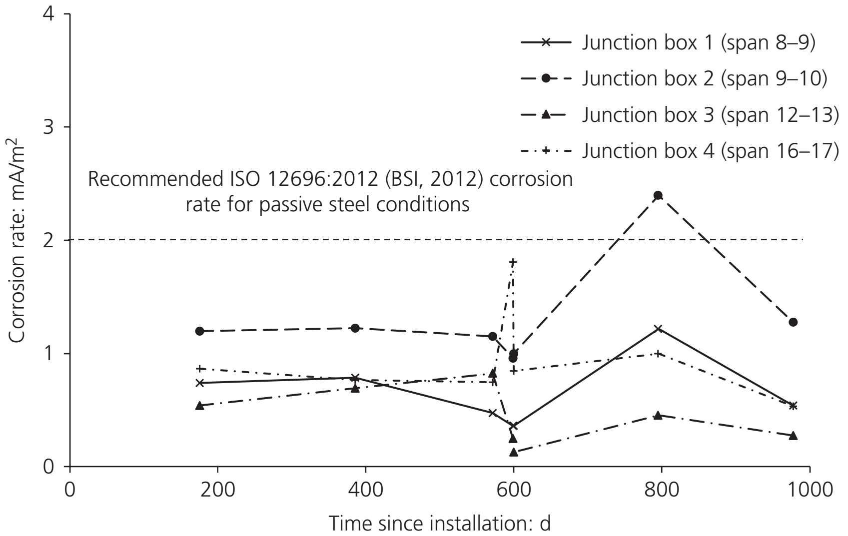

Figure 7. Kyle of Tongue, evolution of corrosion rate with time (Christodoulou and Kilgour, 2013; Christodoulou *et al.*, 2013b)

Although there are no substantial historical data with regard to the performance of system (c), the testing data suggest that there is no corrosion risk and the reinforcement may be considered to be in a benign environment.

System (d): This particular system does not have a continuous data monitoring system; however, manual readings are taken on an annual basis and these are presented in Figures 7 and 8. Overall, it can be observed that the corrosion rates have generally remained below the recommended threshold value, apart from a single occurrence. The latter is not considered significant as it was a single event and the magnitude of increase is negligible.

Furthermore, the open circuit steel potentials demonstrate a trend towards more positive values, which also suggests that the reinforcement is protected and in a passive and benign environment.

System (e): Long-term monitoring data were not available for this structure as no remote monitoring equipment was installed on the bridge. Furthermore, due to a 20 min access limit (without specialist traffic management) it has not been possible to collect full depolarisation data from this bridge. The data collected during a site visit on 23 May 2014 show that the monitored anode zones were effectively distributing a protective current to the steel reinforcement (Table 4). An extended depolarisation test would be beneficial in providing additional performance information and would enable a proper evaluation of the corrosion risk.

The higher corrosion current on the left zone of abutment 3 (Huncote) may be attributed to wetting of the abutment from the carriageway above, as noted in the visual inspection results. In addition, it has not been possible to undertake a complete depolarisation, which may have yielded even lower corrosion current densities.

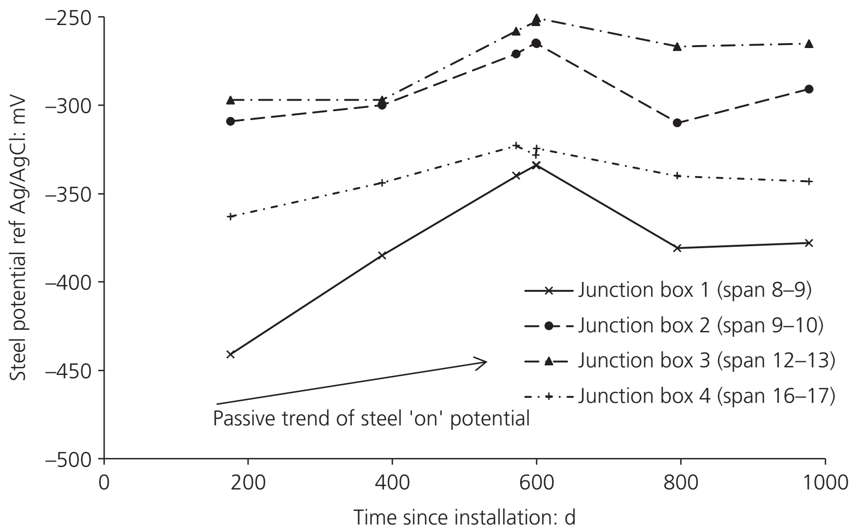

Figure 8. Kyle of Tongue, evolution of open circuit steel potential over time

Abutment	1 (Junction 2)		2 (Junction 2)		3 (Huncote)	
Zone	Left	Right	Left	Right	Left	Right
Instant 'off' potential: mV	−365	−322	−361	−372	−414	−510
Monitoring zone current: mA	0·50	0·47	0·46	0·36	1·80	0·20
Anode driving voltage: mV	223	214	214	177	247	220
Corrosion current density: mA/m^2	0·67	0·63	0·61	0·48	2·40	0·27

Table 4. M69 Junction 2, recorded site data

	Northwest pier				Southwest pier			
	Traffic face		Verge face		Traffic face		Verge face	
Zone	1	2	1	2	1	2	1	2
Instant 'off' potential: mV	−385	−400	−308	−418	−408	−384	−374	−383
Monitoring zone current: mA	0·12	0·54	0·01	2·67	0·73	0·91	1·00	0·11
Depolarised steel potential: mV	−367	−343	−302	−327	−302	−317	−335	−337
Total depolarisation: mV	18	57	6	91	106	67	39	46
Cathodic current density: mA/m^2	0·56	0·56	0·40	0·40	0·50	0·50	0·69	0·69
Corrosion rate: mA/m^2	0·79	0·21	1·73	0·07	0·07	0·15	0·42	0·34

Table 5. Paston interchange west piers, calculated corrosion rates

System (f): Long-term monitoring data were not available for this structure as no remote monitoring equipment was installed at the bridge. The corrosion rates calculated from the site visit on 9 January 2014 indicated passive steel conditions for all 16 monitoring zones tested (Tables 5 and 6). The total depolarisation time for the west and east piers was 25–26 and 23–24 h, respectively. It has also been reported in previous commissioning reports (dated March 2013 and January 2014) that the

	Northeast pier				Southeast pier			
	Traffic face		Verge face		Traffic face		Verge face	
Zone	1	2	1	2	1	2	1	2
Instant 'off' potential: mV	−361	−346	−291	−269	−355	−225	−332	−279
Monitoring zone current: mA	0·88	0·46	0·04	1·12	0·07	0·01	0·04	0·19
Depolarised steel potential: mV	−287	−317	−274	−262	−347	−216	−322	−264
Total depolarisation: mV	74	29	17	7	8	9	10	15
Cathodic current density: mA/m^2	0·32	0·32	0·29	0·29	0·06	0·06	0·08	0·08
Corrosion rate: mA/m^2	0·08	0·27	0·44	1·08	0·19	0·17	0·21	0·14

Table 6. Paston interchange east piers, calculated corrosion rates

hybrid system was performing effectively (Edwards, 2013; Holmes, 2014).

The low corrosion rates for all 16 monitoring zones, combined with the relatively low changes in steel potential between the instant 'off' and 'off' readings (i.e. the total depolarisation over 24 h), suggest that corrosion activity is minimal. This structure therefore has a low risk of corrosion initiation.

5. Discussion

The aim of this study was to conduct the first independent appraisal of the effectiveness of hybrid anode systems in preventing corrosion initiation of the reinforcing steel using the holistic approach of a condition and corrosion risk assessment. This approach combined the absolute values and alternative performance criteria in ISO 12696:2012 (BSI, 2012), together with an assessment of the overall corrosion risk to a structure from the results of a visual inspection, calculated equivalent section loss of the reinforcing steel over time and the trends of long-term monitoring data.

Overall, the results of the visual inspections indicated that the areas protected by the hybrid anode systems were found to have no visual defects, and the structures were generally in a good condition. The most common observation was the ingress of water from the carriageways above due to leaking bridge joints. Using the approach of a holistic corrosion risk assessment, all of the structures were found to have a low associated corrosion risk.

Overall, there have been instances where the measured corrosion rates were somewhat higher than the recommended threshold values. While at face value this may appear to be a system failure, it ought to be reviewed in an overall context. In particular, in all instances where a corrosion rate higher than the recommended threshold was calculated, it was observed that the steel 'on' potentials had shifted over time towards more positive values. In addition, all the current outputs were relatively low, with no physical evidence suggesting corrosion (e.g. rust staining, cracking, delamination etc.). All of these suggest a benign environment with passive reinforcement.

In addition, by undertaking a simple mathematical sensitivity analysis of the Butler–Volmer equation for corrosion rate assessment, it is evident that where there are only very small potential shifts, then the equation can return high corrosion rates, which should not necessarily be related with a high corrosion risk. In fact, this investigation has demonstrated that there is sufficient evidence from a number of structures that had continuous monitoring of steel potentials to indicate that the higher corrosion rates observed in some instances are not necessarily realistic.

In particular, a monitoring area comprising 0·68 m^2 of steel reinforcement can yield a corrosion current density of 2·4 mA/m^2 based on an output anode current of 0·25 mA and a potential shift (ΔE) of 4 mV. However, the very same zone will result in a corrosion current density of 1·28 mA/m^2 based on an output anode current of 0·1 mA and a potential shift of (ΔE) of 3 mV. This demonstrates the overall sensitivity of the equation when dealing with very small currents and potential shifts.

The collected data show that the corrosion rates generally remained below the 2 mA/m^2 threshold recommended by ISO 12696:2012 (BSI, 2012), which indicates passive steel conditions (BSI, 2012; Christodoulou *et al.*, 2010). In most of the applications, low magnitude corrosion rates had been calculated over a period of 8 years since the installation of the hybrid systems. In some isolated cases, the corrosion rate exceeded the recommended threshold; however, this does not necessarily indicate a non-compliant or unsatisfactory system. The highest observed corrosion rate was 3·5 mA/m^2, which equates to an equivalent section loss of reinforcing steel of 3·5 mm over 1000 years. If this is compared against a typical 120-year design life for a bridge structure, then a section loss of ~0·4–0·5 mm should be expected. The trends in the 'on' potential of steel for these structures also confirmed the low risk of corrosion as the reinforcing steel is becoming more passive. The resting steel 'on' potentials for systems (a), (b) and (d) have shifted positively by ~150–200, 40–50 and 20–60 mV, respectively.

Where remote monitoring is available, extensive site data can be collected and the ongoing performance of hybrid systems can be assessed without the need for site visits, access or traffic management. Data logging equipment can be programmed to automatically record depolarisation readings at regular intervals, which can be used to plot the change in depolarised steel potential readings and corrosion rates over time. These data are useful when assessing the performance of hybrid anode systems and subsequent corrosion risk (BSI, 2012; Glass *et al.*, 2012).

The data analysed in this study indicate that the design approach of an initial impressed current phase (50 kC/m^2 of steel surface area), followed by an ongoing galvanic phase for the remainder of the anode's design life, has been effective in preventing the reactivation of reinforcement corrosion for up to about 8 years. This agrees with the majority of published work on the performance of hybrid anode systems and is a positive finding for the implementation of hybrid anodes as an alternative corrosion risk management technique in reinforced-concrete structures (Christodoulou *et al.*, 2014; Dodds *et al.*, 2014; Glass and Buenfeld, 1995; Glass *et al.*, 2004, 2007, 2012; Holmes *et al.*, 2011b, 2013; Polder *et al.*, 2011).

6. Design recommendations

As part of the independent appraisal, the following recommendations should be considered when designing new hybrid anode systems, primarily to improve the redundancy, functionality and robustness of the system. These have been based partly on the data obtained as part of this study, and the experience of the authors in the design, installation and monitoring of hybrid anode systems in reinforced-concrete structures.

It would be beneficial to obtain long-term monitoring data for all new systems, which would enable an assessment of the continued performance of the hybrid system, similar to the data provided for systems (a), (b) and (d) in this study. This should include the installation of reference electrodes in areas of high corrosion risk, and junction boxes for enclosing monitoring equipment. Remote monitoring is particularly useful at sites with limited access, or where traffic management (which can be disruptive and costly) is required. It is also important to position junction boxes in suitable locations on the structure, away from the risk of surface water run-off and potential vandalism and theft.

To improve redundancy within the hybrid systems, it is recommended that a secondary copper feeder wire is introduced to connect the first anode in the treatment zone to the junction box location. This wire acts as a fail-safe connection if the primary titanium feeder wire were to break. The additional feeder wire should be a titanium terminated copper cable (300 mm titanium wire crimped and sealed to a length of copper cable at each end) as this has significant advantages over long lengths of titanium wire. The copper cable significantly reduces the voltage drop when long distances of feeder wire have to be installed between treatment zones and monitoring equipment. The titanium termination of the copper cable at both ends enables a better connection to the terminals in the junction box and also prevents corrosion initiation at the point of connection.

7. Conclusions

The following conclusions can be drawn.

- The six structures were found to be generally in good condition, 1–8 years after refurbishment works.
- The areas of reinforced concrete protected by the hybrid anode technology were found to have no associated visual defects.
- The results of depolarisation tests, in combination with other evidence, suggest that the hybrid anodes effectively protect the steel reinforcement, which is considered to be in a passive condition.
- In the majority of cases, the calculated corrosion rates as set out in ISO 12696:2012 (BSI, 2012) were below the recommended threshold of 2 mA/m^2 for passive reinforcement.
- On some occasions, the corrosion rate exceeded the recommended threshold; however, the structures were still assessed as low corrosion risk based on the absence of any visual defects, open circuit steel potential trending towards positive values, and the fact that the recommended corrosion rate was only exceeded in single and isolated events. In addition, in these isolated instances, the calculated corrosion rate was only marginally higher than the recommended threshold; all of which provide reassurance of a resultant low corrosion risk.

These conclusions highlight the fact that the design approach for these hybrid anode systems to achieve their intended design life was effective. This is a positive finding for the implementation of hybrid anodes as a corrosion management technique in reinforced-concrete structures. This study was the first of its kind to adopt a new method of assessment for hybrid anode systems using a holistic approach to corrosion risk assessment, rather than focusing primarily on the absolute values stated in ISO 12696:2012 (BSI, 2012). It is, however, still recommended to assess the ongoing performance of these hybrid anode systems in conjunction with a principal inspection of the structures (every 6 years).

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