Hybrid corrosion protection of a prestressed concrete bridge

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ABSTRACT

The Kyle of Tongue Bridge in Sutherland, Northern Scotland opened in 1970, has an overall span of 184m of 18 approximately equal spans and carries a single lane dual carriageway. The bridge was repaired in 1989 due to chloride induced corrosion. However, inspections from 1999 onwards reported on-going corrosion and structural deterioration. A refurbishment contract was let in 2011 to extend the service life of the structure for a 20 year period by providing corrosion arrest and prevention.

This paper describes how hybrid corrosion protection was used to offer protection to the prestressed concrete beams of the bridge. The results indicate that hybrid anodes provide an attractive alternative to other corrosion protection systems as they can be targeted to specific areas of need. They offer a temporary energising phase to arrest corrosion, followed by a permanent galvanic mode phase which is particularly beneficial for prestressed concrete structures in order to reduce the risk of hydrogen embrittlement.

1. THE STRUCTURE

The Kyle of Tongue Bridge in Sutherland, Northern Scotland carries the A838 road across the estuary of Tongue (Figure 1). It opened in 1970 and has an overall span of 184m and consists of 18 approximately equal simply supported spans. The bridge width is 8.5m consisting of a single 5.5m wide carriageway with two lanes and 1.2m and 1.8m wide footpaths.

The deck spans are formed by a composite slab of 17 No. precast prestressed concrete inverted T-beams with in-situ concrete infill, and these sit on rubber pads on bearing shelves at all of the in-situ pile caps. The substructure is formed of pairs of long raking hexagonal steel piles capped with an in-situ reinforced concrete pile capping beam referred to herein as a pile cap. There are two steel piles at all of the pile caps except the centre pile cap which has four piles (Figure 2). The bridge was patch repaired in 1989 due to chloride induced corrosion. However, inspections from 1999 onwards reported that corrosion was still continuing both on the prestressed concrete beams and the reinforced concrete pile caps with evident structural deterioration.


Figure 1: General view of the Kyle of Tongue bridge

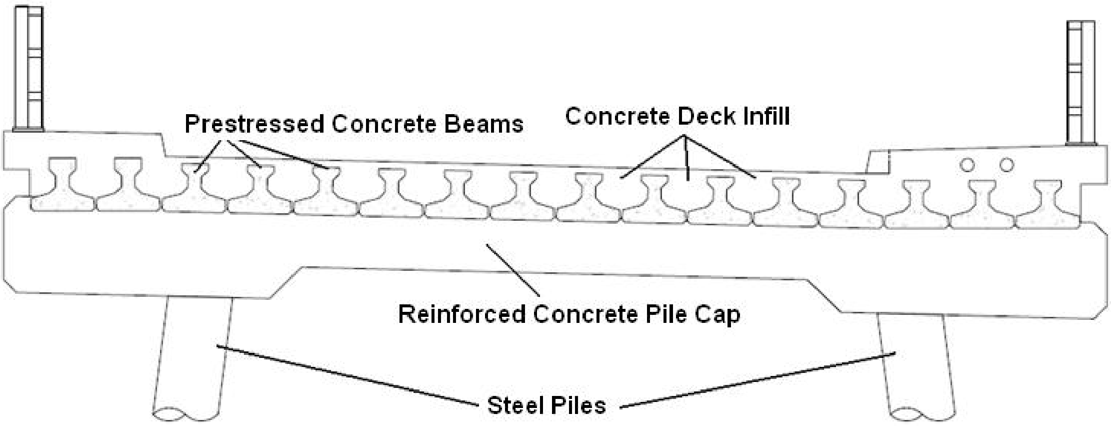

Figure 2: Typical structural cross section of the bridge

2. CONDITION ASSESSMENT

A comprehensive condition survey was undertaken in 2008 to establish the cause and extent of deterioration on the structure. It was identified that the structure suffered from the following:

- widespread chloride contamination
- chloride induced deterioration of the prestressed concrete beams (Figure 3)
- chloride induced deterioration of the reinforced concrete crossbeams (Figure 4)

- chloride induced deterioration of the reinforced concrete footpaths at deck level
- failure of the abutment asphaltic plug joint

Figure 3: Typical chloride induced deterioration of the prestressed concrete beams

Chloride sampling throughout the structure indicated chloride concentrations exceeding 1% by weight of cement at the depth of reinforcement which indicates a high risk of corrosion (Design Manual Roads Bridges 1990). In some cases, chloride concentrations exceeded 2% by weight of cement. With regards to carbonation, depths were generally low and there were no instances where they reached the depth of the steel.

Figure 4: Typical chloride induced deterioration of the bridge

3. CORROSION ARREST

Concrete is normally highly alkaline and steel in this environment is protected by a passive film. Figure 5 shows a section of the potential-pH diagram for iron and its oxides in water (Pourbaix 1990). Passive films are not perfect and some reaction of iron and water does occur. This is usually negligible. However, in the presence of chloride ions, hydrochloric acid is produced and localised pitting corrosion results (Glass et al. 2007). The production of acid is considered to be an essential feature leading to significant corrosion damage on passive steel (Glass et al. 2008). This process is illustrated in Figure 5. The local environment at the steel is moved from a region where insoluble oxides are the most stable product to a region where iron is soluble in the process of corrosion initiation.

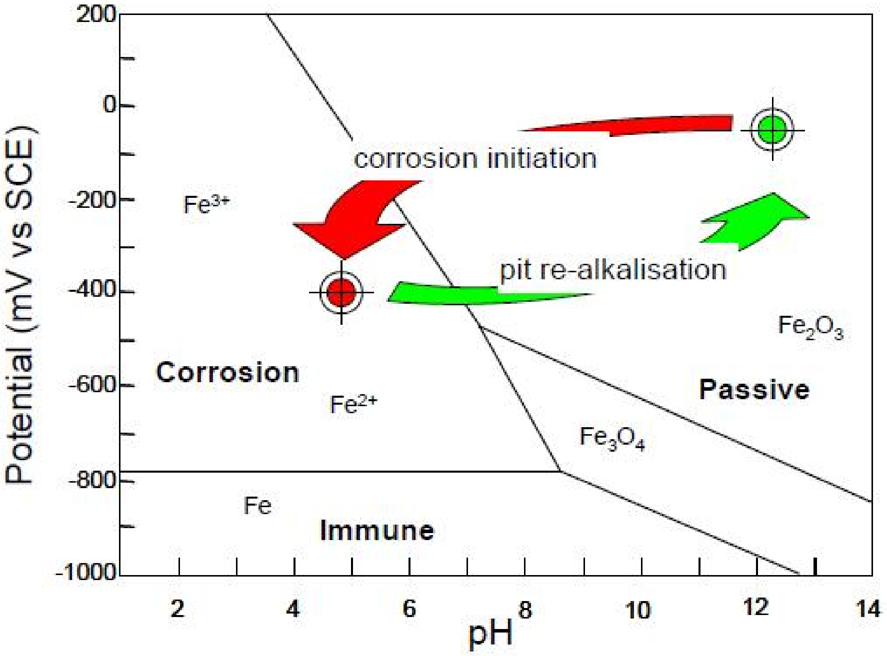

Figure 5: Model of corrosion initiation and arrest showing the stability of iron and its corrosion products (Pourbaix 1990).

A powerful and very popular repair technique to arrest deterioration due to chloride induced corrosion is the use of Impressed Current Cathodic Protection (ICCP). The technique relies on the passage of an electric current through the electrolyte to the corroding metal surface and reverses the direction of the electric current produced by the corrosion reactions. It has a proven track record and it has been used worldwide to protect reinforced concrete structures from future chloride induced deterioration (Broomfield 2007, Concrete Society 2011).

One of the effects of an electrochemical treatment is also to produce hydroxyl ions on the steel raising the pH. The local environment at the steel is then moved from a region where iron is soluble to a region where insoluble oxides are the most stable product. This has been proven to provide sustained protective effects to the steel reinforcement even when the protective current has been interrupted and chloride contamination remains (Christodoulou et al. 2010, Christodoulou et al. 2012). This re-alkalisation process is also illustrated in Figure 5 and would lead to a restoration in steel passivity. It is termed pit re-alkalisation when localised pitting corrosion is arrested (Glass et al. 2008).

However, for prestressed steel the use of electrochemical treatments poses a risk of hydrogen embrittlement (BSI 2012). The steel becomes brittle due to the incorporation of hydrogen so inducing stress corrosion cracking and leading to premature failure of the steel. This effect occurs on high strength stressed steel tendons such as prestressed or post-tensioned tendons.

Standards deal with such risks by limiting the induced change in the potential of the steel reinforcement. For prestressed steel, the potential of the steel is limited to values more positive than -900 mV vs Ag/AgCl/0.5M KCl (Silver/Silver Chloride) (BSI 2012). This limit aims to reduce the amount of hydrogen generated as a result of water hydrolysis during the application of an electrochemical treatment such as ICCP. However the risk to the asset owner remains throughout the long-term use of an ICCP system. An impressed current treatment, delivered using an external DC power supply to re-alkalise the acidic corrosion sites may be applied with a limited duration (typically 3 months) to reduce this risk.

An analysis of the available literature shows that applied charge densities of less than 100kC/m^2 would be sufficient to induce a change in the environment at the steel leading to the arrest of the corrosion process in chloride contaminated concrete (Glass and Buenfeld 1995, Polder et al. 2009, Glass et al. 2004).

Such a charge may be delivered using a sacrificial metal as an impressed current sacrificial anode. Thus the temporary electrochemical treatment may be delivered in a relatively short period using a sacrificial (galvanic) anode and a power supply. Following the initial treatment, the anodes are connected in a galvanic cell arrangement to the reinforcement and a galvanic current is delivered from the anodes to ensure sustained steel passivity. This two-phase treatment is referred to as a hybrid electrochemical treatment.

The use of a hybrid electrochemical treatment on this particular structure was advantageous as there is no longer a need for removing physically sound but chloride contaminated concrete from behind the prestressing tendons which would have otherwise caused structural weakening.

4. METHODOLOGY

This section describes the installation procedure, materials used and testing methods for assessing the performance of the hybrid electrochemical treatment.

4.1 Installation Methods

Only physically deteriorated concrete was removed from the prestressed concrete beams. Hybrid anodes 18mm in diameter and 37mm long were installed in drilled cavities between the prestressing tendons of the beams. The pre-drilled cavities were filled with proprietary low strength mortar to fully cover the anodes and provide separation from the repair concrete (Figure 6).

The hybrid anodes included an integral titanium wire to facilitate the delivery of an impressed current and were connected in a series for each repair. Each series of anodes for the individual repairs was terminated in a junction box which also facilitated a connection to the steel reinforcement. This provided a convenient location to connect them to the temporary power supply for delivering the initial current treatment and later connecting them together in a galvanic cell.

Figure 6: Hybrid anode installation on a prestressed concrete beam

4.2 Materials

Table 1 describes the details of the anode and concrete repair materials used. For commercial reasons the materials cannot be named directly and only their location and characteristics are presented.

Table 1: Repair materials details

Material	Repair location	Characteristics
Hybrid Anodes	Prestressed Concrete Beams	Discrete zinc anodes, 18mm diameter and 37mm long
Repair concrete	Prestressed Concrete Beams and Reinforced Concrete Crossbeams	Dry sprayed polymer modified micro-concrete

4.3 Testing methods

The assessment of the performance of the hybrid anodes was based on:

- corrosion rates
- potential measurements

Corrosion rates are commonly measured using the polarisation resistance method and they are usually expressed as a current density, a rate of weight loss or a rate of section loss (Polder et al. 1993, Andrade and Alonso 2004). A corrosion current density of 1 mA/m^2 is approximately equal to a steel section loss of 1 µm/year. In general, corrosion current densities higher than 1–2 mA/m^2 are considered to be significant.

Corrosion current densities are calculated based on the applied current and the achieved potential shift. A small current density applied to the steel produces a steel potential shift and a voltage drop (IR drop) through the concrete (Christodoulou et al. 2010). The potential shift and applied current density are inserted into the Butler–Volmer equation, which provides the basis for polarisation resistance theory, to calculate the corrosion current density (Figure 7). It has previously been shown the acceptance criteria based on low steel corrosion rates are strongly related to acceptance criteria based on a minimum potential shift (Glass et al. 1997).

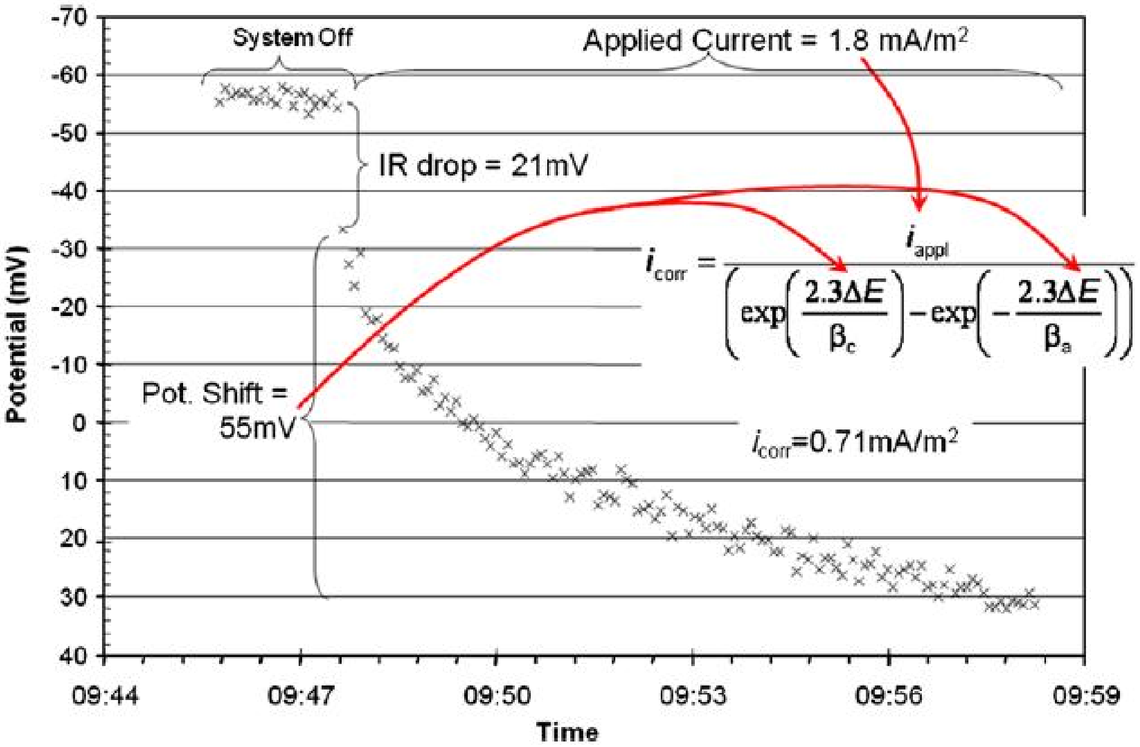

Figure 7: Example corrosion current density calculation (Christodoulou et al. 2010)

Measuring steel potentials against the potential of a standard reference electrode is a well established non-destructive monitoring technique (Concrete Society 2004, ASTM 2009). Following the application of an electrochemical treatment, steel potentials should move towards less negative values. Such an approach is adopted by Australian Standards (AS 2008).

Permanent MnO_2 (manganese dioxide) reference electrodes were embedded within the repairs in order to measure the steel potentials. Readings of steel potentials were taken after the initial high charge treatment had been completed and the anodes have been switched to galvanic mode.

5. RESULTS

Figure 8 illustrates typical monitoring data for the charge density delivered by the hybrid anodes on a repair of a prestressed concrete beams. The minimum charge density was set at 50 kC/m2 delivered over a period of 8 weeks or approximately 60 days. The results presented here are typical and similar data were obtained for all the repairs monitored.

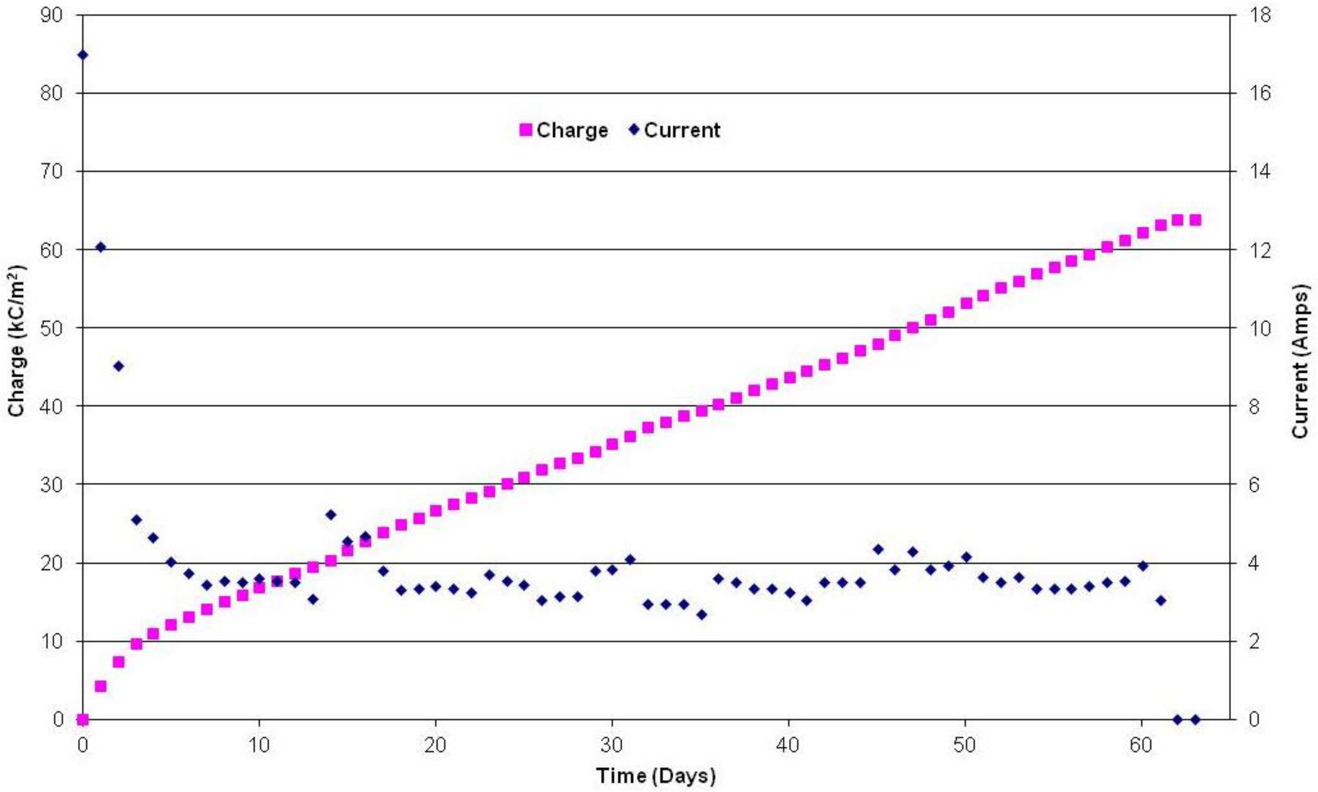

Figure 8: Typical charge density and current applied to a repair area on a prestressed concrete beam.

Figure 9 illustrates the corrosion current density of four monitoring locations before and after the application of the treatment. It can be observed that in all four cases the corrosion rate dropped below the required threshold and has since remained below it. In addition, it can be observed that steel potentials have risen over time to less negative values indicating steel passivity.

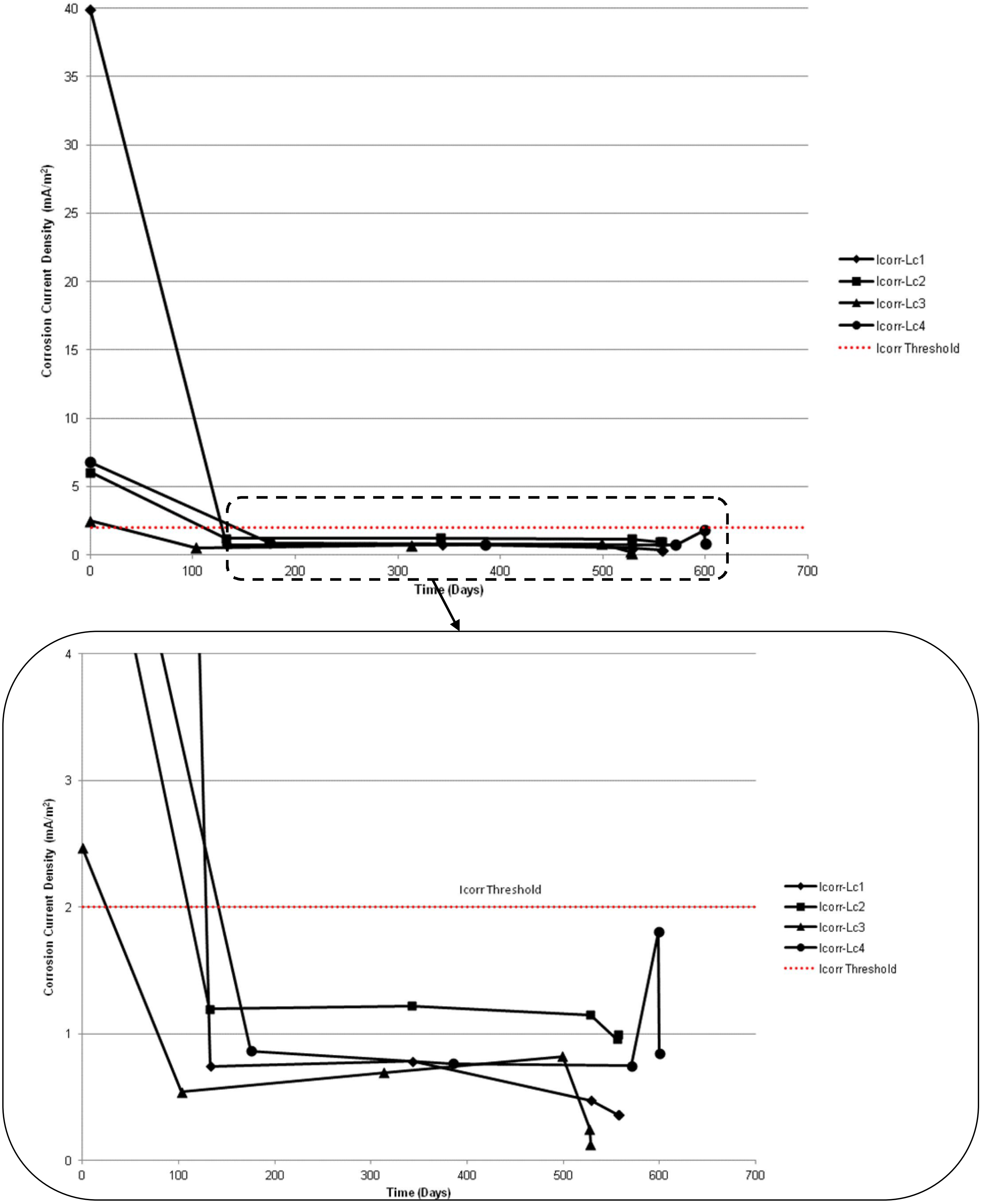

Figure 9: Corrosion rates before and after the application of the hybrid cathodic protection treatment.

6. DISCUSSION

Hybrid cathodic protection is an attractive alternative to traditional electrochemical treatments. In the particular case study examined, it has been successfully applied to arrest corrosion of prestressed concrete beams. The initial high charge treatment was only over a brief period of time (typically. 8 to 12 weeks) and took place during the refurbishment works on the bridge, i.e. at a time where the application can be continuously monitored. Daily readings of the voltage and current applied indicated that the steel potentials during the initial treatment never exceed the limits for prestressed steel (BSI 2012). This presents a significant reduction of embrittlement risk when compared to traditional electrochemical treatments.

The corrosion monitoring data shows that the use of hybrid anodes with an initial brief high charge electrochemical treatment resulted in a substantial decrease in the corrosion rate, to a point where the prestressing tendons in the repair areas can now be considered to be passive.

Following the initial high charge treatment, low density galvanic cathodic protection has been sufficient to maintain the corrosion rates below the required threshold. Monitoring of the steel potentials over a period of up to 600 days has also confirmed that the steel is passive. It has been observed that over-time steel potentials have been moving towards more positive values which is an indication of steel passivity. Most importantly, passivity has been maintained despite the continuous exposure of the bridge to an aggressive marine environment.

7. CONCLUSIONS

It can be concluded that:

- Hybrid corrosion treatment can be successfully applied to prestressed concrete and offer significant benefits over traditional electrochemical treatments.
- Following the application of the brief high current electrochemical treatment, corrosion rates have dropped below a threshold value of 2 mA/m^2 and have remained as such for more than 600 days and continue to do so. This is despite the continuous exposure of the bridge to an aggressive marine environment.

8. REFERENCES

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