Corrosion Control of the Severn Bridge Main Suspension Cables

Paul Lambert, Mott MacDonald, Altrincham, UK

Jeffrey Fisher, Mott MacDonald, Croydon, UK

The Severn Bridge (see Figure 1) is a 988m span suspension bridge located in the United Kingdom carrying the M48 across the River Severn estuary between Bristol and South Wales. It was built in 1966 and featured many novel innovations such as inclined hangers and a pioneering use of streamlined box girder deck construction.

In 2006 the UK's Highways Agency, though its concessionaire the Severn River Crossing plc, commissioned a programme of intrusive examinations of the main suspension cables with Faber-Maunsell (now Aecom) and Weildlinger acting as consultants for the inspection. These investigations provided the data for use in the strength assessment of the cables undertaken by Mott MacDonald who were the Government's Representative for the Severn Crossings concession up to mid 2012.

This article describes the use of a degradation model to predict the performances of the cables under various scenarios and demonstrates the effectiveness of the combined dry air injection system, with the addition of vapour phase corrosion inhibitors, in stabilizing the condition of the main suspension cables.

Introduction

The first intrusive inspection of the main cables, carried out in 2006/7, found the cables to be corroded and to have reduced structural strength. Following this investigation and assessment, an acoustic monitoring system and dry air injection system were installed on both main suspension cables to control the deterioration. Both of these systems were procured through the Severn River Crossing plc with Aecom as their consultant.

The purpose of the dry air injection system was to reduce the relative humidity within the cable to less than 40%, it is accepted within the corrosion industry that the achievement of this figure will prevent corrosion of metals. As a further measure to enhance the dry air injection system it was decided to include a corrosion inhibitor.

As recommended in NCHRP Report 534[1], a further intrusive inspection and corresponding load assessment was undertaken in 2010, the results of which have previously been published[2]. The assessment showed that the strength of the cables were no worse that during the original assessment in 2006.

In addition to an acoustic monitoring system, sensors were installed to monitor vehicle weights and the air condition within the suspension cables. Using this data, Mott MacDonald developed an overall monitoring system for cables based on the principles contained in the Highways Agency's standard BD79/13 'The Management of Sub-Standard Highway Structures'[3]. The data from the monitoring system was used to supplement results of an assessment of the cable to allow annual certification of the cable.

The dry air injection system was installed during 2008 and the drying phase had been completed by September 2009, as demonstrated by the achievement of a relative humidity of 40%.

Deterioration Model

To assist in the management of the suspension cables an analytical tool was developed to model the deterioration of the galvanised steel wires as a result of corrosion. While the present condition can be quantified, an assessment is required of the mechanism and timescale for this condition to be established. Details of the development of the model are described elsewhere2. Using this method it is also possible to predict the long term effects of various remedial measures.

Figure 1: Severn Suspension Bridge, built 1966.

To assist in the development of the model, it was necessary to measure a number of physical parameters. In areas where corrosion has not initiated, the as built condition such as wire diameter and thickness of galvanising can be established. It was also possible to retrieve samples of wires for detailed inspection and physical testing to identify the factors that govern failure. In areas where corrosion has taken place it is possible to measure section losses or depths of penetration that have occurred to date. In addition it is possible to identify failed wires and obtain values for contributory factors.

For the wires making up the main suspension cables, the following assumptions were made with respect to the onset of corrosion:

1) The wires arrive at site adequately protected from corrosion until the cables have been spun.
2) Once in place, the cables are protected by three layers of protection:
   a) The zinc galvanising on the individual wires.
   b) A layer of red lead oxide paste on the outside of the cable.
   c) A protective wrap consisting of wire plus tape plus coating.
3) Initially, the cable is protected from significant corrosion by the cumulative action of the three protective systems.
4) The first to break down in the outer coating, allowing moisture and more importantly moist air to enter the bundle. As the cable cools at night, the moisture in the air condenses to liquid.
5) In time, through exposure to water and the atmosphere, the effectiveness of the red lead paste breaks down allowing the zinc galvanising to start corroding.
6) As patches of the zinc layer become fully consumed, the underlying steel starts to corrode.

7) While the rate of corrosion will be initially fast, the generation of voluminous corrosion products may eventually occlude the corrosion site, slowing down the rate of metal loss.
8) Under stress, the corrosion of the wires can become concentrated, eventually reducing the cross section of the wire sufficiently for it to fail by tensile overload.

Each of these stages needs to be modelled individually, based on both published data and site observations, then combined to produce the overall predictive tool. A series of laboratory investigations were carried out on samples of wire removed from the structure. The failure of the wires was found to be caused by the formation of narrow 'V' shaped corrosion pits reaching a critical depth. The data on the critical defect size was best characterised by a Weibull distribution which confirmed that failure occurred when the defect reaches approximately one third of the thickness of the wire. Based on this observation, the most appropriate data for modelling section loss relates to depths of penetration with respect to time. Published data was employed for the corrosion loss of zinc and unalloyed steel in a range of environments[4]. The data obtained from site was found to correlate well with the section loss predicted by the model, see Figure 2, and provided the necessary confidence to use the model to predict the future performance of the wires and the influence of dehumidification and corrosion inhibitors.

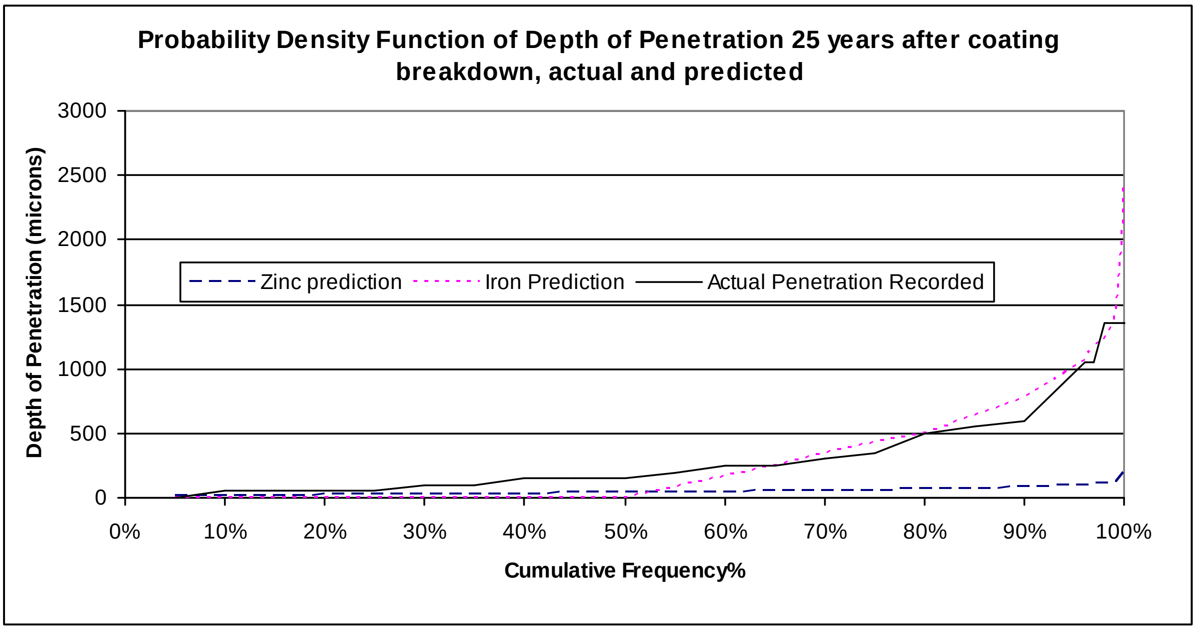

Figure 2: Comparison between actual and predicted depth of penetration

Use of Corrosion Inhibitors

In order to provide additional corrosion protection to the wires during the initial period of moisture reduction when corrosion rates could increase as oxygen becomes more available, and to provide a back-up in the event of the dehumidification system being out of action, for example, for maintenance, a vapour phase corrosion inhibitor system (VpCI) was developed for introduction into the dry air stream[5].

VpCIs have been in use for a number of years, initially for military and aerospace applications but now commonly also for automotive, domestic and construction uses. While the formulation is specific to the manufacturer, VpCIs are typically based on non-toxic volatile organic compounds that form continuous highly-adherent mono-layers on the surface of metals which are effective in controlling the processes that lead to corrosion.

In industry they are generally used with a carrier system which may be a water or hydrocarbon solution or a fine starch or talc powder. Due to concerns regarding the potential blocking of the air voids in the cables, powder-based delivery systems were immediately rejected as a method of introducing the inhibitor. Water based systems were also considered unsuitable, particularly as moisture reduction was a principal aim, while solvent based systems were found to be incompatible with the cable wrap and RH probes that formed integral parts of the dehumidification system.

For these reasons, an approach based on the introduction of the pure inhibitor vapour by using the dehumidification air stream as the carrier was developed. The inhibitor is introduced into the air stream via permeable emitters with no solid or liquid material being employed. In this manner it has been possible to ensure a sufficient level of inhibitor vapour is present within the air voids to protect exposed metal surfaces while avoiding the risks of blockage by solid or liquid material.

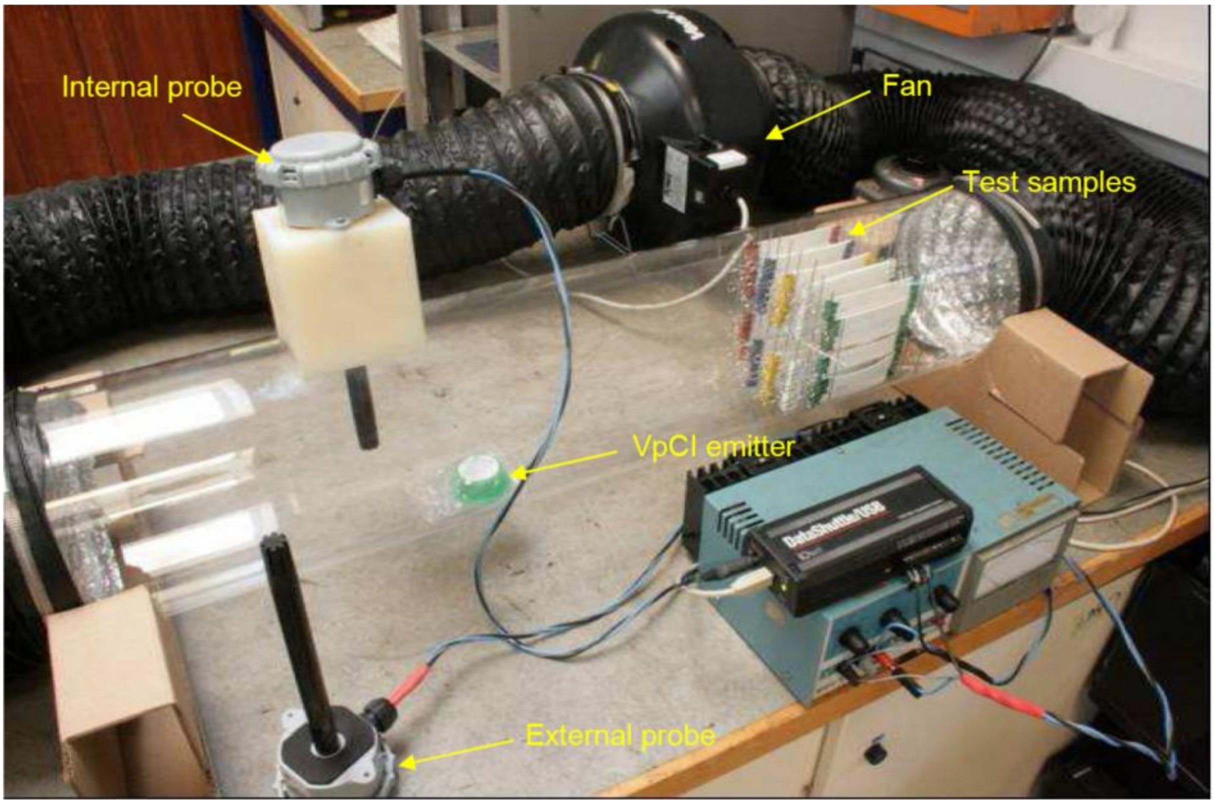

Figure 3: Laboratory test to confirm compatibility of inhibitor with dehumidification system components.

Because the protection layer is only one or two molecules thick, they should have no influence on clearances and only a minimal effect on other physical properties. To confirm this, tests were carried out which found that use of the inhibitor caused a small increase in wire-to-wire friction at low contact pressure and had not significant frictional effect at higher load. Further tests were carried out to confirm the inhibitor would not adversely affect the other components in the system, including cable wraps, sealants and probes. Initially the tests were carried out in the laboratory (see Figure 3), but exposure tests on site are on-going to confirm no long-term influence on properties. The laboratory tests confirmed that the inhibitor had no significant effect on the characteristic of the wrap and sealant materials and did not interfere with the operation of the RH probes.

Site Testing of Inhibitors

In order to confirm the effectiveness of the inhibitor delivery system it was considered advantageous to develop a simple indicator-based test that could be employed on site as part of the on-going inspection of the main suspension cables. Such a system was developed by the inhibitor manufacturer and made available for site trials. In the presence of the inhibitor, the colour of the indicator changed from blue to red and it was possible to confirm the presence of the inhibitor on the surface of the wires, even deep within the cable, by use of swabs containing the indicator solution, see Figure 4.

Figure 4: Swab test for inhibitor during cable inspection.

In addition to the site tests which confirmed the presence of the inhibitor across the full section of the cable, a failed corrosion probe that had been replaced was also retained for testing. Swab tests with the indicator confirmed the presence of inhibitor on the sensor section of the probe that had been exposed to exhaust air from the dehumification system, confirming that sufficient inhibitor was being introduced into the system so as to treat the full length of the suspension cable (see Figure 5).

During the design phase of the dry air injection system there were concerns raised as to the ability of the system to reach all parts of the cable. Site testing for the corrosion inhibitor was found to be present at all locations tested, not just the external surface of the cable but at all locations

Monitoring of Cable

It was recognised early in the assessment process that the future management of the bridge would be required to adhere to the principles contained in the UK Highways Agency’s Standard BD79/06. A monitoring regime and warning system was developed to allow the Highways Agency sufficient confidence as to the reliability of the suspension bridge cables.

The plan for the monitoring system was to assess the cable on a monthly basis using the following methods:-

- Visual observations - the operator, Severn River Crossing, were instructed to record any observations that may be relevant to the condition of the cable. This could include damage to evidence of entrapment of water under the cable sleeving and broken wrapping or main cable wire.
- Dry air injection system – at the air inlet and exhaust locations along the length of the cables, sensors have been located to provide information on the condition of the voids within the cable. These sensors included relative and absolute humidity, temperature, flow, pressure and corrosion.
- Traffic loading – traffic is the dominate live load on the bridge and it represents 20% of the maximum load carried by the cables. Weigh-in-motion sensors have been installed on all road access to the bridge since 2005 which enabled a Bridge Specific Assessment Live Loading to be undertaken in accordance with UK Highways Agency's Standard BD 50/92[6].
- Acoustic emission monitoring – a partial monitoring system for the main cables was installed on the bridge in 2006 will a full system operating from 2008. Any acoustic event detected are reviewed by the specialist system suppliers on the basis of characteristic wire break acoustic signatures to provide a 'confirmed wire break'; and

Figure 5: Positive inhibitor test on the sensor end of a corrosion probe.

Results from the acoustic emission monitoring are shown in Figure 6. It can be seen that:

- Emissions before installation of the dry air injection system represented 0.4% of the total number of wires in the cables;
- Emissions during the cable drying out period reduced to about 15 breaks per year representing 0.1% per year; and
- Emissions after drying out were less than 10% of the emissions before installation of the dry air injection system.

The large increase in wire breaks during 2010 can be attributed to the removal of the wrapping wire and wedging operations that took place during the 2nd intrusive inspection.

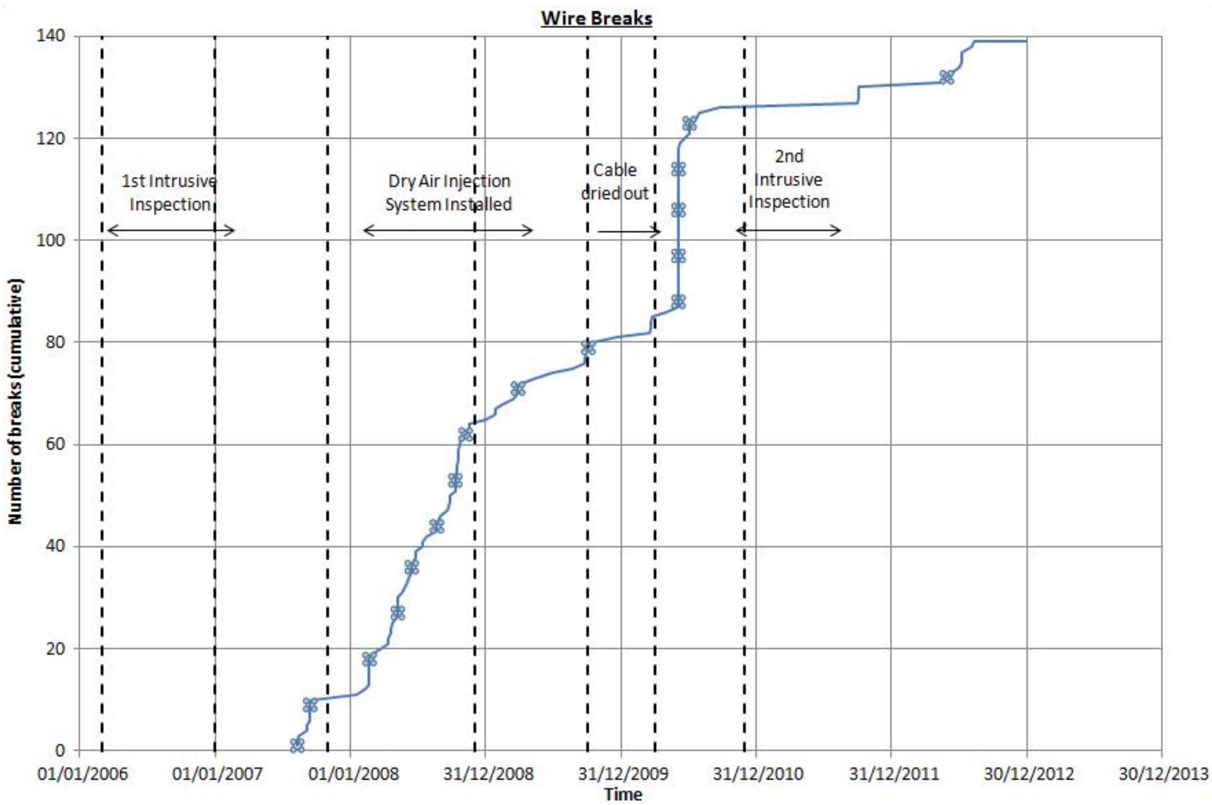

Figure 6: Results from the Acoustic Monitoring of Cables.

Conclusions

The installation of a dry air injection system and the introduction of vapour phase corrosion inhibitor appear to have stabilised the condition of the cable. This has been demonstrated with the reduction in the relative humidity within the cable sheaths and low levels of acoustic emissions since the drying process was established.

The site testing for the corrosion inhibitors during the 2nd intrusive inspection demonstrated the ability and effectiveness of the dry air injection system to reach all parts of the cable.

References

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PAUL LAMBERT is Technical Director at Mott MacDonald in Altrincham, UK. Paul has a PhD in corrosion and specialises in the investigation of structural durability and degradation and the development of novel remedial techniques for many types of structures. He is also Visiting Professor at the Centre for Infrastructure Management at Sheffield Hallam University. He has been a Member of NACE since 1993 and is a NACE-certified Corrosion Specialist.

JEFFERY FISHER is Technical Director at Mott MacDonald in Croydon, UK. Jeffery has a PhD in structural engineering and has over 30 years' experience in the field of bridge engineering including the design and construction of long span steel and concrete bridges with spans up to 1377m in regions of high winds and seismic activity. Structures have included Tsing Ma Bridge, Tsing Lung Bridge and the Stonecutters Bridge in Hong Kong, the Incheon Bridge in South Korea and the new Forth Replacement Crossing in Scotland.