Corrosion Control of the Severn Bridge Main Suspension Cables

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The Severn Bridge in the United Kingdom is a 988-m span suspension bridge built in 1966. An interior inspection of the main suspension cables in 2006-2007 revealed corrosion and reduced strength. Acoustic monitoring, dry air injection, and vapor corrosion inhibitors were installed. A subsequent inspection showed that these protective measures had stabilized the condition of the cables.

The Severn Bridge (Figure 1) is a 988-m span suspension bridge located in the United Kingdom that carries the M48 motorway across the River Severn estuary between Bristol and South Wales. It was built in 1966 and features many novel innovations such as inclined hangers and a pioneering use of streamlined box girder deck construction. In 2006, the U.K. Highways Agency commissioned a program of intrusive examinations of the main suspension cables. These investigations provided data used for strength assessment of the cables. This article describes the use of a degradation model to predict the performance of the cables, and demonstrates the effectiveness of a dry air injection system combined with vapor corrosion inhibitors in stabilizing the condition of the main suspension cables.

The first intrusive inspection of the main cables, carried out in 2006-2007, found the cables were corroded and had 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.

The purpose of the dry air injection system was to reduce the relative humidity (RH) within the cable to <40%, an accepted percentage to prevent corrosion of metals. To enhance the dry air injection system, a corrosion inhibitor was included.

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 RH of 40%.

As recommended by the National Cooperative Highway Research Program (NCHRP),[1] further intrusive inspection and a corresponding load assessment were undertaken in 2010, the results of which have been previously published.[2] The assessment showed that the strength of the cables was no worse than 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 U.K. Highways Agency's Standard BD79/13.[3] The data from the monitoring system were used to supplement results of an assessment of the cable to allow annual certification of the cable.

Deterioration Model

To assist in the management of the suspension cables, an analytical tool was developed to model the deterioration of the galvanized steel wires from corrosion. While the present condition can be quantified, an assessment of the mechanism and timescale is required for this condition to be established. Using this method, it is also possible to predict the long-term effects of various remedial measures. Details of the model development are described elsewhere.[2]

To assist in the development of the model, it was necessary to measure a number of physical parameters. In areas where corrosion had not initiated, the as-built condition such as wire diameter and thickness of galvanizing could be established. It was also possible to retrieve samples of wires for detailed inspection and physical testing to identify the factors that governed failure. In areas where corrosion had occurred, it was possible to measure section losses or depths of penetration that had resulted. Additionally, it was 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:

- The wires arrived on-site adequately protected from corrosion until the cables had been spun.
- Once in place, the cables were protected by three layers:
  - The zinc galvanizing on the individual wires
  - A layer of red lead oxide paste on the outside of the cable
  - A protective wrap consisting of wire, tape, and coating
- Initially, the cable was protected from significant corrosion by the cumulative action of the three protective systems.
- The first protective layer to break down was the outer coating, which allowed moisture and, more importantly, moist air to enter the bundle. As the cable cooled at night, the moisture in the air condensed to liquid.
- In time, through exposure to water and the atmosphere, the effectiveness of the red lead paste broke down, allowing the zinc galvanizing to start corroding.
- As patches of the zinc layer became fully consumed, the underlying steel started to corrode.
- While the rate of corrosion was initially fast, the generation of voluminous corrosion products eventually occluded the corrosion site, which slowed the rate of metal loss.
- Under stress, the corrosion of the wires became concentrated, eventually reducing the cross section of the wire sufficiently for it to fail by tensile overload.

FIGURE 1 The Severn Suspension Bridge was built in 1966.

Tool Development

Each of these stages needed to be modeled individually, based on both published data and site observations, then combined to produce the overall predictive tool. A series of laboratory investigations was 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 that reached a critical depth. The data on the critical defect size were best characterized by a Weibull distribution, which confirmed that failure occurred when the defect reached approximately one third of the thickness of the wire. Based on this observation, the most appropriate data for modeling section loss related to depths of penetration with respect to time. Published data were employed for the corrosion loss of zinc and unalloyed steel in a range of environments.[4] The data obtained from the site were found to correlate well with the section loss predicted by the model (Figure 2), and

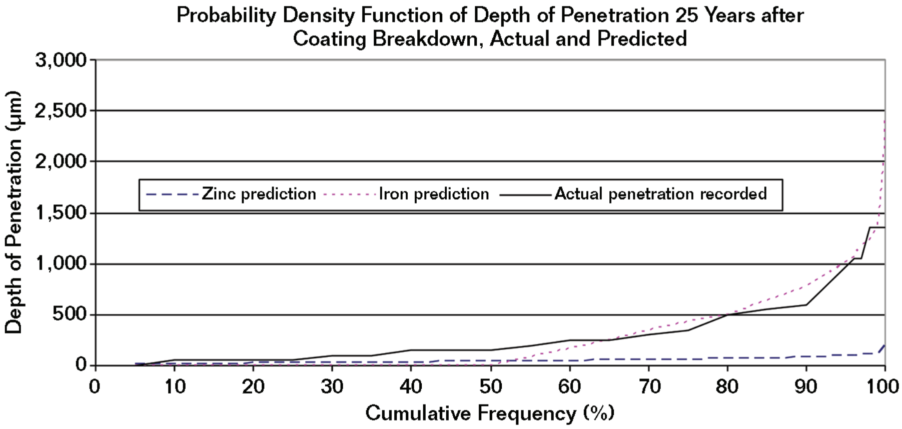

FIGURE 2 Comparison between actual and predicted depth of corrosion penetration.

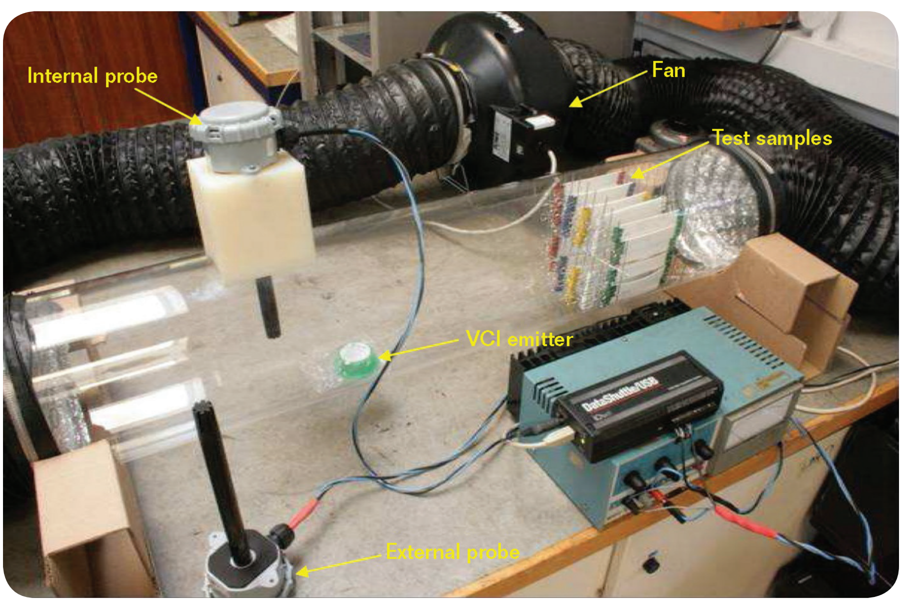

FIGURE 3 Laboratory tests confirm compatibility of the inhibitor with the dehumidification system components.

provided the necessary confidence to use the model to predict the future performance of the wires and the influence of dehumidification and corrosion inhibitors.

Use of Corrosion Inhibitors

To provide additional corrosion protection to the wires during the initial period of moisture reduction—when corrosion rates could increase as oxygen became more available—and to provide a back-up in the event that the dehumidification system went out of service (e.g., for maintenance), a vapor corrosion inhibitor (VCI) system was developed for introduction into the dry air stream.

VCIs have been in use for a number of years, initially for military and aerospace applications and now for automotive, domestic, and construction uses as well. While formulations are specific to the manufacturers, VCIs are typically based on nontoxic volatile organic compounds that form continuous, highly adherent mono-layers on the surface of metals and effectively control the processes that lead to corrosion.

In industry, VCIs are generally used with a carrier system, which may be a water or hydrocarbon solution, or a fine starch or talc powder. Because of concerns regarding the potential blocking of 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, 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.

Laboratory Testing of Inhibitors

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

Because the protective inhibitor layer is only one or two molecules thick, it has no influence on clearances and only a minimal effect on other physical properties. Tests confirmed this, with results showing that use of the inhibitor caused a small increase in wire-to-wire friction at low contact pressure and no significant frictional effect at higher load. Further tests were carried out to confirm the inhibitor would not adversely affect other components in the system, including cable wraps, sealants, and probes. Initially, the tests were carried out in the laboratory (Figure 3). The laboratory tests confirmed that the inhibitor had no significant effect on the characteristics of the wrap and sealant materials and did not interfere with the operation of the RH probes.

Site Testing of Inhibitors

Currently, exposure tests on site are ongoing to confirm no long-term influence on cable properties. To confirm the effectiveness of the inhibitor delivery system, a simple indicator-based test was developed that can be employed on site as part of the ongoing inspection of the main suspension cables. The system was developed by the inhibitor manufacturer and made available for site trials. In the presence of the inhibitor, the color of the indicator changes from blue to red and it is possible to confirm the presence of the inhibitor on the surface of the wires, even deep within the cable, by using swabs containing the indicator solution (Figure 4).

During the design phase of the dry air injection system, concerns were raised regarding the ability of the system to reach all parts of the cable. Site testing for the corrosion inhibitor found it was present at all locations tested, not just the external surface of the cable. In addition to the site tests, which confirmed the presence of the inhibitor across the full section of the cable, a failed corrosion probe was also retained for testing. Swab tests with the indicator confirmed the presence of inhibitor on the sensor section of the probe, which had been exposed to exhaust air from the dehumidification system. This confirmed that a sufficient amount of inhibitor was being introduced into the system for treating the full length of the suspension cable (Figure 5).

FIGURE 4 A swab test for the presence of inhibitor was done during cable inspection.

FIGURE 5 The sensor end of a corrosion probe tested positive for the inhibitor.

Cable Monitoring

It was recognized early in the assessment process that the future management of the bridge would be required to adhere to the principles contained in Standard BD79/13. A monitoring regime and warning system was developed to provide the U.K. Highways Agency with sufficient confidence in the reliability of the suspension bridge cables.

The monitoring system assesses the cables on a monthly basis using the following methods:

- Visual observations: the operator, Severn River Crossing, was instructed to record any observations that may be relevant to the condition of the cable. This could include damage, evidence of entrapment of water under the cable sleeving, and broken wrapping or main cable wire.

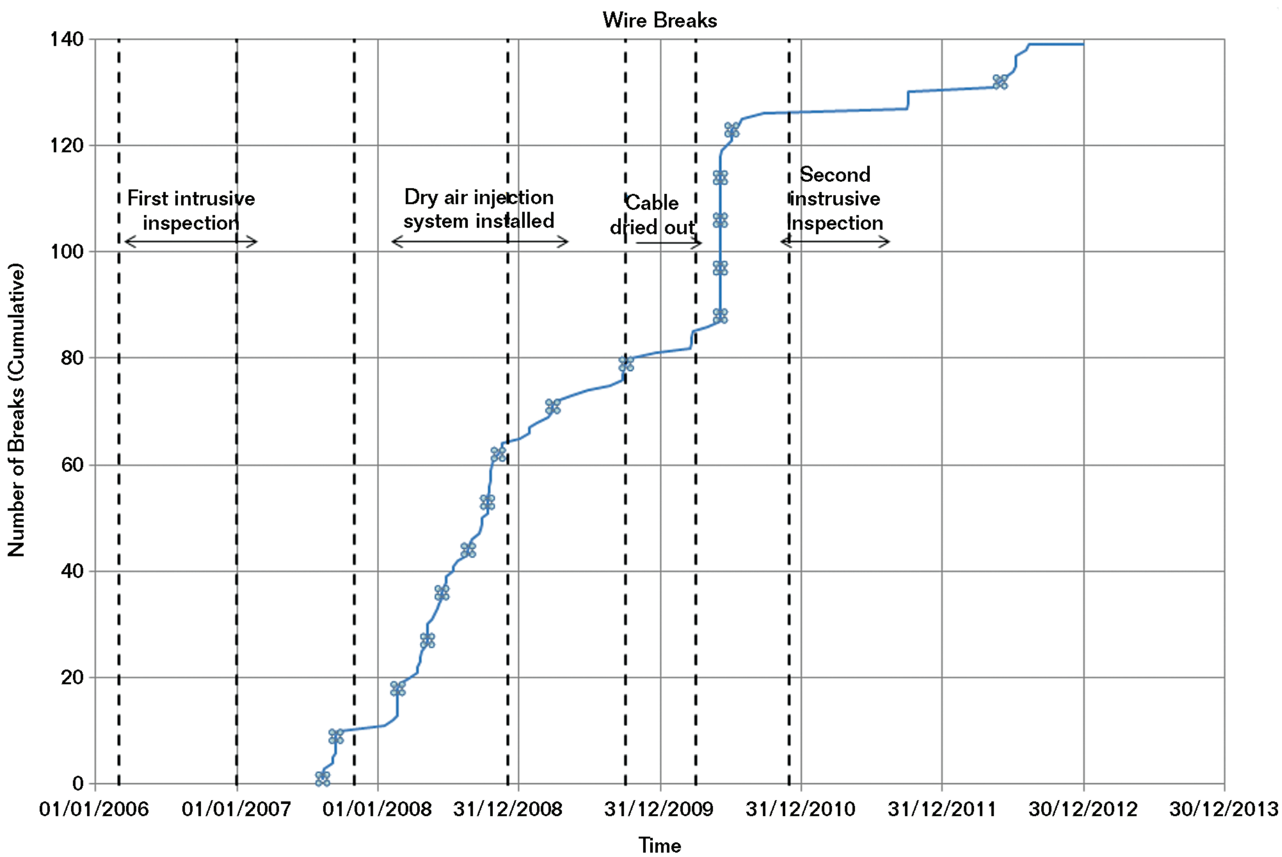

FIGURE 6 Results from acoustic monitoring of the cables.

- Dry air injection system: At the air inlet and exhaust locations along the length of the cables, sensors are located to provide information on the condition of the voids within the cable. These sensors measure relative and absolute humidity, temperature, flow, pressure, and corrosion.
- Traffic loading: Traffic is the dominate live load on the bridge and 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 enables bridge-specific assessment live loading to be undertaken in accordance with the U.K. Highways Agency's Standard BD 50/92.[5]
- Acoustic emission monitoring: A partial monitoring system for the main cables was installed on the bridge in 2006, with a full system operating since 2008. Any acoustic events detected are reviewed by the specialist system suppliers, which determine a confirmed wire break based on the characteristics of wire break acoustic signatures.

Figure 6 presents the results from the acoustic emission monitoring. They show that:

- Acoustic emissions before installation of the dry air injection system represented 0.4% of the total number of wires in the cables.
- Acoustic emissions during the cable drying out period were reduced, indicating ~15 breaks per year or 0.1% per year.
- The level of acoustic emissions after drying out was <10% of the level of acoustic 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 operation that took place during the second intrusive inspection.

Conclusions

The installation of a dry air injection system and the introduction of a VCI appear to have stabilized the condition of the cable. This has been demonstrated with the reduction in the RH 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 second 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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