"HUMBER BRIDGE – SUPPRESSING MAIN CABLE CORROSION BY MEANS OF DEHUMIDIFICATION"

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SUMMARY: The Humber Bridge officially opened in 1981 and carries 4 lanes of traffic across the Humber Estuary between Barton and Hessle to the west of Kingston-upon-Hull in East Yorkshire, England. When opened, it was the longest span suspension bridge in the world with a main span of 1410m but it currently ranks as the fifth longest span in the world. Humber Bridge Board (HBB) commissioned an internal inspection of the main cables following the discovery of extensive corrosion and broken wires in the main cables of two older suspension bridges in the UK. The main cable inspections revealed widespread, if generally light corrosion with localised pitting and a very small number of broken wires. Dehumidification of suspension bridge main cables is becoming standard practice not only in the UK but worldwide. This paper examines the installation of the Humber Bridge system, discusses the mechanics of atmospheric steel corrosion and explains how the cable dehumidification system will suppress future corrosion.

Keywords: Suspension bridges, Corrosion, Dehumidification

1. BRIDGE HISTORY

Prior to construction of the bridge, crossing of the Estuary was only possible by local ferries. Plans for an estuary crossing can be traced as far back to 1872 when proposals were made for a tunnel. Approval for the construction of the bridge was granted in 1959 with passing of the Humber Bridge Act and the creation of the Humber Bridge Board (HBB). HBB has since been responsible for the construction, operation, administration and maintenance of the bridge. The government reached agreement on the building of the bridge and the loan in 1969 and 1971 respectively with construction of the bridge starting in 1973.

The reason a suspension bridge was preferred to other forms was twofold. The bed of the estuary is constantly shifting therefore the clear span does not obstruct the changing navigable channel. In addition, the geology of the area would have required piers with exceptionally large and costly foundations. Along the banks of the estuary upstream there are a number of industrial areas with docking facilities and as such there was a requirement for a navigable corridor.

The Humber Bridge has an asymmetrical span arrangement and with a main span of 1410m it ranked as the longest single span bridge from its opening in 1981 until 1998. The north side span (Hessle side) has a length of 280m and the south side span (Barton side) a length of 530m. This brings the total length between anchorages to 2220m. **Error! Reference source not found.**, shows the elevation of the bridge and Figure 2 is a photograph taken during the installation of the cable dehumidification system, with one of the cable access gantries on the east main span cable.
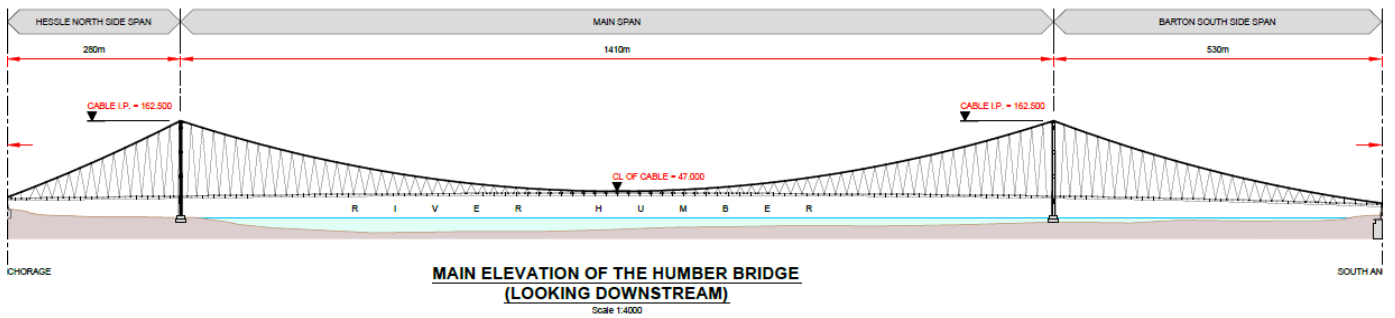

Figure 1: Elevation of the Humber Bridge

Figure 2: Humber Bridge elevation

The north tower is founded on the high water line whereas the south tower is founded within the estuary at approximately 500m from the shore. The ground conditions at the north tower are significantly better than at the south tower, resulting in foundation depths of just 8m for the former and 36m for the latter.

The deck of the bridge is an aerodynamically shaped continuously-welded trapezoidal closed box. The box is 4.5m deep and 22m wide and it carries a dual two lane carriageway, in addition to 3m wide footways supported by cantilever beams on both sides of the deck box. Figure 3, shows a typical cross section of the deck. The deck is supported by inclined hanger cables, spaced at approximately 18m.
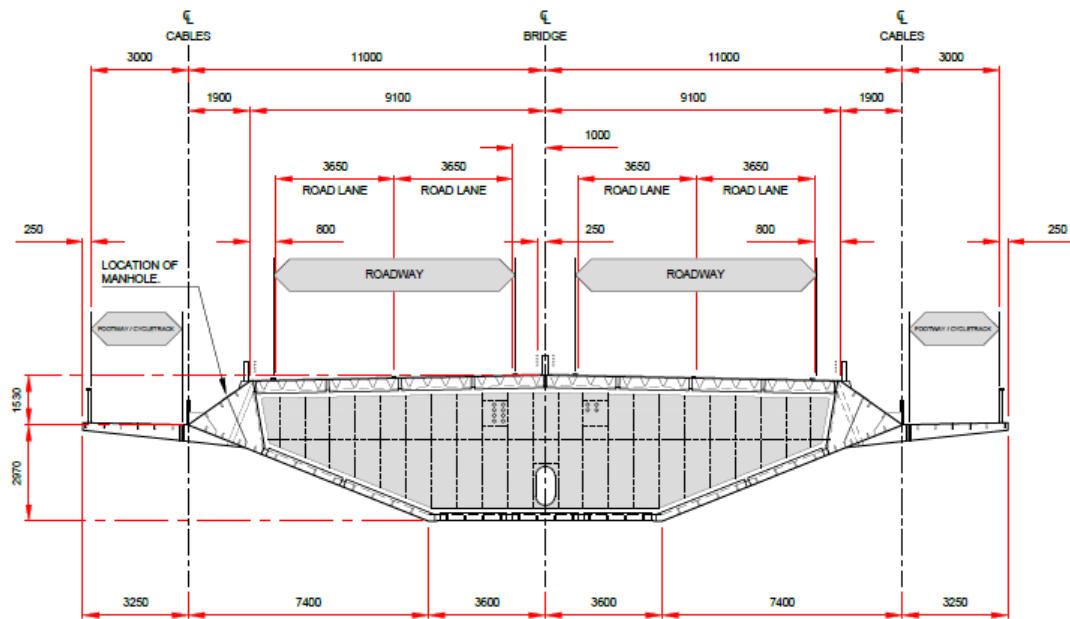
Figure 3: Typical deck box cross section

The main cables consist of 14948 high strength galvanised wires resulting in a cable diameter of approximately 680mm. The north side span is considerably shorter and steeper than the south side span and each north side span cable has an additional 800 wires to withstand the higher tension. Figure 4, illustrates a view of the main cable at the tower top where the additional 800 wires for the north (Hessle) side span can be seen splaying out.
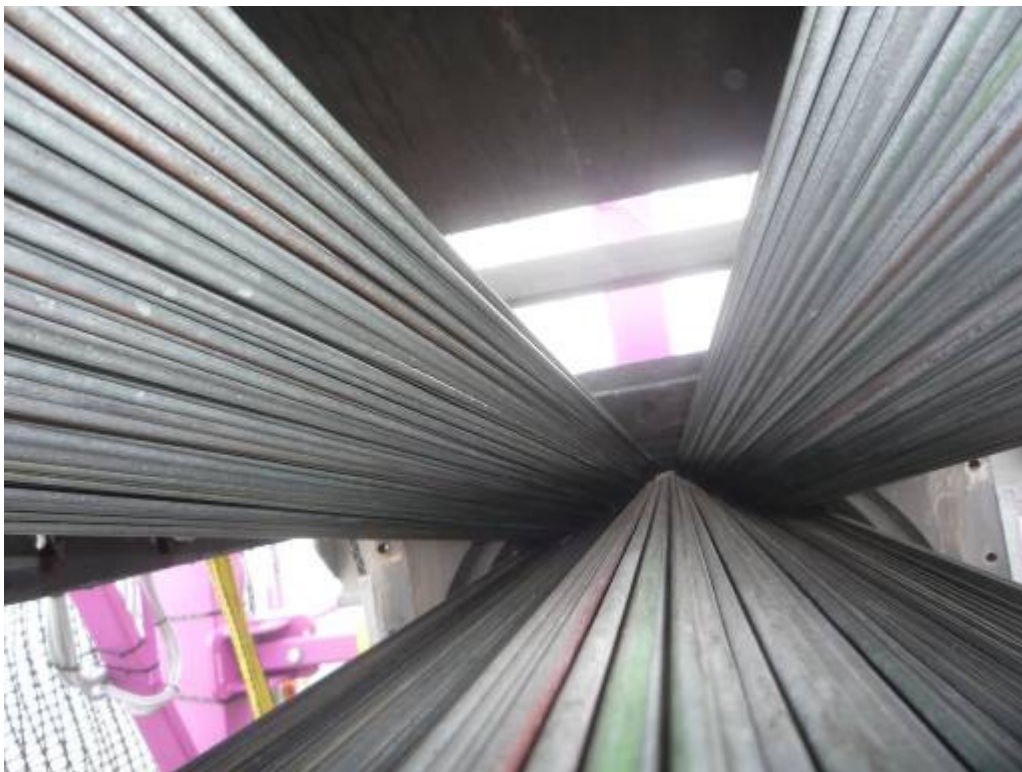

Figure 4: North (Hessle) side span main cable view

2. CABLE CORROSION

Corrosion of steel is a common problem worldwide with billions of dollars spent every year on the repair, refurbishment and rehabilitation of structures. Corrosion of steel in concrete has been investigated in depth and a number of different techniques now exist which aim to arrest and prevent corrosion damage. However, atmospheric corrosion of steel and in particular parallel wire strands for suspension bridges is still a developing field.

Atmospheric corrosion is governed by the similar electrochemical characteristics as for corrosion of metals fully immersed in an electrolyte. However, calculation of electrode potentials and polarisation characteristics are not as simple. Iron is not a noble chemical element and as such it is its natural characteristic to have the tendency to participate in chemical reactions in order to reach energy equilibrium. Iron exposed to the atmosphere will oxidise based on the reaction described by equation (1). This is the so-called anodic reaction. At the same time another reaction will occur, which is termed cathodic reaction, and it is governed by equation (2). This second reaction retains the principle of electro-neutrality.

$$2Fe = 2Fe^{2+} + 4e^- \qquad (1)$$

$$O_2 + 2H_2O + 4e^- = 4OH^- \qquad (2)$$
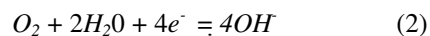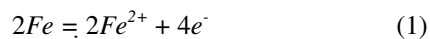
The hydrolysis of dissolving iron ions is further described by equation (3). In the presence of oxygen ferrous hydroxide will form "haematite" ($Fe_2O_3.3H_2O$) which is commonly known as rust.

$$Fe^{2+} + 2H_2O = Fe(OH)_2 + 2H^+ \qquad (3)$$
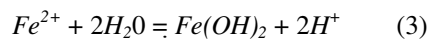
The exposure conditions will largely dictate the corrosion intensity. In industrial areas, atmospheric pollution results in high levels of sulphur dioxide (SO_2) and nitrous oxides (NO_x). These pollutants can react with other molecules present in the atmospheres to form acids creating a highly corrosive environment. In marine environments salt particles are present in the air and they deposit on exposed metal surfaces based on the prevailing wind conditions. In the particular case of the Humber Bridge, both environments are present. Figure 5 illustrates the corrosion condition on a section of the Humber Bridge main cable. The rust pitting areas are evident on the outer wires.

Figure 5: Corrosion condition of a section of the Humber Bridge main cable

Water and condensed moisture occur as a result of changing environmental conditions, creating a film of water on the metal surface. This film can be saturated with salt and other chemical contaminants, which create a very aggressive electrolyte that promotes corrosion activity. Relative humidity also contributes to the deposition of this water film. An increase in the thickness of the water film will promote corrosion activity. However, this increase in thickness is accompanied by reduction in oxygen which is also essential to the corrosion process.

The presence of various sea minerals and salts typically require high relative humidity to create the same effect. However, some chemical elements such as magnesium chloride ($MgCl_2$) present in the atmosphere have a higher moisture binding capacity creating a wet film even at 34% relative humidity.

3. AS-BUILT CORROSION PROTECTION

Galvanising of steel is a commonly used technique to provide successful corrosion management (BS EN ISO 1461, Galvanizers Association). It involves the immersion of steel into a bath of molten zinc after it has gone through pickling and fluxing. The zinc will react with the steel and form zinc alloy and zinc layers. When the steel is removed from the bath the zinc will solidify forming a strong bond with the steel. This bond is superior to other forms of coatings due to its metallurgical nature. The process is quicker as opposed to traditional paintwork systems, provides a more reliable coverage without crevices and overall it is a more cost effective system. Figure 6, illustrates a typical cross-section of the hot-dip galvanised application.
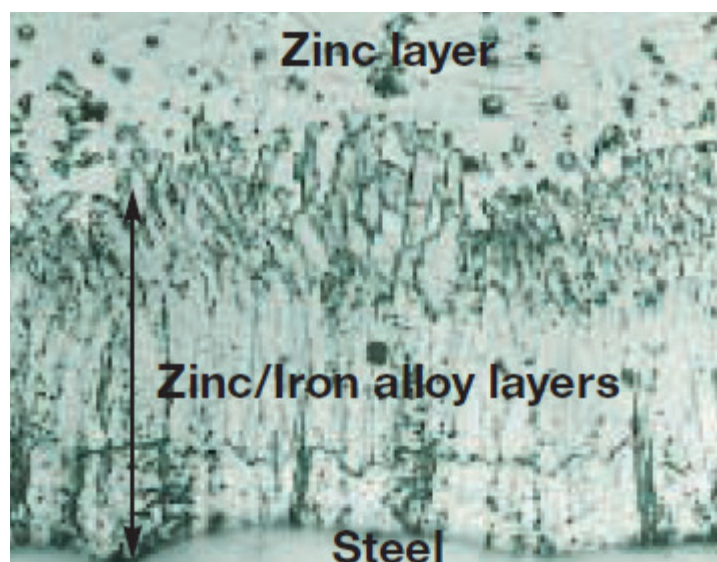

Figure 6: Cross-section through a typical hot-dip galvanised coating (Corus Construction Centre 2002)

In addition, there is sacrificial (galvanic) cathodic protection offered by the zinc to the steel reinforcement. In areas where the protective film has broken down and oxidisation can occur, the remaining zinc product will corrode sacrificially and therefore protect the steel. This feature was first discovered by Sir Humphry Davy (1824). In the last 20 years this sacrificial corrosion mechanism has been extensively developed in the production of sacrificial (galvanic) anodes which are installed on steel structures or within the concrete. A lot of research has also been dedicated in order to understand their protection mechanisms and also their limitations (Christodoulou et al. 2009, Broomfield 2000)

The wires that make up the main cables on the Humber Bridge are hot-dip galvanized. During construction, a layer of red lead paste was applied to the external main cable wires to provide corrosion protection, in addition to a layer of circumferentially applied galvanised steel wrapping wire. A paint system was applied to the surface of the wrapping wire and maintenance painting has subsequently been carried out at intervals of approximately ten years to form a weather resistant coating. This corrosion protection system has been applied to the majority of suspension bridge cables worldwide. Figure 7 and Figure 8 illustrate this conventional protective system. It was envisaged until very recently that this approach would provide adequate corrosion protection for the design life of the bridge.
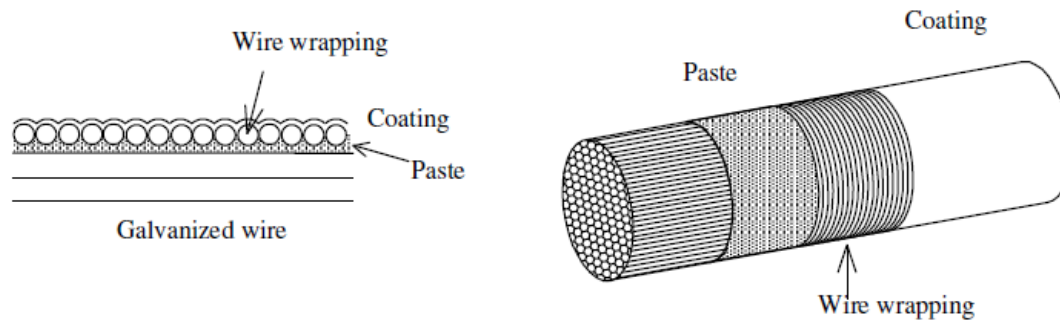
Figure 7: Cable corrosion protective system

Figure 8: Unwrapped main cable

However, intrusive inspections of older U.S. suspension bridge cables in the 1990s revealed significant deterioration had occurred in the form of corrosion and broken wires. Since then significant research has been undertaken into investigating the corrosion initiation mechanism and most importantly assessing the residual strength of the corroded cables. This resulted into a report by the National Cooperative Highway Research Program (2004).

Recent internal inspections of UK bridge cables have revealed that corrosion of the wires has occurred despite regular maintenance painting of the external surface of the cables. The external paint coating is not completely impermeable and over a number of years, red lead paste has been shown to dry out. This has allowed water, salt and other chemicals to penetrate the protective layers and accumulate within the cables. In areas where the protective system remained in good condition, the above elements have become trapped within the cables and as such have created a corrosive environment.

The main cable inspection on the Humber Bridge concluded that external surface corrosion was evident in various areas of the main cable. This was particularly pronounced at the mid main span locations where the slope of the cables diminishes and the cables are within the 'splash zone'. The internal main cable inspection revealed widespread corrosion although the number of broken wires was very low.

Atmospheric corrosion of steel can reach high activity levels before it becomes visually evident as opposed to corrosion of steel in concrete.

Figure 9: Typical outer skin corrosion damage

illustrates such an example where an area of actively corroding wrapping wire was uncovered. The bridge inspectors removed the protective paint coating locally as it appeared to be soft and bulging. It can be observed that corrosion activity has been quite intense as a result of contaminated water and moisture accumulating locally.

Figure 9: Typical outer skin corrosion damage

4. DEHUMIDIFICATION

Based on the condition of the main cables on many suspension bridges worldwide it has become apparent in recent years that conventional cable corrosion protection systems have performed inadequately. As such, a new system of corrosion management is necessary. At the time initial evidence of main cable corrosion was being unveiled, Akashi Kaikyo Bridge in Japan was in the early stages of construction. As this bridge would hold the world record for the longest main span, an improved system of cable corrosion protection was considered to be essential and hence the world's first main cable dehumidification system was developed for the bridge for installation during construction. The Akashi Kaikyo Bridge cable dehumidification system became operational in 1998 and it is understood that it has been performing adequately. Since then a small number of suspension bridges have been retrofitted with this system and the majority of new bridges have been constructed with dehumidification installed as standard practice.

As discussed previously, a metal, an electrolyte and oxygen are required for corrosion to occur. By eliminating one of these elements corrosion will be prevented. The electrolyte is the only element which can practically be removed in order to improve atmospheric corrosion conditions. The dehumidification aims to provide an air tight sealing system around the main cable together with a continuous flow of dry air. Improving the air tightness of the main cables also prevents water ingress. The wrapping material used at Humber should prevent large scale water ingress for a period estimated at approximately 25 to 30 years. Furthermore, the flow of dry air will result in the elimination of moisture within the main cables and consequently the arrest and suppression of further corrosion damage.

For the Humber Bridge main cable dehumidification system a proprietary elastomeric wrapping material was used to provide an air tight covering. The elastomeric material was laid circumferentially on the cable with specified overlaps. Figure 10, illustrates the elastomeric wrap laying procedure.
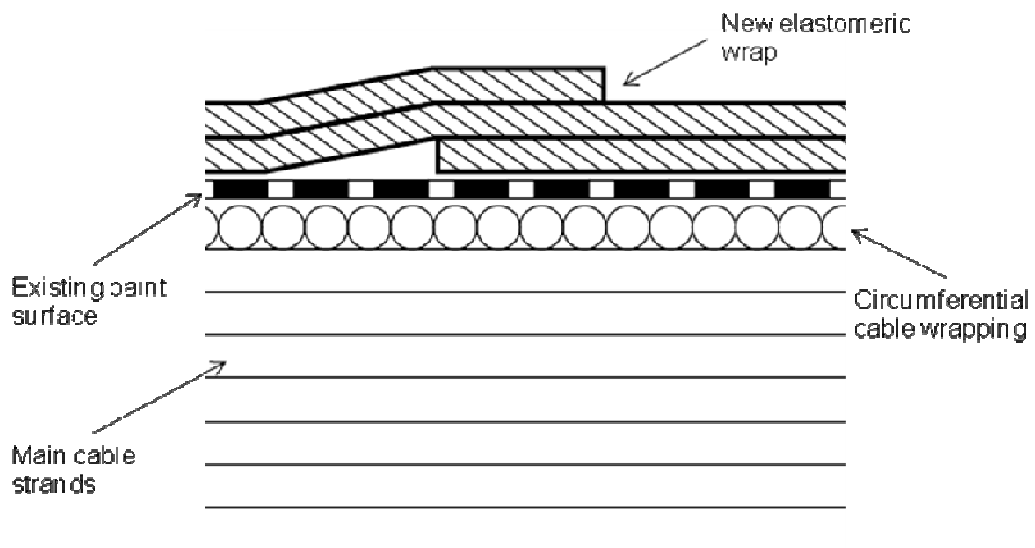
Figure 10: Typical elastomeric wrapping cross section

Following application, the elastomeric wrap material was then heated by means of pneumatic heating blankets. The heating process causes the wrap to melt and creates a strong bond with the other layers, particularly at the overlap positions. Figure 11, shows the heating process with the pneumatic heating blankets and a close up of the finished elastomeric wrapping.
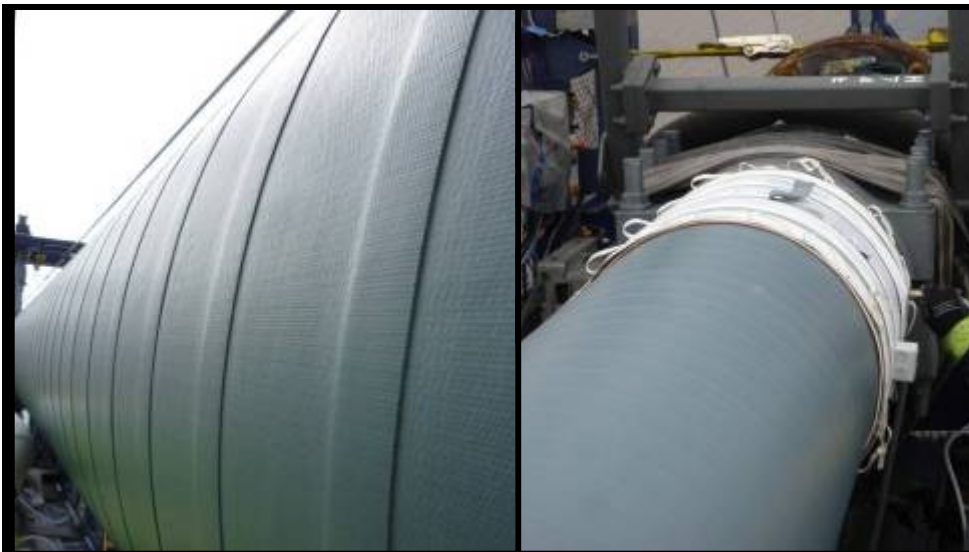

Figure 11: Elastomeric wrapping and heating process

At pre-determined locations, injection and exhaust sleeves were installed (Figure 12). At these locations the circumferential wire wrapping and the red lead paste were removed and the cable was wedged open. Stainless steel manifolds or "sleeves" were then installed in order to inject air into the cables and exhaust air from the cables. The wedging of the cable was necessary in order to help the dry air penetrate into the voids at injection points and the exhaust air escape, thereby reducing humidity levels. Figure 13 shows an injection sleeve after installation, together with the associated housing for the continuous monitoring equipment.
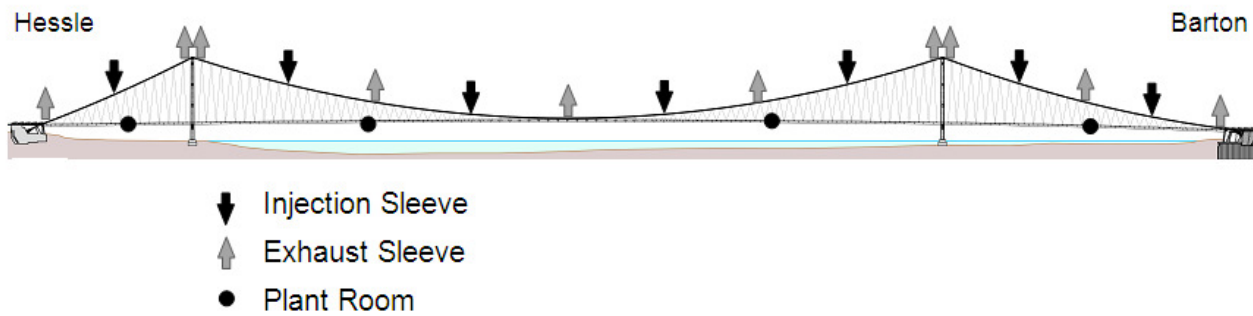
Figure 12: Dehumidification system layout

Figure 13: Finished injection sleeve

The air for the dehumidification system is delivered via air pipes attached to the hangers from a number of plant rooms which are located within the steel deck box of the bridge (see Figure 12). The plant rooms draw in air from below the bridge deck box which is then dried by a desiccant wheel dehumidifier and exhausted into the plant room, which also acts as a plenum chamber. The dry air passes through a HEPA filter and is then delivered to the injection sleeves. The relative humidity of the injected air can be closely controlled. Initially the relative humidity of the dry air has been set at 10% within the plant rooms to accelerate the drying process but as the cables dry out this will be increased to reduce long term running costs whilst maintaining sufficiently low RH figures in the cables.

5. RESULTS

The dehumidification system on the Humber Bridge became fully operational in December 2010. Since then dry air with only 10% RH is being delivered to the injection points. Figure 14 illustrates the data from the continuous monitoring system. It can be observed that after only 3 months of operation the RH within the cable has reduced significantly indicating the successful operation of the dehumidification system. It is anticipated that the long-term operation of the system will arrest the current corrosion activity.**Error! Reference source not found.**
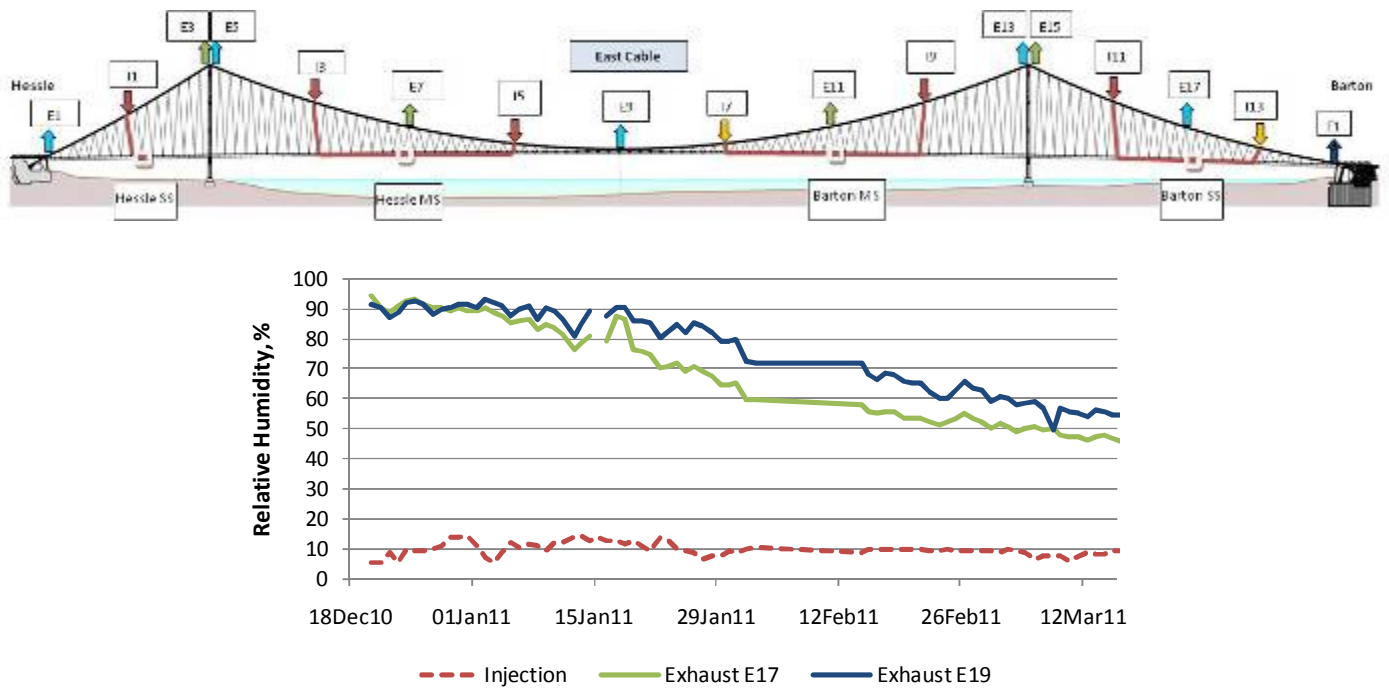
Figure 14: Initial monitoring data for relative humidity

Three different dehumidification systems have been operational on the Humber Bridge for several years. The first was installed within the deck box in order to maintain constant and low humidity levels and as such preserve and extend the service life of the coatings protecting the steelwork. Until today, no significant corrosion damage has been identified within the deck box which would have suggested that the dehumidification system has provided adequate corrosion protection. The second system was installed in the anchorage chambers and until today the splayed cable wires and the associated anchorage points are maintained in a very good condition.

The third system was installed at a later date to protect the main cables locally at the saddles located on each tower top to support the main cables. These areas are difficult to inspect and maintain. For this reason a dehumidification system was installed which aimed to supply dry air locally in these areas in order to suppress corrosion. During the installation of the main cable dehumidification system, the sleeves housing the main cables around the tower tops were opened for the first time since construction of the bridge. This allowed engineers to assess locally the condition of the cables for the first time and in addition to evaluate the performance of the dehumidification system for the tower tops.

The condition of the individual wires was found to be excellent with no signs of corrosion. This can also be observed from Figure 15. However, a small area of staining was observed on top of the cable. Closer investigation of this area revealed that local pitting of the wires had not occurred and there was no observed loss of section. The source of this staining was water slowly leaking through the protective sleeve. This was also verified by evident cracking of the protective sleeve directly above the position where the staining was uncovered.
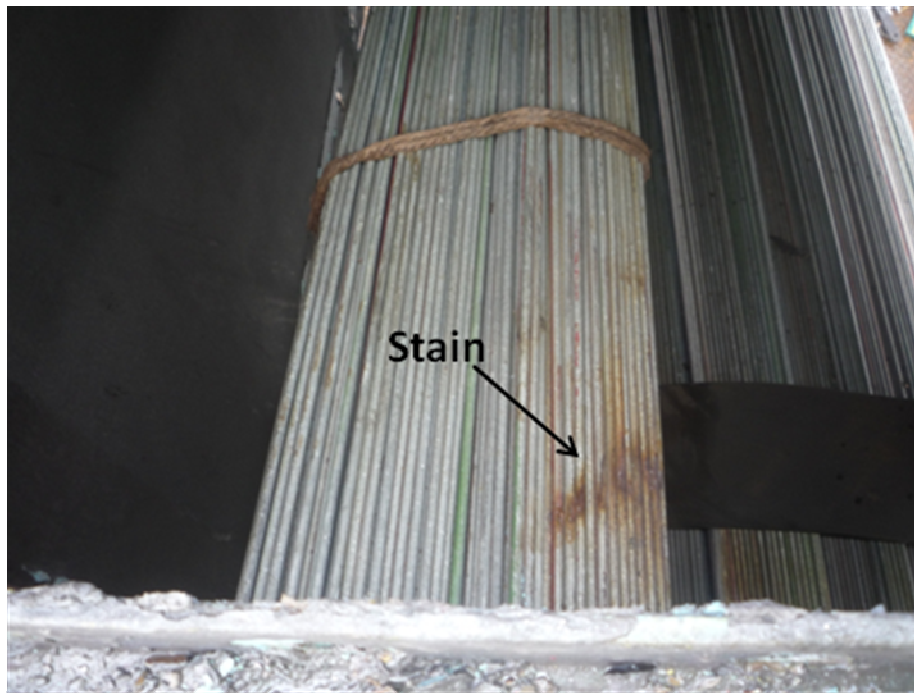
Figure 15: Condition of the main cable at the tower top

This finding was significant as it was the first time the condition of the cables had been verified since the dehumidification system was installed. It is presumed that the leakage of water through the sleeve occurred at some point after the installation of the dehumidification system. If this was not the case, then corrosion pitting should have been observed around the area. The dehumidification system on the tower tops was deemed to be successful in preventing corrosion and it had provided a protective environment despite water leakage. However, it is apparent that the water leakage was not heavy and this allowed rapid drying of the cable by the dehumidification system.

6. CONCLUSIONS

It can be concluded that:

1) Atmospheric corrosion of structural steelwork is a significant issue. Although the use of galvanised steel will delay the onset of corrosion it will not be a sufficient long-term measure to prevent corrosion.
2) The absence of external signs of corrosion when inspecting the main cables of suspension bridges should not be associated with absence of internal corrosion within the main cables.
3) Dehumidification of the main cables is now a technique proven to provide corrosion suppression by eliminating the electrolyte from the corrosion cells. The success of the system is largely dependent on the condition of the main cables when the system is installed, effective system design and the chosen levels of relative humidity and blowing length.

7. REFERENCES

- BS EN ISO 1461:2009, Hot-dip galvanized coatings on fabricated iron and steel articles – specifications and test methods, British Standards Institution, London.
- Corus Construction Centre 2002, Corrosion protection of steel bridges.
- Galvanizers Association, The Engineers & Architects' Guide: Hot Dip Galvanizing.
- Davy H 1824, On the corrosion of copper sheeting by seawater, and on methods of preventing this effect, and on their application to ships of war and other ships, *Proceedings of the Royal Society*, 114 (1824), pp 151-246.
- Christodoulou C, Glass G and Webb J 2009, Corrosion management of concrete structures, *The Structural Engineer*, Volume 87, 23/24.
- National Cooperative Highway Research Program 2004, Report 534, Guidelines for Inspection and Strength Evaluation of Suspension Bridge Parallel-Wire Cables.
- Broomfield J.P. 2000, The principles and practice of galvanic cathodic protection for reinforced concrete structures, Monograph No:6, Corrosion Prevention Association.

8. AUTHOR DETAILS

Christian Christodoulou is a Senior Engineer with AECOM Europe and a Research Engineer with Loughborough University, UK. He has wide experience in corrosion management, structural assessment, strengthening and refurbishment of bridge structures. He is a structural engineer by profession and specialises in corrosion of reinforced concrete structures.

During the Humber Bridge Dehumidification project, he was the Assistant Resident Engineer responsible for site, quality and contract supervision and providing technical expertise.

Mark J Bulmer BEng CEng MICE is a Technical Director for AECOM based in Leeds. He has worked for AECOM for the last 10 years and his areas of expertise include the construction, refurbishment and maintenance of major bridges.

Whilst working for a major bridge contractor in the 1990's he designed temporary works and worked on site for the construction of three major suspension bridges, namely Tsing Ma Bridge in Hong Kong, Storebaelt East Bridge in Denmark and Jiangyin Bridge in China. A common theme on these bridges was his experience in the construction of the main cables, and a firsthand knowledge of how quality can be affected through the day to day practical issues that arise on site, and their implications on future maintenance demands.

He subsequently moved to Canada, where he supervised temporary works design and the replacement of the entire deck and stiffening truss of the Lion's Gate suspension bridge whilst keeping it open to traffic for the majority of the time.

Since joining AECOM he has managed projects for a number of investigations into the condition of the cables on the UK's major suspension bridges, including the installation of acoustic monitoring systems on Forth Road and Severn bridges, and has currently managed projects for the design and installation of dehumidification systems on the Forth Road and Humber Bridge cables.

Charles Cocksedge is a Technical Director and Head of Steel Structures for AECOM Ltd. He has over 30 years experience in the feasibility, inspection, assessment, design and construction of large structures, including many long span suspension, cable stay, arch and steel box girder bridges.

His experience includes involvement in over 25 suspension bridges, including ten with spans in excess of 1000m. His area of greatest knowledge and expertise is in the inspection, assessment, strengthening and rehabilitation of major suspension bridges. He has led the investigations into the condition of the cables of Forth Road and Severn Bridges, and following the discovery of significant deterioration he directed the installation of acoustic monitoring systems and their rehabilitation through the use of cable dehumidification systems.

He was the AECOM Project Director for the Humber Bridge main cable dehumidification and acoustic monitoring project and acted as The Engineer in the implementation projects.

David Wilkinson is a Principal Bridge Engineer with AECOM Europe. He is a Chartered Engineer, Member of the Institution of Civil Engineers.

He has extensive design and site experience in bridgeworks and was Resident Engineer for the Humber Bridge Cable Dehumidification contract. He previously performed the same role on the equivalent Forth Road Bridge contract.

John Cooper is Design & Major Projects Manager for Humber Bridge Board and acted as client representative during the design and installation of the Humber Bridge main cable dehumidification system.

John has a wide range of experience and knowledge of highway structures. He has been involved for 40 years in motorway design and construction and, more recently, in the maintenance and refurbishment of Highways Agency structures and, latterly, the Humber Bridge.

Peter Hill is General Manager & Bridgemaster for the Humber Bridge Board and acted as client representative during the design and installation of the Humber Bridge main cable dehumidification system.

Peter attained chartered status with the Institution of Civil Engineers in 1992 and admitted as a Fellow of the Institution in 2008.

His early career was working in a private consultancy in Doncaster, primarily engaged in heavy engineering and industrial facility contracts, before specialising in bridge engineering with local authority departments. He returned to the private sector in 2003, in WSP, with responsibility for two bridge engineering project offices operating under a Highways Agency commission in Yorkshire.

Peter joined the Humber Bridge Board in 2003 and attained the post of General Manager & Bridgemaster the following year.

Prof Simon Austin BSc PhD CEng MICE is Professor of Structural Engineering in the Department of Civil and Building Engineering at Loughborough University. Prior to this he worked for Scott Wilson Kirkpatrick & Partners and Tarmac Construction. He has undertaken industry-focused research for over 30 years into the design process, integrated working, value management, structural materials and their design.

Dr Chris Goodier PhD MICT MCIOB FHEA is a Lecturer in the Structures and Materials Group in the School of Civil and Building Engineering at Loughborough University, having worked previously at the Building Research Establishment (BRE) and Laing Civil Engineering. His areas of expertise include concrete technology and repair, offsite construction, community energy and construction futures.