Severn Bridge – Recent Assessment of Main Suspension Cables

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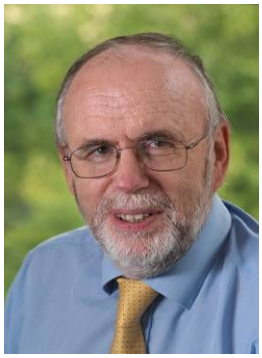

Summary

The Severn Bridge was built in 1966 and was a pioneer of streamlined box girder deck construction. An investigation of the capacity of the suspension cables was commissioned in response to corrosion concerns brought about by inspections of similar suspension bridges. The first intrusive inspection found corrosion of cables resulting in reduced strength. In response, acoustic monitoring and an enhanced dry air injection system were installed. A corrosion-based deterioration model was also developed. An initial assessment of the cable based was then carried out. A second intrusive inspection was then carried out to allow a more realistic assessment of the conditions of the cables to be made and has also been used to calibrate and update the deterioration model. This has shown that the loss of strength of the cables is no worse that the calculated capacity undertaken following the initial examination and the current system of protection has stabilised the condition of the cable.

Keywords: *Severn Bridge, suspension cables, assessment, corrosion modelling.*

1. Introduction

The Severn Bridge is a 988m span suspension bridge located in the United Kingdom carrying the M48 to South Wales. Built in 1966 it featured innovations such as inclined hangers and was one of the early pioneers of streamlined box girder deck construction.

In 2006 the Highways Agency commissioned an investigation of the capacity of the suspension cables of the Severn Bridge, in response to corrosion concerns brought about by inspections of other, similar, suspension bridges both in the UK and abroad. 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 an acoustic monitoring system and dry air injection system were installed on both cables. Over the next four years Mott MacDonald, as the Government Representative, undertook monthly monitoring of the cable and completed an annual assessment of the cable based on this monitoring and the results of a corrosion model.

At the time of the first inspection it was appreciated that this inspection would not be able to provide an accurate assessment for further deterioration of the cable. A realistic assessment of the deterioration of the cable could only be undertaken following a second inspection of the cable. In addition the inspection would achieve the recommendations of the NCHRP Report 534 guidelines [1].

The objectives of the second intrusive inspection were:

a) Visual confirmation of the ongoing condition of the cable;

b) A new assessment of the cable capacity;
c) Provide further data for the calibration of the corrosion model; and
d) Review the impact of the dry air injection system.

The purpose of this paper is to present the results of the assessment of the second intrusive inspection and the calibration of the previously derived deterioration model.

2. Second Intrusive Inspection

2.1 Location of Inspection Panels

At the commencement of the second intrusive inspection work the locations of panels to be inspected were agreed between the inspection engineer, Aecom, and the Government Representative, Mott MacDonald. The agreed panel locations were based on the following criteria:-

- panels should be within one of the defined cable zones;
- some inspected panels should be in previously inspected panels;
- defects reported from a visual inspection of cables; and
- review of the acoustic monitoring over the last 3 – 4 years

The suspension cables of the Severn Bridge were intrusively inspected, following the recommendations of the NCHRP Report 534 [1] guidelines, to investigate their condition and provide samples for material testing. Inspections were undertaken at 9 locations on the suspension cables. The locations inspected in 2006 and 2010 are shown on Figure 1.

2.2 Strength Evaluation

2.2.1 Strength Determination for Limit State Assessment

The two primary sources of data to be used in the strength evaluation consisted of the strength class (based on corrosion) and material properties of wires in each class. Due to the limited sampling this necessitated the use of statistical analysis in order to provide design values of a suitable confidence level that could be used in the strength evaluation of the whole length of the cables.

Whilst the NCHRP Report 534 guidelines are based on the inspection and strength evaluations of suspension bridge cables in the United States, which although older have much similarity to those of the Severn Bridge, the strength evaluation described in the guidelines is not directly applicable to UK limit state based assessments. The key issue is that the NCHRP Report 534 guidelines do not provide information on the confidence level associated with the strength evaluation nor is it related to specific loading conditions.

EN1990 and BS5400 (Part 1) both utilise confidence levels of 95% for sectional resistance and hence the establishment of a strength value for the suspension cables having this level of confidence enables the use of the partial factors adopted in the various UK codes of practice and Eurocodes, in accordance with Highway Agency principles and standards.

2.2.2 Statistical Analyses of Inspection and Test Data

The main factor to be considered in establishing the required level of confidence for the strength assessment is the variation in the proportion of the corrosion stages that could occur outside of the inspected lengths of the cable. The methodology adopted for the analysis of the inspection and test data is summarised as follows:-

a) The suspension cables are considered as a series of panels between adjacent cable bands. No distinction is made between the upstream and downstream suspension cables.
b) The suspension cable is divided into four discrete zones, based on characteristics of location and presumed internal environmental conditions. The zones are described in Table 1.
c) A subjective judgement is made to establish the extent of the cable zones owing to the simplistic zoning descriptions adopted. This is considered to be an appropriate means of

allocating inspection data sets for subsequent statistical analysis Within each cable zone the numbers of actual cable inspections are determined; the basis of this determination was that within each panel that was inspected, data was obtained at up to 6 locations along the panel. The actual number of inspections within each panel is obtained from the factual inspection data.

d) It is assumed that the inspection data obtained within each zone is representative of the cable zone as a whole. Inspection data for each cable zone is then separately aggregated and analysed. The mean and standard deviation of the number of wires within each corrosion stage, as defined in NCHRP Report 534, is determined for typical inspection positions within each cable zone, results are shown in Table 2.
e) The mean and standard deviation information along with the actual number of inspections within each cable zone is then used to determine the number wires within each corrosion stage that has a probability of exceedance of 5% (i.e. a confidence level of 95%) using a single leg t-distribution.
f) The total numbers of wires having a probability of exceedance of 5% in each of the corrosion stages will exceed the actual number of wires in the suspension cable (8322 No). Therefore a process to normalise the results is required to allow the cable strength to be determined.

Table 1: Cable Zones - Description

Zone	Location	Zone Characteristics
A	Cable adjacent to the anchorages	Low level but with exposure to vehicle spray. Water in cable passes into anchorage chamber.
B	Cable adjacent to the towers	High level with greatest degree of exposure to higher speed winds. Steep cable gradient.
C	Cable at the mid-section of the main span	Low level but with exposure to vehicle spray. Flat cable gradient.
D	Cable approximately midway between tower and midspan/anchorage zones	Mid level with moderate exposure to higher speed winds and minimal exposure to vehicle spray. Moderate cable gradient.

2.2.3 Normalisation process

Undertaking the analysis of the cable using the unmodified NHCRP method have shown that the number of wires in corrosions stages 3 and 4 have a critical impact on the cable strength reduction (see Table 5). Therefore to obtain the cable strength with a 95% confidence limit the numbers of stage 3 and 4 wires was retained and the numbers of stage 1 and 2 wires were adjusted by the following normalisation process:

$$K_{4n} = K_4$$
$$K_{3n} = K_3$$
$$K_{2n} = 8322 - K_{4n} - K_{3n}$$
$$K_{1n} = 8322 - K_{4n} - K_{3n} - K_{2n}$$

K_i = number of wires in corrosion stage i having a probability of exceedance of 5%

K_{in} = normalised number of wires for use in strength calculation so that $\Sigma K_{in} = 8322$

K_{in} cannot be less than zero

The results from the normalisation analyses of the inspection data are shown in Table 3.

2.2.4 Strength Determinations with 95% Confidence Level

The strength of the suspension cable is determined using the procedure given in NCHRP Report 534 for each of the cable zones using the normalised numbers of wires in each of the corrosion stages together with the number of broken wires found during the intrusive inspections and the proportion of cracked wires in corrosion stages 3 & 4 identified from the laboratory testing.

Table 2: Tensile test results summary (N/mm²)

Wire Group	2006 Data Tensile Strength		2010 Data Tensile Strength		Combined Data Tensile Strength	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
2	1604	33	1650	28	1618	38
3	1574	67	1606	42	1582	40
4	1546	67	1584	41	1560	61
5	1487	87	1534	111	1501	94

Table 3: Inspection data wires per corrosion stage(normalised)

Corrosion Stage	2006 Inspection Zone				2010 Inspection Zone			
	A	B	C	D	A	B	C	D
1	0	3407	0	382	-	0	0	0
2	4160	2703	2430	4043	-	0	0	2403
3	2978	1613	4110	2568	-	7326	4330	3699
4	1184	599	1782	1329	-	996	3992	2219

The results of these strength evaluations for the panels inspected in 2006 and 2010 are given in Table 4.

2.3 Interpolation of Cable Assessment to Full Length of the Suspension Cables

The cable strengths having a 95% confidence level are used to develop an assessment of the full length of both suspension cables. The interpolation of the assessment follows from the zoning of the cable according to location. It is important to note that the assessment excludes specifically the lengths of the cables within the saddles and the strand shoes in the anchorages.

Ultimate limit state utilisation factors (ULS applied forces / ULS capacities) are then calculated in order that critical locations along the cables for relevant load cases can be readily identified. To cater for cable panels that have not been inspected, linear interpolation of utilisation factors is used to provide values between the inspected panels.

Table 4: Summary of Cable Capacity

Cable Zone	Panel	Utilisation Factor 2006	Panel	Utilisation Factor 2010
A	UpAS16	91.9%	UpAS16	
	DnBS16	91.9%	DnBS16	
B	DnCB2-1	94.4%	DnCB2-1	
	UpCB7-8		UpCB7-8	98.0%
C	DnCB22-23		DnCB22-23	93.9%
	UpCA24-25		UpCA24-25	95.2%
	UpCA25-26	102.6%	UpCA25-26	90.9%
	DnCB25-26		DnCB25-26	90.9%
	UpCB27-26	99.1%	UpCB27-26	
	UpCA27-26	99.1%	UpCA27-26	
	DnCB27-26	99.1%	DnCB27-26	105.6%
	DnCA27-26		DnCA27-26	105.6%
D	DnAS8-7	96.8%	UpAS8-7	99.5%
	UpCA15-16	93.1%	DnCB15-16	89.0%

Note:- UpCA15-16 refers to Up – upstream cable CA 15-16 cable panel

2.4 Results

The second intrusive inspection shows that the capacity of the cable has apparently increased when compared with the findings from the first intrusive inspection in 2006. A significant contributing factor in this increase has been the reduction in the reported number of cracked wires. As the number of tensile tests for both inspections was small, this can result in wide variations in the cable capacity. To give a more representative value a combined percentage of cracked wires was adopted

3. Modelling of Cable Deterioration

3.1 Background

In order to assist in the management of the suspension cables, an analytical tool has been developed to model of the deterioration of the individual galvanised steel wires as a result of corrosion. There are essentially two types of deterioration model for a mechanism such as corrosion. The first predicts the current condition based on standard data and how it varies across the structure based on variations in exposure conditions. The output will typically be in the form of a section loss that can be compared with the actual current condition.

The second approach includes time as a variable and attempts to predict the future condition. While the present condition can be quantified, an assessment is required of the mechanism and timescale for this condition to be established. Using this method it is also possible to predict the long term effects of various remedial measures. It is this second approach that has been adopted for the Severn Bridge suspension cable deterioration model.

To assist in the development of the model, it is 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. In the case of Severn Bridge, it was also possible to retrieve samples of wires for detailed inspection and physical testing to identify the factors that govern failure, as previously described [2].

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. In practice such investigations are always limited by time and access constraints.

Determining corrosion rates based solely on the present condition is not totally satisfactory. Corrosion rates are strongly influenced by a range of factors, the evidence for some of which may be influenced by the inspection procedure. It is therefore preferable to identify other sources of data which can be used to model the present corrosion. Where time and budget allows, data can be obtained from a laboratory study reproducing the specific conditions encountered in site. In most cases, however, it is necessary to rely upon published data, although care must be taken to ensure it relates to the material and environmental conditions under consideration.

In order to establish a corrosion rate for the model it is first necessary to estimate when corrosion starts. Assuming an early onset to corrosion would appear to result in a conservative model. However, where the model is to be compared with data from site, an earlier start of corrosion would mean the observed corrosion had taken place over a longer period of time and would result in any future predictions being underestimated. It is therefore essential to identify correctly the mechanisms by which corrosion initiates and the point from when the loss of steel section has occurred.

For the wires making up the main suspension cables, the following assumptions have been 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 water.
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. 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.
7) 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, and combined to produce the overall predictive tool.

3.2 Development of the model

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 the thickness of the wire. A large number of measurements on the depth of penetration of such defects found on site were also undertaken. This data represented the current condition and was used to benchmark the distribution of thicknesses obtained.

The data obtained from the site inspections was made available from a series of physical inspections of the wires on site, most recently in 2010. The inspections have been based around the visual examination of exposed wires in accordance with NCHRP Report 534 [1]. Each area has been correlated with the following visual assessment categories in accordance with the NCHRP report, as shown in Table 5.

Table 5: Corrosion Classifications for Galvanised Steel Wires (from NCHRP Report 534)

Stage	Description
1	Spots of zinc oxidation on the wires.
2	Zinc oxidation on the entire wire surface.
3	Spots of brown rust covering up to 30% of the surface of a 75 to 150mm length of wire.
4	Brown rust covering more than 30% of the surface of a 75 to 150mm length of wire.

The NCHRP report states that laboratory tests have shown that 5 to 20% of Stage 3 wires and 60% of Stage 4 wires may have cracks. In order to derive a method of comparing the model predictions with the site data it is necessary to estimate thresholds of section loss that correspond to visual assessments, whilst bearing in mind the comments in the NCHRP report regarding the number of wires with cracks.

Laboratory tests have established that the main factor governing the failure of wires is the depth of penetration of defects. Based on this, the most appropriate data for modelling section loss relates to depths of penetration with respect to time and published data was employed for the corrosion loss of zinc and unalloyed steel in a range of environments [3]. The data obtained from site was found to correlate well with the section loss predicted by the model and provided the necessary confidence to use the model to predict the future performance of the wires and the benefits of proposed remedial works, most notably the installation of the dehumidification system.

3.3 Future predictions

As a series of corrosion rates have been used to build up the model the prediction of ongoing deterioration with no intervention is relatively straightforward, with the length of time of corrosion being simply increased until such time as the critical defect size is obtained and the wires fail. Rather than maintaining the status quo, the ongoing management of the cables has involved the implementation of extensive remedial measures in the form of a fully monitored dehumidification system [4], augmented by a vapour phase corrosion inhibitor introduced into the dry air stream, which together should ensure a long term reduction in corrosivity of the environment and thereby extend the life of the cables.

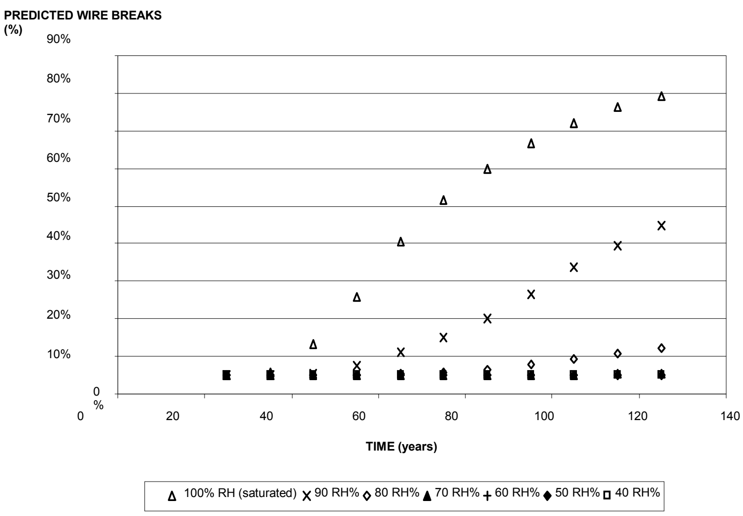

Figure 2: Effect of Relative Humidity on Predicted

The effects of humidity on corrosion have been studied extensively and are well documented [5]. As moisture is a prerequisite for aqueous corrosion, the level of moisture in the air has a direct correlation to risk and extent of corrosion. As relative humidity (RH) drops from near saturation to below 50%, so the rate of corrosion reduces to a negligible and, in most cases, tolerable level. Given that relative humidity is influenced by temperature, it is desirable to reduce the RH to as low a figure as possible to reduce the risk that daily and seasonal drops in temperature do not result in dew point effects resulting in condensation within the cable.

As an example of the model as a predictive tool, Figure 2 shows estimated numbers of wire breaks at 100% (saturation) to 40% relative humidity over a period of 125 years. By comparison, the dehumidification system protecting the suspension cables is currently running at or below 20%

relative humidity.

4. Conclusions

The results of the latest intrusive examination has shown that the loss of strength of the suspension cables is no worse that the calculated capacity undertaken following the first intrusive examination. 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.

As a consequence of the latest intrusive inspection the cables have been recertified.

A deterioration model has been developed based on corrosion rates and calibrated against the current condition of the cables. The model can be used as an analytical tool to predict the future performance of the wires and the effect of dehumidification and other remediations on the life extension of the structure. As more data becomes available through condition monitoring and intrusive inspections, the model will be subject to review and possible update to ensure the highest levels of confidence in its accuracy.

5. References

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