Flint & Neill Partnership
Consulting Engineers

SCOTTISH EXECUTIVE

Audit of the Main Cable Inspection and Assessment

Final Report

1023-Rp-02 r4

January 2006

www.flintneill.co.uk

Document Control Sheet

Rev.	Status	Date	By	Check	Approved
0	Draft for client review	18/12/05	JDC	RNA/PS	DKM
1	Second draft with minor revisions	20/12/05	RNA	JDC	DKM
2	Minor clarification to final conclusion in section 13	21/12/05	RNA	JDC	DKM
3	Updated following review meeting of 5/1/06. Issued as FINAL REPORT	27/1/06	RNA	JDC	DKM
4	Minor comments added For external issue	31/1/06	DKM	RNA	DKM

Flint & Neill Partnership
Stone,
Berkeley,
Gloucestershire
GL13 9LB

Tel: +44 (0) 20 7202 6699
Fax: +44 (0) 20 7202 6688
Email rna@flintneill.co.uk
Web: www.flintneill.co.uk

1 Introduction

Flint & Neill Partnership has been tasked by the Scottish Executive with carrying out an audit of the first internal inspection and associated assessment of the condition of the main cables on the Forth Road Bridge. The inspection and assessment was commissioned by the Forth Estuary Transport Authority (FETA) and was undertaken by Faber Maunsell and Weidlinger. Reports from that inspection indicate that there are serious reservations over the residual strength of the main cables and the projected longer term deterioration of these critical load carrying elements of the Forth Bridge.

The Scottish Executive commissioned Flint & Neill Partnership on 11th November 2005 to audit the findings of FETA’s consultants. The preliminary findings of the audit were to be completed by the middle of December 2005, with the issue of this final report to the client setting out the findings of the audit by the end of January 2006. The purpose of this audit was to carry out a desk study of the findings of FETA’s consultants and to advise the Scottish Executive as to whether those findings were reached using a process of appropriate rigour and whether the conclusions are reasonable. It was also proposed that advice be provided to the Scottish Executive whether there is scope for additional investigation that may alter the conclusions on the long term performance of the bridge.

Flint & Neill Partnership has been aware of the cable investigation works on Forth since their inception in 2002, initially as an independent advisor to the Highways Agency. When the first panel at the low point of the main span was opened up; two representatives from Flint & Neill Partnership attended and their impression at the time was of a well organised and thorough investigation. A second visit was made at a later stage when a high level panel was investigated. As a consequence of these visits, Flint & Neill Partnership was therefore familiar with the investigation methodology at the start of this audit.

Flint & Neill Partnership has engaged New York based Ammann & Whitney to act as sub-consultants providing specialist advice on the consistency of the findings with similar inspections and assessments carried out in recent years in the United States of America.

2 Background

Within the United States of America, there are nearly 50 major suspension bridges with over half of them being more than 50 years old. These bridges represent major investments and are essential transportation links. As the age of these structures increase, the need to assess their condition, load carrying capacity and remaining service life will also increase. In the absence of any reliable and nationally recognised procedures to inspect and evaluate the condition and strength of suspension bridge parallel wire cables there was concern that unreliable methods may result in unnecessary major refurbishment works or in unexpected failures. In 1998, The Transportation Research Board identified a priority need for the development of cable inspection, sampling and testing guidelines as well as the development of models to predict the strength of deteriorated cables. As a result, guidelines were produced and issued by the National Cooperative Highway Research Programme (NCHRP). The document is referred to as NCHRP Report 534 and is entitled “Guidelines for Inspection and Strength Evaluation of Suspension Bridge Parallel Wire Cables”. It is worth noting that the principal compilers of the guidelines are the American consultants, Weidlinger. It is this firm which has advised, supported and assisted Faber Maunsell with the Forth Bridge main cable investigation works.

In the United Kingdom, there are three major suspension bridges with parallel wire cables; these are the Forth Bridge, the Severn Bridge and the Humber Bridge. The Forth Bridge is the oldest of these bridges, opening in 1964. FETA was aware of the development of the American guidelines and the recommendation that an initial series of intrusive inspections should be carried out after thirty years of service. As the Forth Bridge had been operating for nearly forty years, FETA commissioned Faber Maunsell, in conjunction with Weidlinger, to undertake an intrusive inspection of the main cables of the Forth Bridge. In the absence of any recognised UK or European standard or procedure, FETA required their intrusive inspection and associated strength assessment to be based upon the NCHRP Guidelines. (2.1) Figures in Brackets refer to sections of the audit trail document, Appendix A.

3 Audit Methodology

Following the approval by the Scottish Executive to commence work, Flint & Neill Partnership received a copy of the draft report (dated 28/9/05) produced by Faber

Maunsell entitled "Forth Road Bridge – First Internal Inspection of the Main Cables Report (Shortened). This report was used as a basis for drawing up an audit plan.

An audit record has been prepared (Appendix A) that sets down the scope of the audit and list all audit actions that have been carried out. This appendix gives the audit items raised by the audit team and gives the audit team's understanding of the answers to those aspects. The third column in the table provides the audit team's comments or close out action requirements. Appendix B sets out the documentation received and reviewed as part of the audit process.

This document was developed as the project developed and was used first as a basis for discussing the draft report with Faber Maunsell. A meeting was held at their London offices on 16th November 2005 (David MacKenzie and Neil Adamson - Flint & Neil Partnership; Faber Maunsell - Charles Cocksedge and Beverly Camfield) to review the draft report; to understand the process followed by Faber Maunsell in carrying out the inspection and assessment and to determine how the inspection and assessment was carried out by Faber Maunsell and their New York based sub-consultants, Weidlinger. At the meeting a general discussion took place on the background, inspections, testing and analysis and Faber Maunsell agreed to provide FNP with various documents to illustrate Faber Maunsell's work. A list of documents required for the audit process was agreed and Faber Maunsell was tasked to send this information to FNP. The information was received promptly on 21st November 2005.

Following that meeting it was decided that the most effective and efficient process for the audit would be for Flint & Neill Partnership to audit Faber Maunsell's work and for Ammann & Whitney to audit Weidlinger's work. This makes best use of the audit team's experience and geographical disposition.

Ammann & Whitney met with Weidlinger in New York on Tuesday 22nd November, where they were provided with a copy of the initial cable strength calculations. Ammann & Whitney were also advised that Weidlinger were working on a revised degradation model. Calculations for future cable strength projections and details of individual wire test results were subsequently received by Ammann & Whitney on Wednesday 30th November. Ammann & Whitney met again with Weidlinger on Thursday 8th December to discuss the methodology used in developing the strength calculations and degradation models.

On 24th November, a meeting was held at the bridge and was attended by the Scottish Executive, FETA, Faber Maunsell, Fairhurst and Flint & Neill Partnership. A further presentation was given by Faber Maunsell, and Fairhursts explained their role in calculating the loading in the cable. Following the presentation, additional audit questions were raised and further background data was requested from Faber Maunsell; this was received within a few days.

When all the responses had been studied by both Flint & Neill Partnership and Ammann & Whitney, a further set of questions was put to Faber Maunsell who together with Weidlinger, promptly provided answers.

A final series of questions was sent to Faber Maunsell on 12th December and a response received on 15th December. Following the production of a draft report, a meeting was held on 5th January 2006 with the Scottish Executive, Faber Maunsell, FETA and Flint & Neill Partnership to review the report and to address any outstanding matters. Additional feedback was received in written form from Weidlinger which has been incorporated into this final report, either in the audit trail document or as a series of footnotes to this document, cross referenced to Appendix D.

4 Project Tasks

The audit tasks, as defined in the project brief, are set out below as Audit Tasks ‘a’ to ‘d’.

a Load model for main cables

b Strength Model of main cable

c Estimation of a deterioration model

d Establishment of acceptable reliability levels for the structure

Subsequent sections of this report set out further details of each task and the associated audit findings.

5 Audit Task ‘a’. Load model for main cables

The objective of this task is to consider whether the assessed loading of the main cable can be accepted as accurate and whether it has been subject to the level of independent verification expected of a project of this nature.

A detailed load assessment has been carried out of the bridge by Fairhurst examining both the permanent and superimposed dead loads.

From the information made available during the period of the audit, it is understood that assessments of the permanent loads have been undertaken for FETA by both Faber Maunsell and Fairhurst; the latter being well placed to carry this out given their history and involvement with the Forth Bridge over many years. It is understood that close agreement was made between Faber Maunsell and Fairhurst of their separately calculated loadings of the main cables (to around 2%). Although there was no formal requirement for a ‘Category III’ check to be made of the permanent load assessment, both parties indicated that they considered their efforts represented the level of effort and independence required of a Category III check and will certify the structure to this effect. With such close agreement between the two exercises it was considered that there would have been little benefit in repeating this exercise during the period of the audit.

Discussions on the BSALL live load assessment were held between Flint & Neill Partnership and Fairhurst on Tuesday 13th December. Our review leads us to consider that the approach taken by Fairhurst is slightly conservative, albeit the degree of conservatism is sufficiently small with respect to load effects in the main cable that we would not recommend any refinement or third party review at this stage. The load effects in other elements were not reviewed as they were outside the scope of the audit. (1.1 – 1.10)

6 Audit Task ‘b’. Strength Model of main cable

The objective of this task is to consider whether the assessed strength of the main cable, based on the findings of the internal inspection, can be accepted as reasonable. The strength assessment has been based upon the guidelines given in NCHRP Report 534. The audit has therefore considered whether the methodology used to record the condition of the cables, and hence to assess the current strength of the main cables was in line with the NCHRP Guidelines and has also considered whether those guidelines are strictly applicable to the Forth Bridge main cables. This task has been broken down into five distinct sections:

- The scope of the internal investigation.
- The methodology of the site investigations.
- The findings and recording of the internal investigation.
- The findings and reporting of the associated testing.
- The calculation of cable strength from the inspection and testing.

It is considered that because FETA required the investigation to be undertaken using the NCHRP Guidelines, the appointment of Faber Maunsell, in conjunction with Weidlinger, to develop, manage and oversee the investigation was appropriate. (2.2)

6.1 The scope of the internal investigation

The initial scope for the first internal investigation of the main cable is considered to be in line with the guidelines. Six panels were selected based upon the conditions noted during a detailed visual inspection of the cables. The scope was flexible which permitted the number of panels to be increased to ten once the initial intrusive inspections had determined the general conditions of the cable.

It should be noted that the initial six panels were selected for the internal inspection based upon the conditions noted during a detailed visual inspection of the cables. However, once these panels were opened there was little correlation between the initial, external visual inspection and the condition of the wires within that panel. It therefore cannot be assumed that the panels selected will represent the panels with the worst condition wires. (3.1 – 3.4)

The audit has identified the following aspect where the scope of the inspection was not strictly in accordance with the Guidelines:

Removal of a cable band (4.16)

- Page 2-6 of the NCHRP Guidelines states that the parties should be prepared for the removal of one or more suspenders and cable bands, if conditions require it.
- Page 2-26 states that one or more cable bands should be removed wherever numerous broken wires are found.
- Page 2-31 implies that a cable band should have been removed to compare the level of deterioration in areas near the cable band with areas in the middle of the panel. The Guidelines expect this to be done whenever stage 4 or broken wires are present.

Faber Maunsell have stated that consideration was given to the removal of a cable band but the decision to do so was taken no further owing to the difficulty of the work for the perceived benefit[1]. Removal of a cable band is an extremely complex procedure requiring a substantial period for planning and preparation involving long term lane closures and traffic disruption. The decision not to proceed is understood and would have been unlikely to affect conclusions drawn from this initial intrusive investigation. The conditions found in the cable will necessitate further inspections within a five year period and it is expected that the decision to remove of one or more cable bands will be reviewed at that time in the light of the findings. It should also be noted that the NCHRP recommendations are based around the typical US suspension bridge designs that have cable clamps on a 30 ft (9.14m) spacing. On Forth, the spacing is double this, effectively doubling the amount of cable available for inspection.

6.2 The methodology of the site investigations

Overall, the methodology adopted for the work of the site inspection team was considered to be very much in line with the NCHRP Guidelines.

There are a few aspects where the Guidelines would indicate a more detailed examination of the exposed areas of cable was required. The diameter of the Forth Bridge cables is approximately 24”. Within the Guidelines, it is recommended that on larger cables (Diameter >24”) additional wedge lines should be driven in the outer half of the cable radius where the wedges are at a maximum spacing, to avoid reducing the fraction of wires that are observed; particularly when many broken wires are found and

---

[1] See Appendix D – Item 1 for detailed Weidlinger/Faber Maunsell response on this issue. Their response is accepted

Stage 4 is expected to be extensive. The number of additional wedge lines applied to the ten inspected panels was only two and in each instance it allowed a decrease in the recorded severity level of the wires. In view of the statements in the Guidelines and the conditions found, additional, intermediate wedge lines would have been justified. (4.7) However, it is considered that such additional work would be time consuming and unlikely to result in any particular difference in the overall results. It would be justified if there was a particular local anomaly that needed to be further investigated.

6.3 The findings and recording of the internal investigation

The general impression from the records provided (and supported from the site visits made by audit team members during the period that the inspections were carried out) is that a high level of confidence can be given to the quality, accuracy and consistency of the recorded data for the internal investigation. The NCHRP Guidelines provide detailed instructions over the manner in which the cable condition is to be recorded and these have been adhered to in general. Confidence is also achieved by Faber Maunsell using the same two inspectors throughout the investigation and reporting that comparisons of their findings were generally identical. Weidlinger also reviewed some areas and satisfied themselves over the accuracy and consistency of the recorded conditions. (3.11 – 3.12)

We know from our discussions with Weidlinger that the inspectors used a slightly modified Stage classification. Stage 4 wires are defined as having 25% or more of the surface corroded rather than 30%, as specified in the NCHRP Guidelines. This results in a larger percentage of Stage 4 wires and no cracks found in wire classified as Stage 3. It is our opinion that this adjustment in procedure is reasonable as this classification is subject to the judgement of the inspectors in any case. For the cable strength calculations, the larger number of Stage 4 wires will result in a larger strength loss when the NCHRP method is used to project the number of cracked wires in the Stage 4 population. Using Weidlinger's latest assumption that only Stage 4 wires in the outer 6 rings are cracked, the strength calculation will be little affected by this shading of corrosion stages.

Samples of wires for testing were only taken from the outer eleven layers, or “rings” of wire. This is not common practice[2] as it may not be representative of the larger population of wires throughout the cable cross-section. This becomes especially important when one considers the assumption being made in the strength calculations that only wires in the outer six rings are cracked.

It was reported to Ammann &Whitney that it wasn’t possible to remove deeper samples. This is contrary to the audit team’s experience, as we routinely remove samples from several inches into the cable. However, it is very difficult to repair the wires in these deeper locations, thus removing wires for sampling would have a detrimental effect on the main cable strength. Faber Maunsell followed a policy of avoiding any works which would further compromise the strength of the cables.

6.4 The findings and reporting of the associated testing

Eight 6m long sample wires were removed for testing from each of the ten inspected panels, for a total of eighty .These sample wires were cut into 457 mm (18 inch) long specimens and a total of 704 were tested to failure in accordance with the American Standard, ASTM A 586 and A 370. About 10% of these had strain measured to failure. The others had strain measured to about 2% elongation, after which the extensometer was removed and the test continued to failure. Only 17 specimens broke at less than the original, specified strength of 100 tons/in^2, eight of which had cracks. A total of 17 specimens were found to have cracks. Three of the cracked specimens were from the same wire sample 1031, three more were from the same sample 363, two from sample 551 and two from sample 961. The total of 17 cracked specimens therefore came from 11 sample wires.

Uncracked wires appear to be of high quality with good ductility.

Seventeen specimens of Stage 1 and 2 wires were tested for zinc coating weight and were found generally within the specification.

Seventeen specimens were also subjected to Preece tests and it has been reported that only five were within expectations for new wire. It is interesting to note that even two

---

[2] See Appendix D - Item 2 for detailed Weidlinger/Faber Maunsell response on this issue. Their response is accepted

Stage 1 specimens did not meet the standard. It might be inferred that the original wire did not meet the specifications for the zinc coating.

Four specimens had chemical analysis performed on them. All appeared to be generally within the original specifications, although two had low Carbon contents of 0.74 and 0.75%. Original specifications called for 0.75 to 0.80% Carbon. This range indicates good quality, uniform wire (based on these very limited number of samples). Weidlinger reported that there is apparently good correlation between tested wire strengths and carbon content (the stronger wires having the higher carbon) as expected.

No fatigue testing has been performed. Fatigue testing is not specified in the NCHRP Guidelines because it is recognised that fatigue is not normally an issue in the cable service loads. However, it is the audit team's experience that fatigue testing is useful in identifying incipient cracking in wires that perform well in static tests. This may be advisable in determining a more reliable estimate of the percentage of cracked wires in the Stage 3 and Stage 4 population. Faber Maunsell reported in the 5th January 2006 meeting that they would be considering this for the additional tests being programmed at Lehigh University.

6.5 The calculation of cable strength from the inspection and testing

The estimation of cable strength is a probabilistic exercise, due to the impossibility of knowing the properties of each individual wire in the cable. The models for strength estimation depend on data gathered during internal inspections and on laboratory testing of samples removed during those inspections. It therefore follows that a more extensive and detailed investigation will increase the level of confidence that can be given to the estimation of cable strength.

In general, the NCHRP Guidelines have been followed by Weidlinger, with some minor refinements and with some more significant departures and expansions of the degradation model calculations.

A small difference is that Weidlinger used a Normal Distribution for the strength of Stages 1 and 2 wires and a Weibull Distribution for Stages 3 and 4. NCHRP recommendations specify a Weibull Distribution for all stages, but Weidlinger's opinion is that this is more representative of the actual distributions. In our experience, this would affect the results in a very minor way and is not significant.

An important assumption in Weidlinger's latest calculations is that cracking has only occurred in Stage 4 wires located in the outer six rings of the cable. Based on the test data and an extrapolation of it, Weidlinger has assumed that 26% of these outer Stage 4 wires are cracked. This is different to the NCHRP guideline procedure which does not segregate Stage 4 wires based on their locations within the cable.

We received Weidlinger's calculations for both cases; one using the NCHRP assumption that all Stage 4 wires are potentially cracked, and the modified assumption that only Stage 4 wires in the outer six rings are potentially cracked. The more conservative NCHRP method results in a 2004 strength loss of 15.4%, while the modified assumption, which follows also follows a distinctly different mechanism, produces a 2004 strength loss of 6.7% (We have independently calculated the current cable strength using the modified assumption and Weidlinger's data, and have produced the same result)[3].

We are therefore reasonably assured that the mechanics of Weidlinger's calculations are correct. The results hinge primarily on what is assumed regarding the number of cracked and broken wires in the cable.

We believe the NCHRP's assumptions are supportable since the number of cracked wires is projected based on a broad interpretation of test data and observed conditions in the cable. In general, this calculation method is conservative and as reliable as the data (assuming sufficient data has been obtained - however much statistical rigour is brought to bear, the available data in this case is still a small number on which to depend).

Because some US bridges have been found to have extreme variations in conditions from panel to panel, we believe the only sure way to know we have found the worst condition is to open and inspect the entire length of the cables. This has never been done except in conjunction with a cable oiling and re-wrapping project, during which every panel is wedged for oiling, and also inspected as the work progresses.

---

[3] See Appendix D - Item 3 for detailed Weidlinger/Faber Maunsell response on this issue. They have provided some additional clarification of the cable strength models produced; this is included as it is not available for reference until the final Weidlinger/Faber Maunsell report is produced. There are important distinctions that are made between the various models and care is required in making comparisons. Weidlinger's notes are clear on this.

Weidlinger's modified assumption that only the outer six Stage 4 wires contain cracks needs to be considered closely as it is a departure from the NCHRP Guidelines, especially considering the small number of samples taken and the fact that no samples were taken beyond the outer eleven wires. On the other hand, a very small number of cracked and broken wires were found, and these tended to be clustered within the outer few rings at the bottom of the cable (with a few at the sides). This is consistent with our experience on other bridges. We often feel justified in considering these parts of the cable as a separate population. We therefore do not find Weidlinger's assumption unreasonable.

Following the audit review meeting on 5th January 2006, Weidlinger confirmed that having reviewed all strength models they considered the final reported figure for the current strength loss of the cable should be at least 8% owing to inconsistencies in the cracking patterns in the higher strength predictive models (The 8% figure corresponds with their modified NCHRP nominal strength with stage 4 wires in the outer 6 rings potentially cracked). This is an appropriate and reasonable response to take in the light of the amount of data gathered; we are in agreement with their final figures.

7 Audit Task 'c'. Estimation of a deterioration model

The objective of this task is to consider whether the assessed performance of the main cables over the longer term is reasonable. The NCHRP Guidelines were used as the basis for this assessment and the audit has considered not only whether the Guidelines have been followed but also whether the Guidelines are strictly applicable to the Forth Road Bridge main cables.

The strength degradation calculations also follow the general procedures of the NCHRP, but they have been carried out to a more rigorous level. They have also, at FETA's request, been developed for time periods of fifteen years and longer into the future. It should be noted that the NCHRP guidelines stipulate that the method should only be used to project 10% of the current age into the future (which is only four years for the Forth Road Bridge). It should also be noted that there has never been any calibration of the calculation method, and while a ten year look ahead may produce plausible results for a century old bridge, we consider that the results must be used with extreme caution for a forty year-old bridge. The uncertainty in the results is considerably greater than for the calculated strengths for the bridge in the as-inspected condition.

In recognition of this, Weidlinger departed from the basic NCHRP method in an effort to produce meaningful results. A great deal of thought went into the methodology, which we will outline below:

In Weidlinger's latest calculations it is assumed that the cables began corroding immediately after construction (also not in accordance with NCHRP, but more reasonable).

Based on the conditions found during the inspection, Weidlinger had developed a lower bound model which assumed that the cable can be divided into 3 "environmental zones", the top segment, bottom segment and side segments (both sides taken as one segment). The corrosion rates in these zones vary. This in itself is plausible and has been observed in studies of some of the Honshu-Shikoku Bridges (See Structural Engineering International 3/2000).

Using the wire populations in these zones, Weidlinger modelled a hypothetical cable comprised of the three different corrosion zones, with the more severe corrosion occurring at the outer part of the cable and deeper wires having less advanced corrosion. This expedient is used to aid in calculations only and isn't meant to represent the real situation. After projecting the wire deterioration for each zone, the results are then combined to project the strength of the real cable.

The projected corrosion rate of individual wires is not based on repeated inspections of actual bridges (there have not been repeated inspections that can be used to develop such data). Corrosion rates are actually based on laboratory tests being conducted in the US as part of a study commissioned by the Triborough Bridge and Tunnel Authority. This study is headed by Weidlinger with Ammann & Whitney as a named sub-consultant. In these tests, individual wires are being subjected to various corrosive environments and monitored for the advancement of corrosion; the wires are held under varying tensions. It has been observed to date that wires progress from Stage 1 to 2 to 3 to 4 over approximately 6 month intervals for each step. To date (over 2 years of the current testing according to Weidlinger) these tests have not produced any cracked wires. It is intended to continue testing for another 8 years.

From these test data, Weidlinger correlates the corrosion rate inside the cable by a simple proportionality. For example, a Stage 3 wire in the cable got that way after 40 years, while the laboratory wire got to Stage 3 in 1 year. The real case wire therefore corroded at one fortieth the rate of the laboratory wire.

Using the above-described linear correlation, Weidlinger's model predicts how many wires will go from one existing stage to the next in a given time period

During the performance of the audit calculations, it was noted that if one assumes a linear rate of corrosion advancing from one stage to the next, the so-called deterioration rate of the cable becomes independent of the test data and is simply the corrosion stage divided by the number of the years the bridge has been corroding (in this case, the age of the bridge).

Weidlinger's assumptions extend to the rate of cracking and breaking wires, i.e. Weidlinger has assumed a Stage 4 wire becomes a cracked wire (called a Stage 5 wire for convenience in the current calculations) based on the same correlation between the laboratory's 6 months and the actual bridge wire's age. This is done even though the laboratory tests have not produced cracked wires in that time period (no cracks have been produced to date in the current tests nor in earlier tests performed at Columbia University).

The assumption that only the outer six rings of wires are cracked is based on test specimens taken only from the outer 11 wires of the cable. No samples were removed from deeper in. Weidlinger have advised that deeper wires cannot be repaired thus none were removed.

At the time of writing this report, Weidlinger indicated that they were continuing to refine their calculations. It appears they have only performed the analysis for panel 100S-100N of the east cable, so far (albeit that this is the worst panel discovered). Weidlinger did not indicate when their report would be finalised. The outcome of these calculations was a 6.7% strength loss in 2004 as noted in section 6.5.

We have performed independent calculations of the future degradation of the cable using Weidlinger’s assumptions as well as alternative assumptions regarding the length of time a Stage 4 wire becomes cracked (Category 5), then broken (Category 6).

Using the same assumptions and calculation method as Weidlinger (with some approximations), we have independently computed results similar to Weidlinger's. These were advanced to produce the following plots for comparison to illustrate the sensitivity of the calculations to the assumed linear progression from one stage of corrosion to the next. The Weidlinger model assumes all wires advance to the next stage after 6 months. As explained earlier, there is no laboratory data to support the assumption that Stage 4 wires begin to crack after 6 months nor that the next stage of deterioration (the cracked wires begin to break) occurs after another 6 month interval.

We have examined the effect of these final two stages taking a period of T years under the laboratory condition to crack (i.e. Stage 4 wires become Category 5 wires) and that Category 5 wires begin to break T years later (they become Category 6 wires). Values of T of 0.5 (Weidlinger's assumption) to 1.0 and are plotted in Figure 1, but, it should be noted, they have been based on the consensual 8% loss of strength model at 2004, not the 6.7% model. The purpose of this is to demonstrate the variance in the predictive models. Cable strength units are kilonewtons.[4]

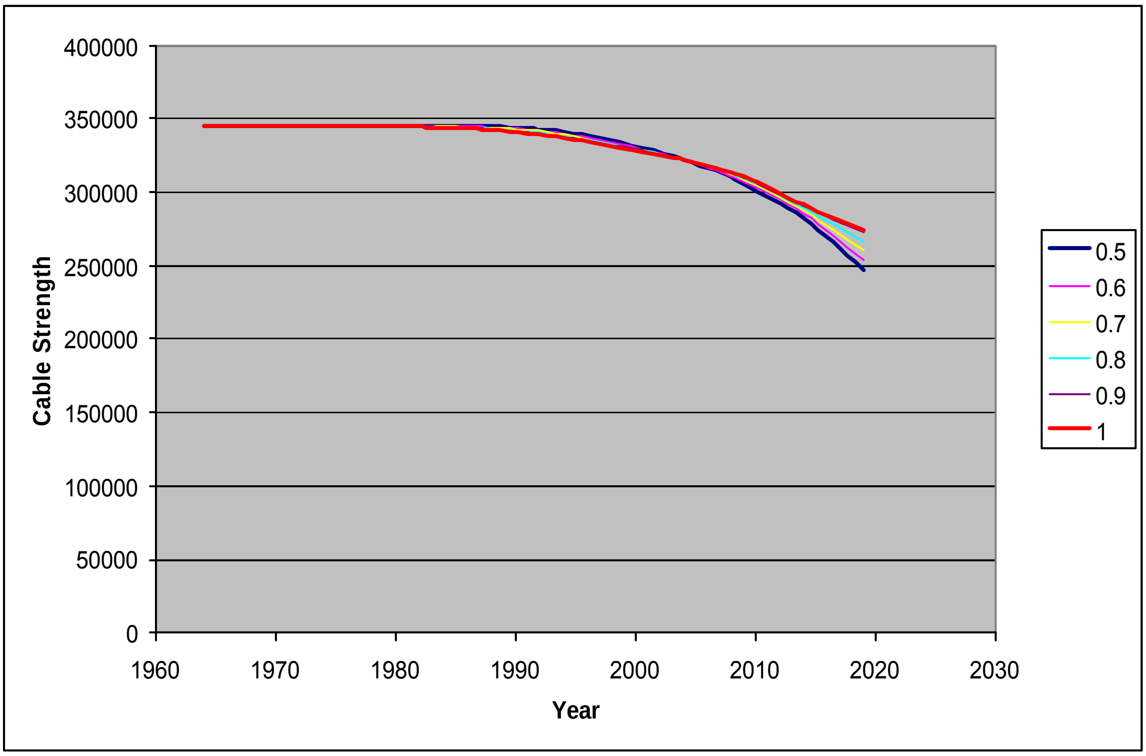


Figure 1 – Cable Strength Deterioration Estimates

---

[4] See Appendix D - Item 4 for detailed Weidlinger/Faber Maunsell response on this issue. Their response is noted.

An additional plot is included to highlight the range of predicted loss of strength models. These are shown against notional factors of safety of 2.0 and 1.9. It can be seen that the point in time when the safety factor for the main cable falls below these values for the BSALL live loading is between 2013 to 2018.

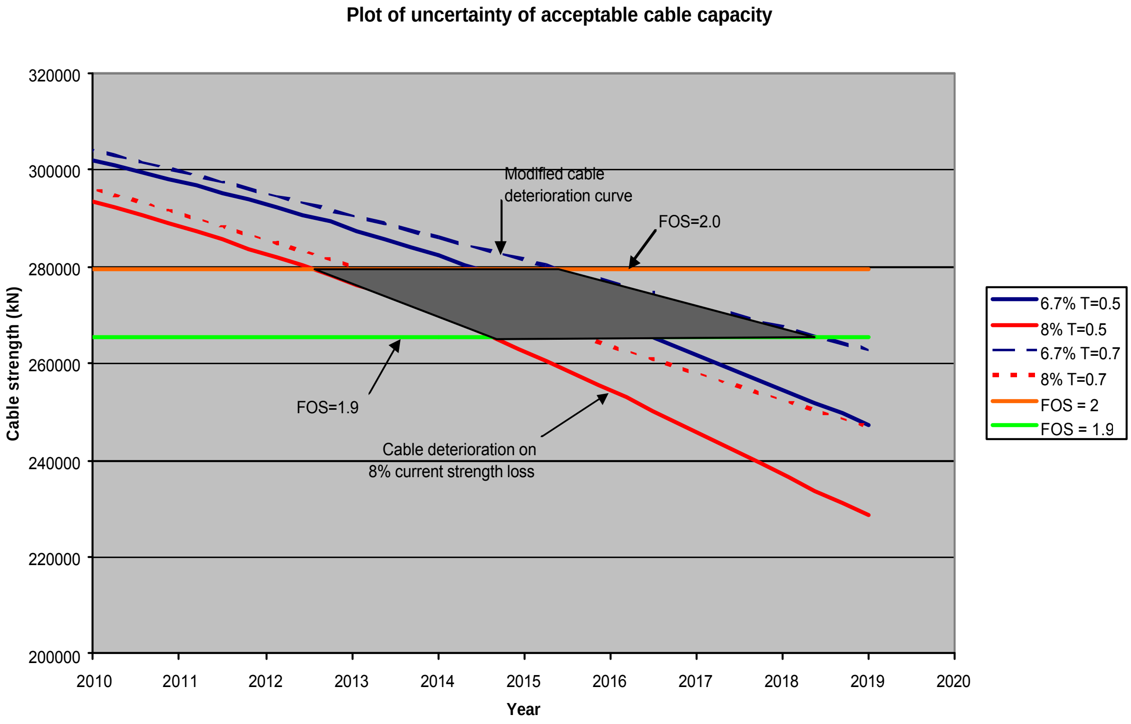


Figure 2 – Range of strength loss models

The results of the above calculations illustrate that the projected strength loss is very sensitive to the rate of deterioration of Stage 4 wires and that the degradation models should not be viewed as definitive, especially for projections beyond the 10% value given in the NCHRP Guidelines. However, it confirms that without intervention there will be a significant loss of strength in the longer term.

8 Audit Task ‘d’. Establishment of acceptable reliability levels for the structure

The objective of this task is to consider whether the assessed current and projected Factors of Safety are reasonable. The stated Factors of Safety combine the assessed loads in the cable with the assessed strength of the cable and provide an estimate of the overall level of reliability for the structure. The audit has reviewed the derivation of both the assessed load (Audit Task ‘a’) and the assessed current strength of the main cable (Audit Task ‘b’) and has reviewed the method for presenting the assessed Factor of Safety of the bridge in its assessed condition. The audit has also considered the projected future reductions in strength based on the deterioration model which was considered under Audit Task ‘c’.

American design practice uses the working stress method of design for cables. The design capacity is commonly defined in terms of a “safety factor,” being simply ultimate strength divided by the unfactored working load (F_u/T). For comparison purposes, if we apply standard AASHTO load factors to a cable designed for 690 MPa (100 ksi) working stress, the factored stress may exceed the proportional limit but will remain below yield point stress. In general, cable stresses reach their maximum value when the bridge is fully loaded and AASHTO load factors may be considered unrealistic for such a long loaded length. To illustrate the equivalency of the two methods, we can “back out” the load factors that will keep the factored stress below the proportional limit. Two examples would be: 1.3(D +L) or (1.1D +2.17L). Present day European designers use the semi-probabilistic limit state design approach. For example, the cables of the Storebaelt Suspension Bridge were designed such that stresses due to factored loads of D + 1.3L + 0.5W + 0.5T are less than or equal to $F_u/2$.

A discussion on the derivation of appropriate safety margins for the main cable of the Forth Bridge is included as Appendix C.

In the United States, a safety factor below two is deemed unacceptable and would lead to traffic limitations or closing of a bridge. In the UK, a reliability based approach would show that the factor should be a function of the bridge specific parameters, thus a safety factor of two on a suspension bridge with a high live load to dead load ratio will not necessarily provide the same overall reliability (and thus safety) as a bridge with a lower ratio. Whereas we would support a factor of safety of two as being acceptable, it is recommended that the factor of safety for the main cables is determined for the bridge specific conditions using reliability analysis at the Forth Road Bridge to facilitate longer term planning issues.

9 Other aspects considered during the audit period.

In undertaking this audit further items have arisen which justify additional comment by the audit team.

It should be noted that the intrusive inspection resulted from experience in the USA. Routine inspections of the Forth Bridge cable undertaken using the standing procedures for such inspections gave no indication of any areas of concern over deterioration of the main cable. Other European bridge owners are now likely to be aware of this ‘failure’ of existing procedures to identify deterioration within the main cables although the only alternative authoritative guidance for inspection is for intrusive inspections under the NCHRP document.

We have not identified within the Guidelines any requirement to inspect and record the condition of all the external wires around the circumference of the cable. The Guidelines require inspection only of the wires on the faces of the wedged openings and that condition is then assumed not only for the unseen wires between the wedge lines but also for the visible wires around the circumference. Inspection of the external circumference wires would be expected to provide additional ‘actual’ condition data rather than ‘projected’ data.[5]

In the US, when similar conditions have been discovered, action has been taken which has been intended to slow or stop the corrosion. This has entailed unwrapping the cables for their full length and pouring oil (usually linseed oil with or without additives) into wedged openings in each panel, followed by installation of a complete new wrapping system (wire wrapping with or without neoprene overwrap).

Recent thinking favours installation of dry air injection systems that force dehumidified air directly into the cable to keep the interior of the cable dry, thus eliminating any further corrosion. This was first developed and adopted in Japan by the Honshu-Shikoku Bridge Authority and has recently been installed on the Aquitaine Bridge in France, the Hoega Kusten Bridge in Sweden and the Lillebaelt Bridge in Denmark. Studies are currently being carried out for its applicability on some US bridges.

---

[5] See Appendix D - Item 5 for detailed Weidlinger/Faber Maunsell response on this issue. Their response is noted and confirms that the additional data to be gained by such inspection is likely to be limited. We agree with their discussion.

We would endorse FETA's decision to study the feasibility of dehumidification.

10 Applicability of NCHRP Guidelines to Forth Bridge

The NCHRP Guidelines offer the only written guidance on the inspection and assessment of parallel wire, aerially spun, main cables for suspension bridges. They were developed in the United States from experiences on American suspension bridges.

However, there are key differences between US and British suspension bridges which may cast doubt on the strict applicability of the Guidelines to the Forth Road Bridge:

- US bridges that have been investigated are *generally* much older (in the approximate range 65 to 120 years old).
- Environment and climate could be significantly different, e.g. New York summers tend to be hot and humid and the average rainfall is twice that at Forth.
- Standards of inspection and maintenance are considered to be better at Forth Bridge than for some of the US bridges, especially those that are not operated by toll facilities.
- Forth wire quality would be expected to be better and more consistent than wire from older US suspension bridges.

The Guidelines appear to be conservative in several aspects for use in the UK possibly because of some of the differences highlighted above. Weidlinger, as the main authors of the Guidelines, should be aware of these differences and are best placed to assess them, but it is not clear from any information provided within the audit if any allowances have been made other than the revised assumptions made regarding the population of wires that may be cracked. This recognised that the Forth Bridge is younger than those used as case studies when the guidelines were developed.

The Guidelines are relatively new as they were published about a year ago. They have therefore not been used on any bridges other than the two case studies used by Weidlinger. No US bridges have actually gone through a series of repeat inspections that could be used to calibrate the NCHRP methods. However, the calculation methods for current cable strength have been used in principal dating back to the late 1980's when the Williamsburg Bridge cables were evaluated in depth. The concepts presented in the NCHRP Guidelines have been generally accepted in American practice.[6]

11 Summary of Findings

- The inspection procedures closely followed the NCHRP Guidelines and current practice in the United States and can be considered reliable and accurate.
- The inspectors “shaded” the distinction between Stage 3 and Stage 4 corrosion in order to ensure a sufficiently conservative projection of potentially cracked wires. This was a reasonable practice.
- The removal of wire samples was limited to eleven wires deep from the outer surface of the cable. This is contrary to usual practice in the United States and may limit the reliability of assessing the extent of cracked wires.
- The wire testing program followed the NCHRP Guidelines and usual practice and the results appear to be reasonable and reliable.
- The calculation of the current cable strength in general followed the NCHRP Guidelines except it was assumed that cracking occurs in a limited proportion of the Stage 4 wires, which is a departure from NCHRP. This results in an estimated loss of strength of 6.7% whereas a strict adherence to the NCHRP method would yield a projected strength loss of 15.4%.[7] In view of the conditions observed this may be considered a reasonable approach.
- The calculation of future strength losses due to continued degradation may be conservative when projected more than a few years albeit that there is significant uncertainty in the methods of calculation available[8]. These calculations also departed from the NCHRP method in the assumption that initially only a portion of the Stage 4 wires were susceptible to cracking, thus yielding somewhat better strength than a strict adherence to NCHRP would have.
- Although a lower bound current strength loss of 6.7% has been examined, a figure of around 8% is best supported by the data presented in the audit process.

---

[6] See Appendix D - Item 6 for detailed Weidlinger/Faber Maunsell response on this issue. Their response is noted.

[7] See Appendix D - Item 7 for detailed Weidlinger/Faber Maunsell response on this issue. Their response is noted.

[8] See Appendix D - Item 8 for detailed Weidlinger/Faber Maunsell response on this issue. Their response is noted.

12 Recommendations for Further Work

We recommend that FETA commission the following work to begin as soon as possible:

- Install an acoustic monitoring system for the full length of both cables. This will detect breaking wires as well as their locations within the cables. Such systems are currently in use in the US on three bridges and are believed to be effective and reliable, although there has not been rigorous testing to confirm the sensitivity to wires that break deep within the cable.
- Develop a design for a dry air injection system for both cables and proceed with construction in the near future.
- Conduct additional internal inspections within five years. Subsequent inspections should include re-inspection of some of the panels inspected in 2004, as well as a larger number of new panels. The NCHRP provides reasonable guidelines in selecting the number of panels to be inspected in the future. If a dry air injection system is installed as recommended, it may be opportune to open and inspect additional panels during its installation, thus taking advantage of the presence of the contractor and approved maintenance and traffic protection procedures.
- Confirm the site specific factor of safety for the main cable rather than use a generic factor of two.

The audit has considered the latest work prepared by Faber Maunsell and Weidlinger. It would be appropriate for the audit team to complete their audit once the final calculations and report are submitted to FETA, particularly if there are any major changes to the information submitted to date.

13 Conclusion

It should be noted that this investigation was not prompted by the discovery of any concerns with the Forth Bridge Cables but as a prudent response to the result of findings in the USA. When the original scope for this initial investigation was determined, the severity of the findings was not anticipated.

Notwithstanding the above, it is apparent that the Forth Bridge main cables have deteriorated to a greater extent than that expected or anticipated prior to the initial inspection. An assessment of the rate of future deterioration has been derived, based upon the information that is presently available. However, this information is an amalgam of fact, theory and hypothesis and as such the assessment can only be verified by a subsequent inspection, probably within five years of the first inspection. It is therefore prudent and necessary for FETA to investigate the full range of options available to them to prevent or minimise the restriction or loss of use of the Forth Bridge in the foreseeable future. These options are expected to include measures to seek to retard the rate of deterioration and to reduce the loading in the main cables.

We conclude that the Faber Maunsell / Weidlinger team has performed the initial internal inspection and cable strength calculations in accordance with accepted practice in the United States and in general conformance with the NCHRP Guidelines. Certain assumptions have been made that differ from the NCHRP methods but they are reasonable and appropriate considering the particular characteristics of the Forth Road Bridge versus the older US bridges upon which the NCHRP study relied on as case studies.

We have reviewed the load assumptions and find that the dead load calculations are reasonable and that very close agreement has been reached between the assessor and the checker. The live load calculations are slightly conservative, however this will have only a small impact on the final global factor of safety

We have independently calculated the current cable strength and are comfortable that a reasonable estimate of the current loss of strength is around eight percent. We have also reviewed the projected strength degradation calculations and find them to be potentially very conservative, depending on the degradation assumptions made. A slight change in the degradation model yields a significant increase in cable life. However, the reliability of the calculation process for the prediction of the rate of future deterioration is inherently low. The process has never been calibrated against actual bridges in the United States nor elsewhere and relies on assumptions that can't currently be validated.

The degradation models become moot if prompt intervention is implemented to stop or slow the corrosion process. It has been the practice in the United States to take action when serious deterioration has been found and such action is recommended.

It is our considered opinion that while the corrosion is of serious concern if left unchecked, there is no urgency to limit the loading on the bridge at this time. However, it is strongly recommended that action be taken to protect the cables from further deterioration as soon as practical.

Appendix A – Audit Trail Document

AUDIT TASK ‘a’. Load model for main cables

Audit Group 1 – Load Assessment of the Bridge

<table>
<tr><th></th><th>Audit Item</th><th>Faber Maunsell/Weidlinger Action</th><th>Commentary/close out actions</th></tr>
<tr><td>1.1</td><td>Calculation of loading in the cable</td><td>Fairhurst and FM are have calculated the bridge dead load and are in close agreement except in an area close to the towers.
Fairhurst adopted a footway loading of 0.15kN/m, and FM adopted a footway loading of 0.15kN/m^2.
Fairhurst results are used in determining cable FOS.
Fairhurst are content that the calculated dead loads are accurate as their computer model profile matches survey work that they have performed.
FM’s check of the dead load was independent except that WAF provided them the thicknesses of the mastic asphalt surfacing</td><td></td></tr>
<tr><td>1.2</td><td>Was the assessment subject to a Category III Check?</td><td>There was no specific requirement for a formal Category III Check but there was very close correlation between the assessments made by FM and Fairhurst, independently.
As agreed at meeting with Scottish Executive on 24 Nov 05, the assessment and checking of dead and super dead loads will be subject to Cat 3 Check certification. Note that derivation of BSALL has not been subject to an independent check.</td><td></td></tr>
<tr><td>1.3</td><td>There was a small difference between the calculated dead loads in the cable. What were the FM and Fairhurst figures and which one was used?</td><td><table><tr><th></th><th>DL</th><th>DL, Ft, BSALL</th></tr><tr><td>WAF</td><td>120074</td><td>139736</td></tr><tr><td>FM</td><td>122590</td><td>142130</td></tr></table>The FM model is our third one, which we considered to be the most accurate.
It was agreed at the meeting with Scot Exec on 24 Nov 05 that the WAF cable loads would be adopted. This reflected Fairhurst’s greater knowledge of the bridge.
Note that Fairhurst used 0.15kN/m footway and FM 0.15kN/m^2.</td><td></td></tr>
<tr><td>1.4</td><td>How has the Live Load</td><td>A Bridge Specific Live Loading (BSALL) has been derived for the structure by Fairhurst. It appears to have been calculated</td><td>We have no issue with this at such lengths, since individual odd vehicle weights will not</td></tr>
</table>

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
	been calculated?	BSALL using a rectangular influence line, where successive sequences of weights of groups of vehicles were looked at with length sufficient to fill the bridge. The BSALL is based on a 3 week period in September 2002 and 2005. Vehicle spacing was taken as 1.5m. The BSALL used in the FOS calculations is based on 2002 data only.	be very important.
1.5	What limits of exceedence were set?	WAF used 5%/120 years / 1.20 = HA, which is normal.	
1.6	What jam assumptions were made?	Traffic jam assumptions are based on records and on incident clearance times (in the order 30 minutes each usually).	Sensitivity is not too great.
1.7	What lane choice assumptions were made?	Lane choice – if lane was not filled they allowed nest vehicle to move over.	This is only really relevant at low traffic flows and is not unreasonable
1.8	What lane load factors were used?	Lane factors: They were quite conservative. They calculated Lane 1, and joint 1+2, and Lane 2 as well. They found Lane 2 alone to be about 0.35 times Lane 1, and had they derived Lane 2 from the Lanes 1+2 total less Lane 1, Lane 2 would have been smaller again. So their use of 0.66 is very safe-sided.	It appears that the process has been logically constructed in accordance with HA recommendations. It is almost certainly safe-sided owing to conservatism especially in Lane 2 loading.
1.9	How was the opposite carriageway loaded?	Opposite carriageway they used average weight of traffic jam (“Turkstra’s rule”) which FNP has used in the past. This gave them 0.33 factors at longest loaded lengths.	This is not too surprising for road with so many cars. We would expect to model simultaneous 4 lane effects, since opposite direction jams are so common. This would not make much difference.
1.10	What vehicle spacings were used?	Vehicle spacings: they used 1.5m between leading and trailing edges.	This is not too different from 5m from axle to axle which is what Eurocode suggests. Their gaps are based on approximate site observations.

AUDIT TASK 'b'. Strength Model of main cable

Audit Group 2 – Requirements for Cable Inspection

	Audit Item	Faber Maunsell/Weidlinger Action	Audit Team Commentary/close out actions
2.1	Why was a cable inspection carried out?	Alastair Andrew (FETA) attended a workshop in 1998 in the US at which the methods of inspecting and assessing main cables were discussed. This led onto the draft NHCRP Guidelines issued in 2002. These recommended that intrusive inspection of cables in major suspension bridges be carried out after thirty years of service and thereafter every ten years. The FETA board were advised of this and they took the decision to implement this draft recommendation. At this stage the bridge was 38 years old but was the oldest major suspension bridge in Europe.	Tamar Bridge in Plymouth is an older suspension bridge but this has locked coil strands, not parallel wires. Limited inspections have been undertaken at Tamar Bridge but no significant remedial work has been proposed as a result of the findings of those inspections.
2.2	How were the consultants selected?	Prequalification then price (30%)/quality tender (70%)	Team given high marks for choosing Weidlinger as sub-consultants because they are the authors of the NHCRP Guidelines.

Audit Group 3 – Scope of Inspection

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
3.1 3.2	What work was carried out in the initial desk studies? How were areas of the cable selected?	The scoping study comprised a review of the construction history and records followed by a visual inspection of each section of the cables. These were examined for defects that might have permitted moisture ingress, such as cracked or missing paint; loose wrapping etc. These were determined from the scoping study and previous experience from the US.	
3.3	What were the reasons for the selection	The NHCRP recommendations suggest that six panels should be inspected, but eight potential locations were originally selected based on the scoping survey, previous US experience and on the basis that the chosen locations would give a good	

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
		spread of results across the complete length of the cables. Two more panels were added as a reaction to the results from the first four panels as those results were varied and some panels were worse than expected. The inspections were targeted at what was thought to be the worst affected panels and those for which results could be obtained quickly bearing in mind the access problems and the desire to complete the work within one season.	
3.4	In what ways (if any) did the results of the external visual inspection correlate with what was found in the later detailed internal inspections?	Generally where there were large areas of paint damage or circumferential cracks in the paint, the outer wires beneath these areas were found to be in poor condition. However, after opening up the groove in the affected area, it was found that the internal wires were not necessarily in the same condition. Generally panels had evidence of dampness on the underside of the cable which was confirmed when unwrapped.	No reliable evidence of correlation – it cannot be assumed that the panels selected for internal inspection would be the worst condition.
3.5	Were other areas of the cable inspected such as the anchorages, the cable between the side span towers?	Approximately one third of the strands in the anchorages were inspected from scaffolding. The cables under the shrouds adjacent to the side saddles were inspected. Loose wires were found which related back to broken wires within the side saddles. The side saddles are not internally galvanised so it is possible that the failure mechanism for these wires is different. (Refer to report for West 00S-02S). It was also not possible to repair those wires that were broken within the saddle. Most of the broken wires were left in place to avoid leaving a void.	
3.6	How many of the four anchorages were inspected?	Strands were inspected in each of the 4 anchorage chambers. There are 37 strands in each anchorage, each of which splay into 4 sub-strands as they approach the strand shoe. 12 out of the 37 strands were selected in each anchorage and 2 of the 4 sub-strands in each of the 12 strands were wedged open both horizontally and vertically for inspection.	
3.7	Have the circumferential seals around the cable clamps been closely inspected?	Seals were visually inspected as part of the scoping study and condition survey prior to unwrapping and were generally found to be in good condition. The undersides of the cable bands are not caulked. Above deck level, the sealant was replaced during hanger replacement in 1998-9.	

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
		In each panel inspected only the upper seal was removed and the outer wires inspected prior to rewrapping. Generally, there were crossed wires close to cable bands but the external wires in this area generally appeared to be in good condition.	
3.8	Have any portions of cable inside the tower or other saddles been inspected?	No. The main tower saddles have C clamps like Severn, therefore access is impossible. FETA expressed great concern over removal of cover plates on side tower saddles as there is only a small fos against bursting. The wires under all 4 side tower cable sleeves have been inspected and the wires beneath the cable sleeves at the top of the north east tower have been inspected in both the main and side spans.	How small is the factor of safety against bursting?
3.9	Which areas were not inspected?	The length of cable between the side saddle and the face of the anchorage was not inspected because nothing un-toward was found in the scoping survey; access is very difficult and that length of cable is less exposed to the elements than other lengths.	
3.10	Were the selected areas influenced by other findings?	The direction of wrapping is known for each section of cable and it was originally postulated that the direction of wrapping may have had some influence on the recently observed levels of corrosion. It is thought that wrapping downhill is preferable to wrapping uphill as the former allows any trapped moisture to escape as the cable is compacted.	This is not considered a valid postulation. All cables are subjected to wetting (at least) during the lengthy construction period, and will all start out their lives with some moisture in them. This initial moisture will have its free oxygen consumed in a short time, limiting the amount of corrosion it can cause. The damage we see today is the result of continuing intrusion of moisture by rain and passage of moist air into the cable under varying barometric pressures.
3.11	How was consistency of inspection assured?	The inspection was carried out throughout by two dedicated inspectors, Beverly Camfield and Kevin Wood. The inspections were occasionally replicated by Weidlinger inspectors, Ron Mayrbaurl and Sante Camo and the results were compared. There was little variation in the recorded condition of the wires. In addition, on their UK visits, Weidlinger inspectors would "oversee" FM inspections at random segments.	Weidlinger reports that both Ron Mayrbaurl and Sante Camo trained the FM inspectors and audited their work.
3.12	When a panel was	There was very close correlation between Weidlinger and FM's	

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
	inspected by both Weidlinger and FM and there were variations in the assessed condition, were they all 'one way' or 'give and take'?	wire gradings. The occasional differences were between late stage 2 and early stage 3, generally 'give and take'. Only two inspectors from FM carried out the entire inspection and their comparisons in results were practically identical. It is worth noting that the same inspector carries out the visual inspection of wires in a groove and selects a wire of a particular classification of corrosion level for tensile testing. Therefore the tensile test results for each corrosion stage will be consistent with the corrosion classification given by the inspector for each panel.	
3.13	When there were variations, what was recorded, the worst condition?	Yes.	
3.14	Was the recording of the stages of corrosion strictly in accordance with the NCHRP Guidelines?	Yes.	

Audit Group 4 – Inspection Findings

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
4.1	How was surface damage recorded at inspection panel sites	This was recorded photographically and also by hand. A typical record sheet has been forwarded to FNP by FM. FNP were shown photographs showing the external condition of the cable prior to wedging and photographs taken looking into a groove. The photographs did not clearly show the condition of the wires at the bottom of the groove.	Within the NCHRP Guidelines, surface wires around the perimeter of the cable are not required to be inspected prior to wedging. Their condition is assumed based upon the condition of the surface wire at the wedge position.
4.2	Condition of corrosion protection	The original red lead paste was always found to be crumbly and dry as expected by NCHRP Guidelines.	This is consistent with inspection findings in the US and Lisbon, Portugal.
4.3	Was any damage attributed to the inspection processes?	There were 2 wires (out of the 86 total broken wires) where there is a possibility that the inspection process may have contributed to their failure:–	

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
		1. W100S-100N - One additional wire break was noticed after inspection had been carried out; this wire may already have been broken but the ends not evident until wires were disturbed during inspection. 2. E100N-98N – One additional outer wire was observed to break at the start of compaction and was subsequently repaired. However, it is likely that these wires were already cracked and near failure.	
4.4	Broken wires	Broken wires were usually found in the outer six layers. However, broken wires deeper within the cable were more difficult to find as the broken ends of the wires did not spring out like those in the outer layers. Some broken wires were found deeper in the cable but only when they were on a wedge line.	NCHRP Page 2-22 recommends additional wedge lines, particularly where several broken or Stage 4 wires are found or if cable larger than 24” diameter.
4.5	Method of recording wire condition	The method followed strictly the NCHRP guidelines. The report “tree circle” plots record the worst recorded condition of an individual wire over a 75 to 150mm length within the total length of groove opened up. Records of the condition of the wires at each ring of wedges are available and samples were sent by FM to FNP. The condition of the wires at the bottom of the groove was assessed by eye with the aid of two powerful torches; endoscopes were not used.	Based on our review, it appears the methodology is consistent with the practice in the US.
4.6	Presumably, only the condition of the visible face of each wire was noted?	Yes.	
4.7	When extra wedge lines were applied in two of the inspected sections it is noted that in both cases they allowed a less onerous condition to be recorded. Should more have been done?	The inspection was carried out in accordance with the NCHRP Guidelines which recommends 8 groove locations around the perimeter. The additional 9th groove opened in two of the panels was specifically to investigate areas where a large congregation of stage 4 corrosion had been found in an adjacent groove, as well as to search for internal broken wires. It should be noted that a 9th groove was opened up at E100S-100N which allowed a slightly less onerous condition to be recorded. However, even with this refinement, this panel was found to contain the largest proportion of stage 4 corrosion out of all ten panels inspected and was subsequently used for the	NCHRP Guidelines recommend additional wedge lines, particularly where several broken or Stage 4 wires are found or if cable larger than 24” diameter. (Forth main cable diameter is approximately 24” diameter).

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
		strength calculation.	
4.8	Stages of corrosion	No correlation between wire breaks and stage four corrosion.	
4.9	Impact of saddle wire breaks?	Considered by FM/Weidlinger to be due to lack of zinc spray at anchorage	
4.10	Recording of pits	Only observed one wire.	
4.11	Position of cracks vs. cast and vs. sector vs. longitudinal position	The wire cracks always initiate on the inside of the cast. FM estimate the residual stress to be 30 ksi (207 N/mm^2) and a stress from straightening of 37 ksi (255 N/mm^2)	
4.12	Was foreign material embedded in the cable associated with locally worse wire conditions?	Yes, embedded pieces of timber and seizing straps which should not have been left inside the cable have caused locally worse wire conditions. Internal seizing straps are impossible to remove during construction.	Inspection records indicate the presence of wood and rope in a few locations. This material has promoted corrosion of the wires in contact with it.
4.13	PH measurements	All PH measurements were neutral or slightly alkaline. Weidlinger reports that PH measurements have been taken where moisture was found on the cable surface.	They appear to be in the range PH 6 to PH 9, but there is no obvious reason for the variation.
4.14	Were all wire failure separations measured and what was the range of dimensions?	Measurement was not practical everywhere. Where gaps between the ends of broken wires were measured, measurements were in the order of 50-55mm.	
4.15	Were all wire sample separations measured and what was the range of dimensions?	All gaps resulting from cutting sample wires were measured. Of the 80 sample wires removed gaps varied from 40-110mm with an average of 55mm. The larger gaps were found in the panels adjacent to the side tower saddles (longer panels).	
4.16	Under the NCHRP guidelines, (C2.2.5.4 and C2.4.3.2.3) should a clamp have been removed as part of this investigation?	C2.2.5.4 refers to the second inspection, not the first. Note that U.S. bridges have suspenders at 20 to 30ft centres, Forth is 60ft. We did consider briefly removal of a clamp, but felt that the significant and expensive temporary works were not justified for the first inspection.	In view of the Stage 4 severity at several locations and that Panel 6 was adjacent to the previously inspected (and worst condition) Panel 1, removal of a cable clamp may have been warranted and should be considered for the future inspections.
4.17	Samples taken for testing	Samples of wires for testing were only taken from the outer eleven layers.	This is not common practice as it may not be representative of the larger population of

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
			wires throughout the cable cross-section.
4.18	Was consideration given to removing wire samples from deeper inside the cable by using a special tool?	It was not considered feasible to remove wires deeper due to clearance problems with the remaining wires within the wedge when cutting, re-splicing and re-tightening. Even if a special tool could be designed to pull a deeper wire out of the wedge, access for cutting and re-tightening would be very limited and damage to neighbouring wires would be more likely. FM stated that their policy was to avoid any further damage to the main cable and therefore decided not to remove samples from areas where they could not replace the wires.	
4.19	Cable diameter measurements/ voids ratio at re-closure	Extensive cable diameter measurements were taken to ensure to correct level of re-compaction was achieved.	
4.20	Was satisfactory re-compaction of the cable always achieved?	Generally satisfactory re-compaction was achieved. There were localised areas around crossed wires and areas where a number of repairs to broken wires had taken place where compaction was fractionally less than the rest of the panel.	
4.21	Were the number and type of wires tested strictly in accordance with the guidelines?	The wire samples selected were in proportion to the quantities of each corrosion stage recommended in the NCHRP report.	
4.22	Were the samples selected from representative locations within the cross-section or limited to outer wires?	The wire samples taken were limited to the depth from which they could be removed – up to 11 wires in from surface.	
4.23	Water analysis	An analysis of a water sample was made but FM advised against placing too much reliance on the results.	Weidlinger states that they believe the water analysis is reliable. It is postulated by Weidleinger that the PH is rapidly neutralized by the corrosion process.
4.24	Static testing – what was the strain rate and were all samples taken to failure?	All wire tests were taken to failure. On nine out of ten tests the extensometer was removed at about 2% elongation. The extensomer was left on for only one in ten tests so that the risk of extensometer damage was reduced.	Weidlinger reports that all wire sample were tested to failure – about 700. About 10% of these had strain measured to failure. The others had strain measured to about 2%

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
			elongation, after which the extensometer was removed and the test continued to failure. Chemical analysis at the fracture surfaces has not been performed.
4.25	Fatigue testing	No fatigue testing of wires has taken place. Fatigue testing is very useful to fairly quickly find cracks in the wires, but each specimen must be fatigue tested. This does not leave any specimens to use for determining tensile strength, as the ENTIRE LENGTH MUST BE FATIGUE TESTED SINCE WE DON'T KNOW IN ADVANCE WHERE THE CRACKS ARE. The normal tension tests are very efficient in finding cracks if the failure surface is carefully inspected; the elongation at failure and the tensile strength of each specimen are extremely good indicators as to which specimen may be cracked. The only way that we would accept fatigue testing is if we doubled the number of sample wires removed, using half for fatigue tests and the other half for tensile tests, both an expensive proposition as well as putting more ferrules into the cable that introduce voids.	Fatigue testing is not specified in the NCHRP Guidelines because it is recognized that fatigue is not normally an issue in the cable service loads. However, it is our experience that fatigue testing is useful in identifying incipient cracking in wires that perform well in static tests. This may be advisable in determining a more reliable estimate of the percent of cracked wires in the stage 3 and 4 population. Faber Maunsell/Weidlinger's comments (opposite) are noted. It was agreed that this would be reviewed again in the brief for the Lehigh University Tests programmed for early 2006.
4.26	Beyond which layer were repairs impossible because of difficult access?	Repairs were not possible beyond 11 wires in from surface.	
4.27	Corrosion protection re-establishment – lead paste/wrapping/painting	Red lead to the original specification has been applied together with an improved paint system on top of the wrapping wire.	
4.28	Selection of testing establishments	FM were very pleased with the firm selected to carry out the wire testing. Bodycote did a very professional job.	
4.29	Has consideration been given to re-inspection of the panel which is in the worst condition ?	No, this is not a requirement of the NCHRP guidelines.	
4.30	Stress/strain plots	FM to supply FNP with some typical Stress/Strain plots including plots for wires with pre-existing cracks. Four plots were handed over on 24.11.5, refs 111.10; 151.10;	

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
		171.09 and 171.10. Ron Mayrbaurl states that 80 specimens have full plots to failure and that the wire is uniform and ductile.	

Audit Group 5 – Cable Strength Assessment

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
5.1	What was the original wire specification?	The wire was manufactured at Dorman Long works in Lackenby. There was only one source for the steel but early results showed two types of Stress/Strain curve. Some wire samples had 0.7% carbon and others 0.8%. FM provided details of the wire specification to FNP.	Original spec called for .75 to .80% Carbon. Four samples have been tested for chemical analysis and ranged from 0.74% to 0.80%, indicating good quality, uniform wire (based on these very limited number of samples). Weidlinger reports that there is apparently good correlation between tested wire strengths and carbon content (the stronger wires having the higher carbon) as expected.
5.2	Has any loss in strength of the cable as it passes around saddles and shoes been taken into account?	No. The major effect on cable strength is cracks in the wires. At strand shoes, the bend is considerably sharpened, which reduces the tensile stress on the inside of the curvature of the wires. We have not found cracks in these wires on three bridges on which wires were removed from around the strand shoes, only general corrosion resulting in loss of area leading to failure of wires. The increased curvature should not have an effect on the strength of a "good" wire. The curvature around saddles also reduces the tensile stress on the inside of the wire cast. Several wires were found broken about 8" inside the cable bent saddle at one location. These wires failed by cracking in the tangent area where the wire separates from the saddle. The transverse pressure on the wires at the bottom of the saddles will reduce the yield strength in longitudinal tension slightly, and probably also the tensile strength, but this was not	

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
		considered.	
5.3	Broken wire vs sector	No analysis of the positions of wire breaks has been performed.	Weidlinger states that with few exceptions broken wires tend to be located within the outer 6 wire rings. Our review of the preliminary report confirms this.
5.4	Cracks vs Stage of corrosion		Ron Mayrbaurl reports that Weidlinger used a slightly modified Stage classification. Stage four wires are defined as having 25% or more of the surface corroded rather than 30%, as specified in the NCHRP Guidelines. This results in a larger percentage of Stage 4 wires and no cracks found in wire classified as Stage 3. Weidlinger is currently reassessing the strength calculations, considering the outer six wire rings as a separate population. This further reduces the projected number of cracked wires, as they are a larger percentage of a much smaller population than the entire Stage 4 population.
5.5	Establishment of crack initiation mechanism	It is understood that FM have instigated research into the causes of crack initiation. No conclusions have been presented.	The exact mechanism of crack initiation is still not fully understood. However, in general it is commonly accepted that it begins with embrittlement due to hydrogen absorption. The hydrogen is generated by the galvanic reaction of the zinc-iron-electrolyte battery. The embrittled wire surface is made susceptible to cracking at pre-existing flaws or corrosion pits.
5.6	What progress has been made to determine the mechanism for crack initiation?	Work is just starting at Lehigh.	
5.7	What percentage of Stage 3 wires have been assumed to have cracks?	None. Tests on 17 Stage 3 wires did not find any cracks. On another bridge, where 3 or 4 cracks were found in wires that were graded Stage 3, two panels were reopened after a few years and samples of Stage 3 and 4 from greater depths removed for testing. No cracks were found in Stage 3, and two of the	

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
		previously tested samples were looked at again; it was determined that they were on the borderline between Stage 3 and Stage 4, and that Stage 3 should be considered without cracks.	
5.8	Calculation of remnant strength based on results of testing	The calculation of the rate of deterioration of the cable strength is based on NCHRP Guidelines which are derived from data from US bridges.	The calculated cable strength is based on the extrapolated number of w ires in each Stage of corrosion as inspected and the tested strength of the wires in those stages, not on any US data. The *rate* of deterioration has been projected using a calculation method proposed in the NCHRP Guidelines. It is based on several assumptions and some very limited (and ongoing) laboratory testing conducted in the US to determine corrosion rates in accelerated corrosion testing chambers.
5.9	What information has been used to model the deterioration through the various stages of corrosion?	The question is assumed to mean "what information has been used to model the deterioration over time?" The starting point is the condition of the cable at the time of inspection. Additional information used is from a study underway in Boston, in which wires under tension are subjected to "environments", either liquid or damp, that would cause first the zinc to dissolve (react to the acidity in the environment) and then the steel underneath to corrode. Each series of tests is scheduled to run for 2 years. In the first series, four of the specimens yielded useful data that indicate that the time taken from one stage to the next is linear up to Stage 4. Thus far, stage 4 has not been exceeded, and no cracks have been initiated. The next series, that is now underway, has been designed to use the most promising environments to attempt to advance corrosion into crack initiation, as well as to verify the data from the first series. In the absence of actual data, it has been assumed that the time from reaching Stage 4 to initiation of a crack, and then for crack growth and failure, and then further to failure of all wires in the group being evaluated is at the same rate.	

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
		Other data used is the location of broken wires in the cable (mostly on the bottom, with one on the side of the cable; the location of cracked wires found in the samples removed (mostly on the bottom and one on the side); and the depth of broken wires and cracked wires inside the cable (again, mostly in the outer six rings, except for three in the interior, one of which is clearly caused by a piece of wood found in the cable. Using the condition at inspection as the starting point, the progression of Stages (or "categories", since the calculation must advance beyond Stage 4) at any location in the cable is a linear calculation.	
5.10	What is the original strength of the cable based on the brittle wire model, and how does this compare with the nominal assumed original strength of the cable.	Original nominal design strength is 349274kN. Original brittle wire strength is 345198kN.	
5.11	C2.2.5.2 of the guidelines gives an estimated error in the minimum strength calculation based on the adequacy of sampling. What estimated error has been calculated?	This has not yet been estimated. It is a time consuming procedure. It will probably be on the order of 5 to 7%.	The response does not appear to fit with the estimated error anticipated in the Guidelines.
5.12	Has the effect of the wrapping wire on the development of tension in broken wires been taken into account?	This would increase the estimated cable strength, but only if the wrapping is removed over several contiguous panels during an inspection prior to measuring wire end separations, in which case the calculated effective development length will be too long, resulting in too low an estimated strength. Since the wrapping was not removed from panels adjacent to the evaluated panels in this inspection (with the exception of one panel adjacent to E100S-100N, and then only after wire end separations were measured), the effect of wire wrapping is automatically included in the calculation of the effective length. The development of tension is only applied to wire breaks in	

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
		adjacent panels, not to wire breaks in the evaluated panel. Some measurements that have been made indicate that, for surface wires, the wrapping could redevelop the wire tension in as little as ten feet, but no information is available for deeper wires (The wire tension is not the same as the wire strength!). We consider that ignoring the wrapping wire is conservative. On the Forth Bridge, the effective development length has been estimated as 5 panels (a broken wire will redevelop its strength in two panels (i.e., after passing through three cable bands).	
5.13	When were the cable clamp bolt tensions last checked and what proportion of the bolts needed re-tightening?	The cable band bolts were replaced in 1998-99. No retensioning has been carried out since.	
5.14	Reliability analysis Contribution of broken wires	The contribution of broken wires to the strength of the cable away from the breaks has been taken into account in the calculations.	This is standard practice.
5.15	Have the repaired and replaced wires been taken into account?	Yes	
5.16	What are the latest figures for loss of strength?	Current cable strength (based on nominal fraction of cracked wires and only outer 6 rows containing cracked wires, brittle wire model) is 322095kN. Original strength (brittle wire model) is 345198kN.	

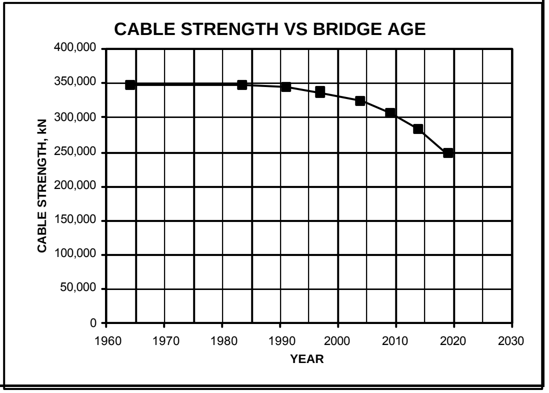
AUDIT TASK ‘c’. Estimation of a deterioration model

Audit Group 6 – Deterioration Modelling

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
6.1	Would say 12 months of acoustic monitoring provide any data useful for the deterioration model?	Acoustic monitoring will provide data on wire breakage rate and location only. It will not provide data on rate of corrosion – e.g. rate of stage 3 to stage 4.	
6.2	How has Weidlinger calculated the rate of strength degradation in future years?	Weidlinger has used the hypothesized method presented in the NCHRP Guidelines, which are not supported by historical or other data except for some limited laboratory testing conducted in the past at Columbia University and currently underway at Altrans in Massachusetts. These tests have attempted to mimic the conditions inside a bridge cable and produce accelerated corrosion conditions that could be correlated with the observed conditions on bridges. We will review the methodology and results in detail as soon as we receive the calculations from Weidlinger. In the first deterioration model presented, no loss in strength has been assumed for the first ten years. Thereafter, a linear deterioration from Stage 1 to Stage 4 has been assumed.	This is related to the calculation of remnant strength discussed above.
6.3	In the deterioration model it is assumed that the cable begins to deteriorate from Day 1, but at what age is it considered that strength loss begins?	From the table in 6.6 below, it can be seen that strength loss starts to occur just before 1991.	
6.4	What is considered to be a ‘wide’ range for carbon content? i.e. at what point does the ‘Brittle Wire Method’ become the inappropriate method to use for the estimation of	On the Williamsburg Bridge, the carbon content varied from 0.60% to 1.00%. This is a wide range. On the Forth the carbon content varies from 0.74% to 0.80%. This is a normal range for bridge wire, that results in an approximately 2% lower cable strength when using the brittle-wire model. (see below, under brittle-wire vs. limited ductility models. No investigations have been made into the exact range that would be considered too	

<table>
<tr><th></th><th>Audit Item</th><th>Faber Maunsell/Weidlinger Action</th><th>Commentary/close out actions</th></tr>
<tr><td></td><td>cable strength?</td><td>wide.</td><td></td></tr>
<tr><td>6.5</td><td>Using the brittle wire model may give a conservative estimate of the loss in strength. What would be the difference if the limited ductility model was used?</td><td>This will be the first bridge inspection in which a reasonably accurate calculation using the limited ductility model will even be possible, since most tensile tests have the extensometer removed from the specimen at a maximum of 2.5% elongation, nowhere near failure. An estimate made using this model on another bridge with the ultimate strain for each sample wire calculated by projecting upward from the elongation measured after failure using Young's modulus resulted in a cable strength that was 3% greater that that found using the brittle-wire model.

Weidlinger has developed a revision to the brittle-wire model that uses the full length stress-strain diagrams that were developed for one specimen from each of the 80 sample wires removed from the Forth Road cables. This should bring the results from the brittle-wire and limited ductility models closer, as the wires in both models will break in the same order. Preliminary results indicate that this revision will result in about a 2% increase in the current cable strength at panel E 100S-100N and about 3% for the new cable condition. The final numbers will be provided after checking.

The application of the limited ductility model is still to be done; the data from the above mentioned analysis is to be used for this.</td><td></td></tr>
<tr><td>6.6</td><td>What are the latest estimates of Factors of Safety and over what future period are they projected?</td><td>
<table>
<tr><th>Year</th><th>nom cbl strength kN</th><th>strength loss %</th><th>FOS</th></tr>
<tr><td>1964</td><td>345198</td><td>0.0%</td><td>2.47</td></tr>
<tr><td>1983.4</td><td>345,198</td><td>0.0%</td><td>2.47</td></tr>
<tr><td>1991</td><td>343,321</td><td>0.5%</td><td>2.46</td></tr>
<tr><td>1997</td><td>336,777</td><td>2.4%</td><td>2.41</td></tr>
<tr><td>2004</td><td>322,095</td><td>6.7%</td><td>2.31</td></tr>
<tr><td>2009</td><td>305,838</td><td>11.4%</td><td>2.19</td></tr>
<tr><td>2014</td><td>282,327</td><td>18.2%</td><td>2.02</td></tr>
</table>
</td><td> </td></tr>
</table>

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
		2019 247,446 28.3% 1.77	
6.7	What is the latest deterioration model plot?	See Deterioration Model Plot, opposite	

AUDIT TASK ‘d’. Establishment of acceptable reliability levels for the structure

Audit Group 7 – Establishment of Acceptable Factor of Safety

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
7.1	Are the FoS conclusions based on the maximum load being applied to the worst section of cable?	Yes, on the basis that only a small sample of the cable has been inspected.	
7.2	Is adopted practice consistent with UK practice on reliability?	The use of a single factor for all structures is not supported by the reliability based methods of analysis in use in the UK. However, the use of a global factor as an indicative value is not without merit, but must recognise the relative uncertainty in the load prediction and strength assessment of each individual structure.	

Audit Group 8 – Deterioration Intervention

	Audit Item	Faber Maunsell/Weidlinger Action	Commentary/close out actions
8.1	What is being proposed as an intervention strategy?	FETA is seeking consultancy services for dehumidifying the cables.	

Appendix B – Register of Audit Documents

Incoming Document Register

Print date : 18-Dec-05

Project : Forth Road Bridge - Audit of the main cable inspection and assessment

Job No. : 1023

Document Type	Document Title	Document Number	Rev.	Date Received	Location Stored	Distribution
Report	FETA - Main cable - Post Inspection	-	-	3.11.5	e mail	DKM/IF 3.11.5
	Strategy Briefing Paper					
P'sentation	FETA presentation to ministers 2/11/5	-	-	3.11.5	File	DKM/IF 3.11.5
Report	FM report (shortened)	First draft 28 Sep 05	-	11.11.5	File	DKM/RNA/AW
e mails	Fairhursts to FETA 10/10/05	Shanks to BC 18.03	-	16.11.5	File	DKM 17/11/05
	Fairhursts to FETA 10/10/05	Moran to BC 10.57	-	16.11.5	File	DKM 17/11/05
	Fairhursts to FETA 11/10/05	Shanks to BC 16.28	-	16.11.5	File	DKM 17/11/05
	Fairhursts to FETA 1/11/05	Allan to BC 13.35	-	16.11.5	File	DKM 17/11/05
Letter +	FM to FNP (Stone and London)	34901/800/01	-	21.11.5	File	A&W 21.11.5
information						
Information	Cable strength calcs for 100S-100N East;	-	-	22.11.5	-	AW
	Summary wire sample test results					
	Summary wire conditions 100S-100N					
	Calc of prob max no of cracked wires St 4					
Graphs	Bodycote wire load/extension graphs	111.10;151.10;171.09	-	24.11.5	File	DKM/RNA/AW
				(by hand)		
Graphs	FM letter to FNP Stone	151.10;171.10363.109	-	30.11.5	File	DKM/RNA/AW
	ref 34901/800/02					
Summary	Stress strain variation plot	Camfield to RNA/DKM	-	30.11.5	e mail	RNA/DKM/AW
Graph by						
e mail						
Calculations	Est of future cable strengths, brittle wire	Hand delivery to AW	-	30.11.5	-	AW
and results	model, one panel inspected, future cable	from Weidlinger				
	strengths, cable divided into 3 zones					
Information	Wire carbon contents graph	e mail to AW from	-	6.12.5	-	AW
		Weidlinger				
Calcs	For cable bottom zone	By hand Weidlinger to	-	8.12.5	-	AW
		AW				
Calcs	56120.00 to 56120.08 nominal cable	e mail to AW from	-	8.12.5	-	AW
		Weidlinger				
	50120.01 summary of current cable	e mail to AW from	-	8.12.5	-	AW
	strengths	Weidlinger				
	91003 List of calculations	e mail to AW from	-	8.12.5	-	AW
		Weidlinger				
Audit trail	FM and FETA responses to additional	e mail to FNP from FM	-	15.12.5	e mail	FNP/AW
answers				and		
				16.12.5		

Appendix C – Commentary on Notional Factors of Safety

C Notional Factors of Safety

C.1 Introduction

Bridge design standards changed several times during the latter half of the 20th Century. These changes affected load specifications and safety margins.

Safety of civil engineering structures is normally assured by applying safety factors to provide a margin between theoretical strengths and theoretical loading effects. Neither strengths nor loads can normally be exactly established, so they are represented by mathematical models based on observation and experiment. Some aspects of designs (such as structural weights) can often be assessed more accurately than others (such as road traffic load effects). More modern UK design standards cater for such variations by providing higher safety factors to those parts of the calculations where uncertainty is greatest.

This section of the document discusses the derivation of appropriate safety margins for the main cable of the Forth Bridge

C.2 BS153 Assessment

The Forth Bridge was originally designed to the current British Standard, BS153. According to the original designer's published information in the ICE paper (1967), the theoretical strength of the wires was 100 tons/sq.in, or 1550 N/mm^2. The working stress in direct tension was defined as 40 tons/sq.in., or 620 N/mm^2. The design target factor of safety was thus 2.50.

The cross section area was 350 sq. ins, (225800 mm^2), and the 0.2% proof stress was taken to be 75 tons/sq.in., giving the relationships between loading and resistance in Table 1.

Item	Force	Relative value
Theoretical dead load per cable	12,150 tons	0.866
Theoretical live load per cable	1,430 tons	0.102
Theoretical total load per cable	13,580 tons	0.97
Allowable working load per cable	14,000 tons	1.0
Theoretical proof strength (permanent yield begins)	26,250 tons	1.875
Theoretical breaking strength	35,000 tons	2.50
Overall Factor of safety	**35,000/13580**	**2.58**

Table 1: Original Basis of Design Relationships

Therefore actual theoretical safety factor between the theoretical load and breaking strength was 2.58, and the safety factor between load and the permanent extension was 1.9.

At that time, the safety factor between load and yield capacity for steel structures was usually approximately 1.7.

C.3 Cable Angle Effect

The maximum cable loads presented in Table 1 appear at the top of the side span cables, where the slope is steepest. The cable slope at this point is close to 25°. Therefore we can deduce that the theoretical cable forces at the middle of the main span (where the cable is horizontal) are reduced to 91% of the Table 1 values.

The theoretical factor of safety at mid span was thus originally 2.83.

Since that time, the theoretical live load model has become heavier, thus reducing the theoretical safety factors. A 50% increase in live load would lead to a theoretical safety factor of total load of 2.45 in the side span near the tower tops, and 2.69 at mid span.

C.4 Review of Other Bridges

C.4.1 Severn Bridge

At the Severn Bridge (built shortly afterwards) the overall theoretical factor of safety that was used to prepare the design for the main cable was reduced from 2.5 to 2.25. This implies that, at the centre of the main span, the factor of safety was close to 2.45. (The cable geometry is slightly different).

This implies that the cable at Severn is some 10% less strong relative to the theoretical loads used in design than the cable at Forth Bridge.

C.4.2 Messina Crossing

The design specification for the projected Messina Crossing bridge differs from UK practice. A summary of the main cable design requirements follows.

Strength factors are:

- At SLS, main cable load <= Ultimate stress / 2.10
- At ULS, main cable load <= Ultimate stress / 1.67

Load factors are:

- 1.15 for steel elements
- 1.25 for concrete elements
- 1.50 for non-structural elements
- 1.50 for "dense variable load" = traffic load, deterministic model used that is not perhaps too different from HA

Therefore the "factor of safety" against ultimate strength is somewhere between:

- 1.15x1.67 = 1.92 for steel weight
- 1.50x1.67 = 2.50 for superimposed load and live load

If we assume (without actual figures being available) that the superimposed plus live load portion is some 20% of the total, this implies a factor of safety of close to 2.1.

If the total of superimposed load plus live load was 15% of total (which is probably more realistic), the factor of safety is then only 0.15x2.5 + 0.85x1.92 = 2.007, or close to 2.0.

It is notable that, at Messina, the partial factor on material strength has been reduced to a value that is close to the BS153 overall safety factor for steel bridges. However, the BS153 factor at that time included safety margins on live load etc. so the Messina criteria for cable design are still considerably more onerous than traditional Mid-20th Century design requirements for structural steel elements in bridge works.

C.4.3 Eurocode Recommendations

The Structural Eurocodes present another set of values. It is again difficult to make direct comparisons. In particular, prEN 1993-1-1, "Design of structures with tension components" specifically excludes aerial spun parallel wire suspension bridge cables from its scope, although it does state that some of its provisions may be applicable. It recommends that the limiting strength of parallel wire strands be the lesser of the proof strength (with a factor of 1.0) and the theoretical breaking strength divided by 1.50. The proposed Eurocode partial factors are different from current UK practice, and the National Annex values have not yet been ratified and are not in the public domain. However, the proposed strength factors on normal structural steelwork are currently equal to 1.00. If we assume that the reliability currently implied by UK structural steel design codes will not be significantly altered by implementation of Eurocodes, we see that the Eurocode system still requires parallel wire cables to have factors of safety 50% greater that those for structural steelwork.

Since the current UK partial factor system provides similar structural economy overall to that obtained using BS153, we see that the Eurocodes, as implemented in the UK, are likely to provide a factor of safety for parallel wire cables close to 1.7x1.5 = 2.55. This is as we saw with the Forth Bridge in the ICE paper of 1967.

C.5 Target Reliability and Safety Factors

The main cable of a suspension bridge comprises typically several thousand parallel wires, each of which has been created by a process that requires it to withstand the tensions of the wire drawing process whilst it is being manufactured. The large number of parallel elements allows a very reliable strength model to be developed for a new cable. Therefore, a new main cable is one of the most reliable structural elements that an engineer can specify. The obvious question is why they are then provided with higher safety factors than any other structural element.

There appear to be a number of reasons, some of which are more easily justified than others. They include:

- Individual wires are relatively fragile, and might be damaged on assembly. This may be so, but main cables are assembled using carefully designed machines and methods, and significant numbers of wires are not likely to be mis-handled.
- Wires might not share equal loads. However, the spinning process ensures they all hang in the same catenary to begin with, and their initial loads are a consequence of their geometry and weight, both of which are essentially fixed.
- Wires cross over and cut each other, so aggregate strength is not the same as true strength. This has some effect in wire ropes, but even there its effect can be determined by testing. It is not relevant to suspension bridge cables.
- Wire ropes used in lightweight structures such as guyed masts may suffer from all manner of unexpected duty cycles, including galloping vibration, vortex excitation effects, and uncertainties in end-connection strengths. None of these applies to large suspension bridge cables.
- Ropes may corrode more quickly than other steel elements, because they are thinner and more difficult to protect. This is a real issue, and will be discussed below.
- Wire ropes used for general engineering purposes are frequently mishandled in use, by being pulled around unsatisfactory radii, dragged through dirty ground, allowed to lie in rain water, and generally exposed to dirt and grit. They wear when they are repeatedly pulled through guides, and suffer from fatigue when they are repeatedly bent around sheaves. None of these effects is relevant to suspension bridge cables.
- Tradition dictates to the engineering profession that wire ropes shall have large factors of safety. Engineers are familiar with the fact that ropes used in lifting equipment typically have safety factors of about 6 or 7, and some engineers have difficulty in accepting safety factors as low as 2.50 for cables that are as important as those used for suspension bridge cables.
- Finally, safety factors are employed to provide enough margin between theoretical loads and theoretical strengths for structures to remain safe and serviceable even if the theoretical loads and strengths do not precisely model the actual.

The main justification for retaining a safety factor as high as 2.5 for suspension bridges would appear to be to ensure that they withstand the real problem of long term corrosion and to cater for uncertainty in loading and resistance. We would not advocate constructing a new bridge with significantly reduced cable safety factors unless the problem of corrosion could be reliably solved.

However, where we are looking at an existing structure the arguments are very different, always bearing in mind that the objective is to protect public safety.

C.5.1 Strength Reduction

We have seen that the main justification for the relatively high safety factors in suspension bridge cables is to cater for the future prospect that the strength will be reduced. Therefore we should not be unduly concerned by the fact that cables do indeed behave as expected, since we had already designed to cater for this very effect.

Now that the partial factor format for safety factors has become widely accepted, it would be logical to redefine the strength factors for suspension bridge cables. Thus: if we use the BS5400 arrangement of factors, an aggregate factor of 2.50 could be interpreted as follows:

- Permanent loads (maybe 80% of all loads): Factor = 1.15
- Live loads (maybe 20% of all loads): Factor = 1.50
- Aggregate load factor therefore = .80x1.15 + .20x1.50 = 1.22
- Uncertainty in analysis: 1.10
- Main cable strength factor: 1.86

Thus the effective factor of safety = 1.22 x 1.10 x 1.86 = 2.50

However, we have just seen that the high cable factor (i.e. the ‘1.86’ value) caters for strength reduction. However, if ‘strength reduction’ is a ‘design action’ (in Eurocode parlance), it ought to be explicitly included in the model. That would allow the wire strength itself to provided with the same factor as any other steel element, which in BS5400 is typically between 1.05 and 1.20. If we decide to retain the ‘1.20’ value, we still see that our cable is as safe as any other steel element even after it has lost 45% of its strength.

These values can be discussed and re-calculated, but the principle seems to be clear. If we can obtain reliable strength models, we should use them as the basis for cable strength: but we should not expect to strengthen a cable to restore it to provide a high that was originally provided in order to allow strength to fall safely in the first place.

C.5.2 Rational Partial Factor Format for Main Cable

The logical process of determining the acceptable overall factor of safety on the cable ought to use the same partial factors as those used for normal steel elements for which we have a similar degree of uncertainty in our strength predictions.

Partial factors should be applied to ‘Actions’ and “Resistances’ individually. Factors should not be employed to model physical processes (such as corrosion). They should only be used to protect structures from uncertainty. The strength model for a cable should comprise the following:

- Initial cross section area. This is probably close to being deterministic, with a factor of 1.0.
- Material properties. For steel, the factor in BS5400 format is typically 1.05
- Strength reduction model. This is derived for the Forth Bridge from the theoretical analysis of cable strength reduction. It effectively applies a factor onto the wire area.
- Partial factor on the strength reduction model.

- Corrosion model. This provides a predictive model for the future progress of corrosion.
- Partial factor on the corrosion model. This may be greater than the factor on the strength reduction model.

C.6 Conclusion

A rational safety assessment can only be made if the origins of loads and capacities are rationally considered.

Partial factors should not be used to model physical processes.

It is irrational to be concerned when a structure which has been designed to be safe after it has deteriorated has indeed deteriorated – unless the deterioration has progressed to such an extent that its reliability is becoming unacceptably low.

Appendix D – Response on Draft Report by Weidlinger/Faber Maunsell

PROJECT 34901MLNB **File 93001**
FORTH ROAD BRIDGE **By RMM**
FIRST INTERNAL CABLE INSPECTION **By: RMM 01/01/06**

RESPONSE TO AUDIT REPORT DATED DEC 2005

Item 1

The audit states that the NCHRP 534 Guidelines require that a cable band be removed whenever (numerous) broken wires or stage 4 are present. The more detailed requirements for the first and second internal inspections give clearer requirements for cable band removal:

1. There is no statement requiring removals during the first inspection, which is intended to be an exploratory inspection providing information upon which future inspections will be based. Only six locations are recommended; eight locations were in the original project statement for the Forth because the cable was already 40 years old, rather than 30.
2. In the second inspection, at least two cable bands are to be removed "to facilitate inspection to the center of the cable and under the bands".
3. On the Forth Road Bridge, the cable band spacing is (about) 20 meters, which is more than adequate to inspect to the center of the cable and bands need only be removed if "numerous" broken wires or Stage 4 corrosion to a depth of more than 3 wires are present.
4. Clearly, cable band removal will be required during the second inspection because of the depth of Stage 4. The term "numerous" is not defined, but seven broken wires is not considered numerous. On the Ben Franklin Bridge, one cable band was removed during the first inspection (at the age of about 75 years) because internal broken wires at locations where the wires crossed were found, and with a cable band spacing of only 6 meters, deep wedging was impossible. Another was removed when over 120 broken wires were found in a single panel during the subsequent oiling operation.
5. The decision to remove a cable band is thus flexible and, especially during a first inspection, at the discretion of the engineer when unusual conditions are found. During the first inspection, it is rare that provision for removal is made, and the resulting delay makes it impractical to include removal into the work unless the need is very clear. This was not the case on the Forth, and cable bands were not removed.

Item 2

The audit states that it is not common practice to take samples only from the outer 11 rings of wires. While this is true, the taking of deeper samples is usually done in inspections later than the first, when some knowledge of conditions is available. On the Forth, the first panel that was opened was East 100S-100N, which was only later found to be the worst panel opened (it is, of course, not known to be the worst on the bridge; only if all are opened can one say this with any certainty). Because it was the first, and 8 broken wires were found, the inspection team focused primarily on Stage 4 wires for sampling. The first strength estimates were made using the data from the Bronx-Whitestone Bridge, with 64% of Stage 4 cracked, because tests were not yet available; this resulted in a low cable strength. Realizing that the cracked wires were the key to the cable strength, wires from the outer few rings, which usually contain a higher percentage of cracked wires, were removed to obtain an early estimate of the fraction of Stage 4 wires that are cracked (of the seven Stage 4 wires tested, none were found with cracks. This was surprising, because where there are broken wires there must also be cracked wires. In other panels, the emphasis continued to be on the outer wires). In this first panel, the additional wedge line was driven to investigate further the large amount of Stage 4 in the top of the cable and one sample was removed from the eleventh ring (there are Stage 4 wires to a depth of 14 rings at this wedge line and the last 3 were not as corroded as the eleventh). By the time that the first 6 panels had been inspected, it was intended that some deeper samples be taken; none were found.

The sampling of outer wires in the first panel was also the result of:

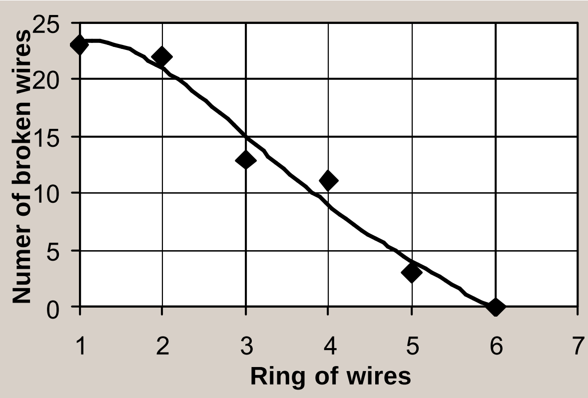
1. The crew had not done wire splicing on the actual cable before, and some training was necessary. This is best done on outer wires. Inner wires are difficult to reach for the purpose of tightening the ferrules, and often a wire would be spliced with zero or small stress.
2. It had been decided that only one sample would be removed from each wedge line to minimize the introduction of too many ferrules, which introduce voids that can collect water inside the cable. There would be enough ferrules from splicing broken wires.
3. Since no broken wires were found in the interior of the first panel opened (except for one adjacent to a wood inclusion in the cable, an anomaly), it was expected that fewer cracked wires would be present in the interior (this has also been found on several other cables).
4. It was expected that a reduced sample (compared with the sample recommended in the Guidelines) would be taken because this was a first internal inspection, and it was desired to learn as much as possible about cracked wires that are prevalent in the outer rings.

The distribution of cracked wires found in the samples is as follows:

Row	Number of samples	Samples with cracks	Fraction of samples cracked
1	8	4	0.50
2	12	2	0.17
3	14	3	0.21
4	8	2	0.25
5	0	0	
6	1	0	0.00
totals	42	11	0.26

The fraction of samples cracked is a maximum at the outer ring and is smaller in the next three rings. A larger sample would probably show the fraction dropping as the depth increases. The 72 broken wires found in all 10 panels are distributed vs. depth as shown in the following chart.

RESPONSE TO AUDIT REPORT DATED DEC 2005



This chart does not include the three wires found broken at depth which are assumed to be anomalies.

Item 3

The cable strengths quoted are like comparing apples and bananas. Several different assumptions have been made in computing the current cable strength. These are listed below, along with the resulting current estimated loss in cable strength for each.

Assumption number	Assumption	Fract of Stage 4 cracked	Loss in Strength
1	NCHRP nominal strength (all Stage 4 potentially cracked)	0.24	12.7%
2	Modified NCHRP nominal strength (Stage 4 in outer 6 rings potentially cracked)	0.26	8.0%
3	NCHRP minimum strength* (all stage 4 potentially cracked)	0.38	15.4%
4	Modified NCHRP minimum strength* (Stage 4 in outer rings potentially cracked)	0.40	9.1%
5	Nominal strength with Stage 4 in outer 6 rings potentially cracked, counted separately in each of 3 zones	varies	6.7%

* The “minimum strength” is based on a statistical estimate of the maximum fraction of cracked wires that may be present given the total number of samples and the number of those samples found to be cracked.

The percent loss in cable strength in all these cases is based on the initial cable strength using the Normal distribution for Stage 1 & 2 wires, which have been found in other investigations to have the same properties as new wires. The Normal distribution results in an initial strength that is 1.2% lower than the nominal design strength, while the Weibull distribution results in an initial strength that is 1.6% lower than that. The first of these differences may be the result of simplifications used in the NCHRP Brittle-Wire Model; the second is the result of the use of the Weibull distribution for these wires. The Weibull distribution has a bias towards lower strength wires that is appropriate for a degraded population, and, for the same mean and standard deviation of tensile strength will result in a lower strength than the Normal distribution.

The minimum tensile strengths, based on a probable maximum fraction of cracked wires, are calculated only to estimate the error caused by the small number of samples and the error is considered to be covered by the safety factor. The probable maximum fraction was continuously estimated as the data from the laboratory was received (testing was by batches on wires from several panels) to determine whether or not it was stabilizing (it was).

The 6.7% strength loss should thus be compared with a strength loss by NCHRP of 12.7%. The difference between the nominal and “minimum” cable strengths is 2.7% at the most; this is accommodated by the “safety factor”, though it should be considered in reliability calculations.

The assumption of cracks occurring only in the outer 6 rings is made to assess an upper bound on the cable strength. It is based on the observation that broken wires (other than three anomalies) are found only in the outer 5 rings. This assumption is applied to the entire cable despite no broken or cracked wires being found in the top portion of the cable, to account that more rings of cracked wires may be present in the bottom portion of the cable. The calculation of cable strength using 3 zones is made to further check this assumption, resulting in strength 1.3% greater. This same 3 zone assumption is also used to estimate future cable strengths to avoid excessive conservatism that may occur from the assumption of linear progression of corrosion “category” with time.

Item 4

It is agreed that when different assumptions are made for the rate of deterioration for each category, the future strength will be different. Tests made to date indicate that a uniform rate (linear) through Stage 4 is reasonable. There are no test results to date for higher categories. Extending the calculations out fifteen years is excessive when the cable is only 40 years old; five years (about 10% of the age) is as far into the future that can be reasonably estimated. At this age, the strength loss would vary from 9.8% to 7.6% by these calculations, barely different from the 6.7% estimated at the current time. Even a linear rate of strength loss assumption from the completion of the cable would result in 6.7 x 45 / 40 = 7.5%; a linear rate from the onset of Stage

3 (estimated to be about 19 years age, in 1983) would result in 6.7 x (21+5) / 21 = 8.3% five years hence. This same linear rate would result in a strength loss of 11.5% in 15 years (2019). Assumption 2 with half the rate of deterioration after Stage 4 is reached is about the most that could be considered reasonable.

It is noted that the values for T that are used seem to be applied to all categories of wires (not likely) and that the strength loss is taken as a percentage of the strength in 1983, since the strength given for 1983 is smaller than the initial strength; it should be taken from the initial strength of 345144 kN, resulting in 17.2% in 2019 (admittedly a quibble, but the difference increases with increasing T. For T = 2, the loss becomes 15.4%, and for T = 5, it becomes 14.3%).

Future planning should be based on conservative assumptions, and waiting for 5 or 10 years to start remedial action, which could be assumed reasonable if T = 5 is assumed, is not prudent. The numbers are, of course, useful in providing an indication of the effects of deterioration rate, and how inaccurate estimating 40% of the age of the cable into the future can be.

Without further effort to estimate the effect of changing the rate only after Stage 4 is reached, we would not guess how your tables would change. The effect on the table for assumption 2, of course, would be minor

Item 5

The outer ring of wires represents 3.2% of all the wires in the cable. The refinement in the total number of wires in each stage of corrosion in the cable would be affected by perhaps 0.5% if each wire were assigned a stage in accounting for the wires. If, for example all the wires were Stage 4 and Stage 3 was seen at the wedge, the inspectors should assign Stage 4 at the wedge lines, or they should move the wedge over by two wires. When these wires are half Stage 3 and half Stage 4 between the wedge lines all around the cable and all are recorded as Stage 3, the error in counting could be about 1.7%. This last scenario is extremely unlikely, and there has to be some reliance on the inspector to use judgment. Quite honestly, with 97% of the wires being inside the cable and counted by half octants, there was to be no compelling reason to make a separate calculation for the outer ring. The statement, however is correct, and perhaps should be clarified in the Guidelines if the opportunity presents itself.

To try to inspect the entire second ring of wires would be very time consuming, except for broken wires, which almost always make themselves known. For broken wires, which are often more prevalent in the outer two rings, interior wires and exterior wires are counted separately.

Item 6

The paragraph is, for the most part, correct. It would be most desirable to have a series of repeat inspections to calibrate the methods, and it is assumed that eventually, as repeat inspections are made as recommended, this will occur. It will take many years, because of the recommended inspection intervals. It should be assumed that when a five year inspection interval is recommended, that other steps to remediate the conditions inside the cable will be taken, and calibration in this case will not be effective.

Item 7

As discussed in Item 3 above, the strength losses to be compared should be 8.0% strength loss when cracks are assumed to occur only in the outer 6 rings and 12.7% by the NCHRP method. When refined further to analyzing the cable in 3 zones with a different fraction cracked in each zone, the strength loss is 6.7%; this analysis breaks the test data into smaller units, resulting in larger probable errors.

Item 8

We agree with this statement. However, with the current data and lack of knowledge of deterioration rates beyond Stage 4, we are not comfortable with any assumptions other than those made.

ISBN 0 7559 1331 0 (web only publication)