AGENDA ITEM No. 6

Forth Estuary Transport Authority

Cable Band Bolt Assemblies Update

24 April 2009

1 Purpose of Report

1.1 To provide members with an updated report on the condition of the cable band bolt and nut assemblies.

2 Background

2.1 The main cables of a suspension bridge are its primary load carrying members and the deck of the suspended spans of the Forth Road Bridge are linked to the main cables by 192 sets of steel wire rope hangers at 18.29 metre centres. These hangers vary in length from 2.5 metres at mid span to 90 metres adjacent to the main towers.

2.2 The hangers loop around a metal casting which is bolted to the cables. Each casting is held in place by a number of 35 mm diameter high tensile bolts which are pre-tensioned to a load of around 80 tonnes. There are 944 of these bolts.

2.3 The cable band bolts and accompanying nuts and washers were replaced between 1997 and 2000 as part of the Hanger Replacement Project. The consulting engineers who designed and specified the scheme were W A Fairhurst and Partners. The contractor was Monberg & Thorsen.

2.4 Cracks were found in a small number of the nuts forming part of the cable band bolt assemblies following a routine inspection by FETA staff in 2007/2008.

2.5 Faber Maunsell, Consulting Engineers, were asked to carry out an investigation into the cause of the cracking and they have now reported their initial findings.

3 Main Report

3.1 The cable band bolt assemblies are inspected as part of FETA's inspection regime. The bolts can have a tendency to lose some pre-tension over time and, as convenient access to the main cables was available from the platforms being used as part of the dehumidification works, FETA staff were making use of this access, where possible, to inspect and check the bolts. Arrangements were also put in place to retighten any bolts that were found to require further tensioning.

3.2 During the inspection, four nuts on the west cable and five nuts on the east cable were found to have cracked. There are, in total, 1888 nuts making up part of the cable band bolt assemblies. Therefore, the number of nuts found to be cracked make up less than 0.5% of the total.

3.3 The consulting engineers, Faber Maunsell were appointed to investigate the cause of the cracking and that investigation, which includes laboratory testing and a desk study of the details on other suspension bridges throughout the world.

3.4 The four bolt assemblies on the west cable where cracked nuts were found have already been changed and retightened using the dehumidification works access platform. The five nuts or bolt assemblies on the east cable will be replaced this year during the wrapping of the cable again using the dehumidification works access platforms.

3.5 Faber Maunsell have now reported their initial findings based on the examination of the four faulty assemblies from the west cable. The investigation will be completed when the five assemblies on the east cable are replaced this year. A further report will be brought to the Board following completion of the investigation. This is expected to be later this year following removal of the five cracked nuts on the east cable.

The initial findings of the Faber Maunsell investigation show that:

- Nine failed nuts have been discovered across the bridge on both cables and in all spans, although all failed nuts on the east cable were located in the north east side span. Overall, the failures are not limited to a small area.
- All failed nuts were located on the live (jacking) side of the bolt, suggesting that the tensioning method or arrangement may have contributed significantly to the mode of failure.
- All of the nuts removed from the west cable exhibit a characteristic circumferential crack at the shoulder and vertical cracks in the hexagonal part. The east cable nuts appear to follow a similar pattern, hence the failures appear to have the same cause.
- It appears that there may have been some misalignment of the spherical washer assemblies that could lead to uneven loading in the nuts. This could be a significant factor, and further checks should be made on the east cable nuts prior to their replacement.
- Laboratory testing of the first failed nut recovered suggested that the circumferential crack was formed first, initiating at the re-entrant corner in a corrosion pit where the cadmium plating was missing. In this nut there were a number of initiation sites from which the circumferential crack

grew. The vertical cracks followed later and were fibrous and ragged indicating overload.

- The laboratory testing confirmed that the steel material was within the specification, so that the cause of defective material could be ruled out.
- There was no evidence of hydrogen embrittlement resulting from the cadmium plating process.
- The steel used in the replacement nuts and bolts has a higher alloy content which has allowed heat treatment to achieve higher yield and tensile strengths than the original bolts. The replacement bolts have only slightly increased strength, but the strength of the nuts has increased significantly. The original bolts were matched with nuts that were much softer. It is possible that the use of a higher strength of steel for the nuts (with associated loss in ductility) could be a contributory factor.
- The dimensions of the new nuts and bolts closely replicate the originals, although the conversion from a $1^1/_2$ inch diameter imperial bolt to a M39 metric bolt has resulted in the nuts having thinner sections than the originals.
- The dimensions of the new nuts are small in comparison with current standards for "normal" nuts. They are particularly small in comparison with nuts used on other suspension bridge cable band bolts. This, combined with the increase in bolt size outlined in the previous point, is likely to be significant.
- The method of tensioning has changed from that used during original construction. The original bolts were tightened by torque wrench, and the bolts were re-tensioned several times during construction as the load in the cable increased and its diameter reduced. Finally, all nuts were given an extra half turn to ensure the bolt was in the plastic zone. This allowed the redistribution of any moment arising from misalignment at ends.
- The replacement bolts were tensioned to the same nominal load (approximately 80 tonnes) using hydraulic tensioners. This load would keep the stress level below yield, i.e. within the elastic zone. The achieved tensions were assessed on the basis of a value of Young's Modulus calculated for each bolt. The values of Young's Modulus had a variation far in excess of what would be normally expected. Analysis of the calculation method used suggested the incorrect bolt length had been used in calculating the Young's Modulus for each bolt. Reassessment of the tensions achieved using the conventional measured extension applied to a load/extension curve suggested a much wider variation than thought by the designer. However, no excessive tensions were found. It was concluded that although the methodology used was flawed, it was unlikely to be detrimental to the bolts or nuts.
- Records of the tensions in the bolts with failed nuts were reviewed and it appeared that there was nothing exceptional. Installation dates were

reviewed to check if the failed nuts fitted any pattern. However, none were found.

3.6 In summary, no single factor has yet been established as the cause of the failures. It would appear that there are a number of contributory factors including the misalignment of washers; poor coating in the re-entrant corner plus moisture ingress; use of a much higher grade of steel for the nuts with associated loss in ductility, and dimensional conversion from imperial to metric reducing the nut cross sections plus the nut size being small by modern standards. These contributory factors are a result of both design and specification decisions and construction methods.

The consequence of this conclusion is that, potentially, any of these nuts could fail in this way. The first stage of crack initiation and growth in the circumferential direction cannot be observed without dismantling and the use of NDT is unlikely to be helpful. Therefore, it is possible for other nuts to have this first stage cracking.

This leads to the inevitable conclusion that, to ensure the long term integrity of the bridge, all the nuts should be replaced. An appropriate timescale for this would be the short to medium term. It may be possible to reuse the bolts, but this would depend on the design of the new nuts. Assuming that a somewhat larger nut would be employed, the overall length would need checked to see if it were still adequate. Also, if the nut were to be modified or replaced, then new washers might be required.

3.7 Before any action plan for wholesale replacement is put into place the following actions will be carried out:

- The five failed nuts on the east cable will be replaced and the failures examined to confirm their similarity.
- One nut will be sent to the laboratory for examination and further confirmation of the above.
- Prior to replacement of the five failed nuts, the verticality of the washer faces will be measured combined with spot checks on other washers with nuts that have not failed to establish if this is a significant factor.

3.8 Once these actions are completed the investigations report will be finalised and reported to a future meeting of the FETA Board. As discussed above, it is expected that this will be later this year.

3.9 Given the preliminary outcome of the investigation, legal advice has been sought to determine if either the designer or the contractor had exercised the standard of skill and care required to carry out this project. A definitive legal opinion will also be dependent on the outcome of the final report.

4 Conclusion

4.1 During a FETA routine inspection a small number of cable band bolt nuts were found to have cracked. These have already been replaced in the west cable and those on the east cable will be replaced in the coming year when the dehumidification works platform affords access. There are no concerns over the safety of the bridge. However, an investigation was set up to determine the cause of failure and what actions are required to ensure the long term structural integrity of the cable band bolt assemblies.

4.2 The preliminary results of the investigation are now available based on examination of the four cracked nuts from the west cable. No single contributory factor to cause the cracking has yet been found but a number of design and construction issues have been identified as possible contributory factors. The five cracked nuts on the east cable will be replaced and then examined this summer. Once this examination is completed a final report will be brought to the FETA Board later this year.

4.3 Legal advice has been sought to establish if there is liability on the part of the designer or contractor. This advice will also be brought to the Board later this year.

4.4 A sum of £630,000 has been allowed within the Capital Plan for remedial works. However, it should be noted that this sum was estimated before completion of the initial investigation work.

5 Recommendation

5.1 It is recommended that members note the contents of this report.

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Appendices
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Background Papers:
Faber Maunsell – Failed Cable Band Bolt Nuts – April 2009 Draft