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In Service Modelling of the Humber Bridge

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Summary

The Humber Bridge, until recently the world's longest span suspension bridge, has been carefully maintained and monitored during its 17 year life. As part of the monitoring programme, the Humber Bridge Board commissioned the development of a Finite Element computer model which has been validated against existing engineering data and which gives a good description of actual behaviour. The model has been used to investigate the effects of modified or updated bridge loading and can also be used to give a rapid structural assessment in unexpected conditions. Other potential uses of such a tool are outlined.

1. Introduction

The Humber Bridge is a suspension bridge which was completed and opened in 1981, and has remained in good working order throughout its life. The Humber estuary is in the north-east of England, and the bridge runs north (Hessle) - south (Barton). The main span is 1410 m. The Hessle side span is 280 m. and the Barton side span is 530 m. (Figure 1). The two towers, each 155.5 m. high, are concrete, while the main deck is a slim, streamlined, steel box suspended from inclined hanger ropes. The aerial-spun main cables (14948 wires each) terminate in concrete gravity anchorages founded on the Kimmeridge clay of Barton, and the chalk rock at Hessle. The deck is discontinuous at the towers, with deck movements accommodated by a system of rolling-leaf expansion joints and A-frames. The A-frames also provide restraint against vertical, lateral and torsional loads.

Consultants Freeman Fox and Partners designed the bridge on the basis of their experience gained on the first crossings of the Severn (England) and the Bosphorus (Turkey), both of which were conceptually similar. Humber Bridge incorporates the innovative features of concrete towers, A-frame arrangements and special welding details in the box deck, as well as inclined hangers. These have all performed very well in service.
The site is an exposed marine location and significant temperature variations can be expected. The box deck is de-humidified to minimise maintenance painting. The inspection regime includes formal inspections every two years, and Principal Inspections every six years.
The construction cost was £98m (US$155m) but capitalisation of interest caused the bridge debt to grow to £435m (US$690m) by 1993 and necessitated the restructuring of the Bridge Board's finances. Operation of the bridge (toll collection, traffic safety, security) costs £1.6m (US$2.5m) per annum, and maintenance costs £1.0m (US$1.6m) per annum. In the financial year 1997/98 the toll income from 6.2m vehicles was £13.9m (US$22.0m).

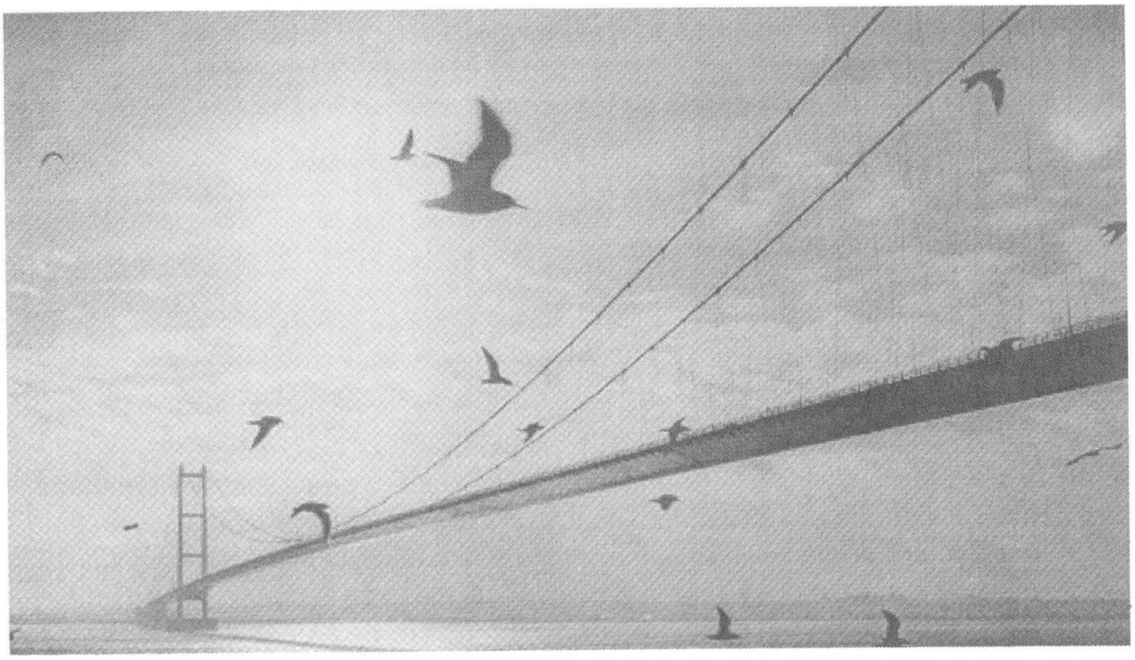

Figure 1 - Humber Bridge showing slender box and inclined hangers

2. Why should the Humber Bridge Board commission a Finite Element model?

The Humber Bridge Board is responsible for the operational safety of the bridge. Its staff inspect and maintain the bridge either directly or by using contractors or consultants. The original design calculations are used as a maintenance tool but, having been prepared at a time when computer-based design was in its infancy, they consists mainly of hand calculations. Consequently they can be unwieldy to use, are of limited value for investigating the consequences of revised Highway Loading Standards and are not suitable for assessing the effects either of unforeseen service loads or of structural damage. Computer models can now be prepared at reasonable cost, run efficiently on a PC and are relatively user-friendly. Such a model facilitates rapid structural appraisal after accidents, allows investigation of various "what if" scenarios and assists with decisions regarding traffic management in unusual circumstances, as well as being an important maintenance tool.

3. Finite Element Modelling

The finite element method applied to structural analysis is well known. To fulfil the brief, the model has to be validated against known in-service performance criteria. It is not initially predictive, but must be fully descriptive. This is a different challenge to that faced when designing *ab initio*.

The finite element model was built to run on a P.C. using a commercially available version of ANSYS [5]. In developing a descriptive model, assumptions made in the original design may not be acceptable (e.g. rotation capacity at connections or supports may have been simplified), and care must be taken to identify the effect of such assumptions in modelling. During development, different levels of sophistication have been built into a number of models, but only two models are used for calculations presented here. They are referred to as the *full model* and the *plate model*, the difference being the extent of detailed representation of the deck. They are run as both linear elastic and geometrically non-linear analysis. The use of a non-linear elastic model is essential for large span structures. While the major design forces change very little, deformations can be significantly modified, and 5% changes on non-trivial values can be expected. On such large deformations, this can give values up to 0.1m and these are clearly measurable quantities.

The *full model* has 68924 degrees of freedom, and mainly uses link, plate and beam elements. The cable is modelled as a series of link elements, and they connect the nodal points at which hangers are supported. The hanger elements have the "birth and death" capability which ensures they carry tension only. The towers are modelled as a series of beam elements, while the deck consists of inter-connected plate elements. The material of construction for deck, cables and hangers is steel, while the towers are in-situ reinforced concrete. The *plate model* simplifies the deck to a two-dimensional flat plate system with equivalent flexural properties. Simplification of the deck reduces the total degrees of freedom to 22760, and reduces run times with virtually no change in predicted hanger or cable forces.

There is clearly no unstrained position for the bridge, as the self-weight is such a significant proportion of the total load. In order to represent this feature which is important in modelling the non-linear response, the designer's original initial strain values were applied. Subsequent application of gravity loading gave a deflected form under dead load which must match that given by the initial strain data. There were few inaccuracies which required minor adjustment of initial strain values to give a smooth deflected form. This process cannot be validated, except that the geometry of the final as-built structure is known and follows smooth lines.

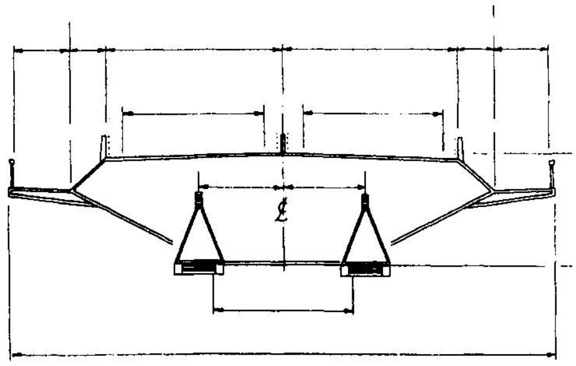

Figure 2 - General cross-section of deck and A-frames (all dimensions in m.)

A-frames support the deck at two transverse positions at each end of the side and main spans. Their primary function is to prevent both vertical and lateral movement from both symmetric and asymmetric loading. The inclined hangers also provide significant longitudinal stiffness in this respect. A detail showing the deck cross-section and A-frames is given in Figure 2.

In order to validate the model, it was essential to compare predicted behaviour to measured data. Partly because it was the world's longest span suspension bridge, it has already been the subject of several investigations.
Reliable and extensive data are available from dynamic studies carried out by a group from Bristol University[1]. They used ambient vibration testing from several locations on the bridge to determine natural vibration frequencies and associated modes. Natural frequencies of the deck section had also been determined for design purposes from (unpublished) wind tunnel tests carried out at the National Physical Laboratory.
Data from tests involving a single heavy lorry crossing have also been obtained [2,3] although these data are slightly less reliable as the load is not *precisely* known. Haulier's records suggest their estimate of the load at 172t, but this is doubted from observations made at the time.
More recently GPS data have been reported[4], although these are yet to be calibrated against known loads.

Measured and predicted natural frequencies are given in Table 1, while a comparison of deflections under the action of the travelling load is given in Figure 3. More detail of the calibration process has been given elsewhere [6].

	Vertical				Lateral			Torsional	
Mode No.	1	2	3	4	1	2	3	1	2
F.E. Model (Hz)	0.108	0.116	0.169	0.207	0.054	0.119	0.178	0.318	0.524
Measured (Hz)	0.116 (0.104)	0.154 (0.107)	0.177	0.218	0.056	0.143	0.218	0.311 (0.300)	0.482 (0.519)

Table 1. Natural frequency values from F.E. analysis and measurements
Figures in brackets are data provided by the National Physical Laboratory, UK.

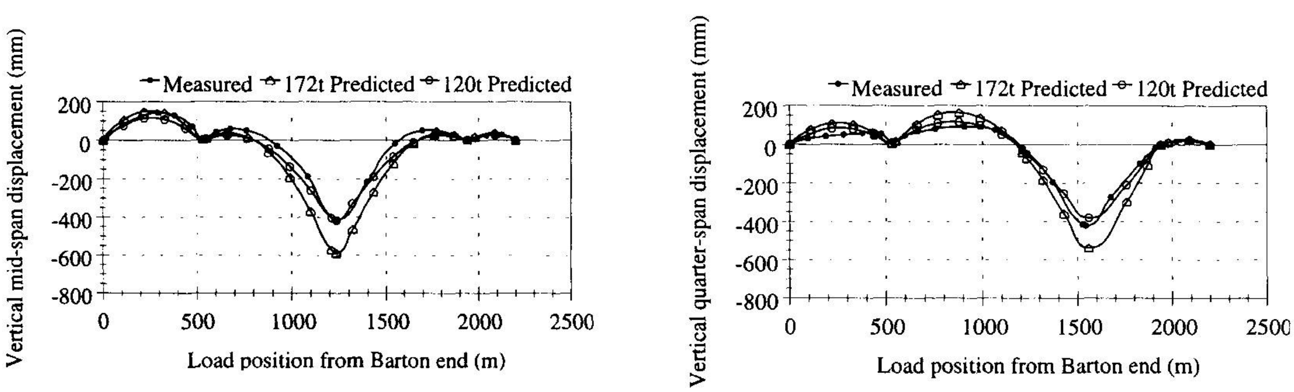

Figure 3 - Single Heavy Lorry Crossing - Comparison of Measured and Predicted Vertical Displacements at a) Midspan b) Quarter Point of Centre Span

It is shown from Table 1 that good agreement is obtained between predicted values and the best available measured data. It may also be noted that some modes predicted by the current computer model have not been reported in Reference 1. The quasi-static tests of the single heavy lorry, as shown in Figure 3, also give excellent qualitative agreement.

4. Applications

There are many possible uses to which such a model may be put, including:

- Assessment in connection with revised Loading Codes
- Assessing special or abnormal vehicles
- Structural assessment after accidents
- Investigating the viability of maintenance or repair procedures
- Assisting with the development of traffic management procedures
- Assessing the consequences of foundation movements

By way of example, removal of a hanger in the model (chosen at random - not highest or least loaded) indicated in Figure 4 leads to the change in hanger forces shown in Figure 5. The loading used has been a case from BSALL - Bridge Specific Assessment Live Loading (used to assess the bridge in line with national UK guidelines), and subsequently a Special Vehicle Load of 180t. The bridge operator is able to assess the integrity of the structure under possible combinations of maintenance and exceptional load conditions, and in the case shown, the hanger loads remain within design values (1450kN).

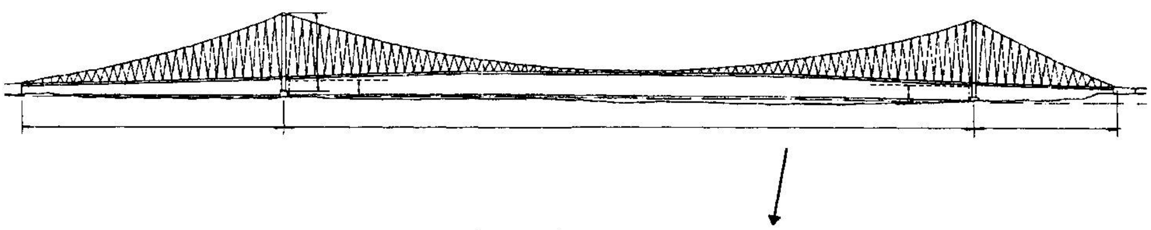

Figure 4 - Bridge Elevation

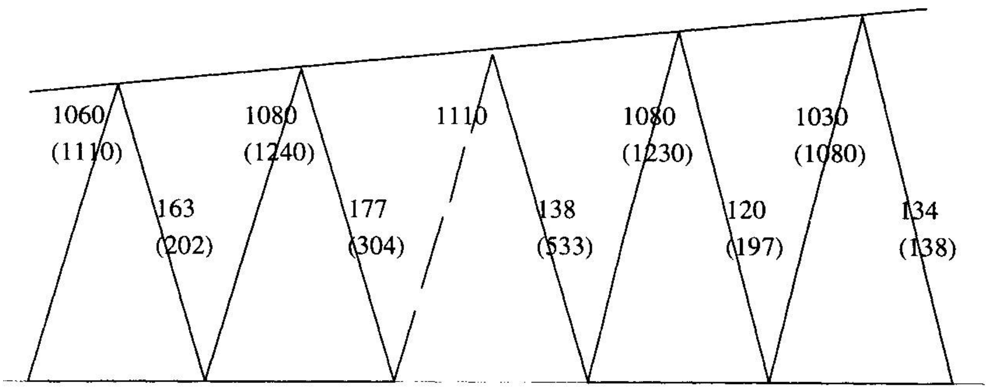

Figure 5 - Hanger Forces (kN) under BSALL and Special Vehicle loading (figures in brackets with Hanger removed)

An alternative example could involve the determination of maximum wind speeds in which the bridge may continue to be used, again combined with BSALL loads and loss of a hanger. For the removal of the same hanger, the bridge may operate in winds up to 33 m/sec at deck level without exceeding the permitted working load in the hangers. The design wind speed (i.e.with no hanger removed) is 48m/sec.

Other structural elements can be considered in the same way under this, or any other loading.

5. Concluding comments

There is a need for bridge operators to have ready access to tools which help ensure safe operation of bridges. Technology change (particularly with respect to computational capability) over the last decade or so has made this process more attractive and achievable. Improved understanding of real loads and their characteristics leads to a need to be constantly reassessing safety and structural response.

This paper has demonstrated how a finite element model has been developed which describes the behaviour of a long-span suspension bridge as-built. The model has been used for an assessment of the bridge under revised loading requirements, and with the possible loss of structural elements.

Future uses might include an increased potential for on-line control systems, enhanced condition monitoring, and more accurate determination of any actual traffic and wind loads that are present.

The authors would conclude that for many major bridge structures it would be advantageous for a model to be supplied to the bridge operators by the designers, along with the design calculations.

References

1. Brownjohn, J.M.W., Dumanoglu, A.A., Severn, R.T. and Taylor, C.A. (1986), Ambient vibration survey of the Humber Suspension Bridge, Research Report UBCE-EE-86-2, Civil Engineering Department, Bristol University, U.K

2. Brownjohn, J.M.W., Bocciolone, M., Curami, A., Falco, M. and Zasso, A. (1994), Humber Bridge full-scale measurement campaigns 1990-1991, J Wind Eng. Ind. Aerodyn. Vol. 52 pp185-218.

3. Zasso, A., Vergani, M., Bocciolone, M., and Evans, R. (1993), Use of a newly designed optometric instrument for long-term, long distance monitoring of structures, with an example of its application on the Humber Bridge, 2nd Int. Conf. on Bridge Management, 18-21 April 1993, University of Surrey, U.K.

4. Ashkenazi, V. and Roberts, G.W. (1997), Experimental monitoring of the Humber bridge using GPS, Paper 11296, Proc. Instn Civ. Engrs, Civ. Engng, Vol 120, pp177-182

5. ANSYS (Revision 5.3), Swanson Analysis Systems, 1993

6. Karuna, R., Yao M.S., Brown C.J.and Evans R.A., "Modelling and Analysis of the Humber Bridge" IASS International Colloquium on Computation of Shell and Spatial Structures (ICCSS'97), Taiwan, November 1997