Bridge Engineering

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ice | proceedings

Proceedings of the Institution of Civil Engineers

http://dx.doi.org/10.1680/jbren.15.00008
Paper 1500008
Received 27/03/2015 Accepted 03/02/2016
Keywords: bridges/concrete structures/fatigue

ice
Institution of Civil Engineers
publishing

Reinforced-concrete beam hinge joint fatigue assessment

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A major highway underbridge has been subjected to a complex fatigue assessment to determine its present and future serviceability. Similar to approximately 100 other structures within Great Britain, reinforced-concrete deck hinge joints are positioned within longitudinal beams providing rotational flexibility. Concerns were raised as to the fatigue condition of the hinge joints considering repetitive rotations applied by traffic loading and pitting corrosion found on reinforcement bars. This paper describes the assessment work and associated research relating to this structure including finite-element analysis, laboratory models and space frame modelling of the structure. Comments are made on the applicability of current codes of practice for fatigue assessment of reinforced-concrete deck hinge joints.

Notation

D	nominal diameter of the scissor bars
H	horizontal forces used to control rotation in laboratory models
h	depth of the hinge, measured as the clear depth between hinge formers
K	an empirically defined value
V	shear force applied to hinge join
α	rotation applied to hinge joint
σ–N	relationship between fatigue stress and number of cycles to failure
σ_{S}	axial stress in a tension bar assuming all the shear force is carried by the tension scissor bars
σ_{SB}	extreme fibre stress on a tension bar

1. Introduction

1.1 Background

A major highway underbridge was subjected to a complex assessment and category 3 check (by an independent company) to determine its present and future serviceability, regarding the fatigue condition of the reinforced-concrete hinge joints. The author was involved on behalf of the checking organisation and managed the laboratory testing regime.

The initial assessment check followed the philosophy outlined in the draft Assessment Approval in Principle document, including plane stress finite-element analysis (FEA) but differing by using Abaqus software. Similar results to that of the principal assessor were established, confirming concerns over the fatigue condition of hinge joints.

For a period of four years, the author performed progressively more detailed non-linear finite-element modelling and conducted laboratory research, which verified the quality thereof. This paper briefly describes the work conducted by the author on behalf of the checking organisation, Atkins, throughout the project.

1.2 The structure

The in situ reinforced-concrete five-span twin-deck structure totals 135 m in length. Each deck is supported by four beams connected at the pier crossheads. Figure 1 shows general arrangement details of the underbridge.

Each beam length includes reinforced-concrete beam hinge joints at the two points of contra-flexure in the central span and at the outer points of contra-flexure in the intermediate spans.

The hinge joints transfer shear force and restrain longitudinal movement, but provide rotational flexibility at discrete points along the length of each beam. Thus, at the time of design, these points of contra-flexure were known and the structure would have been analysed as statically determinate, as shown in Figure 2.

At hinge joints the beam decreases in depth to 432 mm (17 in), which is one third of that elsewhere, for a length of approximately 38 mm (1 1/2 in). Six triplets of bars cross through the joint, each including one horizontal dowel bar flanked by opposing ‘scissor’ bars inclined at 45° to the horizontal all of which have a diameter of 31·75 mm (1 1/4 in). Scissor bars are referred to as ‘tension’ and ‘compression’ bars

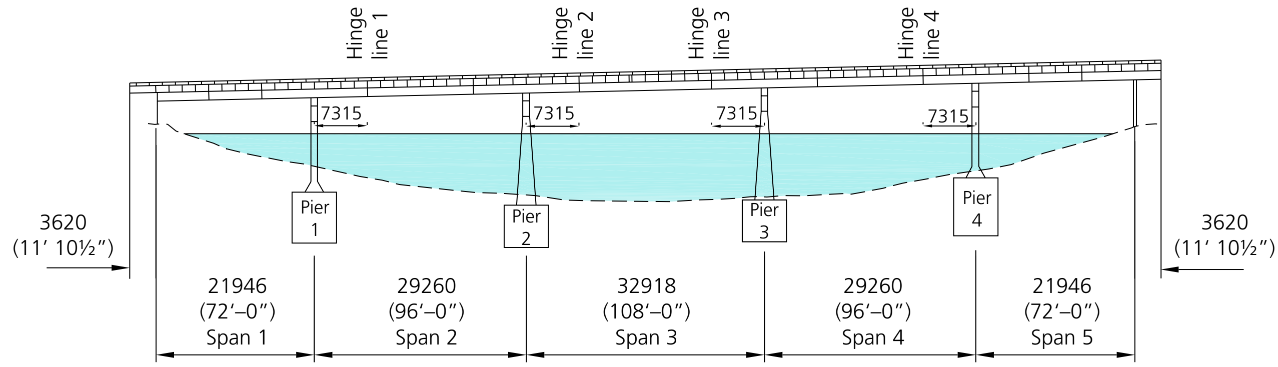

Figure 1. General arrangement details of the underbridge. Elevation looking upstream (dimensions in mm)

Figure 2. Schematic bridge structure

with respect to the predominant forces experienced in each under shear load. Shear bars, of diameter 22·22 mm (7/8 in), referred to as 'C-bars', are positioned either side of the hinge throat, resisting cracking. Hinge details are shown in Figure 3. Such beam hinge details are also referred to as 'thrust hinges', and are similar to slab decks known as 'deck hinges'.

1.3 Condition inspections

Owing to the complex arrangement of the structure, access to inspect hinge joints is very difficult. Cracks are apparent on the underside of the formed concrete throat of every hinge joint. This cracking is to be expected due to either early thermal shrinkage or cyclic hinge rotations under live loading in sequences of hogging and sagging. It is presumed that a construction joint was formed at each hinge, as found on bridges in Staffordshire (Wilson, 1995), which subsequently defined initial vertical hinge cracking.

Inspections conducted by the principal assessor found rust staining emanating from hinge joints at some locations. The worst of these was on an external face, which was broken out to reveal small amounts of pitting corrosion in hinge reinforcement bars local to the centre of the hinge.

It is apparent that chlorides from de-icing salts enter the joint from the carriageway through damaged waterproofing and joint sealant into the recess above the hinge. This then runs down through the construction joint, which is opening with cyclic rotations. This is evident in localised pitting corrosion recorded during intrusive investigations and appears to only occur local to the centre of hinge joints.

1.4 Fatigue concerns

Small levels of pitting corrosion are relatively insignificant for a static strength assessment. The structure had, even with very conservative assumptions, been assessed for static strength and deemed adequate. However, corrosion of reinforcement causes localised high-stress concentrations and is severely detrimental to its fatigue life, as described in BA38/93 (HA, 1993).

Early investigations suggested an onerous fatigue condition. Under traffic loading, cyclic applications of both shear force (V) and rotation (α) to the hinge joints were suspected to cause high stress ranges on the reinforcement bars local to the centre of the joints. The scenario considered is demonstrated in Figure 4.

2. Research

2.1 Available research

Reinforced-concrete hinge joints have largely been used in compression members, positioned at one or both ends to remove bending moments introduced from connecting members. In compression members, these are generally known as Freyssinet hinges. Apparently unique to highway structures constructed in the 1960s in Great Britain, similar hinges were introduced to deck members. Known as 'deck hinges', these were used to make multi-span structures statically determinate, but appear to have been used without any prior published

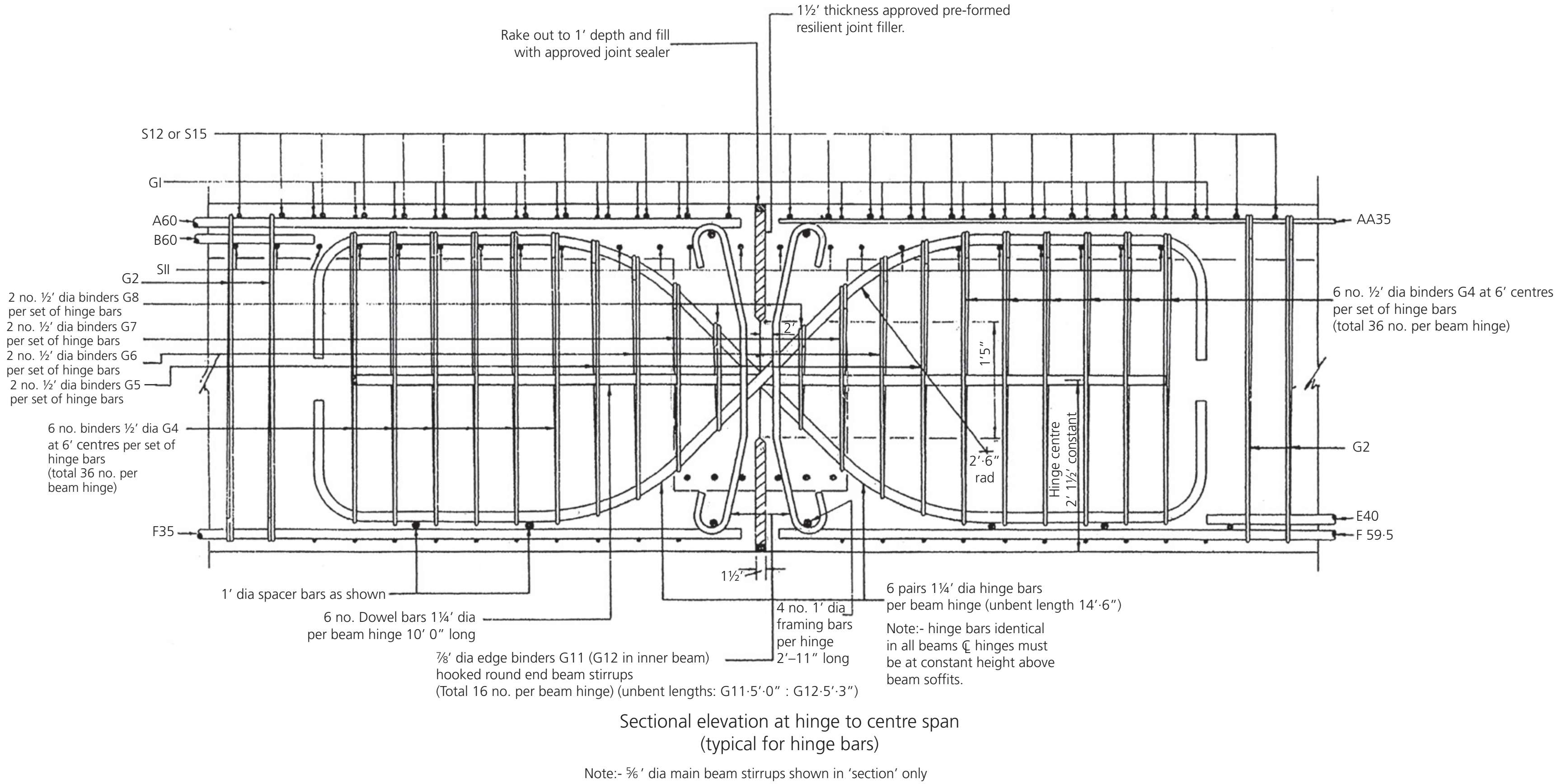

Figure 3. Hinge joint details

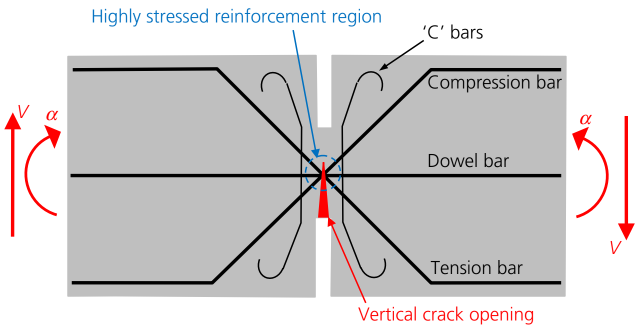

Figure 4. Schematic hinge joint under applied shear force (V) and rotation (α)

relevant research. It is possible that use of deck hinges may have been justified as a means of accommodating differential settlement.

More recently, two research programmes have been conducted in relation to assessments of these structures. The first is presented in the paper by Wilson (1995); the second, concluding in 2004, is publicised in the advice note BA93/09 (HA, 2009).

Both research programmes focussed on the resulting static shear capacity of hinge joints. For this bridge, it had already been established that the static condition for the structure under assessment was adequate. The latter research presented a method for calculation of fatigue stresses, but is based upon the condition predicted in an ultimate shear scenario with certain conditions. This is shown in Figure 5.

2.2 Need for further research

For the particular bridge assessment with which this project was concerned, a worst possible failure mechanism was envisaged in which tension bars of the hinge joints would fail due

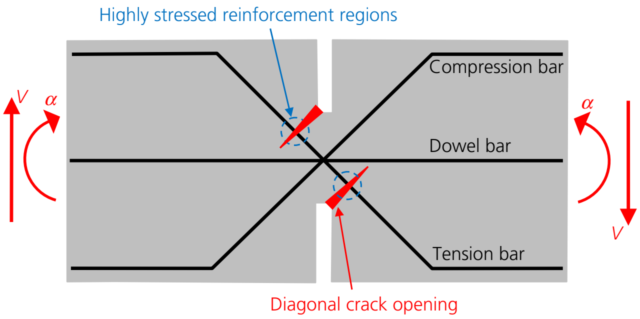

Figure 5. Schematic hinge joint under ultimate shear load typical of research for development of BA93/09

to fatigue, induced by cyclic combinations of shear and rotation, leaving a reduced static shear capacity in the hinge joint. Neither of the programmes gave a suitable assessment method for this serviceability fatigue condition.

Finite-element models by both the principal assessor and the checker predicted stresses (and stress ranges) on hinge reinforcement bars local to the cyclically opening construction joint at the centre of a hinge. However, owing to a number of differing opinions on modelling philosophy and assumptions taken, as well as differences in software used, the two could not agree on a definitive (as per codes of practice) fatigue life of the structure.

In order to resolve the unknowns and discrepancies, the client instructed to propose a laboratory research programme.

The laboratory tests were intended to provide answers to four unknown factors.

- Do high concentrations of axial stress occur on hinge reinforcement bars?
- Are those hinge reinforcement bars bent around tight radii (owing to dowel action and/or hinge rotation) causing yet higher extreme fibre stresses?
- Can a finite-element model be qualified as suitably accurate representation of hinge reinforcement stresses under serviceability loads?
- Is it appropriate to analyse fatigue life based on axial or extreme fibre reinforcement stresses?

The client gave approval for the research programme.

2.3 Laboratory testing

Two physical hinge models were tested and analysed. The two specimens were similar except in some details of the fabrication and instrumentation, which were amended in light of the first tests. The models were based on the beam hinge joints of the bridge, but were not replicas, allowing them to be manageable within the laboratory.

To keep the sizes and magnitudes of required loads suitably convenient, the six sets of hinge bars in the bridge joints were reduced to two, in a correspondingly reduced section width. 32 mm (1 1/4 in) high yield bars were replaced with 25 mm bars of modern grade B500B. Proportions of the hinge detail were reduced by the ratio 25/32, with the exception of the height of the beam which was increased above and below the hinge throat by 295 mm to facilitate the application of small loads used to control hinge rotation. In agreement with the bridge, a construction joint was formed vertically through the centre of the hinge throat.

The hinge detail was positioned at a quarter span in a symmetrical three-point bending arrangement. A combination of rockers and rollers at supports and load application avoided unwanted restraints. Primarily, the support arrangements were chosen to avoid forming a direct compression strut through the hinge throat, between the load application and support. The specimen details are shown in Figure 6.

Shear loads and rotations, in magnitudes representing the range of serviceability loads on the structure, were applied to the hinge detail of each specimen in increments. Fatigue loads were not applied to the specimens; it is unknown whether cyclic loading would cause fatigue failure in the concrete or reinforcement first. This assessment considers only fatigue of the reinforcement in accordance with BS 5400: Part 10 (BSI, 1980).

Measurements of strains were taken on the upper and lower surfaces of hinge bars at close intervals local to the hinge throat. On the first specimen, gauges were positioned between consecutive transverse ribs on reinforcement bars; however, the presence of gauges and associated protection limited the bond to surrounding concrete. The second model was adjusted to position gauges between alternate ribs, allowing better bond.

Some of the conclusions drawn from the hinge testing are outlined below.

- Under representative serviceability loading, the hinge appeared to crack only vertically, opening and slipping on the formed construction joint. Some internal cracking is assumed to have occurred relating to reinforcement bond slip.
- Shear load was resisted by tension and compression in the opposing scissor bars and dowel action in these and the dowel bars.
- There is no indication that a compression strut through the throat resisted the shear applied.
- Rotation of the hinge causes the reinforced-concrete section to act like a beam in which a portion of the concrete is in longitudinal compression and the horizontal components of the reinforcement act in tension.
- Resulting from the above items, high concentrations of stress do occur in reinforcement bars local to the centre of the joint as predicted by FEA.
- Dowel action and hinge rotation both cause reinforcement bars to bend, inducing locally high extreme fibre stresses as predicted by FEA.
- Vertical slippage on the construction joint owing to serviceability shear loads is small and would be immeasurable on the bridge.

2.4 Finite-element analysis

The author created a new finite-element model, the accuracy of which was qualified by comparing with reinforcement strains measured on the laboratory specimens. A local region of a laboratory specimen was represented by a three-dimensional (3D) stress analysis model of length 600 mm and half the model thickness, containing one set of hinge reinforcement bars.

Concrete material properties were specified in accordance with Model Code 90 (CEB, 1993). Hinge reinforcement bars (tension, compression and dowel bars) were modelled by wire beam elements of circular section and ‘C’ bars were modelled with smeared properties over a membrane surface; both were restrained to move with the surrounding concrete. Elastic properties were used for steel components as these were not loaded to yield.

The cracked vertical construction joint through the centre of the hinge was represented by contact faces. Opening or partial opening of the joint was freely allowed, determined by the loading condition. Shear force across the joint was partially restrained by a frictional coefficient of 0·5, representing the lightly scabbled face; this was therefore only effective in regions of compression.

Loads were applied to the cut end faces of the FE model in combinations of vertical shear (V) and rotation (α), which were unrestrained in the longitudinal direction, allowing the model to determine its own neutral axis at the hinge throat. The FEA model is shown in Figure 7 (deformations exaggerated).

The FEA was compared to results from the laboratory specimen by means of considering the variation in strain at peak location relating to the full range of shear forces and hinge rotations applied, as demonstrated in Figure 8.

The flat bottom to the physical model results at shallow hog rotations is attributed to debris of concrete caught within the vertical crack, preventing full closure. The finite-element model was shown to be a good representation of the hinge joint behaviour as tested, able to predict fatigue stress ranges on reinforcement bars to an accuracy within 10%. It was therefore justified that finite-element modelling of the same philosophy could suitably represent hinge joints of the bridge for the purpose of fatigue assessment.

2.5 Fatigue bar bending tests

In addition to the hinge model tests conducted, bar bending fatigue tests were also undertaken in order to resolve whether fatigue damage calculations should consider extreme fibre or axial reinforcement stress ranges.

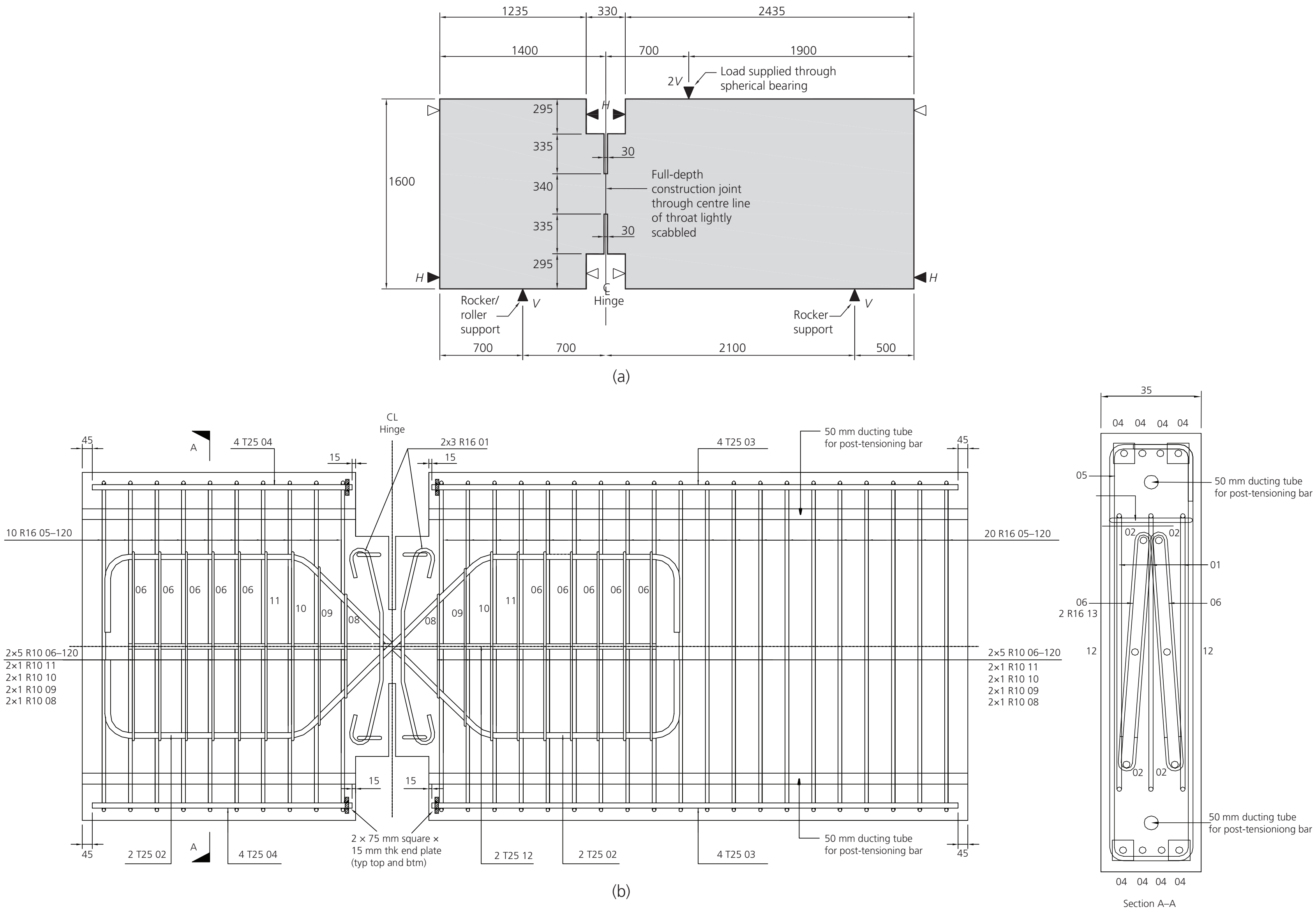

Figure 6. Hinge model (a) outline and (b) reinforcement details

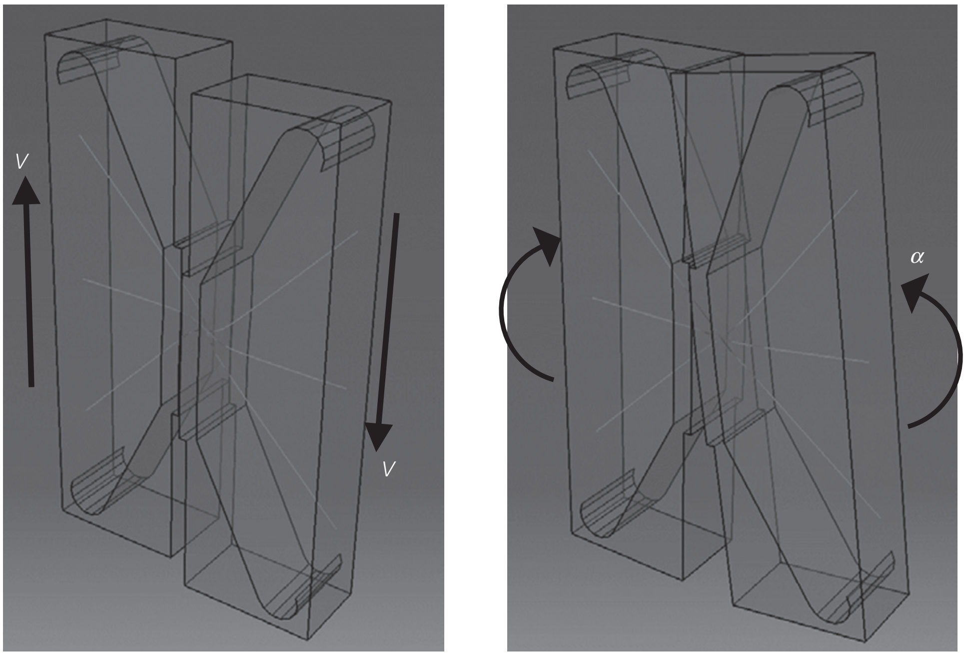

Figure 7. Three-dimensional finite-element model subject to (a) shear (V) and (b) rotation (α)

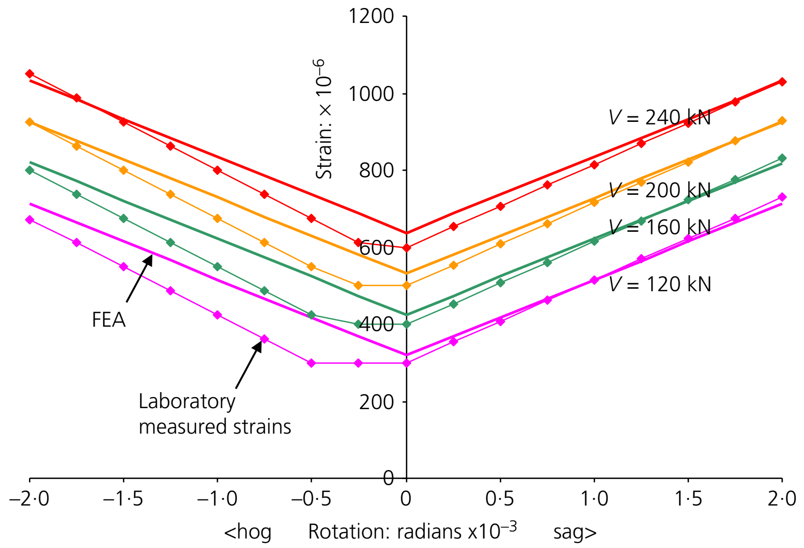

Figure 8. 3D FEA compared to physical model for peak axial strain in tension hinge bar

The 3D finite-element model described above and the physical model's implied extreme fibre stress ranges on hinge reinforcement were typically 40% greater than axial. σ–N curves found in current codes of practice are based largely on axial fatigue tests of reinforcement bars in air. Fatigue calculations based on extreme fibre stress ranges are therefore considerably more onerous if the same σ–N curves are assumed.

Details of these tests are not the subject of this paper. However, to summarise, the findings demonstrated a potential extension of fatigue endurance for stresses on extreme fibres to that of axial bar stress by a factor of 6 or greater.

These findings were not directly applied to the fatigue assessment of the structure, but supported evidence that there was yet more 'hidden strength' available.

3. Structure load testing and space frame modelling

A space frame (stiffness) model was created to represent one of the two decks along with the supporting piers and crossheads.

The space frame model assumes elastic uncracked concrete sections. The one exception to this was for members representing hinge joints, which were modelled with half their formed depth. Similar models were presented by the principal assessor, leading to comparable results.

The principal assessor had conducted load testing on the bridge in 2002. Longitudinal displacements were measured at intervals down the external face over the full depth of the beam, with a 60 t vehicle at various positions on the bridge. These results, which were analysed for hinge rotations, implied that space frame and finite-element models by both the principal assessor and Atkins were over-estimating hinge rotations by significant factors. If modelled rotations were reduced by this proportion, reinforcement stresses would be greatly reduced and thus calculated fatigue lives would be much longer.

The author demonstrated that the measurements were not comparable with the space frame models. Measurements had been taken on the outside face of an external hinge, as these were the only freely accessible joints. By means of a full 3D finite-element model of the structure, it was demonstrated that load distribution and vertical deformation were not equal over the width of deck, resulting in reduced hinge rotations at external faces.

A second series of tests were conducted in 2007 with an applied load of a 96 t mobile crane, measuring

- deck vertical deformation for the load positioned centrally within the central span
- longitudinal displacements above and below the internal and external faces of one internal and one external hinge joint within the central span, with the load positioned at a series of chainages to cause sagging, hogging and shear force across the hinge.

These tests confirmed reservations regarding lateral effects and compared more favourably to space frame models as demonstrated in Figure 9.

The space frame model presented was therefore demonstrated to be suitably accurate for the purpose of predicting hinge rotations for the fatigue assessment of hinge joints of the structure. It was therefore assumed that the model was equally accurate for predicting shear forces applied across hinge joints.

The space frame was used to simulate the passage of vehicles over the structure to determine influence lines of shear force and rotations applied to hinge joints. The finite-element model was then used to define empirical formulae for hinge reinforcement stress resulting from applied shear and rotations. Thus stress influence lines were determined for fatigue analysis in accordance with BS 5400: Part 10 (BSI, 1980).

4. Use of BA93/09

The Highways Agency advice note BA93/09 Structural Assessment of Bridges with Deck Hinges (HA, 2009), is intended to give guidance for the static and fatigue assessment of such joints. The findings of this project have concluded that these approaches are not appropriate to the bridge assessment concerned. Until such a time when BA93/09 may be amended, the following is a summary of the alternative considerations that may be required for assessments of similar structures based on the understanding developed in this project.

4.1 Inspections

Before assessing a structure in detail, the present condition of deck hinge joints of the structure should be investigated. Inspections should consider the following factors.

- Any cracking visible at or near to the hinge. Is there a vertical crack (potentially from a formed construction joint)? Are there diagonal shear cracks emanating from the formed throat? Cracking found may determine the assessment formulae used.
- Evidence of any corrosion to reinforcement or likelihood thereof. Evidence may include rust staining, delamination of concrete cover or moisture from road level found under the formed throat. (Note: corrosion caused by chlorinated water seeping through a cyclically opening crack, may not be indicated by chlorine content tests of the surrounding concrete.) If there is no corrosion to hinge reinforcement, it is unlikely that a fatigue condition would be critical.

The above items may be difficult to determine as hinge joints tend to be inaccessible. On conducting numerical assessment

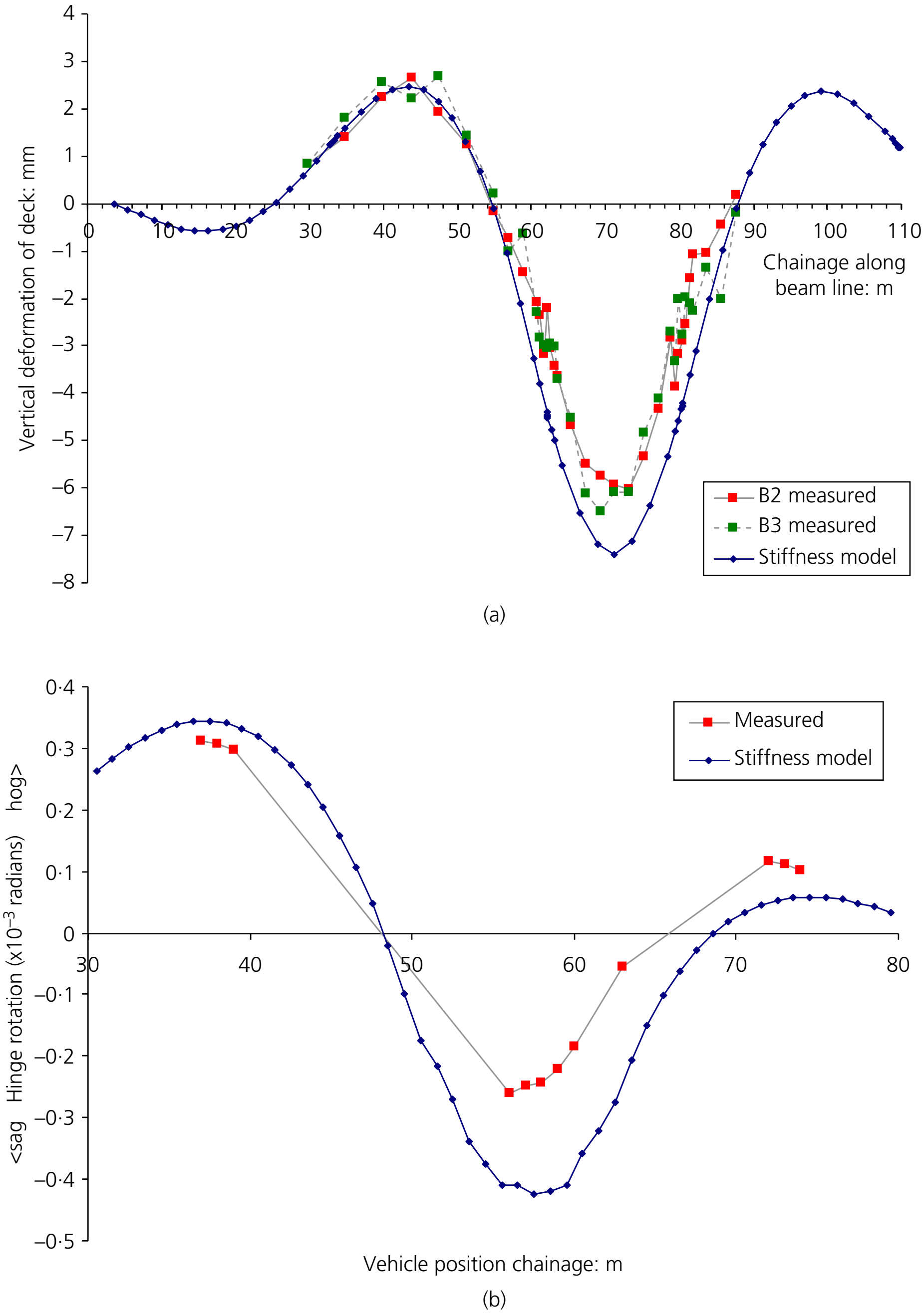

Figure 9. Comparison of space frame model (stiffness model) and site measured deformations: (a) deck vertical deformation and (b) hinge rotation

based upon initial assumptions, more detailed inspections may be required specific to sensitive factors found in the assessment.

4.2 Structural modelling

The structure should be modelled in a space frame using suitable stiffness analysis software.

BA93/09 (HA, 2009) recommends modelling the presence of a hinge joint as pinned connections. However, this has been found to be unduly conservative for the above detailed assessment. Rather, a member representing the short length of the hinge throat with section properties equal to the width and half the formed depth is shown to give reasonable correlation.

4.3 Static shear capacity assessment

For a deck hinge joint to be deemed satisfactory at ultimate limit state, an assessment of the static shear capacity is required.

The strut-and-tie model presented in BA93/09 (HA, 2009) is based upon the assumptions surrounding diagonal crack formations from the associated research. If diagonal cracks are formed, the guidance given is reasonable, but one must justify fully the presence of any horizontal compression formed through the hinge. If this were to be generated by opposing tension in the dowel bar, sufficient anchorage and subsequent load path would be required.

Alternatively, if a vertical crack is present through the hinge, in agreement with Wilson (1995) and the current paper, the following components may be used to contribute to the hinge shear strength

- the vertical component of the axial yield force in the tension bars
- the vertical component of the axial yield force in the compression bars
- the dowel action contribution of the tension, compression and dowel bars; which may be calculated by Rasmussen's formula (Rasmussen, 1963).

Appropriate partial safety factors should be considered.

4.4 Fatigue assessment of hinge reinforcement bars

It is assumed in all deck hinges that the tension bar is most prone to fatigue damage as it is exposed to cyclic tension owing to both shear across the hinge and rotation of the joint. BA93/09 (HA, 2009) gives a hand calculation method for reinforcement stress due to serviceability loading, reproduced below

1. $$\sigma_{SB} = 0{\cdot}30\sigma_S + K\alpha h/D$$

where σ_{SB} is extreme fibre stress on a tension bar; σ_S is axial stress in a tension bar assuming all the shear force is carried by the tension scissor bars; K is value of 0·30 MPa (empirically defined by the writers of BA93/09); α is hinge rotation (although not stated – in units $\times 10^{-3}$ radians); D is the nominal diameter of the scissor bars; h is depth of the hinge, measured as the clear depth between hinge formers.

The first component assumes 30% of the shear load to be taken by the axial force in the tension bar. Investigations in this research programme (involving vertical crack formation) suggest that this figure would be better replaced with 40%.

The second component is additional stress on the extreme fibre of the reinforcement owing to hinge rotation at the location along the bar coincident with a diagonal crack. This does not relate to stresses induced on hinge reinforcement local to a vertical crack when the joint is rotated.

Alternative hand calculation methods have been investigated to predict the axial and extreme fibre reinforcement stresses owing to hinge rotation. At present, no accurate methods have been derived and further investigation is outside of the scope of the bridge assessment conducted. The only suitable method known to date for predicting fatigue stresses on hinge reinforcement is by detailed non-linear FEA.

5. Conclusions and applications

5.1 Summary

A complex fatigue assessment has been conducted and checked by an independent consultant. Non-linear FEA was used to predict reinforcement stresses within reinforced-concrete beam hinge joints under serviceability conditions. Two physical scale models were tested and demonstrated the suitability of the FEA philosophy. A space frame model was used to simulate the passage of vehicles over the structure, which was qualified by comparison to deformation measurements taken in the structure.

5.2 Application to other projects

A number of other structures containing reinforced-concrete hinge joints exist within the same geographical region and shall be assessed, influenced by the research and findings of this project.

Approximately 100 structures across Great Britain include similar deck hinge joints. It is anticipated that the research undertaken will also influence their assessments.

5.3 Further research

A number of areas of further research could be conducted, each of which may serve to extend the assessed fatigue life of similar or other structures. These include

- comparison of the applicability of this research to other structures with deck hinge joints, considering their typical and unique features
- derivation of formulae for estimating fatigue stresses on deck hinge reinforcement bars local to a vertical construction joint crack
- further bar bending fatigue tests (which may also serve scenarios such as dowel bars on other structures) to produce guidance on fatigue of reinforcement subject to combinations of axial and bending stresses.

Acknowledgement

The authors would like to thank the unnamed client organisation for permission to publish. It is their wish and that of the author that the benefits of this research be known for other schemes.

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