SUPPLEMENTARY LOAD TESTING IN ASSESSMENT OF BRIDGES

Dr. S Mehrkar-Asl (Associate, Gifford and Partners, UK)

ABSTRACT

Effectiveness of infrastructure of all countries relies heavily on the performance of their bridges. Increases in vehicle loads, degradation and general corrosion of bridges often leads to a need to assess their load carrying capacity. Design of these bridges was often based on conservative analytical methods, therefore using alternative load paths can often increase their assessed load capacities. These include membrane action, surface stiffening and bearing restraints. As quantifying these effects is not straight forward, instrumented load tests have been used to calibrate analytical models.

Load testing can be carried out on newly constructed bridges to provide data about novel methods of design or construction and give assurance about the performance of the bridge. In the past, this was fairly common in the UK but has rarely been carried out in recent years. In contrast, new bridges are routinely load tested in some countries, for example Switzerland (Hassan et al 1995).

In the UK the introduction of heavier lorries from Europe started a programme of assessment of all the bridges. This resulted in the production of Guidelines for Load Testing. The Guidelines define and distinguish the types of static load testing: supplementary, proof and proving. Supplementary load testing, as the name implies, is carried out to supplement numerical calculations and, most importantly, loads are sufficient to give measurable responses without causing permanent strain or damage.

Mehrkar has carried out supplementary load tests on more than 50 bridge spans since 1989. In this paper the application of supplementary load testing on a number bridge types is discussed with emphasise on instrumentation, load application and calibration of computer models.

1. INTRODUCTION

Effectiveness of infrastructure of all countries relies heavily on the performance of their bridges. Increases in vehicle loads, degradation and general corrosion of bridges often leads to a need to assess their load carrying capacity. Bridges in the United Kingdom designed before the introduction of BD37/88 loading are being assessed for live loads including 40 tonne vehicles. The assessment programme started in the mid-1980's to bring allowable gross vehicle weights in line with other European countries. A number of bridges have failed assessments mainly as a result of lower original design loads or because of strength deterioration. In concrete bridges strength reductions have been mainly due to corrosion of reinforcement and prestressing tendons but in extreme cases poor concrete quality, coupled with defective waterproofing and bad detailing, has permitted the ingress of water and de-icing salts and this has resulted in severe corrosion.

2. ALTERNATIVE LOAD PATHS

Safe and conservative assumptions were often used in the analysis of the original designs of these bridges. However, with the introduction of higher loads or reduced strengths, additional load paths must be proven to demonstrate safety. Literature is full of results of load tests that indicate the existence of other mechanism in the bridges by which the loads are transferred to the supports. Amongst these mechanisms are membrane action, surfacing stiffening, composite action and bearing restraint. Quantifying the effect of each mechanism is not straightforward and often cannot be based solely on better analytical models. Instrumented load tests have been used to calibrate analytical models in order to take advantage of the actual performance of the bridges.

3. CURRENT ASSESSMENT METHOD

In the UK bridge assessments are based on the requirements of BD21/97 prepared by the Highway Agency. According to this document assessments are initially based on a simplified structural analysis using the information on the as-built drawings, including dimensions and characteristic strengths, with a visual site inspection to determine the deterioration since construction. Condition factors are applied to allow for any deterioration. If this simplified approach fails, further steps are required to improve the load rating of the bridge.

Mehrkar and Brookes 1996 recommended a flowchart for the bridge assessment which incorporated load testing. A modified version of this flowchart has been used in a number of projects and even used in the Guidelines For The: Supplementary Load Testing of Bridges 1998. Figure 1 shows the original flowchart for a typical bridge assessment.

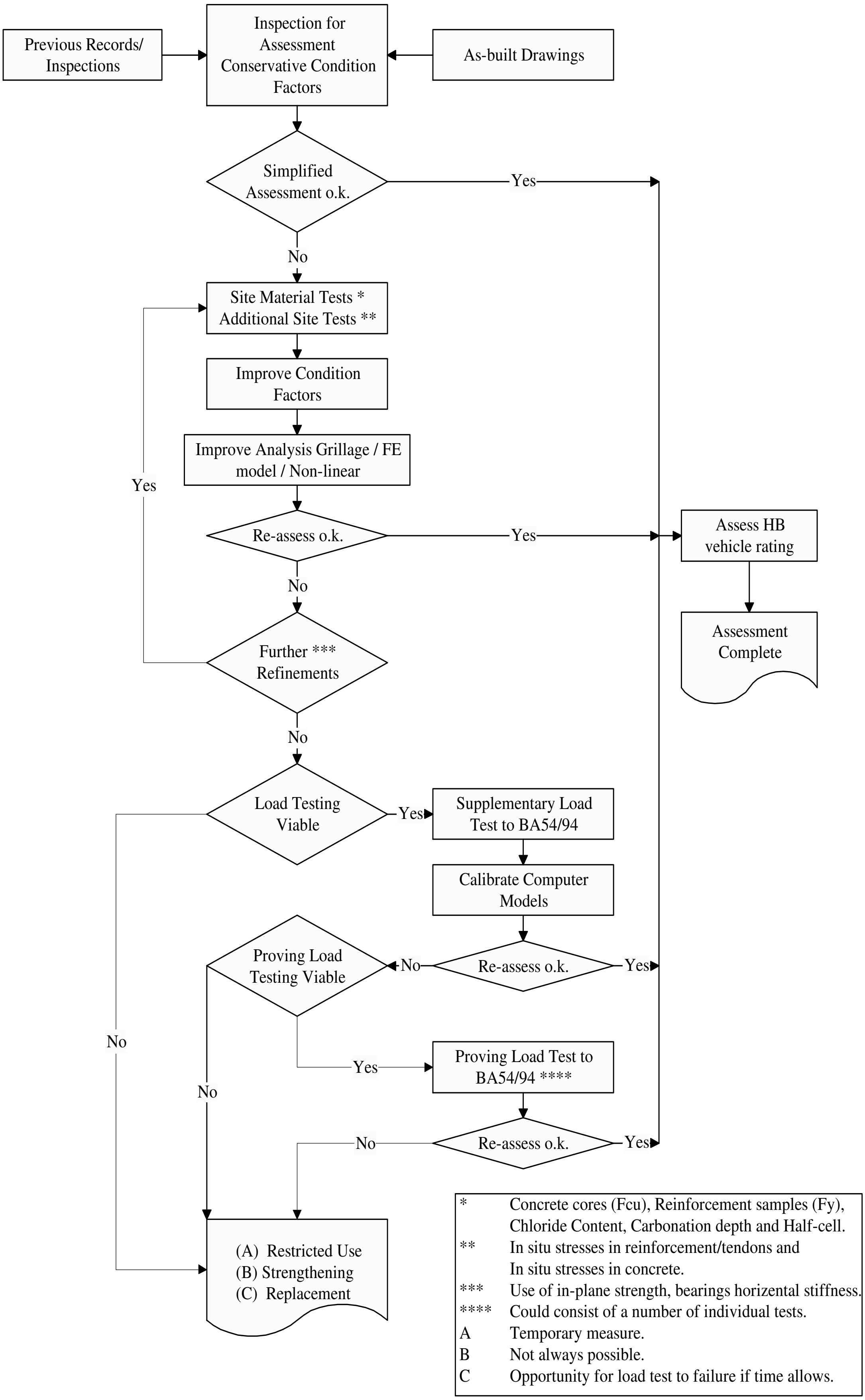

Figure 1. Flowchart of Bridge Assessment including Load Tests

The additional steps include physical tests to establish the characteristic strength of concrete, reinforcement and prestressing tendons and chemical tests such as carbonation depth, chloride content and cement content which along with covermeter and half-cell potential surveys indicate the likely degree of corrosion vulnerability of the structure (Bungey 1989 and Neville and Brooks 1987). On certain occasions in situ stress determination could also improve the understanding of the degree of prestress loss in the prestressed bridges. Moore (1994) has explained the method in steel referred to as blind hole technique. Mehrkar (1988 and 1996) has developed the instrumented stress-relief core in concrete and under his supervision instrumented slot-cut method was developed (Forder 1992). The overall results of the site tests and measurements can then be used to obtain a more accurate condition factor for the bridge. Additional steps may also include improved analytical methods such as grillage or finite element analyses.

When further refinement in the bridge analysis or material understanding is not achievable or when it becomes uneconomic, load testing should be considered. Load testing has been categorised by BA54/94 as “Supplementary Load Test” or “Proving Load Test”. The former is used to improve the theoretical modelling of the bridge whereas the latter is used as a complete assessment by itself in place of the theoretical assessment in the context of an assessment flowchart such as Figure 1. The viability of the use of a load test on a structure depends on a number of points as follows:

- Safe application of the load test.
- Economical advantage from the load test.
- Practicality of the load test on the type of structure and the corresponding deficiency in the structure.
- Remaining life of the existing structure.

The Author has carried out Supplementary Load Tests and the computer model calibrations that followed. Load tests have been applied either by static or moving loads. The static loads included jacking against a support and using concrete or steel weights. Moving loads included using pre-weighed aggregate lorries or a single axle of 45 tonne similar to the HB vehicle in BS5400.

The Proving Load Test in principle is a high-risk approach for an assessment. Some research workers and certain organisations inside and outside the UK have used it apparently with success. Basically, Proving Load Tests should not be used unless the bridge is fully instrumented to measure strains in steel and concrete, and rotation and deflection at critical positions. When shear strength of the bridge is suspect, consideration should be given to the use of a displacement control loading system. In addition, diagonal strain in concrete and strain in stirrups must be measured. There is always a risk that Proving Load Test will cause structural damage to the bridge and that this may not be evident initially but may lead to a rapid deterioration and sudden collapse. Therefore, bridges that have been the subject of a Proving Load Test should be monitored periodically.

4. LOAD TESTING REVIEW

Improved analysis of the bridge deck is normally carried out either by the use of a grillage or a finite element computer model. This step is carried out before any consideration to load testing is given, see Figure 1. Therefore, it would be possible to determine a safe level of load to be used on the bridge as a Supplementary Load Test. The load testing regime and the corresponding instrumentation should have the following characteristics:

- Instrumentation is so arranged to pick up the effects envisaged.
- Applied loads do not cause a permanent deflection or strain in the structure.
- Applied loads introduce measurable values compared to the accuracy of the instruments used (strains, deflections, rotation, temperature etc.).

Instrumentation

The choice of the instrumentation depends on a number of factors. These include the logging method, frequency of monitoring, accuracy of readings and the environment in which they need to function. These limitations and the nature of Supplementary Load Testing lead to the use of the following instruments:

- Vibrating wire gauges to monitor strains.
- Linear Variable Displacement Transformers (LVDT) to monitor deflection.
- Inclinometers to monitor rotation.

- Thermocouples to monitor temperature.
- Load cells to monitor loads.

All of the above can be monitored using a data logger. The results would then be checked as the test is in progress to provide immediate feedback to the engineer in charge. Normally it is expected that predicted behaviour based on reasonable assumptions be already in hand to provide guidance during the load test.

4.1 Loading Methods

The Supplementary Loads can be applied in a number of ways. These include either moving or static method. The static method can use steel or concrete weights, water bags or even loading against a reaction frame or anchor. Moving methods include pre-weighed lorries or special load testing lorries or axles. Most of the load tests are conducted using moving loads to reduce disruption to traffic and reduce the load testing time on site. In addition it provides more flexibility to rearrange and amend the load test if necessary. In case of an emergency the Test Loads can be moved off the bridge to provide a clear passage on the bridge.

4.2 Load Test Method Statement

Test Loads are normally applied in stages that correspond to incremental increases in the internal forces in the structure. A method statement is required in which the necessary actions dependent on the response of the bridge to the Test Loads are identified. Actions could include increasing the loads in the case that no measurable response was observed or abandoning any further increase of the loads if the response becomes non-linear or well outside the predicted values.

Test Loads are applied asymmetrically and gradually made symmetrical both with respect to midspan and longitudinal axis of the deck. If a static load is used, some form of partial or total lane closure is required. If a moving load is used, the test could be carried out with minimum disruption to traffic, preferably before or after midnight when temperature effects are minimal. Mehrkar 1994 details typical instrumentation and a loading regime.

5. CALIBRATION OF COMPUTER MODELS

Results of the Supplementary Load Tests are normally in the form of variation of strains at predetermined sections across the deck for the load at specific points or variation of the longitudinal strains along the span. The former would help to define the degree of transverse load distribution and the latter reflect the existence of any bearing restraints or continuity. In addition, the summation of the total moments applied compared to those induced across the deck would indicate the degree of the composite action between the structural deck and the surfacing layers. However, it is not straight forward to isolate the effect of each individual item. Any composite action, bearing restraint or continuity at the supports could change with the level of loading and the ambient temperature. However, the lateral load distribution capability is less influenced by the above factors. Therefore, computer models are calibrated to produce similar lateral load distributions as the load tests by introducing orthotropic behaviour and varying the ratio of the elastic moduli in the two directions.

Monitoring deflection and rotation are carried out when practical. In a number of occasions the soil-structure interaction has to be investigated. This is normally the case for buried structures such as culverts or arches. In these occasions the ratio of the soil stiffness to that of the structure is also an influencing factor in successful calibration of the computer models.

6. CASE STUDIES

Mehrkar has tested over 50 deck-spans since 1989 using a variety of loading systems. These include pre-weighed aggregate skips, loading against a reaction frame, pre-weighed aggregate lorries and a single axle 45tonne load similar to an HB vehicle. The load tests were applied on a number of different types of structures including the following:

- Single simply supported spans of precast prestressed beams and transversely post-tensioned.
- Multi-span complex deck structure.
- Trough and filler decks.
- Culverts and arches.
- Continuous concrete box girders.
- Cable-stayed decks.

In this section the specifics of the load tests on each type are discussed with particular attention to the Test Loads used, the instrumentation and the calibration of the computer models.

6.1 Simply supported precast prestressed beams with transverse post-tensioning

The decks of these bridges consist of a number of precast pre or post-tensioned concrete beams that are transversely post-tensioned to provide load distribution. A number of bridges of this nature were tested in Hampshire, England. The instrumentation consisted of vibrating wire strain gauges, normally installed on the soffit across the midspan, with additional gauges along certain beams to investigate bearing restraint or continuity to the foundation. Pre-weighed aggregate lorries and single axle 45tonne vehicles have been used. Test Loads were applied at quarter span or one-third span initially. If the structure had not shown any undue sign of strain then Test Loads were applied to the midspan region. Computer modelling used orthotropic plate elements. The net outcome has been that a ratio of 0.25 between the transverse and longitudinal elastic moduli would provide the best comparison between the predicted and measured stains. One of the key performance parameters in these cases is the level of residual prestress in the transverse direction between the beams. A value of 1.7N/mm^2 was measured for the calibrated model using the orthotropic elements. Further information is also available in a paper by Mehrkar and Brookes 1996. In certain cases, even in the presence of very low or zero residual transverse prestress, a significant distribution of the load was observed, Mehrkar 1994.

6.2 Multi-span Complex Deck Structures

The Angel Road Railway Viaduct was built in 1960 to replace an earlier road bridge constructed in 1908. It is situated in the London Borough of Enfield, about six miles north of the centre of London, and carries the North Circular Road, A406. Mason described the construction details of the bridge in 1962. It consists of three traffic lanes per carriageway, a central reserve and a wide footway either side of the deck.

The decks of the ten span viaduct are made from 59 rectangular pre-tensioned beams 610mm deep and 381mm wide, placed side by side. The width of the beams reduces to 362mm at the top, allowing a concrete topping to infill between the beams. The decks are post-tensioned in the transverse direction by Freyssinet cables positioned every 1.5m along the length of the bridge.

The first seven spans of the bridge from the west are of continuous construction. In these spans, half joints at the end of pier cantilevers support precast beams. Post-tensioning of the beams through the pier cantilevers provides the continuity. The remaining three spans are simply supported.

In the early 1980's, corrosion of the longitudinal post-tensioning was noticed at the anchorage points. Gifford and Partners were commissioned to strengthen the bridge and in 1982 a series of steel frames were added to the support ends of the precast beams in the continuous spans. Mehrkar became involved in the latter half of 1990 to make a present condition assessment of the bridge as part of the Department of Transport assessment programme. It was decided, due to the complex nature of the structure, that a direct approach was required to establish the load distribution of the bridge and the actual level of prestress left in the structure. The former was achieved by running a 45 tonne axle similar to an HB vehicle over the bridge and monitoring longitudinal strains on the soffit of the precast beams at midspan using 11 vibrating wire gauges per span. The latter was achieved by taking 6 instrumented stress-relief cores and 2 instrumented slot-cuts on the soffit of precast beams in the main railway span over a 30-hour weekend possession. In addition, material tests were carried out on the cores retrieved from the structure. The load test was performed after midnight to minimise any disruption to traffic. The HB axle was run along the fast lane of one carriageway and along the slow lane of the other.

The measured values of in situ stresses indicated a residual compressive stress of between 0.5 and 2.5N/mm^2 in the longitudinal direction and 1.5N/mm^2 in the transverse direction. The load test results were used to calibrate a full 3D finite element model of the deck. The final calibration concluded that there should be no continuity in the transverse direction between the beams. This result was not unexpected as almost all the packing mortar between the beams was missing in the middle part of the deck. In addition, calibration indicated that the topping concrete should be an orthotropic plate with a ratio of 0.5 between the transverse and longitudinal elastic moduli. Almost a perfect match between the analysis and the Supplementary Load Test was obtained for the distribution of the load at the slow and fast lanes of the bridge.

The 3D model was then used to calculate all the internal forces in the bridge. The bridge was found to be capable of carrying the 40 tonnes Assessment Loading to BD21. In addition, the HB rating and Abnormal Indivisible Load rating of the deck was assessed to be 45 units and 280 tonnes, respectively.

6.3 Trough and Filler Decks

A trough deck in Hampshire and five filler deck bridges in London have been tested. The 11m wide trough deck has a clear skew span of 5.2m. The deck consists of 18 No. steel troughs at 610mm intervals, infilled with concrete. The steel troughs span between mass concrete abutments and have an overall height of 197mm. The infill concrete extends 100m above the top of the steel troughs.

The deck was instrumented to measure strains on the soffit of top and bottom flanges to pick transverse load distribution and composite action with the infill concrete. In addition, one of the troughs was instrumented at quarter span and next to the abutment in order to investigate the continuity or restraints at the supports.

Test Loads consisted of pre-weighed aggregate lorries. In advance of the load test, tables were prepared of the predicted strains at the gauge positions for different degrees of composite action and for different lateral load distribution scenarios. The load test concluded that the steel troughs were acting in a composite manner with the infill concrete and with the surfacing layer. In addition, the point of contraflexure was at quarter span. An interesting point about this bridge was the existence of a sunken repair on one side of the bridge. This was producing an impact whenever a lorry ran over it resulting in a reduction of stiffness possibly due to debonding between the different layers of the composite section.

Instrumentation on the filler deck bridges in London was limited to the soffit of the bottom steel and cast iron beams at midspan. The measured lateral load distribution along with non-linear computer modelling of the concrete indicated the bridge was satisfactory for 40tonne Assessment Live Loads.

6.4 Culverts and Arches

One box culvert and one arch both in reinforced concrete have been tested. The culvert has a effective span of 2.77m between the centre line of the walls and 2.4m between the centre line of the top and bottom slabs. The fill on top of the culvert is about 0.4m. The initial assessment has resulted in a limited load rating for this culvert. Two sections of the culvert were instrumented with 13 vibrating wire gauges at each section. This was to allow for different width of the running lanes at each section. Five gauges were installed at midspan and close to support of the top slab and three gauges on the mid-height of one of the walls.

Load Testing was carried out using a 45tonne axle similar to HB vehicle. The axle was placed at a certain distance from the instrumented wall, over the wall and at midspan. The box culvert was modelled as a unit width frame. Comparison between the load test results and the predicted values indicated that the surfacing acted in a composite manner with the box. In addition, by changing the spring stiffness of the soil model, it was deduced that the structural response of the culvert is as though it is surrounded with stiff clay. It was also noticed that the stiffness of the culvert was affected by the existence of cracks in the surfacing at one of the instrumented sections. Therefore, long-term performance of such structures is affected by the condition of the surfacing above them. The Supplementary Load Test and the calibrated model increased the rating of the bridge to 40tonne Assessment Live Loading and 45 units of the HB vehicle.

The reinforced concrete arch has a rise of about 4.3m and span of about 7m. The arch barrel thickness varies from 190mm at crown to 267mm at the springing points. The initial assessment had indicated that the arch should not even take the permanent loads. A section of the arch with least amount of fill of 1.4m, was instrumented with 35 vibrating wire gauges. The gauges were so arranged to pick up both lateral load distribution of the arch and also the distribution of the load from crown to springing points. Further 2 vibrating wire gauges were placed on the connecting ties beams between the springing points. The deflections of the crown and quarter span were measured with LVDT's.

Load test was conducted using two pre-weighed 32tonne lorries. Lorries were placed at quarter span intervals from outside the arch to directly above it. The arch was modelled as a unit width frame including all the soil around it. Therefore, the model directly incorporated the soil-structure interaction. Comparison of the theoretical and experimental results indicates that the live load is hardly noticed by the arch and has little to no effect on the internal forces generated. However, the theoretical model after allowing for suitable material properties for soil could closely match those from the load test. It was concluded that similar strains to those obtained during load test could be generated if 22% of the load from a lorry is used in the unit width frame. For two loaded lanes this value increased to 33%. The assessment rating of the arch was increased to 40tonne Assessment Live Loading and 45 units of HB.

6.5 Continuous Concrete Box Girder

This bridge, the A3/A31 Flyover, comprises a two span voided single cell pre-cast segmental externally post-tensioned concrete box deck supported on a reinforced concrete pier. The main span is 50m over the A3 and the side span is 20m. The structure was built in the mid 1970's and since then has had series of problems. Corrosion of some of the tendons and their severance resulted in its strengthening in the mid 1990's. More detail of its construction and historical problems leading to its strengthening is explained by Brooman and Robson 1996. Mehrkar conducted an upward load testing before its strengthening to estimate the remaining level of prestress. This was carried out by first conducting a significant amount of initial analysis to identify the critical areas and levels of prestress loss that would lead to the initial cracking in the concrete.

The bridge was initially instrumented and monitored for a period to identify the diurnal temperature fluctuation effects on strains. The instrumentation was extended to 16 vibrating wire gauges to cover the concrete segments and the corresponding joints between the segments at midspan and over the central pier. Midspan deflection was also measured with the use of LVDT's. Upward load was applied in increments up to 100tonne at mid main span. The maximum upper bound of prestress loss was determined in the absence of any crack detection in the joints. In addition, the relative stiffness modulus of the segment joints to that of the precast sections was determined to be 59%.

6.6 Cable-Stayed decks

A load test was carried on the Pont Sir Y Fflint (Dee Crossing) that carries A548 over the river Dee in north Wales, just before its official opening. The total length of the crossing with its approach spans is 1000m. The bridge is the centrepiece of the crossing and comprise of an asymmetric cable-stayed bridge with main span of 194m and a back span of 100m divided into two parts with tension piers. The deck is only 1.5m deep. The main tower is an A-frame of 118m in height of which 93m is above the deck. The main span is supported by 19 pair of stays at 8m centres. Curran (1996) has explained the design features.

The load test was carried out with the use of eight pre-weighed 32tonne lorries. They were placed on the bridge under a strict regime approved in a method statement. The deck was instrumented during the construction for this test and future monitoring of the bridge. In total 25 buried vibrating wire gauges were installed in the bridge to pick up either local or global behaviour of the bridge at certain sections including:

- A longitudinal section of the deck.
- Four stay anchorage pockets.
- A transverse beam.

Loads in the stays were monitored by load cells already installed on some of the stays. During the load tests, in addition to monitoring of strains and stay forces, vertical deflection of the deck and horizontal movements of the tower were also monitored. Mehrkar and Ricketts 1998 explain details of the load test and the results.

The results of the load test in terms of strains and deflection and loads were compared against 2D and 3D models of the bridge. Deflections of the main span were on average 90% of the predicted values. The tower horizontal movements were on average 85% of the predicted values. Stay forces were on average 84% of the predicted values. Anchorage strains were close to predicted values. The average strains in the longitudinal section were equal to predicted values. However, although the equilibrium of the moments induced in the transverse beam was satisfied, its relative stiffness to the edge beams on the bridge had caused a shift in the moment diagram.

7. CONCLUSIONS

Supplementary Load Testing has proved to be of value in highlighting the structural actions that are not normally considered in a traditional design or assessment. Although, for simple designs their influence is not significant, their contribution in the assessment or complicated designs should not be ignored. This normally would lead to significant cost savings in terms of:

- Eliminating the need for either strengthening or replacing of a bridge including disruption costs during strengthening or reconstruction periods
- Increasing the load carrying capacity of a bridge hence relieving other routes
- Releasing the funds for more urgent remedial measures
- Better understanding of a design performance to improve and make more cost effective designs in the future.

The use of Supplementary Load Testing without initial investigations and analysis, as pointed in the flowchart of Figure 1, should be avoided. It is emphasised that engineers experienced in this field should carry out load tests.

8. REFERENCES

BD21/97 (Design Manual for Roads and Structures 3.4.3), The Assessment of Highway Bridges and Structures. Highway Agency, UK.

BA54/94 (Design Manual for Roads and Structures 3.4.8), Load Testing for Bridge Assessment. Highway Agency, UK.

Brooman, H. and Robson, A. 1996, "A3/A31 Flyover - Case History of an Externally Post-tensioned Bridge". In the proceeding of the 3rd Bridge Management - Inspection, Maintenance, Assessment and Repair, edited by Harding, Park and Ryall, published by E & FN Spons, 1996, pp 473-479.

Bungey, JH. 1989, Testing of Concrete Structures. Second Edition, Surrey University Press.

Curran, PN. 1996, "Dee Estuary Bridge - The Design of the Post-tensioned Asymmetric Cable-stayed Crossing". Proceedings of FIP Symposium, London 25-27 September 1996, "Post-tensioned Concrete Structures", pp 94-101.

Forder, S. 1992, "Calibration of Saw Cutting Technique for In Situ Stress Determination". MEng Project Dissertation, University of Surrey.

"Guidelines For The: Supplementary Load Testing of Bridges" The Institution of Civil Engineers National Steering Group for the Load Testing of Bridges, Thomas Telford, 1998.

Hassan, M., Burdet and Favre, R. 1995, "Analysis and Evaluation of Bridge Behaviour under Static Load Testing Leading to Better Design and Judgement Criteria". Fourth Bridge Engineering Conference, TRB, San Fransisco, USA. Publ Nat Acad Press, Washington DC.

Mason, J. 1962, "The Reconstruction of the Angle Road Bridge". The Structural Engineer, pp. 45-71, February 1962.

Mehrkar-Asl, S. 1988, "Direct Measurement of Stresses in Concrete Structures". PhD Thesis, University of Surrey.

Mehrkar-Asl, S. 1994, "Testing and Assessment of Post-Tensioned Concrete Bridges in Hampshire" in "Bridge Assessment, Management and Design" Proceedings of the Centenary Year Bridge Conference, Cardiff. Edited by Barr, B.I.G. and Evans, H.R. Published by Elsevier, pp347-352, September.

Mehrkar-Asl, S. and Brookes, CL 1996, "Load Testing in Bridge Assessment", Proceedings of the City University International Seminar, London 1-3 July 1996, "Structural Assessment: The Role of Large and Full Scale Testing" Edited by Virdi, K.S., Garas, F.K., Clarke, J.L. and

Armer, G.S.T, Published by E & FN Spon, pp45-52. Proceedings printed in 1997.

Mehrkar-Asl, S. 1996, “Concrete Stress-relief Coring: Theory and Practice”, Proceedings of FIP Symposium, London 25-27 September 1996, “Post-tensioned Concrete Structures”, pp 569-576.

Mehrkar-Asl, S. and Ricketts, NJ 1998, “Load Testing of Pont Sir Y Fflint”, Hidden Strength Conference 17 November 1998, paper presented at the surveyor’s conference on, ICE London.

Moore, DR. 1994, In Situ Stress Tests - Finding the Dead Load Stresses in Metal Bridges. Proceeding of the Hidden Strength Seminar, London, 25 Feb. 1994.

Neville, AM. and Brooks, JJ. 1988, Concrete Technology. Longman Scientific and Technical (John Wiley & Sons in USA).