Further Vibration Modelling of Beam/Slab Scale Model

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Abstract

A large number of bridges in Western Australia were constructed in the early 1960s and 1970s and many of them currently do not meet the requirements of current standards. This is because of updates in codes, increase in traffic loads, flooding of regions and deterioration of the bridge structure itself. In some of these bridges, the shear connectors appear inadequate to provide shear transfer from the deck of the bridge to the supporting girders under service loads. Therefore there is a need to investigate non-destructive strategies for repair/strengthening and to evaluate their effectiveness in improving the capacity of the existing bridge superstructure. The use of Fibre Reinforced Polymer (FRP) has been recognised as an efficient strategy for bridge strengthening which also minimizes disruptions to the traffic network. However the application of FRP is a relatively new method and many researches are still being undertaken to understand its effectiveness on bridge structures. This paper mainly focuses on the evaluation of the effectiveness of FRP on their application for shear transfer between the bridge deck and the supporting girders using dynamic and static tests.

1.0 Introduction

In Western Australia, a vast number of bridges constructed in the Pilbara region consists of pre-fabricated presstressed I-beams supporting a reinforced concrete deck which is cast-in-situ. Steel stirrups were embedded in the beams and cast into the slab as shear connectors so that the slab and beams act as a composite section. Deteriotation of the shear connectors due to local floods and increase in traffic loadings may affect the capacity of the structure, therefore it was necessary to find alternative means such as the use of Fibre Reinforced Polymers (FRP) to strengthen the existing structure.

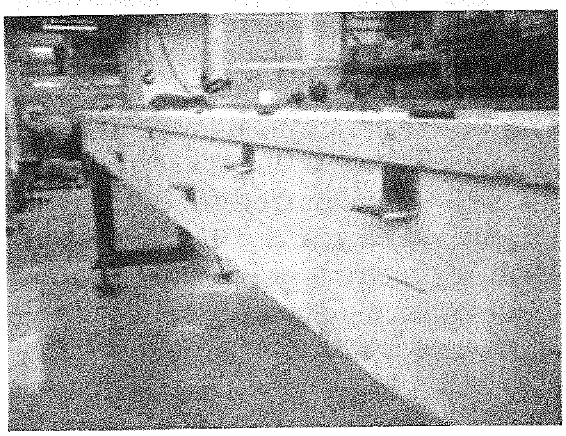

Fig. 1- Scale Bridge Model

A reduced scale bridge model (Figure 1) has been constructed in the structures laboratory at the University of Western Australia. Removable anchors were designed and fabricated to link the beams and slab to simulate the shear connectors. A vibration test and static loading test was performed with and without the shear connectors so that the initial stiffness and dynamic properties of the scaled bridge model could be identified and used as a baseline model for comparison. Glass and Carbon FRP are used to strengthen the model without the shear connectors intact and a series of vibration tests are performed to detect changes in dynamic properties of the structure. These results will then be compared to the baseline property via a global approach – direct comparison. In most real bridge cases, a baseline model is usually not available, hence a local approach will also be used to verify the effectiveness of FRP as a strengthening material on bridge structures.

2.0 Methodologies

2.1 Dynamic Testing

5 by 12 magnetic sensor plates are placed along the slab at locations shown in Figure 2, and 12 magnetic sensor plates are also placed along each of the three beams.

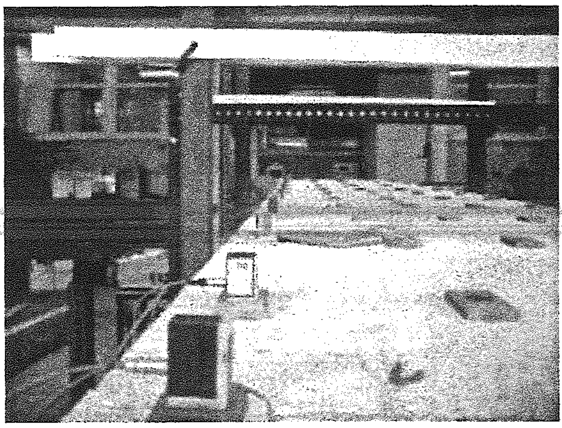

Fig. 2 – Sensor Locations on Slab

12 accelerometers (ADXL 105 5G with calibration factor of 250mV/G) are placed along the slab or beams when measuring the vibration signals, which is connected through a collection of equipments such as sensor cables, acqusition boxes, distribution box and a computer (shown in Figure 3 and Figure 4) so that the vibration signals can be collected along the length of the bridge at locations on the slab that are directly above the beams and directly below the beams.

The dynamic properties of the scale bridge model were measured by exciting the structure with a instrumented sledge hammer which is connected to a computer so the magnitude of the impact could be recorded. For all cases, four impact tests were conducted and the data averaged.

Fig. 3 – Acquisition Units

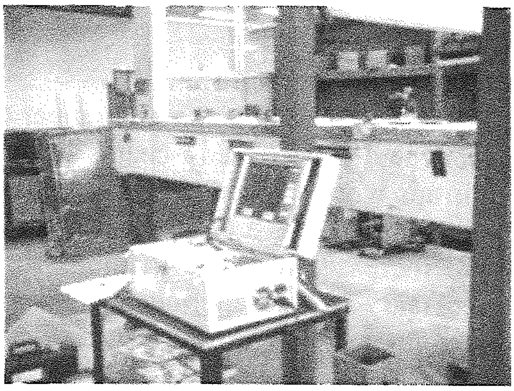

Fig. 4 – Computer used for data collection

The vertical responses are picked through the accelerometers by a program developed using Labview. The data are then processed on Matlab so the modal data of the slab and beams can be extracted. Then a direct comparison via a global method or a local method can be used to detect changes in modal properties between the baseline model and the model with FRP applied. The change in dynamic properties may give a fair indication of the effectiveness of the FRP for shear transfer from the slab to beam. Benefits realised from dynamic testing (over static testing) are principally associated with the versatility of the instrumentation used to perform response measurement (Haritos and Hira, 2004).

2.1.1 Modal Assurance Criterion (MAC)

The MAC is used to determine the correlation between a pair of modeshape vectors or matrices (Doebling el al. 1996) over all measured points and is defined as follows:

$$MAC(\{\phi_i\},\{\phi_j\}) = \frac{\left|\{\phi_i\}^T\{\phi_j\}\right|^2}{(\{\phi_i\}^T\{\phi_i\})(\{\phi_j\}^T\{\phi_j\})}$$ Equation (1)

Where $\{\phi_i\}$ corresponds to the i^{th} modeshape, and $\{\phi_j\}$ corresponds to the j^{th} modeshape.

A MAC value of 1 indicates an identical modeshape whereas a value of zero indicates an unrelated modeshape.

2.2 Static Testing

Static testing was also performed as it was necessary to simulate realistic loadings on the scale bridge structure. The static load test comprises of two 10 tonne hydraulic jacks, two 20 tonne load cells to measure the magnitude of the loads, two reaction frames constructed two metres from each support, and a few Linear Variable Displacement Transducers (LVDT) used to measure the downward deflection of the scale bridge model when the load was applied. The LVDTs are placed at the mid span of the scale model and directly below the loads so a direct load-displacment graph can be plotted. The load is spreaded across the slab directly over the supporting beams by using a spreader. This way each beam is forced to take the same static loading. The setup and configurations of the static loadings can be observed from Figure 5, 6 and 7.

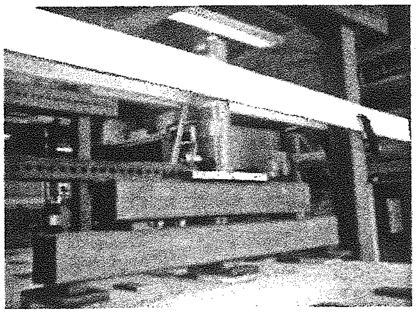

Fig. 5 – Hydraulic Jacks pushing off reaction frame

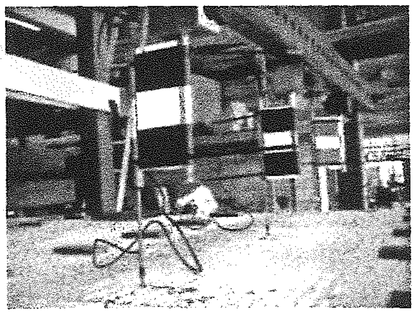

Fig. 6 – LVDTs at midspan for central deflection

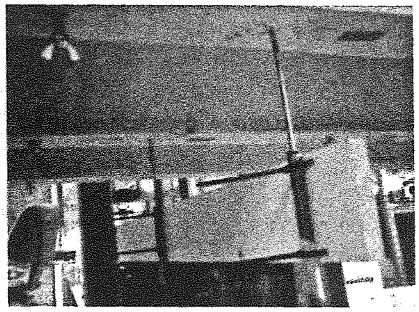

Fig. 7 – LVDTs on beams directly under load

Only two static load cases has been studied for the time being, i) with shear connectors, ii) without shear connectors. Both cases were loaded to their serviceability limit (cracking of concrete) which is calculated from basic solid mechanics and concrete theory outlined in the Australian Standard Bridge Design Part 5: Concrete (AS5100). The formulas used for these calculations are shown:

Flexural concrete strength: $f'_{cf} = 0.6\sqrt{f'c}$ Equation (2)

Second moment of inertia of a general section: $I = \int_A y^2 dA$ Equation (3)

Distance of Neutral axis from extreme tension fibre: $\bar{y} = \frac{\sum_{i=1}^{n} A_i y_i}{\sum_{i=1}^{n} A_i}$ Equation (4)

Cracking moment of concrete: $M_{cr} = \frac{I.f'_{cf}}{\bar{y}}$ Equation (5)

The purpose of these two cases was to detect the difference in the structural stiffness by plotting a load-displacement graph for each case. A additional static loading will be performed after the bridge has been strenghthened with both Glass FRP and Carbon FRP. It will be loaded up to its serviceability limit, and a vibration test will be conducted to test for any changes in the structural property. This allows us to assess its effectiveness under service conditions. Further a final static test will be performed and the scaled bridge model it will be loaded to its ultimate limit state so comparisons between its theoritical capacity can also be evaluated by comparing it with its actual capacity.

3.0 Results

3.1 Baseline Model

The frequencies and modeshapes of the first four modes for the baseline model with shears connectors connected and disconnected are extracted from measurements with the Rational Fraction Polynomial (RFP) method and is shown below in Figure 8 and Figure 9.

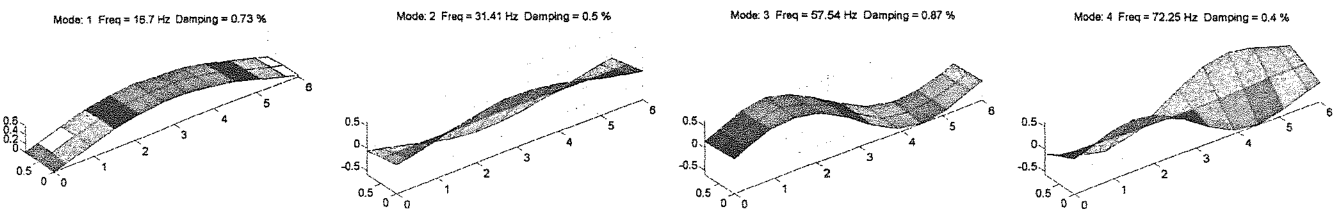

Fig. 8 – Modeshapes of first 4 modes with shear connectors fully intact.

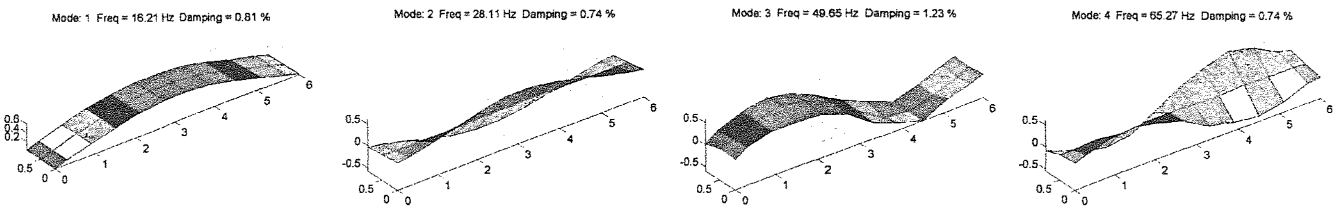

Fig. 9 – Modeshapes of first 4 modes with shear connectors disconnected.

The frequency differences and MAC of the two cases are shown in Figure 10.

With connectors intact		Without connectors			
Mode	Freq (Hz)	Mode	Freq (Hz)	Error (%)	MAC
1	16.70	1	16.21	-2.98	1.00
2	31.41	2	28.11	-10.50	1.00
3	57.54	3	49.65	-13.71	0.97
4	72.25	4	65.27	-9.66	0.94

Fig. 10 – Table showing the error and MAC of the two different cases.

Visual inspection of the modeshapes or the table above, we can see large frequency changes in the first 4 modes. The reason is because the slab and beam member are vibrating independently in the disconnected case, the slab becomes less stiff and therefore will vibrate at a lower frequency. The MAC value of all 4 cases are at unity or near unity indicating a good correlation between the modeshapes that are being compared.

3.2 Baseline Model after Static Loading

3.2.1 Static Loading Results

The load-displacement graphs for both static load cases are plotted and shown in Figure 11.

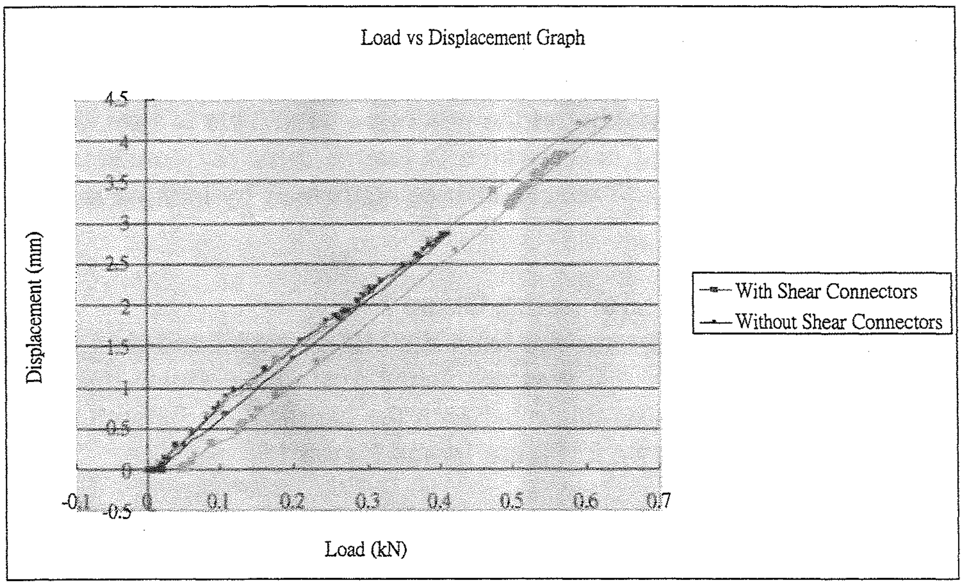

Fig. 11 – Load-Displacement graph for both static loading configurations.

The load-displacement graph for both cases indicates that the section has the same bending stiffness as both curve shows the same gradient. This is mostly likely due to the fact that under service loads, the beam and slab are still held tightly together by mechanical friction. This friction force is further increased by the increase in normal force due to the static loadings on the slab. Another possible reason is that there a diaphrams casted at the end of the bridge that holds the slab and beam sections together, and hence responsible for the similar static behaviour for both connected and disconnected case as shown in the load-displacement graph.

3.2.2 Dynamic Test Results

Since frequency of different modeshapes are related to the stiffness and mass of the structure, any lost in stiffness (or damage) should change frequencies if compared to the baseline test as mass is constant in this case. A dynamic test was performed to test whether the static load cases has affected the frequency of the scale bridge model. The comparison of the connected and disconnected cases of the first four modes are shown in Figure 12 and Figure 13.

With connectors before load		**With connectors after load**			
Mode	Freq (Hz)	Mode	Freq (Hz)	Error (%)	MAC
1	16.70	1	16.50	-1.24	0.99
2	31.41	2	30.14	-4.09	0.96
3	57.54	3	53.80	-6.46	0.93
4	72.25	4	68.86	-4.70	0.91

Fig. 12 – Table showing the error and MAC of the connected model before and after static loading

Without connectors before load		**Without connectors after load**			
Mode	Freq (Hz)	Mode	Freq (Hz)	Error (%)	MAC
1	16.21	1	16.50	-0.39	1.00
2	28.11	2	28.03	-0.40	0.99
3	49.65	3	49.98	0.80	0.93
4	65.27	4	65.45	0.13	0.97

Fig. 13 – Table showing the error and MAC of the disconnected model before and after static loading

By observing the table above, we can see that the static loading has not caused any damage to scale model, especially for the disconnected case even though there are differences in the frequencies in the connected case. The reason for this is due to errors in the sensor connections which could be observed by looking at the processed data. This is a reasonable argument since by observing the disconnected case (which is loaded after the connected case) there are no observable frequency changes. (This can also be confirmed by looking at the processed data in the spectral analysis.)

3.3 Half Reinforced Model using Glass FRP

The shear connectors were all removed from the bridge model and then it was half reinforced using Glass FRP. A vibration test was conducted again to evaluate the changes in vibration properties and a comparison was made between the baseline model with and without the shear connectors. The results are shown in Figure 14 and Figure 15.

With connectors before load		**With Glass FRP**			
Mode	Freq (Hz)	Mode	Freq (Hz)	Error (%)	MAC
1	16.70	1	15.48	-7.33	1.00
2	31.41	2	29.11	-7.36	1.00
3	57.54	3	55.14	-4.13	0.99
4	72.25	4	66.86	-7.47	0.96

Fig. 14 – Table showing the error and MAC of the connected model and Glass FRP model.

By observing the connected case and the half reinforced case, there is a major reduction in the frequencies. However it should be noted that the bridge is only half reinforced at this stage.

Without connectors before load		**With Glass FRP**			
Mode	Freq (Hz)	Mode	Freq (Hz)	Error (%)	MAC
1	16.21	1	15.48	-4.49	1.00
2	28.11	2	29.11	3.45	1.00
3	49.65	3	55.14	11.22	0.96
4	65.27	4	66.86	2.27	0.89

Fig. 15 – Table showing the error and MAC of the disconnected model and Glass FRP model

However by observing the disconnected model with the half reinforced model, there is a slight increase in the frequencies in three modes. This possibly means that the Glass FRP are acting and holding the slab and beam together as a composite section. Again, the MAC values are close to unity idicating a good correlation between the modeshapes that are being compared.

4.0 Conclusion

From the dynamic testing done so far to the half reinforced scaled bridge model, it was observed that the frequency values for nearly all the modeshapes lied inbetween the two cases, the case where the shear connectors were intact and the case where connectors were loosened. The reason why the first modeshape in the half reinforced scenario had a much lower frequency is unknown however retesting of the model will need to be done after the reinforcement of the second half of the bridge model to verify this. Neverless this gives a fair indication for the time being that the glass fibre does link the slab and beam together. However further static loading needs to be done to verify that the glass FRP continues to work under and after service loads. Furthermore, dynamic testings will be done to the bridge model after the application of carbon FRP on the other half of the scaled bridge model and further load testing would need to verify its effectiveness under operational loads and lastly ultimate loads. This will be done to verify its ultimate capacity so that the effectiveness of FRP under ultimate loading conditions can also be verified.

5.0 References

Doebling, S. W., Farrar, C. R., Prime, M. B., and Shevitz, D. W. 1996, *Damage Identification and Health Monitoring of Structural and Mechanical Systems From Changes in Their Vibration Characteristics: A Literature Review*, Los Alamos National Laboratory Report LA-13070-MS.

Yong Xia, Hong Hao, Andrew Deeks, 2005, *Vibration-based Damage Detection of Shear Connectors in Nickol River Bridge and Balla Balla River Bridge, Part II: Laboratory Study*, University of Western Australia Technical Report ST-05-02.

N. Haritos *, A. Hira, 2004, 'Repair and strengthening of RC flat slab bridges using CFRPs', *Composite Structures*, pp. 555-562

Standards Australia International, 2004, *AS5100.5 Bridge Design Part 5: Concrete*, Standards Australia International.

MATLAB, 1999, *Optimization Toolbox User's Guide,* Version 2, The Mathworks, Inc., Natick, USA.