

# **Testing and Assessment of a 3-span Steel-Concrete Highway Bridge Using Dynamic Methods**

## **A Case -Study**

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### **ABSTRACT**

This paper describes the testing and assessment of a three span steel and concrete highway bridge based on a cost-effective dynamic technique. It describes the application of a recently developed dynamic method used to assess the structural condition of Redbank Creek Bridge at North Richmond NSW.

The data obtained from the field tests is presented and the method for predicting the load-deflection response and load capacity based on this data is detailed. The results obtained from conventional static load tests and from the dynamic and static finite-element analyses undertaken as part of this investigation are also given.

Comparison of the stiffness and strength results obtained from the dynamic tests with those based on the results of static load tests and finite element modelling show excellent agreement.

The case study described in this paper as well as a large number of bridge tests conducted as part of a major project show that the dynamic techniques that were used provide a reliable cost-effective method for the assessment of the structural condition of a wide variety of short and medium span bridges. The case-study presented illustrates that the methods described in the paper provide quantitative information on the structural behaviour and integrity required for the rational long-term management of bridge assets.

### **1. Objectives and Scope of the Project**

The testing and assessment of the bridge over Redbank Creek near Sydney was undertaken as part of a major collaborative research and development project between the Roads and Traffic Authority of NSW and the Centre for Built Infrastructure Research, University of Technology, Sydney [Ref.1]. The assessment of the structural integrity and load carrying capacity of Redbank Creek Bridge was based on comprehensive test data and extensive dynamic and finite element analyses as described in this paper.

The testing and assessment of Redbank Creek Bridge was part of a project that had as its principal goal the development of a procedure and requisite enabling equipment and software for the cost-effective determination of the load deformation characteristics and load capacities of bridges through dynamic testing procedures. The load deformation characteristics obtained by the proposed dynamic procedures are

validated with respect to corresponding values obtained by conventional static load tests.

The comparison of measured flexural stiffness of the bridge deck with that of the deck 'as-built' provides a measure of the current status of the bridge. The data obtained from the dynamic tests provides a reliable basis for conducting numerical analyses to determine the current load capacity of the bridge. The procedures devised through this project aimed to provide the clients with the means to develop and maintain databases on the condition of their bridge stocks and to monitor the rates of change in their serviceability and load capacity.

## **2. Description of Field Tests**

### ***Brief description of the bridge***

The bridge, built in 1945, has a 6.1m wide carriageway and consists of three simply supported spans (10.46m, 10.67m, 10.46m). As depicted in Figure 2-1, the bridge deck is made of reinforced concrete slabs supported by five R.S.J. (22" x 7") steel girders spaced at 1.37 meter centres. Transverse reinforced concrete diaphragms are found at each support and at mid-span. Exact dimensions and design details are given in Ref.2.



Figure 2.1. Redbank Creek Bridge - installation of instrumentation

### ***Equipment, hardware and software***

Accelerometers (ICP piezoelectric type) with high sensitivity and a low frequency-range are usually the best choice for recording the accelerations of bridge structures (Figure 2.2). A large 12 lb Modally Tuned ICP Sledge Hammer was used to provide excitation in bridge tests (Figure 2.3).

Portable Yokagawa (AR1100A) dynamic signal analysing recorders are deemed adequate for field data recording and quick data analyses. Although the Yokagawa analyser is equipped with a Fast Fourier Transform (FFT) function, the frequency resolution is low (400 spectral lines only). A MATLAB programme was therefore developed for post processing of data including FFT and FRF calculations.



Figure 2.2. Redbank Creek Bridge - showing accelerometers attached to steel girder and concrete diaphragm



Figure 2.3 The 12 lb Modally Tuned ICP Sledge Hammer used for bridge tests

Due to the research and development nature of the project, a large number of sensors were used to define the dynamic response of the bridge. A total of twenty two piezoelectric type accelerometers were attached to two spans to record the accelerations of the bridge deck. Yokagawa dynamic signal analysing recorders were used to record hammer force and acceleration response signals during the tests.

### ***Testing regime***

In addition to testing Redbank Creek Bridge the tests were used to assess and demonstrate the potential of the proposed dynamic procedures. The tests also served to refine the methodologies to derive recommended procedures for testing similar bridges. A large number of test scenarios were undertaken, with various sensor arrangements, incremental mass distributions and locations of impact points [Ref.1]. The results given in this paper were obtained with accelerometers placed on the bottom flanges of the steel girders at the middle of all the girders and at the quarter points of alternate girders of two spans. Three sets of tests were carried out, one set without any additional mass and then one set each with mass increments of 10% and 20% of the mass of one span of the bridge deck respectively.

### ***Data processing and analysis***

From recorded dynamic response time histories, the auto spectrum of a given signal can be obtained using FFT. The Frequency Response Functions are computed from the auto spectra of the impact force and response of the bridge. A computer programme using MATLAB has been developed for the purpose. Advanced Modal Analysis software LMS CADA-X from LMS Incorporated was also used in the analysis stage where highly non-linear and coupled dynamic modes occur, for which normal peak picking method was no longer valid (see the next section for details).

## **3. Estimation of Flexural Stiffness and Load Capacity**

### ***Stiffness prediction by adding mass***

For bridge decks, which are linearly elastic under service loads, it is possible to estimate their flexural stiffness through dynamic tests by measuring the changes in natural frequencies, which are caused by changes in modal masses. For an assumed single degree of freedom system (SDOF) the flexural stiffness can be expressed as:

$$k = \frac{48EI}{\alpha L^3} = \frac{\omega_1^2 \omega_2^2}{\omega_1^2 - \omega_2^2} \Delta M \quad (1)$$

where  $\omega_1$  is the initial frequency,  $\omega_2 = \Delta\omega + \omega_1$  and  $\Delta M$ , is the added mass.

The stiffness can also be expressed in terms of the normalised natural frequency shift

$\xi = \frac{\Delta\omega}{\omega_1}$  by the equation:

$$k = \omega^2 \Delta M \left[ \frac{1}{(2 - \xi)\xi} - 1 \right] \quad (2)$$

Where  $\xi = 1 - \frac{1}{\sqrt{1 + \frac{\mu}{\beta}}}$  (3)

and  $\mu = \frac{\Delta M}{M}$  (4)

In the above equations,  $\alpha$  and  $\beta$  are constraint factors owing to different boundary conditions and modal mass coefficients, respectively. For a simple beam these constants are

- i) For fixed end conditions:  $\alpha=0.25$  and  $\beta=0.37$ ;
- ii) For pinned end conditions:  $\alpha=1.00$  and  $\beta=0.49$ ;

The relationship between stiffness and frequency shift is expressed by Figure 3.1.

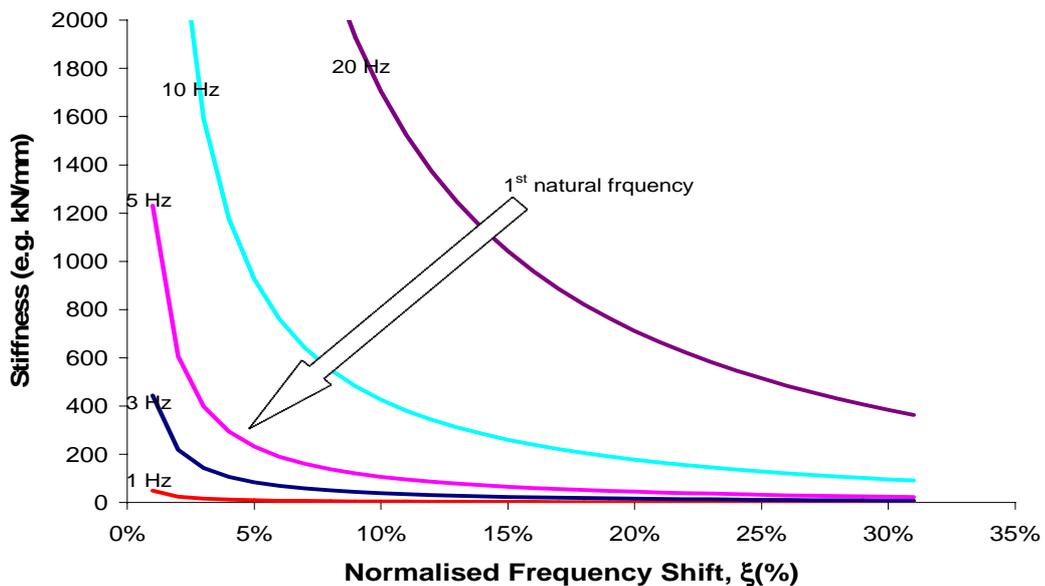


Figure 3.1 - Factors influencing the prediction of stiffness in the proposed method

From this figure one can see that for a structure possessing a natural frequency of say 10 Hz, a frequency shift of 5% is not sufficient as the predicted stiffness is sensitive to frequency shift variation. However, for a structure possessing a natural frequency of say 5 or 3 Hz, a frequency shift of about 5% can lead to an accurate prediction of stiffness.

More advanced methods for data analysis and dynamic system identification available in the LMS CADA-X software used are described in Ref.1 and are summarized in Figure 3.2

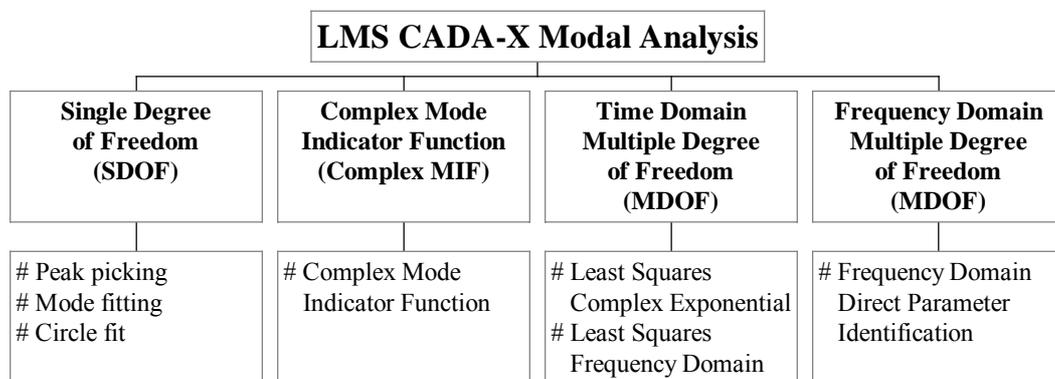


Figure 3.2 Parameter estimation techniques

### ***Finite element modelling***

A finite element model of one span of the bridge comprising 1460 four node shell elements was prepared using the ANSYS general-purpose F.E. program.

The F.E. model was used for:

- Initial modeling of the bridge based on known geometric and material properties of the bridge;
- Performing static and frequency analyses of the bridge;
- Performing transient response analyses using field recorded impact load time histories;
- Updating of model based on the results of dynamic field testing;
- Performing strain and serviceability analyses for estimation of load carrying capacity of the bridge .

#### Static analysis

The static analysis aimed to establish the flexural stiffness of the given span of the bridge, which will be used for comparison with the flexural stiffness obtained through the new dynamic method.

#### Dynamic analysis

The FE model was the subject of two types of dynamic analysis.

- 1) A frequency analysis to extract the first few natural modes of vibration. This included the mode shapes and corresponding frequencies.
- 2) A transient dynamic analysis to establish the response time-histories of the bridge due to a prescribed excitation (impact loading).

When compared with the test results, it was found that the natural frequencies extracted by the FEA were lower by approximately 1Hz for the first mode. Consequently, the stiffness of the F.E. model was adjusted to calibrate its dynamic response more closely with the measured dynamic response of the bridge.

#### ***Prediction of flexural stiffness from dynamic response of FE model***

As part of verification of the proposed dynamic method, dynamic tests conducted on the FE bridge model simulated the same procedures as those used in field testing. The time history of impact force, obtained from field testing, was used in the analysis. Figure 3.3 shows the FRFs of the FE bridge with/without added mass and Table 3.1 shows the results of predicted flexural stiffness of the FE bridge. Table 3.2 compares the stiffness predicted by static and dynamic FE Analyses.

Table 3-1 The results of predicted flexural stiffness for the FE bridge

Mass Added (tonnes)	Freq (Hz)	Damping Assumed (%)	Predicted Stiffness (kN/m)
0	10.73	1.6	
10	8.77	1.6	92,000

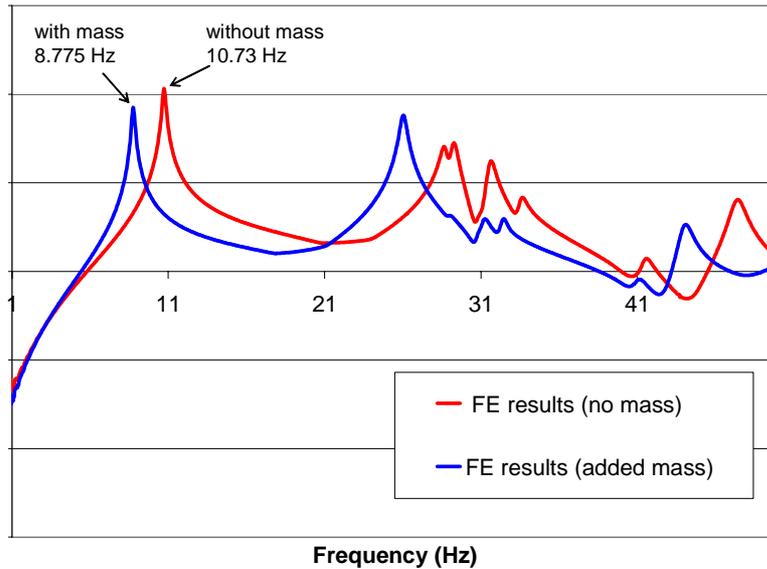


Figure 3.3 Comparison of sum FRFs with/without added mass

Table 3-2 Comparison of flexural stiffness obtained from static and dynamic FEA

Static method			Dynamic method	
MidSpan Deflection (mm)	Max Load (kN)	stiffness (kN/m)	Predicted stiffness (kN/m)	Error (%)
5.3	500	95,000	92,000	3.4

**Prediction of load capacity**

The load capacity is commonly specified in term of Live Load Factor (LLF). Based on the FE model modified by field testing, the LLFs can be calculated as follows:

*Estimated LLF assuming full composite action*

The following is a summary of the method used to estimate the Live Load Factor for this bridge with respect to the 42.5t Legal Truck, assuming full composite action between steel beams and concrete deck.

The Live Load Factor was estimated from the relationship:

$$LLF = [\emptyset \times M^* - 1.2 \times M_{DL} - 2 \times M_{SDL}] / [M_{LL}(1 + DLA) \times LMF] \quad (5)$$

Where

- Capacity reduction factor  $\emptyset = 0.9$
- Ultimate composite moment capacity of internal girder  $M^* = 1,360 \text{ kNm}$
- Dead load moment  $M_{DL} = 87.9 \text{ kNm}$
- Superimposed dead load moment  $M_{SDL} \approx 0$
- Live load moment from FE analysis  $M_{LL} = 151 \text{ kNm}$
- Dynamic load allowance (first flexural frequency >6 Hz)  $DLA = 0.25$
- Load modification factor for two lane loading  $LMF = 0.9$

Based on the above values the Live Load Factor with full composite action  $LLF = 6.6$

*Estimated LLF assuming no composite action*

The following is a summary of the method used to estimate the Live Load Factor for this bridge with respect to the 42.5t Legal Truck, assuming no composite action between steel beams and concrete deck.

The Live Load Factor was estimated from the relationship:

$$LLF = [\phi \times M^* - 1.2 \times M_{DL} - 2 \times M_{SDL}] / [M_{LL}(1 + DLA) \times LMF] \quad (5)$$

Where

Capacity reduction factor	$\phi = 0.9$
Ultimate composite moment capacity of internal girder	$M^* = 726 \text{ kNm}$
Dead load moment	$M_{DL} = 87.9 \text{ kNm}$
Superimposed dead load moment	$M_{SDL} \approx 0$
Live load moment from FE analysis	$M_{LL} = 151 \text{ kNm}$
Dynamic load allowance (first flexural frequency >6 Hz)	$DLA = 0.25$
Load modification factor for two lane loading	$LMF = 0.9$

Based on the above values the Live Load Factor with no composite action  $LLF = 3.5$

It is noted that no evidence was observed indicating any loss of composite action during the tests or over the service life of the bridge. It is therefore considered that the assumption of no composite action is conservative and that the LLF estimated on the basis of this assumption represents a lower bound of the load carrying capacity of Redbank Creek Bridge

**4. Summary of Results and Conclusions**

The field testing and finite element modeling of the bridge over Redbank Creek have been conducted using the proposed dynamic method. Table 4-1 provides a summary of flexural stiffness predictions using the dynamic method from both FE model and bridge tests.

Table 4-2 shows the comparison of flexural stiffness obtained using static and dynamic tests.

Table 4-1 Summary of flexural stiffness predictions using the dynamic method

<i>using FE model</i>	<i>Mass Added (tonnes)</i>	<i>Frequency (Hz)</i>	<i>Damping (%)</i>	<i>Predicted stiffness (kN/m)</i>
	0	10.7	1.6	
	10.6	8.8	1.6	92,000
<i>using bridge test data</i>	<i>Mass Added (tonnes)</i>	<i>Frequency (Hz)</i>	<i>Damping (%)</i>	<i>Predicted stiffness (kN/m)</i>
	0	12.0	1.6	
	10	9.7	1.6	107,800.

Table 4-2 Comparison of flexural stiffness obtained using static and dynamic tests

	Static Test			Dynamic Test	
	<i>MidSpan Deflection (mm)</i>	<i>Max Load (kN)</i>	<i>Stiffness (kN/m)</i>	<i>Predicted stiffness (kN/m)</i>	<i>Error (%)</i>
<b>using FE model</b>	52.6	5,000	95,000	92,000	3.4
<b>using bridge test data</b>	2	198.5	99,500	107,800	8.4

This project indicates the potential of the proposed dynamic method in predicting the ‘in-service’ flexural stiffness of the bridge accurately. Any significant difference between this stiffness and the ‘as built’ stiffness predicted from a FE model is likely to be indicative of some form of deterioration. Using the calibrated FE model, based on the results of field testing, can provide an estimate of the load carrying capacity of the bridge in terms of a Live Load Factor (LLF) which will assist the asset managers in determining load limits and maintenance priorities.

### 5. Acknowledgment

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### 6. Disclaimer

The opinions expressed in this paper in this paper are entirely those of the authors, and do not necessarily represent the Policy of the RTA

### 7. References

1. Samali, B., Bakoss, S.L., Li, J., Crews, K.I. and Saleh, A., (2003). “ Field Testing and Assessment of Redbank Creek Bridge”, Report, Centre for Built Infrastructure Research, UTS, p.56
2. Roads and Traffic Authority of NSW, Department of Main Roads Drawings, No. DMR 184