Overview of Assessing the Load Carrying Capacity of Timber Bridges Using Dynamic Methods

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SYNOPSIS

A key element of an effective asset management system for bridges is the ability to undertake cost-effective load assessment and evaluation of the current state of bridges and to be able to understand the causes and quantify the rate of their deterioration. Whilst proof-load testing and health monitoring procedures provide valuable tools, such procedures are generally too complex and too costly to be applied across the entire inventory of short span timber bridges. Such testing is costly to conduct, requires equipment and expertise not readily available to many local government bodies and has significant inherent uncertainties in regard to the assumed relationship between stiffness and strength of timber girders.

This paper describes procedures that have been specifically developed to address the need for relatively inexpensive load assessment, costing less than 25% of the expenditure required for static load tests, (and no more than 1%-5% of the replacement cost of the asset) that will provide reliable, quantitative information on the performance of short and medium span bridges. These procedures contain two significant innovations – the first is accurate determination of the global deck stiffness of a timber deck using dynamic frequency analysis; the second is prediction of load capacity of a bridge deck, using a probabilistic relationship between bending strength and gross stiffness (EI) of timber girders.

1 INTRODUCTION

There are about 40,000 bridges in Australia – current estimates indicate that 27,000 of this total are timber bridges; 85% of which are in local government, with the other 15% owned by State Road and Rail Authorities [1]. Most are in excess of 50 years old and many are in a degraded or structurally weakened condition. Despite this, these bridges are highly valued, not just for economic reasons, but also for the social and historical value placed on them by rural communities.

Managing this aging infrastructure is an enormous problem, of national significance. Replacement of these bridges is neither feasible nor practical – so strategies and techniques must be implemented that will maintain the national bridge asset in a manner that ensures public safety and manages the risks associated with aging infrastructure, within the constraints of limited funding and resources.

For managers of timber bridge assets in local government the cost of traditional load assessment has meant that it has often been used as a “last resort”, usually in response to a political agenda. The challenges facing managers of bridge assets are compounded by the fact that the assets often comprise a large number of ageing short to medium span bridges of relatively low value.

2 SAFETY AND RISK MANAGEMENT OF BRIDGES

2.1 Load Testing

Currently, reliable determination of the structural condition of a short to medium span timber bridge requires a load test, which involves the application of a loaded vehicle, representative of the design load, and the measurement of the deformations caused by the applied loads. Such testing is costly to conduct, requires equipment and expertise not readily available to many local government bodies. In some cases where significant degradation has occurred, it also has the potential to actually damage the bridge being assessed.

To address this problem and the need for cost – effective risk management systems for assessing safe load capacities of timber bridges, a programme of research and development was undertaken between 2000 and 2003, through the Centre for Built Infrastructure Research (CBIR), at the University of Technology, Sydney (UTS). The project was funded by two Commonwealth Department of Transport and Regional Services Grants and undertaken in collaboration with the Institute for Public Works Engineering Australia (IPWEA) and a number of local Councils in NSW. Additional funding from the Roads and Traffic Authority (RTA) of New South Wales (NSW) and AUSTROADS, extended the scope of the project to encompass application for steel and concrete bridges.

2.2 Non Destructive Evaluation using Dynamic Frequency Analysis

The aim of the project was to research and develop a cost – effective and accurate method for assessing the structural condition and predicting the load capacity of timber bridges, based on analysis of fundamental frequency of the superstructure to determine the global stiffness of a bridge deck.

This assessment procedure involves the attachment of accelerometers underneath the bridge girders. The vibration response and natural frequency of the bridge superstructure is measured when a "calibrated sledgehammer" is used to hit the unloaded deck, and then again with a relatively small mass applied at mid-span. The difference in response allows the load carrying capacity of the bridge to then be calculated, using a reliability based strength model, derived from extensive testing of aged timber girders.

By the time these series of projects were successfully completed in July 2003, over $0.5m (AUD) had been expended and a total of 69 bridges / 127 spans had been assessed using the new methodology.

The research and development program was undertaken in two distinct phases:

1 - Laboratory based testing using known material properties and quantifiable boundary conditions, to prove the viability and accuracy of the concept

2 - Development of the system for field application, involving assessment of the load deflection characteristics and live load capacities of different types of timber bridges (and several concrete bridges) across a variety of local government regions.

3 THE NEED FOR IMPROVED INSPECTION AND ASSESSMENT METHODS

3.1 Factors Influencing Degradation and Weakening of Bridges

The nature and effects of progressive deterioration of bridges can vary widely due to local environmental effects and operational influences such as increased traffic volume and loading intensity which can cause cumulative incremental damage. The influence of these effects on the rate of deterioration of timber bridges can be particularly significant. Such damage to the strength and stiffness may, in general, not be identifiable from visual inspections, even by staff experienced in bridge maintenance. Reliable assessment of the structural state of a bridge requires not only the discovery of any damage but also the determination of the effects that such damage has on the structural integrity of the bridge. Furthermore, to enable maintenance and/or rehabilitation priorities to be established it is necessary to quantify the damage and the rate at which the structure is deteriorating.

3.2 Current "Best Practice"

Currently managers of bridge assets have two general approaches to assess the structural state of a bridge. Firstly, the bridge can be inspected, the visible (or otherwise detectable) defects noted and their effects analytically assessed. Secondly, the bridge can be assessed through static or dynamic load testing, involving a heavy vehicle of known mass. Although currently available load testing and dynamic assessment procedures constitute a valuable tool for managers of bridge assets, they are too complex and far too costly to be used as an asset management tool to cover the full inventory of bridge stocks.

In the case of timber bridges in particular, the ratio of the cost of load testing to the value of the asset is generally far too high to be an effective asset management tool. Not only are static load tests and dynamic modelling procedures complex and expensive but also, in general, the results obtained are applicable only to the bridge tested and to those which are very similar, but can not be readily applied across the class of bridges to which the tested bridge belongs. What is required is a low-cost and simple procedure that will provide reliable quantitative information about the load-deflection characteristics and enables the estimation of the load capacity of short and medium span bridges.

4 ASSESSMENT BASED ON DYNAMIC FREQUENCY ANALYSIS PROCEDURES

4.1 Overview of Methodology

As noted above, the project to develop such a cost-effective dynamic frequency analysis (DFA) diagnostic procedure to assess the structural condition of short and medium span bridges was undertaken by CBIR in collaboration with two major stakeholders, IPWEA and RTA. Development of the procedure and the results of extensive laboratory prototype tests and field tests on the first two field bridges: Cattai bridge - a single span timber bridge and Redbank bridge - a three span steel girder-concrete deck bridge, are described elsewhere [2 - 5].

The field testing component of the DFA bridge assessment procedure involves the attachment of a small number of accelerometers underneath the bridge girders and the measurement of the vibration response of the bridge superstructure unloaded and with one or more loads equivalent to approximately 10% of the mass of the deck being tested applied at midspan. The excitation is generated by a modal impact hammer.

The resulting dynamic responses are measured with uniaxial accelerometers that are robust and simple to attach. The data is logged and the bridge deck properties evaluated, using dynamic signal analyser. Two sets of bending frequencies are measured for the bridge, 'as is', and when loaded by the extra weight. By loading the bridge, the bending frequency of the bridge decreases. From the resulting frequency shift due to added weight, flexural stiffness of the bridge can be calculated.

4.2 Prediction of Load Capacity

User friendly software has also been developed which calculates the estimation of bridge load carrying capacity relative to the load effect of standard vehicles, from the calculated stiffness, using a regression function relating the 5th percentile flexural capacity (bending moment) to stiffness (EI) of the girders. This function has been derived from statistical analysis of data obtained from full scale testing. The software also considers corbel and continuity effects, in calculating the effective length for the spans of each bridge. Figure 1 summarises the testing and analysis procedure using the DFA approach.

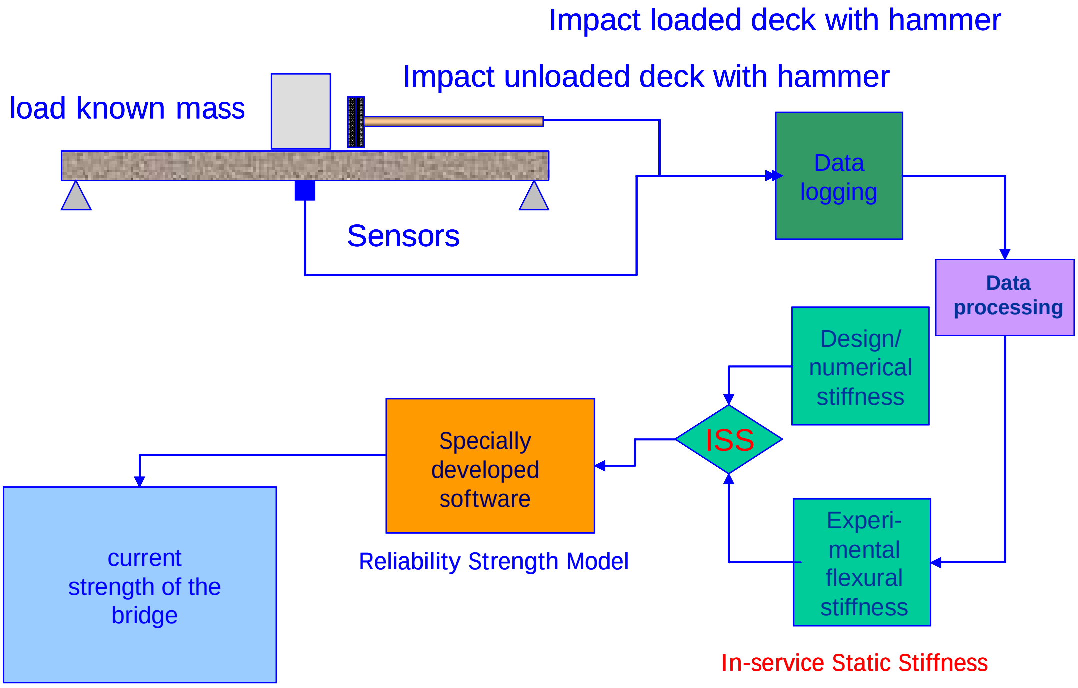

Figure 1: Schematic diagram of the DFA procedure for bridge assessment.

The DFA test procedure does not require the precise measurement of deformations and/or strains as is the case for static load tests and 'health monitoring' procedures. It is also much quicker to conduct compared with load testing, requiring minimal disruption to traffic and hence is less expensive than load testing. It is also safer than load testing, particularly with respect to old bridges where applying a large test load may further jeopardise the integrity of the bridge.

5 APPLICATION OF THE "DFA" METHODOLOGY – CASE STUDIES

5.1 Description of Bridges

Following the evaluation results obtained at the tests of the Cattai and Redbank bridges, which showed good agreement with results obtained by conventional load tests [2 - 5], a programme of field-testing and analysis of nearly 100 timber bridge spans was undertaken.

The following sections describe the testing and present the stiffness and load capacity results obtained for two of these bridges. The first bridge is a recently constructed timber bridge located in Cabonne Shire of NSW (refer figures 2 and 3). The bridge comprises two 9m spans each with four round timber girders supported on concrete abutments and pier skewed at an angle of 26° from the normal to the centre line of the bridge. Transverse treated hardwood decking provides two traffic lanes with a carriageway of 4.3m.

The second bridge (figure 4) is also a two span timber bridge located in the Hunter Valley that has been in service for about 50 years and at the time of testing exhibited signs of significant degradation. This bridge has 5 girders per span, with a carriage way width of 4.4m and spans of 10.6m and 9.2m and at the time of testing, had a load limit of 5 tonnes.

Figure 2: Side view of Cabonne bridge

Figure 3: Pier details of Cabonne bridge

Figure 4: Side elevation of Hunter Valley bridge

5.2 Field Testing – Instrumentation

Accelerometers with high sensitivity and low frequency-range are used to record the accelerations of the timber bridge structure, by attaching them to the underside mid-span of each girder. A large 12 lb Modally Tuned ICP Sledge Hammer is used to excite the bridge. In the initial stages of development, two (one eight-channel and one four-channel) Yokagawa dynamic signal analysing recorders with a 16 channel signal conditioner were used to record hammer force and acceleration response signals during the tests.

MATLAB programs have been developed for data processing, including FFT and Frequency Response Function (FRF) calculations. The acquisition and analysis system has now been updated with a more portable PC based instrumentation system, as seen in figure 5.

Figure 5: Data Acquisition System

Figure 6: Testing with mass applied at mid span

5.3 Testing Procedure

The field tests included two sets of results.
Set 1 - No mass test: The bridge 'as is', without additional mass, is impacted by the modal hammer at midspan on bridge centre line of each of the two spans.

Set 2 – Added mass test: The bridge, carrying additional mass, is impacted by the modal hammer similarly to the no mass test, with the added mass distributed uniformly at midspan of the bridge on each of the two spans, one at the time, as indicated in figure 6.

5.4 Data Processing and Analysis

From recorded dynamic response time histories and using FFT, the Frequency Response Functions can be computed. A computer programme was developed using MATLAB to provide flexibility when processing the test data. It produces the required Frequency Response Functions at a given bandwidth with good resolutions. The software will be further developed to incorporate more functions such as data acquisition and probabilistic models so that it can become a more comprehensive, 'all-round' software for bridge assessment. Advanced Modal Analysis software is also used in the analysis stage where highly nonlinear and coupled dynamic modes occur, for which normal methods are no longer valid.

5.5 Frequency Results

As direct results of the modal analysis, dynamic properties of the tested bridge, such as natural frequencies, damping and mode shapes, can be obtained. However, the DFA method requires only the first flexural natural frequency for both the "with" and "without" added mass cases, to calculate the global deck stiffness. Figures 7 and 8 show the comparison of Frequency Response Functions with and without added mass, for characteristic spans of the Cabonne Bridge and the Hunter Valley Bridge, respectively.

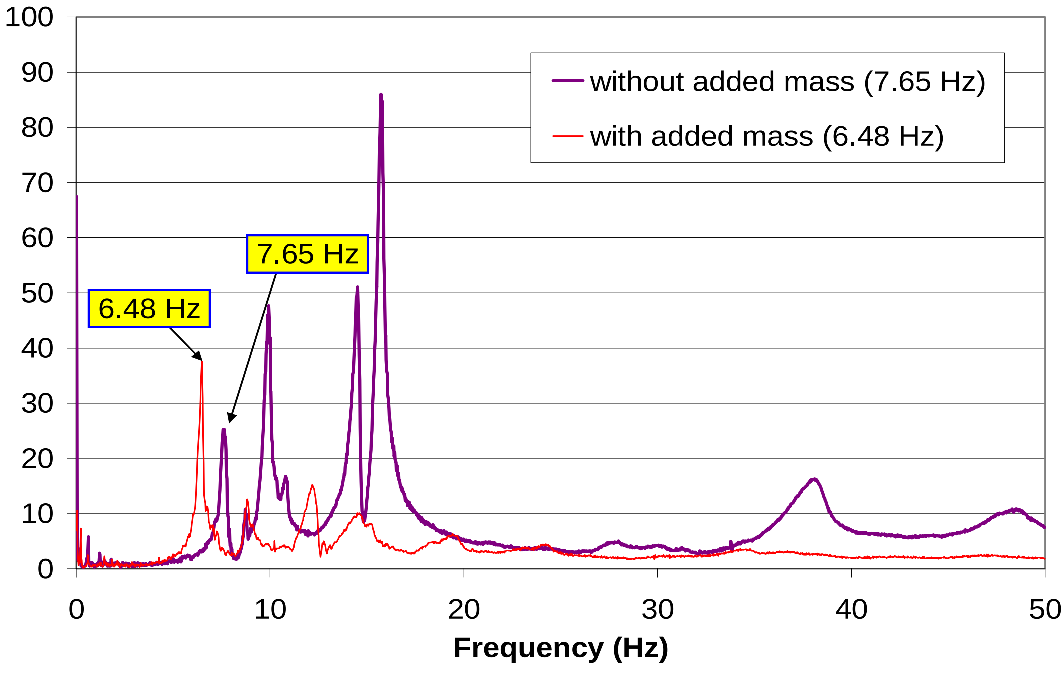

Figure 7: Comparison of sum FRFs for Bridge 1 (new) with and without added mass

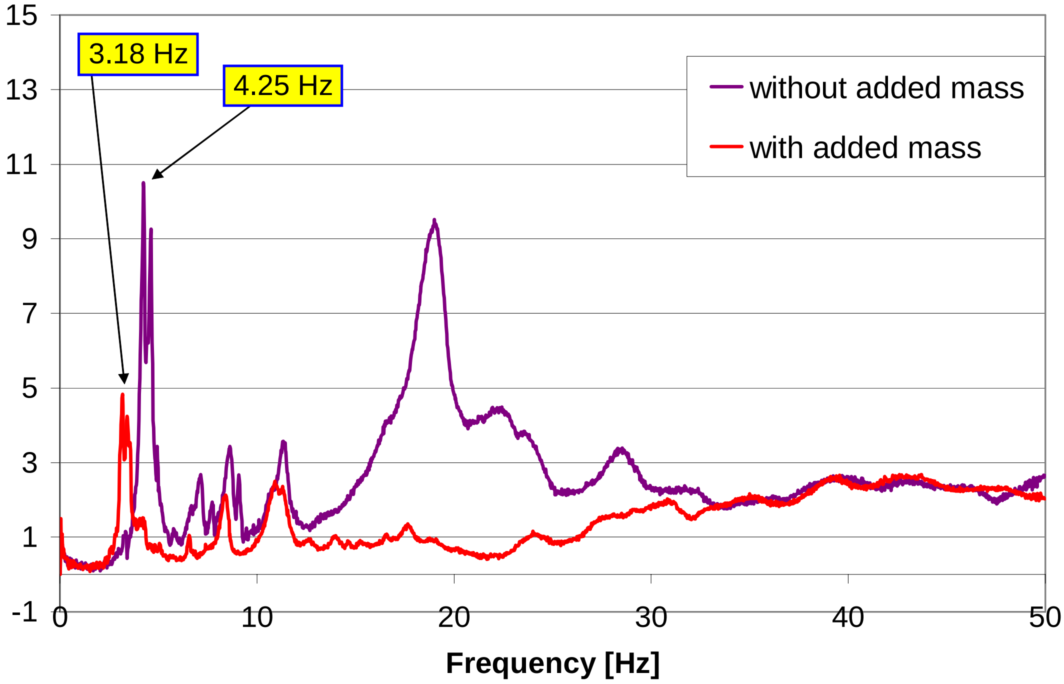

Figure 8: Comparison of sum FRFs for Bridge 2 (old) with and without added mass

A point to consider is that although this methodology is capable of assessing the load carrying capacity of bridges, the load is dynamic in nature and its impact on the bridge is not just a function of the magnitude of the load. A major contributing factor is the surface condition of the bridge deck. A smooth surface will allow a much larger load to be carried safely due to low dynamic amplification attributable to smooth decks, but a similar level load may cause much distress and damage to the bridge if the surface is not sufficiently smooth. This conclusion was reached by Pesterev, et al [6] in studying the effects of dynamic loads on bridges.

5.6 Flexural Stiffness of the Tested Bridge

With added mass and frequencies with and without mass known, the flexural stiffness of the bridge decks can be easily calculated. Table 1 shows the amount of mass added, the first natural frequency with and without mass and prediction of the flexural stiffness for each span of the two bridges.

Bridge / Span	Mass added to deck (tonnes)	First Natural Frequency (Hz)	Predicted stiffness (kN/mm)
1 / 1	0 3.85	7.65 6.48	20.2
1 / 2	0 3.85	7.63 6.25	17.8
2 / 1	0 6.0	4.25 3.18	5.4
2 / 2	0 6.0	6.25 4.1	7.0

Table 1: Results of predicted stiffness using the DFA method

6 PREDICTION OF LOAD CAPACITY

6.1 The Natural Variability of Timber

Unlike concrete and steel, where the properties are usually relatively easy to verify, the determination of strength of bridge girders in-situ is extremely difficult and complex, unless of course the girder is broken and the failure load and loading pattern is known.

Current "best practice" in Australia generally assumes that the fibre strength of any girder is 80 to 100 MPa (depending upon the species). Bending capacity is predicted by multiplying the assumed section modulus "Z" (based on the gross section) by the assumed fibre strength. Whilst previous work undertaken by the RTA has involved some full scale destructive testing of girders, the basis of current load rating systems is essentially reliant upon testing of "small clear" specimens cut from these structural members, to estimate fibre strength.

Proof loading of timber bridges is expensive and inherently risky, since it is a well established fact that high load levels are prone to causing permanent and irrecoverable damage to the wood fibres. This may result in subsequent failure of a timber girder at load levels significantly less than that indicated by the proof test. It is for this reason that most rating of timber bridges has been based on applying serviceability load levels, measuring the deflections in order to estimate the stiffness and then using an assumed relationship between strength and stiffness to predict the load carrying capacity of each girder.

6.2 Deficiencies in relating Stiffness to Strength

The relationship between strength and stiffness used in current load assessment methods is based on the assumed relationship between Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) defined in the Australian Timber Structures Code, AS1720.1. However, it is not commonly understood that this relationship is both idealised and theoretical. Figure 9, illustrates the problems associated with this approach.

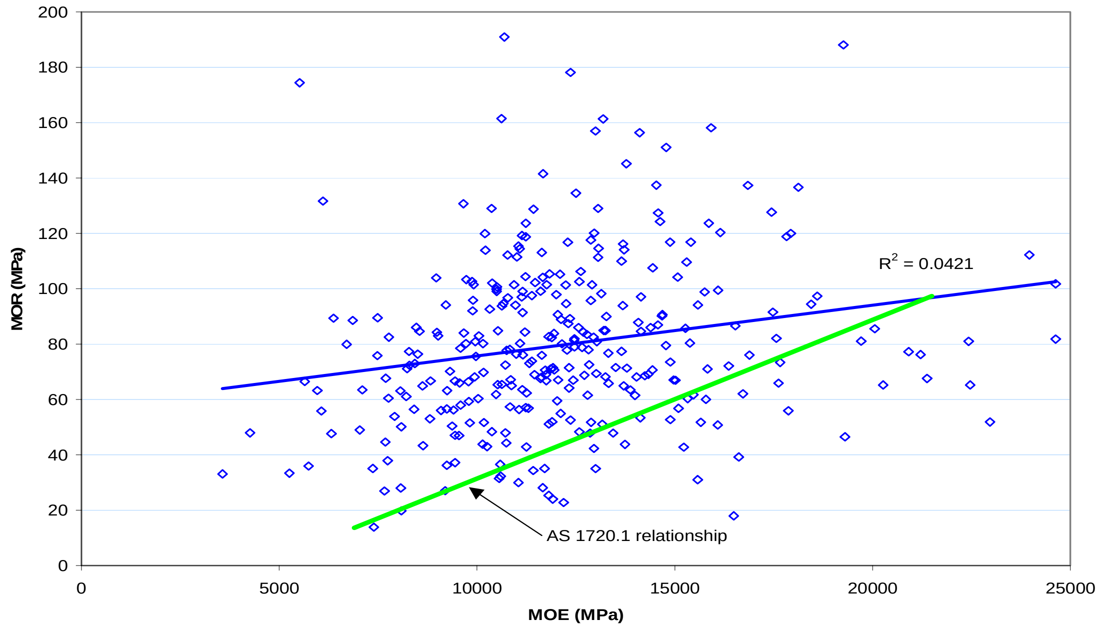

Figure 9: MOR vs MOE for round timbers

This chart presents a plot of MOR vs MOE data obtained from full scale testing of round timbers extracted from service with an average life of 30 years and also compares this with the AS1720 relationship. It is obvious from the linear regression co-efficient for the test data that the relationship between strength and stiffness for aged poles / girders is not statistically significant. Furthermore, the theoretical relationship assumed in AS1720 is not reliable for these timbers, as many round timbers have a rupture strength significantly lower than that predicted by the Code relationship.

For example, extensive testing of some 1200 round timber poles indicates that the actual 5th percentile strengths for strength group 1 & 2 timbers range between 30 and 55 MPa, not 80 to 100 MPa as usually assumed by Engineers.

6.3 Developing a Reliability Basis for Bending Strength

In order to assess the strength of timber bridge girders with any degree of reliability, it is necessary to develop strength models, which reflect the actual bending capacity of timber. This should take into account the uncertainties associated with determination of the geometric section properties and the actual strength properties. Such a model has been developed to form the basis of the DFA testing system developed in this project.

Based on test data obtained from extensive testing of full scale round timbers, a relationship between actual measured stiffness (EI) and actual bending capacity has been derived. Using a probabilistic approach, this relationship can be used in reliability-based models to predict the load capacity of a deck from the stiffness data obtained from the dynamic frequency method, with acceptable and transparent degrees of uncertainty. This research and analysis has been used to develop some proprietary algorithms that are now incorporated into the DFA analysis software.

Another critical issue that is not understood by most Engineers and fails to be addressed by most traditional assessment methods for timber bridges, are continuity effects and the interaction of corbels in the load responses of a timber bridge deck. The DFA software quantifies these effects and considers them in the predicting the strength capacity of timber bridges.

6.4 Load Capacity predictions of Case Study Bridges

Applying the probabilistic approach described above, the estimated live load factor (defined as the ratio of the net factored moment capacity and the moments, including live load allowance, caused by a T44 truck) is noted in Table 2.

Bridge / Span	LLF	Approx Capacity (tonnes)
1 / 1	2.8	125
1 / 2	2.5	110
2 / 1	0.6	25
2 / 2	0.8	35

Table 2: Predicted 5th percentile load capacities using the DFA method

It should be noted, that the DFA testing does not currently detect structural deficiencies in the sub structure (particularly the piles) of a bridge and is supplemented by detailed visual inspection, which whilst essentially qualitative, is used at times to quantify the strength reducing effects of degraded members on the safe load carrying capacity of a bridge. This has relevance for the Hunter Valley bridge, due to the fact that the load limitation was governed by the condition of the headstock and one abutment. The test results confirm that with minor repairs to these elements, the load restriction can be raised to 25 tonnes.

7 CONCLUSIONS

7.1 Project Objectives

A new method, based on dynamic response of timber bridges to an impact load, has been developed to measure the in-service flexural stiffness of timber bridges. Utilising a statistically based analysis, the knowledge of flexural stiffness can be converted into an estimate of the load carrying capacity of the bridge, using well-proven reliability modelling techniques. The method is quick and cost effective (less than 20% of traditional load testing), enabling Council's and Road Authorities to undertake appropriate testing that enables them to manage risks and prioritise maintenance.

The reliability and simplicity of the DFA system has been demonstrated by testing some 100 bridge spans covering a wide range of single and multi-span timber bridges. The methodology adopted and results obtained for two of these bridges, have been reported in this paper. The method also has direct applicability to concrete and steel bridges, and rail, as well as road bridges.

7.2 Continuing Research and Development

The model used for R&D projects undertaken by CBIR involves a cycle of linking innovation, with application and laboratory investigations with field implementation. Ongoing research and development is continuing, that will form the basis of the “next generation” of the DFA system. Current research focuses on two distinct areas: (1) refinement of the algorithms that model the boundary conditions and effects of corbels and continuity effects of decking, and (2) analysis of higher frequency modes for damage detection in individual members in the bridge superstructure.

7.3 Final Comments

The results clearly indicate that the DFA procedure can provide local governments with a cost-effective and reliable tool to assess the structural adequacy of their timber bridge assets. This fact was recently acknowledged (December 2003) with two National Awards for Local Government:

- “Infrastructure Management” Category, “Assessing the Load Capacity of Timber Bridges”
- Major Award (Special Category) - Outstanding Achievement in Local Government for Innovation and Excellence

Following the extensive testing and implementation program, the DFA method has now reached a level of refinement, which can be applied to most, if not all, timber bridge types constructed in Australia.

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