Monitoring the Health of Timber Bridge Beams

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Moore, J. C., Glencross-Grant, R., & Patterson, R. (2010). *A review of non-destructive test methods: Appropriate choice of a method for use with timber beam bridge girders.* Paper presented at the Proceedings of World Congress of Timber Engineering, Italy, Published on CD-ROM, ID 848.

Moore, J. C., Glencross-Grant, R., Patterson, R., & Mahini, S. (2011). Towards Predictability of Bridge Health. In R. Patterson (Ed.), *Sustaining our regions: The Engineering Challenge. Proceedings of the 2011 Regional Convention, Newcastle Division, Engineers Australia* (pp. 103-110). Armidale, NSW, Australia: Engineers Australia. ISBN 978-0-85825-870-9

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The problem I have addressed was one that has in many ways been avoided for many years. Instead of timber bridges being maintained to a high standard, they have been replaced by alternative materials. However, it is possible to create new strategies to give many of these extant bridges a new lease of life. This project began at the suggestion of Rex Glencross-Grant and with initial direction from Professor Iain Young and Associate Professor Dr Richard Faulkner. Professor Young provided me with the guidance that I needed that enabled me to gain generous funding support from Forest and Wood Products Australia (FWPA). To enable me to realise these new strategies required the support of far sighted engineers and I thank my supervisors for their understanding and strength of purpose in supporting me. Dr S Saeed Mahini, my principal supervisor, directed my interest to Structural Health Monitoring and ensured that my fledgling understanding and interest was able to grow. He also ensured that I was able to apply my electrical instrumentation engineering experience into a Civil Engineering application; a task that required an understanding of the Civil Engineering aspects of timber-bridges. My co-supervisors provided extensive advice: Rex Glencross-Grant helped me better understand timber and the history of timber bridges in Australia; and Adjunct Associate Professor Dr Robert Patterson helped me in addition with field work and publication quality.

To determine the health of a timber bridge I needed to measure in-service bridges and I thank Armidale and Uralla Shire councils for their support. In particular the Shire engineers, David Steller and Robert Bell, saw the importance of these measurements. They ensured that there were both test bridges to measure and support staff available for field work. It was not possible to carry out destructive tests on a sufficient number of girders, but staff of The Roads and Traffic Authority interested in history managed to find test data that had been conducted two decades ago. This data when combined with other test data allowed a more complete picture to be created of timber girder performance that would have been otherwise impossible. Laboratory experimental work required support from University research support staff and they gave their time whenever needed. Finally of course, without very extensive support from my wife Rita I would not have been able to achieve this research and I thank her most of all. She managed to ensure that family life was not entirely forgotten while I pursued my research aim.

ABSTRACT

There are over 2000 timber-bridges in regional New South Wales (NSW) and many more are still in use throughout Australia. Many of these bridges are of unknown structural integrity. They were built in an era when structural components were expected to survive their lifetime without failure. Many of these bridges are now degraded and need to be monitored to determine their integrity. The aim of this research was to test the hypothesis that continuous deflection monitoring can be used to assess the probability of timber-bridge girder failure.

To achieve this aim, new Structural Health Monitoring (SHM) strategies were created together with new laser-based deflection measuring equipment and high speed camera recording techniques. Bridge performance was evaluated by firstly determining Modulus of Elasticity (MoE), Modulus of Rupture (MoR) and percentage loading from load-v-deflection measurements. Then the probability of girder failure and a safety index were calculated. Bridge performance benchmarks were set and structural integrity ensured by checking that limit state safety indices were not exceeded.

The testing of timber-bridges, by measuring girder deflection, has historically been restricted to non-linear static proof-load testing. Strength testing with lighter, in-service loads has not been developed because of the lack of a relationship between girder deflection and girder strength. More recently, dynamic techniques have been utilised. Strain sensors have been applied to the surface of timber girders to determine the peak stress levels. This approach is limited for long term use. As the surface of the girder degrades, sensors cease to accurately measure the peak stress, unless it is continually recalibrated throughout the monitoring period. In another approach, the vibration of a complete structure is analysed. This technique works well for rigid structures, but is too complex for long term use with timber-bridges that have loosely connected girders and deck planks.

In the first part of the project, data representing over 300 timber-bridge girders removed from service, were statistically analysed in a manner performed by previous investigators. A relationship was identified that utilised MoE and girder assessable condition state as predictors of girder MoR. An unexplained variation of 42% to a confidence level of 95% was achieved by just using MoE, but this was reduced to 14% by including girder condition state. It was also identified that girder MoE and MoR do not act independently, but that a combined MoE-v-MoR vector could be predicted to remain within statistically defined bands.

In the second part, measurement techniques were developed to record in-service static and temporal dynamic load-v-deflection data without interfering with traffic flow. SHM strategies were developed to show how these deflection measurements and statistically defined prediction bands can be used to identify and predict the structural health of timber-bridge girders within specific strength and limit state failure criteria. As part of these strategies, in-service traffic loading distributions were compared with material parameter distributions using well known Monte Carlo techniques by using scripts written for the purpose in both Matlab® and R programming languages.

In the third and final part, these new SHM strategies were used to examine the structural health of two in-service timber-bridges: one single span and one multi-span. These case studies were monitored by measuring mid-span deflection using the newly developed equipment. Light test vehicles were used that had equivalent point loads of less than 35% of the maximum legal loading to ensure that the girders deflected linearly with load. Deflection measurements and long term recordings were made at both low and high vehicle speeds. Measured traffic loading distributions and girder MoE data distributions were used to determine the probability of limit state failure. Two limit states were considered: a span to deflection limit state and a girder structural failure limit state.

Based on the research outcomes, it was demonstrated that in-service mid-span deflection is a valid determinant of girder MoE, which in turn is used to predict girder MoR. By application of the developed strategies in this research, it was shown that the probability of limit state failure of timber-bridge girders in regional Australia can be determined from deflection data by utilising the developed low cost and effective laser-based technique. It was also demonstrated in a practical manner, that temporal deflection data can be used to predict structural safety, thereby achieving the original aim.

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GLOSSARY AND LIST OF ACRONYMS ABBREVIATIONS AND TERMS

Term	Description
ABS	Australian Bureau of Statistics
BDM	Bridge Deflection Meter, a device for recording peak deflections caused by traffic.
Capwales	Horizontal timber component at the top of piles or posts providing bearing for superstructure.
Corbel	Longitudinal timber bearing members under girders providing support and some continuity between girders in adjacent spans. (RTA, 2008: Section 1, page 2)
Check	A separation of the wood fibre along and parallel to the grain. It is caused by surface stresses. A check does not extend from one surface to another (Bootle, 2004, p. 29)
CV	Coefficient of variation
Coefficient of variation	Defined as: standard deviation / arithmetic mean x 100
Coefficient of determination	A summary measure of the quality of fit of the regression line to the experimental data. Defined as the ratio of the regression sum of squares to the total sum of squares. It is represented by the quantity r^2.
cwt	One hundred weight or centum weight. A unit of mass of about 51 kg.
Design perspective	Structural design from a design engineers perspective (Refer Section 2.2.4).
Distributed load	A force distributed over a length of beam.
DS	DataSet, DS-1 through to DS-8.
Explained variation	The percentage of the variation of a dependent variable that is directly related to the variable used to predict the independent variable. It is the value of r^2 expressed as a percentage.
Factor of Safety (FoS)	The arbitrary ratio of the actual strength to the required strength.
Failure rate	Number of tests / number of failures. One example of the probability of failure is 4 in 10^6, the failure rate for this probability is then 0.000004.

Girder	Large round timber component used as a structural load bearing beam in a timber bridge.
G-4	Span four of Munsie bridge, Gostwyck, NSW.
G-6	Span six of Munsie Bridge, Gostwyck, NSW.
Green timber	Timber not dried to 12% MC but in its original moisture content as newly harvested.
GVM	Gross vehicle mass
Headstock	Horizontal timber component at the top of piles or posts providing bearing for superstructure.
In-service	The description of a component or structure that is part of the road network and in normal use by traffic. The component or structure will be stressed by being subjected to vehicular loading.
Kerb girder	One of the outside girders of a timber beam bridge supporting the kerb of the bridge.
KD	Downstream kerb girder.
KU	Upstream kerb girder.
Limit state	The allowed performance of a designed structure, which should be: serviceable; safe; and stable. That is it should not crack or sag, not break and not fall over. If performance by any of these criteria is unsatisfactory, a 'limit state' has been exceeded (Boughton & Crews, 1998: Section 2.3). An example limit state is: "the deflection for serviceability limit state under live load…shall not be greater than 1/600 of the span" (Standards Australia, 2004c: AS 5100.2, Section 6.11).
Light Load	A vehicle of about three tonne GVM, refer Section 2.4.4
Live load	Load applied to a structure.
Main girder	One of the central girders of a timber beam bridge. There are commonly four, or five, girders the middle two, or three, are the main girders.
Maintenance Perspective	Structural design from a maintenance perspective (Refer Section 2.2.5).
MatLab®	MatLab® is an analysis program that allows complex equations to be solved and provides a wide range of graphs and diagrams to be created. The software allows analysis of data and algorithm development more quickly than would occur with a high level language where all the code has to be created (MathWorks, 2011).

MC	Moisture content.
MU	Upstream main girder.
MD	Downstream girder.
MoE	Modulus of Elasticity. The rate of change if stress for changes in strain. In practical engineering materials strains lie in the range of ± 1% either side of the neutral, unstressed, position. Within this small range the relationship is linear and the material can be stressed and unstressed many millions of times with no change in performance. At larger strains, between 5% and 10%, stress is not linearly proportional to strain. (Gordon, 1991, p. 37)
MoR	The Modulus of Rupture is the stress at which a material will fail as it is increasingly stressed.
NORMSINV(failure rate)	The spread sheet function NORMSINV(failure rate) calculates the inverse of the normal cumulative distribution function. As an example if the probability of failure is 4 in 10^6 then the failure rate is 0.000004 and NORMSINV(0.000004) = −4.5 and which is the Safety Index, β.
NAASRA	National Association of Australian State Road Authorities.
NDE	Non destructive evaluation
Neutral axis	The line of zero stress in a girder undergoing bending.
NSW	New South Wales, Australia.
PC	Powers Creek bridge span.
Piles	Round timber poles driven into the ground to provide support for a structure.
Pipe, piping	A longitudinal cylindrical or tubular hole through a beam or pile.
Point load	A load applied at a single point.
Probability of failure	The probability of failure is an indication of the number of times a limit state is exceeded when a system is tested a large number of times. As an example, it is expressed as 1 in 10^6.
Proof load	The load that causes identifiable non-elastic behaviour.

R	R is a programming language. It is an, open source, interpreted language written primarily in C and widely used for statistical computing and graphics generation. Although new functions can be written in C to suit any special need, only standard functions are used for the purposes of this research. Scripts are prepared that enable the creation of graphs that statistically represent source data (Crawley, 2007; Dalgaard, 2008).
RMS	Roads and Maritime Services of New South Wales. This organisation was titled RTA prior to the year 2012.
Royal Species	A vague term used to describe some of the eucalypt species that were used for bridge girders. Still in commercial use but no clear definition found as to its origin.
RTA	Roads and Traffic Authority of New South Wales.
Safe Load limit	The load that can be applied to a bridge and not cause structural failure. Normally equivalent to the maximum load limit that is legally specified (refer Section 2.2.5).
Safety index, β	An indicator of the probability of failure. It is the number of standard deviations below the mean value of the limit state function.
SAP2000®	SAP2000® (CSI, 2010) is a finite element software package. It allows the calculation of the response of complex structures to complex loads. The specific software used was the SAP2000® Education edition V15 which is limited to about 300 equations and 100 joints. The SAP2000® model equations incorporate Timoshenko beam theory which accounts for the effects of shear in the calculation of mid-span bending of large beams.
Six sigma limit	The range that includes all values of a statistic within ± 3 standard deviations from the mean value. It includes 99.7% of the values.
S2	Strength group classification value for unseasoned timber. Mean bending strength of 86 MPa and mean MoE of 14 200 MPa (14.2GPa). It is used in this thesis as a limit state. An in-service girder should be above both limits. (Standards Australia, 1986: AS/NZS 2878 Table 2.1)
SMA	Second moment of area.
Substructure	Typically a combination of round timber piles and a pair of capwales that supports the superstructure.
Superstructure	Typically round timber girders mounted on corbels, transverse timber decking and optional longitudinal timber sheeting supported by the substructure.

Split	A split is a grain separation that extends from one surface to another.
Temporal change	A change that occurs from one moment in time to another
Temporal MoE factor, k_E	The factor that represents temporal change in MoE. MoE is the material parameter as measured at one moment in time. The temporal factor provides an indication of how MoE temporally varies.
Temporal SMA factor, k_I.	The factor that represents temporal change in SMA. SMA is the material parameter as measured at one moment in time. The temporal factor provides an indication of how SMA temporally varies.
Timoshenko beam theory	The beam theory embodied in the SAP2000® software (CSI, 2010)
ton	Imperial unit of mass, 2240 lbs, 1016 kg, 20 cwt (non SI unit).
tonne	Unit of mass, 1000 kg (SI unit).
Unexplained variation	100% - explained variation%
QDMR	Queensland Department of Main Roads. This name has been changed to the Department of Transport and Main Roads (QTMR).
Quartile	Value of a variable within which 25% of observations fall. The first quartile is the 25th percentile, the second quartile is the median or 50th percentile and the third quartile is 75th quartile.
Quantile	A point taken at regular intervals from the cumulative distribution function.