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TOWARDS PREDICTABILITY OF BRIDGE HEALTH

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ABSTRACT

Any assessment document pertaining to existing bridge infrastructure requires an accurate record of each individual bridge in service, the history of repairs and modification as well as the current state of structural health after each inspection. Bridge inspections need not only be regularly documented, but compared with previous inspections and the probability of ongoing performance assessed. Such knowledge allows the planning of regional sustainability of rural bridges over major and minor transport corridors.

This paper examines the variety of timber bridges on rural NSW roads with the data that describe the likely limitations to normal loading. The discussion outlines the level of measurement accuracy required for documenting bridge health and experimental evidence verifying the level of accuracy achievable.

Because many timber bridges have had a variety of owners, and society has for many years restricted the funds available for infrastructure maintenance, bridge structural health is poorly understood at any level of quantifiable predictability. Alternative methods of monitoring heavy traffic on rural roads have not been well examined and bridge load limits may often not reflect actual bridge carrying capacity. In the absence of suitable data, some of the structures being replaced may not be the ones at most risk of failure. This is not a new issue and has changed little in the last twenty years. To extend the serviceable life of bridges and to sustain a low probability of structural failure, new low cost measurement systems are required. This paper discusses one such method of measuring mid-span deflection that can be readily used by bridge maintenance crews after short periods of training.

Keywords: bridge, continuous monitoring, maintenance, timber, sustainable.

1 INTRODUCTION

Timber bridges abound on rural and regional roads throughout Australia, carrying loads of all descriptions from light passenger vehicles around one tonne, to legally loaded multi-axle vehicles up to 42 tonnes. These bridges, the inventory of rural local authorities or state agencies, require maintenance to ensure that their performance is commensurate with the road corridor they serve. That the bridges form an inventory should dictate that there is some record that they exist, if nothing more. However, that same inventory needs to store: accurate records of bridges in service; periodic and on-going inspections; and maintenance activity leading to a regular assessment of their state of structural health. Such knowledge allows planning for the sustainability of rural bridges. A method by which timber bridges can be inspected and their progressive structural health assessed will be examined here.

In 2008, the Institute of Public Works Engineering Australia (IPWEA), as a step towards providing sustainable infrastructure assistance to local government, published the details of a second survey of New South Wales (NSW) local councils (Howard 2009; Roorda 2006). These two reports contain recent data about the state of over 2000 timber bridges that are maintained by local government in NSW. Very few timber bridges have been built in NSW in recent years. The majority of extant timber structures were built in the first half of the 20th Century; some date to the19th Century. Examples in the New England region include the bridge over the Styx River at Jeogla south of Armidale; Horton's Creek Bridge on the Armidale-Grafton Road; the bridge over Salisbury Waters at Gostwyck; and the bridge that has been recently built to replace Leslie's Bridge on Thunderbolts Way over the Manning River, north of Gloucester.

The bridge over the Styx River (Figure 1) is a Type C (Allan) truss, which was erected in 1899 (Glencross-Grant 2009). Horton's Creek Bridge (Figure 2) is representative of many bridges built in the inter-war period and carries traffic plying the New England Tableland with the North Coast. Munsie's Bridge over Salisbury Waters (Figure 3) is another one during this period, being built in

1938. This bridge services an agriculturally diverse area of wool and cattle production on the New England Tableland. A recent replacement of a multi-span timber bridge is the Leslie's Bridge (Figure 4) on the Walcha/Gloucester Road. This bridge was constructed using round timber girders with a composite concrete deck, supported on round steel piles.

Figure 1: Bridge over Styx River

Figure 2: Horton's Creek Bridge, Armidale-Grafton Road

Figure 3: Munsie's Bridge over Salisbury Waters, east of Uralla

Figure 4: Leslie's Bridge replacement, Thunderbolts Way over the Manning River (Walcha-Gloucester)

Bridges in Figures 1 to 4 were chosen to demonstrate the diversity and versatility of rural timber bridges. The history and maintenance records of many of the earlier bridges are not readily available since their management has changed numerously during their long lives. Many bridges that were initially owned by the Public Works Department (PWD) were passed on to subsequent road authorities (Main Roads Board, Dept of Main Roads and latterly Roads and Traffic Authority) and then to relevant local councils. In Armidale, for example, further changes in ownership have occurred as councils have been amalgamated; Dumaresq Council and Armidale Council amalgamated in 2000 to become the Armidale Dumaresq Council. Such amalgamations are commonly associated with a reduction in workforce size; a reduction in operational and record space; and often a loss of, or diminution of corporate knowledge. For example, historical records might be stored in places that are not quickly accessible and become forgotten, especially when such records were handwritten journal entries from a previous generation. It can, therefore, be costly for councils to contribute meaningful data to surveys of the type conducted by IPWEA (Howard 2009; Roorda 2006).

Table 1 summarises statistics relating to the more common practices of testing from a range of inspection methods available, including visual testing and direct or indirect measurements. A significantly and concerning result of the survey was that 41% of councils in NSW had no knowledge of the load capacity of their bridges (Roorda 2006). It is important to stress this figure in order that it is very clear that knowledge about the carrying capacity of many rural bridges is not well known. In order to improve current knowledge of carrying capacity, new measurement methods are required. Methods that are both simple and inexpensive to implement in order to continuously monitor the health of these bridges.

Table 1: Inspection methods cited in IPWEA roads and transport directorate NSW bridge survey

Inspection method	Respondents' selected method
Instrumental methods	Less than 50% by councils
Drill testing	58 out of 98 respondents (59%)
Load testing	29 out of 96 respondents (30%)
Knowledge of load capacity	62 of 152 NSW councils had no knowledge (41%)

(Roorda 2006)

As can be seen from the examples (Figures 1 – 4), each structure is different, and a 'one-size-fits-all' approach is difficult to manage and often does not work. However, they all have some common characteristics. There are also a variety of failure modes, which can be grouped into substructure failure and superstructure failure. An example of a substructure failure is given in Figure 5 and one of superstructure failure in Figure 6.

Figure 5: Somerton Bridge west of Tamworth, which connects Somerton village to Oxley Highway

(Source: Glencross-Grant)

Figure 6: Overload -shearing first deck plant and then fracturing the kerb girder

The substructure failure of the Somerton Bridge (Figure 5) involved the subsidence of the piers leading to loss of deck stability. In such a situation, if the last vehicle to cross the structure does so safely they may well not report the damage, even if aware of the problem, more especially if the incident happens at night. The structure then becomes the potential site of a serious accident. In order to minimize the risk of a second incident, a sensing method is required that detects the failure and transmits the bridge status to a maintenance centre. Such a sensing method should be able to respond to small, yet significant changes in headstock position or small, but significant changes in the position of the girder mid-span position. One method is to locate the position of important components by laser location. An example of this method is provided by Moore (2009; Moore *et al.* 2009), who identifies a method of continuously monitoring the mid-span deflection.

2 TIMBER BRIDGE MONITORING

The ability to accurately identify deficient timber components is still not a developed science. Although several techniques that can be used to evaluate timber components have been known for over 50 years, significant skill is required in utilizing them. Strain gauges and linear variable differential transducers (LVDTs) have long term mounting problems when used with aged timber bridges. Such devices can only be realistically used in short term, intensive structural engineering evaluations. Acoustic, electromagnetic, ultrasonic and nuclear particle attenuation techniques require skilled personnel to apply such sensors and interpret the measured results. Unfortunately, the funds to support such activities are limited, and costly measurement processes can be beyond the resources of many small rural and regional types of council.

As an example, in 2008 $20M was allocated for the upgrade of timber bridges in the rural and regional areas of NSW (NSW Parliament 2008). Averaged across all councils in the State, that equates to about $150,000 per council and with a unit rate of about $800 per m^2 (Howard 2009:15) to one three span single lane timber bridge. Maintenance funds must therefore be spent very wisely, not only in dollars per square metre, but also in priority order of safety. It is important to identify which structures are in danger of falling down or failing and which are in a sufficient state of repair to continue in operation. This is not just a bridge monitoring function, but also a research function, since new methods are required to identify what needs to be done. In short, there should be funds budgeted to enable such research to be undertaken.

It can be identified from research that has been carried out in areas not directly related to timber bridges that significant cost savings can be made by ensuring that components remain in Condition States One and Two and do not decline to higher Condition States (Kadar *et al.* 2011; RTA 2007). However, 27% of timber bridges in NSW have been assessed as being in Condition State Three and 52% in Condition State Two. An abbreviated description of the Condition States as specified by the RTA for timber girder condition is: State One: Timber in good condition with no evidence of decay; State Two: Minor decay; State Three: Medium decay; and State Four: Advanced deterioration (RTA 2007). To ensure that structures are highly reliable and have a low probability of failure, components should be replaced before the onset of wear out; that is at the end of the period during which they have a low failure rate. If they are replaced during the wear out period the system failure rate can become excessively high, which is the current situation pertaining to timber bridges in NSW (Bazovsky 1961:58). The difficulty that arises from these concerns is that the onset of wear out may be characterised by only small uncharacteristic movements that may not be visually obvious. The specific loading event that resulted in the Somerton Bridge failure crossed all 10 spans. Yet it was only one set of piers that substantially failed. If the movements of the piers had been continually monitored, then any uncharacteristic movement may have been identified with sufficient advanced notice for remedial work to be started.

The questions that then arise are what level of accuracy is required to identify an uncharacteristic movement and can an uncharacteristic level of movement be readily detected? Certainly there are high-cost sensors that can be used to measure movements of fractions of a millimetre, or less, but components in a typical timber bridge will move several millimetres under normal loading. The linear expansion coefficient of timber parallel to the grain is typically 5 x 10^{-6} per °C. For example, a 20°C change in temperature will cause an expansion of about 0.1 mm/m. Shrinkage or expansion due to a change in moisture content can be about: 0.1% parallel to the grain, which will produce an expansion of one mm/m along its length; and 2% to 10% transverse to the wood grain producing an expansion of about 20 mm/m (Standards Australia 2010:Section 1.4.4.4). Thus, under normal conditions a 5 m support pile can expand about five millimetres vertically, a 10 m girder about 10 mm horizontally, and a 500 mm diameter girder 10 mm or more in diameter.

The mid-span deflection of girders under normal loads can be about 20 mm and not exceed the deflection limit state (Standards Australia 2004:Section 6.11). Many timber bridges are 5 m or more above the stream bed and vertical movements of the deck, caused by changes in environmental conditions, of about a millimetre should not be unexpected.

A laser movement detection system such as proposed by Moore (2009) can be readily used to detect movements of a few millimetres to an accuracy of 0.5 mm. Such a system is of suitable accuracy and thus could be used on timber bridges to detect uncharacteristic movement. It is likely that there will be situations where a small movement of the piles occurs before catastrophic failure occurs. If such a system had been in place on the Somerton Bridge, and small movements had occurred over several days prior to the eventual failure, it may have been possible to provide a warning of an increased probability of failure. Low cost telemetry systems are available to enable the measured deflection and movement data to be transmitted back to bridge maintenance and service centres to allow a warning to be acted upon immediately.

3 EVALUATION OF MONITORING TECHNIQUES

3.1 Field evaluation

Laser movement detection systems can also be used to provide low cost and simple to use load test measurement systems such, as developed by Moore (2009). In a field test situation, a laser detector was set up on a single lane, single span timber bridge on the outskirts of Armidale. Set up time was relatively short, with the device taking about 30 minutes to fit to the headstock and beam.

Data are recorded for each vehicle traversing the bridge and the deflection, which is proportional to the load, is measured and recorded in real time. Not only is the mass of the vehicle inferred by the deflection, but vehicle counts are recorded in real time and large heavily laden axles can be identified at a particular time and temporal variation of vehicle movement can be monitored. These larger events may coincide with the local school bus, stock carriers heading to saleyards, or other identified road users. As an example, a measurement system read to a resolution of 0.5 mm has been used to identify the deflection under load over a load range of 1-7 tonnes with a standard error of 0.14 mm and a coefficient of determination of 0.999 (Figure 7). Measurement resolution of 0.5 mm is thus sufficient to provide stiffness data of reasonable accuracy.

Simply by measuring deflection several factors can be determined. Firstly, vehicle mass can be estimated as shown by Figure 7. More importantly, when a vehicle of known mass traverses the bridge, comparisons over time can be made and the health of the girders implied by the increased deflection for that known mass. This method would allow councils to proof-load with a truck of known mass, at say monthly or quarterly intervals, and build a set of deflection data for each timber bridge in their local government area. The actual cost to the council could be as low as a few person-hours per bridge for each monitoring session. Secondly, from the slope of the curve in Figure 7, the girder stiffness can be inferred; any small, but significant change in temporal stiffness is indicative of degradation. Thirdly, larger significant changes in effective stiffness can be indicative of degradation to the support region of the girder and headstocks.

3.2 Field calibration

Figure 8 shows the optical source mounted on a rigid tripod on firm bank under the bridge, such as would be used for measurement over a day where the instrument was attended at all times. For field calibration, a graduated chart target is attached to a girder and the position of the optical source image on the chart adjusted to zero. Data can be gathered statically by loading the bridge with a vehicle of known mass and recording the movement of the laser image observed on the chart. If dynamic measurements are required, then the movements of the laser image on the chart, caused by a moving vehicle, can be recorded with a high speed camera (see Figure 8). By interpretation of the video images, the range of deflections for a particular girder can be developed as shown in Figure 7. These data are then used as calibration of an enclosed system that can be mounted more permanently on one of the girders and connected to a data recorder (refer Figure 9).

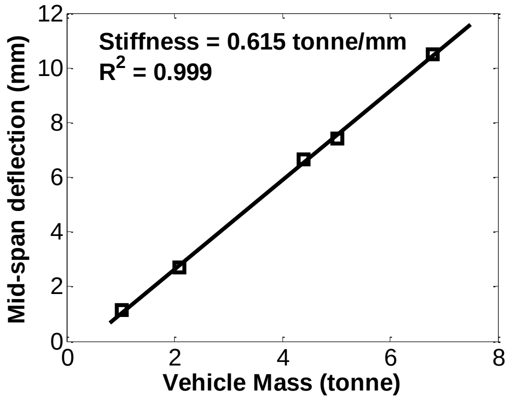

Figure 7: Mid-span deflection plotted against vehicle mass (tonnes) for static load test of study bridge

3.3 Long-term monitoring

The field version of the laser device is encapsulated in a 100 mm PVC tube, housing the laser at one end and the target at the other end. The laser end of the tube is secured to the headstock of the bridge where minimal vibration will occur. The distal end of the tube is secured near the centre of the girder (see Figure 9). An on-site adjustment is required to set the quiescent position of the laser, but this is simply a screw adjustment.

Figure 8: Optical source, high speed camera and graduated chart target

Figure 9: Under-bridge view of field version of laser device

3.4 Technical interrogation

The modulus of elasticity and the modulus of strength, or rupture, for SD1 material is identified in AS1720.1 by single values; being 21.5 GPa and 150 MPa respectively, which are minimum values that should be used for design purposes (Standards Australia 2000). If the Modulus of Elasticity (MoE), or Modulus of Rupture (MoR) of a single particular girder is measured several times in constant conditions, then the mean measured value is obtained together with a measurement error; this error could be of the order of one percent. A particular girder can, therefore, be identified as having a MoE of say 24 GPa, with a variation of one percent. The MoE and strength are therefore, not single values, but a range of values, which comprise a distribution of values. The mid-span deflection of a bridge girder is inversely proportional to the elasticity, so the variation in deflection is also one percent.

Once a particular girder is installed in a structure, such as a regional timber beam bridge, it will be affected by the environment. Consequently, the elasticity and strength moduli will vary in a temporal manner. This is because these moduli are affected by the girder moisture content; the modulus of rupture will change by about four percent and the modulus of elasticity by about two percent for a one percent change in girder moisture content (Bootle 2004). As the seasons change the moisture content of the extreme fibres of the girder could vary by as much as three percent. The elasticity would, therefore, vary about six percent. The variation in the mid-span deflection will increase by a similar amount so that the variation thus becomes a variation of seven percent (being one plus six percent).

As the surface of the same girder temporally erodes, the capability of that girder to support a load will decrease. If the surface is eroded at a constant rate of 0.2 mm per year and the girder moisture content is constant, then a 10% increase in deflection can occur for a constant loading condition over a 30 year period. The variation in mid-span deflection could thus increase to 17%. Degradation in elasticity of the support region of the girder, due to termite and fungal activity, can further increase the variation in deflection to 20%, which may be safe and to 30% which may not be safe.

In order to identify temporal changes in deflection, deflection must be measured under similar conditions. One method to make these measurements is to measure the deflection caused by a stationary vehicle of known mass using a laser and a graduated chart. After several measurements have been made it is possible for a bridge maintenance engineer to identify the level of variation that pertains to that bridge. The measurements can be scaled from the measured range to the maximum allowed bridge load range and the probability that the mid-span deflection will exceed the deflection limit state of 1:600 (Standards Australia 2004:section 6.11) can be calculated. A variation to this static method is to measure the deflection caused by a moving load using a laser, a graduated chart and a high speed camera and generate data representing deflections caused by dynamic moving loads. However, both these methods require maintenance staff on-site to perform the measurements and can only be justified for longer regular maintenance intervals (e.g. six months or more).

Another alternative is to adopt the long term monitoring approach as discussed in Section 3.3. Such an approach enables the traffic loading distribution to be identified and also any temporal variation in mid-span deflection. Calibration can be achieved by vehicles of known mass crossing the bridge at known times so their passage can be correlated to particular deflection measurements. It is not necessary for maintenance staff to be present at the time of measurement. A range of vehicles that regularly cross the bridge could be used; one such example is the school bus. Such a vehicle can be fitted with telemetry equipment to communicate both with the bridge measuring equipment and the bridge service and maintenance centre. A high percentage of the traffic that typically crosses small rural and regional bridges consists of vehicles below three tonnes gross vehicle mass (GVM). Significant changes to this ratio of the number of vehicles that exceed a deflection caused by a vehicle of about three tonnes to the number of vehicles that exceed the deflection caused by a vehicle of about one tonne will not vary significantly for a particular bridge. It may vary over short periods because of a change in traffic distribution, but this can be observed in the recorded traffic statistics. Significant changes to this ratio can thus provide a first level indication of whether the bridge is performing correctly. Example data obtained from a three week observation period of one, single lane, single span timber bridge are shown in Table 2. The stiffness of 0.615 tonnes per mm and a ratio (Level2:Level1) of 12% is indicative of a bridge that requires stiffening and monitoring of future performance.

Table 2: Summary of a data set from a three week observation period

Parameter	**Value**
Measurement period	22 Days
Level 1: Number of vehicles exceeding one tonne	5585
Level 2: Number of vehicles exceeding three tonne	647
Ratio (Level 2:Level 1)	12%

The next step in evaluating the structural health of a timber bridge is to determine the probability of failure. The first failure condition of concern is that the deflection limit state will be exceeded and the second is a tendency toward catastrophic bending failure. Both of these can be indicated by ongoing temporal changes, which can be monitored by the instrumented methods already described. Methods of applying this research are ongoing in order to provide a direct line of action from simple field measurements, to identifying the probability of failure of a particular structure. Initial aspects of this work are reported in recent papers (Moore *et al.* 2011a, 2011b).

4 CONCLUSION

There is a need to identify timber bridge structures that are structurally sound from those that need remedial action and to achieve this in a low cost manner so that timber bridge maintenance can become sustainable. Laser movement detection systems can be constructed that achieve a suitable level of resolution and accuracy to be used effectively in this task.

Such systems provide the opportunity for engineers to regularly monitor the health of each and every timber bridge for the cost of a few maintenance staff hours in fitting a measurement device. After a specific monitoring period, that includes using the transit of a vehicle of known mass, the data can be assessed and compared with previous monitoring results. Variations in data distributions can be used to identify changes in structural condition. Timber bridges can be returned to being highly reliable structures by ensuring that damaged components are identified and replaced when they no longer comply with a high order condition state.

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