Predicting the remaining life of timber bridges

T. Abbott[1], N. Gamage[2], Weena Lokuge[3], S. Setunge[4]

Abstract This paper documents the current state of knowledge relating to the deterioration of timber bridges in Australia. The aim of this research, was to comprehend the present state of knowledge regarding maintenance of timber bridges and address any gap in knowledge. This involved: identifying key defects in timber, investigating the inspection methods utilised to detect these faults and finding the preventive measures used to mitigate bridge deterioration. Enclosed are figures which demonstrate how simple industry practices and procedures implemented by each states' governing authority can reduce these impacts and concludes with an empirical model for predicting the remaining lifespan of a bridge.

1 Introduction

Of the roughly 40,000 bridges in Australia, 27,000 of them are constructed of timber. Most of these are over 50 years old and in a weathered condition (Ranjith et

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[1] T. Abbott
School of Civil, Environmental and Chemical Engineering, RMIT University, Melbourne, Australia
e-mail: tano_abb@hotmail.com

[2] N. Gamage
School of Civil, Environmental and Chemical Engineering, RMIT University, Melbourne, Australia
e-mail: nirdosha.gamage@gmail.com

[3] W. Lokuge(✉)
School of Civil Engineering and Surveying, University of Southern Queensland, Australia
email: weena.lokuge@usq.edu.au S. Setunge
School of Civil, Environmental and Chemical Engineering, RMIT University, Melbourne, Australia
e-mail: sujeeva.setunge@rmit.edu.au

[4] S. Setunge
School of Civil, Environmental and Chemical Engineering, RMIT University, Melbourne, Australia
e-mail: sujeeva.setunge@rmit.edu.au

al. 2013). From government documents and first hand correspondence with engineers in the industry it has been discovered that a lot of these bridges have been replaced by steel elements. The majority of remaining timber bridges in Victoria, are of the girder deck system type and located on forest walk trails and tourist roads or are local roads which are controlled by municipalities (Vicroads, 2014). There are a number of considerations which affect how a bridge will perform throughout its service life. The design load, environmental factors, type of timber and size of members used all contribute to which known defects each bridge element will be most susceptible to and the best method of detection (Ranjith, 2011). With the knowledge contained in this report and previous history a matrix has been developed highlighting these key aspects. Inspectors can use this for their reference to check typical symptoms of decay and take appropriate actions.

The major defects that all Australian timber bridges are susceptible to are splitting and rot due to fungal attack. If the bridge is used as a water crossing, marine borers and flood are other possible factors. Termite infestation is not as predominate in southern states, although reports do suggest that in warmer states such as Queensland, this may be more of threat to timber structures. Inspectors have reported that it is more likely to see timber shrink and be pulled off their fasteners than it is to see the iron nails corrode, thus this form of deterioration is not very significant. The stringers of a bridge are subjected to substantial load distributed from the superstructure and may undergo excessive deflection over time in a phenomenon known as creep. Inspection techniques are divided into destructive and non-destructive. The most common and reliable destructive tool involves drilling into a timber member to grasp its interior condition. Currently in Australia, state governing bodies are responsible for the upkeep of their timber bridges intrust their skilled engineers to visually inspect the structures and decide which course of action to take.

2 Industry Practice

The following is a paraphrased excerpt from a conversation with two structural engineers who have decades of experience in inspecting timber bridges. Their knowledge outlines the current Victorian practice and highlights their conclusions about deterioration they gathered from practical inspections in the field. The governing authority employed a number of cost-effective methods of preventing damage to timber elements including a range of epoxies and paints to protect the outside surface from moisture and debris build up which could lead to decay. The implementation of anti-split bolts and washers were installed on the piles to reduce the impact deep checks would have to the column. Petroleum jelly was also used as a water proof barrier. These measures are implemented on a case by case manner as recommended by the inspecting engineer, without any formal standard to follow.

There are a number of major factors to look for when attempting to estimate the remaining lifespan of a bridge. It is imperative to inspect the condition of every elements' surface, checking for moisture and debris accumulation which could lead to decay and risk in case of fire. It is important to check for splits and cracks in corbels and cross beams. There is no cause for alarm if sapwood is seen rotting as this always rots first and doesn't contribute to section capacity. It is humidity, soil presence and moisture govern how a timber will deteriorate. Timber bridges were abundant in Victoria during the 1940's due to availability of wood. The mindset back then was to aim for fifty years life from the structure through inexpensive, low level maintenance.

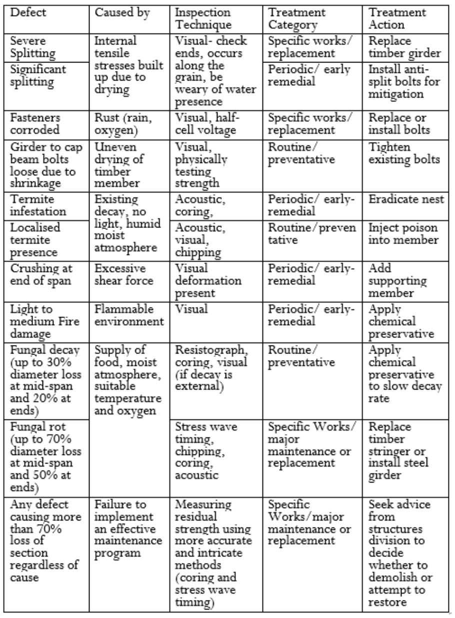
2.1 Treatment Methods

Treatment methods are often referred to as maintenance because of the existing proactive understanding in the industry. The ethic is that it is more beneficial to increase the lifespan of a bridge and its components through regular inspection and maintenance than to replace decrepit members on a need to basis. Frequent upkeep and inspection can report on the derogation rate and suggest recommendation for planned works in the future. The method of replacing members once they have decayed beyond repair is a costly exercise and by the time the deterioration is detected the operational effectiveness of the structure can be compromised, resulting in serviceability failure and a risk to safety. (Main Roads Western Australia, 2012)

The maintenance methods can be divided into three branches which are distinguished by the cost, timeframe and level of work performed. The simplest and cheapest form of treatment is Routine Maintenance/ Preventative Treatment. This consists of mainly minor reactive works which are anticipated and allocated for in the budget and planned on a short term basis, usually about two weeks or less (Main Roads Western Australia, 2012). This commonly includes controlling factors which provide favourable conditions for decay such as moisture content. Periodic Maintenance/ Early Remedial Treatments are carried out at regular intervals of longer than one year. These are designed to fix problems associated with early stage defects, such as rot. It is undertaken on a proactive rather than reactive basis (Main Roads Western Australia, 2012). Examples include baiting systems to deter termites, the installation of pile jackets and more rigorous application of sealants. Specific works/ major maintenance occurs when decay is so advanced that the member simply does not have the structural strength to support the loads acting on it. Expensive replacement type improvement maintenance or rehabilitation maintenance is used when a member is so decayed regular treatments will not repair its structural integrity. These include one-off repairs, refurbishment and upgrade works to retain the bridge as close as possible to its original condition.

3 Defect Treatment Protocol

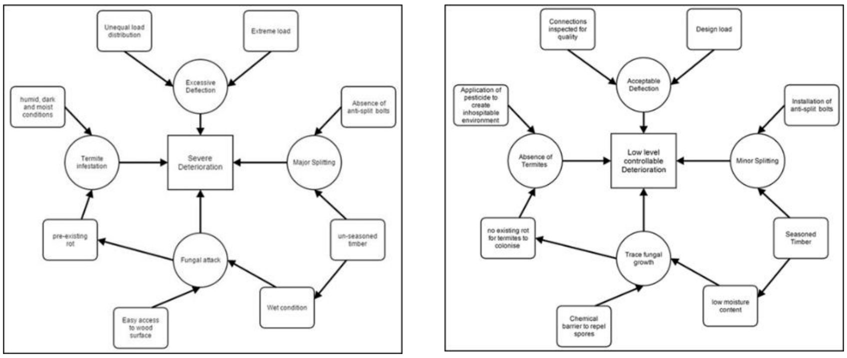
Deterioration is a cause and effect process. Each type requires certain factors to manifest. These can be detected with different methods and catagorised into routine maintenance mitigation, periodic maintenance and major works or rehabilitation maintenance. The following (Figure 1) is an amended defect treatment matrix adopted from the Queensland Department of Transport and Main Road's Timber Bridge Maintenance Manual (2015).



Defect	Caused by	Inspection Technique	Treatment Category	Treatment Action
Severe Splitting	Internal tensile stresses built up due to drying	Visual- check ends, occurs along the grain, be weary of water presence	Specific works/ replacement	Replace timber girder
Significant splitting			Periodic/ early remedial	Install anti-split bolts for mitigation
Fasteners corroded	Rust (rain, oxygen)	Visual, half-cell voltage	Specific works/ replacement	Replace or install bolts
Girder to cap beam bolts loose due to shrinkage	Uneven drying of timber member	Visual, physically testing strength	Routine/ preventative	Tighten existing bolts
Termite infestation	Existing decay, no light, humid moist atmosphere	Acoustic, coring,	Periodic/ early-remedial	Eradicate nest
Localised termite presence		Acoustic, visual, chipping	Routine/preven tative	Inject poison into member
Crushing at end of span	Excessive shear force	Visual deformation present	Periodic/ early-remedial	Add supporting member
Light to medium Fire damage	Flammable environment	Visual	Periodic/ early-remedial	Apply chemical preservative
Fungal decay (up to 30% diameter loss at mid-span and 20% at ends)	Supply of food, moist atmosphere, suitable temperature and oxygen	Resistograph, coring, visual (if decay is external)	Routine/ preventative	Apply chemical preservative to slow decay rate
Fungal rot (up to 70% diameter loss at mid-span and 50% at ends)		Stress wave timing, chipping, coring, acoustic	Specific Works/ major maintenance or replacement	Replace timber stringer or install steel girder
Any defect causing more than 70% loss of section regardless of cause	Failure to implement an effective maintenance program	Measuring residual strength using more accurate and intricate methods (coring and stress wave timing)	Specific Works/major maintenance or replacement	Seek advice from structures division to decide whether to demolish or attempt to restore

Figure 1 Defect treatment matrix

Matrix shown in Figure 1 is a tabulated illustration condensing all the information found in the maintenance manuals. This figure details the type of defects, how they are identified and how they are mitigated through maintenance techniques. It provides a snapshot to inspectors at what to look for, how to detect and how to treat various forms of deterioration. The matrix does not give an indication to how long a bridge may last until it is unsafe, it only gives protocols to follow at the time of inspection. Therefore current practice shows that there is no concise methodical approach to quickly ascertain the required information about how to mitigate or predict the rate of timber bridge deterioration, which is reinforced by other researchers (Ranjith et al., 2013). Equipped with this knowledge, a procedure collaborating all the necessary data has been developed to address the gap in current knowledge. It is anticipated that these tables can be used by inspectors to empirically rate and score the level of deterioration of a bridge.



Severely deteriorated bridge

Barely deteriorated bridge

Figure 2 Flowchart of bridge, highlighting the causes and factors contributing to this state

Taking a closer look at stringers the usual causes for deterioration are: pipe rot, splitting and termite infiltration. Depending on the design and member dimensions, excessive deflection may also prematurely weaken the member. Figure 2 shows a worst case scenario for the prognosis of a stringer in a poorly fabricated and executed maintenance regime. Using the stringer member as an example, the flowchart shown above displays the major contributors to the element's structural demise as well as indicating the cause of each defect. The exterior boxes describe the factors present which cause the four most common types of decay to the stringer element. Interestingly, termite infestation occurs when rot breaks down the wood fibers allowing the organisms to enter the dark cavities, which occurs when timber shrinks releasing water attracting fungal spores to grow and start decaying the wood. Therefore, for termites to be present, the wood must first have been weakened by fungal rot to improve the conditions for termites to thrive. This shows a more appealing outcome for the condition of a bridge. With an effective mitigation protocol in place, this bridge will outlast its above counterpart. One noteworthy remark is that this flowchart only shows the major causes affecting the deterioration rate. Other less common factors such as flooding or fire may contribute to the ultimate design life.

4 Bridge Deterioration Prediction Model

After researching the current state of knowledge and delving into the information provided in the states' maintenance manuals, it became apparent that there was no documented way to predict the remaining service life of a bridge based on environmental factors which manifested the identifiable defects within it. Within this section is a prototype of an empirical model to produce an educated estimate of the amount of time, in years, until the overall condition of a timber bridge surveyed reduces to condition state 4.

This model depends on the type of decay present to predict the serviceability of the bridge. Therefore the first step is identifying the modes of deterioration. The five main constituents are fungus, splitting, termites, corrosion of fasteners and marine borers, which affect the three elements differently. Below are clauses to be considered when applying this model.

- Clause a) Termites are only considered for bridges in warm climates. For the purpose of this model, “warm climates” include Queensland, Western Australia and the Northern Territory regions.
- Clause b) Marine Borers are only considered for bridges where there is significant water presence that has prolonged contact with timber surfaces, such as rivers and creeks.
- Clause c) Each form of decay affects each bridge element to various degrees of significance. Bridge Stringers will be susceptible to: Fungal attack, termite attack (if located in region defined in clause a) and splitting. Bridge Piles will be susceptible to: Fungal attack, termite attack (if located in region defined in clause a), splitting and marine borers (if situation satisfies clause b). Bridge Corbels will be susceptible to: Fungal attack, termite attack (if located in region defined in clause a), splitting and fastener corrosion.
- Clause d) Any defect which causes more than 50% loss of section (beyond the parameters of Condition state 4) is said to be unsafe as it has failed and requires immediate replacement of the member.

4.1 Limitations

This prototype focuses on three critical structural members that make up the substructure of the bridge. These are the stringers, corbels and piles. For this model to be implemented accurately, the inspector has to comment on the presence of each type of decay prone to a particular member. That is, they should not conclude a condition state based purely on one mode of deterioration, but should endeavor to observe other forms applicable to the element which may accelerate decay. The values assigned to each condition state are purely estimated with no laboratory testing to authenticate the figures delegated. It is also possible for one element to have a different condition state to another element of the same type. When this happens, it is up to the inspector’s discretion to implement a value which best fits the description for the entire number of members of that type. For simplicity of the model and due to resource restrictions, it is assumed that degradation of a bridge is linear in nature.

4.2 Model

The following tabulates all of the steps required to classify the condition of a bridge via its empirical score (S) and therefore compute its remaining lifespan. This model encompasses all information which has been gathered from this research and will need to be referred to acquire figures. Table 1 demonstrated the allocated distribution for each decay type for each element. The element in question and number of applicable methods of degeneration determine how much each type of decay contributes to the total amount of deterioration; see procedure clauses a,b and c.

Table 1 Deterioration weighted splits

Decay type	Weight as a percentage			
Fungus	60	45	50	40
Splitting	40	30	30	30
Termite	-	10	20	15
Marine Borer	-	15	-	-
Corrosion	-	-	-	15
Element	Stringer /Pile	Pile	Stringer	Corbel

As shown in Table 2, points are assigned for each condition state. Using the condition states listed earlier in this report the inspector can match the description of the bridge element to the most suitable condition state. This process will have to be repeated for each element (stringer, corbel and pile). See also procedure clause d. There may not be four decay types for every element based on environment.

Table 2 Points assigned for each condition state

Condition state	1	2	3	4
Points assigned	9	6	4	2

The total weight for each element thus found is inputted into the cell under the respective element. The average is then calculated. Before the final score is given the entire bridge can be subjected to environmental factors which may adjust its overall score (Table 3).

Table 3 General observations modification adjustment.

Discolouration	-0.1	Fresh, new coating	+0.1
Loss of fill in abutments	-0.1	Deck well maintained	+0.1
Deck cracking	-0.2	Sapwood still intact	+0.2
Undersize members	-0.3	No visible deflection under load	+0.2
Visible decay in other bridge members	-0.3	No debris on any bridge component	+0.3

Sum the values of both columns that are applicable based on inspector's general observations. Table 4 provides a numerical and descriptive indication of a bridge's integrity. This result can be compared to future inspections to summarise a trend and determine the rate of deterioration.

Table 4 Timber bridge classes.

Score (S)	0-3	3.1-5	5.1-7.5	7.6-10
Classification	Poor	Fair	Good	Excellent

Following equation can be used to determine the time the bridge has until it reaches condition state 4. The equation is based on the scores for two extreme ends of the spectrum in Table 4. As shown in Table 2, a bridge in condition four still receives points and allocated a score of 3 in Equation 1.

$$\upsilon = \frac{S-3}{10-S} * T \qquad \textit{Equation 1}$$

where υ = Remaining time in years until condition state 4 is reached; S = Score calculated from table 6; and T = Age of bridge when inspection was conducted, in years. Inspectors would then refer to the defect treatment matrix for maintenance options and recommended mitigation techniques to preserve existing infrastructure to prolong the service life of the bridge.

4.3 Demonstration of the model

20-year-old two span simple beam wooden bridge constructed from seasoned F grade timber is selected to demonstrate the developed model. Bridge deck consists of timber planks installed transversely with bitumen sealed to support loads up to 20t. Mid-span piles are submerged up to half the length of the pile in a river. Considerable discolouration and decay (~20%) was observed throughout all elements of the superstructure and substructure. Deck is still within serviceability limit state and deck and top of headstocks were littered with debris. Pile is in a more serious decayed state due to multiple types of decay present.

Table 5 Element Designation and Point Matrix.

Element	Decay	Description	Condition	Points	Weight
Stringer	Fungus	~20% pipe rot	2	6	3
	Splitting	Minor-medium splitting	2	5	1.5
	Termite	Minor presence	1	9	1.8
Total				20	6.3
Corbel	Fungus	~20% pipe rot	2	6	2.4
	Splitting	Minor splitting	2	6	1.8
	Termite	Minor presence	1	9	1.35
	Corrosion	Fasteners slightly loose	2	6	0.9
Total				27	6.45
Pile	Fungus	~30% pipe rot	3	5	2.25
	Splitting	Moderate splitting	3	5	1.5
	Termite	None	1	10	1
	Marine	Significant activity	3	4	0.6

Total	24	5.35

Table 6 Computation of final score (S)

Stringer Weight	Corbel Weight	Pile Weight	Average Weight
6.3	6.45	5.35	6.03
General Observations Modifications	No visible deflection +0.2 Visible decay -0.3 Discolorations -0.1	Final Score (S) Classification	5.83 Good

Table 5 and Table 6 demonstrates the calculations for the final score and using Equation remaining life of this bridge can be calculated as 13.57 years [(5.83-3)/(10-5.83)]. Treatment matrix such as the one shown in Figure 1 can be used to determine the maintenance process for this bridge.

5 Conclusions

This research has been conducted through a highly theoretical and analytical approach. From the beginning the purpose of this research has been to report on the characteristics of timber as it degrades throughout its lifespan and what current authorities are doing to mitigate damage and maintain their infrastructure. The bridge deterioration prediction model has been completed which was the key deliverable in this paper. This model should satisfactorily address the gap in knowledge regarding this subject matter. Further research is necessary to access and validate the accuracy of the model. With more data and analysis of how deterioration develops, better time estimates can be recorded and the model can be recalibrated to improve its application throughout Australia's timber bridges. The best way to validate this research is to apply it to previously documented bridges or to conduct a study to observe and record in-service bridges' deterioration rates to check if they follow the predicted relationship.

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