**Predicting the failure of timber bridges by using current inspection reports**

Weena Lokugea\*, Matthew Wilsonb, Huu Tranc, Sujeeva Setunged

a Senior Lecturer, b Honours Student, Centre for Future Materials, School of Civil Engineering and Surveying, University of Southern Queensland, Springfield, QLD 4300

(\*Corresponding author: Tel.: 07 3470 4477; E-mail: Weena.lokuge@usq.edu.au

c Research Fellow, d Professor, School of Engineering, RMIT University, Melbourne, VIC 3001

**Abstract**

There is a large timber bridge stock in service within Australia and currently over 300 timber bridges on Queensland state controlled roads. Majority of these timber bridges are in the latter half of their service life and require constant maintenance as the timber components deteriorate over time. Detailed level 2 inspections are performed as part of the bridge management systems used by road authorities. This paper discusses a simple method to use an inspection report to predict the chance of the failure of the bridge in a given number of years. Although the Markov process adopted in this research was based on inspection reports for several timber bridges for three time periods, it can further be refined using a data base of inspections for many time periods and environmental conditions. The proposed method is demonstrated using an inspection report for a hypothetical timber bridge.

**Introduction**

There is a significant number of timber bridges still in service in the road and rail network of Australia. Timber bridges are relatively economical in terms of the associated costs as well as the construction time (Crawford 2014), which allowed for the rapid expansion of Australia’s nascent road and rail net-works. The short-term benefits of timber such as low cost, availability and ease of construction were the dominant factors influencing early decision makers. It is important to recognize the contribution provided by timber bridges in the rapid social and economic expansion of Australia. However, timber bridges have a shorter design life than concrete or steel bridges, and require more in-service maintenance. They were never intended to handle present day traffic volumes and loads. However, the popularity of timber in the past has left behind a legacy of ongoing maintenance, rehabilitation and eventual replacement of Australia’s timber bridge stock assets (Ranjith, Setunge et al. 2013). Slow rates of replacement mean there will be a requirement to keep timber bridges in service for decades to come. This requirement is a huge challenge to transportation authorities, who need to minimize the cost of inspecting and maintaining timber bridges, while planning future rehabilitation and replacement programs.

In 2005, there were approximately 500 timber bridges in services on state con-trolled roads in Queensland. The mean age of timber bridges is approximately 60 years and at current rates of replacement, some of these bridges will need to remain in service for the next 30 to 40 years. All timber truss-type bridges have been removed from service on the Queensland state controlled road network. The remaining timber bridges are mostly timber girder bridges which typically include timber piles, headstocks, corbels, girders and decks, although sometimes steel or concrete components are substituted. Early diagnosis of possible deterioration scenarios will be useful for formulating an effective asset management strategy. Thus, infrastructure managers from many road authorities and councils across Australia need predictive deterioration models for condition assessment to optimize the repair and maintenance management process over the life cycle of a given timber bridge.

This paper outlines the condition-based reliability analysis to provide the predicted probability of future conditions for key components of timber bridges. The reliability analysis is based on the use of discrete Markov chain process for modelling the deteriorated condition change of timber bridge components. The predicted probability of future failure of the timber bridge is then evaluated by using a fault tree analysis on timber bridge components and their predicted probabilities (Lokuge, Gamage et al. 2016). The outcomes of this study can help focusing routine inspection and maintenance on timber bridge components with high likelihood of failure and help conducting risk assessment for network of timber bridges.

**Probability of failure of each element**

Timber bridge inspection reports from a regional council were used to assess the deterioration and to predict the probability of failure of each element in the bridge. The inspection reports of timber bridges are conducted by visual inspection and provide the condition rating from 1 (best) to 4 (worst) for each timber element for each inspection report. This is a common cost-effective practice used by bridge management agencies across Australia as per a survey (Sonnenberg 2014). The condition rating is based on a combination of different structural defects listed in the inspection manual and thus is considered to provide an overall and snapshot condition of timber element. However, the condition rating has not been related to the load rating of timber bridge as a whole structure, which is a very important factor for maintenance and rehabilitation decision. Furthermore, the deterioration mechanisms such as cracking and decaying causing structural defects are not the focus of the visual inspections and condition ratings.

The interest in utilizing the inspection data and condition rating for predicting failure probability to support the cost-effective management strategy regarding maintenance timing and prioritised action is high among bridge agencies. In utilizing the inspection data, the notion of ‘failure’ of bridge and its element might not be an actual or imminent event but is rather used as ‘in danger’ or ‘at risk’ that requires maintenance action. In this sense, the condition 3 or 4 can be assumed as the failure condition.

This study is based on a collection and analysis of inspection reports for timber bridges in a region in Queensland (Wilson 2016). Use of the collected inspection reports were limited by the following:

* Whenever a timber element is rehabilitated or replaced by a new material, this element is ignored.
* If a bridge does not have inspection reports for at least two time periods, then this data is also ignored.

Time period considered was 2001, 2003 and 2006 and the data were analysed for 2 and 3 years which demonstrates the deterioration of each element.

The Markov chain process was commonly used to model the condition rating data for understanding the deterioration rate (i.e. rate of condition change) and for determining the probability of condition state movement for each element in a timber bridge. One important property of the Markov model is that the history of deterioration process is accumulated and captured as the last inspection and future prediction can be based only on the last inspection information. This is very well suited for snapshot inspection data of timber bridges. Figure 1 shows the scatter plot of condition data versus age (showing the uncertainty of condition change) and the poor fitness of the well-known linear model and the non-linear model in modelling such random data. Therefore, the stochastic models such as the Markov model is often used.



Figure 1: Scatter plot of condition vs age of timber pile and fitted linear and non-linear curves

For four condition states, the core of the Markov model is the so-called transition probability matrix, which can be expressed as follows:

 (1)

The description of the transition matrix *M* is that for example, *P23* is the probability of an element in *CS2 (i.e. condition state 2)* moving onto *CS3* over a unit time step (often 1- year interval). Furthermore, if the current condition is known as condition 2, then there are probabilities to move from condition 2 to better condition 1 (for accounted maintenance action), and to worse conditions 3 (for gradual deterioration) and to worst condition 4 (for random damage event). If maintenance data is not available, the probability of moving to better condition is assigned zero (i.e. *P21*=0 or *Pij*=0 if *i*>*j*).

The transition matrix *M* can be estimated by using expert opinions or can be calibrated from the observed condition data. Table 1 shows the calibrated transition matrix from the condition data of each timber element.

Table . Transition probability matrices (one year)

|  |  |
| --- | --- |
|  |  |
|  |  |
|  |  |
|  |  |

Figure 2 shows the deterioration curves for pile element as an example.



Figure 2: Deterioration curves for pile element

If the current condition of an element is known with certainty [*P01 P02 P03 P04*], then the condition of the same element in *T* years can be predicted as follows:

 (2)

For example if the calculated probability matrix for girders at *T* years is, *P1* is the probability that a girder which is at *CS1* in the current year remains in *CS1* in *T* years in the future.

# **Predicting the failure of bridges**

The methodology adopted to predict the probability of failure of a timber bridge of interest in the current study is the Fault Tree Analysis (FTA). Fault tree for a timber bridge is shown in Figure 3. If either the superstructure or the substructure fails, then the main catastrophic event happens, ie the bridge failure. Since the superstructure and substructure failure can be due to the failure of its main structural elements, they are all contributing to the failure of each of them as shown in the figure. *P1…P7* are the probability of failure of deck, kerb… whales and bearings respectively. If these probabilities are known, then the “OR” function in FTA can be used to find the probability of failure of superstructure (*P8*), substructure (*P9*) and eventually the whole bridge (*P10*).



Figure 3: Fault tree diagram for a timber bridge

# **Application of the method to a hypothetical timber bridge**

Once an inspection is performed on a bridge, the condition states (CS) of each element are known.

## *Application of Markov process*

Table . Condition state predictions for bridge elements

|  |  |  |
| --- | --- | --- |
| Element | Inspected condition in 2015 | Predicted condition in 2018 using developed model |
| DeckGirderCorbelPileHeadstockWhales and bearings | [1 0 0 0][0.2 0.8 0 0][0 1 0 0][0.2 0.6 0.2 0][0 0.5 0.5 0][0.1 0.7 0.2 0] |

|  |  |  |  |
| --- | --- | --- | --- |
| [0.7196 | 0.1485 | 0.1301 | 0.0014] |
| [0.1941 | 0.719 | 0.0575 | 0.0294] |
| [0.0000 | 0.9017 | 0.0912 | 0.0071] |
| [0.1956 | 0.5709 | 0.188 | 0.0455] |
| [0.0000 | 0.4518 | 0.024 | 0.5242] |
| [0.0877 | 0.6973 | 0.0056 | 0.2094] |

 |

Second column of Table 2 shows the condition states for each element based on an imaginary inspection in 2015. Table 1 and Equation 2 are used to predict the condition of each element in 2018 (column 3 of Table 2). The meaning of these predictions can be explained using pile as an example. In 2015, 20%, 60% and 20% of the piles were in CS1, CS2 and CS3 respectively. By 2018, 19.56% of the piles will be in *CS1* while 57.09% will be in *CS2*.

## *Application of FTA*

If the probability of CS movement to the worst case scenario for each element can be established, Figure 4 can be used to find the probability of failure of the entire bridge.



Figure 4: FTA for the hypothetical bridge

It is assumed that an element fails when its CS reaches 4. For the hypothetical bridge, there is 65.44% chance that it will fail in 2018 and the major contribution comes from the substructure. This is evident from the inspection data in Table 2.

# **Discussion and limitations**

Proposed Markov process method can be combined with the fault tree analysis to predict the probability of failure of a timber bridge of interest given the inspection report is available for the current year. There are several limitations of the proposed transition probability matrix as it is based only on limited number of inspection reports. It can be applied to a bridge having similar attributes. Therefore the model can be further refined if a large database can be developed so that bridge elements can be categorised based on similar attributes. It is assumed that the bridge failure occurs when all the elements reach CS4. While reaching CS4 will be critical for some elements, it may not be the same for other elements.

**Conclusion**

Timber bridges are the legacy of past developments in Australia. Due to the limited replacement budget, timber bridges are still in service but their high maintenance costs are well recognized and become a challenge to bridge management agencies. This study has presented a condition-based reliability method that utilizes the visual inspection reports of timber bridges to predict the future condition of bridge components. This is achieved by adopting the stochastic Markov model, which is more suitable than the linear and non-linear deterministic models. Furthermore, the failure probability of the whole timber bridge can also be assessed by using the fault tree analysis. The predicted failure probability of timber bridge and its components can be used to reduce inspection and maintenance cost through prioritization and timely manner, ensuring the safety of timber bridge network.

More inspection data together with relevant factors such as daily traffic volume and environmental data are needed for accurate prediction in order to utilise the proposed method efficiently.

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