Fault Tree Analysis Method for Deterioration of Timber Bridges using an Australian case study

Abstract

Purpose

Deterioration of timber bridges can often be related to a number of deficiencies in the bridge elements, connectors and or as a result of been in aggressive environments which they are exposed to. The maintenance cost of timber bridges is affected significantly by a number of deterioration mechanisms which require a systematic approach for diagnosis and treatment. Evaluating the risk of failure of these bridges is of importance in bridge performance assessment and decision making to optimize rehabilitation options.

Design/ methodology/ approach

This paper identifies common causes for timber bridge deterioration and demonstrates an integrated approach based on fault tree analysis (FTA) to obtain qualitative or quantitative estimation of the risk of failure of timber bridge sub-systems. Level 2 inspection report for a timber bridge in Queensland, Australia has been utilized as a case study in this research to identify the failure modes of the bridge.

Originality/ value

A diagnostic tool for timber bridge deterioration will benefit asset inspectors, managers, and engineers to identify the type, size and the distress mechanisms in order to recognize the proper corrective measures either to prevent or to reduce further deterioration. Timber bridge maintenance is a major issue in Queensland, Australia. The proposed framework can benefit road authorities and local councils.

Keywords: timber bridges, deterioration, fault tree analysis, evaluation, preventive maintenance, road structures

Introduction

Australia has about 40,000 timber bridges and most of which are more than 50 years old thus require immediate attention to maintain them as serviceable assets (Ranjith 2010; Ranjith et al. 2013; Wallace 2015). The majority of the frames of these bridges has reached their ultimate structural lives that have become a substantial part of the asset management for many road authorities and councils across Australia. Thus, repair and rehabilitation of deteriorated timber bridges to meet current safety standards has turned into a strong financial commitment with a limited budget. There are many methods such as visual, probing and nondestructive used to assess the condition of bridges around the world (Kurz and Boller 2015; Sangree and Schafer 2008; Wacker et al. 2015) and in some researchers validated visual inspections with the numerical modelling as well (Sangree and Schafer 2008). A systematic, yet efficient planning is required to prepare a comprehensive timber bridge management program to keep these assets in an operative condition. There are many methods such as reliability analysis (Brites et al. 2013) and risk analysis (Sorensen 2011), reported as important tools to evaluate the performance of timber bridges. Furthermore, damage models are used to calculate the existing service life of partially deteriorated timber structures (Van de Kuilen 2007).

Deterioration of timber bridges can often be related to a number of deficiencies in the bridge elements, connectors (Brites et al. 2013) and or as a result of been in aggressive environments. Early diagnosis of possible deterioration scenarios will be useful for formulating an effective asset management strategy. Thus, infrastructure managers need predictive models for bridge deterioration to optimize the repair and maintenance management process over the life cycle of a given timber bridge. Pultruded composites are proposed as possible replacement for timber beams (Radford et al. 2002).

Probabilistic models for vulnerability evaluation are used in the past to predict any damages to bridge infrastructure under hurricane events (Ataei et al. 2010). Current risk analysis methods and tools used in bridge maintenance can be grouped into three categories: field inspections, computer simulations, and real-time monitoring by using on-site sensors. Despite the numerous practical advantages; risk assessment methods still have several limitations. FTA could be used to resolve majority of these issues (Davis-McDaniel et al. 2013). In FTA, if the exact information is not known, an educated guess can be used as input for the probability of basic events. Majority of the visual inspections, computerized simulations, and computerized knowledge-based systems only evaluate the condition of individual bridge components instead of assessing individual components and their interrelationships (Sianipar and Adams 1997).

Fault tree analysis

Fault tree model has been used in the analysis of bridge failure due to scour and channel instability (Johnson 1999). Some researchers (Sianipar and Adams 1997) demonstrated a method that uses FTA to quantify the interaction phenomena in a bridge system. A top level fault tree model has been developed by them to examine the effect of malfunction of bearings and expansion joints on deterioration of a concrete deck. It is possible to develop a fault tree model to represent various interactions involved in possible events that would lead to a bridge failure (LeBeau and Wadia-Fascetti 2000). Since most bridges are redundant structures, failure of an individual component does not imply the system failure (Enright and Frangopol 1998).

A fault tree is a graphical model which uses logic gates and fault events to model the interrelations involved in producing the undesired event. A logic gate may have one or more input events but only one output event. AND gate means the output event occurs if all input events occur simultaneously. The output event of OR gate occurs if any one of the input events occurs. This graphical model can be converted into a mathematical model to compute failure probabilities and system importance measures. The equation for an AND gate is

$$P = \prod_{i=1}^{n} p_i \tag{1}$$

and the equation for an OR gate is

$$P = 1 - \prod_{i=1}^{n} (1 - p_i) \,. \tag{2}$$

n is the number of input events to the gate, p_i is the probability of failure of input event i

and it is assumed that the input events are independent (Faber 2006). The equation for a voting gate (*m* out of *n* events to occur the main event) is,

$$P = 1 - \prod_{i=1}^{n} (1 - p_i * p_{i+1})^{C_n^m} \quad . \tag{2}$$

FTA has been used for reinforced concrete bridges to assess the deterioration and predict the probability of failure of entire bridge or certain bridge sub-systems. FTA to establish the potential failure mechanisms and their interactions in a complex system such as a bridge has been used in the past mainly for concrete bridges (Ericson 2005; FHWA 2011; Liu and Frangopol 2005; Zhu et al. 2008). While FTA had been mainly illustrated using case study bridges (Davis-McDaniel et al. 2013; LeBeau and Wadia-Fascetti 2007; Sianipar and Adams 1997), integrated approach to establish the risk of failure of deteriorated concrete bridges is also reported (Setunge et al. 2015).

Research significance

FTA has been widely used in the past to predict the failure of concrete bridges but this has not been done for timber bridges. Queensland Transport and Main Roads (TMR) already has a risk based prioritisation methodology which can rank the bridge stock in descending order of risk based on a relative risk rating. Having investigated the bridge asset management tools available in Queensland, it can be concluded that deterioration models for steel, concrete and timber are not incorporated in them. This is a major gap in practice. This paper aims to develop the basis for the development of FTA for deteriorated timber bridges.

Common causes for timber deterioration

Deterioration of timber can be classified into two main groups, biological and non-biological attack. Fungi, termite and marine borers are the main biological attacks while shrinkage causing splitting, sniping and effects from corrosion of fasteners can be classified as non-biological attacks..

Timber structural elements can suffer from a number of deteriorations simultaneously. For example sap rot of the outer covering, pipe rot of the center and fungi attack could worsen a splitting initiated due to shrinkage (VicRoads 2006). The stability of the outer sapwood is critical for the stability of connections between stringers because the loss of the outer sapwood reduces the stability of connections. Pipe rot within a stringer is mainly caused by microscopic fungus and bacteria reducing the structural resistance (Austroads 2009). Recently researchers suggested recommendations to control the onset of snipe failures due to higher stress concentrations in the notched regions (Wilkinson et al. 2005).

Fungi Attack

White rot, brown rot or soft rot fungi mainly attack external surfaces of timber bridge members. Another type of fungi such as mold, sap-stain fungi may produce discoloration on the timber but may not cause any significant decay (Austroads 2009). Moisture change in timber could accelerate fungi infection as drying and often shrinking leads to surface cracks, which may expose untreated timber or create water trapping pockets (Austroads 2009; Ejechi 2003).

Termite attack

Australia has a large number of different species of termites but subterranean termites cause most damages to Australian timber bridges (Mainroads 2014). Termite attack usually starts from timber elements that have direct contact with the soil, e.g. embankments, girders or piles. Once a termite colony is established, timber degrades faster than fungi and spreads to the other areas or other bridge elements through split or on the surface of the timber (Austroads 2009; Bootle 1983).

Marine Organisms

Two species of marine organisms, Molluscs (Teredinidae) and Crustaceans, pose a threat to fully submerged timber bridge elements (Austroads 2009; Bootle 1983). Molluscs is a free-swimming organism that immediately starts boring the timber if they accommodate onto it. It can significantly destroy a pile through an internal tunnel that may not be noticeable from outside.

Corrosion of Fasteners

Corrosion of steel fasteners can cause serious strength reductions for two related reasons. Firstly, the steel fastener reduces in size and weakens, and secondly a chemical reaction involving iron salts from the rusting process can significantly reduce the strength of the surrounding wood (Bootle 1983; Ranjith 2010).

Splitting

Splitting can initiate due to various reasons such as shrinkage and fasteners. Once it has started, it can further extend due to overloading. Bridges are normally constructed from green timber that gradually dries below its fibre saturation point until it is in equilibrium with the surrounding atmosphere. More serious splitting occurs at the ends as the timber dries more rapidly through the ends of the member than through the sides.

Overloading

Abrupt sectional changes (associated with notches) can cause unnecessary stress concentration that leads to defects in structural members. Abrupt changes in girders near connection may also lead to splitting if imposed shear force or combination of shear and bending at the cross section exceeds the acceptable level (VicRoads 2006). Notches can develop splitting and snipping that lead to a failure of the structural element. Queensland timber bridge maintenance manual (MainRoads-Queensland 2004) recommends 1: 5 gradient at the notch. Girders and corbels in old timber bridges can suffer from structural splitting or snipping due to overloading from higher axel loads than the design loads (Wilkinson et al. 2005). These snipping can be vertical, horizontal, or slanted.

Weathering

Weathering of timber is a combined effect due to wetting, drying and exposure to UV radiation during its service life. The decay due to weathering occurs slowly at a rate of about 6 – 13 mm depth of the surface per 100 years (Austroads 2009).

Following section presents a case study that identifies various deterioration mechanisms for a timber bridge.

Case study

Strategies for the selection of a case study has been researched in the past (Flyvbjerg 2006). It is important to select a critical case study which gives the information needed to complete at least one sub tree of the fault tree diagram for timber bridges. From the several timber bridge inspection records, the selected case study is the Middleton's Bridge crossing Lockyer Creek on the Lockrose Road North in Lockyer Valley Regional Council area in Queensland, Australia (Figure 1). It is a two span, single lane timber Girder Bridge with an overall length of 19.35 m, a width of 5.48 m and a load limit of 35 tons. The superstructure was made up of hardwood timber curb and hardwood timber deck planks installed transversely, supported by five timber girders, corbels at the piers and two timber headstocks at the abutments and pier. The substructure is made up of four timber piles and eight timber wales/bracings. The bridge is about 20 degrees skew to the road alignment. Both approaches are bitumen sealed.

Figure 1: Middleton's Bridge

The analysis is based on a Level 2 inspection report conducted as per Queensland Main Roads Bridge Inspection Manual (MainRoads-Queensland 2004). The main reason for the selection of this case study is that, in Level 2 inspection report, it was identified that there are defects in some timber components, the most serious being the splitting in timber superstructure girders. The inspection report recommended that the defective timber elements be replaced. It also recommended that if the bridge is to remain open for public until the members are replaced, there should be load restrictions enforced to the use of the bridge. Hence LVRC commissioned another company to carry out a Level 3 inspection to recommend suitable load restrictions for the bridge.

The condition of each element of the bridge is rated using four condition states where condition state 1 is the best and condition state 4 is the worst (MainRoads-Queensland 2004). Figure 2 shows some selected photos to demonstrate the failure modes of structural members of this bridge.

Figure 2: Deteriorated bridge elements

Table 1 and Table 2 give inspection details of the case study bridge. The information given in the table is limited to the structural members in condition states 3 and 4.

Table 1: Failure modes of each element in the bridge (Superstructure)

Table 2: Failure modes of each element in the bridge (Substructure)

Development of a fault tree for timber bridges

Main difference between a FTA for a concrete bridge and timber bridge would be the basic events that lead to the final failure of a bridge. Therefore a similar approach used in the FTA for concrete bridges can be extended if the causes of failure can be established using case studies. However, there are a couple of challenges in using this analysis method for timber bridges. The first challenge is the development of the fault tree diagram for the timber bridge failure due to deterioration. This is the research area that the authors are trying to investigate in this paper. The second challenge is how to establish the probability of occurrence of contributing factors so that the fault tree can be used to find the probability of occurrence of the top event (LeBeau and Wadia-Fascetti 2000).

Based on the observations from the case study bridge (Table 1, 2 and Figure 2*)* and the available literature (Austroads 2009; Bootle 1983; Mainroads 2014), the top level of a fault tree diagram for a timber bridge was developed as shown in Figure 3. The main event, timber bridge failure can be triggered because of either the superstructure or substructure deterioration. Each of the basic events is connected to the main event using OR gate because the output event occurs if any one of the input events occurs.

Figure 3: Top level fault tree frame

There are many causes for timber deterioration as shown in Figure 4. One or many factors/events can contribute to the deterioration of timber as explained before. It is important to understand the probability of occurrence of each event to predict main event, 'timber deterioration' reliably. Therefore a voting gate which is capable of representing the combination of inputs to trigger the output has been used in this part of the FTA. For example out of the 6 intermediate events in Figure 4, if 2 events occur then the leading event will also occur.

Figure 4: Major sub system fault tree of timber deterioration

Out of all different types of deterioration for the case study timber bridge, splitting and snipping of girders is the most common mode (Figure 2 and Table 1). It can be due to various events such as shrinkage of green timber element, changed cross section and snipping initiated due to notches and fasteners and spread due to overloading. Figure 5 illustrates the fault tree for the splitting of timber bridge stringers.

Figure 5: Fault tree for Splitting Failure

Few more case studies are to be used to develop the other parts of the fault tree diagrams in the future.

Probability of occurrence of contributing events

Once the fault tree diagram is developed, evaluating the failure probability of an individual event is the next challenge. This could be achieved using one or a combination of the following options:

- A rough estimate can be made considering the case studies of failure. For example: for a given structural configuration and a given exposure classification, if 50 out of 100 bridge piers have failed due to fungal attack then probability of failure of piers due to fungal attack can be crudely estimated as 50%. However, this may include other causes as well and hence may not be the most accurate method.
- A detailed analysis of design loads and the loads applied to the structure can be used to calculate a time-dependent reliability analysis considering deterioration, which can be used to evaluate the failure probability of a bridge component.
- Expert judgment can be used to identify the failure probability as high, medium or

low, which can be converted to a numerical representation.
This part of the analysis is beyond the scope of this research paper.

Application of the developed framework
Splitting branch of the FTA for timber bridge deterioration is demonstrated using assumed probabilities for basic events (Figure 6). For example, it was assumed that the probability of having a changed cross section for a member is 0.002 and that for using a green timber is 0.001. Either the use of green timber or changed cross section will lead to shrinkage. Hence an OR gate (Equation 2) is used to link these 2 basic event to the shrinkage. The same approach was used to find the snipping probability (Equation 1) and ultimate probability of splitting (Equation 2) to be 0.00299 (Figure 6). This is the probability that can be used for splitting in Figure 4.
Similar approach can be used to establish the probability of failure due to other causes such as fungal attack, termite attack etc in Figure 4. If the probability of these causes is assumed to be equal to that of splitting (0.00299) then if timber deterioration occurs when 2 out of 6 causes occur, then the probability of timber deterioration can be calculated as, $P = 1 - (1-0.00299^2)^6 = 0.0000536$. This is the probability for timber deterioration in Figure 4. The bottom events of Figure 3 are all related to timber deterioration though these values may differ from one another. If it is assumed to be the same as 0.0000536, then the probability of substructure and superstructure damage will be 0.00016079 and 0.00010728 respectively. Hence the probability of failure of the bridge will be 0.000268.

Figure 6: Application of the method for splitting branch of FTA

Discussion
Findings
This research mainly focuses on the deterioration of timber bridge elements due to splitting as it was the main cause of failure for the major structural elements in the superstructure as well as sub structure of the case study timber bridge. Most of the girders in the case study bridge (6 out of 10 total in both spans) were given a replacement decision due to severe splitting at ends. Installing anti-splitting bolts were recommended for all the four piles in order to cater for severe/moderate vertical splitting. Both the headstocks were recommended to be replaced due to the fact that they had severe to moderate horizontal splitting which extended to the pile interface connection. However, the framework is demonstrated using assumed probabilities for basic events.

Limitations
This study focuses only on one case study and developed a sub tree for the splitting of timber elements because the selected case study gives good examples to this effect. Although there are many beliefs about case study research about its inability to give generalized conclusions, it certainly broadens the knowledge in that particular research area (Flyvbjerg 2006). However this sub tree needs to be strengthened by using at least few other timber bridges that fail due to splitting. There may be environmental effects that enhances the splitting of timber bridges. The limits or boundaries of the case study are a definitive factor of case study methodology (Yin 2009). The developed sub tree for splitting may be applicable for a similar climate in Queensland. More case studies from different states of Australia will justify its broader utilization.

Way forward

The method described in this paper for the splitting sub tree of the fault tree can be further extended to each cause of timber deterioration based on similar case studies and then fault tree can be completed. The developed framework is demonstrated using assumed probabilities. A detailed analysis should be undertaken to obtain the failure probabilities of each structural component. The proposed overall method eventually will allow bridge engineers to relate the probability of failure of a bridge component under a given distress mechanism to the failure of the system. The method is capable of obtaining the relative severity of likelihood and the risk of occurrence of distress mechanisms of bridge components, rank the overall risking of failure of serviceability among different components in a bridge or a group of bridges. For example, if the engineer can establish the likelihood of occurrence of snipping failure of a girder due to overloading, a fault tree diagram can be drawn for the sub-system with the voting gate model to develop a fault tree for the failure of the bridge as a “system”.

Conclusions

This research paper proposes a framework for the assessment of the probability of failure of a timber bridge due to various deterioration mechanisms. It identifies the development of a fault tree for timber bridge deterioration using a case study from Lockyer Valley Regional Council. The analysis of the case study also led to following observations:

- Major failure criteria for timber bridge of interest is the damage to bridge girders, piles, headstock and corbels. Splitting and snipping in the girders and piers was the common reason while severe rot and pipe are the other contributing factors.
- A top-down direction fault tree diagram was developed to establish the failure path for a particular bridge that will be subjected to normal deterioration. The fault tree diagram developed in this paper could be expanded to other branches as well using different case studies.
- The developed fault tree diagram can be used to predict the failure of a timber bridge if the probability of occurrence of the main events can be established. There are three methods identified in this research paper in doing that. However, this needs further investigation.

The proposed framework is demonstrated using assumed probabilities and it can be used effectively in predicting the failure of timber bridges eventually and support in the decision-making process of prioritizing the rehabilitation of timber bridges. FTA is to be strengthened using more case studies and calculations of probabilities of basic events. The method proposed in this study contributes to knowledge in the area of timber bridge asset management.

Acknowledgement

The authors appreciate the support of Mr Tony Mcdonald from Lockyer Valley Regional Council for providing the inspection report for the case study bridge.

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Figure 1: Middleton’s Bridge

(a) Splitting (girder with a fastener)

(b). Vertical splitting (pile)

(c). Severe rot and pipe (wingwall pile)

(d). Incorrect splice (abutment)

(e). Vertical splitting (overloading-top of pile)

(f). Vertical splitting (changed section-top of pile)

Figure2: Deteriorated bridge elements

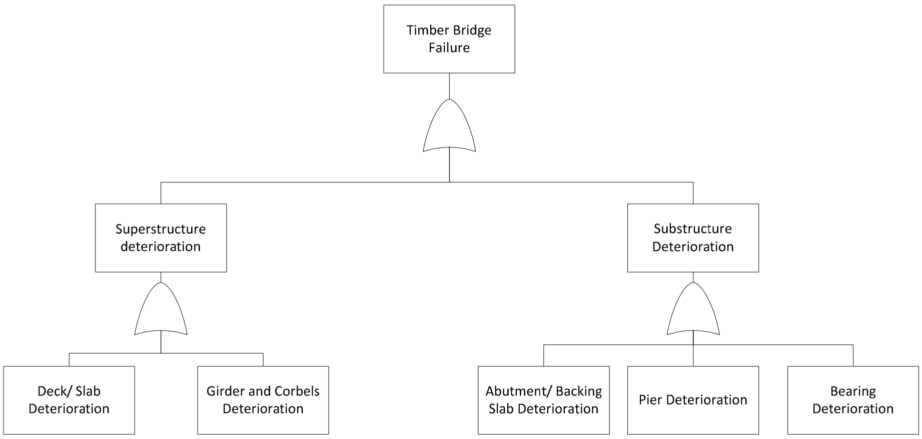

Figure 3: Top level fault tree frame

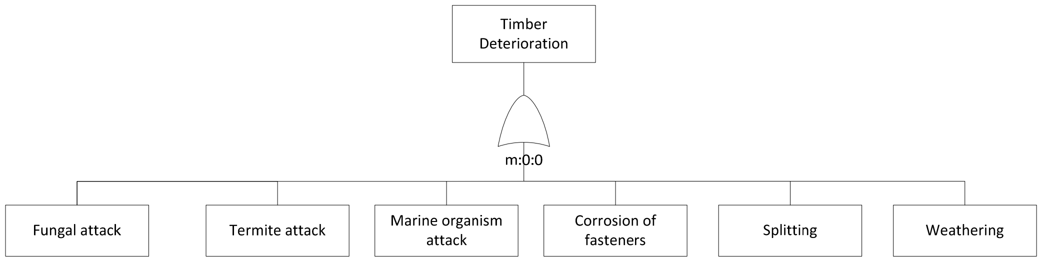

Figure 4: Major sub system fault tree of timber deterioration

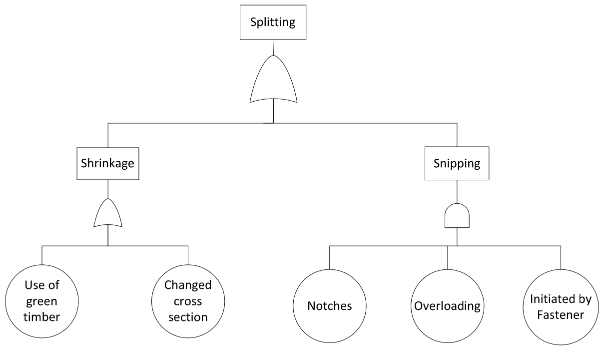

Figure 5: Fault tree for Splitting Failure

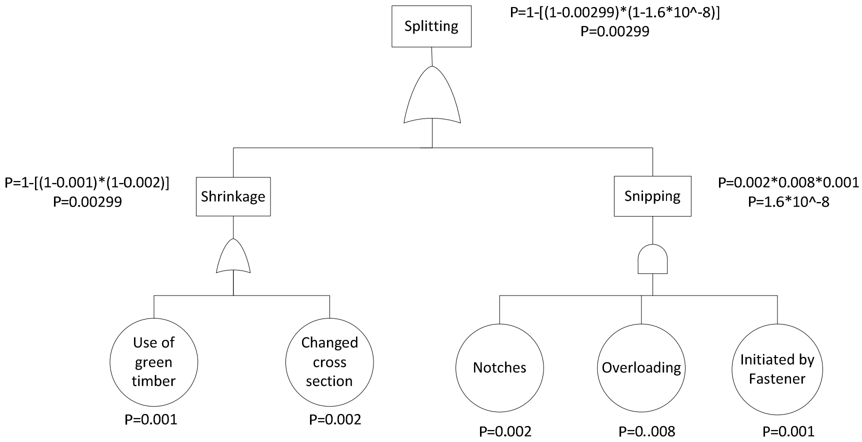

Figure 6: Application of the method for splitting branch of FTA