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Vulnerability assessment of bridges subjected to extreme cyclonic events

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Vulnerability assessment of bridges subjected to extreme cyclone events

Abstract:

Over the past few years Queensland in Australia has suffered from a number of severe tropical cyclones, the most recent one being Marcia, that took place in 2015. Damage bill of Cyclone Marcia exceeded $50 million which included cost of repairing a number of damaged road structures. Failure of road structures such as bridges isolates communities from accessing essential services and commodities. This necessitated a methodical approach to evaluate the failure of bridges to improve their resilience and provide base knowledge for developing emergency maintenance response. Although there are several methods available to evaluate the vulnerability of bridges , fault tree analysis (FTA) was selected in this study by considering its positive attributes over the other methods. FTA was used to estimate the probabilities of failure of main components (superstructure and substructure) and elements of timber and concrete bridges. Secondary data (level 1 and level 2 bridge inspection reports from Transport Main Roads in Rockhampton) before and after the Cyclone Marcia were used in conjunction with expert advice to construct fault trees for both timber and concrete bridges. Potential failure mechanisms were observed and the degree of susceptibility of main components of timber and concrete bridges to cyclonic events were evaluated. This research was based on selected bridges under specific cyclone in one region, which is a limitation of the study. Few other case study bridges subjected to cyclonic events can be used to strengthen the understanding of the complete dynamics of the bridge failure under these extreme events.

Keywords: cyclone, bridge failure, fault tree analysis, vulnerability, preventive maintenance

1. Introduction

Over the past century, severe tropical cyclones caused devastating damage on properties, livestock, forests, buildings and infrastructure and most importantly disrupted the livelihoods of the communities that have been exposed to the event. In some occasions the damage to the community was in terms of deaths and injuries and illnesses by restraining access to clean water and food. Queensland in Australia has a road network of more than 30000 km and 6500 road structures (Kuhlicke 2010; Setunge et al. 2014) which experienced the impacts of numerous disaster events over the past few decades. In 2011, Cyclone Yasi (category 5) caused significant damages to buildings and road infrastructure in North Queensland which accounted for 5% of the total damage cost. Cyclones also cause significant impacts on road infrastructure, isolating the affected areas from ground assistance. During the evacuation support activities for disaster response and recovery, road structures play an important role in establishing the communication with the affected community.

Devastating impacts of past cyclones have imposed tighter regulations on building codes and technological advancements and warning systems associated with cyclones, including the use of satellite imagery and meteorological modelling have shown marked improvements in recent years. Bridges in Australia are designed based on different guidelines/ standards depending on the time the design was undertaken (Setunge et al. 2014). Bridges constructed in Australia after 2004 generally complies with AS5100 (2004), which is mainly written for rural constructions (Pritchard 2013). Pitchard (2013) suggested that AS5100 (Standards Australia 2004) should be amended to include potential loads that may be applied in natural disasters such as floating objects and bridge design should consider the context and connectivity and post disaster functionality. Ataei et al. (2010) suggested that probabilistic models of structural vulnerability are required to predict any damages to bridge infrastructure under cyclonic event.

2 Impact of cyclones on bridges

The annual economic loss in the USA due to natural hazards is estimated to be at an average of $1 billion a week (Chen 2004). Inspection reports and damage estimations of Hurricane Katrina show an economic loss of $125 billion (Yadav and Barve, 2019) with an overall damage bill on repairing and replacing bridges alone goes over $1 billion (Padgett et al. 2008). In a cyclonic event, bridges are mostly damaged by the storm surge that arises from the severe weather condition (Chorzepa et al. 2016). In most occasions bridges have failed due to unseating or drifting of the superstructure which depends on the connection type between decks and bents (Chen et al. 2009; Meng and Jin 2007; Padgett et al. 2008). Padgett et al. (2008) studied bridge damage mechanisms using observations of 44 bridges during Hurricane Katrina. Their study revealed that predominant causes for bridge damage are uplift forces and impact from debris and objects near the bridge, induced by the storm surges, and partially by high winds, scour, and malfunction of electrical and mechanical equipment due to water inundation. In a hurricane or cyclone, bridges are mainly damaged by debris/impact, scouring and surge induced loadings (Padgett et al. 2008).

2.1 Damage due to debris/ impact

Impact damage is quite common for bridges associated with large water ways. It is generally caused by floating objects such as debris, boats Pitchard (2013) or any other items that are transported due to flooding resulted from the intensive rainfall caused by cyclones (Figure 1). Post disaster inspections revealed that in most occasions, impact damage contributed to the superstructure as well as substructure failure of a bridge (Padgett et al. 2008).

Figure1: Damage due to impact (Padgett et al. 2008)

2.2 Damage caused by catastrophic winds

Suspension bridges are mostly vulnerable for wind damage because they should be able to withstand the huge drag forces caused by wind. Additionally those bridges are prone to many other effects such as aeroelastic effects, oscillation and galloping (Chen 2004). In Australia there are very few suspension bridges. During Cyclone Marcia in 2015, a timber bridge at Mt Morgan was found to be damaged by strong winds.

2.3 Damage due to surge induced loadings

Bridges with spans of the same or lower elevation than peak surge levels experience severe structural failure during cyclonic events (Irish and Cañizares 2009). In storm surges, the superstructures are moved away from the supporting substructure due to the damage in the anchorages from surface waves (Chen et al. 2009; Douglass et al. 2006; Lehrman et al. 2012). Robertson et al. (2007) described the phenomena behind the damage to anchorages as the contribution of the reduced self-weight of the deck for the uplift force.

2.4 Damage due to scouring

Observations reveal that damage due to scour may come together with other cyclone induced damage modes or it may not be the case all the time (Padgett et al. 2008). Damage to a bridge due to scouring is normally associated with the erosion of abutment and the approaches or relieving slab (Figure 2).

Figure 2: Damage caused by scouring (Padgett et al. 2008)

Erosion around the foundations or abutments leads to their failure when the depth of foundation is so small that they lose the stability and pier or abutment may start moving in the vertical direction. It is reported in the literature that the major contribution for bearing failure comes from the severe lateral forces (Davis-McDaniel et al. 2013; LeBeau and Wadia-Fascetti 2007).

In Australia a few studies have been conducted to assess the resilience of buildings and road infrastructure under natural disaster events (Lebbe et al. 2014; Lokuge and Setunge 2013). Information on the probabilistic response of road bridges during cyclones appears to be sparse in scientific literature. This study endeavors to understand the response of timber and concrete bridges to cyclone Marcia and comprehend their potential response to any tropical cyclones with high magnitude that might occur in the future.

3 Case study- Damaged timber and concrete bridges during cyclone Marcia

Cyclone Marcia was expected to reach category 5, however when it reached the landslide, it has reduced to category 2/3 (James Cook University Cyclone Testing Station 2015). Despite lowering its intensity, the damage bill of Cyclone Marcia approached to $53.4 million after a weeks' time, at least 1000 houses suffered structural damage from the disaster, and 385 properties have been deemed uninhabitable. It destroyed numerous properties in Yeppoon and road infrastructure including bridges in Monto, Gladstone Biloela Road and in Mount Morgan (Figure 3).

Figure 3: Damaged bridges during Cyclone Marcia

Bridges Inspection System (BIS) is used by the Queensland Transport and Main Road (TMR) to keep all the records of the bridges. In this case study, pre-disaster and post-disaster inspection data for the damaged bridges were obtained from TMR in Rockhampton, Queensland. Level 1 (Routine Maintenance Inspections) and level 2 (Bridge Condition Inspections) inspection reports were used to gather the information required for the analysis. Purpose of Level 1 inspection report is to understand whether the bridge is safe to be used immediately after the extreme event and identify any emergency maintenance needs (Bridge Inspection Manual 2004). Level 1 inspection was carried out immediately after the Cyclone Marcia for all the damaged bridges. Purpose of the level 2 inspection report is to evaluate the condition of the road structure to assess its suitability for public use. This will identify any future maintenance needs, evaluate the suitability of the past rehabilitation methods, predict the chances for condition change and estimate financial requirements. Level 2 inspections are conducted by a trained personnel who has extensive experience in the inspection, construction, design, maintenance and repair of road structures and be guided by a qualified professional engineer in decision making related to interpreting visual defects. A brief description of the Condition States (CS) adopted by TMR are as follows:

- CS1: Good (free of defects with little or no evident deterioration)
- CS2: Fair (free of defects contributing to the structural performance, integrity and durability)
- CS3: Poor (defects affecting the strength, durability and serviceability requiring monitoring or further assessment by a structural engineer)
- CS4: Very poor (Structural integrity may be compromised and immediate intervention including an inspection by a structural engineer)
- CS5: Unsafe (Structural integrity is severely compromised and the structure must be taken out of service)

Level 1 Inspection reports were available for 41 pre stressed concrete bridges and 18 timber bridges. Level 2 inspection reports were available for 6 concrete bridges and 8 timber bridges. Data were analysed separately for level 1 and level 2 inspection reports before and after the cyclone Marcia. Microsoft Excel was used to analyse the nature of damage for each element of the bridges individually.

4 Fault tree analysis (FTA)

Fault tree analysis (FTA) is a technique adopted to determine the root cause and the probability of failure of a structure due to an undesired event (Ericson 2005). It can be used for risk assessment based on the likelihood and consequence ratings of various events of fault tree. FTA is also a systematic analysis and often used in evaluating large complex dynamic systems to identify and prevent potential problems. The bridge can be considered in its entirety, including element interactions, redundancy, deterioration mechanisms such as corrosion and fatigue, and environmental factors (LeBeau and Wadia-Fascetti 2007). FTA has been used before in predicting the probability of failure of aged timber bridges (Lokuge et al. 2016, Lokuge et al. 2019). These studies are based on the damage due to general deterioration and not due to any natural hazards.

The use of qualitative as well as quantitative analysis is common in fault tree method (Davis-McDaniel et al. 2013). Qualitative analysis illustrates the possible contribution from each structural element to the failure of the bridge of interest. Construction of fault tree diagram requires a sound understanding of the specific bridge stock. In the quantitative analysis of FTA, comprehensive set of data is needed to establish the probabilities of occurrence of the basic events that may follow the failure path for bridge failure eventually (Davis-McDaniel et al. 2013). In the FTA, bridge failure is related to Condition State 5 of the TMR inspection. FTA uses an illustration to integrate the possible causes for the failure of the bridge (reaching CS5). It is discussed in the past that inspection reports for the damaged bridges are a good source for the FTA (Davis-McDaniel et al. 2013) quantitative analysis. The use of FTA in establishing the chance of a bridge failure (closure or reaching CS5) during an extreme natural hazard is very well documented (FHWA 2011). It is also used as a prognostic tool in the design stage of a bridge which troubleshoots all possible events that could cause a bridge to collapse (LeBeau and Wadia-Fascetti 2007).

In FTA, either one or several input events may be combined together to form the output event through a logic gate (Setunge et al. 2015). These input events are connected to the output event using logic gates such as AND or OR (Davis-McDaniel et al. 2013). In order to use an AND gate, all the input events must contribute at the same time for output event to occur while OR gate can be used if any one of the input events contribute for the output event (Setunge et al. 2015). In this analysis, a general fault tree diagram was developed for pre stressed concrete bridges and timber bridges.

4.1 Development of Fault Tree Diagram for concrete/timber bridge failure due to cyclone

Bridges can deteriorate before the end of service life, if the design does not give the structure resilience to the environment to which it is exposed. However, deterioration of a structure does not necessarily imply structural collapse but could lead to loss of structural serviceability, such as poor durability and poor appearance with cracking, spalling, splitting, etc. Risk assessment is important in decision making in relation to identifying different rehabilitation options to manage aging bridges.

Considering the basic events described in the previous section, using the analysis of bridge inspection data, and referring to the models used by previous researchers (Davis-McDaniel et al. 2013; Johnson 1999; Zhu 2008), a fault tree diagram was developed for concrete and timber bridge failure during cyclone Marcia (Figure 4).

Figure 4: Fault tree diagram for bridge failure during a cyclone

Bridge failure (closure or reaching Condition State 5) can occur due to either superstructure failure or substructure failure. Girder or deck/slab failure are the main reasons for the superstructure to have less functionality. Debris/impact loading or the surge-induced loadings are the reasons for deck/slab or girder damage during a cyclonic event. On the other hand, possible reasons for substructure damage/ failure are debris/ impact loading, surge-induced loading as well as scour. These events are connected using OR gates to the main event (bridge failure) because any of these event will contribute to the main event as shown in Figure 4. In order to use this FTD for the purpose of finding the probability of failure of bridges, it is important to find the probabilities of occurrence for each event. The main purpose of this study is to find the basic event probabilities for superstructure and substructure failure of a bridge.

4.2 Probability calculation based on the case study

In order to estimate and assign probabilities for basic events, level 1 and level 2 bridge inspection reports from TMR were used. Focus of this study is to understand the damage caused by a cyclonic event to timber and concrete bridges by using the inspection reports before and after the event. The severity of the damage will depend on the location of the bridge and all the bridges considered in this research are from the same region. Modelling the behaviour of bridges under flood/ cyclonic loads is out of the scope of this study hence the effect of flood height or the wind speed were not considered in the process.

4.2.1 Assigning probabilities for condition states

Qualitative ratings were extracted from the TMR Bridge Inspection manual and assigned probabilities were selected in consultation with the experts and resource personal with substantial knowledge and experience in the field of road bridges. This was organised through a focus group session which included the director of the infrastructure management and delivery section, two structural engineers, two senior civil engineers (all from two branches of TMR) and three researchers from two universities who work in the bridge resilience areas. The experts consulted have agreed with the following approach in assigning probabilities;

- Change of condition state 1 to condition 2 is negligible.
- Change of condition 2 to 3 is a concern but it doesn’t need immediate action.
- Change of condition 3 to 4 needs immediate action.
- Condition 5 was allocated as the worst case scenario and normally before any element reaches condition 5; TMR immediately repairs that particular component/element or repair the whole bridge.

Based on these general agreement, assigned probabilities are shown in Table 1.

Table 1: Probabilities for condition states

In order to show the calculation for the probabilities a girder in a timber bridge was selected.

4.2.2 Girder failure of a Timber Bridge

There are seven girders in Span 1 of this bridge. Condition states of these girders before and after cyclone Marcia are shown in Table 2.

Table 2: Condition states for the girders (Span 1) in a Timber Bridge

Five girders that were in CS2 (probability of 12%) before cyclone, changed to CS4 (probability of 50%) after the cyclone. Change in probability between these 2 condition levels is 38%. Therefore the probability of failure of these 5 girders in span 1 is 1.9 (0.38*5). Similarly the probability of failure of the other 2 girders in span 1 is 0.5. Therefore the probability of a girder failure using span 1 can be calculated as 0.343. Similar calculation process was continued for the girder failure in other 3 spans of the bridge and the findings are summarised in Table 3.

Table 3: Probability of girder failure using a Timber Bridge

4.2.3 Probability of a girder failure using all timber bridges

Using the same method, the probability of a girder failure for eight bridges were calculated. The results are shown in Table 4.

Table 4: Probability of girder failure using all the damaged timber bridges

In the above table, the probability of failure for four bridges is stated as 0. This is because the condition state of girders did not change after the cyclone Marcia for all the spans in those bridges. Using the findings from Table 4, the probability of a girder failure in a timber bridge during cyclone Marcia can be calculated as 0.0729. Using the same method, the probability of failure of the deck, piles, abutments, and headstock were calculated.

4.2.4 Probabilities for basic events

From the previous section, the probability of the girder failure was calculated as 0.0729. In the fault tree diagram (Figure 4) the girder failure can happen due to two basic events, debris/ loading or surge induced loading. Top to bottom method was used to find the probabilities for basic events.

41 concrete bridges and 18 timber bridges were analysed using level 1 inspection reports before and after cyclone Marcia. Timber bridges were predominantly damaged due to scour (9), debris/ impact (3) and surge induced loading (6). Twenty five of the 41 concrete bridges were damaged due to scour, while 3 and 8 were damaged due to debris/ impact and surge induced loading respectively. It is understood from the inspection reports that the superstructure (girders and deck) was damaged due to debris/impact and surge induced loadings while additional basic event, scour also contributed for the substructure (pile, abutment and headstock) damage. Based on the inspection reports and expert advice from the industry, Table 5 gives the probabilities for the basic events.

Table 5: Assigned probabilities for basic events

In the fault tree diagram developed (Figure 4) OR gate was used to connect the basic events to the girder failure. Equation for OR gate is:

$$P = 1 - \prod_{i=1}^{n} \left(1 - P_i\right) \qquad \text{Equation 1}$$

If the probability of damage due to debris and surge are pdebris and psurge, then the following relationship can be written for the OR gate connection.

$$\text{Probability of a girder failure} = 1-[(1-p_{debris})*(1-p_{surge})] \qquad \text{Equation 1}$$

From Table 5, for the members in the superstructure,

$$p_{surge} = 3 * p_{debris} \qquad \text{Equation 2}$$

By using the sample calculation for a girder failure (0.0729) and above equations, probability of failure of a girder due to debris and surge can be calculated as 0.0185 and 0.0554 respectively. Similar approach was used to find the probabilities of basic events for superstructure (deck) as well as for substructure (pile, abutment and headstock).

5 Observations and results

5.1 General observations

Post cyclone inspection data (level 1 inspection) for all the 59 bridges were used for analysis.

Figure 5: Observed damaged behavior for bridges during cyclone

Preliminary observations showed that there are no significant difference between potential cyclone induced damage on superstructure and substructure on both timber and concrete bridges. Potential cyclone related impact on substructure was most prevalent in timber bridges (Figure 5).

5.2 Results from fault tree analysis

5.2.1 Failure of timber bridges due to cyclone

Fault tree analysis for timber bridges indicated that substructure is more susceptible for cyclone induced damage than superstructure (Table 6). Failure of substructure was found to have mostly influenced by damages to piles and headstock.

Table 6: Probabilities for main element failure of timber bridges

Using the top down method described in the previous section, the probabilities for the basic events for the superstructure were calculated (Table 7).

Table 7: Probability of basic events of the superstructure for timber bridges

A number of authors have also discussed similar observations where superstructure failure was found to be influenced by damage or displacement of the deck due to storm surge (Chen et al. 2009; Douglass et al. 2006). Douglass et al. (2006) suggested that surface waves generated by storm surge, can overcome the anchorage and subsequent waves may dislocate them causing bridge to collapse. Fault tree analysis for timber bridges indicated that the substructure failure is mostly influenced by surge forces followed by weakness caused by scouring (Table 8).

Table 8: Probability of basic events of the substructure for timber bridges

Surge induced loading seems to have caused the majority of the substructure element failures. The intensity of the damage may have been compounded due to the age of these timber bridges in this case study as anchorage and joints may have weakened over the years. Some of the bridges that have been included in this study are as old as 35 years.

5.2.2 Failure of concrete bridges due to a cyclone

According to the FTA (Table 9), probability of substructure failure in concrete bridges at the presence of cyclonic forces is greater than that of superstructure failure. Similar to timber bridges, failure of superstructure in concrete bridges has found to be mainly caused by girder damage.

Table 9: Probability for main element failure of concrete bridges

Similar to timber bridges, surge induced loadings have caused superstructure element failure (Table 10).

Table 10: Probability of basic events of the superstructure for concrete bridges

Results (Table 11) suggested that surge induced loading closely followed by structural weakness caused by souring are responsible for substructure element failure. In contrast to timber bridges, abutment failure has shown significant impact on substructure failure for concrete bridges (Table 11).

Table 11: Probability of basic events of the substructure for concrete bridges

6 Discussion

6.1 Findings

Probabilities of failure for both timber bridges and concrete bridges as a direct or indirect impact from cyclone were calculated using FTA as discussed in this paper. The resultant probabilities obtained from this fault tree analysis are consistent with the reported work for hurricanes in USA.

The probability of a timber bridge failure due to a cyclone =32%

The probability of a concrete bridge failure due to a cyclone =18%

Probability of timber bridge failure due to cyclonic events is higher than that for concrete bridges. The main reasons for this may be due to the age of the timber bridges. Components of timber bridges are vulnerable to decay if exposed to moisture. Different timber standards were used by the time these bridges were built.

Figure 6: Damaged behavior based on FTA analysis for bridges during cyclone

Results indicated that substructure of timber bridges is more sensitive to surge induced forces compared to those of concrete bridges (Figure 6). The main contribution for this failure comes from the surge induced loadings to the piles and abutment. The exposure conditions must be playing an important role for this major contribution. Most concrete bridges do not have a relieving slabs for abutment, and show poor compaction at the approaches. Load distribution in timber bridges are different to that of concrete bridges and hence it impacts on the piles of concrete bridges (Eberhard el al. 1993). Results (Figure 7) indicated that the majority of the elements of timber bridges have low resilience to cyclonic events compared to that of concrete bridges. However there was a marked variation in the probability of abutment failure in concrete bridges, which impacted overall response of the substructure.

Figure 7: Element failure of bridges during a cyclone

6.2 Limitations

This study focusses only on one case study for a cyclone by using 59 damaged bridges due to Cyclone Marcia in Queensland. The probabilities of basic events were calculated based on the available data for this case study region. 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 fault tree diagram needs to be strengthened by using at least few other case studies. There can be other failure mechanisms for the elements in the bridges and the probability of failure of each element could be varying in a different cyclone event. The limits or boundaries of the case study are a definitive factor of case study methodology (Yin, 2009). The developed fault tree diagram and the probabilities that were found may be applicable for bridge failure due to a cyclonic effect in Queensland, Australia. More case studies from different parts of Australia such as Northern Territory and Western Australia will justify its broader utilization.

6.3 Way forward

In the case study used in this research, the effect of the cyclone on approaches, surface of the road was not prominent and in the FTA, aging effect was not considered too. The study was limited to the overloading due to the forces induced by cyclone effect. However this may not be the scenario for a general situation. Figure 8 expands the fault tree diagram to include these effects into a main element in the superstructure (girder) and the substructure (pier). Depending on the availability of detailed inspection reports, overloading on the pier can be further categorized into vertical or horizontal movement or a rotation.

Figure 8: Detailed fault tree diagram for bridges

The FTA reported in this paper can be further extended by using the detailed diagram in Figure 8. Although it gives very general fault tree diagram for bridges it can be customized for timber and concrete bridges by using proper basic events.

6.3.1 Timber bridges

Basic event 1 shown in Figure 8 for the time effects of beam or girder could be due to the corrosion of fasteners in each bridge element while basic event 2 for the aging effect of the beam or the pier could be due to the environmental effect such as weathering and splitting. There could be additional basic event for timber bridges which will take into effect the fungal, termite and marine organism attacks.

6.3.2 Concrete bridges

Basic event 1 shown in Figure 8 for the time effects of beam or girder could be due to the corrosion of the girder while that for the pier could include the corrosion of pier, pile or capping beam. Basic event 2 for the aging effect of the beam or the pier could be due to the fatigue that they experience.

7 Conclusions

This research investigates a method to evaluate the vulnerability of timber and concrete bridges subjected to an extreme cyclone event. It identifies the development of a fault tree for bridge closure. A set of case study bridges that damaged due to Cyclone Marcia in 2015 has been used to develop a basic fault tree method. Although this fault tree was developed based on a specific case study, it can still be used/ refined for another case study. Detailed investigation on the structural member failure of these bridges resulted in obtaining the probabilities of occurrence of basic events which causes the complete bridge failure. The analysis of the bridges in the case study leads to the following conclusions:

- Timber bridges are more vulnerable in cyclonic events than the concrete bridges. As expected, the substructure of a bridge is susceptible to damage more than the superstructure irrespective of whether it is timber or concrete.
- Timber bridge failure is mainly governed by the pile and headstock failure in substructure and girder and some contribution for superstructure failure was made by the girder and deck failure. However the governing failure mode for concrete bridges was the abutment and girder failure.
- Surge induced loadings and scouring were the main failure mechanisms for pile and headstock failure in timber bridges and for the abutment failure in concrete bridges.
- A fault tree diagram was developed in this study to demonstrate the possible contribution of each structural member in the bridge to its complete failure if it is subjected to cyclonic loadings. The fault tree diagram developed in this paper could be expanded to other branches as well using different case studies.
- Probabilities obtained through this study are specific for the considered case study which is a limitation of the research. The probabilities obtained for occurrence of basic events and other events can be used as a basis in doing fault tree analysis for bridges subjected to cyclonic events.

The proposed framework can be used as a guide and using few other case studies, it can be refined further for its broader use.

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process

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Figure1: Damage due to impact (Padgett et al. 2008)

Figure 2: Damage caused by scouring (Padgett et al. 2008)

Figure 3: Damaged bridges during Cyclone Marcia

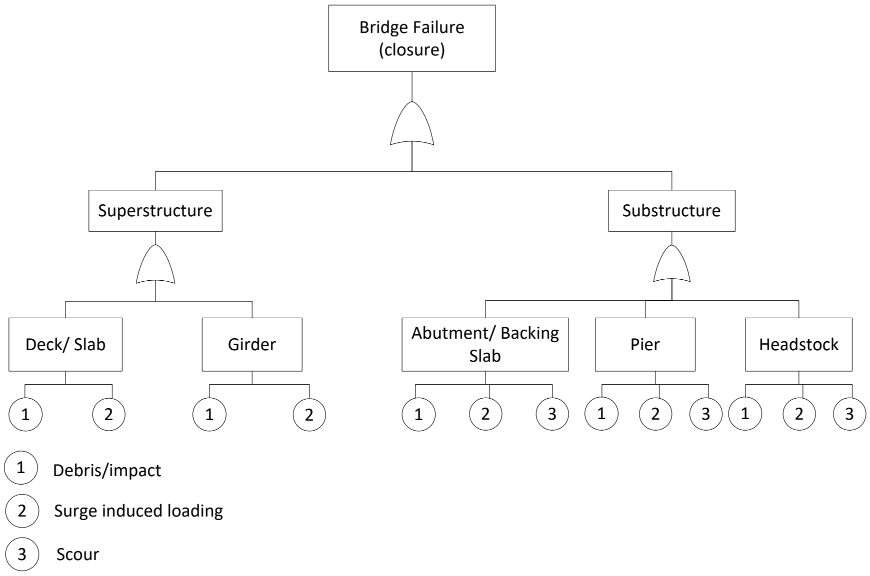


Figure 4: Fault tree diagram for bridge failure during a cyclone

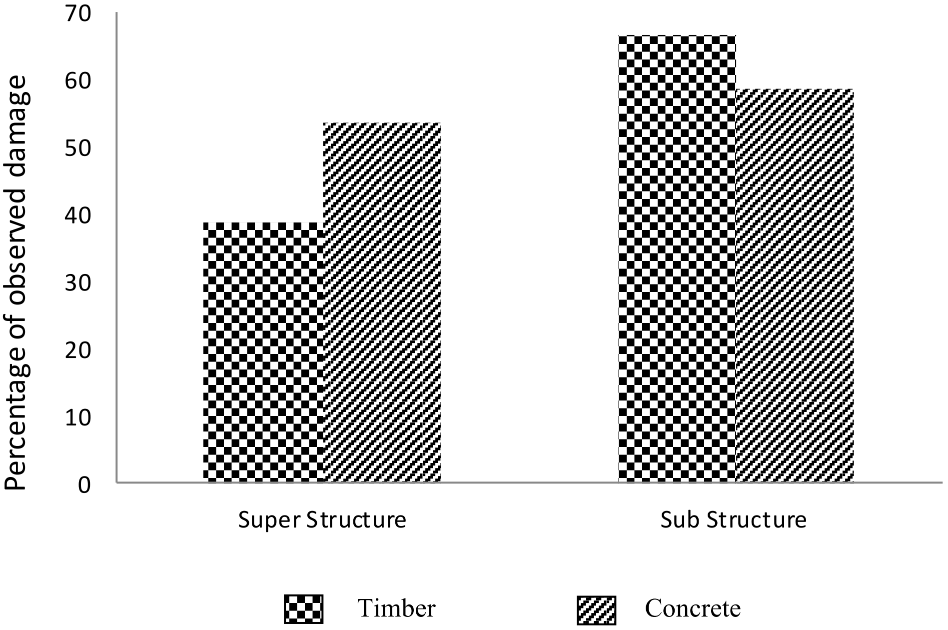


Figure 5: Observed damaged behavior for bridges during cyclone

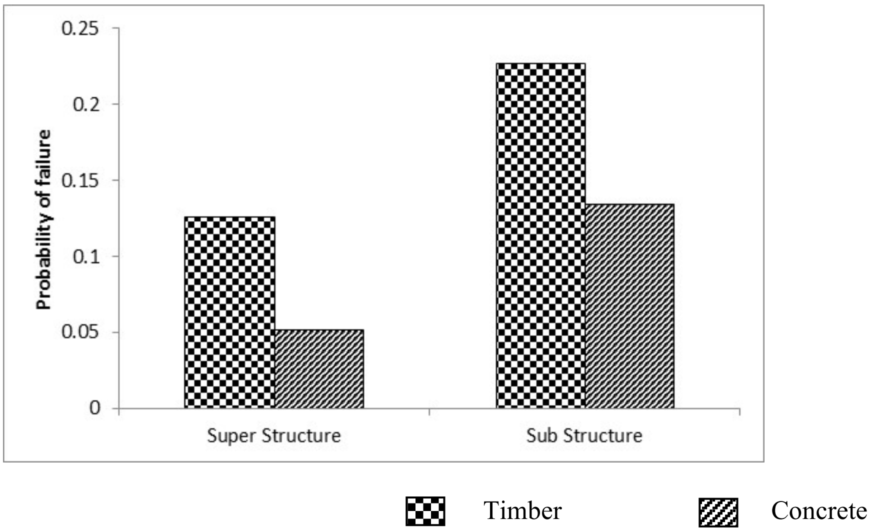
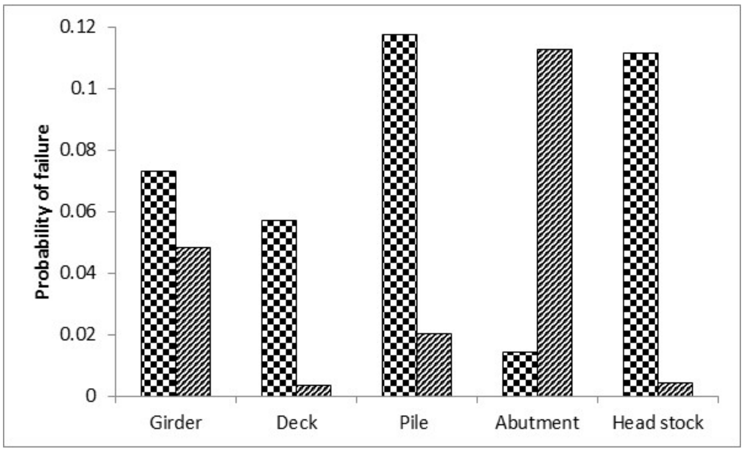


Figure 2: Damaged behavior based on FTA analysis for bridges during cyclone



▦ Timber ▨ Concrete

Figure 7: Element failure of bridges during a cyclone

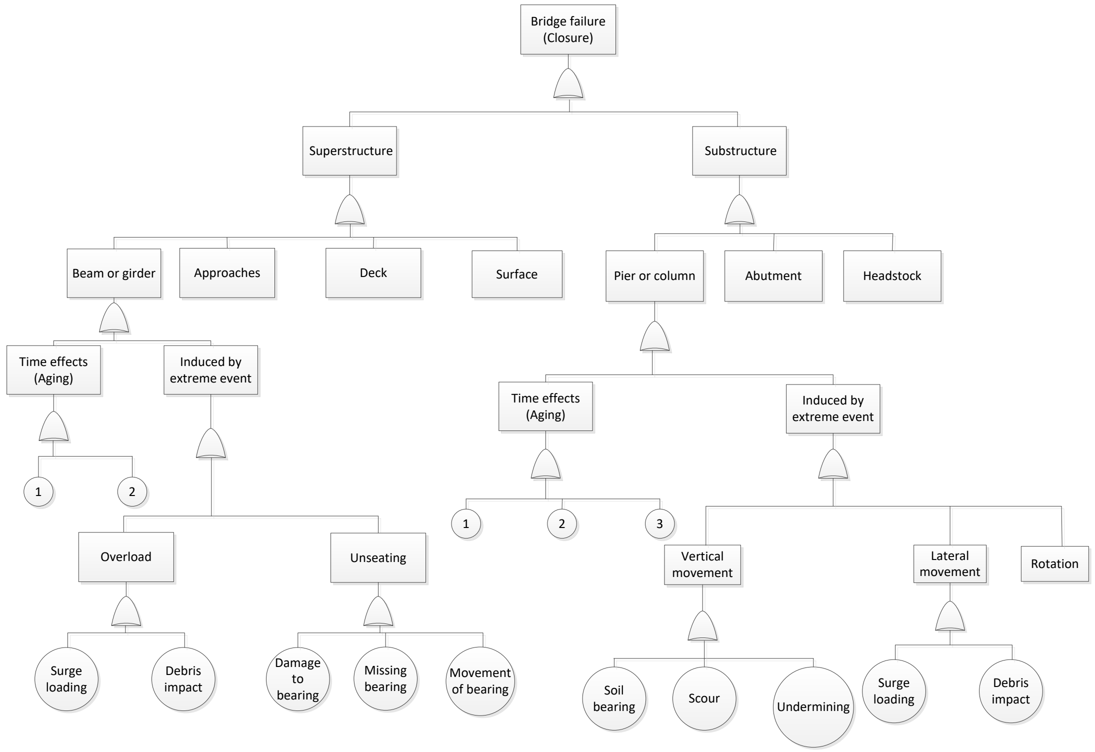


Figure 8: Detailed fault tree diagram for bridges

List of tables

Table 1: Probabilities for condition states

Condition levels	Qualitative Rating	Assigned Probability
CS1	Good	7%
CS2	Fair	12%
CS3	Poor	25%
CS4	Very poor	50%
CS5	Worst	65%

Table 2: Condition states for the girders (Span 1) in aTimber Bridge

	CS1	CS2	CS3	CS4
Before cyclone	0	5	2	0
After cyclone	0	0	0	7

Table 3: Probability of girder failure using a Timber Bridge

Span	1	2	3	4
Probability	0.3430	0.3583	0.3429	0.3314
Probability of a girder failure = 0.3439				

Table 4: Probability of girder failure using all the damaged timber bridges

Bridge	Probability of a girder failure
1	0
2	0
3	0
4	0.0625
5	0.1275
6	**0.3439 (sample calculation)**
7	0
8	0.05

Table 5: Assigned probabilities for basic events

Basic event	Superstructure	Substructure
Debris/impact	25%	20%
Surge induced loading	75%	45%
Scour		35%

Table 6: Probabilities for main element failure of timber bridges

Probability of failure of a timber bridge due to a cyclone (0.3244)				
Superstructure-0.1260		Substructure-0.2269		
Deck	Girder	Piles	Abutments	Head stock
0.057	0.0729	0.1175	0.01423	0.1114

Table 7: Probability of basic events of the superstructure for timber bridges

Deck		Girder	
Debris/Impact	Surge induced loading	Debris/Impact	Surge induced loading
0.01439	0.04319	0.0185	0.0555

Table 8: Probability of basic events of the substructure for timber bridges

Piles			Abutment			Head stock		
Surge	Scour	Impact	Surge	Scour	Impact	Surge	Scour	Impact
0.0549	0.0428	0.0244	0.0062	0.0048	0.0028	0.0519	0.0404	0.0231

Table 9: Probability for main element failure of concrete bridges

Probability of failure of a concrete bridge due to a cyclone (0.1792)				
Superstructure-0.0518		Substructure-0.1344		
Deck	Girder	Piles	Abutments	Head stock
0.0036	0.0483	0.0204	0.1127	0.00417

Table 10: Probability of basic events of the superstructure for concrete bridges

Deck		Girder	
Debris/Impact	Surge induced loading	Debris/Impact	Surge induced loading
0.0009	0.0027	0.0122	0.0366

Table 11: Probability of basic events of the substructure for concrete bridges

Piles			Abutment			Head stock		
Surge	Scour	Impact	Surge	Scour	Impact	Surge	Scour	Impact
0.0091	0.0071	0.0041	0.0523	0.0407	0.0233	0.0016	0.0012	0.0007