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Analysis of Flood Impact on Reinforced Concrete (Pre-stressed) Girder Bridges – a Case Study

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ABSTRACT: In recent years, frequencies of flood events in Australia have increased. It is noted that flood events cause the most damage to infrastructure compared to any other natural hazards in the world. Bridge structures located over waterways are prone to failure under flood events. Failure of a bridge can impact on the community significantly by reducing the evacuation capability and recovery operations during and after a disaster. A recent research project commenced at RMIT University aims to examine failure of road bridges under flood events. The paper has reviewed different bridge design codes used over several years in Australia for designing the bridges. Various failure mechanisms of bridges due to flood events have been investigated and the most common failure mechanisms of the bridges in Queensland have been identified by examining bridge inspections conducted after the 2011 and 2013 flood events. A case study bridge, which failed under flood loading, has been modeled and the effects of different flood scenarios have been investigated. The impacts of different types of debris, urban and regional, have also been studied. Damage indices have been derived for a concrete girder bridge to demonstrate the methodology for vulnerability modeling of bridge structures.

1 INTRODUCTION

Flooding is a common natural hazard in many regions of the world and fast becoming the most costly in terms of mortalities, economic losses and damages to infrastructure. Understanding the frequency and causes of extreme events is crucial for environmental, social and economic protection and planning. In Australia this was never more apparent than in January 2011 when widespread flooding occurred across Queensland, New South Wales (NSW), and Victoria (van den Honert and McAneney, 2011). Communications by road and rail are often disrupted when creeks rise and the larger rivers overflow, inundating not only the roads, but causing washouts of the railways and at bridge approaches, and contributing to the break up and pot-holing of the bitumen and gullying of dirt surfaces . Bridge infrastructure is vital in post disaster activities such as search and rescue operations because bridges help access to the disaster affected area (Ellingwood, 2009). After 2011/2012 extreme flood events in Queensland, the helicopters were required for post disaster operations as well as rigorous inspection of bridges prior to reopening for recovery operation(Pritchard, 2013). It is reported that the flood in March 2009 inundated 62% of the state costing $234 million damage to infrastructure in Queensland (IBISWORLD, 2011). The direct cost of flood in Australia for the period between 1967 and 2005 has been estimated as 377 million Australian Dollars per annum (Bureau of Meteorology, 2014).

Bridge could be damaged in many ways when it is under an extreme flood event(Farook et al., 2014). If the bridge is completely inundated during the flood, the damage to the bridge depends on the length of time it was submerged as well as the types of debris collected around or passing the bridge components. Extra care should be taken to inspect the supports of the bridges, even after the flood water recedes. Approaches of a bridge could be damaged due to debris impact, settlement or depressions. Debris against substructure and superstructure, bank erosion and damage to scour protection will damage the waterways. Bridge substructure could fail due to movement of abutments, wing walls, piers, rotation of piers and missing, damaged dislodged or poorly seating of the bearings while the superstructure could fail due to the debris on deck, rotation of deck, dipping of deck over piers or damage of girders. It is identified that urban debris such as cars; containers etc. and the insufficient bridge span to through that debris were the main cause for damaging bridges aftermath of 2011/2012 extreme flood events in Queensland(Pritchard, 2013). Fig. 1 depicts the damaged Kapernicks Bridge from Lockyer Valley

Region in Queensland, which is the case study covered in this paper.

Fig 1: Damaged Kapernicks Bridge in Lockyer Valley Region in Queensland, Australia

2 SIGNIFICANCE

Analysis of the performance of bridges under 2011/2013 flood in Lockyer Valley Region, Queensland, covered in (Farook et al., 2014) indicates that the bridge deck is the most commonly affected component followed by the bridge approach, pier/abutment scouring, cracks in the abutment wing walls and misalignment of abutment headstock connections to piles. Reinforced or pre-stressed concrete girder bridges are a common design configuration used in Australia. During the Lockyer Valley floods in 2013, vulnerability of girder bridges was observed by significant damage to these structures.

Bridge structures have a major impact on resilience of road infrastructure and the damage to bridges could increase the vulnerability of the community served by the road infrastructure significantly. A systematic method of quantifying vulnerability of bridge structures under varying flood loading is currently a significant gap in knowledge.

Using the concrete girder bridges as case studies, the methodology to derive structural vulnerability models for bridge structures and determine vulnerable structures in the road network have been proposed.

3 CASE STUDY – IMPACT OF URBAN DEBRIS CAUSING FAILURE

Lockyer Valley region in Queensland, Australia is the most adversely affected area during recent flood events. It suffered two nationally prominent extreme flood disasters in the recent past, one in 2011 and the other in 2013. It’s situated to the west of state’s capital, Brisbane and is one of the most fertile farming areas in the world. Subsequent to this natural calamity, a need was arisen to assess the condition of all affected bridges before they were open for traffic. A bridge inspection report was compiled by Lockyer Valley Regional Council for 46 affected bridges in the region. Detailed analysis of these bridges revealed that different bridges failed due different failure mechanisms. It also revealed that some of the bridges failed mainly because of unusual floating debris such as shipping containers, cars and rivercraft (for example 300t vessels). This paper investigates the impact of a floating container on Kapernicks Bridge in the case study area together with other flood induced forces.

Kapernicks Bridge is a three span, two lanes precast concrete Girder bridge located on Flagstone Creek Road in the case study area. The superstructure consists of a steel Bridge Barrier with cast-in-situ Kerbs on the left hand side and right hand side and a cast-in-situ concrete wearing surface topping four precast concrete Girders that are supported by elastomeric bearings at the abutments and piers. The substructure consists of two cast-in-situ abutments and two piers with a cast-in-situ headstock and two cast-in-situ piles. Abutment one is deemed to be the southern end (closest to Carpendale Road). The Approaches are bitumen sealed. There is room for vehicular parking on the right hand side of approach two. Upstream is on the right hand side of the structure. Fig. 2 depicts the details of the Kapernicks Bridge (section view).

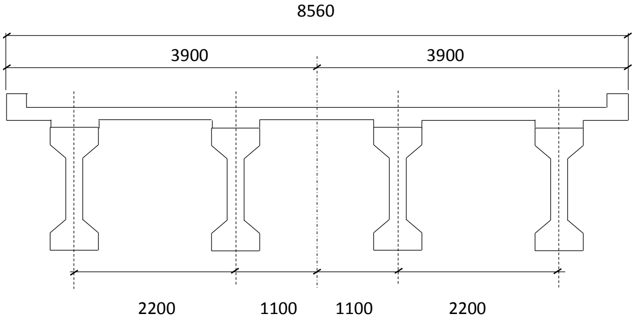

Fig 2: Section view of Kapernicks Bridge

4 FORCES ON BRIDGE RESULTING FROM FLOOD EVENT

AS 5100 Bridge Design code (Section 15 of AS 5100.2-2004) gives relevant equations to calculate the flood induced forces on bridge resulting from water flow, debris and log impact (Australian Standard, 2004).

4.1 *Forces on superstructure due to water flow*

When the bridge superstructure is partially or fully inundated in a flood, it is subjected to a horizontal drag force (F_d) normal to its longitudinal axis and a vertical lift force (F_l) as given in AS 5100.

$$(F_d) = 0.5 C_d V^2 A_s \qquad \text{Equation (1)}$$

Where C_d = drag coefficient read from the chart given in the code

V = mean velocity of water flow (flood)

A_s = wetted area of the superstructure, including any railings or parapets, projected on a plane normal to the water flow.

$F_l = 0.5 C_l V^2 A_l$ Equation (2)

Where C_l = lift coefficient read from the chart given in the code

V = mean velocity of water flow (flood)

A_l = Plan deck area of the superstructure.

4.2 *Forces due to Debris*

Debris load acting on superstructures is given by the code as,

$F_{deb} = 0.5 C_d V^2 A_{deb}$ Equation (3)

Where C_d = drag coefficient read from the chart given in the code

V = mean velocity of water flow (flood)

A_{deb} = Projected area of the debris mat described in the code.

4.3 *Forces due to Log Impact*

Where floating logs are a possible hazard, the drag forces exerted by such logs directly hitting bridge girder (superstructure) superstructure shall be calculated on the assumptions that a log with a minimum mass of 2t will be stopped in a distance of 75mm for such solid girder (superstructure). However for the bridge in question, this mass was taken equivalent to a mass of a shipping container to simulate the actual condition.

Flog shall thus be given by the following equation.

$F_{log} = mV^2/2d$ Equation (4)

Where m= mass of a shipping container d= stopping distance and V= flood velocity (m/s)

5 DERIVING DAMAGE INDICES

Damage Indices are first derived to generate vulnerability curves for Kapernicks Bridge under different flood exposure conditions. The effects of flood flow, debris and the log impact on the bridge girder have been considered to derive the damage indices. The damage index can be defined using either the existing moment capacity of the bridge girder or the costs associated with retrofitting/repairing the bridge under flood. This paper considers the damage index defined by the existing moment capacity. In this method the Damage Index (DI) is defined as the ratio between the existing moment capacity of the bridge girder (ϕM_u) and the moment induced by flood loading on the bridge girder (M^*) as given in equation 5.1.

DI = $\phi M_u / M^*$ Equation (5)

5.1 *Calculation of the existing moment capacity of the girder (ϕM_u)*

In accordance with the Australian codes of practice for structural design, the capacity analysis methods contained in this section are based on ultimate limit-state philosophy. This ensures that a member will not become unfit for its intended use. The capacity analysis results would be compared with structural analysis results to identify the deficiencies. This approach sets acceptable levels of safety against the occurrence of all possible failure situations. The nominal strength of a member is assessed based on the possible failure modes and subsequent strains and stresses in each material.

A typical beam section of the headstock is shown in Figure 4.2. The positive and negative flexural and shear capacities of the section were calculated in accordance with Australian standards (AS3600, 1988). The nominal steel reinforcing bars areas; nominal steel yield strength of 400 MPa for longitudinal reinforcement and 240 MPa for shear reinforcement and nominal concrete compressive strength of 20 MPa were used in the section capacity analysis. The degradation due to corrosion of the steel and creep and shrinkage of the concrete were ignored. Based on these assumptions, the existing moment capacity of the concrete girder section was found to be 600 kNm.

5.2 *Estimating flood induced bending moment (M^*)*

In order to estimate flood induced bending moment on the bridge girder, general purpose finite element software, ANSYS was used to model the Kapernicks Bridge deck. This is a single span reinforced concrete, prestressed I-girder bridge built in 1980's. The bridge is 65.50 m long and about 8.56 m wide and is supported by 4 pre-stressed 22 m long beams over the mid-span and another 8 pre-stressed 21.75 m long beams over the end spans. The beams are supported by two abutments and two headstocks. The middle span of bridge deck was analysed. All four girders were assumed simply supported and rest on the headstock of the piers. Self-weight of the bridge, the drag and the lift force due to water flow, debris force and the log impact force were considered in the analysis.

ANSYS model was run for different flood velocities ranging from 0.5 m/s to 5.0 m/s in steps of 0.50 m/s increment. The model was run separately for the effect of flood flow, debris impact, log (container in this case) impact and the level of submergence. Fig. 3 depicts the bridge deck model used in the analysis.

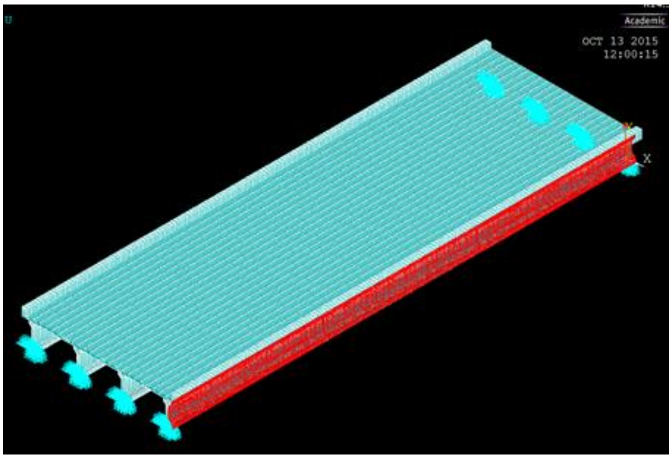

Fig 3: ANSYS bridge Deck Model

Horizontal support reaction of the end girder was obtained each time from the ANSYS Postprocessor. Using these reaction values flood induced bending moment of the end girder was calculated with the help of an excel sheet as shown in table 1

Table 1: Support Reaction Table

Velocity (m/s)	Reaction (kN)	W (kN/m)	M^*y(kNm)	$ØM_u/M^*$
0.5	16.02	1.46	85.68	5.60
1.0	20.10	1.82	107.54	4.46
1.5	26.91	2.45	144.00	3.33
2	36.45	3.31	195.00	2.46
2.5	48.70	4.43	260.57	1.84
3.0	63.67	5.80	340.72	1.41
3.5	81.40	7.40	435.45	1.10
4.0	102.00	9.26	544.74	0.88
4.5	125.00	11.36	668.64	0.72
5.0	151.00	13.71	807.10	0.60

M_u= 600 kNm (Existing capacity of the girder as calculated from the section analysis of the reinforced concrete girder)
Ø = 0.8 (Safety factor for the moment capacity as per AS 5100)

Table 2 summarizes Damage Indices calculated for all three different types of flood impact conditions considered in the analysis.

Table 2: Damage Indices for different types of flood impact

	$ØM_u/M^*$		
Velocity(m/s)	impact #1	impact #2	impact #3
0.5	5.60	5.07	2.45
1.0	4.46	3.32	0.88
1.5	3.33	2.12	0.42
2.0	2.46	1.41	0.25
2.5	1.84	0.98	0.16
3.0	1.41	0.72	0.11
3.5	1.10	0.54	0.08
4.0	0.88	0.43	0.06
4.5	0.72	0.34	0.05
5.0	0.60	0.28	0.04

Flood impact #1: Impact from flood flow only
Flood impact #2: Impact from (flood flow + Debris)
Flood impact #3: Impact from (flood flow + Debris + Container)

6 DEVELOPMENT OF VULNERABILITY CURVES

Damage Index values are plotted against the flood exposure condition (flood velocity in this case) to develop vulnerability curves. These curves are generated for the above three different types of flood impacts and are shown in fig. 4.

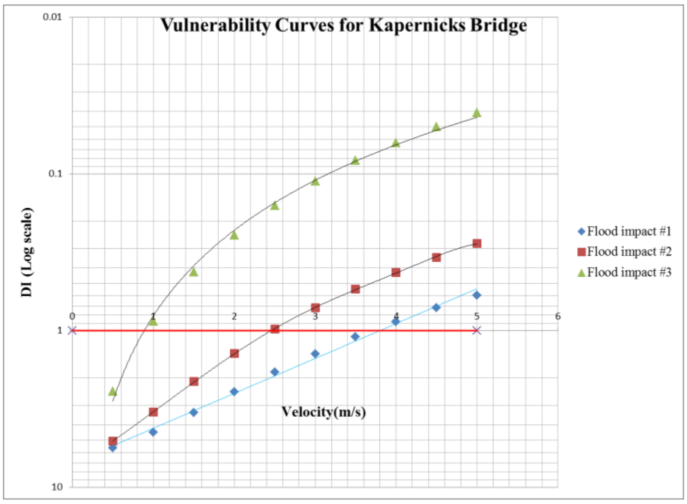

Fig 4: Vulnerability curves for Kapernicks Bridge

7 DISCUSSION

The impact of hydrodynamic loads due to traditional rural flood and urban flood on Kapernicks Bridge has been studied in this paper. These loads include fluid flow drag force, a vertical uplift force, debris force and Log (containers, cars and rivercrafts in an urban environment) impact force. As identified by (Lamond and Proverbs, 2009) lessons learnt from a disaster are valuable in forming future design practices. AS 5100 (Standards Australia 2004) along with many other codes and standards worldwide assume typical rural flood events in designing bridges. It is obvious that the recent flood event in Queensland was an urban flood event in contrast to the rural flood event as assumed in AS 5100: 2004 Bridge Design Code. Current tools and techniques available for risk-cost optimization do not take into account the increased loading conditions on the structures that are exposed to extreme weather events. On the other hand, rural debris loads experienced by the bridges in the recent floods are much higher than the loads recommended in the Design Code. Hence these design codes of practice should require examining of the Annual Exceedance Probabilities adjusted for recent increase in frequency and intensity of flood events.

8 CONCLUSION

Reinforced or pre-stressed concrete girder bridges are a common design configuration used in Australia. During the Lockyer Valley floods in 2013, vulnerability of girder bridges was observed by significant damage to these structures. Structural performance of Kapernicks Concrete Girder Bridge has been studied in this paper. For the girder not to fail under flood loading, the existing moment capacity of the girder ($\varnothing M_u$) must be greater than the moment induced by the flood force (M^*). In other words $\varnothing M_u/M^*>1$. The maximum allowable flood velocity to satisfy this condition could be read from the above structural vulnerability curves. For Kapernicks Bridge under investigation, the maximum allowable flood velocity is shown in table 3.

Table 3: Maximum allowable velocity for different types of flood impact

Type of Flood Impact	**Maximum allowable flood velocity (m/s)**
Flood only	3.66
Flood+Debris	2.46
Flood+Debris+Container	0.89

It has been observed that when the intensity of flood increases, the bridge structure becomes more vulnerable. The intensity of flood accounts for flood velocity, the accumulation of debris that it carries along in it and any other floating objects such as containers, vehicles and river-crafts. The outcomes will enable identification of the vulnerable girder bridges in the road networks and will assist road authorities to make optimized hardening decisions. On the other hand, emergency management services will be able to avoid vulnerable structures in determining evacuation routes.

The new design for the Kapernicks Bridge has used 4 m/s as the design flood velocity.

The research is being continued to improve the vulnerability models considering the fluid structure interaction replacing the code equations and replacing the deterministic approach with reliability- based approach to cover variability of the flood loading and the material degradation of the structures.

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