Evaluating disaster resilience of bridge infrastructure when exposed to extreme natural events

Abstract

Disasters can be natural or human made, predictable or totally unexpected and can be of any size. However, they cause considerable damage to the built environment. Disaster resilience of a society mainly depends on the physical robustness of structures and infrastructure and resilience of the community. This research paper focuses on the damage caused by the recent floods in Queensland, Australia on the bridge infrastructure. Bridges in one council area were selected as a case study. For the damaged bridges, data such as level of damage, material used in these bridges, type of bridge (girder/precast/insitu), age of the bridge, annual average daily traffic, heavy vehicles and inspection data before and after the flood were collected and analysed. In structural engineering, vulnerability is a term used to define the damage tolerance of structures.

This case study is used to find a relationship between the collected data and the vulnerability of the bridges. It is interesting to observe that there is an inverse relationship between the age of the bridge and the damage level. The reasons for this could be due to different construction practices adopted in the past or they had been rehabilitated after previous disaster event. However these reasons should be further analysed for confirmation. It can be concluded that the bridges on arterial roads, which are normally designed for heavy load platform loadings, are more resilient than those on the rural collector roads during an extreme flood event. However since arterial roads may have some redundancy during a flood event, rural roads may become the only means of traffic movement. The resilience of the community will depend on the resilience of the bridges on rural roads which are at the moment vulnerable in extreme flood events. Therefore when classifying roads for design, it is necessary to consider the impact on the community during and after an extreme event.

Keywords: disaster, resilience, vulnerability, bridge

1. Introduction

In an idealised situation, community prefers to have a consistent and stable environment with predictable future where all the changes happening lie within the tolerable limits. Since the future is always uncertain and potentially hazardous, in the recent past, natural and manmade disasters have clearly shown the importance of resilient infrastructure. The predicted 9 billion world population by 2050 (Hudson et al. 2012) will increase the natural and manmade hazards as well as the effects of such uncertainties. Lamond and Proverbs (2009) discussed few barriers related to the flood plain population such as emotional constraints, aesthetic considerations, finance and regulatory requirements that need to be overcome for a successful resilient program for flooding.

Resilience of critical infrastructure such as roads and bridges is vital in evacuation support activities for disaster response and recovery (Oh et al. 2010). 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. During an emergency event, community relies heavily on road infrastructure to enable them to evacuate the area fast. During the re-building period after a disaster, bridges play a major role in ensuring access to the affected areas. Therefore, understanding the influencing factors which affect resilience of the bridge structures in extremely important to ensure that the design specifications as well as maintenance regimes for bridge structures consider the resilience and vulnerability of structures during a disaster.

The recent flood events in Queensland, Australia had and adverse effect on the country’s social and economic growth. Queensland state controlled road network included 33337 km of roads and 6500 bridges and culverts (Flooding on roads in Queensland 2010). Frequency of flood events in Queensland, during the past decade appear to have increased. In 2009 March flood in North West Queensland covered 62% of the state with water costing $234 million damage to infrastructure (Increasing Queensland's resilience to inland flooding in a changing climate 2010). Theodore in Queensland was flooded three times within 12 months in 2010 and it was the first town, which had to be completely evacuated in Queensland. 2010-2011 floods in Queensland had a huge impact particularly on central and southern Queensland resulting in the state owned properties such as 9170 road network, 4748 rail network, 89 severely damaged bridges and culverts, 411 schools and 138 national parks (Rebuilding a stronger, more resilient Queensland 2012). Approximately 18000 residential and commercial properties were significantly affected in Brisbane and Ipswich (Queensland floods: The economic impact Special Report 2011) during this time. More than $42 million was paid for individual, families and households while more than $121 million in grants has been paid to small businesses, primary producers and not-for-profit organisations and more than $12 million in concessional loans to small businesses and primary producers (Rebuilding a stronger, more resilient Queensland 2012). The Australian and Queensland governments have committed $6.8 billion to rebuilding the state.

The research presented here aims to understand the factors influencing the resilience and vulnerability of bridge structures with the longer term goal of feeding in to design specifications of new bridge structures and maintenance and management decisions taken on existing structures.

2. Background

Typically bridges are designed for a 100 year service life and more recent structures eg: Gateway bridge in Brisbane has been designed for a 200 year design life. However, with the increase in frequency of extreme events, the probability of failure would increase, resulting in a reduction in expected design life. Furthermore the damage to structures will require some restrictions to be placed on the structures which will affect the service provided to the community.

2.1 Increase in frequency of extreme events

It is reported in the recent literature that due to climate change, frequency of flood events has increased as well as they have become more intense. Queensland local governments are suggested with a 5% increase in rainfall intensity per degree of global warming as the climate change factor to be incorporated in the flood studies (*Increasing Queensland's resilience to inland flooding in a changing climate* 2010).

Climate change will not have a huge impact on the infrastructure as the effect due to short-term impact loads are built in the safety factors in the design process (Kong et al. 2013). However, extreme natural disasters will have an impact on the vulnerability as the infrastructure may not be designed for such a long-term intense event.

2.2 Impact analysis

The resilience of a society in an extreme event depends mainly on the robustness of the critical infrastructure and their interrelationship with the associated industries and the community. A basic cell model has been proposed in the literature to demonstrate this relationship (Oh et al. 2010). In order to understand this complex relationship between critical infrastructure, industries and communities, it is important to define their impacts considering economic, social and technical factors.

2.2.1 Economic impact

Lian et al. (2007) used a mathematical model to find the impact on companies using their input-output exchange of goods and services while Burrus et al. (2002) used full day equivalents lost to measure the impact on the frequent business interruption in hurricane regions. Rose et al. (2007) established economic factors for a community that are highly dependent on electricity based on the output loss of customers, suppliers and output loss measured by the decreased number of customers.

2.2.2 Social and environmental impact

Although it is straightforward to gauge economic impacts, measuring the damaged quality of life is difficult. It is necessary to research more about the influence of flood on the characteristics such as commercial, agricultural, industrial and tourism industries, type of work people do and demographic factors such as gender, low-income employees, age etc. Social Flood Vulnerability Index which includes three social characteristics and four financial deprivations indicators were reported in the literature to measure the impact of floods on the community (Oh et al. 2010). Some researchers (Reed et al. 2011) proposed to conduct surveys for the affected community as a measure of investigating social impacts. They gathered information such as resources required by the community after the event and how long they require it, whether they are connected by the extended family, neighbourhood or the government institutions, importance of religious organisations and preferences for shelter and assistance etc.

2.2.3 Functional impact

Many researchers discussed about the interdependencies among infrastructure and the effect of them on the functioning of the industries (McDaniels et al. 2007; Rinaldi et al. 2001) while others (Oh et al. 2010) provided decision support tools to help developing disaster mitigation strategies based on the relationships between communities, industries and associated economic, social and technical impacts. Rinaldi et al. (2001) developed a conceptual framework which includes a range of factors such as infrastructure characteristics, state of operations, types of interdependencies, environment, coupling and response behaviour and type of failure. McDaniels et al. (2007) characterised infrastructure failure interdependencies in terms of the sectors affected and the consequences for the society.

2.2.4 Impact due to recent Queensland floods

Floods will have significant adverse effect on the Australian economy in addition to the world products and agriculture prices. Australia is the world’s largest coal exporter and Queensland is the highest contributor for that. IBISWorld (Queensland floods: The economic impact Special Report 2011) reported that the floods reduce 0.6% from the previous GDP forecast for the third quarter of 2010-11, $2 billion in lost coking coal production and $1.6 billion damage to agriculture. Although the revenue from tourism industry was forecast to be $84.2 billion (Queensland floods: The economic impact Special Report 2011), the floods reduced this by 0.7%. During the 2011 floods in Queensland, hundreds of families were evacuated from their homes in the middle of the night leaving very little time to gather their personal valuables and with a very unstable physiological status. Psychologists who are specialized in management of people’s emotional response to disasters say that it takes a very long time to get their lives back on track.

2011 floods in Queensland have devastated the landscape, many rivers and creeks became unhealthy as they were eroded, contaminated and littered with debris. Erosion of river banks was detrimental for the freshwater turtles. During the floods only 15% of the coal mines in Queensland were operational and it is reported that Government had to drop environmental regulations and allow 44 mines to pump millions of litres of contaminated water into creeks and rivers (*Environmental impacts of floods- Febriary 2011* 2011). This contaminated water is a huge threat to marine environment and the nation's most notable tourist attraction, coral reef. In order to reduce these detrimental impacts on the economy and the community it is necessary to investigate the effect of robustness of bridge infrastructure on these impacts.

2.3 Typical failure modes during floods

There are many ways that a bridge could be damaged in an extreme flood event. If the structure is completely inundated during the flood, the damage to the property depends on the length of time it was submerged as well as the elements collected around or passing the structure. Even after the flood water recedes, extra care should be taken to inspect the supports of the bridges. 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. Movement of abutments, wing walls, piers, rotation of piers and missing, damaged dislodged or poorly seating of the bearings are the major reasons for substructure failure. Superstructure could be damaged due to the debris on deck, rotation of deck, dipping of deck over piers or damage of girders. Due to any of these reasons, the members of a bridge could be damaged and bridge may not be completely functional.

When the damaged bridges around Queensland are carefully analysed, it is realized that they were damaged mostly due to the unprecedented load due to debris and the impact load due to very large rocks flowing with the flood water.

3. Research Objectives

In any country, transport infrastructure plays an important role in the normal daily life as well as in the event of an extreme weather condition. Transport infrastructure consists of all types of roads and bridges and identifying the vulnerable infrastructure or vulnerable parts or sections of the critical infrastructure is a timely concern so that it is possible to address the social, economic and functional impact of floods on community to some extent.

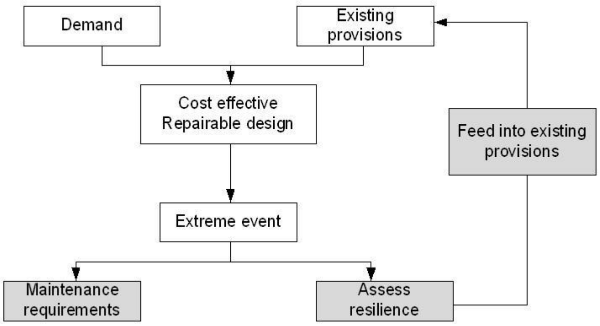

Figure 1: Resilience of bridge infrastructure

The main focus of this research is to study the factors affecting the vulnerability of bridge infrastructure when exposed to extreme flood events. The importance of this research is shown in Figure 1. The bold blocks of Figure 1 cover the main objectives of this research. Considering a network of bridges in Queensland during the recent floods, it is expected to formulate the factors affecting the vulnerability of a bridge to an extreme flood event.

4. Research methodology

In this research, two parameters are selected to establish the performance of bridge infrastructure. There are many definitions reported in the literature for resilience. It can be defined as the ability to maintain functionality and return to normality following an extreme event making sure that the damage is tolerable and affordable (Hudson et al. 2012; Lamond & Proverbs 2009). It was defined as the ability of a system to reduce the chances of a shock, to absorb a shock if it occurs and to recover quickly after a shock (Cimellaro et al. 2010). According to their definition a resilient system should have low probability of failure, even if it fails, very low impact on the society in terms of loss of lives, damage and negative economic and social consequences and most importantly low recovery time.

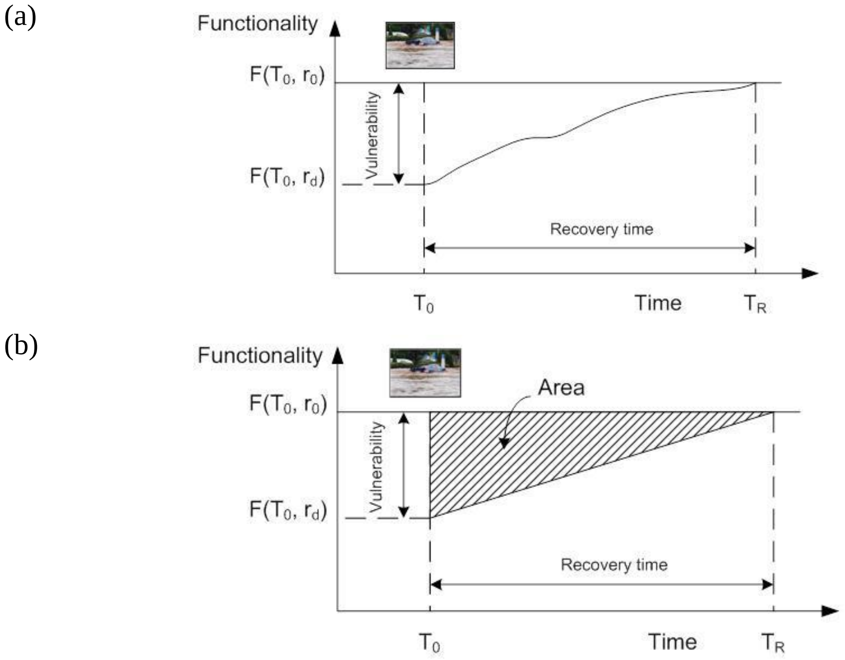

Figure 2: Representation of resilience and vulnerability

Figure 2 (a) shows the functionality of an infrastructure with time. At time T_0, the system was fully functioning [$F(T_0, r_0)$] when the extreme event occurred. Functionality was reduced to $F(T_0, r_d)$ due to the damage to the infrastructure system. At time T_R, the system completely recovered and started functioning as it was at time T_0. By considering the above qualities for a resilient system, it can be concluded that if the functionality due to damage is not much and/ or if the recovery time is less then the system is more resilient. Therefore if the area shown in Figure 2 (b) is less the system is more resilient. Delivering resilience is a cycle of identification, assessment, addressing and reviewing (Hudson et al. 2012). Evaluating or re-evaluating resilience can be related to the aftermath of an event, a near miss, or event affecting a similar infrastructure elsewhere.

A probabilistic measure of vulnerability is defined as the ratio of the failure probability of the damaged system to the failure probability of the undamaged system (Frangopol & Saydam 2011). Vulnerability of a bridge will depend on the failure probability of the sections of that bridge. Using a case study, it is aimed to investigate the factors that affect the vulnerability of a bridge in an extreme event.

5. Case study

Lockyer Valley area is one of the most adversely affected regions due to the January 2013 flood event in Queensland. It is situated to the west of state's capital, Brisbane and is one of the most fertile farming areas in the world. The valley is enclosed on either side by the Great Dividing Range. Lockyer creek and its tributaries drain the valley and through Brisbane river empty into Morten bay. In 2011 some areas of Lockyer Valley region were severely affected by the surge created by the flash flooding in the higher grounds of the Lockyer creek. Lockyer Valley region has been selected for the case study because 2011 and 2013 floods had a huge impact on the community of that area.

Bridge No. 2 abutment headstock damaged

Bridge No. 16 completely washed away

Bridge No. 8 damaged due to debris

Bridge No.1 with damaged relieving slab

Figure 3: Damaged bridges

There were 46 bridges all together in the selected Lockyer Valley Regional Council area and 43 bridges were damaged in some form and needed repair due to the 2013 floods (Figure 3). Bridge numbers refer to those presented in Table 1. Lockyer Valley Regional Council appointed a private organisation to investigate the flood damage to bridges and they prepared a comprehensive report for the 46 bridges. Data for selected 15 bridges is shown in Table 1. The inspections were based on the Level 1 bridge inspection of Queensland's Department of Transport and Main Roads and recommendations were made for the Council on the opening of roads after the floods. Based on the recommendations such as "bridge ok to open", "bridge requires work prior to opening" and "further assessment required", and the inspection details, the authors have given approximate level of damage percentage for each bridge (According to the inspection reports, flood damage to the bridges could be classified based on the damage to the elements. Bridge approaches are susceptible for damage due to high water velocities and they may be scoured or undermined. Erosion around abutments can remove structural support and lead to collapse of the bridge. Bridge structure, approaches and the relieving slabs are damaged due to heavy debris which is nowhere near the designed predicted debris load. Abutment headstock from the piers could be dislodged and wingwalls could be damaged.

Based on the functional classes of roads of Austroads Bridge Design Code (1992), road types shown in Table 2 can be classified as follows:

Rural areas: Class 3- Roads whose main function is to form an avenue of communication for movement of an arterial nature (Rural arterial). Class 4- Roads whose main function is to provide access to property within a town in rural area (Rural collector, rural access).

Urban areas: Class 6- Roads that provide the avenue of communication for massive traffic movements (Urban arterial). Class 8- Roads that provide access to abutting property (Urban collector)

Table 2).

Table 1: A summary of collected data for selected bridges

Bridge	Fully covered	Bridge Material	Type	Span	Length (m)	Width (m)	Age (yrs)
1	Yes	Concrete	deck unit	2	22	3.7	1
2	Yes	Concrete	deck unit	4	54.1	3.3	1
3	Yes	Timber	deck unit		20.9	5.6	49
4	Yes	Concrete	deck unit	2	21.6	4.1	41
5	Yes	Concrete	I girder	2	17	7.3	24
6	Yes	Concrete	deck unit	4	64.2	8	9
7	Yes	Concrete	deck unit	3	42	9.6	3
8		Concrete	precast	1	9.5	3.6	1
9		Concrete	precast/ Hume slab	1	15.3	4.5	1
10	Yes	Concrete	deck unit	4	36.9	5.9	48
11	Yes	Concrete	deck unit		36.6	3.4	23
12	Yes	Concrete	precast	1	15	5	3
13	Yes	Concrete. Timber Girders		2	22.1	5	8
14	No	Concrete. Timber Girders		4	36.8	8.4	6

15	Yes	Concrete	deck unit	3	40	8	4
16	Yes	Timber			6.1	7.4	49

According to the inspection reports, flood damage to the bridges could be classified based on the damage to the elements. Bridge approaches are susceptible for damage due to high water velocities and they may be scoured or undermined. Erosion around abutments can remove structural support and lead to collapse of the bridge. Bridge structure, approaches and the relieving slabs are damaged due to heavy debris which is nowhere near the designed predicted debris load. Abutment headstock from the piers could be dislodged and wingwalls could be damaged.

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Table 2: Traffic data and recorded damage for selected bridges

Bridge	Road type	Avg Daily Traffic	Percentage of heavy vehicles	Level of Damage
1	Rural Access	30	10	80%
2	Rural Access	30	10	80%
3	Rural Collector	309	13.6	20%
4	Rural Collector	1444	4.3	50%
5	Urban Arterial	1453	6.3	20%
6	Rural Arterial	1161	10.2	40%
7	Rural Access	247	18.8	80%
8	Rural Access	24	4.5	40%
9	Urban Collector	230	7.5	20%
10	Rural Arterial	294	34.1	20%
11	Rural Collector	191	12.1	70%
12	Rural Collector	121	5.3	70%
13	Rural Arterial	77	11.8	20%
14	Rural Arterial	1193	6.7	20%
15	Rural Collector	290	47	20%
16	Rural Access	100	10	100%

According to the Austroads Bridge Design Code (1992), bridges on roads of functional class 3 and 6 should be designed for heavy load platform HLP320 design loads while for class 4 and 8, the Authority will determine whether the bridge should be designed for heavy load platform loadings. Although data for 15 bridges is recorded in Table 2, the data available for all the bridges in the Council area was used to find the factors affecting the vulnerability of bridges for flood events (*Figure 4*).

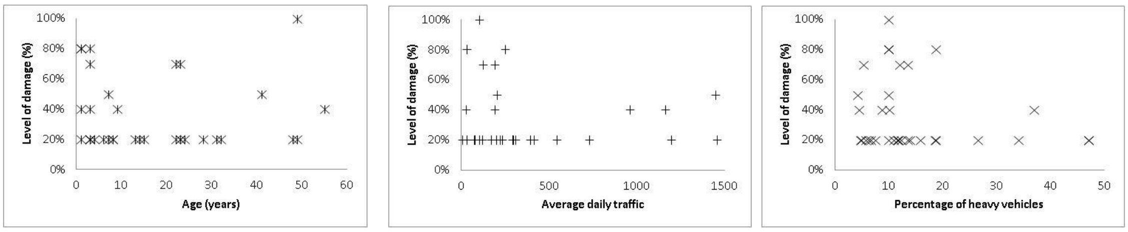

Figure 4: Factors affecting level of damage

5.1 Data analysis

As a preliminary step, a multiple regression analysis was performed using the data in According to the inspection reports, flood damage to the bridges could be classified based on the damage to the elements. Bridge approaches are susceptible for damage due to high water velocities and they may be scoured or undermined. Erosion around abutments can remove structural support and lead to collapse of the bridge. Bridge structure, approaches and the relieving slabs are damaged due to heavy debris which is nowhere near the designed predicted debris load. Abutment headstock from the piers could be dislodged and wingwalls could be damaged.

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Table 2 with age, average daily traffic and number of heavy vehicles as variables and level of damage as the output. Results from this analysis using Microsoft Excel is shown in Table 3. The R squared is quite low and therefore the outcomes can be taken as qualitative rather than quantitative. More detailed analysis is currently been undertaken covering numerous other parameters such as the elevations, approach road conditions etc.

Table 3: Multiple regression results

Regression Statistics				
R Square	0.012465			
	Coefficients	Standard Error	t Stat	P-value
Intercept	0.360424	0.068799	5.238804	1.19E-05
Age	-0.00044	0.002809	-0.15661	0.876601
Average daily traffic	8.06E-05	0.000131	0.61371	0.544033
Number of heavy vehicles	-0.00046	0.001016	-0.45185	0.654631

From the preliminary analysis following can be seen. The intercept p-value =0.00001 indicates that the probability that the intercept is zero is 0.001%, so we can reject the hypothesis that the intercept is 0 at the 5% level (standard level). On the other hand for variable age p-value = 0.876. There is 87.6% probability that the coefficient of variable “age” on the age is zero and as a result, there is no evidence to reject the null that age does not affect damage level. From this analysis, it is observed that with the increase in age and the number of heavy vehicles, damage level goes down.

Increase in heavy vehicles is directly related to the importance of the road as identified in the Austroads bridge design code. The data indicates that class 6 and class 3 roads, which should have been designed for higher design loads, have sustained a reduced damage level. This partially explains the inverse relationship between the damage and the heavy vehicles.

Inverse relationship between the damage and the age is quite interesting, indicating that older bridges have sustained a lower damage level. This could be due to a combination of factors:

- Older bridges may have sustained damage previously and would have been strengthened. We are currently looking in to the records of older bridges to confirm this hypothesis.

- The design practice of the superseded NASRA bridge design code leads to a more resilient design. The previous bridge design code didn't classify roads in to different classes as covered in the Austroads Bridge design code (1992). All the road bridges were designed for the T44 truck load with distribution factors calculated using an empirical and a conservative approach.

- The construction practices adopted in the older bridges led to more resilient structures.

These hypothesis requires further anlaysis and confirmaiton.

5.2 Impact of resilience of bridge structures on the community resilience

Road infrastructure becomes extremely important in enhancing the resilience of a community during and after a disaster event. The bridges which sustained a damage level above 80% would have a serious impact on the ability of the community to evacuate during a disaster as well as the time taken for a community to return to normal life. Whilst it is extremely important to design bridges on urban and rural arterial roads to be resilient under extreme events, these routes often have a redundancy in the design with a number of possible alternative routes. Lower class rural roads such as class 8, often is the only access road to the community. From the outcomes of the analysis of the case study, it is observed that the bridge design standards require a re-visit with a focus on the impact of failure of bridges on community resilience, which can feed in to the design process.

6. Conclusions

The paper presents the importance of road bridges in enhancing community resilience during a disaster. Based on the analysis of a case study data set which indicates the damage to road bridges during floods in Queensland, Australia in 2013, following early conclusions are drawn:

- The damage sustained in road bridges has been observed to have an inverse relationship with the number of heavy vehicles using the bridges. Further examining this observation revealed that the bridges used by a higher number of heavy vehicles usually are classified as arterial roads, which are designed for heavy load platform loadings.

- There is an inverse relationship between the age of bridges and the damage level. This possibly is related to a number of factors which require further research such as: construction practices adopted during the construction of the aging bridges, possible strengthening after a previous disaster event etc.

- The community resilience is currently not incorporated in to the design practice. Arterial roads which carry a larger number of heavy vehicles, may have some redundancy during and after an extreme flood event with alternative routes. Rural access and collector roads may be the only access to a community. This aspect of community impact requires further consideration in classifying roads for design.

A current research project is examining the failure modes of different types of bridges during the flood event with the intention of further identifying resilient features of the bridges which can lead to enhancement of the design practice for flood affected areas.

Acknowledgement

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References

Austroads Bridge Design Code (1992)

Burrus, JRT, Dumas, CF, Farrell, CH & Hall, JW (2002), 'Impact of Low-Intensity Hurricanes on Regional Economic Activity.', *Natural Hazards Review*, vol. 3, no. 3, pp. 118-25.

Cimellaro, GP, Reinhorn, AM & Bruneau, M (2010), 'Seismic resilience of a hospital system', *Structure and Infrastructure Engineering, Taylor and Francis*, vol. 6, no. 1, pp. 127-44.

Environmental impacts of floods- Febriary (2011), Wildlife Queensland, viewed April 08, <http://www.wildlife.org.au/news/2011/flooding5.html>.

Flooding on roads in Queensland, (2010), viewed April 03, <http://www.tmr.qld.gov.au/~/media/communityandenvironment/Research%20and%20education/Fact%20sheets/flooding.pdf>.

Frangopol, DM & Saydam, D (2011), 'Performance indicators for structures and infrastructures', *Structures Congress, ASCE*, pp. 1215-26,

Hudson, S, Comie, D, Tufton, E & Inglis, S (2012), 'Engineering resilient infrastructure', *Civil Engineering Special Issue*, vol. 165, no. CE6, pp. 5-12.

Increasing Queensland's resilience to inland flooding in a changing climate (2010), Queensland Government, viewed April 08, <http://www.ehp.qld.gov.au/climatechange/pdf/inland-flood-study.pdf>.

Kong, D, Setunge, S, Molyneaux, T, Zhang, G & Law, D (2013), *Structural resilience of core port infrastructure in a changing climate, Enhancing the resilience of seaports to a changing climate report series*, National Climate Change Adaptation Research Facility, Gold Coast.

Lamond, JE & Proverbs, DG (2009), 'Resilience to flooding: lessons from international comparison', *Urban Design and Planning*, vol. 161, no. DP2, pp. 63-70.

Lian, C, Santos, JR & Haimes, YY (2007), 'Extreme Risk Analysis of Interdependent Economic and Infrastructure Sectors', *Risk Analysis*, vol. 27, no. 3, pp. 1053-64.

McDaniels, T, Chang, S, Peterson, K, Mikawoz, J & Reed, D (2007), 'Empirical framework for characterizing infrastructure failure interdependencies', *Journal of Infrastructure Systems*, vol. 13, no. 3, pp. 175-84.

Oh, EH, Deshmukh, A & Hastak, M (2010), 'Vulnerability Assessment of critical infrastructure, associated industries, and communities during extreme events', *Construction Research Congress*, pp. 449-58.

Queensland floods: The economic impact Special Report, (2011), viewed April 03, <http://www.ibisworld.com.au/common/pdf/QLD%20floods%20special%20report.pdf>.

Rebuilding a stronger, more resilient Queensland, (2012), viewed April 03, <http://www.qldreconstruction.org.au/u/lib/cms2/rebuilding-resilient-qld-full.pdf>.

Reed, DA, Zabinsky, ZB & Boyle, LN (2011), 'A framework for optimizing civil infrastructure resilience', *Structures Congress, ASCE*, pp. 2104-12.

Rinaldi, SE, Peerenboom, JP & Kelly, TK (2001), 'Identifying, understanding, and analyzing critical infrastructure interdependencies', *IEEE Control System Magazine*, pp. 11-25.

Rose, A, Oladosu, G & Liao, S-Y (2007), 'Business Interruption Impacts of a Terrorist Attack on the Electric Power System of Los Angeles: Customer Resilience to a Total Blackout', *Risk Analysis*, vol. 27, no. 3, pp. 513-31.