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Resilience-based Bridge Asset Management

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ABSTRACT: Bridges are typical vulnerable links within transportation networks and are susceptible to damages induced by natural or man-made hazards. Their closures can have repercussions on economies, human health and community functionality; hence their resilience is of vital importance. This paper presents a practical framework for assessing the resilience of bridges which could subsequently be used to inform the prioritisation of resources and strategic investments in bridges and surrounding regions. This framework is built around four dimensions of infrastructure and network, place and environment, organization and governance, and economy and community. Each dimension has associated which can be assigned a score based on the best-case and worst-case scenario descriptors. The application of this holistic framework is demonstrated through the original I-35W bridge. The proposed framework is easy to use by bridge practitioners and planners and is a step towards resilience-based bridge asset management.

KEYWORDS: resilience; bridges; disaster preparedness; recovery.

1 INTRODUCTION

There is an increasing pattern in the frequency and intensity of damage caused by severe adversities, such as natural disasters, structural deterioration and infrastructure accidents, to economies and mankind. Data accumulated between 2005 and 2015, from the implementation of the Hyugo Framework for Action, revealed that total economic losses experienced in relation to natural disasters was in excess of 1 trillion pounds; a total of 700,000 lives were lost and 1.4 million injuries were induced (UNDRR, 2015). These worldwide statistics highlight the threats that disasters impose on economic health, soundness of physical assets and human safety, enforcing that it is critical to expand governance for resilience assessment and disaster planning. Transportation networks hold numerous interdependencies with the community, economy, environment and other critical sectors, and their resilience plays a contributing role in defining city resilience as a whole. This paper focuses on the resilience of bridges as they are typically susceptible links within transportation networks and their management requires timely resource allocations and strategic project investments. Traditional risk-based approaches consider the potential for hazard induced negative impacts on bridge infrastructures (MacAskill and Guthrie, 2013), and are often based on the assessment of intrinsic environmental influences such as location, geology and climate. However, they do not adequately address recovery trajectories of the bridge or the communities it serves. Agarwal (2015) argued for robust models for spatial and temporal analysis of infrastructure systems that would allow a range of social behaviours and recovery options to be explored.

This paper presents an integrated resilience framework which incorporates consideration of potential hazards to a bridge as well as impact on bridge, organization, community, local economy and environment, and recovery thereof. Bridge resilience is defined in the next section followed by a critical review of existing general and bridge specific resilience assessment schemes. This is supplemented by an analysis of selected bridge failures. The proposed framework is then presented and demonstrated through the assessment of the resilience of the I-35W Bridge

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using the best- and worst- case scenarios. Finally, conclusions are drawn and future research directions are suggested.

2 BRIDGE RESILIENCE

There are many definitions of resilience in literature and a few are listed in Table 1 (see Rus, Kilar & Koren, 2018 for more). The following are common to all definitions: the occurrence of a disruptive event; system performance before, during and after an event; and the idea that resilience is time-sensitive.

Table 1. Definitions of resilience in literature.

Source	Definition
Bruneau et al. (2003)	"The ability of social units (e.g., organisations, communities) to mitigate hazards, contain the effects of disasters, and carry out recovery activities in ways that minimise social disruption and mitigate the effects of future disasters."
UNDRR (2015)	"The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner"
Minaie and Moon (2017)	"The ability to maintain a level of robustness during or after an extreme event, and to return to a desired performance level in the shortest possible time to minimise the impact on the community"

The fundamental function of a bridge is the provision of service (carrying of traffic) to the transportation network. As such, bridge resilience shall be defined here as the ability of a bridge to withstand structural degradation or the loss of ability to carry traffic in the event of a disruption, and the capacity of the bridge to return to pre-disruption (or improved) structural form or service levels in a timely manner whilst minimising social, environmental and economic impacts and mitigating the effects of future disruptions.

Bruneau et al. (2003) introduced the fundamental concept of the 'resilience triangle' (the dark area in Figure 1) which has been referred to and used by many researchers in the quantitative analysis of resilience. Bocchini and Frangopol (2011) further developed Bruneau's concept to consider actual resilience instead of loss of resilience and also introduced a normalisation factor, t_h. Actual resilience is found as the area beneath the performance curve (lightly shaded area in Figure 1). This has the advantage of enabling resilience calculation for recovery paths that do not result in a final performance level of 100%. It is also considered to be the most practically viable and easy to understand equation by bridge practitioners due to its basis on the well-defined concept of the resilience triangle and normative capabilities.

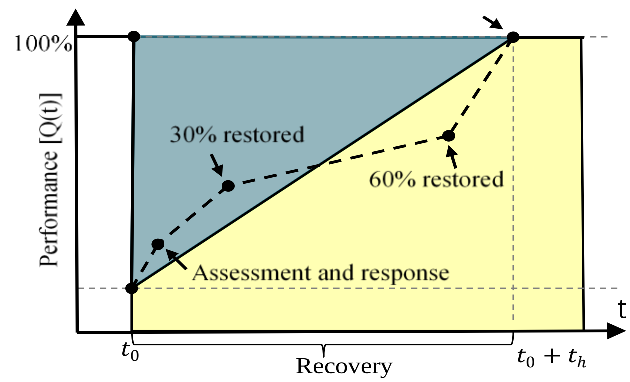

Figure 1. Resilience concept (adopted from Minaie & Moon 2017).

Bruneau et al. (2003) define four properties of resilience, also known as the 4R's. These are discussed below in relation to bridges:

Robustness: The intrinsic ability of a bridge to withstand a natural or man-made hazard without suffering degradation to its structural form.

Redundancy: This property assesses the extent to which a bridge, or the network it is part of, can satisfy average daily traffic levels in the event of disruption, degradation or loss of functionality.

Rapidity: The capacity to restore the pre-disruption level of service in a timely manner that mitigates losses and protects against future hazards.

Resourcefulness: The ability to organise and manage people, problems, and materials (financial, technological, physical and informational) including the prioritisation and allocation of resources prior to disruption, as-well as effective mobilisation and use of resources during and post-disruption.

3 EXISTING RESILIENCE FRAMEWORKS

Hosseini et al. (2016) conducted a comprehensive review of resilience quantification models for engineering systems. Two categories of models were classified: (a) qualitative and (b) quantitative; these are also recognised by Rus, Kilar & Koren (2018). Both categories have been reviewed here and are segregated into general frameworks and bridge specific frameworks.

3.1 *General resilience frameworks*

Brownjohn and Aktan (2013) discuss the issue of how to leverage only useful and reliable information from bridge structural monitoring and condition assessment valuations to inform effective decision support systems. Aside from the common metric or framework approaches, Brownjohn and Aktan (2013) ultimately conclude three suggestions for improving bridge resilience: increasing funding for international and large-group research agendas, incorporating operation and maintenance focuses into the education of engineers at all levels (under-graduate, post-graduate and doctoral), and encouraging fusion with specialties outside of the engineering domain to enforce the resilience paradigm as a multi-stakeholder initiative.

Arup's City Resilience Index (CRI) (Arup, 2016) generates a systemic resilience definition through the use of resilience 'dimensions' and 'indicators' which are each provided with numerical ratings based on qualitative or metric assessments. Four dimensions of city resilience are defined: health and well-being, economy and society, infrastructure and environment, and leadership and strategy, which respectively address factors in relation to people, organisation, place and knowledge. Collectively, the qualitative judgements and the reliability of objective data provided by assessors are evaluated to generate the final index score profile.

UNDRR's Disaster Resilience Scorecard for Cities (UNDRR, 2015) follows a similar principle to Arup's CRI and provides a set of semi-quantitative assessments which describe city resilience to acute shocks against UNDRR's 10 Essentials for Making Cities Resilient. The scorecard monitors the implementation of the Sendai Framework for Disaster Risk Reduction 2015-2030, which is the successor to the Hyugo Framework, and is the current agenda in place providing global guidance on resilience assessment and risk reduction. To consult each Essential, critical sub-questions are introduced; each assigned a score by relevant stakeholders.

Parajuli et al (2020) presented a multidisciplinary framework for resilience of educational communities which not only aims to create better school buildings but also supporting infrastructure, institutions and communities that are resilient to different shocks and stresses.

Arup's CRI and UNDRR's Scorecard allow governments to evaluate an over-arching baseline measurement of disaster resilience and prompt the creation of city-wide resilience action plans. In support of Brownjohn and Aktan's (2013) conclusions, they facilitate the improvement of awareness of resilience challenges whilst encouraging co-operation between city stakeholders. The segregation of domains enables the identification of sector-specific focuses and qualitative assessments account for differing values held by bridge owners. Common to all these frameworks is the assessment of organisational preparedness. Bridge resilience is inherent however it can be improved by preparatory actions that are put in place prior to disruption. These are efforts that can impact system absorptive and restorative abilities (Vulgrin et al., 2011) and encompass governance, funding and planning. The assessment of preparedness mainly embraces the property of Resourcefulness with some application of Redundancy (i.e. outlining alternative routes), and overall assesses the organisational means to ameliorate resilience levels (Minaie and Moon, 2017).

3.2 *Bridge specific frameworks*

Minaie and Moon (2017) produced a mathematical framework which ranks the resilience of bridges to natural disasters and applied the framework against case studies of bridges affected by Hurricane Katrina. The framework is based on the implementation of a simplified single-path recovery resilience triangle thus focusing on the calculation of system Robustness and Rapidity. Robustness is calculated as a function of hazard probability and the vulnerability of the system, and rapidity of reaching full restoration is figured as a function of the size of the area affected by the bridge trauma, and the severity of the imposed hazard.

Vulgrin et al. (2011) quantified infrastructure resilience as a function of the total recovery-dependent costs (RDR) required post-disaster, where a lower RDR value indicates higher resilience. They opin that consideration of cost in the measurement of resilience is imperative. An accompanying qualitative analysis model is conceptualised which assesses the intrinsic system characteristics that have impact on resilience by either reducing or increasing the system's RDR. The qualitative framework evaluates three system capacities: absorptive capacity, adaptive capacity and restorative capacity.

Freckleton et al. (2012) rated transportation network resiliency as low, medium or high based on 16 metrics which feed into 4 higher tier metric groups: metrics related to the individual, community, economy and to recovery. Metrics are mostly assigned objective indicators such as the number of alternative transportation modes available or the density of specific resources per kilometer squared, whilst others are ranked based on discrete qualitative descriptions.

Quantitative frameworks, such as that proposed by Minaie and Moon (2017), have the merit of being practicable and offer clear measurements for elements that would otherwise be difficult to assess qualitatively. Yet, the work performed by Freckleton et al. (2012) and Vulgrin et al. (2011) infer that quantitative and qualitative assessments are complementary and neither should be neglected.

4 CASE STUDY ANALYSIS

In order to identify the critical measures that influence bridge resilience it is vital to first evaluate well-known cases of previous bridge disaster events. This enables insight into what a successful (and unsuccessful) emergency response involves, how communities effectively prepare for a disaster event, and what efforts require strengthening in order to improve inherent bridge resiliency. In this section, three unique case studies are reviewed and the resilience indicators offered by each case identified.

4.1 *M1 Mototorway under-bridge fire, UK, 2011*

The M1 is a key north-south arterial route in the UK's transport network, inherently causing great travel disruptions following its closure. The fires were initiated in an area surrounded by residential houses, businesses and rail infrastructure leading to inevitable evacuations and interruption to rail services; had the bridge been located in a rural setting surrounded by little infrastructure, these disruptions would not have been induced. The urban setting also posed difficulties concerning working conditions, wherein Highways England (HE) dealt with confined spaces and trouble in maneuvering the equipment required for repairs (Meikle, 2011). Fire fighters played the essential role of taming the blaze prior to the initiation of engineering works, making it clear that the availability, accessibility and engagement of emergency services are key elements which influence recovery.

4.2 *Morandi Bridge collapse, Italy, 2018*

The Morandi Bridge was constructed from pre-stressed concrete; this was seen as innovative at the time of construction yet understanding of the technology was still in its infancy (Calvi et al., 2018). Many realisations of Polcevera's design flaws have been realised since its erection. Questions were raised about the regularity and scrupulousness of maintenance performed by bridge managers, Autostrade per l'italia, however it is common knowledge that the bridge had undergone continuous preservation during its lifetime and the issue is instead raised regarding the inadequate advancement of the surveillance systems used (Hansford, 2018). The bridge spanned over residential land and a 150m width of railway, thus immediate evacuations were executed employing the work of hundreds of volunteers. There is no doubt that the failure largely destabilised the socio-economic activity of the area as divulged by Rania et al. (2019); however community efforts including fundraisers and exhibitions were initiated to remedy community cohesion.

4.3 *Hammersmith Flyover, London, UK, 2011*

TfL's (Transport for London) implementation of Europe's largest structural monitoring programme using 400 acoustic monitors found internal tendon wire breaks to be occurring on a daily basis – a rate much higher than other comparable structures in the UK – calling for the immediate closure of the major link 6 months before the 2012 Olympics. The acoustic monitoring systems used were the "central tools in avoiding a catastrophic collapse" (Clark, 2019) and the scale and level of technology must be credited. Prior to the discovery, TfL distributed their Emergency Preparedness Plan (EPP), which detailed alternative routes, personnel responsibilities and 'trigger levels' which require the action of closure to stakeholders in the London Borough of Hammersmith and Fulham. This ultimately enabled a rapid response to the event of a major defect discovery. The success of the second phase of strengthening was vastly dependent on the attainment of funding and highly developed resources including specialist contractors, ultra-high strength concrete and a bespoke external pre-stressing system designed by Freyssinet. Total works amounted to £100M (Cambridge Enterprise, 2016).

5 PROPOSED BRIDGE RESILIENCE FRAMEWORK

Following a synthesis of concepts emerging from literature and case study analysis, four domains have been identified which contribute towards bridge resilience: organisation and governance; infrastructure and network; community and economy; and place and environment. The proposed framework is thus divided into these domains with associated indicators as shown in Figure 2. The following sections provide elaborations for each domain as well as justifications for key indicators.

5.1 *Organisation and governance*

Effective management of resources is essential in certifying an integrated disaster response, thus, this domain measures the efforts of actors (see Section 5.5) in making decisions and responding to emergencies. London's Hazard Risk Register (HRR) is updated bi-annually (London Resilience Group, 2019) therefore bi-annual HRR appraisal is assumed to be good regularity. The Federal Emergency Management Agency (FEMA) states that response within 48 hours can "allay the effects of a disaster" (Freckleton et al., 2012). Freckleton et al. (2012) consider the first 2 hours to be the most critical response period and additionally propose a 1-5 ranking scale for network management practices where a higher number indicates better management. These notions have been collectively considered in the assessment of disaster response. If bridge closure is well anticipated, warnings can be released well in advance. Bridge users can then take active efforts in avoiding the bridge if a significant portion of the population (>75%) is reachable by such warnings.

Figure 2. Proposed bridge resilience framework.

5.2 *Infrastructure and network*

Structural soundness and the importance of a bridge within the transportation network are vital indicators of how robust the bridge will be to specific hazards and how traffic performance may be impacted. In the appraisal of bridge condition, engineering agencies should be encouraged to gather and utilise objective data as much as possible and should have thorough comprehension of the bridge's design and construction. An analysis of annual average daily traffic (ADT) flow and distribution data for major and minor roads has been found useful to determine the criticality of bridge. A bridge that lies on more important transport routes is expected to carry a higher ADT and the closure of such a bridge would induce greater traffic build ups; if tailbacks disperse within a short time, it is suggested that the traffic network can effectively cope with the loss of the bridge and high resilience is thus indicated. Regarding the facilitation of repair, a simpler bridge (i.e. single span) is quicker and easier to restore than a complex bridge. Furthermore, if a disaster event has occurred within the past few months, emergency resources may be exhausted making responses less efficient.

5.3 *Community and economy*

This domain relates to the ability of social and economic systems to maintain community well-being and minimise economic losses post-disaster. The disaster preparedness of communities and businesses increases their ability to continue functioning as normal. In order to effectively support community networks, governments should have a sound understanding of the relative risks that groups are vulnerable to; this is achieved through the maintenance of a Community Risk Register. Ultimately, human health hazards imposed by bridge disasters can be managed by the sufficient training and resourcing of health services, and in support of those who are negatively affected, community awareness initiatives may be launched.

5.4 *Place and environment*

The climate that a bridge is susceptible to and the features of a bridge's local place have influence on the severity of trauma induced as well as on the speed of recovery. It is assumed that more severe hazards are likely to cause greater structural damage. The issue of a lack of space is expressed by the cases of the Morandi Bridge and Hammersmith flyover; larger open space would facilitate the transportation, storage and use of emergency equipment and would thus increase the speed of repairs. Critical infrastructures close to the bridge are likely to be negatively impacted by the same hazard as the bridge, whilst critical infrastructures that are further away may induce extended travel times and difficulty in accessing them during an emergency. Thus, the middle distance range is desirable (Freckleton et al., 2012). Communities require access to emergency facilities (hospitals, police stations) and foods and goods providers (groceries, post offices, gas stations); the availability of such resources is measured as the number of suppliers that are available within, for example, 3-9 mile distance range.

5.5 *Using the framework*

Resilience assessment is performed by 'actors' (or 'assessors') who are the relevant individuals, groups and organisations that hold responsibilities in improving bridge resilience. They include, as defined by the Cabinet Office (2019): governments, engineering agencies, utility distributors, businesses, higher education, transport agencies and emergency services. Central actors are the groups who hold the necessary convening powers and skills for bridge resilience planning. Governments are the main central actors followed by engineering and transport agencies that hold specific experiences in relation to infrastructural and network resilience.

Indicators are scored 1, 2 or 3 based on indicator descriptor criteria which outline the respective best- and worst-case scenarios. Only a few are listed in Table 2 but are available in Basilio (2020). Assessors assign the score for which the description is most representative of their situation; the best case scenario is assigned a score of 3, the worst case scenario is assigned a score of 1, and a score of 2 should be allocated if the situation aligns with neither the best- nor worst-cases. Two types of descriptors are specified: (a) subjective descriptors; and (b) objective descriptors for which simple numerical metrics have been decided (i.e. the number of alternative routes available). Subjective descriptions enable high tier assessments which require little time or effort thus increasing practicability; however, where subjective description is too vague and cannot effectively describe conditions, objective descriptions have been allocated. Once indicator scores have been decided, domain scores are calculated by averaging the scores of the indicators within each domain allowing assessors to identify which domain(s) perform worse than others. Finally, the overall bridge resilience score is calculated by averaging the domain scores though weights may be assigned in future work. Such scores can enable a classification of bridges according to their resilience.

Table 2. Bridge resilience: example (best-case) scenarios.

Indicator	Example scenario
Hazard awareness and integration	Public and all actors have unified understanding of specific local hazards and likelihood of occurrence Hazard risk register updated bi-annually
Monitoring & evaluation practices	Analytical, visual, non-destructive evaluations (NDE) and experienced engineering judgement techniques used during inspections
Community risk mapping	High level mapping of community vulnerabilities Effective prioritisation of resources to community networks
Nearby critical infrastructure	Bridge closure or failure will cause no or minor disturbance to the performance of other critical sectors

6 EXAMPLE APPLICATION: I-35W BRIDGE

To illustrate the application of the framework, the case of the collapse of the Interstate 35W (I-35W) Mississippi River Bridge in Minneapolis, Minnesota is used. The bridge first opened to traffic in 1967 and was 581m long comprised of 8 lanes and 14 spans – three of which catastrophically collapsed on August 1, 2007 killing 13 people and injuring 145 others (NTSB, 2008). A replacement bridge was completed in September 2008. The assessment performed in this section relates to the original bridge and uses information available in the public domain including records from the Minnesota government website (mn.gov), Minneapolis Department of Transportation (MnDOT), Twin Cities Urban Area (TCUA), FEMA and two key reports: NTSB (2008) and USFA (2007). Some assumptions have been made based on available information and are denoted with an asterisk (*).

6.1 *Organisation and governance*

Minnesota hazard mitigation plans are annually updated and despite the 2007 plan not being found in the public domain, it is assumed to exist in abidance with the Disaster Mitigation Act of 2000*. The roles of emergency relief groups such as fire, law enforcement and public works are clearly established by the City's Incident Command System (ICS). Further evidence of public involvement in State policy decision making includes the establishment of community-based forums such as the Minnesota Department of Health (MnDOH) Mental Well-being and Resilience Learning Community. Specialist and highly developed equipment and resources are provided by FEMA in the event of an emergency, and other resources are offered by the TCUA region including a collapsed-structure rescue team, and a hazardous materials team. It is assumed that emergency responders will arrive on site within 2 hours* thanks to the City's $5.2 million computer aided dispatch system. Police officers, 800MHz radios and variable message signs (VMS) are additionally available to manage any traffic redistribution, thus achieving an excellent* level of Network Management. Regarding financial capacity, FEMA offers up to $5M of federal funding for relief efforts, and finances are well managed by Minnesota's Finance Department. All responders are well-trained under the National Incident Management System (MnNIMS) and in 2002, 80 officials attended a management course to test the city's Emergency Operations Plan. The bridge's collapse was unforeseen, however the use of VMS and major communications channels is assumed to deliver route closure warnings to ≥50% of the population*. Minneapolis' Public Information Officer establishes consistent communications with public information officials, therefore reputational damage is assumed to be well managed and mitigated*.

6.2 *Infrastructure and network*

In abidance with the US Federal Highway Administration (FHWA) National Bridge Inspection Standards, MnDOT carried out annual bridge examinations, which included in-depth fracture-critical inspections using ultrasonic and NDE techniques. A black ice anti-icing system was put in place during the bridge's second major renovation in 1998 and was due to be replaced in 2007, indicating that it was in need of restoration at the time of collapse. MnDOT's 2006 inspection report suggested a National Bridge Inventory (NBI) deck rating of 5 which indicates fair condition. The respective NBI ratings for the sub- and super-structure were 6 (satisfactory) and 4 (poor); overall classifying the bridge as 'structurally deficient'. These ratings are based on the NBI bridge condition rating standards, where higher numbers indicate better conditions. The bridge was recognised to be in need of maintenance, repair or eventual rehabilitation (but the insufficient thickness of the gusset plate remained unknown). The bridge's design was based on the 1961 American Association of State Highway Officials (AASHO) Standard Specifications for Highway Bridges and the 1964 MnDOT Standard Specifications for Highway Construction. It is notable that the fatigue behaviour of steel was not fully comprehended at this time. The bridge carried an ADT of 141,000 vehicles and serves a major interstate highway. Two possible alternative routes, the I-94 and the arterial Trunk road Mn280, are of a similar road classification and have sufficient capacity (Levinson and Zhu, 2010). Traffic tailbacks are presumed to clear within one day*.

6.3 *Economy and community*

The Minnesota Department of Community Planning and Economic Development provide expansion opportunities to local businesses, however, their 2004-2008 Business Plan states that there had been no efforts to determine the effectiveness of their work. Therefore the perceived number of businesses with reviewed business plans prior to the collapse is unclear. For scoring purposes, the range of 20-60% is assumed*. The Office of Sustainability conducts vulnerability assessments of communities indicating sound governmental understanding of susceptible community networks. Catastrophic bridge collapses are reputed to cause major injuries and loss of life. This was indeed the case for the I-35W. Similarly, negative impact on community cohesion is expected. To mitigate these, local charities such as Survivor Resources, non-profit organisations such as the Minnesota Community Foundation, and community groups offer monetary donations, advice and counselling services to persons affected by disaster events. All schools are required by the Minnesota Department of Education to schedule regular safety drills and MnDOH has curated a home-guide which encourages families to create personal disaster plans, gather emergency supplies and document key contact information. These guides are available online and are assumed to be distributed to the public*. The Division of Homeland Security and Emergency Management (HSEM) Citizen Corps engages individuals in volunteer activities that support all stages of emergency management. Community capabilities are therefore well recognised, managed, and integrated into emergency response.

6.4 *Place and environment*

The bridge is located within a 100 year flood plain and spans over a navigable channel. Minneapolis has low risk for hurricanes and the region seismicity is Seismic Design Category A (defined by ASCE 7-05 design standards) with low risk of earthquakes. A geological survey completed by the University of Minnesota recognises a history of minor to moderate earthquakes in Minneapolis, with the largest earthquake being the 4.6 magnitude Morris Earthquake of 1975 (Chandler, 2014). Renovations performed on the bridge in 1977 and 1998 resulted in an increase of the bridge deck thickness, and subsequently, an increase in the bridge dead load by around 20% contributing to the risk and hazard of bridge collapse. Interstate highways are the highest classification of arterial roads designed for long-distance travel and link major urban areas of the United States. Due to the interconnectivity and complexity of interstate highways, closure/failure of the I-35W bridge is considered to impact regional traffic. The heavy urban development of the area means that multiple infrastructures near to the bridge are vulnerable to damage including residential houses, business complexes, educational institutions such as the University of Minesota, and sports infrastructures such as the U.S. Bank Stadium. The city's urban design and the spanning of the bridge over the Mississippi river indicate some difficulties in the transportation and loading of equipment thus clearing of land and the utilisation of nearby open spaces may be required to set up team command posts and bases for equipment storage. Available community amenities located within a 3-9 mile distance range from the bridge include several emergency facilities such as the UMN, Minneapolis Police Department and Hennepin County Medical Centre, as well as a large number of food and goods providers.

6.5 *Results and discussion*

Figure 3 displays the indicator and domain scores for the I-35W case study. The external numbers correlate to the indicators shown in Figure 2. The grey radar diagram shows the individual indicator

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scores and the black dashed-line displays the averaged scores for each domain. Averaging the domain scores achieves an overall resilience score of 2.2/3.0 which classifies the bridge as having moderate resilience.

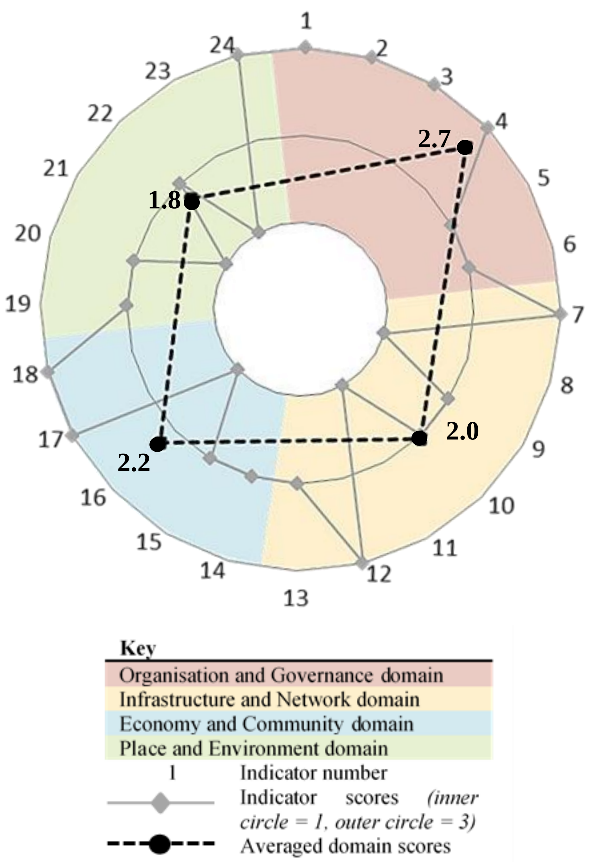

Figure 3. Resilience score mapping for I35W bridge.

The bridge scores the highest in the organisation and governance domain which proposes that the City of Minneapolis is well prepared for a disaster. The bridge scores the lowest in the place and environment domain; this is inherent given the urban location of the bridge and the proximity of other critical infrastructures (business, residential, educational, transport, water, utilities, health). The domain with the next lowest score is the infrastructure and network domain due to the poor condition of the bridge and the deterioration of the anti-icing system.

To improve the resilience the bridge, it can be recommended to implement the use of NDE and ultrasonic techniques in earlier inspections. The establishment of designated city emergency command bases for land and water disaster relief teams may also prove useful due to the congested urban design and lack of available nearby space.

7 CONCLUSION

In this paper, a new and practical scoring framework for the appraisal of bridge resilience has been presented. The framework diverges from purely risk-based methodologies to integrate social, economic, environmental and organisational aspects as well as capabilities to recover in a timely manner. Accordingly, four domains of resilience have been recognised which are: governance and organisation; infrastructure and network; economy and community; and place and environment. Indicators within each domain have been defined. They are scored on a 1 to 3 linear scoring index based on best- and worst- case descriptors. Domain scores are then computed by averaging respective indicator scores, followed by the averaging of domain scores to achieve the overall resilience score. These scores can be related to a discrete resilience classification system after further benchmarking studies. From an application of the framework to the case of the I-35W Bridge, it is clear that resilience assessments can enable actors to progress all stages of emergency management. This framework can be applied to a number of bridges allowing the high tier resilience screening of bridge inventories, thus informing the prioritisation of resources to certain bridges. Nevertheless, improvements to the framework can still be made such as the refinements to the indicators and scoring following further case study analyses.

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