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Bridge and transport network resilience – a perspective

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Abstract

Bridges and critical transport infrastructure (CTI) are primary infrastructure assets and systems that underpin human mobility and activities. Loss of the functionality of bridges has consequences on the entire transport network, which is also interconnected with other networks, therefore cascading events are expected in the entire system of systems, leading to significant economic losses, business, and societal disruption. Recent natural disasters revealed the vulnerabilities of bridges and CTI to diverse hazards (e.g. floods, blasts, earthquakes), some of which are exacerbated due to climate change. Therefore, the assessment of bridge and network vulnerabilities by quantifying their capacity and functionality loss and adaptation to new requirements and stressors is of paramount importance. In this paper, we try to understand what are the main compound hazards, stressors and threats that influence bridges with short- and long-term impacts on their structural capacity and functionality and the impact of bridge closures on the network operability. We also prioritise the main drivers of bridge restoration and reinstatement, e.g. its importance, structural, resources, organisational factors. The loss of performance, driven by the redundancy and robustness of the bridge, is the first step to be considered in the overall process of resilience quantification. Resourcefulness is the other main component of resilience here analysed.

keywords: bridge, transport, network, multiple hazards, climate change, restoration, reinstatement, resilience, monitoring, perspective, SDGs 9 & 13

1 Introduction

Bridges are important components of transport networks (Guikema and Gardoni, 2009), yet they are the most relevant assets as they are key points within the network, being their recovery after a loss of functionality and/or safety much more complicated than for other assets. Their restoration is challenging and costly (Smith et al., 2021; Rokneddin et al., 2013). Bridges are disproportionately exposed to and hit by multiple natural and human-induced hazards, e.g. floods (Argyroudis and Mitoulis, 2021) and earthquakes (Freddi et al., 2021), collisions, overload, whilst they deteriorate due to corrosion, fatigue and accumulation of other stressors accelerate their degradation (Akiyama et al., 2020; Wardhana and Hadipriono, 2003). The fragility of bridges and transport networks to single and multiple hazards is described in Argyroudis et al. (2019). Table 1, adopted by the latter publication describes the effects of critical natural hazards on bridges, but the table has been extended to include potential risks to climate change as per Nasr et al. (2019) and potential restoration and/or adaptation measures, based on the literature and engineering judgement. It is noted that the hazards relating and/or influenced by climate change might be compound events, in which case two or more events that are not necessarily themselves extreme happen simultaneously or shortly after one another leading to an extreme impact (IPCC, 2012).

This paper identifies compound hazards related to climate change and the level of vulnerability, i.e. the damage (fragility) and functionality loss (operability) that is expected on bridges and transport networks during and after the occurrence of such stressors. The paper discussed **single hazards**, which are partially covered by the international literature, but the emphasis is placed on **multiple hazards** and provides the sequence of such stressors based on expert judgement, the literature and past events. The paper also discusses the need for the development of bridge restoration models, which are necessary for feeding resilience assessments, to prioritise and adapt to climatic deviations, which are widespread, spatiotemporally variable and depend on organisational and financial constraints that affect the speed of recovery.

Fragility and functionality losses are discussed in the following subsections of Introduction along with available restoration models for bridges and transport networks. Focusing on large scale infrastructure resilience, Section 2 is devoted to discuss how resilience can be affected not only by the main hazard event but also by cascading effects. Furthermore, available simulation approaches are also discussed to model different physical and technological layers, and their interdependencies to assess the community response to disasters. Section 2 also analyses in detail resilience components with reference to bridges in transport networks. Section 3 presents the beneficial effects to resilience that come from the implementation of Structural Health Monitoring and Structural Control, to identify damage occurrence and to compensate performance losses, respectively.

1.1 Fragility and functionality loss of bridges and networks

The fragility of bridges has been extensively discussed in the literature for a range of hazards, i.e. single and multiple hazards, compound events, such as climate change, and consequences of their damage have been extensively researched (Dong and Frangopol, 2015; Morelli and Cunha, 2021). For example, combined flood-induced scour and earthquake on the fragility of bridges has been studied by Dong et al. (2013), Kameshwar and Padgett (2014), Yilmaz et al. (2017). The influence of deterioration effects, such as corrosion on the seismic fragility has been investigated by Ghosh and Sood (2016) among others.

Table 1. The effects of critical natural hazards on bridges, the impact of climate change, damage and relevant mitigation measures (adopted and revised by Argyroudis et al, 2019 – does not include human-induced damage).

Hazard	Exacerbated by climate change?*	Bridges affected	Damage and/or Impact	Mitigation adaptation measures
fluvial/river flood due to extreme precipitation (including overbank and flash floods)	yes frequency and intensity of flash floods and precipitation is expected to increase	bridges over a river or stream	scour of piers/abutment foundations (general, contraction, local scour)	improve existing scour protection system; retrofitting of bridge foundations with additional piles; bridge scour monitoring; bridges tolerant to settlements eg with bearings (see more in Mitoulis et al., 2021; Misra et al., 2020)
			hydraulic forces on the piers, abutments and deck	
			impact on the deck due to overtopping; failure of bank and riprap protections	
underground water; soil salinity	yes, in some cases it might reduce	coastal roads, causeways over a lake or sea	corrosion of reinforcement; degradation of concrete strength	improve/maintain drainage; component/asset replacement and strengthening; improvement of foundation; anti-corrosion measures; component replacement
sea-level rise and storms (flood & storm surge) / pluvial flooding	yes, in some cases it might reduce	coastal roads, causeways over a lake or sea, foundations	scour effects; overtopping and wave erosion, softening by soil saturation, seepage (internal erosion), piping, corrosion	renewal/replacement considering the sea level rise; adaptation measures; improvement of foundation
extreme heat and drought	yes, prolonged heatwaves	long-span bridges & bridge components, change in material properties; damage to bridge pavement	expansion of the deck, impact on the structural behaviour/strengths; restrained thermal stresses; damage to pavement	use of new/larger expansion joints; use of bearings with larger movement tolerances; frequent replacement of bearings; improvement to pavement

extremely low temperatures / cold spells	yes, in some cases it might reduce	long-span bridges & bridge components, change in material properties	contraction of the deck, impact on the structural behaviour/strengths	use of new/larger expansion joints; use of bearings with larger movement tolerances; more frequent replacement of bearings
wind; storms	yes	cable-stayed and suspension bridges; other flexible bridges e.g. pedestrian; cable vibration	aerodynamic effects (vortex shedding, galloping, flutter); turbulence; failure of secondary components eg lightning; rain-wind cable instabilities	use dampers and stiffeners; use spoilers
earthquake (ground shaking, ground failure due to liquefaction or fault rupture)	no	all bridges with low fundamental periods (e.g. <3 s)	different damage modes to structural elements (piers, abutments, bearings, foundations) and geotechnical assets (settlement, heave, rotational/slump failures etc).	strengthening/replacement of bearings; restrainer cables; seat extension; steel, fibre composite or steel jacketing of piers; pier cap strengthening or replacement; energy dissipation devices
any hazard that leads to impacts due to geographic interdependencies (mainly in urban environments)	no	all bridges carrying utilities; lifelines	damage of cables (electric power, fibre-optic communication) or pipes (water, gas) carried by the bridge	protection of pipes through the coating, wrapping or fibreglass shields; provision for shut-off systems for gas, oil and hazardous material pipes

*extensive research on the impact of climate change as a compound of events on bridges can be found in Nasr et al., (2019).

The capacity loss of bridges, i.e. damage, is usually correlated with the functionality loss of the bridge and, as a consequence, to the network operability, e.g. traffic volume, (Mackie & Stojadinović, 2006). However, the latter is usually based on expert judgement and is rarely estimated on the basis of the duration, duration overlap and sequence of restoration and mitigation tasks and other non-engineering factors, e.g. the importance of the bridge, the accessibility of the site of the affected asset (Mitoulis et al., 2021). As a result, a bridge might have minor damage after a hazard occurrence, e.g. a flood, but is kept open to serve traffic, as there might be no alternative routes, which is the case in local small networks of low redundancies.

1.2 Restoration and reinstatement of bridges and networks

In transport networks, bridges are often the most important components and their operation is of paramount importance. Even in networks for which most of the unserviceable joints can, in most cases, be bypassed, bridges are usually bottlenecks (Frangopol and Bocchini, 2012). There are two important parameters for which optimisation of bridge restoration would be appropriate and these are the resilience of the network and the cost, as per Bocchini and Frangopol (2012a; 2012b), Twumasi-Boakye and Sobanjo (2018). This requires a different perspective in the modelling of natural extreme events and involves models for the interaction between the individual components (i.e. bridges) and the overall network. Costs include the physical losses, i.e. the one relating to the structural damage and the consequent repair cost. In addition, costs include the indirect losses (Kilanitis and Sextos, 2019), which overwhelm the monetary loss owing to the structural damage - as this can be in some cases one order of magnitude higher than the direct physical losses (Argyroudis et al., 2020). These indirect losses (Dong and Frangopol, 2015) are owed to the loss of functionality, i.e. reduction in traffic capacity (Burns et al., 2021), but also due to the disturbance to social and professional life, business interruption (Hofer et al., 2018), additional transportation cost and environmental implications (Kiremidjian et al., 2007; Dorra et al., 2013). Interdependencies affect not only assets within the same network (e.g. transport network), but also other networks (e.g. energy and water networks) which have physical, logical, proximity and other dependencies on the transport network (Rinaldi et al., 2001).

Therefore, the reinstatement of the transport network functionality heavily depends on the recovery of bridges, rendering the development of restoration models an urgent need toward: i) better-informed projection models and preparedness for future hazards and threats, ii) accurate quantification of losses in monetary terms, iii) development of resilience models for prioritisation of proactive and reactive adaptation measures in transport network assessment, planning and renewals. Today, the available recovery models for bridges are scarce in the international literature, and hence we are unable to assess and quantify the resilience of transport networks to diverse threads (Argyroudis et al., 2020). Restoration functions are typically based on expert judgment, following a linear, e.g. Bocchini et al., (2012), stepwise, e.g. Padgett and DesRoches (2007), or lognormal, e.g. HAZUS-MH (2011) formulation and they may consider complete and partial closure of bridges (Kameshwar et al., 2020). Functionality-fragility surfaces for recovery after multiple hazard occurrences has been proposed before by Karamlou and Bocchini (2017).

In particular, the bridge type, structural configuration and static system influence the restoration tasks and recovery processes after an extreme event, e.g. see in Mitoulis et al, (2021), the tasks are different for integral bridges and bridges with bearings. Similarly, the availability of diverse resources, e.g. specialist engineers and labour, materials, finance and availability of structural components, are important but also the effectiveness of their use during the restoration is of paramount importance. The latter is because certain tasks are overlapping with others temporally, i.e. take place simultaneously and/or in parallel with other tasks, whereas some tasks are expected to occur in series, i.e. this is the case where one task has to be completed before the other take place. For example, after a flood, the diversion of the river flow is used to redirect water and allow for reconstruction and restoration activities to take place in a specific section of the water body, and this is required when e.g. the bridge foundations are scoured. Therefore, resourcefulness is a requirement for resilience in bridge engineering, but not adequate in isolation to accelerate bridge recovery and road traffic reinstatement unless appropriate planning is in place. The appropriate planning is fully dependent on the bridge type in two senses: first, the bridge type will influence the type of failure and the amount of work to be developed during the recovery process (a very robust bridge will only be affected by local damage, a non-robust bridge can be affected by the progressive collapse and damage might be disproportionate in comparison with the intensity of the hazard (see for instance the bridges in Figures 3 and 4). Second, the schedule of the operations to be carried out for the complete recovery is also dependent on the bridge type.

2 Large scale infrastructure resilience

After recent hazard occurrences such as earthquakes and floods, field investigations confirmed that several bridges and transport networks were severely damaged and assets collapsed not only due to the hazard event, as an independent hazard, but also due to the subsequent events, e.g. a flood can trigger wetter soil conditions, scour, hydrodynamic loads and debris accumulation, landslides and rockfall. In addition, long-term material deterioration might have an important impact on the fragility of bridges to hazards. Therefore, it is important to study both independent and interacting hazards and their effects on the risk and resilience of bridges and road networks containing a large number of bridges and other assets. Although particular hazards e.g. floods and collisions might be dominant hazards to bridges and have an abrupt and sudden effect on bridges, evolving environmental threats, e.g. corrosion and material deterioration should not be neglected in risk assessments of transport networks.

2.1 Hazards that challenge bridge and transport network resilience

Hazards here are classified in Table 2 into three categories, i.e. geophysical, meteorological-hydrological and climatological. The emphasis is given to those that exert damage and/or disruption to bridges and transport networks. The geophysical hazards are earthquake and tsunami, landslide, rockfall, volcanic eruption, volcanic ashfall. The hydro-meteorological hazards are extratropical cyclones, wind storm, storm surge leading to coastal floods and wave loading, river floods, pluvial floods, avalanches, debris flow, coastal erosion. Climatological hazards can be extreme temperature, wildfire and drought.

Table 2. Hazards and their potential impacts (capacity, functionality, other) on bridges and transport networks

geophysical hazard type→ impact on	**earthquake (G.1)**	**tsunami (G.2)**	**landslide/ rockfall (G.3)**	**volcanic eruption (G.4)**	**volcanic ashfall (G.5)**
bridge	D	D, F	f	d, f	F
network	D, F	D, F	f	f	d, F

meteorological-hydrological hazard type→ impact on	**extratropical cyclones, windstorm (M.1)**	**storm surge, coastal floods, wave loading (M.2)**	**river floods (fluvial), pluvial (M.3)**	**avalanches, debris flow, rockfall (M.4)**	**coastal erosion (M.5)**
bridge	d, f	d,f	D, F	f	d,f
network	d, F	D, F	D, F	d, F	D, F

climate change→ impact on	**extreme temperatures (low/high) (C.1)**	**wildfire (C.2)**	**drought, heatwaves (C.3)**	**sea-level rise (C.4)**	**frequent/intense precipitation (C.5)**
bridge	d,F	d, F	-	D, f	F
network	d, F	d, F	F	D, F	d, F

D=extensive damage, d=minor damage, F= extensive functionality loss and economic impact, f=minor/local functionality loss

Compound events and subsequent hazard stressors become triggers or drivers of other hazards. For example, climate change is a compound hazard, and it triggers more intense and frequent precipitation and therefore leads to flooding and coastal erosion of transport networks. Table 3 below maps the dependencies between these hazards which might affect bridges and networks i.e. which sequences of interdependent hazards, i.e. geophysical (G.i), meteorological (M.i) and climatic (C.i) can cause damage and functionality loss to bridges and networks.

2.2 Large scale resilience evaluation

The highly urbanized areas that characterize modern societies are highly dependent on their critical infrastructures that provide significant services and contribute essentially to social and economic transformations. The disaster vulnerability represents the sensitivity of a community exposed to a given hazardous event and can be characterized by a more comprehensive view of critical infrastructures and their interdependencies. Therefore, identifying vulnerabilities of critical infrastructures is of paramount importance to effectively predict community resilience and its components (i.e., *robustness*, *redundancy*, *preparedness*, *resourcefulness*). Indeed, *resilience* is defined as the ability of a system to respond and recover from a disaster (Cimellaro et al., 2010).

In light of this urgent need, and due to the increasing frequency of disasters, the challenge of creating large-scale simulation models has become of great importance. Several simulation approaches have recently been developed to explore community response to natural disasters. Such models are mainly intended to support decision-makers during emergency operations by allowing them to create a comprehensive view of the emergency by identifying the consequences. Furthermore, they can be used to plan strategic interventions to increase community resilience by improving preparedness and planning resources.

Current practices of infrastructure modelling incorporate both facilities (e.g., commercial, housing) and lifelines (e.g., hospitals, transportation network). However, limited tools and methods allow assessing resilience at the urban level. The integration of all computing resources into a unified platform remains a challenge. The first contribution in that direction is the integrated platform presented by (Marasco et al., 2021a) that implements a hybrid community model with real-time simulation capabilities (Figure 1). The objective of the platform is to assess the seismic resilience and vulnerability of critical infrastructures at the large-scale level, using a virtual city called *IdealCity*, taking into account their interdependencies through suitable models. It would provide a more effective problem-solving approach that is useful to assist the decision support system. The computational platform is presented to analyse the effects of seismic events (Figure 1a) but it has been implemented also to consider multi-hazard scenarios, as the fire-following-earthquake or tsunami events on an urban community. The platform implements different layers, such as buildings, road transportation networks, power grid, water distribution networks, and socio-technical networks. Interdependencies between the different layers have been also developed and implemented through specific models. Therefore, the individual seismic response of each building is analysed through a surrogate physical model (Marasco et al., 2021b) and the damage and serviceability conditions for each layer can be computed and also visualized through a graphical user interface (Figure 1b). The platform allows also to consider the emergency evacuation process through an agent-based model along with the first-aid operations in post-disaster conditions (Battegazzorre et al., 2021).

Database: PEER (NGA)
Component: N-S
Norcia_1979_NS.t
Event Name: ["earthquake name: ['Norcia']", "station name: ['Bevagna,', 'NS']"]
Event Date: event date: 9/19/1979
dt [s]: 0.002
Scale Factor: 1
Acc. units: g
○ Bandpass and filter
Magnitude [Mw]: 6.5
Epicenter
X [km]: 0.8
Y [km]: 0.6

Figure 1. Integrated platform by (Marasco et al., 2021a): (a) seismic scenario selection, (b) building damage visualization on the *IdealCity* computed by the surrogate physical model (Marasco et al., 2021b).

Table 3. Impact of interdependent hazards on bridges and road networks

Symbols

x same hazard

⇒ the hazard of the relevant line can lead to the hazard of the column

⇐ the hazard of the relevant column can lead to the hazard of the line

⇔ both hazards can cause the other hazard

\- no interaction between hazards

🟩 minor consequences

🟧 moderate consequences

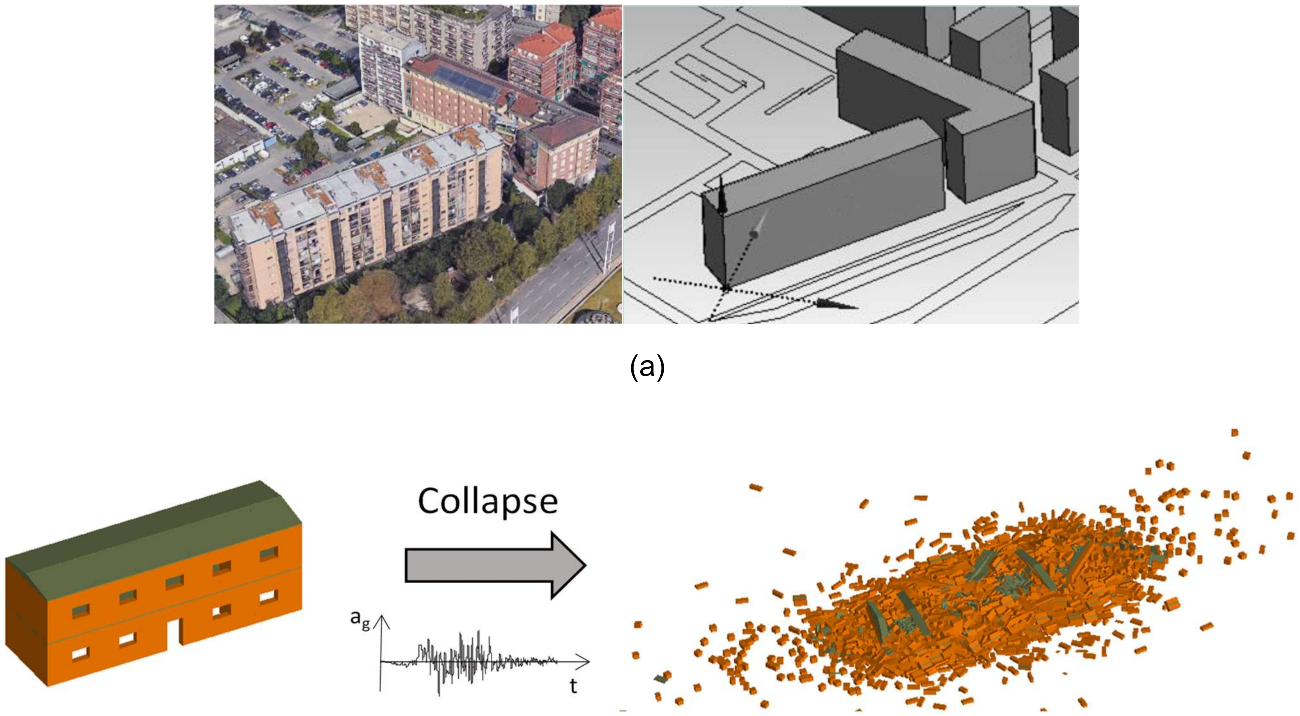
🟥 severe consequences

	(G.1) earthquake	(G.2) tsunami	(G.3) landslide/ rockfall	(G.4) volcanic eruption	(G.5) volcanic ashfall	(M.1) extratropical cyclones, windstorm	(M.2) storm surge, coastal floods, wave loading	(M.3) river floods (fluvial), pluvial	(M.4) avalanches, debris flow	(M.5) coastal erosion	(C.1) extreme temperatures (low/high)	(C.2) wildfire	(C.3) drought, heat waves	(C.4) sea-level rise	(C.5) frequent/intense precipitation
earthquake (G.1)	x	🟥 ⇒	🟥 ⇒	🟩 ⇔	🟩 -	🟩 -	🟩 -	🟩 -	🟩 ⇒	🟩 -	🟩 -	🟩 -	🟩 -	🟩 -	🟩 -
tsunami (G.2)		x	🟧 ⇒	🟥 ⇐	🟩 -	🟩 -	🟥 ⇒	🟥 ⇒	🟧 ⇒	🟧 ⇒	🟩 -	🟩 -	🟩 -	🟩 -	🟩 -
landslide/ rockfall (G.3)			x	🟧 ⇐	🟩 -	🟥 ⇐	🟥 ⇐	🟥 ⇐	🟧 ⇔	🟧 ⇐	🟩 -	🟧 ⇐	🟩 -	🟥 ⇐	🟧 ⇐
volcanic eruption (G.4)				x	🟧 ⇒	🟩 -	🟧 ⇒	🟩 -	🟧 ⇒	🟩 -	🟧 ⇒	🟧 ⇒	🟩 -	🟩 -	🟩 -
volcanic ashfall (G.5)					x	🟩 -	🟩 -	🟩 -	🟩 -	🟩 -	🟩 -	🟧 ⇒	🟩 ⇒	🟩 -	🟩 -
extratropical cyclones, windstorms (M.1)						x	🟥 ⇒	🟥 ⇒	🟧 ⇒	🟥 ⇒	🟩 -	🟧 ⇒	🟩 -	🟩 -	🟩 -
storm surge, coastal floods, wave loading (M.2)							x	🟥 ⇒	🟥 ⇒	🟥 ⇒	🟩 -	🟩 -	🟩 -	🟩 -	🟩 -
river floods (fluvial), pluvial (M.3)								x	🟥 ⇔	🟥 ⇒	🟩 -	🟧 ⇐	🟩 -	🟥 ⇐	🟥 ⇐
avalanches, debris flow, rockfall (M.4)									x	🟧 ⇐	🟩 -	🟧 ⇐	🟩 -	🟥 ⇐	🟩 -
coastal erosion (M.5)										x	🟩 -	🟩 -	🟩 -	🟥 ⇐	🟥 ⇐
extreme temperatures (low/high) (C.1)											x	🟧 ⇔	🟧 ⇔	🟥 ⇒	🟩 -
wildfire (C.2)												x	🟧 ⇔	🟩 -	🟩 -
drought, heat waves (C.3)													x	🟩 -	🟩 -
sea-level rise (C.4)														x	🟩 -
frequent/intense precipitation (C.5)															x

By focusing on the transport infrastructure network, the platform can simulate the closure of bridges following the impact of external hazards and thus enable the simulation of scenarios in which alternative routes can be planned. In this respect, the platform makes it possible to check the resilience of the transport infrastructure network and the possible implementation of alternative measures that can improve the post-event conditions. The interdependence of the transport network, for example, with the built environment is also modelled. In the first instance, debris generated, e.g. by local damage, can affect the efficiency condition of the network and the platform can consider these aspects and quantify the recovery time and measures needed to overcome these difficulties.

Several approaches have been developed to assess the debris generation and extension: e.g., in Domaneschi et al (2019a) a methodology has been introduced to evaluate the debris areas generated by the collapse of masonry buildings from the geometric structural characteristics (Figure 2). A different approach has been presented in (Marasco et al. 2021a) to assess the amount of generated debris using pictures collections in the aftermath of seismic events and comparing different machine learning algorithms. These approaches, apart from the assessment of the debris extension, also allows the exploration of the community response to a disruptive event and planning resilience strategies to limit performance losses and recovery time.

Therefore, the platform enables the analysis of different infrastructure networks and their interdependencies. Among these the transport network is also included; it is composed of both roads and specific components such as bridges, viaducts and tunnels. However, the study of the specific element of the network (e.g, a bridge) may need a small-scale analysis to understand the peculiar structural vulnerabilities to different hazards, such as earthquakes or floods. In this respect, robustness and redundancy as components of resilience play a significant role for bridges in infrastructural networks and the next subsection discusses these properties.



(a)

(b)

Figure 2. Detail of a district mechanical model (Marasco et al., 2021) (a), simulation of debris generation (Domaneschi et al., 2019a).

2.3 Robustness of bridges

The recent disasters of the disproportionate collapse of the Morandi Bridge in Genoa (August 14, 2018) and the bridge in Kolkata (India, September 4, 2018) have highlighted the importance of building robust structures for our communities. Redundancy and robustness play a significant role, respectively to have alternative resources and load paths in the event of local out-of-service structural elements and to sustain performance or stress levels without showing degradation or loss of functionality.

Robustness is defined as the ability of a structure, e.g. bridge, to withstand adverse and unforeseen events without being damaged to an extent disproportionate to the original cause, as per Eurocodes. Besides, redundancy is another structural characteristic that is often required at the design level for the benefits it provides against unwanted behaviours. This last one is defined as the quality of having alternative paths in the structure by which the forces can be transferred, which allows the structure to remain stable following the failure of any single element (Domaneschi et al., 2019b).

Such characteristics, whose interconnection has also been recognised by Kanno & Ben-Haim (2011), are desirable in structural systems, being able to reduce vulnerability and therefore avoid the disproportionate collapse. It occurs when an initial local failure that is produced by a small triggering event leads to the widespread failure of other structural components, such that the structure collapses. It is also referred to as progressive collapse (Domaneschi et al., 2019). Robustness and redundancy are important components of the whole resilience of the structure, as they define the starting point (after the event is produced) from where the recovery actions should start (Anitori et al., 2013, Cavaco et al., 2013 and Domaneschi et al. 2019a).

2.4 Resourcefulness and resilience

In order to examine how much the collapse of a single structure in a transport infrastructure network can affect the resilience of the community, it may be useful to mention two recent examples that have occurred in Europe and specifically in Italy. These are the Polcevera Viaduct in Genoa (Figure 3) and the bridge over the Magra river in Albiano (Figure 4), about 100 km from each other. The first one is a bridge considered iconic, supporting the main connection across European countries, and positioned inside a large industrial city and an important port of the Mediterranean Sea, while the second one is positioned in a local network link that serves mobility between villages with a local significance.

The tragic collapse of the Pila #9 of the Polcevera Viaduct on August 14 of 2018 in Genoa, Italy was responsible for 43 deaths and many injuries (Figure 3). It collapsed after approximately 50 years of service on one of the busiest freeways in Europe and it was also a witness of the increase of the frequency and the magnitude of the loads in the last decades, due to the increase of the volume of traffic and the axle loads of the trucks (Calvi et al., 2019, Invernizzi et al., 2019, Invernizzi et al., 2020, Domaneschi et al., 2020a, Domaneschi et al., 2020b, Morgese et al., 2020, Bazzucchi et al., 2018). The collapse of the balanced system of the Polcevera Viaduct is an example that, although the scientific community is developing robust and efficient monitoring solutions to assess bridge condition and safety, difficulties persist in the acceptance of their efficiency by the bridge authorities (Clemente, 2020, Nuti et al., 2020). This focused the public opinion and media attention and, as a consequence, already a few days after the disastrous collapse, the planning of the reconstruction of a new bridge started, compatibly with the development of the necessary investigations. The result of this attention has allowed the restoration of the area and a new viaduct in a short time, using all the most advanced administrative, public procurement and technological tools. For example, controls on the bridge components were anticipated at the factory where they were assembled. Furthermore, the construction of the new bridge took advantage of an administrative simplification for the demolition, removal, disposal and landfill of the resulting materials of the Polcevera Viaduct, as well as for the design, commissioning and reconstruction of the infrastructure and the restoration of the related road system. This allowed time to be reduced: the new Polcevera Viaduct ("Viadotto Genova-San Giorgio") has been designed by the Architect Renzo Piano from Genoa and the bridge was inaugurated on August 3rd, 2020.

The collapse of the balanced system of the Polcevera Viaduct (Pier #9) was one of a series of several collapses in transportation infrastructure in the Italian country (Bazzucchi et al., 2018), including, the April 9th, 2020 sudden collapse of the bridge over the Magra River in Albiano, Massa Carrara (Figure 4). However, similar examples of bridge collapses have occurred around the world, particularly in the western part, where a significant number of structures have been in service for decades and are still believed to need to be in the future, for both economic issues of replacement and logistical reasons (e.g., difficulty to interrupt traffic).

Focusing on the bridge over the Magra River in Albiano, if this bridge is compared with the case of the Polcevera Viaduct, highlights some peculiar aspects with respect to the resilience of the transport infrastructure system. Both cases have been subject to subsequent official investigations to understand the reasons that led to the collapse and possibly the responsibilities. However, the case of the Magra River bridge shows how media attention, public opinion, and the local importance of the bridge greatly influence resilience. Focusing for example on the speed of intervention and recovery, the Magra River bridge can be an example of low resilience level. Indeed, as more than one year after the collapse the situation was still in the same state as when it collapsed, i.e. with debris still in the river bed, and the rebuilding of the new bridge was still uncertain despite the disruption to the local community in terms of supplies and healthcare (Truscia, 2021, Luparia, 2021).


(a) (b)

Figure 3: (a) Polcevera Viaduct in Genoa by Riccardo Morandi (Licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license. Author: Bruno). (b) The collapse of Pier #9 (Licensed under the Creative Commons Attribution-Share Alike 4.0 International license. Author: Salvatore1991). The replacement bridge is open to traffic.

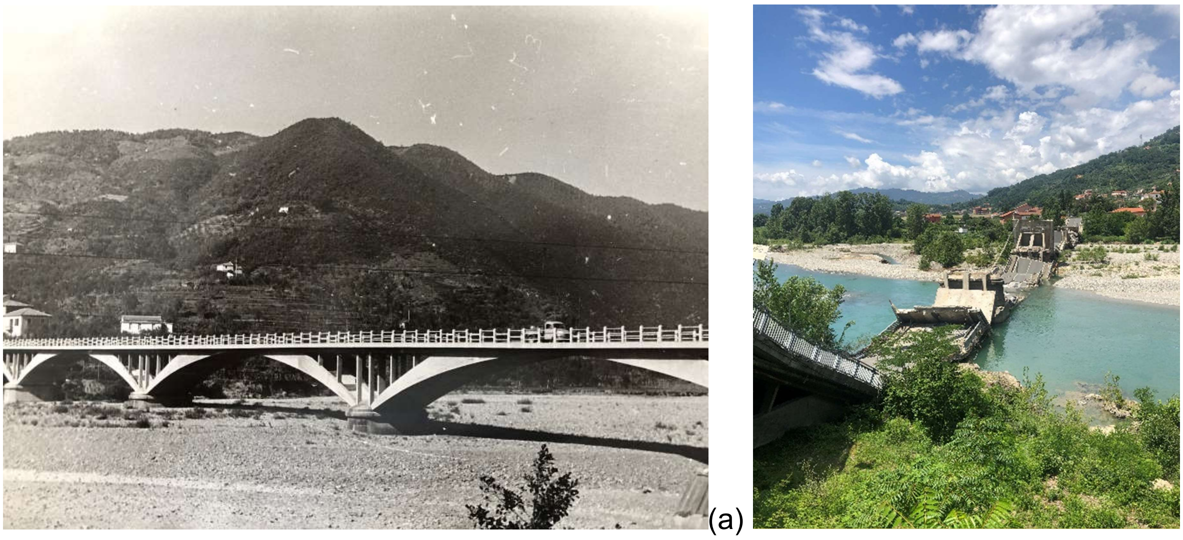

(a) (b)

Figure 4: The bridge of Albiano over Magra River (a) and the same bridge just after its collapse (b).

3 Structural control, SHM and resilience

Beneficial effects to structural resilience can also be obtained from the implementation of control systems to compensate for performance losses. The Immediate Resilience concept, for example, has been introduced by Domaneschi et al., (2016), i.e. when the shock hits the structure and some damage occur, the semi-active control system is able to compensate the part of the loss of functionality. The semi-active function of the devices is exploited online to compensate for losses of performance due to the failure of some of the control elements. Such control solution shows the ability to automatically reduce the time interval between the damage occurrence and restoration (even if not complete) of system performance to few instants.

Focusing on benefits to structural resilience that may come from Structural Health Monitoring (SHM) implementation, they mainly refer to warning/alarm triggering and/or damage identification processes. As previously mentioned, control systems can be implemented to compensate performance losses quickly, and the best way to accurately know about these losses is by means of SHM systems Monitoring systems may be useful to obtain information on the degradation conditions, to be able to adopt in advance the necessary actions and, thus, reduce risks of collapses and loss of structural performance. However, they can also be effective in providing tools to alert from the sudden occurrence of an undesired event or hazard and, therefore, provide in advance the preparedness and resourcefulness necessary to gain a high level of resilience. For instance, the implementation of an acoustic emission system in the main cable of a cable-supported bridge or the stays of a cable-stayed bridge can alert the bridge managers about the fatigue problems of the material and increase the resilience in a double sense: decreasing the vulnerability of the bridge component to foreseen hazards and also by assisting in preparing the material and the human resources necessary for a fast repair in case of the failure. A monitored bearing in a bridge can detect non-normal movements due to the blocking of the sliding system. As soon as this is detected, the repair operation can start, avoiding problems in future that would have greater consequences (e.g. collapse of a pier) that would require substantial time to be restored, thus affecting the overall resilience.

SHM can also be useful in the post-disaster scenario after damage is produced by a sudden event (e.g. earthquake, flash-flood) provided that the SHM system performance is not itself affected by the damage. This may be the case of sudden events of low to medium intensity that does not affect the capacity and strength but can affect the functionality. The SHM can be still in use and provide essential information on the post-disaster functionality of the asset (for instance the loss of the correct alignment of the tracks in a railway bridge after and small earthquake). If the monitoring system (or part of it) survives the stressors and can send data to the bridge operator, this data will be of paramount importance when deciding the recovery tasks more appropriate to enhance the bridge resilience. SHM system will be providing information on the actual condition of the bridge (something that sometimes cannot be possible to have based on visual inspection due to difficulty in accessing the assets after natural hazard events) and this will be the only information allowing to plan the best intervention sequence to restore the bridge functionality and safety. This aspect is represented in Figure 5, which illustrates the resilience over time for assets, e.g. bridges, tunnels, retaining with and without monitoring systems. The resilience is measured based on different performance indicators that are the capacity or functionality for the assets and networks. The fluctuation of resilience is illustrated over time, from the completion of the construction (t_0) to the end of its design lifetime ($\boldsymbol{t_{end}^{I}}$) or to the extended life cycle ($\boldsymbol{t_{end}^{ext}}$). The figure shows the resilience curves for extreme hazard occurrences, which are abrupt and the loss of capacity/functionality is sudden.

The figure argues that the use of monitoring on bridges and transport networks enhances the responsiveness and hence the resilience of critical infrastructure. The black solid lines in Figure 5 illustrate the conventional approach, where only traditional inspections are performed periodically. The red plots illustrate the enhanced resilience models as a result of the deployment of monitoring systems (M). Each segment of the resilience curves is accompanied by the corresponding uncertainty, with an indicative probability density function (PDF). The capacity and functionality of components at the beginning of the life-cycle of assets and networks is equal to 1 which is the theoretical design performance. There are different distinct periods at the life-cycle i.e. **1: normal** function, followed by **damage and loss of functionality**, **2: mitigation measures**, **3: bounce back to normal function/adaptation** and potentially life extension. Based on the literature (Mattsson and Jenelius 2015; Ganin et al. 2017, Linkov et al. 2018), monitoring has the potential to influence the aforementioned periods by (a) compressing the post-damage response time, i.e. $t_{resp}^{M} < t_{resp}^{NM}$, and by reducing the lag time in the strategic planning for decision-making ($\boldsymbol{t_{resp} - t_{strat}^{pla}}$) or the idle time that is the period of no or limited use of the asset or network, (b) helping to recover faster, $t_{rec}^{M} < t_{rec}$ due to prognosis, i.e. better and expedient understanding of the infrastructure condition, (c) increasing the reliability of the data, (d) permitting recovery to initiate from a level higher than the residual capacity ($c_{resp}^{M} > c_{residual}$) and fully regain the performance level, and (e) enabling timely decision-making and recovery, prior to infrastructure reaches its critical functionality or capacity $c_{critical}$, i.e. $c_{resp}^{M} > c_{residual}$. Hence, monitoring enables continuous and expedient adaptation to new demands, e.g. climate change ($t_{adapt}^{Mi} < t_{rec}^{p-M} < t_{adapt}^{NMi}$). It is noted that the concept of resilience is mainly linked to abrupt events, provoking a sudden loss of performance (as shown in Figure 5), i.e. a discontinuity in the performance curve. In the case of slow evolving damage (e.g. deterioration by corrosion, fatigue, accumulation of scour at bridge foundations) the concept of maintenance is better suited, the effect of which will be to counteract the negative derivative of the performance curve along time. Maintenance is understood as the set of activities trying to restore a null, positive (in this case is more appropriate to refer to repair) or less negative value of the derivative of the curve.

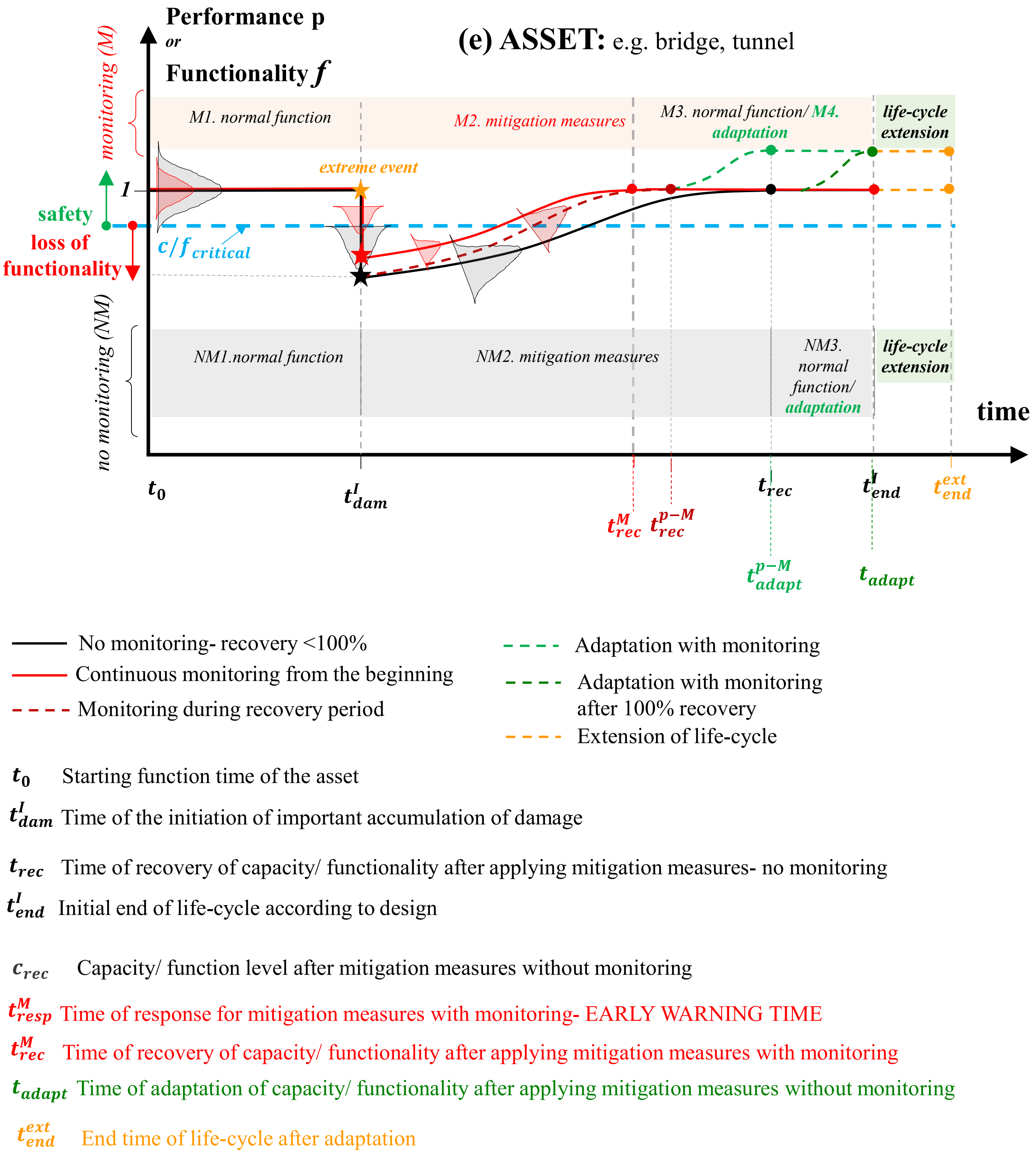


Figure 5. Resilience curves of bridge assets throughout their life-cycle due to natural hazards, e.g. flash-floods, landslide and fire and figure nomenclature with or without monitoring systems (adopted by Achillopoulou et al., 2020).

4 Conclusions

This paper provides the perspectives of the authors, also supported by an extensive literature review of the current state of the art, on the resilience of transport systems with an emphasis on bridges.

Two scales of the problem are analysed: (i) small scale - the bridge structure and its resilience to multiple and combined hazards; (ii) the resilience of large-scale systems including the authors' perspectives on transport network resilience and the recovery of urban areas after natural hazard occurrences, which is a regional challenge, the latter followed by a description of a computer platform which is in support of community resilience analysis.

Initially, the effects of critical natural hazards and climate change, potential damage and relevant mitigation measures for bridges are discussed. The assessment of bridge and network vulnerabilities have been discussed on the basis of potential loss of capacity of the assets and functionality loss at the system level. Short- and long-term impacts, damage and functionality loss are also discussed for the most common typical geophysical, meteorological and climatic hazard stressors, followed by a discussion on multiple and/or combined hazards that have proven to impact bridges and transport networks, leading to minor, moderate and severe consequences, also summarised in a table to facilitate future resilience assessments.

This perspective paper concludes with a discussion on the critical role of structural control and health monitoring, which can be useful for planning, e.g. ordinary (maintenance) and extraordinary post-event interventions, to ensure an acceptable level of functionality and safety over time and facilitate proactive and reactive climate adaptation measures.

The focus of research and practice in the future should be on the development of realistic and practical restoration and reinstatement models for bridges and networks, as this is what is currently missing in view of the urgent need for adaptation to the forthcoming climate changes. What is more, the dependencies of transport networks to other critical systems, e.g. energy systems, is an area that requires significant efforts for modelling and quantification, as bridges and transport networks reside within complex and diverse assets, networks and systems the operability of which influences the operation of our transport systems.

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