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Editorial

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Editorial: The crux of bridge and transport network resilience – advancements and future-proof solutions

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This Editorial introduces the themed issue on bridge and transport network resilience. The themed issue was a collection of papers and is split into three parts. The papers are grouped into three issues: (*i*) bridge and network resilience; (*ii*) monitoring of critical infrastructure in support of resilience modelling; and (*iii*) resilience by design for earthquake-resistant bridges. The first part of the themed issue includes seven papers, while the second and the third part include six contributions each.

This Editorial aims to go beyond the typical presentation of papers in that it describes the scientific contributions and summarises the novel findings that emerged from the papers across the board of resilience, monitoring and earthquake resistance. The Editorial concludes with a vision on future developments in the field of bridges and transport infrastructure resilience. In doing so, the editors invited authors of the papers to provide their opinions on the advancements in bridge and network management from the lenses of resilience and discuss what is needed to deliver future-proof solutions, especially in view of the ongoing climate crisis. Resilience frameworks provide the complete picture of infrastructure capability to efficiently and promptly overcome damage and operational disruption. In this multifaceted endeavour, bridge and transport network digitalisation and openly available data are key to achieving accuracy and visualisations of the condition of bridges. They enable enhanced designs, assessment and efficient communication of findings to bridge and network operators and decision-makers.

Bridges and critical transport infrastructure (CTI) are primary systems that underpin human mobility and activities. Loss of functionality of a bridge has consequences on the entire transport network, which is also interconnected with other networks. Recent natural disasters revealed the vulnerabilities of bridges and CTI to diverse hazards (e.g., floods, blasts, earthquakes), which are exacerbated due to climate change, leading to significant economic losses and societal disruption. Therefore, assessing bridge and network vulnerabilities against multi-hazard conditions and climate emergency by quantifying capacity and functionality losses is of paramount importance.

The first contribution of this special issue (Mitoulis *et al.*, 2022) summarises the main compound hazards, stressors and threats that have short- and long-term impacts on the structural capacity and functionality of bridges and the impact of bridge closures on network operability, including aspects of bridge restoration and reinstatement. Redundancy and robustness of a bridge against performance losses are firstly considered in the overall process of resilience quantification, shown in Figure 1.

The second manuscript of the issue (Blagojević *et al.*, 2022) focuses on the community disaster recovery approach that accounts for community components' accessibility for repair using a demand–supply framework. It is illustrated on a virtual community with 3600 inhabitants supported by several interdependent infrastructure systems (Figure 2).

The third contribution (Ientile *et al.*, 2022) provides a methodology to evaluate the influence of road links in the risk assessment and management strategies of critical transport infrastructures. The methodology is applied to a Spanish motorway, the main case study of the paper. An index to quantify the serviceability losses is developed and presented, combining the results of road link failure scenarios based on the shortest paths and travel times to estimate road network resilience.

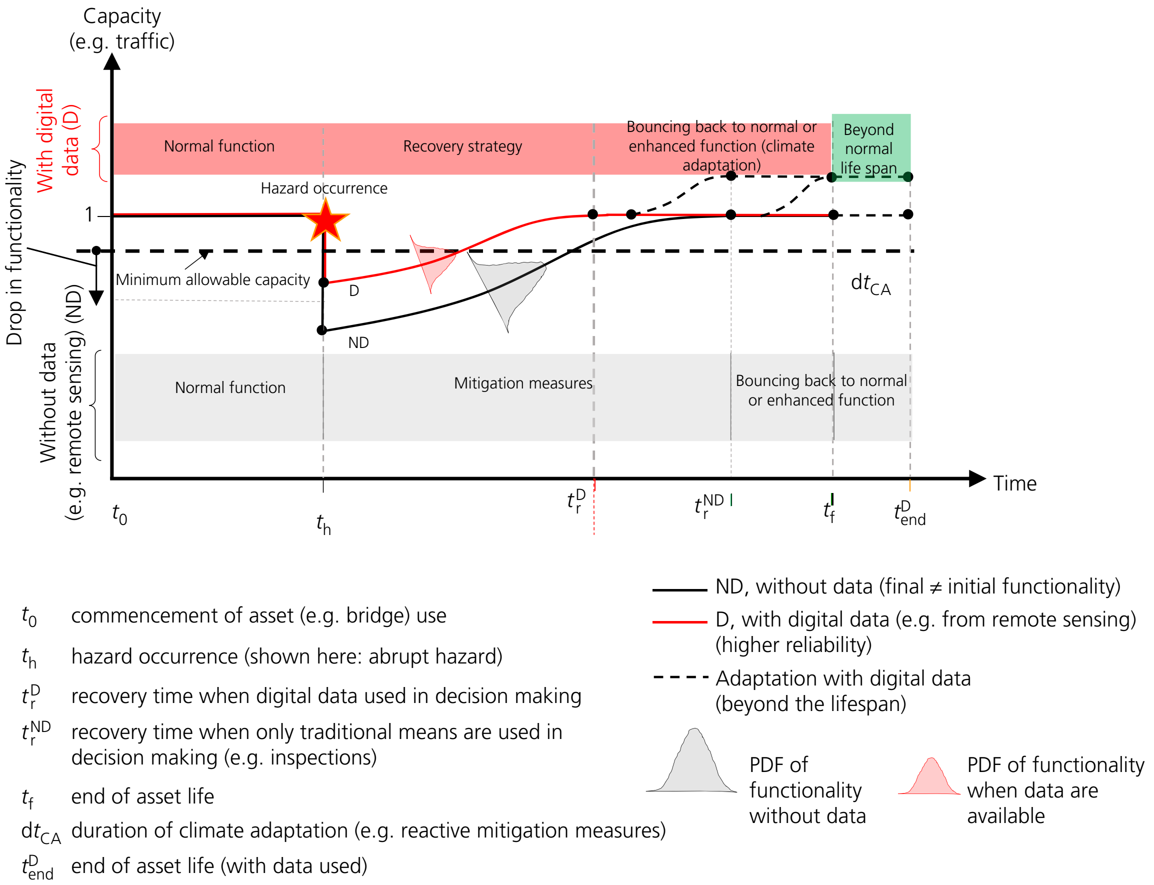

Figure 1. Resilience curves of critical transport assets throughout their lifecycle due to natural hazards with or without the deployment of digital data (Mitoulis *et al.*, 2022).

The increasing flood-induced damage to bridges due to climate change and rising urbanisation hazard is deepened by the fourth contribution of the themed Issue (Degan Di Dieco *et al.*, 2022). A taxonomy of 20 attributes for riverine roadway bridges susceptible to flood hazards is proposed and subsequently verified by considering three bridge datasets in the UK.

Several resilience metrics have been proposed in the literature. In the fifth article of the themed issue, Argyroudis (2022) reviewed these methods and metrics and provided practical applications and a worked example to facilitate their use by engineers and researchers, whilst putting emphasis on the main properties of resilience – that is, robustness, redundancy, resourcefulness and rapidity. The main steps of resilience assessment for transport infrastructure such as bridges are discussed and the use of fragility and restoration functions to assess the robustness and rapidity of recovery is demonstrated. Practical examples are provided using a bridge exposed to scour effects as a benchmark, discussing different aspects of resilience-based decision making and their impact at the network level, as shown in Figure 3.

The last two contributions focus on two significant case studies. Godazgar *et al.* (2022) provided a probabilistic resilience curve for the Chemin des Dalles Bridge in Quebec, Canada. This model incorporates fragility and restoration profiles available in the literature. In the last paper, Langley (2022) provides the background to the replacement project for the moveable bridge on the A554 Tower Road in the UK. The civil, mechanical and electrical designs are described and some of the significant issues encountered during implementation and commissioning are discussed.

Innovation from the papers of this issue

The paper of Mitoulis *et al.* (2022) introduced two scales in resilience assessment – that is, (*a*) small-scale bridge structures and their resilience to multiple and combined hazards, and (*b*) the resilience of large-scale systems, including transport networks. The effects of natural hazards, exacerbated by climate change, potential damage and functionality loss, and relevant mitigation measures for bridges have been discussed along with the assessment of bridge and network vulnerabilities. The

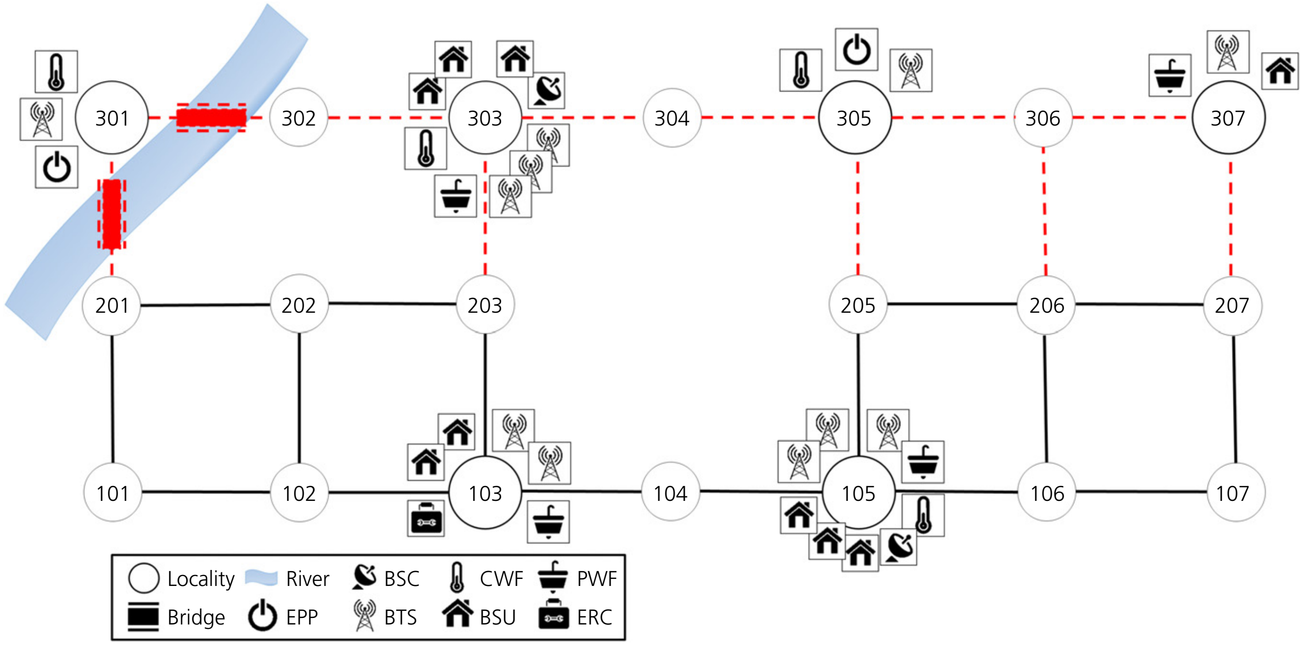

Figure 2. Case study of a virtual community, with complete interruption of networks' branches (dashed lines) (Blagojević *et al.*, 2022)

paper also considers the critical role of structural control and structural health monitoring, which can be useful for planning 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. Large-scale simulation platforms have been introduced in Mitoulis *et al.* (2022), and further detailed in Blagojević *et al.* (2022). Both studies can to reproduce the transport network, but also the critical interdependencies with other infrastructure systems. Blagojević *et al.* (2022) in particular presents a way to use a demand–supply-based community disaster recovery and resilience quantification framework to simulate accessibility of damaged components for repair, using a virtual community of 3600 inhabitants impacted by a virtual disaster. The case study highlights that damage to the transportation network can reduce the ability of a community to mobilise its repair resources. Both papers conclude with the urgent need of realistic validation studies for accurately assessing the ability of numerical modelling and available platforms to capture real-life community disaster resilience.

The index proposed by Ientile *et al.* (2022) has been used to measure the vulnerability of individual road links in a Spanish highway case study in order to obtain a measure of network resilience. A statistical combination of the results, evaluating the median and quartile values of the length of service indices, allows an overall assessment of the vulnerability of the road links and thus of the functionality of the road network by exploiting openly available data and information, such as the structure of the network, using an open-source geographical database.

The verification exercise of the proposed taxonomy in Degan Di Dieco *et al.* (2022) with three UK bridge datasets shows that the significance of the taxonomy is multi-fold and fills the gap of a specific taxonomy for bridges at flood risk, developing a common language that could make data collection and cataloguing of bridges at flood risk more uniform. This is of paramount importance in developing resilience models for portfolios of bridges that have similarities and hence reduce the cost of bridge-specific fragility and resilience modelling, toward more efficient management of our transport networks.

Argyroudis (2022) reviews the available resilience metrics and through applications paves the way to their use in bridge and transport network management. This practical paper is useful especially in view of the urgent climate adaptation measures that we need to incorporate into our resilience-based designs for bridges and networks.

The last two contributions with significant case studies include the papers by Godazgar *et al.* (2022) and Langley (2022). They provide insights on the seismic resilience of the Chemin des Dalles Bridge in Quebec, Canada (Godazgar *et al.* 2022) and on the requirements (e.g., the need for an integrated multi-disciplinary team of civil, mechanical and electrical engineers) to ensure a resilient project development (Langley 2022).

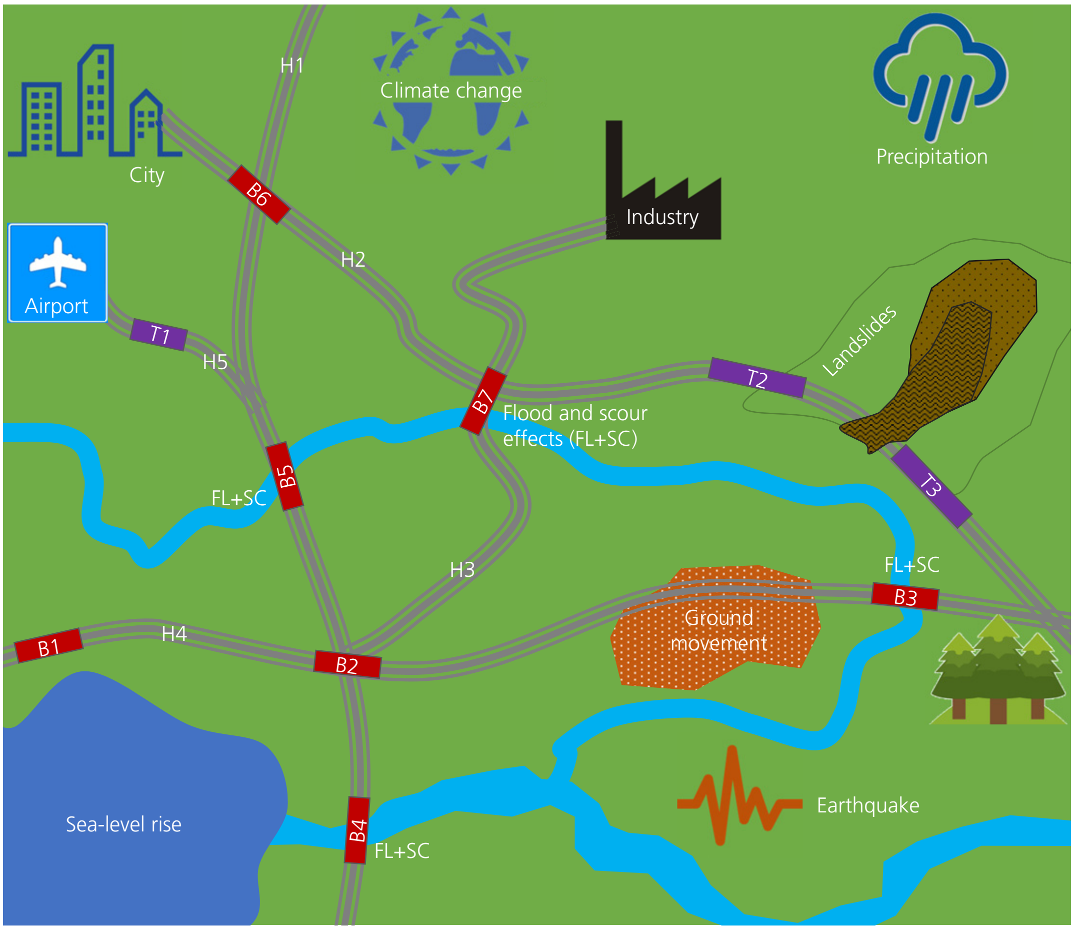

Figure 3. Interconnected transport assets (highway, bridges, tunnels) in multi-hazard conditions (Argyroudis, 2022).

Conclusions – future-proof solutions including climate projections

Resilience simulation frameworks, tools and metrics presented in this Editorial need to travel in time. First, to the past, in the process of validation against recorded events. Second, and often, to the future, to think and design bridges for realistic and/or unforeseen climate scenarios. We expect to use resilience simulation models to predict the vulnerability and the recovery of bridges and transportation networks in possible future disasters, to plan retrofits of existing structures, to design new structures and transportation systems, all the while informing operators and the public about the costs and benefits of resilience to their communities.

To do this well, resilience simulators must consider the changes in existing structures due to their use and local environmental effects, as well as the evolution of their service demands and loads owing to the changes in our climate, growth of our society and deployment of new technologies. Structural health monitoring and digital twinning offer promising ways forward to update and future-proof resilience models of individual structures. Evolution of climate, technologies and society, however, requires comprehensive integration of systemic engineering resilience models with climate, territorial planning and technology forecasting models. The contributions presented herein are the basis for this difficult task.

For more accurate resilience modelling, the focus of research and practice in the future should be on the development of realistic and practical restoration and reinstatement of models for bridges and networks – this is currently missing in view of the urgent need for adaptation to predicted climate changes. The interdependencies of transport networks and other critical systems (e.g., energy systems) is another area that requires significant efforts in modelling and quantification as bridges and transport networks reside within other complex and diverse assets, networks and systems – the interoperability of which is vital.

Multidisciplinary solutions are of paramount importance for planning resilient bridges and transport infrastructure and this effort can be complemented with ongoing technological developments. Smart infrastructures of the future, including bridges, will have to be conceived in a holistic context of multi-functionality. Thus, the load-bearing structural skeleton will be integrated into a larger context and harmonised with other components (e.g., plant engineering, traffic, environment). Thus, the implementation and development of computational tools and data management algorithms (e.g., machine learning and Big Data), for data sensed by, for example, fibre optics, embedded sensors and miniaturisation, are destined to become the backbone of the smart and resilient infrastructure of the future, thus they need to be further developed and calibrated, federated and supported by policy. The goal is to optimise their operation, assuming an evolutionary scenario, both with a view to increasing their safety (including with respect to the structural capacity of existing assets) and improving their operation for unforeseen hazards and threats.

Modelling and simulation approaches at small and large scales, underpinned by emerging technologies (e.g., remote sensing and monitoring) are vital tools for accurate resilience assessments of critical infrastructure. In this context, the deployment of virtual simulations of environments that include large inventories of digital twins and real assets equipped with sensor networks also need to be used in harmony and complement each other. Therefore, we urgently need realistic validation studies to calibrate simulation platforms that quantify community disaster resilience in real life as a result of bridge and transport network functionality loss.

As indicated by Yang and Frangopol (2018), for bridging the gap between resilience and sustainability, the novel concept of lifetime resilience can be used to grasp the full understanding of the life-cycle of civil infrastructure systems in terms of resilience. Using this concept, resilience is embedded into sustainability-informed life-cycle design, assessment and management of bridges and road networks.

In the complex context of various stressors and climate change, how to improve the resilience of bridges and transport network to deal with various uncertain and unpredictable threats is a critical topic with both theoretical and practical challenges. Meanwhile, the multi-dimensional research on bridge and network resilience has been investigated by many engineers and researchers to meet the current and future demands. While quantitative assessment tools such as simulation models, probabilistic methods and optimisation models have been widely used to assess the level of bridge and transport network resilience, these models heavily rely on useful and actionable data. State-of-the-art techniques have been introduced in bridge health monitoring (BHM) applications in the last couple of decades thanks to the advancements in sensing and computing technologies. These methods can be listed as LiDAR, photogrammetry, virtual reality, augmented reality, digital twins, computer vision, machine learning and deep learning. These methods and technologies need to be utilised for real bridge engineering issues, such as change in load characteristics, increased traffic and freight demands as well as resilience demands due to extreme events. Ultimately, BHM technologies effectively used for decision making for repair, maintenance or future life while improving resilience, enhancing safety and saving costs would fully justify traditional or novel technologies.

Future-proof solutions require adoption of technological and scientific advancements, but what is more important is to nurture the next generation of civil and bridge engineers with the principles of resilience and sustainability and to train them on new technologies. It is therefore necessary to create new integrated and interdisciplinary curricula for the new generation of resilience and sustainability engineers. The same applies for taught modules and curricula on bridges and transport infrastructure, where more specialised knowledge on resilience would be required. Resilience engineering is in its infancy and has been adopted by leading universities and technical institutions, but needs to be consolidated in the future and extended to all academic institutions that offer degrees in engineering.

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