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Final published version

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Citation (APA)
Shaban, N., Arango, E., Jiménez Rios, A., Rincon, L. F., Shang, Y., Habeeb, B., Martín-Pérez, B., Ferreira, T. M., Mendoza-Lugo, M. A., Ramírez Eudave, R., Bastidas-Arteaga, E., Sousa, H. S., & Nogal, M. (2026). Perspectives on the resilience of existing bridges to short- and long-term impacts of climate change. *Structure and Infrastructure Engineering*. https://doi.org/10.1080/15732479.2026.2651414

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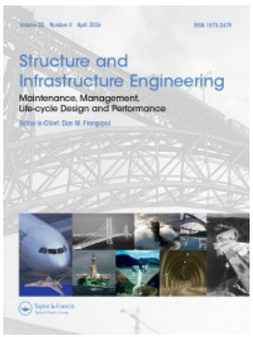

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Structure and Infrastructure Engineering
Maintenance, Management, Life-Cycle Design and Performance

ISSN: 1573-2479 (Print) 1744-8980 (Online) Journal homepage: www.tandfonline.com/journals/nsie20

Perspectives on the resilience of existing bridges to short- and long-term impacts of climate change

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To cite this article: Nefize Shaban, Erica Arango, Alejandro Jiménez Rios, Luis F. Rincon, Yue Shang, Bassel Habeeb, Beatriz Martín-Pérez, Tiago Miguel Ferreira, Miguel Angel Mendoza-Lugo, Rafael Ramírez Eudave, Emilio Bastidas-Arteaga, Hélder S. Sousa & Maria Nogal (20 Apr 2026): Perspectives on the resilience of existing bridges to short- and long-term impacts of climate change, Structure and Infrastructure Engineering, DOI: 10.1080/15732479.2026.2651414

To link to this article: https://doi.org/10.1080/15732479.2026.2651414

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STRUCTURE AND INFRASTRUCTURE ENGINEERING
https://doi.org/10.1080/15732479.2026.2651414

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REVIEW ARTICLE

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Perspectives on the resilience of existing bridges to short- and long-term impacts of climate change

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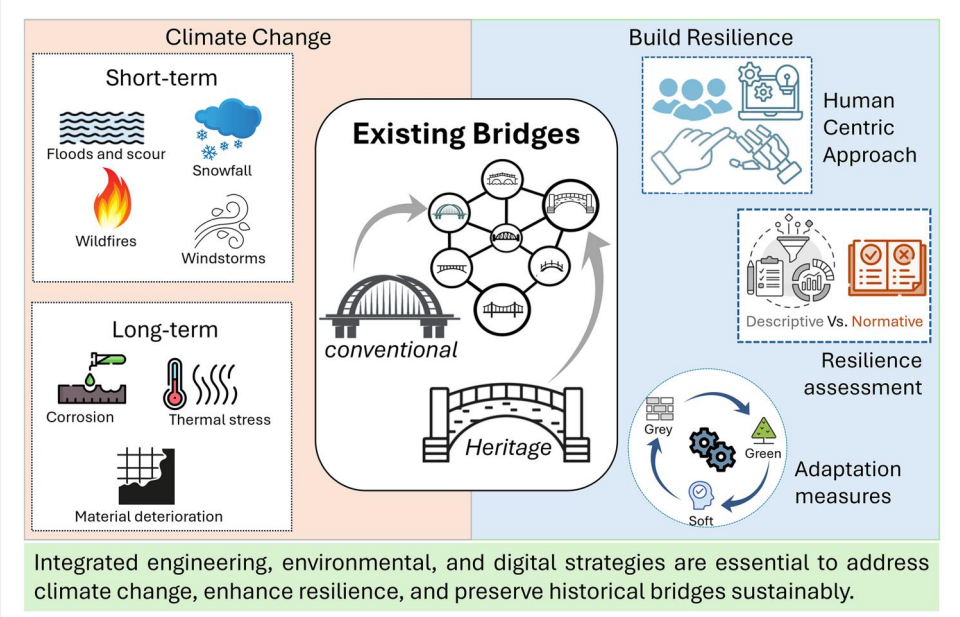
ABSTRACT

Climate change poses escalating risks to bridge infrastructure, with short-term hazards – such as flash floods, scour, snowfall, wildfires and windstorms – interacting with long-term stressors like corrosion and thermal effects to compromise safety and functionality. The paper synthesises interdisciplinary research on these challenges, and highlights actionable adaptation strategies to enhance resilience at both asset and network levels. Two critical yet often overlooked dimensions in resilience-based bridge management are emphasised: the unique challenges of adapting heritage bridges, and the integration of human-centered approaches. These dimensions, supported by emerging digital technologies such as digital twins, IoT-enabled monitoring and AI-driven predictive tools, contribute to both the resilience and social sustainability of bridge infrastructure. By integrating technical, cultural and social considerations, the paper provides a foundational perspective for rethinking current design, preservation and maintenance practices, and for advancing infrastructure that is not only resilient to physical stressors but also socially sustainable amid accelerating climate challenges.

ARTICLE HISTORY
Received 1 August 2025
Revised 23 January 2026
Accepted 17 February 2026

KEYWORDS
Adaptation; bridges; climate change; cultural heritage; digital twin; resilience

GRAPHICAL ABSTRACT



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1. Introduction

As climate change accelerates, the capacity of bridges to withstand both extreme weather events and gradual environmental changes is critical for maintaining transportation networks operational and ensuring economic stability. Existing bridges, including many heritage bridges designed under outdated climatic conditions, are particularly vulnerable to these evolving threats. The adaptation challenge is immense due to the vast number of bridges needing upgrades or retrofitting, placing a considerable economic burden on infrastructure operators. To address this challenge, it is essential to adopt a comprehensive approach that considers the full spectrum of climatic hazards alongside a diverse array of innovative and cost-effective solutions.

The climate emergency and the need for climatic adaptation of structural components of transport systems have drawn significant attention from scholars over the past two decades, resulting in a substantial body of knowledge. Research efforts have explored various dimensions of this challenge within the context of bridges. Many studies have concentrated on understanding the impacts of climate change on structural safety, particularly the risks posed by extreme weather events, as reviewed by Nasr et al. (2021) and Feng et al. (2023). Others have focused on adaptation interventions, addressing the need for retrofitting, upgrading and designing bridges to withstand evolving climatic conditions (Mondoro et al., 2018; Nasr et al., 2020). In some cases, an explicit resilience perspective is incorporated, emphasising the importance of maintaining functionality and minimising disruptions in the face of climatic hazards (Devendiran et al., 2021). Adaptation interventions are mainly examined at the individual bridge level, with limited attention to system-level strategies that encompass a portfolio of bridges. Scaling up these interventions introduces additional financial and technical complexities, including the need for comprehensive cost-benefit analyses and careful consideration of sustainability aspects. These broader considerations are critical and cannot be overlooked.

Current efforts exhibit a predominantly structural engineering-focused perspective, highlighting a clear single-disciplinary orientation in addressing the problem. This focus has led to two significant aspects being consistently overlooked. First, the inclusion of heritage bridges in adaptation strategies remains minimal. While precise global figures are unavailable, in Europe alone, more than 1,000 bridges enjoy formal heritage protection. Their protection status ranges from UNESCO World Heritage inscription to inclusion on national registers such as the UK's National Heritage List, France's Monuments Historiques, Spain's 'Bienes de Interés Cultural'. The damage or collapse of a heritage bridge not only results in significant human and economic losses but also leads to irreplaceable loss of cultural heritage, which embodies historical, architectural and social values passed down through generations. The preservation of these structures is therefore essential, not only for their practical functions but also for maintaining the cultural identity and continuity of the communities they serve (Pachón et al., 2018). The principles of the Historic Urban Landscape (HUL), as developed by UNESCO (2016), advocate moving beyond the development-conservation dichotomy towards a model where preservation serves as one of the key strategies for comprehensive urban development (Veldpaus et al., 2013).

Second, the integration of a human-centric perspective in adaptation efforts is often neglected. This approach emphasises placing human actors at the centre of both the design and adaptation stages. Traditionally, humans are viewed as passive, vulnerable recipients of external impacts, rather than as active participants capable of interacting with structures and dynamically adjusting their behaviour in response to changing conditions.

This paper aims to address these two gaps by providing an overview of potential adaptation strategies to enhance the resilience of both heritage and non-heritage bridges affected by the short- and long-term impacts of climate change. Additionally, it emphasises the importance of incorporating a human-centric perspective and explores tools that facilitate scaling the decision-making process to the system level.

This perspective paper reflects a collaborative effort by experts from diverse disciplines. The breadth of expertise provides an integrated and forward-looking interpretation of how climate change is reshaping the vulnerabilities of heritage and non-heritage bridges alike, and why a shift towards holistic, system-aware and human-centered resilience strategies has become imperative. Drawing on an extensive synthesis of research across multiple domains, the paper frames a collective perspective on gaps in research and operationalisation, emerging challenges and strategic future directions for advancing resilience assessment and management of bridges under accelerating climate pressures.

The remainder of the document is organised as follows: Section 2 provides an overview of the current state of existing bridges worldwide, including heritage bridges. The most relevant climatic hazards are then addressed within Section 3 focusing on those associated with short-term impacts and Section 4 on long-term impacts. Section 5 presents a perspective on resilience quantification and operationalisation, highlighting conceptual gaps, methodological needs and priorities for advancing resilience-based bridge management. Section 6 unifies research, practice and policy perspectives, discussing both established adaptation strategies and emerging directions such as AI-assisted, data-driven and human-centered digital twins. Finally, conclusions are presented in Section 7.

2. State of the existing bridges

Over the past two decades, the collapse of more than 120 bridges worldwide has resulted in significant economic losses and casualties, demonstrating the vulnerability of this critical infrastructure (Wang et al., 2022b). The intersection of ageing infrastructure and climate change-driven hazards creates an urgent need for more robust and adaptive maintenance frameworks. For instance, in Europe, the percentage of structurally deficient bridges is alarmingly high, with

France, Germany and the United Kingdom reporting values of 39%, 30% and 37%, respectively (Gkoumas et al., 2019). According to ASCE (2021), there are more than 617,000 bridges across the United States, of which 42% are at least 50 years old. Moreover, 7.5% of the United States' bridges are considered structurally deficient, which means they are in a poor condition. In Colombia, a 2009 study analysed almost 2,000 bridges and determined that 28% were in significant damage condition, and 4% required urgent maintenance due to severe damage and risk of collapse (Munoz & David, 2013). Recently, Colombia's National Infrastructure Agency stated that 35% of the bridges are in critical condition and estimated that their maintenance would cost about 330 million dollars (Radio, 2023). These examples demonstrate the need for strategies that integrate short-term response and long-term maintenance at the system level.

Many existing bridges are now recognised as cultural assets due to their pioneering engineering solutions and historical significance. The unique design and construction features of these structures, often tailored to specific environmental conditions, serve as proof-of-concept examples of pioneering engineering techniques. These attributes are acknowledged under UNESCO's World Heritage criteria. Although only seven European bridges are individually listed as UNESCO World Heritage sites (see Figure 1), thousands of bridges worldwide also receive this classification because they are integral parts of larger cultural ensembles or urban clusters.

Existing bridges, including both heritage and non-heritage structures, were not originally designed to withstand the emerging challenges posed by climate change. Their design parameters are typically based on historical climate data, which no longer reliably reflect current or future conditions. Climate change introduces risks through both short-term and long-term mechanisms. Short-term impacts, such as flash floods, extreme wind events, snowstorms, and wildfires, can cause immediate damage or disruption to bridge functionality. In contrast, long-term effects, including increased rates of corrosion, thermal expansion, and material degradation due to elevated temperatures, gradually undermine structural integrity and service life. This paper provides perspectives based on the most significant climate-induced hazards affecting bridge infrastructure, with a particular emphasis on those most relevant to current and projected climate conditions.

Climate projections that inform resilience assessments for bridge infrastructure are typically based on standardised emission scenarios developed by the Intergovernmental Panel on Climate Change (IPCC). Earlier assessments introduced four Representative Concentration Pathways (RCPs), reflecting alternative emissions trajectories (IPCC, 2014). These range from RCP2.6, a low-emission scenario consistent with strong global mitigation efforts, to RCP8.5, a high-emission pathway often cited as a worst case. In the Sixth Assessment Report (AR6), these have been updated to Shared Socioeconomic Pathways (SSPs), which integrate emissions projections with narratives of global socioeconomic development (IPCC, 2022). The five SSPs outline alternative futures shaped by differing levels of sustainability, inequality, fossil fuel reliance and international cooperation. For instance, SSP1-2.6 reflects a sustainability-oriented, low-emission future, while SSP5-8.5 represents a fossil fuel-intensive pathway with high emissions.

These scenarios provide the forcing conditions for Global Climate Models (GCMs) and Earth System Models (ESMs), which in turn generate global projections of climate variables on coarse grids (typ. 50–200 km). To make these projections relevant for bridge performance assessments, they are further downscaled to estimate localised changes in temperature, precipitation, extreme weather frequency and other hazard indicators. Downscaling approaches fall into two broad categories – dynamical and statistical – each offering different advantages for climate-impact assessment. Dynamical downscaling embeds a high-resolution Regional Climate Model (RCM) within a GCM to explicitly resolve mesoscale processes such as orographic precipitation, convection and land–atmosphere interactions that are not captured at coarse global scales. These RCMs typically operate at grid resolutions of 10–50 km and have been shown to provide 'added value' in regions with complex topography or strong regional forcing (Fowler et al., 2007). However, RCM-based downscaling inherits biases from the boundary conditions of the parent GCM and introduces its own structural uncertainties, meaning that multi-model RCM ensembles are generally recommended for robust impact analysis.



Figure 1. UNESCO-listed bridges in Europe.

Statistical downscaling, in contrast, establishes empirical relationships between large-scale climate predictors (e.g., geopotential height, sea-level pressure, specific humidity) and local climatic responses. A wide range of techniques exist, including regression models, weather-typing methods and stochastic weather generators and these methods are computationally efficient and capable of producing point-level projections (Fowler et al., 2007). Together, these methods provide complementary perspectives: dynamical downscaling offers physically consistent, high-resolution simulations driven by topography and regional processes, while statistical downscaling enables rapid generation of localised projections across multiple GCM–scenario combinations. Modern climate-impact studies therefore combine multiple downscaling approaches (Alizadeh, 2022).

3. Short-term impacts of climate change (shocks)

3.1. Flash floods and scour

Over time, the climate has undergone significant changes due to various natural processes, resulting in long-term shifts in weather patterns. One major consequence of these changes is the increasing variability in precipitation patterns, which can result in an increase in the frequency and intensity of floods in certain regions around the world. The anticipated increase in river discharge under a changing climate poses significant risks to humans, causes damage to infrastructure assets, and profoundly impacts the environment and surrounding areas. In particular, flash floods are highly destructive natural hazards characterised by rapid, sudden flow and dramatic increases in water levels due to failure of hydraulic infrastructure such as dams, or due to intense rainfall, mostly caused by thunderstorms. Such floods can reach heights that exceed 10 metres (Davis, 2001).

In Europe alone, climate-related risks to transport infrastructure caused by riverine and coastal flooding are projected to increase significantly, with estimated damages increasing from €0.5 billion to over €10 billion by the 2080s (Forzieri et al., 2018). Recently, the impacts of climate change on transportation networks in the United Kingdom have already cost an average exceeding £50 million each year, which is expected to increase due to scour-related failures of infrastructure assets (Network, 2014).

Scour refers to the gradual removal of the bed material around substructure elements due to flowing water. It is categorised into two main types: general and local. Both types can lead to significant erosion, forming cavities around substructure elements and changing the riverbed's morphology as displaced materials are transported and deposited downstream. Several factors influence scour, including sediment properties, geometry of substructure elements, approach water depth, water flow velocity, angle of flowing water, and kinematic viscosity of the water around bridge supports (Deng & Cai, 2010). It is noted that without sediment transport, scouring develops slowly as a long-term process. However, under conditions that promote sediment transport, anticipated during extreme events such as floods and storm runoff, the scour hole forms very rapidly. Moreover, local scour is difficult to estimate accurately by site inspections when the riverbed material is granular soil. As a result, it could be considered as a shock-induced deterioration process causing sudden failures (Richardson & Davis, 2001).

Scour is a leading factor contributing to bridge failures worldwide (Briaud et al., 2014; Cook et al., 2015; Flint et al., 2017). In recent years, the intensified flood frequency and severity caused by climate change have accelerated the scour-risk progression (Sasidharan et al., 2023). In UK alone, scour is expected to increase by over 8 % for riverine bridges (Argyroudis et al., 2019). Higher impacts from rising sea levels and more intense storm surges are expected to erode the foundations of bridges in coastal regions, affecting their stability (Imam, 2019). In this context, a recent study by Habeeb et al. (2024) stochastically investigated the influence of a changing climate on bridge stability due to local scour, revealing a significant increase in the probability of failure under the most pessimistic scenario (RCP 8.5).

3.2. Snowfall

Climate change impacts snowfall *via* two competing mechanisms: higher humidity can intensify snowfall, while rising temperatures reduce its likelihood. Higher temperatures increase evaporation and atmospheric moisture, potentially intensifying snowfall if temperatures remain cold enough for snow (optimally around $-2\ ^{\circ}C$). This dynamic interaction between temperature and humidity, further influenced by elevation and regional atmospheric circulation,results in highly region-specific impacts of climate change on snowfall.

Both primary drivers of extreme snowfall events – temperature and extreme precipitation – are projected to intensify with climate warming (IPCC, 2022). As a result, mean snowfall is expected to decrease across much of the Northern Hemisphere, especially in mid-latitudes (e.g., Western Europe and parts of North America) (O'Gorman, 2014; Quante et al., 2021). However, extreme snowfall events (99th and 99.9^{th} percentiles of daily snowfall distribution) are predicted to become more severe in colder, high-latitude areas like Northern Asia and North America, with average intensities exceeding historical maxima. Moreover, even in mid-latitude regions such as Western Europe, the average magnitude of the most severe snowfall events is expected to increase beyond the historical 99.9^{th} percentile.

Snow load – the weight of snow accumulating on structures – is determined not only by the amount of snowfall but also by the moisture and duration of snow cover, and melt-freeze cycles. Climate change can lead to more wet, heavy snow due to warmer, wetter conditions, which increases snow load even if snowfall amounts decline. Rain-on-snow (ROS) events and melt-refreeze cycles can also densify the snowpack, making it heavier (IPCC, 2022; Strasser, 2008).

Climate projections show that ROS events will increase in frequency and intensity under warming, particularly at high elevations (Bajracharya & Zhang, 2025). ROS events pose disproportionate risks due to their ability to rapidly densify snowpacks, and are identified as one of the major

causes of snow-related structural failures (Geis et al., 2012). Moreover, ROS events can be a triggering mechanism for avalanches, especially in alpine areas where elevated conditions create instability (IPCC, 2022).

Studies agree on a significant regional variability in future snow loads (Croce et al., 2018; Hong et al., 2021; Ivanov et al., 2022; Ohba & Sugimoto, 2020). Although average snow loads are generally expected to decrease, the standard deviation of annual maxima may increase, suggesting a higher likelihood of occasional extreme events exceeding historical records. For a 50-year return period, which defines extreme snow loads in Eurocode, snow loads are expected to decline across most of Europe, except in regions such as the UK and Scandinavia, where localised extremes may intensify (Croce et al., 2021). Colder mountainous areas like northern Scandinavia and the Alps may experience increases of up to 30–40% under the RCP 4.5 scenario (Ivanov et al., 2022). The substantial dispersion in projected snow loads and changes in snow cover duration require proper consideration in load combinations for structural design and resilience assessment.

Projected increases in extreme snowfall and associated snow loads pose structural risks to bridges, especially to covered bridges (Nasr et al., 2021). The majority of these structures are recognised as heritage assets. Many of them continue to serve as vital infrastructure, e.g. the Hartland Bridge in Canada, the Kapellbrücke Bridge in Lucerne, Chengyang Wind and Rain Bridge in China, and the Holzbrücke Bad Säckingen Bridge connecting Germany and Switzerland. While the majority of covered bridges today are limited to pedestrian use, a number remain in operation for vehicular or rail traffic, such as the Conwy Railway Bridge in North Wales, UK and Cornish–Windsor Covered Bridge in the US.

Further relevant risks associated with increased snowfall include the more frequent use of de-icing salts, which accelerates the deterioration of bridge materials and structural components. Moreover, heavy snowfall and ROS events can result in increased risk of avalanches. A notable bridge failure caused by a snow avalanche is the collapse of the Ri di Rialp road Bridge in the Swiss Alps in 1998 (Nasr et al., 2021). These conditions pose significant threats to structural integrity and public safety. Beyond these, increased snowfall imposes additional maintenance demands on bridges. In regions where snowfall is projected to intensify, operational costs related to snow removal are expected to rise, along with the likelihood of bridge closures due to snow accumulation.

Although often overlooked, decreases in snowfall may also introduce additional risks, particularly in mountainous regions. In the European Alps above 1,500 m, shorter snow seasons in future winters and springs are likely to affect the recurrence and timing of landslides (Stoffel et al., 2014), increasing the risk of secondary climate-induced hazards to the infrastructure.

3.3. Other types of short-term impacts

Although hazards such as floods have traditionally been the primary focus of bridge studies affected by climate change, others, like geotechnical hazards, strong winds and wildfires, have received comparatively less attention. Historically, these hazards were considered less critical to bridge performance. However, with climate change increasing the frequency and severity of such events, addressing their short-term impacts on bridge functionality has become even more critical.

3.3.1. Geotechnical hazards

Beyond scour, climate change is expected to amplify several other short-term geotechnical hazards that critically affect bridge approaches and foundations. One key group of hazards concerns the stability of embankments and natural slopes adjacent to bridges. Intense and more frequent rainfall events are a well-established trigger for slope failures and landslides, as they increase pore-water pressures and reduce effective stresses in the soil. Climate projections indicating more frequent heavy precipitation in many regions therefore imply a systematic reduction in slope safety factors (Kristo et al., 2017). Numerical studies have shown significant decreases in slope stability under projected future rainfall regimes, while case-study analyses in Scandinavia suggest that increased precipitation will lower the safety of a wide range of slope types (Hultén et al., 2007). Additional drivers include changes in groundwater table (GWT) and vegetation cover: a rising GWT can further destabilise side-slopes and abutment backfills, whereas elevated temperatures and prolonged droughts may lead to vegetation die-off and loss of root reinforcement, both of which exacerbate the likelihood of bridge side-slope failures and landslides (Lann et al., 2024; Svennevig et al., 2024).

Rockfalls and debris flows constitute another important class of geotechnical hazards with direct implications for bridge resilience. Climate-driven shifts in temperature and precipitation patterns – including more frequent freeze–thaw cycles, intense rainfall and rapid snowmelt – can destabilise rock masses and mobilise loose material on steep slopes above bridge approaches or along access roads, leading to increased rockfall activity. Similarly, high-intensity rainfall events are a primary trigger for debris flows, especially in catchments with erodible soils or where previous land-use changes, wildfires, or vegetation loss have reduced surface cohesion (Nasr et al., 2021). These flows can impact bridge decks, piers, abutments and approach embankments, causing partial blockage, structural damage, or complete loss of access even if the main superstructure remains intact.

3.3.2. Wind loads

Climate change is altering atmospheric conditions, resulting in stronger and unpredictable wind patterns. As global temperatures rise, increased atmospheric energy contributes to more intense storms and extreme wind events (Mattiello & Larose, 2024). These effects are particularly evident in coastal regions, where rising sea temperatures and shifting ocean currents amplify wind speeds. In this context, climate change can trigger feedback loops that further intensify wind patterns. For example, melting ice caps disrupt ocean

Table 1. Typical mechanisms affecting bridge structures due to fires. Source (BNHCRC, 2018).

Reinforced concrete	Steel	Timber
· Concrete spalling · Concrete cracking · Concrete delamination · Compressive strength reduction · Steel reinforcement and prestressed strands strength reduction	· Steel distortion · Deflection of steel elements · Formation of plastic hinges · Buckling (web buckling) · Reduction of tensile and yield strength · Post-fire steel toughness · Steel pitting and flaking · Paint and coating degradation	· Timber ignited · Charring (charring rate) · Strength loss · Elasticity loss

currents and alter wind circulation, leading to more volatile and severe weather conditions (Hamlyn & Nguyen, 2024).

Wind effects on bridges can be categorised into direct structural impacts and indirect effects on functionality and safety, both of which influence bridge performance in distinct ways. Direct impacts primarily involve structural loads and aerodynamic forces that affect the stability and integrity of bridges. According to Wu et al. (2023), wind-induced loads can be classified into three key types: static forces, buffeting forces and self-excited forces. Static forces act directly on the bridge structure, while buffeting forces caused by wind turbulence induce vibrations that may compromise structural integrity (Chen et al., 2023). Self-excited forces are more relevant for suspension bridges and are often negligible in continuous beam bridges due to their weaker aeroelastic interaction. Furthermore, during extreme weather events, wind pressure distribution across bridge surfaces varies, necessitating advanced simulation techniques to assess the transient wind flow and its interaction with structural components (Kazemian et al., 2021). Wind-induced aerodynamic phenomena, such as flutter and vortex excitation, pose stability challenges, particularly for long-span bridges (Chen et al., 2023).

Beyond direct structural effects, wind also impacts traffic safety and bridge operations. Crosswinds can compromise vehicle stability on bridge decks, increasing the risk of sideslip accidents, particularly in regions prone to strong winds (Chou et al., 2024). Wind can also increase accident risks, particularly when combined with ice loads (Wu et al., 2023). Further operational disruptions arise from wind-induced hydrodynamic forces, where storm-driven waves impose additional stresses on bridge decks, potentially leading to temporary closures due to safety concerns (Snaiki et al., 2020).

3.3.3. Wildfires

Although wildfires have historically played a crucial role in maintaining ecological balance, their duration, intensity and frequency have significantly increased over the last two decades. This has led to unprecedented Extreme Wildfire Events (EWE) in regions previously unaffected, such as northern European countries. The unpredictable nature of EWE has led to unprecedented economic, social and infrastructural costs, exceeding all previous records.

According to the latest IPCC report (IPCC, 2022), climate change is expected to make wildfire events more prolonged and destructive. Meteorological factors that potentially increase the risk of wildfires include unstable atmospheric conditions, pyro-convection and the complex interaction between drought, high air temperatures, low relative humidity and wind variations (Duane et al., 2021; Nauslar et al., 2018). Additionally, biological and physical factors resulting from meteorological drivers, such as aridity and increased vapour pressure deficit, further influence the likelihood of EWE.

Wildfires can have direct impacts on road infrastructure, including structural damage to roads and associated elements. In addition, they degrade the surrounding environment, leading to landslides, erosion, falling trees, which may also subsequently increase the risk of flooding. The generated extreme heat during wildfires can deform the structural materials and influence their mechanical characteristics, potentially leading to structural failure in bridges. The severity of damage depends on the material composition of the bridge. Between 1997 and 2015 in the US alone, nine steel bridges and 15 wooden bridges collapsed due to fires, while 35 others were so severely damaged that they had to be replaced with new structures (Garlock et al., 2012; Peris-Sayol et al., 2017). However, reinforced concrete (RC) can also be damaged by wildfires, especially given the intensities associated with the new wildfire regime. Table 1 summarises the damage mechanisms that fire can cause to bridges based on their construction materials.

EWE have become a major challenge for wildfire management, particularly in terms of extinguishing capacity, as current technology and resources often prove inadequate (Wotton et al., 2017). Although fire resilience has improved over the years, the suppression-based approach is insufficient to adequately address the evolving wildfire regime (UNEP, 2022). This underscores the need for a paradigm shift towards a preparedness perspective, especially with the expected increase in EWE intensity in the coming years.

4. Long-term impacts of climate change (stress)

4.1. Corrosion

The accelerated degradation of materials due to climate change is a growing concern. Projected changes in humidity, ocean pH, CO_2 concentration and temperature are expected to accelerate corrosion processes (Wu et al., 2018). Indirect effects such as wetting/drying and freeze-thaw cycles, as well as the use of de-icing salts, also contribute to the deterioration of reinforced concrete (RC) structures (Li et al., 2022; Ting et al., 2021). These changes may cause infrastructure to degrade faster than designed, prompting revisions to

design codes and maintenance strategies (Talukdar & Banthia, 2016).

Corrosion is one of the most widespread and costly deterioration mechanisms for steel and RC structures, with an estimated global cost exceeding 1.8 trillion USD (Schmitt et al., 2009). Besides economic losses, it poses serious risks to public safety. This process reduces structural capacity and produces expansive byproducts that cause cracking and spalling, reinforcing degradation. Other secondary effects of corrosion are bond strength reduction, inelastic buckling and low-cycle fatigue of the reinforcement (Kashani et al., 2015). Reinforcement corrosion in RC is mainly triggered by (i) carbonation and (ii) chloride ingress, the latter being the most common worldwide due to marine exposure and de-icing salts (Centre, 2020; Nasr et al., 2022; Rincon et al., 2024).

4.1.1. Carbonation-induced corrosion

Carbonation is a chemical reaction where calcium hydroxide ($Ca(OH)_2$) and other alkaline components in concrete react with atmospheric CO_2, leading to steel depassivation and accelerated corrosion initiation. This process is most active in environments with 50–70% humidity, common in inland regions (Russell et al., 2001).

The carbonation rate is influenced by CO_2 concentration, temperature and humidity (Yoon et al., 2007). Climate change may increase carbonation rates due to higher CO_2 levels and temperatures, though this effect could be offset in drier areas (Bastidas-Arteaga & Stewart, 2015). An increase in carbonation-induced damage risk of up to 16% in inland Australia by 2100 has been projected (Stewart et al., 2011). Similarly, a study showed that the active corrosion period in Lapland could drop from 37.5 to 19.7 years by 2100 (Köliö et al., 2014), highlighting regional vulnerabilities.

4.1.2. Chloride-induced corrosion

Chloride-induced corrosion is a major cause of deterioration in RC structures, especially in coastal areas and regions using de-icing salts (Nasr et al., 2022; Rincon et al., 2024; Y. Zhang et al., 2022). It involves chloride penetration into concrete, reaching a threshold near the reinforcement and initiating corrosion (Jaffer & Hansson, 2009; Papakonstantinou & Shinozuka, 2013).

This leads to expansive rust, cracking and strength loss. In the U.S., climate change may reduce RC service life by 0.7–2.7% (Zhang et al., 2022b). However, this impact is region-dependent, emphasising the need for localised adaptation strategies (Bastidas-Arteaga et al., 2010; Gao & Wang, 2017). Climate change intensifies this through several mechanisms:

- Effect of temperature increase: Studies show that the corrosion rate of steel in concrete increases exponentially with temperature due to changes in concrete resistivity and electrochemical processes, with rates rising to 6–8-fold under projected temperature ranges (Pour-Ghaz et al., 2009).
- Effect of wetting/drying cycles: RC structures in marine environments are frequently exposed to alternating wetting and drying processes, especially in tidal and splash zones (see Figure 2), which are considered the most aggressive due to the combined effects of high chloride and oxygen levels (Ting et al., 2021). This alternating cycle creates steep concentration gradients that amplify chloride penetration (Zhang et al., 2022a). These differences in wetting/drying ratios directly affect chloride transport mechanisms, with splash zones often showing faster deterioration rates (Ting et al., 2021).
- Effect of sea level rise: Numerical studies project that a sea-level rise of 49 cm over the next century, combined with the increase of temperature globally, could reduce the service life of concrete structures by 5%, compared to a 2% reduction when considering the increase of temperature globally alone (Gao & Wang, 2017).
- Synergy with frost damage in cold regions: In cold regions, the freeze–thaw (FT) cycles induce surface scaling, micro-cracking and internal expansion (Jiang et al., 2023). These micro-cracks provide additional pathways for chloride and sulphate ions to penetrate, exacerbating structural deterioration (Li et al., 2022). Research highlights that the FT cycles significantly increase chloride ion diffusion rates, as shown in experiments where the diffusion coefficient rose more than 160% after 100 FT cycles (Zhang et al., 2017).
- Synergy with concrete carbonation: The interaction between carbonation and chloride ingress significantly impacts the durability of RC structures, particularly under environmental conditions shaped by climate change (Yoon et al., 2007). Chloride ions transported into the concrete during wetting phases can be released during carbonation, increasing the risk of reinforcement corrosion. Experimental data show that this combined mechanism can significantly reduce the initiation time of corrosion – by up to 40% in some cases (Zhu et al., 2016).

4.2. Material deterioration of heritage bridges

Evolving climatic stressors can impact not only the structural integrity, but also the historical value, and long-term preservation of heritage bridges. Historical value can be diminished when original materials are lost, or the bridge's authenticity and context are compromised due to climate-induced damage or adaptation measures. Mosoarca et al. (2017) documented how increased wind pressure and wind-driven rain, attributed to climate change, have accelerated the erosion of limestone, brick and mortar in the historic railway viaduct in Oravita, Romania. Such environmental stresses are exacerbating the deterioration of traditional building materials, especially in regions already vulnerable to extreme weather conditions (Pinheiro et al., 2024).

Another worrying case of the long-term impact of climate change on material deterioration is observed in Svalbard, Norway, where the permafrost that used to act as a stable foundation for infrastructure assets has begun to

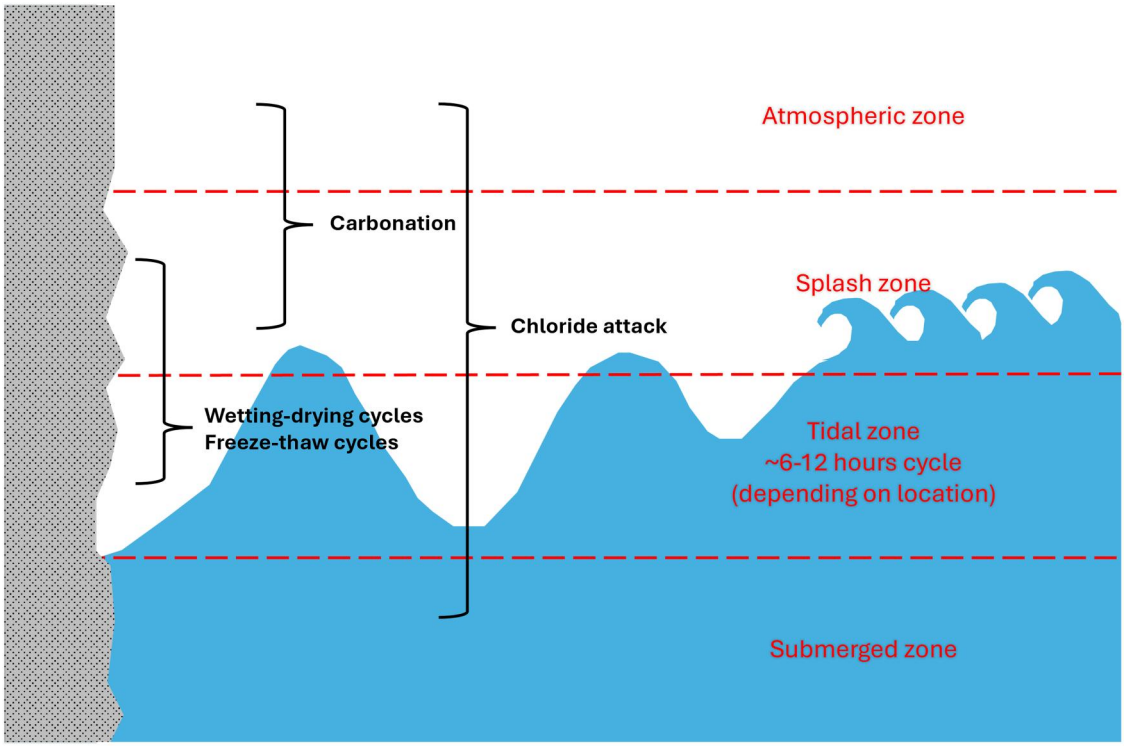


Figure 2. Marine exposure zones and associated deterioration. Adapted from Wang et al. (2022a).

thaw. This destabilises the foundations, which are mainly built with timber piles. Moreover, the wooden foundations of the heritage bridges on this island are now suffering from accelerated fungal decay, fostered by the rising temperatures caused by global warming (Flyen et al., 2020). Similarly, Cucuzza et al. (2024) reported on the impact of weather-related factors and leaching – both of which are expected to intensify due to climate change – on the growth of invasive vegetation and moisture, which negatively affect the preservation of masonry materials. Using a masonry arch bridge in Southern Italy as a case study, the study highlighted the significant role of material decay in the overall degradation of that heritage bridge, manifested as the detachment of the cementitious conglomerate and the subsequent exposure of the reinforcement to the detrimental effects of weathering. This phenomenon was also observed in many other similar structures, particularly those located in regions with more aggressive weather conditions.

4.3. Thermal stress due to high temperatures

Thermal loads from daily and seasonal temperature fluctuations can affect the long-term response and durability of bridges (Borah et al., 2021). Temperature variations in a bridge can be described in terms of a uniform component and temperature differentials (or gradients) (Barr et al., 2005). The uniform component is mainly governed by annual variations in air temperature, reflecting long-term changes in the surrounding climate. In contrast, temperature gradients are mainly influenced by short-term variations in the surrounding environment, such as variations in solar radiation and rapid changes in daily temperature (Larsson, 2015). The average (uniform) temperature change leads primarily to variations in the axial length of the structure, whereas temperature gradients cause bending deformations (Barr et al., 2005).

Xia et al. (2018) analysed the temperature characteristics of a long-span suspension bridge from monitoring data and showed that temperature load is one of the main causes of bridge deformation during long-term operation. The magnitude of thermally induced deformation in the studied bridge can be even greater than that caused by vehicular loads (Borah et al., 2021; Koo et al., 2013). Thermal actions also have a notable effect on the modal properties of the bridges. An increase in temperature leads to a reduction in structural frequencies, which is mainly caused by the change in the modulus of materials at different temperatures. This effect is more pronounced in concrete structures than in metallic structures (Xia et al., 2012).

The projections of long-term temperature changes show that global mean temperatures are expected to increase by 1.5 to 4 °C by 2100, depending on the representative concentration pathway (Masson-Delmotte et al., 2021). This may entail substantial changes in the shade air temperature, which has considerable influence on the uniform temperature component and is also of great significance to the design of thermal actions for bridges (see, e.g., EN 1991-1-5 (European Committee for Standardization, 2003)). Moreover, the frequency and intensity of hot extremes, including heatwaves, are very likely to increase, while cold extremes will become less intense and less frequent (Masson-Delmotte et al., 2021).

The changing climate, with the resulting more extreme weather events, will likely make the bridges more vulnerable to thermal actions. Nasr et al. (2021) mapped the risks to

infrastructure performance and safety associated with climate change and identified that the temperature rise may cause the highest number of risks in the future. The most relevant effect is associated with thermally induced stresses. The increased shade air temperature will intensify the uniform temperature component of the thermal loading on the structures. This may increase the restrained thermal stresses and cause volume changes in the unrestrained structures, thereby placing a higher demand on the deformation capacity of bridges (Athanasopoulou et al., 2020; Nasr et al., 2021). If these stresses are not properly managed, they can damage the bridge over time.

Durability of bridges is also vulnerable to the increase in ambient temperature. Farreras-Alcover et al. (2017) investigated how pavement temperature and traffic conditions influence the fatigue life of welded joints in steel bridge decks. Their study reveals that an increase of 2.9 °C in the mean air temperature can significantly reduce the reliability profile of the bridge. Similarly, Gudipudi et al. (2017) found that high temperatures can accelerate pavement deterioration, leading to defects such as rutting, fatigue cracking and joint faulting. These issues can occur much earlier than expected, increasing the need for frequent maintenance and reconstruction of road infrastructure (Daniel et al., 2014; Mills et al., 2009).

The projected rise in temperature and the increasing frequency of heat waves can also affect the serviceability of bridges. Concrete is particularly sensitive to ambient environmental conditions, as its long-term deformation, i.e., creep, accelerates with higher temperatures and lower relative humidity (Nasr et al., 2021). This accelerated creep can lead to excessive deformations, resulting in an average measured prestress loss of up to 50% (Bažant et al., 2012). Such deformations may subsequently cause cracking, excessive vibrations and reduced riding comfort. Similarly, timber structures are vulnerable to creep due to fluctuations in temperature and moisture content. This is especially critical for stress-laminated timber bridge decks, where prestress loss can compromise the timber lamination, leading to further excessive deformations (Nasr et al., 2021).

5. Resilience-based management of bridges

Climate change poses both short- and long-term threats, affecting infrastructure and its users. This challenge extends to decision-makers, designers and infrastructure owners, requiring them to proactively plan and prepare for these impacts. In this context, concepts such as resilience and adaptation have become increasingly relevant.

5.1. Definition of resilience

In the context of the built environment, resilience is defined as the ability of buildings, infrastructure and communities to resist, absorb, accommodate, adapt to, transform, and recover from various shocks and stresses (Bocchini et al., 2014; Council, 2012). Shocks and stresses align with the discussed short- and long-term impacts, respectively. In some cases, the concept of resilience is often confused with or considered similar to other concepts, such as reliability and risk.

Reliability refers to the probability that a structure or system will perform its intended function without failure under specified conditions for a defined period. It is assessed by evaluating the likelihood of failure by considering uncertainties in loads, modelling and structural capacity. Limit state functions are used to define failure criteria (Wang et al., 2023). Risk analysis goes further by combining this probability with the consequences of failure, thus providing a more comprehensive assessment for decision-making by considering both the likelihood and the impact of adverse events. Resilience, on the other hand, acknowledges that a system may temporarily fall below acceptable performance levels (for instance, not fulfilling the serviceability criteria), yet still retain the capacity to recover. The *temporal* functional degradation entails a recovery process; therefore, resilience inherently implies recovery. These concepts can be distinguished across the phases of a disruptive event: before, during and after its occurrence. As summarised in Figure 3, reliability and risk are more focused on the pre-event stage. They quantify the likelihood of unsatisfactory performance (and risk considers an additional dimension from consequences) before each disruptive event and guide design and preventive measures. Resilience is an overarching concept that covers the whole timeline. In this paper, the focus is primarily on the concept of resilience.

Given the centrality of recovery and sustained functionality in these definitions, it is also important to clarify the complementary concept of resilience failure. In probabilistic and decision-analytic formulations of resilience, a system is understood to accumulate 'capacity capital' over time, encompassing technical, economic, social, organisational and environmental resources that enable reorganisation, repair and adaptation following adverse events (Faber et al., 2020, 2017). Resilience failure takes place when this accumulated capacity is exhausted, such that the system cannot restore its required level of functionality without external support, nor maintain acceptable performance under subsequent disturbances (Faber et al., 2020; Santamaria-Ariza et al., 2023). A non-recoverable threshold of functionality is crossed when the losses induced by shocks or long-term stressors exceed the system's available recovery capacities, and can be expressed using probabilistic state variables, such as minimum acceptable functionality, time-to-recover, or

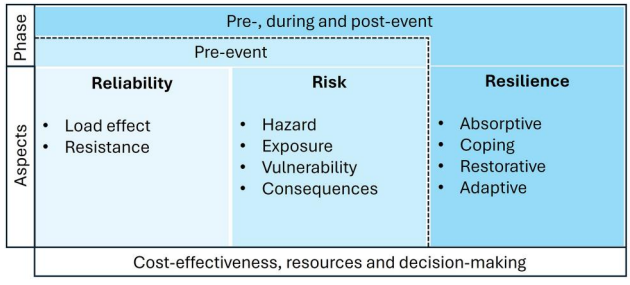


Figure 3. Comparing the aspects considered by reliability, risk, and resilience across phases of hazardous events.

required intervention level, that signal when the system transitions from recoverable to irrecoverable performance states.

Resilience of bridges can be assessed by evaluating their ability to withstand, adapt to, and recover from both long- and short-term impacts. A resilient bridge minimises disruptions, ensures safety and extends its service life, ultimately contributing to the sustainability of transportation networks. This concept also applies to heritage bridges, which exemplify resilient infrastructure, as many have withstood the test of time, demonstrating the durability and adaptability of traditional engineering techniques. Preserving and integrating these structures within modern transportation networks supports the development of resilient infrastructure, thereby fostering long-term socio-economic growth. Moreover, maintaining and retrofitting heritage bridges is essential for ensuring their structural safety, contributing to the broader resilience of urban infrastructure. In many cities, these bridges are vital transportation links, and their preservation is critical to ensuring safe, functional and sustainable urban mobility. Nevertheless, providing standardised or generalised approaches to study heritage bridges is challenging, as their design and lifespan are closely tied to the unique characteristics of their location (Pietrostefani & Holman, 2021).

5.2. Frameworks for resilience quantification of bridges

There is little consensus on the resilience operationalisation. One of the most common resilience assessments is based on four key principles (Argyroudis et al., 2020): i) robustness, which refers to the intrinsic strength or capacity of a system to endure external stresses, such as hazard events, without experiencing deterioration or a reduction in functionality; ii) redundancy, the characteristics of a system that enable it to offer alternative pathways, options, or substitutions when subjected to stress or disruptions; iii) resourcefulness, which embodies the ability to effectively mobilise essential resources and services during emergency situations, ensuring a swift and efficient response to unforeseen challenges; and iv) rapidity, which refers to the rate at which a perturbation can be resolved and the desired level of performance restored. These principles only highlight certain relevant aspects to be considered; however, there is no standard approach for measuring them or under which conditions they should be applied.

5.2.1. Non-heritage bridges

Various frameworks have been developed to quantify resilience, often employing performance-based engineering concepts. A common approach involves time-dependent functionality curves, where performance (e.g., traffic flow, structural capacity) is tracked before, during and after a hazard event. Key resilience metrics derived from this curve include the resilience index, recovery time, residual functionality and loss of functionality (Poulin & Kane, 2021). Mathematical formulations often integrate stochastic modelling to account for uncertainties in hazard occurrence, damage mechanisms and repair logistics (Li et al., 2020). However, simplified and practical approaches, that enable ranking bridges according to their annual resilience, are also available (Minaie & Moon, 2017). At the same time, as resilience metrics become more integrated into decision-making, modern resilience frameworks increasingly intersect with sustainability objectives (Bocchini et al., 2014; Kopiika et al., 2025; Mitoulis et al., 2023).

5.2.2. Heritage bridges

A number of frameworks have been proposed in recent years that, while not specifically developed for heritage bridges, provide valuable insights into resilience assessment and management. For instance, the HAPI framework described by Vamvatsikos & Chatzidaki (2022) adopts a total probability discrete event simulation approach to assess resilience before, during and after perturbation events. Although this formulation was not designed for heritage bridges, its ability to account for cascading and concurrent hazards, coupled with a near-real-time prediction module enabled by multimodal sensors, offers concepts that could be adapted to the heritage context. Similarly, Ishibashi et al. (2020) explored the integration of Life-Cycle Cost (LCC) considerations with resilience at the bridge network level. While this work does not specifically address heritage structures, it highlights the importance of coupling resilience with sustainability in bridge management.

More directly relevant to heritage assets, Turksezer et al. (2020) proposed a system identification framework tailored for managing the resilience of historic bridges exposed to natural hazards, degradation, failures and human or organisational errors. Their continuous approach guides decision-making before, during and after perturbation events, with a focus on identifying system characteristics that can be represented as resilience indicators. In contrast, the work of Dimitrios et al. (2023) focuses on the vulnerability assessment of masonry heritage bridges by conducting a detailed evaluation of their structural integrity. Their study combined non-destructive evaluation techniques with numerical analysis to assess the vulnerability of stone arch bridges in the Balkan Peninsula to seismic and flood hazards. While highly significant in highlighting integrity risks for heritage structures located in multi-hazard regions, the work primarily quantifies vulnerability and does not fully capture the multidimensional aspects of resilience, such as adaptive capacity or recovery potential.

Recent research has further advanced resilience-related approaches that can be applied to heritage bridges. Rogulj & Pamuković (2025) developed a sustainable planning–based decision-making framework that integrates resilience into asset management strategies, emphasising multi-criteria evaluation of interventions that balance safety, functionality and cultural value. Jiménez Rios et al. (2025) discussed the potential of Industry 5.0 principles, particularly human-centric digitalisation and stakeholder integration, to enhance resilience by embedding monitoring, predictive maintenance and participatory governance into heritage bridge

management. Cavuslu & Ülger (2025) investigated the structural enhancement of historic masonry bridges through the use of iron and FRP connectors, demonstrating their effectiveness in improving seismic resilience while maintaining compatibility with heritage values. Collectively, these studies expand the methodological and practical basis for resilience in heritage bridges, ranging from decision-making and digital innovation to structural retrofitting strategies.

Although the above-mentioned works represent significant contributions to the current state of knowledge on resilience management, further research is necessary to address the challenges of heritage bridge resilience. This research should not only focus on technical resilience but also incorporate cultural and social values. For example, integrating community-based resilience metrics could provide valuable insights into how the loss or degradation of a heritage bridge might affect the local population's identity and cultural continuity (Holtorf, 2018). Additionally, advancing the use of digital twins and predictive maintenance tools, specifically designed for heritage structures, could significantly enhance real-time monitoring and preventive intervention strategies (Kong & Hucks, 2023). Such advancements will ensure that bridges, especially heritage ones, continue to function safely and effectively in the face of climate change and other hazards.

5.2.3. Bridge networks

Bridges are not standalone assets; they are critical links in broader road and transportation networks. The failure or reduced functionality of one bridge can disrupt traffic flow, emergency access and freight transport far beyond the immediate area. Therefore, system-level resilience assessment for bridge networks is important to capture the real-world functionality and societal impact of disruptions more accurately than analysing individual bridges in isolation.

Network assessments capture interdependencies among bridges, redundancy (e.g., availability of alternative routes) and cascading failures, where the failure of one bridge impacts the performance of others and of the system as a whole. These frameworks evaluate how rerouting and traffic redistribution can either mitigate or amplify the consequences of localised failures (Ouyang, 2014). Such analysis enables the identification of critical links, i.e., bridges with no viable alternatives and supports the prioritisation of interventions based on systemic importance rather than isolated structural vulnerability. Network-level resilience uses system-wide metrics, such as connectivity, travel time, network efficiency and accessibility, to evaluate how damage to individual bridges affects overall transportation functionality (Ouyang, 2014; Zhang & Wang, 2016). To enable the information flow across scales, i.e., linking the bridge level resilience to the system level, digital twin frameworks (see Section 6.4) are increasingly used. As such, digital twins serve as a bridge between engineering-scale insights and system-level decision-making, offering a unified platform for resilience assessment, management and optimisation.

As an alternative conceptual perspective, for interlinked systems, joint analyses of resilience and robustness as distinct but interrelated system characteristics have been proposed within a probabilistic decision-analysis framework (Faber et al., 2017). Within this framework, robustness is defined at the system level as the ability to limit disproportionate and cascading consequences relative to the initiating disturbance, quantified through direct and indirect consequences. As a result, the coupled analysis of resilience and robustness as causally linked distinct system characteristics enables improved management decision optimisation of system performance under repeated stochastic disturbances.

5.2.4. Long-term resilience quantification

In short-term sense, resilience focuses on a system's response dynamics – how quickly and effectively it returns to an acceptable level of functionality after a discrete shock. In contrast, long-term resilience extends the concept to include cumulative and progressive effects over the service life of an asset, integrating both sudden hazards and chronic stressors. It encompasses the system's capacity to maintain and adapt its functionality under evolving environmental, climatic and operational conditions. Rather than focusing on a single recovery process, long-term resilience captures the interaction of degradation, adaptation and multiple recovery cycles across decades. It thus reflects the sustainability and adaptive capacity of the infrastructure, accounting for material deterioration, climate-induced loads, maintenance and retrofitting interventions and changing societal demands.

The quantification of long-term resilience is challenging due to several interconnected issues. First, there is a proliferation of competing metrics, each derived from functionality curves but emphasising different aspects. No single metric is universally applicable; a representative metric must be selected that accurately reflects system behaviour, a choice that is inherently dependent on stakeholder priorities and the specific system context. Second, modelling the recovery process itself is a challenge, as it is a complex socio-technical-economic process influenced by unceratin time-evolving factors like available resources, institutional capacity and social dynamics, which are difficult to capture in a simplified mathematical model.

Third, and of particular relevance to climate change, the context of multiple, sequential shocks and chronic long-term stressors requires multi-hazard models founded on stochastic processes. A system may be hit by a second disaster before recovering from the first, or its baseline performance may be deteriorating due to a persistent stressor. The uncertainty in the timing and sequence of these events creates a complex temporal profile. Consequently, a promising path forward involves using context-specific metrics, multi-dimensional dashboards of indicators, and scenario-based probabilistic approaches that express resilience as a distribution of potential performances across a range of possible futures. The future lies not in a single formula but in developing practical frameworks, simulations and decision-support tools that help planners understand system behaviour and compare intervention strategies under complex and uncertain conditions.

5.3. Managing uncertainties

Quantifying the resilience of bridge infrastructure under climate change is fundamentally an exercise in managing deep, cascading and compounding uncertainties. These originate from the climatic forcings projected for the future and the current and future performance of the structural systems themselves.

5.3.1. Climatic uncertainties

Regional climate change projections are subject to uncertainties arising from four key sources: model structure, future socioeconomic scenarios, internal climate variability and the downscaling technique (Giorgi, 2019). The first three are inherent to GCM projections and are often amplified when propagated to regional scales through downscaling.

Model structural uncertainty, also referred to as model, response, or GCM uncertainty, results from differences in how GCMs represent the coupled dynamics of the atmosphere, ocean, cryosphere and land surface. Even under identical radiative forcing from a given emissions scenario, these structural differences lead to a spread in projected climate responses. The diversity of these structures is evident in the sixth phase of the Coupled Model Intercomparison Project (CMIP6), which includes over 130 distinct GCMs developed worldwide (ECMWF, 2025). Scenario uncertainty reflects the unknown trajectory of future socio-economic, technological and policy developments. Climate scenarios, such as the SSPs, represent plausible alternatives based on assumptions about population growth, technological progress, energy use and mitigation efforts, leading to different trajectories of greenhouse gas emissions and radiative forcing. Critically, for both scenario and model structural uncertainty, there is no scientific consensus for assigning likelihoods to the different alternatives. This lack of knowledge about which scenario or model is most correct is a defining characteristic of deep uncertainty, moving beyond simple probabilistic risk into a realm where decision-making must be robust to a wide range of plausible futures.

Furthermore, internal climate variability – representing natural, unforced fluctuations of the climate system that occur independently of external forcing – can, on decadal timescales, temporarily mask, reverse or amplify the long-term climate change signal (Hawkins & Sutton, 2009). Finally, uncertainty due to downscaling stems from the techniques used to refine coarse GCM outputs to regional or local scales. Both dynamical and statistical downscaling introduce methodological and data-related errors associated with model assumptions, boundary conditions and calibration datasets. As a result, projections may diverge even when driven by the same GCM and scenario.

The relative dominance of these uncertainty sources is time-dependent. GCM and internal variability typically dominate in the near term, while scenario and GCM uncertainties prevail towards the end of the century. Downscaling uncertainty is particularly significant for variables controlled by local topography or convective processes (Giorgi, 2019).

5.3.2. Structural uncertainties

Complementing the climatic uncertainties are those related to the bridge infrastructure. The current and future performance of existing bridges is influenced by uncertainties in material properties, structural geometry, the rates of material degradation, and the history of maintenance and retrofitting. Furthermore, the interactions between changing environmental stressors and structural resistance are not fully understood, introducing additional uncertainty in predicting long-term capacity.

5.3.3. Synthesising uncertainties for resilience quantification

To produce meaningful resilience metrics, these parallel streams of uncertainty need to be integrated. This is achieved through probabilistic and simulation-based approaches, such as Monte Carlo simulation, which jointly model the stochastic nature of future climatic hazards and structural response. Consequently, resilience indicators, such as functionality loss, recovery time and residual capacity, are not deterministic values but probability-based metrics.

However, it is critical to recognise that a standard probabilistic framing, while powerful, is not entirely sufficient to address deep uncertainty. The core of the deep uncertainty problem – that we cannot assign reliable probabilities to different climate models or socioeconomic futures – means that a single probability distribution can be misleading. Therefore, the results of such analyses are best interpreted not as precise forecasts, but as exploratory projections that reveal the system's sensitivity across a wide range of plausible futures.

In this context, ensemble-based strategies are indispensable. Rather than seeking to reduce the deep uncertainties, which is often impossible, ensembles are used to characterise them. By running simulations across the entire ensemble of available climate models (GCMs) and scenarios (SSPs), analysts can map the full decision-relevant range of potential outcomes. This approach does not eliminate uncertainty but provides a more robust and honest basis for stress-testing adaptation strategies and for prioritising investments that perform adequately across many plausible futures, thereby supporting decision-making under deep uncertainty. Eventually, this ensemble-driven process fundamentally shifts the goal of resilience quantification from predictive optimisation to robust decision-making.

5.4. Thresholds for actionable resilience

Many authors consider resilience as a normative concept; that is, resilience is not just a descriptive property of a system, but also reflects value-based judgments about what outcomes are desirable, acceptable, or prioritised. It implies that defining and assessing resilience involves choices such as what level of performance is acceptable, how much recovery time is tolerable, and which functions are critical to preserve based on the perspectives and values of stakeholders.

Resilience goals can be communicated through threshold values of representative metrics, providing quantitative benchmarks to guide the prioritisation of interventions and decision-making. Without such thresholds, resilience metrics remain abstract and difficult to interpret in terms of acceptable or unacceptable system behaviour. The establishment of such target values requires collaborative efforts by engaging all involved stakeholders, including engineers, asset owners, managers, community representatives, and, in the case of heritage bridges, cultural heritage specialists. In this context, Kielhauser et al. (2019) and Adey et al. (2021) investigated the development of threshold values for infrastructure resilience metrics aligned with varying resilience objectives, with and without cost-benefit analysis.

While essential, defining and operationalising such thresholds in the context of climate change is challenged by severe uncertainties in future projections and resulting impacts. Although resilience is investigated within probabilistic frameworks, operationalisation is commonly practiced through deterministic targets due to simplicity and ease of communication. One pathway forward is to frame the thresholds probabilistically, capturing a range of acceptable system states linked to graded adaptation measures, and enabling regular updates as new data and stakeholder perspectives emerge. Such an approach can balance realism about uncertainty with the need for operational targets.

6. Adaptation measures to increase climate resilience

Adaptation focuses on combating the consequences of climate change, increasing the resilience of infrastructure and minimising the impacts of potential hazards (Vajjarapu & Verma, 2021). This concept differs from climate mitigation measures, which aim to minimise the causes of climate change, such as reducing or capturing greenhouse gas emissions. Both adaptation and mitigation measures, collectively termed 'climate action' (Group, 2022), are critical and must be implemented without delay. However, there is a lack of knowledge and tools to effectively apply adaptation measures. Thus, this section describes adaptation measures that can address different impacts of climate change on bridges.

There are different classifications of adaptation measures, but this paper adopts the classification by the European Environment Agency, which categorises adaptations into grey, green and soft measures (EEA, 2024). Grey measures refer to interventions involving physical infrastructure, such as reinforcing foundations, installing flood barriers, or improving drainage systems to withstand extreme weather events. Green measures focus on strategies that leverage natural and ecological solutions, for example vegetated floodplains to reduce water flow and pressure on bridges, restoring riverbanks to limit erosion, or using permeable surfaces in surrounding areas to improve storm-water management. Soft measures pertain to non-structural approaches that rely on social, institutional, educational, or policy interventions to promote adaptive and behavioural changes, such as updating emergency evacuation plans, real-time flood warnings, or training local authorities and bridge users on adaptive responses.

In the case of heritage bridges, it is highly recommended that any intervention must adhere to the principles outlined in international conservation guidelines, such as the Venice Charter (ICOMOS, 1964). This charter advocates for evidence-based, minimal, incremental and reversible interventions that are compatible with the original materials and aim to preserve the authenticity of the bridge (ICOMOS, 1994). Additionally, the principles and guidelines from ISCARSAH (ICOMOS and ISCARSAH, 2003a, 2003b) and Annexe I of the ISO 13822 standard (International Organization for Standardization, 2010) must be followed to ensure the proper conservation of such valuable assets.

Heritage bridges often serve as integral parts of contemporary infrastructure, with their serviceability conditions continuously evolving. Unlike other cultural assets, where modern uses can diverge significantly from the original purpose, the value of heritage bridges is closely tied to their functional performance as an infrastructure. As such, their resilience is inherently linked to the infrastructure network in which they are embedded. The resilience of heritage bridges aligns closely with the objectives of the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Build resilient infrastructure, promote inclusive and sustainable industrialisation, and foster innovation) and SDG 11 (Make cities and human settlements inclusive, safe, resilient and sustainable). Important guidelines on enhancing the resilience of built cultural heritage and improving post-disaster recovery processes of heritage bridges have been established in the ICOMOS Lima Declaration (Gibu et al., 2010) and the Sendai Framework (UNDRR, 2015).

The ICOMOS Lima Declaration emphasises that post-disaster recovery (particularly after earthquake events) of heritage structures should preserve integrity and authenticity through a multidisciplinary approach integrating structural assessment, use of traditional materials and techniques where appropriate, and development of periodic inspection tools tailored to seismic and environmental risks. It further stresses the responsibility of the authorities towards preparedness as well as the involvement of local communities, education and coordinated policies among structural engineers, architects and heritage specialists to prevent unnecessary demolition of historic fabric after disasters. In addition, the Lima Declaration's Action Recommendations for Educational and Research Institutions (Points 16 and 17) stress the development of training programmes on repair and retrofitting, alongside raising awareness among future generations, which can directly contribute to capacity building in the conservation and resilience of heritage bridges by equipping professionals and communities with the necessary knowledge and skills to safeguard heritage bridges' structural integrity while preserving cultural values.

Building on these recommendations, the Sendai Framework reinforces the urgency of protecting cultural heritage, explicitly including infrastructure such as heritage bridges, by anticipating and reducing disaster risks through systematic documentation of losses and impacts, as well as

investing in risk reduction strategies. Together with the Lima Declaration, these provisions highlight the need for integrated assessment, monitoring and targeted investment to ensure that heritage bridges are safeguarded both as critical infrastructure and as cultural assets, thereby strengthening their resilience against future hazards.

6.1. Grey adaptation measures

6.1.1. Scour

Various adaptation approaches for scour can be implemented to maintain bridge integrity under a changing climate, each addressing the challenge in a distinct way (Bento et al., 2020; Mondoro et al., 2018). Countermeasure techniques such as rip-rap, geotextile fabrics, gabion walls and concrete block mats absorb the flow energy around the installation location and prevent the erosion of bed material around substructure elements (Singh et al., 2022; Zarrati et al., 2006). Further measures to minimise erosion are the flow-altering techniques that redirect the flow patterns to reduce turbulence and shear stress (Tafarojnoruz et al., 2010). Examples include artificial barriers, weirs, guide vanes and spur dikes.

In areas subjected to strong hydrodynamic forces, bed stabilisation methods are employed to enhance structural stability and preserve bed morphology by conserving flow patterns. For instance, grouted bed protection involves injecting cement into bed materials around substructure elements to create a cohesive erosion-resistant layer. Alternatively, concrete aprons, are reinforced slabs installed above critical areas to provide a durable layer against erosion (Lagasse et al., 2007). Crucial for formulating any of these proactive adaptation strategies is the prediction of discharge magnitudes under a changing climate by using techniques such as time series analysis, flood frequency analysis and machine learning.

6.1.2. Floods

Adaptation solutions to floods rely on engineered structures and technological measures for containing floodwater, controlling water flow and reinforcing riverbanks. Structural defences such as levees, dikes, storm surge barriers and dams contain floodwater and mitigate rising flood levels and prevent inundation of bridge approaches and abutments (Aerts, 2018). Alternatively, floodgates and coastal barriers are flood control systems that regulate water flow (Mooyaart & Jonkman, 2017; Pollard et al., 2008). Reinforcement techniques, such as gabion walls and ground anchors, are used to stabilise slopes and riverbanks and reduce the risk of landslides triggered by floods (Heibaum, 2014; Uray, 2022). Solutions with retaining walls backfilled with infiltrating porous materials and integrated pipes allow for the dispersion of excess water around bridge abutments, helping to reduce hydrostatic pressure during flood events and are implemented mainly around riverbanks and coastal roads (Sajedi et al., 2019).

6.1.3. Corrosion

Traditional methods to mitigate corrosion in structures, often recommended by design codes, have focused on delaying the ingress of corrosive agents and protecting steel. Common approaches include increasing the thickness of the concrete cover of RC bridges, which serves as a physical barrier to the penetration of chloride and carbon dioxide, and applying surface coatings or barriers to isolate the materials from direct exposure to aggressive environments (Stewart et al., 2012). Protective systems such as cathodic protection and electrochemical chloride extraction are also widely implemented to prevent steel reinforcement from reaching critical corrosion thresholds. Additionally, the use of galvanised reinforcement and corrosion inhibitors has proven effective in minimising the electrochemical reactions that lead to corrosion (Nasr et al., 2020). However, the performance of traditional methods may be limited in increasingly aggressive environmental conditions.

Moreover, innovations in material science, such as incorporating supplementary cementitious materials (SCMs) and advanced concrete mixes like ferroaluminate cement (FAC), have shown potential to enhance corrosion resistance. For instance, the use of SCMs, including recycled concrete powder (RCP), has shown promise in enhancing durability and mitigating chloride ingress, although challenges related to porosity and long-term performance remain (Liu et al., 2023; Yang et al., 2025). Additionally, FAC demonstrates reduced CO_2 permeability and lower chloride diffusion coefficients compared to ordinary Portland cement (OPC), suggesting its suitability in marine and de-icing salt environments (Cheng et al., 2022). However, challenges persist, such as the reduced alkalinity of FAC, which may lower the critical chloride threshold for steel passivation (Xue et al., 2025). Similarly, polyamine-based corrosion inhibitors, with their protective film-forming and adsorption capabilities, present an environmentally friendly option for safeguarding RC. These organic compounds can self-heal damaged films, ensuring continuous protection in aggressive environments (Gharieb et al., 2024). Despite these advancements, further research is needed to refine their application and understand long-term behaviours under variable climatic conditions.

Adaptation measures must also account for the lifecycle and environmental footprint of these solutions. The integration of recycled materials like RCP, combined with nanotechnology innovations such as nano-SiO_2, holds the potential to balance durability and sustainability goals. Studies have shown that nano-SiO_2 not only enhances the early strength and compactness of concrete but also improves chloride resistance through pozzolanic and nucleation effects. However, excessive use of nanomaterials can detract from their benefits, underscoring the need for optimised dosages (Liu et al., 2023). The interplay of these strategies demonstrates that effective adaptation to the evolving challenges of climate change requires a holistic approach, incorporating both innovative materials and refined design practices to extend the lifespan of critical infrastructure.

6.2. Soft adaptation measures

Soft adaptation measures refer to improvements in monitoring, diagnosis, forecasting, early warning, emergency response and maintenance planning. Within this context, emerging digital technologies act as powerful enablers of soft adaptation, offering new capabilities. Tools such as IoT-based sensing, UAV inspection, digital twins, cloud-based monitoring platforms and AI-driven analytics facilitate rapid data acquisition, continuous condition assessment and predictive modelling of risks (Argyroudis et al., 2022; Makhoul et al., 2024; Tubaldi et al., 2021). By reducing epistemic uncertainty and supporting real-time, informed decision-making, these technologies strengthen every phase of the resilience cycle, from preparedness and early warning to targeted maintenance, emergency interventions and long-term adaptation planning.

6.2.1. Adaptive traffic management

Adaptive traffic management (ATM) complements green infrastructure and grey engineering by dynamically managing the demands placed on bridges before, during and after climate-induced hazards. It involves the responsive and flexible control of traffic operations through real-time monitoring, data-driven decision-making, and automated systems that adapt to changing conditions. Unlike conventional static traffic control, ATM continuously adjusts variables such as signal timing, routeing, speed limits and access restrictions based on live information about traffic flows, hazards and infrastructure status (Djahel et al., 2013; Pregnolato et al., 2016).

ATM improves the adaptive capacity of bridges and bridge networks across all phases of the resilience management cycle. In the preparedness stage, it proactively limits exposure on vulnerable bridges by restricting loads or smartly rerouting traffic in anticipation of extreme weather. During disruptive events, ATM supports safe and efficient emergency response by imposing timely closures, dynamically prioritising emergency vehicles and coordinating detours. In the recovery phase, ATM facilitates staged reopening, regulates access for inspections and repairs, and prevents secondary damage, accelerating restoration efforts. Network-based prioritisation shows that even partial adaptation of strategically critical bridges can stabilise traffic across entire corridors and prevent bottlenecks on bridges, which are typically critical choke points (Pregnolato et al., 2016).

ATM relies on an integrated suite of tools, including traffic and environmental sensors, IoT-enabled communications, GIS platforms, data fusion systems, predictive models, and artificial intelligence (AI) (Djahel et al., 2013; Lilhore et al., 2022). This makes ATM closely integrated with structural health monitoring (SHM) systems. While SHM focuses on monitoring the capacity and safety state of bridge structures, ATM regulates the demand placed on them in real time. Although they use different sensor toolkits reflecting their distinct objectives (capacity vs. demand), they increasingly benefit from shared data streams in a smart-city framework to deliver holistic bridge resilience. Together, SHM and ATM form a synergistic framework that can transform bridges from static assets into actively monitored and dynamically controlled lifelines.

6.2.2. Structural health monitoring

SHM refers to the process of implementing a damage detection and characterisation strategy for engineering structures using periodically or continuously collected data from sensors (Wilson et al., 2018). Therefore, it does not itself constitute an adaptation measure; rather, it is a supporting tool for decision makers and has emerged as a crucial tool for condition assessment of bridges. Traditional inspection methods, such as visual assessments, are often subjective and provide limited information after deterioration has already begun (Figueira, 2017). In contrast, SHM systems integrate embedded sensors that continuously collect real-time data

Recent advancements in SHM technologies have significantly broadened the scope and precision of monitoring. Modern SHM systems integrate multiple types of sensors, including:

- Vibration-based sensors (e.g., accelerometers, piezoelectric elements, vibrating-wire sensors) for modal analysis and structural response characterisation (Deng et al., 2023).
- Electrochemical and electro-resistive sensors for corrosion monitoring, including embedded electrodes and chloride ion detection (Rincon et al., 2024; Rizzo & Enshaeian, 2021).
- Non-destructive evaluation (NDE) methods such as ultrasonic testing, radar, lidar and image processing, thermography and X-ray imaging for detecting internal defects (Deng et al., 2023; He et al., 2022).
- Micro-electro-mechanical systems (MEMS) and piezo-resistive sensors enabling dense, low-cost networks with high sensitivity (Gharehbaghi et al., 2022).

Recent developments in SHM have extended beyond sensor hardware, incorporating advanced data analytics, machine learning and digital twin approaches for predictive maintenance (Gharehbaghi et al., 2022; Zhang et al., 2025). Multi-sensor systems are increasingly integrated with real-time data processing and edge computing, enabling early detection of structural anomalies (Zhang et al., 2025). Studies have demonstrated the combination of vibration-based, electrochemical and NDE sensors with AI algorithms to track corrosion progression, assess load-induced damage and improve long-term performance predictions (Farrar et al., 2025; Gharehbaghi et al., 2022). These approaches highlight the shift from mere condition monitoring towards proactive, data-driven infrastructure management (Farrar et al., 2025).

However, challenges remain, including sensor durability, high installation and maintenance costs, the management and processing of large volumes of data, missing information, data interpretation complexities and the need for more robust predictive models to enhance decision-making in maintenance planning (Rizzo & Enshaeian, 2021; Zhang

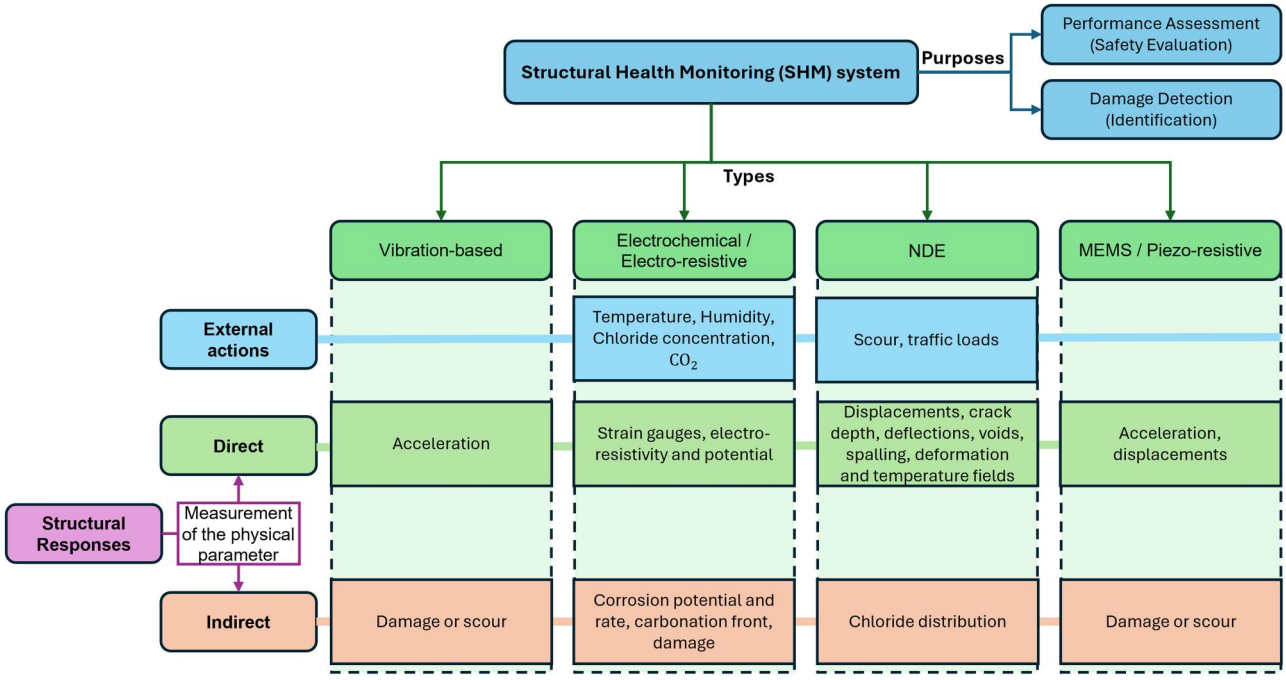


Figure 4. SHM sensor types and their relationship with monitored parameters and structural health objectives.

et al., 2025). Figure 4 illustrates the most common measurements and SHM sensors according to their type and clarifies the distinction between direct and indirect measurements of physical parameters, highlighting the relevance of each sensor type to monitoring structural health objectives.

The effectiveness of SHM systems depends on the strategic selection of sensor types, placement and data analysis techniques. Recent studies emphasise the importance of multi-sensor systems to provide a comprehensive assessment of bridge health (Rincon et al., 2024). These systems can measure electrochemical variations in steel, quantify chloride ingress in RC, and track material deterioration over time. Additional advances in AI and computer vision have further expanded SHM capabilities, allowing for automated detection of corrosion and other structural defects in bridges (Deng et al., 2023). Despite these advancements, SHM data can be influenced by environmental conditions such as temperature and moisture, which affect sensor accuracy and signal stability. He et al. (2022) suggests that data-driven methodologies and machine learning approaches can improve the reliability of SHM systems by accounting for these external variables.

As climate change intensifies, the role of SHM in adaptation strategies becomes even more significant. Rising temperatures, increased frequency of extreme weather events, and accelerated material degradation due to environmental stressors necessitate continuous monitoring to ensure the longevity of RC infrastructure (Rizzo & Enshaeian, 2021). The integration of SHM with finite element models has proven valuable in predicting long-term structural performance and optimising maintenance interventions (He et al., 2022). Moreover, the development of self-powered and wireless sensor networks aims to address limitations related to sensor lifespan and data loss (Rincon et al., 2024). While challenges persist, including high installation costs and data management complexities, SHM remains a key component in climate adaptation strategies for critical infrastructure.

6.3. Green adaptation measures

6.3.1. Scour

Nature-based solutions against scour rely on environmentally friendly materials to stabilise riverbeds by reinforcing the bed around substructure elements, modifying the flow patterns, and reinforcing riverbanks. An innovative technique is the use of calcareous deposit agglomerates, applied to the bed layer around substructure elements to promote sedimentation of sand grains and chippings. Over time, these deposits form a durable cohesive layer that significantly reduces the displacement of bed materials (Carré et al., 2020). Geo-bags are a sustainable short-term alternative to gabion walls and riprap. Depending on their placement, they are used for shore protection, riverbank reinforcement and flow redirection. For example, geo-bags have been used in the Moldova River for scour mitigation and flow management (Sion et al., 2020). Vegetative stabilisation is another solution that reinforces riverbanks and reduces erosion by planting trees such as willows, whose deep and widespread roots bind soil particles (Hickin, 1984). Alternatively, coir logs made from coconut fibres dissipate flow energy along the riverbanks and promote vegetation growth, thereby conserving the bed morphology and protecting bridge substructure against localised scour (Santha, 2006).

6.3.2. Floods

Green solutions for flood mitigation focus on restoring natural landscapes to manage excess water. Wetland restoration is a key strategy to absorb floodwater (Zhao et al.,

2016). Similarly, floodplain restoration allows floodwaters to spread over large areas by reconnecting rivers to their natural floodplain, thereby creating natural storage (Hughes & Rood, 2003). In addition, mangroves and coastal vegetation act as a natural barrier, protecting against storm surges and floods by reducing floodwater flow energy (Fernández-Montblanc et al., 2020; Guannel et al., 2016). Reforestation in upland watersheds particularly enhances soil infiltration and decreases surface runoff, which reduces the potential of flash floods (Van Meerveld & Seibert, 2025).

6.3.3. Wildfires

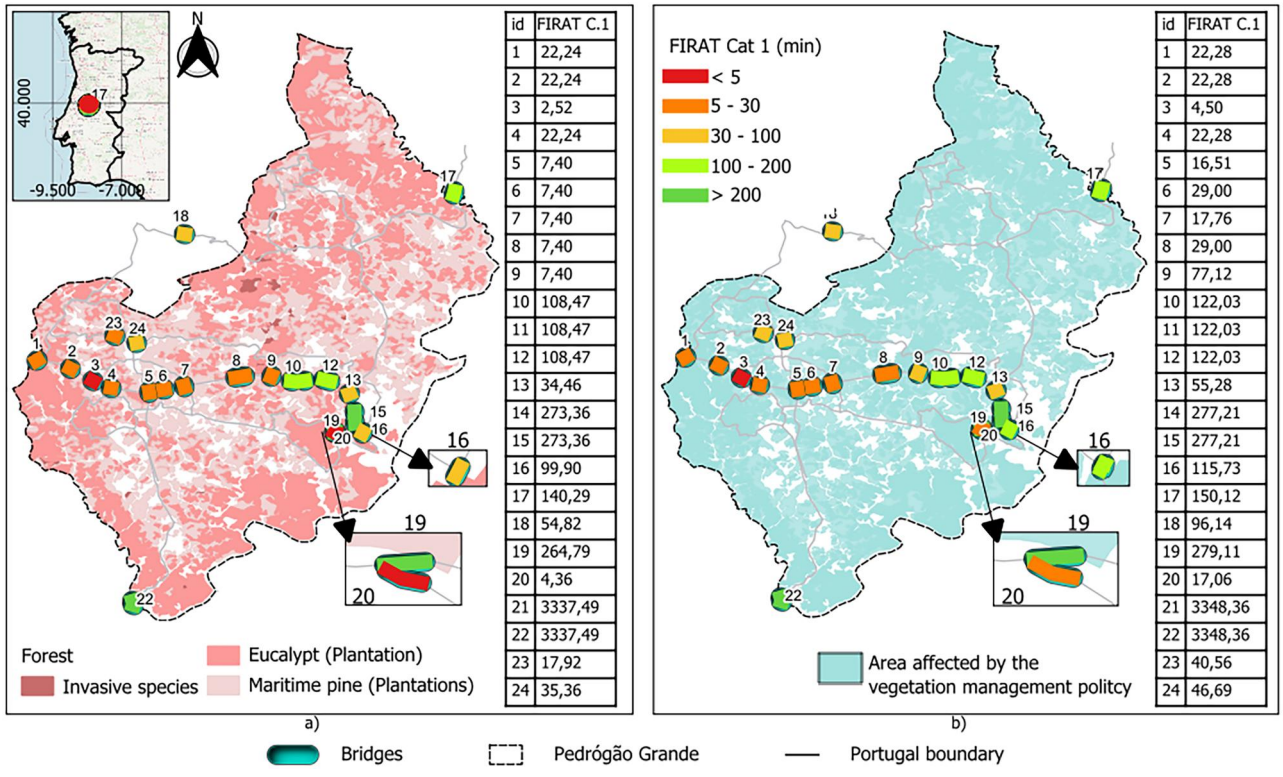
In the case of wildfires, green adaptation measures can be an efficient way to reduce the exposure level and increase the resilience of the system. These measures may include, among others, creation of wildfire barriers (e.g., open fields, artificial lakes) and vegetation management. Infrastructure exposure to wildfires can be measured through the FIRAT (FIRe arrival time) integrated in the GIS-based tool proposed by Arango et al. (2023). The approach provides exposure maps for a given target of study (i.e., bridges) for different wildfire intensities, considering the sources and barriers closest to the study target, such as forest, urban areas, etc. While this tool allows for assessing different gray, green and soft adaptation measures, Arango et al. (2024) assesses the capacity of green measures to increase resilience. Specific focus is on vegetation management, which involves actions such as clearing weeds and invasive species, protecting heritage trees and maintaining crops to create breaks in fuel continuity and shield high-fire-exposure zones.

This methodology is applied to the bridge network of the municipality of Pedrógão Grande in the district of Leiria, Portugal. In this case, replacement of vegetation such as invasive species, plantation of eucalyptus, plantation of maritime pine, grassland and scrub with hardwood trees is analysed. Figure 5 shows the difference between the initial exposure (Figure 5a) and the exposure that would be obtained by applying the vegetation change management measure (Figure 5b).

In this case, the change in vegetation management would significantly reduce the exposure of Bridges 16 and 20. All changes can be observed in the tables accompanying Figures 5a and b. However, the implementation of such measures would require major efforts to modify the vegetation over a very large area.

6.4. Industry 5.0 and the human-centric digital twin paradigm

In recent years, the European Union has embraced a novel paradigm, Industry 5.0, that builds on the human-centric, sustainable and resilient principles missing from Industry 4.0. Human-centrism is arguably the most distinguishing feature of Industry 5.0, aiming to position humans and a human-deterministic approach (an approach where human needs, values and decision-making play a central role in shaping technological and industrial advancements) at its core. A human-centric approach ensures that the design of adaptation measures addresses diverse user needs, including accessibility for all demographics, and emphasises rapid recovery post-disruption. Enhanced collaboration between



id	FIRAT C.1
1	22,24
2	22,24
3	2,52
4	22,24
5	7,40
6	7,40
7	7,40
8	7,40
9	7,40
10	108,47
11	108,47
12	108,47
13	34,46
14	273,36
15	273,36
16	99,90
17	140,29
18	54,82
19	264,79
20	4,36
21	3337,49
22	3337,49
23	17,92
24	35,36

id	FIRAT C.1
1	22,28
2	22,28
3	4,50
4	22,28
5	16,51
6	29,00
7	17,76
8	29,00
9	77,12
10	122,03
11	122,03
12	122,03
13	55,28
14	277,21
15	277,21
16	115,73
17	150,12
18	96,14
19	279,11
20	17,06
21	3348,36
22	3348,36
23	40,56
24	46,69

Figure 5. Comparison of exposure maps using FIRAT (in min) for the bridge network of Pedrógão Grande (Portugal). (a) current state for wildfire category 1. (b) After applying vegetation management policies for wildfire category 1.

humans and machines is facilitated by advanced monitoring systems such as IoT sensors and AI-driven predictive models. This transformative vision is integral to achieving the European Green Deal objectives, harnessing the benefits of advanced enabling technologies such as digital twins. A digital twin encompasses the entire lifecycle of built assets, including: (i) planning and design, (ii) construction, (iii) inspection, maintenance and operation, (iv) rehabilitation or replacement and (v) demolition, decommissioning, or reuse.

Heritage bridges, in particular, require thoughtful adaptation to ensure their preservation while addressing the broader climate challenges. In this context, the implementation of a Human-Centric Digital Twin (HCDT) paradigm is proposed as an adaptation strategy to enhance the resilience of heritage bridges. The HCDT for a heritage bridge integrates an as-is historical asset information model (the 'digital asset') with its physical counterpart (the 'physical asset') *via* a structural health monitoring system. This system combines model-based techniques, such as multi-scale finite element models, with physics-informed, data-driven components like AI algorithms for anomaly detection (Jiménez Rios et al., 2023). The Human-Centric aspect of the HCDT framework adds an essential layer – focusing on digital technologies that enhance the performance of human stakeholders (the 'human asset'). These tools, such as exoskeletons, augmented reality (AR), virtual reality (VR), wearable trackers, intelligent personal assistants, collaborative robots, social networks and big data analytics (Mourtzis et al., 2022), contribute to the creation of a sustainable and resilient built environment. By integrating these technologies, human capabilities are amplified, allowing for more effective and efficient decision-making in heritage conservation.

In practice, data-driven surrogate models within the HCDT allow for real-time damage detection and early warning alerts, while detailed finite element models support synthetic data generation, damage prognosis, and what-if scenario simulations. Combined with probabilistic and risk analyses, these simulations empower asset managers to make informed decisions about optimal maintenance, retrofitting and repair strategies. Furthermore, hybrid physics-informed modelling approaches address the limitations of both purely model-based and data-driven methodologies (Martakis et al., 2023). This innovative HCDT paradigm offers significant potential to extend the operational life of heritage bridges, reduce operational costs, and enhance both resilience and sustainability. It represents a transformative shift in how behaviour, institutions, and technology can converge to conserve valuable assets while simultaneously fostering climate change mitigation strategies.

Although HCDTs can be used in any type of bride, their application results particularly useful in heritage bridges conservation. Unlike conventional bridges, heritage bridges present distinct challenges for resilience enhancement and climate adaptation due to constraints imposed by conservation principles related to their historical significance and material authenticity. These structures often require context-sensitive interventions that preserve original fabric, craftsmanship, and aesthetic integrity while ensuring safety and functionality. By placing human expertise, experience and decision-making at the core of resilience enhancement measurements, the HCDT enables craftspeople, conservators and engineers to interact intuitively with real-time monitoring data through augmented and virtual reality environments, facilitating informed and minimally invasive maintenance actions. Moreover, human-centric frameworks support participatory governance by engaging local communities, heritage authorities and policy makers in the adaptation process, ensuring that structural interventions align with both technical requirements and cultural values. This integration of technological intelligence with human judgement makes the HCDT particularly well-suited to the conservation and resilience enhancement of heritage bridges in the context of climate change.

6.4.1. AI applications within the HCDT paradigm for the resilience enhancement of heritage bridges

AI plays a pivotal role within the HCDT paradigm by enabling the data-driven resilience enhancement of heritage bridges. Advanced AI models, including deep learning and hybrid physics-informed approaches, can process heterogeneous sensor and inspection data to automatically detect and classify damage patterns, identify anomalies and predict structural degradation trends (Plevris et al., 2025; Seghier et al., 2024). These capabilities support early warning systems and allow asset managers to prioritise maintenance or retrofitting actions before critical failure occurs, thus avoiding authenticity lost of historic fabric. Moreover, AI-driven surrogate models can approximate complex numerical simulations, facilitating rapid assessment of multiple hazard and intervention scenarios – an essential feature for resilience planning under uncertainty (Glascoe & Wang, 2024; Liu & Lin, 2024). In the context of heritage bridges, where destructive testing and invasive interventions are restricted, AI provides an advance aid for decision support that improves both the structural and cultural resilience of heritage bridges.

Looking ahead, several research avenues are critical to fully leverage AI within the HCDT framework for resilience enhancement. A primary challenge is enhancing the explainability and physical realism of AI models. This includes creating robust, physics-informed architectures that can reliably extrapolate to extreme events and provide explainable outputs to build trust among engineers and policymakers. Concurrently, the deep integration of AI with operational digital twins presents a transformative direction. Such integration can facilitate dynamic, self-updating models that autonomously assimilate real-time sensor data, enabling probabilistic forecasting of long-term degradation under climate stressors and permitting near real-time resilience assessment. Ultimately, to translate these technical capabilities into actionable strategies, interdisciplinary research is essential for creating AI-driven multi-criteria decision-support systems. These systems shall be designed to explicitly quantify and balance competing objectives, such as engineering safety and the preservation of cultural heritage value,

ensuring that resilience solutions are both structurally effective and culturally sensitive.

Beyond individual adaptation measures, enhancing the resilience of bridge infrastructure requires an integrated and forward-looking strategy that combines engineering robustness, operational preparedness and adaptive management. At the structural level, resilience can be improved through targeted retrofitting, strengthening and material rehabilitation to extend service life under climatic stressors. At the operational level, resilience enhancement involves predictive maintenance and digital monitoring, where data from sensors, inspections and simulations feed continuously into decision-support systems and digital twins to anticipate deterioration and optimise interventions. Governance aspects are equally critical: embedding resilience-based performance indicators within asset management frameworks supports informed prioritisation and efficient resource allocation. Effective and balanced resilience enhancement requires integrating actions across these levels to enable coordinated decision-making and avoid fragmented interventions. The proposed measures are scalable across multiple levels – from individual bridges to entire transportation networks – where systemic resilience depends on the coordinated bridge management. Ensuring that bridge-level strategies are harmonised at the network scale strengthens the overall robustness and adaptability of the transport system. To ensure long-term effectiveness, these strategies should operate within adaptive management cycles, where performance thresholds and intervention priorities are periodically reassessed based on updated climate projections, monitoring data and technological advances. Embedding such iterative feedback within digital twin environments enables continuous learning and future-proof planning, ensuring that bridge resilience evolves in step with changing climate conditions.

7. Conclusions

The document presents an integrated perspective on resilience-based management of existing bridges under both short- and long-term climatic impacts and their anticipated evolution under climate change. Major short-term impacts include flash floods, scour and snowfalls, while wildfires, geotechnical hazards and increased wind loads have gained prominence in recent years due to evolving climate conditions. In the long term, corrosion remains a critical concern, along with thermal stress resulting from elevated temperatures. These long-term effects pose substantial challenges, especially when combined with acute short-term hazards, potentially exacerbating structural vulnerabilities.

To ensure the resilience of bridge infrastructure under changing climatic conditions, comprehensive adaptation strategies are required. These should incorporate an appropriate combination of grey, green and soft adaptation measures. The strategies are discussed from a human-centered perspective, where user interaction with infrastructure plays a key role in its management and long-term sustainability. From this perspective, human expertise, behaviour and decision-making play a central role in identifying, designing and implementing adaptation actions that are technically effective, socially acceptable and operationally feasible. Grey measures, such as structural strengthening or retrofitting, benefit from human-centred decision support tools that enable engineers and asset managers to evaluate intervention options while accounting for safety, serviceability, constructability and user disruption. Green measures, including nature-based solutions for flood attenuation or thermal regulation, require engagement with local communities, planners and environmental stakeholders to ensure their long-term acceptance, maintenance and integration within the surrounding landscape. Soft measures, such as inspection regimes, emergency planning, operational protocols and policy instruments, are inherently human-driven and rely on training, institutional coordination and stakeholder awareness. By embedding these measures within a human-centred approach, adaptation strategies can better align technical performance with societal needs, enhance implementation effectiveness and support the long-term sustainability of bridge infrastructure at both asset and network levels. In this context, network-level analysis is essential to support the development of efficient and coordinated adaptation strategies across the broader infrastructure system.

Furthermore, it is crucial to integrate heritage-classified bridges and those of historical significance into the adaptation framework. These structures are not only functional assets but also cultural landmarks, often exemplifying significant architectural or engineering achievements from distinct historical periods. Their preservation and adaptation demand tailored approaches that balance structural resilience with conservation priorities, thereby ensuring their continued relevance and integrity in the face of climate change.

Digital twins, along with advanced monitoring capabilities, such as IoT-based sensor networks and AI-driven predictive models, offer considerable potential to inform and support the assessment of the adaptive capacity of bridge infrastructure. By enabling continuous structural assessment, early detection of anomalous behaviour and scenario-based analysis, these tools provide evidence-based insights that support planning, prioritisation and implementation of adaptation and maintenance measures, thereby contributing to more informed and resilient infrastructure management.

Acknowledgement

This study is a result of the collaborative effort of IABSE TG5.8.

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Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

We gratefully acknowledge the European Commission for its support of the Marie Sklodowska Curie program through the Horizon Europe DN FOURIER project (GA 101169429). This work was financed by national funds through FCT – Foundation for Science and Technology, under grant agreement 2021.05862.BD (https://doi.org/10.54499/2021.05862.BD) attributed to the fourth author. This work was partly financed by FCT/MCTES through national funds (PIDDAC) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB/04029/2020 (https://doi.org/10.54499/UIDB/04029/2020), and under the Associate Laboratory Advanced Production and Intelligent Systems ARISE under reference LA/P/0112/2020. This research was funded in part by the Fundação para a Ciência e a Tecnologia, I.P. (FCT, https://ror.org/00snfqn58) under Grant UID/6438/2025 (https://doi.org/10.54499/UID/06438/2025) of the research unit CERIS.

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