

Adapting Bridges to Climate Change: Impacts, Regulatory Responses, Case Study, and Challenges

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Abstract

Climate change increasingly exposes critical infrastructure systems, like bridges, to hazards for which these systems were neither originally designed nor adequately maintained. Over the past decade, both researchers and stakeholders have produced a growing body of scientific studies and practice-oriented guidelines aimed at enhancing infrastructure resilience, but there is still a lack of studies focused on bridges. This paper applies an integrated assessment approach, combining local monitoring data, bias-corrected regional climate projections, physics-based finite element modelling, and reliability analysis, to evaluate the structural implications of future temperature scenarios. After reviewing projected climate impacts and current regulatory responses, with particular emphasis on the evolution of the Eurocodes, the methodology is applied to an existing prestressed concrete bridge in Portugal. Temperature projections derived from regional climate models are downscaled to the bridge site and incorporated into a probabilistic structural assessment. Results indicate that, under a high-emission scenario, projected temperature increases may lead to reductions in reliability index and increases in expansion joint displacements for a long-term period. The comparison between the first and second generations of Eurocodes highlights the transition from historically calibrated thermal actions to climate-adjusted design values. This study demonstrates that climate change represents a quantifiable structural action for bridges and underscores the need for reliability-based, forward-looking design and lifecycle management approaches.

Keywords: *Bridges, climate change, temperature, adaptation, codes.*

1. Introduction

Bridges are typically designed and built to be resilient to past climate conditions. What will happen if the climate ceases to be stable? Early and well-planned adaptation action can save money and, ultimately, human lives. Adaptation refers to the implementation of design, maintenance, or retrofitting measures that reduce vulnerability and enhance the resilience of bridges to current and projected climate-induced hazards.

According to the AR5-IPCC (2013), human influence on the climate system is clear. Recent anthropogenic greenhouse gas emissions have had widespread impacts on both human and natural systems. In 2023, the AR6-IPCC (2023) concluded that limiting global warming to 1.5°C above pre-industrial levels requires immediate greenhouse gas emission reduction.

Although the magnitude of the impacts is surrounded by considerable uncertainty, the fact that our climate is changing is unequivocal as demonstrated by the growing occurrence of extreme events in recent years. Despite the “certainty of uncertainties,” should we “wait and see” until we fully understand climate change? This is a scientifically unacceptable and extremely dangerous option.

Adapting bridges to climate change requires moving from awareness to quantification, and from quantification to engineering practice supported by codes and standards. Therefore, in 2023, the authors proposed multi-hazard integrated assessment approach – combining local monitoring data, bias-

corrected climate projections, physics-based modelling, and life-cycle analysis – to support risk-informed adaptation strategies of concrete bridges (Figueiredo et al., 2023). Herein, based on ongoing studies and publications, this article summarizes the application of the approach on the bridge over the Angueira River to highlight structural elements most susceptible to temperature-induced effects arising from future climate scenarios. Additionally, a summary of regulatory responses is provided in an international context and the comparison between the first and second generations of Eurocode 1 – Part 1-5 is provided.

2. Impacts, structural resilience, and climate change scenarios

Climate change is currently one of the major concerns for the integrity of existing bridges. As in Figueiredo et al. (2023), Figure 1 summarizes the main **impacts of climate change** on reinforced concrete bridges according to the projected changes, assuming the health of bridges are compromised by four main projected changes and associated impacts: (1) an increase in the frequency of heavy precipitation events, which can cause flooding and scouring; (2) higher temperatures and a greater frequency of heat waves, which can cause additional stresses in bridge components, deficient behaviour of expansion joints, and damage to non-structural elements, such as pavements and railways; (3) increased concentrations of anthropogenic CO₂ and higher relative humidity, which may trigger, or increase the likelihood of, concrete carbonation and accelerate corrosion; and (4) sea-level rise, which may result in the relocation of bridges. There are other projected changes that can also be considered, but they are not considered a priority at this stage, due to the uncertainty in either the projections or their impacts on bridges.

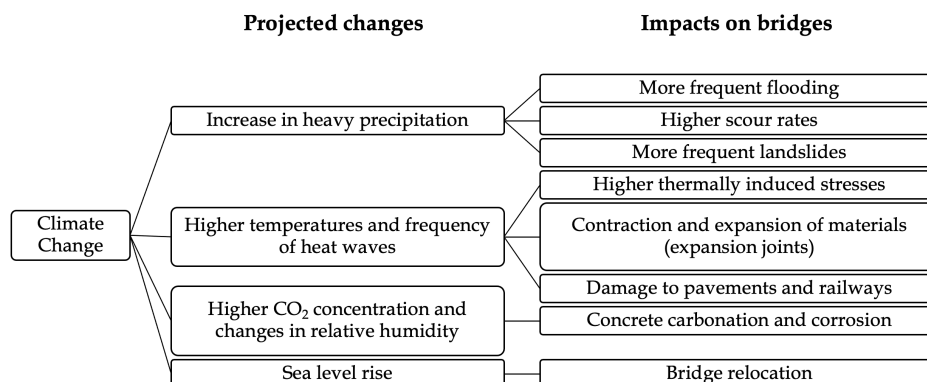


Figure 1. Impacts of climate change on reinforced concrete bridges.

Due to their long service life (>100 years), significant construction cost (e.g., the Vasco da Gama Bridge ±€1 billion), and high economic value, making bridges resilient to climate change is a major challenge. The structural **resilience** of bridges is generally defined as their ability to absorb, withstand, and rapidly recover from severe adverse events. As illustrated in Figure 2, structural resilience can be described through the “resilience triangle,” which represents the loss of functionality (or service) due to disruption (or damage) caused by an adverse event, as well as the recovery time. Resilience corresponds to the shaded (grey) area: the smaller this area, the greater the resilience.

It is not the average changes in climate that are usually most noticeable, but rather the associated extreme events (such as floods, inundations, and heatwaves) that have the greatest impact on the safety, functionality, and durability of our bridges. Climate model projections indicate an increased frequency and intensity of such events as the 21st century progresses. For example, in the case of temperature, increases in both the mean and variability lead to a greater occurrence of extreme temperature events (very high maximum temperatures and heatwaves).

There are several **climate change scenarios** (Figure 3) that consider emissions and concentrations of greenhouse gases, aerosols, and chemically active gases, as well as land-use changes. These scenarios are defined through Representative Concentration Pathways (RCPs). Each RCP represents just one of many possible scenarios that could lead to specific changes in radiative forcing, namely:

- RCP8.5 – the worst-case climate change scenario, despite its relatively low probability (high-emission scenario);
- RCP6.0 – emissions peak around 2080 and then decline;
- RCP4.5 – an intermediate climate change scenario (most likely scenario);
- RCP2.6 – requires carbon dioxide (CO₂) emissions to start decreasing by 2020 and reach zero by 2100 (low-emission mitigation scenario).

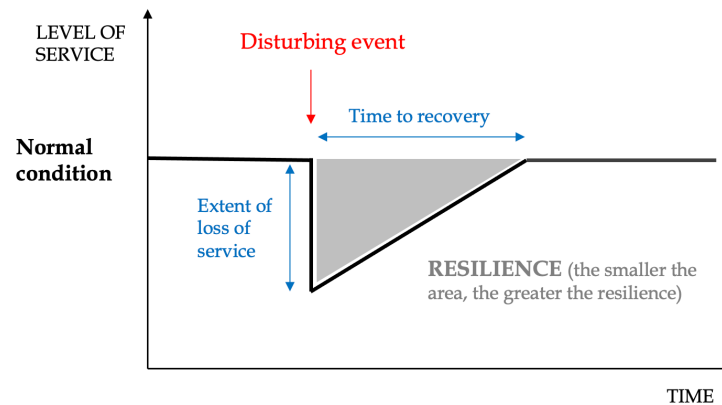


Figure 2. Structural resilience in bridges.

The climate models currently available to represent the climate system are Atmosphere–Ocean General Circulation Models (AOGCMs). Regional Climate Models (RCMs) are derived from Global Climate Models (GCMs) using downscaling techniques, which make it possible to obtain higher-resolution climate simulations for limited regions.

Climate models are built upon our understanding of fundamental physics and Earth system processes and are grounded in observations and measurements. These models consist of different modules that describe the atmosphere, oceans, ice/snow, and land surface, seeking to represent the global climate in terms of grid cells arranged side by side and stacked vertically. Each grid cell contains mathematical equations that represent physical characteristics and processes. These equations are translated into computational code to define climate variables and/or output indicators in the form of projections.

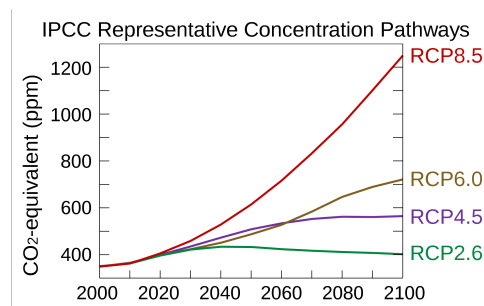


Figure 3. Climate change scenarios.

3. Integrated Assessment Approach for the Adaptation of Bridges to Climate

The adaptation of bridges to climate change can be addressed following the comprehensive understanding consisting in four key steps: (1) understanding the problem; (2) identifying critical impacts, vulnerabilities, and risks; (3) weighing consequences; and (4) identifying suitable adaptation measures to reduce vulnerability and increase the resiliency of bridges (i.e., strengthen, do nothing, or simply manage the increased risk?).

Acquiring a better understanding of the phenomena affecting bridges is paramount and highly multidisciplinary because these structures are susceptible to many different climate-dependent actions

that have considerable uncertainty and different magnitudes in different regions of the world. With so few studies having been performed on bridges, any effective adaptation strategy must be assessed at the physics level through further laboratory, numerical, and field bridge data. To accomplish this, Figueiredo et al. (2023) proposed an approach to climate adaptation built on three interconnected dimensions (Figure 4): (1) climate data; (2) physics-based modelling; and (3) cost-effectiveness of adaptation measures.

Basically, the approach starts with the construction of climatic records and climate-change data for the location of each bridge. Then, the vulnerability of the bridge to floods and scouring, degradation of the construction materials, and excessive thermally induced stresses and deformations is assessed, followed by an analysis of the cost-effectiveness of the adaptation measures required.

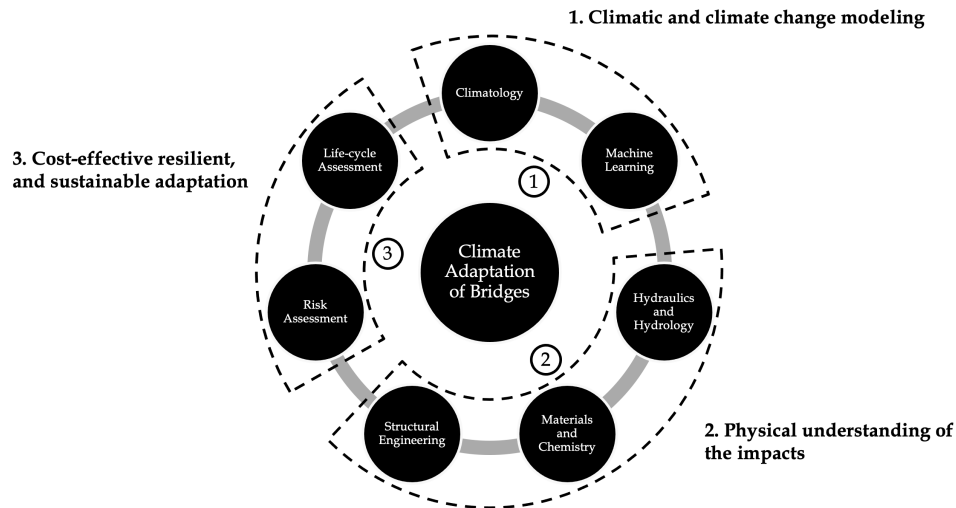


Figure 4. Integrated assessment approach for the adaptation of bridges to climate change.

In this context, **adaptation** means intervening in bridges (or in their surroundings) to reduce vulnerability and increase their resilience to climate change. For example, temperature as a climate variable may show higher extreme values (leading, for instance, to more frequent and intense heatwaves), which implies that critical structural performance limits may be exceeded more often.

With adaptation measures, the normal operating range can be expanded by adjusting those critical limits so that service interruption is reduced (Figure 5). The system is considered “resilient” within normal operation. Some examples of climate adaptation measures are: designing bridges for higher maximum temperatures; designing higher bridges to accommodate sea level rise; installing wider expansion joints; painting bridges white to increase the albedo effect; strengthening or protecting existing foundations; Increasing concrete cover thickness and using stainless steel reinforcement.

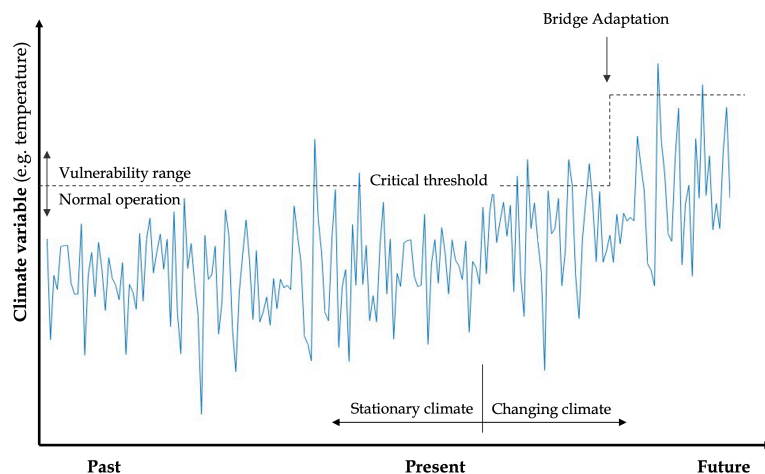


Figure 5. Normal operation and vulnerability range before and after adaptation.

4. Regulatory responses: from infrastructure to bridges

The risk assessment and the resilience of existing infrastructure in the context of climate change have been approached through a variety of strategies by different countries and international organizations. At the European level, the two standardisation organisations are The European Committee for Standardisation (CEN) and the International Standards Organisation (ISO). Both organizations are developing, or have already developed, guidelines and standards to consider potential climate change impacts into different types of construction. In 2021, the ISO published a specific guideline that focuses on developing a set of rules for vulnerability assessment, planning, and monitoring of climate change adaptation (ISO, 2021). The CEN is actively updating standards, particularly within the framework of the second generation of Eurocodes, which will implement specific analyses to consider the future variability related to the climate change (CEN-CENELEC, 2022).

As reported by Vallejo and Mullan (2017), approximately one-third of Organisation for Economic Co-operation and Development countries are in the process of revising at least one mandatory national infrastructure standard to incorporate climate change adaptation measures. The report indicates that revisions have been completed in seven countries – Australia, Canada, Denmark, Germany, Korea, Norway, and Sweden. However, to date, only Australia has published a standard specifically addressing the structural adaptation of infrastructure, while the other codes primarily focus on the geotechnical, hydraulic, or drainage systems of road infrastructure (Standards Australia, 2013).

In the United States (US), the Federal Highway Administration (FHWA) has issued comprehensive standards for the planning, design, and operation of highways within riverine and coastal environments. In 2016, the FHWA released a guide to support people in transportation management, operations, and maintenance (FHWA, 2016). More recently, in 2020, the same organism updated the manual for coastal transportation infrastructure affected by extreme events such as storms, tsunamis, and anticipated sea level rise (Douglass and Webb, 2020). In certain cases, specific regions of the US have incorporated dedicated chapters into existing standards or have created new standards to infrastructure adaptation. For instance, this approach has been adopted in State of New York (2022), Virginia (2020), and Maine (2018). Similarly, Canada is advancing its own design standard to address the growing necessity for climate change adaptation in infrastructure planning and maintenance to increase the resilience of bridges (Cannon et al., 2021).

In Europe, the first generation of Eurocodes – European standards for structural design – was published from 1990 to 1999. The standards based the evaluation of the external loads on the Probabilistic Model Code published by Joint Committee on Structural Safety (JCSS), and the climate change problem was not addressed (JCSS, 200; Vrouwenvelder, 2002). Currently, the CEN is undertaking an effort to publish the second generation of Eurocodes in which the potential impacts of climate change on various types of construction are assessed, with particular attention to structures with long design lifespans (Dora et al., 2018). To support this process, in 2022, the CEN published a guide that provides a step-by-step process, which must be followed to consider the effects of climate change in new standards and to include them in existing standards (CEN-CENELEC, 2022): (i) screening, (ii) diagnostic, (iii) embedding adaptation to climate change, (iv) revision cycles (Ghosn and Ellingwood, 2024).

The issue of revising the Eurocodes has also been discussed in scientific literature. Indeed, a considerable number of articles have been published which propose methods and recommendations for the integration of climate change issues into the design and management of infrastructure, with a view to their inclusion in new editions of standards. For illustrative purposes, one might cite the cases of Rianna et. al (2023), Markova et. al (2022), Nogal (2020), and Nasr et. al (2021).

5. Case study: The bridge over the Angueira River

5.1. Structural description and monitoring data sets

The continuous pre-stressed box girder concrete bridge over the Angueira River was completed in 1994 and is in the northeastern region of Portugal, a predominantly mountainous area characterized by complex topography.

The deck has a variable cross-section which, together with the two supporting piers, ensures the structural continuity. The total length of the bridge is 230 m, divided into three spans: a 115 m central

span and two 57.5 m side spans (Figure 6). The carriageway is 9 m wide. The piers extend 42 m from the girder's intrados to the shallow foundations' extrados. As can be seen in Figure 6, the upper parts of the foundations remain visible due to the lower level of the river.



a) General view of the bridge



b) Orientation and dimensions of the bridge

Figure 6. Case study – the bridge over the Angueira River.

A monitoring system was installed in the bridge during construction, comprising vibrating-wire strain gauges and thermocouples embedded in the concrete during construction. The system was initially designed to monitor the evolution of stresses in the deck resulting from the time-dependent behaviour of concrete, particularly during the early years of service. Due to the technological limitations at the time of the bridge's construction, the data from the monitoring system were manually collected by operators until 2011. To add more data to study the climate change impacts on the structural behaviour of the bridge, the monitoring was recently resumed over a one-year period, namely from March 2022 to March 2023.

5.2. Qualitative vulnerability analysis

The climate change adaptation process starts with a vulnerability analysis to identify how and to what extent a bridge is susceptible to climate-related hazards. This involves collecting and analysing meteorological data, consulting climate change models, and considering variations in the climate variables for different scenarios. The goal is to retrieve reliable information and projections of how the extreme climate conditions are expected to evolve in the specific site over time and what challenges they may pose to the bridge's structural integrity.

As published in Figueiredo et al. (2024), the analysis was based on bridge engineering experience, the impacts reported in the news on bridges in the area, the main climate variables and indices, in terms of anomalies, for the case under study, covering maximum temperature, average relative air humidity, number of days with temperatures above 35 °C, number of heatwaves, and precipitation. In the context of climate change, an anomaly is defined as the difference between the projected future climate (2071–2100) and the reference period (1971–2000).

The anomalies were based on nine regional models. The maximum and minimum values correspond to the models with the highest and lowest signals of change. The analysis of the climate variables and indices for the bridge site led to the following conclusions:

- the increase in temperature (and associated indices) is the most significant climate variable. For the worst-case scenario (RCP8.5), an average increase of 5.4 °C in maximum temperature and a maximum increase of 25 heatwaves are projected for the period 2071–2100;
- anomalies in relative humidity ($\leq 5\%$) and precipitation are not expected to have a significant impact on the bridge. Regarding precipitation, there is a projected decrease in the number of days with precipitation (-39) and a slight increase (7) in the number of days with precipitation ≥ 20 mm. Therefore, as the river typically has a very low flow throughout the year, and the

bridge foundations are located on rocky terrain and elevated relative to the river's average water level, the precipitation is not considered one main climate stressor.

5.3. Structural evaluation of thermal effects under the worst-case scenario

This section applies the integrated assessment approach to the case study for evaluating the structural condition of a bridge under temperature variations imposed by climate change, as defined as the main climate variable or hazard. This approach involves: (i) analysing local temperature conditions at the bridge site using structural monitoring data complemented by three surrounding weather stations that triangulate the bridge location, (ii) applying downscaled and bias-corrected climate change projections and compare with the Eurocode 1 – Part 1-5, (iii) the development of a numerical model of the bridge to simulate bridge behaviour under temperature effects, and (iv) the impact of climate change projections on the structural elements at given sections in terms of reliability analysis.

5.3.1. Historical temperature and temperature projections under different climate change scenarios

Table 1 summarizes the temperature projections for the bridge site using RCMs from the EURO-CORDEX. The data have been organized according to three different time periods (2011-2040, 2041-2070, and 2071-2100) under three climate change scenarios (RCP2.6, RCP4.5, and RCP8.5), assuming the average temperature, T_{mean} , and the extreme maximum temperature for a 50-year return period (T_{r50y} or $p = 2\%$) as indicated in Eurocode 1. As the RCMs have a spatial resolution of, approximately, 10–15 km, statistical techniques are employed to downscale the projections into the bridge site. The historical measurements of temperature variations were obtained from the monitoring system installed on the bridge and three nearby weather stations.

A comparison between temperature projections and design provisions from the first (IPQ, 2009) and second (CEN, 2024) generations of the Eurocode 1 – Part 1-5, considering a 50-year return period, is summarised herein. According to the first generation of the Eurocode, the maximum uniform bridge temperature is defined as

$$T_{N,\text{max}} = T_{\text{max}} + 2 \quad (1)$$

with a prescribed characteristic value of maximum shade air temperature for the site bridge site, $T_{\text{max}} = 38 \text{ }^{\circ}\text{C}$, and maximum uniform temperature, $T_{N,\text{max}} = 40 \text{ }^{\circ}\text{C}$. Therefore, as the maximum temperature for the worst-case scenario (RCP8.5) is $43.91 \text{ }^{\circ}\text{C}$, this means that the Eurocode value represents, approximately, 91% of the projected range.

However, the second generation of the Eurocodes introduces an additional climate change component, $\Delta T_{\text{cc,max}}$, such that

$$T'_{\text{max}} = T_{\text{max}} + \Delta T_{\text{cc,max}} \quad (2)$$

In this case, $\Delta T_{\text{cc,max}}$, should be $= 3.91 \text{ }^{\circ}\text{C}$. This adjustment effectively aligns the design value with the projected temperature range for the worst-case scenario.

From an engineering standpoint, this comparison shows that while the first generation of the Eurocode 1 was calibrated to historical temperature data, the second generation moves toward incorporating forward-looking climate information. Nevertheless, the adequacy of this correction depends on the emission scenario considered, the evolution of extremes beyond the 50-year return period, and the service life of the bridge (typically >100 years), which may expose structures to even higher thermal demands.

Table 1. Temperature projections at the bridge site after the bias correction.

	'71-'00	2011-2040			2041-2070			2071-2100		
	Hist	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
T_{mean}	16.06	17.28	17.20	17.43	17.59	18.19	18.91	17.55	18.74	20.85
$p = 2\%$	37.03	38.16	38.37	38.84	38.62	40.11	41.40	38.29	39.68	43.91

5.3.2. Three-dimensional finite element (FE) model

A three-dimensional finite element (FE) model of the bridge was constructed using the CSi Bridge software to investigate its structural response (Figure 7). The concrete properties and geometrical characteristics were defined in accordance with the available design documentation – the piers and the girders were built using the currently defined C20/25 concrete. The contribution of structural steel to the modulus of elasticity was approximated as a percentage of the concrete cross-sectional area.

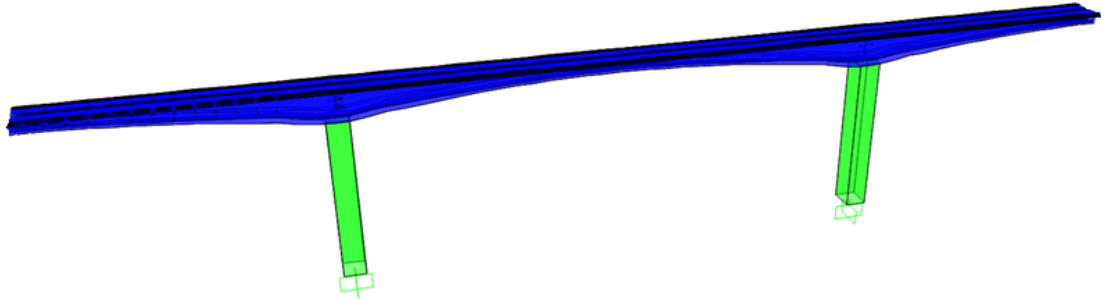


Figure 7. FE model of the case study.

5.3.3. Reliability and serviceability analysis

At the base of the piers and using the FE model, Figure 8 compares the distributions of stresses resulting from the Monte Carlo simulations under the worst-case climate change scenario (RCP8.5) and time periods with the tensile strength and historical data. The variations in strength induced by climate change were not considered in the reliability analysis. It can be observed that for latter time periods, both mean and variance of the stress distributions increase. Furthermore, stress distributions become more dispersed and shift to higher values as the severity of the climate scenarios increases.

The reliability analysis conducted at the base of the piers indicates an increased probability of cracking and a corresponding reduction in the reliability index when the worst-case scenario is applied to the bridge. As shown in Figure 8, for a distant time period (2071-2100), a reduction of up to 35% in the reliability index is projected. This decrease in reliability reflects a higher probability of cracking, which may accelerate the overall deterioration process by triggering additional degradation mechanisms beyond the structure's normal aging.

Furthermore, the increase in longitudinal displacements at the expansion joints was also evaluated. As shown in Figure 9 for the worst-case scenario, it is estimated 47% rise of displacements for a distant time period (from 18.29 to 26.87 mm). The analysis reveals that insufficient maintenance of these components may restrict girder movement, leading to elevated stress levels and an increased risk of cracking.

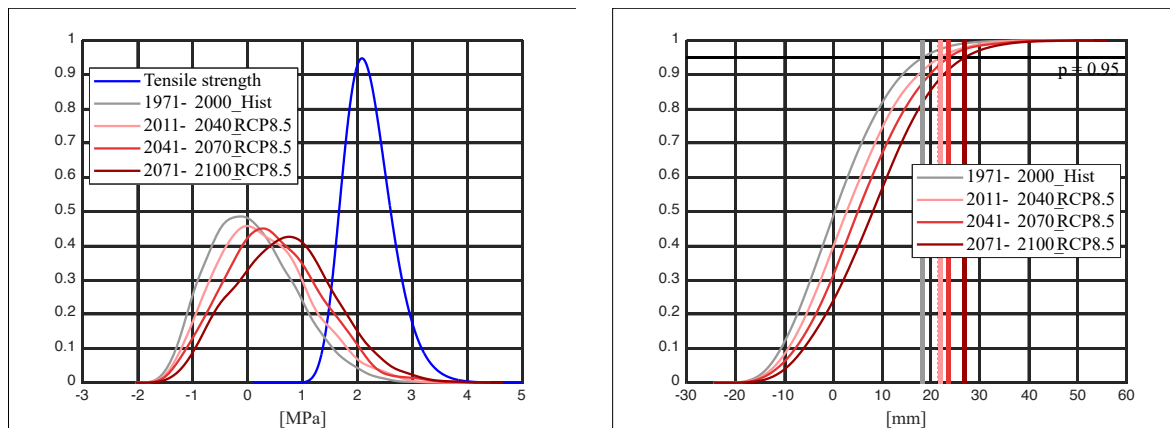


Figure 8. Distributions of stresses and tensile strength at the base of the piers for the historical and for the worst-case scenario (RCP8.5) in different time periods.

Figure 9. Cumulative distributions of the longitudinal displacement at the joints for the worst-case scenario (RCP8.5) in different time periods.

6. Conclusions

The integrated assessment approach presented – combining local monitoring data, bias-corrected climate projections, physics-based modelling, and reliability analysis – demonstrated that climate change can be translated into structural performance metrics. This study demonstrates that temperature increase caused by climate change is not an abstract concern for bridge engineering, but a quantifiable structural action that can affect the reliability and serviceability of existing bridges.

The case study of the bridge over the Angueira River shows that projected temperature increases – particularly under a high-emission scenario – lead to measurable reductions in reliability index (up to 35%) and substantial increases in joint displacements (up to 47%), potentially accelerating deterioration mechanisms.

The comparison between the first and second generations of the Eurocodes highlights an important regulatory evolution. While the first generation was calibrated to historical climate data and may underestimate future thermal actions, the second generation introduces explicit climate change adjustments, representing a decisive step toward forward-looking design. Nevertheless, uncertainties related to emission pathways, return periods, and long service lives (>100 years) suggest that further refinement of reliability-based approaches will be necessary.

Although the present application focused on a single hazard (temperature rise), future research should address multi-hazard interactions (e.g., temperature or heat waves and precipitation or flooding), advance the harmonization of bridge-specific adaptation guidelines, integrate climate scenarios into lifecycle-based management frameworks, and translate scientific projections into practical maintenance and retrofitting strategies.

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References

- Cannon, A. J.; Il Jeong, D.; Zhang, X.; and Zwiers, F. W. (2021). Climate-Resilient Buildings and Core Public Infrastructure. Environment and Climate Change Canada.
- CEN (2024). FprEN 1991-1-5 – Eurocode 1: Actions on structures – Part 1-5: Thermal actions. Final draft, European Committee for Standardization, Brussels.
- CEN-CENELEC, “Tailored guidance for standardization technical committees: how to include adaptation to climate change in European infrastructure standards,” 2022.
- Dora, J. (2018). Climate change: Standards, and their role in improving the climate resilience of infrastructure investments. A Report prepared for EBRD. John Dora Consulting Limited, April.
- Figueiredo, E.; Moldovan, I.; Santos, L.O.; Dias, L. (2024). Roteiro para adaptação climática de pontes de betão armado: Ponte sobre o Rio Angueira. Betão Estrutural 2024, 13-15 de novembro, FEUP, Porto.
- Figueiredo, E.; Santos, L. O.; Moldovan, I.; Kraniotis, D.; Melo, J.; Dias, L.; Coelho, G. (2023). A roadmap for an integrated assessment approach for climate change adaptation of concrete bridges. Journal of Bridge Engineering, 28(6).
- Ghosn, M.; and Ellingwood, B. R. (2024). Risk-informed design and safety assessment of structures in a changing climate: a review of U.S. practice and a path forward. Structure and Infrastructure Engineering, vol. 20, no. 7–8, pp. 1159–1173. doi: 10.1080/15732479.2023.2265334.
- IPCC (2013), “Climate Change 2013: The Physical Science Basis- Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.” Geneva, Switzerland.

- IPCC (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland.
- IPQ (2009). NP EN 1991-1-5:2009 – Eurocódigo 1: Ações em estruturas – Parte 1-5: Ações térmicas. Instituto Português da Qualidade, Lisboa, Portugal.
- ISO, ISO 14091:2021 (EN) Adaptation to climate change - Guidelines on vulnerability, impacts and risk assessment. 2021.
- JCSS – Joint Committee on Structural Safety, “Probabilistic Model Code – Part 2: Load Models,” 2001.
- Maine Department of Transportation, “Bridge Design Guide Update 2018,” 2018. [Online]. Available at: <https://www.maine.gov>
- Marková, J.; Sýkora, M.; and Nadolski, V. (2022). Implication of climate changes on design of structures. Acta Polytechnica CTU Proceedings, Czech Technical University in Prague, Dec. 2022, pp. 450–455. doi: 10.14311/APP.2022.38.0450.
- Molon, N.; Figueiredo, E.; Moldovan, I.; Soares, P.M; Faber, M.H.; Lima, D.; Santos, L.O.; Cabral, P.; Porto, F. (2025). Impact of climate change on concrete bridges: A case study on temperature effects. 11th International Conference on Experimental Vibration Analysis for Civil Engineering Structures, EVACES, Porto, Portugal. 10.1007/978-3-031-96110-6_89
- Molon, N.; Figueiredo, E.; Moldovan, I.; Soares, P.M; Faber, M.H.; Lima, D.; Santos, L.O.; Cabral, P.; Porto, F. (2025). Modeling Climate Change Effects on Bridges: A Predictive Framework for Temperature and Strain Analysis. IABSE Congress Ghent 2025 the Essence of Structural Engineering for Society Proceedings 2025, pp. 1903–1911.
- Nasr, A.; Ivanov, O. L.; Björnsson, I.; Johansson, J.; and Honfi, D. (2021). Towards a conceptual framework for built infrastructure design in an uncertain climate: Challenges and research needs. Sustainability (Switzerland), 13(21). doi: 10.3390/su132111827.
- Nogal, M. (2020). Prescription of Maintenance Interventions by the New Generation of Eurocodes for Climate-Change Resilient Structures. XV International Conference on Durability of Building Materials and Components.
- NYC Mayor’s Office of Climate and Environmental Justice, “Climate Resiliency Design Guidelines,”. Accessed: March 2022. [Online]. Available: <https://www.nyc.gov>
- Rianna, G.; Reder, A.; Sousa, M. L.; and Dimova, S. (2023). Harmonised procedure to update thermal loads in the Eurocodes. Case study for Italy. Clim Serv, vol. 30. doi: 10.1016/j.cliser.2023.100391.
- S. L. Douglass and B. M. Webb, “Highways in the Coastal Environment: Hydraulic Engineering Circular Number 25 - Third Edition,” 2020. Accessed: Apr. 29, 2025. [Online]. Available: <https://rosap.nrl.bts.gov/view/dot/55727>
- Standards Australia, AS-5334-2013 Climate change adaptation for settlements and infrastructure: A risk-based approach. 2013.
- U.S. Department of Transportation Federal Highway Administration (2016). Highways in the River Environment- Floodplains, Extreme Events, Risk, and Resilience.
- Vallejo, L.; and Mullan, M. (2017). Climate-resilient infrastructure: Getting the policies right. OECD Environment Working Papers No. 121, April. doi: 10.1787/02f74d61-en.
- Virginia Department of Transportation (2020). Manual of the Structure and Bridge Division. [Online], Available: <https://www.virginiadot.org>
- Vrouwenvelder, T. (2002). Developments towards full probabilistic design codes. Structural Safety, [Online]. Available: <http://www.jcss.ethz.ch>