



TU Delft

Climate Change Adaptation for Reinforced Concrete Bridges: Examining Co-benefits and Future Directions for the Evolution of Eurocodes

M.Sc. Construction Management and Engineering

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Climate Change Adaptation for Reinforced Concrete Bridges: Examining Co-benefits and Future Directions for the Evolution of Eurocodes

A thesis submitted to the Delft University of Technology in partial fulfillment of the requirements for the degree of

Master of Science in Construction Management and Engineering
Specialization of Engineering & Systems
Faculty of Engineering & Geosciences

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Preface

This thesis concludes my studies in the master's program of Construction Management and Engineering. This research stems from my interest in climate change adaptation and how this concept can be applied to infrastructure. It concentrates on reinforced concrete (RC) bridges, a critical component of Europe's transportation networks and economic stability, and explores how climate change affects them, and how adaptation measures and their co-benefits can be integrated into Eurocode standards.

The journey to this point has been both challenging and rewarding. I have studied extensive literature to map the impacts of climate change and the co-benefits of adaptation measures for RC bridges. This work reflects my dedication to advancing knowledge in the field and my commitment to contributing to a more sustainable future. I hope that the conclusions and suggestions made here will help build more sustainable and resilient infrastructure that can withstand the effects of climate change and ensure a more secure and safe future for everybody.

My sincere gratitude goes out to my supervisors, Dr Ir. Maria Nogal Macho, Dr Rita Esposito, and Dr Emilio Bastidas-Arteaga for their guidance, kindness, and support during this process. Their advice has been invaluable in helping to shape this thesis. I also want to express my gratitude to my friends and family for their understanding and support during this time.

Delft, 14 September 2024

Victoria Koliou

Summary

In recent years, climate change has posed new challenges for reinforced concrete (RC) bridges, primarily because of the increased frequency of extreme weather events and changes in climatic conditions. Although much research has been done on climate change impacts and adaptation measures for RC bridges, the interrelationships between them, the co-benefits of adaptation measures and the compound effects of climate change have not been properly mapped and considered.

This thesis explores the co-benefits of climate change adaptation measures for RC bridges and how they might be incorporated into the Eurocode standards, ensuring resilience and sustainability throughout the bridge's life cycle. It addresses the urgent need for resilient infrastructure in the face of climate change. The study is based on examining the effects of climate change, the co-benefits of different adaptation measures, and the barriers to their implementation.

The thesis is structured around a research paper that maps and analyses how climate change affects RC bridges, highlighting the co-benefits of various adaptation measures. It provides a visual representation of the relationships between climate change impacts and their corresponding adaptation measures. Moreover, the study highlights the gaps in the current Eurocode standards for addressing climate change.

The thesis also identifies the co-benefits of several adaptation measures and assesses their performance against sustainability. It addresses the implementation barriers, such as knowledge gaps, technical challenges, financial constraints, and regulatory issues. Furthermore, it proposes actions to overcome these barriers, such as updating current standards, introducing maintenance protocols, and offering financial incentives.

The final chapter of the thesis reflects on the research's limitations and its practical implications in the field of construction management and provides recommendations for future research. The inherent uncertainty of climate change along with the lack of consideration of the cost-benefit ratio of adaptation measures, represent the main limitations. Moreover, it emphasizes the importance of incorporating climate change adaptation into construction management procedures, highlighting the crucial roles of asset management (maintenance) and stakeholder management in ensuring the sustainability and long-term resilience of critical infrastructure.

Recommendations for future research involve creating flexible adaptation measures, evaluating their cost-effectiveness, and introducing specific provisions for maintenance. Overall, this thesis takes a step towards considering co-benefits in climate change adaptation, ultimately contributing to the development of resilient and sustainable infrastructure.

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Chapter 1: Introduction

In the face of escalating climate change challenges, the resilience and sustainability of critical infrastructure have become major concerns. Reinforced concrete (RC) bridges, which are essential to transportation networks and economic stability, face significant vulnerabilities due to the increased frequency of extreme weather events and the various changes in climatic conditions. These vulnerabilities are often not properly addressed by the existing Eurocode standards in terms of design, construction, and maintenance practices.

Eurocode standards play a crucial role in climate change adaptation because they set the guidelines for the design, construction, and maintenance of RC bridges in Europe. Through Eurocodes climate change adaptation can be translated into practical guidelines that will help RC bridges become more resilient to the effects of climate change. However, according to Tiza (2022), current standard regulations and strategies for sustainable construction projects are lacking. In the same vein, Nogal (2020) suggests that Eurocodes ought to introduce maintenance specifically for climate change impacts. This indicates a significant gap in Eurocodes, highlighting the urgent need for climate change adaptation to be incorporated into the standards. The integration of climate change adaptation should address immediate risks and enhance the long-term resilience and sustainability of RC bridges.

This can be done by implementing the right adaptation measures. However, usually, the right choice is not clear. This is why, according to Orcesi et al. (2022) and Bastidas-Arteaga and Créach (2020), future research should study and compare different adaptation strategies considering effective risk reduction and system resilience improvement. Consequently, identifying and mapping the co-benefits of different adaptation measures, in terms of addressing simultaneously different kinds of impacts, is an important step towards their implementation.

Besides the limited research regarding their co-benefits, adaptation measures face additional barriers to their implementation, such as knowledge gaps, technical challenges, financial constraints, and regulatory issues. Therefore, actions need to be taken not only at the Eurocodes level but also on a broader scale to ensure successful implementation.

The implementation of climate change adaptation measures will ensure that RC bridges, and other critical infrastructure, are resilient in the face of climate change, preserving economic stability and transportation networks, and promoting environmental sustainability in Europe. Achieving these objectives and assuring the long-term resilience and sustainability of critical infrastructure depends on overcoming the barriers to adaptation measures' implementation.

1.1 Problem Statement

Climate change poses unprecedented challenges to infrastructure due to the increased frequency of extreme weather events and the uncertain changing trends in climatic parameters such as temperature, humidity, and precipitation. RC bridges are especially vulnerable because of their high exposure to climatic impacts and their long service lives. Despite ongoing research on the influence of climate change on infrastructure, current Eurocode standards fail to provide updated design and maintenance practices to address these risks. Moreover, they do not offer guidance on implementing climate change adaptation measures and their co-benefits or specifications for promoting sustainability and resilience.

Consequently, the safety and functionality of RC bridges are threatened. Furthermore, the discouraged application of adaptation measures translates into higher maintenance and repair costs. Therefore, to ensure the long-term resilience and sustainability of RC bridges, climate change considerations need to be integrated into the next generation of Eurocodes through provisions that consider the co-benefits of adaptation measures and their complicated interdependencies with climate change impacts.

1.2 Research Gap

Despite many research efforts examining climate change impacts on RC bridges and their corresponding adaptation measures, most of them have a narrow focus. Most research revolves around specific types of hazards, degradation mechanisms, or groups of adaptation measures (Proske et al., 2011; Chen et al., 2023). Studies on how climate change affects RC bridges (Nasr, 2020; Nasr, 2024) and materials like steel and concrete (Orcesi et al., 2022; Medeiros et al., 2024; Stewart et al., 2011) offer insightful information, but their scope is still limited. Other studies (Stewart et al., 2012; Bastidas et al., 2021) examine a single deterioration mechanism like corrosion through case studies and probabilistic modelling, while others (Markova, 2021; 2022) address the design of structures under changing climatic conditions.

Moreover, an integrated approach is usually absent from studies that explore the integration of climate change adaptation into Eurocodes (Nogal et al., 2020; Bastidas et al., 2021). These approaches lack in considering and mapping the co-benefits of different adaptation measures and the compound effects of climate change in RC bridges. This thesis aims to bridge this gap by providing a mapping and analysis of climate change impacts and the co-benefits of adaptation measures.

1.3 Objectives

The primary objective of this thesis is to take a step towards the consideration of co-benefits in climate change adaptation for RC bridges. This includes identifying the gaps in the current Eurocode provisions, mapping and analyzing the effects of climate change on RC bridges and the co-benefits of various adaptation measures. Moreover, this research assesses the sustainability of various adaptation measures, identifies the barriers to their implementation and proposes actions to overcome them.

By providing a map of the co-benefits of adaptation measures and the effects of climate change on RC bridges, this thesis seeks to highlight these areas and how they can be incorporated into the future generation of Eurocodes for a more efficient climate change adaptation. The goal is to contribute to the development of new or the enhancement of existing RC bridges that can withstand climate change risks while maximizing co-benefits and encouraging sustainability and resilience.

1.4 Research Question

The problem statement and the objective presented in the previous sections form the basis for the main research question and sub-questions of this thesis.

Main Research Question

How can climate change adaptation for RC bridges maximize co-benefits and be incorporated into Eurocode standards while ensuring resilience, and promoting sustainability?

Sub-questions

1. What are the impacts of climate change on RC bridges at the material and structural level?
2. How does the current generation of Eurocodes address the impacts of climate change on RC bridges?
3. What are the co-benefits of climate change adaptation measures in RC bridges, considering sustainability and resilience, throughout their life cycle?
4. What barriers prevent the implementation of climate change adaptation measures in RC bridges?
5. What actions are required to overcome these barriers to ensure sustainability and resilience throughout the life cycle of RC bridges?

1.5 Research Relevance

This research aims to take a step further towards climate change adaptation for RC bridges by mapping the co-benefits of various adaptation measures. Additionally, it builds on existing research regarding climate change impacts and explores their interrelationships. This study seeks to provide engineers, designers, and policymakers with useful insights for updating Eurocodes and facilitating the implementation of adaptation measures by identifying barriers and recommending solutions. The study aims to close the gap between theoretical research and real-world application by proposing actions to ensure the effective implementation of adaptation measures and enhance the resilience and sustainability of RC bridges.

1.6 Practical Relevance

This thesis connects theoretical research with real-world application by highlighting important aspects that are very often overlooked, the compound effects of climate change and the co-benefits of different adaptation measures. Moreover, it identifies both the conceptual and practical obstacles to adaptation measures implementation for RC bridges. Policymakers and regulatory bodies can use the findings of this study to develop more effective guidelines and regulations that will enable the implementation of updated design and maintenance practices.

By mapping the co-benefits of adaptation measures and the climate change impacts on RC bridges, this research contributes to understanding the relationships between them and achieving a smoother implementation of adaptation measures. Moreover, it brings attention to the importance of optimized maintenance practices that extend the lifespan of RC bridges. Ultimately, this research provides valuable information on the effects of climate change on RC bridges and the necessary steps towards the incorporation of climate change adaptation in the next generation of Eurocode standards.

However, this thesis also has several limitations. These include the inherent uncertainty of climate change and its projections. The absence of a specific case study means that the cost-benefit ratio of adaptation measures is not considered. Additionally, the study does not explore social and political barriers to climate change adaptation.

1.7 Thesis Outline

This paper-based thesis is structured into three main chapters. Chapter 1 introduces the problem statement, research gap, objectives, research questions, and the practical and research relevance of the study, forming the basis for a detailed investigation of the topic. The research paper is presented in the second chapter and includes a detailed mapping and analysis of the co-benefits of adaptation measures and climate change impacts on RC bridges, as well as an examination of how the current generation of Eurocodes addresses climate change impacts and of the obstacles to climate change adaptation. Finally, Chapter 3 concludes the research findings, acknowledges its limitations and discusses how this study fits into the larger framework of the field of construction management.

Chapter 2: Climate Change Adaptation for Reinforced Concrete Bridges: Examining Co-benefits and Future Directions for the Evolution of Eurocodes

This chapter presents the thesis's main research paper that focuses on mapping the co-benefits of climate change adaptation for RC bridges. The paper offers an extended mapping and analysis of climate change impacts on RC bridges and the co-benefits of various adaptation measures in addressing multiple impacts simultaneously. It examines how climate change impacts are addressed in the current generation of Eurocodes and points out the existing gaps. Moreover, it identifies barriers to their implementation and proposes actions and ideas for improving the sustainability and resilience of RC bridges and for including climate change and co-benefits considerations in Eurocode standards. The paper aligns with the objectives and research questions mentioned in the introduction and serves as the thesis's foundation.

Climate Change Adaptation for Reinforced Concrete Bridges: Examining Co-benefits and Future Directions for the Evolution of Eurocodes

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Abstract

In the face of climate change, reinforced concrete (RC) bridges encounter significant risks, indicating the need for effective adaptation measures. This paper explores the co-benefits of climate change adaptation for RC bridges and how sustainability and resilience can be achieved through adaptation measures. It also investigates the integration of climate change adaptation into Eurocode standards. The chosen approach includes mapping and analysing (i) climate change impacts on RC bridges and (ii) the co-benefits of different adaptation measures. Moreover, it includes an examination of the current generation of Eurocodes and an exploration of barriers and proposed actions towards climate change adaptation. The research highlights the complex relationships and compound effects characterising climate change impacts on RC bridges and the co-benefits of several adaptation measures. Moreover, it emphasises gaps in existing Eurocodes that need to be addressed to achieve climate change adaptation. Future actions, such as the economic viability of adaptation measures, their long-term performance, and the trade-offs of the bridge's life extension, especially for measures non-sustainable at first glance, should be further investigated.

Keywords: Climate change; Adaptation; RC bridges; Co-benefits; Failure mechanisms; Eurocodes

Title: Climate Change Adaptation for Reinforced Concrete Bridges: Examining Co-benefits and Future Directions for the Evolution of Eurocodes

1. Introduction

Climate change constitutes an unprecedented challenge to structures, requiring a paradigm shift in design and planning approaches to ensure their successful adaptation. Globally, climate change poses serious risks to critical infrastructure, with European reinforced concrete (RC) bridges being especially vulnerable, such as the Rion-Antirion Bridge in Greece. This bridge faces geological and climatic difficulties due to its location in a seismically active and windy area [1]. In some cases, bridges have collapsed due to climate change-related hazards. An example is the Morandi Bridge in Italy, which collapsed partly due to corrosion-induced damage in its cross-sectional area [2]. To help ensure the resilience of such infrastructure, the European Climate Risk Assessment (EUCRA) report highlights how critical it is to understand these vulnerabilities and implement efficient adaptation measures considering their co-benefits [3].

Co-benefits in the context of climate change refer to measures that simultaneously address different climate change impacts. The value of considering co-benefits lies in enhancing efficiency and reducing resource waste. Given the uncertainty of climate change and its different scenarios, implementing measures that

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address multiple hazards can be advantageous and provide an approach towards "no-regret" adaptation measures. Adopting measures that provide numerous benefits can optimise adaptation efforts and ensure the sustainability and resilience of RC bridges in the face of climate change. Therefore, mapping co-benefits and failure mechanisms, and identifying directions for the evolution of standards, play a crucial role in guiding and managing adaptation measures designed to reduce the effects of climate change on RC bridges.

Eurocode standards play an important role in climate change adaptation since they guide the design, construction, and maintenance of RC bridges across Europe. Incorporating climate change considerations into Eurocodes can translate adaptation strategies into practical guidelines that will help RC bridges withstand climate change impacts.

Various studies have explored the different impacts of climate change on RC infrastructure including adaptation measures. These works usually focus on a single hazard type or degradation mechanism or present a review of climate change risks and adaptation measures for RC bridges, without considering the influence of their interconnectedness. Some studies concentrate on providing a review of the potential impacts of climate change on RC bridges and their possible adaptation measures by listing and explaining them, paying no attention to their relations (e.g.,[4, 5]). Many works focus on materials, such as concrete and steel, and how climate change affects their properties and performance [6, 7, 8]. Other studies refer to the way climate change can affect the design weather parameters for the design of structures in accordance with Eurocodes (e.g.,[9, 10]).

Climate change adaptation has been investigated through case studies about corroded reinforced concrete structures and bridges subjected to scour (e.g.,[11]). In some cases, concrete deterioration has been investigated with the use of probabilistic modelling to predict the probability of the initiation of a single deterioration process, such as corrosion (e.g.,[12]). In contrast, other works examine a specific set of adaptation measures for a single climate change hazard such as debris impact or scour (e.g.,[13, 14]). Towards the consideration of climate change adaptation into Eurocodes, existing studies focus on a single deterioration mechanism, such as corrosion, presenting adaptation strategies to be potentially addressed by the standards and discussing the challenges of adaptation measures' standardization (e.g.,[15, 16]).

Based on these studies several research gaps are identified:

- no consideration of adaptation measures' co-benefits,
- no consideration of the compound impacts of climate change on RC bridges,
- insufficient focus on multi-hazard scenarios and their combined effects on RC bridges,
- lack of mapping/visual representation and analysis of the relationships between climate change impacts and their corresponding adaptation measures,
- lack of assessment of how Eurocodes address climate change impacts and how they can incorporate co-benefits of adaptation measures.

The co-benefits of implementing certain climate change adaptation measures are not considered in these studies. This approach does not allow a broader perspective of how the implementation of adaptation measures can be optimized and address multiple climate change impacts. Many studies do not account for the compound impacts of climate change and the multi-hazard scenarios. This is an important gap because, in reality, RC bridges will likely face multiple climate change impacts simultaneously, such as experiencing both corrosion and flooding. Moreover, these studies do not analyze the relationships between climate change impacts and their corresponding adaptation measures at a global level, resulting in limited knowledge about their effective implementation. Also, the absence of visual representations, such as maps, in existing studies does not provide a clear understanding of the complex interactions and dependencies involved.

To cover the existing gaps, this paper focuses on the co-benefits of adaptation measures and the compound impact of climate change on RC bridges. It analyses the co-benefits of adaptation measures and assesses the adaptation measures against resilience and sustainability. Moreover, it provides a detailed mapping and analysis of the climate change impacts on RC bridges and their corresponding adaptation measures, considering the dependencies between them.

In addition, this paper examines how current Eurocodes address climate change impacts to identify the gaps and indicate directions towards successful climate change adaptation. Moreover, it discusses the barriers to implementation and proposes practical actions to overcome these barriers, facilitating the effective integration of climate change adaptation measures into Eurocodes.

The detailed examination of a case study, including cost-benefit analysis and life-cycle assessment, is not covered in this paper. Additionally, the uncertainty of climate change and the different climate change scenarios are not addressed. This study also does not explore the social and political barriers that might affect the implementation of adaptation measures.

The main goal of this research work is to facilitate climate change adaptation by mapping the co-benefits of adaptation measures and the effects of climate change on RC bridges. Moreover, it identifies the gaps in the current Eurocodes regarding climate change impacts and provides a sustainability assessment of selected adaptation measures. It discusses the barriers to adaptation measures implementation and proposes actions to overcome them. By providing an analysis of these aspects, this paper aims to close the current knowledge gap and offer a different approach, that considers co-benefits, to integrating climate change considerations into the future generation of Eurocode standards.

The remaining document is organized as follows: Section 2 discusses the impacts of climate change on RC bridges and analyses their relationships with degradation mechanisms, structural changes, and failure mechanisms. In Section 3 an examination of the current Eurocodes that would be impacted by climate change is presented. Section 4 presents various adaptation measures, highlighting the co-benefits they offer. Moreover, it assesses these measures based on their performance regarding sustainability and resilience of the bridge and discusses the role of maintenance within the context of climate change adaptation. Section 5 presents the barriers to adaptation measures implementation and proposes actions to overcome them. The limitations of this paper are addressed in Section 6 along with suggested directions for future research. Finally, in Section 7 some conclusions are drawn.

2. Impacts of climate change on RC bridges

This section discusses climate change impacts on RC bridges and analyses how they affect structures. The impacts and their effects on RC bridges are mapped in Figure 1. The section begins with a general description of the impact map and continues with its analysis. In Section 2.1, climate change's direct and secondary impacts on RC bridges are discussed. Then, Section 2.2 explains the processes of material deterioration and performance degradation. Lastly, Section 2.3 investigates the failure mechanisms.

Mapping the impacts of climate change on RC bridges is crucial because of the distinct characteristics they exhibit during the bridge's lifetime. Some impacts have an immediate effect on the bridge, lasting only a few seconds or hours, such as floods (sudden changes in Figure 1). In contrast, others impose a continuous, long-lasting influence, such as temperature and humidity variations (progressive changes). Moreover, sudden and progressive changes could occur simultaneously and/or be interdependent. Because of that, it is important to develop adaptation measures that provide co-benefits, meaning that they address multiple climate change impacts at once. Consequently, a clear understanding of climate change's impact on RC bridges will help to develop and implement more effective adaptation measures and use the co-benefits that can arise.

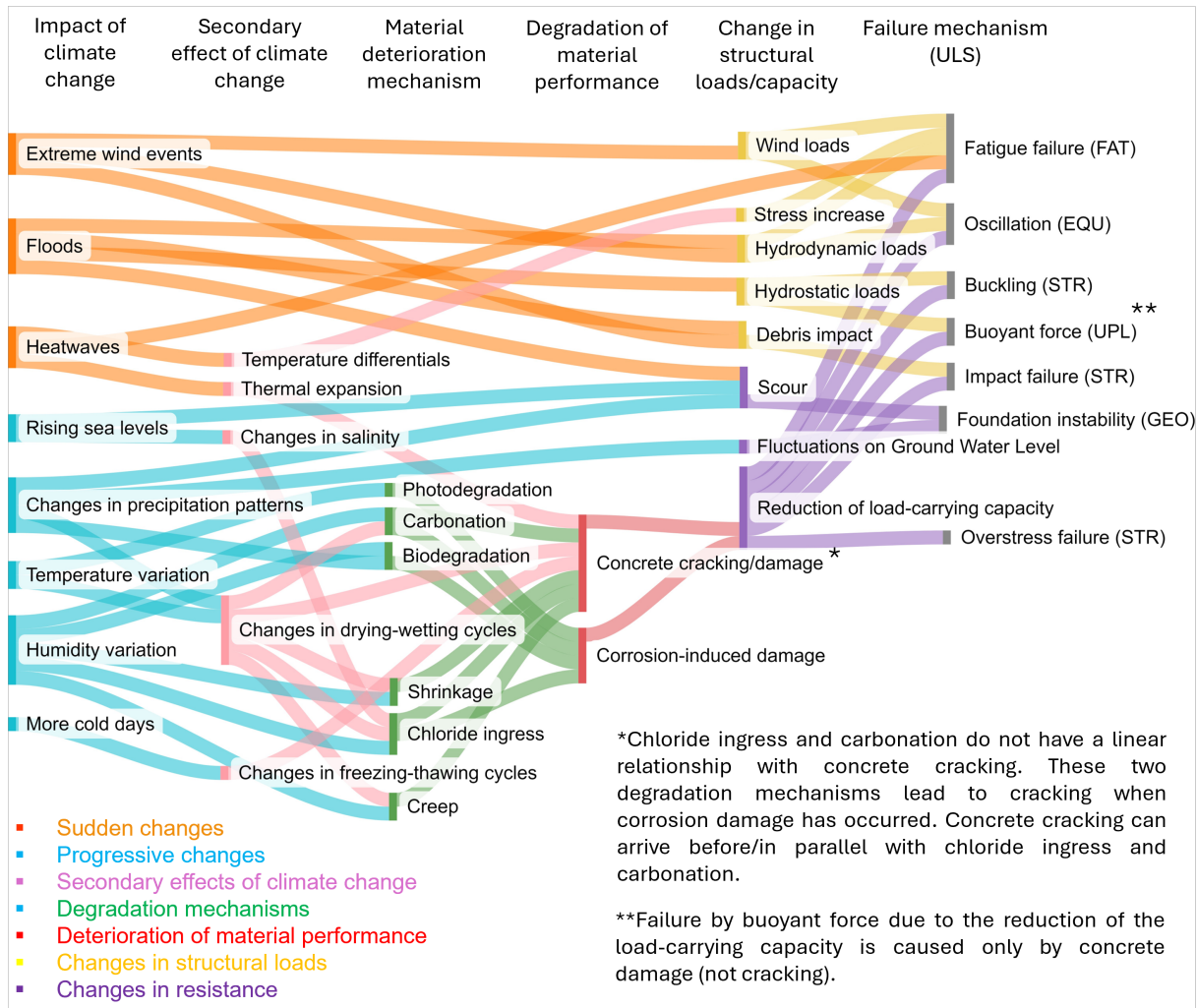


Figure 1: From Climate Change Impacts to Degradation, Deterioration and Failure Mechanisms of RC Bridges.

Figure 1 shows an overview of the potential impacts of climate change, the mechanisms and changes they may initiate, the consequent failure mechanisms and their interrelationships. The diagram consists of six columns and seven colours that characterize different types of changes. The first column presents the primary impacts of climate change and identifies sudden changes (e.g. floods) in orange and progressive changes (e.g. temperature variations) in blue. The second column introduces the secondary effects of climate change, such as changes in salinity and drying-wetting cycles, in pink. The third column lists material deterioration mechanisms (e.g. carbonation) in green, while the fourth column presents degradation processes (e.g. corrosion) in red. The fifth column introduces changes in structural loads (in yellow) and the bridge's capacity (in purple). The last column includes the failure mechanisms in terms of Ultimate Limit States, as defined by the Eurocodes [17]. The connecting lines illustrate how climate change impacts create secondary effects, leading to degradation mechanisms, material deterioration, changes in loads and structural capacity, and ultimately, structural failure mechanisms. For example, extreme wind events can cause an increase in wind, hydrodynamic and debris impact loads that can lead to fatigue failure, impact failure, and failure due to oscillation, as shown in Figure 1.

Table 3 in the Appendix presents a detailed overview of the literature that was used for the creation of the map shown in Figure 1. The table is organized to correspond with the format of Figure 1, listing the

relevant studies for each identified impact, secondary effect, deterioration mechanism, degradation process, change in structural load or capacity, and failure mechanism. This information is presented to validate the connections and relationships shown in Figure 1. Moreover, it provides references for further research and verification of the mapped data.

2.1. Direct and Secondary Impacts of Climate Change

As mentioned before, the impacts of climate change on RC bridges can be divided into two main categories, impacts that cause sudden and progressive changes in the structure. Sudden changes are mostly related to additional (extreme) loads acting on the bridge that can potentially lead to overloading and structural failure [11]. They have a short-lived effect because they are derived from extreme weather events, such as hurricanes, heat waves, and floods. These impacts are presented in Figure 1 in orange.

Extreme wind events are sudden and can create changes in the bridge's structural loads, by increased wind and hydrodynamic loads, and debris impact [18]. Larger wind loads can cause oscillation of the bridge, dynamic stresses, and fatigue damage [19, 20]. Moreover, strong wind speeds might initiate large waves, storm surges, debris impact, and rainfall that can lead to flooding.

Floods belong also to sudden changes and similarly to extreme wind events, impose extreme loads on the bridge [21]. Three load effects usually account for the physical forces of the floodwaters acting on the structure, namely, hydrostatic, hydrodynamic, and debris impact [22, 23]. Besides the forces posed by floodwaters, debris impact can create significant forces on the bridge. Another effect initiated by flooding characterised as a leading cause of bridge failure, is scour. Scour decreases the lateral capacity of the bridge-foundation system and therefore, changes the bridge's capacity. As shown in Figure 1, scour can lead to foundation instability [22].

Regarding heat waves, which are characterized as sudden changes, an increase in air temperature amplifies the uniform component of thermal actions. This condition can potentially lead to thermal expansion of the materials and higher thermal-induced stresses [20, 24, 9]. Both cases could lead to progressive growth and linkage of cracks within the material, causing deterioration of material performance and resulting in structural failure due to buckling [6]. Moreover, the increased solar radiation in some locations can create a temperature differential between the top and bottom of bridge decks that can raise stress levels and lead to fatigue failure [20, 10].

On the other hand, impacts included in progressive changes, distinguished by blue in Figure 1, are derived from changing climatic conditions and affect the materials' properties [11]. These impacts are long-lived and involve temperature and humidity variations, rising sea levels, and changes in precipitation patterns. They affect the bridge by creating changes in its capacity, as shown in Figure 1. Progressive changes usually initiate deterioration mechanisms that could lead to degradation of the material performance and failure if no maintenance action is carried out.

Rising sea levels can progressively change the bridge's capacity, especially in coastal areas, by creating changes in salinity that can initiate or exacerbate chloride ingress. Seawater and deicing salts can expose the concrete to chloride ions initiating corrosion of the steel reinforcement [25, 26]. Furthermore, the increased water flow might cause erosion and lead to scour, as shown in Figure 1.

In the same way, changes in precipitation patterns might lead to increased scour rate. Groundwater level is also influenced by precipitation changes that might cause fluctuations in it. Moreover, increased rainfall and moisture in conjunction with micro-cracks, due to changes in drying-wetting cycles, can create a favourable environment for concrete bio-degradation [20, 27].

Changes in precipitation patterns and temperature variation can modify drying-wetting cycles, which in turn influence carbonation and chloride ingress mechanisms, as well as concrete cracking, as shown in Figure 1 [28, 29]. Future temperature increases can also lead to additional evapotranspiration, which causes an increase in drying-wetting cycles and hence in shrinkage and creep [4, 30]. In addition, higher temperatures, and

especially, the UV-B component of solar radiation can cause photo-degradation on the concrete's protective layers [4]. On the other hand, a decreasing trend in temperature in some regions, which results in more cold days, influences the freezing-thawing cycles and may lead to premature concrete cracking and spalling [31, 32, 33].

Humidity variation is a progressive change that influences mostly degradation mechanisms, as shown in Figure 1. However, its influence depends on the local characteristics and conditions of each region, as well as on its interaction with other climate change variables. While high precipitation and humidity slow down the process of drying, lower relative humidity affects shrinkage losses by increasing them [34, 4]. In the same way, an increase in humidity prevents creep, but a decrease results in a higher creep rate for concrete, especially in combination with an increased temperature [6, 4, 35]. Relative humidity affects also the kinematics of carbonation and chloride ingress [6]. As relative humidity leads to an optimum relative humidity, carbonation depth increases, with the highest rates observed for 55-75% humidity. Carbonation decreases, for humidity values above 85% and lower than 50% [36, 8, 7, 37]. In the case of chloride ingress, its mechanism decelerates when there is a reduction in relative humidity [11]. Moreover, relative humidity can contribute to creating a favourable environment for bio-degradation [38]. The complexity of humidity's variation effects on deterioration mechanisms cannot be fully captured in Figure 1, since their relationships are not linear.

2.2. Material Deterioration and Performance Degradation

Concrete deterioration mechanisms are presented in the third column of Figure 1, in green. They may lead to degradation of the material's performance, indicated with red in Figure 1. They usually cause corrosion-induced damage, cracking, or both.

In the case of shrinkage and creep, concrete cracking can occur. Shrinkage can create tensile stresses resulting in cracking [34]. Although shrinkage is regarded as a long-term effect, it can influence the crack resistance and deformations of RC members under short-term loading [39]. Regarding creep, it decreases the cracking load of prestressed structures, during their service life, by reducing the concrete's prestressing force [34]. Whereas it is considered a serviceability problem that mostly affects maintenance and repair costs, there are several structural collapses partly ascribed to creep deformations [35].

Bio-degradation of concrete occurs when microorganisms cause undesirable changes in the material. It can increase concrete's porosity, reduce its compressive strength, and stimulate crack growth [27]. Because of its slow kinematics, it is not easily detected. Although it is not considered a direct source of structural failure, it leads to a reduction of load-carrying capacity in the long term and an increase in maintenance costs [38, 27]. Moreover, it accelerates other deterioration mechanisms such as chloride ingress and carbonation. Concerning photo-degradation, it can cause chemical bonds of the material to break and create damage to concrete's protective layers (paint, sealants, etc.) [40, 41]. As a result, the inner concrete layers become exposed and more vulnerable to environmental conditions and other deterioration mechanisms [4]. Both bio- and photo-degradation mechanisms contribute to corrosion development.

Chloride ingress is one of the primary deterioration processes for RC structures in marine environments [7, 42]. For this mechanism, chloride ions penetrate concrete causing a reduction of its alkalinity and an increased risk of corrosion [36]. It leads to corrosion initiation, rebar deterioration, and concrete cracking and spalling [43]. However, it is worth mentioning that these damage processes do not always take place [43]. As a consequence, the damage is not always visible.

Carbonation affects the load-carrying capacity of the structure after corrosion initiation, under both dynamic and static loads [42, 36, 42]. Besides reducing the pH, carbonation produces a decrease in concrete's porosity which in turn would affect the resistance of RC to chloride penetration [44].

As shown in Figure 1, both chloride ingress and carbonation lead to corrosion-induced damage [45, 46]. They also lead to concrete cracking due to the expansion of corrosion products. However, it should be noted

210 that their relationship with loading-induced concrete cracking is not linear, since it can occur before or in parallel with these deterioration mechanisms and in some cases accelerate the rate of penetration of chlorides and carbon dioxide.

Degradation of material performance is presented in the fourth column of the map in red in Figure 1 and includes corrosion-induced damage and concrete cracking. As shown in Figure 1, concrete cracking can 215 be caused by secondary climate change effects (e.g., thermal expansion) and deterioration mechanisms (e.g., corrosion-induced damage). However, the relationship between these factors and their cumulative impact on concrete cracking is complex and cannot be fully illustrated in Figure 1.

Corrosion can be initiated by the majority of deterioration mechanisms, as shown in Figure 1. It has two phases, corrosion initiation and propagation [15]. Corrosion initiation requires various decades while 220 propagation has a duration of only a few years [16, 47]. Corrosion involves concrete cracking due to pressures from the corrosion's voluminous sub-products and reduction of the effective steel cross-section [16]. Without maintenance, corrosion leads to spalling, cover cracking, and loss of the bond between steel and concrete [15]. Furthermore, corrosion can result in decreased safety due to early in-service failures and changed structural behaviour [48]. It seriously affects the seismic performance and load-carrying capacity of RC structures [36]. 225 Especially, RC bridges are more vulnerable to corrosion than buildings, since all their structural components are exposed to environmental actions. It is worth mentioning that corrosion processes caused by carbonation and chloride have a compounding effect, which has not been studied properly yet [15].

2.3. Loads, Structural Capacity, and Failure Mechanisms

As already mentioned, climate change causes changes in loads or structure's capacity. In the first case, 230 changes are sudden and can lead to immediate failure. In the second case, changes are more gradual and can have a compound effect with sudden changes, leading to structural failure [5]. In Figure 1 changes in structural loads are indicated by yellow and changes in the bridge's capacity by purple.

Sudden changes involve additional (extreme) loads that can extend above the structure's load-carrying capacity and activate one or more failure mechanisms. Larger wind loads can create vortex-induced vibrations, 235 bridge flutter, and bridge oscillation [4, 49, 19]. Extreme stresses and deformations due to oscillation can lead to structural failure. On the other hand, cyclic loading caused by vortex-induced vibrations can trigger fatigue failure. Moreover, stress increases coming from temperature differentials can also result in fatigue failure [9].

Another type of load that causes fatigue failure and oscillation is the hydrodynamic load. Drag and inertia 240 forces act in both the horizontal and vertical directions and create the hydrodynamic force due to waves [23]. The bridge can sway or oscillate because of these loads. If the force exceeds the bridge's resistance, this can cause structural instability or collapse.

Hydrodynamic loads can also lead to fatigue failure over time by inducing vibration and resonance in the bridge. On the other hand, hydrostatic loads are vertical and cause pressure on the bridge's vertical 245 structural elements [50]. This can result in excessive compressive stresses on piers and abutments. If the stresses exceed material strength and structural capacity, they can trigger the buckling of these elements, resulting in structural failure. Moreover, the buoyant force, caused by water displacement, is a significant hydrostatic force capable of displacing the bridge [23]. Except for forces posed by waves, debris can create significant forces, especially on bridge piers, which can result in impact failure [51, 52].

250 Scour can cause loss of the lateral capacity of the bridge-foundation system and lead to foundation instability [22, 53, 54]. Fluctuations in groundwater levels also cause foundation instability. When groundwater decreases the foundation load increases, and when groundwater increases the bearing capacity of the soil decreases [55].

Corrosion-induced damage and concrete damage, caused by the various deterioration mechanisms, ultimately 255 result in the reduction of the structure's load-carrying capacity, as shown in Figure 1. This affects

the structural capacity of the bridge, especially in combination with changes in structural loads, potentially leading to different failure mechanisms such as fatigue failure, oscillation, buckling, buoyant force, impact failure, and overstress failure [7, 56].

3. Eurocodes and Climate Change Impacts

260 Design and construction standards provide recommendations based on existing knowledge to ensure structural serviceability and safety when bridges are subjected to several failure mechanisms as presented in Figure 1. However, bridges will be subjected to unknown non-stationary related hazards under a changing climate. Therefore, this section examines how existing Eurocodes will be impacted by climate change and identifies existing gaps to determine how the new generation of Eurocodes can be developed to incorporate climate change adaptation for RC bridges [17, 56, 57, 58, 59, 60, 61]. Figure 2, imprints the climate change impacts mentioned at the Eurocodes, mirroring the climate change impacts map of Figure 1. Colourful dots on the impacts indicate their mention in the Eurocodes, with blue representing Eurocode 1: Actions on Structures, purple for Eurocode 2: Design of Concrete Structures, and green for Eurocode 7: Geotechnical Design. In addition, Table 1 provides references to the specific sections of these Eurocodes. This mapping and referencing highlights both current considerations of climate change impacts and gaps within the Eurocodes.

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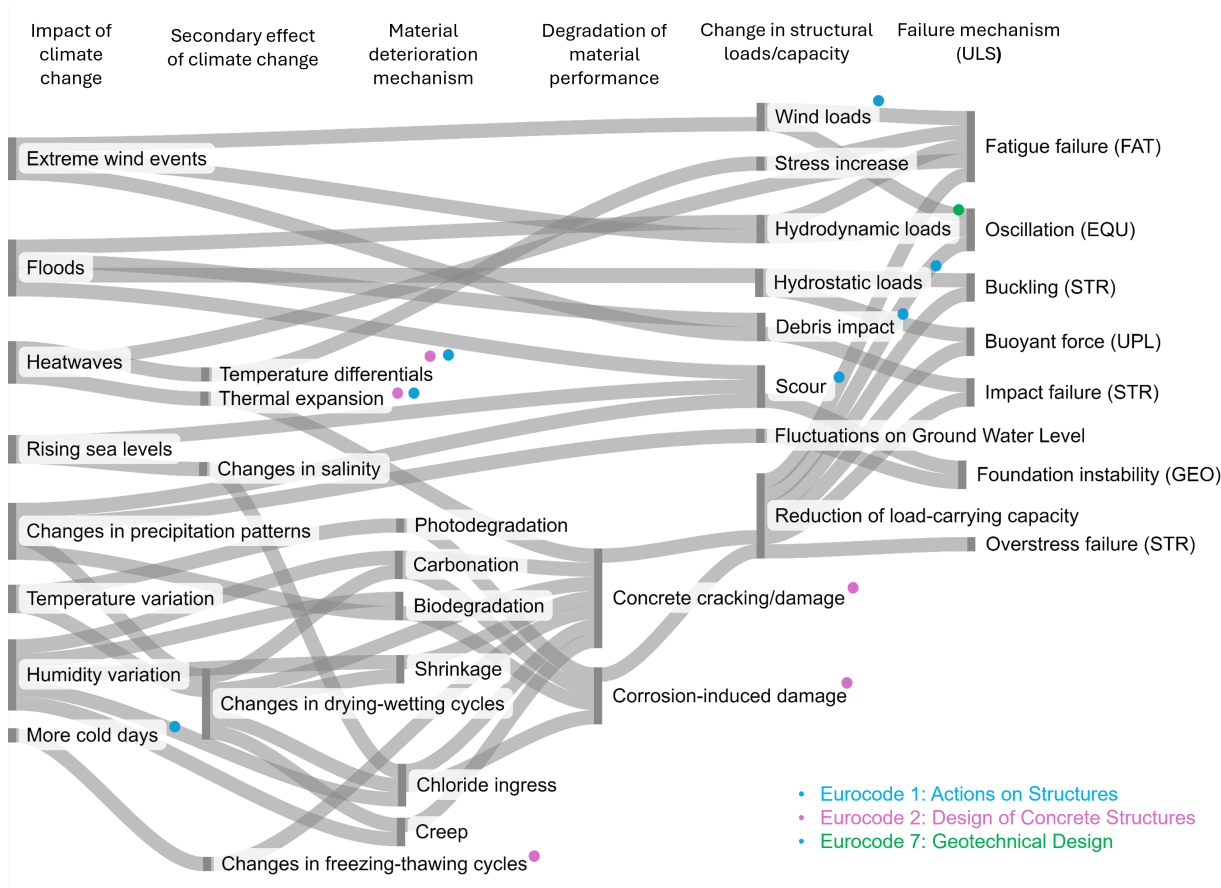


Figure 2: Eurocodes addressing climate change impacts.

In the European standards series, Eurocodes 1, 2 and 7 include sections relevant to climate change impacts and RC bridges. Eurocode 1 refers to the different actions applied to structures, while Eurocode 2 contains general rules for the design of concrete structures and a specific section about the design of RC bridges

[60, 58, 56]. Although Eurocode 7 involves general rules about geotechnical design, it has some relevant sections about water pressures [57]. It should be noted that Eurocode 0 mentions environmental influences that could affect the structure’s durability, but it mostly refers to other Eurocodes, such as Eurocode 1 which addresses these environmental actions more directly [17].

Climate Change Impact	Standard	Section	Description
Wind loads	EN 1991-1-4:2010	Section 8	Wind actions on bridges
Wind loads	EN 1991-1-6:2005	Section 4.7	Wind actions (during execution)
Debris Impact/Hydrostatic loads	EN 1991-1-6:2005	Section 4.9	Actions caused by water
Hydrodynamic loads	EN 1997-1:2004	Section 9.6	Water pressures
Snow loads	EN 1991-1-3:2003	Section 4	Snow loads
Scour	EN 1991-1-6:2005	Section 4.9	Actions caused by water
Thermal actions	EN 1991-1-5:2003	Section 6	Temperature changes in bridges
Thermal actions	EN 1992-1-1:2004	Section 2.3.1.2	Thermal effects
Freezing-Thawing cycles	EN 1992-1-1:2004	Section 4.2	Environmental conditions
Corrosion	EN 1992-1-1:2004	Section 4.2	Environmental conditions
Concrete cracking	EN 1992-1-1:2004	Section 7.3	Crack control

Table 1: Climate Change on Structural Standards

For wind loads, as stated in Table 1 there is only an indirect consideration of climate change. To determine wind action, factors such as terrain type, meteorological data quality and availability, and location, are considered [58]. These parameters are provided in the National Annex. Similarly, thermal actions do not explicitly address climate change, however, the uniform temperature component and temperature differences are considered [60, 56]. The values of the minimum and maximum uniform bridge temperature components for restraining forces are determined by the minimum and maximum (T_{max} , T_{min}) shade air temperatures for the site location, which are derived from the national maps of isotherms [60]. The values of linear temperature differences for bridge piers and walls are specified by the National Annex [60]. It is evident, that parameters specific to the region and its climate are taken into account to calculate wind and thermal actions. Climate change is expected to cause variations in these parameters.

Concerning corrosion, some protection strategies are proposed such as increasing concrete’s durability properties and implementing some protective measures such as coatings [56]. Concrete cracking is addressed only under normal environmental conditions [56]. The framework presented for calculating snow loads is based on historical data and regional parameters, but they don’t take into account future climate change projections [56]. It is worth mentioning that although shrinkage and creep are addressed in Eurocodes, the focus is on the mechanical and durability aspects of concrete without specific provisions for future climate change impacts.

Overall, existing Eurocode standards address climate change effects in an overly limited way. This current generation of Eurocodes was formulated based on climatic data from approximately 20 years ago [9, 62]. Eurocodes provide limited guidance to load adjustments for more extreme weather events. However, they do not explicitly list specific climate change projections as well as adaptation measures, except for some actions for corrosion protection. Concerning sustainability and resilience, although the structure’s durability, robustness, efficient use of materials, and life cycle are considered, there are no specific guidelines for integrating sustainability and resilience into the standards.

Concerning maintenance, it is addressed only superficially in the aforementioned Eurocodes. It is mostly addressed in Eurocode 7, Section 4, which provides specifications for construction supervision, monitoring

and maintenance. More specifically, the level and type of inspection and monitoring are determined by the structure's Geotechnical Category (1, 2, or 3). The structure's Geotechnical Category depends on its type and use (e.g., single-storey buildings, bridges, deep foundations), the ground conditions, and the geotechnical activities required (e.g., excavation depth, soil improvement techniques) [57]. Moreover, a subsection about maintenance states which information should be provided on maintenance specifications (e.g., frequency of inspection) [57]. Consequently, it is a topic that needs to be considered directly in the new generation of Eurocodes by introducing provisions encouraging maintenance strategies that include proper inspection, monitoring and even adaptation.

4. Adaptation Measures from a Co-benefits Perspective

An adaptation measure is defined as a response (e.g., changes in structural design, maintenance practices, etc.) to ensure appropriate levels of serviceability and safety when the structure is subjected to new (climate change-related) environmental conditions [63]. A given climate change impact requires a specific adaptation measure. However, the application of one adaptation measure can address multiple climate change impacts, offering co-benefits. As mentioned before, co-benefits are defined as actions that simultaneously address various impacts of climate change. This section presents a variety of climate change adaptation measures for RC bridges, emphasizing on their co-benefits. Section 4.1 discusses adaptation measures that address impacts causing load changes, while Section 4.2 focuses on adaptation measures for material deterioration mechanisms. Both sections highlight the additional benefits (co-benefits) that some measures provide for RC bridges. In Section 4.3 the role of maintenance in climate change adaptation is discussed. Lastly, Section 4.4 provides an analysis of the effectiveness of the adaptation measures against two criteria: resilience and sustainability.

Figure 3 shows the mapping of various RC bridges' adaptation measures for each climate change impact and the potential co-benefits they might have. The map consists of six columns. The first five columns mirror those in Figure 1: impacts of climate change, secondary effects, deterioration mechanisms, degradation of material performance, and changes in structural loads and bridge capacity. The sixth column, however, lists the adaptation measures. The colours indicate the application phase of each measure: blue for measures applicable only in the design phase, orange for those in the service phase, and red for measures that can be applied in both phases. The design phase involves the design and construction of the bridge, while the service phase refers to the bridge's operational life. The connecting lines illustrate the relationships between the impacts of climate change and the corresponding adaptation measures.

To provide a better understanding of the adaptation measures listed in Figure 3, a detailed table is provided in the Appendix. This table (Table 4) provides the main climate change hazard that each measure addresses, a short description of the measure, its application phase (design phase, service phase, or both), and the relevant literature. Thus, Table 4 offers a useful source for understanding how these measures can be effectively implemented to address specific climate change impacts.

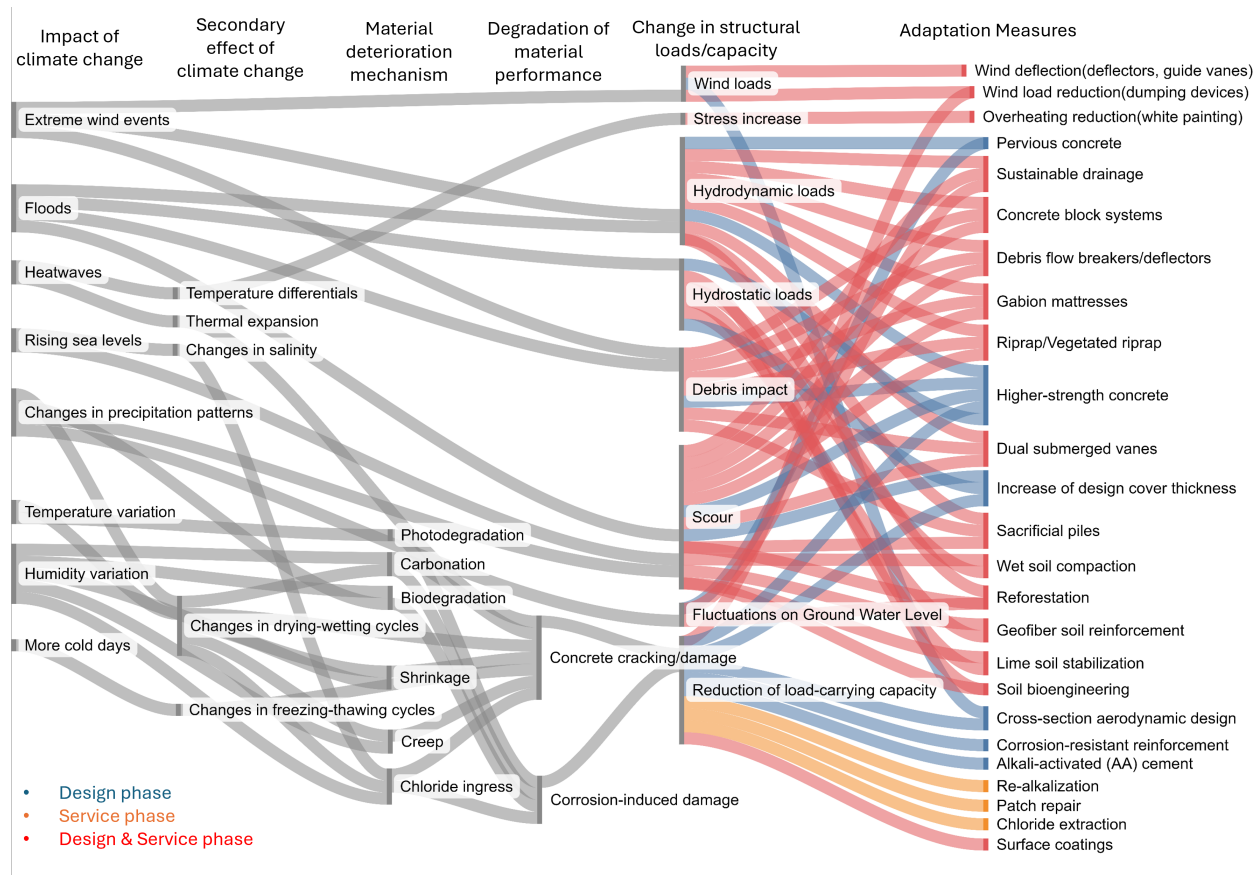


Figure 3: Climate Change Adaptation Measures and their Co-Benefits.

4.1. Adaptation measures for load changes

340 Load changes occur when additional forces act on the bridge, usually because of impacts that cause sudden changes. These impacts, presented in orange in Figure 1, include extreme wind events, floods, and heat waves. They require adaptation measures that can ensure the bridge’s structural integrity and resilience against unpredictable and extreme weather conditions.

345 Measures that help the bridge adapt to extreme wind events involve cross-section aerodynamic design, damping devices, deflectors, or guide vanes. Aerodynamic design improves aerodynamic stability by optimizing load distribution and increasing fatigue resistance [49]. It can be applied in the design phase. Moreover, aerodynamic performance is improved by deflectors that redirect the wind in a desired direction. Guide vanes may be fastened to deflectors, serving the same purpose [64]. Damping devices absorb dynamic vibrations that result from the wind. They also have the co-benefit of absorbing vibrations due to earthquakes and traffic loads [49].
 350 These measures can be implemented both in the design and service phases of the bridge. Besides reducing wind loads acting on the bridge, they offer the co-benefit of enhancing the bridge’s load-carrying capacity, as shown in Figure 3, by helping to the even distribution of loads across the bridge.

White painting reduces the amount of solar energy absorbed by the structure. Its co-benefits are the reduction of overheating and heatwave-related thermal stresses [65]. Debris flow breakers decrease debris impact on the bridge. Their additional benefits include contributing to scour reduction by controlling erosion and protecting the bridge foundations by reducing the hydrodynamic loads acting on them [66].
 355 These adaptation measures, indicated by red in Figure 3, can be applied both in the design and the service phase of the bridge.

360 Flooding, as the main cause of failure for RC bridges over rivers, can cause additional forces on the bridge [67]. Adaptation measures for floods involve mostly measures for soil stabilisation and managing the water flow. Pervious concrete, implemented in the bridge’s design phase, can be used to help manage stormwater because of its high porosity. In addition, it reduces hydrodynamic loads and recharges groundwater, as shown in Figure 3. Pervious concrete is a green adaptation measure with co-benefits such as reducing traffic noise and urban heat island effects [68]. Moreover, it works as a filter for stormwater, improving groundwater
365 quality [68]. Dual submerged vanes, in addition to water redirection, offer the co-benefit of preventing scour by helping in sediment management, depth maintenance, and improvement of aquatic habitat [69]. Furthermore, altering the flow direction can help deflect debris away from the bridge piers. They can be applied in the design or service life of the bridge.

Measures that increase soil’s bearing capacity, such as wet compaction, lime stabilisation, and geofiber
370 reinforcement, provide the co-benefit of supporting scour mitigation around bridge foundations, as illustrated in Figure 3 [70]. In the same way, soil bioengineering, sustainable drainage, and reforestation also prevent scour and control slope stabilisation [66, 71, 72]. Moreover, planting new vegetation mass offers the following co-benefits: reduction of superficial erosion, increased biodiversity and increased recreational quality of the area. All these measures can be implemented in both the design and service phases of the structure (indicated
375 by red in Figure 3), except for sustainable drainage which should be applied in the design phase (indicated by blue in Figure 3).

4.2. Adaptation measures for changes in structural capacity

Changes in the bridge’s capacity are usually caused by variations in climatic conditions causing progressive changes (deterioration) in the structure (indicated by blue in Figure 1). As illustrated in Figure 1, these
380 changes may initiate various deterioration mechanisms or create changes in the structure’s capacity directly. Their effects can be prevented, slowed down, or repaired with the right adaptation measures.

More specifically, scour can be prevented by using structures such as concrete block systems, gabion mattresses, and riprap [14]. All these measures act as barriers and prevent erosion. In addition, they provide the co-benefit of not allowing large debris to impact the structure and therefore, they protect the
385 bridge foundations. Another measure for scour is sacrificial piles, which prevent debris, and have several co-benefits such as hydrodynamic load reduction and foundation protection [73]. In the case of vegetated riprap, its additional benefits are supporting vegetation growth and providing a natural habitat for wildlife [74]. Additionally, as a green solution, vegetated riprap can benefit local communities by supporting activities such as fish and wildlife observation. All these measures can be applied both in the design and the construction
390 phase of the structure, as shown in Figure 3.

Concerning corrosion, there are adaptation measures that can be applied in the design phase, service phase, or both. Higher strength concrete and increase of design cover thickness improve the bridge’s durability and load-carrying capacity, especially regarding hydrostatic loads [12, 15, 5]. In terms of increased durability, these measures provide the co-benefits of improving the structure’s resistance to hydrodynamic loads and
395 debris impact. Both of them are implemented during the bridge’s design phase. Moreover, Alkali-Activated (AA) cement, besides increasing corrosion resistance, reduces the penetration of harmful substances in the concrete and has a lower environmental impact than traditional Portland cement, representing a sustainable solution with multiple benefits [15]. Another measure that prevents corrosion is the use of corrosion-resistant reinforcement. The aforementioned measures are indicated by blue in Figure 3, therefore, they can be imple-
400 mented during the bridge’s design phases. However, higher-strength concrete, alkali-activated cement, and an increase of concrete cover can be also implemented in the service phase of the bridge in case reconstruction of polluted concrete is required.

Solutions that involve restoration or repair such as chloride extraction, patch or global concrete repair [75], and re-alkalization are applied in the service life of the structure and are indicated by yellow in Figure

405 3. Especially, the re-alkalization of concrete is characterised as an environmentally sustainable solution [15].
Another adaptation measure for corrosion is the use of surface coatings which can be applied during both
the design and service phases. By preventing or reducing corrosion, these measures offer the co-benefit of
increasing the structure’s load-carrying capacity.

4.3. *Maintenance considering climate change adaptation*

410 This section discusses the important role of maintenance in the context of climate change adaptation.
Some adaptation measures could be implemented during a maintenance operation and/or maintenance is
necessary to ensure the effectiveness of adaptation measures during the service phase of RC bridges.

In a resilience-based approach, in which a certain impact of climate change can be addressed by adaptation
measures applied in the design phase, maintenance can address the uncertain impact of climate change by
415 measures applied in the bridge’s service phase [16]. Effective maintenance should ensure the durability and
longevity of the structure, ensuring its safe operation and expanding its service life. Moreover, it should
be cost-effective, minimizing long-term costs by preventing major failures, and enhancing the structure’s
resilience. Maintenance should maximize serviceability and safety performances and minimize life cycle costs
and environmental impact.

420 Deciding which adaptation measures should be applied and on which phase of the structure’s life cycle,
requires a risk assessment framework to identify, evaluate, and prioritize potential risks that could affect the
bridge throughout its life cycle. In addition, a Life-Cycle Analysis (LCA) should be performed to identify
opportunities to reduce environmental impacts and enhance sustainability, along with a Life-Cycle Cost
assessment (LCC) to ensure that the chosen adaptation measures are cost-effective. However, the timing
425 and frequency of a bridge’s maintenance can vary significantly under different climate change scenarios [76].
That is because, as climate conditions worsen, the amount of maintenance required increases.

Selecting a maintenance strategy, especially in the context of climate change, is case-dependent and should
consider the following factors: risk level, changes in risks over time, predictability and detectability of failure
and costs [77]. The management scenarios should be regularly updated throughout the service life to account
430 for ongoing and projected changes in climate-related risks, expenses, and environmental impacts and benefits.

Maintenance can be proactive or reactive. Proactive maintenance includes preventive and predictive
maintenance. The application of climate change adaptation measures in the design phase of the bridge,
as well as regular proper inspections, are considered preventive maintenance. Monitoring and data-driven
decision-making belong to predictive maintenance. Monitoring is particularly important, as it can reduce to
435 a degree the uncertainties related to climate change effects [10]. Adaptation measures are applied during the
structure’s service life according to climate-changing conditions and the data gathered from the monitoring.
Predictive maintenance optimises the use of resources and is considered the most cost-effective approach
because it reduces unnecessary maintenance and prevents major failures. On the other hand, corrective
maintenance involves applying adaptation measures after the damage has already occurred by repairing or
440 replacing damaged parts.

For incorporating climate change adaptation, a combination of proactive types of maintenance is recom-
mended. Depending on the region and its climatic data, preventive maintenance should be considered to
address high-probability climate change impacts in the design phase of the structure. Predictive maintenance
should address climate change impacts, that cannot be predicted, by monitoring and applying adaptation
445 measures when needed.

4.4. *Sustainability assessment of adaptation measures*

The effectiveness of adaptation measures can be addressed by considering several factors such as cost-
effectiveness, risk, sustainability, resilience, and co-benefits [63, 78]. This section assesses adaptation measures
based on their performance on two criteria: sustainability and resilience. The Eurocodes, mentioned in Section

3 (Eurocodes 1, 2, and 7), are also mentioned to highlight their connection with climate change impacts and the necessary adaptations. This connection becomes evident by identifying which specific parameters within the Eurocodes are influenced by these impacts. Additionally, the assessment considers co-benefits in terms of mitigating other impacts beyond the primary target impact. It should be noted that a cost-benefit analysis has been used previously in the literature for the assessment of the adaptation measures [63]. However, this approach falls outside of the scope of the current research because no case study was investigated and the focus of this paper is on co-benefits.

The following definitions are considered in this assessment:

- **Sustainability** is defined as the capacity of an adaptation measure to minimize CO₂ emissions, energy consumption and material use, e.g., using innovative low-carbon materials, using recycled resources and protecting nature [79].

While sustainability's central idea is to reduce negative impacts on the environment to prevent climate change, resilience's central idea is the ability to adjust to change.

- **Resilience** is defined as the ability of a structure to resist, adapt to, and recover from various changes, including extreme weather events.

Each adaptation measure is qualitatively assessed by its influence over two criteria (sustainability and resilience) and is presented in Figure 4. Figure 4 consists of six different columns. The first column presents the primary climate change impacts addressed by the adaptation measures listed in the second column. The third column identifies the relevant Eurocode specifications that correspond to the climate change impacts, while the fourth column mentions the specific Eurocode parameters affected. The fifth column highlights any additional impacts mitigated by the adaptation measure (co-benefits). The final column states the measure's influence on the two criteria. Positive influence is represented by green, which means that the measure positively contributes to the analysed criterion. Negative influence is represented by red and translates as a negative contribution to the criterion. The asterisk (*) in the Sustainability column indicates that the sustainability of these measures depends on case-specific factors, such as material choice and quantity, long-term co-benefits, and cost-benefit ratio. This approach offers a qualitative assessment of how each adaptation measure interacts with Eurocode parameters and its overall contribution to the bridge's resilience and sustainability.

All adaptation measures presented in Figure 4 contribute positively to the bridge's resilience. Each measure addresses one or more climate change impacts, making the bridge able to withstand both extreme weather events and changes in climatic conditions. For example, higher-strength concrete strengthens structural components. Similarly, measures that include external devices (e.g., dumping devices) and added constructions (e.g., riprap) reduce the action of extreme weather events such as flooding, on the bridge. Moreover, the implementation of adaptation measures can extend the bridge's service life and reduce future repairs.

Concerning sustainability, its assessment is complex because it involves considering several aspects to determine whether an adaptation measure is sustainable in the short and long terms. Natural-based solutions, such as soil bioengineering, reforestation, and vegetated riprap involving plants and natural materials can be considered sustainable because they have a low environmental impact. More specifically, they are resource-efficient (by using natural, locally available materials) and have long-lasting benefits such as improved air and water quality, habitat creation, and aesthetic value.

Adaptation measures promoting the use of innovative green materials such as pervious concrete and alkali-activated cement are sustainable solutions. Pervious concrete helps manage rainwater more effectively, benefiting both water quality and groundwater levels. Particularly for urban areas, it helps with the heat-island effect and the traffic noise problem [68]. Pervious concrete and vegetated riprap are two of the measures Sustainable Drainage Systems (SUDS) promote. Sustainable Drainage Systems support water infiltration,

495 stormwater absorption, urban cooling, heat-island effect, and biodiversity through practices such as green surfaces and rain gardens [72]. Alkali-activated cement produces lower CO₂ emissions than regular Portland cement and uses industrial and agricultural waste as source materials solving waste disposal issues [80, 81].

For many adaptation measures, sustainability depends on material choice, structure, cost-benefit ratio, and required maintenance. Higher-strength concrete can become sustainable by integrating supplementary cementitious materials (fly ash, slag cement, silica fume) that have a lower environmental impact [82, 83].
500 Moreover, it can potentially reduce the required amount of concrete during the structural lifetime due to its increased durability. Although corrosion-resistant reinforcement may minimize the bridge's long-term environmental impact, its production usually involves more energy consumption than regular reinforcement and presents recycling challenges. Re-alkalization is more sustainable in comparison with other corrosion
505 repair techniques, such as patch repair and coatings, because it addresses the problem of corrosion directly by restoring concrete's alkalinity [15, 84]. Also, it does not require frequent maintenance or replacement in comparison with patch repair and coatings. However, its effectiveness depends on its appropriate application. Chloride extraction is a non-invasive technique that uses electricity to draw chloride ions out of concrete. In these terms, it might be sustainable, however, the duration of its effectiveness has not been properly
510 investigated yet [15].

Concerning riprap, its placement reforms the bank surface. While this can create new habitats, it can also disrupt existing ecosystems [85]. Moreover, it is considered a hard engineering solution in comparison with natural ones such as soil bioengineering or vegetated riprap. Gabion mattresses can be considered sustainable if they are filled with recycled clothing instead of rocks, which acts similarly to a geotextile [86]. However,
515 further research is required to investigate the use of alternative materials in combination with other scour adaptation measures. Similarly, geofiber reinforcement can be a sustainable solution when using recycled or natural fibers, since synthetic fibers contribute to plastic pollution [87]. White painting is sustainable because it has a cooling effect on the surfaces. Nevertheless, paints usually use environmentally hazardous materials [65]. In addition, regular cleaning or reapplication may be required to ensure its effectiveness.

520 Dumping devices contribute to sustainability by reducing potential earthquake damage and as a result the demand for large-scale repairs [49]. However, their production and disposal have a negative environmental impact. Regarding wind deflectors and guide vanes, their sustainability depends mostly on their material, whether it is sustainable, recyclable, and on its environmental impact. Dual submerged vanes can be a suitable alternative for riprap while causing less disruption in the aquatic habitat in comparison with larger
525 construction interventions [69]. Aerodynamic design can result in more efficient use of materials lowering the bridge's environmental impact. However, it depends on the project since it may result in a complex design that requires advanced construction techniques and high maintenance.

Lastly, there are adaptation measures that cannot be considered sustainable such as the increase of design cover thickness. That is because it increases the amount of concrete required for the bridge and
530 consequently, the CO₂ emissions produced. Similarly, surface coatings, especially organic, are used widely to address corrosion but are not environmentally friendly. Green technologies are required to avoid using toxic substances and heavy metals [88]. Patch repairs cannot be considered sustainable since they are temporary solutions, especially in the case of chloride-induced corrosion [15]. However, generalized repairs allow extending/ensuring the operational lifetime [75].

535 The production of lime for lime stabilization produces a serious amount of CO₂ emissions and requires high energy consumption, resulting in negative environmental impact [89]. On the other hand, wet compaction has a high water requirement and produces greenhouse gasses by affecting the concentration of carbon dioxide in the soil [70]. Sacrificial piles are not considered sustainable since they are a short-term solution that requires periodic replacement, and additionally, their placement disrupts the local habitat. Concrete block systems
540 serve the same purpose as riprap and gabion mattresses. They do not represent a sustainable solution since they have a considerable environmental footprint. In the same way, debris flow breakers are usually made of

concrete and require a significant habitat disruption [66].

545 Although these solutions do not appear sustainable initially, they can have long-term benefits that contribute to the structure's extended lifespan. For example, increasing the design cover thickness may have a negative environmental impact because of higher material use. However, this measure's added durability and longevity can reduce the need for frequent repairs and replacements, ultimately resulting in an overall reduction of material use. Therefore, further research is needed to understand the trade-offs involved in service life extension, especially for adaptation measures that may appear unsustainable.

Climate change impact	Adaptation measure	Eurocode	Eurocode parameters affected	Co-benefits	Influence of measure's implementation	
					Sustainability	Resilience
Extreme wind events	Dumping devices (MR dumpers, Dynamic vibration absorbers (DVAs), etc.)	EN 1991-1-1: Actions on Structures	Wind load, Dynamic response	Reduction of load-carrying capacity	*	
	Deflectors/Guide vanes		Wind load		*	
	Cross-section aerodynamic design		Wind load, Load distribution		*	
Heatwaves	White painting	EN 1991-1-1: Actions on Structures EN 1992-1-1: Design of concrete structures	Thermal properties		*	
Debris Impact	Debris flow breakers	EN 1991-1-1: Actions on Structures	Impact resistance, Load-bearing capacity	Scour, Hydrodynamic loads		
Floods	Sustainable drainage	EN 1991-1-1: Actions on Structures	Soil stability	Scour, Fluctuations of groundwater level		
	Soil bioengineering		Soil stability	Scour		
	Reforestation			Scour, Fluctuations of groundwater level		
	Wet soil compaction		Soil density, Bearing capacity	Scour		
	Lime soil stabilization	Soil strength				
	Geofiber soil reinforcement	EN 1997-1: Geotechnical Design		Scour	*	
	Dual submerged vanes			Debris impact, Scour	*	
	Pervious concrete		Water permeability, Load-bearing capacity	Fluctuations of groundwater level		
Scour	Concrete block systems	EN 1991-1-1: Actions on Structures		Debris impact, Hydrodynamic loads		
	Gabion mattresses				*	
	Riprap	EN 1997-1: Geotechnical Design			*	
	Sacrificial piles					
	Vegetated riprap					
Corrosion	Higher-strength concrete	EN 1992-1-1: Design of concrete structures	Compressive Strength Class, Durability Requirements, Cover to Reinforcement	Debris impact, Hydrostatic and hydrodynamic loads, Reduction of load-carrying capacity, Scour	*	
	Increase of design cover thickness			Hydrostatic loads, Reduction of load-carrying capacity, Scour		
	Corrosion-resistant reinforcement		Material Properties	Reduction of load-carrying capacity	*	
	Alkali-activated (AA) cement					
	Chloride extraction				*	
	Patch repair					
	Re-alkalization				*	
	Surface coatings					

*The sustainability of these adaptation measures depends on factors such as the choice of materials.

Figure 4: Climate Change Adaptation Measures and their Co-Benefits.

5. Identifying and Overcoming Barriers to Adaptation Measures Implementation

550 While the sustainability of many adaptation measures may depend on material choice or other factors mentioned in Section 4.4, some adaptation measures are characterized as sustainable and the majority of them contribute to the bridge’s resilience. Yet, their widespread implementation remains limited. This section discusses the reasons behind this by identifying the barriers to adaptation measures implementation and outlining the necessary actions to overcome them. Each adaptation measure faces specific technical challenges. 555 However, most barriers are common across all measures. These barriers and their corresponding suggested actions are presented in Table 2, categorized into five distinct groups: knowledge, technical, institutional, financial, and regulatory barriers. In addition, a stakeholder map is presented in Figure 5 which states the stakeholders involved in climate change adaptation according to their interest and power.

5.1. Barriers to Adaptation Measures Implementation

560 The left column of Table 2 shows the identified barriers to adaptation measures’ implementation. One of the most fundamental categories of barriers is knowledge gaps both at the academic level and in technical expertise. Standard guidelines for adaptation measures implementation are limited or non-existent. As already mentioned in Section 3, current Eurocodes do not promote the application of adaptation measures. For new materials, such as alkali-activated and pervious concrete, there are not sufficient standards for 565 mixture design methods, mechanical characterization, durability testing, and structural performance [80]. Moreover, there is limited research on how ecosystems interact with infrastructure, making it challenging to design effective adaptation measures. Knowledge gaps on measures’ long-term performance may increase the risk of maladaptation resulting in increasing the structure’s vulnerability instead of reducing it. Additionally, these gaps complicate the evaluation of the measures, which should consider their long-term performance.

570 Because of knowledge barriers, designers and constructors face technical barriers. They are unclear on how to utilize new materials or measures effectively and discouraged from applying them. The lack of skilled labour in combination with the unique conditions of each region further limits adaptation measures’ application. Some measures might have specific space requirements, such as reforestation, and require regular maintenance, especially measures involving vegetation (e.g. vegetated riprap) or regular cleaning/reapplication (e.g., white 575 painting). There is also the challenge of aligning the implementation of each measure with the specific regional conditions and existing infrastructure [90]. Moreover, the availability of resources such as land, soil and water can significantly disrupt the implementation of several measures (e.g., reforestation).

This limited application creates a considerable gap in real-world data, which makes it challenging to assess the measure’s long-term performance and other important factors such as cost-effectiveness and so- 580 cial acceptability. Without sufficient real-world usage, comprehensive assessments and improvements of the adaptation measures remain challenging, delaying their potential adoption and development. Institutional barriers such as inconsistent policies, bureaucracy, and insufficient collaboration among stakeholders pose further challenges to implementation.

In addition, regulatory barriers such as design limitations, ecosystem compatibility issues, and inconsistent 585 policies pose significant challenges. Design limitations and ecosystem compatibility may restrict the types of adaptation measures that can be implemented. Inconsistent or regularly changing policies across different regions and countries can slow down the implementation of adaptation strategies by creating confusion, making it difficult to achieve successful long-term outcomes.

590 Consequently, stakeholders are hesitant to invest due to performance uncertainties, high initial costs, and the potential for an uncertain return on investment. This investment hesitation, in conjunction with the lack of standardised guidelines, further perpetuates the cycle of discouraged implementation.

Barriers	Actions
Knowledge Gaps:	Knowledge Gaps:
<ul style="list-style-type: none"> • Insufficient technical expertise and data • Ecological knowledge gaps • Lack of standards for tests on innovative materials and application practices • Insufficient standard guidelines • Insufficient standards for mixture design methods • Lack of practical data about measures' long-term performance 	<ul style="list-style-type: none"> • Training • Pilot cases • Up-to-date database • Research and development for tests and guidelines for the use of new materials • Climatic maps • Monitoring and evaluation after implementation • Risk assessment of existing structures
Technical:	Technical:
<ul style="list-style-type: none"> • Regular maintenance • Lack of skilled labor • Unique geographical and environmental conditions • Land availability, space requirements • Integration with existing infrastructure 	<ul style="list-style-type: none"> • Maintenance protocols • Monitoring and evaluation after implementation • Risk assessment of existing structures
Institutional:	Institutional:
<ul style="list-style-type: none"> • Bureaucracy • Lack of coordination among stakeholders 	<ul style="list-style-type: none"> • Stakeholder Engagement • Collaboration among stakeholders
Financial:	Financial:
<ul style="list-style-type: none"> • Availability of resources • High initial costs • Uncertain Return on Investment (ROI) • Stakeholder resistance 	<ul style="list-style-type: none"> • Cost-benefit analysis • Incentives, subsidies
Regulatory:	Regulatory:
<ul style="list-style-type: none"> • Design limitations • Ecosystem Compatibility • Inconsistent policies 	<ul style="list-style-type: none"> • Update Eurocodes • User-friendly standards • Alignment between National and European policies • Alignment between adaptation and mitigation measures

Table 2: Barriers and Actions to Adaptation Measures' Implementation

5.2. Actions to Overcome Barriers

Stakeholders play a pivotal role to overcome these barriers and achieve effective implementation of climate change adaptation measures [11]. The key stakeholders for climate change adaptation are presented in Figure 5 and the proposed actions that should be taken in the right column of Table 2. Figure 5 presents a stakeholder map with two axes, the horizontal axis measures stakeholder interest (low, average, high) and the vertical axis stakeholder power (low, average, high). Every group of stakeholders corresponds to a number on the map.

Governments and their bodies (ministries, local authorities, provinces) along with the European Union are responsible for policy-making and resource allocation. The European Union is more interested in facilitating climate change adaptation because of its commitment to several environmental agreements such as the Paris

Agreement [91]. Given the global nature of climate change, coordinated actions at the European level are more powerful than individual actions at the national level. Both the European Union and the governments of the Member States have a high interest in and power over climate change implementation. However, they often slow down progress due to regulatory complexities and bureaucracy. By allocating resources, they also define research directions and as a result, are responsible for existing knowledge gaps.

Academia contributes crucial research and technical expertise. It has a strong interest in climate change adaptation, however, its influence is limited without resources provided by governmental bodies and the European Union. Despite these constraints, academic institutions are important in advancing knowledge and developing innovative solutions. Nevertheless, they face challenges in forming standardized guidelines for climate change adaptation.

Regulatory bodies such as CMA ("Conference of the Parties serving as the meeting of the Parties to the Paris Agreement") have global influence in setting international policies and commitments [92]. However, the European Union has the authority to enact regulations and directives that its Member States are obligated to implement and enforce. If a member state fails to comply with EU law, the European Commission can take action that may result in the European Court of Justice imposing penalties, including fines. Although regulatory bodies are essential for ensuring compliance, they may struggle to keep pace with evolving standards (e.g., for innovative materials).

Designers and constructors, as already mentioned, encounter barriers due to a lack of standard specifications and practical feedback (case studies, data, etc.) that lead to uncertainties in climate change adaptation implementation. Both have an average interest and power in comparison with other stakeholders because of their limited authority. They are responsible for implementing standards and policies but are not able to create them. Nevertheless, designers have the authority to integrate climate change adaptation into the overall design and consequently, hold more power than constructors.

Since they are directly impacted by adaptation measures, communities and users play a crucial role in shaping acceptance and creating a supportive environment for sustainable adaptation measures implementation. Users have more interest and power than communities because they are directly affected. Communities, on the other hand, may have a more generalized interest in climate adaptation, focusing on collective well-being and long-term environmental impacts. Although both of them have low power, they can influence climate change adaptation by their ability to shape public opinion and by voting (e.g., candidates with strong climate policies).

Environmental NGOs (Non-Governmental Organizations) such as Greenpeace and the European Environmental Bureau (EEB) can influence policymakers and raise awareness about climate change adaptation to the public [93, 94]. They can hold governments responsible for keeping their promises and draw attention to areas that require further action or where progress is being slow.

Stakeholder engagement and collaboration are required to achieve successful adaptation measures implementation. Successful engagement can be achieved by promoting active participation and open communication among stakeholders and ensuring inclusivity. Steps towards these strategies are i) through partnerships between NGOs and governments, such as the one between WWF (World Wildlife Fund) and the governments of Colombia and Brazil to protect the Amazon rainforest [95], and ii) through movements such as the Rotterdam Climate Initiative, which regularly arranges public forums and workshops where locals, companies, and experts can express their worries and recommendations, resulting in more comprehensive and successful flood adaptation strategies [96].

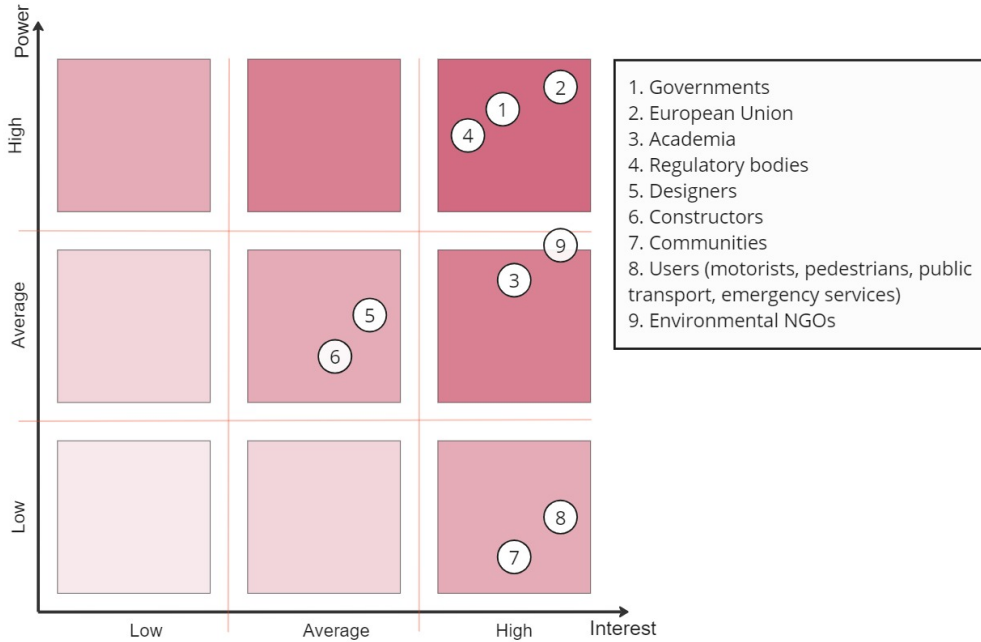


Figure 5: Stakeholders Involved in Climate Change Adaptation for RC Bridges

645 Collaboration between institutions and academia is essential to identify research gaps, standardize new materials, design innovative adaptation measures, and develop guidelines for the design and assessment of adaptation measures. Bridging these knowledge gaps will help the development of new standard regulations that effectively address climate change. Up-to-date climatic data (historical and predictions) should be incorporated into the new generation of Eurocodes to improve the decision-making and effectiveness of adaptation measures implementation. To ensure a smooth transition to the next generation of Eurocodes, comprehensive training programs may be offered both at the design and technical levels. These may include conferences, seminars or workshops on understanding the new Eurocodes and climatic maps and how to incorporate them into design practices. Moreover, courses focused on technical training can be offered to cover topics such as material selection based on climatic data.

655 Monitoring is essential to gather data on the long-term performance of adaptation measures. This can be achieved through pilot cases that help to evaluate adaptation measures. Gathered data should be shared among institutions, academia, designers, and constructors through a centralized up-to-date database. Establishing sharing-data protocols can enhance Eurocodes and national standards, and ensure that they are updated with the latest information and best practices. Such a system allows for a thorough evaluation of adaptation measures through multiple case studies, providing stakeholders with valuable insights. It should be mentioned that cost-benefit analysis is essential to achieve a comprehensive evaluation. Access to this data can not only enhance confidence among investors but also significantly reduce uncertainty, encouraging further investment in climate change adaptation.

660 Introducing a framework for risk assessment of existing structures will help design targeted and more efficient adaptation measures. The EUCRA (European Climate Risk Assessment) report analyses the damage risk to infrastructure due to climate change and extreme climate events [3]. The report addresses risks on a continental level, focusing on large-scale impacts. European countries can adopt a similar framework at a national, and/or regional level. Such an evaluation may reveal interconnected risks between different infrastructures and help to identify high-risk assets and areas. This will allow for prioritization and efficient allocation of resources in bridges' adaptation measures implementation. To achieve this, collaboration between different stakeholders (e.g., infrastructure owners) is required.

Moreover, establishing a comprehensive framework for maintenance and asset management is important. Through maintenance protocols including routine inspections, advanced monitoring technologies and data analytics, potential failures can be predicted and prevented. This proactive approach can gather valuable data on the performance of the measures, and contribute to continuous improvement and informed decision-making in adaptation measures.

National governmental institutions, including ministries and municipalities, alongside the European Union, can provide the necessary resources and encourage investment in climate change adaptation through frameworks, financial incentives, subsidies, and regulatory measures. Achieving climate change adaptation requires long-term alignment between national and European policies. Furthermore, an alignment between mitigation and adaptation measures is needed to maximize co-benefits (e.g., sustainable drainage systems).

Some of these actions are already underway. The second generation of Eurocodes standards is expected to incorporate climatic maps that will provide detailed information on the climatic conditions of different regions. This will help engineers adjust measures' design to the local climatic conditions, improving the bridge's resilience. The new Eurocodes are expected to be ready after 2026 [21].

6. Limitations and Future Directions

This section addresses the limitations of this paper and suggests directions for future research. It outlines recommendations for practitioners, policymakers and scientists based on this research's findings and discusses how present policies should be refined to better support climate change adaptation.

While this research provides valuable insights into climate change adaptation, it is important to acknowledge its several limitations:

- Firstly, the uncertainty that characterises climate change. As climatic conditions are expected to follow diverse trends across Europe, it is difficult to draw definitive conclusions on which adaptation measures should be prioritized. In addition, the uncertainty of climate change scenarios is an important limitation. An adaptation measure might be implemented based on a scenario with a high probability of impact, but if a different scenario occurs, the investment might not have the expected benefits, resulting in a waste of resources. In case a worse scenario than predicted occurs, regular inspections and continuous monitoring will become more important to ensure that a bridge will adjust to the new conditions. Future works should concentrate on creating adaptable and flexible measures that can handle a variety of potential climate change scenarios. Moreover, creating frameworks for regional-level applications could enhance impact prioritization and efficient allocation of resources.
- A second limitation of this work is the exclusion of cost considerations from the assessment of co-benefits. This aspect was not addressed because the costs of adaptation measures are bridge-specific and then can vary according to the project size, materials used, and region. Future studies need to conduct comprehensive life-cycle analyses, to evaluate the economic and environmental impacts of adaptation measures. Moreover, due to the broad concept of sustainability, it is essential to establish clear sustainability criteria for assessing the environmental impact of climate change adaptation measures. Another limitation, regarding the evaluation of adaptation measures, is the limited real-world data on their long-term performance. This barrier could be addressed by long-term monitoring and data collection from implemented adaptation measures. Moreover, predictions on the long-term performance of adaptation measures can be made through climate (climate change scenarios) or economic (assessing cost-effectiveness) models (e.g.,[11, 97]). Future research is required to evaluate the effectiveness of adaptation measures over extended periods.
- Thirdly, social and political barriers, that can influence the implementation of regulations and the effectiveness of governmental bodies in driving climate change adaptation, were not addressed. Future

715 research should identify these social and political barriers and explore how they affect climate policy
and action.

The following recommendations are made:

- 720 • **Maintenance:** It is evident, from this research, that maintenance plays a crucial role in climate
change adaptation. That indicates that future research should focus on providing specific provisions or
protocols for maintenance practices to be included in the new generation of Eurocodes.
- 725 • **Research and Innovation:** Scientists should fill in the knowledge gaps by researching adaptation
measures' economic viability and long-term performance, especially for new materials and adaptation
solutions. This could be achieved through experimental research and pilot projects to bridge the gap
between theory and practice.
- **Policy and Standards Development:** Policymakers should establish standard tests and guidelines
for new materials, update Eurocodes (which is already underway), and provide financial incentives to
encourage climate change adaptation. Moreover, they should introduce a framework for evaluating
existing structures, potentially at a regional level.
- 730 • **Practical Implementation:** Practitioners should be able to assess existing structures and integrate
adaptation measures successfully. Moreover, they should be able to utilize the necessary maintenance
strategies.

7. Conclusions

This research takes a step towards considering co-benefits in climate change adaptation. It presents a
map of climate change impacts on RC bridges as a starting point and then progresses to outline adaptation
735 measures and their co-benefits. Moreover, it highlights the dependencies of climate change impacts and
adaptation measures while examining the relevance of Eurocodes in climate change adaptation. It identifies
barriers to their implementation and suggests actions for effective integration.

The mapping of climate change impacts and co-benefits of adaptation measures is an area that has not
received much attention in previous studies. Consideration of co-benefits is a critical point in adaptation
740 because it shifts the focus towards measures that address the compound impact of climate change. It can
increase efficiency and facilitate decision-making under the uncertainty of climate change.

In addition, this paper provides new insights into the interconnectedness and relationships between cli-
mate change impacts, material deterioration mechanisms, structural changes, and failure mechanisms in RC
bridges. It looks into how Eurocodes address climate change, identifying gaps and outlining directions for
745 their future development. Moreover, this research discusses the sustainability of adaptation measures and
the importance of maintenance in climate change adaptation.

The study identifies barriers and suggests actions for the successful implementation of adaptation mea-
sures. It also discusses the role and power of the stakeholders involved in climate change adaptation. Through
this, this research aims to initiate a dialogue among stakeholders, considering all relevant aspects studied in
750 this paper, to enhance their engagement and collaboration.

Furthermore, the study offers suggestions for the implementation of climate change adaptation. It also
makes recommendations for the development of the next generation of Eurocodes, expected after 2026, to
better incorporate climate change adaptation measures.

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Table 3: Relevant Literature Addressing the Impact of Climate Change on RC Bridges

A summary of the literature review on climate change impacts on RC bridges is given in Table 4. It mirrors Figure 1, which was created based on the given references. The goal of this table is to offer a useful reference for future research.

Impact of climate change	Secondary effect of climate change	Material deterioration mechanism	Degradation of material performance	Change in structural loads/resistance	Failure mechanisms (ULS)
Extreme wind events: [18], [19]	Temperature differentials: [10]	Creep: [35], [30], [34]	Corrosion-induced damage: [48], [15], [47], [42], [36], [16], [98]	Wind loads: [49]	Fatigue failure: [99], [100]
Floods: [67], [22], [101]	Thermal expansion: [24]	Photodegradation: [20], [40], [41]	Concrete cracking/damage: [8], [102], [103]	Stress increase: [9]	Oscillation: [104], [105]
Heatwaves: [106]	Changes in salinity: [107], [26], [108]	Shrinkage: [39], [34]		Hydrodynamic loads: [23], [109]	Buckling: [110], [111]
Rising sea levels: [112]	Changes in drying-wetting cycles: [28], [29]	Carbonation: [45], [44], [46], [42]		Hydrostatic loads: [50]	Buoyant force: [113]
Temperature variation: [114], [115]	Changes in freezing-thawing cycles: [31], [32]	Biodegradation: [116], [27], [117], [38]		Debris impact: [66]	Impact failure: [52], [51]
Humidity variation: [37], [98], [118], [119]		Chloride ingress: [25], [43], [120]		Scour: [48], [53], [54], [121]	Foundation instability: [122], [123]
Changes in precipitation patterns: [124]				Fluctuations on Ground Water Level: [125], [71], [55]	Overstress failure: [126]
More cold days: [33]				Reduction of load-carrying capacity: [127]	

Table 3: Relevant Literature Addressing the Impact of Climate Change on RC Bridges

Table 4: Adaptation Measures for Various Climate Change Hazards

A summary of the climate change adaptation measures presented in this paper is given in Table 4. It provides a brief description of each measure, the particular climate impacts it addresses, the structure's phase it can be applied, and the relevant references. The purpose of this table is to provide a clear reference for the different measures examined in this research, emphasizing their potential uses and efficiency in boosting the resilience of reinforced concrete (RC) bridges.

Climate hazard	change	Adaptation Measure	Description	Application phase	Reference
Extreme events	wind	Dumping devices (MR dumpers, Dynamic vibration absorbers (DVAs), etc.)	Reduce wind loads by restraining the swaying motion that occurs in case of vibrations and oscillations.	Design & Service Phase	[128, 49]
Extreme events	wind	Wind deflectors/Guide vanes	Deflectors redirect wind in a desired direction and improve aerodynamic performance. They can have guide vanes attached. Guide vanes are fixed grooves that redirect water, gas, or air in the desired direction.	Design & Service Phase	[64, 129]
Extreme events	wind	Aerodynamic design	Selection of orthotropic plates (material properties in the two principal material axes, higher stiffness in desired directions) for bridge deck cross-section to increase aerodynamic stability.	Design Phase	[4, 49]
Heatwaves		White painting	Reduces overheating and thermal stresses by minimizing the amount of solar energy absorbed by the structure.	Design & Service Phase	[65]
Debris Impact		Debris flow breakers	Barriers that are located upstream of the bridge to prevent large debris from impacting bridge piers or abutments directly.	Design & Service Phase	[66]
Floods		Sustainable drainage	Lowers the Ground Water Level by pumping groundwater from shallow wells or installing drainage pipes alongside existing sewer pipes.	Design Phase	[71, 66, 72]
Floods		Soil bioengineering	Use of living plants and inert materials such as rocks, to enhance groundwater recharge, reinforce soil structures, control erosion, and stabilize slopes.	Design & Service Phase	[66]
Floods		Reforestation	Reduces groundwater recharge by increasing evapotranspiration.	Design & Service Phase	[66]
Floods		Wet compaction	A mechanical compaction method is applied to increase soil density.	Design & Service Phase	[130, 70]
Floods		Lime stabilization	Lime (calcium hydroxide) is incorporated into the soil to improve its engineering performance.	Design & Service Phase	[89]

Continued on next page

Table 4 – *Continued from previous page*

Climate change hazard	Adaptation Measure	Description	Application phase	Reference
Floods	Geofiber soil reinforcement	Fiber materials are incorporated into the soil to improve its engineering properties.	Design & Service Phase	[131, 87]
Floods	Dual submerged vanes	Redirect water flow to achieve erosion control. They are typically installed on the river bed.	Design & Service Phase	[69]
Floods	Pervious concrete	Characterized by high porosity that allows water to infiltrate the ground. Helps to manage stormwater and recharge groundwater.	Design Phase	[132, 68, 133]
Scour	Concrete block systems	Precast structures placed along the banks of rivers or around bridge abutments and piers. Prevent erosion and increase bridge stability.	Design & Service Phase	[14, 4]
Scour	Gabion mattresses	Wire mesh containers filled with stones or other materials. They are used for erosion control.	Design & Service Phase	[86]
Scour	Riprap	Layer of large stones, or other durable materials that are placed along bridge abutments and other areas to protect against erosion.	Design & Service Phase	[85]
Scour	Sacrificial piles	Additional piles placed strategically around the structure to decrease water velocity and prevent erosion.	Design & Service Phase	[73]
Scour	Vegetated riprap	Placing live cuttings of rootable plant material into the soil in the small gaps or joints of rocks that have previously been set on a slope. Increases stream-bank's stabilization by preventing erosion and reducing the force of water flow.	Design & Service Phase	[90, 134, 74]
Corrosion	Higher-strength concrete	Concrete with a 28-day cylinder compressive strength greater than 42 MPa. Reduces concrete's diffusion coefficient.	Design Phase	[12, 114, 80]
Corrosion	Increase of design cover thickness	Increasing the distance between the outer surface of the concrete and the embedded steel reinforcement. Prevents corrosion.	Design Phase	[15, 12, 114]

Continued on next page

Table 4 – *Continued from previous page*

Climate change hazard	Adaptation Measure	Description	Application phase	Reference
Corrosion	Corrosion-resistant reinforcement (low carbon, stainless/galvanized steel, glass-fiber-reinforced polymer rebars)	Reinforcing steel coated with a protective layer of zinc metal. Prevents corrosion.	Design Phase	[15, 12, 114, 5]
Corrosion	Alkali-activated (AA) cement	AA cement includes one or more alumino-silicate sources, one or more alkali activators, water, fine, and coarse aggregates. Increases corrosion resilience by reducing the penetration of harmful substances.	Design Phase	[80, 81]
Corrosion	Chloride extraction	Reduction/removal of chloride ions from concrete that has been exposed to chloride-rich environments.	Service Phase	[15, 5]
Corrosion	Patch repair	Physical removal of damaged concrete and replacement with new concrete. Repairs small affected areas of concrete.	Service Phase	[15]
Corrosion	Re-alkalization	Restores concrete's alkalinity by increasing its pH, which has been lost due to carbonation or other aggressive substances.	Service Phase	[15, 114]

Table 4: Adaptation Measures for Various Climate Change Hazards

Chapter 3: Conclusions

This chapter presents the findings of this research and draws conclusions. Section 3.1 provides answers to the main research question and sub-questions posed at the beginning of this thesis, emphasizing the key insights. Section 3.2 addresses the limitations of this research and finally, Section 3.3 offers a reflective analysis linking the study's findings to the field of construction management.

3.1 Responding to Research Questions

At the beginning of this thesis, four sub-questions were composed to progressively address the main research question of this research, which is how Eurocodes can develop to incorporate climate change adaptation in RC bridges. A response to both the main research question of this thesis and its sub-questions is given below.

1. *What are the impacts of climate change on RC bridges at the material and structural level? (Section 2)*

The answer to this sub-question is given in Figure 1. Reviewing the relevant literature as presented in Table 3 (in the Appendix), the impacts of climate change on RC bridges and their relationships were identified. The literature review reveals that not much research has been done on several material deterioration mechanisms such as photo- and bio-degradation. Moreover, no detailed mapping of the impacts and the connections between them exists. The compound effects of climate change and how multiple hazards can affect RC bridges have not been properly investigated.

Figure 1 presents an overview of the primary and secondary impacts of climate change and the mechanisms they may initiate, ultimately leading to the failure of RC bridges. As can be observed in Figure 1, the effects of climate change on RC bridges are multifaceted, both at structural and material levels. At the structural level, extreme weather events such as floods, increase the loads and stresses on the bridge which can lead to failure by fatigue, buckling, or oscillation. At the material level, variations in climatic parameters such as temperature and humidity, can initiate degradation mechanisms that might lead to concrete cracking. As a result, the load-carrying capacity of the bridge decreases, potentially leading to failure. In addition, floods and rising sea levels can create scour, which affects the foundation's stability.

Overall, the combination of these impacts creates changes in the load-carrying and structural capacity of RC bridges. These findings highlight the interconnected nature of climate change impacts, emphasizing the need for adaptation measures and strategies that can address multiple impacts simultaneously. Figure 1 emphasizes the necessity of adaptation measures that offer co-benefits to ensure the resilience of RC bridges in the face of climate change.

2. *How does the current generation of Eurocodes address the impacts of climate change on RC bridges? (Section 2)*

Many studies have revealed the inadequacy of Eurocode standards in addressing climate change and highlighted the need for an update. This research confirms these findings. Figure 2 and Table 1 illustrate the parameters that are mentioned in the current generation of Eurocodes, related to climate change. This examination of the Eurocodes concludes that the standards address climate change in a quite limited way. Limited guidance is provided for load adjustments due to extreme weather events, while no specifications exist for adaptation measures' implementation or for integrating resilience and sustainability in the structures. Moreover, there is no consideration of the co-benefits of adaptation measures or the compound effects of climate change. These are significant gaps because, in practice, RC bridges will probably have to face several effects of climate change at once. Therefore, there is an

urgent need to update the standards to incorporate climate change considerations. Action has been taken to address this gap, with the updated generation of Eurocodes expected after 2026.

3. *What are the co-benefits of climate change adaptation strategies in RC bridges, considering sustainability and resilience, throughout their life cycle? (Sections 3)*

Figures 3 and 4 answer Sub-question 3. The answer is twofold: Figure 3 shows the corresponding adaptation measures for the various climate change impacts and their co-benefits, meaning how the implementation of one measure can help with additional impacts beyond their primary focus. Figure 4 qualitatively assesses the performance of these adaptation measures on sustainability and resilience.

It is observed that most of the adaptation measures have a positive impact on the bridge's resilience. Regarding sustainability, its evaluation is more complex because of the absence of clear sustainability criteria and the need to consider additional factors, such as the cost-benefit ratio and the long-term performance of the measures, which are out of the scope of this thesis.

Natural, green solutions and innovative materials are considered in general sustainable due to their low environmental impact (e.g., soil bioengineering, vegetated riprap). Other measures can be characterized as sustainable depending on their choice of material, cost-effectiveness, and maintenance requirements (e.g., high-strength concrete, gabion mattresses). Lastly, measures initially considered non-sustainable might extend significantly the bridge's service life, reducing the need for frequent repairs and replacements (e.g., an increase in design cover thickness). The findings indicate that most adaptation measures improve the resilience of the bridge, while more research is required to assess their performance regarding sustainability throughout their life cycle.

4. *What barriers prevent the implementation of climate change adaptation measures in RC bridges? (Section 5)*

There are several barriers to adaptation measures' implementation. Knowledge gaps, technical difficulties, financial limitations, and legal constraints are some of the main obstacles. Table 2 provides an overview of all the identified barriers. The lack of comprehensive guidelines and consistent practices for incorporating new materials and technologies results in knowledge gaps. Moreover, the lack of consideration for multi-hazard scenarios and the various co-benefits of adaptation measures prevents the development of adaptable and flexible adaptation strategies. In addition, adjusting the design of adaptation measures according to the region or integrating it into an existing structure creates technical challenges. High initial costs and uncertain return on investment discourage investors from implementing adaptation measures. The situation is exacerbated by a lack of awareness regarding the co-benefits these measures can provide. Moreover, regulatory frameworks and standards, such as Eurocodes, usually do not encourage climate change adaptation.

5. *What actions are required to overcome these barriers to ensure sustainability and resilience throughout the life cycle of RC bridges? (Section 5)*

Several steps can be taken to overcome these barriers, as presented in Table 2. Filling in knowledge gaps and providing training programs (e.g., workshops, seminars) can guarantee that engineers and designers know how to utilize the most recent knowledge and methods. The introduction of guidelines that consider the compound effects of climate change and the co-benefits of adaptation measures can reduce both knowledge and technical difficulties. Economic barriers can be eliminated with financial incentives and subsidies. Moreover, thoroughly informing stakeholders about the co-benefits of adaptation measures and actively engaging them can eliminate their hesitation to invest. Including provisions for climate change adaptation to regulatory frameworks will encourage the measures' implementation. By taking these actions, climate change adaptation can be successfully integrated.

Main Research Question:

How can Eurocode standards incorporate climate change adaptation in RC bridges while maximizing co-benefits, ensuring resilience, and promoting sustainability?

Eurocode standards require an update to incorporate climate change adaptation in RC bridges while maximizing co-benefits, guaranteeing resilience, and promoting sustainability. This update should incorporate specific provisions for a variety of adaptation measures to address the complex effects of climate change, considering their co-benefits. High-strength and corrosion-resistant materials, environmentally friendly and natural solutions, and innovative technologies should all be part of the recommended measures. Eurocodes need to include procedures for routine maintenance and long-term performance monitoring, along with comprehensive advice on load modifications for extreme weather events. Economic barriers should be eliminated through financial incentives and funding mechanisms, and knowledge gaps should be filled through research, education and training initiatives. By applying a holistic approach that considers sustainability, resilience, and economic viability, the updated Eurocode standards can be better prepared to help RC bridges withstand the challenges posed by climate change.

3.2 Limitations

Although this research offers insightful information about how RC bridges can adapt to climate change, it is important to acknowledge several limitations. First, the inherent uncertainty that characterizes climate change causes difficulties in the decision-making of climate change adaptation. Climatic conditions are expected to follow different trends across Europe, depending on each region. In addition, because climate change scenarios involve high uncertainty, an adaptation strategy based on a high-probability scenario may not work as planned if a different scenario materializes, potentially resulting in a waste of resources. This makes it difficult to prioritize climate change impacts and adaptation measures. In this context, considering co-benefits and having measures that address multiple hazards becomes especially valuable.

Not considering the cost-benefit ratio is another important limitation. Depending on the scope of the project, the materials utilized, and geographical considerations, adaptation measures can come at a wide range of costs. Therefore, without covering a specific case study and conducting a cost-benefit analysis, it is not possible to draw concrete conclusions regarding their sustainability. Furthermore, because sustainability is a broad and complex concept, it is essential to establish clear sustainability criteria to evaluate adaptation measures.

The lack of real-world data for adaptation measures implementation makes it also hard to evaluate them because there is limited information on their long-term performance. Finally, there was no consideration of the social and political barriers that may have a negative effect on the enforcement of laws and the ability of governments to promote climate change adaptation.

3.3 Reflection

This reflection aims to highlight the relevance of the research to the larger ecosystem of construction management and the practical implications of incorporating climate change adaptation measures and their co-benefits into construction management practices.

This study offers construction managers the insights and knowledge they need to improve the resilience and sustainability of RC bridges by mapping the effects of climate change and the co-benefits of adaptation measures. There is a direct link to asset management, specifically to RC bridge maintenance. The study emphasizes that routine maintenance and long-term performance monitoring are critical elements of adapting to climate change, ensuring that infrastructure assets continue to be safe and functional throughout their service lives.

Furthermore, this research identifies the stakeholders of climate change adaptation and provides a stakeholder map (Figure 5). This map shows each stakeholder's interest and power. The European Union, governments, and regulatory authorities have the highest levels of interest and power in climate change adaptation. Academia and environmental NGOs also show significant interest but have less influence. Users and communities, while highly interested, have limited power. Designers and constructors have average levels of both interest and power.

The European Union, governments, and regulatory authorities have the most power to shape climate change policies and drive changes. Academia and environmental NGOs, while less powerful, can still influence adaptation through research and raising awareness. Users and local communities, despite having less power, can influence adaptation measures implementation through their acceptance. Designers and constructors put adaptation strategies into practice and therefore, are directly responsible for their effectiveness.

To successfully implement adaptation measures, construction managers should consider the interests, concerns, and influence of all stakeholders. Ensuring that all stakeholders are engaged and working toward the same goal, of building resilient and sustainable infrastructure, is made possible through effective stakeholder management.

In the face of climate change, construction managers need to consider a new set of variables and uncertainties. As a result, planning, designing, executing, and maintaining procedures are changing. Climate risk assessments should be included in strategic planning procedures, defining possible climate-related risks and assessing how they may affect infrastructure projects. Moreover, the selection of materials and design should consider resilience and sustainability. Managers need to cultivate an innovative culture within their teams by promoting the exploration of innovative technologies and approaches that enhance climate resilience.

Overall, climate change pushes construction managers to take a more progressive approach to project management. They should be able to develop resilient and sustainable infrastructure that satisfies the demands of a changing climate by combining climate risk assessments, sustainable design practices, proactive asset management, effective stakeholder management, thorough financial planning, regulatory compliance, and innovation.

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