# Adaptation strategies

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# Impact of climate change on the corrosion of the European reinforced concrete building stock

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# 8 Adaptation strategies

## 8.1 Adaptation measures of new buildings

In addressing the impact of climate change on the corrosion of RC buildings, it is crucial to distinguish between two adaptation strategies. The first refers to measures integrated during the design phase for new structures. The second involves strategies implemented during the service phase to enhance the resilience of existing structures. This differentiation ensures that both new and existing buildings are equipped to withstand the challenges posed by a changing climate. This section focuses on the first while the strategies implemented during the service life of the existing buildings are discussed in the following section.

The process of RC corrosion encompasses two critical phenomena: the initiation of concrete cracking, induced by the by-products of corrosion, and the diminution of the steel's effective cross-sectional area, both manifesting during the propagation stage. The former typically affects aesthetics, while the latter bears implications for structural robustness. The dominant concern between these two phenomena depends on the functionality of the specific structural component. Moreover, the integrity of a structural component, when compromised by corrosion, depends on the applied loads and its inherent structural design. This makes its assessment highly case-specific, presenting challenges for broad generalizations. Hence, in formulating adaptation strategies in response to climate change, it is prudent to prioritize the initiation stage. This stage not only occupies a substantial segment of a structure's service lifespan but also offers the advantage of being less influenced by variables such as applied loads and structural design.

Concrete composition and cover depth play pivotal roles in determining the durability of concrete buildings (Eurocode 2[84]) Their interrelation is clear: denser concrete can reduce the need for a deeper cover and vice versa. When designing a structure, factors such as its typology, intended use, production oversight, and prevailing environmental conditions are integral to setting these parameters. Specifically, as climate evolves, environmental exposure will be factored into these conditions, thus necessitating the European standards (mainly EN 206 and the Eurocodes) to address these shifting challenges.

Increasing the prescribed cover depth emerges as a primary strategy to bolster the durability of new structures impacted by climate change. Augmenting this cover depth, alongside employing a higher-grade concrete and minimizing the water-cement ratio, can yield structures more resilient to corrosion. Adapting the building stock with these measures has stirred considerable debate in the scientific community. Stewart et al. (2012) projected that such measures—including increasing the design cover by up to 8 mm or elevating the concrete compressive strength by a grade—would hike construction costs by 1-3%. Yet, the economic implications at a global scale are intricate. Studies by Bastidas-Arteaga & Stewart (2016) and Stewart & Bastidas-Arteaga (2016) dived deeper, probing the cost-benefit terrain of amplifying the cover thickness to 5 or 10 mm across an array of structural elements and climate scenarios. Their findings suggest that such interventions may not consistently offer a favourable economic return.

Furthermore, the push for a sustainable future in the European policies advocates for blended and alkali-activated (AA) cements over traditional Portland cement (PC). AA cements, particularly AA slag cement which integrates slag as a partial PC substitute, present dual advantages: a denser matrix reducing harmful substance permeability and reduced greenhouse gas emissions (Provis and van Deventer, 2014; Alelweet and Pavia, 2019). While slag cement's use in the USA spans over a century, its complete efficacy as a primary PC alternative remains under investigation. Lastly, when contemplating corrosion-resistant reinforcements, the market offers low carbon, stainless or galvanized steel, and even glass-fiber-reinforced polymer rebars. Yet, transitioning to these alternatives demands a rigorous cost-benefit scrutiny.

## 8.2 Adaptation measures of existing buildings

Adaptation strategies during a structure's service life diverge into two primary categories: reparative actions for damaged RC and protection measures against corrosion. On the reparative side, the initial task is discerning the extent of damage. Based on this, two possible approaches exist: (i) patch repair for located or small affected areas with easy access, and (ii) electromechanical methods, otherwise. Patch repair implies the physical removal of the compromised concrete, including areas behind reinforcement bars, replacing the removed concrete with

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[84] EN, EN 1992 Eurocode 2: Design of concrete structures, CEN, Brussels, 2005

new one. Insufficient removal can precipitate rapid corrosion post-repair. For structures where concrete removal is structurally unfeasible, electrochemical re-alkalization emerges as a greener alternative, demanding fewer interventions than patch repairs or coatings.

Once the structure is repaired, protective measures can be applied. Protective measures ae also recommended for improving the corrosion resistance of new structures. Protective measures encompass the utilization of corrosion inhibitors and concrete coatings. Corrosion inhibitors are chemical substances that, when added to the concrete surface, permeate the concrete, reducing the corrosion rate without significantly altering the concentration of other corrosion agents. They typically maintain their effectiveness for 10-15 years. However, their efficacy hinges on the uniformity of the product's penetration depth, which can be challenging to ascertain. Furthermore, conventional corrosion inhibitors, such as chromates and nitrites, possess toxic properties. Hence, alternative products like agro-waste/natural substances (e.g., heena or bamboo) are under investigation as non-toxic alternatives with minimal adverse environmental impacts.

Concrete coatings, also known as sealers, create a protective barrier on the concrete surface, reducing its permeability to aggressive substances and moisture. These coatings come in three main types: (i) Organic coatings: These are polymeric films based on epoxy, polyurethane, or chlorinated rubber polymers. (ii) Hydrophobic impregnation: This method establishes a water-repellent layer using substances like silanes, siloxanes, and silicate-based compounds. (iii) Cementitious coatings: These coatings, composed of cement, are applied through brushing or in the form of overlays via plastering or spraying. According to Stewart et al. (2012), acrylic-based surface coatings can reduce carbonation depths by 10-65%. While their application is straightforward and cost-effective, they provide a temporary solution as they typically endure for less than 15 years. Additionally, they may impact the future inspection of structures.

There are other techniques aimed at repairing and protecting ion-induced corroded structures, including electrochemical chloride extraction and cathodic protection. Although these methods can also be beneficial in cases where carbonation-induction is detected, due to the combined presence of both types of corrosion, they are not elaborated upon here. For a comprehensive review of these techniques, the reader is directed to Goyal et al (2018).

## 8.3 A resilience-based adaptation strategy

The influence of the condition of the built environment on the Member States' economy is profound, necessitating a meticulous approach to incorporating recommendations and regulations to adapt European building stock to climate-induced corrosion. When considering adaptation measures for climate change, several challenges emerge: (a) the evolution of climate change is still uncertain, highly influenced by the global socio-political landscape; (b) while design-phase measures can effectively prolong the lifespan of structures against climate change-induced corrosion, their cost-effectiveness is not guaranteed; and (c) interventions during the service life generally incur greater costs than those implemented in the design phase. As such, a thorough cost-benefit evaluation of these adaptation strategies is essential. Also, it is important to note that many European structural durability codes, guidelines, and specifications largely overlook maintenance's role in ensuring durability throughout a structure's operational life. While some standards assume that "adequate maintenance" is essential for durability (e.g., EN 1990 (2002)[85], JCSS 2006[86], DM 14/01/2008[87]), others offer specific maintenance recommendations [CEB-183[88], fib17[89]]. Although inspection and monitoring are infrequently addressed, as seen in fib86[90], some standards underscore their importance for ensuring durability, as cited in [JCSS 2006, CEB-183]. Given this landscape, there is a pressing need for the European Standards to incorporate distinct maintenance guidelines tailored to the challenges posed by climate change (Nogal et al, 2021).

Cost-benefit analyses are inherently complex, built on numerous assumptions. In the corrosion case, they assesses whether the financial investments made in corrosion mitigation and repair measures yield greater benefits, such as increased structural lifespan and reduced maintenance costs, compared to the initial and ongoing expenses associated with those measures. The analysis of the cost-effectiveness of several adaptation

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[85] EN 1990 (2002): Eurocode - Basis of structural design. The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC.

[86] Probabilistic Model Code, JCSS. Joint Committee on Structural Safety (2006).

[87] DM 14/01/2008: Norme Tecniche per le Costruzioni (Italian Code) Ministero Delle Infrastrutture, Decreto 14 gennaio 2008 (G.U. 4 febbraio 2008 n. 29 - S. O. n. 30).

[88] CEB Bulletin n.183: Durable Concrete Structures—CEB Design Guide (1992); ISBN 978-0-7277-1620-0; 120 pages

[89] fib Bulletin n.17: Management, Maintenance and Strengthening of Concrete Structures (Technical Report, April 2002).

[90] fib Bulletin n.86: Safety and performance concepts: Reliability assessment of concrete structures—Guide to good practice, August 2018.

strategies for various structural members under diverse climate scenarios conclude that the merit of such measures is influenced by climatic conditions, structural design, size, and discount rate (Bastidas-Arteaga & Stewart, 2016; Stewart & Bastidas-Arteaga, 2016). Selecting strategies based solely on cost-effectiveness for a particular climate scenario poses risks; underestimating climate change impact might lead to unexpected maintenance costs, while overestimating could waste resources during design.

Over the past few years, there has been a marked transition from methodologies anchored in traditional risk assessment towards those emphasizing resilience. The pressing need for such a resilience-driven perspective arises particularly in scenarios where potential hazards are either poorly understood or the associated uncertainties cause a substantial underestimation of true risks. This is very often the case of climate change, prompting policymakers to adopt resilience-enhancing strategies (Val et al., 2019). Risk- and resilience-oriented strategies are not mutually exclusive. In fact, by weaving in a temporal component, resilience approaches enrich the foundational risk methodologies. These strategies not only improve the system's preparedness but also facilitate its adaptive evolution over time.

To address the adaptation of RC building stock to climate change, Nogal (2020) advocates for adopting a resilience-centric framework that involves a dual approach: (i) design-phase adaptation measures aligned with a set confidence level in climate change projections, and (ii) preventive maintenance strategy at the design stage that will be adjusted with evolving climate change data. It is noted that both phases are considered at the design stage. During the first phase, proactive and cost-effective adaptation measures should be implemented to address the impact of climate change associated with lower levels of uncertainty. The utilization of innovative, eco-friendly concrete mixtures could be pivotal in this stage. Conversely, for the more unpredictable ramifications of climate change, adaptation actions should be strategized, predominantly encompassing maintenance. Pertinently, the European standards should advocate for climate-specific maintenance guidelines for RC buildings. During the design phase, it is imperative to define maintenance strategies that specify the regularity of maintenance tasks. At the same time, the design project should enumerate possible measures in anticipation of future climatic projections, coupled with their economic implications. To ensure the project's economic feasibility, provisions should be made for a financial framework addressing potential adaptation costs. It is noted that certain prescribed maintenance interventions might not always be as economically efficient as the preventive measures integrated during the initial design phase. Hence, a thorough economic analysis must be conducted balancing the total cost throughout the structure's lifespan accounting with the uncertainty of the future climate.