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Prescription of Maintenance Interventions by the New Generation of Eurocodes for Climate-Change Resilient Structures

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Abstract. *The new generation of structural Eurocodes will include climate change adaptation measures in order to enhance the climate resilience of infrastructures across Europe. This paper discusses the impact that climate change might have on reinforced concrete structures subjected to corrosion, and the associated challenges of the standardisation of adaptation measures. A resilience-based framework is proposed for the adaptation of structural codes to climate change-induced actions. Such an approach aims to provide the required adaptive capacity to the new structures in order to be able to respond to the uncertain future minimising the investment under unlikely scenarios. In that way, the strategy can be summarised as a climate change-adapted design plus an in-design maintenance plan. Future actions, such as mapping the future climate-related drivers of corrosion, the determination of the design values of these drivers, and the prescription of maintenance activities, should be further investigated. Although this paper focuses on the new structures that will be designed with the new codes, some of the insights can be extrapolated to the existing structures.*

Keywords: *Corrosion, Climate change, Resilience, Maintenance, Eurocodes.*

1 Introduction

The pressure imposed by climate change has reached all sectors within the European Commission, which is now forced to take adaptation measures. In Union Innovation (2013), they acknowledged action gaps in a context where late responses could result in non-affordable economic, social, and environmental costs. Consequently, they proposed a road-map to include climate change adaptation considerations where technical standards were identified as an effective strategy to enhance the climate resilience of infrastructures across Europe.

In the construction sector, the first generation of EN Eurocodes was launched in 2007 with the aim to homogenise structural design within the Member States. The second generation of Eurocodes is planned by 2023, which will reflect the new market needs (e.g., new materials and construction techniques) and also the European commitment with the sustainable development goals. Therefore, the second generation of Eurocodes is planned to incorporate the adaptation of structural design to climate change.

Within the long list of impacts upon structures caused by climate change, corrosion has been identified as a priority theme, as it has been estimated that the increased maintenance and repair costs worldwide resulting from the acceleration of the corrosion process due to climate change might be of hundreds of billions of dollars annually (Bastidas-Arteaga & Stewart (2015)).

In this context, this paper discusses the adaptation strategy to be applied to the new generation of Eurocodes in relation to the corrosion of reinforced concrete (RC) structures. At present, the structural corrosion is addressed in EC2 (2005).

It is noted that the impact of climate change on man-made systems has a large component of uncertainty, given that the future climatic scenarios mainly depend on the evolution of the global sociopolitical context. Therefore, including climate change adaptation measures in the design phase of buildings and infrastructure is challenging because underestimating its impact would result in significant societal consequences, whereas overestimating it would imply an unnecessary waste of resources. A resilience-based approach is proposed to address the issue, where the adaptation measures included in the design phase should tackle part of the impact of climate change, and during the service phase, upgrading mechanisms should be implemented to guarantee the system is prepared for the non-accounted impact of climate change if the evolution of climate change requires it.

Therefore, this work aims to provide an overview of the problem of corrosion induced by climate change to better understand the need for a resilience-based approach to address the standardisation process. The general framework proposed for the adaptation to climate change by the new generation of structural Eurocodes is outlined and the associated challenges are further discussed.

The remaining document is organized as follows; Section 2 provides an overview of the impact of climate change in Europe on the main drivers of the structural corrosion, Section 3 presents the corrosion problem in the context of climate change. In Section 4, the need for a resilient-based approach is discussed in the context of the standardising process. Finally, in Section 5 some conclusions and future research lines are drawn.

2 Climate Change in Europe

The durability of RC structures is threatened by the increment of carbon dioxide (CO₂) concentration levels and climate change entailing variations in temperature and atmospheric humidity. These three parameters are the principal environmental drivers of corrosion.

To study the expected variations of air temperature and relative humidity (RH), the Representative Concentration Pathways (RCPs) proposed by IPCC (2014) are used. They are the so-called RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios, with RCP2.6 being closer to the scenario aimed by the Paris Agreement and RCP8.5 relating to the business-as-usual scenario. There exists a consensus amongst climatologists that RCP2.6 is naively optimistic, thus in practicality, the RCP4.5 is very often proposed as the potential optimistic scenario.

The definition of each scenario allows climatologists to determine the general atmosphere patterns and oceanic circulation dynamics at the global scale. Then, through complex processes of downscaling, climate changes at a regional level can be estimated with a significant level of confidence for each scenario providing a horizontal resolution of up to 0.11° (about 12 km).

In Europe, it is clear that climate change will increase air temperature. The extent of the variation will depend on the geographical location, period of the year, and scenario considered; for instance, North Europe, which is the most affected area when analysing air temperature,

Table 1: Variation of air temperature due to climate change in Europe. The level of agreement among climatic models is given in brackets: L-low, M-medium, H-high, V-very high.

Area	Winter (DJF)	Summer (JJA)	Autumn (SON)	Spring (MAM)
RPC4.5				
North Europe	2°-8° (M)	0°-6° (H)	2°-6° (H)	2°-6° (M)
Central Europe	0°-4° (H)	0°-4° (H)	0°-4° (M)	0°-2° (V)
Mediterranean area	0°-4° (H)	2°-4° (H)	0°-4° (H)	0°-4° (H)
East Europe	2°-6° (H)	0°-4° (M)	0°-4° (H)	0°-4° (H)
RPC8.5				
North Europe	4°-10° (M)	2°-6° (H)	2°-6° (H)	2°-8° (H)
Central Europe	2°-4° (V)	2°-4° (V)	2°-6° (H)	2°-4° (H)
Mediterranean area	2°-4° (V)	2°-6° (M)	2°-6° (H)	2°-4° (V)
East Europe	2°-6° (M)	2°-6° (H)	2°-6° (H)	2°-6° (H)

presents increments ranging between 4°-10° during the winter months (December to February) under the RCP8.5, whereas the RCP4.5 provides increments of 2°-8° during winter. The range of values is given by the use of different climatic models. Table 1 summarises the variation of air temperature due to climate change in Europe.

The impact of climate change on the RH is smaller. Regardless of the climatic scenario considered, only during the summer months (JJA), Europe might experiment reductions of up to 10% of the RH.

It is noted that an important source of the uncertainty of the climate estimations is linked to the uncertainty regarding the trajectory of greenhouse gas emissions (i.e., the RPC considered), which depends on factors such as the economic and societal trends. In the present context, this type of uncertainty cannot be reduced. Nevertheless, considering one or another scenario might differ in billion of euros in the long term. This should be kept in mind when updating the structural codes.

3 Impact of Climate Change-Induced Corrosion

3.1 Corrosion Mechanisms

RC corrosion refers to the phenomenon of the corrosion of the steel reinforcement of concrete caused by the infiltration into the concrete members of carbon dioxide, which reduces concrete pH till values below the steel passivation threshold, and chloride, which reduces concrete alkalinity. Both processes are affected by temperature and RH.

When studying the RC corrosion, the stage characterised by the ingress process of the CO₂ and chloride ion into concrete is known as the initiation stage. In this stage, it is of interest to determine the chloride concentration at the rebar level and also when the carbonation reaches this level, that is, the carbonation depth.

Several studies have analysed the impact of climate change in the carbonation ingress process when assuming different CO₂ levels, RH, and temperature conditions. As shown in Table 2, the estimated increments of the carbonation depths are up to 45% by 2100 under the RCP8.5

Table 2: Effect of climate change on the carbonation and chlorine ion ingress processes in RC structures.

Ref.	Location	Assumptions	Estimation		Scenarios	
			Target	Value	Baseline	Target
CARBONATION INGRESS PROCESS						
Talukdar et al. (2012)	Canada	(a) increasing mean yearly temperature, (b) increasing duration of the hot season, (c) constant RH over time, and (d) increasing concentration of CO ₂	carbonation depths of non-pozzolanic, unloaded concrete structures	increment of 45%	year 2000	A1FI, year 2100
Talukdar & Banthia (2013)	Mumbai, London, New York City, Sydney, Toronto, Vancouver	(a) time dependent temperature	carbonation depths	increments between 27% and 45% (15 and 35 mm)	year 2000	A1FI, year 2100
Saha & Eckelman (2014)	Boston metropolitan area	(a) increasing temperatures, (b) increasing concentrations of CO ₂	carbonation depths	increment of 40%	year 2000	A1FI, year 2100
Peng & Stewart (2014)	China	(a) CO ₂ concentration, (b) local temperature, and (c) RH variable over time	carbonation depths	increment of 45%	year 2010	RCP8.5, year 2100
Mizzi et al. (2018)	Malta	(a) increasing CO ₂ concentration, and (b) increasing temperatures	carbonation depths for different concrete grades	increment up to 40%	RCP 2.6	RCP 8.5, year 2070
CHLORINE ION INGRESS PROCESS						
Saha & Eckelman (2014)	Boston metropolitan area	(a) increasing temperatures, (b) increasing concentrations of CO ₂	chloride penetration depths	increment of 12%	year 2000	A1FI, year 2100
Xie et al. (2018)	China	(a) increasing temperatures	chloride concentration at the rebar level of offshore RC bridges	increments of 6%-15%	year 2000	RCP8.5, year 2100
Khatami & Shafei (2017)	U.S. Midwest region	(a) increasing temperatures, (b) decreasing, constant and increasing RH, and (c) increasing surface chloride concentration	chloride concentration at the rebar level	increment of 37%	RCP2.6, year 2100	RCP8.5, year 2100

scenario (or the equivalent A1F1 scenario given by the SRES, Nakicenovic et al. (2000)) when comparing with the year 2000. It is noted that the results are very sensitive to local exposure conditions (Talukdar & Banthia (2013)).

In the case of the impact of climate change to the chlorine ion ingress process, the studies report more modest values, though still relevant, for the increment of chloride concentration at the rebar level when comparing the 2000-year values to the RCP8.5 by the end of century, reaching values around 15% (see Table 2). Khatami & Shafei (2017) report larger values, as they introduce in their model an increment of use of de-icing salts as a consequence of the observed consumption in the USA, which increased 200% in the last 25 years.

The second stage of the corrosion is known as propagation stage, which occurs once that the corrosion of the reinforcing steel is initiated, and finishes with the loss of steel area, cover cracking and spalling, and loss of the bond between steel and concrete. Whereas the initiation stage dominates the service life of the structure, the propagation stage lasts only a few years. For instance, Xie et al. (2018) report that the corrosion propagation stage of the offshore RC structures in China designed according to MOHURD (2008) would last less than one year considering future climatic conditions.

3.2 Impact on Reliability and Service Life

As a consequence of climate change, both the reliability and service life of RC structures are highly impacted. The extent of this impact depends on the geographical location, the structural codes used for design, and the climatic scenario considered. Table 3 summarises some of the findings regarding the impact of climate change on the reliability and service life of RC structures by the end of this century if the most pessimistic scenario, i.e., the business-as-usual scenario, is considered. Even when the compound effect of the carbonation- and chlorination-induced corrosion has not been studied yet, the enormous impact that climate change has on structural durability cannot be ignored.

Table 3: Impact of climate change on reliability and service life of RC structures.

Ref.	Location	Assumptions	Estimation		Scenarios	
			Carbonation-induced	Chloride-induced	Baseline	Target
M. G. Stewart et al. (2011)	Australia	(a) Increased CO ₂ levels, temperature and humidity, (b) different exposure classifications of the Australian code AS3600 (2009)	Increment of damage risk over 400% for inland arid or temperate climates	Increment of damage risk up to 15%	year 2000	A1B & A1FI, year 2100
Saha & Eckelman (2014)	Boston metropolitan area	(a) Structural design according to ACI (2011)	Reduction of service life of 26 years. Penetration depths in 60% of existing buildings exceeding the recommended cover thickness by 2050.	Reduction of service life of 10 years	year 2000	A1FI, year 2100
Pakkala et al. (2019)	Finland	(a) Changes in ambient T, RH and wind-driven rain, (b) different locations with respect to the solar radiation	Increment of corrosion rates of up to 200% during winter in coastal areas facing to the South		year 2000	A2, year 2100
Bastidas-Arteaga & Stewart (2015)	Continental, oceanic and tropical environments	(a) Increasing temperatures and length of hot periods, and (b) increasing RH	Lifetime reductions ranging up to 18%		year 2000	year 2100

4 Structural Codes

4.1 Adaptation Measures

The limit state of RC corrosion should include two phenomena, the cracking of concrete due to the sub-products generated by the corrosion and the reduction of effective steel cross-section, both occurring during the propagation stage. While the first is more related to aesthetic issues and the latter is linked to the structural integrity, the functionality of the structural member will determine which of the two phenomena is more critical. Given that the integrity of a structural member affected by corrosion will depend on the applied loads and structural configuration, its study becomes very case-specific and difficult to be generalised. Thus, when defining standardised strategies to adapt to climate change, it is better to focus on the initiation stage, which implies a larger portion of the structural service life and is less dependent on the applied loads and structural configuration.

Structural codes worldwide share a similar rationale when addressing the problem of corrosion; they focus on structural durability. Figure 1 generalises this approach. There exist two decision variables in regard to the structural design affecting the RC corrosion, that is, materials

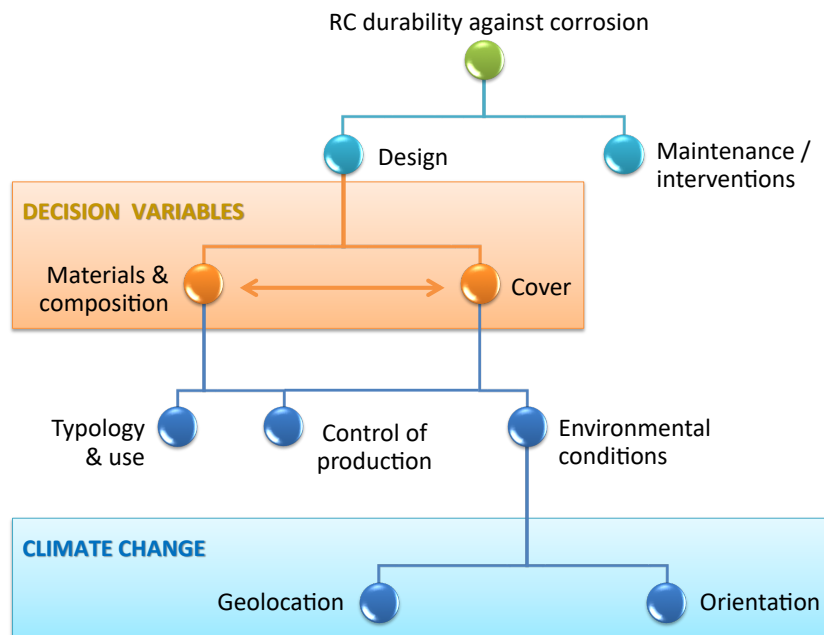


Figure 1: Rationale of structural codes to guarantee the structural durability against RC corrosion.

and composition and cover depth. Both of them are related, as the selection of a more dense concrete allows for a reduction of the cover depth. To determine these values, aspects such as typology and use, the control of production and the environmental conditions must be considered. Initially, the new environmental conditions given by climate change should be reflected here.

Regarding the materials and composition, two possible solutions can be taken, either improving steel corrosion resistance, e.g., through low carbon, stainless or galvanised steel reinforcement and glass-fiber reinforced polymer rebars, or improving concrete durability by increasing the concrete grade, the water-cement ratio or applying concrete coatings. In addition, other concrete mixes, such as blended and alkali-activated (AA) cement, can be used that present higher density matrices than the standard and commonly used Portland cement (PC). The structure of their matrices reduces the permeability of the harmful substances. In addition, the AA slag cement, where the slag substitutes part of the PC, presents higher resistance to corrosion and its production generates lower greenhouse gas emissions than PC. Despite the slag cement has been used in the USA for more than 100 years, the feasibility of replacing PC blinders should be further investigated.

Nevertheless, it is estimated that the measures required to adapt to climate change, such as increasing design cover by up to 8 mm or increasing concrete compressive strength by one grade would imply an increment of 1-3% of the construction costs (M. Stewart et al. (2012)). Other authors (Bastidas-Arteaga & Stewart (2016); M. Stewart & Bastidas-Arteaga (2019)) have addressed the cost-benefit analysis of increasing the cover thickness to 5 or 10 mm in

different structural components under different climate scenarios. They conclude that in many cases, this measure is not cost-effective. The factors affecting the efficiency of this type of adaptation measures do not depend only on the structural typology and member size, but also on the climatic conditions and the future discount rate.

Keeping in mind the impact that Eurocodes has in the economy of the State Members, standardising adaptation measures in a context of high uncertainty, where if the impact of climate change is underestimated by considering very optimistic scenarios, it would result in a significant reduction of the service life of new infrastructure and buildings, or if it is overestimated, in unnecessarily expensive investment. Apparently, there is not a fair solution.

4.2 Resilience-Based Approach

In the last years, there has been a clear shift from the traditional risk-oriented approaches to a perspective based on resilience. The need for a resilience-based approach has been made evident in those cases where either, the lack of knowledge about the potential hazards or their level of uncertainty was so large that the existing risk was underestimated. For that reason, the problem of climate change along with its associated uncertainty is pushing decision-makers to implement measures that boost resilience (Nogal & O'Connor (2018a); Val et al. (2019)). In this point it is important to note that risk- and resilience-based approaches are not incompatible; on the contrary, the latter complements the first one by adding a temporal dimension to the problem (Nogal & O'Connor (2018b)) and proposing a number of strategies to increase the preparedness level of the system and so allow for an adaptive response over time.

Therefore, to approach the issue of climate-change induced corrosion from a resilience-based view, the adaptation measures should be twofold. On the one hand, the measures addressing the impact of climate change that is certain should be implemented in the design stage, through cost-effective measures. More sustainable concrete mixtures might play an important role in this stage. On the other hand, the uncertain impact of climate change should be covered in a post-design stage, that is, through maintenance. In that regard, Eurocodes should prescribe specific maintenance in relation to climate change. It is clear that there is room for improvement in terms of maintenance in the present standards, as they merely define maintenance, mentioning that the structure will be adequately maintained.

Such an approach implies a number of challenges. The values of CO₂ concentration levels, temperature and atmospheric humidity associated with low values of uncertainty should be determined based on the climate models for the end of the structural design life. Let's call them certain thresholds (CTs) of the corrosion drivers.

The maintenance strategies, which should be studied during the design phase, should state the frequency of the maintenance activities in which the updated information regarding climate change will be used to determine the short- and medium-term actions. Also at the design phase, a number of potential actions should be included considering the future climatic scenarios along with their economic cost. Finally, an economic program to face the potential structural upgrades should be included to guarantee the economic viability of the project. It is noted that some of the required maintenance interventions are usually less cost-effective than the measures adopted

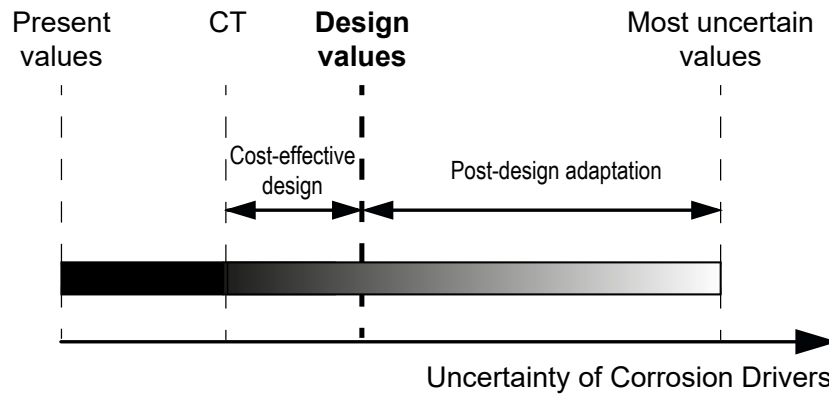


Figure 2: Representation of the design value of the corrosion drivers based on the cost-effectiveness of the adaptation measures and the uncertainty regarding the future value of the corrosion driver.

in the initial design. Therefore, the most cost-effective design should not cover only the CTs of the corrosion drivers, but more uncertain values in order to minimise the life cycle cost (see Figure 2). In other words, the new generation of Eurocodes should provide a design value of the corrosion drivers that will be established based on both, the uncertainty regarding the future value of the corrosion driver and the cost-effectiveness of the adaptation measures.

5 Conclusions

Beyond the geographical differences across countries, the main challenge of standardising “low-cost and no-regret adaptation measures” (Union Innovation (2013)) in the context of structural codes is posed by the uncertainty related to climate change, which mainly depends on the trajectory of greenhouse-gas emissions. For this reason, a resilience-based strategy for coping with climate change-induced corrosion has been suggested in this paper. Such an approach aims to provide the required adaptive capacity to the new structures in order to be able to respond to the uncertain future minimising the investment under unlikely scenarios. In that way, the strategy can be summarised as a climate change-adapted design plus an in-design maintenance plan. It is highlighted the need for an improvement of the structural Eurocodes in the area of maintenance.

Although the impact of climate change on temperature and atmospheric humidity is of interest in the context of RC corrosion, the CO₂ levels should be also considered. The maintenance activities, which will be defined according to the on-going weather-related variables and CO₂ emissions will further motivate countries to reduce their CO₂ emissions in order to minimise their medium and long-term investments. Note that whereas climate change is a global issue, CO₂ concentrations have an important local component, and thus, the proposed strategy will penalize more heavily those areas producing a larger amount of CO₂.

This paper has shown a general framework for the adaptation of structural codes to climate change-induced actions under a resilience-based approach. Specific actions, such as mapping the future climate-related drivers of corrosion, the determination of the design values of these drivers, and the prescription of maintenance activities, should be further investigated.

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