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Investigating the effects of climate change on material properties and structural performance

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Abstract

One major issue when considering the effects of climate change is to understand, qualify and quantify how the changing climate will likely impact infrastructure assets and services as it strongly depends on current and future climate variability, location, asset design life, function and condition. Expected changes to local climatic conditions may potentially lead to changes in the degradation processes of building materials, affecting the durability and service life of structures. A key question is how climate change may produce changes of vulnerability owing to physical and chemical actions affecting structural durability or changes of exposure in terms of the intensity/frequency of extreme weather events. In this context, this article focuses on the impact on structural resistance and associated challenges, considering some recent activities of members of the IABSE TG6.1. Several case studies of infrastructure assets worldwide are presented and discussed in this article.

Keywords: Climate change, impacts, vulnerability, durability, structural resistance

Introduction

The ageing and deterioration of civil engineering structures is likely to be exacerbated in the coming decades by the adverse effects of climate change (IPCC 2014). On the resistance side, one may observe a change in kinematics of the materials degradation mechanisms being influenced by the surrounding environmental conditions (Nasr et al. 2020). As climate change may accelerate or decelerate processes depending on specific exposure and environmental conditions, there is a need to advance the understanding of how climate change may impact structural resistance and thereby structural reliability, and to gain better insights into the vulnerability to both slow and rapid phenomena (Bastidas-Arteaga and Stewart 2019). At the European level, some work on standards integrating climate change formally started with the set-up of the Adaptation to Climate Change Coordination Group (ACC-CG) in early 2015 which focuses on buildings, infrastructures in the energy sector and infrastructures in the transport sector. The main expected contributions of this Group include revision or development of standards for infrastructures in the above sectors, linking infrastructure standards to future climatic conditions and scaling adaptation measures to the European level. Additionally, a new American

Concrete Institute (ACI) committee was formed to assess the potential effects of a changing climate on sustainability of concrete structures.

In this context, the IABSE TG6.1 was established in 2017 to gather an international expert panel to study the effects of climate change on buildings and civil engineering structures with the aim of promoting technical discussions and gathering existing global knowledge. The strategy is to focus on a number of relevant case studies and to highlight common points between them when dealing with climate change (e.g. the scale of the analysis, the types of structure, the methodology and objectives) (Orcesi et al. 2021). The goal of TG6.1 is to characterize not only the severity of impacts but also to give recommendations concerning adaptation strategies for management of structures in view of climate changes (Orcesi & O'Connor 2021).

Some of the aspects covered in this task group are presented herein to provide insights on how climate change may produce changes to structural performance owing to physical and chemical actions on different types of building materials and how such changes are path dependent and place specific. Several parameters are considered such as changes in temperature, relative humidity, precipitation, wind patterns and potential increase in pollutant concentrations, when investigating impacts on the structural service life. In particular, the changes of these parameters are based on the Representative Concentration Pathways (RCPs) used in the synthesis Report (SYR) of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), which include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and one scenario with very high Green House Gas (GHG) emissions (RCP8.5) (IPCC 2014). It is noted that the latest IPCC AR6 refers to Shared Socioeconomic Pathways (SSPs) representing scenarios of projected socioeconomic global changes to 2100. Hence, SSP1-2.6 corresponds to RCP2.6, SSP2-4.5 corresponds to RCP4.5 and SSP5-8.5 corresponds to RCP8.5.

This article starts by focusing on chloride and carbonation ingress, then considers corrosion propagation in Reinforced Concrete (RC) structures. This is followed by investigating the effects of climate change on the corrosion of steel structures, both in atmospheric and marine environments. A section presenting a broad review of research work dedicated to timber decay is then introduced as timber is susceptible to changes in climatic conditions as well as to biodegradation. Finally, an holistic analysis framework is introduced to consider simultaneously climate change impacts on deteriorating infrastructure resistance and intensifying hazards.

1. Chloride ingress, carbonation and corrosion propagation in reinforced concrete structures

1.1. Effects on deterioration processes

Chloride ingress and carbonation are two main deterioration processes that affect the durability of RC structures by inducing corrosion initiation. The kinematics of both mechanisms could depend on surrounding conditions such as the atmospheric CO₂ concentration, temperature, and humidity (Nguyen et al. 2017, Bastidas-Arteaga 2018). These environmental conditions could be affected by climate change. For example, some climate change scenarios suggest that the environmental CO₂ concentration could increase from 379 ppm in 2005 to about 1000 ppm by the year 2100 (IPCC 2007, 2013). On the other hand, new temperature and humidity variations expected for certain climate change scenarios could also impact the rates of chloride and CO₂ diffusion as well as corrosion initiation that could lead to greater corrosion damage. For the above-mentioned reasons, the effects of climate change should be considered for assessing the resistance of RC structures under new climate change conditions.

Assessing the effects of climate change on the kinematics of these deterioration processes requires using models able to account for environmental variations. For chloride ingress and carbonation, such models usually consider factors that increase or decrease the diffusion coefficients (chlorides, CO₂, and moisture) when environmental variations in temperature and relative humidity are expected. For example, the effect of a time-variant temperature ($T(t)$ in kelvins) on diffusion could be modeled based on the Arrhenius law for a reference temperature $T_{ref}=20^{\circ}\text{C}$:

$$f_T(t) = \exp(E/R [1/T_{ref} - 1/(T(t))]) \quad (1)$$

where E is the activation energy of the diffusion process and R is the gas constant (8.314×10^{-3} kJ/mol.K). The effects of temperature variations on f_T are illustrated in Figure 1. It is noted that for several values of E the CO₂ diffusivity will increase for higher temperatures because f_T multiplies the CO₂ diffusion coefficient in the chloride

ingress and carbonation models. Therefore, chloride ingress and carbonation rates will increase for higher temperatures. Specific expressions can be found in the literature for considering relative humidity (Bastidas-Arteaga, 2018; de Larrard et al 2014).

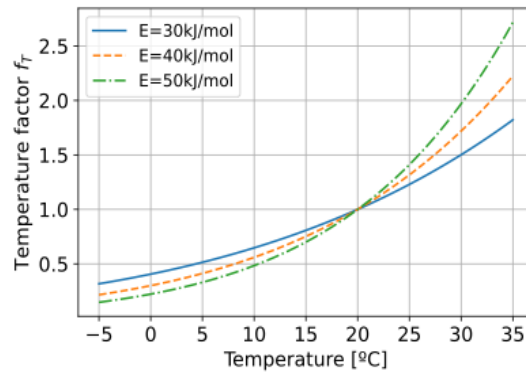


Fig. 1. Effect of temperature variations on the temperature factor.

Assessing the effects of climate change on the corrosion rate of steel bars is not an easy task because of the complexity of the corrosion process itself. After corrosion initiation, the corrosion rate will depend on steel and concrete properties as well as surrounding environmental conditions (temperature and the availability of water and oxygen), which could in turn be affected by the presence of cracks. Therefore, there is no consensus about the best model that could be used for lifetime assessment purposes. Among the available models, the one proposed in the framework of the Duracrete project (2000) suggested a bilinear formulation to account for the effects of temperature on the corrosion rate in microamperes per square centimetre:

$$i_{corr}(t) = i_{corr,20}(1 + K_c[T(t) - 20]) \quad (2)$$

where $i_{corr,20}$ is the corrosion rate at 20 °C, which depends on the exposure conditions, $T(t)$ is the temperature at time t (in degrees Celsius) and K_c is a factor that depends on the value of $T(t)$. For instance, $K_c = 0.025$ if $T(t) < 20^\circ\text{C}$ or $K_c = 0.073$ if $T(t) > 20^\circ\text{C}$.

The effects of temperature variations on the corrosion rate estimated by using Equation 2 are illustrated in Figure 2. It is observed that larger corrosion rates can be expected when temperature increases. Therefore, a greater reduction in the structural resistance could be expected where temperature increases as a result of climate change. Further research is still required to assess better the evolution of the corrosion rate when RC structures are subjected to realistic exposure conditions including the effects of climate change.

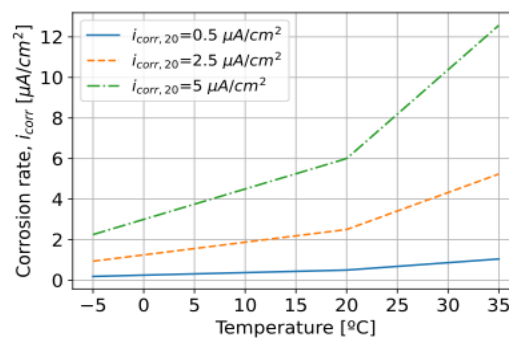


Fig. 2. Effect of temperature variations on the corrosion rate.

1.2. Concrete carbonation

Several studies have estimated the increase of the carbonation depth due to climate change in a number of countries. (Talukdar et al. 2012) found, for a pessimistic climate change scenario, potential increases in carbonation depth over 100 years of 45% in Toronto and Vancouver in Canada. Maximum increases ranging between 40% and 45% were also reported by (Saha & Eckelman 2014, Peng & Stewart 2014, Mizzi et al. 2018) for other locations in the USA, China/Australia and Malta, respectively.

Climate variables and their effect on concrete deterioration is region specific – there is a need to consider corrosion damage impact in time and space. For example, Stewart et al. (2012) used advanced simulation procedures to predict increases in carbonation-induced corrosion damage risks under a changing climate in Australia in terms of changes in the probability of reinforcement corrosion initiation and corrosion induced damage. The detailed spatial and time-dependent probabilistic analysis included the random variability of cover, concrete strength, water–cement ratio, diffusion coefficient, corrosion rate, model uncertainty, time-dependent concentration of CO₂, yearly mean temperature and relative humidity. In Figure 3, the variability of CO₂ projection modelling errors is represented by a COV of 0.05. The uncertainty of climate projections for temperature and relative humidity was based on nine General Circulation Models (GCMs). For Sydney, this represents a variability in temperature of $\pm 1.5^{\circ}\text{C}$ and in relative humidity of $\pm 4\%$ by 2100 for the A1FI emission scenario. In the arid zone in central Australia, carbonation does not occur due to a lack of moisture. The area is extended when the future climate becomes drier around central Australia with a projected reduction of relative humidity of up to 15%. Hence, when compared to the 2000 baseline (no climate change) scenario, carbonation depths will be lower than otherwise would be the case. On the other hand, the damage probability is higher around the boundary between the arid climatic zone in central Australia and the temperate climatic zone in the west, south as well as the east of Australia. This is mostly caused by a lower cover requirement for concrete structures in arid and temperate climatic zones, which are also away from coasts. If damage is defined as corrosion-induced cracking greater than 1 mm, then carbonation-induced damage risks could increase by up to 16% by 2100. This suggests that up to one in six structures will experience additional and costly corrosion damage by 2100.

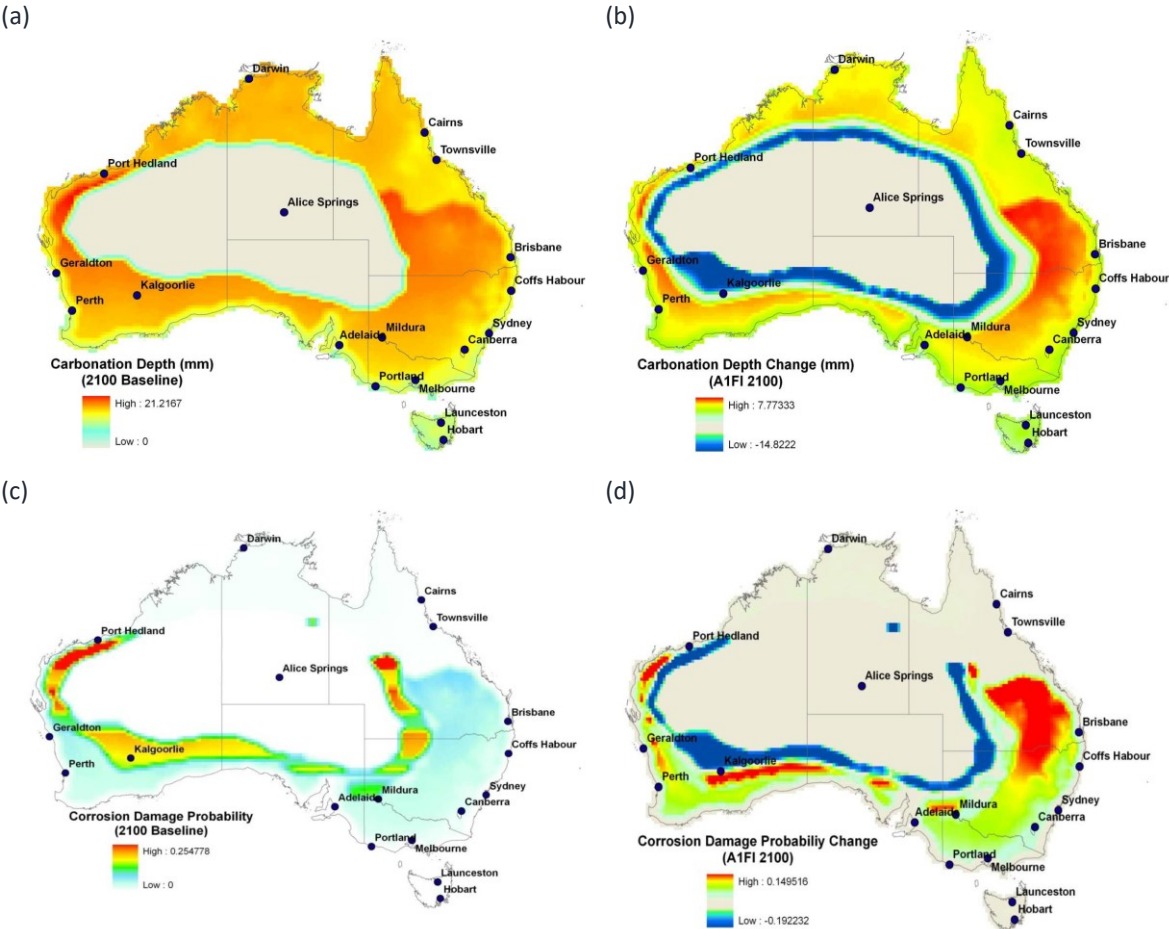


Fig. 3. Carbonation-induced corrosion of concrete structures by 2100: (a) mean carbonation depth without consideration of climate change, (b) change in carbonation depth for A1FI emission scenario, (c) probability of corrosion damage without consideration of climate change, (d) probability of corrosion damage for A1FI emission scenario (Stewart et al 2012). Note that in (d) a negative value indicates a reduction in damage probability).

It is important to recognize that CO₂ levels in urban, suburban and rural locations are usually higher than the global mean value because of anthropogenic and natural sources. Peng and Stewart (2016) estimate that the CO₂ levels in urban centres are about 14% higher than the global mean value often reported by the IPCC. While many studies report only on the worst case (and least likely) unmitigated emission scenario (A1F1, RCP8.5), the corrosion impact of less severe CO₂ projections is also considerable. For example, Peng and Stewart (2016) show that under the medium RCP 4.5 emission scenario mean carbonation depths can increase by 18% from 19 mm in 2000 to 22.5 mm by 2100 for some cities in China (see Figure 4). Carbonation depth will increase to 28 mm for the RCP8.5 scenario. Sensitivity analyses show that concrete cover has the largest effect on damage risks, followed by relative humidity, and concrete strength has a negligible effect on damage risks.

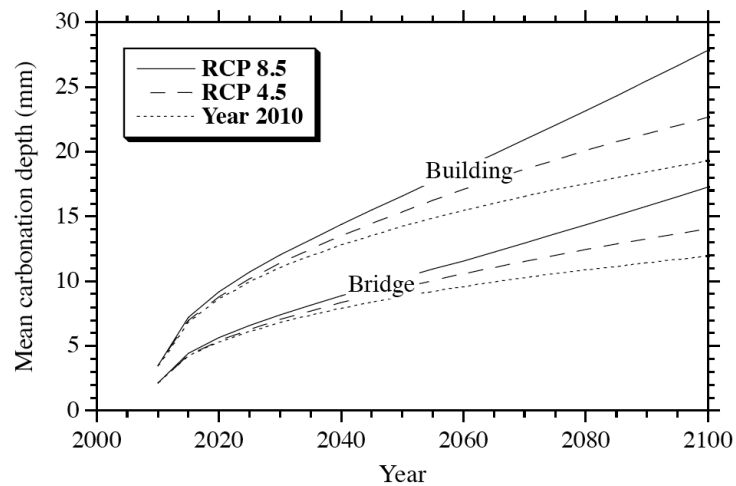


Fig. 4. Mean carbonation depths for Xiamen in China (Peng and Stewart 2016).

1.2. Chloride ingress

RC structures also suffer from deterioration issues related to the coastal environment. Reductions in the cross sectional area of steel reinforcement bars, reductions in loading resistance, and concrete cover cracking are examples of the negative effects of the presence of high chloride concentrations in coastal areas. A characteristic example of a deteriorated RC structure is given in Figure 5. In this figure, the deterioration of a coastal RC power station on a Mediterranean island is shown. As sea level rise is a potential effect of climate change, coastal structures may become closer to the sea, which means that they will be more exposed to decay and corrosion actors (Gao and Wang 2017). Therefore, the marine environment effect is expected to be intensified on structures and to reduce their service life.

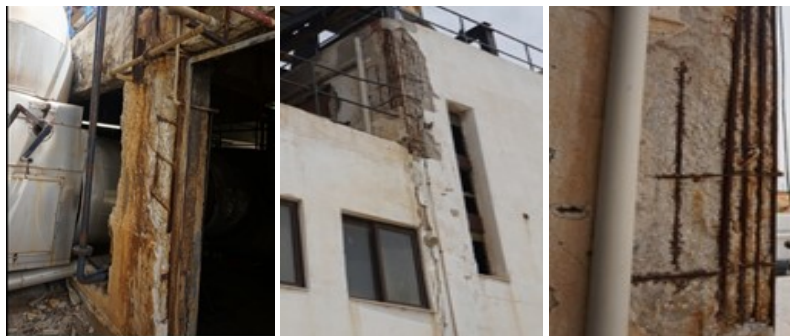


Fig. 5. Concrete cover spalling, steel rebar corrosion and loss of concrete cross-section.

Concerning chloride ingress, (Bastidas-Arteaga 2010) found that climate change could produce lifetime reductions varying from 2% to 18% depending on the exposure conditions and climate change scenarios. Larger chloride concentrations in the vicinity of rebars (increments of 37%) have been reported by (Khatami & Shafei 2017) for structures located in the US Midwest region. Previous studies indicate that increases in carbonation depth, chloride concentration at the rebar level and corrosion rate produced by climate change, would result in premature corrosion initiation or time to failure. Therefore, it is paramount to account for these effects for

designing and maintaining more climate resilient RC infrastructure. Additionally, it should be noted that in some regions, a decrease on cold spells during winter may have a beneficial effect in terms of less need to use de-icing salts on bridge decks (Railway Safety and Standards Board, 2011), making projections region specific.

A recent case-study based investigation by the IABSE working group in this area includes the study of Ferrycarrig Bridge, an Irish bridge in a chloride rich environment (Figure 6). This bridge was repaired in 2007 using five different concrete repair types on the bridge's seven crosshead beams (Ryan and O'Connor, 2013, 2014). The recent research has explored the possible effects of climate change on two of the concrete types used on the bridge, namely the Ordinary Portland Cement (OPC) repair and the 40% OPC + 60% Ground Granulated Blast Furnace Slag (GGBS) repair. The work considered the RCP4.5 and RCP8.5 scenarios, and modelled the chloride initiation phase based on the work of Bastidas-Arteaga et al. (2011), who developed a combined finite element and finite difference modelling approach. The crack initiation phase in the study was modelled using the work of El Maaddawy and Soudki (2007), while the work of Mullard and Stewart (2011) was utilized to represent the crack propagation phase for the bridge. The study examined how each concrete was affected by predicted climate change, and how the performance of the OPC + GGBS relative to the OPC changed under various climate scenarios. This relative merit metric was obtained by dividing the time to severe cracking for OPC + GGBS by the time to severe cracking for OPC. As expected the OPC + GGBS repair outperformed the OPC repair in the model, with a relative merit of 4.75 for the no climate change scenario i.e. the predicted time to severe cracking was 4.75 times longer for the OPC + GGBS than for the OPC concrete under the no climate change scenario. This relative merit was however found to reduce owing to climate change, dropping to 4.11 under the RCP8.5 climate change scenario. This was primarily due to the fact that climate change affects OPC + GGBS concrete to a greater extent as this concrete will last longer into the future climate owing to its increased durability in aggressive marine environments. Further details of the findings of this study can be found in (Wallace et al., 2022).



Fig. 6. Ferrycarrig Bridge showing the seven repaired crosshead beams.

1.3. Corrosion propagation

The corrosion rate of steel bars could be also affected by climate change. Corrosion acceleration could lead to premature structural failure. The assessment of climate change effects after corrosion initiation will depend on specific structural characteristics. Bastidas-Arteaga et al. (2013) assessed reductions in time to failure for corroded reinforced concrete bridge girders up to 31% for the most pessimistic climate change scenario. More recently, Bastidas-Arteaga (2018) estimated the time to failure for RC beams subjected to cyclic loading, chloride-induced deterioration and climate change. Cyclic loading was modelled by a random wheel load with traffic frequencies varying from 20 to 200 cycles/day. A bending limit state was considered where failure was reached once the bending moment capacity (M_c) was lower than the bending moment due to the applied cyclic loading (M_a), i.e. $M_c < M_a$.

Stochastic processes were used to model temperature and relative humidity variations by considering two climate change scenarios. For instance, the pessimistic scenario considers that there is a large use of fossil sources of energy, appreciable growth of population, with no policies to develop and extend the use of clean technologies (equivalent to scenarios RCP6–RCP8.5, depending on the location). Average increases of 6.5°C and 0.1 were considered for the temperature and relative humidity, respectively. Seven random variables were considered to account for the uncertainty related to chloride ingress, moisture and heat transfer. Two additional random variables were included to consider the uncertainty linked to concrete and steel resistance. The details of these stochastic processes and random parameters are to be found in (Bastidas-Arteaga, 2018). In Table 1 are presented the mean and the coefficients of variation of the times to failure for various traffic frequencies, exposure conditions, and climate change scenarios. Two levels of aggressiveness are included in the analysis where each level is characterized by an environmental (surface) chloride concentration (C_{env}) and a corrosion rate ($i_{corr,20}$): high ($C_{env} = 2.95 \text{ kg/m}^3$ and $i_{corr,20} = 5.0 \text{ } \mu\text{A/cm}^2$) and low ($C_{env} = 0.35 \text{ kg/m}^3$, $i_{corr,20} = 0.5 \text{ } \mu\text{A/cm}^2$). The results in Table 1 show that the mean time to failure decreases for more aggressive environments and larger traffic frequencies. This trend is expected because larger environmental chloride concentration, corrosion rates and traffic frequencies would lead to shorter times to failure.

The environmental exposure includes two weather conditions (without climate change and a pessimistic scenario) for an oceanic environment placed in a middle latitude where the average temperature is 15°C and the average relative humidity is 0.7. The pessimistic climate change scenario is equivalent to an RCP8.5 scenario where it is expected that the temperature increases by 6.5°C and the relative humidity by 0.1. The results show that climate change could induce a reduction of a maximum 7% of the total lifetime for the worst case. Nevertheless, these findings are conservative because they neglect the effect of climate change on the corrosion rate that was illustrated in Figure 2 for the Duracrete model. In addition, further research is required to establish an accurate model of corrosion rate accounting for relative humidity variations, which will improve the assessment of climate change consequences after corrosion initiation.

Table 1. Mean (in years) and coefficient of variation (between brackets) of the time to failure for a RC beam placed in a oceanic environment and subjected to two climate change scenarios (Bastidas-Arteaga 2018).

Traffic frequency (cycles/day)	High aggressiveness		Low aggressiveness	
	Without	Pessimistic (RCP 8.5)	Without	Pessimistic (RCP 8.5)
50	54.1 (16%)	52.7 (15%)	159.3 (35%)	153.1 (36%)
500	36.4 (22%)	35.1 (22%)	105.8 (41%)	99.4 (42%)
1000	33.8 (23%)	32.6 (22%)	99.3 (41%)	92.5 (42%)
2000	32.3 (24%)	30.8 (23%)	93.2 (40%)	86.7 (40%)

2. Corrosion of steel structures

There have been a number of reviews and discussions on possible impacts that climate change may have on corrosion of metals (Cole & Paterson 2010, Roberge 2010, Kumar and Imam 2013). The loss of material due to corrosion is the most significant effect on structural steel members because of the reduction in cross section thicknesses leading to loss of structural resistance and stiffness. The rate of corrosion penetration, which is the amount of thickness that is lost due to uniform corrosion, is influenced by several factors, such as the steel composition, the steel surface homogeneity, the Time Of Wetness (TOW) of the steel surface to be corroded, the water's chemical characteristics (temperature T , pH , dissolved oxygen O_2 , salinity S), nutrients (bio-corrosion) and the microclimate conditions. In the tide and immersed areas, the effect of these parameters on the corrosion rate has been quantified from an experimental study (Liu et al., 2005). A response surface of the corrosion $C(t)$ calibrated from this database is proposed as

$$C(t) = (0.1576 + 0.0033 T - 0.0108 pH - 0.0030 S + 0.0133 O_2)t \quad (3)$$

This model can be used for updating the probabilistic long term corrosion model without climate change effect (Schoefs et al. 2020) where the corrosion rate is computed from the corrosion at $t = 30$ years divided by 30 years.

The content of pollutants (sulphur dioxide and chlorides) in the atmosphere surrounding the steel member also has a significant influence on the level of corrosion. Potential changes in temperature would affect the rate of electrochemical reaction of the corrosion process. Changes in relative humidity affect the TOW of the metal surface, which is the basic condition for the corrosion process to take place.

The prediction model for atmospheric corrosion of low-alloyed steels is based on the Dose-Response Function (DRF) according to ISO 9223 (Mikhailov et al. 2004, Knotkova, & Kreislova 2007), which defines the one-year corrosion rate as follows:

$$A = 1.77 SO^{0.52} e^{(0.02RH+f_{St})} + 0.102Cl^{0.62} e^{(0.033RH+0.04T)} \quad (4)$$

where SO is the average annual deposition of SO_2 ($mg/(m^2.d)$), RH is the average annual relative humidity (%), Cl is the average annual deposition of Cl^- ($mg/(m^2.d)$) and T is the annual (average) temperature ($^{\circ}C$). f_{St} is a temperature factor where $f_{St} = 0.15(T - 10)$ if $T \leq 10^{\circ}C$ and $f_{St} = -0.054(T - 10)$ otherwise. The average amount of corrosion (thickness loss) over time $C(t)$, at any time t , can then be estimated using the classical exponential corrosion model:

$$C(t) = At^B \quad (5)$$

where B is an experimentally determined coefficient obtained through regression analysis on test results in different environmental exposure conditions. Equation (5) is useful in estimating the first year corrosion based on the actual exposure conditions (SO_2 , T , etc). However, the influence of long-term changes of exposure conditions (due to climate change and/or increase/decrease of the concentration of atmospheric pollutants) on the rate of corrosion over time cannot be considered using this model. To overcome this, the model of Klimesmith et al. (2007), given by Equation (6) below, allows the calculation of thickness loss due to corrosion considering the evolution of the different climatic and atmospheric variables:

$$C(t) = At^B \left(\frac{TOW}{C_1}\right)^D \left(1 + \frac{SO_2}{E_1}\right)^F \left(1 + \frac{Cl}{G}\right)^H e^{J(T+T_0)} \quad (6)$$

where TOW is the time of wetness ($h/year$), SO_2 is the sulphur dioxide concentration ($\mu g/m^3$), Cl is the chloride deposition rate ($mg/(m^2.d)$), $C_1 = 3800$ h/year (mean value), $E_1 =$ mean of measured values of SO_2 ($\mu g/m^3$), T is the air temperature ($^{\circ}C$), and $T_0 = 20^{\circ}C$. For flat carbon steel specimens: $A = 13.4$, $B = 0.98$, $D = 0.46$, $F = 0.62$, $H = 0.34$ and $J = 0.016$.

A very significant parameter for corrosion of steel is chloride deposition. The model of atmospheric corrosion includes salinity parameters – the deposition rate of airborne salt spray for natural sources (e.g. sea salts) or de-icing salt for winter maintenance of roads. The deposition rate of both these salinities is affected by climate change. Increase in seawater temperature results in increase in the amount of chloride concentration in water; storms and strong waves may also increase the effect of chloride deposition on the surfaces of steel structures. Climate change projections provide estimates of likely changes in mean wind speed (IPCC 2013) and by using the DRF these changes can be used to estimate changes of airborne salinity. Accordingly, the corrosion rate of carbon steel may decrease or increase depending on local climate changes.

The corrosion of steel structures begins after degradation of corrosion protection coatings that have been applied on them. Low alloyed steel structures are protected against corrosion by various types of protective coatings – metallic, organic or duplex. The most frequently applied metallic coatings are various types of zinc or zinc-alloyed coating. The zinc coatings are more sensitive to the effect of high humidity than steel. Unfortunately, there is no model for service life prediction of paint systems. A DRF for coatings has been suggested in the past (Tidblad et al. 2001) but the effect of climate change on the deterioration of coatings has not been investigated (Sousa et al. 2020). Research efforts for developing deterioration models for assessing the effectiveness of

coatings on structural resistance can be found in Kallias et al. (2016). Practical experience shows that the maximum service life of paint systems is 25 years in contemporary conditions. In addition to the climate and pollution parameters, the service life of paint coatings is significantly affected by UV radiation. Thirty years of satellite data show that the amount of ultraviolet (UV) radiation reaching the Earth's surface has markedly increased over the last three decades (Herman 2010). Most of the increase has occurred in the mid-and-high latitudes, e.g., at latitude 32° the UV radiation has increased by 6% on average since 1980. These changes decrease the service life of paint coatings, but the amount of the degradation increase is based on laboratory data only (Artemova et al. 2019).

2.1. Steel structures in atmospheric environment

Since 1986, one-year exposures of carbon steel panels have been performed every three years on the network of European atmospheric test sites within the framework of the United Nations Economic Commission for Europe (UNECE) International Cooperative Programme (ICP) Materials. Comparisons carried out on corrosion loss between exposures in the years 2012 and 2015, have shown some interesting results: (i) the increase of yearly corrosion loss of carbon steel was 50% on test sites where the yearly average temperature increased by 2°C; (ii) the amount of precipitation had a more significant effect although this parameter is not included into the dose-response function – in the period 2014-15 the yearly amount of precipitation was higher by 60% on some test sites and yearly corrosion rate on the same test sites increased by 70%. It should also be noted that the winter season of 2014-15 was warmer and more humid than usual in Europe.

Nguyen et al. (2013) have conducted a study of climate change effects on atmospheric corrosion rate of steel and zinc structures. They found that corrosion rates vary quite markedly between different regions in Australia due to changes in temperature, relative humidity and airborne salinity. Table 2 shows that the corrosion rate is predicted to decrease by up to 11% for steel and zinc structures in Melbourne to 2100, most likely as a result of a 3% lowering of relative humidity. On the other hand, corrosion rates are predicted to increase by up to 36% in Brisbane, a city 2000 km to the north of Melbourne.

Table 2. Average effects of climate change on relative corrosion rates at certain years for Melbourne and Brisbane under A1FI scenario (adapted from Nguyen et al., 2013).

City	Relative corrosion rates	Year 2030	Year 2050	Year 2070	Year 2100
Melbourne	Zinc	0.973	0.949	0.926	0.907
	Steel	0.963	0.929	0.893	0.858
Brisbane	Zinc	1.020	1.045	1.083	1.139
	Steel	1.019	1.045	1.082	1.138

A sensitivity analysis on the effect of different climatic and atmospheric variables on the long-term predictions of corrosion thickness losses is shown in Figure 7. The parameters investigated were TOW, temperature, chloride and sulphur dioxide concentrations. The results show that the latter two concentrations have the greatest impact on the long-term rate of corrosion with TOW having a smaller impact. Similar trends have also been reported by Chico et al. (2017). A similar analysis carried out by Tidblad (2012) showed that future atmospheric corrosion of metals in Europe will be dominated by the effects of chloride deposition in coastal and near-coastal areas. This effect will be higher in the future than it is today since a fixed chloride deposition will have a higher impact when the temperature increases.

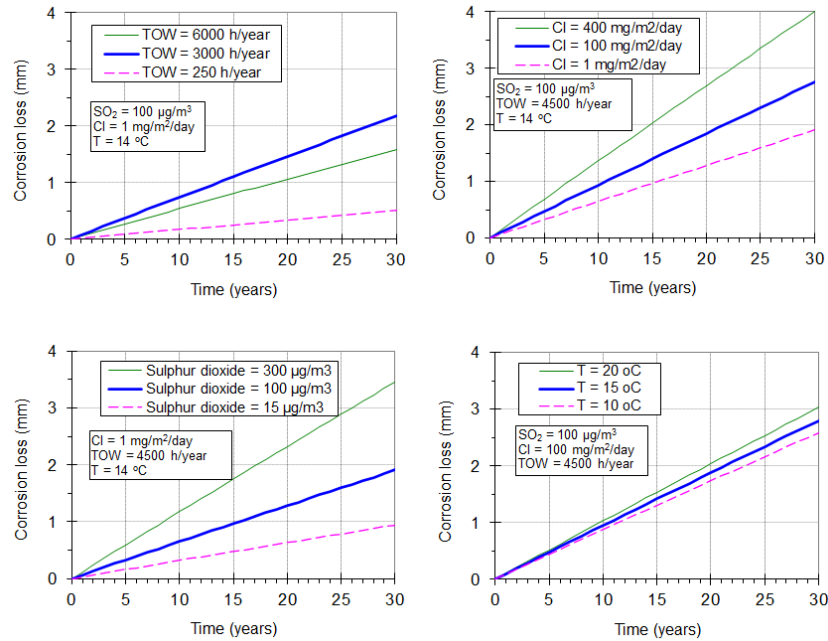


Fig. 7. Effect of varying climatic and atmospheric pollutant parameters on the corrosion losses with time estimated through Equation (5): (a) Time-Of-Wetness (*TOW*), (b) *Cl* deposition rate, (c) *SO*₂ concentration and (d) temperature.

Fom (2017) investigated the effect of climate change on the buckling strength of steel plates, representing parts of bridge plate girders. By combining different climate change scenarios and finite element analysis of various steel plate configurations, it was shown that under a high emissions scenario (RCP8.5), up to 25% more reduction in plate buckling strength can be expected by the 2100s, compared to a low emissions scenario (RCP2.6).

In another study, Imam (2019) estimated the time-dependent reliability of a typical plate girder railway bridge under different climate change and atmospheric pollution scenarios. It was found that the overall direct effect of increasing solely average annual temperature on bridge reliability is relatively small. On the other hand, the effect of *TOW* on bridge reliability was found to be more influential, resulting in an order of magnitude increase in the probability of failure in the 2100s, for this specific case study, when *TOW* increased from a range of 250-2500 hours/year to 2500-5500 hours/year, according to the ISO 9223 *TOW* categories. A risk-based assessment carried out in the same study also showed that mitigation of the atmospheric pollution (i.e. the reduction of *SO*₂ over time) can have a positive influence but only after a period of several decades has evolved. Hence, any mitigation actions on improving air quality in urban areas may only be beneficial in the long-term. However, although the long-term reduction of *SO*₂ concentration in an area can enhance the reliability and hence reduce the risk of the exposed structure, it was shown that the probability of failure over time and associated risk remain higher compared to a bridge exposed to a less polluted environment throughout its service life.

2.2. Steel structures in marine environment

In marine environments, climate change affects the long-term structural reliability of coastal infrastructures through three mechanisms: corrosion rate due to the decrease of sea water pH, structural stability and the corrosion location, both due to the rise in sea water levels. This section investigates the potential impacts of climate change on steel walls in harbor areas. Harbors play a major socio-economic role all over the world for trade exchange and defense and efficient management of steel structures, particularly steel walls, is crucial.

Concerning sea water pH, IPCC reports that pH could fall from 8.1 (in the 1980s) to 7.7 in 2100 according to the RCP8.5 projection (Abram et al. 2019). This can result in small changes in the corrosion rate (Liu et al. 2005). Sea water level rise could be in the range 0.7–1.1 meters in 2100 in comparison with the 1980's with a large scatter around the world. This can drastically affect the reliability of sheet piles by moving the location of extreme corrosion (area of low tidal sea level) (Schoefs et al. 2020) and the pressure of water level in the embankment

(Boéro et al. 2012). Note that the mean elevation of sea level in 2100 is planned to reach 0.55m for scenario RCP 2.6 and 0.82m for scenario RCP8.5. Figure 8 gives the translation of mean corrosion profile of a sheet pile designed in (Boéro et al. 2012) for a sheet pile in a tidal environment for scenario RCP 2.6. It is observed that the maximum corrosion (area 3, low tide) will move upwards causing more corrosion in the zone [-4m; -3m] where the tie-rod (see Figure 8 left) can be placed. The immersion area moves upwards also and the area (4) will be less corroded than predicted: which is usually the location of high stresses. This example illustrates the complexity of the effects that can decrease or increase the resistance of a structure.

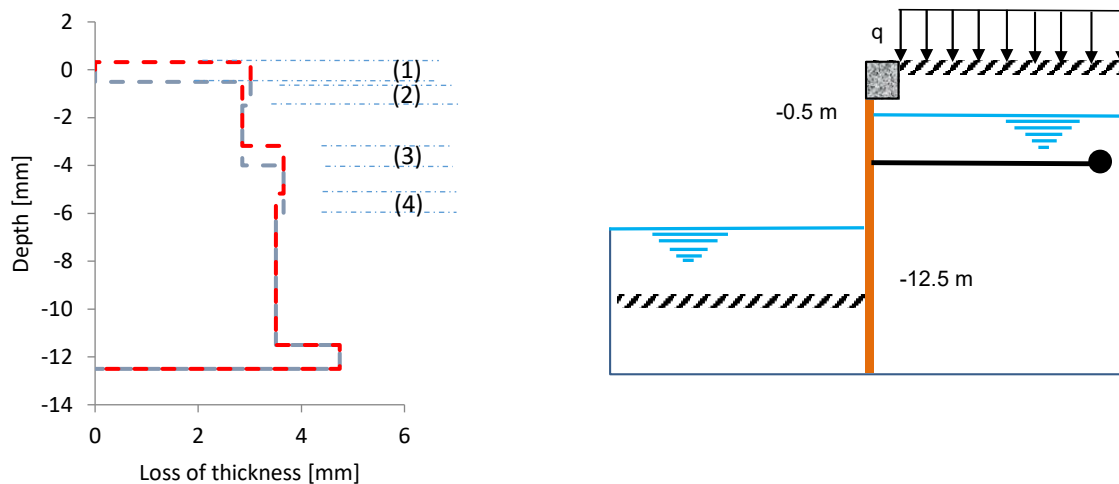


Fig. 8. Left: evolution of a typical corrosion profile for a sheet pile in a tidal area due to sea water level: without climate change (dashed blue) and with climate change (dashed red). Right: typical sheet pile

Pitting corrosion is a serious concern for steel structures, and particularly so for those in marine conditions such as pipelines where perforation of steel can lead to leakage of pollutants. Many environmental factors are known to influence corrosion in sea water including bacteria, biofouling, nutrients, temperature, oxygen concentration, pH of the environment, carbon dioxide concentration, salinity, carbonate concentration, pollutants, pressure, stress, fatigue loading and stress, suspended solids, wave action and water velocity (Melchers 2015). Climate change may affect many of these variables, especially nutrient levels in sea water. A complete model was recently developed to account for more effects such as biocorrosion: an increase of up to 10% in the probability of failure of a sheet pile was computed (Chaves et al. 2016). Peng et al. (2017) found that sea temperature rise in itself will increase the mean of pitting corrosion depths by up to 10% for steel sheet piling. However, this effect is largely offset by sea level rise caused by climate change as it will shift the corrosion zone upwards and so expand the corrosion area resulting in shallower corrosion depths. Hence, sea water temperature increase and sea level rise can delay pit perforation by at most two years compared to the reference year 2015 scenario (Peng et al. 2017). This highlights the important need to model carefully the interdependencies associated with climate change.

3. Timber decay

The decay rate of timber is site- and material-specific and depends on exposure conditions (in-ground versus above ground), climatic conditions (temperature, rainfall, humidity), wood species, initial preservative treatment, and nature of fungal attack, among other factors. The main climate parameters that affect timber decay are humidity and temperature (Teodorescu et al. 2017). The exposure of timber to a humid environment increases its moisture content. An increase in the moisture content above the fibre saturation point will provide a viable environment for the establishment of a fungal mycelial mat and further fungal growth (Viitanen & Ritschkoff 1991). Moisture content above the fibre saturation point results in the availability of free water in the timber, which is easily accessible to the fungi and leads to rapid decay (Wang & Wang 2012). The growth of decay

fungi is also significantly affected by air and timber temperature (Brischke & Rapp 2008). It is, therefore, clear that the long-term structural resistance of timber will be affected by any potential future climate variations.

Deterioration over time for timber structures has been incorporated into previous studies. Decay models are based on in-field or in-lab measures and report results for specific wood species and climatic conditions (Brischke & Rapp, 2008). Decay models developed for above-ground conditions include Leicester et al. (2009), Isaksson et al. (2013), and Viitanen et al. (2010). Decay models for timber in ground contact are relatively rare. (Li et al. 2005) developed a decay model based on field data from 13,940 poles ranging from age 1 to 79 years. About 8% of the poles showed various degrees of decay. Wang et al. (2008b) developed a decay model for wood in ground contact using in-field data from 77 commonly used commercial timber species buried at five test sites in eastern and southern Australia over a 35-year period. The developed model is a function of the type of timber, mean annual rainfall (including the number of dry months in a year), and the mean annual temperature. (Ryan et al. 2014) used this model to assess the effects of decay on the structural capacity of both treated and untreated timber power poles, with the effects of deterioration and network maintenance incorporated in the analysis. Salman et al. (2020) also used this model to study the impact of climate change on the decay rate of timber utility poles. Timber has been the material of choice for supporting power distribution lines around the world. For example, there are between 160 million and 180 million timber poles in the USA worth billions of dollars (Mankowski et al., 2002). Timber poles are preferred over other materials because they are relatively cheap to purchase, lighter and easier to transport, easy to climb and non-conductive, making them safer for utility workers (Mankowski et al., 2002). However, timber poles are susceptible to decay, which usually occurs at or just below the ground level. The decay rate of timber poles is expected to be affected by climate change, which can increase the decay rate. Such an increase will require utility companies to invest more in periodic inspection and replacement of poles.

A study by Salman et al. (2020) investigated the impact of climate change on timber poles in two locations in the USA: Miami and New York City. These cities correspond to different types of climate. Miami is in the south-eastern part of the USA and has a tropical monsoon climate with hot and humid summers and short and warm winters. New York City (NYC) is in the north-eastern part of the USA and has a humid subtropical climate, with cold winters and hot, moist summers. Projected precipitation and temperature data were obtained from the Coupled Model Intercomparison Project phase 5 (CMIP5) multi-model ensemble (Maurer et al., 2007). Figure 9 shows the effect of climate change on the decay rates for the RCP4.5 and 8.5 scenarios. Under the RCP8.5 scenario, the decay rates are expected to increase by about 9% and 17% compared to the 2005 rate in Miami and NYC, respectively, by the end of the 21st century. The higher increase in the decay rate in NYC can be attributed to a projected higher increase in precipitation. Figure 9 also shows how increased timber pole decay due to climate change will increase the number of poles that will fail due to extreme wind in the two locations at the end of the 21st century.

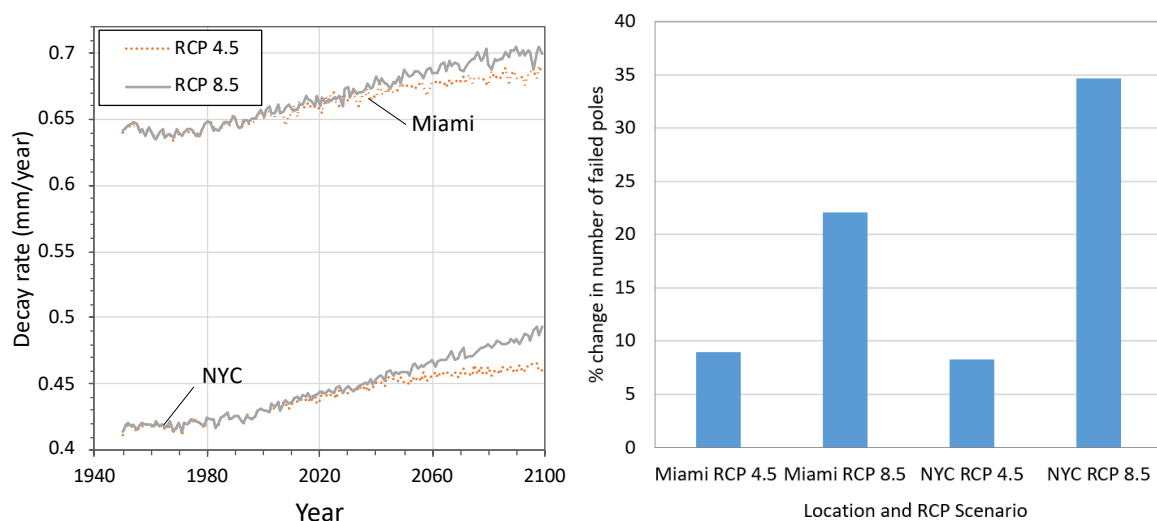


Fig. 9. Left: impact of climate change on timber decay rate. Right: impact of climate change on number of failed poles.

The regional variation of the impact climate change on timber decay and resulting structural resistance has also been illustrated by Ryan et al. (2016), who examined the climate change impacts on timber power pole performance in five different regions of Australia. This analysis indicated that climate change impacts on power pole networks are likely to be substantial for some locations in Australia, with Brisbane experiencing a projected 12% increase in pole condemning rates, and a 59% increase in wind failure rates of deteriorated poles over the period 2015 to 2070. However, results were highly-regionally variable, with Melbourne experiencing negligible or even slightly positive climate change impacts (3% reduction in pole failures rates under medium climate scenario). Indeed the nature of the impacts across the five regions were not intuitive, depending on opposing interactions of temperature, rainfall and wind, the baseline climactic conditions in a region, and the nature of the uncertainty associated with future climatic predictions. Other work by these authors examined the probabilistic cost benefit analysis of climate adaptation options for power pole networks in Brisbane (Ryan and Stewart, 2017), and the regional variability of climate change adaptation feasibility for such networks across Australia (Ryan and Stewart, 2021). The latter study showed that the cost-benefit performance of adaptation strategies are also highly regionally variable. This emphasized the need for detailed and regionally specific modelling of climate change adaptation feasibility to inform national and international policies, and increase the resilience of timber critical infrastructure to climate change in a cost effective manner.

More recent work by IABSE TG6.1 members has examined the impacts of climate change on timber power pole networks in Europe (Ryan et al. 2021). This analysis, which also utilized the probabilistic decay model developed by Wang et al. (2008a,b), explored climate change impacts on power pole networks in two Irish cities, namely Cork and Dublin. The study incorporated network maintenance, inspection error and structural reliability modelling. To incorporate the uncertainty associated with climate change projections in this study the changes in temperature, wind speed and rainfall were modelled probabilistically using distributions developed from the full ensemble of downscaled climate projection simulations available for Ireland. Further details are provided in Ryan et al. (2021). Figure 10 shows the cumulative wind failures of deteriorating poles under a number of climate change scenarios for the two cities. It is noted that wind failure in this study was defined as the bending failure of a deteriorated timber power pole under wind loading. This limit state was selected based on the most common failure model of timber power poles (Winkler et al., 2010). Climate change impacts on both cities were similar, with approximately 16% more wind failures of deteriorated poles under the RCP4.5 scenario and 25% more for the RCP8.5 scenario. Figure 10 also illustrates the role that timber deterioration plays in power pole wind failures for any climate scenario. At the start of the modelling period (the year 2000), when the network of one million power poles were in an undeteriorated state, the power pole failure rate was very low (the slope of the line in the plot); however as the poles deteriorated prior to the first inspection after 20 years, deterioration led to a steady increase in power pole failure rates. Figure 10 thus illustrates the impact of timber decay on infrastructure, and the impacts of climate change on the performance of timber power pole networks in Europe.

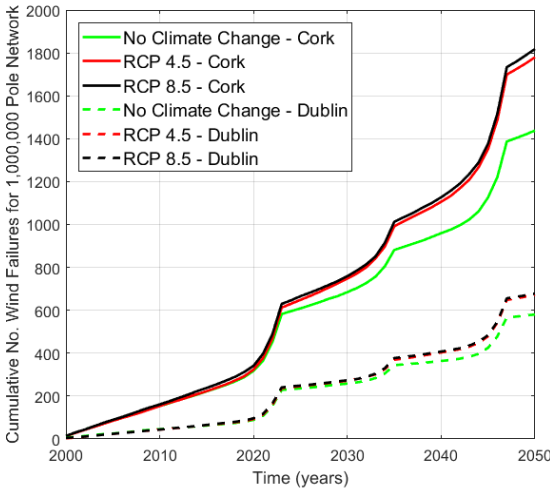


Fig. 10. Impacts of climate change on the cumulative number of wind failures of decaying poles in Ireland (Ryan et al. 2021).

4. Deteriorated structural resistance under intensified actions

The effects of climate change on long-term structural reliability result not only from the modification of structural resistance, but also from the influence on structural actions. Hence, it is important to consider both aspects (capacity and demand) under a changing climate. While more and more attention has been placed on the time-dependent reliability analysis considering climate change impacts either on intensity and frequency of natural hazards (e.g. hurricanes) or on structural deterioration (e.g., corrosion of RC beams), an holistic analysis framework is lacking that simultaneously considers climate change impacts on deteriorating infrastructure resistance and intensifying hazard. Merschman et al. (2020) considered the potential impact of climate change on both pole decay rate and hurricane hazard risk in their study investigating the effectiveness of Fiber-Reinforced Polymer (FRP) sleeving reinforcement of timber poles. It was found that, if climate change is only assumed to affect the decay of the pole, the probability of failure of the timber pole at the end of the 21st century under the RCP8.5 emission scenarios in Miami, Charleston and New York City increase by about 5%, 22%, and 20%, respectively. On the other hand, if both the decay of timber poles and the increase in hurricane risk (determined by hurricane intensity and frequency changes) under changing climate are considered, the corresponding increases in failure probability are 30%, 70%, and 73%, respectively. Salman & Li (2016) conducted a life-cycle cost analysis of timber poles that incorporated strength deterioration models in the fragility analysis. These studies have highlighted the susceptibility of the timber components of the critical infrastructure networks to deterioration, the influence of climatic parameters, and the resulting importance of considering potential changes in future climate when assessing timber infrastructure assets.

Masonry material decay and soiling is affected by freeze-thaw cycles, the time of wetness associated with projected warmer and wetter winters and exposure to chlorides (Sesana et al. 2021). Different parts of Europe are likely to experience different changes in the climate parameters that affect brick and stone masonry structures but, in general, it has been suggested that freeze-thaw cycles, common now for mild climate e.g. in Central Europe, may newly endanger structures in regions with colder climates (Lacasse et al. 2020). On the other hand, any projected decrease in summer rainfall is likely to increase the soiling potential of masonry material.

In terms of prestressed-concrete, projected decreases in relative humidity along with higher expected temperatures may result in a higher creep rate for concrete leading to higher long-term deformations which can result in loss of pre-stressing forces (Nasr et al. 2021). Furthermore, higher solar radiation in some places may increase the temperature gradient between the top and bottom of bridge decks and result in stress increases.

Finally, it is noted that current studies of deteriorating structure failures subjected to intensified hazards under a changing climate are essentially based on static analyses, while the dynamic behaviour of structures may significantly complicate the analysis and corresponding results. One representative example is the effects of climate change on dynamic instability (i.e. the flutter phenomenon) of long-span bridges under strong winds. According to Selberg (1963), the change of bridge critical flutter wind speed depends on the relative deterioration degree of the first-order vertical and torsional modal frequencies. With the example of long-span suspension bridges with steel twin-box girders, some long-term field monitoring data suggest that the decrease of the first-order vertical modal frequency due to structural deterioration is more obvious compared to that of the first-order torsional modal frequency (Chu et al. 2021). Accordingly, the intensified deterioration due to climate change may potentially enhance the flutter performance of long-span bridges.

Conclusions

In this study, some potential climate-change impacts on structural resistance have been proposed through a review of recent research work on several construction materials, also including recent research outcomes of an international expert panel on the effects of climate change gathered by IABSE TG6.1. By considering specific examples where climate change may produce changes of vulnerability, this article provides projections of additional degradation under different scenarios of climate change (RCPs), on structural resistance.

Concerning corroding RC structures (initiation and propagation phases), different environmental conditions are introduced considering climate change effects. The projected higher temperatures, increased precipitation and relative humidity in some areas, and higher carbon dioxide concentrations in the atmosphere may all contribute to an increased risk of structural deterioration. For the particular case of chloride ingress, as sea level rise is a

potential effect of climate change, coastal structures may become closer to the sea, which means that they will be more exposed to decay and corrosion factors. However, it is highlighted that climate variables and their effect on concrete deterioration is regionally specific, and that there is a need to consider corrosion damage impact in time and space.

Concerning the corrosion of steel structures, the goal is to investigate the potential change in structural performance, in terms of strength and stiffness, capturing climate change effects on the long-term corrosion of steel elements, both in atmospheric conditions and also in a marine environment. It is shown how the rate of corrosion penetration is influenced by several factors, such as the steel composition, the steel surface homogeneity, the Time Of Wetness (TOW) of the steel surface being corroded, the water's chemical characteristics (temperature, pH, dissolved oxygen, salinity), nutrients (bio-corrosion), the microclimate conditions, the content of pollutants (sulphur dioxide) in the atmosphere and chloride deposition. A particular type of critical steel structure in harbour areas is considered namely steel sheet piles, where resistance might depend on sea water acidity (corrosion kinetics), change of mean level of tide (stability) and rise in sea water level (corrosion location).

Also, the effects of deterioration on the structural resistance of timber, a natural material susceptible to decay, are considered, to see how deterioration may be affected by climate change in the future. Site- and material-specific models from the literature are used to quantify the decay rate of timber under several exposure conditions (in-ground versus above ground), climatic conditions (temperature, rainfall, humidity), wood species, initial preservative treatment, and the nature of fungal attack, among other factors. This additional degradation can then be integrated in a structural reliability analysis to characterize how different scenarios of climate change may affect the residual capacity of timber structures.

Finally, it was discussed how the modification of structural resistance can depend on the influence of structural actions, under intensified hazards. While this article focuses on the structural resistance side, the main challenges for designing and maintaining climate-resilient infrastructures are (i) to consider both resistance and load processes in the context of risk-based approaches, all the more so when intensified actions change the resistance of structures, and (ii) to include cost-benefit optimization under uncertainty of solutions to enhance the resilience of infrastructures to extreme weather events in the short, medium and long term.

Future work in the area should focus on investigating and comparing different climate change adaptation strategies based on their effectiveness in reducing risk, improving system resilience, reducing repair and replacement costs, their potential to reduce indirect losses to stakeholders and developing a system-level risk management framework to facilitate more targeted climate change adaptation that focuses on critical components that have a greater impact on system performance. Considering the large uncertainties associated with projections, it should be analysed how structural health monitoring techniques can play a key role in decision making for existing structures and in the design optimization of new structures.

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