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Climate adaptation of existing reinforced concrete structures in coastal areas

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Abstract:

This work focuses on assessing costs and effectiveness of climate adaptation strategies for existing reinforced concrete structures subject to chloride penetration and climate change. We will study on existing reinforced concrete structures built in France at different years under different building codes. Concerning environmental actions, we considered historical meteorological data and two climate change scenarios. It is hoped that the results of this study provide practical guidance to decision makers to improve the management of reinforced concrete structures under a changing climate.

Keywords: Chloride ingress, Corrosion, Climate change, Adaptation, Existing structures.

1. Introduction

There are environmental and operational actions that affect performance, serviceability and safety of reinforced concrete (RC) structures. Among these actions, chloride ingress into concrete leads to: corrosion initiation, loss of cross-sectional area of reinforcing steel, cover cracking and spalling, and loss of concrete-steel bond. Then, the interaction of these deterioration consequences with service loading could reduce operational life of RC structures. Experimental evidence and numerical studies indicate that chloride ingress and corrosion propagation are highly influenced by weather conditions in the surrounding environment (BASTIDAS-ARTEAGA *et al.*, 2011). Therefore, a potentially important factor for asset management is the possible influence of climate change. Since structures have been designed against past climate, structural design and maintenance should be adapted to these new environmental conditions.

The present paper will focus on the assessment of costs and benefits of a climate adaptation strategy (increase in design cover) for existing RC structures in France. The Benefit-to-Cost Ratio (BCR) is selected for comparing the cost-effectiveness of adaptation strategies because it seems to be a metric that government and policy makers are familiar with. The paper focuses only on one adaptation strategy and specific places

in France (Saint-Nazaire and Marseille). However, it provides a methodology for the assessment of the cost-effectiveness of climate change adaptation strategies for existing structures that could be extended to other adaptation strategies or deterioration processes worldwide.

2. Climate change effects and modelling

The IPCC Fifth Assessment Report (AR5) uses Representative Concentration Pathways (RCPs) including a mitigation scenario leading to a low forcing level (RCP 2.6), two medium stabilization scenarios (RCP 4.5/RCP 6) and one high baseline emission scenario (RCP 8.5) (MOSS *et al.*, 2010). This study covers RCP 8.5 and RCP 4.5 scenarios representing high and medium emission scenarios, respectively. From an engineering point of view, these scenarios correspond to expected and pessimist climate change scenarios.

The economic assessment of adaptation measures is influenced by time-dependent changes in environmental parameters (temperature, relative humidity (RH)) that are site-specific. This work studies the effects of climate change on two port locations in France: Saint-Nazaire and Marseille. These locations correspond to different types of climate. Saint-Nazaire is close to the Atlantic Ocean in the Northern part of the country and it has a temperate oceanic climate. Marseille is placed in the South-East on the Mediterranean coast and it has a Mediterranean climate rather hot and dry.

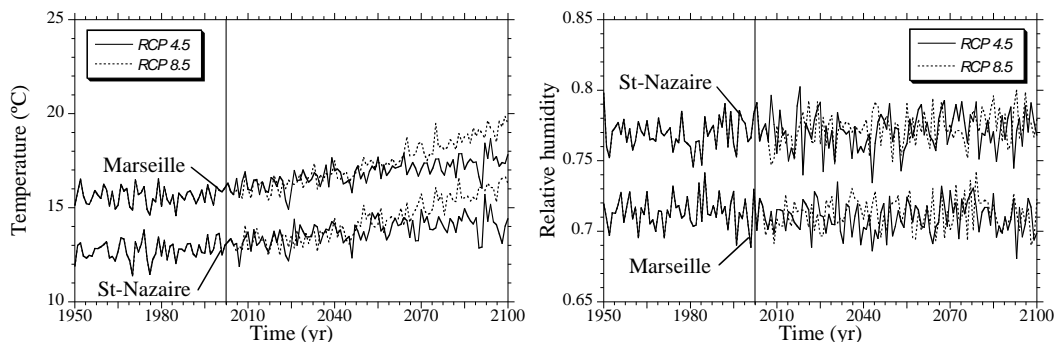


Figure 1. Yearly temperature and relative humidity projections for Saint-Nazaire and Marseille.

The overall impact of climate change on the future weather of the selected locations was estimated by using data computed by the French general circulation model CNRM-CM5. Figure 1 presents the yearly projections of temperature and RH for Saint-Nazaire and Marseille for the selected climate change scenarios (RCP 4.5 and RCP 8.5) since 2005. By comparing climate (before 2005) in both locations, it is noted that Marseille is hotter and dryer than Saint-Nazaire. Climate change projections announce mainly temperature increase without significant changes in RH for both locations until the end of the next century. By comparing mean temperatures over the periods (2001-2010) and

(2091-2100) for both places, it was found that climate change could increase temperature by approximately 1.5 °C and 3.5 °C for RCP 4.5 and RCP 8.5 scenarios, respectively. Although climate change effects are relatively similar for both locations, the kinematics of chloride ingress and corrosion propagation could be affected by the climate specific to each place. Climate projections are subjected to considerable uncertainties, and depend on CO₂ emission scenarios and accuracy of general circulation models. This work considers a simplified stochastic approach for modelling climate (BASTIDAS-ARTEAGA *et al.*, 2011 & 2013).

3. Deterioration modelling

Deterioration modelling allows estimating the effects of chloride ingress with regard to serviceability or ultimate limit states. Ultimate limit states are highly dependent on both, geometrical characteristics (cross-sectional dimensions, span length, etc.) and loading (Dead, Live, Seismic, etc.). Therefore, to generalise the results, this work focuses on a serviceability limit state in which the cost-effectiveness of adaptation measures is evaluated in terms of its effect on the time to corrosion damage of the concrete cover (severe cracking or spalling). Corrosion-induced cover cracking and damage occurs on the concrete surface above and parallel to the rebars. The time to corrosion damage, (severe cracking or spalling), T_{sp} is thus obtained as the sum of three stages: (i) corrosion initiation (T_i); (ii) crack initiation (T_{1st} , time to first cracking - hairline crack of 0.05 mm width), and; (iii) crack propagation (T_{sev} , time for crack to develop from crack initiation to a limit crack width, w_{lim}) – *i.e.*, $T_{sp}=T_i+T_{1st}+T_{sev}$. After corrosion initiation, the kinematics of T_{1st} and T_{sev} is controlled by corrosion propagation.

The time to corrosion initiation, T_i , is estimated by comparing the chloride concentration at the cover depth with a threshold concentration for corrosion initiation. The adopted chloride ingress model considers the interaction between three physical processes: *chloride ingress*, *moisture diffusion* and *heat transfer* (BASTIDAS-ARTEAGA *et al.*, 2011).

After corrosion initiation, the diameter reduction of reinforcing bars induced by corrosion can be estimated in terms of a change in the volumetric rate by using Faraday's law. The residual diameter of the reinforcing bar at time t is mainly dependent on the corrosion rate i_{corr} . Given the complexity of the corrosion process, i_{corr} depends on many factors such as concrete pH and availability of oxygen, and water in the corrosion cell. This study considers a time-variant corrosion rate model that takes into account the effect of temperature changes (DURACRETE, 2000).

The time to crack initiation, T_{1st} , is based on the model developed by EL MAADDAWY & SOUDKI (2007). The time to severe cracking, T_{sev} , is the time when concrete cover cracking reaches a limit crack width of 1 mm and is estimated by using the model proposed by MULLARD & STEWART (2011) that accounts for the effect of concrete confinement. Times of crack initiation and propagation depend on the corrosion rate.

They are also dependent on concrete strength – *i.e.*, tensile concrete strength, f_t , and elastic modulus of concrete E_c . These parameters are computed in terms of the characteristic compressive strength, f_{ck} .

4. Repair and adaptation strategies for existing structures

The repair strategy is often defined by taking into account various criteria such as: remaining lifetime, extent of damage, costs, etc. Probabilistic modelling of deterioration can be used to: (i) determine the remaining lifetime, (ii) calculate the extent of damage and (iii) optimise maintenance costs. However, for existing structures, probabilistic modelling should also take into consideration the evolution in time of design standards, construction technologies, repair materials, etc. Under a changing climate, the repair strategy could be combined with a climate adaptation strategy to account for these new environmental conditions. Since adaptation strategies could lead to additional costs, a comprehensive framework should: (i) compare the cost-effectiveness of adaptation strategies with respect to existing repair techniques, and/or (ii) optimise the effectiveness of adaptation strategies.

4.1 Damage risks and repair strategy

The time-dependent damage risks of the repaired material will not be the same as the original material due to changed temperature and humidity at the time of repair (*i.e.* when the concrete is new). Hence, the damage risk for repaired concrete exposed to the environment for the first time, at time of repair, will change depending on the new climatic conditions and time of repairs:

$$p_s(i\Delta t, t) = \Pr \left[t \geq T_{sp,i} \right] \quad (1)$$

where $T_{sp,i}$ is the time to severe cracking when new concrete is exposed to the environment for the first time after repair and Δt is the length of the inspection interval.

A patch repair is the most common technique to repair corrosion damage in RC structures – *e.g.*, (BRE, 2003). For a patch repair, the concrete cover is typically removed to approximately 25 mm past the steel bars (which are then cleaned of corrosion products) and a repair material is installed. The maintenance strategy assumes that: (i) concrete is inspected at time intervals of Δt ; (ii) patch repair is carried out immediately after corrosion damage has been discovered at time of i^{th} inspection at time $i\Delta t$; (iii) patch repair includes an updating to the current design standard (increase of concrete cover); (iv) damage limit state exceedance results in entire RC surface being repaired; (v) repair could improve durability performance of the structure when there is an updating of cover requirements before repair or by using a different repair material. However, for simplicity, it is assumed that the repair material has the same

characteristics than the construction material; (vi) damage may re-occur during the remaining service life of the structure, *i.e.*, multiple repairs may be needed.

4.2 Evolution of design standards in France

Construction standards provide design recommendations to account, in a simplified way, for uncertainties related to material properties, models, loading, geometry, etc. Advances in understanding the behaviour of materials and physical phenomena and practical experience imply evolution of construction standards. In the case of RC structures subject to chloride ingress, Figure 2 shows the evolution in time of the minimum concrete cover recommended by design standards. These standards were published as circulars of the official diary in France. The circular of the 20th Oct. 1906 recommended a minimum concrete cover varying between 15 and 20 mm for the main reinforcement without distinction of the kind of exposure. In 1934, a new circular recommended 35 mm cover for structures close to the sea and 20 mm for structures built in land. Concrete cover was increased to 40 mm and 50 mm in 1964 and 1992, respectively for structures close to the sea. Finally, the Eurocode (European standard, 2004), which is mandatory after 2010 in France, suggests concrete covers for different exposure conditions. For example, there are three exposure zones for marine structures: atmospheric XS1, submerged XS2 and splash and tidal XS3. Figure 2 plots the concrete cover for a XS3 exposure (55 mm).

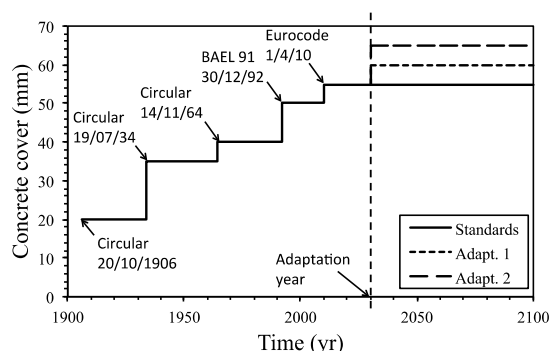


Figure 2. Recommended concrete cover and adaptation measures for RC structures subject to chloride ingress in a splash and tidal zone.

5. Cost benefit analysis of existing structures

Costs and benefits may occur at different times so in order to obtain consistent results it is necessary for all costs and benefits to be discounted to a present value. Costs and benefits of existing structures are measured from the time of assessment. If an existing structure is built in the calendar year $t_{construct}$, and if it is assumed that corrosion damage is always detected when the structure is inspected, then the expected damage cost measured from year of assessment t_{assess} to end of service life T_t , is $E_{damage}(T_t)$ is:

$$E_{\text{damage}}(T_t) = \sum_{i=1}^{T_t/\Delta t} \Delta P_{s,i} \frac{C_{\text{damage}}}{(1+r)^{i\Delta t - t_{\text{assess}}}} \text{ with } i\Delta t > t_{\text{assess}} - t_{\text{construct}}, t_{\text{construct}} < t_{\text{assess}} \quad (2)$$

where T_t is the service life (typically $T_t=100$ years), i is the number of inspection, $\Delta P_{s,i}$ is the probability of damage incident between the $(i-1)^{\text{th}}$ and i^{th} inspections which is a function of time since last repair which is also affected by damage risks $p_{s,i}(i\Delta t, t)$, C_{damage} is the damage cost, and r is the discounting rate. The risk reduction caused by an adaptation measure is thus:

$$\Delta R(T_t) = \left[E_{\text{damage-BAU}}(T_t) - E_{\text{damage-adaptation}}(T_t) \right] / E_{\text{damage-BAU}}(T_t) \quad (3)$$

where $E_{\text{damage-BAU}}(T_t)$ and $E_{\text{damage-adaptation}}(T_t)$ are the cumulative expected damage costs (economic risk) for no adaptation measures (business as usual BAU or existing practice) and adaptation measures, respectively. If an adaptation measure is effective then $E_{\text{damage-adaptation}}(T_t)$ will be significantly lower than $E_{\text{damage-BAU}}(T_t)$ resulting in high risk reduction $\Delta R(T_t)$. The cost of adaptation, in this case, additional repair costs associated with increased cover, will occur at the same time as the damage (repair) costs are incurred. It follows that the expected cost of adaptation is directly proportional to damage costs

$$E_{\text{adapt}}(T_t) = \sum_{i=1}^{T_t/\Delta t} \Delta P_{s,i} \frac{C_{\text{adapt}}}{(1+r)^{i\Delta t - t_{\text{assess}}}} \text{ with } i\Delta t > t_{\text{adapt}} - t_{\text{construct}}, t_{\text{construct}} < t_{\text{assess}} \quad (4)$$

where C_{adapt} is the cost of adaptation measures that reduces risk by ΔR , and t_{adapt} is the adaptation year (Figure 2). The ‘benefit’ of an adaptation measure is the reduction in damages associated with the adaptation strategy, and the ‘cost’ is the cost of the adaptation strategy. The benefit-to-cost ratio $\text{BCR}(T_t)$ is:

$$\text{BCR}(T_t) = E_{\text{damage-BAU}}(T_t) \Delta R(T_t) / E_{\text{adapt}}(T_t) \quad (5)$$

Note that the additional cost of repair for concrete with a higher cover is treated herein as an adaptation cost, and not as a reduced benefit. Clearly, an adaptation measure that results in a benefit-to-cost ratio exceeding unity is cost-effective.

The analysis assumes that many input variables are random variables (see Table 3) and so the output of the BCR analysis is also variable. By using Monte-Carlo simulation, it is therefore possible to estimate: (i) the mean BCR, and (ii) the probability that an adaptation measure is cost-effective $\text{Pr}(\text{BCR} > 1)$.

5.1 Cost of damage (C_{damage})

The cost of repair or replacement and associated user losses are considerable and for some structures user losses are often greater than direct repair, replacement and maintenance costs. User losses and other user disruption costs are site and structure specific, but for many RC structures such costs will be minimised if the RC element to be repaired is an external structural member such as walls, columns or facade panels.

This study considers costs estimated for the repair of RC slabs and beams of the Agri-foodstuffs terminal of the Nantes-Saint-Nazaire Port (SRIFI, 2012): $C_{\text{damage}}=323\text{€m}^2$. This value considers costs related to: studies, site installation, scaffolding, demolition, repair, operating loss. The repair consisted of removing and rebuilding cracked/chloride polluted concrete cover between 4 and 8 cm for slabs and beams without replacing corroded bars.

5.2 Cost of adaptation (C_{adapt})

Table 1 gives the adaptation costs for various structural elements (per mm of extra cover). This table also provides the adaptation costs for two adaptation measures: $\Delta c_{\text{adapt}} = 5$ and 10 mm increase in extra cover (Figure 2). Clearly, adaptation costs are higher for a square column if cover is increased on all four faces of a square RC column, and damage can occur on all four faces. D is the column width.

Table 1. Adaptation costs for various structural elements.

<i>Structural element</i>	<i>D (mm)</i>	<i>C_{adapt}^a (€/m²)</i>	<i>5 mm increase (€/m²)</i>	<i>10 mm increase (€/m²)</i>
<i>Slabs</i>	<i>100</i>	<i>0.85</i>	<i>4.23</i>	<i>8.45</i>
<i>Slabs</i>	<i>300</i>	<i>0.49</i>	<i>2.44</i>	<i>4.88</i>
<i>Beams</i>	<i>200 to 800</i>	<i>0.98</i>	<i>4.88</i>	<i>9.75</i>
<i>Sq. columns</i>	<i>300</i>	<i>1.56</i>	<i>7.80</i>	<i>15.60</i>
<i>Sq. columns</i>	<i>600</i>	<i>1.01</i>	<i>5.01</i>	<i>9.75</i>

^aPer mm of extra cover

6. Illustrative example

6.1 Problem description

This example illustrates the probabilistic assessment of the cost-effectiveness of adaptation strategies for existing RC structures placed in Saint-Nazaire and Marseille under a splash and tidal exposure. Table 2 describes the design cover according to the recommendations of French standards for structures built between 1970 and 2010 (Figure 2). For structures built in 2010, the cover was selected for a splash and tidal zone (XS3 exposure (EUROPEAN STANDARD, 2004)) and a rebar diameter of 16 mm. This paper considers also that the same concrete was used for the construction and repair of all the structures. This concrete has a characteristic compressive strength, $f'_{ck}=35$ MPa, as recommended by the Eurocode 2 for XS3 exposure (EUROPEAN STANDARD, 2004).

Other assumptions are summarised as follows: (i) the structural lifetime is $T_t=100$ years, (ii) the limit crack width for repair is $w_{lim}=1$ mm, (iii) the environmental chloride concentration, C_{env} , corresponds to a XS3 exposure, (iv) all structural components will be subjected to the same environmental conditions, (v) the chloride ingress is one-dimensional, (vi) the time of adaptation will vary between 2010 and 10 years before the

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end of the structural lifetime (Table 2), (vii) the time for assessment of costs is $t_{\text{assess}} = 2013$, (viii) the discount rate is 4%.

The probabilistic models used to estimate damage probabilities (p_{si}) are presented in Table 3. (BASTIDAS-ARTEAGA *et al.*, 2013; BASTIDAS-ARTEAGA & SCHOEFS, 2012). It is assumed that all the random variables are statistically independent. Monte Carlo simulations were used for the assessment of damage probabilities and the propagation of uncertainties throughout the cost-benefit analysis.

Table 2. Design cover and adaptation years for structures built between 1970 and 2010.

Construction year	End of lifetime	Standard	Design cover (mm)	Adaptation years
1970	2070	Circular 14/11/1964	40	[2020:10:2060]
1980	2080	Circular 14/11/1964	40	[2020:10:2070]
1990	2090	BAEL 91	50	[2020:10:2080]
2000	2100	BAEL 91	50	[2020:10:2090]
2010	2110	Eurocode 2	55	[2020:10:2100]

Table 3. Probabilistic models of the random variables.

Variable	Units	Distribution	Mean	COV
Reference chloride diffusion coefficient, $D_{c,ref}$	m^2/s	log-normal	3×10^{-11}	0.20
Environmental chloride concentration, C_{env}	kg/m^3	log-normal	7.35	0.20
Concentration threshold for corrosion initiation, C_{th} wt% cem.		normal ^a	0.5	0.20
Cover thickness, c_t	mm	normal ^b	Table 2	0.25
Reference humidity diffusion coefficient, $D_{h,ref}$	m^2/s	log-normal	3×10^{-10}	0.20
Thermal conductivity of concrete, λ	$W/(m^\circ C)$	beta on [1.4;3.6]	2.5	0.20
Concrete specific heat capacity, c_q	$J/(kg^\circ C)$	beta on [840;1170]	1000	0.10
Density of concrete, ρ_c	kg/m^3	normal ^a	2400	0.04
Reference corrosion rate, $i_{corr-20}$	$\mu A/cm^2$	log-normal	6.035	0.57
28 day concrete compressive strength, $f_c(28)$	MPa	normal ^a	$1.3(f_{ck})$	0.18
Concrete compressive strength, f_t^c	MPa	normal ^a	$0.53(f_c)^{0.5}$	0.13
Concrete elastic modulus, E_c^c	MPa	normal ^a	$4600(f_c)^{0.5}$	0.12

^atruncated at 0, ^btruncated at 10mm, ^c $f_c = 1.162f_c(28)$

6.2 Results

6.2.1 Damage probabilities and climate change effects

Figure 3a illustrates the time-dependent probability of severe cracking for the RCP 4.5 climate change scenario and structures built under different construction standards in Saint-Nazaire and Marseille. Although the concrete properties and cover are the same for both locations, probabilities of severe cracking are larger for structures built in Saint-Nazaire. As indicated in Section 2, RH is about 8% larger in Saint-Nazaire than Marseille by increasing water content in the capillary pores and chloride diffusion rate. This higher RH will therefore shorten the time to corrosion initiation by increasing the

probability of severe cracking. It is also observed the effects of the evolution of constructions standards that, for a given time after construction, decrease the probabilities of damage. These results indicate that although increasing design cover is an effective protection for reducing damage induced by chloride ingress, the effectiveness of this measure depends on specific exposure conditions.

For Marseille, climate change projections announce an increase of temperature with respect to year 2000. Figure 3b shows the effects of the climate change scenarios on the probability of severe cracking. As expected, probabilities of severe cracking are larger for RCP 8.5 exposure because higher temperatures accelerate chloride ingress and corrosion propagation (BASTIDAS-ARTEAGA *et al.*, 2011). The effects of the RCP 8.5 scenario are larger for recent structures because the differences in temperatures between both climate change scenarios announced by general circulation models increase after 2050 (Figure 1). As a consequence, for structures built in 1970 the difference of temperature between both climate change scenarios is about 0.7 °C (in 2070) whereas for recent structures (built in 2010), this difference is 1.7 °C (in 2110). From an engineering point of view, RCP 8.5 and RCP 4.5 climate change scenarios could be interpreted respectively as upper and lower bounds for carrying out sensitivity studies.

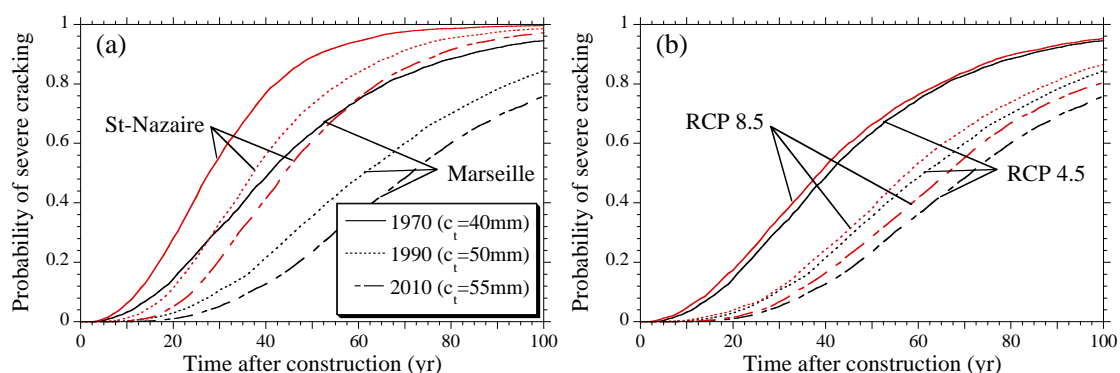


Figure 3. Probability of severe cracking for: (a) structures under the RCP 4.5 scenario, and (b) structures built in Marseille under RCP 4.5 and RCP 8.5 scenarios.

6.2.2 Cost-effectiveness of damage adaptation strategies

Figure 4 shows the mean BCR for several structural components in Marseille and Saint-Nazaire under a RCP 4.5 scenario. These results were obtained for structures built in 2010 and $t_{adapt} = 2020$. The overall behaviour indicates that the mean of BCR is highly dependent on both the location and the type of structural component. The mean BCR is lower for Marseille and small structural components. For most part of structural components in Marseille the mean BCR is lower than 1 indicating that the adaptation strategies are not cost-effective. This means that, for the studied material, current design cover (55 mm) is cost-efficient for Marseille. Contrarily, adaptation strategies are cost-

effective for all components in Saint-Nazaire. Thus, recommendations of current standards and adaptation measures could be more or less adapted to local climate conditions. It is also noted that the mean BCR decreases for small structural components for which the adaptation cost is higher (e.g., Table 1). For both locations, increasing extra cover by 10 mm is less cost-effective. Thus, it is possible to conclude that the mean BCR for the whole structure could be maximised by performing different actions for individual components: (i) optimising the extra cover, (ii) considering different types of adaptation strategies, and/or (iii) doing nothing.

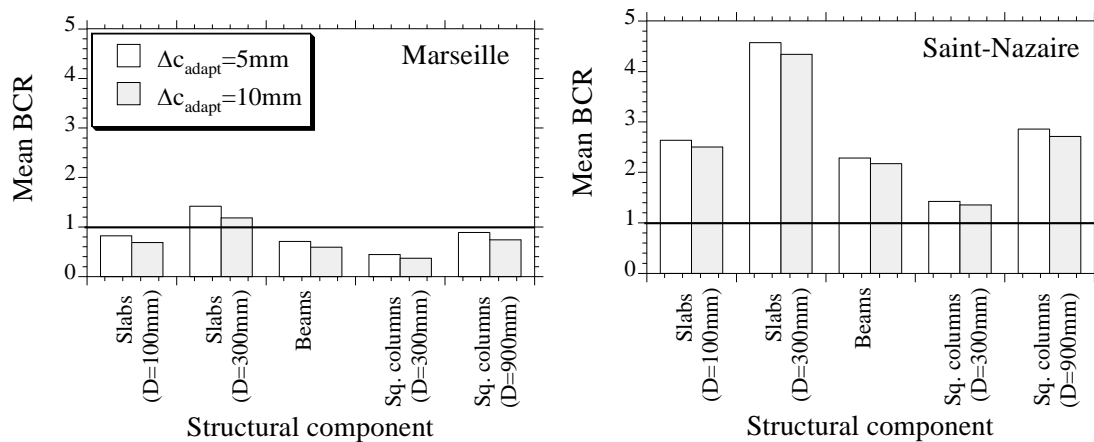


Figure 4. Mean BCR for structural components under a RCP 4.5 scenario.

Figure 5 shows the mean BCR as a function of the construction year for slabs built in Saint-Nazaire. The considered adaptation is $t_{\text{adapt}}=2020$. The BCR is lower than one for the oldest structures and increases for recent ones. A $\text{BCR} < 1$ implies that the adaptation measure is not cost effective for old structures and that the standards recommendations are more cost effective during the structural lifetime. The increase of BCR is due, on the one hand, to the increase of concrete cover recommended by the standards and/or considered by the adaptation measures. This means that larger concrete cover is more convenient for this kind of exposure. The increment of BCR is also related to the increase of climate change effects on deterioration rates that justify the implementation of adaptation measures. Figure 5 also indicates the effects of the climate change scenario. It is noted that higher mean BCR are expected for the RCP 8.5 scenario that announces more important changes with respect to actual climate. The differences between results for both scenarios are larger for recent structures because they will be exposed to the largest climate variations that are announced after 2050 (Figure 1). These climate variations will induce more corrosion damage by increasing the cost-effectiveness of adaptation strategies.

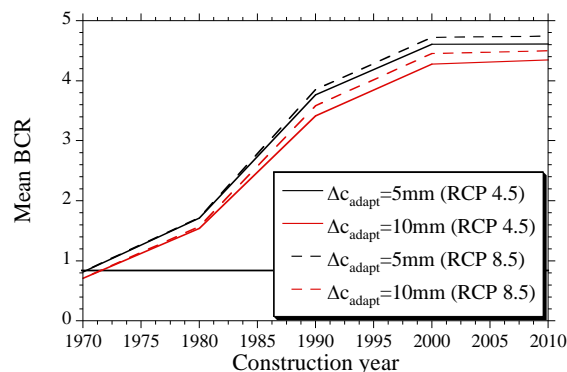


Figure 5. Mean BCR for existing slabs ($D=300$ mm).

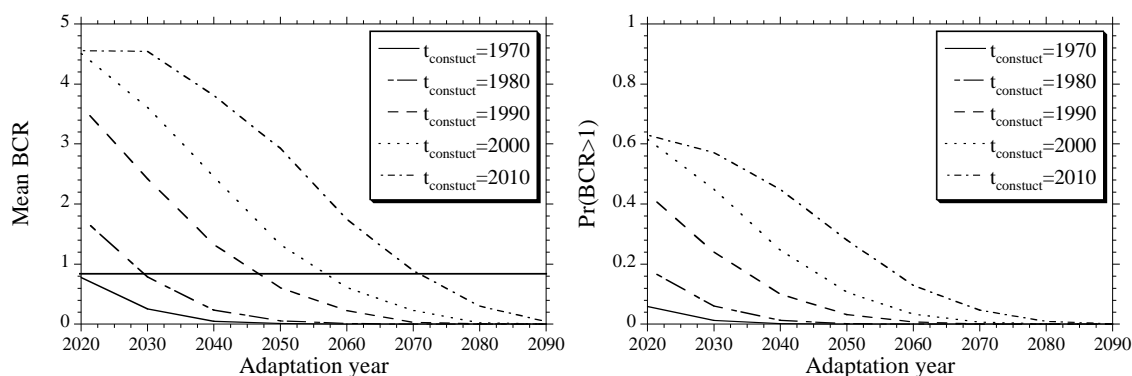


Figure 6. Effect of the adaptation year on the mean BCR and $\Pr(BCR > 1)$.

Figure 6 illustrates the effect of the adaptation year on the mean BCR for slabs ($D=300$ mm) built at several years in Saint-Nazaire for $\Delta c_{\text{adapt}}=5$ mm and the RCP 4.5 scenario. It is noted that both the mean BCR and the $\Pr(BCR > 1)$ decrease when the adaptation year is close to the end of the structural lifetime. There is a year after which the mean BCR is lower than 1 indicating that investments are not cost-effective after given times. These results could be used by an owner/stakeholder to evaluate the benefits and the risks of implementing adaptation strategies at various years. For example, it is observed that mean BCR and $\Pr(BCR > 1)$ are small for older structures and therefore the owner/stakeholder could prioritise investments in adaptation measures for new structures. These curves could be also used to evaluate the risks of the selection of a given adaptation year. For example, for structures built in 2000, if the owner/stakeholder decides to postpone the adaptation actions until 2040 the mean BCR is about 2.5 which is still interesting. However, the $\Pr(BCR > 1)$ for this adaptation time is less than 0.3 indicating that the risks of having no benefits are larger.

7. Conclusions

This paper focused on climate adaptation for existing RC structures built at different years (and therefore under different durability standards), and subject to two different

types of climate in France. The results indicate that although increasing design cover is an effective protection for reducing damage induced by chloride ingress, the effectiveness of this measure depends on specific exposure conditions, the construction and adaptation times.

8. Acknowledgements

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