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Considerations for probabilistic assessment of the effect of global warming on durability of corroding RC structures

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1 INTRODUCTION

Chloride ingress and carbonation lead to corrosion of reinforcing bars that reduces the service life of reinforced concrete (RC) structures. Experimental evidence indicates that carbonation and chloride ingress are highly influenced by the weather conditions of the surrounding environment—i.e., temperature and humidity. According to the International Panel of Climate Change (IPCC, 2007), several changes in the future climate produced by global warming are expected. Consequently, the effect of global warming on both chloride ingress and carbonation should be considered for a comprehensive management of corroding RC structures. Within this context, the objective of this paper is to describe some considerations for estimating the effect of global warming on durability of corroding RC structures.

2 DURABILITY OF CORRODING RC STRUCTURES

The deterioration of RC induced by corrosion involves the interaction between three mechanisms: ingress of the corroding agent—i.e., chlorides or carbon dioxide, corrosion of reinforcing steel and concrete cracking. Chloride ingress is modeled by using a numerical approach that considers the interaction between three physical problems: chloride ingress, moisture diffusion and heat transfer. The carbonation model accounts for: larger carbon dioxide concentrations in urban areas, the effect of temperature and the increase of CO₂ concentration produced by global warming. Both models are used to determine the time to corrosion initiation. After corrosion initiation, the diameter reduction of reinforcing bars is controlled by the corrosion rate. This study considered a time-variant corrosion rate model

where the maximum corrosion rate depends on environmental corrosion aggressiveness.

3 MODELING GLOBAL WARMING ACTIONS

Chloride penetration and carbonation are governed by diffusion coefficients that depend, among other factors, on the surrounding humidity and temperature. Therefore, the assessment of the behavior of corroding RC structures should also include a comprehensive model of weather (humidity and temperature). A simplified model of climate is presented in this study. It accounts for the following aspects: (i) influence of global warming, (ii) seasonal variations, and (iii) random nature of weather. The change of temperature and humidity produced by global warming for the upcoming years is modeled by a linear time-variant function. A sinusoidal function is implemented to take seasonal variations of humidity and temperature into consideration. Taking into account the simplicity of the implementation and the computational time, Karhunen-Loève expansion is used to include the uncertainties related to weather parameters.

On the other hand, the increase of environmental CO₂ concentration produced by global warming will raise carbonation-induced corrosion risks. This phenomenon is difficult to model because it depends on several factors that differ for a particular problem. Therefore, this work uses the Model for Assessment of Greenhouse-gas Induced Climate Change (Wigley et al., 1996) that considers the influence of natural and anthropogenic forcings on CO₂ concentrations.

Global warming is influenced by several factors such as human activities, environmental protection measures, etc. Therefore there are important uncertainties related to the consequences of climate change that come mainly from the lack of knowl-

Table 1. Scenarios of global warming.

Scenario	Description
Without Expected	Climate change is neglected Use of alternative and fossil sources of energy, birthrates follow the current patterns and there is no extensive deployment of clean technologies
Pessimistic	Vast utilization of fossil sources of energy, appreciable growth of population and there are no policies to develop and extend the use of clean technologies

Table 2. Mean and standard deviation of the time to failure for the oceanic environment.

Corrosion aggressiveness	Scenario	Mean (yr)	σ (yr)	Reduction (%)
High	Without	62.2	9.4	0.0
	Expected	61.6	9.1	0.9
	Pessimist	61.4	8.9	1.4
Moderate	Without	124.8	20.3	0.0
	Expected	123.4	19.9	1.1
	Pessimist	122.6	19.7	1.7
Low	Without	411.2	75.5	0.0
	Expected	405.3	75.9	1.4
	Pessimist	401.7	76.3	2.3

edge about the societal policies and the response of the earth before global warming. To account for this uncertainty, this work defines three possible scenarios of global warming. These scenarios are called *without*, *expected* and *pessimistic* global warming (Table 1, Bastidas-Arteaga et al., 2010a).

4 NUMERICAL EXAMPLE

The influence of global warming on the reliability a simply supported RC girder placed in various chloride contaminated environments is illustrated with a numerical example. This analysis included: two environments (oceanic and tropical); three scenarios of global warming (without, expected and pessimistic) and three levels of corrosion aggressiveness (low, moderate and high). Structural reliability was evaluated in terms of the limit state of bending by using Monte Carlo simulations and Latin hypercube sampling. Table 2 presents the computed mean and standard deviation of the time to failure for the studied cases. The maximum reduction in time to failure is 2.3%. However, these results are non-conservative because the implemented corrosion model does not include the effect of global warming after corrosion initiation.

Corrosion rate can be influenced by temperature and humidity, and therefore, should be affected by global warming (Stewart and Peng, 2010). This effect should be taken into account to improve the prediction after corrosion initiation.

5 ADAPTATION STRATEGIES

Adaptation measures may be needed to ameliorate the increased damage risks due to climate change. Time of application is highly variable and dependent on extent and location of corrosion damage. Some adaptation strategies will be applied at time of construction (coatings/surface treatments, reinforcement), others at time of corrosion initiation (realkalization, chloride extraction). Clearly, it is preferable to use adaptation strategies that are implemented during design and construction rather than in-service (e.g., when corrosion damage occurs) as the latter will be much more costly in terms of direct costs and inconvenience/user delays and other indirect costs.

Stewart and Peng (2010) have conducted a preliminary life-cycle cost assessment to assess the cost-effectiveness of increasing design cover as an adaptation measure to mitigate the effects of carbonation of concrete. The preliminary analysis found that life-cycle costs for the current situation ('do nothing'—use existing covers) are lower than life-cycle costs for proposed increases in design cover. This suggests that although enhanced greenhouse conditions will lead to increased carbonation-induced corrosion of RC structures it may not be cost-effective to increase design covers. However, a more detailed assessment of risks, costs, benefits of adaptation measures and environmental impact may reveal a different conclusion.

6 CONCLUSIONS

This study presented some considerations to assess the effects of global warming on the durability of corroding RC structures subjected to chloride ingress or carbonation. This effect could be assessed by implementing deterioration models that take into account the changes in environmental factors (temperature, humidity and CO₂ concentration) produced by global warming. These environmental factors could be altered by climate change. Consequently, the computation of the changes in temperature, humidity and CO₂ concentration should also included in the analysis. All these points are treated in the paper and were illustrated with a numerical example that studies the effects of climate change on the reliability of a RC bridge girder placed in a chloride-contaminated

environment. The results showed that global warming could produce reductions in time to failure of up to 2.3%. Concerning to adaptation strategies that can be used to mitigate the effect of deterioration processes and global warming on structural safety, it is concluded that an optimal adaptation strategy should be selected by considering its risks, costs, benefits and environmental impact.

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