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Development of a tool for corrosion prediction in reinforced concrete structures

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ABSTRACT This article details the operation of a predictive tool for corrosion initiation and propagation in reinforced concrete. Its use is intended for managers and project owners and constitutes a decision-making tool regarding maintenance and repair operations. The developed application consists of a graphical interface developed in Python that allows the user simplified access to various (numerical and analytical) models for estimating the durability of reinforced concrete. The phenomena of carbonation, chloride ion penetration, and associated corrosion propagation are considered. Different mathematical methods allow the user to estimate the various input parameters of the models based solely on the knowledge of the concrete formulation and its environment. Finally, a probabilistic approach (FORM) can be implemented for all the models and allows for the estimation of various values such as the probability of depassivation. A case study on a reinforced concrete bridge is carried out as an example.

Key-words Corrosion initiation, Modelling, Probabilistic approach, Maintenance, Reinforced concrete

I. INTRODUCTION

The maintenance of reinforced concrete structures in civil engineering and maritime works constitutes a significant challenge for project owners tasked with maintaining and repairing existing infrastructures. One of the main causes of failure in reinforced concrete structures is the corrosion of steel reinforcements [1]. This phenomenon is generally described in two stages: the initiation phase and the propagation phase [2]. The concrete that protects the steel reinforcement is an alkaline material with a pH higher than 13 in the case of traditional concrete [3]. Therefore, the steel in the concrete is maintained in passivation conditions that protect it from corrosion (pH > 9, Pourbaix diagram [4]). The initiation phase of corrosion corresponds to the penetration of aggressive species into the concrete that will alter the cementitious matrix. When these species reach the vicinity of the reinforcement, depassivation of the steel occurs, followed by the propagation of corrosion.

The two main phenomena responsible for the initiation of corrosion are chloride ion penetration and carbonation [5]. Sufficient penetration of chloride ions at the level of the reinforcement, whether of marine or other origins, leads to the dissolution of the depassivation film [6].

Carbonation corresponds to the penetration of CO2 into the material and its reaction with the hydrates of the cementitious paste. It causes a decrease in pH and instability of the passive oxide film that protects the reinforcements [7].

Indeed, there is a real need for civil engineers to predict these phenomena to optimise the planning of maintenance and repair operations for reinforced concrete structures. Various durability models [5, 8, 9] can be used to consider these phenomena and the resulting corrosion adequately.

To account for the complexity of phenomena related to the durability of reinforced concrete, as well as the variability of intrinsic material parameters, a probabilistic approach can be used. This type of approach, more advanced than a simple deterministic approach, allows the user to consider the uncertainty of input parameters of a model using distribution laws, and estimate the probability of the occurrence of an event, such as reaching a limit state.

This work aims to develop a tool that combines multiple models and different algorithms to easily predict the time before corrosion initiation in a reinforced concrete structure and the need for maintenance operations. Among these tools, a probabilistic approach using the First Order Reliability Method (FORM) allows the user to estimate the structural reliability associated with the different durability models. The following sections detail the overall functioning of the tool.

II. INPUT DATA

The first step in using the tool is to enter the necessary data to operate all the models. In general, the parameters accessible to users of the tool, namely civil engineers, do not always correspond to the input parameters of advanced numerical models. Therefore, it is necessary to integrate models into the tool which estimate more complex input data from the almost systematically provided formulation and environmental parameters. For the user, the input parameters would be:

- The composition of the concrete: the quantities (and types) of cement, mineral admixtures, aggregates, admixtures, and water;
- Geometry: the cover thickness, the diameter of reinforcement, and the type of steel;
- Environmental conditions: exposure classes [10], relative humidity, temperature, exposure to rain and de-icing salts.

However, if they have the knowledge, it is still possible for the user to input test results or data on the microstructure required for the models' functioning. This aspect is detailed in the following section. Geometry must be provided as a mandatory input as it is necessary and cannot be estimated without experimental measurements.

III. SPECIFIC PROPERTIES

Among the parameters required for the functioning of the different durability models, the application may require:

- The compressive strength of the concrete;

- Data on the composition of the cementitious matrix, including the quantities of hydrates such as portlandite, C-S-H, monosulfoaluminates, and ettringite;
- Transfer properties, such as the desorption isotherm;
- Durability indicators, such as water-accessible porosity and electrical resistivity;
- Quantities associated with durability including natural or accelerated carbonation rate, chloride ion diffusion coefficient, and associated ageing factor.

Therefore, it is necessary to have at least one estimation method based on the formulation parameters for each parameter of paragraph II.

Models described in the literature have been translated into Python and integrated into the application. The porosity model proposed by Powers [11], as well as the hydration model developed by Lacarrière [12] and Kolani [13] are included.

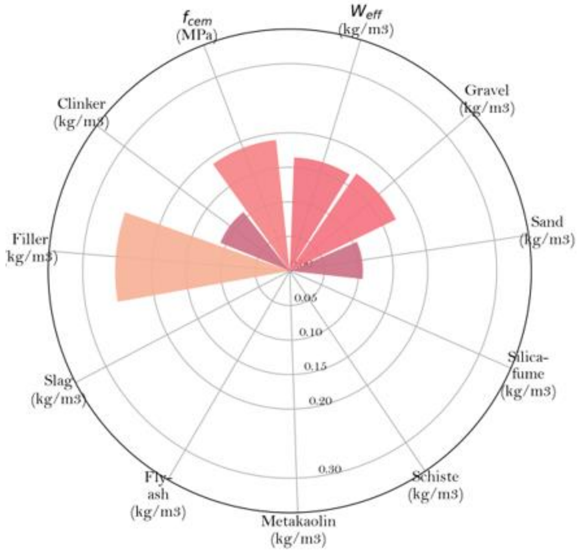

FIGURE 1. Graphical representation of the relative differences (-) computed on the composition parameters of two concrete mixes.

In addition to the models, a database of results extracted from the literature is associated with the application. Currently, it contains results from 54 sources, totalling 1661 concrete formulations for all the parameters integrated into the application. This allows the tool to automatically generate and utilise various regressions (artificial neural networks or polynomial regression) for each of the previously mentioned test results. Moreover, an algorithm allows the identification of concrete materials with parameters close to the one entered by the user. It consists in computing for all mixes of the database, the sum of the absolute relative difference (*SER*) of each formulation parameter (X_i) relative to the studied formulation (using Equation 1). A graphical representation is then proposed to check if the parameter of the database mixes can be used as replacement for the mix entered by the user. An example is displayed in Figure 1.

$$SER = \sum_{i=0}^{n} \frac{\left|\left(X_i^{user} - X_i^{database}\right)\right|}{X_i^{user}} \quad (1)$$

Once all the test parameters are obtained, the user can choose which models to execute for predicting the phenomena of depassivation (and corrosion).

IV. DURABILITY MODELING

To ensure greater accuracy in estimating the depassivation time of reinforced concrete structures or other durability-related parameters, a significant choice of carbonation and chloride ion penetration models has been made available to the user. The goal is to offer a comparative study to verify the consistency of results obtained from different models. For each of these models, a description is provided to the user to enable them to make a choice based on the specific situation they are considering. Each model is developed and validated for one or more specific situations. Therefore, a model utilisation can only be reliably done with the knowledge of its validity domain. An integrated sorting algorithm in the tool assists the user in the selection process by eliminating certain models based on the formulation and environmental data provided by the user.

In this section, computations and predictions are performed on two reinforced concrete bridges subjected to carbonation. The exposure class XC4 defined in the NF EN 206/CN+A2 (2022) [10] is considered, while the materials used are CEM I-based concretes with E/C ranging from 0.47 to 0.56. A confidentiality agreement prevents the revealing of the names and locations of these 2 structures. 6 and 4 zones are investigated on the two bridges respectively. Mean carbonation depth values were experimentally measured after 40 years of exposure on core samples. The tool is first used to verify the precisions of the models on the experimental results, then probabilistic predictions of the time before depassivation are conducted.

Table 1 describes some of the models integrated into the tool, defined as usable for exposure class XC4 [10] and the formulations studied here, along with the probabilistic properties for the PerfDuB model used for the probabilistic approach. The deterministic verifications on the carbonation depths realised on the 10 zones allow the acquisition of the Mean absolute Relative Error (MRE, expressed in %) and Mean Absolute Error (MAE, expressed in mm) shown in Figure 2 for each model.

The results obtained on the different parts show the difference of precision of each model for these cases. The SDReaM-crete model leads to the lowest difference, while the models of Morinaga and Parrott are less accurate in average for these cases. It demonstrates the importance to write guidance for the user concerning the potential of the different models and when it is unadvised to use therm.

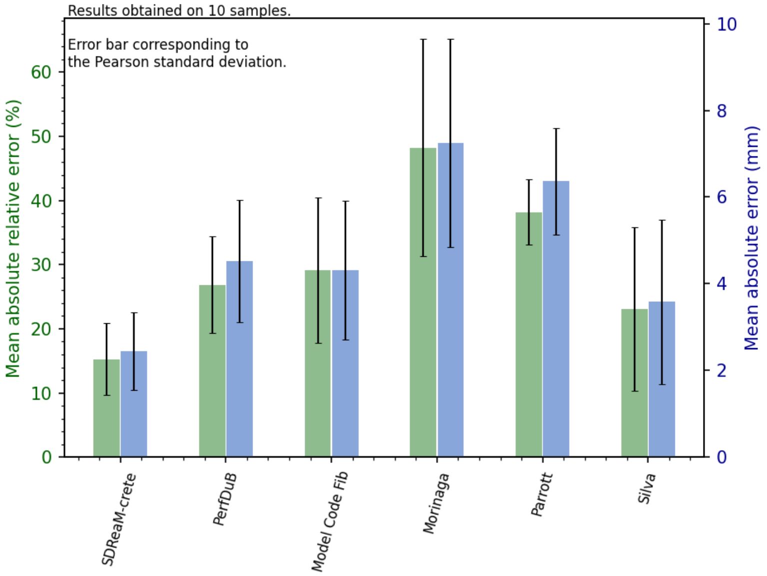

FIGURE 2. MAE and MRE obtained on the 10 structure zones investigated using the different models.

The models presented are all analytical, except for SDReaM-crete (SC 2023), a numerical model (finite element method) [14, 5]. To reduce the long computation time, a surrogate model is constructed using polynomial chaos (R2 = 0.986). It can consider the coupling of carbonation, chloride ion penetration and induced corrosion.

TABLE 1. Means and standard deviations of the different parameters of the carbonation models - μ (σ).

Parameters	Valeurs μ (σ)	SC 2023 [5, 14]	PerfDub 2022 [8]	*fib* 2006 [15]	Parrott 1994 [16]	Morinaga 1990 [17]	Silva 2014 [18]
Rain ratio (-)	0.18 (0.01)		X	X			
P_{CO2} (%)		X		X		X	X
RH (%)	65 (10)	X	X	X	X	X	
Water (kg/m^3)						X	
Cement (kg/m^3)							X
QCaO (kg/m^3)					X		
CH (mol/m^3)		X					
CSH (mol/m^3)		X					
Afm (mol/m^3)		X					
Aft (mol/m^3)		X					
Porosity (-)		X					
Kacc (mm/day$^{0.5}$)	μ_{mat} (0.4)		X	X			
fc (MPa)							X

V. PROBABILISTIC APPROACH

A probabilistic approach using First Order Reliability Method (FORM) can be performed. It allows for estimating the probability of steel depassivation [19]. To simplify the study, normal distributions are considered for all parameters. However, other distributions such as log-normal or beta can be considered in the application as needed. The tool allows the user to make different estimations using this approach. The simplest one is to estimate the evolution of the probability of depassivation over time. The results of this method are shown in Figure 3 for the different zones of the structures presented in Section IV, using the PerfDuB model (2022). A cover thickness of 35 mm, considered with a normal distribution and a standard deviation of 6 mm, is chosen, following the recommendations of the EC2 [20] for a 100-year design life.

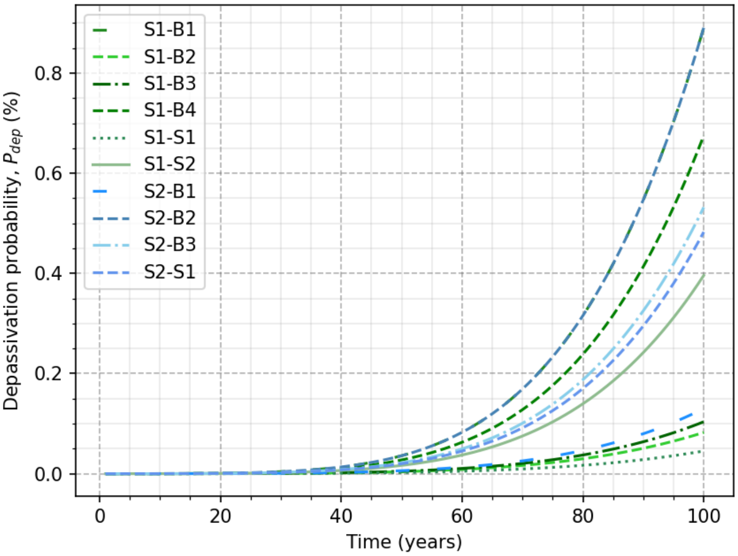

FIGURE 3. Probability of depassivation over time estimated with the PerfDuB model (2022) considering an average cover thickness of 35 mm (FORM).

The results obtained on Figure 3 show the evolution of the depassivation probability for the different parts. The first letter "S" refers to the structure studied, while the second letter designs a strut with the letter "S" and a beam with the letter "B". Extremely low probabilities (P_{dep}) are obtained with the PerfDuB model, even for a time of 100 years. It certainly denotes of the high quality of the concrete used in these environmental conditions, meaning that a lower concrete cover could have been used while keeping a good reliability for the different structure parts. If a new structure is designed, the tool can be used to compute the minimal concrete cover required to withstand aggressions associated to given exposure classes. In this case, a value of depassivation probability is chosen as threshold not to be exceeded. In the example below, a value of P_{dep} equals to 2.28% is selected, which corresponds to a reliability index β of 2. The reliability index is defined such that the probability P_{dep} corresponds to the probability density of β according to a standard normal distribution. The concrete cover required to withstand 50 and 100 years of exposure are computed and exposed in Table 2.

The values of concrete covers obtained show that for all parts, the model PerfDuB previsions would allow a reduction of 2 to 8 mm while keeping a low depassivation probability, even after 100 years. For the design of new structures, this type of computation could permit a reduction of the overall cost and carbon footprint by demonstrating the possibility to reduce the material content needed for certain cases.

TABLE 2. Concrete cover (CC) required to withstand an XC4 aggression for 50 and 100 years computed considering a threshold β of 2.

Part	S1-B1	S1-B2	S1-B3	S1-B4	S1-S1	S1-S2	S2-B1	S2-B2	S2-B3	S2-S1
$CC_{50years}$ (mm)	26.5	23	23.5	26	22.5	25.5	24	26.5	26	25.5
$CC_{100years}$ (mm)	33	28	28.5	32	27	31	29	33	31.5	31.5

VI. CONCLUSION

The work presented above has several objectives. The first one is operational: This kind of tool should allow civil engineers and project owners to save time and costs. Indeed, predictions of indicators associated with the durability of a structure, such as the time before steel depassivation, can help define opportune moments for repairs and maintenance [21]. This work's second objective concerns optimising model utilisation in an operational context. The ability to employ different models simultaneously allows for the comparison of a significant amount of literature works, similar to a state-of-the-art review. Moreover, the developed results database, which includes concretes based on decarbonised binders or recycled concrete aggregates, provides an initial overview of the literature on the durability of these concretes.

Currently, the literature does not report the development of such comprehensive tools for predicting the corrosion of reinforced concrete structures. The development of this tool presents an evident technical advantage due to its nature, but it requires consideration of multiple integrated durability models or mathematical methods for obtaining input and output data. This level of complexity is necessary to ensure greater safety in its use.

The present methodology is developed in the frame of the first author’s Ph.D. and will be publicly available.

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