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Characterization of depth cover randomness in reinforced concrete structures: Study of its influence on the probability of corrosion initiation induced by chlorides penetration

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ABSTRACT. In corrosive environments, cover depth is one of the dominant parameters that controls time to corrosion initiation. Consequently, probabilistic modeling of this variable is essential to determine the performance of structures during the time. In this work, we study the influence of cover depth on probability of corrosion initiation. Towards this aim, we compare the effect of the models commonly used in probabilistic modeling with models determined from image analysis. Preliminary results illustrate the importance of accurate characterization of this random variable for a realistic assessment of structural lifetime.

KEYWORDS: reinforced concrete, corrosion, chloride penetration, image analysis, cover, reliability.

1. Introduction

The reinforced concrete structures located in non aggressive environments respect the structural life predicted. However, the structural durability can be reduced by degradation processes of environmental and/or functional origin like the penetration of chlorides, the carbonation, fatigue, creep, etc. In this work we are interested in the penetration of chloride ions in the concrete which one produces the corrosion of the reinforcements. This process begins when a threshold level of chlorides concentration is reached at the steels of reinforcement. When corrosion begins, the durability of the structure is affected by several phenomena like the reduction of the cross section of the reinforcements, the bursting of the concrete and the loss of adherence between steels and the concrete, as presented in Stewart (2000) and Duprat (2007).

The time of corrosion initiation is the time necessary for the threshold concentration of chlorides reaches the reinforcements. This time depends mainly on the properties of the concrete (coefficient of diffusion, degree of cracking, etc), characteristics of the medium (concentration of chlorides on the surface, temperature, moisture, etc) and the cover as

shown in Bastidas-Arteaga et al (2009). Consequently, knowledge the initiation time of corrosion proves to be essential in order to ensure an optimal level of safety throughout structural life time. The success of this modeling depends on the level of precision of the adopted model as well as the quality of its data input.

This work is address to study the influence of the depth cover on the probability of corrosion initiation. Section 2 describes the method of image analysis used to propose our probabilistic models. The stochastic model to simulate the penetration of ions chloride is presented in section 3. Finally, the influence of choice of the depth cover model on the probability of corrosion initiation is studied in section 4.

2. Characterization of the depth cover randomness

The cover depth is defined by design codes according the environmental conditions which the structure will be exposed (i.e., Eurocode), several studies show the importance to include the randomness of this variable in the estimate of the structural life. According Duracrete (2000), the main source of randomness for the cover is related to the quality of construction. Table 1 collects several models for cover depth used in probabilistic studies on the penetration of ions chloride in the concrete. It is observed that the most used types of distribution are: lognormal, normal and normal truncated. The mean value is evaluated according the value specified in the design codes or defined by the specialists. Generally, the average has a value larger than the value specified in the design. On the other hand, the range of variation of the coefficients of variation COV is very large (between 0.10 and 0.45). This high variability justifies the interest to find a COV value more representative of the reality.

Table 1. Probabilistic models of cover depth

Reference	Distribution	Mean	COV
Duracrete, 2000	Log-normal	VS	0.30
Vu et Stewart, 2000	Normal tr. in 15 mm	VS + 8.6	$\sigma = 14.7$ mm
Vu, 2003	Normal	VS + 3.2mm	$\sigma = 9.5$ mm
Val et Stewart, 2003	Normal	VS + 6mm	$\sigma = 11.5$ mm
Lounis, 2005	Normal	VR	0.45
Duprat, 2007	Log-normal	VS	0.10-0.20
Val et Trapper, 2008	Normale tr. à 10 mm	VS + 6mm	0.25
Sudret, 2008	Log-normal	VS	0.20
Suo et Stewart 2009	Normal	VS + 3.2mm	$\sigma = 9.2$ mm

VS : Value specified in design code or for specialist.

VR : real value.

This study contributes to the characterization of the variable cover depth. The data used for this characterization are digital photographs coming from a building site of the Atlantic Port of Nantes St Nazaire (figure 1a). The figure 1a shows beams used for the data acquisition, where we can observe the lower part of these beams was demolished by hydrodémolition (water with high pressure). The cell of competences IXEAD of the

company CAPACITIES, subsidiary of the University of Nantes, developed Visiodefect®, a numerical tool in Matlab® which makes possible a semi-automatic analysis of images (figure 1b).

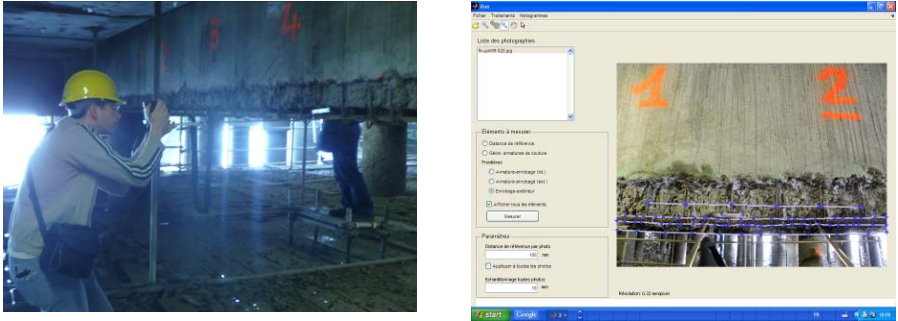


Figure 1. (a) Specimens for the data acquisition. (b) Visiodefect.

The values of depth cover evaluated using visualdefect have 36.2 mm as mean value and 8% of COV. The minimum and maximum values are 27 mm and 37 mm respectively.

3. Probabilistic modeling of the ions chlorides penetration

3.1. Penetration of ions chloride in the concrete

The penetration of ions chloride in the concrete is controlled by a complex interaction between physical and chemical mechanisms which were often simplified by problems controlled only by diffusion phenomenon (second Fick's law). Moreover, most studies use a simplified solution of the Fick's law which one estimates the concentration of ions chloride in a point and on a date specified starting from the function of error complementary, Tuutti (1982). This classical approach of the diffusion regards the apparent coefficient of diffusion as constant in time and homogeneous in space, it supposes the concentration of ions chloride in the environment as constant and it admits the concrete in saturated condition. This simplified approach thus comprises several limits like the taking into account the convection phenomenon, important in non-saturated environment (spray, marling). In the extension in work of Sætta et al (1993) and Martín-Pérez et al (2001), Bastidas-Arteaga et al. (2009) it were presented a wide model which considers the interaction between three physical phenomena: (I) penetration of ions chloride, (II) diffusion of moisture and (III) heat transfer. The coupled phenomenon is described by a set of partial derivative equations which is solved by mixing methods with the differences and the finite elements. This approach takes into account:

- capacity of fixing ions chloride (i.e the interaction between ions chloride and the products of cement paste hydration);

- the nature random in time and the influence of the temperature, moisture and the concentration of ions chloride in the environment;
- the modification (reduction) of the diffusivity of ions chloride in the concrete with it age and;
- the flow of ions chloride in unsaturated medium.

In this article, we will exploit this model but will not detail its formulation.

3.2. Probability of corrosion initiation

The time of corrosion initiation, t_{ini} , is generally evaluated as the moment when the concentration of ions chloride in a depth equal to cover thickness, C_t , is higher than a limit value, C_{th} . For this event, the function of absolute limit becomes:

$$g(\underline{x}, t) = C_{th}(\underline{x}) - C_{tc}(\underline{x}, t, C_t) \quad [1]$$

where \underline{x} is the vector of basic random variables and $C_{tc}(\underline{x}; t; C_t)$ is the total concentration of ions chloride in depth C_t at time t , obtained by resolution of the system of equations that controls the penetration of ions chloride. The evaluation of the limit state function [1] led to the probability of corrosion initiation defined by:

$$p_{corr}(t) = P[g(\underline{x}, t) \leq 0 | t] \quad [2]$$

Due the non-linearities and the complexity of the system of partial derivative equations, the methods of simulations seem most suitable to solve the problem. To reduce the computational time consuming, this study combines simulations by the Monte Carlo method and sampling by Latin Hypercube.

4. Influence on the probability of corrosion initiation

The probability of corrosion initiation is evaluated based on the probabilistic models presented in table 3. The influence of climatic conditions on the chlorides penetration is considered taking into account that the structure is placed in a oceanic climate with a temperature varying from 5 to 25 °C, with a relative humidity between 0.6 and 0.8. The stochastic nature of the climatic conditions and the chloride concentration in the environment is integrated into the problem using the methodology presented in Bastidas-Arteaga et al (2009). Figure 5 presents achievements (trajectories of the process) of the temperature and concentration of ions chloride in the environment. To model the

temperature, a stochastic disturbance is added to a sinusoidal deterministic tendency of the seasonal variations, by using a discretization of Karhunen-Loève, Ghanem et al (1991). The truncated discretization established in this calculation includes 30 terms and the length of correlation is 0.1 year. As several studies indicate that the concentration of ions chloride in the environment, C_{env} , follows a lognormal distribution, as presented in Vu et al (2000) and Duracrete (2000), our work adopts a stochastic process generated by independent numbers according to a lognormal law (rustled lognormal). The mean is of 6 kg/m³ and it corresponds to the limit between the high and severe levels of corrosive environment, Weyers (1994). A coefficient of variation of 0.2 is considered.

The other assumptions are:

- the isotherm of Langmuir is used to determine the connection of chlorides; the coefficients are $\alpha_L=0.1185$ and $\beta_L=0.09$;
- the dates of repair are given with the assumption of penetration of ions chloride following one dimension;
- the first repair is carried out after 15 years of exposure for all the techniques of repair and;
- the random variables are independent and not varying spatially and their characteristics are presented in table 2. The explanation of the choice of the presented values is detailed in Bastidas-Arteaga et al (2009).

Table 2. *Randon variables*

Variable	Unit	Distribution	Mean	COV
– Reference chloride diffusion coefficient, $D_{c,ref}$	m ² /s	log-normal	$3 \cdot 10^{-11}$	0.20
– Concentration threshold of corrosion initiation, C_{th}	wt% cim	normal	.48	0.30
– Activation energy of the chloride diffusion process, U_c	kJ/mol	beta sur [32;44.6]	41.8	0.10
Aging factor, m		beta sur [0;1]	0.15	0.30
– Reference humidity diffusion coefficient, $D_{h,ref}$	m ² /s	log-normal	$3 \cdot 10^{-10}$	0.20
– Parameter representing the ratio $D_{h,min}/D_{h,max}$, α_0		beta sur [0.025;0.1]	0.05	0.20
– Parameter characterizing the spread of the drop in D_h , n		beta sur [6;16]	11	0.10
– Thermal conductivity of concrete, λ	W/(m°C)	beta sur [1.4;3.6]	2.5	0.20
– Specific heat capacity of concrete, c_q	J/(kg°C)	beta sur [840;1170]	1000	0.10
– Density of concrete, ρ_c	kg/m ³	normal	2400	0.20

In order to study the randomness influence of depth cover on the probability of the corrosion initiation, we compare seven models of random variables. The description of these models is presented in table 3. In this work, one is interested, initially, in the impact of the type of distribution by comparing the distributions generally used in the literature. We will also study the effect of a Beta limited type distribution on the values maximum and minimum found. For all cases, the mean value is equal to value identified from the image analysis (36.2 mm). The coefficients of variation for the models B1, B2 and B3 were defined according to the values announced in table 1 and for the models E1, E2, E3 and E4, one used the values determined in section 2.

Name	Distribution	Mean (mm)	COV
B1	Log-normal	36.2	0.30
B2	Normal	36.2	0.30
B3	Normal truncated in 15 mm	36.2	0.30
E1	Log-normal	36.2	0.08
E2	Normal	36.2	0.08
E3	Normal truncated in 27 mm	36.2	0.08
E4	Beta sur [27;47]	36.2	0.08

Tableau 3. *Nomenclature et modèles de la profondeur de l'enrobage comparés.*

The evolution of the probabilities of corrosion initiation for the different models of depth cover is presented in figure 2. It is obvious that the coefficient of variation of C_t influence strongly the probabilities of corrosion initiation. For the models B1, B2 and B3, we observe that p_{corr} increases earlier and progresses in a low rate. The more critical case corresponds to model normal (B2) where the increase begins two years after. This behavior was awaited because a normal distribution, with coefficient of variation of 30%, gives small or negative values without any physical signification. The normal truncated or lognormal distributions do not present this type of problems. Moreover, it is remarked that the type of distribution does not influence the probability of corrosion initiation when we use the values determined with the image analysis because the COV is small.

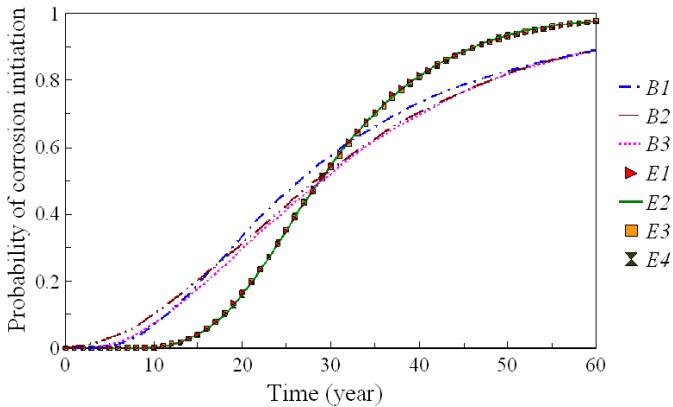


Figure 2. *Influence of the depth cover model on the probability of corrosion initiation.*

The results presented show the importance of an accurate characterization of the randomness of depth cover. By comparing the models proposed in the literature, we conclude that distributions: normal truncated, lognormal normal and beta can be used to model this random variable. Preferably, we recommend use beta limited distribution since it enables us to establish boundaries respecting a physical signification. About the coefficient of diffusion, we identified coefficients lower than those available in the literature. However, the COV presented in this article can not be general because it is specific to a category of works carried out under specific conditions: one could imagine, from the point of view of regulation, which this code may be grouped in classes. Due the importance of this parameter in the estimate of the structural life, we hope to carry out other measurements to supplement this study. The measurement of C_t by nondestructive methods can also help with the identification of randomness of this variable. These techniques can be also used as procedure of control of C_t , because the construction is completed. We recommend decreasing the COV of the depth cover by increasing the control during the process of construction.

5. Conclusions

In this work, we study the influence of the depth cover randomness on the probability of corrosion initiation in a structural component. For this study we used a robust model of chlorides penetration to compare the probabilistic models obtained from the image analysis with those available in the literature. The results show the importance of the accurate characterization of the depth cover randomness for more realistic estimation of the structural life time.

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