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# USE OF IMAGE PROCESSING FOR STRUCTURAL COMPUTATION UP-DATING DURING REPAIR WORKS OF CONCRETE STRUCTURES

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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.

## 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 focus on 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 as the reduction of the cross section of the reinforcements, the cracking of the concrete and the loss of adherence between steels and the concrete (Stewart, 2000; 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 environment (concentration of chlorides in the surface, temperature, moisture, etc) and the cover as shown in Bastidas-Arteaga *et al.* (2009). Consequently, the assessment of the initiation time of corrosion is essential to ensure an optimal level of safety throughout structural lifetime. 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 studies the influence of the cover depth 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 to the environmental conditions at which the structure will be exposed (i.e., Eurocode). Several studies show the importance of including the randomness of this variable in the assessment of the structural lifetime. According to Duracrete (2000), the main source of randomness for the cover is related to the quality of construction. Table 1 gathers several models for cover depth used in probabilistic studies on the penetration of chlorides in concrete. It is observed that the most used types of distribution are: lognormal, normal and normal truncated. The mean value is evaluated according to the value specified in the design codes or defined by the specialists. Generally, the mean 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 in determining a COV 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	Normal 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 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 the beams used for the data acquisition, where we can observe that the lower part of these beams was demolished by hydrodemolition (water with high pressure). The group IXEAD of the company CAPACITES-University of Nantes, developed Visiodefect®, a numerical tool in Matlab® which makes possible a semi-automatic analysis of images (figure 1b).

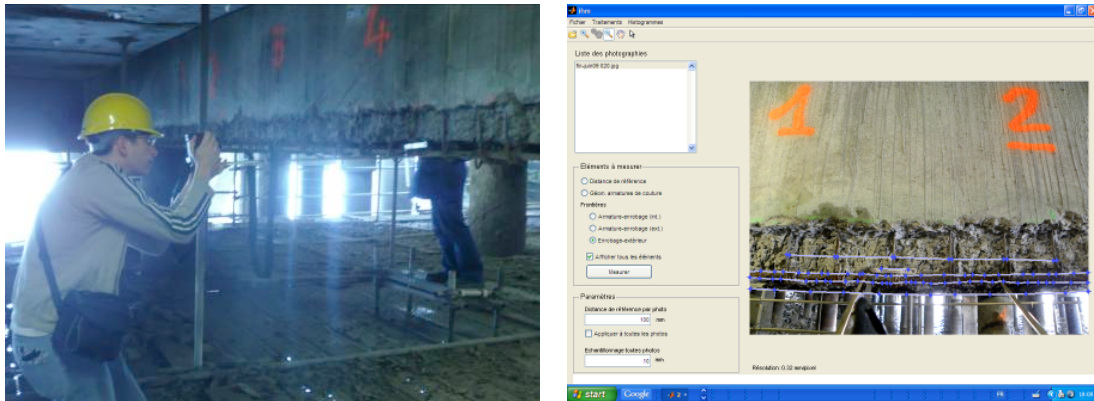


Figure 1. (a) Specimens for the data acquisition. (b) Visiodefect.

Few trajectories of values of depth cover  $c(x, \theta_i)$  (where  $\theta$  is the hazard) evaluated using Visiodefect are presented on figure 2: they represent the evolution of the cover depth along a 1,2 meter long portion of four concrete beams. They have been measured during the repair of the Agri-foodstuffs terminal of the port of Nantes Saint-Nazaire. This terminal is part of the port of Nantes Saint-Nazaire (fourth largest port in France) which is linked to 400 ports worldwide. This wharf was built in 1971 and is located at the west of France (Montoir de Bretagne) in the estuary of the Loire River. Note that the scatter is large (from 30 to 50 mm). However the trajectories  $\mu(x)$  of the mean value and  $\sigma(x)$  of the standard deviation are stable (see figure 2). The average  $\mu$  of the mean values of the cover depth is 38.2 with a standard deviation of 1.4, thus the coefficient of variation is only 3.7% when the average  $\sigma$  of the standard deviation values of the cover depth is 5.7 with a standard deviation of 1, thus the coefficient of variation is 18%. This large value comes from the fact that 4 trajectories are not enough from statistical point of view. In further studies, this analysis will be deepened in view to analyze more in detail the random field of cover depth and analyze its second order stationnarity (correlation is a function of the distance between measurements only).

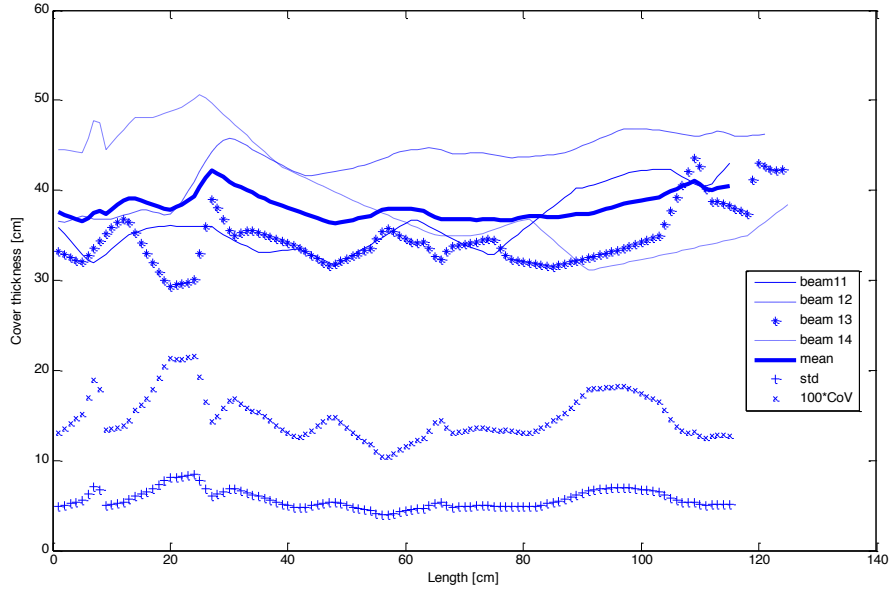


Figure 2. Trajectories of cover depth.

### 3 PROBABILISTIC MODELING OF THE IONS CHLORIDES PENETRATION

#### Penetration of ions chloride in concrete

Chloride penetration in concrete is controlled by a complex interaction between physical and chemical mechanisms which are often simplified as diffusion phenomenon (second Fick's law). Many studies use a simplified solution of the Fick's law which estimates the concentration of chlorides from the complementary error function (Tuutti, 1982). In this classical approach, the diffusion coefficient is constant in time and in space, supposes that the concentration of chlorides in the environment is constant and is only valid for saturated conditions. Thus, this simplified approach does not consider the convection phenomenon which is important in non-saturated environments. Based on the works of Saetta *et al* (1993) and Martín-Pérez *et al* (2001), Bastidas-Arteaga *et al.* (2009) presented a comprehensive model which considers the interaction between three physical phenomena: (i) penetration of chlorides, (ii) diffusion of moisture and (iii) heat transfer. The coupled phenomenon is described by a set of partial differential equations which is solved by combining finite element and finite difference methods. This approach takes into account:

- chloride binding capacity;
- the time-variant nature and the influence of the temperature, moisture and the concentration of chlorides in the environment;
- the reduction of the chloride diffusivity with age and;
- the flow of chlorides in unsaturated media.

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

#### Probability of corrosion initiation

The time of corrosion initiation,  $t_{ini}$ , is generally evaluated as the time at which the concentration of chlorides at the cover thickness,  $c_t$ , is higher than a threshold value,  $C_{th}$ . For this event, the limit state function is:

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

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

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

Taking into account the complexity of the system of partial differential equations representing the phenomenon, simulations methods seem most suitable to solve the problem. To reduce the computational time, this study combines Monte Carlo simulations and Latin Hypercube sampling.

#### 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 chlorides penetration is considered taking into account that the structure is placed in an oceanic climate with a temperature varying from 5 to 25 °C and 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). To model temperature and humidity, a stochastic perturbation is added to a sinusoidal deterministic tendency that represents the seasonal variations, by using a discretization of Karhunen-Loève. 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 (lognormal noise). The mean to generate this noise is 6 kg/m<sup>3</sup> and 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 consider chloride binding; the coefficients are  $\alpha_L=0.1185$  and  $\beta_L=0.09$ ;
- the random variables are independent, do not vary 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. Random variables

Variable	Unit	Distribution	Mean	COV
– Reference chloride diffusion coefficient, $D_{c,ref}$	m <sup>2</sup> /s	log-normal	$3 \cdot 10^{-11}$	0.20
– Concentration threshold of corrosion initiation, $C_{th}$	wt% cim	normal	0.48	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 <sup>2</sup> /s	log-normal	$3 \cdot 10^{-10}$	0.20
– Parameter representing the ratio $D_{h,min}/D_{h,max}$ , $\alpha_0$		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, $\lambda$	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, $\rho_c$	kg/m <sup>3</sup>	normal	2400	0.20

In order to study the influence of the randomness of cover depth on the probability of corrosion initiation, we compare seven models of random variables. The description of these models is presented in Table 3.

This study focuses, initially, on 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 distribution limited between the values maximum and minimum measured experimentally. For all cases, the mean value is equal to 36.2 mm which is a conservative value of the one identified from the image analysis (38,2) due to its standard deviation of 1.4 mm. The coefficients of variation for the models B1, B2 and B3 were defined according to the values showed in Table 1. For the models E1, E2, E3 and E4, we use the mean and COV determined in section 2.

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 with a low rate. The more critical case corresponds to model normal (B2) where the increase begins two years after exposure. This behavior was expected because a normal distribution, with coefficient of variation of 30%, gives small or negative values without any physical sense. The normal truncated or lognormal distributions do not present this type of problems. Moreover, it is noted 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.

Table 3. Nomenclature and description of the compared cover depth models

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

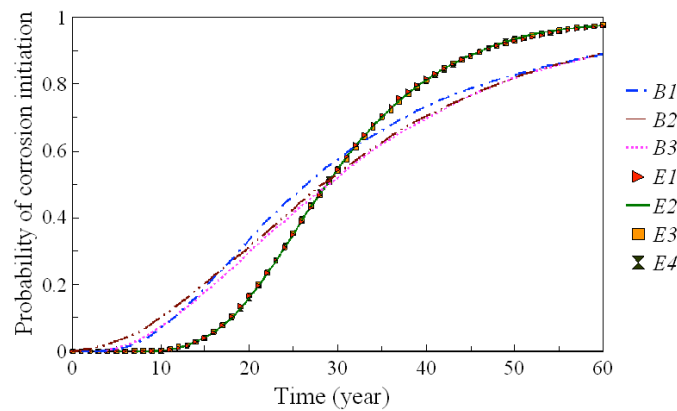


Figure 2. Influence of the depth cover model on the probability of corrosion initiation.

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 a beta distribution because it allows us to establish boundaries that follow a physical signification. About the coefficient of variation, we identified coefficients lower than those available in the literature. However, the COV presented in this article is specific to a category of works carried out under determined conditions and cannot be used in all cases. We could imagine, from a regulation point of view, that a construction code may give values grouped in classes. Due the importance of this parameter in the assessment of structural lifetime, we hope to carry out other measurements to complement this study. The measurement of  $c_t$  by nondestructive methods can also help with the identification of randomness of this variable. These techniques can also be used as procedure of control of  $c_t$  when the construction is completed. We recommend decreasing the COV of the cover depth by increasing the control during the process of construction.

## CONCLUSIONS

In this work, we study the influence of the randomness of the cover depth on the probability of corrosion initiation in a structural component. For this study we used a robust model of chloride 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 randomness of the cover depth for more realistic estimation of structural lifetime.

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