



## NRC Publications Archive Archives des publications du CNRC

### **Probability-based modeling of chloride-induced corrosion in concrete structures including parameters correlation**

Lounis, Z.; Saassouh, B.; Zhang, J. Y.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. / La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

#### **Publisher's version / Version de l'éditeur:**

*Applications of Statistics and Probability in Civil Engineering*, pp. 1206-1212, 2011-07-15

#### **NRC Publications Record / Notice d'Archives des publications de CNRC:**

<https://nrc-publications.canada.ca/eng/view/object/?id=f762b18e-15b3-4d12-b6f1-acd12652fbb7>

<https://publications-cnrc.canada.ca/fra/voir/objet/?id=f762b18e-15b3-4d12-b6f1-acd12652fbb7>

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at

<https://nrc-publications.canada.ca/eng/copyright>

READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site

<https://publications-cnrc.canada.ca/fra/droits>

LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

**Questions?** Contact the NRC Publications Archive team at

PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

**Vous avez des questions?** Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.





## **Probability-based modeling of chloride-induced corrosion in concrete structures including parameters correlation**

---

### **NRCC-53612**

Lounis, Z.; Saassouh, B.; Zhang, J.Y.

September 2011

A version of this document is published in / Une version de ce document se trouve dans:  
11th International Conference on Applications of Statistics and Probability in  
Civil Engineering, ETH, Zurich, Switzerland, August 1-4, 2011, pp. 1206-1212

The material in this document is covered by the provisions of the Copyright Act, by Canadian laws, policies, regulations and international agreements. Such provisions serve to identify the information source and, in specific instances, to prohibit reproduction of materials without written permission. For more information visit <http://laws.justice.gc.ca/en/showtdm/cs/C-42>

Les renseignements dans ce document sont protégés par la Loi sur le droit d'auteur, par les lois, les politiques et les règlements du Canada et des accords internationaux. Ces dispositions permettent d'identifier la source de l'information et, dans certains cas, d'interdire la copie de documents sans permission écrite. Pour obtenir de plus amples renseignements : <http://lois.justice.gc.ca/fr/showtdm/cs/C-42>



National Research  
Council Canada

Conseil national  
de recherches Canada

Canada



# Probability-Based Modeling of Chloride-Induced Corrosion in Concrete Structures including Parameters Correlation

Z. Lounis, B. Saassouh, and J. Zhang  
*National Research Council Canada*

**ABSTRACT:** This paper presents a practical approach for probabilistic modeling of chloride-induced corrosion of steel reinforcement in concrete structures based on the first-order reliability method (FORM). The method enables to take into account the uncertainties in the parameters that govern the physical models of chloride ingress into concrete and corrosion of carbon steel including concrete diffusivity, concrete cover depth, surface chloride concentration and threshold chloride level for onset of corrosion. The governing parameters are modelled as random variables with different levels of correlation and the probability of corrosion is determined and compared to the predictions obtained by more rigorous approaches, such as second-order reliability method (SORM) and Monte Carlo simulation (MCS). The approach is applied to predict the level of corrosion in the top layer of reinforcing carbon steel of a highway bridge deck that was exposed to chlorides from deicing salts. The results illustrate the accuracy and efficiency of FORM when compared to SORM and MCS. The paper also shows that the impact of correlation between the chloride diffusivity and chloride threshold level on the corrosion probability is negligible and can be ignored.

## 1 INTRODUCTION

In porous solids, such as concrete structures, chlorides can penetrate into concrete via different physical mechanisms, such as diffusion, capillary absorption, etc. which lead to the corrosion of the steel reinforcement.

The corrosion of the steel reinforcement leads to concrete fracture through cracking, delamination and spalling of the concrete cover, reduction of concrete and reinforcement cross sections, loss of bond between the reinforcement and concrete, and reduction in strength and ductility. As a result, the safety and serviceability of concrete structures are reduced.

In the last decades, the Fickian diffusion process were used to model the chloride diffusion and by consequence, modeling the initiation time to corrosion using the concept of chloride threshold as an indicator of corrosion resistance of reinforcing steel to chloride attack. Therefore, the governing parameters of this diffusion-based corrosion model include the concrete cover depth, chloride diffusion coefficient, surface chloride concentration, and chloride threshold level (Zhang and Lounis, 2006).

In practice, the design of durable concrete structures is mainly based on specifying a minimum concrete cover depth (depending on the environmental exposure), a maximum water-to-cement ratio (to

achieve low chloride diffusivity), and as well the use of more corrosion resistant reinforcing steels.

However, a considerable level of uncertainty may be associated with one or more of the above identified parameters. This is due to: (i) heterogeneity and aging of concrete with temporal and spatial variability of its chloride diffusivity; (ii) variability of concrete cover depth, which depends on quality control, workmanship and size of structure; (iii) variability of surface chloride concentration, which depends on the severity of the environmental exposure; and (iv) uncertainty in chloride threshold level that depends on the type of reinforcing steel, type of cementing materials, test methods, etc. (Alonso 2000). It is clear that the combination of these uncertainties leads to a considerable uncertainty in the model output (e.g. the time to corrosion initiation). This uncertainty in the model output could have serious consequences in terms of reduced service life, inadequate planning of inspection and maintenance and increased life cycle costs.

The objective of this paper is twofold: first to present a simplified probabilistic model for corrosion initiation based on the first-order reliability method (FORM) where the impact of parameter correlation on the probability of corrosion is investigated; and second is to assess the accuracy of FORM for

modeling the corrosion by comparing its predictions to the second order reliability method and Monte Carlo simulation. Through an illustrative example, the service life is modeled for a reinforced concrete highway bridge deck exposed to deicing salts during winter.

## 2 CHLORIDE TRANSPORT PROBLEM

### 2.1 Chloride diffusion process

The main transport mechanisms of chlorides into concrete are diffusion and adsorption. However, adsorption occurs in concrete surface layers that are subjected to wetting and drying cycles, and it only affects the exposed concrete surface down to 10-20 mm (Weyers et al. 1993; Tuutti 1996). Beyond this adsorption zone, the diffusion process will dominate (Tuutti 1996, DuraCrete 1997). Chloride diffusion is a transfer of mass by random motion of free chloride ions in the pore solution, resulting in a net flow from regions of higher to regions of lower concentration (Crank 1975). The rate of chloride ingress is proportional to the concentration gradient and the diffusion coefficient of the concrete (Fick's first law of diffusion). Since in the field, chloride ingress occurs under transient conditions, Fick's second law of diffusion can be used to predict the time variation of chloride concentration for one-dimensional flow, it can be expressed as a relationship between the diffusion coefficient and the gradients of concentration, by direct analogy with the equations of heat conduction (Crank 1975, Fick 1855, Zhang et Al. 2006):

$$\frac{\partial C_{x,t}}{\partial t} = \frac{\partial}{\partial x} \left( D \frac{\partial C_{x,t}}{\partial x} \right)$$

where  $C_{x,t}$  is the concentration of chlorides at depth  $x$  and time  $t$ ;  $D$  is the diffusion coefficient. Under the assumptions of a constant diffusion coefficient, constant surface chloride content  $C_s$  as the boundary condition, and the initial condition specified as  $C=0$  for  $x>0$ ,  $t=0$ , Crank's solution yields (Crank 1975):

$$C_{x,t} = C_s \left( 1 - \operatorname{erf} \frac{x}{2\sqrt{Dt}} \right)$$

where  $\operatorname{erf}(\cdot)$  is the error function.

In the modeling of chloride ingress as Fickian process, the following assumptions are made:

- The phenomena of capillary flow, chloride binding (chemical reaction that some of the

chlorides within the concrete) are not considered.

- Using Crank's solution for a plane sheet assumes dealing with plane isotropic concrete structures (one dimensional diffusion)
- The diffusion coefficient and surface chloride concentration are assumed constant
- The initial concentration of chlorides in the concrete is negligible.
- Interaction with other ions and with electrical double layer is ignored (Chatterji, 1995).

Some of these conditions do not apply, for many reasons. For example, the diffusion coefficient cannot be constant because:

- a) Concrete is not homogenous;
- b) Moisture is unlikely to be uniform;
- c) Chlorides are bound by cement hydrates;
- d) It is influenced by the concentration of chlorides ; and
- e) Chloride binding changes with time.

Therefore, the diffusion coefficient is often referred to as the "apparent" diffusion coefficient and the surface concentration is termed the effective surface concentration.

### 2.2 Corrosion initiation

Corrosion in concrete structures can be described as a two stage process (Tuutti 1982): (i) corrosion initiation; and (ii) corrosion propagation. The corrosion initiation stage corresponds to the process of chloride ions (chlorides) ingress into concrete (and/or carbonation) while the steel remains passivated. The corrosion propagation stage starts after the initiation of active corrosion. The corrosion initiates when the amount of chloride (in contact with the steel) is high in such a way to destroy the passivation of the steel. Therefore, the corrosion of the reinforcing steel is assumed to start when the concentration of chlorides at the level of the reinforcement has reached a so-called "chloride threshold"  $C_{th}$  (Tuutti 1982). Therefore, the duration of the initial stage, which is often used as a quantitative indicator of service life or durability of concrete structures, depends on the rate of chloride penetration in concrete.

Ideally, the corrosion initiates at time  $\tilde{T}_i$  at which the concentration of chlorides at the steel level becomes equal or greater than the chloride threshold ( $C_{th}$ ):

$$C_{d,\tilde{T}_i} \geq C_{th}$$

Where  $d$  represents the concrete cover depth of the steel. From this equation, the approximated initiation time to corrosion can be deduced as follows:

$$\bar{T}_i = \frac{d^2}{4D \left[ \operatorname{erf}^{-1} \left( 1 - \frac{C_{th}}{C_s} \right) \right]^2}$$

In this deterministic model, the four parameters are assumed as four independent design parameters that are critical for corrosion protection: (i) structural parameter: concrete cover depth  $d$ ; (ii) material parameters: chloride diffusion coefficient  $D$ , which is an indicator of the rate of chloride penetration into concrete, and chloride threshold value  $C_{th}$ , which is an indicator of the corrosion resistance of reinforcing steel; and (iii) environmental parameter: surface chloride concentration  $C_s$ , which is a measure of the corrosivity or load or exposure risk of concrete structures.

Given the inherent complexity and heterogeneity of concrete as a corrosion medium, there exists large uncertainty in the above mentioned parameters and in the proposed model.

In the following sections, practical approaches to model the above uncertainties are presented taking into account the correlation that may exist between parameters. The next section exposes the physical correlation between the model parameter.

### 3 PHYSICAL CORRELATION OF PARAMETERS

In concrete mix design, it is well understood that both water/cement ( $w/c$ ) ratio and the chemical compositions of cementing binding materials, particularly of the use of supplementary mineral admixtures such as silica fume and slag, are key factors for the development of high performance concrete with good properties. The use of low  $w/c$  ratio directly reduces the porosity and refines the pore structure, and therefore reduces the permeability of concrete and other transport indices such as  $D$ . Jensen et al. (1999) observed that  $D$  was a direct function of the paste porosity and can be reduced by a factor of 50 by a drop of the  $w/c$  ratio from 0.7 to 0.2 in the cement paste.

It has been found that the use of mineral admixtures improves the pore structures of concrete, such as pore closure, pore size distribution and a finer pore structure. Hassan et al. (2000) showed that the porosity of condensed silica fume concrete was 25%

lower than that of ordinary Portland cement concrete. Silica fume was also found to : (i) have the powder filling effect in concrete mixes (Li et al. 1999); (ii) modify the inherent nano-structure of C-S-H (hydrate); and (iii) reduce its porosity and thus increasing the resistance to chloride diffusion (Bentz et al. 2000). Besides these physical properties, the use of mineral admixtures was also found to increase binding of chloride binding effect by forming more Fiedel's salt (Glass and Buenfeld 2000). For example, the diffusion rate in concrete using ordinary Portland cement could be reduced to 2-5 times by the use of mineral admixtures, especially slag cement (Gjorv, 1995); a replacement of silica fume by 10% of Portland cement would reduce the chloride diffusivity 15 times (Bentz et al., 2000). The following mechanisms are summarized from literature.

The lowering of  $w/c$  ratio and use of mineral admixtures lead to the beneficial effect of reducing chloride diffusion coefficient; however, they may have parting effects on the chloride resistance of embedded steel. The effect of reducing  $w/c$  ratio would increase the chloride threshold level (Pettersson, 1996), because a low  $w/c$  ratio helps to stabilize the micro-environment at the depth of the reinforcement as the moisture permeability decreases. The effect of using mineral admixtures, on the other hand, may reduce the chloride threshold. Most of the mineral admixtures are involved in the hydration process through the pozzolanic reaction ( $\text{Pozzolan} + \text{CH} + \text{H} \rightarrow \text{C-S-H}$ , in which CH represents  $\text{Ca}(\text{OH})_2$  and H represents  $\text{H}_2\text{O}$ , and C-S-H is the hydrate), where the calcium hydroxide is consumed and thus the level of pH could be reduced compared to ordinary Portland cement concrete. A reduced pH level means a reduction in the threshold concentration of chlorides required to break the passive film; Page and Vennesland (1983) have found that the concentration of  $\text{OH}^-$  was substantially lowered for increasing replacement of a normal Portland cement with silica fume. Bentz et al. (2000) reported that for 15% to 20% cement replacement by silica fume the CH could be completely consumed.

Despite the potential negative effect of reducing the chloride diffusivity by using mineral admixtures on the chloride threshold value, Gjorv (1995) suggested that the penetration of chlorides was a controlling factor for passivity of the embedded steel over the possible drop of pH value by using mineral admixtures. It implies that although the use of mineral admixtures can have adverse effects on the chloride threshold values, however, this negative effect

is outweighed by their positive impacts on the reduction of the chloride diffusion coefficient. For the purpose of this study, a weak to medium correlation between  $D$  and  $C_{th}$  in the range of +20 % to -20% can be assumed. The negative correlation reflects the effect of changing the w/c ratio; i.e. reducing w/c ratio decreases  $D$  but increases  $C_{th}$ . The positive correlation reflects the possible effect of using mineral admixtures in decreasing  $D$  and  $C_{th}$ .

#### 4 PROBABILISTIC MODELING OF CORROSION IN HPC STRUCTURES

##### 4.1 Uncertainty modeling

As mentioned above, the model and its associated parameters can exhibit a considerable level of variability (e.g. concrete cover depth, diffusion coefficient, etc.), which may have coefficients of variation of 20% or higher, while some other variables (e.g. bar diameter, concrete strength, Poisson's ratio, etc.) present a narrow scatter with coefficients of variation of 5% or lower (Frangopol *et al.* 1997; Stewart and Rosowsky 1998; Fanous *et al.* 2000; Lounis and Mirza 2001; Val and Stewart 2001). The values of these parameters used in deterministic models are mainly based on the mean values or some conservative characteristic values of the variables [e.g. lower values for the resistance parameters (Chloride threshold) and higher values for the loading parameters ( $C_s$  or  $C_{d,t}$ )]. The deterministic models can predict two states only, i.e. failure or non-failure (e.g. corroded or non-corroded), for each limit state investigated.

For illustration purposes, an example of the limit state of corrosion of reinforcing steel is given. If after a period of time, the mean value of the chloride concentration at the steel level ( $C_{d,t}$ ), is found lower than the mean value of chloride threshold level ( $C_{th}$ ), as shown in Figure 1, the deterministic model predicts no corrosion (i.e. the steel is in the passive state). Conversely, if  $C_{d,t}$  is found higher than  $C_{th}$ , then the model predicts that the reinforcing steel is corroded.

In actual field conditions, after the measurements of chloride concentrations at the steel, the frequency distribution or probability density function (pdf) of the chloride concentration can be represented (see Figure 1). Similarly, the chloride threshold concentration has also a scattered distribution with a pdf as shown in Figure 1, then the probability of corrosion is given by the shaded area, where  $C_{d,t}$  and  $C_{th}$  over-

lap. Hence, the extent of corrosion is neither zero nor 100%, as predicted by the deterministic models, but is equal to a finite value, which starts at zero at the start of the chloride ingress stage and increases with time and can reach 100%.

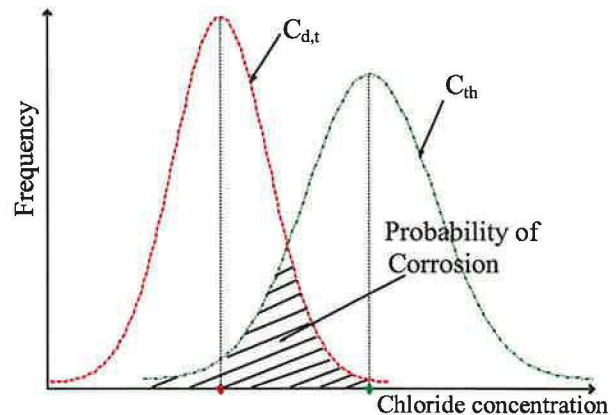


Figure 1: Deterministic vs. probabilistic predictions of corrosion

It is therefore clear that the use of deterministic models, which assume concrete as a homogeneous medium, cannot predict the extent of damage for a reference period of time (it is either 0% or 100% damage). Hence, although such models present a powerful tool for selection of proper parameters in the design stage for new structures, they have serious shortcomings regarding the selection of appropriate maintenance and rehabilitation strategies for structures in service. A probabilistic modeling of the performance of RC structures has much to offer with regard to simplicity as compared to attempts to formulate purely deterministic models (Ditlevsen 1984; Melchers 1987; Mori and Ellingwood 1993).

##### 4.2 Prediction of Corrosion Probability

In order to calculate the probability of corrosion of reinforcing steel embedded in concrete structures several methods can be used, depending on the complexity of the model (e.g. linear or non-linear ...) and the accuracy desired. The probability of corrosion corresponds to the integral of the probability density function  $f_X(x)$  on the corrosion domain (See equation below).

$$P_f = \int_{g(C_s, d, D, C_{th}) < 0} f_X(C_s, d, D, C_{th}) dx$$

With

$$g(C_s, C_{th}, D, d) = C_{th} - C_s \left( 1 - \operatorname{erf} \frac{d}{2\sqrt{Dt}} \right)$$

Where  $g$  is the limit state or performance function, which is a highly nonlinear function.

To calculate this integral (i.e. probability of corrosion  $P_f$ ), several methods can be proposed. The most obvious and simple to implement is the Monte Carlo Simulation (MCS). This method attempts to characterize the whole domain of failure so it needs an important number of simulations (i.e. slow convergence rate). Advanced methods use a more efficient way to select simulations, which are based on two main concepts: (i) the approximation of the nonlinear state function; and (ii) efficient method of simulations (e.g. experimental designs). Below are the most important comparisons between the advanced methods:

- FORM/SORM methods: based on the Taylor's expansion series for the limit state function near the "design point" (see next section). These methods allow the computation of estimates of the probability of corrosion at a relative low computational cost compared to MCS.

- Other advanced simulation methods include Importance Sampling (Harbitz 1983), Directional Simulation (Ditlevsen et Al. 1987), Latin Hypercube Sampling (McKay et Al. 79) and subset simulation method (AU and Beck 2001) and Line Sampling technique (Koutsourelakis et al. 2004, Schueller and Pradlwarter, 2007).

## 5 ILLUSTRATIVE EXAMPLE

- The probabilistic model proposed herein is illustrated on a high performance concrete (HPC) highway bridge deck reinforced with conventional carbon steel with two different types of HPC that yield similar diffusion coefficients of  $0.2 \text{ cm}^2/\text{yr}$ . HPC1 is made with a low w/c ratio (no supplementary mineral admixtures) and HPC 2 contains 10% of silica fume. This example will include: probabilistic modeling applied of the diffusion and corrosion processes in HPC structures;
- Present Capability and accuracy of the simplified first order approximation method even for this non-linear problems ; and

- Highlight the importance of taking into account the variability of different parameters and its effect on the probability of corrosion; and
- Assess the impact of considering the correlation of parameters on accuracy of the results

The parameters values are based on examples taken from Lounis and Daigle (2008) and are listed in the table below (see Table 1):

Table 1: Data for bridge deck case study

	$C_s$ Kg/m <sup>3</sup>	Depth mm	Diffusion cm <sup>2</sup> /year	$C_{th}$ Kg/m <sup>3</sup>
Mean value	6	70	0.2	0.7
Coef. Of variation	30%	20%	25%	20%

In this section, the parameters are assumed to be independent and follow a normal distribution. The time-varying probability of corrosion is evaluated over 50 years. The approximation methods are presented to show their performance in case of nonlinear model.

### 5.1 First-Order Reliability Method (FORM)

To test its efficiency, three analyses were done. The first one, taken as the reference solution, is performed using MCS with a large number of simulations.

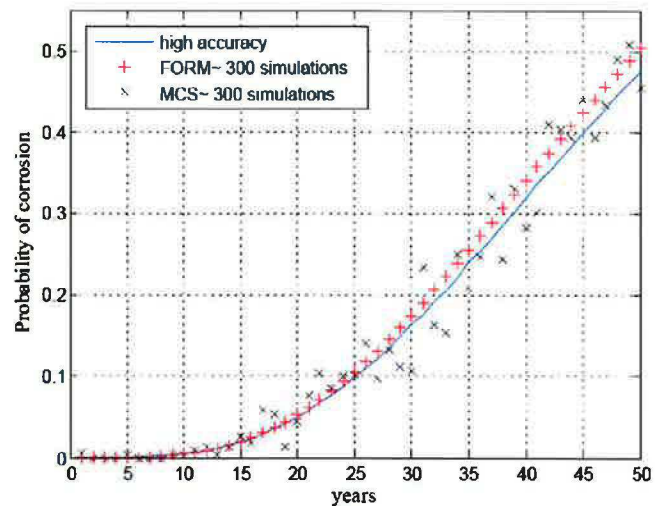


Figure 2: Efficiency of FORM vs. MCS

Second, the method FORM was implemented. It requires around 300 iterations to provide satisfying results (smooth curve). The third analyses were done using MCS with the same number of simulations needed to determine the design point with the

FORM approach. Figure 2 shows the efficiency of FORM vs. MCS as it almost yields the same corrosion probability curve as the MCS with a negligible error that overestimates the probability of corrosion (i.e. conservative estimate).

## 5.2 Second Order Reliability Method (SORM)

SORM uses the curvature of the limit state function at the design point (second order approximation). It is more accurate and needs more simulations. In Figure 3, the two methods (FORM and SORM) are compared.

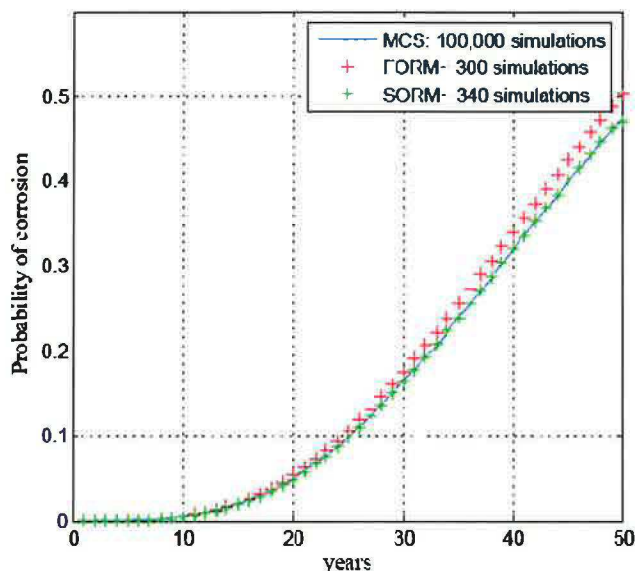


Figure 3: Comparison of FORM, SORM and MCS

By considering the interval 20 to 30 years, it can be seen that the error between the two methods is not significant as shown in Figure 3 (maximum relative error less than 4%).

## 6 IMPACT OF PARAMETERS CORRELATION ON CORROSION PROBABILITY

As mentioned above, there is some correlation between some of the model parameters. The results presented above do not take into consideration any correlation between parameters. In this section, the influence of correlation on the probability of corrosion is investigated. The most probable correlation that may exist is between the diffusion coefficient and the chloride threshold value. As discussed earlier, this correlation may vary from negative to positive with a maximum range of  $\pm 20\%$ .

Most of the cases treated in the literature assume that the parameters of the diffusion model are independent. The aim of this section is to test the validity

of this assumption. In case of significant impacts, this correlation should be modeled; otherwise the assumption of independent parameters can be accepted.

The example presented above is revisited, but a new assumption is taken into consideration that a correlation between the diffusion coefficient and the chloride threshold exists. The probability of failure was calculated by considering a service life of 40 years

By considering, a normal law to model the different parameters and by varying the correlation between  $C_{th}$  and  $D$  from  $-30\%$  to  $+30\%$ , its impact on the probability of corrosion is negligible as shown in Figure 4, with maximum change of 1%.

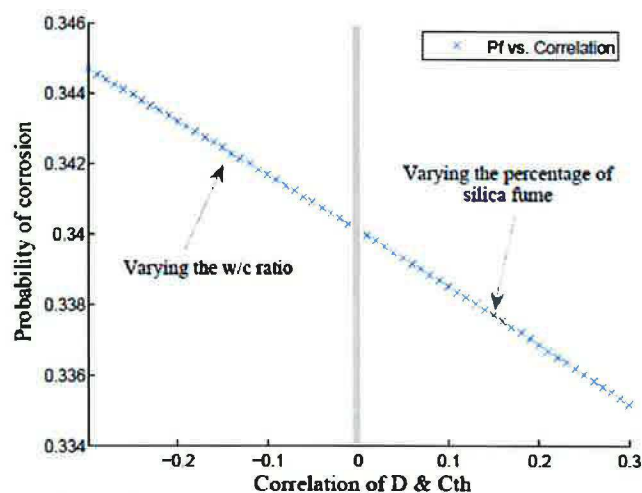


Figure 4: Impact of correlation of  $D$  &  $C_{th}$  on the corrosion probability

Many other examples were also tested to see the impact of their correlation, by changing the mean values and the coefficients of variation in the other parameters; e.g. the variation in the probability of corrosion does not exceed 4% [e.g., Carbon steel ( $C_{th}=4$ ), Severe exposure (12 to 20  $\text{kg/m}^3$ ), other depth values (from 5 to 15 cm) and with HPC (diffusion coefficient till 1.5  $\text{cm}^2/\text{year}$ ). The modeling results of these tested showed the variation in the probability of corrosion does not exceed 4%, which confirmed that the impact of their correlation is negligible, and  $C_{th}$  and  $D$  can be treated as independent parameters for corrosion of steel in concrete bridge decks.

## 7 CONCLUSION

In the paper, a probabilistic modeling of chloride-induced corrosion of concrete structures, including the correlation of chloride diffusivity and chloride threshold is presented. It is found that the first order

reliability method provides accurate results and is more efficient than Monte Carlo simulation and remains conservative compared to the SORM method, despite the high nonlinearity of the performance function.

The probabilistic modeling enables to study the impact of potential correlations between governing parameters for corrosion of steel in concrete structure, especially chloride diffusivity and chloride threshold value. It is found that its impact on the probability of corrosion is marginal and can be ignored.

## 8 REFERENCES

- Alonso, C. Andrade, C. Castello, M. Castro, P. 2000. Chloride threshold values to depassivate reinforcing bars embedded in a standardized OPC mortar, *Cement and Concrete Research* 30 1047–1055.
- Au, S. and Beck, J. 2001. Estimation of the small failure probabilities in high dimensions by subset simulation. *Prob. Eng. Mech.* 16(4), 263-277.
- Bentz, D. P., Jensen, O. M., Coats, A.M., and Glasser, F. P. 2000, Influence of silica fume on diffusivity in cement-based materials. I. Experimental and computer modeling studies on cement pastes, *Cement and Concrete Research*, 30 (6), pp. 953-962.
- Chatterji S. 1995. A Critical Review of the Factors Affecting Ion Migration Through Cement Based Materials. *II Cement* to 92, pp. 139–150.
- Crank J. 1975. *The mathematics of diffusion*. Oxford: Clarendon press
- Ditlevsen, O. 1984. Probabilistic thinking: an imperative in engineering modeling. *Danmarks Tekniske Højskole*, Lyngby, 1-23.
- Ditlevsen, O., Olesen, R., and Mohr, G. 1987. Solution of a class load combination problems by directional simulation. *Structural Safety* 4, 95-109.
- DuraCrete 1997. Design Framework. *BRITE –EURAM-Project BE95-1347/R1*.
- Fanous, F, Wu, H., and Pape, J. 2000. *Impact of Deck Cracking on Durability*, Project 97-5, Center for Transportation Research and Education, Iowa State University, Iowa.
- Fick, A. 1855. Über diffusion. *Annalen der Physik und Chemie* 94, pp. 59–96.
- Frangopol, D.M., Lin, K.Y., and Estes, A.C.1997. Reliability of reinforced concrete girders under corrosion attack. *ASCE J. of Struct. Eng.*, 123(3), 286-297.
- GjØrv, O. E. 1995. Effect of condensed silica fume on steel corrosion in concrete, *ACI Material Journal*, 92 (6), pp591-597.
- Glass, G. K. and Buenfeld, N. R. 2000. Influence of chloride binding on the chloride induced corrosion risk in reinforced concrete, *Corrosion Science*, 42 (2), pp. 329-344.
- Harbitz, 1983 Efficient and accurate probability of failure calculation by the use of the importance sampling technique. In: *Proc. Fourth Int. Conf. on Applications of Statistics and Probability in Soil and Structural Engineering*, pp. 825–836.
- Hassan, K. E., Cabrera, J.G., and Maliehe, R. S. 2000. Effect of mineral admixtures on the properties of high-performance concrete, *Cement and Concrete Composites*, 22 (4),pp. 267-271.
- Jensen, M. O., Freiesleben-Hansen, P., Coats, A. M., and Glasser, F. P. 1999. Chloride ingress in cement paste and mortar, *Cement and Concrete Research*, 29 (9), pp. 1497-1504.
- Koutsourelakis, P. S., Pradlwarter, H. J. and Schuëller G. I. 2004. Reliability of structures in high dimensions, part I: algorithms and applications, *Prob. Eng. Mech.* 19, 409-417
- Li, Z. J., Peng J., Ma, B. G. 1999. Investigation of chloride diffusion for high-performance concrete containing fly ash, microsilica and chemical admixtures,” *ACI Materials Journal*, 96(3), pp. 391-396.
- Lounis, Z., and Mirza, M. S. 2001. Reliability-based service life prediction of deteriorating concrete structures. *Proceedings of the Third International Conference on Concrete Under Severe Conditions*, Vancouver, 965-972.
- Lounis, Z. and Daigle, L. 2008. Reliability-based decision support tool for life cycle design and management of highway bridge decks. *Annual Conference of the Transportation Association of Canada (TAC)* (Toronto, Ontario, 2008-09-21), pp. 1-19, 2008-10-07.
- Melchers, R.E. 1987. *Structural Reliability: Analysis and Prediction*. Ellis Horwood Ltd., England.
- McKay, M.D., Beckman, R. J., Conover, W. J. 1979. A comparison of three methods for selecting values of input variables in the analysis of output from a computer code. *Technometrics* 2, 239-245.
- Mori, Y., and Ellingwood, B. 1993. Reliability-based service life assessment of aging concrete structures. *ASCE J. of Struct. Engrg.*, 119(5),1600-1621.
- Page, C. L. and Vennesland, O. 1983. Pore solution composition and Chloride binding capacity of Silica fume cement pastes, *Material and Structures*, 16 (91), pp.19-25.
- Pettersson, K. 1996. Chloride threshold values in reinforced concrete,” *Durability of Concrete on Saline Environment*, Uppsala, p. 95.
- Schueller, G. and Pradlwarter, H. 2007. Benchmark study on reliability estimation in higher dimensions of structural systems – An overview. *Structural Safety* 29, 167 – 182.
- Stewart, M., and Rosowsky, D.V. 1998. Structural safety and serviceability of concrete bridges subject to corrosion. *ASCE J. of Infrast. Systems*, 4(4), 146-155.
- Tuutti, K. 1982. Corrosion of Steel in Concrete. *Swedish Cement and Concrete Research Institute*. Stockholm.
- Tuutti K. 1996. Chloride induced corrosion in marine concrete structures. In: *Durability of Concrete on Saline Environment*, Uppsala; pp. 81-93
- Val, D.V., and Stewart, M.G. 2001. Reliability-based life cycle cost analysis of reinforced concrete structures in marine environments. *Proc. of ICOSSAR'01-8th Int. Conf on Structural Safety and Reliability*, Corotis, R.B. et al. (eds.), A.A. Balkema, Rotterdam.
- Weyers, R.E., Prowell, B.D., Sprinkel, M.M., and Vorster, M. 1993. Concrete Bridge Protection, Repair, and Rehabilita-

tion Relative to Reinforcement Corrosion: A Methods Application Manual, SHRP-S-360, Strategic Highway Research Program, National Research Council.

Zhang J, Lounis Z. 2006. Sensitivity study of control parameters for onset of corrosion Induced by chloride diffusion. *Cem Concr Res*; 36 (7):1312-1323.