Development of a Finite-Element Framework to Evaluate the Deterioration of RC Structures

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ABSTRACT: To study the deterioration of reinforced concrete (RC) structures subjected to various exposure conditions, a comprehensive finite-element framework is developed. This framework evaluates the effects of the most critical factors that may expedite or slow down the corrosion process. The parameters related to the concrete properties and diffusion characteristics are categorized as internal parameters, while the environmental stressors, such as ambient temperature, relative humidity, and concentration of carbon dioxide and chloride ions are considered as external parameters. Using a set of detailed finite-element models, the influential parameters are examined as individual physical environments. The analysis of each environment is based on the concept of transient thermal analysis with appropriate modifications. The novelty of the proposed framework is to consider the major nonlinear time-dependent characteristics of the internal and external parameters along with their mutual interactions. By taking into account various sources of uncertainty, this approach results in a more realistic estimation of the extent of degradation for the reinforced concrete structures subjected to multiple environmental stressors.

1 INTRODUCTION

Chloride-induced corrosion in reinforced concrete (RC) structures is a mechanism caused by the intrusion of chloride ions into the concrete. This mode of corrosion is expected when RC structures are located in coastal regions and exposed to aggressive environmental conditions. Because of the penetration of chloride ions in structural members, the chloride content of the concrete gradually increases and when the concentration of chloride ions in the pore solution on the vicinity of reinforcing bars reaches a threshold value, the structural degradation initiates.

The chloride transport mechanism in the concrete is a complex phenomenon that may occur in several forms, such as ionic diffusion, capillary suction, and permeation. The rate of this mechanism depends on the characteristics of concrete, degree of pore saturation, chloride binding capacity, free chloride content, and exposure conditions. By increasing the duration of time through which a structure is exposed to aggressive conditions, the corrosion of reinforcing bars propagates. This results in cracking and spalling of RC members and may lead to severe reduction in serviceability of structures.

The time between corrosion initiation and serviceability failure is usually smaller than the time required for corrosion to initiate. Therefore, a realistic estimation of the corrosion initiation time has a significant role in the accurate performance prediction of RC structures during their service life. In the present paper, an integrated computational framework is proposed to simulate

the penetration of chloride ions into the concrete. For this purpose, the effects of parameters, such as water-to-cement ratio, ambient temperature, relative humidity, age of concrete, free chloride content, and chloride binding capacity, are considered to calculate the chloride content in different time intervals. This will lead to a deterministic approach for the estimation of the corrosion initiation time.

The developed computational framework is then improved by taking into account the effects of uncertainties of influential parameters. Through a probabilistic approach, the probability distribution function of the corrosion initiation time is determined and the results are compared with the estimated initiation times obtained from the deterministic approach.

2   CHLORIDE INTRUSION

To study the chloride intrusion process, different empirical and numerical models have been proposed during the past three decades. The majority of these models are based on the solution of Fick's second law as expressed in Equation 1.

$$C_{Cl}(x,t) = C_S \left[1 - erf(\frac{x}{2\sqrt{D_{Cl}t}}) \right]$$

(1)

where $C_{Cl}(x,t)$ = total chloride content at the spatial coordinate x and time t; C_s = surface chloride content; D_{Cl} = diffusion coefficient; and erf (.) = error function. To obtain a closed-form analytical solution for the total chloride content (Equation 1), it is assumed that the diffusion coefficient and boundary conditions are constant over the time. Chatterji (1995) and Kong et al. (2002) have questioned the accuracy of this equation for two main reasons: first, the chloride diffusion coefficient and boundary conditions are assumed to be constant while they may vary over the time; and second, the solution is formulated in terms of total chloride concentration while in reality only free chloride ions are responsible for corrosion initiation in the concrete.

To improve the Equation 1, Saetta et al. (1993) developed a numerical approach using the conventional diffusion theory (Fick's first law) and the mass conservation principle to model the chloride diffusion into the concrete. In the proposed diffusion process, the coupling between moisture and heat flow is based on a model proposed by Bažant and Najjar (1972). Xi and Bažant (1999) suggested a model for chloride penetration in saturated concrete, which was dominated by binding capacity and chloride diffusivity. Kong et al. (2002), later, used the Xi and Bažant's model to examine the rate of chloride ingress into concrete by taking into account the influence of water-to-cement ratio and curing time. Ababneh et al. (2003) contributed to the work of Xi and Bažant (1999) by developing a mathematical model for the chloride penetration in the non-saturated concrete by considering the binding capacity, chloride diffusivity, and moisture diffusivity. In this paper, the numerical model have been extended to consider the effects of chloride binding capacity, free chloride content, ambient temperature, and relative humidity in addition to the concrete aging (Alipour et al., 2013).

2.1   Chloride diffusion process

It is assumed in this study that the dominant mode of chloride intrusion into the concrete is diffusion. The diffusion is the motion of chloride ions within the pore solution in response to the ion concentration gradient, which is described with the Fick's first law based on the mass conservation principle. The chloride ions concentrated on the exposed concrete surface diffuse into the cement matrix due to the ion concentration gradient. The diffusion process into the

partially saturated concrete can be described using the following partial differential equation (Saetta et al., 1993):

$$\frac{\partial C_f}{\partial t} = -div\left[\frac{D_{Cl}}{1+(1/w_e)(\partial C_b / \partial C_f)}\nabla(C_f)\right] \tag{2}$$

where C_f = free chloride concentration in the unitary volume of porous body (kg/m³ of concrete); t = time; w_e = evaporable water content; and $(\partial C_b/\partial C_f)$ = chloride binding capacity in which C_b is the bound chloride content. The chloride binding capacity characterizes the relationship between free and bound chloride ions in the concrete at a specific temperature and it is also referred to as the "binding isotherm". Martin-Perez et al. (2001) studied three different binding isotherms for the concrete, including: idealized linear, Langmuir, and Freundlich binding isotherms. The proposed relationships for these isotherms along with the suggested coefficient values are listed in Table 1.

Table 1. Three different binding isotherms

Isotherm	C_b	$\partial C_b/\partial C_f$	α	β
Linear	αC_f	α	0.07	-
Langmuir	$\alpha C_f/(1+\beta C_f)$	$\alpha/(1+\beta C_f)^2$	0.39	0.07
Freundlich	αC_f^{β}	$\alpha\beta C_f^{\beta-1}$	1.05	0.36

Given the relationship between the free and bound chloride content, the total chloride content, C_t, of the concrete can be expressed as:

$$C_t = C_b + w_e C_f \tag{3}$$

2.2 Chloride diffusion coefficient

The diffusion coefficient in Equation 2 is calculated by taking into account the contribution of all influential parameters, as below:

$$D_{Cl} = D_{Cl,ref}\, F_2(T)F_3(h)F_4(t_e)F_5(C_f) \tag{4}$$

where $D_{Cl,ref}$ = chloride diffusion coefficient estimated at a reference temperature and humidity. In Equation 4, $F_2(T)$ accounts for the dependence of the chloride diffusion coefficient on temperature T; $F_3(h)$ represents the influence of relative humidity h; $F_4(t_e)$ denotes the effect of concrete age t_e; and $F_5(C_f)$ considers the influence of free chloride content on the diffusion process.

To evaluate the extent of contribution of the mentioned parameters to Equation 4, the following mathematical expressions are suggested (Saetta et al., 1993, Bamforth and Price, 1996, Xi and Bažant, 1999, Martin-Perez et al. 2001, and Kong et al. 2002):

(1) Reference chloride diffusion coefficient:

$$\log D_{Cl,ref} = a + b\log(w/c) \tag{5}$$

where a and b = empirical factors, assumed equal to -10.6 and 1.9; and w/c = water-to-cement ratio, assumed equal to 0.5 in the current study.

(2) Temperature effects:

$$F_2(T) = \exp\left[\frac{E}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \tag{6}$$

where E = activation energy, equal to 44.6 ± 4.3 (kJ/mol) for $w/c = 0.5$; R = gas constant, equal to 8.314 (kJ/mol.$^{\circ}$K); T_{ref} = temperature at which reference chloride diffusion coefficient is measured, equal to $296\,^{\circ}$K; and T = absolute ambient temperature at the location of the structure, obtained from the available data.

(3) Humidity effects:

$$F_3(h) = 1/\left[1 + \left(\frac{1-h}{1-h_c}\right)^4\right] \tag{7}$$

where h_c = humidity level at which D_{Cl} drops halfway between its maximum and minimum values, equal to 0.75; and h = relative humidity at the location of the structures, obtained from the available data.

(4) Effects of concrete age:

$$F_4(t_e) = \left(\frac{t_{ref}}{t}\right)^m \tag{8}$$

where t_{ref} = reference time, equal to 28 day; m = empirical age factor, equal to 0.04; and t = actual time of exposure.

(5) Effects of free chloride content:

$$F_5(C_f) = 1 - \kappa(C_f)^n \tag{9}$$

where empirical parameters, κ and n, are assumed equal to 8.33 and 0.5, respectively.

Considering the influential parameters mentioned above, the time-varying diffusion coefficient at the reinforcing bar level is calculated using the Freundlich isotherm (Figure 1). The strong fluctuation of the chloride diffusion coefficient is resulted from $F_2(T)$ and $F_3(h)$, due to the seasonal variations in the ambient temperature and relative humidity, respectively.

Because of the dependence of D_{Cl} on nonlinear, time-dependent parameters (Equation 4), the governing partial differential equation given by Equation 2 cannot be solved without using numerical methods. The current study develops a finite-element framework to solve the partial differential equation of the chloride diffusion process as a boundary value problem. This helps to study the effects of all influential parameters at different time intervals and results in more accurate estimations of the corrosion initiation time. In this framework, a set of equations are solved simultaneously in each time step until a specified chloride threshold value is reached. The time corresponding to this threshold indicates the corrosion initiation time.

The initial conditions and boundary values used for the numerical solution are expressed as below:

$$\begin{cases} t = 0: \quad C_f = 0 \quad at \ x > 0 \\ t \geq 0: \quad C_f = C_S \quad at \ x = 0 \end{cases} \tag{10}$$

where C_s = surface chloride content, which may depend on the composition of the concrete, location of the structure, orientation of its surface, chloride concentration in the environment, and general conditions of exposure with regard to rain and wind (Bertolini, 2008). To determine the range of surface chloride content, McGee (1999) conducted a field-based study of 1158 bridges in the Australian state of Tasmania. This work suggests that the surface chloride content is a function of distance from the coast, d, and for the structures located on the coast lines ($d <$ 0.1 km), the C_s value is 2.95 kg/m^3. Val (2004) also collected some surface chloride content data from Mediterranean coasts and proposed a value of 7 kg/m^3. In this study, an average value of 5 kg/m^3 is assumed for C_s.

2.3   Chloride initiation time

The time to corrosion initiation is determined as the time when the chloride concentration near reinforcing bars (at a depth equals to the concrete cover depth) reaches the threshold chloride concentration, $C_{critical}$. The threshold total chloride content for this study is taken as the 1 % of cement weight, assumed equal to 3.5 kg/m^3. The values of free, bound, and total chloride content through a 30-year period of exposure at the cover depth level of 50 mm is depicted in Figure 1 for the Freundlich isotherm.
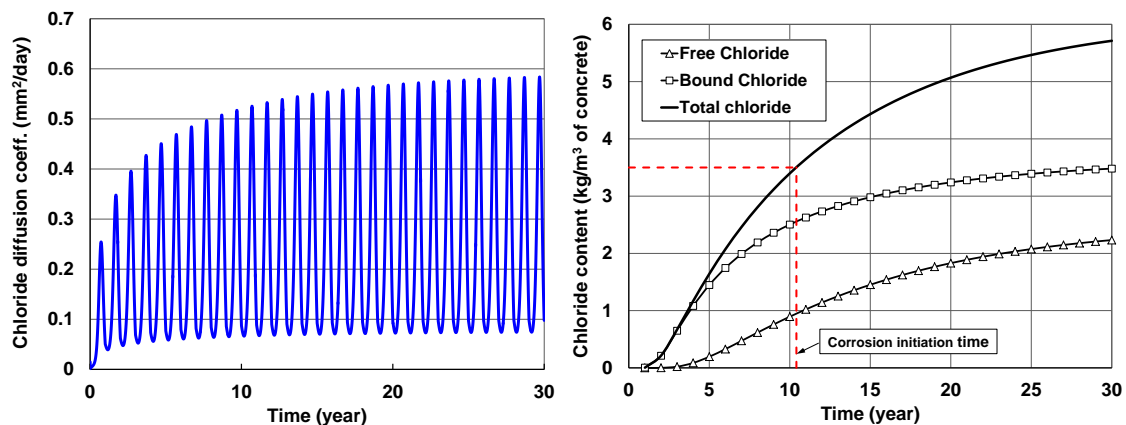

Figure 1. Chloride diffusion coefficient (left) and chloride content (right) estimated at the rebar level

Considering the total chloride content profile in Figure 1, the corrosion initiation time is estimated by finding the intersection of chloride profile and the threshold value (3.5 kg/m^3). In the current case, it can be seen that the corrosion initiation time is equal to 10.40 years. By repeating the same procedure using the other two isotherms (i.e., idealized linear and Langmuir isotherms), the corrosion initiation time will change to 9.33 and 12.66 years, respectively. These values of corrosion initiation time are within the typically observed range of 7 to 20 years, as suggested by Kong et al. (2002).

3   PROBABILISTIC APPROACH

The computational model discussed in the previous section carefully studies the diffusion process and estimates the corrosion initiation time through a deterministic approach. Although the developed model significantly reduces the uncertainties associated with the simplifying assumptions, it does not still consider the uncertainties corresponding to the model parameters as independent random variables.

Based on the existing literature, parameters affecting the corrosion initiation time, such as surface chloride content, threshold chloride value, concrete cover, diffusion coefficient, ambient temperature, and relative humidity, have high variability (Shafei et al., 2012). Hence, their variations must be considered to improve the developed deterministic model to a more reliable probabilistic approach. Towards this goal, those parameters which have the most influence on the corrosion initiation time are studied. Selected random variables in the current paper include chloride diffusion coefficient, D_{cl}, surface chloride content, C_s, and concrete cover depth, d_c.

As stated in Equation 5, the chloride diffusion coefficient is a function of water-to-cement ratio. A normal distribution function can be assigned to the water-to-cement ratio with the mean value of 0.5 and coefficient of variation (COV) of 3 to 5 %, according to ACI (2009). Using Equation 5, a mean of 6.688×10^{-12} (m^2/sec) and a COV of 0.076 is obtained for the chloride diffusion coefficient. The surface chloride content is assumed to have a lognormal distribution with the mean of 5 kg/m^3 and COV of 0.50. Finally for the concrete cover depth, a normal distribution with the mean of 50 mm and COV of 0.20 is identified (McGee, 1999). The mean and COV of the required random variables are summarized in Table 2.

Table 2. Description of the random variables

Parameter	Mean	COV	Dist.
D_{Cl}	6.688×10^{-12} (m^2/sec)	0.076	LN
C_s	5 (kg/m^3)	0.50	LN
d_c	50 (mm)	0.20	N

As mentioned earlier, the corrosion initiation time is defined as the time required to reach the chloride threshold value at a specific depth of the RC member. With this definition, the chloride content at the level of the reinforcing bar can be considered as a demand parameter, D, and the chloride threshold value for corrosion initiation can be assumed as a resistance parameter, R. Employing a probabilistic approach, the demand parameter can be expressed as a probability distribution function at each time step by taking into account the uncertainties associated with the influential parameters, such as chloride diffusion coefficient, surface chloride content, and concrete cover depth. On the other hand, the resistance parameter is an indicator of the capacity of the RC member before corrosion initiates and can be identified by the chloride threshold value, $C_{critical}$. In the current study, a normal distribution function with the mean of 3.5 kg/m^3 (equal to 1 % of cement weight) and COV of 0.20 is assumed for the chloride threshold value.

To predict the probability distribution function of the demand at different time steps, a set of Monte Carlo simulations is performed to calculate the chloride content at the level of the reinforcing bars. In these simulations, the chloride diffusion coefficient and surface chloride content are random variables with lognormal distributions, as summarized in Table 2. The calculated chloride content is recorded at three different levels of concrete depth. These levels include the mean cover depth (50 mm) and the mean cover depth ± standard deviation, equal to 40 mm and 60 mm.

Considering the probability distribution of chloride content (demand) obtained from Monte Carlo simulations at each time step, the measure of risk in terms of probability of exceeding the capacity level can be expressed as:

$$P_f = P(exceedance) = P(C_{critical} < C_t)$$

$$= \int_0^\infty \left[\int_0^{c_t} f_{C_{critical}}(c_{critical}) \, dc_{critical} \right] f_{C_t}(c_t) \, dc_t \qquad (11)$$

$$= \int_0^\infty F_{C_{critical}}(c_t) f_{C_t}(c_t) \, dc_t$$

where $F_{Ccritical}(c_t)$ is the cumulative distribution function of $C_{critical}$ evaluated at c_t. Equation 11 can be considered as the fundamental equation of reliability analysis used in this study to find the probability distribution of the corrosion initiation time. Based on the described approach, the probability distributions of chloride content (demand) and chloride threshold value (capacity) are depicted in Figure 2 for two different time steps. It can be seen in this figure that while the probability distribution of capacity is independent of time, the probability distribution of demand moves to higher chloride levels over the time. As expected, this illustrates that the probability of corrosion initiation increases by the age of the structure.
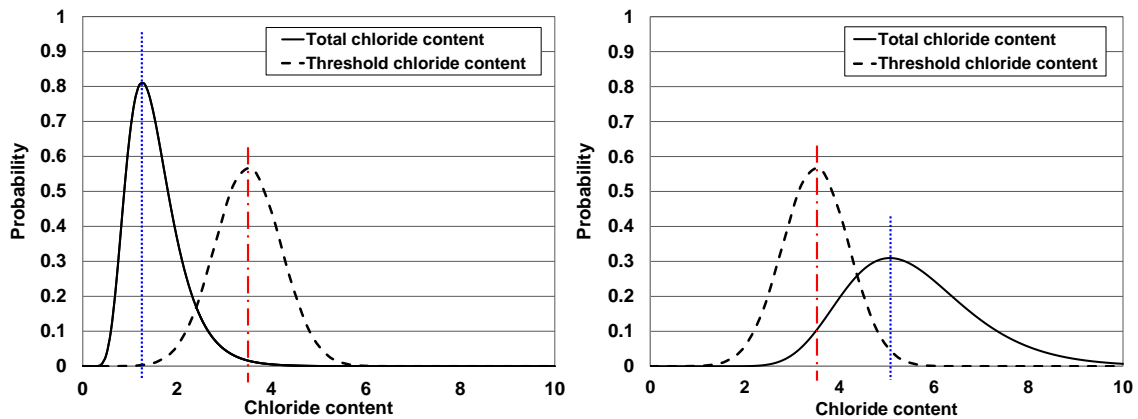

Figure 2. Probability distributions of chloride content and threshold values for two different time steps

By repeating the procedure of Equation 11 for different time intervals during the 30-year life cycle of the structure, the cumulative distribution function of the corrosion initiation time is calculated. This function is shown in Figure 3 for the mean cover depth and the mean cover depth ± standard deviation. It can be seen from Figure 3 that the expected value of the corrosion initiation time is 7.90, 11.50, and 15.80 years for the concrete cover depths of 40, 50, and 60 mm, respectively. At the cover depth of 50 mm, a slight difference can be seen between the corrosion initiation time obtained from the probabilistic analysis (11.50 years) and the time calculated from the deterministic approach (10.40 years, according to Section 2.3). By increasing the number of simulations, the estimated corrosion time from the probabilistic analysis is expected to get closer to the time determined from the deterministic approach.

4   CONCLUSIONS

This study develops a comprehensive computational framework to estimate the corrosion initiation time in RC structural members. For this purpose, a deterministic approach is first introduced to calculate the corrosion initiation time by taking into account the effects of a variety of influential factors. Although the developed approach significantly reduces the

uncertainties associated with the simplifying assumptions, it does not consider the uncertainties corresponding to the model parameters. Hence, the effects of parameter variability are considered through a probabilistic approach. In the latter approach, the chloride content at the level of reinforcing bars is taken as the demand parameter while the chloride threshold value is given as an indicator of the capacity. The probabilistic estimations of the corrosion initiation time can be used to evaluate the actual extent of structural degradation and eventually to provide appropriate inspection and maintenance strategies.
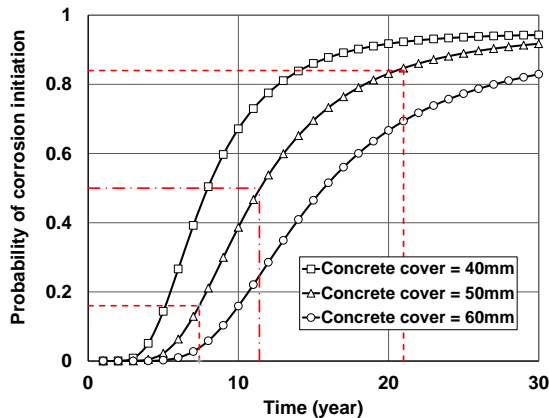

Figure 3. Cumulative distribution function of the corrosion initiation time for three cover depths

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