COMPUTER-AIDED MODELING OF SERVICE LIFE OF CONCRETE STRUCTURES IN MARINE ENVIRONMENTS

Dao Ngoc The Luc

The University of Danang, University of Science and Technology; lucdao@dut.edu.vn

Abstract - Corrosion of steel reinforcement due to chloride penetration is identified as a main cause of damage to reinforced concrete (RC) structures exposed to marine environments. In this paper, reliability-based service life model by integration of finite element chloride penetration model into Monte Carlo Simulation is proposed to predict the chloride penetration profile in concrete and the service life of concrete structures in probabilistic manner. The model is capable of effectively accommodating the time- and space- three dimensional chloride transport, chloride binding as well as the effect of steel reinforcement, cracks and concrete cover replacement/repair. The model thus offers a more realistic and reliable tool for the service life design of reinforcement concrete structures in marine environments.

Key words - service life; RC structures; corrosion; numerical modeling; chloride penetration.

1. Introduction

Chloride-induced corrosion of steel reinforcement is considered as the major deterioration mechanism of reinforced concrete structures exposed to marine environments [1]. Initially, the embedded steel is protected against corrosion by a thin passive layer of iron oxide on the steel surface in the highly alkaline pore solution of the concrete. However, concrete is permeable, and if exposed to marine environment, chloride ions from sea water may penetrate through the concrete cover and reach the reinforcing steel. If the chloride concentration at the surface of the steel bar exceeds a certain threshold limit, the protective passive film breaks down and corrosion begins [2].

Despite the significant expenditure of much research effort by earlier researchers, currently available models are still limited in their predictive capability and reliability due to their simplifications of various aspects of concrete behavior under chloride attack. In this paper, an improved numerical solution based on finite element method (FEM) for the time- and space-dependent three dimensional governing equation is developed. The model is capable of effectively accommodating the time- and space-dependent chloride transport, chloride binding as well as the effect of steel reinforcement, cracks and concrete cover replacement/repair.

Another issue calling for particular attention is that most current durability designs are based on a deterministic approach. However, as for concrete structures, due to uncertainties in materials properties (e.g., the mix composition and pore structures), geometries, environmental conditions (e.g., temperature, humidity, salt concentration), the input for models should be in probabilistic manner. It is clear that the combination of these uncertainties leads to a considerable uncertainty in the model output, i.e., 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. Thus, to evaluate the service life of concrete structures under chloride ingress considering corrosion initiation as an ending criterion in a probabilistic manner, an integration of the above chloride transport model into a Monte Carlo Simulation is carried out to form reliability-based service life model.

2. Description of reliability-based service life model

2.1. General scheme for reliability-based service life modeling

Reliability-based service life can be predicted by the scheme in Figure 1. The scheme starts at time t=0 and increases one year at each step. At each time t, the probability of failure (P_f) which are defined according to Durability Limit State I (DLS-I) is calculated. The failure probability is then compared with critical failure probability (P_{cr}) to determine the end of service life. In this model, the value of 0.1 is used for critical failure probability.

To calculate the probability of failure at time t, the Monte Carlo method randomly generates N samples of input data from the given probability distribution of the input variables. Input variables for the model include diffusion coefficient at 28 days, time dependent constant of diffusion coefficient m; surface concentration and constants k_1, k_2 for time dependent surface concentration; chloride threshold; constants of Freudlich binding isotherm [3]. Each sample of input data is inserted in FEM model for chloride penetration to get chloride concentration at reinforcement surface. The above value are then compared with chloride threshold to decide whether they reach the DLS-I. Finally the probability of failure is calculated by the ratio of the number of samples (M) that violate limit state function to the total number of samples (N).

2.2. Durability limit state I (Corrosion initiation)

Durability Limit States I is the initiation limit state corresponding to the time when chloride content the steel surface reaches chloride value to initiate the corrosion. The failure probability $P_f(t)$ at time t corresponding to DLS-I are shown in Equation **Error! Reference source not found.**.

$$P_f(t) = P[C_{st}(t) \geq C_{th}] \tag{1}$$

Where $C_{st}(t)$ is the chloride content at the surface of steel bars, C_{th} is threshold chloride concentration.

Threshold chloride concentration is usually expressed in terms of the chloride concentration or chloride/hydroxide ratio, above which a local breakdown of the protective oxide film on the reinforcement occurs and localised corrosion attack subsequently takes place. Various threshold values have been suggested [2, 4], but all of these proposed limits are not absolutely fixed; they depend on the pH of the concrete, which varies with the type of cement and concrete mix, on the extent to which the chlorides are bound chemically and physically, on the presence of oxygen and moisture, and on the existence of voids at the steel/concrete interface. In this study, a chloride threshold value of 1.2 kg/m^3 proposed by JSCE [5] is adopted. Other threshold values can be easily incorporated into the currently proposed model.

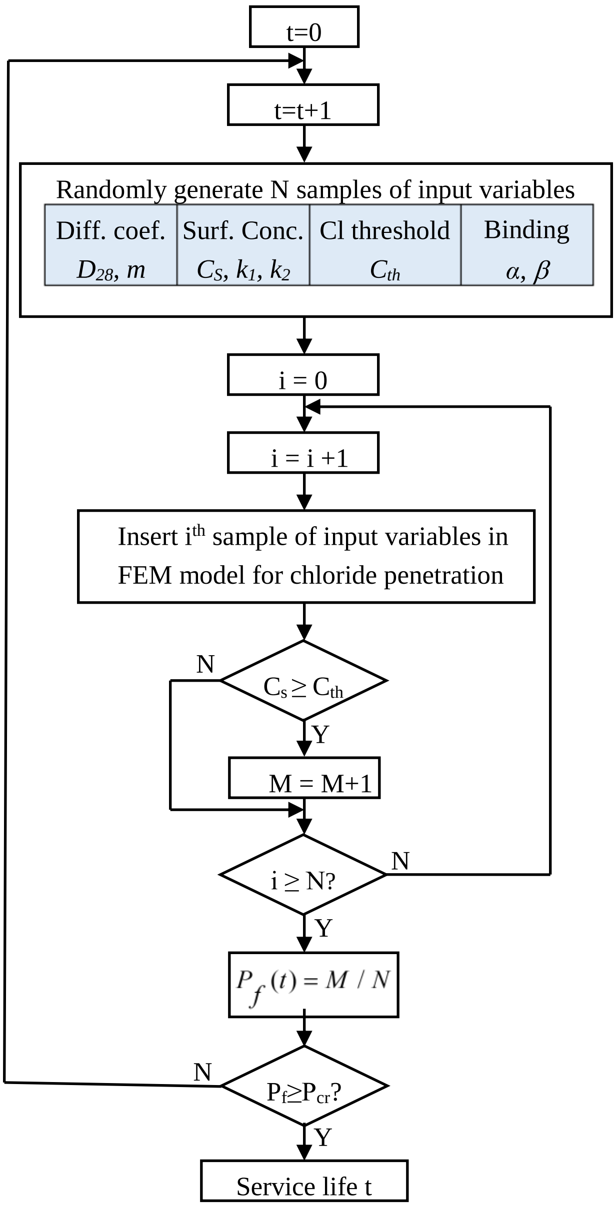


Figure 1. *Reliability-based scheme for service life prediction*

2.3. FEM model for chloride penetration

2.3.1. Governing equation for chloride transport

Despite its complexity, it has been widely accepted that the chloride transport in concrete can be modeled by the Fick's second law of diffusion [6].

$$\frac{dC_f}{dt} - div(D\nabla C_f) + \frac{dC_b}{dt} = 0 \qquad (2)$$

Where C_f is the free chloride, C_b is the bound chloride, D is the diffusion coefficient, and div, ∇ are divergence and gradient operators, respectively.

The second term in Equation **Error! Reference source not found.** represents the contribution from surrounding chloride to the rate of increase of diffusing substance in the unit element at a certain location:

$$div(D\nabla C_f) = \frac{\partial}{\partial x}\left(D\frac{\partial C_f}{\partial x}\right) + \frac{\partial}{\partial y}\left(D\frac{\partial C_f}{\partial y}\right) + \frac{\partial}{\partial z}\left(D\frac{\partial C_f}{\partial z}\right) \qquad (3)$$

The third term in Equation **Error! Reference source not found.**, often referred to as the sink term, is responsible for the binding of chloride. In this study, the Freundlich binding isotherm [3] relating binding chloride with free chloride is adopted:

$$C_b = \alpha C_f^{\beta} \qquad (4)$$

Where α and β are binding constants. Differentiation of Equation **Error! Reference source not found.** gives:

$$\frac{dC_b}{dt} = \frac{dC_b}{dC_f}.\frac{dC_f}{dt} = \frac{d(\alpha C_f^{\beta})}{dC_f}.\frac{dC_f}{dt} = \alpha\beta C_f^{\beta-1}.\frac{dC_f}{dt} \qquad (5)$$

Combining Equations **Error! Reference source not found.** and **Error! Reference source not found.**, the governing equation can be given as:

$$(1+\alpha\beta C_f^{\beta-1})\frac{dC_f}{dt} - div(D\nabla C_f) = 0 \qquad (6)$$

Or equivalently,

$$\mu\frac{\partial X}{\partial t} - div(D\nabla X) = 0 \qquad (7)$$

where $\mu = 1+\alpha\beta C_f^{\beta-1}$ and $X = C_f$.

2.3.2. Time dependent diffusion coefficient

The diffusion coefficient has been known to decrease with time [7, 8], which is mainly attributable to the continued hydration process of concrete and its effect on the pore system within the concrete. In this study, the exponential function proposed by Mangat and Molloy [8] is adopted to account for the time-dependent nature of the diffusion coefficient.

$$D(t) = D_{28}\left(\frac{t_{28}}{t}\right)^m \qquad (8)$$

Where D_{28} is the reference diffusion coefficient at time of 28 days (t_{28}); m is a constant accounting for the rate of decrease of diffusion with time and depends on the type and proportion of cementitious materials; and t is the time in days when diffusion coefficient is evaluated. In addition, to reflect the fact that the diffusion coefficient cannot decrease with time indefinitely, for concrete of more than 30 years, t is taken as 30 years, or 1095 days [9].

Typical values of D_{28} and m are given in Table 1, and their effects on the variation of the diffusion coefficient with time for different concretes are illustrated in Figure 2. It can be readily seen that the w/c ratio as well as the inclusion of silica fume, fly ash and slag has significant implication on the time-dependent diffusion coefficient, and hence service life of concrete structures.

Table 1. *Typical values of D_{28} and m [10]*

	D_{28}	m
With Portland cement only	$10^{(-12.06+2.4w/c)}$	0.2
With *SF*% of Silica Fume	$10^{(-12.06+2.4w/c)}e^{-0.165SF}$	2
With *FA*% Fly Ash and *S*% of Slag	$10^{(-12.06+2.4w/c)}$	0.2+0.4(FA/50+ S/70)

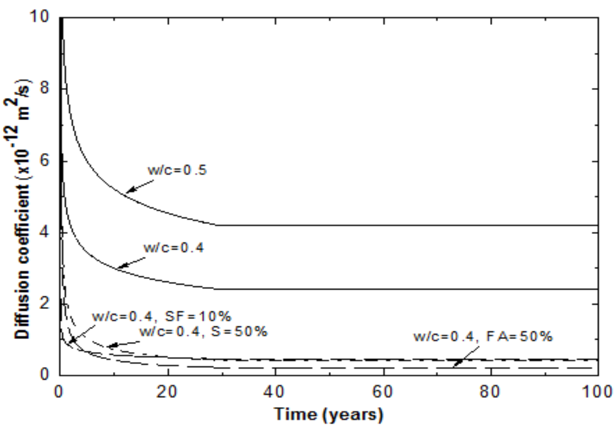


Figure 2. *Typical variation of the diffusion coefficient with time [10].*

2.3.3. Time dependent surface chloride concentration

The surface chloride concentration of concrete structures is dependent upon many factors, including exposure conditions, distance from the sea, and duration of exposure. Several models accounting for these factors at different levels have been proposed, all of which can be easily incorporated into the model presented herein. In this study, a recent model proposed by Song et al. [9] which represented relatively well much experimental data available, is adopted as the boundary condition for solving Equation **Error! Reference source not found.**.

$$C_S(t) = k_1\left[\ln\left(k_2 t + 1\right)\right] \tag{9}$$

Where k_1, k_2 are constants determined by regression analysis of available data, and t is the time of exposure in years. Typical values of k_1, k_2 are given in Table 2.

Table 2. *Surface chloride concentration C_S (kg/m^3)*

		JSCE [5] (C_S=constant)	Song et al. [9] ($C_S(t)=k_1\left[\ln\left(k_2t+1\right)\right]$)	
Parameters		C_S	k_1	k_2
Distance from the sea (kg/m^3)	0	9.0	1.52	3.77
	100	4.5	0.76	
	250	3.0	0.51	
	500	2.0	0.34	
	1000	1.5	0.25	

2.3.4. Numerical solution for chloride tranport

The governing equation, Equation **Error! Reference source not found.**, can be solved by two steps of discretization: space discretization and time discretization. First, discretization is carried out over the whole space using Galerkin method [11]. Newmark method [11] is then used to discrete over time for each time step.

a. Space discretization

For a single element, the field variable X can be expressed in terms of element nodal values as

$$X^e = [N]\{X\}^e \tag{10}$$

Where $[N]$ is a row vector containing element interpolation functions associated with each node, and $\{X\}^e$ is the vector of nodal degrees of freedom. Using the element interpolation functions as weighting functions in the Galerkin weighted residual method for governing equation, and rearrange the equation, yields

$$\left[c^e\right]\left\{\dot{X}^e\right\} + \left[k^e\right]\left\{X^e\right\} - \left\{f^e\right\} = 0 \tag{11}$$

Where:

$\left[c^e\right] = \int_\Omega \mu[N]^T[N]d\Omega$ is the capacitance matrix,

$\left[k^e\right] = \int_\Omega [B]^T D[B]d\Omega + \int_{\partial\Omega}[N]^T\lambda[N]ds$ is the stiffness matrix, with B being the matrix of element interpolation gradient vectors $[B] = \left[\frac{\partial[N]}{\partial x} \quad \frac{\partial[N]}{\partial y} \quad \frac{\partial[N]}{\partial z}\right]$

$\left\{f^e\right\} = \int_{\partial\Omega}\eta[N]ds$ is the environmental load vector.

After assembly of all elements for the whole mesh, a system of linear first-order differential equations in the time domain is obtained

$$C\left\{\dot{X}\right\} + [K]\{X\} - \{F\} = 0 \tag{12}$$

b. Time discretization

In this study, Newmark method with θ=0.667 [11] is used to solve time dependent governing equation in matrix form as in Equation **Error! Reference source not found.**.

For time step t_n to t_{n+1}, the residual $R^{i+1}_{n+\theta.\Delta t}$ of Equation **Error! Reference source not found.** for iteration $i+1$ at time $t_{n+\theta.\Delta t}$ (Δt is time step) is assumed to be zero, which results in the following

$$\Delta X^{i+1}_{n+\theta.\Delta t} = \frac{-R^i_{n+\theta.\Delta t}}{\left(\dfrac{C_n}{\theta.\Delta t} + K_n\right)} \tag{13}$$

Based on the above formula, in step from t_n to t_{n+1}, the iteration continues until the convergence condition is reached:

$$\frac{\sum_1^{nnode}\left(X^{i+1}_{n+\theta.\Delta t}\right)^2}{\sum_1^{nnode}\left(X^{i}_{n+\theta.\Delta t}\right)^2} \le \delta_{allow} \tag{14}$$

Where *nnode* is the number of nodes and δ_{allow} is the allowable limit value.

Then the values of variables at nodes in time t_{n+1} are updated for next time step running:

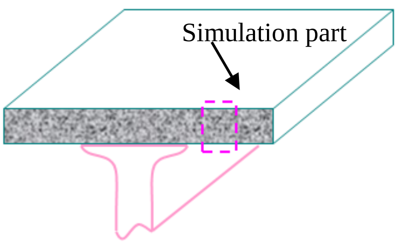
$$X_{n+1} = X_n + \frac{\sum_{i=1}^{niter} \Delta X^{i}_{n+\theta.\Delta t}}{\theta} \tag{15}$$

where *niter* is the number of iterations needed for time step from t_n to t_{n+1}.

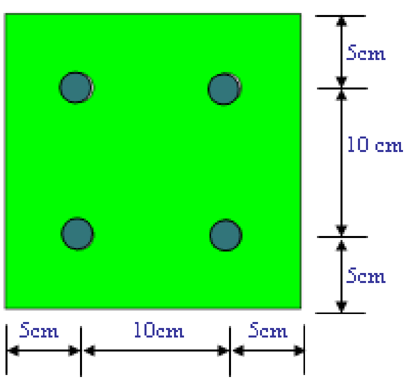
The initial values of chloride concentration X_0 in concrete need to be specified at time t=0. As X_0 at t=0 is known, X_1 can be calculated. Then, using a known X_1, X_2 can be derived using Equation **Error! Reference source not found.**. Following this way, the history of nodal values is generated.

3. Application of the reliability-based model to concrete structures in a chloride environment

A reinforced concrete bridge slab under chloride attack is considered in this case study. The geometry of the simulation section and the boundary conditions for the cover cracking model are shown in Figure 3.



a) Reinforced concrete bridge slab

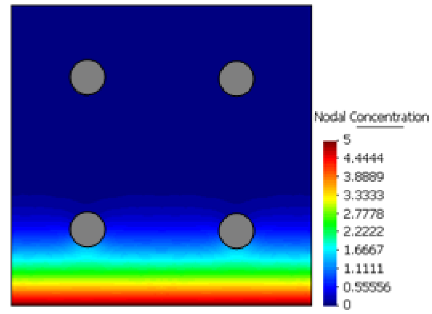


b) Geometry of the simulation section

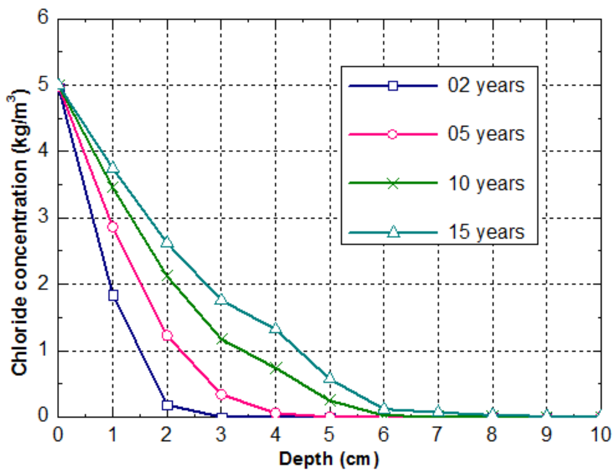
Figure 3. *A reinforced concrete bridge deck*

The input data for the reliability-based model are as follows (with the first and second values in brackets representing the mean and standard deviation, respectively): diffusion coefficient D=(1,0.1)x10^{-12} m/s^2; surface concentration C_s=(5,0.5) kg/m^3; chloride threshold value C_{th}=(1.2,0.12) kg/m^3 [5].

Figure 4 through to Figure 6 show the results from an analysis using deterministic model. The chloride concentration profiles together with their changes with time obtained from the FEM model for chloride penetration is given in Figure 4. The increasing chloride concentration at the reinforcement surface with time of exposure, also taken from the chloride penetration model, is shown in Figure 5. Based on Figure 5, the time to corrosion initiation (corresponding to DLS-I) when the chloride concentration at reinforcement surface reaches the chloride threshold can be easily determined.



a) Contour of chloride concentration after 15-year exposure



b) Chloride concentration profile with time

Figure 4. *Chloride concentration profiles with time in a concrete slab*

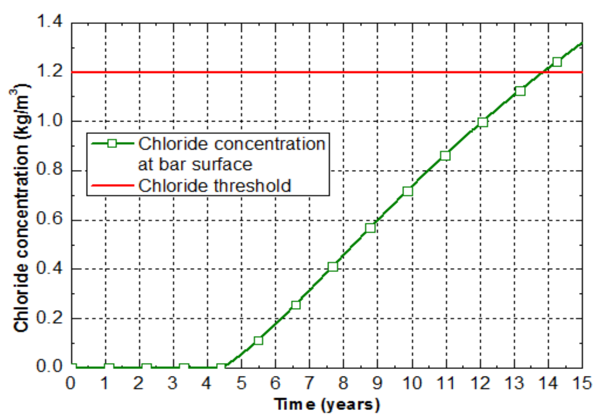


Figure 5. *Chloride concentration at reinforcement surface versus time*

The service life corresponding to durability limit state I predicted by the deterministic and reliability-based service life models is shown in Figure 6. The service life determined by the deterministic model are 13.8 years for DSL-I. On the contrary, the service life predicted by the reliability-based model is not fixed but varies with the chosen critical probability of failure, which typically varies between 0.1 and 0.5 depending on required safety level.

Since predictions by the two models are similar for a critical probability of failure of 0.5, the service life corresponding to DSL-I predicted by the reliability-based model is smaller than that by the deterministic model. For a commonly-used critical probability of failure of of 0.1, the service life is 11.7 years for DSL-I.

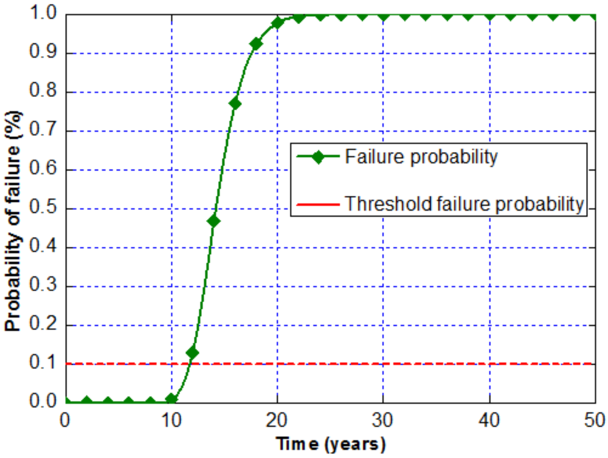


Figure 6. *Prediction by reliability-based model*

4. Conclusions

In this paper, both deterministic and reliability-based service life model for chloride-induced corrosion subjected to marine environments are presented. The model is capable of predicting chloride profile in concrete as well as the service life of concrete structures for Durability Limit State I (DLS-I) of corrosion initiation, and can be expanded to DLS II and DLS II (cover cracking and structural damage) in a probabilistic manner. The model thus offers a more realistic and reliable tool in design, decision making for repairs, strengthening and rehabilitation of deteriorated concrete structures in marine environment.

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