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Condition assessment of reinforced concrete structures subject to chloride ingress: A case study of updating the model prediction considering inspection data

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ABSTRACT

The durability of reinforced concrete structures is affected by the corrosion of steel reinforcement due to chloride ingress. In general, the service life of a reinforced concrete structure is determined by considering the time to initiate and the time to propagate corrosion. Probabilistic models have been used to estimate the service life of a concrete structure by taking into account the inherent randomness observed in this process. Within this aim, it is vital to inspect the structure after several years of exposure using destructive or non-destructive testing to update the service life prediction models and to schedule proactive maintenance. This paper discusses a case study to analyze inspection data (i.e. potential mapping) to update the condition of the structure using a probabilistic service life prediction model. It also discusses the effect of the variation of water/cement (w/c) ratio on updated model prediction probabilities.

1. Introduction

Marine reinforced concrete structures are vulnerable to deterioration, either by forces of nature or by human influences. The embedded steel in reinforced concrete structures is susceptible to chloride-induced damage due to exposure to the severe marine environment. In general, Fick's second law of diffusion is used to model the chloride ingress by considering diffusion as the dominant transport mechanism [1,2]. Both probability-based models and deterministic models have been proposed in literature to estimate the time to initiate corrosion. However, the probability-based models can help to make more realistic decisions than deterministic models [3]. For example, Duracrete [4,5] and *fib*_bulletin_34 [6] are probability-based models extensively used to make such predictions. Moreover, the use of the most appropriate prediction models to predict the corrosion initiation period and corrosion propagation period can provide useful information for scheduling proactive maintenance in concrete structures [2,7]. The periodic monitoring of corrosion initiation in critical areas of a reinforced concrete structure (i.e. splash zone, tidal zone, etc.) is of the utmost importance, because the presence of cracks/rust/spalling in a reinforced concrete structure is an indication of an advanced stage of corrosion leading to cost-intensive repairs [2]. Therefore, it is very important to evaluate the probability of initiating corrosion in a structure at different exposure intervals.

Periodic monitoring also plays a vital role in finding out the time to initiation of corrosion and the extent of corrosion [1,8]. The collection of existing data, such as general information on the structure, material/structural properties (e.g. cement type, w/c ratio or water/binder ratio, compressive strength, etc.), and exposure conditions is an essential part of a condition assessment process [7,8]. For example, the use of incorrect w/c ratio to update the service life prediction model will mislead the final outcome of the condition assessment process. Therefore, as most authors [1,9,10] have highlighted, it is important to use correct information on the w/c ratio in a service life prediction model. In addition, there are various non-destructive tests (i.e. Half-Cell Potential (HCP), chloride content in concrete, resistivity, rebound hammer, ultrasonic pulse velocity, etc.) and destructive testing methods used in the condition assessment process [11]. HCP mapping is a widely used and standardized non-destructive method for monitoring steel corrosion in reinforced concrete structures [10,12]. Therefore, the HCP measurements have been used in this study to evaluate the present condition. Furthermore, the HCP data can be used to update the service life prediction models [2,8], repair prediction models and thus update the expected future maintenance costs [13,14]. However, the analysis of existing HCP data

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to update the service life prediction model is a challenging task due to the availability of few analysis methods and few application examples of the methods available in literature [8].

This manuscript discusses a case study of a reinforced concrete structure exposed to a marine environment for 30 years. It also determines the probability of corrosion initiation using the Duracrete [4,5] model for different w/c ratios. It updates the service life prediction model with information received from half-cell potential mapping, utilizing the method illustrated in *fib*_bulletin_59 [8].

2. Modeling of corrosion of steel reinforcement in concrete

The level of damage due to the corrosion of embedded steel in a reinforced concrete structure over time can be described using Tuutti's model as shown in Fig. 1. Essentially, the model categorizes the service life of a structure into the corrosion initiation period and the corrosion propagation period [15]. The corrosion initiation period can be defined as the time taken to activate corrosion at the concrete-steel interface, whereas the propagation period is the period between corrosion initiation and structural failure. Once corrosion propagation has started, degradation will continue to reduce the area of the steel section until it reaches a critical level where it may no longer be able to resist loads as required at design [2,13,10]. The main outcomes of corrosion propagation are a loss of steel cross-section, loss of stiffness, loss of concrete–steel interface bond, cracking of concrete cover, local or global failure of structure, etc. [1,16]. Therefore, at the right time, the routine inspection of reinforced concrete structures is an essential task before the appearance of visible signs of corrosion.

Chloride penetration is a process where chloride ions will access to the concrete cover and eventually reach the embedded steel. When the chloride concentration reaches its "threshold value" near the reinforcement, the passive film dissolves and corrosion can occur. This will happen even if the pH-value in the pore solution is high. There are several ways for chlorides to enter concrete, such as from additives to the concrete mixture, from seawater, ground water, and or de-icing salts [1,10]. Most research has used Fick's second law to model the ingress of chloride ions to the un-cracked concrete, considering diffusion as the dominant transport mechanism [2,4–6]. In this paper, the DuraCrete [4] model derived using Fick's second law is adopted to include environmental and material parameters as given in Eq. (1). Additionally, the diffusion coefficient is modeled as time-dependent, and an age factor is introduced to reflect the decrease of the coefficient due to material and environmental influences.

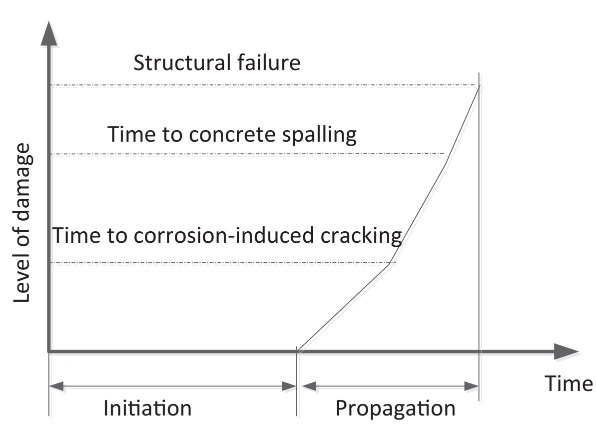

Fig. 1. Model of corrosion of steel reinforcement in concrete [15].

$$C(Z,t) = C_s\left[1 - erf\frac{Z}{2\sqrt{k_e \times k_t \times k_c \times D_o \times \left(\frac{t_o}{t}\right)^n \times t}}\right] \quad (1)$$

where

D_o the diffusion co-efficient measured at a reference time t_0,

t_0: reference time measured in days,

k_e: environmental variable correcting D_o to account for the influence of the exposure environment,

k_t: test method variable correcting D_o to account for the influence of the test method,

k_c: execution variable correcting D_o to account for the influence of curing method,

n: the age factor that takes into account the time dependency D_o,

t: the exposure period,

Z: depth with a corresponding content of chlorides $C(Z, t)$,

Cs: the chloride concentration at the concrete surface.

A corrosion initiation process is usually initiated when the chloride concentration at the site of the reinforcement reaches a certain critical threshold value (C_{CR}). Eq. (2) represents the time to corrosion initiation at the first layer of reinforcement so that 'Z' in Eq. (1) is replaced by 'd', which is the concrete cover depth.

$$T_{cl} = \left(\frac{d^2}{4 \times k_e \times k_c \times k_t \times D_o \times (t_0)^n} \times \left(erf^{-1}\left(1 - \frac{C_{CR}}{C_S}\right)\right)^{-2}\right)^{\frac{1}{1-n}} \quad (2)$$

3. Reliability concepts to model the corrosion initiation

The safety margin (M) or limit state function for corrosion initiation can be defined as Eq. (3), where 't' is the exposure period and 'X' is random variables.

$$M = G(X,t) = T_{cl} - t \quad (3)$$

Assuming that an element fails when corrosion initiation takes place, the probability of corrosion initiation (P_f) is evaluated by integrating: $G(X, t) \leqslant 0$ over the failure domain, considering the statistical distribution of each random variable (i.e. $X = D_o$, C_{CR}, C_s, d, k_e, k_t, k_c, n). In the space-variant context, Eq. (4) shows how to estimate "P_f" using the joint density function $fx(x_i)$ with random variables ($x_1, x_2, x_3 \ldots x_n$, i.e. D_o, C_s, C_{CR}, etc.). It is also assumed that the spatial variability of certain components of 'X' is negligible and the random field components are homogenous fields.

$$P_f = \int_{M\leqslant 0} fx(x_i)dx_i = \int_{M\leqslant 0} I(x_i)fx(x_i)dx_i = E[I(x_i)] \quad (4)$$

In addition, Monte Carlo simulation can be used to calculate 'P_f' by simulating the limit state function for a range of sampling [9,13]. In this approach, the mean value of $I(x_i)$ can be an estimator for the probability of corrosion initiation as given in Eq. (5).

$$E[I(x_i)] = \frac{1}{N}\sum_{i=1}^{N} I(X_i) \quad (5)$$

where $I(x_i) = \begin{Bmatrix} 1 \to M \leqslant 0 \\ 0 \to M > 0 \end{Bmatrix}$

In estimating 'P_f', it is vital to identify the basic set of random variables (i.e. D_o, C_{CR}, C_s, d, k_e, k_t, k_c, n), of which uncertainties have to be considered. Then, the randomness of all the variables is modeled recognizing the probability distributions of the variables. These probability distributions can be defined by physical observations, statistical studies, laboratory analysis, and expert opinion [6,9,10,13].