



An Ensemble Kalman Filter approach for service life prediction of reinforced concrete structures subject to chloride-induced corrosion



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HIGHLIGHTS

- Robust SHM technique for early prediction of the corrosion initiation time.
- EnKF to assimilate chloride sensor measurement data.
- Monte Carlo simulations to predict the time corresponding to corrosion SLS.

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ABSTRACT

Chloride induced reinforcement corrosion is one of the most common causes of deterioration of reinforced concrete structures. Condition assessment of such structures is typically based on comparing the chloride content at steel level to the critical threshold chloride concentration. This study aims at developing a robust non-destructive structural health monitoring (SHM) methodology for assessing the state of the structure and predicting its remaining corrosion free service life. The presented methodology relies on embedded sensors that measure the chloride concentration at certain locations, and a predictive model that governs the dynamics of chloride ingress. The system is propagated forward in time using a finite element/finite difference scheme, and the Ensemble Kalman Filter (EnKF) is employed to calibrate the predictive model parameters. The calibrated parameters are then used to assess the remaining corrosion free service life of the structure. The robustness of the presented methodology is demonstrated on 1-D and 2-D numerical examples yielding accurate estimation of the spatial and temporal variability of the chloride content and consequently enhancing maintenance efficiency and structural sustainability.

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1. Background and literature review

With the increasing expected lifetime of structures and high sustainability design demands, corrosion is becoming widely considered as one of the main problems impacting durability, serviceability and safety. Corrosion of the reinforcement steel inside the concrete is the main cause of structural deterioration and failure. Corrosion leads to loss in the reinforcing steel cross-section, decrease in steel ductility, loss in the steel/concrete bond, and cracking of concrete cover [1,2]. The rate of corrosion directly affects the effective remaining life of the corroded structure. Therefore, to avoid catastrophic failures, periodic monitoring and maintenance of reinforced concrete structures subject to extreme environmental conditions is required.

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Structural deterioration caused by the chloride-induced corrosion of steel reinforcement is typically regarded as a two stage process: the corrosion initiation stage and the corrosion propagation stage [3,4]. During the first stage, the de-passivation of the protective film that is due to the high alkalinity nature of concrete occurs. The corrosion initiation time is defined as the time needed for the chloride content at the reinforcing bar location to exceed a certain threshold [3,5,6]. Once corrosion is initiated, steel starts to corrode generating iron oxides. Corrosion then progressively propagates causing cracking, delamination and spalling of the concrete cover. Many researchers use post-corrosion models to assess the structural behavior after corrosion initiation [7–9]. However, since the time between corrosion initiation and initial cracking of concrete cover is relatively shorter than the time required for the corrosion initiation [4,10], this study will focus on presenting a methodology to accurately predict the corrosion initiation time. The accurate estimation of the corrosion initiation time early on during the life

of the structure will allow engineers to take mitigating measures before internal cracking starts and it becomes too late for proactive maintenance.

Different phenomena govern the ingress of chloride ions into concrete pores depending on the state of the structure and the depths of concrete cover. In unsaturated concrete, chloride ingress is initially driven by convection [11] where chloride ions are absorbed into the top layers of the concrete that are up to 10–20 mm below surface [12]. After several wetting and drying cycles, the top layers reach a limiting value. Then, due to the concentration gradient, diffusion process will move the chloride ions further into the concrete. However, in saturated and fully submerged concrete structures, the diffusion process is the governing mechanism after initial wetting [6,11]. Since the principal objective is to estimate the chloride concentration at rebar level, chloride ingress is typically modeled as a diffusion only process according to Fick's second law [13].

Many sources of uncertainty are identified once developing an accurate mathematical model to simulate the chloride ingress process. These uncertainties can be attributed to simplifications associated with the adopted mathematical model, parametric uncertainties, and measurement and human errors [6]. Probabilistic models are utilized in the literature to properly represent these uncertainties and overcome some of the limitations associated with deterministic models [6,7,9,14,15]. The probabilistic models can be used to estimate the probability of corrosion initiation, yet the quantification of statistical input is usually very difficult due to limited data. This could lead to large errors when the probabilistic predictions are compared to experimental data [16].

Therefore, to accurately identify the corrosion initiation time, engineers are resorting to structural health monitoring (SHM). The process of monitoring the corrosion initiation time is theoretically tied to monitoring the free chloride ions in concrete and sometimes to total chloride content [17]. Once the concentration of the chloride ions approaches the critical threshold content, corrosion initiates and stress starts building up causing internal cracking in the concrete cover. In the literature, there are different forms, units and ranges for representing the critical chloride content [18]. In this study, the critical chloride content is modeled as a log-normal random variable, correlated to the free chloride content only and reported as a percentage by weight of cement binder (% bw).

The process of monitoring the corrosion initiation time is an old practice that was initiated by means of destructive testing, but recently research is oriented towards improving and implementing non-destructive monitoring techniques for quantifying free chloride content [19,20]. Destructive testing is mainly characterized by taking samples from the element to be examined, and then testing them either in situ or in the lab according to the ASTM [21,22] and AASHTO [23] standard testing procedures. Recently researchers started investigating non-destructive testing approaches such as the use of embedded chloride detection sensors [19,20,24–29]. Two main types of sensors were mainly examined, optic fiber sensors and sensors that rely on Ag/AgCl electrodes to measure chloride content. Both types have been extensively studied in the literature and proved adequate for measuring free chloride content in concrete.

SHM has been utilized in literature for better prediction of probability of corrosion and corrosion initiation time and showed a significant improvement in prediction behavior. However most of the studies investigated post corrosion behavior such as galvanic potential, cracks, subjective measures, conductivity, etc. [30–33], while only few focused on pre-corrosion initiation monitoring for proactive maintenance [34,35]. In [34] a destructive testing method for determining free chloride concentration was conducted over a 10-year period, and using deterministic regression

analysis the collected data was fitted to update the surface chloride concentration and diffusion rate parameters. While in [35] the probability of corrosion at rebar level was updated using corrosion detection sensors' at lower depths.

The objective of this study is the development of an automated robust structural health monitoring strategy that relies on actual field measurements to calibrate the diffusion mathematical model parameters to better predict the actual corrosion initiation time. The presented methodology relies on a set of embedded sensors that measure the chloride concentration at certain locations and a predictive finite element model using a time varying chloride surface concentration and diffusion coefficient to simulate the chloride ingress. The EnKF is employed to calibrate the predictive model parameters so as to minimize the mismatch between the measured and predicted chloride concentrations. The calibrated parameters are then used to assess the remaining corrosion free service life of the structure. The novelty of work lies in using pre-corrosion data from rebar location and other locations, for early prediction of corrosion initiation. The collected data and the forward model are analyzed in a probabilistic setting for optimal update of chloride profile and time varying parameters.

The application of the presented scheme to 1-D and 2-D diffusion problems, using simulated measurements, demonstrate its ability to accurately estimate variability of the model parameters and consequently predict the temporal changes in the chloride concentration profile due to diffusion. The numerical examples are also used to assess the convergence tolerances of the presented framework with variations in the system's initial conditions.

2. Chloride ingress mathematical model

Chloride ingress is typically simulated via the diffusion mechanism according to Fick's second law [13]. The diffusion of chlorides is the random motion transfer of mass free chloride ions in a pore solution from higher concentration regions to lower ones [36]. Fick's second law presents a relation between the diffusion coefficient and the gradient of the concentration:

$$\frac{\partial C}{\partial t} = \nabla \cdot (D(t)\nabla C) \quad (1)$$

where C (% bw) is the chloride content at a given spatial location and time interval. $D(t)$ is the diffusivity coefficient at time t generally represented as a time decaying function [3,4,14]:

$$D(t) = D_R \left(\frac{t_R}{t} \right)^m \quad (2)$$

where D_R is the reference diffusion coefficient at time t_R (usually $t_R = 28$ days) and m is a constant depending on concrete mix proportions. $D(t)$ accounts for the effects of the binding action of chlorides in concrete, temperature and relative humidity. While binding of chlorides tends to decrease the rate of diffusion within the porous medium, temperature and relative humidity effects are directly proportional to propagation of chlorides in concrete [3,4]. Both analytical and numerical solutions for the chloride diffusion equation are presented in the literature. The simplest analytical solution is referred to as the Crank solution presented in Eq. (3) and assumes a constant diffusivity coefficient, D_c , a constant chloride concentration at the surface and negligible initial chloride concentration in the concrete [36]:

$$C(x, t) = C_s \left[1 - \operatorname{erf} \left(\frac{x}{2\sqrt{D_c \times t}} \right) \right] \quad (3)$$

where C_s is the chloride surface concentration, x is the location away from the surface, and t is the time period in years. To overcome the constant diffusion limitation used in deriving the Crank

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