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Application of large-scale non-Gaussian stochastic fields for the study of corrosion-induced structural deterioration

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ABSTRACT

Since reinforced concrete structures are normally exposed to several environmental stressors during their service life, it is necessary to measure the extent of corrosion of structural components as a function of time. While a number of predictive models have been developed to evaluate the vulnerability of deteriorating components, most of them are unable to take into account the inherent uncertainties that exist in the corrosion process. To address this issue, a comprehensive finite-element framework is developed to incorporate various sources of uncertainty into the life-cycle predictive models. To consider the probabilistic aspects of the corrosion process, a number of large-scale Gaussian and non-Gaussian stochastic fields are generated using the Spectral Representation method. These fields reflect the spatial and temporal variability of the parameters that represent material properties, structural characteristics, exposure conditions, and limit state criteria. The generated stochastic fields are imported to the finite-element framework to update the corresponding element properties and boundary conditions at each step of analysis. The time-dependent likelihood of corrosion initiation is evaluated by comparing the distribution of chloride content with the expected threshold values. The probabilistic approach introduced in this study not only improves the current deterministic models, but also directly contributes to the procedures proposed for the life-cycle performance and cost assessment of deteriorating civil infrastructure components.

1. Introduction

Corrosion of steel rebars is one of the major causes of the structural degradation, service disruption, and safety failure in reinforced concrete (RC) structures. The service life of the RC structures subjected to the attack of aggressive agents, such us carbon dioxide and chloride ions, can be divided into three main stages: (1) time before corrosion initiation, (2) time after corrosion initiation, but before crack formation, and (3) time for crack formation and propagation. While critical RC components normally undergo a visual inspection at regular time intervals (e.g., every two years for highway bridges in the United States), the first stage of corrosion remains undetected in most cases. This is mainly because conventional visual inspection techniques can only identify the visible signs of damage (e.g., hair crack and rust color on the concrete surface), which become detectable when a RC component has already experienced the second or third stage of corrosion. It should be noted that there are advanced detection techniques that can examine the possibility of corrosion initiation during the early age of the RC component. Those techniques are, however, not cost-effective and cannot be widely used for civil infrastructure systems that have several components.

Considering the limitations of the available inspection techniques, the current study proposes a stochastic computational framework to predict the extent of degradation of RC components under various exposure conditions. Incorporation of such a framework into the existing vulnerability assessment procedures can improve the accuracy of long-term performance estimates and minimize the cost and effort required for the inspection and maintenance of deteriorating components. The framework presented in this paper provides a step-by-step approach that takes into account the most current condition of the structure [33]. The condition of the structure is introduced by a comprehensive set of time-dependent parameters representing the material properties and environmental characteristics. Since the obtained estimates are based on the finite-element (FE) analysis of the structural components, the element properties as well as initial and boundary conditions of the developed models can be updated at each time step. Through a series of transient analyses, the intrusion of external agents into concrete is investigated considering the mutual

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interactions of the major environmental stressors. The outcome of this procedure can be expressed in terms of the extent and pattern of corrosion.

Among various measures of potential for corrosion, this study chooses the corrosion initiation time. The time at which the corrosion initiates is a critical measure, which separates the first stage of the life cycle of a deteriorating structure from the second and third ones. The importance of this measure can be better understood by considering the fact that the second stage of corrosion (i.e., time between corrosion initiation and crack formation) is normally short and somehow negligible compared to the other two stages [12,8,2]. Hence, the corrosion initiation time can be considered as a practical indicator of the degradation state of the component of interest. Furthermore, since this measure cannot be directly estimated by conventional inspection techniques, its accurate estimate through computational simulations can significantly enhance the reliability of the corresponding life-cycle performance and cost analyses. Although several predictive models have been developed to determine the corrosion initiation time (e.g., [21,4]), most of them are based on simplistic assumptions and do not take into account the contribution of all the influential factors. To address this issue, the comprehensive FE model developed by Shafei et al. [35] is used in this study and the corrosion initiation time is obtained for a set of expected exposure conditions.

One of the main contributions of the current investigation is to estimate the extent and likelihood of corrosion through a probabilistic approach. Inspection of existing RC components indicates that the level of damage due to corrosion may significantly change from one to another part of the same component. This spatial variation challenges the efficiency of the available predictive models, which mostly follow a deterministic approach [33,30,31]. To address this issue, there have been some research efforts that benefited from spatial models to investigate the deterioration of structural components. Li et al. [22] was one of the first studies that used the random field theory to determine the extent of deterioration of structures. For this purpose, Monte Carlo Simulations were utilized to generate random fields for the chloride diffusion coefficient. The chloride penetration model, however, was based on the approximate solution of the Fick's second law in one dimension. Vu and Stewart [51] developed a two-dimensional random field to estimate the likelihood of corrosion-induced cracking in RC structures. In this study, the spatial correlation of the parameters on the surface of the concrete deck was considered. Since the study was focused on the estimation of the time to the first crack and time to specific crack widths, the one-dimensional model provided by Liu and Weyers [23] was used to estimate the time to cracking while the uncertainty in the time to corrosion initiation was not accounted for. Furthermore, the correlation length for all the introduced parameters was assumed to be equal to 2.0 m. In a later study, Frier and Sorenson [14] developed a FE reliability method to obtain the probability of exceeding a critical chloride concentration in the vicinity of reinforcing rebars. The study was conducted using Monte Carlo Simulations. A first-order reliability method (FORM) was then employed to estimate the likelihood of deterioration in the model. Sudret [44] developed a probabilistic model to estimate the extent of damage in degrading RC structures and used random fields to model the spatial variability of a set of parameters. The carbonation-induced neutralization was the main focus of the study and the simplified model proposed by CEB [7] was used to model the penetration of carbon dioxide into the concrete. While the listed studies and a few similar ones have provided a range of probabilistic approaches to consider the parameter variability, they were all based on approximate predictive formulas with no representative stochastic fields. Furthermore, in all of the former studies, the correlation length was either completely neglected or simply assumed equal to a constant value. Among the most recent efforts, Papakonstantinou and Shinozuka [28,29] proposed a probabilistic model for chloride-induced corrosion in RC members considering the cracking effects. Furthermore, an Unscented Kalman Filter (UKF) approach was employed to update the parameters of the probabilistic model.

Based on the wealth of knowledge available in the literature, the current study takes advantage of the flexibility of the developed FE model to obtain reliable estimates of corrosion initiation time. This capability makes it possible to directly incorporate the spatial variability of the involved parameters into the FE analyses. A study conducted by Alipour et al. [1] showed that there are two categories of internal and external parameters that can potentially affect the process of chloride intrusion into concrete. The internal parameters include concrete age and mixture, quality of ingredients, casting and curing condition, porosity, and chemical composition. On the other hand, the external parameters consist of ambient temperature, relative humidity, carbon dioxide, and surface chloride content. There are also geometric parameters, such as structural dimensions, rebar properties, and concrete cover depth, which influence the durability of RC components. The variability of all these parameters along with their interdependencies is examined through the proposed probabilistic approach. An important point that must be considered in the simulation of the involved parameters is that most of them follow non-normal distributions. While most of the previous studies used simple random or Gaussian fields, the current study puts a special emphasis on employing appropriate non-Gaussian stochastic fields that can better represent the actual spatial distribution of both internal and external parameters. To achieve this goal, the procedure required for the simulation of non-Gaussian stochastic fields is discussed in detail and the application of the generated fields in the estimation of the corrosion initiation time is demonstrated through the proposed probabilistic approach.

2. Stochastic field simulation

To investigate the spatial variation of the major parameters involved in the corrosion process, appropriate stochastic fields must be generated. Considering the fact that the random variables that represent the parameters of interest have either normal or non-normal distributions, the techniques required for the simulation of both Gaussian and non-Gaussian stochastic fields are presented in this paper. A review of the available literature indicates that the main concern of all the current simulation techniques is to generate sample functions that can accurately represent the probabilistic characteristics of the corresponding stochastic fields. These fields can be stationary or non-stationary, homogeneous or non-homogeneous, one-dimensional or multi-dimensional, one-variate or multi-variate, and Gaussian or non-Gaussian. Among various methods suggested for the simulation of stochastic fields, the Spectral Representation Method (SRM) is found to be a reliable yet efficient method. This method was first introduced by Shinozuka and Jan [37] and later improved by Yamazaki and Shinozuka [53], Shinozuka and Deodatis [38], Grigoriu [17], Shinozuka and Deodatis [39], Deodatis and Micaletti [9], Shi and Deodatis [40], and Bocchini and Deodatis [6]. Based on the SRM, the equations required to generate homogeneous Gaussian stochastic fields are introduced in this section and the extension of them to non-Gaussian stochastic fields will be investigated in the following section.

A two-dimensional (2D) univariate stationary stochastic field, $f(x_1,x_2)$, is defined with the mean equal to zero (without any loss of generality), autocorrelation function, $R_{ff}(\xi_1,\xi_2)$, and power spectral density function, $S_{ff}(\kappa_1,\kappa_2)$. These parameters can be expressed as:

$$E(f(x_1,x_2)) = 0 \tag{1}$$