

Time-Dependent Structural Performance Analysis of RC Slab Exposed to Chloride Attack by Incorporating Spatial Variability

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ABSTRACT: It is well recognized that the material properties of a reinforced concrete (RC) structure and its dimensions are random due to the spatial variability associated with workmanship, environment and other factors. This randomness causes spatially corrosion damages such as corrosion crack, cover spalling and steel corrosion. Therefore, it is of great importance to simulate deterioration processes of RC structures in a stochastic field context. In this paper, based on a probabilistic model for steel corrosion in RC structures, steel corrosion distributions over RC slab is estimated using 2D Gaussian stochastic fields. In an illustrative example, a time-dependent structural performance of RC slab represented by the stochastic field was estimated using 2D nonlinear finite element method.

1. INTRODUCTION

The deterioration process of RC structures due to chloride induced corrosion is spatial and temporal. The material properties and structural dimensions are random due to the spatial variability associated with workmanship, environment and other factors. This randomness causes spatially corrosion damages such as corrosion cracks and cover spalling. Stewart (2004) and Stewart and Suo (2009) indicated that ignoring the localized corrosion potentially overestimate the structural safety. To estimate the structural performance of RC structures correctly, spatial variability in the deterioration process should be investigated further.

One of the major complications in evaluating the long-term structural performance of RC structures exposed to chloride attack is the uncertainty associated with the physical

parameters involved in the problem. Akiyama et al. (2010) presented a procedure for estimating the failure probability of aging RC structures during their lifetime by assuming that the steel corrosion is uniformly distributed over the entire structure. However, this assumption is an oversimplification because the corrosion damage is not uniformly distributed along the structure, leading to highly spatial variability. Therefore, the probabilistic model for deterioration process of RC structures should be considered by incorporating spatial variability.

In this paper, the time-dependent structural performance of a RC slab exposed to chloride attack is estimated considering spatial variability. The stochastic model for deterioration of RC slab due to the chloride induced corrosion is developed for the life-cycle performance assessment. The spatial variation of the associated variables is represented by 2D Gaussian stochastic fields

using the spectral representation method (Shinozuka and Deodatis 1996). Finally, the structural performance of the RC slab is estimated using 2D nonlinear finite element method.

2. GAUSSIAN STOCHASTIC FIELD

The spectral representation method (SRM) is a very versatile method for generating stochastic fields and processes (Shinozuka and Deodatis 1996). This method can be used with the Monte Carlo Simulation (MCS) for solving the stochastic problems in structural engineering. According to Papakonstantinou and Shinozuka (2013), spatial variability associated with the Gaussian random variables used in the deterioration model of RC slabs is represented by the 2D Gaussian stochastic field.

The 2D Gaussian stochastic field is represented by (Shinozuka and Deodatis 1996)

$$f(x_1, x_2) = \sqrt{2} \sum_{n_1=0}^{M_1-1} \sum_{n_2=0}^{M_2-1} \left[A_{n_1 n_2} \cos(\kappa_{1n_1} x_1 + \kappa_{2n_2} x_2 + \Phi_{n_1 n_2}^{(1)}) + \tilde{A}_{n_1 n_2} \cos(\kappa_{1n_1} x_1 - \kappa_{2n_2} x_2 + \Phi_{n_1 n_2}^{(2)}) \right] + \mu \quad (1)$$

where

$$A_{n_1 n_2} = \sqrt{2S_{f_0 f_0}(\kappa_{1n_1}, \kappa_{2n_2}) \Delta \kappa_1 \Delta \kappa_2} \\ \tilde{A}_{n_1 n_2} = \sqrt{2S_{f_0 f_0}(\kappa_{1n_1}, -\kappa_{2n_2}) \Delta \kappa_1 \Delta \kappa_2} \quad (2)$$

$$\kappa_{1n_1} = n_1 \Delta \kappa_1; \quad \kappa_{2n_2} = n_2 \Delta \kappa_2$$

$$\Delta \kappa_1 = \frac{\kappa_{1u}}{M_1}; \quad \Delta \kappa_2 = \frac{\kappa_{2u}}{M_2}$$

$$S_{f_0 f_0}(\kappa_1, \kappa_2) = \sigma^2 \frac{b_1 b_2}{4\pi} \exp \left[-\left(\frac{b_1 \kappa_1}{2} \right)^2 - \left(\frac{b_2 \kappa_2}{2} \right)^2 \right] \quad (3)$$

μ = mean value, σ = standard deviation, $\Phi_{n_1 n_2}^{(1)}$ and $\Phi_{n_1 n_2}^{(2)}$ = independent random phase angles distributed uniformly over the interval $[0, 2\pi]$, κ_{1u} and κ_{2u} = upper cut off wave numbers corresponding to the x_1 and x_2 axis in the space

domain, respectively, and $S_{f_0 f_0}$ = power spectral density function.

In this study, the power spectral density function for Gaussian random fields is given by Eq. (3) in which b_1 and b_2 are proportional to the correlation distance of the stochastic field along the x_1 and x_2 axis, respectively. The parameters, b_1 and b_2 , are equal to 3 based on a parametric analysis with respect to these parameters (b_1 and b_2) in a similar problem (Papakonstantinou and Shinozuka 2013). An example of the Gaussian stochastic field derived from SRM is shown in Figure 1.

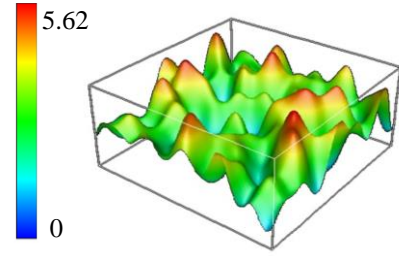


Figure 1: Example of 2D Gaussian stochastic field ($\mu = 3$, $\sigma = 1$).

3. PROBABILISTIC MODEL FOR THE DETERIORATION OF RC SLABS DUE TO CHLORIDE ATTACK

Papakonstantinou and Shinozuka (2013) presented a procedure for estimating the life-cycle reliability of corroded RC structures due to chloride attack. Once the passive film breaks down due to airborne chlorides, corrosion will start in presence of moisture and oxygen, resulting in a formation of expansive corrosion products. These products create tensile stresses on the concrete surrounding the corroding rebars. This can lead to cracking and spalling of concrete cover, and increase of the steel corrosion rate (JSCE 2002). Since the random variables associated with the prediction of steel corrosion are spatially-dependent, the structural performance of RC slabs has to be estimated taking into consideration the spatial distribution of the steel weight loss.

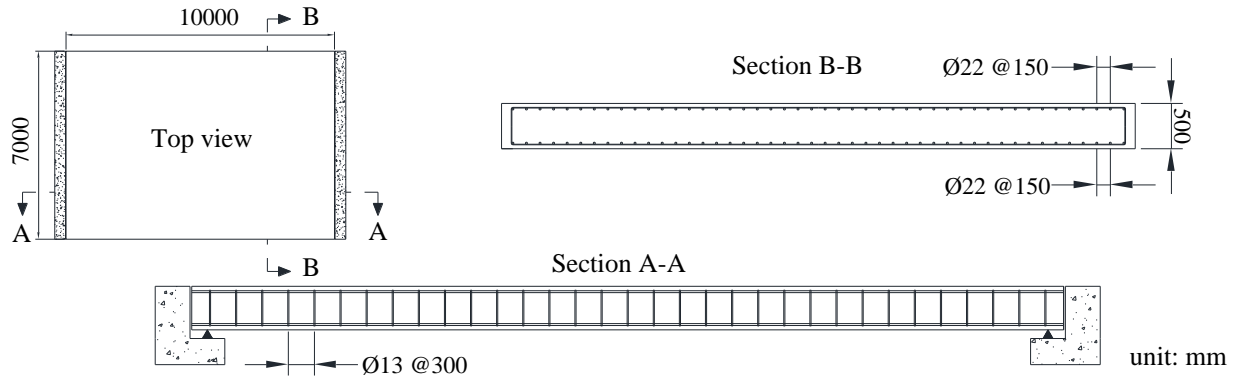


Figure 2: The analyzed one-way RC slab

In this paper, the following random variables are considered as spatially correlated

- 1) diffusion coefficient at reference time;
- 2) concrete cover;
- 3) chloride content at concrete's surface;
- 4) critical chloride value
- 5) mix proportions;
- 6) concrete's elastic modulus; and
- 7) concrete's tensile strength

The means and standard deviations of these random variables are assumed to be the same as those reported in Papakonstantinou and Shinozuka (2013).

4. ILLUSTRATIVE EXAMPLE

As an illustrative example, time-dependent flexural strength of a RC slab exposed to chloride environment is estimated by incorporating spatial variations. In this example, a one-way RC bridge slab with a span of 10 m along the longitudinal direction and a width of 7 m along the transverse direction is used. The reinforcing steel and the dimensions of the RC bridge slab are shown in Figure 2.

To consider spatial variability, the RC slab is discretized into small elements having a length of 75 mm in both directions. The spatial variability of the random variables associated with the probabilistic model is represented by 2D Gaussian stochastic field for each discrete element using SRM. The Monte Carlo Simulation (MCS) is applied with SRM to solve the probabilistic corrosion problems. Figure 3 shows an example

of spatial steel weight loss distributions of the one-way RC slab at 30, 60 and 100 years after construction. As shown in Figure 3, the amount of corrosion varies depending on locations and the extent of increase of corrosion damage with time.

When the spatial steel weight loss distributions over the corroded RC slab are obtained, these are used as input information of 2D nonlinear finite element method. Nonlinear modeling of concrete and steel, and the effect of steel corrosion on the constitutive model of corroded RC slab were provided by Lim et al. (2016) and Molina et al. (1993). The uniformly distributed load is applied to the entire upper surface of the RC slab in the finite element computations until the tensile reinforcing steel rebar yields.

As an example, 10 different spatial realizations in a time period of 30, 60 and 100 years are simulated for the structural performance assessment. Figure 4 shows the relationship between time and flexural strength ratio (defined as flexural strength of the corroded RC slab divided by the flexural strength of the uncorroded RC slab). As shown in Figure 4, the flexural strength ratios decrease with time. Also, the difference between upper and lower ratios of flexural strength increases with time. Because of the uncertainty and spatial variability associated with the prediction of material corrosion, the flexural strength ratio is different among the 10 spatial realizations. For example, at 100 years, the lower and upper ratios are 0.863 and 0.982, respectively. The computational procedure presented in this paper can be applied to safety

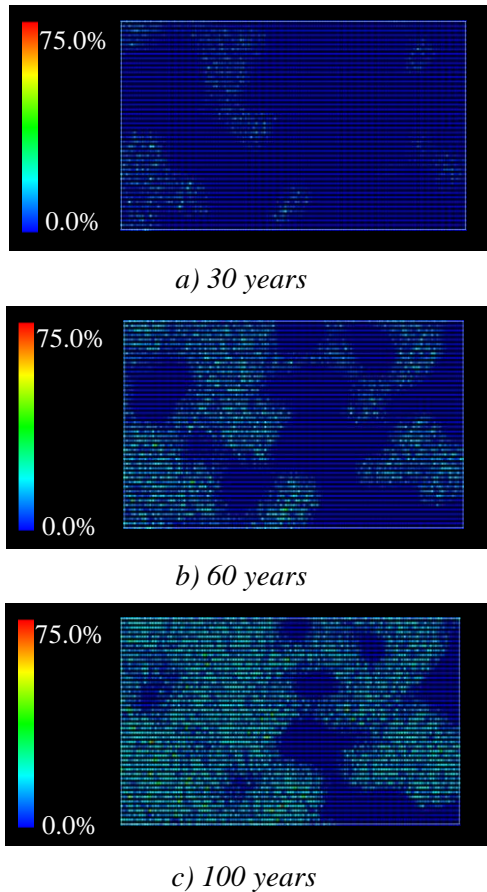


Figure 3: Spatial steel weight loss distributions of the one-way RC slab at 30, 60 and 100 years.

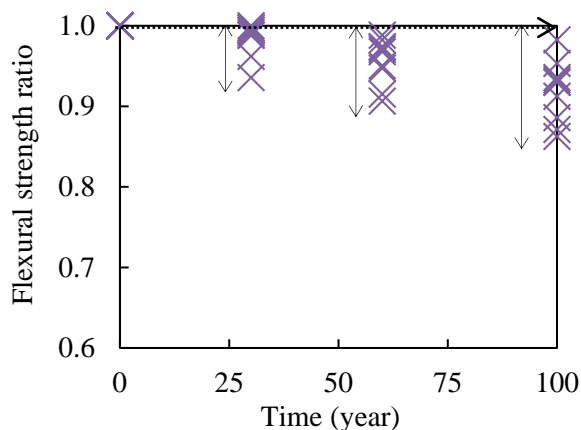


Figure 4: Relationship between time and flexural strength ratio of the one-way RC slab.

assessment of aging existing large-scale RC structures in which it is very important to consider the spatial variability associated with parameters used in the deterioration process.

5. CONCLUSIONS

A method to estimate the time-dependent structural performance of deteriorating RC slabs exposed to chloride attack by incorporating spatial variability is presented. The results indicate that the variations of the structural performance of RC slabs increases with time. The probabilistic model incorporating spatial variability is needed when life-cycle structural performance of a RC structure in a harsh environment is predicted.

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