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Seismic fragility analysis of deteriorating RC bridge substructures subject to marine chloride-induced corrosion

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ABSTRACT

This paper presents an improved reinforced concrete steel bar deterioration model that incorporates pitting corrosion and considers the change in after-cracking corrosion rate to assess the time-dependent seismic fragility of RC bridge substructures in marine environments. The proposed deterioration model is applicable for both existing and new RC bridge substructures and could be employed for life-cycle analysis of RC bridge substructures in marine environments. In this paper, the model is implemented to conduct a probabilistic seismic fragility analysis of a three-span continuous box girder bridge accounting for uncertainties in establishing bridge geometry, material properties, ground motion and corrosion parameters. Differences in the results obtained when reinforcing steel is subjected to general and pitting corrosion are investigated. The results show that the effect of chloride-induced corrosion cannot be neglected when performing the seismic fragility analysis of RC bridge substructures in marine environments. Additionally, the calculated time-dependent fragility curves indicate that there is a nonlinear accelerated growth of RC column vulnerability along the service life of highway bridges, especially after twenty-five years of exposure to chlorides.

1. Introduction

Corrosion of reinforcement in reinforced concrete (RC) components is a matter of increasing concern. For highway bridges in seismic zone, RC columns are designed to withstand the inertia forces caused by the ground motions. However, RC columns exposed to chloride environments inevitably suffer from the effect of chloride-induced corrosion. Corrosion reduces the load carrying capacity of the steel while the accumulation of corrosion products leads to cracking or spalling of concrete protective layers causing long-term reduction in the structural performance of RC columns [1,2]. As a consequence, RC bridge substructures that meet applicable seismic design requirements in their pristine states may not survive seismic hazards as they deteriorate over their service lives due to chloride contamination.

Significant research efforts have been devoted to studying the effect of chloride-induced corrosion on the seismic performance of RC bridge substructures. For example, Choe et al. [3,4] proposed probabilistic models for corroding reinforced concrete columns taking into account the reduction in their structural capacity. The sensitivity of seismic fragility to various structural characteristics was investigated using nonlinear dynamic analysis. Ghosh et al. [5] developed a time-dependent seismic fragility model considering the joint effects of column deterioration and steel bearing corrosion. The cost estimates of aging RC bridge substructures considering their seismic performance have been discussed by Alipour et al. [6].

Generally, current analyses [3–6] of RC bridge substructures hold the assumption that reinforcement bars in concrete are subject to uniform corrosion under chloride environment, which is more likely to be true in ideal experimental conditions. In fact, studies have observed that pitting corrosion rather than uniform corrosion is the primary deterioration form leading to localized losses in reinforcing bar areas when subjected to chloride-induced corrosion in field conditions [7–11]. However, few previous studies have focused on the probabilistic analyses of steel pitting corrosion in concrete structures. In addition, experimental investigations [12–14] have shown that once concrete cracking takes place, reinforcing steel corrosion rate increases significantly due to the easier access of oxygen and water. However, current corrosion rate models neglect the increase in corrosion rate after the cracking of concrete protective layers [15–20]. This could underestimate the impact of steel corrosion on the long term structural seismic performance of RC bridge substructures. Hence, an important missing link for evaluating the durability and seismic fragility of deteriorating bridge substructures consists of establishing a pitting corrosion rate model that can consider the effect of concrete cover cracking.

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In this paper, a new time-dependent corrosion rate model is proposed for RC bridge substructures exposed to typical marine environments. The proposed model accounts for the impact of concrete cover cracking on corrosion-causing current density which was not considered in previous studies. The proposed post-cracking model is developed based on available experimental data. The combination of post-cracking corrosion rate and pitting corrosion model are integrated to accurately simulate the effect of chloride-induced steel corrosion on bridge substructure capacities. A time-dependent probabilistic framework is then implemented to evaluate the seismic fragility of deteriorating RC bridge substructures over their service lives. As an application, the fragility of a typical continuous girder bridge with RC columns is investigated considering the combined uncertainties in earthquake intensity, structural parameters and deterioration process. Fragility curves obtained at different time intervals of the bridge's service life give new insights into the potential impact of steel pitting corrosion on the structural performance and seismic vulnerability of RC bridge substructures over time.

2. Deterioration model for RC members

Chloride-induced steel corrosion is considered to be one of the major factors in reducing the performance of deteriorating RC bridge substructures located in marine environments. The chloride-induced reinforcement corrosion process could be divided into three main phases as shown in Fig. 1.

In the initiation phase, chloride ions from the external environment diffuse into the concrete to reach the surface of the reinforcement bars. After the initiation of corrosion, the corrosion propagation phase continues until the concrete cracks. The last phase is defined as the deterioration phase [21,22].

2.1. Corrosion initiation

It is widely recognized that the diffusion process of chloride ions in the concrete could be modeled by Fick's second law based on the semi-infinite solid assumption. Thus, the diffusion process is expressed as [5]:

$$\frac{\partial C(x,t)}{\partial t} = \frac{\partial}{\partial x}\left[D\frac{\partial C(x,t)}{\partial x}\right] \tag{1}$$

where D = diffusion coefficient; $C(x,t)$ = chloride ion concentration; x = depth from concrete surface; and t = time in years.

While the concentration of chlorides, C_0, due to deicing salts on the surface of concrete bridge decks may not be constant [23], it is common to assume the concentration to be constant on the surface of concrete in marine environments [2–4,15,24–26]. Assuming that the initial chloride concentration inside the concrete is zero, the initial diffusion condition of chloride in concrete is expressed as follows:

a. When $t = 0$, $C(x,t)$ is equal to zero for all points within the concrete section; $x > 0$;

b. at $x = 0$,when $t > 0$, $C(x,t)$ is equal to C_0.

Combining these initial diffusion conditions with Eq. (1) and integrating, the chloride concentration $C(x,t)$ at time t of the concrete at depth x could be represented as [24]:

$$C(x,t) = C_0\left[1-erf\left(\frac{x}{2\sqrt{tD}}\right)\right] \tag{2}$$

where C_0 = chloride concentration on the concrete surface; and $erf(\cdot)$ = Gaussian error function that is expressed as:

$$erf(z) = \frac{2}{\sqrt{\pi}}\int_0^z \exp(-z^2)dz \tag{3}$$

It has been proven that the initial corrosion tends to occur when the chloride concentration at the steel reinforcement's surface reaches a critical value C_{cr} [19,27,28]. This point in time which is defined as t_{corr} is influenced by many factors related to external environmental conditions and structural characteristics [4,5,15,24–26]. The widely recognized probabilistic model for estimating the initial time of corrosion in marine environments is expressed by [29]:

$$t_{corr} = X_1\left[\frac{d_c^2}{4k_e k_t k_c D_0 (t_0)^n}\left[erf^{-1}\left(1-\frac{C_{cr}}{C_0}\right)\right]^{-2}\right]^{\frac{1}{(1-n)}} \tag{4}$$

In which X_1 = model uncertainty coefficient to account for the idealization implied by Fick's second law and variation in input parameter; k_e = environmental factor; k_t = test method factor for determining the empirical diffusion coefficient; k_c = curing time correction factor; D_0 = diffusion factor at reference period; t_0 = reference period (28 days); n = aging factor; and C_0 = chloride ion concentration on the concrete surface that can be represented as:

$$C_0 = A_{cs}(w/c) + \varepsilon_{cs} \tag{5}$$

where w/c = water-to-binder radio; A_{cs} and ε_{cs} = model parameters that account for the uncertainty in estimating C_0.

Depending on the exposure condition of concrete structures, DuraCrete [29] divides concrete members in marine environments into four categories: a) submerged, b) tidal, c) splash and d) atmospheric exposure. DuraCrete [29] also provides the statistical properties for the parameters in Eq. (4). Given that surface chloride concentrations vary significantly with the distance from the coastline, Chinese durability assessment code for concrete structures (CECS) [30] provides a more detailed model for reinforced concrete exposed to marine environments based on data collected in several field investigations. The CECS-recommended parameters for use in Eq. (4) are summarized in Appendix A. It should be noted that the parameters in Appendix A are only applicable to Portland cement.

2.2. Corrosion propagation

Continuous chloride ingress leads to the dissolution of protective passive film of steel reinforcement in concrete [1–8]. Once the corrosion of reinforcement is initiated, the corrosion rate becomes the key factor influencing the propagation of corrosion. The deterioration process in chloride environments may take two possible corrosion forms: a) uniform also known as general corrosion; or b) pitting corrosion [7–9,21]. Even though most previous studies on seismic fragility assumed general steel corrosion forms, several investigations found that

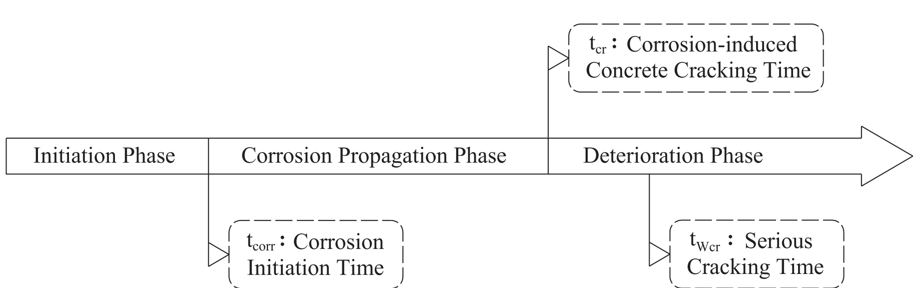

Fig. 1. Phases of chloride-induced corrosion process of reinforcing steel.