Chloride-induced reinforcement corrosion and concrete cracking simulation

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Abstract

This paper develops an integrated computational methodology for chloride-induced degradation assessment of reinforced concrete structures by considering all three phases of the deterioration process. The chloride penetration process is simulated using a finite element-based method by following an analogous transient thermal analysis. A reinforcement corrosion and rust expansion model based on Faraday's law is developed, and the rust expansion is characterized by an equivalent time-varying radial displacement boundary condition. Two established corrosion rate models – the constant model and the dynamic model – are included in the rust expansion model. Finite element analysis with a smeared cracking approach is implemented to simulate the rust expansion and the associated concrete cracking process. Simulation results are presented for a reinforced concrete slab exposed to a constant chloride environment.
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1. Introduction

The durability of reinforced concrete structures is impacted by the chloride penetration and susceptibility of the reinforcement to chloride-induced corrosion, when exposed to marine environment or deicing salts. Once the chloride content at the reinforcement reaches a threshold value and enough oxygen and moisture are present, the reinforcement corrosion will be initiated. Corrosion products then accumulate in the concrete–steel interface transition zone (ITZ), generate expansive pressure on the surrounding concrete, and cause crack initiation and propagation.

Quality concrete is able to prevent the embedded reinforcing steel from potential corrosion in three ways. First, hydration products of cement in concrete form a high alkaline pore solution environment, where the passivated film covering the steel surface remains chemically stable enough

to protect reinforcing steel from corroding [1]. Second, quality concrete usually possesses low porosity and permeability, which greatly minimizes the penetration of corrosion-induced agents (such as chloride, carbon dioxide, oxygen, moisture, etc.) through porous concrete. Third, the high electrical resistivity of quality concrete restricts the corrosion by reducing the electrical current flow between the anodic and cathodic sites. However, quality concrete cannot always be attained in practice, especially when concrete with initial flaws (including micropores and microcracks) is exposed to adverse environments. Chloride penetration may result in the accumulation of chloride content at reinforcement to such a level that the high alkaline environment is destroyed and then the passivated film on the steel surface is disrupted [2,3]. Once enough oxygen and moisture are present, the reinforcement corrosion will be initiated.

After the initiation of corrosion, the corrosion products (including various iron oxides) with relatively lower density occupy much more volume than the original iron. As the corrosion progresses, the corrosion products accumulate in ITZ and generate expansive pressure on the surrounding

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concrete. The pressure builds up to such high level that cause crack initiation and propagation. In addition to the cracking in surrounding concrete, chloride-induced reinforcement corrosion results in loss of the concrete–steel interface bond, and reduction of the cross-sectional area of reinforcement, thus reducing the load carrying capacity of concrete structure [4].

The entire chloride-induced reinforcement corrosion process of reinforced concrete structures can be divided roughly into three phases as shown in Fig. 1. The first phase is characterized by the chloride penetration, during which the chloride diffuses gradually from the concrete surface through the concrete cover toward the reinforcement. When the chloride content at reinforcement reaches a threshold value to initiate the corrosion process at time $t_{initiation}$, the second phase is assumed to begin. The second phase is dominated by the reinforcement rust expansion, during which the rust (i.e., the corrosion products) accumulates in the concrete–steel ITZ. Once voids in ITZ are occupied completely with the rust at time t_{stress}, further rust accumulation will trigger expansive stress and then cracking in the surrounding concrete, which indicates the start of the third phase. During the third phase, the rust expansion-induced cracks propagate in concrete surrounding the reinforcing steels until some critical failure mode, such as the spalling or delamination of concrete cover, occurs at time $t_{spalling}$, which indicates the end of the third phase.

Among the three phases, the first phase usually lasts for a relatively long period, depending on corrosion resistance of the reinforcement, thickness and quality of the concrete cover, ambient chloride content, etc. The second phase is much shorter than the first one, which is determined mainly by the porosity of ITZ. The third phase is the shortest one since the rust expansion-induced cracks propagate rapidly through the surrounding concrete. Considering only the chloride-induced reinforcement corrosion, the entire service life may be defined as the sum of all three phases. Under specified design requirements, the termination of service life can also be defined by an acceptable level of corrosion indicated on the vertical axis of Fig. 1.

The chloride-induced reinforcement corrosion and cracking patterns corresponding to the three phases defined in Fig. 1 are illustrated in Fig. 2 [5].
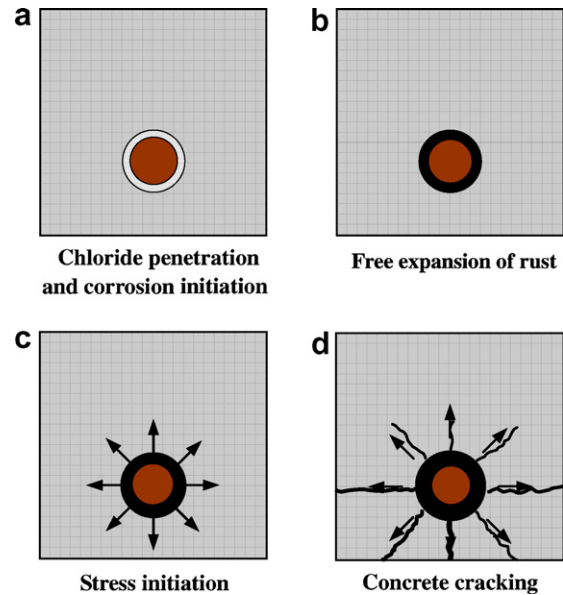

Fig. 2. Chloride-induced reinforcement corrosion and cracking patterns.

During the past decades, various empirical and numerical models have been proposed to estimate the deterioration caused by the chloride-induced reinforcement corrosion and to predict the service life of the reinforced concrete structure. Tuutti [6] suggested a model to predict the service life, where the maximum acceptable corrosion level is related to the appearance of cracks. The deterioration process consists of two periods: initiation and propagation. The initiation period can be estimated as the time required for chloride to reach the reinforcement surface and trigger active corrosion, while the propagation period can be taken as the time elapsed until repair becomes mandatory. Cady and Weyers [7] developed a deterioration model to estimate the remaining life of concrete bridge components in corrosive environment, assuming that chloride-induced reinforcement corrosion is the main cause of deterioration. The model predicts bridge deck deterioration level in terms of percentage area of the entire deck. Based on the physical mechanism for corrosion of reinforcing steel in concrete exposed to marine environment, Bazant [8,9] proposed a mathematical model to determine the time to cracking of the concrete cover. In this model, the time to cracking is assumed to be a function of corrosion rate, cover depth, spacing of steel rebars, and mechanical properties of concrete. Based on field and laboratory observations, Morinaga [10] developed an empirical model to predict the time to cracking. It is assumed that concrete cracking will first occur when there is a critical quantity of corrosion products forming on the reinforcement. Liu and Weyers [5] suggested a similar corrosion-cracking model to compute the time to cracking using the critical amount of rust, which consists of the amount of corrosion products needed to fill the ITZ voids plus the amount of corrosion products needed to generate sufficient tensile stresses to crack the cover concrete. In summary, a realistic
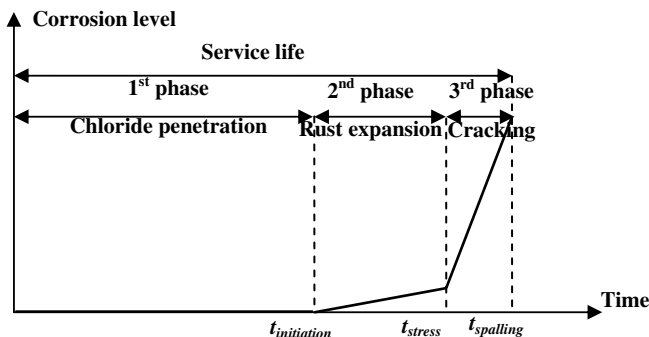

Fig. 1. Chloride-induced reinforcement corrosion process.