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Finite element modeling of concrete cover crack propagation due to non-uniform corrosion of reinforcement

Juhui Zhang [a,*], Xiaozheng Ling [a], Zhongguo Guan [b]

[a] Department of Civil Engineering, the University of Shanghai for Science and Technology, Shanghai, China
[b] State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai, China

HIGHLIGHTS

- A FEM model of concrete cover cracking due to non-uniform corrosion was developed.
- The crack propagation of cover concrete and evolution of crack width was monitored.
- The corrosion pressure of cover concrete and failure pattern were studied.
- Limiting criteria for the cracking modes were established.

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ABSTRACT

Non-uniform corrosion of reinforcement causes concrete cracking in chloride contaminated RC structures. Due to an interaction existed between the concrete cover cracking and the ingress of aggressive agents in chloride environments, chloride ingress is significantly enhanced by cracks. Thus the investigation on the cracking paths and cracking propagation process resulting from steel corrosion is very essential. This work proposed a numerical model to study the cracking of cover concrete. The physical model was focused on the middle-located rebar corrosion, and the effect of the neighboring longitudinal reinforcing bars on the cracking of cover concrete was mainly considered. A damaged plasticity model for the study on the failure behavior of concrete cover was built. The non-uniform radial displacement distribution was adopted to simulate the corrosion expansion behavior of the rebar. The cracking propagation process of cover concrete with two neighboring longitudinal reinforcing bars embedded was simulated and monitored with the level of corrosion build-up. The present approach was verified by the available experimental observations. The influences of concrete cover thickness, rebar diameter and rebar spacing on the failure patterns of concrete cover and crack width propagation were examined. And limiting criteria for the cracking modes were established.

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1. Introduction

Although reinforced concrete (RC) is one of the most durable construction materials, the presence of soluble chlorides from deicing salts or marine exposure could destroy the passive film protecting the steel and induce corrosion of reinforcement [1]. Once corrosion is initiated, the corrosion products continuously accumulate around the circumference of the rebar causing the surrounding concrete to crack, delaminate, or spall with the expansion effect and affecting both safety and serviceability of RC structures. In the practice engineering, it's of great importance to grasp the propagation of internal cracks due to rebar corrosion in case that the internal-cracking-induced spalling of concrete becomes a risk to human safety [2]. And it is also acknowledged that an interaction exists between the concrete cover cracking and the ingress of aggressive agents in chloride environments [3–4]. Win [5] pointed that chloride ingress was significantly enhanced by cracks because the ions can penetrate the concrete cover from the walls of the crack as well as from the outer surface of the concrete. Thus, investigation on cracking paths and crack propagation process resulting from steel corrosion is very essential for the interaction study between crack and chloride ingress as well as service life prediction of corroded structures in engineering practice.

During the past two decades, many studies have been conducted towards the experimental, analytical and numerical simulation of corrosion-induced concrete cover cracking process. Andrade et al. [6] indicated that only a few micrometers of loss

* Corresponding author.
E-mail address: zhjhui@usst.edu.cn (J. Zhang).

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in rebar cross-section are needed to induce visible cover cracks (0.1 mm width) under accelerated corrosion tests with impressed current technique. Alonso et al. [7] also conducted accelerated corrosion tests by applying constant currents, and found that radius losses of about 15–50 μm are necessary to generate the first visible crack (<0.1 mm width), and a linear relationship exists between the amount of corrosion and crack width. Bazant [8] initially proposed an analytical model of corrosion-induced cracking. Bhargava et al. [9] proposed an improved analytical model by considering the residual strength of the cracked concrete and the stiffness provided by the combination of the reinforcement and expansive corrosion products. Bossio et al. [1] proposed a sophisticated analytical model to evaluate crack propagation, indicating that the maximum tensile stress is attained close to the bar in the circumferential direction and the crack develops in the radial direction until it reaches the external surface of concrete. Molina et al. [10] developed a numerical model with smeared-crack approach relating the crack-width rate to the specific volume of the rust being formed. Sanz et al. [11] proposed a combination of finite elements with an embedded adaptable cohesive crack (which describe the cracking of concrete), together with expansive joint elements, leading to crack localization in a manner similar to that found experimentally. Du et al. [12] conducted a finite element analysis, and found that the amount of corrosion in term of radial expansion required to cause Internal Cracking, Internal Penetration and External Cracking varies almost linearly with bar diameter, bar clear distance and concrete cover, respectively. German and Pamin [13] employed the damage-plasticity and the cracking models to describe the concrete response to chloride corrosion effects, and numerically confirmed that the appearance of vertical cracks going through the cover depends on the cover thickness. In particular, Zhang [14] and Du et al. [12] have conducted numerical analyses to establish a qualitative relationship between the amount of corrosion and the concrete crack propagation state. And Benin et al. [15] proposed a methodology of corroding state monitoring based on the crack opening width. However, all the aforementioned researches were based on the uniform corrosion assumption.

In fact, uniform corrosion is rarely the case in practice as chloride ions generally take a longer time to transport to the steel/concrete interface which faces the interior concrete because of the impermeability of steel bars [16]. Zhang et al. [17] dealt with two corroded reinforced concrete beams, which have been stored under sustained load in a chloride environment for 14 and 23 years, respectively, and found that in chloride-induced non-uniform corrosion process, corrosion cracking affects significantly the corrosion pattern. Khan et al. [18] studied the relationship between crack width and steel cross-section loss for a 26-year-old non-uniform corroded reinforced concrete beam. Based on accelerated aging tests under artificial climate environment, Yuan and Ji [19] revealed a half-elliptic model for corrosion products distribution, then Zhao et al. [20] proposed a Gaussian function. These empirical non-uniform rust expansion models have been utilized for modeling of corrosion-induced concrete cover cracking process. For example, Du et al. [21] studied cover concrete cracks due to non-uniform corrosion expansion based on the meso-scale numerical method and conducted parametric study on rebar diameter and cover thickness, indicating that the cracking of concrete cover due to rebar corrosion-induced expansion occurs much earlier when corrosion is localized at the outer region of rebar. Besides, Du et al. [22] and Chen and Leung [23] developed numerical models for corrosion-induced crack propagation in concrete as corrosion progresses and indicated that non-uniform corrosion was more detrimental to structure durability than uniform corrosion. Although many studies have been carried out on the mechanism of corrosion-induced concrete cover cracking process as above, they haven't been able to quantitatively model the crack width.

In the practice engineering, crack width is an important indicator since it's one of the easiest measurements relating to structural degradation. Therefore, the newly developed computational models for corrosion-induced concrete fracturing should not only show the crack propagation pattern, but also calculate the crack width evolution. Liu and Li [24] proposed a numerical method which can be observed directly the direction, width and length of track of crack propagation caused by corrosion and expansion of steel bars, but haven't expounded the solution procedure of crack width value. Qiao et al. [2] presented the development of surface crack width against corrosion for the series with 30 mm cover, focusing on the effects of corrosion distribution but not the configuration characteristics.

Thus, in the present paper, a damaged plasticity finite element (FE) model of concrete cover cracking due to non-uniform corrosion of reinforcement was proposed. And dynamic propagation process of various cracking modes and the evolution of crack width were monitored as the corrosion products build up, which is vital in further study of service life prediction of RC structures. The model was introduced in Section 2 and verified in Section 3; then the configuration parametric study was conducted and corrosion cracking modes were discussed in tion 4; finally, conclusions were drawn in Section 5.

2. Model description

2.1. Geometry model

Although due to the special boundary conditions, the concrete cover with corner located rebar is often subjected to the attack of chloride ions in a marine environment from two directions, and thus the corresponding cracking behavior of concrete cover induced by corner located rebar corrosion is different from the one for middle-located rebar [25], the physical model proposed in this study was only focused on the middle-located rebar corrosion, and the effect of the neighboring longitudinal reinforcing bars on the cracking of cover concrete was mainly considered, as shown in Fig. 1, in which two neighboring longitudinal reinforcing bars are embedded in the concrete cover. Three configuration parameters, namely the concrete cover thickness C, the rebar diameter D_b, and the rebar spacing s were considered. Since the condition of $a \geqslant 3C$ (Fig. 1) ensures the independence of simulation results on the location of the boundaries [26], horizontal movement was restrained at the left and right concrete boundaries because of symmetry, while the horizontal and vertical movements were both restrained at the bottom. Thus, the corrosion induced concrete cracking process was modeled as a plane-strain problem.

2.2. Corrosion modeling

2.2.1. Corrosion distribution pattern

To obtain a more realistic stress field and corrosion cracking state, a realistic corrosion distribution should be adopted for the displacement-load input in numerical modeling [27]. In the present study, the volume expansion of corrosion products was modeled by applying half-elliptic radial displacements on the outer semi-circumference and uniform radial displacements on the inner semi-circumference. The radial loss of corroded steel section can be expressed under polar coordinate as [28]:

$$d_{l\theta} = \begin{cases} R_b - \dfrac{R_b \cdot (R_b - d_l + d_{ld})}{\sqrt{(R_b - d_l + d_{ld})^2 \cdot \cos^2\theta + R_b^2 \cdot \sin^2\theta}} + d_{ld} & (0^\circ \leqslant \theta \leqslant 180^\circ) \\ d_{ld} & (180^\circ \leqslant \theta \leqslant 360^\circ) \end{cases} \quad (1)$$

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