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Meso-scale numerical investigation on cracking of cover concrete induced by corrosion of reinforcing steel

Xiuli Du, Liu Jin *

Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing, China

A R T I C L E I N F O

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Concrete cover cracking induced by corrosion of steel reinforcement is a major influencing factor for durability and serviceability of reinforced concrete structures. Here in this study, the influence of concrete meso-structure on the failure pattern of concrete cover is accounted for. The concrete is assumed to be a three-phase composite composed of aggregate, mortar matrix and the interfacial transition zone (ITZ). And a concrete random aggregate structure is established for the study on the mechanical behavior of radial corrosion expansion. In the present simulations, the plasticity damaged model is used to describe the mechanical behavior of the mortar matrix and the ITZ, and it is assumed that the corrosion of steel reinforcement is uniform. The cracking of concrete cover due to steel reinforcement corrosion is numerically simulated. The simulation results have a good agreement with the available test data and they are between the two analytical results. The failure patterns obtained from the macro-scale homogeneous model and the meso-scale heterogeneous model are compared. Furthermore, the influences of ratio of cover thickness and reinforcement diameter (i.e. c/d), the location of the steel reinforcement (i.e., placed at the middle and corner zones) and the concrete tensile strength on the steel corrosion rate when the concrete cover cracks are investigated. Finally, some useful conclusions are drawn.

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1. Introduction

The durability of reinforced concrete structures is affected 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 surface of the reinforcement reaches a threshold value and enough oxygen and moisture are present, the reinforcement corrosion will be initiated. For instance, Hausmann's work [1] indicates that rebar corrosion in concrete starts at the threshold concentration ratio $C_T = [Cl^-]/[OH^-]$ of 1.4 in ambient atmosphere and 0.9 when oxygen bubbles (O_2) are present on the bar surface. Corrosion products then accumulate in the concrete-steel interface transition zone (ITZ), generate expansive pressure on the surrounding concrete, and cause cracking initiation and propagation. The main consequences of corrosion of steel in reinforcement concrete are as follows [2]: (a) reduction in steel area, resulting in losses in strength of reinforced concrete members; (b) the corrosion products occupy a volume larger than the original steel. At the onset of corrosion, these products migrate into any voids adjacent to the concrete. At this stage, although the effective bar area is reducing, the corrosion does not affect the integrity of the surrounding concrete. Once the voids have been filled, any corrosion products produced

* Corresponding author. Tel.: +86 15811171018/10 67392430.
E-mail address: kinglew2007@163.com (L. Jin).

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subsequently exert an expansive pressure which can result in cracking, spalling and delamination of the cover concrete; (c) the nature of the bond between the steel and the concrete changes and can deteriorate, resulting in loss of composite action and change in mode of structural behavior. Moreover, the cracking of cover concrete would cause the accelerated changing of structural behavior [3,4]. Therefore, it is of great significance to explore the cracking behavior of cover concrete caused by corrosion of steel reinforcement.

A lot of efforts have been devoted to investigate the cracking behavior of cover concrete caused by corrosion of steel reinforcement by using experimental, analytical and numerical methods. In experimental studies, the accelerated corrosion test e.g. in [5–7] and the simulated corrosion test e.g. in [2,8] were often used to investigate the radial expansion of corroded reinforcement and its effects on concrete structures. Williamson and Clark [2] carried out a series of tests to investigate the magnitude of pressure created by corrosion products on steel in reinforced concrete that would cause surface cracking of the concrete cover. Their test observations showed that the failure pressures were influenced by cover/bar diameter ratio, aggregate size, bar diameter, and bar location. The time-to-corrosion cracking was experimentally was determined by Liu and Weyers [6] from simulated bridge deck slabs, in which the corrosion rate, concrete cover depth, reinforcing steel bar spacing and size were taken into account. The accelerated corrosion test methods were adopted by Val et al. [7] to investigate corrosion-induced crack initiation and propagation within concrete cover. And they found that the amount of corrosion products penetrating into the concrete pores before cracking initiation was larger than that obtained by other researchers. Wong et al. [9] conducted some experimental work on the penetration of corrosion products from reinforcing steel into concrete due to chloride-induced corrosion. Their test results showed that only a small amount of corrosion was needed to induce visible cover cracking. However, the two test methods has their own drawbacks, for instance, it is difficult for the accelerated test method to measure the radial expansion of corroded reinforcement, and erroneous predictions may occur if the results are extrapolated to the behavior of real structures [10]. In addition, the test results are mainly based on the external observation of the physical specimen. They are not utilized to reveal the internal mechanism and the process of concrete cracking caused by radial expansion of corroded reinforcement.

In analytical investigations, the closed-form solution of a thick-walled cylinder under uniform internal pressure derived from plane-strain isotropic linear elasticity has been used by Bažant [11] to model the internal pressure exerted by the corroding bar on the surrounding concrete. However, in the case of the corroded bar, the times to cover splitting calculated from the thick cylinder model generally fall significantly shorter than reported times from field observation. Many different amendments have been attempted in the effort to increase the estimated time to splitting, e.g. in the work of Liu and Weyers [6] and Martin-Perez [12]. Liu and Weyers [6] explored the effects of corrosion rate, cover thickness, spacing and diameter of reinforcement on the radial expansion, and they proposed a computational model to predict the damage of cover concrete. However, in their work cracking of the cover was assumed to occur instantaneously when the maximum hoop stress equals the tensile strength of concrete, thus ignoring the residual strength of concrete that may account for longer times to cracking. Besides that, lots of models based on the thick-walled cylinder theory with different levels of sophistication have been utilized e.g. in [13–16]. Despite their widespread use, a common limitation of these developed models derived from the thick-walled cylinder solution is in the representation of the boundary conditions around the hole that is occupied by the corroding reinforcing bar. Moreover, they also cannot describe the failure process and the failure pattern of cover concrete.

The introduction of computer simulation into this research field has facilitated an effective tool as an additional approach to study the effect of reinforcement corrosion on structural concrete. In numerical investigations, Du et al. [10] studied the radial expansion of corroded reinforcement on concrete cracking by using finite-element analysis, and they explored the relationship between amount of corrosion for concrete cracking and ratio of concrete cover to bar diameter (c/d), as well as that between reinforcement bond strength and amount of corrosion. Val et al. [7] investigated the cracking of concrete cover subjected to corrosion expansion by using experimental and numerical approaches. Besides that, more and more sophisticated models have been introduced, for instance in the work [17–21]. All these efforts have been carried out based on the assumption that concrete is a homogeneous medium, i.e. its mechanical or transport properties are the same in the entire computational domain, ignoring the different cracking properties of aggregate, cement hydrates, and their interface.

In reality, the mechanical behaviors of concrete, for instance the macroscopic mechanical properties and the failure pattern are closely associated with the micro-/meso-structure of concrete [22–24]. In the numerical simulations, concrete heterogeneity should be accounted for, and thus it calls for the adoption of a meso-scale mechanical model in which heterogeneity can be explicitly simulated. Recently, a step further in that respect have been taken by Pan and Lu [25], who included the effect of heterogeneous concrete material structure in their analyses. Moreover, Šavija et al. [26] used the meso-scale lattice model to study the radial expansion behavior. These should result in improved understanding of the cracking process due to expansion of corrosion products. Nevertheless, further work is still needed.

As a heterogeneous composite consisting of four different phases (voids, aggregate, cement hydrates and the interfacial transition zone), concrete involves very complex transport phenomenon. In this study, a meso-scale mechanical model was proposed to study the effects on radial expansion due to the formation of corrosion products, on the cracking of cover concrete. The aim of the present work is, therefore, to explore the cracking mechanism of concrete cover. Herein the present meso-scale simulations, concrete is assumed to be a three-phase composite composed of aggregate, mortar matrix and the interfacial transition zone. A sensitivity analysis has also been carried out by considering variation of the various parameters of the meso-scale model.

The paper is decomposed as follows. The next Section describes the radial corrosion expansion behavior of steel reinforcement and shows the assumptions used in the simulations. Section 3 presents the meso-scale computational model for

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