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Modeling the cracking of cover concrete due to non-uniform corrosion of reinforcement

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ABSTRACT

In situations when external chloride penetration is the cause of depassivation, the corrosion process may start from the outer region of a rebar, which might expand non-uniformly. Therefore, the main objective of the present work is to explore the effect of non-uniform corrosion on cracking behavior of cover concrete. The influences of concrete heterogeneities and the porous layer generated at the rebar/concrete interface on the failure patterns and the corrosion level of cover concrete are considered. The random aggregate structures of concrete are built, and the concrete is regarded as a composite composed of three phases, i.e. the aggregate, mortar matrix, and the interfacial transition zones (ITZs). The plasticity damaged model is employed to describe the mechanical properties of the mortar matrix and the ITZs, and it is assumed that the aggregate is elastic. Non-uniform radial displacement with a half ellipse shape is adopted to describe the expansion distribution of the corrosion products. The failure pattern and the corrosion pressure of cover concrete, and the critical corrosion level when the cover concrete cracks due to non-uniform corrosion expansion are studied based on the meso-scale numerical method. The comparison of the simulation results with the available test results on the failure pattern of cover concrete shows fairly good agreement. Moreover, the influence of meso-structural heterogeneities is explored, and the cracking behavior obtained under non-uniform and uniform expansion conditions are compared. Finally, the influences of cover thickness, rebar diameter and the location of rebar (namely side-located rebar and corner-located rebar), on the failure pattern and the corrosion level are examined.

1. Introduction

Corrosion of steel reinforcement is one of the main pathologies of reinforced concrete structures. It involves generation of an oxide layer on the bar surface, which results in a decrease of the net cross-sectional area, thus, reducing its strength and decreasing the overall safety of the structure [1]. When a significant reduction in area is reached, the volumetric expansion of the oxide induces internal pressure on the surrounding concrete, causing the cracking of cover concrete and, eventually, the full spalling of the cover [2,3]. Accordingly, corrosion-induced cracking of cover concrete is an important and essential issue in concrete structures because it directly affects not only durability, but also the service life of these engineering structures.

Much effort, involving experimental, analytical and numerical effort, has been carried out to investigate the failure pattern of cover concrete and determine the critical corrosion amount which causes the cracking of cover concrete. Experimental effort has been carried out to investigate the cracking behavior of cover concrete and the critical corrosion amount when the cover concrete cracks due to steel reinforcement corrosion, e.g. based on the electric corrosion test method [2,4–7] and the mechanical dilatation method [8,9]. These experimental studies are mainly focused on testing the critical amount of the rebar corrosion required for the cracking of cover concrete and developing corresponding empirical models. Therefore, the cracking mechanism and the cracking process of cover concrete cannot be captured by these experimental approaches.

In the analytical studies, a number of analytical models [10–13] have also been developed for the study of the cracking of cover concrete induced by corrosion. These models have been widely used to evaluate the critical corrosion amount and predict the time to crack initiation in the concrete cover. However, most of these analytical models were based on the theory of elasticity and the

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effect of the residual strength of cracked concrete was not considered. Furthermore, all these analytical methods have assumed that the corrosion of reinforcing bar was uniform and thus the corresponding expansion pressure was uniform around a rebar. In situations when external chloride penetration is the cause of depassivation, the corrosion process may start from the outer region of a rebar, which might expand non-uniformly [14–16]. In such a case, a model assuming uniform expansion may be used only as a very rough approximation [17].

Except for these experimental and analytical efforts, a lot of studies have been carried out by using nonlinear fracture mechanics or finite element methods [1,15,18–22]. For instance, Jang and Oh [15] used the macro-scale finite element method to explore the effect of non-uniform corrosion on cracking behavior of concrete cover, and they have found that the pressures to cause cracking of concrete cover under non-uniform corrosion conditions are much smaller than those under uniform corrosion cases. Tran et al. [6] adopted a three-dimensional Rigid-Body-Spring (RBSM) method combined with a three-phase material corrosion–expansion model to simulate the crack propagation in cover concrete due to rebar corrosion. Recently, Ozbolt et al. [23] have employed the micro-plane model to study the damage in concrete caused by corrosion of reinforcement, and they also explored the influence of the anode–cathode regions on the corrosion behavior. Sanz et al. [1] developed a model – called expansive joint element to simulate the expansion of the oxide, and they used finite elements with an embedded adaptable cohesive crack to describe concrete cracking. All these simulation studies have made great contributions in analyzing the corrosion behavior of steel reinforcement and the relevant cover cracking. Some of the effort assumed that the corrosion process was uniform. Furthermore, in these investigations, the concrete was often assumed as homogeneous, without considering the influence of heterogeneities of concrete on the cracking behavior. As known, the failure behavior of concrete is closely associated with the heterogeneities of concrete meso- or micro-structure [16,24–26], and the concrete heterogeneities should be accounted for in the simulations. At the micro- or meso-scale, the macro-nonlinearity and the size effect of concrete can be described well. And therefore, a lot of micro-mechanical and meso-mechanical methods have been developed to study the failure behavior of concrete. For more details about these micro- or meso-mechanical methods, refers to [25].

In our previous work [27], considering the influence of concrete heterogeneities, a meso-scale mechanical method was developed to explore the cracking behavior of cover concrete due to corrosion of steel reinforcement. However in the work, the assumption of uniform corrosion was made, and the effect of the porous layer existed at the interface of reinforcing bar and surrounding concrete on corrosion level was ignored. As mentioned previously, the corrosion process should be non-uniform, and the uniform corrosion assumption should be a rough approximation. Therefore, the present work concentrates on the cracking behavior of the heterogeneous cover concrete induced by non-uniform corrosion expansion.

Non-uniform corrosion behavior leads to a non-uniform distribution of expansion pressures. And the non-uniform distribution of expansion pressure may cause adverse effect for the cracking of concrete cover because higher pressures are concentrated at the outer region of rebar toward concrete cover [15,22]. This may cause higher tensile stress development and fast occurrence of cracks in concrete cover, which reduces time-to-cracking and eventually service life of concrete structures [15,28].

In light of this, both the heterogeneities and the porous layer existed at the steel/concrete interface were considered, and concrete was assumed to be a three-phase composite composed of aggregate, mortar matrix and the interfacial transition zones (i.e. ITZs) in the present study. A meso-scale mechanical model was established for the investigation on the cracking of cover concrete. In the model, non-uniform radial displacement with a half ellipse shape was utilized to describe the expansion distribution of the corrosion products. A series of simulations have been carried out, and some influencing factors have also been studied.

After this introduction, the paper is decomposed as follows. The next Section describes the expansion pattern of corrosion products (i.e. the half ellipse-shape distribution) and presents the corresponding corrosion level considering the effect of the porous layer generated at the steel/concrete interface. Section 3 presents the concrete meso-mechanical model for simulation of the cracking behavior of cover concrete due to non-uniform corrosion-induced expansion of steel reinforcement. In Section 4, the cracking process of cover concrete was simulated, and the present meso-mechanical model was verified with the available test observations. In Section 5, the numerical results obtained by macro-scale homogeneous and meso-scale heterogeneous models were compared. Uniform and non-uniform corrosion expansion behavior was also studied. Moreover, some influencing factors, including the thickness of cover, the diameter of reinforcing bar, and the location of steel bar on the failure patterns of cover concrete and the critical corrosion level when cover cracks were explored. Finally, Section 6 presents the conclusions.

2. Non-uniform corrosion-induced cover cracking analysis

Steel in concrete is protected from corrosion by surface film of ferric oxide. The corrosion will start when the film is broken or depassivated [29]. The depassivation can be caused by reaching a threshold concentration of chloride ions in concrete near the steel surface [30]. The chloride-induced reinforcement corrosion process and cracking patterns are illustrated in Fig. 1 [19]. Once the chloride content at the surface of the steel rebar reaches a threshold value, the corrosion of steel reinforcement will be initiated (see Fig. 1(a)). The corrosion products expand into the porous transition zone between the steel rebar and the surrounding concrete, as presented in Fig. 1(b). As the corrosion progresses, the corrosion products accumulate in the steel/concrete interface and generate expansive pressure on the surrounding concrete, as shown in Fig. 1(c). The pressure arising from corrosion-induced expansion of the steel bar in concrete generally induces tensile stresses and strains in the surrounding concrete. The tensile strains in concrete increase as the corrosion of the steel bar progresses. Further increase of the tensile strains will cause cracking in the surrounding concrete and the cracking will also occur at the surface of the concrete cover during the expansion process [19], as depicted in Fig. 1(d). Therefore, to study the cracking behavior of concrete cover due to corrosion-induced expansion, one should analyze the quantitative relationship between the corrosion amount of the steel rebar and the internal pressure generated from corrosion.

In the previous work [27], the cracking of cover concrete due to uniform corrosion-induced expansion was modeled and explored. And as mentioned in the Introduction part, the corrosion process may start from the outer region of a rebar, which might expand non-uniformly [14–16]. The assumption of uniform expansion should be an approximation. The non-uniform corrosion behavior of a reinforcing bar was therefore to be discussed in the present work.

To develop the corrosion cracking model of cover concrete, the following four assumptions are made in this work:

1) Failure behavior of concrete is closely associated with meso-structure of concrete. Meso-scale heterogeneous concrete models were employed.