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Time to surface cracking and crack width of reinforced concrete structures under corrosion of multiple rebars

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HIGHLIGHTS

- A time-dependent non-uniform corrosion model is established.
- A cohesive crack model for simulating arbitrary cracking in concrete is formulated.
- Two typical cover failure modes have been simulated.
- Time to surface cracking after corrosion initiation and crack width have been determined.

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ABSTRACT

Concrete cover cracking caused by corrosion of reinforcement is one of major deterioration mechanisms for reinforced concrete structures. In practice, time to surface cracking and crack width evolution are of significance in regards to the assessment of serviceability of reinforced concrete structures. Literature review suggests that, although considerable research has been undertaken on corrosion-induced concrete cracking, little has been focused on corrosion of multiple reinforcing bars, especially by considering the non-uniform corrosion process. In this paper, a time-dependent non-uniform corrosion model is established. A cohesive crack model is then formulated to simulate arbitrary cracking in the whole cover of concrete structures. Two typical cover failure modes (i.e., "delamination" and "combined delamination and corner spalling") have been simulated under the non-uniform corrosion of multiple reinforcing bars and found dependent on spacing of reinforcement and fracture energy of concrete. The effects of corrosion, geometric and mechanical parameters on the time to surface cracking after corrosion initiation and the crack width evolution are also investigated and discussed. The developed model is partially verified by comparing the results with those from experimental tests on uniform corrosion of multiple reinforcing bars.

1. Introduction

Corrosion of reinforcement is a significant problem affecting the durability of reinforced concrete (RC) structures, e.g., bridge decks, retaining walls, piers, tunnels. Practical experience and observations suggest that corrosion-affected RC structures are more prone to cracking than other forms of structural deterioration. Consequently, the corrosion induced cracks destroys the integrity of the concrete cover, deteriorate the bonding strength of the interface between reinforcement and concrete, and lead to premature failure of RC structures. Moreover, the reinstatement cost of corrosion-affected RC structures is significantly high; worldwide, the maintenance and repair costs for corrosion-affected concrete infrastructure are estimated around $100 billion per annum [1].

Considerable research has been carried out in concrete cover cracking induced by corrosion of reinforcement [1–8]. Liu and Weyers [2] were amongst the first to model the surface cracking time of concrete cover due to corrosion of reinforcement, based on a series of experimental tests. Their formula for the critical amount of corrosion products has been widely cited in the research literature. Pantazopoulou and Papoulia [4] established a relationship between the amount of corrosion products and internal pressure from which the cracking time of the concrete cover can be obtained. Li et al. [9] developed an analytical model to calculate the crack width of concrete cover caused by corrosion of reinforcement. Amongst these existing studies, most are focused on uniform corrosion of a single reinforcing bar.

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However, due to the fact that chlorides, as well as moisture and oxygen, penetrates into surface of steel at different rates on different sides of the concrete, it is rare to have a uniform corrosion on the reinforcing bar. Recently, some researchers have started to model the cracking of concrete cover induced by non-uniform corrosion. According to geometry and diffusion properties of concrete, non-uniform corrosion model can be built by considering chloride concentration via Fick's second law of diffusion [10–12]. However, the actual environmental conditions of concrete may differ significantly from the hypothesis under Fick's law [13]. Meanwhile, experimental tests or field surveys have been carried out to determine the distribution of corrosion rust which is found not uniform along the circumference of the reinforcement [14–16]. Almost all the experimental results in literature have shown that only the part of reinforcement facing concrete cover is corroded and the further towards the concrete surface the location is, the more corrosion products that are produced at this location. Some studies introduced a factor defining the ratio of the depth of non-uniform corrosion to that of uniform corrosion, and found that its value ranges about 4–8 in natural conditions [17–19]. Yuan and Ji [16] conducted corrosion tests on reinforced concrete samples in an artificial environmental chamber and found that, only a half of the reinforcement, facing concrete cover, was corroded and the expansion was in a semi-elliptical shape. Similar corrosion distributions were also found in other experiments [20].

Moreover, corrosion rate is the most important single parameter controlling the corrosion development [2,9,21,22]. Previous work on predicting of corrosion-induced cover cracking mainly assumes a constant mean annual value of corrosion rate for the whole life-cycle of RC structures after corrosion initiation [18,19,23]. However, the corrosion process of steel reinforcing bar is an electrochemical reaction process influenced by three factors, i.e., chloride concentration, oxygen content and resistivity of concrete [24]. In natural environment, the actual corrosion rate should change throughout the year and the full life-cycle of RC structures. A number of researches have been made to analytically establish the corrosion rate model for the entire lifetime of RC structures based on the electrochemical theory and/or to conduct experiments under artificial and nature climate environment conditions for verifications [25–28].

Under the expansive force caused by non-uniform corrosion of reinforcement, concrete cover can be cracked which leads to delamination of the cover. To investigate the structural effects of corrosion on the concrete cover, most previous work is focused on a single reinforcing bar, e.g., in [11,18,29]. It has been proved that the location of rebar (i.e., corner and middle rebars, respectively) and boundary conditions have significant effect on cover cracking induced by reinforcement corrosion [11,29]. Moreover, spacing between the reinforcement, in case of multiple reinforcing bars, can influence the stress fields and thus the time to surface cracking and the cracking patterns. Very few of the existing models can well explain the effect of corrosion of multiple rebars on cracking of the whole concrete cover, including those of uniform corrosion [30]. Amongst the limited studies on corrosion of multiple rebars, Chen et.al [19] simulated the crack patterns of concrete cover induced by uniform corrosion of two reinforcing bars via lattice model. Further, Zhang et.al [31] modelled the cover cracking of RC structures with two reinforcing (middle) bars under non-uniform corrosion via damage plastic model. Literature review suggest that very little work has been carried out on cover cracking induced by non-uniform corrosion of multiple reinforcing bars of RC structures and; the relationship between the cover cracking and the time-dependent corrosion rate of the whole life-cycle under corrosion of multiple reinforcing bars has not been established.

This paper attempts to develop a combined analytical and numerical method to predict the time to cover cracking after corrosion initiation and the crack width under time-dependent non-uniform corrosion of multiple reinforcing bars of RC structures. A non-uniform corrosion model is first formulated based on available experiment results. The time-dependent corrosion rate in the whole life-cycle of RC structures is introduced. Under the expansion caused by corrosion of multiple reinforcing bars, arbitrary discrete cracks are modelled in cover concrete by cohesive elements with finite element method. Time to concrete cracking, crack width and crack patterns of the whole cover are obtained. The developed model is partially verified by comparing the results of uniform corrosion from the developed method and experiments, due to the lack of experimental data on non-uniform corrosion. Moreover, a parametric study is carried out to investigate the effects of some key parameters, e.g., fracture energy of concrete, spacing between the reinforcing bars and corrosion rate, on the time to surface cracking and crack width, under non-uniform corrosion of multiple reinforcing bars.

2. Research significance

Considerable research has been conducted in the last few decades in modelling corrosion of reinforcement in concrete and its effects on concrete cover cracking. However, most of existing studies are focused on corrosion of a single reinforcing bar and model the cover cracking as a thick-wall cylinder (mainly analytical) or other geometries (mainly numerical). Very few models could address the interactive behaviour of corrosion of multiple reinforcing bars of RC structures, e.g., beams with 4 tensile rebars. In fact, the cover cracking patterns, time to surface cracking and crack width development could be significantly affected by the combined stress fields generated from corrosion of multiple steel bars. Therefore, a rational model for predicting concrete cover cracking should employ a system approach, by considering all corrosion-affected reinforcing bars, rather than a simplified approach by simulating a single bar only. Moreover, corrosion is actually a time-dependent process and non-uniform along the circumference of reinforcing bars. It would be ideal to derive a time-dependent non-uniform corrosion model for failure prediction of the whole cover of RC structures with multiple reinforcing bars. It is in this regard this paper is presented.

3. Time-dependent non-uniform corrosion

Chloride-induced corrosion of reinforcing bar in concrete produces rusts (mainly ferrous and ferric hydroxides, $Fe(OH)_2$ and $Fe(OH)_3$) which accumulate and result in cracking, spalling and delamination of RC structures. The corrosion rusts first fill in the annular porous layer in concrete around the reinforcing bar, often referred to "diffusion zone" or "porous zone". This initial stage normally does not produce stresses in concrete. As schematically shown in Fig. 1, D is the diameter of the bar and d_0 is thickness of the "porous zone". The thickness d_0 varies from 10 to 20 μm according to the porosity of concrete and compaction degree, which is constant once concrete has hardened [23]. Depending on the level of corrosion, the products of corrosion may occupy up to a few times more volume than the original steel. As corrosion of the reinforcement propagate further, a band of corrosion products forms, as shown in Fig. 1. If corrosion process is assumed uniform, the band becomes a circular ring which causes uniform stresses in the concrete. However, due to the fact that the chlorides, as well as moisture and oxygen, reach the reinforcement surface at different rates through top side of the concrete structure, it is rare to have uniform corrosion around the reinforcement. Experiments results suggest that the front of corrosion products for the half of rebar facing concrete cover is in a semi-elliptical shape, while corrosion of the opposite half of rebar is negligibly small [16].