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Concrete cover cracking and service life prediction of reinforced concrete structures in corrosive environments

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HIGHLIGHTS

- Finite element analysis is conducted for cover crack initiation and propagation.
- Crack patterns under non-uniform corrosion differ from that under uniform corrosion.
- Non-uniform corrosion may lead to earlier concrete cover cracking.
- The parameters that affects the crack initiation time the most is identified.
- A parametric study reviews the most influential parameters on crack initiation time.

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ABSTRACT

Crack initiation of concrete cover due to corrosion defines the end of functional service life where repair or replacement is required for corroded reinforced concrete (RC) structures. This study provides a comprehensive and critical analysis for the analytical and numerical models of corrosion-induced cover crack initiation for both uniform and non-uniform corrosion. Parametric studies are conducted to investigate the effects of different factors on crack initiation time and crack propagation patterns using a thermal analogy approach defined in three dimensional nonlinear finite element (FE) models. The results show that the type of corrosion products, thickness of interfacial transition zone and rate of corrosion are the parameters that affect crack initiation time the most significantly. The developed FE models are able to study crack initiation and propagation for both uniform and non-uniform corrosion and quantify the extent of concrete damage due to cracks. The FE results show that crack patterns under uniform and non-uniform corrosion differ. Under uniform corrosion, the major crack occurs vertically in the cover. But under non-uniform corrosion, major cracks form diagonally at the location of the pit in the cover. The vertical crack appears later and then becomes the third major crack. The results also show that non-uniform corrosion causes high concentrated pressure at the pits which would lead to earlier cover cracking. It is shown that assuming uniform corrosion may result in non-conservative service life estimation. The efficiency and applicability of the existing empirical models have been analyzed using the outcomes from the finite element models. Recommendations on how to select proper models to estimate crack initiation time have been provided. The outcome of the research provides a reliable approach to predict corrosion-induced cover crack initiation and propagation for RC structures.

1. Introduction

The deterioration of infrastructure has been of great concern globally in the recent decades, as the infrastructure is aging, rapidly deteriorating, and becoming increasingly vulnerable to catastrophic failures during probable natural or man-made hazards. One of the main causes of deterioration of concrete structures is the corrosion of reinforcement [1–3]. In coastal regions with airborne sea salt particles or areas with harsh winters and high exposure to deicing salts, chloride-induced reinforcement corrosion is the dominant mechanism of deterioration. In general, there are three stages in the deterioration process of reinforced concrete (RC) structures due to chloride-induced corrosion. The first stage is corrosion initiation, governed by the intrusion of chloride ions. The alkaline environment of concrete surrounding reinforcing steel results in the formation of a passive film at the steel

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surface, which can protect the steel from corrosion. When chloride ions penetrate into the concrete and their concentration reach a threshold value, the PH value changes and the protective film on the reinforcing steel becomes depassivated and corrosion initiates. This is the end of the first stage. The second stage is crack initiation, controlled by the expansion of corrosion products. After corrosion initiates, steel is consumed and corrosion products (rust) are formed at the interface zone between concrete and steel due to chemical reactions with the presence of both moisture and oxygen. Rust is a porous material with less strength and larger volume compared to the original steel consumed in the process. After it fills the porous area around the steel, internal pressure is applied to the surrounding concrete, leading to initiation of cracks in concrete, which marks the end of the second stage. The third stage is crack propagation in concrete. The expansion of rust leads to crack propagation and eventually spalling of concrete cover marking the service failure of structures. In some cases this service failure is also associated with extreme capacity loss and limit state failure of structures. Among the three stages, the first stage normally takes the longest time. It can take many years for the corrosion process to initiate, depending on the influencing parameters. The second stage defines the end of functional service life where repair or replacement is required for corroded RC structures. The third stage is the shortest stage among the three. Because the depth of concrete cover is usually 50 mm, once cracks are formed around the reinforcement, it will quickly propagate to the surface. Since crack initiation of concrete cover caused by corrosion is a critical point in evaluating the service life of corroded RC structures, it is very important to be able to predict crack initiation time with sufficient accuracy.

Extensive research has been conducted on corrosion initiation due to various exposure conditions [4–8], as well as capacity assessment, cyclic response, and fragility analysis under different levels of corrosion [9–19]. Experimental tests have been conducted to investigate corrosion-induced crack initiation [20–28], and crack propagation [21,26,29–32]. Most of the models have been developed and calibrated based on limited test data, thus it is hard to identify the efficiency of those models. This results in some uncertainty when selecting the proper model to estimate the corrosion-induced crack initiation. There are a few articles that reviewed the available models for corrosion-induced crack initiation available in the literature [33,34], however, the models being reviewed do not include the recently proposed crack initiation models and are for uniform corrosion only. The available numerical models have either looked into crack propagation mechanism or used parametric analysis to study the factors affecting crack initiation [30,32,35,36]. However, no numerical models studied both crack propagation and influencing parameters on crack initiation. Moreover, most of the numerical methods are focused on one type of corrosion only, either uniform or non-uniform. This paper aims to provide a critical and comprehensive analysis on the accuracy and applicability of the existing models used to predict crack initiation time for both uniform and non-uniform corrosion. Additionally, the paper aims to develop an explicit and reliable finite element (FE) approach to investigate crack initiation and propagation for the two types of corrosion. Based on the developed FE models, parametric studies are conducted in order to assess the effects of different parameters on corrosion-induced concrete cover cracking, and the crack propagation patterns under both uniform and non-uniform corrosion.

To study the corrosion-induced concrete cover cracking, the following sections will be presented in this paper: i) a critical review of the major analytical models of crack initiation in the literature for both uniform and non-uniform corrosion, ii) an overview and comparison of existing numerical models for both types of corrosion, iii) the development of proposed FE models for both types of corrosion and the validation, iv) parametric study of factors that affect crack initiation, v) parametric study on parameters affecting crack propagation under uniform corrosion, and vi) crack propagation under non-uniform corrosion. The outcome of this study will provide a solid approach for reliable assessment of the effects of corrosion-induced cracking on the performance of RC structures in the absence of field observations or experimental data.

2. Corrosion-induced concrete cover cracking models

A large number of models have been proposed to predict the time to crack initiation, which can be generally divided into three categories: empirical models [20,23,37], analytical models [21,26,29,31,33,38,39] and numerical models [30,36,40,41]. The empirical models are normally based on regression analysis of the experimental data and use simple mathematical equations to determine the controlling parameters. Analytical models are mainly based on cracking mechanics, and involve more parameters and mechanistic considerations.

This section gives a critical overview of existing analytical models for cover cracking, discusses the characteristics of each model, and provides recommendations for applying proper models to estimate the time to crack initiation. In the literature, there are two common types of analytical models to predict the time to crack initiation: the thick-walled uniform cylinder model (TWUC) and the thick-walled double cylinder model (TWDC) (Fig. 1) [39]. The TWUC model assumes concrete as a single layer, the thickness of which is equal to the thinnest concrete cover. The TWDC model divides the concrete into two parts: a cracked inner cylinder and an un-cracked outer cylinder.

Previous research suggests that not all of the corrosion products contribute to the expansive pressure on the concrete. In fact, some diffuse into the voids and pores of the concrete medium. It has been reported that there is an interfacial transition zone (ITZ) around the steel bar [21,42,43]. The corrosion products only exert expansive pressure on the surrounding concrete after this ITZ is filled. Therefore, the crack initiation time can be treated as the time required for corrosion products to fill the ITZ and then apply internal pressure to the surrounding concrete until the first crack appears. The next stage – crack propagation is the time when additional tensile stress builds up, resulting in cracks appearing on the concrete cover and propagation of cracks that results in spalling. Depending on the service design requirements, a crack width of 1.0–3.0 mm would mark the service failure of the concrete member [44,45].

Bažant [29] was the first to use a TWUC model to predict the time to cover cracking, considering concrete around a steel bar as a thick-walled cylinder subjected to an expansive pressure created by the formation of corrosion products. The stress in the cylinder wall is calculated based on plane strain linear elasticity theory. In this model, the concrete is presented as a homogenous linear elastic material. The rust expansion is modeled by a uniform increase in the diameter of the hole around the steel bar. It is assumed that the rate of rust production is constant. This model has been used extensively in the literature to estimate crack initiation time. Later on, comparisons were made with experimental data and it was shown that the model underestimated the time to crack initiation [21,32]. This mostly attributes to the fact that this model ignores the ITZ around the rebar and assumes that all of the corrosion products contribute immediately to the expansive pressure.

To overcome this issue, Liu and Weyers [21] modified this model by including the ITZ around the rebar in their calculations. They conducted a series of corrosion experiments on 44 concrete slabs over five years and updated the model based on their observations. In this model, corrosion products first fill the ITZ during