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Corrosion induced stress field and cracking time of reinforced concrete with initial defects: Analytical modeling and experimental investigation

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ABSTRACT

This paper presents an analytical model for calculation of corrosion induced stress field and cracking time of concrete cover with initial defects in a reinforced concrete. In the proposed model, two types of initial defects in concrete cover (surface and middle defect) were considered. Experiments were also performed to validate the effectiveness and accuracy of the proposed model. Based on the model analysis, it was found out that initial defects have significant influence on the stress distribution, the corrosion induced expansion pressure in concrete cover, the critical mass of corrosion products, and the cracking time of concrete cover.

1. Introduction

The reinforcement corrosion in marine environments is a major cause of the deterioration for reinforced concrete (RC) structures, which leads to series of structural degradations including reduction of the cross-sectional area of steel reinforcement, loss of concrete-steel bond strength, and cracking or spalling of concrete cover [1–3]. Among these degradations, corrosion-induced cover cracking or spalling is the most important one to influence the durability of RC structure. Moreover, the cracking time of concrete cover is a critical parameter for evaluating the service life of RC structures under corrosive environment in practical engineering projects [4–6]. Therefore, accurate prediction of the corrosion induced cover cracking is of great importance [7].

During the past two decades, intensive research efforts have been made to predict the behavior of corrosion induced cover cracking of corroded RC structures through experimentation [8–11], empirical formulas [12,13], theoretical modeling [14–19], finite element method (FEM) [20], and stochastic analysis [21]. Most of these studies were based on the assumption that the pores and voids around steel-concrete interface are uniformly distributed and the induced cracks propagated homogenously from inside to outside [22–24]. However, in actual RC structures and in most cases, the initial defects may not be uniformly distributed on the surface of the rebar. Actually, various types of concrete defects have been observed in actual engineering structures. The examples are scaling, pop-outs (holes), blisters, spalling, and cracking, where cracking is the most frequently defect that occurs in among all the concrete defects [25]. The defects can be the results of a single factor or combined factors such as overloading, shrinkage caused restraint, weather (such as extreme dry, cold, or hot), poor workmanship, and improper proportions of the ingredients. The possibility of initial cracks (defects) to occur is high and it can occur at any time and position of concrete (on the surface or in the middle of concrete cover as well as at the steel-concrete interface) [26,27]. The location and size of initial defects can be identified and characterized by different methods including infrared thermography, ground penetrating radar, and radiographic methods, etc [28]. Once these are determined, the information of defects can then be included in a model for further analysis.

Previous studies about the effect of initial defects on cracking time were limited to the interface of reinforcing bar and con-

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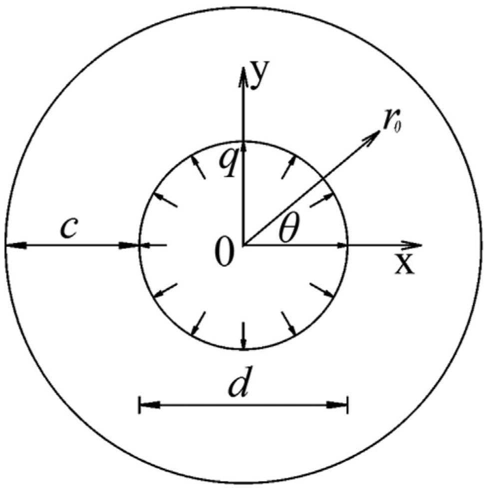

Fig. 1. Cross-section of reinforced concrete in concrete cover without considering initial defect (based on elastic mechanics).

crete [27,29]. The results from these studies showed that the size and the number of initial defects at the interface could significantly affect the cracking time [27,29]. However, the effect of initial defects in concrete cover (outside the steel-concrete interface) is still unknown. Thus, in order to predict the cracking time of concrete cover more accurately, the influence of initial defects in concrete cover with different sizes and locations should also be studied. The comparison between the stress and critical axial tensile stress of concrete cover is an intrinsic condition for the crack to occur. Hence, in order to calculate cracking time with consideration of initial defects in concrete cover, the corrosion-induced stress field in concrete has to be determined. Moreover, relationships between initial defects, corrosion-induced stress field, and cracking time should be established. We would like to mention here that an analytical solution of the stress field caused by non-uniform volume expansion around the corroding reinforcement bars was presented by Xia et al. [30]. However, this study only focused on the modeling of stress field under a non-uniformed expansion pressure without consideration of initial defects inside concrete cover.

Hence, as per author's knowledge, until now, neither theoretical model for stress field nor cracking time of concrete cover in reinforced concrete with initial defects in concrete cover has been reported. Therefore, in this study, an analytical model for calculating stress field and cracking time of concrete cover has been proposed with consideration of initial defects present in surface or in the middle of concrete cover. Finally, experiments were performed to validate the proposed model.

2. Analytical solutions for corrosion-induced stress field

The concrete with embedded reinforcing steel bars are usually modeled as a thick-walled cylinder [18,27,31] for evaluating the corrosion-induced cover cracking (Fig. 1), in which d is the diameter of reinforcement bar and c is the thickness of concrete cover. It is assumed that the porous band on the concrete-steel interface will firstly be filled with corrosion products. Thereafter, the increase in corrosion products will inevitably cause an internal pressure q in the inner surface of the concrete-steel interface. Finally, the gradual accumulation of rust product will eventually reach the critical expansion pressure $q_{\lim}$, leading to the cracking of concrete cover. According to elastic mechanics theory, in polar coordinates the radial stress σ_r and circumferential stress σ_θ in a thick-walled cylinder subjected to an internal radial pressure q can expressed as follows:

$$\begin{cases} \sigma_r = \dfrac{\left(n^2/{r_0}^2\right)-1}{\left(n^2/m^2\right)-1}q \\ \sigma_\theta = \dfrac{\left(n^2/{r_0}^2\right)+1}{\left(n^2/m^2\right)-1}q \end{cases} \tag{1}$$

where r_0 is the distance from a specific position of concrete cover to the center of reinforcing bar, m is the radius of inner cylinder (i.e. $m = d/2$), and n is the radius of outer cylinder (i.e. $n = d/2 + c$).

The studies reported in literature [4,6,15,26] which were based on Eq. (1), did not take into consideration the actual initial defects inside the concrete cover. Therefore, the circumferential stress σ_θ around steel bar in Eq. (1), decrease gradually from inside to outside of concrete cover. Moreover, when the circumferential stress exceeds the tensile strength of concrete, the crack expands from inside to outside of concrete cover. However, when initial defects are taken into account, the stress concentration around initial defect would occur and thereby might cause the stress distribution different from that obtained in Eq. (1). This would possibly affect the accuracy to estimate the cracking process of concrete cover.

Therefore, in the next sections, initial defects (in surface or in the middle of concrete cover) will be considered so as to derive analytical solutions for stress field induced by corrosion expansion.

2.1. Corrosion-induced stress field for surface initial defect

Assume initial defect occurs on the surface in the form of fine crack having cuboidal shape (length of $2a$ and width $w \ll 2a$) and is able to longitudinally penetrate the whole cylindrical specimen. Thus, the height of crack equals to the height of cylinder. The value of $2a$ could range from sub millimeter to more than one hundred millimeter as reported in [32]. The global solutions of the stress field around steel reinforcement can be determined under the corrosion-induced pressure q. The corresponding stress value in the XOY plane can be expressed in polar coordinate system as:

$$\begin{cases} \sigma_x = \dfrac{\sigma_r + \sigma_\theta}{2} + \dfrac{\sigma_r - \sigma_\theta}{2}\cos 2\theta \\ \sigma_y = \dfrac{\sigma_r + \sigma_\theta}{2} - \dfrac{\sigma_r - \sigma_\theta}{2}\cos 2\theta \end{cases} \tag{2}$$

where σ_x is the stress in x direction and σ_y is the stress in y direction.

With respect to local solutions of stress field for surface initial defect (Fig. 2) and in the region ($y = 0, x \in (m,\ n)$), the interior and exterior geometric boundary conditions, load boundary conditions, and stress boundary condition should satisfy the following conditions:

1) At the position far from the crack, the stress at any point in the concrete cover can be approximately expressed by Eq. (2).
2) At the position close to the left tip of initial crack, the stress components σ_x and σ_y increase along with the increase of x. Hence, at the tip, the stress reaches the maximum value.
3) In the region ($y = 0, x \in (n - 2a,\ n)$), the stress components σ_x and σ_y are equal to zero since the position is inside the defect.

For the corrosion-induced stress field with the initial defect in the surface of concrete cover (Fig. 2), the basic bi-harmonic equation in planar elastic mechanics can be solved by Muskhelishvili and Westergaard method [33]. The Airy stress function U for the problem shown in Fig. 2, generally satisfy the following bi-harmonic equation

$$\nabla^4 U(x,y) = \frac{\partial^4 U}{\partial x^4} + 2\frac{\partial^4 U}{\partial x^2 \partial y^2} + \frac{\partial^4 U}{\partial y^4} = 0 \tag{3}$$