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Mechanical aspects of simulating crack propagation in concrete under steel corrosion

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HIGHLIGHTS

- Limitations and accuracy of different mechanical models are discussed.
- Approach for modeling rust expansion affects stress, displacement and cracking.
- Corroded depth is more accurate to represent corrosion level than rust thickness.

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ABSTRACT

This paper presents mechanical consequences in concrete caused by steel corrosion with various types of models. According to the simulation approach for rust expansion, numerical models are classified into hollow concrete model with applied radial displacement or pressure, concrete/steel composite with steel expansion and full model of concrete/rust/steel composite with rust layer expansion. Qualitative and quantitative comparisons of results from various models are made in order to assess their accuracy. In various models, besides the stress and displacement states in concrete are different, the corrosion level is also represented differently, which should be noticed when interpreting the modeling results of corrosion level-crack level relation. Under the same corrosion penetration depth, corrosion expansion represented by the free increase of steel radius due to corrosion in the analytical cylinder models and hollow concrete model is larger than the final rust thickness calculated in the full model. In addition, the final rust thickness around the steel perimeter and the rust thickness/corroded depth ratio is shown to be non-uniform under both uniform and non-uniform corrosion, which is caused by the local cracking in concrete.

1. Introduction

Steel corrosion is one of the biggest threats to the durability and safety of reinforced concrete structures under severe environmental conditions [1]. The depassivated oxide film on the rebar embedded in concrete can be destroyed by carbonation or chloride penetration, which initiates steel corrosion [2]. Under the volume expansion of corrosion products, tensile stresses are produced in concrete cover, leading to cover cracking and spalling which impair the bond between concrete and steel and safety of structures. In recent decades, many studies on corrosion-induced cracking in concrete, including experimental investigations and developing analytical or numerical models, have been carried out [3–30]. By developing the model that relates concrete crack width and corrosion penetration depth of steel, the corrosion level can be estimated through the visible concrete crack so that the residual service life of existing structures can thus be predicted with this relation [31]. Some researchers [27–30,32] experimentally studied the relation of concrete crack width and corrosion level in terms of the corrosion penetration depth. Based on experimental data, empirical models for the relation of corrosion level and concrete crack width were also proposed in these studies. On the other hand, many theoretical models [3–11,13–26] including analytical and numerical models were proposed based on the mechanical theory to predict the concrete crack propagation during the steel corrosion process.

In existing analytical models based on the theory of elasticity [3–8], concrete surrounding the steel reinforcement was modeled as a hollow cylinder with the uniform wall thickness equal to the minimum cover around the steel. To consider cracking of concrete, the cylinder was assumed to be double-layered with an inner

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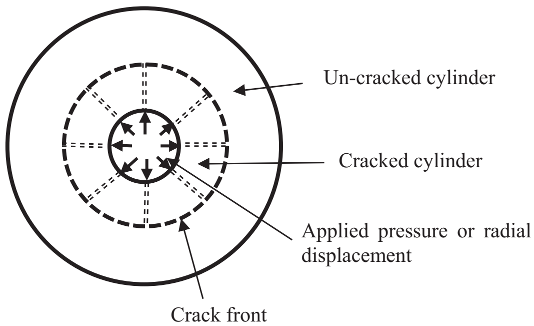

Fig. 1. Thick-walled double cylinder models.

cracked cylinder and an outer un-cracked cylinder (Fig. 1) [4,5,7,8,33]. However, the crack localization cannot be considered. The cracked cylinder was treated as an equivalent anisotropic continuum with degraded material properties in the direction normal to the crack orientation. That means cracks were assumed to be evenly distributed along every circumferential direction. This assumption allowed establishing governing equations based on the theory of elasticity. With the tensile strength criterion, the governing equations were analytically solved to calculate the crack front evolution with corrosion time. A critical review on representative analytical models, from the viewpoint of assumed properties of the cracked cylinder, has been made by Chernin and Val [33].

The common feature of different double cylinder analytical models [4,5,7,8] is that stress and crack distribution along the circumferential direction is assumed to be uniform. However, cracks actually become localized along several main paths instead of being uniformly distributed. In addition, most of analytical models [4,5,8] are often only applicable up to the situation when the cracked zone reaches the concrete surface (which occurs when the hoop stress on the surface reaches concrete tensile strength), hence the crack width evolution on the concrete surface under further corrosion cannot be predicted. However, for the repair and service life assessment of concrete structures, it is of practical significance to predict the amount of steel loss for the surface crack to reach a certain width. In addition, the crack width influences the diffusion of chloride, moisture and oxygen and the corrosion propagation rate [34,35]. So predicting the surface crack width evolution is much important when considering the interaction effects of diffusion, corrosion and mechanical processes in concrete and

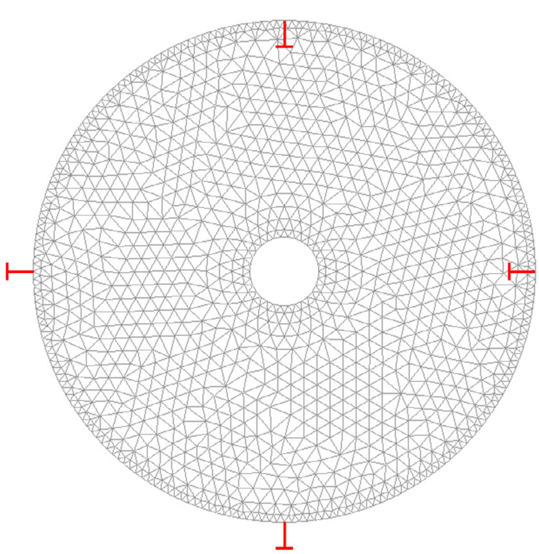

Fig. 2. Meshes and supports for p-hole model and u_r-hole model in ATENA.

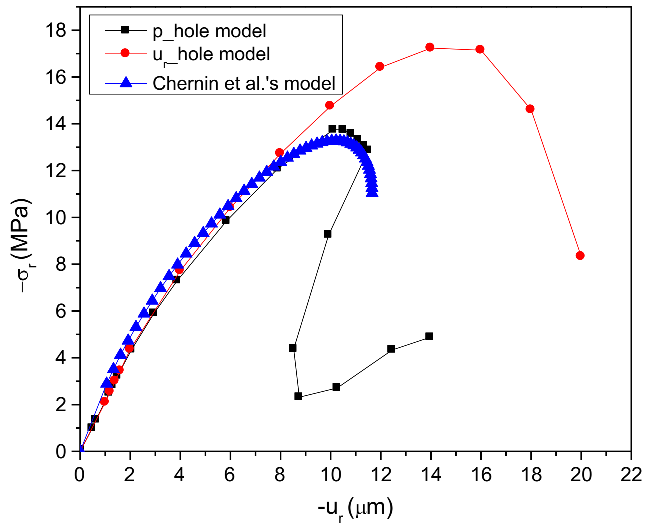

Fig. 3. Radial displacement-radial stress curves from analytical cylinder model and numerical hollow concrete models.

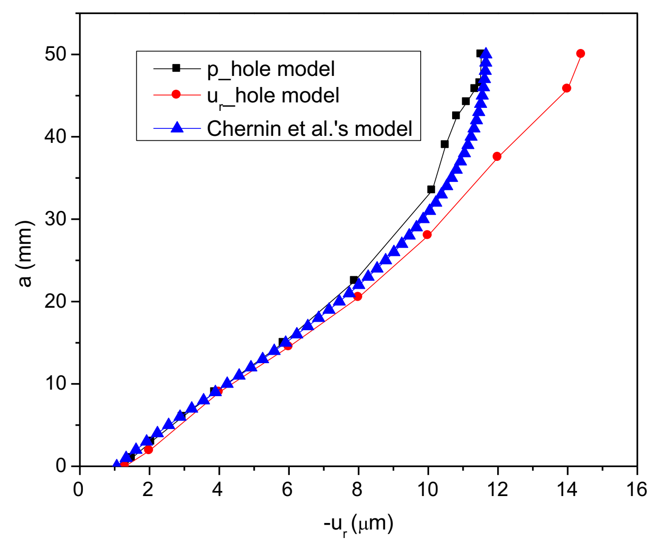

Fig. 4. Relationship between crack length and radial displacement from analytical cylinder model and numerical hollow concrete model.

service life prediction of concrete structures. Fracture mechanics can be employed to simulate the crack propagation in concrete. There are only a few studies [12,36] using the analytical approach based on fracture parameters and criteria to calculate the crack propagation due to steel corrosion, as concrete is a quasi-brittle materials so nonlinear fracture mechanics should be adopted, which makes analytical solutions very difficult to obtain. Numerical approaches such as finite element method or boundary element method have therefore been utilized to perform fracture mechanics analysis by a number of researchers [10,11,15–19,21,23,25,26,37].

2. Objective of the study

Although there have been a variety of analytical and numerical models for corrosion-induced cracking of concrete proposed in the literature, comparisons among mechanical results from different models have seldom been made in the past, which makes it difficult to select an effective model for practical use and further