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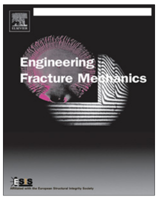

Finite element modeling of concrete cover cracking due to non-uniform steel corrosion

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ABSTRACT

Steel corrosion in reinforced concrete structures can lead to cracking of concrete cover when corrosion products expand. In this study, a finite element model has been developed to study crack propagation in concrete as corrosion progresses. The model considers the practical situation of chloride penetration from the member surface, which leads to non-uniform corrosion distribution around the steel cross section. To highlight the necessity to consider non-uniform corrosion in practical situations, the evolution of crack width under non-uniform corrosion for concrete with different boundary conditions is compared with that under uniform corrosion.

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1. Introduction

Steel corrosion is the main culprit impairing the durability and safety of reinforced concrete structure. When corrosion-inducing chemicals (such as chlorides) reach a threshold concentration on the steel surface, the passive film on the steel will be damaged and reinforcement corrosion starts to occur. As steel depletes, corrosion products form and expand under the presence of water. The expansion of corrosion products subjects the surrounding concrete to internal pressure which induces tensile stress in the concrete cover. Once the stress reaches the tensile strength of concrete, a crack will form. Its propagation on further corrosion will eventually lead to spalling or delamination of the cover. These effects severely affect the serviceability of structures. With cover spalling or delamination, water, oxygen and other chemicals can easily reach the steel surface. The rate of rusting will then greatly increase. With significant loss of steel area and steel/concrete bond, the load carrying capacity will be reduced, thus threatening the safety of structures.

Due to its great harmfulness, steel corrosion and the associated cracking process have been studied by many investigators. The analytical and numerical models to predict corrosion induced-cracking usually assumed uniform corrosion around the rebar. Such models are applicable to experimental studies, where corrosion is accelerated by applying current and/or adding chloride into the mix, so that the distribution of rust around the steel is essentially uniform. However, the results cannot be extended to real situations, where steel corrosion occurs earlier at locations closer to the exposed surface(s) of structure, leading to non-uniform rust distribution. The non-uniform corrosion distribution around the steel cross section has been observed in [1–3]. [4,5] also pointed out that the depassivation of steel occurred at the external part of steel first and corrosion initiation event of the rebar was not instantaneous in their modeling. Therefore, the depassivation progresses

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Nomenclature

C_{crit}	critical chloride concentration
D_x	chloride diffusion coefficient in x direction
D_y	chloride diffusion coefficient in y direction
r_b	initial radius of steel
n	volume ratio of rust to steel
w_{st}	mass of consumed steel due to corrosion
ρ_{st}	density of steel
x_p	radius loss of steel due to corrosion
v	corrosion rate
t	corrosion time
Δr_b	increase of radius of steel under free expansion of rust
ε_r	radial strain of rust under free expansion
ε_θ	circumferential strain of rust under free expansion
ε_x	strain of rust under free expansion in x direction
ε_y	strain of rust under free expansion in y direction
θ	angle defined in Fig. 6
f_t	tensile strength of concrete
$d_{\max}$	maximum diameter of aggregate in concrete
σ_s	bridging stress at the kinked point of the bilinear softening law of concrete
w_s	crack opening at the kinked point of the bilinear softening law of concrete
w_c	critical crack opening of the bilinear softening law of concrete

around the steel cross section should not be ignored and it is not right to assume uniform corrosion distribution around the steel cross section as in most previous models.

In the next section, "non-uniform corrosion" modeled in this study will be defined to avoid confusion with "pit corrosion" or "local corrosion". Then, the development of a coupled diffusion-mechanical model to study corrosion induced cracking with the finite element method is described. Crack development under non-uniform corrosion with various boundary conditions is then analyzed and compared to the uniform corrosion case with the same volume of expanding rust.

2. Definition of non-uniform corrosion in this study

In the traditional classification of corrosion types, two kinds of corrosion are distinguished: general corrosion (or uniform corrosion), and pit corrosion (or local corrosion). The former refers to uniform corrosion attack along the axis of steel and also around steel cross section. It is generally caused by carbonation of concrete over a wide area or very high uniform chloride contents in the vicinity of the steel [6]. In general corrosion, anodes and cathodes are very close and randomly distributed, consisting of numerous microcells. If the chloride concentration is very different along the steel surface, the anodic area is where the critical chloride content has been reached, while the other parts of steel are cathodic areas, in which macrocells are formed leading to pit corrosion [6]. The harmfulness of pit corrosion is widely known and has been a research topic for a long time.

The "non-uniform corrosion" herein refers to "non-uniform corrosion distribution around the steel cross section", but the corrosion is still general (or uniform) along the rebar axis over a certain length of the rebar so that a two-dimensional model on the steel cross section can be assumed. The general corrosion along the steel axis is a result of homogeneous environment and materials, while the "non-uniform corrosion" around the steel cross section is a result of the asynchrony of corrosion initiation at different locations around the steel cross section. It is caused by the specific condition faced by the embedded steel in concrete: chlorides diffuse into concrete from the exposed surface(s) to the inside, and the region nearest to the external chloride source would reach the critical chloride concentration and start corrosion at the earliest. This makes the corrosion mechanism of steel embedded in concrete different to that of exposed steel.

The "non-uniform corrosion" is easy to be confused with "pit corrosion". They are both uneven, but the former corrosion is widespread along the reinforcement while the latter is localized. Their mechanisms are different, and so are the corrosion configurations. The work of Jang and Oh [7] studied the mechanical effect of non-uniform corrosion around the steel cross section, but the assumed non-uniform variation of corrosion depth around the steel section (given by a parameter α) was based on the work of Gonzalez et al. [8] where α is defined as the ratio of the pit corrosion depth and the average corrosion depth. In other words, the non-uniform corrosion distribution assumed in [7] does not represent the variation of rusting around the steel bar, but the variation along the rebar axis due to pitting. The results are therefore not applicable to the situations studied in this paper.

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