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3D simulation of localized steel corrosion in chloride contaminated reinforced concrete

Chong Cao *,[1]

Department of Civil Engineering and Applied Mechanics, McGill University, 817 Sherbrooke Street West, Montréal, QC H3A 0C3, Canada

HIGHLIGHTS

- Pitting corrosion is examined through electrochemical corrosion analysis.
- Both circumferential and longitudinal macrocells contribute to localized corrosion.
- Macrocell corrosion controls pitting factor evolution.

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ABSTRACT

Pitting corrosion of reinforcement often causes localized concrete cracking in chloride contaminated RC structures. This paper presents a 3-D computational model to examine the localized corrosion of steel rebar under chloride attack. Both circumferential and longitudinal macrocell corrosion have been integrated into the numerical model. Modeling results show that macrocell corrosion controls the localized/pitting corrosion process. Highly localized corrosion pattern may occur due to extremely large cathode/anode ratio. As corrosion front advances around reinforcement, macrocell corrosion may reduce drastically and pitting factor also decreases. Parametric study indicates that chloride diffusion significantly influences pitting factor while longitudinal cathode/anode ratio controls localized macrocell corrosion.

1. Introduction

Chloride-induced steel corrosion in Reinforced Concrete (RC) structures normally takes localized/pitting pattern, as illustrated in Fig. 1. Pitting corrosion causes localized iron dissolution by forming intensively corroding anodes in chloride rich zones. The self-propagating pitting cells are further aggravated by galvanic coupling with nearby passive steel. Corrosion rusts accumulate locally around the anodes and therefore concrete surrounding active pitting zones suffers the most severe corrosion damage [1–4]. The localized cracking pattern induced by non-uniform rust expansion is schematically shown in Fig. 2a and b.

Service life prediction of RC bridges under pitting corrosion attack requires accurate modeling of concrete deterioration process. Corrosion rust distribution shape and electrochemical corrosion rate are the two key parameters for numerical simulation of corrosion-induced concrete cover cracking: non-uniform rust distribution shape governs the amount of corrosion products needed to reach certain damage level, while localized corrosion current density controls the rust expansion rate.

Empirical pitting factor α, representing the ratio between maximum pitting depth p_{pit} (m) and uniform attack penetration x (m), has been introduced to numerically describe both residual cross-section of corroded rebar and non-uniform rust expansion shape (Fig. 3). Experimental results indicate that pitting factor approximately falls in the range of 4–8 [5–8]. However, due to a lack of comprehensive understanding of localized corrosion mechanism in concrete, previous quantitative depictions of pitting configuration are mostly based on statistical characterization of maximum pit depths by assuming a Gumbel distribution for pitting factor [9,10].

Moreover, empirical corrosion rate models are often adopted for numerical modeling of concrete cracking and these models tend to ignore the possible effects of localized macrocell corrosion on pitting [11]. Nonetheless, numerical and experimental results have shown that macrocell corrosion may significantly increase the iron dissolution rate around localized anodes. The formation of pitting corrosion are found to be mainly caused by macrocell corrosion circulating around rebar circumference and along reinforcement length [12–15].

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* Tel.: +1 514 398 2424.
E-mail address: chong.cao@mail.mcgill.ca

[1] Formerly, MPhil Candidate and Visiting Scholar at with Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong, China.

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In order to achieve a more precise simulation of pitting effects on structural performance of RC bridges, both dynamic corrosion rate and pitting shape should be accurately predicted. Although there have been several attempts towards numerical modeling of macrocell corrosion during the past two decades, existing approaches are not able to simulate localized rust accumulation along with pitting corrosion formation [16–19]. Currently, there are few numerical methods for modeling the pitting corrosion evolution in chloride contaminated RC structures.

The objective of this paper is to develop a 3-D computational model for analysis of localized steel corrosion in chloride contaminated RC structures. The coupled micro- and macro-cell corrosion process involved in typical chloride-induced pitting corrosion is modeled through numerical polarization equations. Finite Element Method (FEM) has been employed to numerically simulate corrosion potential distribution and corrosion current flow within concrete. Both circumferential and longitudinal macrocell corrosion are simulated in order to capture the corrosion characteristic of pitting corrosion in natural conditions. This numerical model has been utilized to identify crucial factors influencing pitting corrosion pattern of reinforcing steel in concrete. Special attention has been paid to the dynamic corrosion rate evolution and non-uniform rust expansion.

2. Corrosion model

In the case of chloride-induced steel corrosion in concrete, two kinds of electrochemical corrosion cells may coexist during the corrosion propagation stage: microcells leading to uniform/generalized corrosion and macrocells causing pitting/localized corrosion [13,20]. The coupled micro- and macro-cell corrosion behavior is illustrated in Fig. 4a and b. For a better simulation of localized/pitting corrosion in RC structures, the 3-D computational model shall be developed by integrating both circumferential and longitudinal macrocell corrosion.

2.1. Geometric configuration

The geometric configuration of a typical slab-on-girder bridge under chloride attack is shown in Fig. 5a. In countries where deicing salts are employed for winter maintenance of highway bridges, bridge deck suffers the most severe corrosion damage and leakage at expansion joints is a major cause of chloride attack for beam girder. For bridges exposed to marine environment, beam girder may also be exposed to airborne chlorides from seawater [1]. In all cases, the corrosion problem can be numerically described by a simplified model with concrete cover thickness of C (m), steel diameter of D (m), slab/girder section thickness of W (m), bar spacing of S (m) and slab/girder section length of L (m), as illustrated in Fig. 5b. The length of localized corrosion zone is specified as L_a (m).

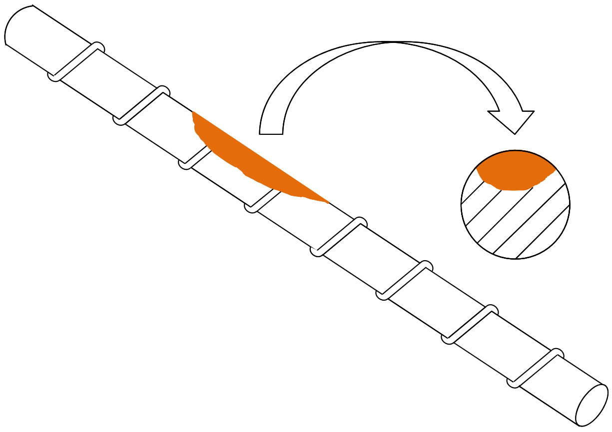

Fig. 1. Chloride-induced pitting corrosion in RC structures.

Specific points around the steel-concrete interface are referenced by angle θ. The upper surface of steel with shortest distance to the concrete cover surface is referred to as "front" of the rebar and assigned $\theta = 0°$, while the lower surface with longest distance from the concrete cover surface is referred to as "back" of the rebar and assigned $\theta = \pm 180°$. Thus, the chloride/oxygen transport distance X (m) around the rebar perimeter ($0° \leqslant \theta \leqslant 180°$) shall be expressed as

$$X(\theta) = C + \frac{D}{2}(1 - \cos\theta) \tag{1}$$

2.2. Chloride penetration

The transport process of chloride ions through porous concrete cover can be numerically described by diffusion equation, written as

$$\frac{\partial C_{Cl}}{\partial t} = \nabla \cdot (D_{Cl} \nabla C_{Cl}) \tag{2}$$

where C_{Cl} (wt.% of cement) denotes chloride concentration in concrete, D_{Cl} (m^2/s) represents diffusion coefficient of chloride, and t (seconds) gives diffusion time. Different chloride exposure conditions can be reflected by chloride concentration profiles on concrete cover surface (C^s_{Cl}). Also, initial chloride concentration within concrete is denoted as C^0_{Cl}.

The localized corrosion is confined to the area of steel where the threshold chloride content (C^{crit}_{Cl}) for depassivation is exceeded. According to many experimental studies, the critical chloride content to trigger steel corrosion in concrete is dependent on several factors including steel-concrete interface, binder type, steel potential, and PH of concrete pore solution, etc [21]. The threshold is generally recognized among researchers as a distributed parameter, which apparently arises because of the heterogeneous nature of concrete [22]. Here, to simplify our analysis, the critical chloride content in RC structures is chosen to be constant as 0.4% by weight of cement.

The reinforcement serves as an impediment to inward chloride migration and thus chloride ions build up at the top rebar surface. This can lead to uneven chloride concentration around rebar perimeter, as illustrated in Fig. 6. Previous experimental observations show that corrosion rusts tend to accumulate around rebar circumference facing the concrete cover surface exposed to chloride attack [23,24]. Macrocell corrosion is responsible for promoting localized corrosion, which will be demonstrated through numerical analysis in this study.

2.3. Potential distribution

In order to simulate the potential distribution and electrical current flow during the corrosion process, the concrete can be treated as a conductor with effective resistivity ρ (Ω m) [16–20]. The potential distribution ϕ(V) is governed by Laplace's equation, written as

$$\nabla \cdot \left(\frac{1}{\rho}\nabla\phi\right) = 0 \tag{3}$$

According to Ohm's law, the electrical current flux $\mathbf{i}$ (A/m^2) within the concrete electrolyte can be obtained as

$$\mathbf{i} = -\frac{1}{\rho}\nabla\phi \tag{4}$$