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Non-uniform corrosion states of rebar in concrete under chloride environment

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This study proposes and verifies a numerical framework that can efficiently quantify non-uniform corrosion penetration depth along the perimeter of the rebar in concrete exposed to chloride environment. Moreover, this framework considers the effects of rebar size and location on the process of chloride ingress into concrete and evaluates the non-uniform corrosion states that correspond to two scenarios of corrosion penetration depth: corrosion of segment of the rebar and uneven corrosion along the rebar perimeter. Qualitative comparisons of the evaluated non-uniform corrosion states with the variety of available laboratory and field data show good agreement.

1. Introduction

Corrosion of embedded rebars is a classical deterioration mechanism that remains as one of the most significant problems limiting the service life of concrete structures exposed to chloride-laden environments. The total service life of reinforced concrete (RC) components subject to chloride-induced corrosion is generally represented as a two stage process consisting of an initiation phase and a propagation phase [1,2].

Corrosion initiation phase refers to the depassivation process of rebar by the presence of chloride ions and involves the coupled transport processes of chloride, moisture, and heat through the porous concrete cover [3,4]. An alkaline passive layer (pH ~ 13–14) around the steel and a thick concrete cover, acting as a barrier against the intrusion of aggressive species, provide chemical and physical protection to the embedded rebar, respectively. Nevertheless, steel depassivation occurs when the concentration of chloride at the rebar level reaches a critical chloride content thereby destroying the passive layer. Critical chloride content for RC is the amount of chloride at the depth of the rebar necessary to sustain localized breakdown of its passive film and hence initiate its active corrosion. [5]. The time taken by chloride ions from external environments to reach the critical value at the rebar depth is defined as time-to-corrosion initiation (TCI).

The process of chloride ingress into concrete is very complex for the following three reasons: (1) interaction between many physical and chemical phenomena; (2) dependence on many internal parameters (level of hydration in concrete, porosity, binder type, etc); and (3) external environmental conditions (temperature, relative humidity, chloride, etc). Therefore, various models have been developed, from analytical models based on Fick's second law of diffusion to highly sophisticated mathematical models taking the mechanisms of chloride ingress process into account. The complex process of chloride ingress into concrete is commonly simplified as a diffusion problem and the same is represented through the mathematical expression proposed by Fick in 1855 [6]. The Gauss error function based analytical solutions to Fick's law are also widely reported in literature for limited initial and boundary conditions. However, these analytical solutions are valid only under the following conditions: (1) concrete is homogeneous; (2) weak temperature gradients in concrete; (3) concrete remains fully saturated and not subjected to any water movement; (4) constant chloride diffusion coefficient in time and space; and (5) concrete surfaces subject to a constant chloride exposure [7,8]. As an alternative to Fick's law, researchers (e.g. [3,9]) proposed physics based mathematical models with various levels of complexity for enhanced modeling of chloride ingress into concrete. These mathematical models incorporate detailed transport equations and provide more reliable service life predictions.

The existence of rebar is of greater importance with respect to chloride ingress into RC, mainly because: (1) length of the corrosion initiation phase is determined in large part by the rate at which the chloride builds adjacent to the rebar; and (2) higher accumulation of chlorides around the steel-to-concrete interfaces of larger-size bars results in faster corrosion [10–12]. However, in many studies based on mathematical models, the rebar in concrete is either modeled as a fully insulated region or neglected in

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Nomenclature

Acronyms

2D	two-dimensional
FE	finite element
PDE	partial differential equation
RC	reinforced concrete
TCC	total chloride content
TCI	time-to-corrosion initiation

Symbols

A_g	aggregate volume fraction
B_c	chloride transfer coefficient at the exposed boundary (m/s)
B_h	relative humidity transfer coefficient at the exposed boundary (m/s)
B_T	temperature transfer coefficient at the exposed boundary (W/m^2 K)
c_p	specific heat capacity of concrete/rebar (J/kg K)
C_b	bound chloride content (kg/m^3)
C^b	chloride content at the exposed boundary (kg/m^3)
C_{env}	chloride in the surrounding environment (kg/m^3)
C_f	free chloride content (kg/m^3)
C_f^b	free chloride at the exposed boundary (kg/m^3)
C_t	total chloride content (kg/m^3)
d	rebar diameter size (m)
d_c	concrete cover thickness (m)
D_c^a	apparent chloride diffusion coefficient (m^2/s)
$D_{c,\text{ref}}$	reference chloride diffusion coefficient (m^2/s)
D_h^a	apparent relative humidity diffusion coefficient (m^2/s)
$D_{h,\text{ref}}$	reference relative humidity diffusion coefficient (m^2/s)
D_T	thermal conductivity of concrete (or) rebar (W/m K)
$D_{T,\text{ref}}$	reference thermal conductivity (W/m K)
h	relative humidity
h^b	relative humidity at the exposed boundary
h_{env}	relative humidity in the surrounding environment
i_{corr}	corrosion rate (A/m^2)
$i_{\text{corr}(0)}$	corrosion rate up to one year (A/m^2)
$i_{\text{corr-20}}$	corrosion rate at 20 °C (A/m^2)
k	adsorption isotherm constant
p_d	corrosion penetration depth (m)
R_c	resistivity of concrete cover (Ω)
s/a	fine aggregate fraction
t	time (s)
t_c	time-to-corrosion initiation (s)
t_e	equivalent hydration time (s)
T	temperature (K)
T^b	temperature at the exposed boundary (K)
T_{env}	temperature in the surrounding environment (K)
T_r	rebar temperature (K)
T_{ref}	reference temperature (K)
T_s	temperature at the surface of the rebar (K)
V_m	monolayer capacity
w/b	water-to-binder ratio
w_e	evaporable water content (m^3 of water/m^3 of concrete)
X_c^b	chloride flux at the exposed boundary (kg/m^2 s)
X_h^b	relative humidity flux at the exposed boundary (m/s)
X_T^b	temperature flux at the exposed boundary (W/m^2)
ρ	density of concrete (or) rebar (kg/m^3)
δ	corrosion layer thickness (m)
τ	adsorption isotherm constant

the numerical analysis (e.g. [4,13,14]). Although rebars are impermeable to intrusions by moisture and chlorides, they can transport heat much faster than the surrounding concrete because of their higher thermal conductivity. Furthermore, the numerical algorithm of Saetta et al. [3] has a general applicability for understanding the process of chloride ingress into concrete under various environmental exposure conditions (e.g. [4,15]). This numerical algorithm; (1) incorporates the dependence of chloride diffusion coefficient on the material parameters of concrete, internal relative humidity, and temperature; and (2) considers the effects of nonlinear chloride binding. Nevertheless, the numerical algorithm of Saetta et al. [3] has not yet been exploited to examine the effect of not only the existence of rebar but also its size and location on the process of chloride ingress into RC. Therefore, it is highly desirable that such a numerical algorithm be enhanced by incorporating the existence of rebars. In the authors' previous work [12], a detailed parametric study on TCI of rebars was presented to explore qualitatively the effects of various factors such as critical chloride content, structural configuration and distance from the coastline, by limiting diffusion as the dominant mode of chloride transport.

Corrosion propagation phase refers to the mechanical degradation process of RC structures under corrosion attack and involves much more complex procedures such as the formation of electrochemical corrosion cells (microcell and macrocell), reduction in the cross-sectional area of rebar, rust expansion induced concrete cover cracking, spalling and delamination [16]. In recent years, greater emphasis has been placed on investigating the corrosion propagation phase [2,15–20]. This allows for the realistic estimation of various damage parameters such as time-to-cover cracking, crack width, and cover spalling [21]. However, vast majority of models [15–20] developed assume a uniform corrosion penetration depth along the entire perimeter of the rebar, which is contrary to field observations (e.g. [22]). Owing to the spatially and temporally evolving chloride ion content through concrete cover thickness and to the impermeable nature of steel bars, rebar may not be corroding uniformly along its entire perimeter. Fig. 1 illustrates this phenomenon due to the gradual chloride-induced corrosion initiation process around corner and middle rebars in an RC component exposed to the natural chloride environment.

The rebar surfaces facing the external environment, where chloride accumulations are faster and higher, begin to corrode first. In a rectangular or square RC cross-section, such surface regions for corner bars are around the midpoints of quadrants facing the adjacent concrete cover surfaces and for middle bars are around shortest distances from respective concrete cover surfaces. Whereas, over the steel surfaces facing the interior of concrete, amount of chloride ions remain at a very low-level because of the impermeable nature of steel bars. Hence, breakdown of passive protection layer and corrosion of steel could hardly happen in this region before the cracking of concrete cover. Thus, variations in the onset of corrosion reaction along the perimeter of the rebar lead to non-uniform corrosion states. Non-uniform corrosion states correspond to corrosion scenarios where only a region of the rebar perimeter is corroding and where corrosion is occurring unevenly along the perimeter of the rebar. The importance of considering the real state of corrosion in rebar is also supported by the fact that the effect of non-uniform corrosion induced stresses in RC are more conducive to cover cracking than uniform corrosion [23,24].

The primary objective of this study is to propose and verify a numerical framework that can efficiently quantify non-uniform corrosion penetration depth along the perimeter of the rebar in