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NUMERICAL SIMULATION OF NON-UNIFORM CORROSION STATES IN REBARS UNDER NATURAL CHLORIDE ENVIRONMENT

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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. Vast majority of models [1–3] developed to investigate the corrosion propagation phase assume a uniform corrosion penetration depth along the entire perimeter of the rebar, which is contrary to field observations (e.g. [4]). 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. The objective of this study is to propose and verify a numerical framework that can efficiently quantify the non-uniform corrosion penetration depth along the perimeter of the rebar in concrete exposed to chloride environment. This framework investigates the corrosion process during both the corrosion initiation and propagation phases by exploring the effects of not only the rebar existence but also its sizes and locations.

The corrosion initiation phase is examined through a comprehensive chloride ingress model that identifies the most important parameters (both external and internal) that influence the intrusion of chlorides into the reinforced concrete. The environmental parameters, namely, ambient temperature, relative humidity and chloride content are categorized as external parameters, while the concrete properties and diffusion characteristics are considered as internal parameters. The corrosion propagation phase is studied based on a decisive parameter, namely, corrosion rate, which is considered to depend on various factors, such as concrete resistivity, concrete quality, cover depth, temperature, humidity and chloride content.

The problem of chloride ingress into concrete can effectively be studied as the interaction between three phenomena, namely: heat transport; moisture transport; and chloride transport [5]. Each of these phenomena is represented by a partial differential equation (PDE) and their interaction is considered by solving them simultaneously. The governing PDEs representing the process of chloride ingress into concrete can be expressed in the following general form:

$$\Upsilon \dot{\Phi} + \underbrace{\vec{\nabla}\cdot\left(\Theta \vec{\nabla} \Phi\right)}_{\text{diffusion}} + \underbrace{\vec{\nabla}\cdot\left(\Psi \Phi \vec{\nabla} \Gamma\right)}_{\text{convection}} = 0 \tag{1}$$

The correspondence between Υ, Θ, Φ, Ψ, Γ and the terms for the transport quantity is presented in Table 1.

Table 1: Correspondence between Eq. (1) and the governing field equations

Transport quantity	**Diffusion terms**			**Convection terms**	
	$\boldsymbol{\Phi}$	$\boldsymbol{\Upsilon}$	$\boldsymbol{\Theta}$	$\boldsymbol{\Psi}$	$\boldsymbol{\Gamma}$
Chloride	C_f	1	D_c^a	D_h^a	h
Moisture	h	$\dfrac{\partial w_e}{\partial h}$	D_h	–	–
Heat	T	ρc_p	D_T	–	–

By incorporating various corrosion rate (i_{corr}) empirical models summarized in the literature [6], time-dependent penetration depth, $p_d(t)$ at depassivated region along the perimeter of the rebar, at time t after corrosion initiation, t_c can be estimated as:

$$p_d(t) = \int_{t_c}^{t} 0.0116\, i_{\mathrm{corr}}(t)\, dt \qquad (2)$$

Three PDEs are solved numerically in space as a boundary-value problem and in time as an initial-value problem by means of a 2D finite element formulation, in which appropriate boundary conditions are enforced to simulate monthly variations in temperature and relative humidity. The evolution of spatial distribution of the different variables with time is integrated by adopting the finite difference method.

Estimated corrosion penetration depth values reveal the following: (1) Their spatial distribution along the perimeters of rebars are either complete or incomplete, (2) The spatial locations of its maximum value along the perimeter of the rebar are different for a corner bar and a middle bar, (3) Its length along the perimeter of a corner bar is always longer than that of a middle bar, and (4) Its spatial distribution along the perimeters of middle and corner bars are non-uniform or uneven.

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