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Modeling pull-out resistance of corroded reinforcement in concrete: Coupled three-dimensional finite element model

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ABSTRACT

Aggressive environmental conditions, such as exposure to the sea climate or use of de-icing salts, have considerable influence on durability of reinforced concrete structures due to reinforcement corrosion-induced damage. In the present paper, a recently developed coupled three-dimensional chemo-hygro-thermo-mechanical model for concrete is discussed [1,2]. The model takes into account the interaction between non-mechanical processes and mechanical properties of concrete (damage). The mechanical part of the model is based on the microplane model. It is validated through a 3D transient finite element analysis of a pull-out of corroded steel reinforcement from a concrete beam-end specimen, which was exposed to aggressive environmental conditions. For the corrosion phase, the influence of the anode and cathode position on the electric potential, current density, corrosion rate and corrosion induced damage is investigated. Moreover, the effect of corrosion on the pull-out capacity of reinforcement and the influence of transport of corrosion products through cracks are studied.

1. Introduction

Degradation of reinforced concrete (RC) structures caused by the chloride-induced corrosion of steel bars in concrete is a major concern for durability of RC structures [3]. Especially vulnerable are structures exposed to harsh sea climate conditions or highways and garages treated with de-icing salts during winter seasons [3,4]. Due to the expansion of corrosion products around the reinforcement bar, concrete cover exhibits cracking and spalling which leads to degradation of mechanical properties of RC structures. Corrosion-induced damage exerts relatively high direct and indirect costs of repair and therefore it is of great importance to develop a mathematical model as a tool for realistic simulation of corrosion processes and their effects on structural behavior.

The inadequate thickness of the concrete cover or its damage in aggressive environmental conditions leads to corrosion of reinforcement steel. Damage can be caused by mechanical action (too high tensile stress), or can appear because of non-mechanical effects (temperature, shrinkage, etc.) or be induced by corrosion of reinforcement. Due to corrosion of the reinforcement, its cross-section area is reduced, which has obvious negative implications on the bearing capacity of the reinforced concrete. Additionally, as a consequence of the pitting effect [5,6], ductility and bond properties of reinforcement can be substantially reduced [4,7].

To predict the increase of volume of the corrosion products, it is necessary to calculate the corrosion current density in the corrosion unit, because the rate of rust production is proportional to corrosion current density. Furthermore, transport of corrosion products into the pores and through cracks needs to be taken into account considering its effect on decreasing the corrosion-induced pressure. Namely, soluble species involved in the process of corrosion diffuse through the concrete, away from the corroding reinforcement and so do not contribute to stress due to the expansion of corrosion products around the reinforcement cross-section. Generally, calculation of corrosion current density depends upon the following physical, electrochemical and mechanical processes: (1) transport of capillary water, oxygen and chloride through the concrete cover; (2) immobilization of chloride in the concrete; (3) transport of OH^- ions through the electrolyte (pore solution) in concrete pores; (4) cathodic and anodic polarization; (5) transport of corrosion products into pores and cracks and (6) damage of concrete due to mechanical and non-mechanical actions [8].

Currently, there are a number of models in the literature that are able to simulate processes before and after depassivation of reinforcement in uncracked concrete [3,8–16], i.e. the transport of water, oxygen, chlorides and heat that are responsible for initiation of corrosion and for corrosion processes of steel in concrete. For such computational models to be considered as realistic, chemo-hygro-thermal processes have to be coupled with mechanical

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processes, and also vice versa. The localization of damage (cracking) is a characteristic response of structures made of quasi-brittle materials, such as concrete, subjected to mechanical or non-mechanical loading. Computational modeling of damage in concrete is still a challenging task, especially its interaction with transport processes. Presently, there are only a limited number of coupled 3D chemo-hygro-thermo-mechanical models capable of realistically simulating corrosion processes in cracked concrete [1,2,17,18]. Transport of corrosion products in cracked concrete and its effect on the corrosion-induced damage so far has not been addressed by any model, i.e. the current models do not account for the transport of soluble species that are involved in the process of corrosion. The main problem in defining such models is quantifying controlling parameters for processes before and after depassivation of the reinforcement [7,19].

In the following, the recently developed 3D chemo-hyrgo-thermo mechanical model for concrete is presented. The model is able to simulate non-mechanical and mechanical processes and their interaction before and after depassivation of steel reinforcement [1,2]. It was implemented into a 3D finite element (FE) code and the results showed that the model is able to realistically predict relevant processes before [1] and after depassivation of reinforcement [2]. Here, more attention is devoted to the modeling of the corrosion-induced damage and transport of corrosion products into the pores and through the cracks, which is a further development of the model [20,21]. The first part of the paper gives a short overview of the theoretical framework and its application into a 3D FE code. In the second part, the verification and application of the model is carried out through a transient 3D FE analysis of a pull-out of the corroded reinforcement bars from a beam-end specimen. The numerical prediction is compared with experimental results [7]. The comparison confirms the ability of the model to realistically simulate the corrosion processes and their consequences for concrete structures.

2. Chemo-hygro-thermo-mechanical model for concrete

A surface layer of ferric oxide covers and protects the steel in concrete. Upon this layer being damaged or depassivated, the corrosion of reinforcement in concrete can be activated. Depassivation of the protective layer can occur by reaching a critical threshold concentration of free chloride ions near the reinforcement bar surface or as a consequence of carbonation of concrete [3,22,23]. Here is discussed only the chloride-induced type of corrosion that is generally the more severe one. Corrosion of steel in concrete is an electrochemical process dependent on the electrical conductivity of the concrete and steel surfaces, presence and conductivity of electrolyte in the concrete and the concentration of dissolved oxygen in the pore water near the reinforcement [8,24,25]. The developed 3D chemo-hygro-thermo-mechanical model couples the above mentioned physical and electrochemical processes with the mechanical behavior of concrete (damage).

2.1. Non-mechanical processes before depassivation of reinforcement

2.1.1. Transport of capillary water

Due to the fact that concrete is in practice rarely saturated, permeability is not a suitable parameter to describe the transport of capillary water through the concrete. At complete saturation, the suction exerted by concrete is reduced to zero and therefore an "extended" Darcy equation to formulate unsaturated flow is employed [26]:

$$\mathbf{j}_w = K_w(\theta_w)\mathbf{F}_c(\theta_w) \tag{1}$$

where $\mathbf{j}_w = \theta_w \mathbf{v}_w$ is the specific water discharge, $\mathbf{v}_w$ is the mean water velocity, K_w the unsaturated hydraulic conductivity, $\mathbf{F}_c$ the capillary force and θ_w is the volume fraction of pore water. Capillary force can be expressed as the gradient of capillary potential:

$$\mathbf{F}_c = -\nabla\Psi(\theta_w) \tag{2}$$

so that the "extended" Darcy equation can be written as:

$$\mathbf{j}_w = -K_w(\theta_w)\nabla\Psi(\theta_w) \tag{3}$$

As the capillary potential depends on the volumetric moisture content, Eq. (3) reads:

$$\mathbf{j}_w = -D_w(\theta_w)\nabla\theta_w \tag{4}$$

where

$$D_w(\theta_w) = K_w(\theta_w)\frac{\partial\Psi}{\partial\theta_w} \tag{5}$$

is the water diffusivity.

The mass balance equation for pore water, without source or sink terms, becomes:

$$\frac{\partial(\theta_w\rho_w)}{\partial t} = -\nabla\cdot(\theta_w\rho_w\mathbf{v}_w) = -\nabla\cdot(\rho_w\mathbf{j}_w) \tag{6}$$

where ρ_w is the density of water. Substituting (4) into (6), under assumption that $\rho_w = const$, it follows:

$$\frac{\partial\theta_w}{\partial t} = \nabla\cdot[D_w(\theta_w)\nabla\theta_w] \tag{7}$$

Eq. (7) describes transport of capillary water in terms of the volume fraction of pore water in aged concrete. Capillary water diffusivity is a function of moisture content that can be expressed as [27]:

$$D_w(\theta_w) = D_0 e^{n\bar{\theta}_w} \tag{8}$$

where $D_0 = 2.2 \times 10^{-10}\ \mathrm{m^2/s}$ is the limiting magnitude term, $\bar{\theta}_w = (\theta_w - \theta_{wi})/(\theta_{wd} - \theta_{wi})$ is a reduced water content, θ_{wi} and θ_{wd} are initial and saturated water content, respectively, and $n = 6.4$ is a shape term.

2.1.2. Transport of oxygen

Transport of oxygen through concrete will be considered as convective diffusion. Oxygen dissolved in the pore water is transported through concrete by molecular diffusion and convection as a consequence of capillary suction and moisture diffusion.

The macroscopic flux $\mathbf{j}_{o,diff}$, due to molecular diffusion of oxygen is expressed as:

$$\mathbf{j}_{o,diff} = -D_o(\theta_w)\nabla C_o \tag{9}$$

where C_o is the oxygen concentration in pore solution (kg of oxygen/m^3 of pore solution) and $D_o(\theta_w)$ is the effective oxygen diffusion coefficient (m^2/s), while the macroscopic flux $\mathbf{j}_{o,conv}$, due to capillary suction and moisture diffusion is expressed as:

$$\mathbf{j}_{o,conv} = C_o\mathbf{v}_w \tag{10}$$

The total mass flux of oxygen, $\mathbf{j}_o$ takes the form:

$$\mathbf{j}_o = C_o\mathbf{v}_w - D_o(\theta_w)\nabla C_o \tag{11}$$

The mass balance for oxygen in the pore water is given as [26]:

$$\frac{\partial(\theta_w C_o)}{\partial t} = -\nabla\cdot(\theta_w\mathbf{j}_o) \tag{12}$$