



# A 2D mechano-chemical model for the simulation of reinforcement corrosion and concrete damage



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## HIGHLIGHTS

- An electrochemically coupled model is developed for the corrosion of RC structures.
- The influence of corrosion-induced cracks on the diffusion process is considered.
- The growth of the anode is determined as a part of the solution procedure.
- A simple model is proposed for the expansive pressure due to the uneven corrosion.

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## ABSTRACT

This paper presents a comprehensive model for the prediction of the process of steel reinforcement corrosion and concrete damage in two dimensions. The ingress of chloride ions, carbonation, electrochemical reaction and corrosion-induced mechanical damage are coupled in this model. The evolution of the active zone on the reinforcement is determined automatically. Using this model, we can predict the non-uniform distribution of the corrosion product, the expansive pressure, and the growth of corrosion-induced cracks.

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## 1. Introduction

The corrosion of steel reinforcements is a significant durability problems causing damage to reinforced concrete structures. If a reinforced concrete (RC) structure is exposed to an environment with a high concentration of chloride ions or carbon dioxide, corrosion is initiated [1–4]. The subsequent reduction in the cross-sectional area of the reinforcement and corrosion-induced cracks in the concrete cover decrease the load-carrying capacity of the structure [5–7]. The corrosion of a steel reinforcement is a complex physical and chemical process, involving mass transport, electrochemical reactions, and cracking [5–9]. Therefore, a comprehensive model needs to be developed for the entire corrosion-induced failure process.

Following its construction, a thin passive layer forms on the surface of a RC reinforcement because of the high alkalinity of

the concrete. This protects the reinforcement against corrosion. However, this passive layer may be damaged via the ingress of chloride ions and carbonation, which is known as the depassivation process [1,2,10,11]. Corrosion products are generated upon the intrusion of oxygen in a complicated electrochemical reaction.

Once part of a steel reinforcement is depassivated, the reinforcement undergoes a polarization process. The active part transforms into an anode zone and the passive part into a cathode zone. Electrochemical reactions driven by the electric current between the anode and the cathode zones are called macrocell corrosion [6–9,12]. In addition to this, microcell corrosion occurs on the active part of the steel reinforcement [8]. With the transport of hydroxide ions, corrosion products form in the active zone. Once the expansive pressure exceeds a critical value, the concrete cover will be damaged.

Due to the penetration of chloride ions and carbon dioxide, the active zone will continuously grow. This changes the characteristics of corrosion over time, such as the generation rate and the distribution of corrosion products. Many long-term observations

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support the view that localized pitting corrosion (due to macrocell corrosion) is the most common pattern at the beginning of corrosion spreading to form almost evenly distributed corrosion products (via microcell corrosion) [13,14]. The expansion in volume of corrosion products causes cracks in the concrete near the reinforcement. Obviously, the patterns of the cracks and their growth are strongly influenced by the mechanisms of the corrosion [15]. In turn, the corrosion-induced cracks will influence the mass transport and the ratios of anode and cathode.

The ingress of chloride ions, carbonation, electrochemical reactions and mechanical damage are all interact with each other in the corrosion process. In other words, the transport of various masses, their chemical and electrochemical reactions, and fracture processes need to be considered simultaneously. The separate analysis of each process is only suitable for laboratory studies, not for practical durability problems.

Even in a normal environment, the influence of carbonation on chloride-induced corrosion cannot be ignored. As described in the literature [1,2], carbonation can reach 10–20 mm in depth after only twenty years of service. Numerous experiments have proven that carbonation significantly influences the transport of chloride ions, moisture, and oxygen in concrete through changes in pore structure and chemical composition [16–22].

The influence of cracks on the transport of chloride ions has been studied in many papers [23–28], and various numerical methods have been proposed for this subject. Expansive pressure on the concrete cover arising from corrosion has also been studied [8,29–32]. These studies were limited to problems with uniform corrosion. It is extremely difficult to consider the non-uniform distribution of corrosion products in the evolution of expansive pressure. However, some of empirical formulae have been proposed to estimate the non-uniform thickness of the rust layer [33–35].

Ožbolt et al. [5–7] recently developed a comprehensive model in which mass transport, electrochemical reactions, and the cracking of the concrete cover were coupled. However, the distribution of the anode and cathode zones was pre-set as a constant in his model, the distribution of corrosion products was considered to be uniform in the active zone, and the effect of corrosion-induced mechanical damage on mass transport was not studied.

This paper is structured as follows. The mechanisms behind reinforcement corrosion are described in Section 2. Section 3 presents the mechanical process of concrete damage and the influence of corrosion-induced cracks on mass transport. A new method for determining expansive pressure is also provided in this section. Numerical implementation is provided in Section 4, and the model is verified in Section 5. An illustrative example is provided in Section 6, and this study is concluded in Section 7.

## 2. Mechanisms of reinforcement corrosion

### 2.1. Transport of mass and heat

We assume that the steel reinforcement is in a passivated state before the concentration of free chloride ions or the pH value in the concrete surrounding the reinforcement reaches threshold values. This assumption has been accepted in many studies on the corrosion of steel reinforcements [1–9,12].

The coupled transport of carbon dioxide, free chloride ions, oxygen, heat and humidity has been previously studied by the authors [36]. A simplified version of the governing equations are as follows:

$$\frac{\partial(\phi - \phi_{w_e})C_{CO_2}}{\partial t} = (\phi - \phi_{w_e})D_{CO_2}\nabla^2 C_{CO_2} - I_{ch} - I_{CSH} \quad (1)$$

$$\frac{\partial\phi_{w_e}C_{fc}}{\partial t} + \nabla \cdot \mathbf{J}_{fc} = I_{rc} \quad (2)$$

$$\frac{\partial C_{CO_2}}{\partial t} = \nabla \cdot (D_{CO_2}^{car}\nabla C_{CO_2}) + \nabla \cdot (C_{CO_2}D_h^{car}\nabla h) \quad (3)$$

$$\rho c_q \frac{\partial T}{\partial t} - \lambda \nabla^2 T = I_h \quad (4)$$

$$\frac{\partial\phi_{w_e}}{\partial h} \frac{\partial h}{\partial t} = \nabla \cdot (D_h^{car}\nabla h) + I_{w_e} \quad (5)$$

where  $\phi$  is the porosity of concrete,  $\phi_{w_e}$  is the volume fraction of evaporable pore water,  $C_{CO_2}$  is the molar concentration of carbon dioxide,  $D_{CO_2}$  is the diffusion coefficient of carbon dioxide,  $I_{ch}$  and  $I_{CSH}$  are the reaction rates of carbon dioxide with calcium hydroxide and CSH, respectively,  $C_{fc}$  is the concentration of free chloride ions in the pore solution of concrete,  $\mathbf{J}_{fc}$  is the flux of chloride ions,  $I_{rc}$  is the free chloride ions released from the Friedel's salt,  $C_{O_2}$  is the molar concentration of dissolved oxygen in the pore water of the concrete,  $D_{O_2}^{car}$  is the effective diffusion coefficient of the dissolved oxygen in the concrete,  $T$  is the absolute temperature,  $\rho$  is the mass density of the concrete,  $c_q$  is the specific heat,  $\lambda$  is the thermal conductivity,  $I_h$  is the internal source of heat,  $D_h^{car}$  is the diffusion coefficient of humidity,  $I_{w_e}$  is the generation of water. For more detailed information, refer to [36].

### 2.2. Development of the anode zone

For chloride-induced corrosion, the evolution of the anode zone is mainly affected by variation in the chloride ions around the steel. This mechanism was considered by Kim et al. [37] in the development of a numerical model for the growth of the active zone due to the ingress of chloride ions. We extend their idea to simulate the evolution of the active zone based on the combined action of carbonation and the ingress of chloride ions. The procedure is as follows: (1) the surface of steel reinforcement is divided into many finite elements; (2) if either the concentration of free chloride ions or the pH value of any point on an element exceeds the threshold value, this element will be activated and defined as the active zone; and (3) with further ingress of chloride ions and carbonation, the active zone increases gradually.

After the electrochemical reaction of corrosion has been initiated, the corrosion current circulating from the anode zone to the cathode zone induces the transport of chloride ions in the opposite direction because they are negatively charged ions, as previously described in the literature [38]. The chloride ions are thus concentrated in the area where the attack occurs. Especially for pit corrosion in three-dimensional problems, a macrocell current forms between the anode area and the neighboring cathode area along the longitudinal direction of the reinforcement. In this case, the interaction between the migration of the chloride ions and the corrosion current (or the electric potential) is important. Eq. (2) may then be modified as

$$\frac{\partial\phi_{w_e}C_{fc}}{\partial t} + \nabla \cdot \mathbf{J}_{fc} + Q_e = I_{rc} \quad (6)$$

where  $Q_e$  is a term reflecting the influence of the electric potential on the diffusion of chloride ions.  $Q_e$  may be given by the electric field. Another paper is in preparation on this subject.

However, for relatively uniform corrosion in the longitudinal direction of the reinforcement, it has been reported that the localization of the anode zone caused by the chloride ions driven by macrocell corrosion current is not that significant [39,40]. Microcell corrosion governs two-dimensional problems during the long-term process of corrosion. In particular, as the concrete cover cracks, the rapid delivery of chloride ions to the reinforcement governs the growth of the anode zone. Therefore, we did not consider the coupling of the corrosion current and the transport of chloride ions in our model because our model focuses only on two-dimensional problems.

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