Cement and Concrete Research 71 (2015) 78–92

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Modeling of concrete cracking due to corrosion process of reinforcement bars

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ARTICLE INFO

Article history:
Received 23 December 2013
Accepted 9 January 2015
Available online 12 February 2015

Keywords:
Corrosion (C)
Reinforcement (D)
Modeling (E)
Degradation (C)

ABSTRACT

The reinforcement corrosion in Reinforced Concrete (RC) is a major reason of degradation for structures and infrastructures throughout the world leading to their premature deterioration before design life was attained. The effects of corrosion of reinforcement are: (i) the reduction of the cross section of the bars, and (ii) the development of corrosion products leading to the appearance of cracks in the concrete cover and subsequent cover spalling. Due to their intrinsic complex nature, these issues require an interdisciplinary approach involving both material science and structural design knowledge also in terms on International and National codes that implemented the concept of durability and service life of structures.

In this paper preliminary FEM analyses were performed in order to simulate pitting corrosion or general corrosion aimed to demonstrate the possibility to extend the results obtained for a cylindrical specimen, reinforced by a single bar, to more complex RC members in terms of geometry and reinforcement. Furthermore, a mechanical analytical model to evaluate the stresses in the concrete surrounding the reinforcement bars is proposed. In addition, a sophisticated model is presented to evaluate the non-linear development of stresses inside concrete and crack propagation when reinforcement bars start to corrode. The relationships between the cracking development (mechanical) and the reduction of the steel section (electrochemical) are provided. Finally, numerical findings reported in this paper were compared to experimental results available in the literature and satisfactory agreement was found.

1. Introduction

Reinforced Concrete (RC) is one of the most durable construction materials. However, the presence of soluble chlorides from deicing salts (15 million tons of de-icing salts are used each year in the United States of America and 4 to 5 million tons in Canada [1]) or marine exposure and the loss of alkalinity due to the carbonation of the concrete could destroy the passive film protecting the steel inducing corrosion of reinforcement [2,3]. Corrosion of steel reinforcement represents the major concern of degradation of RC structures. The corrosion process leads to the following coupled effects: (i) longitudinal cracking of concrete cover due to the expansion of corrosion products [4–9], (ii) steel cross section reduction and, (iii) the variation of bond at the steel–concrete interface [10,11]. As a result of these effects, service life and load-bearing capacity of RC elements are considerably reduced [12–14].

In U.S.A., for example, during the 1996, 2 billions of dollars has been spent to repair damages to highway bridges and the cost is increasing at a rate of 500 million of dollars per year [15]. According to the World Corrosion Organization (WCO) the annual cost of corrosion worldwide is over 3% of the world's Gross Domestic Product (GDP) [16].

Nowadays, prevention and detection of deterioration of RC infrastructures is one of the greatest challenges. Various non-destructive quantitative techniques based on electrochemical methods [17–19] can be used to detect the corrosion at an early stage in order to predict residual life, and suggesting the most suitable repair technique to be used [20–24].

Nomenclature			
c_c	Concrete cover	R_4	External radius of concrete section
d_{MAX}	Maximum diameter of aggregate	S_{1oxide}	Internal oxide displacement
E_c	Elastic modulus of concrete	$S_{2concrete}$	Internal concrete displacement
E_{ci}	Elastic modulus at concrete age of 28 days	$S_{2crackedconcrete}$	Internal cracked concrete displacement
E_o	Elastic modulus of oxides	S_{2oxide}	External oxide displacement
E_s	Elastic modulus of steel	$S_{3concrete}$	External cracked concrete displacement

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http://dx.doi.org/10.1016/j.cemconres.2015.01.010
0008-8846/

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Nomenclature			
P_{cr}	Internal pressure causing the c_c cracking	S_{steel}	Steel displacement
f_{ck}	Characteristic compressive strength of concrete	w_c	Crack width
f_{cm}	Compressive strength of concrete	w_p	Length of the pitting zone
f_{ct}	Tensile strength of concrete	x	Corrosion penetration
G_F	Fracture energy	y	Oxide displacement
i_c	Distance between two consecutive bars	α_E	Corrective factor of E_c
l_c	Characteristic length	ε_{ct}	tensile strain of concrete at peak
n	Volumetric expansion factor of oxides	ε_{cu}	Ultimate tensile strain of concrete
q_1	Pressure at interface oxide–steel	ν_c	Poisson coefficient of concrete
q_2	Pressure at interface oxide–concrete	ν_o	Poisson coefficient of oxide
q_3	Pressure at interface oxide–cracked concrete	ν_s	Poisson coefficient of steel
R_0	Radius of steel reinforcing bar	σ_{rpit}	Radial tension in case of pitting
R_1	Reduced bar radius of steel	σ_θ	Circumferential tension
R_2	External radius of oxide crown	ϕ	Creep factor
R_3	External radius of cracked concrete crown	Δf	8 MPa

1.1. Corrosion process

It is currently accepted that the alkaline nature of concrete provides a corrosion protection to the embedded steel reinforcement whereas concrete electrical resistivity and porosity act as barrier to the aggressive agents such as CO_2, H_2O, O_2 and Cl^-. The high value of pH (in the range of 12.6 ÷ 13.5) assures the formation of a thin stable passive layer in the range of 10 to 100 nm on the steel surface. This thin protective layer is mostly composed of γ-Fe_2O_3 and Fe_3O_4 [24–27].

The corrosion rate of steel in this passive state is significantly reduced. Passivity, however, is often unstable and subjected to breakdown under some conditions. As described by Tuutti [28] during the life time of a RC structure, two phases can be defined: (i) initiation and (ii) propagation of corrosion. The initiation phase is the time needed by aggressive agents to reach the steel surface with a minimum concentration to induce corrosion. The propagation phase is related to the rate of corrosion after the steel de-passivation process occurred. The most common de-passivation agent is the chloride ion. Good quality of concrete (low water-cement ratio, w/c, adequate curing) leads to low permeability delaying the penetration of corrosion-inducing agents (chloride ions, carbon dioxide and oxygen). However, depending on the exposure class, corrosion of the reinforcement can be initiated at a certain point of the service life of a structure. Two forms of corrosion are currently observed and reported as general corrosion (usually due to carbonation) and pitting or “localized” corrosion (due to the build-up of chloride ions). Unlike general corrosion, where corrosion products are insoluble iron oxides, pitting attack results in the formation of soluble ferric chlorides. The latter corrosion products may diffuse into the concrete matrix yielding to microcracking and altering the material structure before any visual sign of structural damage.

2. Research significance

The aim of this paper is to propose an analytical model for predicting the amount of oxide leading to concrete cracking in both general and localized attack. The proposed model can represent a good support also to design durable new buildings. In fact, once geometrical and the main parameters of materials are known, the model allows to estimate the appearance of first visible crack on concrete surface. This is the appropriate stage to restore concrete before the penetration of a large amount of aggressive agents onto the reinforcement through forming cracks.

The proposed model accounts for the main parameters involved in the overall degradation process namely: concrete strength class, concrete cover, size and type of aggregates, exposure class of concrete and bar diameter. In addition, volumetric expansion factor of oxide, Young's moduli and Poisson coefficients of steel, oxide, and concrete, and creep effect were also accounted for. Preliminary FEM simulations were carried out in order to evaluate the possibility to correlate results for cylindrical specimens, like those usually adopted in laboratory tests, to real RC cross sections. Once the effectiveness of cylindrical models to estimate the behavior of real members was verified, two mechanical analytical models are proposed. The former simulates the effects of corrosion yielding to the initiation of the crack where concrete stress–strain behavior is assumed to be linear. The latter simulates the propagation of the crack where concrete stress–strain behavior is mainly non-linear, until it reaches the external surface of concrete cover. Both models allow discussing the influence of main parameters on cracking process based on the reduction of the bar cross section due to corrosion.

It is well known that the timing of cracking process is influenced by many parameters. However, the evaluation of time dependent process is out of the scope of the present paper. Hence parametric analyses were performed on creep effect while evolution of corrosion penetration was simulated starting from a non-corroded situation up to a value of corrosion penetration yielding to full concrete cover cracking.

3. Mechanical parameters affecting oxide and concrete behavior

Numerical modeling was limited to preliminary analyses to establish the differences between pitting corrosion and general corrosion, being these the two representative forms of corrosion processes affecting reinforcement bar. Subsequently, FEM analyses aimed to correlate the results obtained on cylindrical laboratory specimens to real RC members have been performed.

Analytical and numerical models discussed in the subsequent part of this paper require the definition of mechanical parameters for oxide and concrete. As far as the oxides are concerned, their formation, structure and composition have been summarized in a simple volumetric expansion factor, n. However, the oxide layer has to be considered with an elastic behavior since from the mechanical point of view it affects the behavior of concrete.

3.1. Constitutive modeling of oxide layer

Since the oxide layer transfers normal and shear stresses between the steel surface and the surrounding concrete, model parameters characterizing deformability and shear behavior of corrosion products need to be defined. A survey of literature data on the elastic modulus of oxide can be found in a paper of Chernin and Val [6] summarizing the findings of Samsonov et al. [29], Yoshioka and Yonezawa [30], Suda et al. [31] and Ouglova et al. [27]. According to Samsonov [29], the modulus of elasticity of iron oxide crystals (Fe_2O_3 or Fe_3O_4) is in the range from 215 to 350 GPa. However, it must point out that these values cannot be used directly for corrosion products because of their granular nature, which results in a significant reduction of their stiffness. Yoshioka and Yonezawa [48] measured expansive strains in steel plates subjected to galvanostatic corrosion and confined by concrete. Based on the latter data, Suda et al. [31] estimated that the Young's modulus of corrosion products, E_o, was in the range from 0.1 to 0.5 GPa. Ouglova et al. [27] using a number of techniques found that as the degree of compaction increased, the modulus of elasticity of oxide increased nonlinearly from 1 ÷ 2 GPa up to several hundreds of GPa for pure oxide crystals (showing the typical