Cement and Concrete Research 42 (2012) 365–376

Contents lists available at SciVerse ScienceDirect

Cement and Concrete Research

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

Prediction of corrosion initiation in reinforced concrete members subjected to environmental stressors: A finite-element framework

Behrouz Shafei [a,*], Azadeh Alipour [a], Masanobu Shinozuka [b]

[a] Department of Civil and Environmental Engineering, University of Massachusetts, Amherst, MA 01003, United States
[b] Department of Civil and Environmental Engineering, University of California, Irvine, CA 92697, United States

ARTICLE INFO

Article history:
Received 10 March 2011
Accepted 2 November 2011

Keywords:
Corrosion (C)
Diffusion (C)
Finite Element Analysis (C)
Chloride (D)
Concrete (E)

ABSTRACT

To study the corrosion of reinforced concrete members subjected to various exposure conditions, a finite-element framework is developed. This framework evaluates the effects of the most critical parameters that may expedite or slow down the corrosion process. Some of these parameters, such as concrete properties and diffusion characteristics, are categorized as internal parameters. In contrast, the environmental parameters, such as ambient temperature, relative humidity, and concentration of carbon dioxide or chloride ions, are considered as external parameters. Using detailed three-dimensional finite-element models, the influential parameters are examined as individual physical environments. The analyses of these environments are based on the concept of transient thermal analysis with appropriate modifications. The novelty of the proposed framework is to consider the nonlinear time-dependent characteristics of the involved parameters along with their mutual interactions. This will result in a more realistic estimation of the extent of degradation over the service life of a structure.

1. Introduction

Corrosion of steel rebars embedded in the concrete is identified as one of the major causes of deterioration in reinforced concrete (RC) members. This phenomenon usually occurs due to the existence of carbon dioxide or chloride ions in the concrete. The penetration of these ions is mostly through the pore structure of the concrete or the concrete micro cracks caused by drying shrinkage or temperature changes [7]. The presence of carbon dioxide or chloride ions in the concrete results in the neutralization of the protective film around the rebar. This increases the vulnerability of steel rebars to corrosive agents. After corrosion initiates, steel is consumed during chemical reaction and it forms a layer of porous material with less strength and more volume compared to original steel. The increasing volume of corrosion products gradually fills out the porous area around the rebar and then pressurizes the surrounding concrete. This causes crack initiation in the concrete and decreases the bond action between the concrete and rebars [7,16,41]. In addition to the concrete degradation, it has been found that the effective cross sectional area and material strength of steel rebars are reduced due to the corrosion process [13–15]. Hence, considering the fact that the corrosion of rebars directly affects both strength and serviceability of RC members [1,2], an accurate estimation of the stage and extent of corrosion is necessary for the reliability analysis and performance assessment of RC members subjected to environmental stressors.

Towards this goal, the current paper proposes a comprehensive finite-element framework to examine the corrosion process in detail and to evaluate its effects on the life-cycle performance of RC structures. This study first identifies the most important parameters that influence the penetration of corrosive agents into the concrete. Some of these parameters, such as concrete properties and diffusion characteristics, are categorized as “internal” parameters, while the environmental parameters, such as ambient temperature, relative humidity, and concentration of carbon dioxide or chloride ions, are considered as “external” parameters. Based on a thorough investigation of available literature and resources, all the required assumptions and coefficients for each of the influential parameters are evaluated and discussed in the finite-element framework. The developed framework utilizes transient thermal analysis and applies the nonlinear time-dependent effects of each parameter to the three-dimensional model of the RC member. By taking advantage of this comprehensive yet rigorous framework, the chloride content at various depths of the RC member is calculated considering the appropriate initial and boundary conditions. The obtained results can be used to determine the chloride initiation time and to evaluate the extent of structural degradation over the service lifetime. This provides engineers and decision-makers with invaluable information to ensure the safety of RC structures while minimizing the associated inspection and maintenance costs.

2. Finite-element framework

To investigate the chloride-induced corrosion in the RC members subjected to various exposure conditions, an integrated finite-element

* Corresponding author. Tel.: +1 413 545 0434.
E-mail address: shafei@engin.umass.edu (B. Shafei).

0008-8846/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconres.2011.11.001

framework is developed. This framework evaluates the effects of the most critical internal and external parameters that may expedite or slow down the corrosion process, particularly during the initiation period. Since these parameters are nonlinear in nature and vary over time, they are modeled by following an analogous transient thermal analysis. A transient thermal analysis is capable of calculating the distribution of temperature or similar quantities in the concrete as a function of time. Since the developed framework takes into account the simultaneous contribution of all the influential parameters along with their mutual interactions, it can provide a precise estimation of chloride content at various depths of the concrete.

Through a three-dimensional finite-element model of the concrete, the influential external parameters are examined as individual physical environments. The analyses of these environments are all based on the concept of transient thermal analysis but with appropriate modifications and assumptions. To simulate the four major mechanisms of heat transfer, moisture transport, carbonation process, and chloride penetration, the ANSYS program has been used. For each physical environment, particular characteristics, such as geometry, element type, material properties, boundary conditions, and applied loads, are first defined. Then the procedure begins by solving all the mechanisms one-by-one at each time step. At the end of a time step, the obtained results are collected and used to update the model for the next step. One of the novelties of this procedure is that while it considers all the nonlinearities involved in each of the physical environments, their time-dependent interactions are also taken into account.

To perform transient thermal analysis in ANSYS, it is necessary to select an appropriate element type. Among various element types available in ANSYS, SOLID70 has been chosen in this study for the previously defined physical environments. According to the ANSYS Elements Reference, SOLID70 has eight nodes, each with a single degree of freedom for temperature. This element has a three-dimensional thermal conduction capability and can be used for steady-state or transient thermal analysis. By using this element type, a three-dimensional finite-element model of a concrete member is generated. As shown in Fig. 1, a typical segment of this member has a total thickness of 25 cm with the longitudinal rebars placed 20 cm center-to-center of each other. The cover depth is defined as the perpendicular distance from the center of a rebar to the concrete surface and here is assumed equal to 5 cm. This model can represent an actual bridge deck subjected to deicing salts or a RC slab of port facilities exposed to air-borne sea salts.

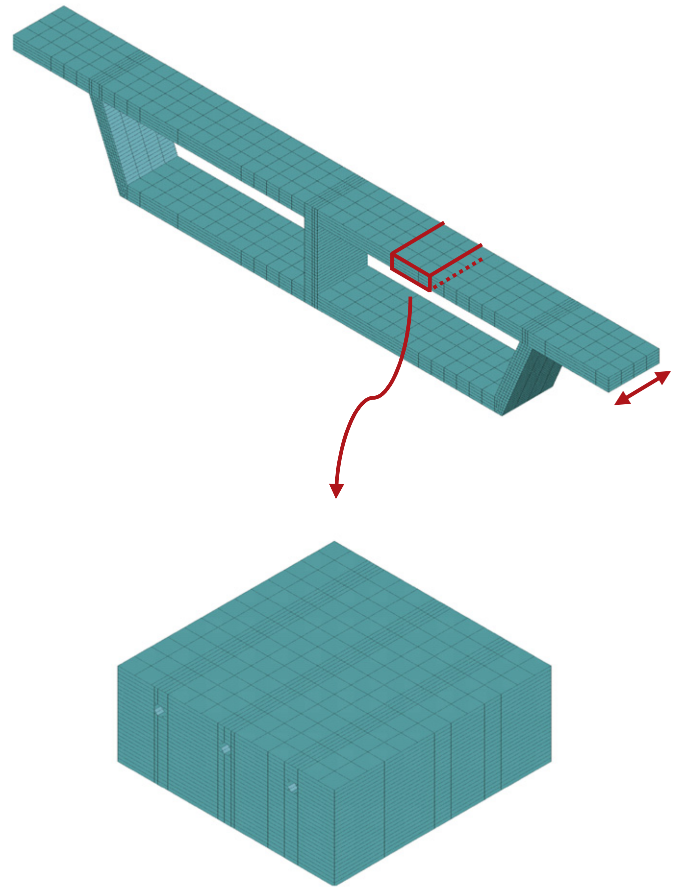

Fig. 1. Three-dimensional finite-element model of a typical reinforced concrete member (unit length).

3. Chloride intrusion into concrete

Chloride-induced corrosion is initiated by the ingress of chloride ions into the RC member during the concentration and diffusion cycles. The sources of chloride ions are mainly air-borne sea salts in coastal areas or deicing salts used over winter months. This paper focuses on the corrosion caused by the sea-salt particles floating in the air and assumes that the diffusion process is the dominant mode of chloride intrusion. To study the diffusion process, it is essential to find the change of the chloride content at different depths of the RC member. The total chloride content refers to the total acid-soluble chloride in the concrete, which is the summation of free chlorides and bound chlorides. The relationship among the total, C_t, free, C_f, and bound, C_b, chloride content in the unsaturated concrete can be described as follows [33]:

$$C_t = C_b + w_e C_f \tag{1}$$

where w_e is the evaporable water content (m^3 of evaporable water per m^3 of concrete). It should be noted that the water in the concrete is composed of evaporable water, w_e, and non-evaporable water, w_{ne}. The non-evaporable water is produced because of hydration reactions and has no effect on the transfer of chloride ions. On the other hand, the evaporable water, which is considered as the water held in concrete pores, takes part in the diffusion process as one of the internal parameters. According to [31], the evaporable water content can be calculated as the summation of the capillary pore water, w_c (m^3 of capillary pore water per m^3 of concrete), and gel pore water, w_g (m^3 of gel per m^3 of concrete), as below:

$$w_e = w_c + w_g = [(w/c - 0.36\alpha) + (0.18\alpha)]c/\gamma_w \tag{2}$$

where c is the cement content, w/c, the water-to-cement ratio, γ_w, the water density, and α, the degree of hydration. The degree of hydration can be calculated as a time-dependent parameter following the equation suggested by [18]. It should be noted that Eq. (2) is a simplified formulation only for ordinary portland cement (OPC) and it does not take into account the effects of a few parameters, such as carbonation, interfacial transition zone, non-porous aggregates, air voids, and curing conditions.

At the constant temperature of 23 °C and the water-to-cement ratio of 0.5, the change of evaporable water content with concrete age is shown in Fig. 2 for a set of cement contents ranging from 300 to 450 kg/m^3. It can be understood from this figure that the amount of evaporable water decreases during the aging process of the concrete until it reaches a constant level within less than 100 days. As a case in point, the evaporable water content for the cement content of 350 kg/m^3 experiences no change after reaching 0.136 (13.6%) within only 60 days.

According to Fick's second law, which is based on the mass conservation principle, the diffusion process is expressed as the change in the free chloride content over the time, t [25]:

$$\frac{\partial c_f}{\partial_t} = -div\left[\frac{D_{Cl}}{1 + (1/w_e)(\partial C_b/\partial C_f)}\nabla(C_f)\right] \tag{3}$$

where D_{Cl} is the chloride diffusion coefficient and $\partial C_b/\partial C_f$ is the binding capacity. The chloride binding capacity in Eq. (3) characterizes the