Cement and Concrete Composites 84 (2017) 62–73

Contents lists available at ScienceDirect

Cement and Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Damage model for simulating chloride concentration in reinforced concrete with internal cracks

Mao Kurumatani [a,*], Hisashi Anzo [a], Kenji Kobayashi [a], Shinichiro Okazaki [b], Sohichi Hirose [c]

[a] *Department of Urban and Civil Engineering, Ibaraki University, 4-12-1 Nakanarusawa, Hitachi, Ibaraki, 316-8511, Japan*
[b] *Department of Safety Systems Construction Engineering, Kagawa University, 2217-20, Hayashi, Takamatsu, Kagawa, 761-0396, Japan*
[c] *Department of Civil and Environmental Engineering, Tokyo Institute of Technology, 2-12-1, Ookayama, Meguro-ku, Tokyo, 152-8552, Japan*

A R T I C L E I N F O

Article history:
Received 9 December 2016
Received in revised form
28 July 2017
Accepted 21 August 2017
Available online 24 August 2017

Keywords:
Damage model
FEM
Reinforced concrete
Internal crack
Chloride ion

A B S T R A C T

We present a method to simulate, in three dimensions, the concentration of chloride ions that penetrate into concrete with internal cracks. The method comprises the crack-propagation analysis of concrete and the diffusion analysis of chloride ions. A finite-element model with a damage model that is based on fracture mechanics for concrete was applied in the crack-propagation analysis, and we were able to reproduce the three-dimensional geometry of the internal cracks. Chloride-ion transfer through internal cracks was simulated by diffusion analysis with the simultaneous consideration of damage, and a diffusion coefficient that was expressed as a function of the damage variable obtained from crack-propagation analysis. We present a formulation of crack-propagation analysis by using the damage model and unsteady-diffusion analysis in consideration of damage. We also present a verification analysis of internal cracking in concrete to demonstrate that the crack width and the chloride concentration can be evaluated without mesh dependency. This is followed by a validation analysis. A comparison between the numerical and experimental results shows that the proposed method enables the high-accuracy simulation of chloride penetration into concrete with internal cracks.

1. Introduction

Steel corrosion affects reinforced concrete structures adversely. Chloride ions attack, age and deteriorate reinforced concrete by corroding steel bars. Chloride ions penetrate into concrete and break the passivation film that protects reinforcing bar from corrosion. It is therefore important to prevent chloride penetration into cover concrete.

The accessibility of chloride ions from the concrete surface to the steel bars depends on the thickness of the cover concrete and the concrete quality. If concrete is porous or contains many cracks, the chloride ions transfer easily through the pores or cracks in the concrete. Although the number of pores or cracks affects the diffusion coefficient of the chloride ion, the three-dimensional (3D) geometry of cracks becomes a pathway for chloride ions movement, and is a significant factor that is associated with chloride diffusivity.

Many studies have been conducted on the numerical analysis of chloride-ion penetration into concrete. Maruya et al. [1] modeled the increased concentration of chloride ions in the surface layer of concrete under wet-dry cyclic conditions. Ye et al. [2] studied the transport of chloride ions in cracked concrete subject to cyclic drying-wetting numerically and experimentally. Kato et al. [3] studied the local distribution of chloride ions around cracks in concrete. Ishida et al. [4] modeled the enhancement of chloride diffusivity in consideration of pore structure and electrochemical properties at the micro-scale, and simulated chloride diffusion in concrete with or without cracks. Guzmán et al. [5] presented numerical models to simulate chloride diffusion and corrosion cracking using an embedded cohesive crack model. Šavija et al. [6] simulated chloride migration in heterogeneous structure models with coarse aggregates and cracks from crack-propagation analysis using a lattice model [7]. Du et al. [8] presented a diffusion-analysis method combined with an extended finite-element method (XFEM) [9], which can simulate crack propagation in concrete as a strong discontinuity (discontinuous deformation). Li et al. [10] investigated the influence of crack width on chloride

* Corresponding author.
E-mail address: mao.kurumatani.jp@vc.ibaraki.ac.jp (M. Kurumatani).

http://dx.doi.org/10.1016/j.cemconcomp.2017.08.015
0958-9465/

transmission in concrete, including aggregate heterogeneity by using finite-element (FE) analysis with ABAQUS. Although many studies have been conducted on chloride diffusion in cracked concrete, most models have taken two-dimensional or two-and-a-half-dimensional cracking into account and have offered no insight into 3D crack formation.

Little attention has been paid to the simulation of chloride penetration into concrete involving "internal cracks" formed around deformed bars. Because the formation of internal cracks degrades the concrete quality, the influence of internal cracks on chloride penetration into concrete needs to be investigated. Goto [11] visualized experimentally the internal cracks formed in concrete around deformed bars by using a red-ink injection method. Fig. 1 shows the internal cracks observed in Goto's experiment, which are referred to as "*Goto cracks*". The authors also focused on internal cracking in reinforced concrete, and investigated, mainly experimentally, the influence on mass-transfer resistance [12,13]. Because experimental approaches have several limitations in the observation of internal cracks, numerical studies should also be conducted to simulate internal cracking and chloride diffusivity.

The type of cracking, characterized by the distribution, number, shape, and so on, generally affects the rate of chloride penetration in concrete [14–16]. Because internal cracks are formed and propagate discretely around deformed bars, the 3D geometry of cracks, such as the depth, width and tortuosity, especially impacts the chloride diffusivity. To simulate chloride penetration into concrete with internal cracks with high accuracy, a method of crack-propagation analysis that is capable of representing 3D-crack geometry is required. The rigid-body spring method (RBSM) [17–21], which is a discrete-analysis model, is an effective approach to represent 3D cracks as strong discontinuities. In the RBSM, the crack width can be evaluated easily to model chloride-ion diffusivity [22,23]. The lattice model [24–26] which is a similar approach to the RBSM also exhibits the same characteristics. However, these methods that are based on the discrete model provide analysis results depending on mesh configuration and mesh size. In addition, a type of truss-network model that is based on the Delaunay method is required to simulate mass transfer as an additional task [22–27].

Numerical techniques for fracture analysis that use the finite-element method (FEM), and which replace cracking by degradation of material stiffness [28–31], are useful approaches for simulating 3D crack behavior of concrete because of their good compatibility with the FEM. The authors have developed an isotropic damage model [32] based on fracture mechanics for concrete, to apply crack-propagation analysis with FEM. We demonstrated that the 3D geometry of cracks can be simulated by using the damage model and conforms with the experimental geometry. Because crack-propagation analysis is based on a standard FEM, it can be applied easily to the simulation of chloride penetration without the requirement for additional modeling, such as the use of the discrete model.

In this context, the purpose of this study is to propose a method to simulate the concentration of chloride ions that penetrate into concrete with internal cracks around deformed bars. Internal crack propagation is simulated by using FEM with the damage model based on fracture mechanics for concrete, which is capable of reproducing the 3D geometry of internal cracks. The concentration of chloride ions that penetrate into concrete with internal cracks is simulated by diffusion analysis in consideration of damage that corresponds to internal cracks. Section 2 provides a formulation of crack-propagation analysis with the damage model based on fracture mechanics for concrete. Then, the formulation of unsteady-diffusion analysis along with the diffusion coefficients in consideration of damage is presented. Section 3 presents an analysis of internal cracking and chloride diffusion to verify the performance for providing mesh-independent solutions. Finally, a validation analysis is presented in Section 4 to demonstrate the validity of the proposed method to reproduce an experimental result.

2. Formulation of numerical analysis based on damage model

A formulation of the proposed numerical analysis based on the damage model [32] is presented in this section. The fracture behavior of concrete is expressed by the damage model, and the penetration of chloride ions into concrete is modeled as diffusion in consideration of the extent of damage. After formulating the crack-propagation analysis with the damage model, the unsteady-diffusion analysis of chloride ions in consideration of damage is presented.

2.1. Crack-propagation analysis with damage model

2.1.1. Governing equation

Let us consider the quasi-static equilibrium problem of an elastic continuum that involves damage. The equilibrium equation for stress, the relationship between strain and displacement and the constitutive equation are given as follows:

$$\nabla \cdot \boldsymbol{\sigma} + \overline{\boldsymbol{b}} = 0 \quad \text{in } \Omega \tag{1}$$

$$\boldsymbol{\varepsilon} = \frac{1}{2}\{\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^{\mathrm{T}}\} \quad \text{in } \Omega \tag{2}$$

$$\boldsymbol{\sigma} = (1 - D_\varepsilon)\boldsymbol{c} : \boldsymbol{\varepsilon} \quad \text{in } \Omega \tag{3}$$

where $\boldsymbol{\sigma}$ is the Cauchy stress tensor, $\boldsymbol{\varepsilon}$ is the small strain tensor, $\boldsymbol{c}$ is the elastic coefficient tensor, $\overline{\boldsymbol{b}}$ is the given body force vector, ∇ is the nabla operator and Ω is the whole domain. The scalar-variable D_ε is termed the damage variable, which represents the degree of mechanical degradation and takes $0 \le D_\varepsilon \le 1$. Here, $D_\varepsilon = 0$ means

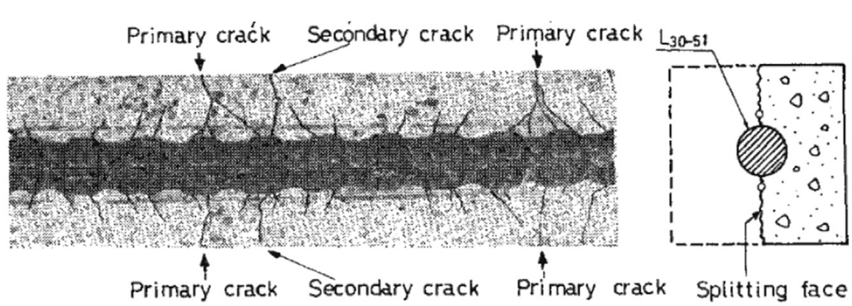

Fig. 1. Internal cracks visualized by Goto [11].