Construction and Building Materials 136 (2017) 57–64

Contents lists available at ScienceDirect

Construction and Building Materials

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

Concrete cover tensile capacity of corroded reinforced concrete

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HIGHLIGHTS

- Concrete cover tensile (CCT) capacity of corroded reinforced concrete is proposed.
- The relationship between CCT capacity and concrete cover thickness is presented.
- A coefficient indicating CCT capacity is defined.
- CCT capacity is applicable to salt-precipitation and ice-formation problems.

ARTICLE INFO

Article history:
Received 16 August 2016
Received in revised form 23 December 2016
Accepted 7 January 2017

Keywords:
Concrete cover
Concrete cover tensile capacity
Characteristic cover thickness
Critical expansive pressure
Reinforcement corrosion

ABSTRACT

In this paper, the concrete cover tensile (CCT) capacity of cracked concrete caused by reinforcement corrosion is investigated. A newly developed double-cylinder model with the consideration of concrete confinement effects is used to evaluate the critical expansive pressure of the corrosion products necessary to cause unstable cover crack propagation in corroded reinforced concrete. After considering the critical pressures associated with wide ranges of tensile capacities of concrete, reinforcement diameters and cover thicknesses, an empirical critical expansion pressure function is determined by the least squares method. The CCT capacity of cracked concrete is obtained by considering the equilibrium of expansive pressure and concrete resistant tensile force at the limiting stage. A generic relationship between CCT capacity and concrete cover in a bilinear form, which is suitable for the design, analysis and modeling of the problems related to reinforcement bar corrosion induced and other internal expansion-caused cover cracking, is proposed for the first time. Parametric studies are conducted to investigate the effects of the tensile strength of concrete and cover thickness on the critical expansive pressure and CCT capacity.

1. Introduction

Deleterious reactions in reinforced concrete (RC) may cause volumetric expansion in one or more of its phases [1], thereby affecting the serviceability, strength, durability, integrity and life span of RC structures [2]. In plain concrete, internal expansion can result from physical attacks associated with salt precipitation and ice formation, and chemical attacks due to alkali-aggregate reaction, sulfate attack and delayed ettringite formation. In RC structures, corrosion of the reinforcement bar due to the electrochemical reaction can lead to volumetric expansion as the volume of the generated corrosion products is larger than that of the original steel [1].

Concrete is particularly sensitive to tensile stresses; small volumetric expansion can cause cover cracking and even spalling of the surrounding concrete. The development of expansive pressure in concrete cover over time due to reinforcement corrosion is illustrated in Fig. 1. During the steel corrosion and concrete cover cracking process, the corrosion products filling concrete pore at steel/concrete interface happens spontaneously with accumulating between steel and concrete as corrosion layer [3–5]. The expansive pressure caused by the corrosion produces in the steel/concrete interface increases with time. When the expansive pressure reaches the maximum value, it is defined herein as the critical expansive pressure, and unstable crack propagation will occur through the whole cover to cause the cover failure. The serviceability, durability, and residual life analysis of RC structures are largely dependent on the stress conditions of the concrete cover. It is imperative, therefore, to know the maximum tensile force that the concrete cover can resist during the unstable crack growth stage, or in other words, the concrete cover tensile (CCT) capacity.

Traditionally, the CCT capacity was simply taken as a product of concrete tensile strength and the cover thickness [6–11] without considering concrete cracking. This approach may be suitable for

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http://dx.doi.org/10.1016/j.conbuildmat.2017.01.021

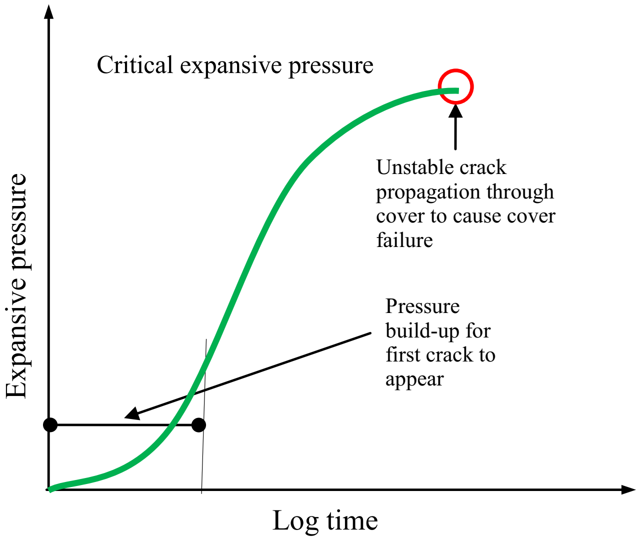

Fig. 1. Illustration of the development of expansive pressure against time.

uncracked concrete but would overestimate the CCT capacity when unstable crack propagation occurs in the cover zone, as only a small portion of concrete cover has reached its tensile strength capacity [12].

In this study, critical expansive pressure and CCT capacity of corroded reinforcement concrete are determined by a newly developed double-cylinder model [13]. A generic relationship between CCT capacity and concrete cover in a bilinear form is proposed for the first time. A numerical parametric study is carried out to investigate the effects of tensile strength of concrete and cover thickness on the critical expansive pressure and CCT capacity. It is worth noting that the equations and findings obtained from this study are applicable to the problems related to general volumetric expansion in concrete caused by not only reinforcement bar corrosion but also salt precipitation and ice formation.

2. The analytical model

To simulate the effect of concrete cracking due to the corrosion of reinforcement, a double-cylinder model [13] developed by the authors was employed. This model features: (1) incorporating residual tensile stress in cracked concrete, (2) considering the stiffness contribution from both reinforcement and corrosion products (i.e. the corrosion products and non-corroded steel are combined together to form a steel-corrosion product composite), (3) modeling the volume compatibility condition in the steel-rust-concrete interface, and (4) simulating the continuity of stress and strain on the common boundary between the uncracked and cracked concrete cylinders. This model is suitable for the present analysis as it has considered the concrete confinement effect outside the concrete cylinders and the boundary effect arising from the thickness difference between concrete covers. Also, it is capable of predicting the time to cracking and the corrosion-caused expansive pressure, which are relevant to this study.

The main principle of this double-cylinder model is briefly presented herein. The reinforcement corrosion problem considered by this model is shown in Fig. 2a. When the reinforcing bar is placed below the mid-depth of the concrete section, c_b and c_t are the thicknesses of the thinner (bottom) and thicker (top) covers, respectively. In the figure, P_{rust} is the expansive pressure caused by the expansion of the corrosion products, d_0 is the thickness of the porous zone, D is the initial diameter of the reinforcing bar embedded in the concrete, r_0 is the crack front, and $t_{c,e}$ is the time to cover cracking for the actual case. The first analytical model, as shown in Fig. 2b, is the traditional model widely adopted in the literature. The radius of the concrete cylinder is the same as the thickness of the thinner cover, and is equal to $D/2 + d_0 + c_{b,0}$, where $c_{b,0} = c_b$. $P_{c,0}$ is the confining pressure provided by the uncracked concrete cylinder, and $\sigma_{\theta,0}(r)$ is the residual tensile stresses provided by the cracked concrete cylinder. The critical expansive pressure necessary to cause cover cracking predicted by this model is likely to be underestimated as the confinement pressure outside the cylinder has been ignored.

To yield a more accurate prediction, the second model, as depicted in Fig. 2c, with a cylinder radius equal to $D/2 + d_0 + c_{b,1}$ ($c_{b,1} \geqslant c_{b,0}$), which is larger than or equal to that of the first model, is introduced. The required radius of the cylinder has been obtained by calibrating the computed time to cover cracking with the available experimental results [13].

The analytical solutions of these two models can be solved by considering the following conditions: (1) the force equilibrium in the tangential direction, (2) volume expansion in the steel-rust-concrete interface, (3) deformation compatibility in the steel-rust-concrete interface, (4) the force equilibrium in the radial direction, and (5) bilinear relationship of the tension softening

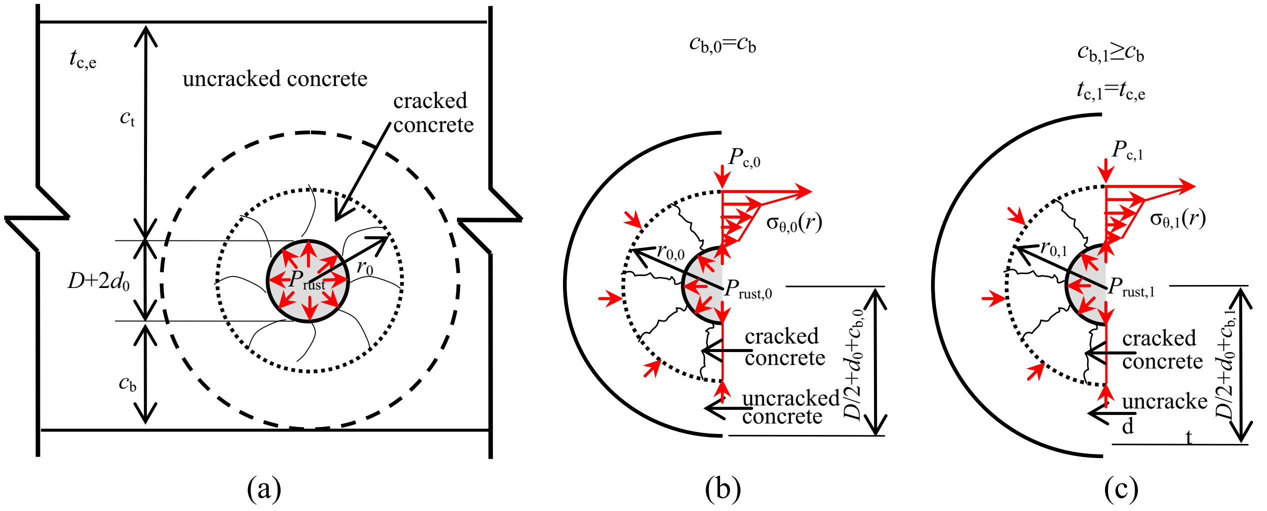

Fig. 2. The corrosion problem: (a) the actual case, (b) the traditional analytical model (the first model), and (c) the equivalent analytical model (the second model).