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Whole-process crack width prediction of reinforced concrete structures considering bonding deterioration

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ABSTRACT

Monitoring the crack width of reinforced concrete (RC) structures is essential to assess their damage and durability. However, traditional methods of crack calculation are confined to the formulas for predicting the crack width in a single RC member at the service limit state. In this paper, based on the theoretical analysis of microscopic interface between concrete and rebar, an approach for the whole-process crack width prediction is proposed to trace the crack evolution of overall RC structures when subjected to cyclic loading such as earthquakes. To describe the tensile behavior characterized by the tension stiffening and tension softening effects, a modified model considering the bonding deterioration—dubbed here as the "*β-ellipse model*"—is formulated as an extension of conventional model based on bond-slip interaction. Then, by implementing the β-ellipse model in the framework of the fiber beam-column element model, the approach for calculating and displaying the crack width in finite element analysis (FEA) is presented. Finally, the accuracy of the developed fiber model is verified by comparing the simulated performance with extensive test results of RC members. The comparisons indicate that the model can elaborately simulate the crack width, crack distribution, crack evolution, and crack-load response of both the single cracking section and overall component, which offers a reliable and efficient tool for the whole-process crack width prediction in nonlinear FEA of RC structures.

1. Introduction

Cracking is one of the most important features for evaluating the overall damage and corrosion resistance of reinforced concrete (RC) structures. Cracking behavior significantly influences the performance of RC structures such as the strength, stiffness, and durability [1–4]. Among the various quantitative indexes for describing the cracking phenomenon, crack width is the most basic and essential one in the design and analysis of RC structures.

A large amount of methods for predicting the crack width have been proposed in the literature [4–11]. However, these researches are primarily focused on the design formulas for calculating the maximum crack width of a single RC member at the serviceability limit state. No method is available for tracing the whole development process of the crack width, especially when the RC structures are subjected to the time-history loading such as earthquakes. Therefore, a reliable approach for the whole-process crack width prediction in the nonlinear analysis of RC structures is urgently needed for both scientific insight and engineering practice.

It is challenging to realize the whole-process prediction of the crack width for RC structures mainly because of the hurdles in modeling the two critical issues involved in cracking behavior, namely the *tension softening* and *tension stiffening* effects. The tension softening effect is one of the basic material properties of concrete, which describes the formation process of a single crack and is represented by a descending branch of the concrete stress-strain curve. Based on the smeared crack concept and the definition of the fracture energy G_F, Bazant and Oh [12] proposed the crack band model and offered an important theoretical foundations for the rational description of the tension softening effect. Then, the subsequent studies related to the tension softening effect were mainly focused on the determination of the value of the fracture energy G_F [13,14] and the profile of the descending branch [15–18]. On the other hand, the tension stiffening effect indicates the capability of concrete between cracks to carry the tensile stress through the concrete-rebar interaction, which significantly contributes to the tensile stiffness of RC structures. Because the bond-slip mechanism

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of the concrete-rebar interface is distributed unevenly and developed in a complicated manner, the tension stiffening effect of the concrete is approximately modeled by various investigators [19–25] through adopting the average stress-strain relationship based on the smeared crack concept. Although the macroscopic mechanical behavior of the RC members in tension can be well captured by these models, the empirical or half-empirical formulas for the stress-strain relationship mainly depend on the regression of experimental results. Therefore, some key parameters involved in the tension stiffening effect such as the local bond stress-slip relationship, average crack spacing, and crack width, are not fully taken account of by these models. Because of the lack of theoretical background and sufficient validations, the models are not reliable or applicable for the quantitative whole-process prediction of the crack width in RC structures.

In this paper, a theoretical model and a numerical approach are developed for the whole-process crack width prediction in nonlinear analysis of RC structures. First, the tension stiffening and the tension softening effects are intensively discussed. A theoretical model is proposed on the basis of the microscopic bond-slip interaction between the concrete and rebar, which takes account of the gradually deterioration of the bonding interface in particular. Then, the equivalent constitutive laws of the concrete and rebar materials are put forward for the finite element analysis (FEA). According to the stress and strain distribution in concrete and rebar, the formulas for calculating the crack width can be derived. Finally, the fiber beam-column element is adopted for the nonlinear FEA of RC members, which include the uniaxial tensile behavior of panels and flexural performance of beams. The width, distribution and whole evolution process of the cracks are simulated to validate the reliability and efficiency of the developed model.

2. Theoretical model based on bond-slip interaction

2.1. Framework of the model for RC members

Distributed cracks emerge when an RC member is subjected to tension as shown in Fig. 1. To clarify the two critical effects relevant to the tensile behavior of the RC member, i.e. the tension softening and tension stiffening effects, the member are divided into two regions: (i) the cracking region (denoted by region C) that stands for the tension softening effect, which indicates the position where the crack develops, and covers the width of the crack; and (ii) the bonding region (denoted by region B) that represents the tension stiffening effect, where the bare rebar is stiffened by the intact concrete between cracks through the bond-slip interaction. Thus, the tensile behavior of different regions can be distinguished and investigated in isolation.

According to the division of the RC component, some basic definitions are discussed herein. In a single unit as illustrated in Fig. 1, the ranges of the regions C and B satisfy

$$l_C + l_B = \frac{L_m}{2}, \tag{1}$$

where l_C and l_B stand for the lengths of the regions C and B, respectively; and L_m represents the average crack spacing.

The average strain of the RC member in the longitudinal direction (x-direction), denoted by $\bar{\varepsilon}$, is defined as the average value of the rebar strain, $\varepsilon_r(x)$, along the length of the average crack spacing L_m as shown in Eq. (2).

$$\bar{\varepsilon} = \frac{2}{L_m}\int_0^{\frac{L_m}{2}} \varepsilon_r(x)dx. \tag{2}$$

According to the compatibility of the strain, $\bar{\varepsilon}$ can also be calculated by the average strain of the concrete, which includes the width of crack as shown in Eq. (3).

$$\bar{\varepsilon} = \frac{\omega}{L_m} + \frac{2}{L_m}\int_0^{l_B} \varepsilon_c(x)dx \tag{3}$$

where the crack width ω equals $2l_C$.

The average stress $\bar{\sigma}$ of the RC member is defined as a nominal value of the sectional stress under uniaxial tensile load P, which can be calculated by Eq. (4).

$$\bar{\sigma} = \sigma(x) = \frac{P}{A_c + A_r} \tag{4}$$

where $\sigma(x)$ is the nominal stress of the RC component along the x-direction; A_c is the sectional area of concrete; and A_r is the sectional area of rebar.

The average concrete stress $\bar{\sigma}_c$ is an average value of the concrete stress $\sigma_c(x)$ along the length of the average crack spacing L_m, which should include the contributions of both regions B and C because the concrete stress in the cracking region does not drop suddenly to zero once the crack opens.

$$\bar{\sigma}_c = \frac{2}{L_m}\int_0^{\frac{L_m}{2}} \sigma_c(x)dx \tag{5}$$

Similarly, the average rebar stress $\bar{\sigma}_r$ is defined as

$$\bar{\sigma}_r = \frac{2}{L_m}\int_0^{\frac{L_m}{2}} \sigma_r(x)dx \tag{6}$$

where $\sigma_c(x)$ and $\sigma_r(x)$ are the longitudinal stress of concrete and rebar, respectively.

Noting that rebar stress satisfies $\sigma_r(x) = E_r \cdot \varepsilon_r(x)$ before yielding, Eq. (6) can be written as follows:

$$\bar{\sigma}_r = \frac{2}{L_m}\int_0^{\frac{L_m}{2}} E_r \cdot \varepsilon_r(x)dx = E_r \cdot \bar{\varepsilon} \tag{7}$$

where E_r is the modulus of rebar.

The equilibrium condition for the resultant of the concrete and rebar stress is always valid as shown in Eq. (8):

$$\sigma(x) \cdot (A_c + A_r) = \sigma_c(x) \cdot A_c + \sigma_r(x) \cdot A_r \tag{8}$$

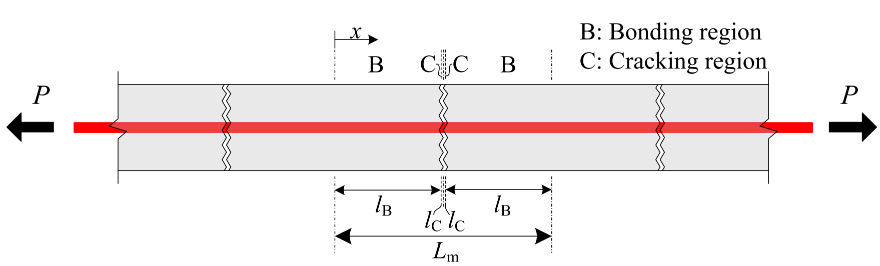

Fig. 1. Partition of RC member as cracking and bonding regions.