Construction and Building Materials 49 (2013) 352–363

Contents lists available at ScienceDirect

Construction and Building Materials

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

On fracture process zone and crack extension resistance of concrete based on initial fracture toughness

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HIGHLIGHTS

- Initial fracture toughness is employed to determine crack propagation in concrete.
- Three types of FPZ evolution depending on a_0/D are discovered for concrete.
- FPZ evolution curve of plates with lower a_0/D envelops those with higher a_0/D.
- FPZ evolution affects the shape of K_R-curve for concrete.
- K_R-curve for concrete is found to be size-dependent by considering FPZ evolution.

ARTICLE INFO

Article history:
Received 28 April 2013
Received in revised form 19 August 2013
Accepted 27 August 2013
Available online 19 September 2013

Keywords:
Concrete
Cracking
Fracture process zone (FPZ)
Initial fracture toughness
Numerical simulation
Crack extension resistance
Complete fracture process

ABSTRACT

In this paper, a numerical approach is developed to investigate the evolution of fracture process zone (FPZ) during the complete fracture process in concrete structures by using stress intensity factor-superposition method. In this approach, the initial fracture toughness K_{IC}^{ini}, as an inherent material property, is introduced to form a crack propagation criterion for concrete. The developed numerical approach is then employed to analyze the complete fracture process of three series of notched concrete beams under three-point bending. It is found that the numerical results agree well with experimental ones published in literature through which the developed numerical approach, with an initial fracture toughness based crack propagation criterion, for fracture analysis of concrete is validated. The verified numerical approach is then utilized to simulate the complete fracture process of a series of concrete square plates with different sizes and/or initial crack length-to-depth ratio (a_0/D). The effects of a_0/D on evolution of FPZ length (a_{FPZ}), especially after the FPZ is fully developed, are examined based on numerical analysis results. It is found that there are three different types of a_{FPZ} variation with respect to a_0/D, viz. (i) a_{FPZ} keeps increasing after FPZ is fully developed. (ii) a_{FPZ} turns to decrease from the peak value after FPZ is fully developed. (iii) FPZ is not fully developed. Finally, features of K_R-curve for concrete are investigated based on the developed numerical method, and it is found that K_R-curve of concrete is size-dependent when the effects of FPZ variation are taken into account.

1. Introduction

At the macro-level, concrete is treated as a continuous and homogeneous medium. In order to describe its strain softening and strain localization behavior, the concept of fracture process zone (FPZ) was introduced into analyzing fracture of concrete based on the argument that damages accumulate as fracture proceeds. Barenblatt [1,2] first introduced the concept of FPZ by considering attractive atomic forces in a small region near the crack tip. Dugdale [3] proposed a mathematically similar but conceptually different FPZ theory, which states that there is a plastic zone near the crack tip and a stress equal to the yield strength of the material acts across the crack within the plastic zone. Later, Hillerborg et al. [4] proposed the fictitious crack model for concrete fracture which features a cohesive zone. Since then, the fictitious crack model has been gradually accepted by scientific and engineering communities and is now widely used for simulating concrete fracture which simplifies the real concrete FPZ by a bridged zone with cohesive stress acting on it. The cohesive stress acting on crack surface is very often formulated with respect to the crack surface displacement w when utilizing this model for analyzing concrete fracture. According to Hillerborg et al. [4], the FPZ length a_{FPZ} is

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http://dx.doi.org/10.1016/j.conbuildmat.2013.08.041

equal to the length of the crack bridged zone, on which the stress acts. On the other hand, Bažant and Oh [5] proposed the crack band model which has been widely used in practice for simulating concrete fracture since then.

By introducing the concept of FPZ, it makes feasible to calculate various fracture parameters and investigate crack propagation in concrete. Moreover, fracture properties of concrete often exhibit strong size-dependence, which is often called size-effect, because of their coarse material structures and large FPZ which varies during crack growing. Due to size effect, investigating the effect of FPZ on fracture of concrete has been catching lots of interests from engineering community in the field of concrete fracture mechanics. It is now well accepted that there are two distinct stages in the evolution of FPZ, i.e., pre-critical crack growth and unstable crack propagation. A number of studies have shown that FPZ length decreases rapidly when crack approaches to the back surface of a specimen [6–8] which is often called boundary effect and has been successfully explained through introducing the concept of local fracture energy [6,9,10]. Extensive experimental and theoretical studies have been conducted to investigate the boundary effect and obtain the fracture properties over the ligament length in terms of FPZ development. Effects of FPZ height, length and width on fracture energy of concrete were investigated by Duan et al. [10,11] and Hu and Duan [12], respectively. Based on the bi-linear model for the local fracture energy distribution along the ligament [13], a formulation of concrete fracture energy, namely the smooth curve model, was proposed based on the assumption that local fracture energy is continuously and smoothly distributed along the ligament [14]. So far most research on boundary effect has been focused on the scenario when crack propagates near the back boundary of a concrete specimen which has also been extended by taking into account the variation of FPZ. Other studies on boundary effect have also been carried out on the critical stress intensity factor K_c. For instance, Cotterell and Mai [7,15] studied the size effect on the critical stress intensity factor K_c of cement paste specimens with the initial crack length-to-depth ratio (a_0/D) equal to 0.05. While studying the same circumstance as Cotterell and Maidid, Hu [13] predicted K_c which agrees well with that provided by Cotterell and Mai [7,15]. On the other hand, the asymptotic approach dealing with the size effect was developed to consider the influence of both the front and the back free surfaces of small sized specimens [10,11]. However, there is very limited research conducted on the variation of FPZ with the front boundary in scientific literature.

Meanwhile, the relationship between the cohesive stress and crack opening displacement in the FPZ is usually utilized to describe the softening behavior of concrete when simulating crack propagation in concrete. It should be noted that the variation of FPZ plays an important role on crack propagation in concrete. By considering the cohesive stress acting on FPZ, Xu and Reinhardt [16] and Reinhardt and Xu [17] studied the crack extension resistance (K_R) in terms of SIF based on the assumption that the length of FPZ keeps constant after FPZ is fully developed, i.e., the crack tip opening displacement (*CTOD*) exceeds the stress-free crack width w_0 in the softening traction-separation law for concrete. As a result, the K_R-curve rises monotonically with the increase of the ratio of the crack length to the beam depth, i.e., a/D. Adopting the same assumption about FPZ as that made by Xu and Reinhardt [16] and Reinhardt and Xu [17], Kumar and Barai [18,19] introduced the universal weight function to calculate K_R-curve [20] based on cohesive stress distribution during crack propagation. The size effect was observed from specimens with different sizes, especially during the unstable fracture stage. Furthermore, the effects of geometry and loading condition on the K_R-curve in concrete were discussed by Kumar and Barai [21,22]. However, many experimental and theoretical studies [23,24] have revealed that the FPZ length increases before FPZ is fully developed and decreases after that. It can be seen from various studies referenced above that the difference in methods determining the variation of FPZ can result in different results of concrete fracture property and so far there is no widely accepted conclusion on features of variation of FPZ in concrete in scientific community. Therefore, it has significance in studying the variation of FPZ during concrete crack propagation.

Accordingly, the main objective of this paper is to study the variation of FPZ during crack propagation in concrete. A crack propagation criterion is introduced to simulate the complete fracture process by utilizing the initial fracture toughness K_{IC}^{ini} as an inherent material property of concrete. Crack can propagate when the difference between the stress intensity factor, K_I^P, caused by the applied load and that, K_σ^P, caused by the cohesive force exceeds the value of K_{IC}^{ini}. Based on this criterion, numerical simulation is conducted on the complete fracture process of a series of concrete square plates with initial crack length to depth ratio a_0/D ranging from 0.05 to 0.9, and the length of slide ranging from 100 to 1000 mm. The variation of FPZ during crack propagation is analyzed and the effect of a_0/D on variation of FPZ length, especially after FPZ is fully developed, is discussed. After that, the proposed method is employed to derive K_R-curve for the complete fracture process, which takes into account the cohesive stress acting on FPZ.

2. Crack propagation criterion and experimental verification

2.1. Crack propagation criterion

Various experimental investigations have revealed that the fracture process of concrete experiences three different stages: (1) crack initiation; (2) stable crack propagation; and (3) unstable crack propagation. Based on the linear superposition theory, the stress intensity factor at the crack tip in a notched beam under three-point bending can be evaluated using the following simple relationship [25]:

$$K_I = K_I^P + K_I^\sigma \quad (1)$$

In Eq. (1), the stress intensity factor K_I^P caused by the applied load P can be directly calculated by using the quarter point singular element approach. K_σ^P is the stress intensity factor caused by the cohesive stress along FPZ. The superposition algorithm for calculating K_I^P and K_σ^P adopted in this research is illustrated in Fig. 1. The relationship between the cohesive stress and crack opening displacement in the FPZ can be used to describe the softening behavior of concrete. So far, several formulations have been proposed for this purpose to describe the softening traction-separation law i.e., softening stress (σ)-crack opening displacement (w) relationship of concrete which include linear, bilinear and nonlinear ones. In this paper, a bilinear formulation is chosen in the proposed numerical approach to describe σ–w relationship which is graphically shown in Fig. 2 and mathematically presented as follows:

$$\sigma = f_t - (f_t - \sigma_s)\frac{w}{w_s}, \quad 0 \leqslant w \leqslant w_s \quad (2)$$

$$\sigma = \sigma_s \frac{w_0 - w}{w_0 - w_s}, \quad w_s \leqslant w \leqslant w_0 \quad (3)$$

$$\sigma = 0, \quad w \geqslant w_0 \quad (4)$$

Using the approach proposed by Peterson [26], σ_s, w_s and w_0 can be determined as follows:

$$\sigma_s = f_t/3 \quad (5)$$

$$w_s = 0.8G_F/f_t \quad (6)$$