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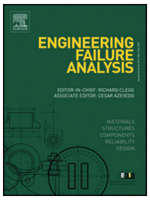

FPZ evolution of mixed mode fracture in concrete: Experimental and numerical

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ABSTRACT

Digital image correlation (DIC) technique is applied to study the evolution of fracture process zone (FPZ) of mixed mode fracture in concrete. By testing a series of beams of various sizes under four-point shearing, the opening and sliding displacements on the crack surfaces are derived using the DIC technique. Meanwhile, a numerical method is employed to simulate the fracture process by introducing a crack propagation criterion. The opening and sliding displacements on the crack surfaces obtained from numerical analysis exhibit a reasonable agreement with the experimental results, which verifies the DIC technique presented in the study. By combining experimental observations with numerical simulations, the evolution of the FPZ during the whole crack propagation process of mix mode fracture is investigated and elaborated in depth. The results indicate that the ratio of crack opening to sliding displacement remains approximately constant as crack propagates before reaching a peak load. Meanwhile, the FPZ evolution during the complete fracture process is influenced by the specimen ligament length and the ratio of mode I to II stress intensity factor component. With the decrease of ligament length and the ratio of mode I to II stress intensity factor component, the full FPZ length decreases. However, when the ligament length is less than 63 mm or ratio of mode I to II stress intensity factor component is less than 0.11, the FPZ cannot fully develop, but keeps increasing as crack propagates.

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1. Introduction

Macro-crack propagation in cementitious materials, such as concrete, is caused by the initiation, micro-crack coalescence, and development of the fracture process zone (FPZ), which usually exists ahead of the crack tip. The existence of the FPZ reflects the strain localization and nonlinear properties of quasi-brittle materials like concrete, which is essentially different from the scenario for brittle materials. As a consequence, some fundamental fracture properties of concrete, including fracture energy and critical

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fracture toughness, are affected by the evolution of the FPZ. Particularly, the applicability of linear fracture mechanics in structure analysis is determined by the FPZ length and structural size. Therefore, the study of FPZ properties in concrete has attracted great attention from science and engineering communities.

So far, most experimental and theoretical studies concerning the FPZ evolution of concrete have focused on mode I fracture. Wu et al. [1] conducted an experimental study on the FPZ development in beams of various sizes under three-point bending (TPB) and concluded that the FPZ length increases at the early stage of crack propagation while decreases after the FPZ fully develops. Dong et al. [2] developed a numerical method to study the FPZ properties by introducing the initial fracture toughness and pointed out that there are three cases for the variation of FPZ length depending on the initial crack ratios (a_0/H, where a_0 is the initial crack length and H is the specimen height). Skarżyński et al. [3] observed the shape and width of FPZ using a digital image correlation (DIC) technique and developed a numerical method [4] to explore the effects of characteristic length and aggregates size on the width and shape of the FPZ. The studies mentioned above provided quantitative information for deeper understanding of the non-linear behavior and explored the failure mechanism of concrete structures.

However, in many engineering structures in the field, e.g. gravity dams, the crack tip is usually under the mixed mode I–II stress condition rather than under a pure mode I stress condition [5]. In the case of mixed mode I–II fracture, the tensile and shearing combination stress field at the crack tip results in the cracking opening and sliding displacements during fracture process. Therefore, the FPZ evolution under mixed mode I–II fracture also affects the crack propagation trajectory and failure mode of concrete structures. To better understand the crack propagation of mixed mode I–II fracture in concrete, experimental and numerical studies have been conducted in previous decades. The single [6–8] and double notched four-point shearing (FPS) tests [9] were carried out to investigate structural responses, including cracking mouth opening and sliding displacements (CMOD and CMSD), loading point displacement and cracking trajectory. Later, the FPS beams with one/double notches became the benchmark for verifying the numerical method for the crack propagation analysis of mixed-mode fracture in concrete [10–14]. Meanwhile, to reflect the actual stress condition for concrete dams in service, model dam tests were carried out by other researchers [10,15]. Similar to the FPS tests, the macro-responses of the dams were targeted so that the load (P) vs CMOD/CMSD curves could be derived in the model experiments. Correspondingly, the experimental results were also employed for the purpose of mixed-mode crack propagation analysis using numerical methods [10,16,17]. However, it should be noted that the objectives of these experimental studies were to obtain the nonlinear behaviors of the structures at a macro-level, rather than to observe the micro-crack initiation and the FPZ evolution. In fact, from an in-depth insight into mixed-mode fracture mechanisms in concrete, the development of the FPZ reflects the cohesive characteristics and strain localization under complex stress conditions. Therefore, the research on FPZ properties provides scientific evidences for developing theoretical and numerical methods to study the fracture failure of concrete structures under complex stress field. The experimental results can also provide a promising way for verifying an analytical or numerical model.

With the development of more innovative optical measurement methods, DIC technique has been implemented to characterize the fracture process by providing a high-resolution measurement of the full-field displacements of cracking surface. It has previously been employed to study the crack propagation of mode I fracture [1,18,19], concrete-concrete interfacial fracture [20] and carbon fiber reinforced polymers (CFRP)-concrete interfacial fracture [21]. Regarding the mixed mode fracture in a single component, Lin et al. [22] studied the fracture process in quasi-brittle materials by taking sandstone as an example. For the case of concrete under mixed-mode fracture, to the best knowledge of the authors, no reported experimental study exists on FPZ evolution during the fracture process. Meanwhile, it should be noted that compared to mode I fracture, concrete under mixed-mode fracture exhibits higher brittleness, making it difficult to obtain a structure's responses at post-peak loading stage. Therefore, in this study, a combined experimental and numerical method is adopted to analyze the FPZ evolution of mixed mode I–II fracture in concrete. Firstly, the DIC technique is used to derive the evolution of FPZ until reaching the peak load. The crack propagation trajectory and opening/sliding displacements on the crack surfaces are recorded on FPS specimens with the same initial mixty ratio $K_{\mathrm{I}}/K_{\mathrm{II}}$. Here, K_{I} and K_{II} are the stress intensity factors (SIFs) for modes I and II, respectively. A numerical method is introduced to analyze the whole fracture process, which is verified by the results from DIC experiment. Finally, the FPZ evolution of mixed mode I–II fracture during a complete crack propagation process is discussed in depth based on the numerical results.

2. Experimental program

2.1. Specimen preparation and experimental setup

Four groups of beams with depths of 60, 90, 120 and 150 mm, respectively, were tested under FPS. The specimens with the asterisk in Table 1 were tested in combination with measurement by using the DIC technique. The geometry and loading arrangement of the beams are illustrated in Fig. 1. Here, H, B and L are the height, width and length of the beams, respectively; C, L_1 and C_1 are the distances from the two loading points and pre-notch, respectively, to the geometric center of the specimens. It should be noted that the initial mixty ratio $K_{\mathrm{I}}^{\mathrm{ini}}/K_{\mathrm{II}}^{\mathrm{ini}}$ is set as 1.6 for all the beams from all four-size groups by adjusting the pre-notch and loading positions (see Table 1). $K_{\mathrm{I}}^{\mathrm{ini}}$ and $K_{\mathrm{II}}^{\mathrm{ini}}$ are the SIFs of modes I and II, respectively, corresponding to the crack initiation.

The concrete mix proportions for this study were 1: 2.77: 4.16: 0.72 (cement: sand: aggregate: water) by weight and the maximum aggregate size was 10 mm. The measured material properties of concrete are as following: cubic compressive strength $f_{\mathrm{cu}} = 29.3$ MPa, splitting tensile strength $f_t = 2.54$ MPa, Young's modulus $E_c = 28.0$ GPa, Poisson's ratio $\nu = 0.18$, fracture energy $G_f = 138.6$ N/m, and initial mode I fracture toughness of $K_{\mathrm{IC}}^{\mathrm{ini}} = 0.56 \mathrm{MPa} \cdot \mathrm{m}^{1/2}$.

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