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An experimental investigation on the FPZ properties in concrete using digital image correlation technique

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ABSTRACT

This paper presents an experimental investigation on the properties of the fracture process zone (FPZ) in concrete using the digital image correlation (DIC) technique. Based on the experimental results, it is found that the FPZ length increases during crack propagation but decreases after the FPZ is fully developed. The FPZ length at the peak load and the maximum FPZ length increase with an increase in specimen height, but decrease by increasing the notch depth to specimen height ratio. It is also found that the crack extension length at the peak load is about 0.25 times the ligament length.

1. Introduction

The microcracking region ahead of the traction-free crack tip in concrete is defined as the fracture process zone (FPZ) [1]. Both the FPZ length and the crack opening displacement in the FPZ are essential for characterizing the fracture behavior of concrete. Much attention has been paid to the study of the FPZ for the following reasons. First, linear elastic fracture mechanics is invalid for concrete due to the existence of the FPZ [2] and the FPZ length is essential for predicting the failure of concrete members and for selecting the dimensions of test specimens [3]. Second, fracture energy is an important parameter for the fracture analysis of concrete and is closely related to the FPZ size [2]. This implies that the existence of the FPZ may be the intrinsic cause for the size effect of fracture energy [4,5]. Finally, the relationship between the cohesive stress and crack opening displacement in the FPZ is usually used to describe the softening behavior of concrete and to simulate the crack propagation path in concrete by the finite element method.

Various techniques, such as the acoustic technique [6], X-rays technique [6], moiré interferometry [7], and optical microscopy [8], have been developed to track the development of microcracks in concrete. Due to high sensitivity to the vibrations from testing machines, time-consuming, low measurement accuracy, or complicated specimen surface disposal in need of special expensive equipments, it is sometimes difficult to adopt these techniques under ordinary laboratory conditions. Digital image correlation (DIC) is an optical technique to visualize surface deformations by successive post-processing of digital images [9]. It provides three primary advantages over other techniques. First, the DIC technique is non-destructive and non-contact in measuring the displacement and strain in concrete so that the development of the FPZ is not interfered. Second, the images on the specimen surface are recorded and processed very conveniently and quickly, which makes displacement measurements possible for a large number of specimens. Finally, the DIC technique can be used for non-structured, random

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Nomenclature

a	crack length
a_0	notch depth
B	specimen thickness
f_t	tensile strength of concrete
G_f	fracture energy
H	specimen height
H_0	knife edge thickness
l_{FPZ}	FPZ length
P	load
P_i ($i = 1,2,\ldots,14$)	loading points
P_{max}	peak load
S	specimen span
u, v	displacements in the Y and X directions, respectively
w	crack opening displacement
w_0	stress-free crack opening displacement
X, Y	coordinates of rectangular coordinate system
Δa	crack extension length
Δa_c	crack extension length at peak load
σ	cohesive stress

patterns on the surface of the object [10]. Due to these advantages, the DIC has been widely applied to the study of concrete. Choi and Shah measured the lateral and axial deformations on concrete members subjected to compression [11]. Corr et al. studied the interfacial transition zone between aggregates and cement paste in plain concrete and investigated its softening and fracture behavior [12]. Huon et al. examined the thermo-mechanical behavior of concrete-like materials [13]. Similar studies can also be found in [10,14].

However, little work has been reported on the use of the DIC technique for characterizing the FPZ length. Therefore, it is necessary to study the properties of the FPZ by the DIC technique.

2. Digital image correlation technique

In the experiment, a digital camera with a resolution of 1024 × 768 pixels was adopted. Images were acquired once per second until the specimen failed. A host-computer was used to store the images for later analysis.

The DIC technique has been developed theoretically and experimentally by many researchers [15,16]. With this technique, the deformation analysis of specimens can be conducted by comparing the deformed images during loading with the reference image before loading. In deformation identification, a small part of the reference image is defined as the reference subset and the corresponding part on the deformed image as the target subset. The target subset can be searched by gray scale distribution. Thus, deformation measurement is transformed into digital correlation calculation and the displacements at the various points in the reference subset are obtained by subtracting the new coordinates from the original ones.

3. Specimen preparation and test setup

3.1. Specimen preparation

Concrete specimens were prepared with a standard P.O 32.5 Portland cement of a 28-day standard compressive strength higher than 32.5 MPa. Crushed stones with a maximum diameter of 8 mm and river sand were used as coarse and fine aggregate, respectively. The mix proportions are listed in Table 1. The measured compressive strength, Young's modulus, and Poisson's ratio of concrete were 42.9 MPa, 35.0 GPa, and 0.2, respectively.

Three point bending specimens as shown in Fig. 1 were tested in the experiment. For all the specimens, the span to height ratio S/H was 4 and the thicknesses B was 40 mm. Six types of specimens with different spans and notch depths as listed in Table 2 were cast to investigate the FPZ properties.

Table 1
Concrete mix proportions.

Water/cement ratio	Cement (kg/m^3)	Sand (kg/m^3)	Aggregate (kg/m^3)	Water (kg/m^3)
0.48	446	593	1102	214