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Investigation on fracture parameters of concrete through optical crack profile and size effect studies

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ABSTRACT

In this paper, Digital Image Correlation (DIC) technique has been used to map the full field of displacement and strain for visualizing the fracture growth, fracture propagation and formation of Fracture Process Zone (FPZ) in notched concrete beams under bending. Further, for exact quantification of concrete fracture parameters such as crack opening displacement, characteristics of FPZ and fracture energy, a new scheme called Optical Crack Profile (OCP) originated through DIC experiments, is developed. In addition, a comprehensive analysis of fracture parameters estimated from Bazant size effect laws, Jenq–Shah model and OCP technique have been carried out.

1. Introduction

Fracture in concrete, results from the coalescence of micro-cracks and formation of a Fracture Process Zone (FPZ) and further development of macro-cracks due to fracture propagation. Fracture propagation and strain localization is a fundamental phenomenon in cementitious materials [1–3]. Fracture in a quasi-brittle material like concrete, is always preceded by the formation of localized cracking zones of a certain width and length termed as FPZ. The width of the localized zones is not negligible compared to the cross-section dimensions of a concrete specimen and is large enough to cause significant stress redistribution in the structure [1,4]. FPZ is very complex since it consists of main cracks with various branches, secondary cracks and micro-cracks. This poses major problem in the design and durability of concrete structures because of the damage in concrete material under mechanical loading contributing to a significant degradation of material strength. In order to ensure the safety of structure, a qualitative description of the fracture mechanism is not sufficient. Perhaps, a complete altogether quantitative study on fracture energy, crack opening displacement, and FPZ size is required, which is still elusive and not commonly available in open literature [1–3,5,6].

In engineering structures, the strain measurements are extremely important because they help in investigating the full-fledged development of concrete fracture process zone. In-depth investigations are required to improve the study of the behavior of materials and structural components under mechanical loads. There exist various experimental methods such as holographic interferometry, the dye penetration, the scanning electron microscopy, and the acoustic emission, to detect the fracture process as reported in the literatures [7–9]. These methods provide the qualitative analysis on micro-features on concrete from which it is very difficult to detect the crack profile. Digital Image Correlation (DIC) experimental technique overcomes several limitations of the above-mentioned methods by providing detailed information on complex deformation

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Nomenclature

a	initial notch depth of beam
D	characteristic size or depth of beam
E	modulus of elasticity for concrete
S	span of beam
t	specimen thickness or thickness of beam
w	crack opening displacement
a_c	notch depth of beam at maximum load P_c
Bf_t	empirical parameter to be identified by optimum fitting of measured σ_{Nu}
c_f	effective length of fracture process zone
c_n	dimensionless coefficient
d_a	maximum size of aggregate in mm
D_0	(transitional structure size) empirical parameters to be identified by optimum fitting of measured σ_{Nu}
f_t	tensile strength of concrete
G_f	fracture energy
K_{Ic}	critical stress intensity factor
P_c	peak/maximum load of beam
w_c	critical crack opening displacement
W_h	self-weight of the beam
α_0	ratio of initial notch depth of beam depth
σ	bridging stresses
σ_{Nu}	nominal strength

states that lead to the initiation and propagation of fracture until complete failure. DIC technique is insensitive to massive rigid body motions, and can capture large deformations in a single measurement as long as the object remains in the field of view of the cameras [1–3,5,6]. In the present study, DIC experiment has been used to map the full field of displacement and strain for visualizing the fracture growth, fracture propagation and formation of FPZ in notched concrete beams under bending. However, the exact quantification of the concrete fracture properties i.e. fracture energy, crack opening displacement and FPZ characterization is not possible through DIC. For this reason, a new scheme of Optical Crack Profile (OCP) originated through DIC experiments, based on analysis and interpretation of strain, displacement and load data, is developed and presented in this paper.

The structural size effect is the most important issue in the fracture mechanics of quasi-brittle material like concrete. The size effect appears on the mechanical response of the concrete structures [4]. The elastic analysis with allowable stress, plastic limit analysis, or any theory based on strength limit, predicts the load capacity of structure in which the material failure criterion is expressed in terms of stress/strain. The load capacity of structure predicted using these theories is independent of the structure size, which came to be known as the case of no size effect. This is still assumed in most of the design codes and standards for concrete [4]. The size effect represents the deviation of actual load capacity of structure from the load capacity predicted by limiting strength based theories. It is characterized in terms of nominal strength representing the value of nominal stress at ultimate load. The size effect on structural strength in terms of the nominal strength σ_{Nu} of structure, which contains a parameter of maximum load P_c is described as:

$$\sigma_{Nu} = \frac{c_n P_c}{tD} \tag{1}$$

where D = characteristic size of the specimen or structure, t = specimen thickness and c_n = dimensionless coefficient. The plot of log σ_{Nu} vs. log D always gives a horizontal line according to the strength criterion, exhibit no size effect as shown in Fig. 1. The failure governed by Linear Elastic Fracture Mechanics (LEFM) exhibit a rather strong size effect, which is described by inclined line of slope $(-1/2)$ in Fig. 1. The reality for concrete structure is a transitional behavior illustrated by the solid curve. With this introductory remark, it is thus important that size effect law be established with a systematic evaluation of important fracture parameters through OCP. The paper presents the salient

With this introductory remark, it is thus important to perform the systematic evaluation of important fracture parameters through the established size effect laws and OCP. The paper presents salient results of OCP obtained during standard RILEM three point bend specimen fracture tests, which has been shown to be useful to address the size effect of quasi-brittle material.