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Experimental and numerical analysis of crack evolution in concrete through acoustic emission technique and mesoscale modelling

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ABSTRACT

In this paper, the fracture process zone (FPZ) is investigated on unnotched and notched beams with different notch depths. Three-point bending tests have been realized on plain concrete under crack mouth opening displacement (CMOD) control. Crack growth is monitored by applying the acoustic emission (AE) technique. The comparison with a numerical model is also realized by using a mesoscopic approach. Such an approach is of particular interest in the analysis of interactions between the cementitious matrix and aggregates. Several AE parameters are examined during the entire loading process, and show that the relative notch depth influences the AE characteristics, the process of crack propagation, and the brittleness of concrete. The numerical load–CMOD curves show that the mesoscopic modelling reproduces well the notch effect and concrete failure. In order to improve our understanding of the FPZ, the width and length of the FPZ are followed based on the AE source locations maps in parallel with the numerical damage fields. An important energy dissipation is observed at the crack initiation in unnotched beams.

1. Introduction

Fracture of concrete is accompanied by the formation and evolution of an inelastic zone, referred to as the fracture process zone (FPZ), around the propagating crack tip. The existence of the FPZ is responsible of the nonlinear behaviour of concrete, and leads to complex phenomena like size effects. In fact, the length and the width of the FPZ are strongly influenced by the sizes of specimens/structures. Many researchers tried to characterize the FPZ and its evolution during crack extension in order to obtain size independent fracture parameters for the application of fracture mechanics of concrete. For Hillerborg et al. [1], the length of the FPZ was related to the length of cohesive zone or the characteristic length which is a pure property of the materials, while Bazant [2] modelled the FPZ as a band with a fixed width related to the size of aggregates in concrete.

The objective of this paper is to characterize the FPZ and its evolution during the fracture process in unnotched and notched concrete beams with different notch depths based on the AE technique and finite elements calculations. Recently,

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Nomenclature

$\tilde{\underline{\underline{\sigma}}}(\underline{y})$	effective stress tensor components
$\underline{\underline{\sigma}}(\underline{y})$	stress tensor components
$\underline{\underline{\varepsilon}}^e$	elastic strain tensor components
ε_{eq}	equivalent strain
$\underset{\sim}{C}^0(\underline{y})$	initial stiffness tensor components
$\underset{\sim}{C}(\underline{y}, \underline{\underline{\varepsilon}}(\underline{y}))$	stiffness of the damaged material tensor components
d	damage variable
E	elastic modulus
f_t	tensile strength
G_f	fracture energy
B_t	parameter of the damage evolution law
h	finite element size
ε_{d0}	strain threshold
$C_Z(\vec{h})$	three-dimensional covariance
s_d	standard deviation
h_{ij}	coordinates of the vector $\vec{h}$ linking two points

various experimental methods have been employed to detect the fracture process: the holographic interferometry, the dye penetration, the scanning electron microscopy, the X-rays, the digital image correlation, etc. However, these methods offer either the images of the material surface to observe micro-features of the concrete with qualitative analysis, or the black-white fringe patterns of deformation on the specimen surface (except for 3D tomography), from which it is difficult to observe profiles of the cracked material. In the present work, the growth of the fracture zone is examined using the AE technique. This latter allows us a continuous real-time data acquisition, and thus the damage evolution during loading tests can be recorded. The AE technique is a passive method that has been proved to be very effective to locate microcracks and to study different failure modes in concrete structures [3–6]. It presents a remarkable potential of applications, and has been used in the past to examine the influence of different parameters on the FPZ, such as the effect of aggregates [7,8], porosity [9], creep [10,11], notch depth [12], specimen geometry and type of loading [13]. The damage is then evaluated based on either statistical analysis and measurement of AE activity [14] or quantitative and signal-based techniques [6].

Several numerical models were capable to capture important characteristics that emerge in failure process and AE measurements [15–17]. A thorough investigation is here performed on this subject by modelling the behaviour of concrete at the mesoscopic scale. The mesoscale modelling presents many advantages in the understanding of the fracture process (i.e. the transition from diffuse damage to localized damage and final discrete failure) and the effect of concrete heterogeneities (size, volume fraction, shape of aggregates...) and mechanical characteristics of the components on macroscopic properties and the fracture behaviour of concrete [18–20]. In particular, the multi-scales approach was found to be very useful to study the size effect on the strength of plain concrete structures [21–23]. In the present paper, the damage model used is the isotropic damage model developed by Fichant et al. [24], which is implemented in the finite element code Cast3m.

In Section 2, experimental methods and damage model are presented. Then, fracture measurements are analysed, and the characterization of crack evolution at different loading stages is examined through AE technique and mesoscopic modelling. Finally, the effects of both the notch to depth ratio and size effect on fracture growth are described based on the experimental and numerical observations.

2. Experimental procedure

2.1. Materials and specimens

The experiments were realized by Grégoire et al. and reported in [25]. In the present work, the comparison between notched and unnotched beams is realized. The tests realized on notched beams were conducted on beams with depth of 200 mm, length of 700 mm, and effective span equal to 500 mm. Two notch to depth ratio values of 0.2 and 0.5 were considered and labeled SN200 and LN200, respectively. Tests realized on unnotched beams were conducted on beams with the same sizes as earlier (labeled UN200) and on beams with depth of 100 mm, length of 350 mm and effective span equal to 250 mm (labeled UN100). The thickness was kept constant for all the beams and equal to 50 mm.

Tests were conducted under closed-loop crack mouth opening displacement (CMOD) control. The CMOD measurement consists in recording the distance between two alumina plates glued on the bottom surface of the beam, on each side of the initial notch. For unnotched beams, the alumina plates were glued at a distance from midspan equal to half the depth of the beam because the location of the fracture process zone initiating from the surface was indeterminate (details may be found in [25]).