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Fracture examination in concrete through combined digital image correlation and acoustic emission techniques

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HIGHLIGHTS

- Image correlation and acoustic emission techniques are simultaneously applied.
- Acoustic energy analysis is performed to find the size of fracture process zone.
- Evolution of fracture process zone by both techniques are compared and analyzed.
- Size effect is discussed on the growth of fracture process zone.

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ABSTRACT

In order to build sustainable structures, the study of mechanical behavior must integrate with local phenomena, e.g. fracture propagation and localization zone. Fracture in concrete usually develops in the form of localized zone of microcracks which then coalesce into macrocrack of significant crack openings. In this paper, fracture process in geometrically scaled concrete beams under bending test is analyzed. Acoustic emission (AE) and digital image correlation (DIC) techniques are simultaneously applied to identify fracture parameters such as crack openings and size of fracture zone. The AE technique is useful to identify the location of fracture growth due to microcracks and macrocrack, however, DIC is useful to measure crack openings at various locations of crack. The location of crack tip is also estimated from both techniques. It is observed that the two techniques in coupled position proved effective in identifying the fracture process zone and cracking mechanisms of concrete.

1. Introduction

Cracking in concrete is a major problem in the design and durability of concrete structures. Various experimental methods already employed to detect the fracture process as the holographic interferometry, the dye penetration, the scanning electron microscopy, the acoustic emission, etc. Such 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, from which it is difficult to observe profiles of the cracked material.

In this study, growth of fracture zone is investigated using synchronized and simultaneous observation with the digital image correlation (DIC) and acoustic emission (AE). Both techniques allow a continuous and a real time data acquisition and thus the damage evolution during the load test can be recorded. The AE technique is a passive method that has been proved to be very effective to locate microcracks and sometimes measure fracture process zone (FPZ) inside the concrete structure [1–4]. It presents a large potential of applications and has been used in the past to study influence of different parameters on FPZ, such as effect of aggregate [5–7], porosity [8], the specimen geometry and type of loading [9]. The damage is then evaluated based on statistical analysis and measurement of energy or the number of AE events [10–12]. However, the spatial distribution of damage has not been precisely located.

DIC technique gives high resolution measurement of the surface displacement field. Based on this later, the fracture lengths and the cumulative crack openings of microcracks present in the FPZ can be easily determined [13–18]. Even so, this method is only limited to the surface of the specimen which does not really represent the population of cracks inside the specimen and inaccessible areas are

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still unknown. Also displacement field is incapable to give information about the development and size of fracture process zone. Therefore, it is interesting to apply simultaneously DIC and AE techniques. Aggelis et al. [19] have recently used this method to analyze the effect of reinforcement on the cracking in reinforced concrete. The recent work of Rouchier et al. [20] has also investigated the simultaneous use of digital image correlation and acoustic emission for the monitoring of progressive damage development in fiber reinforced mortar.

In case of quasi-brittle materials such as concrete, problem of the size effect appears on the mechanical response of the structures. The nominal strength decreases with the increase in size of structure and extrapolation from laboratory specimens to real structures is a major question [21]. In order to improve our understanding of the fracture process and reduce the ambiguity in the modeling of the size effect, local quantities such as the spatial distribution of microcracking and fracture measurements such as fracture process zone size and crack openings patterns are interesting to measure at the same time on a single test. This can be done by simultaneous application of DIC and AE techniques.

In the light of the above mentioned facts, the main objective of this paper is to present an experimental approach to study the evolution of fracture process zone size and crack openings in scaled concrete beams by comparing and correlating the results obtained from DIC and AE technique. In the following, at first material and experimental methods are presented. Secondly, fracture measurements are made and analyzed at important loading stages with simultaneous AE and DIC techniques. Finally, the size effect on fracture growth is described based on the experimental observations.

2. Experimental program

2.1. Materials properties

ASTM type I cement with 28 days strength of 52.5 MPa was used. Coarse aggregates were crushed limestone with maximum size of 20 mm and fine aggregate were crushed fine sand of maximum size not greater than 4 mm. The mix proportion is shown in Table 1. The mechanical properties of concrete were determined at 28 days on three $\varnothing 110 \times 220$ mm^2 cylinders with a compressive strength (f'_c) of 45 MPa, a tensile strength (f_t) of 3.5 MPa assessed through splitting tests and a dynamic elastic modulus (E_{dyn}) of 38 GPa determined with a non-destructive method (Grindosonic®).

2.2. Specimen preparation

Three sizes of specimens, geometrically similar in two dimensions, were prepared. The dimensions of the beams were selected in accordance with RILEM recommendations [22] of size effect method. The beams are classified into three classes depending upon their dimensions and are designated as $D1$, $D2$ and $D3$ for small, medium and large sizes respectively. The cross section of the specimens was rectangular and the span to height ratio was $l/D = 3{:}1$ for all the specimens (Fig. 1). The cross sectional heights (D) of the specimens were 100, 200 and 400 mm respectively. The thickness (or third dimension, b) was kept constant equal to 100 mm for all the sizes. The beams were notched at mid-span for constant notch length to specimen height ratio (a/D) of 0.2 for all the beams. The notch was created using a non stick rigid Teflon strip of 3 mm thickness, placed into the mould before pouring of concrete. The strip was removed with care after initial curing period of 24 h at 20 °C. The beams were covered with a plastic sheet during the initial curing period to avoid the surface evaporation and autogenous shrinkage cracks. The beams were then kept completely submerged for 28 days in a lime water chamber controlled at 20 °C.

Table 1
Concrete mixture proportions.

Constituents	Dosage (kg/m^3)
Coarse aggregate (5–20 mm)	1100
Sand (0–5 mm)	820
Cement (Portland 52.5 N)	312
Water	190

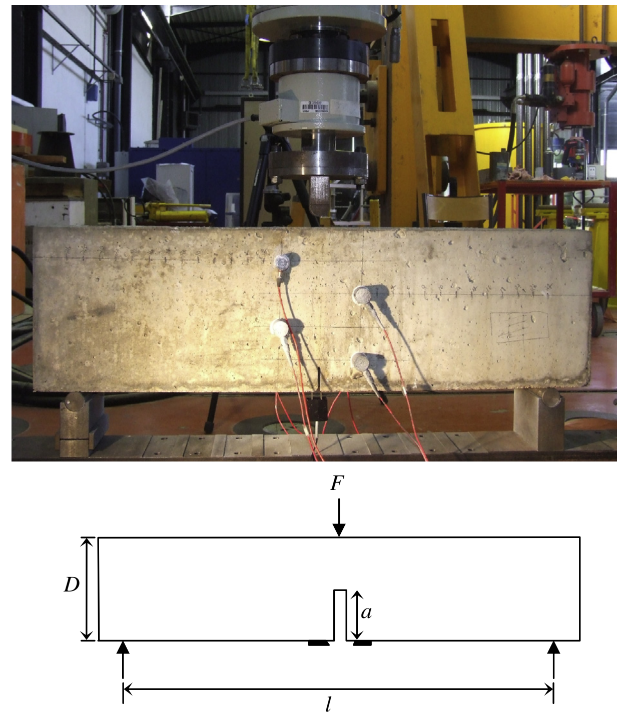

Fig. 1. Experimental setup.

2.3. Procedure for the three-point bending test

The fracture test employs a universal testing machine as per RILEM-TMC50 recommendations. Tests were conducted on a 160 kN capacity servo-hydraulic machine under closed-loop crack mouth opening displacement (CMOD) control. The load was applied with a CMOD rate of 0.05 μm/s using a CMOD gauge. Minimum number of three beams for each class was tested to study the variation of experimental results. During each test, load, crosshead displacement and CMOD were measured and recorded up to final failure with a data acquisition system. A general view of the experimental setup is provided in Fig. 1.

2.4. Digital image correlation

The digital images were acquired continuously as the specimen was loaded. Two digital cameras with 75 mm macro lens were mounted to capture images of both faces of the beam. The digital cameras have a resolution of 1040 × 1392 pixels and give 256 levels of gray output. Two series of tests were performed. In the first series, the cameras are mounted in order to image an area of approx. 60 × 100 mm above the notch of beam. At this location, notch opening and initial crack profile were captured. For this resolution, one pixel in the image represents approx. 35 μm square on the specimen, which is considered sufficient to determine a displacement measurement with 2 μm accuracy [23].

In the second series, the cameras were mounted at a distance required to observe the full height of specimen (except for $D3$). Thus the resolutions obtained for each size of specimen were 1 pixel = 105 μm for $D1$, 1 pixel = 180 μm for $D2$ and 1 pixel = 288 μm for $D3$ specimens. Four lamps, two on either side were used to improve the luminosity of the images. The images were taken at a rate of 6 images per minute for each camera. The images were stored in the system and were analyzed afterwards. The resolution of the system depends directly on the distribution of gray levels which depends on the texture of the material. A speckle pattern of black and white paint was sprayed onto the surface of specimen to improve the displacement resolution.

2.5. Acoustic emission (AE) method

The AE system comprised of an eight channel AEWin system, a general-purpose interface bus (2 × PCI-DISP4 having 4 channels each) and a PC for data storage analysis. A 3D analysis with an AEWin algorithm is performed for the localization of AE events. For the source to be located in 3D, a wave must reach at least five sensors. In this study, 8 piezoelectric sensors of type R15a were used all having same frequency range of 50–200 kHz and the same resonance frequency of 150 kHz.