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A detailed study of crack propagation in cement-based fibre composite beams under bending

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Abstract

Multiple cracking of beams made of cement-based composite was extensively studied by means of a suitable non-contact measurement technique. Images of a grid-pattern bonded onto the surface of a tested specimen were captured by a digital camera. Image processing by means of an appropriate software provided the displacement field within the zone under investigation. Cracks were revealed by discontinuities in the displacement field. Results are presented for three specimens tested in three- or four-point bending. Location, actual length and width are easily and precisely determined for each of the cracks within the zone under investigation. High sensitivity, early crack detection and no need to anticipate crack location are among the main features of this full-field measurement method. Crack propagation is derived from crack diagrams obtained at successive loading levels. Initial length, spacing, opening, propagation and profile of cracks are discussed in terms of mode of loading and bond properties of the material.

Keywords: Cement-based fibre composite; Crack propagation; Full-field measurement; Grid method; Image analysis; Multi-cracking

1. Introduction

The last decades have seen many developments in the composition of cement composites which has led to significant improvements of their mechanical properties. Due to fibres, these composite materials present an interesting feature: they exhibit an elasto-plastic response instead of the brittle response of the plain matrix. Moreover, their mechanical properties can be tailored, within a certain range, to the requirements of the designers. Cracking and crack propagation are key issues to better understand the relationship between certain macroscopic mechanical properties and microstructure. Indeed, the cracks directly cause the degradation of the stiffness, and they directly influence the plastic part of the stress/strain response. Cracking has therefore been studied extensively in the literature, but suitable techniques are required to analyse this phenomenon. For instance, image analysis is an efficient tool to highlight microcracks and some microdefects which appear on the surface of the specimens under investigation either in two dimensions [1] or in three dimensions [2]. Such a technique is used to characterize microcracks, namely those cracks with width less than about 10 μm. Microcrack morphology in terms of width, profile, length, orientation or density can be determined with image analysis, but the use of a microscope is often required in this case. The size of the field to be analysed is therefore limited for obvious practical reasons.

Full-field measurement techniques such as holographic interferometry [3], speckle [4], grid method [5]

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and image intercorrelation [6] provide larger field information. They are therefore suitable for studying heterogeneous materials. In a pioneering work, Dantu [7] measured stress and strain variations in concrete under compression covered with photoelastic coating, but experimental results were processed by hand. Nowadays full-field measurement techniques are coupled with image acquisition by a camera and computerized image processing, leading to efficient tools which can be used to investigate heterogeneous materials and to characterize macrocracks with widths of some tens of micrometers and length of some millimeters. Displacement contours are thus available over a large part of the surface of the specimen *during* a mechanical test. For instance, this feature has been used to analyse the fracture process zone ahead of a crack tip in concrete [8]. A crack appears as a discontinuity in the displacement field. It can be detected provided that its width is greater than the resolution of the method, which depends in practice on several parameters among which are the size of the field, the sensitivity of the camera, and the capabilities of the programme that processes the images. In conclusion, full-field techniques are well suited to study cracking and crack propagation.

Such a technique has been used in the present work to investigate cracked zones in beams made of cement-based fibre composites and loaded in three- or four-point bending. The experimental procedure and the tested specimens are described in the first part of the paper. Results in terms of crack characterization are then presented and discussed. The results highlight the capabilities of full-field measurement techniques to obtain relevant information on the cracking response of cement-based composites.

2. Experimental set-up

2.1. Specimens and materials under investigation

A series of beams were tested under three- and four-point bending. The specimens were made of a *Ductal*® fibre reinforced cementitious composite. This ultra high performance material is expected to exhibit elevated strength and high ductility in compression and tension. It is made of a special cementitious matrix reinforced with metallic fibres. The maximum size of the aggregates does not exceed 0.5 mm, while the fibres are 0.2 mm in diameter and 13 mm in length.

Two types of materials exhibiting different mechanical properties were studied. The cementitious matrix of the first material (called hereafter "Material 1") was optimized in terms of rheological properties. The constitution of the matrix of the second ("Material 2") was purposely modified to reduce the bond conditions between fibres and cementitious matrix, and therefore modify the cracking properties of the composite. The fibre volume fraction was about 2% (160 kg/m^3) and the fibres were randomly distributed in the fresh mixture during preparation. The specimens were prepared and provided by the Lafarge Research Center. No more information was available about specimen preparation.

Table 1
Types of tests and specimens

Specimen	Material	Type of test	Notch
A	1	Four-point bending	None
B	1	Three-point bending	$1 \times 10\,\text{mm}^2$
C	2	Four-point bending	None

The specimens were 280 mm long, and 70 mm × 70 mm square in cross-section. A 10 mm × 1 mm initial notch was machined beforehand in the specimens to be tested in three-point bending. The objective in this case was to initiate and to concentrate the cracks in the mid-span region of the specimens. The difference between the mechanical responses of both materials was expected to be detected and characterized using a full-field measurement technique. The types of tests and specimens are listed in Table 1.

2.2. Full-field measurement technique and preparation of the specimens

The technique used in the present study is based on the grid method developed by Surrel [5,9]. It involves the analysis of the deformation of a grid bonded onto the surface of a specimen under test. It requires a digital camera which captures images of the deformed grid at specified levels of loading of the specimen. The images are stored in a computer. Image-files are finally processed by means of an appropriate software in order to obtain the displacement field of the zone under investigation. The software, called *Frangyne*, was also developed by Surrel [10]. It is suited to the detection of very small variations of the pitch of the grid caused by a deformation of the surface. The principle of this method has been described in recent papers (see Ref. [11] for instance). It is therefore not reviewed here.

The specimens were prepared as follows. A transferable grid pattern of *Mecanorma* type was first bonded onto one external side surface of the specimen to be tested. The pitch of the grid was 0.571 mm. The size of the grid was 120 mm × 70 mm (120 mm × 60 mm for notched beams) as shown in Fig. 1. Since the cracks were expected to be roughly vertical, the grids were bonded in such a way that the stripes were perpendicular to the longitudinal axis of the beam in order to measure the longitudinal component of the displacement field. A crack induces a discontinuity in the longitudinal displacement (called hereafter *x*-displacement), which can