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Damage monitoring in fibre reinforced mortar by combined digital image correlation and acoustic emission

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HIGHLIGHTS

- ► The development of fractures in a cementitious composite is observed.
- ► Digital image correlation and acoustic emission (AE) were simultaneously performed.
- ► Optical measurements allow a reliable quantification of all ranges of fractures.
- ► AE are interpreted on the basis of to the comparison of both techniques.

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ABSTRACT

The present work aims at developing a methodology for the detection and monitoring of damage and fractures in building materials in the prospects of energetic renovation. Digital image correlation (DIC) and acoustic emission (AE) monitoring were simultaneously performed during tensile loading tests of fibre reinforced mortar samples. The full-field displacement mappings obtained by DIC revealed all ranges of cracks, from microscopic to macroscopic, and an image processing procedure was conducted as to quantify their evolution in the course of the degradation of the samples. The comparison of these measurements with the acoustic activity of the material showed a fair match in terms of quantification and localisation of damage. It is shown that after such a calibration procedure, AE monitoring can be autonomously used for the characterisation of damage and fractures at larger scales.

1. Introduction

The ageing of building materials and components has many repercussions on their mechanical, hygric and thermal properties: damaged materials are more permeable to moisture which may increase degradation, cause mould problems, bring health problems or form thermal bridges, sinking the overall energetic performance of the building. In order to properly estimate the overall performance of existing buildings in the prospects of energetic renovation, one must dispose of a reliable way to characterise damage and fractures in such materials. There is a high interest in extending the use of non-destructive damage observation to the case of building materials, in order to help decision processes for maintenance. Moreover, because of environmental concerns, building facades tend to include multi-layered components such as outer thermal insulation, of which durability must be assessed. In such cases, damage monitoring aims at preventing the degradation of hygrothermal properties.

Imaging techniques for crack detection include X-ray radiography and tomography [1] for three-dimensional fracture observation [2] or propagation monitoring [3]. The detection of pre-existing cracks can be facilitated by impregnation techniques [4] allowing their automatic detection and quantification [5] by microscopic examinations. While these techniques may have a good resolution and precision, they are limited in terms of specimen size and thus not applicable on the building scale. Another possible method for such large scale applications is the recording of elastic wave velocities, which can for instance be applied to durability studies or to repair work assessments [6].

Displacement mapping techniques are applicable to damage monitoring, and consist in measuring local displacements of a sample during its deformation. Electronic speckle pattern interferometry [7,8] and digital image correlation (DIC) [9] are optical

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non-destructive techniques and can be used for the observation of the progressive crack development, or more generally of two-dimensional strain mapping. Optical methods have also been recently extended to three-dimensional displacement and strain fields [10,11].

A third category of damage monitoring methods includes the recording of acoustic emissions (AEs). In a material under loading, elastic waves are emitted as a consequence of crack initiation and propagation. Recording and analysis of acoustic activity is of great importance in the fields of civil engineering and material sciences. Among others, it has been used for damage estimation of concrete [12–14], identification of damage mechanisms [15–19], estimation of the fracture energy [20] or failure prediction [21–23].

Acoustic emission and other wave propagation measurement techniques are the most preferable methods for large scale damage monitoring, but the interpretation of recorded waveforms requires preliminary studies. Digital image correlation and acoustic emission recording were simultaneously performed during tensile loading tests of fibre reinforced mortar samples. The methodology aims at correcting the downsides of two techniques by combining them: the applicability of optical techniques hardly extends to field studies, while the interpretation of AE measurements is difficult without a view of the crack evolution. A methodology is presented, that allows interpreting acoustic signals on the basis of a previous characterisation. Mortar samples were loaded by uniaxial tension while the local displacements of their surface were monitored by a camera, and the acoustic activity was recorded by sensors placed around the damaged area. By correlating the data gathered by the two techniques during this lab experiment, it is possible to interpret in field AE measurements with more clarity. The main target is therefore to calibrate the AE technique, so that it can be autonomously used for damage monitoring of building components.

2. Methodology

2.1. Experimental setup

The studied material is a commercial formulation (Lafarge, MAITE monocomposant) used for external thermal insulation composite systems. It is a Portland cement mortar including dry redispersable polymer systems with a water to dry material weight ratio of 0.16 and reinforced with 1% weight of glass fibres. The purpose of the fibres is to improve the ductility of an originally fairly brittle material. A more complete explanation of the elaboration procedure was presented in [24]. The material was cast into prismatic samples of 500 g and dimensions $300 \times 100 \times 10$ mm, kept 2 days at a 90% relative humidity and 21 days at 50% RH. Granulometric analysis of this material has been presented by Chalencon et al. [25], along with a thorough description of its behaviour during hydration. It has already shown an ability for multi-cracking [11], and is thus expected to facilitate the progressive visualisation of crack patterns.

The prismatic samples were notched as to ensure stress concentration on a relatively small area during mechanical loading, on which the observation was focused. Tensile loading was applied along the vertical axis, using a 5 kN force cell imposing a constant displacement speed of 1 mm/min. The tests were carried out until complete failure of the specimen. The setup of the samples and of the observation equipment is displayed in Fig. 1.

The experimental setup includes a CCD camera with a fixed 2.8 focal ratio, focused on the surroundings of the notch. Because of the shallow depth of field of the camera in this configuration, the focus is manually fixed as to prevent an automatic adjustment of the lens during the tests. The camera was positioned as to cover an observation zone of 101×67 mm with a spatial resolution of 22 μm/pixel. A non-uniform speckle pattern was applied on the specimen surface with a black paint spray as to facilitate the procedure of the correlation algorithm: this ensures that the initial grey-scale level distribution. Pictures were taken at time intervals of 5 or 10 s in order to allow computation of the displacement mappings during successive stages of loading. The camera was used as an optical extensometer to monitor the macroscopic strain in the direction of loading. The material presents some ductility before the peak of loading [24], followed by a strain-softening behaviour during which crack propagation is slowed by the presence of fibres. This behaviour facilitated the process of progressive damage monitoring by acoustic and optical measurements.

In addition to the optical monitoring apparatus, four Micro-80 acoustic sensors were placed around the monitored area of the specimen, continuously recording the AE activity during damage and fracture propagation. The sensors form a

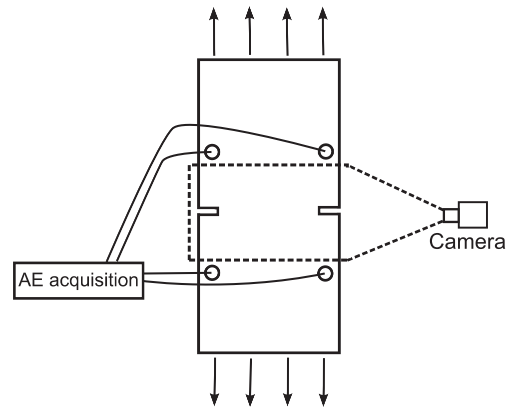

Fig. 1. Experimental setup for tensile loading and damage monitoring.

80×70 mm (height $\times$ width) area and are connected via pre-amplifiers to a MISTRAS data acquisition system. They have a diameter of 8 mm, and are characterised by the position of their centre. The settings of the AE recording setup are detailed below.

The methodology has been applied on a series of samples, 6 of which showed suitable for data interpretation (i.e. stress concentration and fracture occured in the observation area). Results are presented in two parts: first (Section 3), the ability of digital image correlation for the observation of fracture patterns is assessed. Strain mappings are calculated by the DIC algorithm and a procedure is explained for observing the evolution of crack size distributions during tensile tests. In the second part (Section 4), these optical measurements serve as a basis for the interpretation of AE recordings. Measurements performed on all samples were used to establish the ability of AE to quantify, locate and identifty damage and fractures.

2.2. Digital image correlation

Optical techniques such as DIC are non-destructive and therefore do not disturb eventual further testing on the samples. DIC provides a full map of the deformations at the surface of a specimen and allows following the fracture development without restriction of number or size of the cracks. It also presents the advantage of being easily implemented into most experimental setups, requiring no strict operating conditions or time consuming preparation, nor does it require gauges in contact with the specimen which might interfere with the experiment. The technique enables full field measurements of the local displacements of a sample's surface. It has been used for the estimation of stress intensity factors near crack tips [26,27] or the identification of elastic properties [28] or damage laws [29], among other uses. The technique has been proven suitable for the observation of local displacements of brittle building materials such as concrete [30–32]. The principle of DIC is briefly summed up below. For a more complete view of its theory and applications, one can refer to a recent book on the subject [33].

The principle of digital image correlation is the conservation of the optical flow between two pictures of a specimen, taken at different stages of its deformation [9]: it lies on the assumption that two consecutive images contain the same total amount of each grey-scale level, and are only distinguished by their spatial distributions. The planar displacement $\mathbf{u}(\mathbf{x})$ at each pixel of coordinates $\mathbf{x}$ of a surface is defined as:

$$g(\mathbf{x} + \mathbf{u}) = f(\mathbf{x}) \tag{1}$$

where f is the distribution of grey-scale level, or the texture, of a reference image, typically taken at the start of the mechanical loading, and g is that of a deformed image. Eq. (1) means that the grey-scale level of a pixel of coordinates $\mathbf{x}$ on the initial image f is equal to that of a pixel of coordinates $\mathbf{x} + \mathbf{u}$ on the final image g, i.e. that this pixel has been displaced by a vector $\mathbf{u}$. The exact displacement field $\mathbf{u}(\mathbf{x})$ can generally not be explicitely calculated without additional assumptions of regularity. In the prospects of the numerical resolution of Eq. (1), the functional ϕ, operating on displacement fields, is defined:

$$\phi(\mathbf{v}) = \int\int (g(\mathbf{v} + \mathbf{x}) - f(\mathbf{x}))^2 \mathrm{d}\mathbf{x} \tag{2}$$

where $\mathbf{v}$ is an approximation of the solution $\mathbf{u}$, and is constructed as a linear combination of functions v_i:

$$\mathbf{v}(\mathbf{x}) = \sum N_i(\mathbf{x}) v_i \tag{3}$$

where N_i are chosen basis functions (typically bilinear functions of $\mathbf{x}$). The target is to determine the best possible approximation by minimising the value of ϕ on all elements of the grid. Assuming a certain smoothness of the investigated displacement field, g is replaced by its first-order Taylor expansion in Eq. (2), resulting in: