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Bending fracture of textile reinforced cement laminates monitored by acoustic emission: Influence of aspect ratio

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HIGHLIGHTS

- Application of acoustic emission (AE) to an innovative construction material: textile reinforced cement (TRC).
- Monitoring the different fracture mechanisms of TRC under controlled experiments.
- Direct relation of AE parameters to the applied stress field.

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ABSTRACT

Textile reinforced cement based composites (TRC) are a new class of sustainable construction materials with superior tensile strength and ductility. These materials have the potential for becoming load bearing structural members, therefore a wide array of structural and non-structural applications are possible. However, their heterogeneous, laminated, fibrous nature complicates the understanding of their fracture behavior. During bending, the developed stresses lead to the activation of damage mechanisms like matrix cracking, fiber pull-out delamination and in succession or in overlap. In this study, the flexural behavior of TRC laminates is monitored by acoustic emission (AE). AE sensors record the elastic waves radiated from the damage sources and enable the characterization of the fracture behavior in any stage. The aim is to examine if AE is sensitive enough to provide feedback on the applied stress field in such heterogeneous systems. Therefore, the three-point bending span is varied to modify the stress field and specifically the proportion of shear to normal stress. AE waveform parameters like duration and frequency reveal information about the mode of fracture for the different spans, while the stress field is derived by a finite element model (FEM). The results show that AE is suitable to characterize the stress field even from the early loading stages, monitor the corresponding damage mechanisms and provide valuable feedback to the material modeling.

1. Introduction

Acoustic emission (AE) is a technique used widely for structural health monitoring purposes of several types of structures. Piezoelectric sensors are mounted on the surface of the material or structure and record the motion of the surface under the elastic excitation of the cracking sources [1]. The rate and the characteristics of the received signals are strongly dependent on the damage process and enable the monitoring of fracture, corrosion and healing in cementitious materials [2–5]. Though AE is already a part of structural health monitoring procedures [6,7], this is based mostly on the activity rate and amplitude parameters, which are certainly indicative of the severity of the ongoing fracture. However, in most of the cases, fracture comprises of different mechanisms which are successively or simultaneously activated as the material is led to ultimate fracture. Therefore, characterization of the type of fracture, can supply much more information concerning the damage stage. Different fracture processes like for example concrete matrix cracking and debonding of external reinforcing patches, or pull out of steel fibers have a distinct AE signature enabling the characterization of the fracture stage in real time [8,9]. Additionally, the dominant mode of fracture within the cementitious matrix (classified mainly in tensile and shear events), can be characterized based on waveform descriptors [10–12]. A typical AE waveform is seen in Fig. 1. The important parameters include the amplitude, A, the rise time, RT, the RA-value which is RT divided by A. RT and RA are well related to the cracking mode, and specifically obtain low values for tensile phenomena and higher for shearing either in the form of

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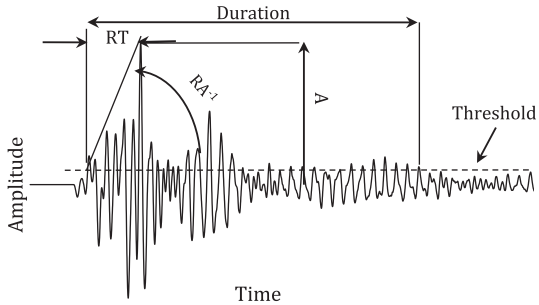

Fig. 1. Typical AE waveform.

delaminations and pull-out [8,9] or cracking due to shear stresses [12,13]. This is connected to the elastic wave modes which are excited by the direction of displacement of the crack sides [14]. The "energy" as measured by the envelope of the waveform is also used for characterization of fracture events [15]. Frequency content is measured by the average frequency, AF, which is the number of threshold crossings (counts) divided by the duration and the peak frequency, PF, which is the frequency component with the highest magnitude in the frequency domain. According to the "moment tensor analysis" [16,17], the identification of the fracture mode of the cracks emitting a signal is theoretically and experimentally possible. However, this requires at least six sensors recording each event, which is not practical in all cases, while in thin laminates it cannot be applied due to the dispersion of the waveform, which masks the original characteristics of the wave front. This is why a simpler characterization is attempted in cementitious media [18]. It is based on a simple two-dimensional plot of the AE characteristics. Tensile-like signals which exhibit higher frequency and lower RA values are discriminated from the shearing ones [18,19]. Though the purpose of this study is not to directly separate classes through a strict pattern recognition procedure, the sensitivity of AE to the fracture mode is utilized in order to passively characterize the developed stress field and provide feedback to the material modeling.

2. TRC laminates

In the present study TRC laminated beams were used as the model material. TRC composites are a combination of Inorganic Phosphate Cement (IPC) with randomly distributed and oriented glass fibers. This material can be used as external reinforcement for strengthening or repair of concrete structures while it is highly resistant to elevated temperatures. Usually TRC is formed in thin elements for lightweight and possibly curved structures. This makes prediction of its behavior not always a straightforward task especially if one considers the laminated, fibrous nature and the complex geometry of the member. While it is convenient for the designers to consider the beams as homogeneous and isotropic, variations in slenderness and curvature may lead to considerable interlaminar shear stresses which complicate the modeling of the material's behavior adding also delaminations and fiber pull out in the possible fracture mechanisms. In an effort to identify the regimes where normal and shear stresses dominate, and gain some understanding on the developed stress fields under variable conditions, thin beams of this material were tested under three-point loading with different spans. As the span increases, the normal stresses are promoted relatively to the shear ones due to the increase of bending moments. Therefore, since the increase of the bending span promotes the normal over shear stresses, the stress field is expected to become gradually more similar to the field developed by a pure tensile loading. In order to test this hypothesis, as well as examine the sensitivity of AE in the dominant fracture mode, reference tensile measurements were also conducted and their AE behavior was monitored. Matrix fracture events are the first manifestation of distress under bending (Fig. 2). As the load increases and the matrix cracks are saturated in the area of maximum bending moment (center), other type of phenomena start to occur related to the debonding between successive layers. Usually this is triggered at the points of discontinuity created by matrix cracks. At the same time, and as load and deformation continue to increase, fibers which are bridging the cracks are continuously being pulled out, as seen again in Fig. 2. The two latter are shearing phenomena and are activated nominally at load levels higher than the ones needed for matrix cracking.

These phenomena are also related to the bottom span of three-point bending. As the span increases, for the same load, the normal stress is higher at the center due to the higher bending moment, while shear forces do not nominally change. Therefore, for low aspect ratios (span over thickness), fracture phenomena related to the interlaminar shear stresses (delaminations) are expected to be more frequent than for high aspect ratios. This, by no means implies the absence of one or the other mechanism in either case rather than the change in proportions of the different phenomena which are anyway interacting. This fracture behavior is reflected in the AE behavior in a quite clear manner, while the changes in the stress field are described in the FEM analysis section.

3. Experimental details

3.1. Materials and testing

The inorganic calcium phosphate (IPC) matrix is a mixture of a calcium silicate powder and a phosphoric acid based solution of metal oxides. The weight ratio of powder to liquid is 0.8. For the mixing a Heidolph RZR 2102 overhead mixer was used. First the liquid and the powder were mixed at 250 rpm until the powder was mixed into the fluid, after which the speed was increased to 2000 rpm. E-glass chopped glass fiber mats with a surface density of 300 g/m^2 (Owens Corning M705-300) were used as reinforcement. All 8 layer IPC laminates were made by hand lay-up with an average matrix consumption of 800 g/m^2 for each layer, which results in an average fiber volume fraction (V_f) of 20%. Laminates were cured under ambient conditions for 24 h. Post-curing was performed at 60 °C for 24 h while both sides were covered with plastic to prevent early evaporation of water. The dimensions of the TRC specimens were: 350 × 50 × 4 mm. The laminates were loaded in a three-point bending test. In this case the span between the supports was set to: 330, 250, 150 and 60 mm. This resulted in span over thickness aspect ratios (h) of 82.5, 62.5, 37.5 and 15. The test was performed using an Instron 5885H universal testing machine using a loading rate of 2 mm/min. For reference purposes tensile tests were also conducted on two specimens of the same plate geometry with length 330 mm, which was notched in the middle in order to concentrate the fracture events in the same area as in the bending tests.

3.2. AE monitoring

For the purpose of AE monitoring the "Pico" type sensors were used. The specific sensors although are resonant at 500 kHz, they exhibit a high bandwidth, compared to other resonant AE sensors. Their small diameter ensures good contact even when the beams obtain strong curvature at high load, while they can record changes of hundreds of kHz for the different fracture stages as opposed to other sensitive resonant sensors with limited bandwidth. Two were placed 25 mm either way of the central loading point. The data of these two sensors are analyzed in this manuscript, while in total five sensors were used as shown in Fig. 3. The use of multiple sensors was applied in order to monitor the same AE sources from different distances and examine the effect of plate wave dispersion and attenuation on the AE parameters. However, in this paper the focus is given on the monitoring by the close-by sensors around the crack (e.g. #1 and #2 in this case) having the least possible effect of distortion and attenuation. The influence of wave propagation is very important but it will be treated separately as it cannot be adequately addressed in the length of the paper along with fracture monitoring. Vaseline grease was used for acoustic coupling and the sensors were secured by tape during the loading. The signals exceeding 35 dB (threshold) were pre-amplified by 40 dB and recorded in a micro-Samos 8 channel acquisition board with sampling rate of 5 MHz. Linear source location was active based on an initial TRC pulse velocity of 3400 m/s that was measured before the start of the experiment. The analysis concentrated on the activity in the range of the sensors. Photographs of the setup can be seen in Fig. 4a and b for the longest span and the shortest span respectively. For