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Effect of propagation distance on acoustic emission fracture mode classification in textile reinforced cement

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HIGHLIGHTS

- Cracking and delaminations/pull-out of TRC are monitored by AE.
- Multiple sensors are used to examine the effect of wave propagation distance.
- Basic parameters of AE change with propagation distance.
- Classification success between different modes decreases for further sensors.
- Classification boundaries depend on the source-sensor distance.

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ABSTRACT

Textile reinforced cement (TRC) is a composite material being increasingly used for load bearing applications. Damage in TRC as in all cementitious materials is an important issue in civil engineering. Acoustic emission (AE) exhibits promising outcomes in laboratory and in-situ monitoring applications. Evaluation of the fracture mode is crucial as generally, shearing phenomena occur later than tensile (bending) cracking and indicate more severe damage. The acoustic signatures of the damage modes influence most of AE parameters including the average frequency AF and RA-value. However, there are no universal classification boundaries between tensile and shear signals mainly due to geometric effects, material properties, as well as sensor location and response function. In order to highlight this problem and discuss the possibility of a solution, the study occupies not only with the evaluation of the damage mode based on AE parameters but in addition uses multiple sensors to investigate the effect of the wave propagation distance. This is crucial in thin cementitious laminates since damping, scattering, reflections and plate wave dispersion seriously distort the signal having a strong effect on the classification result. It is seen that the classification boundaries between tensile and shear fracture should incorporate the information of propagation distance.

1. Introduction

AE is a technique used for health monitoring purposes of several types of structures and materials. Piezoelectric sensors are placed on the surface of the material and record the transient motion of the surface under the excitation of the elastic waves emitted by the cracking sources [1]. The rate and other parameters of the received signals depend on the damage process and are used for the monitoring of fracture, creep, corrosion, healing in cementitious materials [2–6]. AE is already a part of structural health monitoring procedures [7–10]. However, this is still largely based on the activity rate and amplitude of the signals, which are certainly sensitive to the severity of the fracture process. Furthermore, fracture consists of different successive mechanisms as the material is led to ultimate fracture. Therefore, identification of the mode of fracture, provides more information concerning the damage stage and allows predictions relatively to the useful life span. Different fracture processes have distinct AE patterns enabling the characterization of the fracture stage. In a material model like TRC used in this study, these mechanisms can be matrix cracking, debonding of successive layers and pull out of fibres. The first mechanism is easily activated by tensile stress due to the brittleness of the matrix while the other two are more related to shear. Typical AE waveforms are seen in Fig. 1. Among others, some of the most basic

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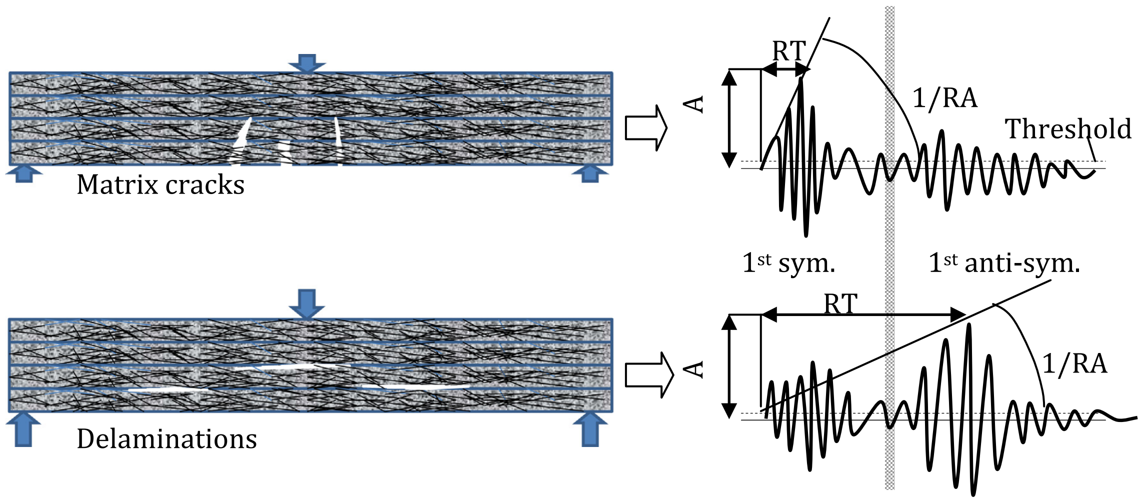

Fig. 1. Typical damage modes and their corresponding AE waveforms.

features are the amplitude, A (Volts or dB), the rise time, RT (μs) and the RA-value (μs/V) which is RT over A. RT and RA have been shown sensitive to the fracture mode, and obtain low values for tension-related phenomena and higher for shear, either in the form of debonding or pull-out [11,12]. This is connected to the elastic wave modes which are excited by the direction of displacement of the crack sides. Specifically for laminated composites, matrix cracking has been connected to stronger first symmetric mode, while debonding to stronger antisymmetric [13,14], see Fig. 1. 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) over the waveform duration and the central frequency, CF, which is the centroid of the frequency spectrum. In certain cases, when six or more sensors are recording each event it is possible to characterize the mode of the source by moment tensor analysis [16]. This is not always practical in all cases while in thin structures it cannot be applied due to plate wave dispersion that distorts the wave front. Therefore, a simpler characterization is attempted in cementitious media [17,18]. It is based on a simple two-dimensional "plot" of the AE characteristics. "Tensile" signals exhibit higher frequency and lower RA values than "shear" and can therefore, be discriminated. This has been confirmed in a number of recent studies [19–22]. In small scale tests the successful classification may reach almost absolute levels [18]. However, the results are not straightforward for larger scale. This is due to the strong effect of wave propagation in the heterogeneous material. Damping, scattering and reflections effectively distort the signals, seriously altering their amplitude, rise time, RA, duration and frequency components. Therefore, more elaborate pattern recognition approaches have been applied with the aim of resulting to classification of acceptable engineering value [21,23]. In any case, the effect of the propagation should be taken into account. Failure to account for this effect, will certainly mask the original information of the AE signals. The reason is that by losing frequency and by "stretching" in time domain, the originally short, high frequency waveforms of matrix cracking tend to resemble the lower frequency and longer shearing ones [20,24].

Since the waveform parameters change with propagation, the classification boundaries between tensile and shear signals should also be adjusted. A previous study in cementitious mortar beams under bending showed that the classification boundaries change even for an additional distance of 40 mm [23]. Furthermore the classification success was increased by treating the data of different sensors separately. This was because the effect of attenuation and scattering dispersion is the same to all the signals travelling the same distance influencing the waveforms in a similar manner.

In this case, a more detailed study takes place since the AE is recorded by five sensors in order to track the changes of the signal for longer distances. As the distance from the fracture zone increases, the effect of attenuation, dispersion and reflections is accumulated on the AE signals, rendering essential some special consideration. In this case the AE populations received at increasing distances are treated separately to examine the effect of the aforementioned factors on the classification success. The material model is textile reinforced cement (TRC), a relatively new material that comes into thin geometries and is used for external reinforcement of concrete members. Details about the material are given in the next section.

2. Brief introduction in TRC materials

Textile reinforced cements (TRC) containing a high content of fibres (more than 20%) results in a strain hardening tensile behaviour. This makes them suitable for structural applications, like strengthening, retrofitting and manufacturing of moulds [25]. The chemically bounded calcium phosphate cement used in this work was developed at "Vrije Universiteit Brussel" and is called Inorganic Phosphate Cement (IPC). Due to its neutral pH after hardening, it is a cementitious material which can be combined with standard E-glass fibres [26]. IPC is mixture of powder and liquid which after hardening becomes a strong, durable, and heat resisting material. The use of TRC made by IPC and E-glass fibres, has certain beneficial aspects mainly related to the material's fire resistance and the reduced cost by using cheap E-glass fibres instead of carbon fibres. Previous research has already indicated the potential of glass fibre reinforced IPC as a strengthening and repair method for concrete beams [27–31]. After these preliminary studies, there is a strong need to understand the mechanisms responsible for the mechanical and fracture behaviour of such materials.

This material exhibits clear changes in its AE behaviour throughout loading until failure making it a good model to study AE populations coming from different sources [32]. This changing AE behaviour is related to the degrading stiffness of such TRC during loading. The evolution of the stiffness of a brittle cementitious composite during loading is described by the ACK (Aveston, Cooper and Kelly) theory [33]. For completeness, the basic stages defined by the theory are given below.