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Fracture mode identification in cementitious materials using supervised pattern recognition of acoustic emission features

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HIGHLIGHTS

- Classification of AE features according to the original fracture mode based on pattern recognition algorithm.
- Quantification of the effect of propagation distance to the classification error.
- Evaluation of different parameters as to their classification power.

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ABSTRACT

Cracking in concrete as a ubiquitous cementitious material in civil structures has been a worldwide critical issue in the field of engineering. Acoustic emission (AE) has demonstrated promising outcomes in research and laboratory experiments for monitoring these structures that led to plethora of reports, articles and recommendations for concrete structures. Many of these studies focus on cracking mode detection to estimate the significance of damage because in general, shear-like phenomena indicate severe damage and occur after tensile (flexural) cracking. The distinctive signs of the cracking modes are embedded in some AE parameters like the RA-value and average frequency (AF). Signals emitted from shear fracture exhibit higher RA-values with smaller AF than tensile ones. However, there are no universally fixed boundaries for classification of these features due to the parameters like member geometry, material properties sensor location and response. In addition, although AE consists of a random set of data, the role of uncertainty is not fully taken into account in data processing. To overcome these deficiencies, this article proposes a pattern classifier technique titled support vector machines. Small-scale fracture experiments were carried out to impose controlled cracking modes, record AE data for each cracking mode, and evaluate the performance of classifiers. The results show that the classification boundaries for AE features and their associate uncertainties could be successfully estimated. The effect of sensor distance as an imperative parameter in variation of classification boundaries could be quantified. Furthermore, the adequacy of other feature sets (i.e., other than RA and AF) for classification was also examined.

1. Introduction

In the past three decades, significant efforts have been made towards the development of structural health monitoring (SHM) systems for concrete structures. A technique that demonstrates promising online monitoring is acoustic emission (AE) [1–6]. The term AE describes the stress waves caused by sudden strain releases due to fracture of the material. Many studies have demonstrated that the modes of cracking (tensile or shear) in concrete structures emit different AE signatures [1,2,7–9]. While loading concrete structures until failure, tensile cracks (mode I) generally develop at moderate loading level (elastic behavior), while shear cracks (mode II) dominate at large loading levels (plastic behavior) [10]. Therefore, it could be beneficial to monitor the mode of cracks as a lead to estimate the structural damage state. Nevertheless, the

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conventional AE analyses are mostly inadequate for real time monitoring and warning systems because they do not allow exploration of the uncertainties prevalent in the structural characterization problem.

Uncertainty is an important issue in damage classification for real world health monitoring systems. Variability in structure geometry, material properties, sensor characteristics, noise, temperature, humidity, measurement inaccuracy, and insufficient knowledge about the process of damage nucleation and evolution [11] are among imperative sources of uncertainty. The above factors increase the inherent variability of AE measurements which inevitably results from the random nature of fracture process. Indeed, each crack propagation event is unique and different from the previous or the next in terms of fractured area or released energy. This implies that all external sources of error or variability should be limited in order not to mask the anyway demanding classification attempted by the AE features. With the aid of ongoing computer science progress, statistical techniques and pattern classification are recently playing a significant role in the field of SHM; in particular, acoustic emission monitoring. It has been used to either understand the underlying source of mechanism or to define criteria for probabilistic decision making [2,12–18].

The issue of cracking mode characterization based on AE signals, has been treated quite adequately in laboratory by the "moment tensor analysis" (MTA) [19,20]. Despite the successful classification achieved in usually small scale experiments, application of MTA to larger scale is not straightforward mainly because each cracking event must be recorded by at least six transducers. This needs expensive instrumentation in an actual case of monitoring since the transducers are dispersed to cover a large volume and supply information for several different zones of the structure. The result is sensor separation distances of the order of meters which do not allow acquisition of AE waves from the same fracture event by as many as six sensors. Therefore, a new procedure is necessary to yield crucial and reliable information using less number of sensors.

A full definition of AE features can be found in literature, e.g. [21], however the definition of the most common features is also done herein. Fig. 1 depicts a typical waveform with its main features. A threshold is always defined by the user in order to avoid noise signals while the first time the waveform crosses the threshold (threshold crossing, count) is considered the onset of the waveform. One of the most important waveform parameters is Amplitude which is the voltage of the highest peak and is commonly measured in Volts or dB. Duration is the time window between the onset and the last threshold crossing, while rise time (RT) is the time between the onset and the maximum peak. "Energy" is another important parameter that measures the area under the rectified signal envelope (MARSE). A parameter taking into account the initial rising angle of the signal is RA value which is RT over amplitude (Eq. (1)) and is measured in μs/V. Frequency indicators can be found in the form of "average frequency, AF" which is defined simply as the number of counts over duration (Eq. (2)) while "central frequency" and "peak frequency" correspond to the centroid and the frequency with the maximum magnitude of the spectrum after FFT of the waveforms.

$$\mathrm{RA} = (\text{Rise time})/(\text{Peak amplitude}) \quad (1)$$

$$\mathrm{AF} = (\text{Counts})/\text{Duration} \quad (2)$$

Energy-related features, like energy and amplitude are connected to the intensity of the cracking source. Additionally, waveform features like duration, RT, RA and AF have been shown to correlate well to the fracture mode and are proposed for crack characterization in concrete [22]. Specifically, it has been consistently observed that tensile mode of cracking results in AE of higher frequency content and shorter duration [23,24]. The actual reason is related to the elastic wave modes excited by the different motion of the tips of the cracks. At the tensile mode, due to the opposing displacement of the sides vertical to the crack plane, a volumetric change occurs in the vicinity of the crack tip emitting most of the energy in the longitudinal wave mode. On the other hand, under shear cracking, the sides of the crack move in opposite directions but in parallel to the crack plane, which introduces a change of shape instead of volume [1].

Due to the large proportion of shear wave energy and the lower velocity of shear waves, the meaningful content of the waveforms is delayed compared to the "tensile" waveforms. Simulation studies concerning through the thickness and surface cracks in concrete have confirmed these trends [24–26]. Additionally, in several dedicated experimental studies, AE parameters like AF and RA have shown a definite change when the fracture mechanism shifts from tensile (micro-) cracking to debonding, fiber pull-out or actual shear [1,2,8,18,22,23,27,28]. AF registers an average decrease of 50% and RA an even stronger increase, which allow identifying the different stages at laboratory scale [1].

Fig. 2 shows a simple representation of classification using the two aforementioned parameters, AF and RA. Though this classification produces quite successful results in discriminating the different modes, it can only be safely applied in laboratory scale and only if the boundaries have been acquired by experiment at similar specimens. Applying similar classification in large scale is more complicated because of the influence of long propagation on the elastic waveforms. Concrete is heterogeneous and effectively scatters and damps the waves. Therefore, depending on the distance between the cracking source and the AE receiver, the wave will undergo changes in vital parameters like its frequency content and amplitude (downshifted) and RT and duration (increased for

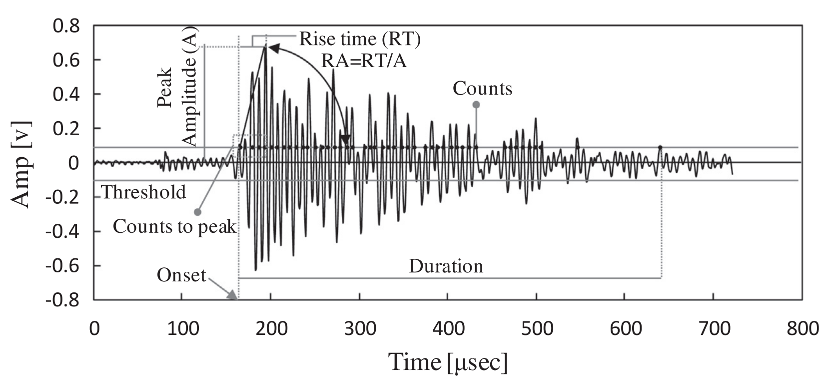

Fig. 1. A typical AE signal with some features x = (Amp, Dur).

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