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Acoustic emission-based classification of energy dissipation mechanisms during fracture of fiber-reinforced ultra-high-performance concrete

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HIGHLIGHTS

- Used unsupervised learning to separate different acoustic emission event types.
- Trained neural net to recognize matrix cracking versus fiber pullout AE events.
- Distinguished different energy dissipation mechanisms during fracture.
- Showed relative magnitude of different energy dissipation mechanisms.

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ABSTRACT

A neural network-based analysis method was developed to characterize acoustic emission (AE) events by the source mechanism during split cylinder fracture of fiber reinforced ultra-high-performance concrete (UHPC). Using AE tests of unreinforced UHPC and tests of individual fiber pullout, the network was trained to distinguish matrix cracking and fiber pullout. The results of the analysis showed that fiber pullout tends to dissipate more energy than matrix cracking, but there are important exceptions, and these exceptions depend on the distribution of fiber orientation inside the specimen. The AE results also showed how the energy dissipation shifts from matrix cracking to fiber pullout during damage progression.

1. Introduction

Damage evolution and fracture of Portland cement-based composite materials are complex phenomena due to a multitude of interacting processes occurring at different length scales. Continued research over the past 40 years has led to a fairly clear picture of the different mechanisms involved [1] as well as approaches to model the processes [2]. However, among the areas in which our knowledge is still lacking is a quantitative relationship between the different microstructural features of the material, the micromechanical mechanisms that dissipate energy during progressive damage and fracture, and the relative magnitude of energy dissipated by each mechanism. The motivation for this work is to enhance our ability to incorporate physical microstructure into computational models that explicitly represent the mechanisms that dictate material performance [3,4].

In the work described here, acoustic emission (AE) measurement and analysis techniques were applied to the problem of damage and fracture characterization of ultra-high performance fiber-reinforced concrete (UHPFRC). This work is part of a broader effort to characterize and measure fracture processes using both AE and X-ray computed tomography (CT) [5]. CT analysis provides high quality, relatively high resolution information about the material at discrete times during a test, but phenomena occurring between scans can only be inferred from subsequent scans. AE is viewed here as a complementary technique, such that while the data is not necessarily as high resolution, processes can be monitored continuously during a test. Techniques to measure energy dissipated by UHPFRC from CT data was previously developed and applied to specimens subjected to flexure [6]. In order for AE to provide complementary information, it was necessary to develop techniques to classify energy dissipation mechanisms from the recorded AE waveforms.

The goal of the work described here was to use AE techniques to characterize different energy dissipation mechanisms during progressive loading of ultra-high performance concrete (UHPC), and to use that information to measure the relative contribution of different mechanisms to the total energy dissipated by fracture in the specimen. In order to realize this goal, an artificial neural network

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(ANN)-based AE event classification scheme was developed, trained and employed to analyze AE data recorded during tests of fiber reinforced UHPC subjected to split cylinder testing. By classifying AE signals as matrix cracking, fiber pullout, or some other mechanism, we hoped to quantify the different contributions of these mechanisms to the total energy dissipated by the specimens during fracture.

2. Background

Acoustic emission (AE) techniques are well established, and have been applied to characterize damage in a wide range of materials [7]. For concrete fracture studies, approaches range from simple empirical correlations [8] to more sophisticated microseismic analyses [9].

With respect to classifying specific fracture phenomena, there have been a number of different approaches. Average frequency, amplitude, and energy have been shown to be sensitive parameters in the study and classification of fracture mode, debonding processes when superimposed with load-displacement history [10–12]. Clustering methodology used by Zarif Karimi et al. [13] were combined with classical acoustic emission parameters to group signals by multiple signatures in order to differentiate damage mechanisms from drilling test of composite laminate. Omkar and Raghavendra Karanth [14] implemented an ant colony optimization-based multi-category pattern classification technique for AE signal sources recognition based on the algorithm of generating classification rules. Wavelet transform used for comparative analysis of acoustic emission done by Burud and Kishen [15] showed the differentiation between AE signature of plain and reinforced concrete. Useful information about fracture mechanisms was obtained from frequency spectrum and wavelet transform that allows to differentiate between unreinforced and steel bar reinforced concrete beam acoustic emission behavior under four point flexural loading by Yoon et al. [16]. Najafi et al. [17] used a wavelet-based scheme to classify AE sources during fracture of oriented strand board. Studies by Kaphle and Tan [18] have shown that if the acoustic emission signal from a known source is recorded, it can be used as a prototype for cross correlation approach in a signal source differentiation analysis. Unsupervised pre training showed to be effective approach in audio signal classification in work done by Gencolgu et al. [19]. Oliveira and Marques [20] successfully combined unsupervised self organizing map of Kohonen with k-means clustering algorithm to classify acoustic emission events recorded during a tensile test of cross-ply glass-fiber laminate. It was shown that if information about the AE event features is available, principal component analysis can be used to separate signal from noise during fatigue test of steel specimens [21]. Back propagation and probabilistic network training algorithms developed by Ativitavas et al. [22] showed to be an appropriate combination in pattern recognition analysis of FRP failure mechanisms. And finally, Anay et al. [23] used unsupervised pattern recognition to distinguish different cracking mechanisms and progressive damage accumulation in plain cement paste.

As the above literature demonstrates, AE techniques can be used to identify different signal signatures depending on the source of energy dissipation in large scale. Different fracture mechanisms can be compared using classical parametric approach. Clustering algorithms can be used to classify signals depending on damage processes developing in the materials. Wavelets showed to be effective in distinguishing between reinforced and unreinforced specimens. Cross correlation can be used to degree of presence of prototype signal in the analyzed data. In the work detailed below, an alternative approach is proposed in which an artificial neural network is trained using a series of simple fracture and fiber pullout tests, and then applied to classify signals in fiber reinforced specimens.

3. Materials and methods

The UHPC used in this work is called 'CorTuf', which was developed by the U.S. Army Engineer Research and Development Center [24,25]. A low water/cement ratio combined with small aggregates and efficient particle packing leads to compressive strengths exceeding 200 MPa. Mix constituents are presented in Table 1. All specimens were prepared as detailed in Williams et al. [24].

Three types of UHPC material were prepared for this study: unreinforced, reinforced with 30-mm hooked steel fibers (Dramix ZP305), and reinforced with 13-mm brass-coated straight steel fibers (Bekaert OL13/.20). Reinforced specimens were all prepared with a nominal fiber fraction of 3.5% by volume.

The specimens of primary interest were nominally 50-mm diameter by 100-mm long cylinders, some of which were cast, and some of which were cored from a larger block. As detailed below, these specimens were later cut in half so to have matched pairs of 50-mm long cylinders. As further detailed below, additional UHPC specimen types were prepared for neural network training. These additional specimens included unreinforced 50-mm diameter cylinders, half dog bone specimens with a single fiber protruding from the throat, and pre-damaged 50-mm square cross-section, 250-mm long reinforced beams. A summary of the different specimen types is presented in Table 2.

Prior to testing, the cylinder specimens were scanned using X-ray computed tomography (CT), a robust 3D imaging tool that has been used to measure internal structure of concrete for several decades [26]. The purpose here, among other things was to measure the distribution of fibers and fiber orientations inside the specimen. After scanning, specimens were cut in half using a diamond saw to produce two 50 mm by 50 mm matched cylindrical specimens. From the CT data, an 'optimum' and 'pessimum' orientation was established for each specimens. The optimum orientation was defined as that for which fibers have the greatest contribution to resisting tensile stresses, while the pessimum orientation was defined as that for which fibers have the least contribution to resisting tensile stresses [27,5]. This is schematically illustrated in Fig. 1. By this definition, each specimen has an optimum and pessimum orientation for split cylinder loading. In most UHPC applications, no effort is made to align fibers during casting. Thus, there is a tendency to presume a random orientation in any model-based analysis. Previous work [6,28] quantified the alignment effects and showed how even small biases in fiber alignment can affect strength and toughness. For the split cylinder tests described here, one specimen of the matched pair was tested in its optimum orientation, while the other was tested in its pessimum orientation. These two orientations can serve as bounds for the fiber alignment bias in these specimens. That is, split cylinder loading of these specimens in an arbitrary orientation is likely to produce a load-deformation response that is between the upper and lower bounds posed by the optimum and pessimum responses,

Table 1
Table of UHPC constituents.

Constituent	Mass (g)
Cement	621
Sand	600
Silica Flour	172
Silica Fume	241
Superplasticizer	11
Water	129