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Investigation of the fracture modes of red sandstone using XFEM and acoustic emissions

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ABSTRACT

Acoustic emissions (AE) and stress–strain curve analysis are accepted methods of analyzing crack propagation and monitoring various failure stages, including crack closure and the crack initiation level, during rock failure under brittle rock loading. This study designed a series of three-point bending tests and shear fracture tests to investigate the features of AE signals for different modes. The Extended Finite Element Method (XFEM) is also adopted to simulate these experiments processes. The obtained results indicate that the maximum load for the shear fracture mode is approximately three times larger than that for the tensile fracture mode and that the displacement in the shear fracture mode is also larger than that in the tensile fracture mode. AE signals had higher AF (average frequency) and lower Rise Angle (RA) (ratio of the rise time to the peak amplitude) values when tensile failure occurred, while they exhibited lower AF and higher RA values when shear failure occurred. Accumulative AE energy for the shear mode is significantly larger than that for type I tensile fracture. The influence of inhomogeneity is also evident, as signals acquired at different distances exhibit distinct characteristics. The results show that AE leads to the characterization of the dominant fracture mode using only two AE descriptors. Note that we also should reasonably arrange AE sensors to monitor large-scale projects in the field.

1. Introduction

In recent years, due to the rapid development of mining engineering and underground engineering projects, much more attention has been paid to the fracture mechanism of fissured rocks [1–3]. However, many questions still exist regarding the research and application of rock fracture mechanics of mixed mode fracture criteria, crack monitoring field methods and crack prevention measures [4,5]. Acoustic emission (AE) detection technology is an effective method of solving the above problems. It is well known that in any type of rock failure, the development results from micro-fracture generation and accumulation until macro damage occurs along with energy release in the form of elastic stress waves [6]. AE is an inspection technique and a nondestructive evaluation (NDE) method of fracture analysis, which is performed by means of detecting elastic waves due to dynamic motions at AE sources, such as cracking, delamination, cleavage, and fretting in rock [7]. Previous studies also indicate that AE waveforms carry rich information about the rock stress state, microstructure, and physical and mechanical properties.

Two basic methods, parameter-based analysis and signal-based analysis, have improved the capabilities of AE technology. Due to the low requirements of the AE apparatus and simple and intuitive analytical methods, AE parameters analysis is widely used. Fig. 1 shows a typical AE signal after a crack propagation event with its main features [8]. Average frequency (AF), one of the crucial parameters, is defined by the ratio of threshold crossings over the duration of the signal. Another parameter that is of great importance and sensitivity to the fracture mode is the RA value, which can be calculated by the ratio of the rise time (RT, delay between the onset and maximum amplitude) over the amplitude A, measured in μs/V [9,10]. AE energy (ENE) is another important parameter that expresses the measure of the area under the rectified signal envelope. It has been demonstrated that different AE parameters, such as the average frequency (AF), RA and ENE, exhibit strong sensitivity to the fracture mode, so they compose a simple but reliable characterization scheme [11].

Many scholars have presented research on the acoustic emission features of rock-like material fractures. Aggelis [12,13] noted that AE signals emitted from samples in shear testing have a longer waveform and lower frequency than those in tensile testing. Cheon et al. [14] evaluated the current damage level of the slope and fracture type using changing trends and variation ranges of AE

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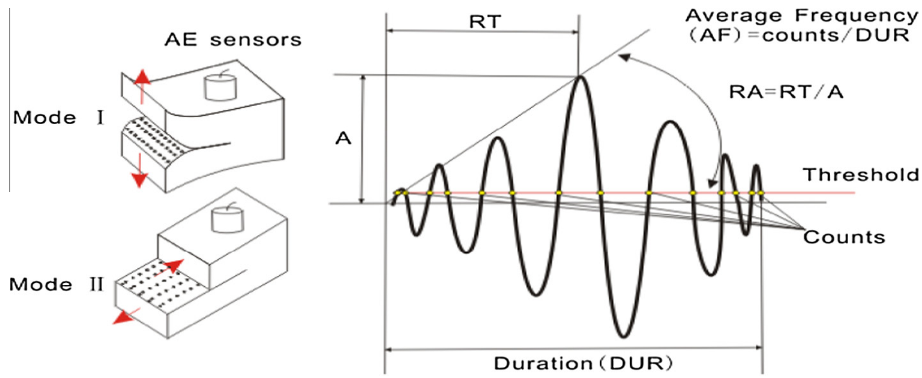

Fig. 1. Crack modes and AE waveform parameters.

parameters. It can be noted that shear failure is the major microscopic failure mechanism of rock under a triaxial compression test according to the results of moment tensor analysis [15]. Using uniaxial compression tests, the deformation, peak and post-peak strength characteristics can be determined; combining real-time spatial AE locations with stress versus strain evolution, the complete crack damage evolution of rock can be successfully characterized [16–18]. Granite and marble specimens can be found to have different fracture shapes and behaviors of associated acoustic emissions due to their heterogeneities by the use of the AE technique to characterize the micro- and macro- failure properties of their plates under uniaxial tension [19]. Meanwhile, Prof. Masayasu Ohtsu has proposed the recommendation of RILEM rules: acoustic emission and related NDE techniques for crack detection [20,21], and acoustic emission (AE) techniques were employed to investigate the fracture formation process in large, shear-critical, reinforced concrete beams or rock and to gain more insight into the mechanisms of shear failure [22,23].

However, previous research mainly investigated the AE characteristics of a single tested specimen failure process, causing a lack of comparative experiment results, and there are few related works focused on AE features for two types of failure modes (mode I and mode II). This paper designed a new experimental method to investigate the fracture features of red sandstone samples using an AE detecting system. All of the AE signals generated during the rock failure process are recorded for parameter analysis, including energy, peak frequency and average amplitude, in three-point bending tests and shear fracture tests; thus, the essence of the failure regularities of rock for different fracture modes can be obtained.

2. Experimental details

2.1. Experimental set up

Two systems are applied to conduct these tests, one is electronic universal testing machine, the other is monitoring system of multichannel acoustic emissions. A MTS-CMT5105 testing machine with maximum loading force of 100 KN is controlled by the visualized operating software on Windows platform. It can record the current load, displacement, stress and strain, and plot corresponding curves simultaneously. NI PXIe-1082 controller and the AE sensors with the frequency range of 100 Hz to 1 MHz produced by National Instruments Corporation is adopted in the monitoring system of multichannel acoustic emissions, and the AE transducers used have a resonant frequency of about 100 kHz. The AE monitoring system can automatically count AE events, store acoustic wave information and transmit signals to computer. Based on above capabilities, we can carry out real-time monitoring of AE events and analyze parameter and waveform according to the obtained results. Fig. 2 shows the schematic diagram of the experimental equipments.

2.2. Sample preparation

Tested samples are homogeneous red sandstones. Their major minerals are 21.3% quartz, 10.3% K-feldspar, 58.2% plagioclase, 6.8% calcite and 3.4% amphibole according to the X-ray diffraction analysis. The samples are divided into two groups and each group has five square bar specimens with the dimensions of 40 mm × 40 mm × 160 mm as shown in Fig. 3. The specimens

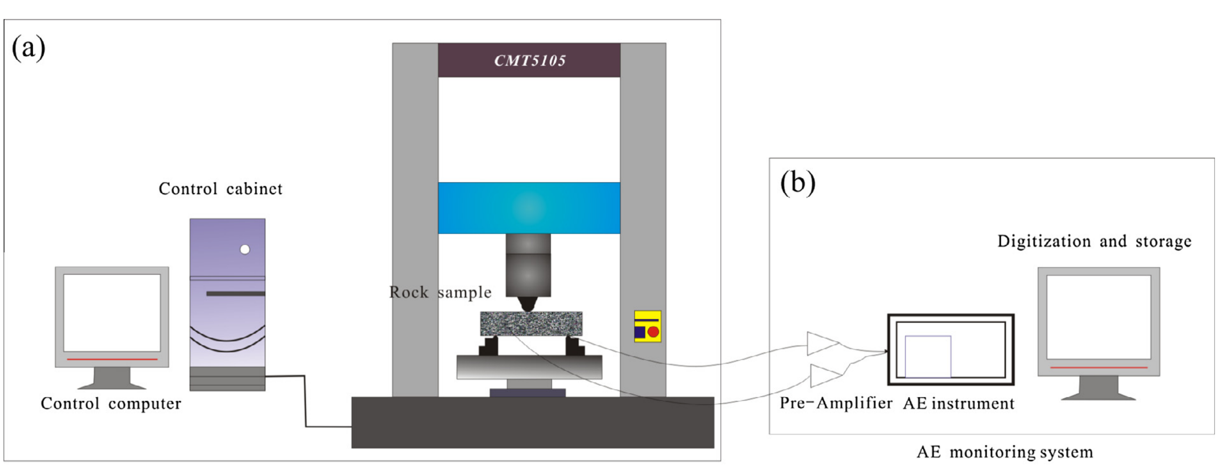

Fig. 2. Detail illustration of the whole experimental set up: (a) front drawing of the digital control system and (b) schematic diagram of the AE monitoring system.

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