Research Article

Experimental Study on Fracture Patterns and Crack Propagation of Sandstone Based on Acoustic Emission

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To investigate the fracture pattern and crack propagation of rock under different stresses, Brazilian split tests, preset angle tests, and uniaxial compression acoustic emission (AE) tests were carried out on sandstone to obtain the mechanical parameters and AE signals of the whole test process. Based on the analysis of the distribution of the characteristic AE indicators rise time/amplitude (RA) and average frequency (AF) combined with the core definition of areal density, the test results showed the following. In Brazilian split tests and preset angle tests, shear fractures and tensile fractures accompanied the whole process of rock damage and failure, and the crack type reflected by the RA-AF distribution was consistent with the theoretical analysis and actual failure results. The fracture pattern of sandstone under uniaxial compression was dominated by shear fracture, and tensile and shear cracks had the same evolutionary trend. In uniaxial compression, the development of cracks was complicated from the stage of steady development of microcracks, and the crack development was different in different specimens, which eventually leads to different failure modes. That is, the failure mode of sandstone could provide positive feedback to the RA-AF distribution. Under different stresses, the characteristics of the cumulative event rate of tensile or shear fractures varied significantly among stages, which corresponded to the various stages of rock damage and deformation.

1. Introduction

In recent years, with the construction of many underground geotechnical engineering projects, the construction depth continues to increase, and geological disasters such as deformation, collapse, and rock-burst of the surrounding rock in underground chambers often occur, seriously threatening construction safety [1–3]. These geological disasters are the macromechanical manifestations of rock instability and failure. As a natural material, the rock contains various defects (e.g., microcracks, pores, joints, and fissures), and the instability and failure of an engineered rock mass are essentially a progressive process from the development of damage of mesoscopic defects to the macroscopic fracture of rock under a stress field [4–6]. Therefore, it is of great theoretical significance and engineering value to study the fracture mechanism and crack propagation trends of rock under loading to thoroughly understand the failure mechanism of the engineering rock mass as well as to evaluate and predict geological disasters.

The laboratory mechanical experiment is one of the main methods to reveal the rock fracture mechanism [7]. Some researchers have studied the fracture mechanism of rocks by analyzing macrophysical phenomena, such as stress-strain curves and fracture angles [8], traditional extensometer and photogrammetry [9], and high-speed photography of specimens [10]. Besides, some researchers have adopted modern technologies such as X-ray computed tomography (CT) [11], scanning electron microscopy (SEM) [12], and acoustic emission (AE) [13] to study rock fracture mechanisms. AE technology has been widely employed [14]. AE is a nonstationary signal and contains much information, and it
involves many time-domain parameters and complex frequency-domain parameters. Currently, the main approaches to analyzing AE signals are the waveform-based approach and parameter-based approach [15, 16]. The waveform-based approach takes the time-domain waveform of AE signals as the object and selects specific signal processing methods to obtain AE waveform characteristics, such as dominant frequency [17], frequency spectrum [18], and frequency band [19]. AE waveform characteristics have been employed for determining the failure mechanisms of intact and jointed rocks [16], identifying the fracture behavior of the concrete [20], exploring the rock AE rate-dependence at different strain rates [21], and extracting the intrinsic dynamical rock-burst precursors [22].

AE signals contain a series of characteristic parameters, such as amplitude, hit count, duration, event, energy, rise time, rise time/amplitude (RA), and average frequency (AF) [23, 24]. Compared with the waveform-based approach, the parameter-based approach requires less calculation time and storage space. It has been employed for studying the failure mechanism of brittle materials widely. Moradian et al. [25] used the AE hits and energy analyses to detect the crack levels in rocks and demonstrated that AE is an effective technique. Wu et al. [26] proposed a new quantitative method to identify the crack damage stress of rock materials based on the AE counts. The AE count and energy parameters were analyzed to examine the relation between shear behavior and AE, and AE was found to be useful and adequate [27]. For the cracking mode classification, two AE parameters of the RA and AF values are widely employed [21, 28–33]. Ohno and Ohtsu [28] applied this classification method to the four-point bending test of concrete and compared it with the results of a signal-based method. Aggelis [29] applied different AE parameters such as AF, RA, and energy to analyze fracture modes of concrete under bending, showing that this method can effectively analyze the fracture behavior of brittle materials. Liu et al. [30] found that the tensile crack is more intensive than the shear crack in the rock fracture process between dry and saturated specimens. According to the RA-AF distribution, Liu et al. [21] showed that tensile cracking gradually becomes the dominant fracture mode with the increase of strain rate. He et al. [31] revealed that tension cracks are the majority during the unloading of the rock-burst test, and the number of cracks in the rock decreases obviously with the decrease of unloading rate. Zhang et al. [32] identified the crack type of the key signal of acoustic emission during the granite’s uniaxial compression test. Zhang and Deng [33] proposed a new method for determining the transition line for crack classification in AE parameter analysis.

The above studies have enhanced the understanding of AE signals accompanying rock fracture. However, understanding the mechanical properties and fracture patterns of rock is problematic, especially for engineering rock mass under complex stress conditions [34]. The AE technique may be a reasonable attempt to carry out experimental research on fracture mode and crack propagation of the same rock under different stresses.

The analyses presented here are based on applying the AE technique to characterize the fracture patterns and crack propagation in sandstone subjected to tensile tests, shear tests, and uniaxial compression tests. The AE signals of rock failure under different stresses were obtained in the tests. The characteristic indicators of the rock fracture pattern in the AE time-domain parameters were selected to thoroughly investigate the intrinsic relations between the AE signal and the fracture pattern and crack propagation. This work enriches the literature on the characterization of the rock fracture process by AE signal.

2. Experimental Setup

2.1 Specimen Preparation. In the experiment, three sizes of specimens were used to study the fracture pattern and crack propagation of sandstone under different stress conditions. There are different rock tensile test methods, including direct tensile test, Brazilian split test, and other alternative tensile test methods [35]. The shape of the direct tensile specimen is to be of the dog bone shape. The specimen is not easy to prepare and is easy to produce stress concentration at the specimen’s ends. For this, the Brazilian split test method was used in this study. The prepared cylindrical disc specimens each had a diameter of 50 mm and a thickness of 25 mm. The specimens for Brazilian splitting were labelled BT. The commonly used rock shear test methods include direct shear [36] and variable-angle compression-shear (with the angle varying between 20° and 70°) [37]. The shape of the direct tensile specimen is to be of the dog bone shape, which is not easy to prepare and is easy to produce stress concentration at the specimen’s ends [36]. So, the Brazilian split test method was used in this study, and the latter with a preset angle of 60° was used in this study (it will be referred to as preset angle shear later). The specimens for preset angle shear testing were cubes with a side length of 50 mm and were labelled CS. The cylindrical specimens used in the rock uniaxial compression tests each had a diameter of 50 mm and a height of 100 mm and were labelled UC. Each group has three specimens, and all specimens were taken from the rock mass in the same area. The physical and mechanical parameters of different specimens are shown in Table 1.

2.2 Experimental Equipment. The Brazilian split tests, preset angle shear tests, and uniaxial compression tests loading for all sandstone specimens were facilitated by a SAS-2000 microcomputer-controlled electrohydraulic servo rock compression-testing machine. The AE signal was acquired by a SAEU2S multichannel uniaxial compression detection system, which was equipped with SR150 high-sensitivity resonance AE sensors with a resonant frequency of 150 kHz, as shown in Figure 1. Platform loading was adopted for the Brazilian split tests [35]; that is, the disc specimen was placed directly between the bearing plates of the compression-testing machine. The preset angle shear tests were carried out with the help of an angle-changeable-shear-box device, which consisted of two inclined moulds with the angle α between the moulds varying between 20° and 70° (60° in this
To measure the strain in the uniaxial compression tests, the deformation in the specimen during the loading process was acquired using a special rock extensometer equipped with the loading system.

2.3. Experimental Procedure. During the tests, a specimen was placed on the compression-testing machine and preloaded to 1 kN so that the specimen was in full contact with the bearing plates; then the AE signal acquisition system was set up with a sampling frequency of 1000 kHz, a sampling length (number of points) of 2048, a preamplifier gain of 40 dB, and a threshold value of 40 dB. An appropriate amount of acoustic coupling agent was applied on the contact surface between the AE sensor and the specimen, and the contact points were symmetrically placed on the side surfaces of the specimen. The sensitivity of each sampling channel was tested by the pencil lead break method to ensure the smooth acquisition of AE signals. The loading system of the compression-testing machine and AE acquisition system were synchronized, and the test was started with axial equal displacement control.

Generally, the tensile strength of rock is relatively low. With the same loading rate, the loading time of rock in Brazilian split tests is short, and the AE signal obtained is less, which is not conducive to subsequent comparative analysis. Therefore, a lower loading rate was adopted for Brazilian split tests. The loading rate was 0.05 mm/min for the Brazilian split tests and 0.1 mm/min for both the preset angle shear and uniaxial compression tests. The specimen was loaded to complete failure. The test results are shown in Table 1, and the failure modes of the specimen are shown in Figure 2.

3. Results

3.1. RA-AF Indicators and Fracture Patterns. Rock under loading can have two main types of fracture patterns, i.e., tensile fracture and shear fracture, and different fracture patterns induce AE signals with fixed characteristics [38], which are often regarded as an effective way to reflect the type of crack. The AE signal indicators, RA and AF, are defined as [28, 29]

### Table 1: Basic physical and mechanical parameters of sandstone.

| Experimental mode          | Specimen number | Specimen size\( \times \) (mm) | Mass (g) | Tensile Strength (MPa) | Shear Strength (MPa) | Uniaxial Compressive Strength (MPa) |
|----------------------------|-----------------|---------------------------------|---------|------------------------|---------------------|-----------------------------------|
| Brazilian split\(^1\)     | BT-1            | D49.20 × T25.70                 | 113.50  | 3.20                   | –                   | –                                 |
|                            | BT-2            | D49.10 × T25.70                 | 112.00  | 2.65                   | –                   | –                                 |
|                            | BT-3            | D49.10 × T25.70                 | 110.80  | 3.07                   | –                   | –                                 |
|                            | CS-1            | L50.60 × W50.20 × H50.20        | 297.40  | –                      | 23.21               | –                                 |
|                            | CS-2            | L50.50 × W50.50 × H50.24        | 300.00  | –                      | 19.79               | –                                 |
|                            | CS-3            | L50.54 × W50.50 × H50.50        | 300.40  | –                      | 19.33               | –                                 |
| Preset angle shear\(^2\)  | UC-1            | D49.10 × H100.74                | 439.40  | –                      | –                   | 79.56                             |
|                            | CS-2            | L50.60 × W50.20 × H50.24        | 300.00  | –                      | 19.79               | –                                 |
|                            | CS-3            | L50.54 × W50.50 × H50.50        | 300.40  | –                      | 19.33               | –                                 |
| Uniaxial compression\(^3\)| UC-2            | D49.02 × H100.86                | 439.60  | –                      | –                   | 91.64                             |
|                            | UC-3            | D49.10 × H100.48                | 440.40  | –                      | –                   | 84.99                             |

\(^1\)The average tensile strength is 2.97 MPa. \(^2\)The average shear strength is 20.78 MPa. \(^3\)The average uniaxial compressive strength is 85.40 MPa. \(^4\)Specimen size, \(D\) is diameter; \(T\) is thickness; \(L\) is Length; \(W\) is width; \(H\) is height.

![Experimental system](image_url)
where RA is the ratio of rise time to the amplitude, ms/V, and AF is the ratio of the hit count to duration, kHz.

The RA-AF distribution can be used to characterize the crack type in the material. Research has shown that the microfractures within rock materials can excite two types of waveforms, longitudinal and transverse [21, 24, 33, 39]. The energy generated by tensile cracks is mainly stored in the longitudinal waves. Because a longitudinal wave propagates faster than a transverse wave, the main energy (the maximum amplitude) arrives earlier, resulting in a shorter rise time and thus a smaller RA value. In contrast, the energy generated by shear cracks is stored mainly in the transverse waves, and the main energy (the maximum amplitude) arrives much later than that of the longitudinal wave, causing the rise time to increase and resulting in a larger RA value. The AF value has a physical significance of average frequency; the signals produced by tensile cracks tend to have a relatively high frequency, while those produced by shear cracks are the opposite. Therefore, an AE signal with high AF and low RA values represents the initiation and development of tensile cracks, while an AE signal with high RA and low AF values represents the initiation and development of shear cracks [21, 24, 31, 40]. The schematic diagram of the AE signal time-domain parameters and crack classification are shown in Figure 3. As shown in Figure 3(b), in the yellow region, AF value > RA value, indicating tensile cracks; and in the blue region, RA value > AF value, indicating shear cracks.

Figure 4 shows that the sandstone failure under the Brazilian split test exhibits a dark red color representing the core region of the RA-AF distribution, which is mainly concentrated in the tensile crack region. In this region, the RA-AF is densely distributed, with a large orange region (the normalized density above 0.6). In the shear crack region, the scatter point data are relatively sparse and relatively discretely distributed, with a large number of blue-colored, independent data points (the normalized density below 0.4). This comparison indicates that the proportion of tensile cracks is much higher than that of shear cracks for sandstone failure in the Brazilian split test.
3.3. Fracture Pattern Analysis of Sandstone under Preset Angle Shear. The RA-AF scatter point density distribution map corresponding to the specimen failure under preset angle shear is obtained using the same calculation and representation method, as shown in Figure 5.

Figure 5 shows that, for sandstone failure under preset angle shear, RA-AF is continuously and uniformly distributed, and there is significant color gradation in the density present in the tensile crack region and shear crack region to varying degrees. However, the core region of the RA-AF distribution, as represented by dark red, is mainly discretely distributed in the shear crack region. In this region, the number of shear cracks is much higher than that of tensile cracks under preset angle shear with a preset angle of 60°. When the angle changes, the fracture mode will change [41], which needs further study.

Figures 4 and 5 show the fracture patterns and crack types of sandstone under two different stress modes, both of which are consistent with the theoretical analysis and actual fracture results [29, 31], indicating that it is effective to use the RA-AF indicator to analyze the rock fracture pattern.

3.4. Fracture Pattern Analysis of Sandstone under Uniaxial Compression. Figure 6 shows a sketch of the failure state and main crack distribution of sandstone under uniaxial compression. Specimens UC-1 and UC-2 exhibited X-shaped shear failure along conjugate inclined planes, and specimen
UC-3 exhibited shear failure on a single inclined plane. Considering the axial stress-strain curve of sandstone under uniaxial compression loading (Figure 7), the rock deformation process is divided into five stages [13], which are successively the compaction of pores and fissures (OA, stage I), elastic deformation (AB, stage II), steady development of microcracks (BC, stage III), unsteady development of fractures (CD, stage IV), and postfailure (after point D, stage V), as shown in Figure 7.

To reveal the fracture pattern and crack type of sandstone under uniaxial compression loading at different deformation stages, the evolution of the RA-AF scatter point density distribution at various stages of specimens UC-1 and UC-3, which are used as examples, is plotted in Figure 8.

In stage I, overall, the RA values are high, and the AF values are low; the dark red colored region representing the core RA-AF distribution is mainly concentrated in the tensile crack region, while, in the orange area representing...
Figure 7: Axial stress-strain curve of sandstone under uniaxial compression.

Figure 8: Continued.
Figure 8: Evolution diagram of RA-AF scatter density distribution of sandstone under uniaxial compression: (a) Stage I of specimen UC-1. (b) Stage II of specimen UC-1. (c) Stage III of specimen UC-1. (d) Stage of specimen UC-1. (e) Stage V of specimen UC-1. (f) Stage I of specimen UC-3. (g) Stage II of specimen UC-3. (h) Stage III of specimen UC-3. (i) Stage IV of specimen UC-3. (j) Stage V of specimen UC-3.
high density, the proportion of shear cracks is significantly larger than that of tensile cracks, indicating that, in the pore and fissure compaction stage, a certain amount of tensile failure is generated in the sandstone, but the failure mode is still dominated by shear failure.

In stage II, the sandstone enters a linear elastic stage; in this stage, due to the end of compaction and closure of primary pores and fissures, the red area characterizing the core density distribution in the tensile crack region no longer increases, and the tensile failure is reduced to some extent.

In stage III, the sandstone gradually yields and approaches failure under increasing loading; the RA-AF scatter points show a clear trend of expansion in both the tensile crack regions and the shear crack region. Especially in the shear crack region, the RA values of scatter points show a clear increasing tendency, and several discrete red spots appear on the orange area. It should be noted that the red spots for specimen UC-1 are accompanied by a few yellow spots, while there are only red spots for specimen UC-3, and specimen UC-1 has significantly more red spots than specimen UC-3. It is indicated that, under high stress, internal cracks develop in the rock in a complex manner, but the failure mode is still dominated by shear failure, and the extent of damage caused by shear failure in specimen UC-1 is significantly higher than that in specimen UC-3.

In stage IV, the main failure plane of sandstone is gradually formed, and there is a more significant trend of RA-AF scatter point expansion. For specimen UC-1, both the orange area and the number of discrete red spots in the shear crack region increase, and the yellow spots disappear, while, for specimen UC-2, more red spots appear at the lower edge of the orange area. There are significantly more discrete blue points in both specimens than in the previous phase, indicating that, due to the aggravation of the unsteady fracture within the specimen, cracks propagate and coalesce with each other, rapidly approaching the shear failure plane.

In stage V, the trend of the RA-AF distribution characteristics of specimens UC-1 and UC-3 is further strengthened. In the shear crack region, the red spots of specimen UC-1 tend to be uniformly distributed, while more red spots appear on the upper edge of the orange area of specimen UC-3, and the red spots tend to be continuously distributed, eventually leading to instability and failure of the sandstone and forming a typical shear failure mode with a notable main crack. The failure modes of specimens UC-1 and UC-3 are shear failure along X-shaped conjugate inclined planes and on a single plane, respectively.

4. Discussion

To further quantitatively analyze the correspondence between the two fracture modes and rock damage, first, the data points where AF value $>$ RA value and the data points where RA value $>$ AF value, which correspond to tensile fractures and shear fractures, respectively, are selected based on the relative magnitudes of RA-AF values. Then, the time of occurrence of each data point is recorded. Next, the number of tensile or shear fractures events per unit time (1 s) is counted. Finally, the evolutionary characteristics of the number of cumulative events of tensile and shear fractures under different stress modes are analyzed. In view of the small amount of shear and tensile fractures produced by the Brazilian split tests and the preset angle shear tests, only the evolutionary characteristics of tensile fractures in the Brazilian split tests (using specimen BT-1 as an example) and the shear fracture in the preset angle shear tests (using specimen CS-2 as an example) as well as the evolutionary characteristics of the tensile fracture and shear fracture in the uniaxial compression tests (using specimen UC-1 as an example) are analyzed. The results are shown in Figure 9.

As seen from Figure 9(a), for the sandstone in the Brazilian split tests, the tensile fracture event rate is extremely low in the early stage of the tests, corresponding to the linear elastic deformation stage of the rock, when the stress increases at a fast rate. Subsequently, cracks begin to initiate and develop, the rate of stress increase is weakened significantly, the variation in the tensile fracture event rate is characterized by alternating high and low values, and the number of cumulative events increases at a fixed slope and with fluctuations. When the main failure occurs, the stress value of the specimen drops instantaneously, and the variations in the tensile fracture event rate and the cumulative event number both stop.

It can be seen from Figure 9(b) that, for sandstone failure under preset angle shear, the shear fracture event rate is low in the early stage of the test. As the stress in the specimen increases, the shear fracture event rate and the cumulative event number show a synchronous increase. After the specimen reaches the peak stress, the shear fracture event rate decreases to some extent, and the increase rate of the cumulative event number decreases. That is, the same fracture mode always increases continuously until the specimen completely fails for the sandstone in the Brazilian split tests and the preset angle shear tests.

Figures 9(c) and 9(d) show that, for sandstone failure under uniaxial compression, the variation trends of the two fracture modes are synchronous, showing the characteristics of synchronized alternating decreases and increases. However, at any moment of time, the number of shear fracture events is far greater than the number of the tensile cracks; the curve of the tensile fracture and shear fracture cumulative event number is “gentle” in the early stage, “steady” in the middle stage, “steep” in the late stage, and “flat” in the end stage. The occurrence of these characteristics is explained as follows. As the specimen starts to be subjected to compression, the primary pores and microfissures within the specimen are rapidly compacted and closed under loading. This process results in high numbers of both types of cracks at the beginning of the test, corresponding to the compaction of the pores and fissures to elastic deformation (section OB in Figure 7), i.e., “gentle” in the early stage. As the loading increases, the process of compaction and closure of the primary pore and microfissures under compression ends, and the specimen enters a linear deformation stage. While new cracks initiate in the specimen, the specimen constantly resists the ductile development of these cracks, so both types of event rate decrease significantly, which corresponds to the steady development of elastic microcracks.
Figure 9: Continued.
As the loading continues to increase, the cracks in the specimen gradually accumulate to a sufficient number enabling qualitative change, and the specimen begins to transition to the stage of unsteady fracture development, causing further development of the ductile fracture of both types of cracks. Therefore, tensile cracks and shear cracks rapidly propagate, approaching the shear fracture plane. Mutual propagation and coalescence between cracks become increasingly active, and the number of cracks increases rapidly. Hence, both types of event rates remain at a high level, and the cumulative event number curve rises steeply, corresponding to the unsteady development of fractures (section CD in Figure 7), i.e., “steep” in the late stage. After the peak stress is reached, shear cracks are formed, and the two types of event rate curve decrease, causing a “flat” stage in the cumulative event number curve that corresponds to the portion of the curve after point D, that is, when the specimen completely fails.

5. Conclusions

(1) Analysis of the distribution of the RA-AF indicator values of the AE signal shows that, for sandstone under both Brazilian split tests and preset angle shear tests, a certain number of tensile cracks or shear cracks are generated, and both types of cracks accompany the whole process of rock damage and failure. However, the type and number of cracks are
correlated with the fracture mode formed in the rock. That is, tensile fractures are dominant under Brazilian split test, while shear fractures are dominant under preset angle shear test.

(2) For sandstone failure under uniaxial compression, the fracture mode is dominated by shear fractures, and the evolutionary characteristics of shear fractures and tensile fractures are synchronous. The development of cracks is complicated from the stage of steady development of microcracks, and the crack development is different in different specimens, which eventually leads to different failure modes. The type of cracks formed can provide positive feedback to the RA-AF distribution. The corresponding cumulative event rate is characterized by synchronized alternating decreases or increases, and the cumulative event number increases, exhibiting significant differences among stages that can correspond to various stages of rock damage and deformation.

(3) Based on the RA-AF distribution and its event rate, the fracture pattern of the rock can be effectively analyzed, which is consistent with the actual failure state of the rock, and can reveal the fracture pattern as well as crack propagation and evolutionary process of the rock to some extent.

Data Availability

The data generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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