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Experimental Study on Mechanical Properties, Energy Dissipation Characteristics and Acoustic Emission Parameters of Compression Failure of Sandstone Specimens Containing En Echelon Flaws

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Abstract: To further understand the fracture behavior of rock materials containing en echelon flaws and determine precursor information for the final collapse of damaged mineral assemblies under compression, a series of uniaxial compression experiments using a loading system, an acoustic emission system and a video camera was conducted on sandstone specimens containing en echelon flaws. The mechanical properties, energy dissipation characteristics and acoustic emission parameters of compression failure of selected specimens were successively analyzed. The results showed that crack initiation was accompanied by a stress drop, step-like characteristics on the energy consumption curve and increased crackling noises, which were used as early warning signals before the final collapse happened. In addition, we used the histogram statistics method and maximum likelihood method to analyze the distribution of acoustic emission energy and determined that the acoustic emission energy distributions of sandstone specimens containing en echelon flaws followed a power law. With the progress of the experiment, the optimum exponents changed in different stages and gradually decreased as failure was approached, which could also be used as an early warning signal before the final collapse happened. This paper may provide some theoretical basis for monitoring and warning about the collapse and instability of engineering rock masses containing en echelon flaws.

Keywords: en echelon flaws; stress drop; energy dissipation; acoustic emission; power law distributions

1. Introduction

Natural rock is damaged material to a varying degree. With the increasing scale and size of rock mass engineering, rock masses transform from an intact state to a heavily fractured state, and the analysis of deformation and prediction of collapse for the rock mass also become more difficult. Among all kinds of flaws, en echelon flaws are seen as a unique set of subparallel flaws, and they have been commonly found in rock masses of high slopes and yield pillars [1,2]. For example, Figure 1 shows a natural rock mass containing en echelon flaws in an open-pit mine. The initiation, propagation and coalescence of cracks between en echelon flaws may occur and result in the instability failure of a rock mass [3–5] because a rock mass containing en echelon flaws is subjected to compressive loading resulting from earthquakes, rock mass gravity, blasting, traffic and so on. Therefore, understanding the fracture behavior of rock materials containing en echelon flaws under compression conditions is very important to predict the collapse and instability of rock mass structures.

Figure 1. Rock mass structure containing en echelon flaws in an open-pit mine.

To avoid the use of expensive large cutting equipment to make real rock samples, it is easy to fabricate pre-existing fissures in rock-like materials by inserting thin steel discs or paper to simulate open or closed fissures, and many scholars have used rock-like materials with pre-existing fissures to study the fracture behavior of rock materials containing en echelon flaws. Sagong and Bobet [6] carried out a series of uniaxial compression tests on rock-like specimens containing en echelon flaws. They found that the crack types and coalescence patterns produced in specimens with two flaws can be extrapolated to specimens with multiple flaws and that crack coalescence was produced by the linkage of two flaws through wing and/or secondary cracks. Cao et al. [7] investigated the crack initiation, propagation, coalescence and interaction mechanisms of multicrack in brittle rock, and identified seven types of coalescence based on the nature of the cracks involved. Prudencio and Jan [8] performed biaxial compression tests on rock-like materials containing en echelon flaws. In their study, the failure mode and maximum strength of the specimen depended on the ratio between the intermediate stress and intact material compressive strength, the orientation of the principal stresses, the geometry of the pre-existing fissures and the degree of fracture persistence. To further understand the fracture behavior of rock materials containing en echelon flaws under compression conditions, some scholars obtained precracked rock materials using mechanical or hydraulic cutting equipment, and studied the specimens by various auxiliary testing methods. Cheng et al. [9] used a loading system, an optical microscope and an image recording system to analyze the fracture characteristics of Carrara marble containing en echelon flaws. They mainly reported the linking behaviors of flaws, correlations between stress and flaw configuration, fracture process zone and structures in fault tips. Yang et al. [10] established the relationship between the axial stress–strain curve of precracked sandstone specimens and the real-time crack coalescence process and used this relationship to evaluate the macroscopic deformation characteristics of precracked sandstone specimens. Among the various auxiliary testing methods, acoustic emission (AE) monitoring technology can record the fracture process of various materials in real time, so acoustic emission test data (count, cumulative count, energy, frequency, etc.) were often used to characterize the fracture properties of rock materials in various experiments [11–15]. In addition, Salje et al. [16–19] conducted a statistical analysis of acoustic emission test data obtained from the experiment. They found that the acoustic emission energy distribution during compression failure of intact rock materials followed a power law distribution, which provided a theoretical basis for disaster prediction.

However, there are few studies on the mechanical properties, energy consumption characteristics and acoustic emission parameters during compressive failure of rock materials containing en echelon flaws to predict the collapse and instability of rock mass structures with echelon flaws. Therefore, we carried out a series of uniaxial compression experiments on sandstone specimens containing en echelon flaws. The real-time acquisitions of the stress–strain curves, fracture process and acoustic emission data of selected samples were carried out using a Shimadzu I-250 (Japan) testing machine, a video camera and an acoustic emission instrument. The mechanical and acoustic phenomena in the failure process of specimens were determined, and the characteristics of these phenomena were used to predict the collapse and instability of the rock mass structure.

2. Specimen Preparation and Testing

2.1. Specimen Preparation

Sandstone is a granular frictional–cohesive material in nature, and its main mineral components are quartz and feldspar. In this study, we used sandstone from Sichuan Province in China. According to the International Society for Rock Mechanics (ISRM) testing guidelines, the ends of the specimens were ground flat by a double-face grinding machine to within ± 0.02 mm. All tested sandstone specimens were rectangular blocks 100 mm in height, 50 mm in width and 25 mm in thickness. Two parallel fissures in specimens were fabricated using a water-jet cutting machine. The length and width of each flaw were 6.0 mm and 1.0 mm, respectively. The parallel fissures in sandstone specimens have different inclination angles (β) of 30° , 45° and 60° . The samples were numbered as “B-flaw inclination angle”. B represents a specimen containing two parallel en echelon flaws. For example, “B-30” represents a specimen containing two parallel fissures and the flaw inclination angle (β) of 30° . Figure 2 shows material objects and detailed geometries of sandstone specimens containing en echelon flaws in this study.

Figure 2. Diagram of selected samples: (a) material objects; (b) detailed geometries (distance unit: mm).

2.2. Testing System

The experimental instruments under conditions of uniaxial compression mainly include a Shimadzu I-250 (Japan) testing machine, a PCI-2 acoustic emission monitoring system and a video camera, as shown in Figure 3. The Shimadzu I-250 (Japan) testing machine was used to carry out the uniaxial compression test of sandstone specimens containing en echelon flaws. The loading method and loading speed were displacement control and 0.05 mm/min, respectively. The acoustic emission

signal was preamplified (40 dB) and recorded with a PCI-2 acoustic emission monitoring system (DISP from American Physical Acoustics Company). The threshold for detection was chosen as the signal of an empty experiment (45 dB). To confirm the initiation, propagation and coalescence of cracks between en echelon flaws, a video camera was used throughout the entire period of deformation. Before the experiment, six piezoelectric sensors were fixed on the surface of the specimen, and their positions are shown in Figure 2b. Every piezoelectric sensor was coated with a special coupling agent and fixed with adhesive. At the same time, we evenly coated a layer of butter on the ends of the specimen to reduce the interference of the end effect on the acoustic emission signals. Finally, the loading system, acoustic emission system and photographic system were simultaneously turned on to synchronously collect the mechanical and acoustic emission phenomena during compression failure of the specimen. After the uniaxial compression experiment was completed, the crack patterns of the failure specimens were reconstructed by CT scanning machine.

Figure 3. Experimental equipment and procedure.

To ensure that the mechanical properties of the selected sandstone samples are within a narrow statistical spread, the mechanical properties of three intact sandstone specimens were tested, as shown in Figure 4a. The averages of the uniaxial compressive strength (σ_c), peak strain (ϵ_c) and elastic modulus (E) of the three intact specimens were 58.28 MPa, 1.01% and 7.94 GPa, respectively, and the corresponding coefficients of variation (the ratio between the standard deviation and mean value) were 0.30%, 3.70% and 2.35%, respectively. Therefore, the variability of the mechanical parameters of the selected sandstone is considered small. The selected sandstone specimens can be used to study the mechanical properties, energy dissipation characteristics and acoustic emission parameters during compression failure of sandstone specimens containing en echelon flaws.

3. Experimental Results and Theoretical Analysis

3.1. Mechanical Properties

Before the uniaxial compression experiment, the height and loading area of the specimen are obtained directly by using vernier calipers. Moreover, the axial force and the corresponding height increment of the specimen can be obtained directly by using the Shimadzu I-250 (Japan) testing system. These data were processed to obtain the axial stress–strain curves of selected samples with different flaw inclination angles, as shown in Figure 4b–d. The experimental results showed that the failure process of the specimens under uniaxial compression passed through the stages of original microcrack closure, microcrack nucleation, macrocrack propagation and coalescence. With increasing axial stress, the axial stress–strain curve shows an obvious stress drop phenomenon in Figure 4b–d. According to

the photographic monitoring results, every stress drop phenomenon corresponded to the initiation or unstable propagation of macrocracks and was accompanied by a crackling noise. When the first stress drop phenomenon of selected samples occurred during the compression failure process, the selected samples did not produce a penetrating failure surface. Furthermore, the selected samples continued to be loaded, we found that they could still bear axial stress, which showed that the selected samples were not completely destroyed.

Figure 4b–d shows that there are two stress drops before the final failures of the specimens, and we infer that the axial stresses of the specimens may decrease suddenly during the loading process near crack initiation and crack coalescence. From Figure 4b–d, points 1 and 2 on the axial stress–strain curves are stress drop points, and the stress and strain values of stress drop point 1 are the initial crack initiation stress and initial crack initiation strain, respectively. The stress and strain values of stress drop point 2 are the peak strength and peak strain, respectively. The corresponding stress and strain values of stress drop points 1 and 2 are calculated, as shown in Table 1. When the corresponding stress value of a point on the stress–strain curve is 20 MPa, the tangent modulus of this point is defined as the elastic modulus (E) of the specimen in this paper. According to Table 1, the initial crack initiation stress and peak strength gradually decrease with increasing flaw inclination angle. After comparing and analyzing the stress and strain values of stress drop points 1 and 2, we found that the initial crack initiation stress is approximately 90–98% of the peak strength, and the initial crack initiation strain is approximately 93% of the peak strain. Therefore, we infer that the selected samples usually exhibited macrocrack initiation at 90% of peak strength.

From Figure 4b–d, point 3 on the axial stress–strain curves is the final failure point of selected samples. The stress value of point 3 on the axial stress–strain curve is not zero, which indicates that the failure specimen still has a certain bearing capacity. The final crack patterns of the specimens are shown in Figure 5. In Figure 5, “T” and “S” represent tensile cracks and shear cracks, respectively. The blue color represents sandstone grains and the white color represents cracks. From Figure 5a–b, crack coalescence between en echelon flaws is mainly produced by the linkage of two tensile cracks. From Figure 5c, the connection of tensile cracks and shear cracks between en echelon flaws produces a fault. Combining this information with the results of photogrammetric monitoring, the crack initiation between en echelon flaws occurred at the time of stress drop point 1. When the axial stress gradually increased to the peak strength, crack coalescence between en echelon flaws began to occur, so the crack further developed into a larger macrocrack. Therefore, we believe that the en echelon flaws of rock materials under compression conditions were usually connected by breaking the rock bridges between the fractures, which was helpful in determining the placement of sensors for monitoring and warning about the collapse of an engineering rock mass.

Figure 4. Cont.

Figure 4. Axial stress–strain curves under uniaxial compression. (a) Intact specimen; (b) B-30; (c) B-45; (d) B-60.

Figure 5. The final crack patterns of specimens containing en echelon flaws: (a) B-30; (b) B-45; (c) B-60. (d) Simplified crack pattern observed in rock in uniaxial compression [4].

Table 1. The corresponding stress and strain values of the stress drop points (units: MPa; %; GPa).

Sample	Point 1		Point 2		E (GPa)
	σ_1 (MPa)	ε_1 (%)	σ_1 (MPa)	ε_1 (%)	
B-30	54.47	0.96	55.68	1.03	7.78
B-45	51.70	0.85	53.58	0.91	7.55
B-60	39.76	0.94	43.96	1.01	6.25

3.2. Energy Dissipation Characteristics

Experimental studies on energy dissipation characteristics have shown that the instability of rock materials is essentially the result of the internal energy stored in the rock materials being suddenly released [20–22]. Therefore, the laws of thermodynamics are often used to describe the deformation and failure of rock material. It is assumed that there is no heat exchange between the experimental system and the outside world, and the kinetic energy loss generated during the process of rock instability is also ignored. Then, the total work, elastic energy and dissipated energy for selected samples under uniaxial compression conditions are shown by Equations (1)–(4) and Figure 6 [23],

$$W = W_e + W_d, \quad (1)$$

$$W = Al \int \sigma_1 d\varepsilon_1 = Al \sum_{k=1}^n \frac{1}{2} (\sigma_{1k} + \sigma_{1k-1}) (\varepsilon_{1k} - \varepsilon_{1k-1}), \quad (2)$$

$$W_e = \iiint_V v_\varepsilon dV = Al \frac{\sigma_1^2}{2E}, \quad (3)$$

$$\eta_d = \frac{W_d}{W} \times 100\%, \quad (4)$$

where W is the total work; W_e and W_d are the elastic energy and dissipated energy for selected samples, respectively; σ_{1k} and ε_{1k} are the stress and strain values at each point of the axial stress–strain curve, respectively; v_ε and V are the strain energy density and volume of selected samples, respectively; E , A and l are the elastic modulus, loading area and height of selected samples, respectively; and η_d is the energy dissipation rate.

From Figure 6, the energy conversions of selected samples with different flaw inclination angles present obvious step-like characteristics. Before the ends of en echelon flaws began to generate new cracks, the total work and elastic energy increased in a parabolic form, and the dissipated energy gradually increased to a stable value, which indicated that the selected samples were generally in the phase of energy storage. As the axial stress increased to the stress of point 1, crack initiation occurred at the tips of the en echelon flaws, and the dissipated energy curves exhibited a significant upward step for the first time, which could be used as an early warning signal before the final collapse happened. The selected samples failed suddenly at the peak strength, and the dissipated energy curves exhibited a significant upward step again. After the peak strength, the releasable elastic energy stored in the selected sample was suddenly released by means of kinetic energy, acoustic emission energy and so on, which resulted in a rapid increase in the dissipated energy curve and a linear decrease in the elastic energy curve. The crack further expanded to form the main fracture surface, and the selected samples eventually became unstable.

Figure 6. Energy dissipation characteristic curves of specimens containing en echelon flaws: (a) B-30; (b) B-45; (c) B-60.

The corresponding total work and dissipated energy of stress drop points 1 and 2 are calculated, as shown in Table 2. According to Table 2, the corresponding total work of stress drop point 1 gradually decreases with increasing flaw inclination angle, which indicates that the total work required for crack initiation is affected by the flaw inclination angle. As the flaw inclination angle increases, the corresponding total work and energy dissipation rate of stress drop point 2 gradually decrease, which indicates that the flyrock phenomena caused by postpeak instability of the selected samples gradually become weaker with increasing flaw inclination angle.

Table 2. The corresponding total work and dissipated energy of the stress drop points (units: J; %).

Sample	Point 1			Point 2		
	W (J)	W _d (J)	η_d (%)	W (J)	W _d (J)	η_d (%)
B-30	25.79	1.96	7.60	30.34	5.43	17.90
B-45	23.29	1.16	4.98	26.79	3.02	11.27
B-60	17.83	2.02	11.33	21.71	2.39	11.01

3.3. Acoustic Emission Parameters

3.3.1. Acoustic Emission Counts

Figure 7 illustrates the variations in the acoustic emission (AE) counts, cumulative acoustic emission (AE) counts and axial stress for sandstone specimens containing en echelon flaws versus time. From Figure 7, in the uniaxial compression tests, the changes in the AE counts, cumulative AE counts

and axial stress of selected samples with different flaw inclination angles are seen to exhibit similar trends. It is worth noting that the corresponding AE counts and cumulative AE counts of stress drop point 1 are significantly increased in Figure 7. Therefore, we divide the process of acoustic emission energy release into two stages, and the time at which stress drop point 1 occurred is seen as the turning point in the process of acoustic emission energy release.

Figure 7. The time evolution of the AE counts, cumulative AE counts and axial stress: (a) B-30, (b) B-45, (c) B-60.

(1) The first stage: According to the photographic monitoring results, no new cracks of the ends of pre-existing fissures were generated at this stage. At the same time, the AE count was smaller, the cumulative AE count increased slowly, and its curve was approximately a straight line.

(2) The second stage: According to the photographic monitoring results, a new crack appeared at this stage; furthermore, with increasing axial stress, the crack continued to extend until the specimen became unstable. Before the final failure of the specimen, the AE count or cumulative AE count could be seen to increase significantly many times, which was regarded as an early warning signal for the final collapse of the specimen.

3.3.2. Distribution of Acoustic Emission Energies

The acoustic emission energies of AE events are determined by fast numerical integration of the square voltage of signals [17], as

$$Q = \frac{1}{R} \int_{t_1}^{t_2} U^2(t) dt, \quad (5)$$

where Q and U are the acoustic emission energy and voltage, respectively, and R , t_1 and t_2 are the reference electrical resistance and the starting and ending times of the voltage transient record, respectively.

Firstly, we used the histogram statistics method to analyze the acoustic emission energies during the whole process of compression failure of the specimens. The probability distribution function is $P(Q)$ and is calculated by appropriate linear binning of acoustic emission energies. Figure 8 shows the energy distributions in log–log plots for selected samples with different flaw inclination angles.

Figure 8. Log–log plots of the energy distribution of the AE events: (a) B-30, (b) B-45, (c) B-60.

From Figure 8, the probability distribution function in log–log plots is quite linear. Therefore, we suggest that the distributions of acoustic emission energies of specimens containing en echelon flaws follow a power law, as

$$P(Q)dQ \sim \frac{Q^{-r}}{Q_{\min}^{1-r}} dQ \quad Q > Q_{\min}, \quad (6)$$

where $Q_{\min}$ and r are the lower cutoff needed for normalization and the optimum exponent, respectively. The optimum exponent is the absolute value of the straight slope in Figure 8. Figure 8 shows that the optimum exponent of the acoustic emission energy distribution of the specimens changes between 1.62 and 1.68. All previous uniaxial compression experiments have identified the power law exponent as ranging between 1.33 and 1.97 [18]. Therefore, the optimum exponent in this study lies within the range of power law exponents from previous studies, which suggests that this result is reliable.

Secondly, to use the histogram statistics method to further analyze the distributions of acoustic emission energies in the two stages of compression failure of the specimens, the large number of acoustic emission energy data analyses required the construction of histograms and the choice of the number of bins. To improve the accuracy of the power law exponent, we used the maximum likelihood method to estimate the power law exponent for the two stages during the uniaxial compression tests, as

$$r'(x_{\min}) = 1 + n \left[\sum_{i=1}^n \ln \frac{x_i}{x_{\min}} \right]^{-1}, \quad (7)$$

$$\sigma = \frac{r'(x_{\min}) - 1}{\sqrt{n}} + O(n^{-1}), \quad (8)$$

where $x_i, i = 1, 2, 3, \dots, n$ are the observed values of x such that $x_i \geq x_{\min}$. In this study, x represents the AE energy. σ is the standard error. Here and elsewhere, we use “prime” symbols such as r' to denote estimates derived from data. A no-prime symbol such as r denotes the optimum value, which is often unknown in practice [24].

Figure 9 shows the results for the two stages during the uniaxial compression test. This analysis leads to a plateau that defines the optimum exponent; while the plateau is not as clean as possible, the optimum exponent can be determined from the vertical position of the shoulder revealed by this curve [18]. From Figure 9, r_1 is the optimum exponent of the first stage, and r_2 is the optimum exponent of the second stage. The optimum exponents of the first stage of selected samples with

different flaw inclination angles are greater than those of the second stage in Figure 9. At the same time, combining Figures 8 and 9, the optimum exponent of the second stage is equal to that of the whole process of compression failure. Therefore, we determine that the optimum exponent of the acoustic emission energy distribution changes in different stages with increasing axial stress and gradually decreases as failure is approached, which acts as a warning signal for the impending major collapse. From Figure 9, the optimum exponents of the second stage of the selected samples with different flaw inclination angles have some differences, which may result from the calculation of standard error with the maximum likelihood method. When $Q_{\min}$ is within the range of 100 aJ to 1000 aJ, the fitted exponents tend to a stable value, and the standard error is mainly within 0.03 using Equation (8). Therefore, we believe that the flaw inclination angle has no effect on the optimum exponent and that the optimum exponents of the specimens are 1.65 ± 0.03 .

Figure 9. Fitted exponent r' as a function of lower threshold $Q_{\min}$: (a) B-30, (b) B-45, (c) B-60.

4. Discussion

The sandstone specimens containing en echelon flaws are cohesive granular materials, and they have the properties of heterogeneity, discontinuity, anisotropy and nonlinearity on the microscopic scale, which may result from the multiscale effects of voids and the existence of flaws. Therefore, it is currently difficult to use a quantitative model to analyze the instability of rock mass structure [25]. However, the sandstone specimens containing en echelon flaws exhibit the behavior of self-organized

critical characters under the action of external forces [26,27]. The result of microcrack nucleation leads to macrocrack initiation at the ends of the en echelon flaws, which is accompanied by various mechanical and acoustic phenomena that make it possible to predict the collapse and instability of an engineering rock mass.

To further summarize the precursory information for the final collapse of specimens containing en echelon flaws, we first analyzed the axial stress–strain curves and energy dissipation characteristic curves. We found that two phenomena could be regarded as early warning signals before the final collapse happened: one was the stress drop phenomenon, and the other was the first upward step phenomenon of the dissipated energy curve. Macrocrack initiation by the intermittent nucleation, propagation and coalescence of microcracks generated crackling noises, which can be detected by acoustic instruments [28]. Therefore, we further analyzed the acoustic phenomena during the compression failure process of selected samples and found that the AE counts and cumulative AE counts of the crackling noises significantly increased many times before the final failure of specimens containing en echelon flaws; these increases could be used as early warning signals before the final collapse happened. At the same time, we studied the distribution of acoustic emission energies using the histogram statistics method and the maximum likelihood method [24] and determined that the distributions of acoustic emission energies of specimens containing en echelon flaws followed a power law. Finally, the maximum likelihood method was used to study the optimum exponents of AE energy distributions for different stages. It was found that the optimum exponent gradually decreased as failure was approached, which was the same as the results of the previously studied complete materials [18]. Therefore, the change in the optimum exponent was an inherent property of the compression failure process of various rock materials and could be used as one of the indicators to monitor the instability of an engineering rock mass. Whatever the flaw inclination angle in this study, the en echelon flaws were connected by breaking the rock bridges between the flaws to produce a fault. This phenomenon was similar to the formation mechanism of the fault zone of earthquakes [29,30], so the optimum exponents of specimens containing en echelon flaws were close to those of earthquakes [19]. In this paper, the optimum exponents of specimens containing en echelon flaws were 1.65 ± 0.03 .

According to the mechanical and acoustic characteristics of compressive failure of specimens containing en echelon flaws in this paper, we can arrange the acoustic emission sensors and stress meters in a rock body, and AE counts, cumulative AE counts, acoustic emission energy and stress can be collected in real time. In addition to the observation of stress drop and the increase in crackling noises, the change in the optimum exponent of the acoustic emission energy distribution can be analyzed by a simple calculation program. It is worth noting that the engineering rock mass is in a complex stress environment which is greatly affected by external disturbance, and there may be no stress drop phenomenon before rock mass failure, which is inconsistent with the research results under perfect laboratory conditions. At the same time, the low-energy acoustic emission signals generated during the failures of some rock masses are obviously attenuated. Therefore, the accuracy acquisitions of the AE counts and AE energy depend on the installation location of acoustic emission sensors. However, the acoustic emission monitoring technology is applicable to various complex stress conditions and has certain application value. To sum up, we observe the stress drop, the increase in crackling noises and the change in the optimum exponent of the acoustic emission energy distribution, which can predict the collapse and instability of rock mass structures more accurately.

5. Conclusions

A series of uniaxial compression experiments have been conducted on sandstone specimens containing en echelon flaws. The focus of this paper is to investigate the mechanical and acoustic phenomena of selected samples and apply these phenomena to predict the collapse and instability of rock mass structures. From this work, the following key points can be concluded:

(1) With increasing flaw inclination angle, the initial crack initiation stress, peak strength, total work and dissipated energy at the peak stress gradually decreased. The specimens containing en echelon flaws usually exhibited macrocrack initiation at 90% of peak strength.

(2) Before the final collapse of sandstone specimens containing en echelon flaws, obvious precursor information appeared, which included a clear stress drop on the axial stress–strain curve, obvious step-like characteristics on the energy consumption curve, and significant increases in the acoustic emission counts and cumulative acoustic emission counts.

(3) With the progress of the experiment, the optimum exponent of the acoustic emission energy distribution of crackling noises changed in different stages and gradually decreased as failure was approached, which was also regarded as an early warning signal before the final collapse happened.

(4) The optimum exponents of specimens containing en echelon flaws were 1.65 ± 0.03 and were close to those of earthquakes.

Author Contributions: Author contributions: D.Z. and S.L. conceived and designed the experiments; S.L., X.B. performed the experiments; S.L., Y.Y., Y.C. analyzed the data; and D.Z., S.L. wrote the paper.

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