Experimental Study on Source Failure Mechanism and Acoustic Emission Characteristics of Red Sandstone Under Uniaxial Compression

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Abstract

In order to study the rock fracture mechanism and precursor characteristics, uniaxial compression experiments of red sandstone were carried out. Using acoustic emission technology and digital speckle correlation method as experimental observation means, the evolution characteristics of deformation field and acoustic emission index during rock deformation were studied. The results show that : (1) The deformation concentration of rock deformation localization zone is the main cause of nonlinear evolution of rock stress-strain curve. (2) The volume parameters of different types of cracks in rock acoustic emission change with the relative displacement rate and dislocation rate of deformation localization zone. (3) In terms of failure types, there are more high-frequency components of tensile fracture main frequency, more low-frequency components of shear fracture main frequency, and wider distribution of mixed fracture main frequency. In the time sequence, the spectrum distribution of acoustic emission signals is wide and the amplitude is small at the sudden change time. At the sudden change time, the spectrum distribution of acoustic emission signals becomes narrow, the amplitude increases, and the spectrum distribution of peak points is greatly narrowed. Therefore, it is considered that the spectrum distribution is greatly narrowed can be used as an early warning precursor.

1 Introduction

The continuous accumulation of internal cracks in rock causes rock fracture instability^[1-5]. Correct understanding of the source evolution process and fracture mechanism plays an important role in the early warning and prevention of engineering disasters such as rock burst, landslide and tunnel collapse induced by rock deformation. The research on the spatio-temporal evolution of rock deformation and failure and the relationship between acoustic emission information is the basis for exploring the mechanism of rock deformation and failure and establishing the accurate prediction and prediction system of rock engineering disasters. Therefore, it is of major theoretical and practical significance to carry out experimental research on rock fracture mechanism and acoustic emission characteristics by using acoustic emission technology.

Domestic and foreign scholars have carried out a lot of research on rock fracture mechanism and acoustic emission characteristics, and have made many meaningful research results. In terms of rock deformation and failure types, such as Linjun Wang et al., Yixiong Gan et al.^[6-7] based on RA and AF indicators, analyzed the rock fracture mechanism. Yean Cao et al., Shida Xu et al. and Shunchuan Wu et al.^[8-10] used the moment tensor inversion method to solve the fracture mechanism, source parameters and fracture energy. Yimin Song et al.^[11-12] used digital speckle correlation method to study the relationship between deformation evolution and acoustic emission characteristics. In the study of acoustic emission characteristics in the process of rock fracture, mainly concentrated in the following three directions : (1) The study of conventional basic parameters, such as : Hongguang Ji^[13] studied the relationship between the ringing count, energy accumulation count of acoustic emission signal and rock stress, time. (2) The study of characteristic parameters, such as : Xianzhen Wu et al.^[14] summarized the

evolution mode of fractal curve fluctuation → continuous decline of acoustic emission parameter sequence in rock mass failure process, and the continuous decline of fractal value was regarded as the precursor of rock failure instability. Yimin Song et al.^[15] used acoustic emission b value index and combined with the evolution characteristics of deformation energy density to study the fracture scale characteristics of interface contact damage during loading. Chunlai Wang et al.^[16] summarized the evolution models of spatial and temporal entropy values, and believed that the sharp decline of the two entropy values can be used as the precursor information of rockburst, and the decline point can be used as the warning point of rockburst. (3) Waveform analysis: Yimin Song^[17] studied the red sandstone specimen deformation field evolution and acoustic emission frequency distribution range, event rate corresponding relationship. Xiaoquan Huo et al.^[18] deduced the fault dislocation process and waveform characteristics by using the concave-convex model and the stick-slip model of fault activity. Scholars had done a lot of research work on rock deformation and failure process and acoustic emission characteristics in the process, and had achieved some valuable results. However, acoustic emission characteristics are not only relate to the mechanical state of rock and the simple deformation localization of rock, but also relate to the formation, evolution mechanism and crack motion mechanism of deformation localization zone. A large number of in-depth experimental studies are needed.

In this paper, a red sandstone material is selected as a rock specimen by uniaxial compression loading. The CCD camera is used to build an image acquisition system in the process of rock deformation and failure. The rock deformation field in the loading process is calculated by digital speckle correlation method, and the spatiotemporal evolution characteristics of rock deformation and failure are studied. The acoustic emission technology is used to construct the physical information monitoring system in the process of rock deformation and failure. The acoustic emission indexes in the process of rock deformation and failure are calculated according to the moment tensor inversion method, and the spatio-temporal evolution characteristics of acoustic emission indexes are studied. Based on the space-time evolution characteristics of rock deformation field and acoustic emission index, the corresponding relationship between relative displacement rate of deformation localization zone and source volume parameters and the fracture mechanism of mutation point of relative displacement rate of deformation localization zone are studied, and the acoustic emission waveform and spectral characteristics of different fracture mechanisms are discussed.

2 Moment Tensor Inversion Analysis Method

According to the elastic wave dynamics theory, under the action of crack propagation, the displacement generated at time t at position x can be expressed as^[19]:

$$u_i(x, t) = M_{jk} \left[G_{ij,k}(x, x_0, t) \right] * S(t)$$

In the formula, $G_{ij,k}(x, x_0, t)$ is the spatial derivative of the Green 's function of elastic dynamics, $S(t)$ is the source time function and is assumed to be a pulse function, M_{jk} is the moment tensor of the acoustic emission source, which is the description of the mechanical properties of the acoustic emission source.

Ohstu^[20] introduced the pulse function and ignored the time function $S(t)$ to obtain the initial amplitude $A(x)$ of SiGMA simplified P wave at the acoustic emission probe in semi-infinite space :

$$A(x) = \frac{C_s \text{Ref}(t, r)}{R} (r_1 r_2 r_3) \begin{pmatrix} m_{11} m_{12} m_{13} \\ m_{21} m_{22} m_{23} \\ m_{31} m_{32} m_{33} \end{pmatrix} \begin{pmatrix} r_1 \\ r_2 \\ r_3 \end{pmatrix}$$

2

Among them, C_s is the correction factor of the acoustic emission sensor probe. R is the distance from the rupture point to the detection point (probe). r_1, r_2, r_3 represent the direction cosine from the rupture point to the probe. $\text{Ref}(t, r)$ is the sensor reflection coefficient, which can be expressed as :

$$\text{Ref}(t, r) = \frac{2k^2 a [k^2 - 2(1 - a^2)]}{[k^2 - 2(1 - a^2)]^2 + 4a(1 - a^2)\sqrt{k^2 - 1 + a^2}}$$

3

Among them, $k = v_p / v_s$, v_p is elastic longitudinal wave velocity, v_s is shear wave velocity $a = r \cdot t$.

The moment tensor is a second-order tensor, and the moment tensor inversion requires at least six effective P-wave initial motion amplitudes. Therefore, this paper selects the source events receiving six or more acoustic emission signals as the research object.

The dominant classification method is used to determine the type of microcracks, and all eigenvalues are regularized based on the maximum eigenvalue :

$$\begin{aligned} m_1 / m_1 &= X + Y + Z \\ m_2 / m_1 &= 0 - 0.5Y + Z \\ m_3 / m_1 &= -X - 0.5Y + Z \end{aligned}$$

4

Among them, X represents the proportion of shear part, Y represents the proportion of tension deviation part, Z represents the proportion of hydrostatic tensile stress part. If $X \leq 40\%$, it is judged as tensile crack. $X \geq 60\%$, judged as shear crack. $40\% < X < 60\%$ was mixed type crack^[21].

Shigeishi and Ohtsu^[22] believed that the evolutionary process of rock damage can be estimated by the trace component of torque tensor, and the experimental study proved that the rock damage obtained by Equation (5) can be regarded as the crack volume relative. Combined with the three fracture types of seismic source, namely tension, mixing and shear, the volume parameters of tension crack, mixing crack and shear crack are calculated.

$$D_r = (m_1 + m_2 + m_3) / l_k n_k$$

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where D_r is the crack volume parameter. m_1, m_2, m_3 are three eigenvalues of moment tensor. l_k is the movement direction of the crack surface. n_k is the normal direction of the crack surface.

3 Tests

3.1 Test method

The space-time evolution characteristics and fracture mechanism of rock source are studied by uniaxial compression loading. The experimental system includes three parts : loading system, image acquisition system and acoustic emission system. The RLJW-2000 test machine is used as the loading system, and the displacement control loading method is used. The loading rate is 0.05 mm / min. The CCD camera is used to build the image acquisition system to collect the speckle image of the specimen surface during the whole loading process. The image acquisition rate is 37 frames / s, the image resolution was 1600 pixels × 1200 pixels, and the surface resolution is 0.089 mm / pixel. The acoustic emission system produced by American Physical Acoustics company is used to collect the acoustic emission signals of whole loading process. The preamplifier gain is 40 dB, the threshold is 50 dB, and the sampling rate is 3 MHz. The schematic diagram of the test system is shown in Figure 1.

A red sandstone material is selected as the uniaxial compression specimen and processed into a cuboid with the length × width × height of 50 mm × 50 mm × 100 mm. Grinding the end face of the specimen to ensure the smooth end face of the specimen. One side of the specimen is selected as the CCD camera image acquisition surface, and the surface artificial speckle field is produced by spraying black paint and white paint. The collected surface speckle field is shown in Figure 3. The other three sides are the layout surfaces of acoustic emission probes. Three acoustic emission probes are arranged on each side, and vaseline is used as the coupling agent to enhance the coupling effect between the specimen and the sensor. The size of the specimen and the layout of the acoustic emission probe are shown in Figure 2, and the position of the acoustic emission probe is shown in Table 1.

Table 1
Acoustic emission probe position

serial number	X coordinate / mm	Y coordinate / mm	Z coordinate / mm
1	25	0	85
2	40	0	30
3	10	0	20
4	10	50	85
5	30	50	85
6	25	50	15
7	0	10	80
8	0	40	90
9	0	25	10

3.2 Experimental process and results

In the experimental process, first of all, to ensure that the test loading system, digital speckle acquisition system and acoustic emission acquisition system strictly consistent time. Then, the specimen is subjected to uniaxial compression loading, the CCD camera is used to collect the speckle image of the specimen surface, and the acoustic emission system is used to collect the acoustic emission signal of the specimen until the specimen is destroyed, and the loading and data acquisition are stopped. Finally, analyze the experimental data.

The loading stress-strain curve of the test process is shown in Fig. 4. According to the analysis results of the deformation field and the characteristics of the loading curve, six typical moments in the whole loading process are selected for identification. The stress values corresponding to each identification point are shown in Fig. 4, where the identification points 1 – 6 are 500 s, 700 s, 800 s, 850 s, the peak value and the end time of the test, respectively. The speckle image at the time of the marker point 0 is used as the reference image to calculate the deformation field at other marker points (the maximum shear strain field, the same below). In order to correspond to the deformation field, the acoustic emission positioning results are displayed according to the identification point time. Using the above experimental loading and control conditions, a total of 3 groups of experiments are carried out, 103 452 speckle images and 3 groups of acoustic emission data are obtained, and the experimental data are analyzed. Figure 5 is a part of the experimental results.

4 Analysis Of Experimental Results

4.1 Spatiotemporal evolution characteristics of rock deformation field

4.1.1 Evolution characteristics of rock deformation field

The digital speckle correlation method is used to calculate the speckle images on the specimen surface collected during the experimental loading process, and analyze the evolution process of rock deformation field.

The speckle images corresponding to the time of the marker point 0 in Fig. 4 are taken as the reference images, and marker 1 – 6 are taken as the deformation images. The experimental images are analyzed by digital speckle correlation method, and the maximum shear strain field of rock specimens at the corresponding time is obtained. The calculation results are shown in Fig. 6.

Marker 1 is located in the linear elastic stage of specimen loading. From the overall evolution of the maximum shear strain field, it can be seen that the specimen is in the uniform deformation stage, and the maximum shear strain value is about 0.005. Marker 2 is located in the late stage of linear elastic stage. At this time, non-uniform deformation occurs on the upper left side of the specimen, and the maximum shear strain value is about 0.04. Marker 3 is located in the early plastic hardening stage of rock specimen loading. Non-uniform deformation occurs at the bottom of the right side of the specimen, and the length and width of the deformation localization zone at the upper left side increase, and the maximum shear strain value is about 0.05. Marker 4 is located in the middle of the plastic hardening stage of rock specimen loading. It can be seen that the two deformation concentrated areas expand in the direction of close, indicating that the evolution of the deformation localization zone in the empty area starts, and the maximum shear strain value is about 0.06. Marker 5 is located at the peak load of the specimen. At this time, the deformation of the upper left side and the bottom right side of the specimen further develops and evolves towards the two directions, and the deformation localization zone is formed by connecting and connecting. The maximum shear strain value is about 0.09. Marker 6 is located in the strain softening stage after the loading peak of the specimen. The deformation localization zone continues to expand, and the maximum shear strain value increases, and the maximum value is about 0.16, which leads to the final failure of the specimen.

According to the whole stress-strain curve and deformation field evolution process of rock uniaxial compression, it can be seen that the marking points 1 and 2 are in the linear elastic loading stage, and the specimen produces local small range of deformation concentration, and the deformation concentration value is small. At this time, the influence on the bearing capacity of rock is small, and the bearing capacity increases linearly. Marker 3 and 4 are in the plastic hardening stage. Deformation concentration occurs in both upper and lower sections. The deformation value further increases, and the bearing capacity increases nonlinearly. Marker 5 is at the peak. The deformation localization zone of the specimen runs through the whole specimen, and the bearing capacity reaches the maximum. Marker 6 is

at the post-peak stage, and the bearing capacity decreases rapidly. It shows that the change of rock bearing capacity changes with the structural change of deformation localization zone.

4.1.2 Displacement evolution characteristics of rock deformation localization zone

Based on the evolution characteristics of rock deformation field, the displacement evolution characteristics of deformation localization zone are further analyzed below.

The displacement analysis method of rock deformation localization zone is as follows : according to the final deformation and failure image of rock specimen, two calculation areas are symmetrically selected on both sides of the deformation localization zone (the size of calculation area is 10 pixels $\times$ 10 pixels), and the displacement of each point in the x and y directions of the frame is calculated respectively. The average value of each point is used to represent the displacement of the center point of the calculation frame, and the difference value of the displacement of the center point of the two calculation frames is used to represent the relative displacement. The relative displacement components of the x and y directions of the center point of the calculation frame are decomposed along the tangent and normal directions of the deformation localization zone. The difference value along the tangent direction of the deformation localization zone is the relative dislocation displacement, and the difference value along the normal direction of the deformation localization zone is the relative tensile displacement. The relative dislocation displacement and tensile displacement of each image are divided by the interval time of each image, and the dislocation rate (clockwise positive) and tensile rate of deformation localization zone are obtained. The deformation localization zone is divided according to the sequence of deformation localization zone (the displacement of deformation localization zone 1 is within 0 – 15 mm in x direction and 0 – 35 mm in y direction). The displacement of deformation localization zone 2 is in the range of 16 – 26 mm in the x direction and 36 – 74 mm in the y direction. The deformation localization zone 3 displacement is located in the range of 26 – 43 mm in the x direction and 75 – 100 mm in the y direction). The analysis methods of deformation localization zone division, dislocation displacement and tensile displacement are shown in Fig. 7.

Figure 8 shows the relative displacement rate evolution curves of deformation localization bands 1, 2 and 3 during loading. In the online elastic loading stage, the relative displacement rate of the deformation localization zone is small. With the loading process, the tensile displacement rates of the deformation localization zones 1 and 2 change significantly, and then show a small fluctuation. The analysis of the displacement rate type shows that this stage is mainly characterized by tensile deformation, which is in the stage of micro-crack accumulation and deformation accumulation. In the plastic hardening stage, the relative displacement rates of the deformation localization bands first fluctuated, and then the dislocation displacement rates of the deformation localization bands 2 and 3 increased rapidly. After that, the tensile displacement rates of the three deformation localization bands increased rapidly, and finally returned to a small fluctuation state. The analysis of the displacement rate type shows that the dislocation deformation and the overall tensile deformation occurred in the deformation localization bands 2 and 3.

In the peak stage, the deformation localization zone 1, 2 and 3 are connected, and the overall dislocation occurs, and the bearing capacity reaches the extreme value. In the post-peak stage, the deformation localization bands 1, 2 and 3 interact with each other in the non-uniform evolution of tensile and shear rates, and the fluctuation of bearing capacity curve decreases.

4.2 Acoustic Emission Characteristics of Rock Deformation and Failure

According to acoustic emission information collected in the process of rock loading, using moment tensor inversion analysis method^[23, 24], according to the calculation method described in section 2, the rock crack volume parameters are obtained. According to the calculation results of moment tensor, the volume parameters of different fracture types are classified and analyzed.

Figure 9 shows the crack volume parameter curves of different fracture types during loading. During the online elastic loading stage, a small amount of acoustic emission events occurred in the specimen. On the whole, the crack volume parameter curve shows a small fluctuation, but the change of the crack volume parameter curve is obvious at some time. The crack type is tensile fracture, and a quiet period appears after the sudden increase of the crack volume parameter curve, and then continues to show a small fluctuation. In the plastic hardening stage, the fluctuation amplitude of the crack volume parameter curve increases, and a sudden increase occurs at some time. The fracture types are shear fracture and tension type. At the peak time, the crack volume parameter curve amplitude reaches the maximum, the fracture type is shear fracture, and the bearing capacity reaches the maximum. In the post-peak stage, the crack volume parameter curve shows a large fluctuation, and the fracture types are shear fracture and mixed fracture.

From the evolution curves of acoustic emission crack volume parameters of different fracture types, a small amount of small cracks are produced in the specimen during the online elastic loading stage. In the plastic hardening stage, the volume and number of cracks in the specimen increase, and the cracks penetrate at the peak time. In the post-peak stage, the cracks continue to develop and penetrate, and the crack volume is large but the number is reduced.

4.3 Study on rock fracture mechanism

As shown in Figure 10, the sudden increase of relative displacement rate in deformation localization zone corresponds well to the sudden increase of acoustic emission volume parameters. Therefore, it is necessary to select the mutation point, further analyze the corresponding relationship between the relative displacement rate and acoustic emission volume parameters, and study the rock fracture mechanism.

At the abrupt change points 1 and 2, the tensile displacement rate of deformation localization zone 1 suddenly increases, and the corresponding tensile crack volume parameters suddenly increase, and the two focal locations are located in the deformation localization zone 1. This indicates that tensile fracture

occurs in deformation localization zone 1 at mutation points 1 and 2, which made the tensile displacement rate of deformation localization zone 2 increase slightly.

At the mutation point 3, the shear displacement rate of deformation localization zone 2 suddenly increases, and the corresponding shear crack volume parameters suddenly increase, and the source is located in the deformation localization zone 2. This indicates that shear fracture occurs in the deformation localization zone 2 at the mutation point 3. Since the deformation localization zones 1 and 2 are located in the upper left corner and lower right corner of the rock specimen, the shear displacement rate of deformation localization zone 2 increases sharply, which made the tensile displacement rate and shear displacement rate of deformation localization zone 3 change.

At the mutation point 4, the tensile displacement rate of deformation localization zone 3 suddenly increases, the corresponding tensile crack volume parameters suddenly increase, and the source is located in the deformation localization zone 3. This indicates that tensile fracture occurs in deformation localization zone 3 at mutation point 4. As the tensile displacement rate of deformation localization zone 3 increases suddenly, the tensile displacement rates of deformation localization zones 1 and 2 increase accordingly.

At mutation points 5 and 6, the shear displacement rate of deformation localization zone 3 suddenly increases, and the corresponding shear crack volume parameter suddenly increases, and the focal location is located in deformation localization zone 3. This indicates that shear fracture occurs in deformation localization zone 3 at mutation points 5 and 6. Due to the sudden increase of shear displacement rate of deformation localization zone 3, the tensile displacement rate and shear displacement rate of deformation localization zone 1 and 2 increase.

At the mutation point 7, the tensile and shear displacement rates of deformation localization zone 3 suddenly increase, and the corresponding mixed crack volume parameters suddenly increase, that is, the fracture type is between tensile and shear fracture, and the source location is located in the deformation localization zone 3. This indicates that the mutation point 7 occur mixed rupture in the deformation localization zone 3. Since the tensile and shear displacement rates of deformation localization band 3 suddenly increase, the tensile displacement rates of deformation localization bands 1 and 2 increase, and the shear displacement rate changes little.

In summary, the acoustic emission information of rock is related to the change of relative tensile and dislocation rate of deformation localization zone. With the change of relative tensile and dislocation rate of deformation localization zone, the volume parameters of acoustic emission crack and the type of source crack change accordingly. The abrupt point 1 and 2 are tensile fracture in deformation localization zone 1, the abrupt point 3 is shear fracture in deformation localization zone 2, the abrupt point 4 is tensile fracture in deformation localization zone 3, the abrupt point 5 and 6 are shear fracture in deformation localization zone 3, and the abrupt point 7 is tensile fracture in deformation localization zone 3.

4.4 Study on acoustic emission waveform and spectral characteristics of different rock fracture mechanisms

Based on the breaking mechanism of each point, the waveform and spectral characteristics of acoustic emission with different breaking types are further studied.

4.4.1 Acoustic emission waveform characteristics of different rock fracture mechanisms

(1) Tension rupture

The mutation point of relative displacement rate at time 1, 2 and 4 are tension fracture, and the waveform at the corresponding time is shown in Fig. 11. The acoustic emission wave had long duration, slow tail wave attenuation and good amplitude symmetry.

(2) Shear rupture

The mutation point of relative displacement rate at time 3, 5 and 6 are shear fracture, and the corresponding time waveform diagram is shown in Figure 12 : the acoustic emission wave duration is short, the tail wave attenuation is fast, the amplitude symmetry is poor, and the asymmetry gradually decreases with the loading. This is because the vibration of the shear rupture source includes two stages of slip dislocation and source rebound. In the process of source rebound, it is bound to be hindered by friction, resulting in amplitude asymmetry in a waveform cycle. And the greater the friction, the more asymmetric the amplitude. In the process of rock fracture, the friction force after the formation of rock through cracks is less than that before the formation of cracks, so the waveform amplitude is more asymmetric at the initial stage of fracture, and the waveform at the peak time is closer to symmetry. Due to the hindering effect of friction, the acoustic emission wave attenuates rapidly and the duration becomes shorter.

(3) Mixed rupture

The mutation point of relative displacement rate at time 7 is a mixed fracture, and the corresponding spectrum diagram is shown in Figure 13. Acoustic emission wave contains both tensile fracture characteristics and shear fracture characteristics, with short duration, slow tail wave attenuation and good amplitude symmetry.

In summary, the acoustic emission waveform of tension fracture has a long duration, slow tail wave attenuation and good amplitude symmetry. The acoustic emission waveform of shear fracture has a short duration, tail wave attenuation and poor amplitude symmetry, and the asymmetry gradually weakens with the loading. The acoustic emission waveform of mixed fracture includes both tension fracture characteristics and shear fracture characteristics.

4.4.2 Acoustic emission spectrum characteristics of different rock fracture mechanisms

(1) Tension rupture

The mutation point of relative displacement rate at time 1,2 and 4 are tensile ruptures, and the corresponding spectrum diagrams are shown in Figure 14-16. Before the mutation, the spectrum of acoustic emission signal is mainly distributed in 0 ~ 1000 kHz, in which the high frequency component is more, the main frequency is not obvious, the main frequency band is distributed in 100 ~ 300 kHz, the vibration velocity is low, and the amplitude of the waveform is small. At the sudden change time, the spectrum of acoustic emission signal is mainly distributed in 0 ~ 300 kHz, and the main frequency band was about 10 ~ 100 kHz. The vibration velocity is high, and the amplitude of the waveform was large. After mutation, the spectrum of acoustic emission signal is mainly distributed in 0 ~ 1000 kHz, and the main frequency band is distributed in 100 ~ 300 kHz. From the time sequence, before and after the mutation, the acoustic emission signal spectrum distribution is wide, the high frequency component of the main frequency band is high, and the amplitude is small. At the sudden change time, the spectrum distribution of acoustic emission signal becomes narrow and the amplitude increases. From the failure type, it shows that the main frequency and high frequency components of tension fracture are more, which are distributed in about 10 ~ 100 kHz.

(2) Shear rupture

The mutation point of relative displacement rate at time 3 and 6 are shear fracture, and the corresponding spectrums are shown in Fig. 17 and Fig. 18, respectively. Before the mutation, the spectrum of acoustic emission signal is mainly distributed in 0 ~ 300 kHz, the main frequency band is distributed in 0 ~ 100 kHz, the vibration velocity is low, and the amplitude of the waveform is small. At the sudden change time, the spectrum of acoustic emission signal is mainly distributed in 0 ~ 100 kHz, and the main frequency band is about 0 ~ 10 kHz. The vibration velocity is high, and the amplitude of the waveform is large. After mutation, the spectrum of acoustic emission signal is mainly distributed in 0 ~ 1000 kHz, and the main frequency band is distributed in 0 ~ 300 kHz. From the time sequence, before and after the mutation, the acoustic emission signal spectrum distribution is wide, the high frequency component of the main frequency band is high, and the amplitude is small. At the sudden change time, the spectrum distribution of acoustic emission signal becomes narrow and the amplitude increases. From the failure type, it shows that the main frequency and low frequency components of shear fracture are more, distributed in 0 ~ 10 kHz.

The mutation point of relative displacement rate at time 5 is shear rupture, which is the peak point, and its spectrum is shown in Figure 19. Before the mutation, the spectrum of acoustic emission signal is mainly distributed in 0 ~ 300 kHz, the vibration velocity is low, and the amplitude of the waveform is small. At the sudden change time, the spectrum of acoustic emission signal is mainly distributed in 0-100 kHz, and the main frequency band is about 10 kHz. The vibration velocity is high, and the amplitude of the waveform

is large. After mutation, the spectrum of acoustic emission signal is mainly distributed in 0 ~ 300 kHz. As shown in the figure, it is in line with the above time and fracture type rules. In particular, the spectral distribution of point 5 with abrupt change of relative displacement rate is significantly narrower than that of all other points, so it is considered that the spectral distribution becomes narrower and can be used as an early warning precursor.

(3) Mixed rupture

The mutation point of relative displacement rate at time 7 is mixed rupture, and the corresponding spectrum is shown in Fig. 20. Before the mutation, the acoustic emission signal spectrum is mainly distributed in 0 ~ 1000 kHz, the main frequency band is distributed in 0 ~ 300 kHz, the vibration velocity is low, and the amplitude of the waveform is small. At the sudden change time, the spectrum of acoustic emission signal is mainly distributed in 0 ~ 300 kHz, the vibration velocity is high, and the amplitude of the waveform is large. After mutation, the spectrum of acoustic emission signal is mainly distributed in 0 ~ 1000 kHz, and the main frequency band is distributed in 0 ~ 300 kHz. From the time sequence, before and after the mutation, the acoustic emission signal spectrum distribution is wide, the high frequency component of the main frequency band is high, and the amplitude is small. At the sudden change time, the spectrum distribution of acoustic emission signal becomes narrow and the amplitude increases. From the point of view of failure types, it is shown that the spectrum of mixed fracture acoustic emission signal includes both tensile fracture characteristics and shear fracture characteristics, and the main frequency is distributed in 0 ~ 300 kHz.

In summary, from the time sequence, before and after the mutation, the acoustic emission signal spectrum distribution is wide, the high frequency component of the main frequency band is high, and the amplitude is small. At the sudden change time, the spectrum distribution of acoustic emission signal becomes narrow and the amplitude increases. According to the failure type, the main frequency and high frequency components of tension fracture are more, distributed in about 10 ~ 100 kHz. There are many low frequency components in the main frequency of shear fracture, which are distributed in 0 ~ 10 kHz. The spectrum of mixed fracture acoustic emission signal contains both tensile fracture characteristics and shear fracture characteristics, and the main frequency distribution is about 0 ~ 300 kHz. The spectral distribution of acoustic emission signals at peak points is significantly narrower than that at all other points, so it is considered that the spectral distribution can be used as an early warning precursor.

5 Conclusions

Acoustic emission double difference positioning, moment tensor inversion method and digital speckle correlation method are used to analyze the relative displacement rate and crack volume parameters of the deformation localization zone of the experimental specimen during the uniaxial compression test of rock. The acoustic emission waveform characteristics of different fracture types are summarized. It can be concluded that :

(1) From the full stress-strain curve and deformation field evolution process of rock under uniaxial compression, it can be seen that the bearing capacity of rock is controlled by the evolution of deformation localization structure, and the deformation concentration of deformation localization zone is the main reason for the nonlinear evolution of rock stress-strain curve.

(2) The comparative analysis between the dislocation rate and the acoustic emission index of the deformation localization zone shows that the acoustic emission information of the rock is correlated with the relative tensile and dislocation rate of the deformation localization zone. With the change of the relative tensile and dislocation rate of the deformation localization zone, the volume parameters of the acoustic emission crack and the acoustic emission crack change accordingly.

(3) The acoustic emission waveform analysis of different fracture types shows that the acoustic emission waveform of tension fracture has a long duration, slow tail wave attenuation and good amplitude symmetry. The acoustic emission waveform of shear fracture has a short duration, tail wave attenuation and poor amplitude symmetry, and the asymmetry gradually weakens with the loading. The acoustic emission waveform of mixed fracture includes both tension fracture characteristics and shear fracture characteristics.

(4) According to the acoustic emission spectrum of different rupture types, the time sequence and rupture type can be analyzed respectively. In the time sequence, before and after the mutation, the acoustic emission signal spectrum distribution is wide, the high frequency component of the main frequency band is high, and the amplitude is small. At the sudden change, the spectrum distribution of acoustic emission signal becomes narrow and the amplitude increases. In the failure type, the main frequency and high frequency components of tension fracture are more, distributed in about 10 ~ 100 Hz. There are many low frequency components in the main frequency of shear fracture, which are distributed in 0 ~ 10 Hz. The spectrum of mixed fracture acoustic emission signal contains both tensile fracture characteristics and shear fracture characteristics, and the main frequency distribution is about 0 ~ 300 Hz. The spectral distribution of acoustic emission signals at peak points is significantly narrower than that at all other points, so it is considered that the spectral distribution can be used as an early warning precursor.

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Figures

1. CCD camera ; 2. White Light Source; 3. Loading Equipment; 4. Acoustic Emission Acquisition System; 5. Computer

Figure 1

Schematic diagram of test system

Figure 2

Sample layout diagram

Figure 3

Actual speckle map

Figure 4

Stress-strain curve

(a) Rock failure diagram

(marker 6)

(b) Speckle calculation results

(marker 6)

(c) Moment tensor inversion calculation

result(marker 6)

Figure 5

Experimental results

Figure 6

Evolution of the maximum shear strain field of the specimen at different loading stages

Figure 7

Schematic diagram of the localized deformation zone and displacement measurement points

Figure 8

Relative displacement rate curve

Figure 9

Evolution curve of crack volume parameter

Figure 10

Correspondence curve of deformation field evolution and crack volume parameters

(a) Mutation point 1

(b) Mutation point 2

(c) Mutation point 4

Figure 11

Waveform of tension crack

(a) Mutation point 3

(b) Mutation point 5

(c) Mutation point 6

Figure 12

Waveform of shear crack

Figure 13

Waveform of mixed crack

(a) Before mutation

(b) mutant moment

(c) After mutation

Figure 14

Spectrum curve at the moment of mutation point 1

(a) Before mutation

(b) mutant moment

(c) After mutation

Figure 15

Spectrum curve at the moment of mutation point 2

(a) Before mutation

(b) mutant moment

(c) After mutation

Figure 16

Spectrum curve at the moment of mutation point 4

(a) Before mutation

(b) mutant moment

(c) After mutation

Figure 17

Spectrum curve at the moment of mutation point 3

(a) Before mutation

(b) mutant moment

(c) After mutation

Figure 18

Spectrum curve at the moment of mutation point 6

(a) Before mutation

(b) mutant moment

(c) After mutation

Figure 19

Spectrum curve at the moment of mutation point 5

(a) Before mutation

(b) mutant moment

(c) After mutation

Figure 20

Spectrum curve at the moment of mutation point 7