

Influence of loading rate on the deformation characteristics of single-fracture rock-like models

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Abstract: The deformation behavior of fractured rock masses is often a key factor causing instability of engineering rock masses and frequent geological disasters. The complex changes in the load acting on engineering rock masses can trigger and alter the mechanical response processes such as deformation and fracture of the rock masses. This study employs physical simulation techniques to replicate the behavior of real rock masses through the use of rock-like models. Specifically, single-fracture rock-like specimens with consistent characteristics are fabricated utilizing river sand, cement, gypsum, and putty powder. Uniaxial compression tests are subsequently conducted on these specimens to examine the impact of loading rate on their deformation behavior. The primary focus lies on the sliding deformation patterns exhibited by the media on either side of the fractures, as well as the fracture behaviors associated with the pre-existing fractures. To monitor the deformation evolution processes both internally and externally within the models, embedded strain rosettes and digital image technology are concurrently employed. This approach facilitates an exploration of the influence of loading rate on the deformation characteristics at the fracture tips and the fracture behaviors observed on the model surface. The results show that: (1) With the increase of loading rate, the failure mode of the model transforms from ductile to brittle, reflecting the differences in the adjustment mode of rock mass bearing structure under different loading rates. (2) The initiation time of strain localization is independent of the rate, and as the loading rate increases, the strain deflection angle of the tension and compression stress zones in the model changes from asynchronous oscillation to synchronous oscillation. (3) At low loading rates, the failure mode of the model is stable. As the loading rate increases, the failure mode becomes more complex, and the surface crack density increases. When the loading rate exceeds a certain threshold, the failure mode of the model changes to "X-shaped" shear failure. (4) There is a significant correlation between the sliding rate of the fracture and the deflection angle of the principal strain at the end, reflecting the coupling effect of rock mass damage and strain field evolution under Griffith's criterion.

Keywords: loading rate; rock-like model; local deformation field; surface cracking; sliding rate

1 Introduction

Under the long-term geological modification process, there are various scale discontinuities (such as fractures, joints, bedding planes and faults) within the rock mass. The existence of these discontinuities not only disrupts the integrity of the rock mass but also alters the mechanical properties such as stress transmission, strain distribution and crack development within the rock mass. The stability of fractured rock masses is jointly controlled by internal discontinuities such as fractures and the rock blocks on both sides of the discontinuities. Geological disasters such as landslides and rockfalls often occur in close relation to the creep deformation along the weak surface in the vicinity of the local weak area. This phenomenon is usually the result of the combined effect of multiple disaster-causing factors. Besides the influence of weak

structural surfaces such as discontinuities, it is also affected by factors such as the stress state of the rock mass and external loading conditions^[1]. It is worth noting that in actual engineering scenarios, rock masses not only bear static loads but also are subjected to the combined effects of dynamic loads such as blasting, earthquakes, mechanical vibrations, and rock bursts; moreover, the mechanical properties of rock masses (such as strength, elastic modulus, and deformation behavior) will undergo significant changes under different loading rates. Therefore, conducting in-depth research on the influence of loading rates on the deformation characteristics and failure behavior of fractured rock masses is of crucial significance for the stability assessment of rock masses and the prediction and prevention of geological disasters.

Scholars have conducted research on the loading rate effect on the deformation characteristics of rock masses.

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Cui et al.^[2] established a new statistical damage model for rocks by using the loading rate-dependent damage density function, which describes the macroscopic damage accumulation process of rock specimens under different loading rates. Fuenkajorn et al.^[3] derived various multi-axial formulas for loading rate-dependent strength and deformability through uniaxial and triaxial compression tests of salt rocks under different loading rates. Lajtai et al.^[4] conducted static and dynamic loading tests to evaluate the loading rate effects of brittle and ductile rock masses, and proposed a strength criterion that combines confining pressure and strain rate. Zhang et al.^[5] used scanning electron microscopy (SEM) to study the fracture surfaces of rock samples under different loading rates and analyzed the influence of loading rate on the fracture characteristics and energy distribution of the rock mass. Sun et al.^[6] studied the entire process of rockburst development and the energy evolution characteristics under the condition of true triaxial single-sided unloading based on the three-dimensional discrete element theory and polycrystalline modeling technology, and explored the loading rate effect on the energy evolution of granite. In the actual process, the failure of the rock mass is closely related to the development of weak structural planes. To better observe the generation and development of fractures, specimens with preformed fractures are widely used in the study of the fracture characteristics of the rock mass. Zhang et al.^[7] used the bonded-particle model (PBM) to numerically load specimens with discontinuities and analyzed the cracking process of specimens with discontinuities under different loading rates. Zhang et al.^[8] used the particle bonding model to numerically simulate the uniaxial compression tests of rocks with single fractures under different loading rates from the perspective of acoustic emission events, revealing the rate effect of rock fracture. Yang et al.^[9] proposed a rate-dependent model combined with element partition method (EPM) to simulate the dynamic fracture of rock masses under different loading rates and analyzed the influence of loading rate on the strength and failure mode of the rock mass. Zhang et al.^[10] used the bonding particle model to simulate the biaxial compression tests of granite and studied the loading rate dependence of acoustic emission loading and the failure mechanism of fractured rocks. Li et al.^[11] studied the influence of loading rate on the local deformation and failure characteristics of the rock model with locking segments and analyzed the mechanical properties, internal deformation characteristics, crack propagation and failure mode under different loading rates. Wang et al.^[12] used acoustic emission monitoring methods to conduct experimental observations of the mechanical and related spatiotemporal micro-fracture behaviors of hard fractured sandstone under different uniaxial loading rates, and semi-quantitatively explained the mechanism of acoustic emission generation during the rock fracture process and the loading rate effect from the energy perspective. The above study analyzed the deformation inside and outside the rock mass, crack propagation, energy response, failure mode, and the loading rate effect on the relevant strength under various loading conditions.

However, the mechanisms of rock fracture sliding and the activities of differential dislocation near the fracture surface caused by different loading rates, as well as the differences in internal deformation response patterns, have not been sufficiently studied. The connection between the evolution of the local deformation field and its activity during the fracture sliding process, and the academic community has not yet fully understood and resolved, remains an unsolved issue. From this perspective, exploring the influence of loading rates on the deformation characteristics of single fracture-type rock mass models is a new research direction.

Therefore, in this study, river sand, cement, gypsum and putty powder were used to prepare single-fracture rock-like models with the same properties. Embedded strain rosettes were employed to monitor the local deformation of the fractures, and digital image correlation (DIC) technology was used to observe the external deformation characteristics of the models. The characteristics of the single-fracture rock-like models undergoing sliding along the fractures and slow deformation under different loading rates were studied, that is, the characteristics of the deformation concentration, accumulation and damage evolution at the fracture tips of the single-fracture rock-like models. The mechanical properties of rock-like models under different quasi-static loading rates were analyzed, and the localized characteristics of fracture deformation during the deformation process of the model and the crack propagation mode related to fracture slip were analyzed. This is expected to provide experimental references for the stability assessment of rock masses, engineering design and construction optimization, and geological disaster prediction and prevention.

2 Test materials and methods

2.1 Test materials and model preparation

The test used gypsum-cement mortar to prepare single-fracture rock-like models^[13]. River sand, cement, gypsum, putty powder, and water were mixed in the proportion as shown in Table 1 to pour the model. The model used river sand as the aggregate, gypsum and cement ($\sigma_{bc} = 22$ MPa) as the binder, and putty powder to adjust the friction between the particles of the sample. The model density was 1.81 g/cm^3 . The fabrication procedure of the specimen was referred to the *Engineering Rock Mass Test Method Standard* (GB 50266—2013)^[14], and the manufacturing process is shown in Fig.1(a). The prefabricated size was $300 \text{ mm} \times 300 \text{ mm} \times 300 \text{ mm}$. During the pouring process, steel plates were inserted to create a $300 \text{ mm} \times 3 \text{ mm} \times 100 \text{ mm}$ fracture in the model. The fracture filling material was gypsum (water-to-gypsum mix ratio 2:1). To enhance the shear stress of the rock mass model and cause it to undergo shear failure, the structural plane was set at a 45° angle to the horizontal direction, so that the shear stress on the structural plane under uniaxial compression reached the maximum value^[15]. Plant protein retarder (0.016 4 kg) was added to the cement mortar during the preparation

process. The mortar was poured in two stages after preparation, with the first stage filling to 1/2 of the model volume. Strain rosettes were placed around the preformed fracture. The strain rosettes were made by adhering resistance strain gauges to the material base with properties such as elastic modulus and wave impedance consistent with the model body^[16]. In this test, regular hexagonal strain rosette bases were made according to the rock mass model ratio, and strain rosettes were pasted on the three mutually perpendicular surfaces. The surface was coated with silicone resin for waterproofing^[17]. After placing the strain rosettes, the mortar was allowed to naturally solidify to a certain extent to ensure firm embedding of the strain rosettes. Then, scrape the surface to avoid interlayer bonding defects during the second pouring. Pour the second stage of mortar. After the pouring was completed, the model was cured for 10 days. Finally, the model was formed as shown in Fig. 1(b).

Table 1 Mix proportion of cement mortar

Materials	Characterization	Main components	Specification/mm	Ratio/%
River sand	Grey crystals	SiO ₂	0.150	57.9
Cement	Dark grey powder	CaO, SiO ₂	0.045	4.7
Gypsum	White powder	CaSO ₄ · 2H ₂ O	0.100	16.2
Putty powder	White powder	Various inorganic salt mixtures	0.045	4.6
Water	Transparent liquid	H ₂ O	—	16.6

2.2 Test equipment

The test involved the following test equipment: ZYSS-2000 press (Fig. 1(c)), DH5922D high-

performance dynamic signal testing and analysis system (Fig. 1(d)), and DIC system (Fig. 1(e)). The ZYSS-2000 press is produced by Changchun Machinery Institute, with a measurement range of 1–100 mm and a displacement measurement resolution of 0.001 mm, with an accuracy of $\leq \pm 5\%$. It can conduct uniaxial compression on rock-like specimens at different loading rates and monitor and record the stress-strain of the rock-like model during the compression process. The DH5922D high-performance dynamic signal testing and analysis system (16 channels) uses a high-precision 24-bit A/D converter and can complete the testing of stress-strain, voltage, current, resistance value, and IEPE (integrated electronics piezo-electric) signals. The instrument's voltage range is ± 100 to ± 10 V, with a voltage indication error of $\leq 0.2\%$ F.S. (fullscale), the strain range is $\pm 100\ 000 \times 10^{-6}$, $\pm 10\ 000 \times 10^{-6}$, and $\pm 1\ 000 \times 10^{-6}$, and the strain display error is $\pm (0.5\% \text{rdg} \pm 3 \times 10^{-6})$, and the bridge connection methods include full bridge, half bridge, and three-wire 1/4 bridge. The frequency response range is from DC to 100 kHz ($+0.5$ dB to -3 dB), with a flat response, and the maximum frequency can reach 50 kHz; during the test, it is connected to the strain sensors on the strain rosette to monitor and record the local strain in the model. The DIC system is a VIC plane strain measurement system, with an instrument strain measurement range and accuracy of 0.005% to 2 000%, and $2D \leq 10 \times 10^{-6}$; it uses a lens with a specification of 2.8/50 mm, and the displacement resolution is 0.01 pixel. It can provide non-contact full-field 2D displacement and strain data for the test to support the analysis of the evolution of the strain field on the model surface.

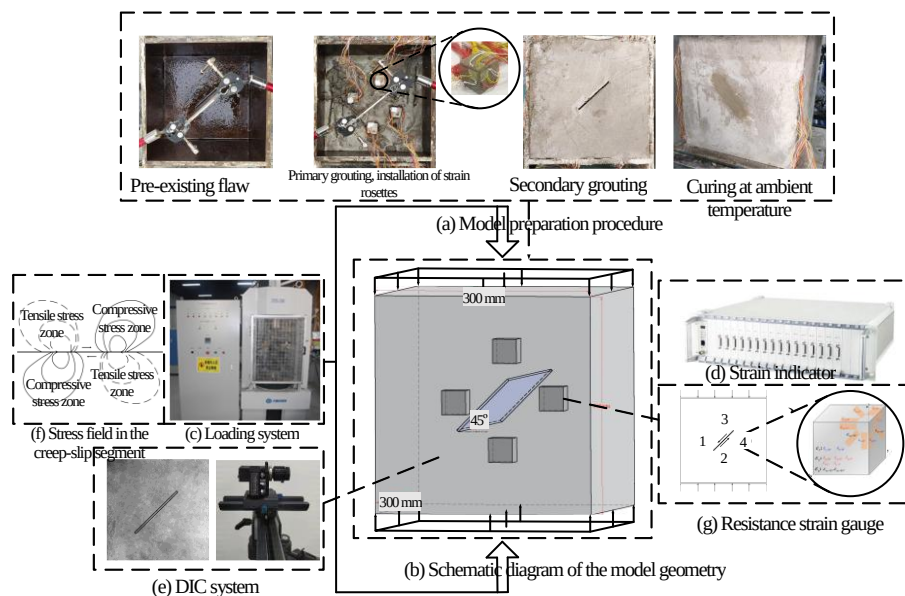


Fig.1 Schematic diagrams of model preparation and testing procedure

2.3 Experimental methods

According to the classification criteria for different strain rates^[18], this test set up four different loading rates of 0.005, 0.02, 0.05, and 0.1 mm/s for the rock-like model to

conduct quasi-static uniaxial compression (Table 2). During the compression process, the relative displacement of the two sides of the fractures is constrained by the locking section: the medium in front of the dislocation

displacement is compressed, forming a compressive stress zone; the medium behind the dislocation point is dragged to form a tensile stress zone (Fig. 1(f)). This test analyzed the relationship between the local stress field of the model and the structural stress field from the two aspects of local force and deformation of the model. Strain rosettes were placed in each of the four stress quadrants to monitor their strain values (Fig. 1(g)). The numbering and centroid coordinates of the strain rosettes are shown in Table 3.

During compression, each strain rosette acquires strain data at nine distinct positions. The analysis is mainly performed on the plane parallel to the loading direction as the reference plane, where ε_x , ε_y denote the in-plane normal strains parallel and perpendicular to the loading direction, respectively. ε_u represents the linear strain measured by the strain gauge oriented at 45° to the loading direction, which is used together with ε_x , ε_y to solve for the in-plane shear strain and principal strains. Based on the measurements of ε_x , ε_y , and ε_u on different reference planes (Fig. 1(g)), the local maximum principal strain $\varepsilon_{\max}$ and the maximum principal strain deflection angle α [16]. In addition to directly testing the internal strains, the external macroscopic failure trend is also analyzed using digital image technology, strain contour diagrams are drawn, surface displacements are measured, and the relative sliding speed between the upper and lower parts of the specimen is obtained to analyze its activity.

Table 2 Loading rate

Serial number	Rate of loading/(mm · s ⁻¹)	Serial number	Rate of loading/(mm · s ⁻¹)
JZ-1	0.005	JZ-3	0.05
JZ-2	0.020	JZ-4	0.10

Table 4 Division of experimental stages by time and strain ranges

Serial number	Time interval/s				Strain interval			
	Stage I	Stage II	Stage III	Stage IV	Stage I	Stage II	Stage III	Stage IV
JZ-1	0–75	75–205	205–420	420–1 003	0–0.004	0.004–0.01	0.01–0.021	0.021–0.05
JZ-2	0–45	45–145	145–650	650–1 155	0–0.003	0.004–0.01	0.01–0.043	0.043–0.072
JZ-3	0–30	30–60	60–145	145–369	0–0.005	0.005–0.01	0.01–0.024	0.024–0.062
JZ-4	0–15	15–30	30–48	48–128	0–0.005	0.005–0.01	0.01–0.016	0.016–0.039

As shown in Fig. 2(a), the stress-strain curves of the model under each loading rate in the figure all exhibit obvious phased characteristics. In stage I, the micro-fractures within the model close, and during this process, the model only undergoes minor deformation, and is not significantly affected by the loading rate. Entering stage II, the stress-strain of the model becomes a linear relationship, and the model undergoes recoverable elastic deformation. In this stage, as the loading rate increases, the slope of the stress-strain curve shows an increasing trend, indicating that as the loading rate increases, the stiffness of the material itself becomes greater, and the deformability of the model relatively decreases. This reflects the loading-rate effect on the elastic modulus of fractured rock masses. This is because the higher loading rate causes the model structure to not

Table 3 Coordinates of strain rosettes

Serial number	Stressed zone	Coordinates (with the base of the hexahedron as the <i>xoy</i> plane)
Z1	Stress- compressed zone	(218.14, 150, 146.96)
Z2	Stress-tensile zone	(153.04, 150, 81.86)
Z3	Stress-tensile zone	(146.96, 150, 221.94)
Z4	Stress- compressed zone	(818.86, 150, 153.04)

3 Results

3.1 Mechanical properties and failure characteristics of single-fissure type rock mass models

Based on the load and displacement values obtained during the test, the stress-strain data of the model under uniaxial compression conditions can be calculated. Fig. 2 shows the stress-strain curves of the rock-like model under different loading rates. As shown in the figure, according to the evolution model of the stress-strain curve, the failure process in the uniaxial compression test can be divided into 4 stages: the pore compaction stage (Stage I) involves the model undergoing varying degrees of compaction, which is manifested by the gradual increase in strain as stress increases; the elastic deformation stage (Stage II), the stress-strain curve is a straight line, and stress increases linearly with strain in this stage; the crack propagation stage (Stage III), cracks begin to form and continuously expand, causing irreversible damage and failure of the specimen, as the slope of the stress-strain curve gradually decreases; The post-peak failure stage (Stage IV) is characterized by the appearance of a negative slope in the stress-strain curve, and the stress begins to decrease. The time/strain intervals for each test stage are shown in Table 4.

have sufficient time to undergo sufficient displacement and adjustment, thereby limiting the degree of deformation. After entering stage III, a large number of micro-new fractures will be generated within the model. Driven by stress, the new fractures will further develop and expand. As the model reaches the peak, macroscopic fractures gradually appear on its surface, and the peak stress shows a trend of increasing first and then decreasing with the increase of the loading rate, while the peak strain shows a trend of increasing first and then decreasing with the increase of the loading rate (Fig. 2(b)). When the loading rate is relatively small, the model has more time to undergo deformation. The micro-fractures within the model will gradually open and expand, resulting in a larger deformation under the same stress level. In stage IV after the peak stress, the slope of the negative slope section

curve decreases as the loading rate increases. Comparing the four groups of tests with different loading rates, the stress-strain curve of model JZ-2 shows a stress stabilization period both before and after the peak stress. The stabilization period of models JZ-1 and JZ-3 occurs after the peak stress, while model JZ-4 does not show a significant stabilization period. The appearance of the stabilization period indicates a significant decrease in model stiffness, resulting in continuous deformation under a constant stress. In the tests, it corresponds to the expansion of cracks, the failure of the bearing structure, and the adjustment of the internal force-bearing units of the model. From the curves in the figure, it can be seen that the larger the proportion of the stabilization period after the peak stress, the gentler the slope of the negative slope section. As the loading rate increases, the proportion of the stabilization period after the peak stress decreases, and the failure mode of the model changes from a relatively stable ductile failure to a more intense brittle failure.

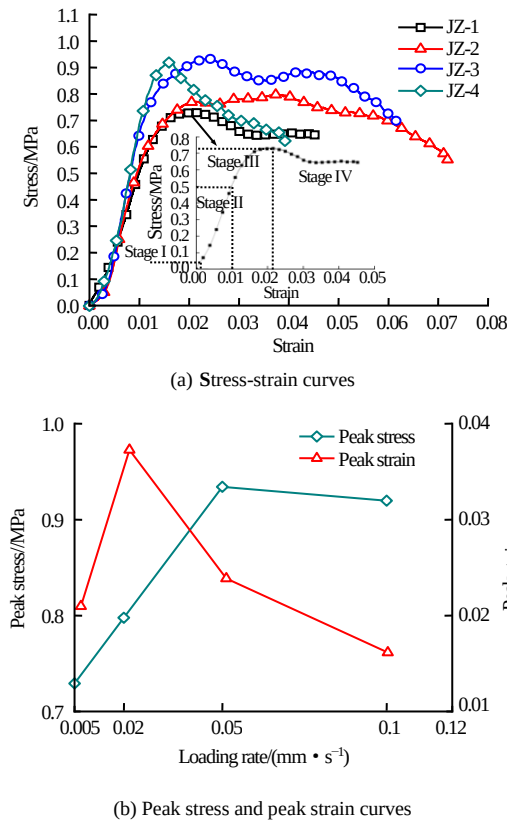


Fig.2 Mechanical characteristics of the model

From the above analysis, it can be concluded that the failure characteristics of the model are affected by the loading rate. When the loading rate is small, the internal deformation structure and force-bearing units of the model have sufficient adjustment space to adapt to the deformation caused by the load, and the model tends to a relatively stable ductile failure; when the loading rate increases, the model undergoes greater deformation in a short period of time, the internal deformation structure and force-bearing units cannot adjust in time, the model tends to a more intense brittle failure.

3.2 The maximum principal strain variation

Based on the Griffith strength criterion, the strain localization of rock mass is manifested as the process of strain energy migrating and concentrating from uniform distribution to specific tiny areas under the action of stress field. Its core feature is reflected in the spatial non-uniformity of strain field and the precursory response of shear band formation^[19]. To reveal the temporal characteristics of local deformation caused by strain localization during the loading process, this study monitored the strain responses of different quadrants through four groups of strain rosettes (Table 3), calculated the maximum principal strain values $\varepsilon_{\max}$ of each measurement point using Equation (1)^[20]:

$$\varepsilon_{\max} = \frac{1}{2} \left\{ (\varepsilon_x + \varepsilon_y) + \sqrt{2[(\varepsilon_x - \varepsilon_u)^2 + (\varepsilon_u - \varepsilon_y)^2]} \right\} \quad (1)$$

All of ε_x , ε_y , and ε_u can be directly monitored by the strain rosettes (Fig. 1(g)). In this study, drew the time-history curves of local maximum principal strain in stage II-III (Fig. 3), and obtained the surface strain cloud map by combining digital speckle technology (Fig. 3), systematically analyzing the spatio-temporal evolution law of the strain localization zone were plotted.

From the curve graphs in Fig. 3, it can be seen that the local maximum principal strain measured for each brick in stage I remained with a relatively small change. The reason for this might be that the main deformation in this stage originated from the compaction of its own pores, and the medium structure had not yet borne the load, and the strain patches on the strain gauges had not yet undergone significant deformation. In this stage, the strain characteristics of the model did not show significant differences with the loading rate. The moments when the strain of different positions of the strain rosettes in Fig. 3 exhibited significant changes and differentiation were taken as the initiation moments of the model's strain localization. Under different loading rates, the initiation moments of strain localization for the rock-like model occurred in the middle of stage II (JZ-1), the end of stage II (JZ-2), and the beginning of stage II (JZ-3, JZ-4), respectively. It can be seen that when the loading rate increased to a certain extent, the model's strain localization would appear earlier. The overall mechanism of strain localization usually involves multiple quasi-rigid blocks sliding along fractures^[21]. The fractures of the complete model usually develop in stage III. In contrast to intact specimens without pre-existing fractures, the pre-fractured specimens in this test exhibited strain localization as early as Stage II. From the strain cloud graph in Fig. 3, in the JZ-1 test, strain localization first occurred at the upper end and middle of the preformed fracture in stage II. The concentrated strain zone ① was perpendicular to the preformed fracture and the loading direction at a 45° angle; the distribution of the concentrated strain zone ② was similar to ①. Moreover, in stage III, a tensile strain localization ③ occurred at the lower end of the model's preformed fracture, and the concentrated strain zone was basically parallel to the loading direction, developing into

wing cracks; the concentrated strain zone ④ developed perpendicular to the preformed fracture direction at the fracture tip and extended along the diagonal of the model. In this stage, strain mainly occurred at the lower end of the preformed fracture, and this phenomenon was manifested in the model as the maximum principal strain Z1, Z2 being significantly higher than Z3, Z4 in the upper and

lower portions. In the JZ-2 test, strain concentration zone ① was formed at an angle to the preformed fracture in stage II; as the loading progressed, strain concentration zone ① developed into a S-shaped crack throughout the model in stage III. At this time, the maximum principal strain at Z1 was significantly higher than other strain rosettes, and the maximum principal strain

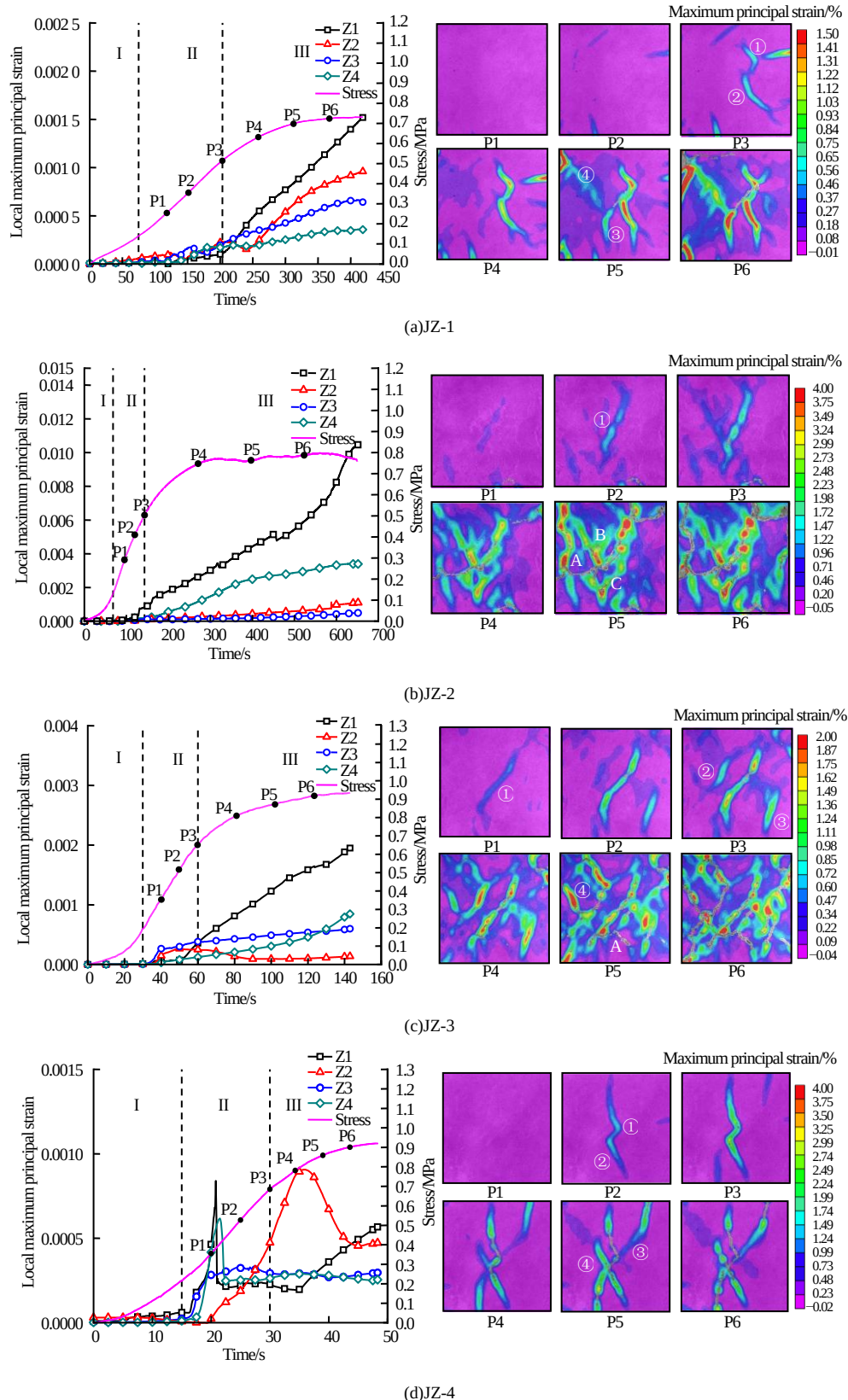


Fig.3 Evolution of local maximum principal strain with time and surface strain contour maps prior to model failure

at the compressive zone Z1, Z4 increased significantly, while the maximum principal strain at the tensile zone Z2, Z3 remained basically unchanged, indicating that in this stage, the model was undergoing shear slip with the upper and lower portions as the main constraints, and the main crack ① developed into a secondary crack AB and wing crack C between the upper and lower portions. In the JZ-3 test, strain localization occurred along the preformed fracture in the model and developed a concentrated strain zone ① along the loading direction at both ends of the fracture in the upper and lower portions. In the middle of stage II, shear-type concentrated strain zones ②, ③ appeared in the upper and lower parts of the specimen. In stage III, ① stopped expanding and the internal strain concentrated at the Z1 position, ② and ③ continued to develop and formed a conjugate shear strain zone ④ at the upper plate of the model, and a secondary inclined crack A was formed at the lower plate. In the JZ-4 test, in the middle of stage II, strain localization occurred approximately perpendicular to the preformed fracture direction at the upper and lower portions in the middle of the preformed fracture, and concentrated strain zones ①, ② developed in the upper and lower portions respectively in the middle of stage II, and developed into a inclined crack extending along the loading direction in the end of stage II. At this time, the strain at Z1, Z4 reached the peak, and a tensile concentrated strain zone ③ occurred at both

$$\left. \begin{aligned} \frac{\partial G}{\partial a} = C\varepsilon\varepsilon' &\geq \frac{\partial R}{\partial a}, & \text{unstable development of cracks} \\ \frac{\partial G}{\partial a} = C\varepsilon\varepsilon' &< \frac{\partial R}{\partial a}, & \text{stable development of cracks} \end{aligned} \right\} \quad (3)$$

where R represents the resistance to crack propagation.

It can be seen that under a fixed strain rate condition, an increase in strain will lead to a significant instability in crack propagation. The data from the JZ-1 to JZ-3 tests show that during Stage III, the strain value at the Z1 monitoring point remained consistently higher than that at other locations, indicating that this area (the major compressive zone in the upper portion) presents the most intensive crack activity. Based on this finding, it is recommended that in engineering practice, by continuously monitoring the dynamic internal strain field, key reinforcement should be implemented in the high strain gradient areas, which can effectively enhance the stability control capability of the rock mass structure.

3.3 Principal strain axis deflection characteristics

One of the characteristics of rock mass shear slip is that the surrounding rock on both sides of the fracture exhibits obvious plastic deformation within a regional scope^[22]. Plastic shear deformation will cause the deviation of the principal strain axis^[23]; and the angle between the maximum principal strain direction in the surrounding area and the loading direction is called the local maximum principal strain direction deflection angle, which is used to reflect the strain pattern in the surrounding area during the shear slip process; Su et al.^[24] believes that the complexification of the structure caused by fracture sliding and the external damage of fractures have a significant impact on the strain field changes near the fractures. The main manifestation is the deviation of the maximum principal strain axis near the fracture during

ends of the fracture and developed into a shear and tension mixed crack throughout the model in stage III. In the early stage of stage III, a secondary strain concentration zone ④ was formed along the concentrated strain zone ②, and evolved into a secondary inclined crack. The model finally presented an X-type failure characteristic. Summarizing the results of the four tests, the initial strain localization of the model exists in two modes along the preformed fracture direction and perpendicular to the preformed fracture direction. The strain localization along the direction perpendicular to the preformed fracture usually leads to the "X" type failure of the model. In the JZ-1, JZ-2, and JZ-3 tests, cracks developed mostly in the compressive zone of the upper plate in stage III. According to the energy formula given by Wang et al.^[12]:

$$\frac{\partial G}{\partial a} = C\varepsilon\varepsilon' \quad (2)$$

where G represents the system energy release rate; a denotes the crack half-length; C is a comprehensive constant related to material properties, geometric dimensions and loading conditions, and is independent of ε , ε' ; ε is the strain; ε' is the strain rate under displacement control, which remains constant in the same test.

Based on the Griffith criterion, the relationship between strain and crack development is as follows:

the fracture sliding process, To study the correlation among loading rate, local strain field, and fracture activity, it is very necessary to conduct a study on the deviation law of the maximum principal strain axis during the loading process. To study the deflection law of the maximum principal strain axis in the tension-compression stress zone of the model during the loading process, the data monitored by four strain rosettes were calculated using the following equation to obtain the maximum principal strain deflection angle^[20], and the time history curve of the maximum principal strain deflection angle is plotted as shown in Fig. 4 (The color of the background of the curves in the figure changes from light to dark in the following stages: Stage I, Stage II, and Stage III.).

$$\alpha = \frac{1}{2} \arctan \frac{\gamma_{xy}}{\varepsilon_x - \varepsilon_y} \quad (4)$$

where γ_{xy} represents the calculation of plane shear strain,

$$\gamma_{xy} = 2\varepsilon_u - (\varepsilon_x + \varepsilon_y).$$

By observing Fig. 4, it can be seen that oscillations of the deflection angle curves occurred to varying degrees during Stage I, which reflects the adjustment and coupling of the internal bearing structure of the model. The expansion of the existing shear bands will lead to stress concentration and redistribution at the tip, thereby causing the deflection of the main stress axis in the expanded control area^[24]. Considering that the elastic modulus of the strain rosettes remains unchanged, it is assumed that the maximum principal stress direction corresponds to the strain deflection angle. The oscillation and sudden change

of the main strain deflection angle curve can reflect the development of fractures around the brick from the side. By comparing the four tests, as the loading rate increases, the development of fractures at the tip of the preformed fractures shifts from Stage III to Stage II. Moreover, at low loading rates, the development of fractures at the tip of the tensile stress area is faster than that of the compressive stress area (JZ-1, JZ-2), while at high loading rates, the development of fractures in the tensile-compressive stress area is basically synchronous (JZ-3, JZ-4). Especially in the JZ-4 test, a very high similarity was found in the strain deflection curves of the same end of the tensile and

compressive stress areas. By analyzing the figures, it can be found that the development and expansion of the crack tip fractures at the surface of the model generally occur in the failure and deformation stage, while the development and expansion of fractures at the same position within the model are generally earlier than that at the surface of the model. This indicates that the distribution of deformation in the section perpendicular to the loading direction is not uniform, and the strain transfer in the center is faster than that on the outside. This is because the unconstrained surface consumes part of the energy through lateral deformation during strain transfer^[25].

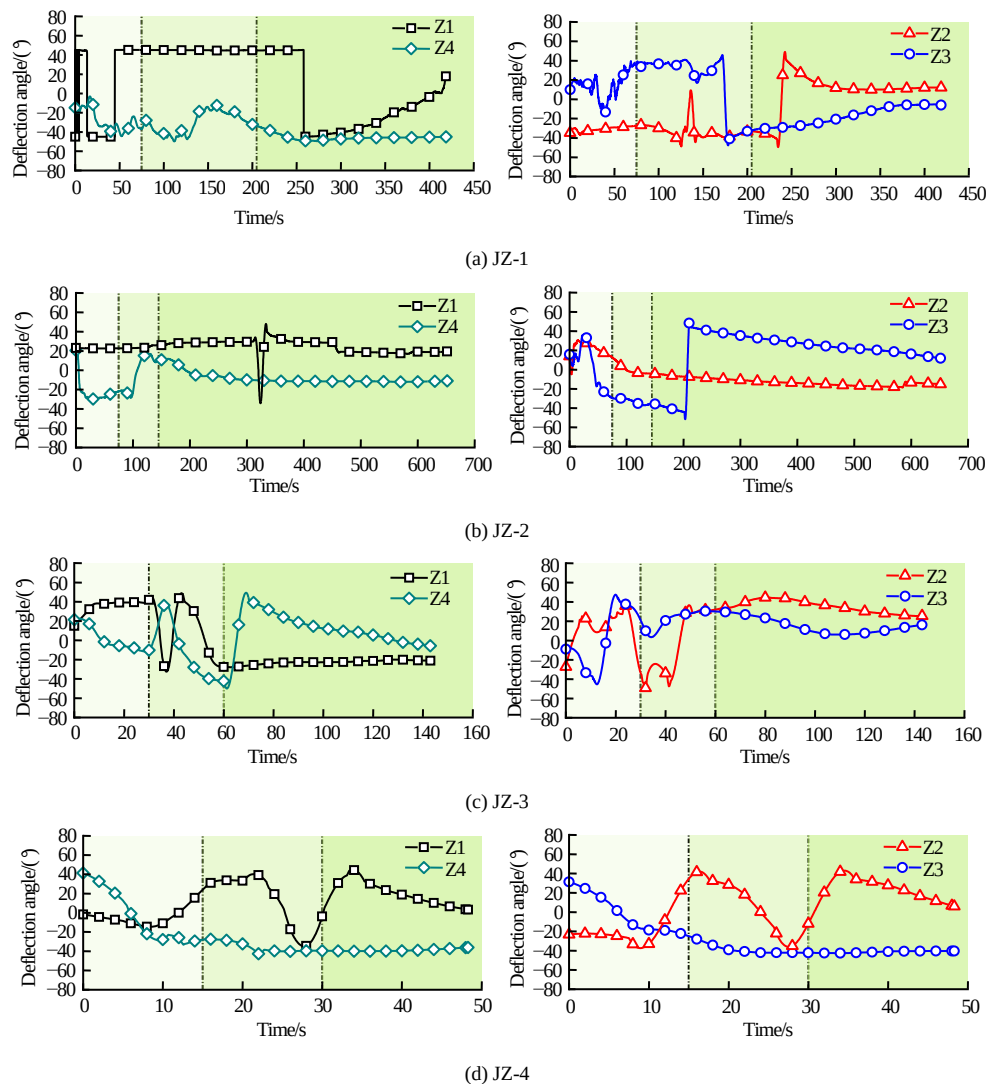


Fig.4 Evolution of local maximum principal strain deflection angle with time

3.4 Analysis of the destruction mode

Due to the varying distribution of the strain field, there are significant differences in the failure patterns of the model under different loading rates. Based on the previous classification of surface failure patterns^[26–28], a failure pattern diagram was drawn (Fig. 5). Failure patterns shown in Fig. 6 were identified, where thin lines denote secondary derived cracks.

As shown in Fig. 6, with the increase in loading rate, the crack density of the model shows a changing characteristic of first increasing and then decreasing.

Among them, the crack density on the surface of the model under the JZ-3 test condition is the highest. Within a specific loading rate range, when the model is compressed under a low loading rate, it has more sufficient time to adjust its force structure, and the crack development is more complete; while when the loading rate increases, the time for stress adjustment of the structure is limited, and the compression process becomes more intense, the duration of crack development is shortened, but the number of derived cracks significantly increases, resulting in an increase in crack density. When

the loading rate exceeds a certain threshold (JZ-4), the failure mode of the model changes significantly. From the original shear failure along the preformed fractures, it becomes X-type failure less affected by the preformed fractures. As shown in Fig. 3, in the JZ-4 test, the failure mode of the model is shear failure along the vertical fractures direction first, and then shear along the preformed fractures. This indicates that at an excessively high loading rate, the control of the weak structure on the failure mode weakens. Analyzing the types of surface cracks on the model, under the control of preformed fractures, the surface of the model in all four tests develops wing cracks on both sides of the fractures in the direction of loading. Unlike the situations in other tests where the wing cracks penetrate the end of the preformed fractures, in the JZ-1 test, the wing cracks penetrate the end of the fractures through secondary coplanar cracks. This indicates that at this loading rate, the stress structure around the preformed fractures is fully adjusted, and the particles at the fracture tips and the fracture filling materials together provide shear resistance, forming a larger shear surface along the preformed fractures. Wing cracks appeared on the surface of all four tests models, indicating that the upper and lower portions are subjected to compressive shear failure along the preformed fractures.

In the four tests, only the JZ-1 test model had wing cracks on both the upper and lower portions, and the crack characteristics were roughly symmetrical around the center, indicating that at a low loading rate, the fracture development is stable and regular. The crack development in the JZ-1, JZ-2, and JZ-3 tests is more complex. The model tends to form through cracks on the surface through the development of secondary and derived cracks. This development mode involves a larger area of failure and cracks developing in different directions, and the regularity of crack development is weak.

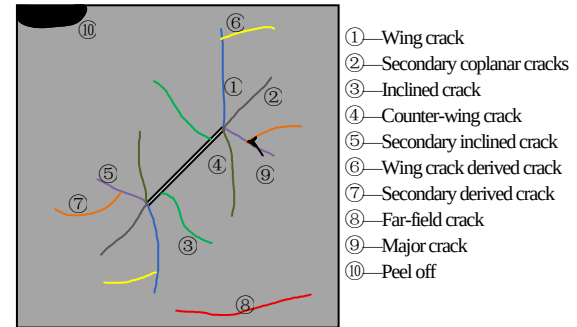


Fig.5 Schematic diagram of failure patterns

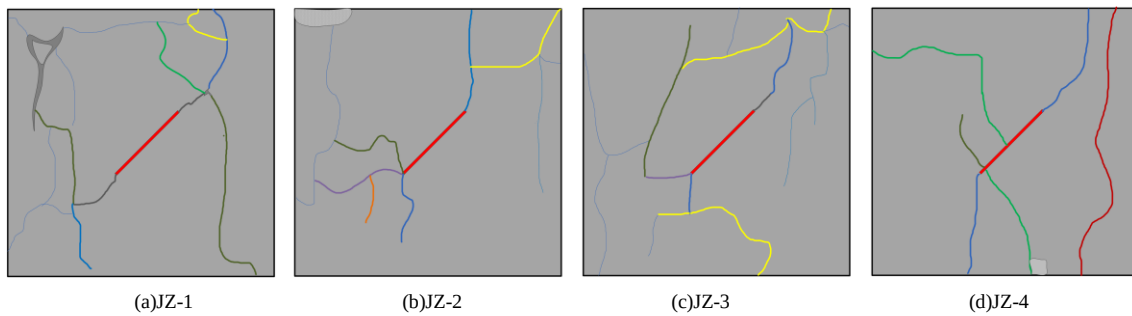


Fig. 6 Schematic diagram of model failure modes

3.5 Relationship between loading rate and fracture activity

From the perspective of fracture activity characterization, the sliding rate, as a key indicator for measuring the cumulative rate of fracture strain, exhibits dynamic changes that not only reflect the accumulation and release characteristics of energy within the fracture zone, but also have a significant spatiotemporal coupling relationship with the fracture activity^[29, 16]. Based on the analysis in Section 2.2, the model surface is not simply shear failure along the preformed fractures. Considering that the rock mass at the end of the fracture restricts the sliding of the fracture during the sliding process, the relative sliding rate on both sides gradually decreases from the main section to the end^[30]. Combined with the lateral displacement cloud map of the model surface, the time interval of the sliding of the preformed fractures can be located. Therefore, monitoring points are set at both ends and the middle of the preformed fractures as shown in Fig. 7. Using the VIC software, the relative displacements of the monitoring points on the upper and lower portions are monitored. According to the following equation, the

relative sliding rates at the middle and end of the preformed fractures are calculated and the relative sliding rate-time curve is drawn.

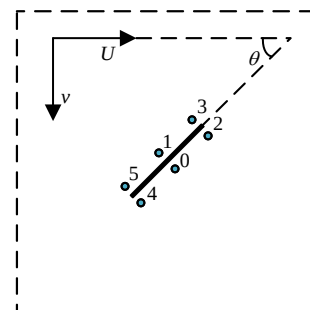


Fig. 7 Layout of monitoring points

$$v_{i-j} = \frac{(U_i \cos \theta - V_i \sin \theta) - (U_j \cos \theta - V_j \sin \theta)}{t} \quad (5)$$

where U_i and V_i are the transverse displacement and longitudinal displacement of the i -th measuring point, respectively; v_{i-j} is the relative slip rate between

measuring points i and j ; and U_j, V_j are the transverse displacement and longitudinal displacement of the j -th measuring point, respectively.

As shown in Fig. 8, it can be seen that except for model JZ-2, all models have a relatively obvious fracture sliding time interval (shaded in gray). The rate curves all experienced certain fluctuations in the initial loading stage. The reason is that the main load-bearing structure of the model was not subjected to force, and the model was in the overall compression stage. The rate curves showed a trend of a sharp increase first and then oscillatory decline. By comparing the data of the four tests, in the JZ-1 test, due to the strain concentration at the upper end of the preformed fracture, there was a slight fluctuation in the upper end rate curve v_{2-3} during the elastic deformation stage (Fig. 8(a)). The initiation time of the preformed fracture sliding was 250 s, as shown in the displacement contour clouds of Fig. 8(a). At this time, there was a regional difference in the surface displacement on both sides of the fracture. The end time of the fracture sliding was 450 s, and at this time, the model surface had developed a shear crack penetrating the model surface along the preformed fracture, marking the end of the fracture sliding. In the JZ-2 test, due to its main fracture being S-shaped distribution (Fig. 8(b)), and bypassing the upper end of the preformed fracture, the sliding rate at the lower end was greater than that at the middle and upper ends. Combined with the direction of crack extension, the sliding rate of the lower end of the preformed fracture can be regarded as the main segment sliding rate of the new fracture. From the displacement contour clouds of Fig. 8(b), it can be known that 110 s was the initiation time of the fracture sliding, at which time there was a displacement difference in the lower part of the fracture along both sides and a crack developed at the lower end of the fracture. The boundary band of the displacement contour clouds at the upper end of the fracture shifted to the upper left. 300 s was the end time of the fracture sliding, at which time the model surface developed an S-type crack and penetrated the model surface. For the JZ-3 test, the fracture sliding time interval was 30–70 s, with the starting and ending characteristics being that the displacement difference appeared on both sides of the fracture and the crack penetrated the model surface. In the JZ-4 test, at the 15 s moment, a boundary line with a slanted Z-shape displacement difference appeared on the model surface. At this time, shear failure dominated with slanted cracks on both sides, and the Z-shape crack fully developed at 30 s. The model surface developed X-type failure at the locking segment of the upper end of the fracture and the upper sliding rate increased. By comparing the stress-time curves in Fig. 3, in the four loading tests, the fracture activity of JZ-1 occurred in the failure deformation stage; the fracture activity of JZ-2 began at the end of the elastic deformation stage and ended in the middle of the failure deformation stage; the fracture activity of JZ-3 began at the beginning of the elastic deformation stage and ended at the beginning of the failure deformation stage; the fracture activity of JZ-4

occurred in the elastic stage. This indicates that an increase in the loading rate will induce the fracture to activate earlier. Comparing the four tests, with the increase of the loading rate, the peak sliding rate of the preformed fracture was 0.001, 0.001 4, 0.004, and 0.002 2 mm/s, showing a trend of increasing first and then decreasing. This indicates that in the loading rate range of 0.005–0.05 mm/s, the activity of the preformed fracture increases with the increase of the loading rate. When the loading rate reaches 0.1 mm/s, the activity of the fracture decreases. For the trend of the fracture activity decline in the JZ-4 test, the reason is that under the high loading rate, the model transforms from single shear failure to X-failure. When the model fails, more plastic units are involved. From the surface strain diagram in Fig. 3, when the model undergoes Z-type shear, the main body of the activity is the slanted cracks on both sides, which bear most of the energy release.

3.6 Correlation analysis of fracture activity and strain deflection angle

The dynamic expansion process of the shear fracture zone will cause a significant deflection of the principal stress axis in the expansion control area. The underlying mechanism stems from the redistribution and concentration effect of the stress at the tip during the shear motion. Some scholars believe that during the sliding process, the undeformed blocks bounded by the main fracture segment of the fracture accommodate the main mutual movements between the blocks^[31–32]. The intense activity of the fracture will promote the deflection of the principal strain axis of the end blocks. To better understand the relationship between the fracture slip rate and the end principal strain deflection during the same period, the mechanism of the influence of fracture activity on the strain field of the on both sides of the fracture is analyzed. Using statistical models, a correlation analysis of the two parameters is conducted. Given that the two sets of test data have non-normal distribution and nonlinear characteristics, the Spearman correlation analysis model is adopted to analyze the data^[33]. Spearman correlation analysis of the fracture slip rate and the end principal strain deflection in Fig. 8 is conducted to obtain the Spearman rank correlation coefficient between the two parameters, where SS and SO represent the displacement contour cloudss of the model surface at the beginning and end of fracture slip, and the results are summarized as shown in Fig. 9. The fracture slip rate and the end strain deflection angle show a high correlation, but there is a weak correlation in some areas (JZ-1 Z2, JZ-2 Z3, JZ-3 Z1, JZ-4 Z4). In the JZ-1, JZ-2, and JZ-3 tests, the correlation relationship between the deflection angles on both sides of the same end and the slip rate is generally opposite. In the JZ-4 test, due to the difference in failure mode, it shows different regional correlation characteristics, with the deflection angles and slip rate showing a negative correlation in all four regions.

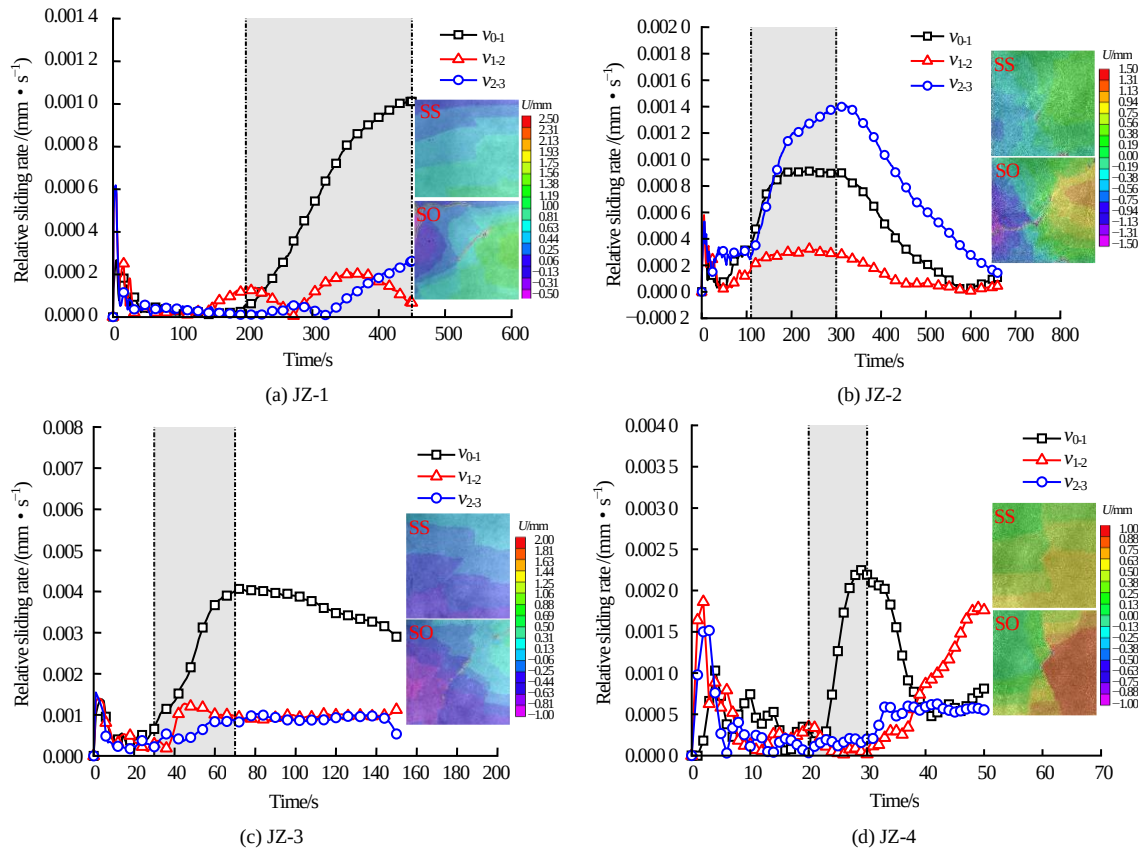


Fig. 8 Time-history curves of relative sliding rate

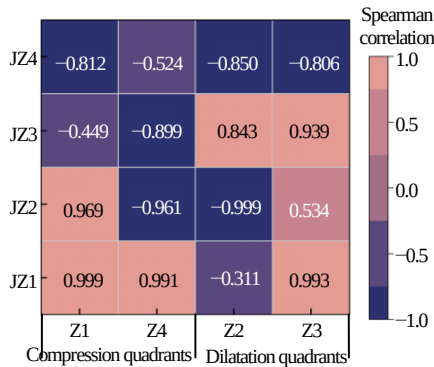


Fig. 9 Heatmap of correlation between sliding rate and strain deflection angle

The failure and damage of rock masses are not only related to the deformation of the rock masses but also control the release of energy. The correlation between the sliding rate and the strain deflection angle can be explained by the relationship between the damage variables of the rock mass and the stress intensity factor. Liu^[34] proposed the expression of rock mass damage variables based on the theory of deformation modulus damage attenuation^[34]:

$$\begin{Bmatrix} \sigma_{y'y'} \\ \sigma_{x'x'} \\ \sigma_{x'y'} \end{Bmatrix} = \frac{K_I}{\sqrt{2\pi r}} \cos \frac{\beta}{2} \begin{Bmatrix} 1 - \sin \frac{\beta}{2} \sin \frac{3\beta}{2} \\ 1 + \sin \frac{\beta}{2} \sin \frac{3\beta}{2} \\ \sin \frac{\beta}{2} \sin \frac{3\beta}{2} \end{Bmatrix} + \frac{K_{II}}{\sqrt{2\pi r}} \begin{Bmatrix} -\sin \frac{\beta}{2} (2 + \cos \frac{\beta}{2} \cos \frac{3\beta}{2}) \\ \sin \frac{\beta}{2} \cos \frac{\beta}{2} \cos \frac{3\beta}{2} \\ \cos \frac{\beta}{2} (1 - \sin \frac{\beta}{2} \sin \frac{3\beta}{2}) \end{Bmatrix} \quad (9)$$

$$D = \frac{1}{1 + e^{a-b\varepsilon}} \quad (6)$$

In the formula, a and b are the Logistic fitting parameters, where a represents the degree of initial damage, and b represents the speed of damage growth.

According to the pattern shown in Fig. 8, assuming that the relative sliding rate during the fracture slip stage is linearly related to time, and in the isochronous loading mode, the strain is linearly related to time, then:

$$v = k(\varepsilon - \varepsilon_1) \quad (7)$$

where ε_1 represents the strain at the moment when the fracture begins to slip, v is the relative slip rate, and k is the strain-sliding rate conversion coefficient.

Substituting Equation (7) into Equation (6) yields $D-v$ relations:

$$D = \frac{1}{1 + e^{a-b(\frac{v}{k} + \varepsilon_1)}} \quad (8)$$

Combining the first-order approximate formula for the stress field at the crack tip in isotropic homogeneous media^[35]:

where $\sigma_{y'y'}$ 、 $\sigma_{x'x'}$ 、 $\sigma_{x'y'}$ are the normal stress and shear-stress components in the local coordinate system at the crack tip, respectively, β represents the rotation angle starting from the central axis of the fracture; and r is the distance from the research point to the tip of the fracture. Obviously, when β and r are determined, the stress state at this point is determined by stress intensity factors K_I and K_{II} .

According to the relationship formula for calculating the damage variable based on the stress intensity factor at the tip of the damage joint proposed by Li et al.^[36], it can be concluded that the strength factor at the joint tip can control both the damage variable of the rock mass and the stress field at the tip of the rock fracture. Combining with Equation (8), it can be considered that there is an equation relationship between the strain-deflection angle and the relative-slip rate. In addition, Li's research indicates that the loading rate affects the value of the stress intensity factor^[11], which suggests that the loading rate can influence the rock mass strain field by affecting the K value. From the above analysis, it can be seen that: as the loading rate increases, the rate of internal strain energy accumulation in the model significantly accelerates. This process directly leads to the occurrence of failure events or causes the energy release process to exhibit more intense non-stability characteristics, thereby exerting a regulatory effect on the spatiotemporal evolution of fracture activities. It is worth emphasizing that during the model failure stage, the dynamic evolution of the strain field and the fracture expansion process present a two-way coupling mechanism—the local adjustment of the strain field (such as the deflection of the principal strain axis, the redistribution of strain energy density) provides the stress gradient conditions for fracture expansion, while the dynamic extension of the fractures, in turn, acts on the strain field reconstruction by changing the stress field distribution. This two-way interaction essentially reflects the intrinsic unity of energy release (mainly in the form of strain energy conversion) and strain redistribution (mainly in the form of microstructural deformation adjustment) in the fracture system.

4 Discussion

This study analyzed the mechanical responses, strain field evolution, failure modes, and fracture activity of the rock-like model under different loading rates. To a certain extent, it demonstrated the correlation between loading rate, strain field evolution, and fracture activity under uniaxial compression conditions. However, this study was limited to a single strength ratio rock-like model and did not consider different strength and fracture characteristic models; Studies have shown that changes in rock mass strength can have a significant impact on the deformation characteristics and acoustic emission features of the rock mass^[17]; This led to the conclusion of this article being insufficiently applicable to different types of rock masses. In future research, based on the findings of this study, the conclusions of this study and conduct research on the mechanical properties of different strength rock-like models from both numerical simulation and physical

simulation aspects, hoping to obtain more scientific and rigorous research results.

Section 3.1 analyzed the changes in mechanical properties and failure characteristics of the rock-like model under different loading rates; from the perspective of energy, as the loading rate increases, the energy input efficiency is higher, and the time for the model to receive, store, and release energy becomes shorter. Combined with the analysis in Section 3.2, Equation (2) gives the relationship between energy release rate and strain rate; when the strain is the same, the increase in strain rate leads to an increase in energy release rate, and the failure mode of the model changes from the ductile failure with slow energy release to the brittle failure with intense energy release. The limitation of this part is that it only provided a qualitative explanation for how the loading rate affects the mechanical properties and failure characteristics of the model but lacked quantitative analysis, resulting in the lack of persuasiveness of the analysis results. In future research, we will conduct more experiments with different loading rates to summarize more accurate laws and carry out quantitative research on the loading rate effect mechanism of the mechanical properties and failure characteristics of the rock-like model.

From the analysis in Section 3.5, it can be seen that the pre-existing fracture activity basically increases with the increase in loading rate. The reason is that during the release of strain energy, a part of the energy is converted into kinetic energy, causing relative sliding of the fractures. In the analysis in Section 3.3, the change in the strain deflection angle was considered to be related to the expansion of the pre-existing fractures, that is, the change in the strain deflection angle is related to the release of energy. Fracture activity characterizes the intensity of energy release, and its correlation with strain-deflection angles deserves further in-depth investigation. Section 3.6 preliminarily discussed the correlation between fracture activity and strain deflection angle, but the research on the mechanism still has limitations. It is worth noting that Su's research^[16] indicates that in the specific stage of rock mass deformation, the correlation between the fracture activity and the strain deflection angle around the fracture can be well fitted by the Logistic model. The fitting formula is

$$\gamma = \frac{m - n}{1 + (v / v_0)^\rho} + b \quad (10)$$

where γ represents the deflection angle corresponding to the local stress field around the fault; v represents the relative deformation rate between the two blocks; m and n are the initial and final values of the regression curve, v_0 is the central value of the displacement rate, and ρ is the power value. By comparing the above conclusion with the analysis in Section 3.6, it can be found that the fitting model for the correlation between the stage fracture activity and the strain deflection angle around the fracture and the fitting model for the rock and soil damage variables have some commonalities. This to some extent can reflect the relationship between the rock damage

variables, fracture activity, and local strain deflection angle, but the theoretical derivation still requires more rigorous discussion. Combining the energy release law during the loading process for analysis will be more helpful for studying the correlation between fracture activity and strain deflection angle. In future research, we will focus on the acoustic emission and energy release characteristics of the rock-like model under different loading rates to conduct a more comprehensive study on these issues.

5 Conclusions

This study, through uniaxial-compression tests combined with strain monitoring and DIC techniques, systematically analyzed the influence of loading rate on the deformation characteristics of single-crack rock mass models. It revealed the intrinsic relationship between the loading rate and the failure characteristics, failure mode, strain field evolution and fracture activity of the rock mass models. The main conclusions are as follows:

(1) The stress-strain curve of the model shows a S-shaped four-stage evolution (compaction → elasticity → crack propagation → post-peak failure). The loading rate has a significant impact on the mechanical properties and failure characteristics. The elastic modulus of the rock-like model increases with the increase of the loading rate. Under low-speed loading, a clear stress stabilization period appears after the peak, and the negative slope of the post-peak curve is gentle, showing ductile characteristics; under high-speed loading, the peak stress increases while the peak strain decreases, and the negative slope of the post-peak curve is steep, presenting sudden brittle failure characteristics.

(2) When the loading rate increases to a certain extent, it will promote strain localization. The strain concentration in the upper side compressive stress zone is significant, and it dominates the initiation and propagation of cracks. At low loading rates, the oscillation of the strain deflection angle at the model fracture tip in the tensile stress zone occurs earlier than that in the compressive stress zone. At high loading rates, the oscillation of the deflection angle in the tensile-compressive stress zone tends to be synchronous.

(3) The low-speed loading mainly causes shear failure along the preformed fractures, with a low density of surface cracks. The anti-wing cracks on the upper and lower portions develop symmetrically. The failure mode is stable. As the loading rate increases, the crack density reaches its peak, and more derived cracks appear. The failure mode becomes more complex, but it still mainly consists of shear failure. At high loading rates, the failure mode changes to "X-type" shear failure. The fractures in the tension-compression stress zone expand synchronously, and the rapid release of energy leads to sudden instability.

(4) Through Spearman rank correlation analysis, the fracture sliding rate was significantly correlated with the end-point principal strain deflection angle. Under uniaxial compression, plastic shear deformation dominated, and the principal strain deflection angle and the sliding rate increased simultaneously, reflecting the coupling effect of

rock body damage and strain field evolution under the Griffith criterion.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

Acknowledgments

This research was led by author Su Zandong in terms of experimental design and data analysis, while Tang Ning ming was responsible for data collection and the initial draft writing. Author Yin Gan and author Tao Zhigang jointly completed the framework construction of the literature review and the preparation of experimental materials, and participated in data verification and result discussion. Author Wang Hong was responsible for proofreading and chart production, and author Gan Fei participated in the final revision of the paper.

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