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Failure characteristics and its influencing factors of rock-like material with multi-fissures under uniaxial compression

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Abstract: The compression test on rock-like specimens with prefabricated closed multi-fissures made by pulling out the embedded metal inserts in the precured period was done on the servo control uniaxial loading instrument. The influence of fissure inclination angle and distribution density on the failure characteristics of fissure bodies was researched. It was found that, the fissure inclination angle was the major influencing factor on the failure modes of fissure bodies. The different developmental states of micro-cracks would appear on specimens under different fissure inclination angles. However, the influence of fissure distribution density on the failure mode of fissure bodies was achieved by influencing the transfixion pattern of fissures. It was shown by the sliding crack model that, the effective shear, which drove the relative sliding of the fissure, was a function of fissure inclination angle and friction coefficient of the fissure surface. The strain-softening model of fissure bodies was established based on the mechanical parameters that were obtained by the test of rock-like materials under the same experimental condition. And the reliability of experimental results was identified by using this model.

Key words: rock-like material; prefabricated fissure; uniaxial compression; sliding crack model; strain-softening model

1 Introduction

Owing to the effect of the geology movement and tectonic stress field, rock mass was not homogeneous medium but block structure incised by structural surfaces, such as faultages, joints and fractures. Therefore, the engineering properties of rock mass were influenced not only by intact rocks but also by the mechanical properties of discontinues surfaces. But due to the difficulties of in-situ tests, the laboratory loading test of rock-like materials was an effective research method and widely used by scholars. On the premise that material was brittle, mechanical property was stable, and machining was easy, different materials which were used to make prefabricated fissures were selected in accordance with different purposes of experiments, for instance, polyester film [1], crack gage, and metal insert [2]. In other cases, prefabricated fissures were also made by piling up small blocks [3, 4] in experiments. Based on the laboratory loading test of rock-like materials, much intensive studies on the expansion mechanism of micro-cracks and fracture failure mechanisms of fissure bodies [5−11] have been done by domestic and foreign scholars.

It was put forward by ZHANG et al [12] that the failure of fissure bodies was caused by the failure evolution on local region of specimen. So, a theoretical formula of localized progressive damage model of rock-like materials with fissures was established. Based on the damage cumulation and structural failure of rock specimens in a failure process, the energy dissipation and energy release principles were proposed by XIE et al [13]. And then, the critical stresses at the time of abrupt structural failure of rock specimens under various stress states could be determined by these principles. Combined with the CT scan and acoustic emission, introducing the damage theory into the failure mechanism analysis [14] has become the new research approach to the damage mechanism of fissure bodies. Currently, many researches about the failure mechanism of fissure bodies mainly focused on the development states of micro-cracks and transfixion patterns of fissures. But the work that considered the influences of both fissure inclination angle and distribution characteristic has been done less. In this work, based on the damage evolution of fissure bodies, the influence of both fissure inclination angle and distribution characteristic of fissure

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bodies was analyzed and summed up. By combining with the numerical calculation and sliding crack model, the experimental result was identified and explained.

2 Experimental

2.1 Specimen preparation

Based on the similar mechanical properties (brittle and dilatant) with natural rock masses, cement mortar specimens were used in this study. Rock-like materials were made of a mixture of water, white cement (Label 425), and silica sand. And the following volume ratio of these materials was used for all specimens: V(water):V(white cement):V(silica sand)=1:2:1. For this kind of specimens, on one hand, silica sand could be considered the skeletal material; on the other hand, it could strengthen the frictional characteristic. The external measurement of specimens was 200 mm×150 mm×30 mm. The prefabricated transfixion fissures were made by pulling out the embedded metal inserts with the thickness of 0.4 mm in the precured period; and the length of fissures was 20 mm. The closure state of fissures must be detected before test.

In this test, the specimens could be divided into four groups according to the fissure inclination angle (25°, 45°, 75° and 90°); from another point of view, they could also be divided into four groups according to the fissure distribution density (15, 20, 25 and 30 fissures). The details of specimens are shown in Fig. 1.

2.2 Loading

Combined with the loading control system named DCS-200, this testing was made on the servo control uniaxial loading instrument. The loading rate was set to be 200 N/s. In order to reduce the influence of the end effect, two rubber cushions coated with butter were placed between the ends of the specimen and pressure plates of the instrument. During the loading process, failure patterns and stress—strain curves of specimens were observed and recorded by camera; and the clock gauge set on the middle part of side was used to indicate the transverse deformation behaviors of specimens.

3 Numerical analysis

Under the same experimental condition, the mechanical parameters of rock-like materials were obtained and shown in Table 1. Because the complete stress—strain curves of numerical models could be given by the strain-softening model, this model of fissure bodies was established by the numerical program FLAC3D in order to verify the reliability of experimental results. The strain-softening coefficients of numerical model are shown in Table 2. This model could also show the yield states of elements in rock-bridge regions during every stage.

During the numerical calculation process, the boundary conditions (shown in Fig. 2) of models kept

Table 1 Mechanical parameters of rock-like materials

Parameter	Value
Density/(g·cm^{-3})	2.019
Elastic modulus/GPa	2.272
Uniaxial compressive strength/MPa	23.13
Uniaxial tensile strength/MPa	2.75
Poisson ratio	0.2251
Bulk modulus/GPa	1.378
Shear modulus/GPa	0.9273

Table 2 Strain-softening coefficients of numerical models

Plastic strain	Friction angle/(°)	Cohesion/MPa
0	42	5
0.01	40	4.8
0.011	35	4
0.012	30	3
0.015	20	2
0.025	5	0.1
0.040	5	0.1

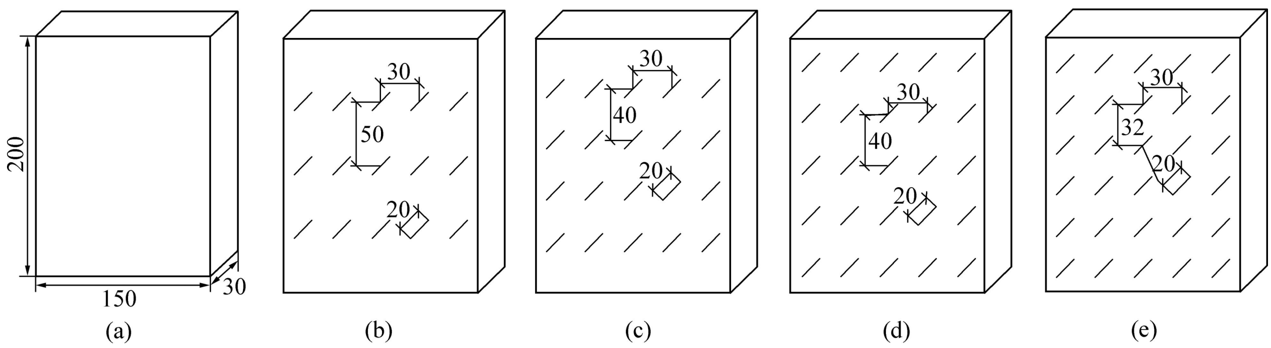


Fig. 1 External measurement of specimens (a) and fissure distribution state on specimen (taking fissure inclination angle being 45° for example) (b, c, d, e)

consistent with the experimental conditions. On the principle of static loading, the loading velocity was set to be 9×10^{-8} m/step during the process of numerical calculation.

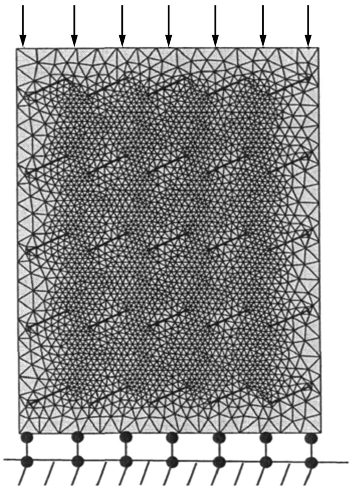


Fig. 2 Sketch of numerical model and boundary condition

4 Results and analysis

4.1 Characteristic of stress—strain curves of fissure body

Because of the existence of prefabricated fissures in the fissure body, the influencing and perturbation on the stress and displacement fields of specimen couldn't be ignored. In this study, it was found that fissure inclination angle was the major influencing factor on the strength of fissure bodies, and the influence of fissure distribution density merely acted on changing transfixion pattern of fissures. This is because the stress concentration phenomenon was limited in the micro-neighborhood around fissure tip. On the premise that the additive effect of stress concentration phenomenon couldn't be caused by the clear distance between adjacent fissures, and the weakening of strength caused by the increase of fissure distribution density was almost negligible. But the changing of transfixion pattern should also be paid attention to, which was caused by the change of fissure distribution density. By observing the complete stress—strain curves of fissure bodies, it was found that stress-dropping phenomenon of stress—strain curves had direct correlation with the developmental states of micro-cracks at fissure tips.

1) When the micro-cracks appeared on the fissure body, frequentative stress-dropping phenomena of complete stress—strain curves would be shown, especially for specimens with the fissure inclination angle of 25° (shown in Fig. 3). By comparing with the failure process, it was found that, after compression phase of micro-fissures in the initial stage of loading, the strength of fissure bodies increased approximately linearly. Before the peak strength, the increasing rate of strength had an obvious moderating process. In this moment, micro-cracks couldn't be found on the surface of specimen. However, when the stress—strain curve passed the peak, micro-cracks began to appear at tips of fissures that distributed in the specimen's clinodiagoal which had the similar trend with fissures, and then connected with each other quickly. It could be anticipated that during the period when the growth rate of strength decreased, the relative sliding of prefabricated fissures occurred, but didn't cause the macro-cracks appear. Because of the existence of rubbing effect on failure surface, although the transfixion of prefabricated fissures appeared, specimens didn't lose their bearing capacity. The strength would increase again after drop rapidly, and partial specimens' secondary peak strength was close to the peak strength. During the frequentative stress-dropping process, micro-cracks began to appear at tips of fissures which distributed in both sides of the transfixion surface, and then expended slowly. Finally, the failure states of fissure bodies would be extremely fractured.

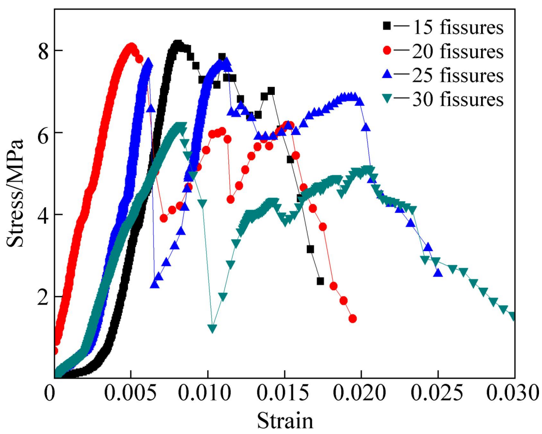


Fig. 3 Stress—strain curves of fissure bodies with inclination angle of 25°

2) With the increase of fissure inclination angle, it would be more and more difficult for the appearance of micro-cracks at the tips of prefabricated fissures. Accordingly, the stress-dropping phenomenon of stress—strain curves was also more and more unobvious (shown in Figs. 3−6). When the failure of fissure bodies occurred, since there did not appear transfixion of prefabricated fissures, the similar brittle failure of intact specimens was shown in these fissure bodies. Therefore, the rubbing effect of transfixion surface did not work in this kind of fissure bodies.

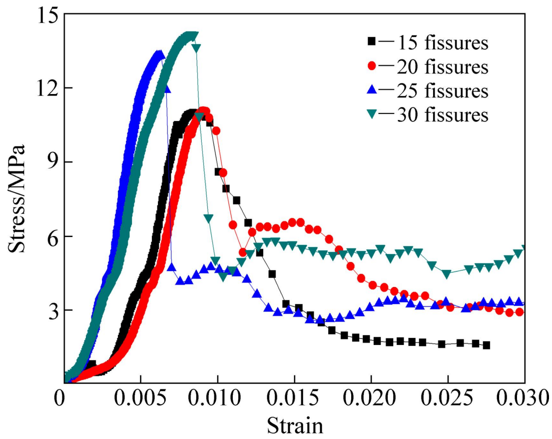


Fig. 4 Stress—strain curves of fissure bodies with inclination angle of 45°

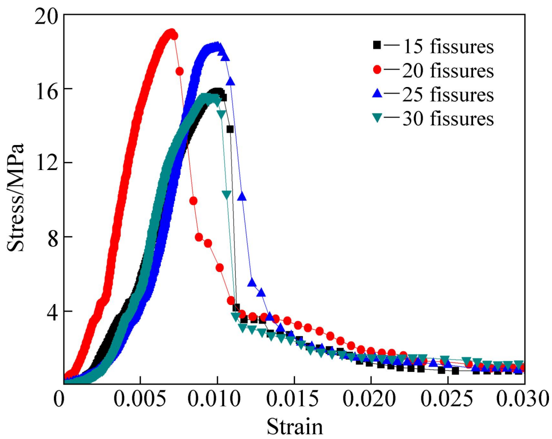


Fig. 5 Stress—strain curves of fissure bodies with inclination angle of 75°

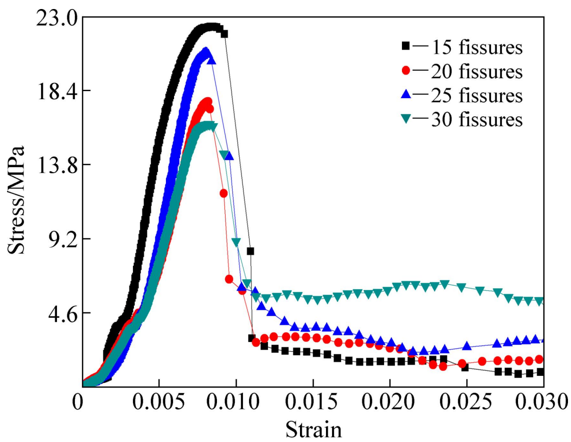


Fig. 6 Stress—strain curves of fissure bodies with inclination angle of 90°

4.2 Strength characteristic of fissure body

It was shown by experimental results that, for fissure bodies, the fissure inclination angle was the major influencing factor on the strength. Development of micro-cracks at the tips of fissures was the essential reason that led to the strength weakening of fissure bodies. It was considered by damage theory that the failure of rock and other brittle materials was caused by the accelerating expansion of micro-cracks which were evoked by the over-accumulation of damage in local region. When the trend of prefabricated fissures was propitious to accelerate the expansion of micro-cracks, the existence of fissures would accelerate the accumulated process of damage. But when the trend of prefabricated fissures was helpless to accelerate the expansion of micro-cracks, the influence of fissures on strength weakening could be negligible.

The strength changing characteristic of rock-like materials with multi-fissures, which were caused by the changing of fissure inclination angle, is shown in Fig. 7. It was shown by experimental results that, under uniaxial compression, the peak strength of specimens with multi-fissures increased along with the increase of fissure inclination angle. It was shown by numerical calculation results that, when the fissure inclination angle was 25°, the peak strength of specimens was the minimum; when the inclination angle was less than 25°, the strength increased a little; when the inclination angle was larger than 25°, the strength would increase along with the increase of fissure inclination angle, and the increasing rate also increased. When the fissure inclination angle was 25°, the weakening effect of prefabricated fissures

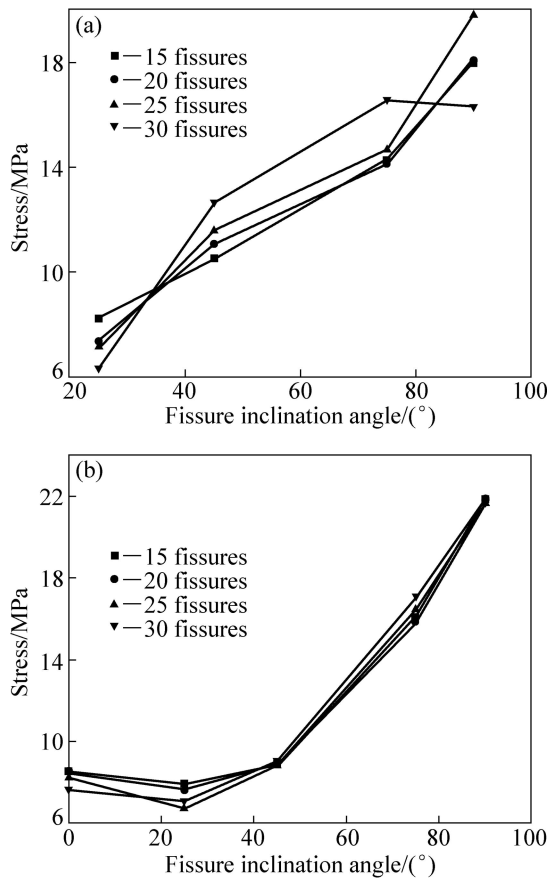
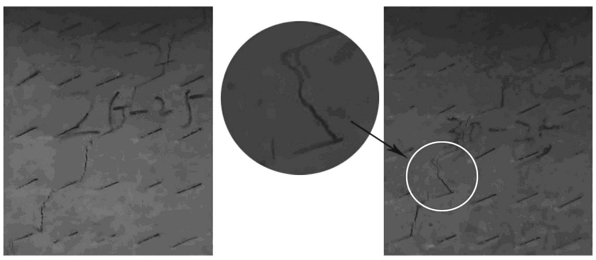


Fig. 7 Strength characteristic of fissure bodies in experiment (a) and in numerical simulation (b)

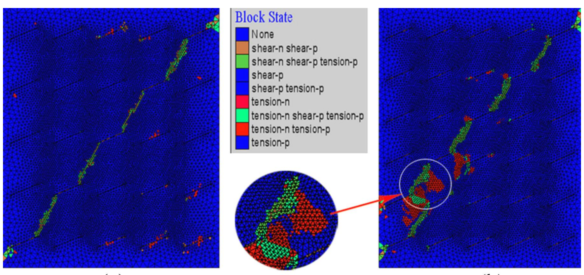
on strength was the most prominent, and the strength of these specimens lost 45%−55% and 60% compared with the intact ones in testing and numerical calculation, respectively. It was found by the comparison between the experimental and numerical calculation results that, for the strength of the rock-like materials, the weakening effect of prefabricated fissures would decrease gradually along with the increase of fissure inclination angle. Ignoring the influence of data scattering of brittle materials, the strength changing characteristic of rock-like materials with multi-fissures in Fig. 7(a) was consistent with that in Fig. 7(b).

It was found by further comparison between the experimental and numerical calculation results that, for specimens with the same fissure inclination angle, when the number of fissures was no more than 25, the strength of specimens decreased slightly along with the increase of fissure distribution density; but when the number of fissures was up to 30, comparing with the specimens with 25 fissures, the strength did not decrease but increased (shown in Fig. 5) when the fissure inclination angle was 25°. Moreover, this phenomenon had a relationship with the development state of micro-cracks at the tips of fissures. For explaining this phenomenon, the observation was put emphatically on the loading videos and numerical calculation processes of specimens with 25 and 30 fissures. It was found that, when the number of fissures was 25, the tension−shear combined failure pattern would appear in rock-bridge regions which distributed in the specimen's clinodiagoal. Especially for specimens with the fissure inclination angle of 25° (shown in Fig. 8(a) and Fig. 9(a)), this



(a) (b)

Fig. 8 Transfixion patterns of specimens with 25 (a) and 30 (b) fissures under experimental condition



(a) (b)

Fig. 9 Transfixion patterns of specimens with 25 (a) and 30 (b) fissures under numerical simulation condition

failure state was the most prominent. But when the number of fissures was 30, not only the tension-shear combined failure but also the transfixion failure of wing cracks appeared in rock-bridge regions (shown in Fig. 8(b) and Fig. 9(b)). Therefore, it was concluded that, although the fissure distribution density couldn't directly influence the strength characteristic of fissure bodies, it could be achieved indirectly by influencing the expansion and transfixion patterns of micro-cracks at tips of fissures.

5 Sliding crack model

The sliding crack model [15], which was generally accepted in the rock mechanics field, was used to analyze the fracture failure mechanism of fissure body and stress distribution state of fissure surface in brittle materials (i.e. plain concrete) with prefabricated fissure under uniaxial compression. And the stress distribution state of fissure surface is shown in Fig. 10.

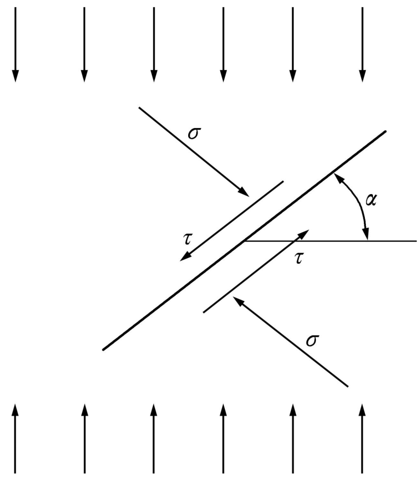


Fig. 10 Stress distribution sketch of prefabricated closed fissure

$$\sigma = p\sin^2\alpha = \frac{p}{2}(1-\cos 2\alpha)\,,$$

$$\tau = p\sin\alpha\cos\alpha = \frac{p}{2}\sin 2\alpha \qquad (1)$$

where σ is the normal stress on the fissure surface; τ is the shear stress on the fissure surface; α is the inclination angle of the prefabricated fissure; p is the uniformly distributed pressure at the end of specimen.

It is held by the sliding crack model that, the shear stress on the fissure surface is the driving force for the relative sliding of fissure, namely, the shear stress τ is the driving force for the development of micro-cracks at fissure tips. But when the friction coefficient of fissure surface is considered, the normal stress σ also influences the relative sliding of fissure. In this study, the friction coefficient is set to be f. Hereby, the effective shear Q_{eff} can be obtained from the following formula:

$$Q_{\text{eff}} = 2a(\tau - f\sigma) = pa[\sin 2\alpha - f(1-\cos 2\alpha)] \quad (2)$$

After derivation calculus to Eq. (2) about α, the fissure inclination angle for the maximum value of effective shear stress can be obtained from the following equation:

$$\alpha = \frac{1}{2}\operatorname{arccot} f \quad (3)$$

Namely, when the friction coefficient is 0, the minimum of effective shear can be obtained with the fissure inclination angle being 45°.

In the similar tests, it was found by LI et al [16] that, when the fissure inclination angle was 45°, the uniaxial compressive strength of rock-like material got the minimum. And the similar experimental results were obtained by domestic and foreign scholars in laboratory tests [6, 7, 17]. By observing their experimental processes, it was found that the prefabricated fissures of their specimens were open. Therefore, the friction coefficient of fissure surface equaled 0 approximately. Hence, their experimental results were consistent with the conclusion of Eq. (3). But in this study, because the fissures were made by pulling out the embedded metal inserts in the precured period, they would be closed due to the swell induced by the hydration reaction of cement mortar during the curing process. For this reason, the friction coefficient of fissure surface was not 0. And then the experimental results that the strength of specimens with fissure inclination angle being 25° was less than that with fissure inclination angle being 45° could be explained and analyzed quantitatively by this model.

6 Conclusions

1) Fissure inclination angle was the major influencing factor on the failure characteristics of fissure bodies. The process of rock failure could be regarded as a process of the damage evolution and macro-cracks expansion. When the trend of prefabricated fissures was propitious to accelerate relative sliding of fissures, the existence of fissure would cause the over-accumulation of damage in local region, and then evoke the development of micro-cracks at tips of fissures.

2) The strength weakening caused by changing of fissure distribution density was not prominent. The influence of fissure distribution density on the strength weakening was achieved indirectly by influencing the transfixion pattern of prefabricated fissures. Because the stress concentration phenomenon was limited in micro-neighborhood of fissure tips, on the premise that obvious additive effect of stress field couldn't be caused by the clear distance between adjacent fissures, the influence of fissure distribution density on damage evolution was less. But when the obvious additive effect of stress field appeared between adjacent fissures, the strength weakening caused by the increase of fissure distribution density would be prominent.

3) The effective shear distributed on the surface of prefabricated fissure was the driving force for the development of micro-cracks at fissure tips, and it was a function of the fissure inclination angle and friction coefficient of fissure surface. It was proved in theory that the fissure inclination angle was the major influencing factor on failure characteristics of fissure bodies.

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单压下多裂隙类岩材料的破坏特征及其影响因素

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摘　要：在伺服控制单轴加载试验机上，对采用养护前期拔出预埋金属插片方式制作的闭合多裂隙类岩试件进行压缩实验，研究裂隙倾角及裂隙分布密度对裂隙体破坏特征的影响机制。结果表明：裂隙倾角是影响裂隙体破坏模式的主要因素，受裂隙倾角的影响，裂隙尖端微裂纹呈现出不同的发育形态；而裂隙分布密度对裂隙体破坏模式的影响是通过影响裂隙贯通方式实现的。滑动裂纹模型表明：裂隙面上的有效剪力是裂隙面相对错动的驱动力，它是裂隙倾角与裂隙面摩擦因数的函数，这与实验所得结论相吻合。基于相同实验条件下类岩石材料的力学参数，建立了裂隙体的应变软化模型，并对实验结果的可靠性进行了验证。

关键词：类岩材料；预制多裂隙；单轴压缩；滑动裂纹模型；应变软化模型

(Edited by YUAN Sai-qian)