Investigation and Numerical Simulation of the Influence of Fracture Inclination on rock Mass Strength and Failure Pattern

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Abstract. The mechanical properties and failure patterns of rock mass are greatly influenced by the presence of numerous initial cracks. This study aims to investigate the impact of crack inclination angle on the strength of damaged rock mass. To achieve this, rock specimens with cracks inclined at 0°, 30°, 45°, 60°, 75°, and 90° were prepared, and laboratory mechanical tests were conducted. The tests examined the influence of different crack inclination angles on rock strength and failure patterns. Additionally, numerical simulations were performed to study the effect of crack angle on stress distribution and deformation size during axial loading. The analysis of the failure patterns of rock mass under different crack angles revealed that the initial cracks weaken the strength of the rock mass. Moreover, the weakening effect decreases as the crack angle increases. The numerical simulations showed that the weakening effect is caused by significant stress concentration at the crack tip, leading to crack propagation from the crack tips. The simulation analysis further demonstrated that crack development aligns with the stress distribution in rock mass, starting from the crack tip where the stress is highest and propagating along the direction of internal stress until the specimen is ultimately destroyed.

Keywords: Damaged rock; Mechanical properties; Numerical simulation; Angle of fracture.

1 Introduction

With the transition of energy mining from shallow to deep, the mining depth is increasing year by year. At present, the mining depth in China's inland areas has gradually entered the 1000-2000 meters depth level [1], and the deep rock mass has the characteristics of three heights and one disturbance. At the same time, under the joint action of excavation disturbance and ground stress, a large number of cracks, joints and other damages are generated inside the rock mass, which seriously affects the strength, deformation and failure form of the rock mass, and causes great troubles to the surrounding rock support of the roadway [2]. Especially under the influence of initial damage

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such as cracks in the rock mass, the strength of rock materials is reduced, the deformation is intensified, and the surrounding rock support of roadway is difficult. In recent years, accidents such as large deformation of surrounding rock and support failure occur frequently in deep mine roadway, which cause great difficulties to the construction and maintenance of deep engineering roadway [3,4]. The fracture surrounding rock shows sudden and violent characteristics during the failure, which brings great challenges for engineers and technicians to predict the failure of surrounding rock. Therefore, it is of great significance to study the mechanical properties of damaged rock mass, master the mechanical properties, deformation rules and failure mechanism of fractured rock mass, and establish the constitutive equation suitable for damaged rock mass to guide the construction and support of deep engineering.

Many scholars at home and abroad have carried out a lot of research on the mechanical properties of different types of damaged rock mass. Li Shuchen [5] et al. conducted an experimental study on the deformation and failure law of multi-fracture rock mass excavation, and found that the displacement and stress values of tunnel surrounding rock present a fluctuating distribution from inside to outside, and the fracture inclination Angle has a certain correlation with the distribution pattern of the failure zone. Li Wenzhou [6] et al. conducted field rock mass modification tests in the working roadway of a kilometer deep well, and proposed the basic principles of deep fracture coal and rock mass modification and the critical value range of modification and strengthening. Zhou Xiaoping [7] et al. studied the influence of rock mass damage on zonal fracture effect and found that as the damage degree of rock mass increased, the range and number of fracture zones increased. From the tunnel wall outward, the spacing between adjacent fracture zones increases and the width of fracture zones decreases. Chen Xin [8] et al. analyzed the shear deformation, strength characteristics and damage evolution law of fractured rock mass under different loading conditions, and found that the model macro and micro cracks originated, expanded and penetrated at the preset crack tip, and finally the middle rock bridge was dominated by tension failure. Zhu Changxing [9] et al. conducted laboratory uniaxial compression tests and particle flow numerical simulation on transparent rock specimens, and found that transparent rock exhibits splitting shear mixed failure, and most cracks develop at the bedding plane. Xian Zhenxing [10] et al. carried out a model rock mass fatigue test based on acoustic wave test, and found that the relationship between fatigue life of single fracture rock mass and fracture Angle was in the shape of "V", and the damage variable of 45° single fracture rock mass increased the fastest under cyclic load. Fu [11] et al. designed a number of dry- and fluid-saturated numerical cracked samples to investigate the roughness influence of crack surfaces on the elastic stiffness. Li [12] et al. carried out numerical simulation tests of rock-coal-rock composite structures with different crack characteristics and found the smaller the crack length, the larger the width of the crack zone. Mahdi [13] investigated the asperity damage response of jointed Aue granite under confined compression. Sisodiya[14] proposed a novel microcrack damage theory for describing the time-dependent behavior of brittle rocks. Ashby[15] proposed a new damage ontology model.

At present, scholars have carried out a large number of researches on the mechanical properties and theories of damaged rock mass. However, most of these researches are from the experimental level and describe the influence of different damage forms on the mechanical properties of rock mass from a macroscopic perspective, and there is a lack of researches on the failure mechanism of damaged rock mass and the distribution law of internal stress, strain and deformation of rock mass caused by damage. Based on the experimental and numerical simulation, this paper analyzed the law of the influence of fracture inclination on the bearing capacity and failure form of rock mass through the mechanical test of damaged rock mass. Through the simulation experiment of damaged rock mass, the influence of fracture dip Angle on the distribution of stress and strain in rock mass is analyzed. Based on the comprehensive analysis of the mechanical test and simulation test results, the influence law and action mechanism of fracture inclination on rock mass strength, deformation and failure are understood, which is a guidance and reference for the establishment of damage constitutive equation theory for deep damaged rock mass.

2 Test materials and processes

In this paper, similar specimens are prepared with similar rock materials as test materials, and cracks with different inclination angles are prefabricated in similar specimens to simulate cracks in rock mass, and the effects of fracture inclination angles on rock mass strength, deformation and failure patterns are studied. The width of cracks in rock mass can be divided into closed cracks (less than 1mm), micro-tensile cracks (1~3mm), open cracks (3~5mm) and wide cracks (greater than 5mm) according to different sizes. This paper mainly studies micro-tensile cracks, so the width of cracks in this paper is 1mm. At the same time, cracks in rock mass appear in all directions. In order to study the influence of crack inclination Angle on rock mass strength, crack inclination angles of rock mass are respectively 0° , 30°, 45°, 60°, 75°, and 90°.

3 Specimen preparation and test process

According to the requirements of *Engineering Rock Test Method Standard* (GB/T50266-2013), cylindrical specimens with dimensions of $\Phi 50\times 100$mm are used in this paper. The specimens were made with cylindrical split molds, as shown in Figure 1, and part of the specimens made in this paper are shown in Figure 2. When the specimen is made, the aggregate, binder and regulator are weighed according to the test plan. In this paper, the aggregate: binder: binder =2:1:0.5. Mix the ingredients well, add water and stir until the ingredients are well mixed. The evenly mixed ingredients are filled into the split mold, and the method of scratching and layering compaction is adopted to make the specimen, so as to ensure that the specimen does not appear layering.

Fig. 1. Mould of Specimen

Fig. 2. Prepared Specimens

In order to ensure that the density and strength of all specimens are in the same range, the compaction pressure of specimens is 2kN, and the steel sheet is inserted into the compacted specimens to form cracks. After the specimen was made, the specimen was numbered and dried in a ventilated place for 28 days to ensure that the drying degree inside and outside the specimen was similar. In this paper, the uniaxial compression test is carried out by a multifunctional material mechanics testing machine. The uniaxial compressive test was carried out according to GB/T 23561-2010 *Method for Determination of physical and mechanical Properties of Coal and Rock*. The loading speed of the testing machine was set at 0.5MPa/s, and the specimens with cracks were loaded until the specimens were damaged. The whole process of cracking, expansion and failure of the surface crack of the specimen was recorded during the loading process.

In order to reveal the crack propagation mechanism and evolution process of specimens with cracks, a three-dimensional model with different inclination angles consistent with prefabricated crack specimens was established in this paper, and the uniaxial compression test of fractured rock mass was simulated by ANSYS static simulation test. In the test, the base of the model was set as a fixed end constraint and the axial load was applied to the top of the model. The crack evolution process and crack propagation mechanism in damaged rock mass are revealed through the stress distribution and strain evolution in fractured rock mass model. In the simulation test, the material of the damaged rock mass is set as sandstone, and its mechanical parameters are shown in Table 1.

Table 1. Main mechanical parameters of sandstone

Parameter	Elasticity Modulus(GPa)	Poisson's ratio	Bulk Modulus(GPa)	Shear Elasticity(GPa)	Cohesive Force(MPa)	Friction Angle(degree)
Value	34	0.23	21.3	13.78	42	0.6

4 Experimental Results and Discussion

The distribution of internal stress within the precast fissure rock mass, as determined through the simulation of an uniaxial compression test, is presented in Table 2. Furthermore, Table 2 also displays the strength of the tested specimen obtained from the same uniaxial compression test. The strength of the specimen corresponds to its maximum value, while the average stress represents the average internal stress experienced by the specimen.

Table 2. Internal stress statistics of fractured rock mass

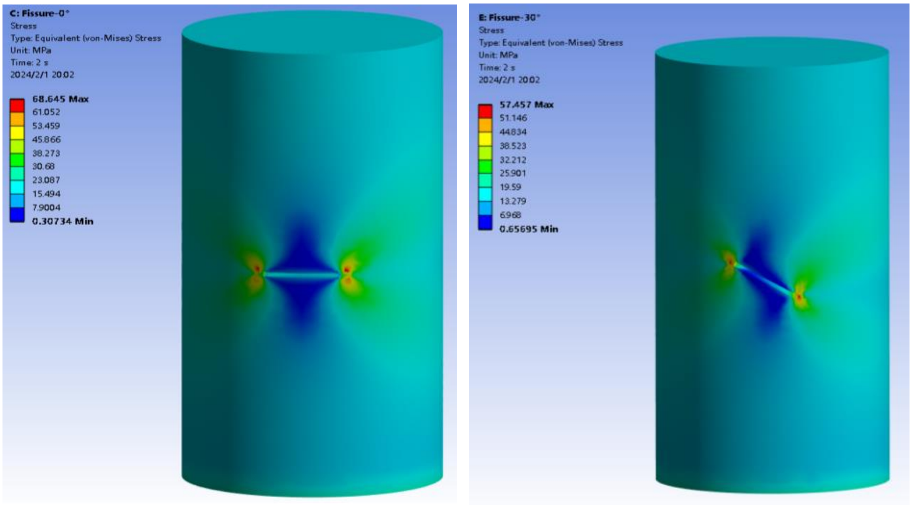
Angle of fracture(°)	0	30	45	60	75	90
Strength(MPa)	16.75	11.78	9.56	13.24	15.23	18.69
Average Stress(MPa)	18.36	20.99	26.84	25.41	22.34	20.56

This paper presents a study where mechanical tests were conducted on rock specimens containing cracks of varying inclination angles. The photographs of the specimens after failure can be observed in Figure 3. Additionally, a static simulation analysis was performed on the rock material to determine the stress distribution during the loading test. By analyzing the experimental results regarding crack propagation direction and the stress distribution within the simulated rock, it was observed that cracks inside the rock primarily initiate from the tips of the prefabricated cracks. This phenomenon was observed consistently in rock specimens with prefabricated cracks at different inclination angles. The crack propagation pattern starts from the crack tip, extending in an X-shaped manner. Furthermore, the strength of the fractured rock mass varies with the change in the prefabricated dip angle. Table 2 provides an overview of the strength of different prefabricated fractured rock masses. It can be deduced from the table that the strength of similar materials initially decreases and then increases as the prefabricated crack dip angle increases, with the rock mass strength reaching its lowest point at approximately 45°.

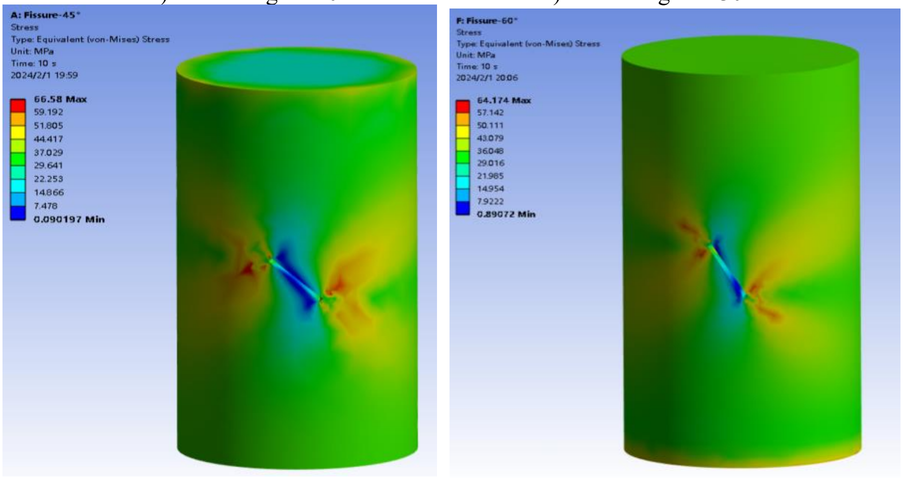
a) Crack Angle of 0° b) Crack Angle of 30° c) Crack Angle of 45°

d) Crack Angle of 60° e) Crack Angle of 75° f) Crack Angle of 90°

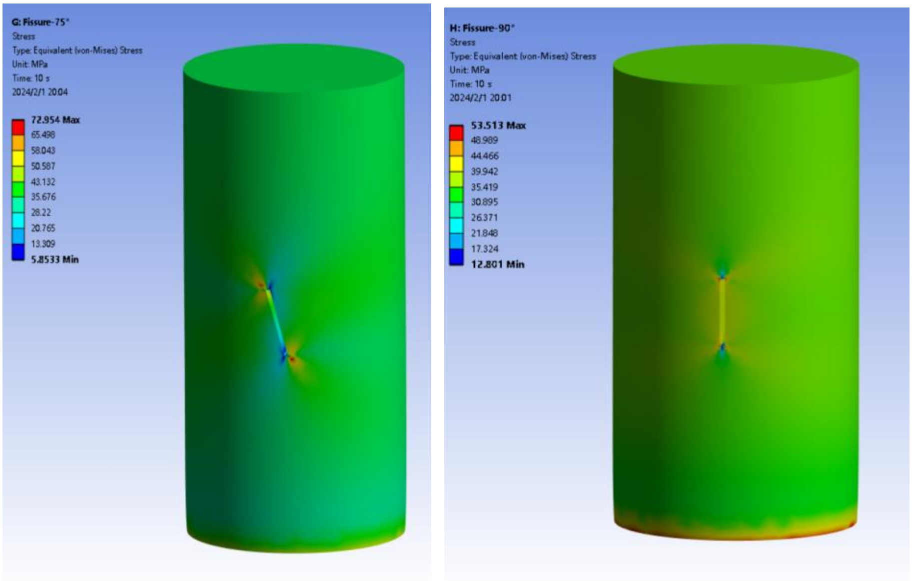
Fig. 3. Failure photograph of fractured rock mass



a) Crack Angle of 0° b) Crack Angle of 30°



c) Crack Angle of 45° d) Crack Angle of 60°



e) Crack Angle of 75° f) Crack Angle of 90°

Fig. 4. Stress distribution in fractured rock mass

In order to investigate the fracture cracking, development, and variation laws of rock mass strength during fracture rock mass tests, uniaxial compressive strength simulation tests are conducted on rock mass specimens with pre-existing cracks. The inclination angle of the pre-existing cracks in the specimens corresponds to that of the pre-existing cracks in laboratory tests, and the specimens are subjected to the same axial load to observe the stress distribution in the rock mass. The simulation results (shown in Figure 4) show that the stress in the cracked rock specimen is mainly concentrated at the top of the crack, and the stress starts from the top of the crack and gradually decreases along the X-direction. This X-shaped distribution of cracks originates from the significant stress concentration at the crack tip. Additionally, the simulation results indicate that, under the same load, the average stress in the rock mass initially increases and then decreases with an increase in the crack angle. Consequently, the strength of the precast fissure rock mass initially decreases and then increases with an increase in the precast fissure angle, reaching its minimum strength at 45°.

5 Conclusions

In this paper, uniaxial compression tests are carried out on rock mass with six prefabricated cracks of 0°, 30°, 45°, 60°, 75° and 90°, and simulation tests are conducted on the uniaxial compression test process of rock mass with prefabricated cracks based on finite element software. It is found that:

(1)It is found that the new crack of fractured rock mass starts from the prefabricated crack tip and distributes in an X-shape. Through the simulation experiment analysis of compression test, it is found that this phenomenon is mainly due to the stress concentration of the internal stress of the rock mass with prefabricated crack at the tip of the prefabricated crack, and the stress is centered on the tip of the crack and gradually decreases in an X-shape.

(2)The strength of rock mass with prefabricated fracture decreases first and then increases with the increase of fracture inclination. The strength of rock mass with fracture reaches the minimum value when the fracture inclination is about 45°. Through the simulation experiment, it is found that this phenomenon is mainly due to the fact that the average stress inside the rock mass increases first and then decreases with the increase of crack inclination Angle, and the average stress inside the rock mass reaches the maximum value when the crack inclination Angle is about 45°.

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