Academic Journal of Engineering and Technology Science
ISSN 2616-5767 Vol.7, Issue 4: 79-83, DOI: 10.25236/AJETS.2024.070412

Analysis of Mechanical Properties and Crack Failure Characteristics of Rock with Pre-Existing Fissures Using Particle Flow Simulation

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Abstract: *To investigate the influence of different fractures on the mechanical properties of rocks and to provide a basis for the stability of rock slope engineering containing fractures.The discrete element method (DEM) was used to establish a model of prefabricated fractured rock. Mechanical tests were conducted on the numerically simulated fractured rock using the Particle Flow Code in 2 Dimensions (PFC2D) software. The study analyzed the crack failure patterns and mechanical property variations of rocks with fractures at different angles under uniaxial compression tests.At the same loading rate, the strength of fractured specimens was lower than that of intact specimens. As the prefabricated fracture angle (α) increased, the compressive strength of the fractured specimens showed a gradual increase. During the uniaxial compression test, the failure characteristics began with damage on both sides of the prefabricated fractures, and the specimens exhibited shear slip failure.The research results provide theoretical support for understanding the failure mechanisms of fractured rocks. This study offers significant insights for the stability analysis and design of rock slope engineering projects containing fractures.*

Keywords: *Fissures; Failure Mechanism; Discrete Element*

1. Introduction

China's economy is developing rapidly, and infrastructure construction is advancing by leaps and bounds. However, along with the development of geotechnical engineering, geotechnical engineering problems and accidents have emerged one after another, which have led to huge economic losses and life safety, and caused a bad negative social impact. Many investigations have shown that the presence of fissures and other defects in the rock mass will cause the strength, deformation properties and stability of the rock mass to be compromised, which is usually the root cause of geotechnical engineering accidents. Therefore, the study of mechanical behavior and rupture characteristics of fissure rock compression is of great significance, and the study can well avoid some problems that may occur in the project, making human production activities more safe and reliable. The study of mechanical behavior and rupture characteristics of compression of fractured rock samples can be divided into theoretical study, physical experiment study and numerical simulation study. At present, theoretical studies are mostly based on assumptions, and the studied rock bodies are regarded as isotropic bodies, which are complicated to calculate and differ greatly from the actual situation. Physical compression tests on fractured rock bodies are costly and time-consuming, and there are large variations between specimens. With the continuous development of computer technology, numerical simulation has been widely used. At present, because it is difficult to make the test model of fissured rock samples, it is necessary to establish the model through numerical simulation software and study its compression mechanical behavior and rupture characteristics. And in the actual engineering, people encounter the most complex different angles of fissure defective rock body, through the study of their compression mechanical properties, people can circumvent some thorny problems, so the study of multi-fissure rock body has great practical engineering significance.

The basic principle of PFC originates from molecular dynamics, where the motion equations follow Newton's second law, allowing for the study of material mechanics and behavior from a microscopic perspective. This includes "particle-particle" and "particle-wall" contacts, constructing a particle assembly model of rock-concrete combinations through interactions between particles. The linear parallel bond model is used for inter-particle bonding, which can transmit both force and moment, effectively reflecting the mechanical properties of rock materials[1]. The Smooth-Joint contact model simulates material cohesion, commonly used for modeling frictional structural surfaces.

2. Numerical Model

2.1 Model Dimensions

To analyze the influence of fissure inclination on the mechanical properties of rocks, seven combinations of specimens were constructed and subjected to numerical simulations of uniaxial compression tests[2]. The model dimensions were 50mm × 100mm in diameter and height, with the fissure located at the center of the model. Fissure angles α ranged from 0° to 90° in increments of 15°, with an additional intact rock specimen. This study investigates the macroscopic and microscopic effects of different fissure angles on the model's mechanical behavior[3].

2.2. Determination of Model Mechanical Parameters

The macroscopic mechanical behavior of specimens is determined by parameters such as effective modulus, particle friction coefficient, and stiffness ratio assigned to the model. The mechanical parameters for all rock specimens are consistent[4](see Table 1).

Table 1: PFC2D model parameters

Particle density/(kg·m^{-3})	Coefficient of friction	Stiffness ratio	Angle of friction	Parallel bond modulus	Tangential bond strength	Normal bond strength
3000	0.7	3.0	20°	10^9	20×6^{10}	100×6^{10}

3. Numerical Simulation Results and Discussion

In this simulation, the sandstone is pore-cemented, with particles primarily in point contact. The contact bond model is used to simulate the normal and tangential bonds between particles. The microparameters primarily include particle elastic modulus, the ratio of particle normal stiffness to tangential stiffness, particle normal bond strength and tangential bond strength, and the friction coefficient between particles. Calibrating these parameters is a very complex process. It generally involves matching the numerical values of the static uniaxial compression of rock samples under the same loading rate conditions with the macroscopic properties obtained from laboratory tests, such as the macroscopic elastic modulus, peak strength, and Poisson's ratio. Additionally, during debugging, the stress-strain curve shape is made as consistent with the laboratory test curve as possible (see Figure 1) to more closely approximate the properties of real materials. Ultimately, a set of microparameters with good reliability for the test sandstone is determined (see Table 1). The qualitative relationships between macroscopic parameters and microparameters are as follows: the macroscopic elastic modulus is mainly determined by the particle elastic modulus, the peak strength is mainly determined by the particle bond strength, and the Poisson's ratio is mainly determined by the particle stiffness ratio. Furthermore, the particle friction coefficient affects the post-peak curve shape and has a slight impact on strength.

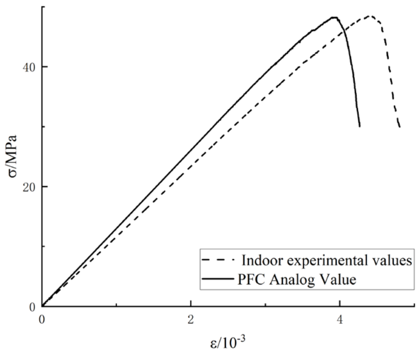

Figure.1 Sandstone's stress-strain curves under uniaxial compression by PFC simulation and lab test

From the perspective of classical mechanics, the mechanical properties of a material are determined by its inherent material structure, such as the mineral composition and defects of the rock, including cracks, pores, and fissures. The load form, such as the loading rate and path, only represents the material's different mechanical responses to different stress environments. Rock mechanics is the study of the various mechanical responses and mechanisms of different types of rock (bodies). In this study, the prefabrication of fractures in the model is achieved by deleting the micro-particles at their locations, resulting in tensile, unfilled fractures. The mechanical properties of the material fall within the range of medium strain rates observed in rock tests, which is also the loading rate range for most engineering rock masses.

Through the analysis of numerical simulation results, the uniaxial compressive strength and failure patterns of sandstone specimens with different fissure angles were determined[5]. Under compressive loading, significant local stress concentrations form around initial defects (fissures) until the strength of the rock mass surrounding the fissure is reached, initiating crack propagation. Consequently, initial extension cracks tend to occur near the defect[6].

4. Analysis of Macroscopic Crack Propagation Patterns

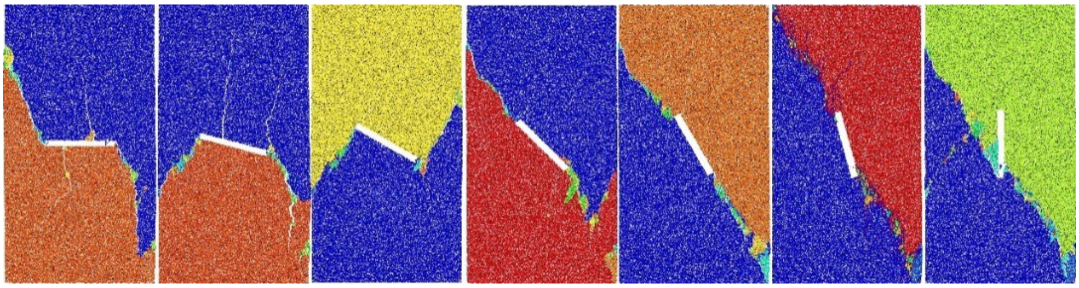

Figure 2: Diagram of fractured rock failure state

(see Figure 2) In simulated specimens, besides macroscopic cracks formed by interconnected microcracks, there are also small and dispersed microcracks[7]. The influence of these small, dispersed microcracks on the failure mode of specimens is minimal. Therefore, this study primarily analyzes the effect of macroscopic cracks on the failure mode. Generally, rocks with pre-existing fissures undergo wing cracks and secondary cracks during compression. Wing cracks primarily consist of tensile cracks, while secondary cracks exhibit shear characteristics. In uniaxial compression simulations of rocks with pre-existing fissures, wing cracks, coplanar secondary cracks, non-coplanar secondary cracks, and remote cracks mainly form around the fissures[8].

From the simulation results, it is observed that specimens with fissure angles α of 0°, 15°, and 30° develop wing cracks and non-coplanar secondary cracks initiated from the fissure tip. Specimens with fissure angles α of 45° and 60° exhibit short wing cracks initiated from the fissure tip and coplanar secondary cracks. Specimens with a fissure angle α of 90° show minimal wing crack initiation from the fissure tip, with non-coplanar secondary cracks forming along the fissure length and near the tip. Additionally, due to experimental conditions, all specimens exhibit remote cracks, with an overall shear failure mode[9].

5. Influence of Fissure Angle on Peak Rock Strength

According to the simulation results of stress-strain and crack numbers in prefabricated fracture specimens, the compressive strength of the fracture specimens tends to increase with the increase of the fracture angle. (see Figure 3) (see Table 2). Specifically, the strengths of specimens with fracture angles of 0º, 15º, 30º, 45º, 60º, 75º, and 90º are 20.6 MPa, 25.0 MPa, 25.8 MPa, 30.1 MPa, 30.7 MPa, 38.5 MPa, and 43.8 MPa, respectively.However, it is noteworthy that the strength of specimens with fracture angles of 45º and 60º do not differ significantly. Preliminary analysis suggests that this is due to the similar failure angles and failure types of these two angles, resulting in insignificant strength differences. (see Figure 2).

The deterioration degrees of the specimens due to the presence of prefabricated fractures are 57.3%, 48.1%, 46.5%, 37.5%, 36.3%, 20.1%, and 9.1%, respectively. This indicates that as the fracture angle increases, the deterioration degree of the specimens significantly decreases and the strength notably increases. When the fracture angle is less than 45º, the deterioration degree of the specimens is pronounced, and the strength significantly decreases. When the fracture angle is greater than 45º, the deterioration degree is not obvious, and the strength reduction is relatively small.This phenomenon demonstrates that the fracture angle has a significant impact on the compressive strength and deterioration degree of the specimens, providing a crucial basis for further scientific research. In practical engineering applications, controlling the fracture angle can effectively adjust the mechanical properties of the specimens, thereby achieving optimized design and improved structural reliability[10].

Table 2: Compressive strength at different fracture angles

Angle α /°	0	15	30	45	60	75	90	Intact
compressive strength σ /MPa	20.6	25.0	25.8	30.1	30.7	38.5	43.8	48.2

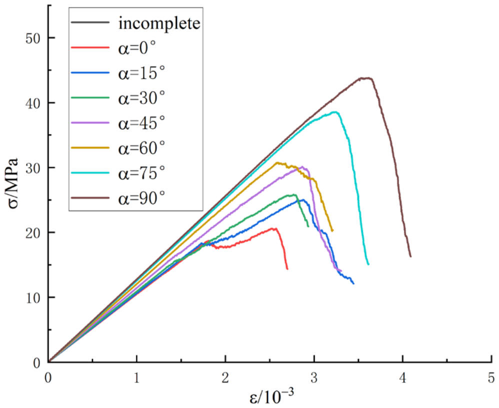

Figure 3: Stress-strain curves

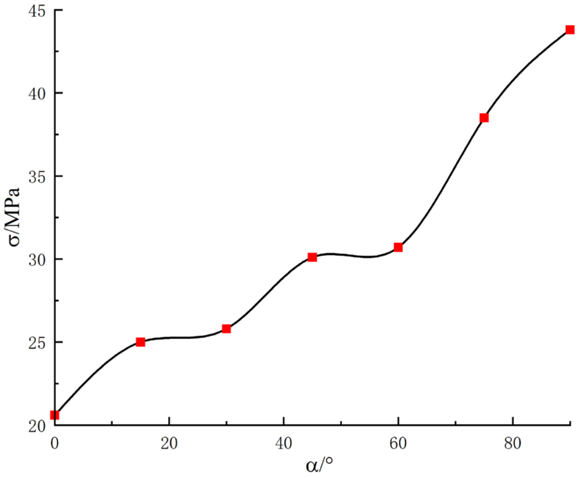

Figure 4: Diagram of compressive strength

6. Conclusion

In this study, uniaxial compression tests of fissured specimens at different fissure angles were simulated using PFC 2D software, analyzing changes in compressive strength and crack failure patterns. The following conclusions were drawn:

1) The Impact of Prefabricated Fractures on the Mechanical Properties of Rock

During the cracking process, prefabricated fractures weaken the stress within the rock and lead to early cracking. This means that prefabricated fractures reduce the bearing capacity of rock specimens after failure. As the prefabricated fracture angle α increases, the compressive strength of the fractured specimens generally increases (see Figure 4).

2) Limitations of the Study

This study only simulates the uniaxial compression test of a single fractured specimen and provides a preliminary investigation into the fracture propagation process. However, in actual rock masses, fractures often appear in intersecting forms, and natural rock masses usually bear triaxial stresses. Under complex stress conditions, the failure mode and crack propagation process of fractured specimens require further research.

3) Scientific Value of the Numerical Simulation Analysis

The numerical simulation analysis elucidates the crack propagation process from a microscopic perspective, providing a reference for further exploration of the instability and failure modes of fractured rock masses in underground engineering, thus enhancing its scientific value. Understanding the microscopic mechanisms of fracture propagation can offer more precise theoretical support for the design and stability analysis of underground engineering.

References

[1] Jiang-Rui, Niu , Y. Chi , and Y. Jian-Hua . "Numerical Simulation of Confining Pressure Effect in Failure Process of Sandstone Containing Single Open Fissure." Water Resources & Power (2017).
[2] Xiao, T., Li, X. , & Jia, S. . (2012). Triaxial test research and mechanical analysis based on structure surface effect of deep rock mass with single fissure. Yanshilixue Yu Gongcheng Xuebao/Chinese Journal of Rock Mechanics and Engineering, 31(8), 1666-1673.
[3] Protosenya, Anatolii G., and Pavel E. Verbilo. "Research of compression strength of fissured rock mass." Записки Горного института 223 (2017): 51-57.
[4] Uxía Castro-Filgueira, L. R. Alejano , and D. M. Ivars . "Particle flow code simulation of intact and fissured granitic rock samples." Journal of Rock Mechanics and Geotechnical Engineering (2020).
[5] Wong RHC; Tang CA; Chau KT; et al. Splitting failure in brittle rocks containingpre-existing flaws under uniaxial compression[J]. Engineering Fracture Mechanics, 2002, 69(17): 1853-1871.
[6] Pu CZ; P Cao. Failure characteristics and its influencing factors of rock-likematerial with multi-fissures under uniaxial compression[J]. Transactions of Nonferrous Metals Society of China, 2012, 22(1): 185-191.
[7] Cundall PA, Strack OA discrete numerical model for granular assemblies[J]. Géotechnique, 2008, 30(3): 331-336.
[8] Fan X; Kulatilake PHSW; Chen X. Mechanical behavior of rock-like jointed blocks with multi-non-persistent joints under uniaxial loading: A particle mechanics approach[J]. Engineering Geology, 2015, 190: 17-32.
[9] Yang SQ; Huang YH; Jing HW; Liu XR. Discrete element modeling on fracture coalescence behavior of red sandstone containing two un-parallel fissures under uniaxial compression[J]. Engineering Geology, 2014, 178: 28-48.
[10] Bahaaddini M; Hagan P; Mitra R; et al. Numerical Study of the Mechanical Behavior of Nonpersistent Jointed Rock Masses[J]. International Journal of Geomechanics, 2016, 16(1): 04015035.