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# Particle Flow Simulation Investigation on The Failure Characteristics of Layered Rock Under Uniaxial Compression

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## Abstract

**To explore the influence of bedding angle(β) on rock failure characteristics, PFC2D particle flow simulation software was used to model layered rock(β=0°,30°,45°,60°,90°) , and the mechanical parameters, brittleness characteristics, and failure modes were analyzed. The results show that the peak stress and elastic modulus first decrease and then increase with the increase in β, and the ratio of the maximum value to the minimum value is 2.65 and 1.29, respectively, indicating that the bedding effect was obvious. When the β increases from 0°to 90°, kci and kcd show a trend of decreasing first, then increasing, finally decreasing, and first decreasing and then increasing, respectively. When the β is 60° and 90°, kci and kcd reach the maximum value. The failure modes of layered rocks are mainly tensile failure (0°, 90°) and tensile-shear composite failure (30°, 45°, 60°).**

## Keywords

**Particle flow simulation; Layered rock; Mechanical properties; Failure mode.**

## 1. Introduction

Layered rocks are widely distributed in nature. Affected by sedimentation, stress environment and hydrogeological conditions, there are a large number of bedding weak planes in sedimentary rocks such as slate, sandstone and shale, which lead to obvious differences in mechanical properties and failure modes of rocks. Therefore, a comprehensive understanding of the failure characteristics of layered rock is of great significance to the design and construction of actual underground engineering.At present, scholars have extensively discussed the mechanical parameters and failure modes of layered rocks through experiments. Cho et al.[1] carried out uniaxial and Brazilian splitting tests on layered gneiss, shale and schist, and discussed the influence of bedding angle(β) on its elastic parameters and strength. Chen et al.[2] analyzed the influence of β on the mechanical parameters of slate by conducting triaxial tests. Li et al.[3] believed that under the Brazilian splitting test, the failure modes of layered rock can be divided into tensile failure, shear failure and combined tensile-shear failure between matrix and bedding plane. Li et al [4] revealed the size effect and anisotropy of slate from the aspects of elastic constants, uniaxial compressive strength(UCS) and triaxial compressive strength(TCS). Hao et al. [5] quantitatively analyzed the influence of β and confining pressure on the mechanical properties of brittle rocks. In summary, there are few particle flow simulation studies on the failure characteristics of layered rock at present. In this paper, PFC2D particle flow simulation software is used to model, and the influence of β on rock failure characteristics under uniaxial load is analyzed from three aspects of mechanical parameters, brittle characteristics and failure modes.

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## 2. Numerical Model Establishment

### 2.1. Model Establishment

Standard slate samples (100*50) from Gansu Province, China were selected for this particle flow simulation test. As shown in Fig.1a, the bedding weak plane is obvious and uniformly distributed. Using PFC2D to establish a numerical model consistent with the slate specimen, as shown in Fig.1b. The particle radius of the rock model is uniformly distributed between 0.25 and 0.38, and the angle between the bedding plane and the horizontal plane is defined as β. Five numerical models with β=0°, 30°, 45°, 60° and 90° were established through the DFN command, and each numerical model contained about 13640 particles. The numerical model of layered rock consists of a homogeneous rock model and a bedding model, and the contact between the two models is set as a parallel bonding model. Additionally, the rock is loaded by displacement loading way, and the loading rate of the upper wall is 0.1 mm/s.

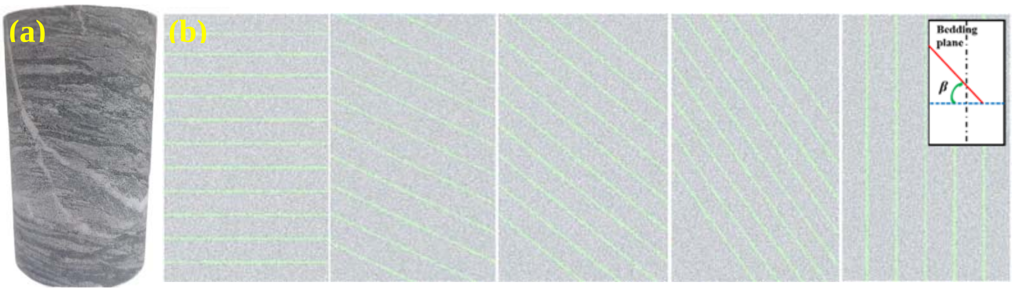


**Figure 1.** (a)Typical layered slate sample, and (b) numerical models of different layered rocks

### 2.2. Parameter calibration

In the parallel bond model, the macroscopic mechanical properties of rock are mainly affected by the microscopic parameters such as particle contact modulus, particle stiffness ratio, friction coefficient, cohesion and tensile strength[6]. The determination of microscopic parameters is mainly based on the mechanical parameters such as elastic modulus, Poisson 's ratio and peak stress obtained from laboratory tests, and the microscopic parameters are continuously adjusted to minimize the error between the simulation results and the test results. In this paper, the slate with 0° is taken as an example. The ' trial and error method ' is used to repeatedly debug the microscopic parameters of the rock model. Under uniaxial compression conditions, the stress-strain curve obtained by simulation is roughly consistent with the results of laboratory tests, as shown in Fig.2. The final microscopic parameters are shown in Table 1.

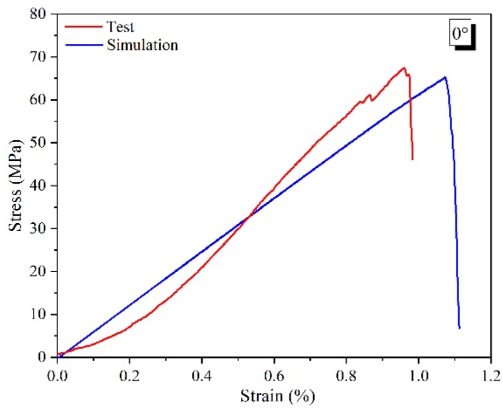


**Figure 2**. Parameter calibration basis diagram(β=0°)

**Table 1.** Parameters of layered rock model

| Rock parameters | Value | Bedding plane parameters | Value | Geometric parameters | Value |
|---|---|---|---|---|---|
| Emod(GPa) | 2.24 | Emod(GPa) | 1.88 | Rmax(mm) | 0.25 |
| Kratio | 1.0 | Kratio | 1.0 | Rmax/Rmin | 1.5 |
| Pb-fric | 0.62 | Pb-fric | 0.35 | Density(Kg/m3) | 2660 |
| Pb-ten(MPa) | 23 | Pb-ten(MPa) | 13 | Damp | 0.7 |
| Pb-coh(MPa) | 26 | Pb-coh(MPa) | 16 | P | 0.15 |
| Pb-fa(°) | 30 | Pb-fa(°) | 5 | H*W(mm) | 100*50 |

Note: Emod is the effective modulus; Kratio is the stiffness ratio; Pb-fric is the coefficient of friction of parallel bonding; Pb-ten is the tensile strength of parallel bonding; Pb-coh is a parallel bonding cohesion force; pb-fa is the friction angle within the parallel bond; $R_{max}$ is the minimum radius of the particle; $R_{max}/R_{min}$ is the particle radius ratio; Density is the model density; Damp is the damping ratio; P is the porosity. H*W is the model dimensions (height and width).

## 3. Results Analysis

### 3.1. Mechanical parameters

Fig.3a shows the stress-strain curve of layered rock. It can be seen from the figure that before the rock failure, the stress-strain curve of the layered rock model increases linearly, showing the characteristics of elastic deformation. Compared with the physical laboratory test, there is a lack of compaction stage. This is mainly because the particles of the model are rigid and evenly distributed, so it cannot reflect the compaction characteristics of specimen under compression failure. Additionally, with the increase of β, the slope of stress-strain curve also has obvious difference, showing the anisotropic characteristics of layered rock. The relationship curve between the peak stress, elastic modulus of layered rock and the β is shown in Fig.3b. With the increase of β, the peak stress and elastic modulus show a ' U ' type (decrease first and then increase). When the β is 45°, the peak stress and elastic modulus are the smallest (29.9 MPa and 4.9 GPa), while the peak stress and elastic modulus of the rock of 90° are the largest, reaching 79.2 MPa and 6.3 MPa, respectively. The ratio of the maximum value to the minimum value is 2.65 and 1.29, indicating that the bedding effect of the rock model is obvious.

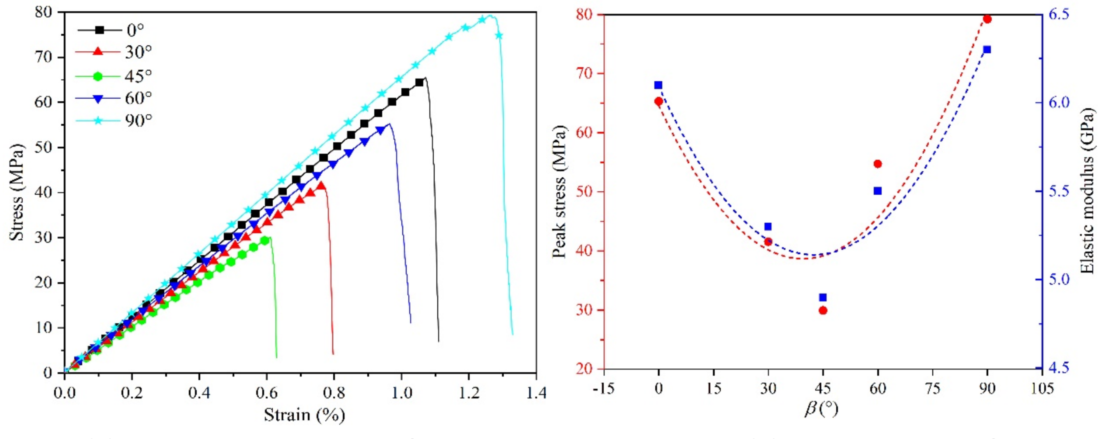


**Figure 3.** (a)Stress-strain curve of layered rock model;and(b)the variation of mechanical parameters with the β

## 3.2. Brittleness characteristics

In the process of rock uniaxial compression, when the loading stress reaches the crack initiation stress ($\sigma_{ci}$), the microcracks inside the rock begin to initiate and expand. When the loading stress reaches the damage stress ($\sigma_{cd}$), the microcracks inside the rock are rapidly connected and penetrate until macroscopic failure occurs, and the crack number also increases rapidly. Therefore, the optional crack initiation point is the initiation stress point, and the rapid growth point of the crack corresponds to the damage stress point. In this simulation, the microcracks of the layered rock model were monitored by the crack monitoring program code of the PFC Augmented Fishtank program code package to determine the crack initiation stress and damage stress, as shown in Fig.4a.

In the process of uniaxial compression, the ratio of initiation stress($\sigma_{ci}$) to peak stress($\sigma_c$) and damage stress($\sigma_{cd}$) to peak stress($\sigma_c$) reflect the ease of crack initiation and propagation in each failure stage. The ratio is defined as the initial stress ratio($k_{ci}$) and the damage stress ratio($k_{cd}$). Fig.4b shows the relation curves of $k_{ci}$ and $k_{cd}$ with the change of $\beta$. With the increase of $\beta$, $k_{ci}$ decreases first, then increases and finally decreases, while $k_{cd}$ decreases first and then increases. The variation ranges of $k_{ci}$, $k_{cd}$ are 0.39-0.55 and 0.71-0.95, respectively. When $\beta$=60°, $k_{ci}$ reaches the maximum value (0.55), indicating that the crack damage is relatively lagging, close to the peak stress. When the $\beta$ is 90 °, the $k_{cd}$ reaches the maximum value (0.95), indicating that the crack will rapidly destroy after unstable expansion, and the brittleness characteristics are the most obvious.

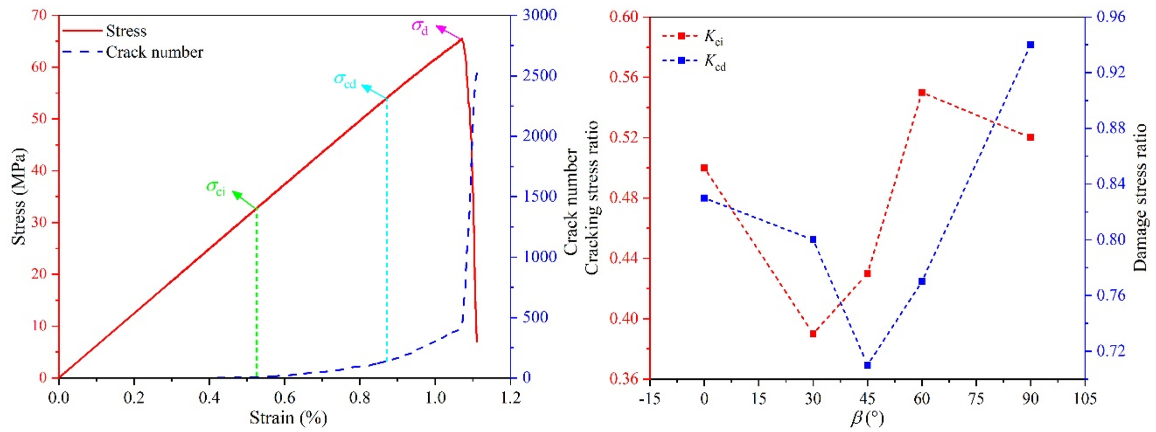


**Figure 4.** (a) Diagram of determination of initiation ($\sigma_{ci}$), damage ($\sigma_{cd}$) and peak ($\sigma_c$) stresses ($\beta$=0°);and (b)the variation of stress ratios ($k_{ci}$ ,$k_{cd}$ ) with $\beta$

## 3.3. Failure mode

Fig.5 shows the failure mode of layered rock. The red and blue colors indicate the tensile cracks and shear cracks generated when the particle bond contact ruptures. It can be seen from the figure that when the $\beta$ is 0°, the failure mode is tensile failure through the bedding plane(BP). Under the action of vertical load, a small amount of tensile cracks are generated on the BP. Due to the Poisson effect, the cracks between the BPs gradually coalesce and expand, forming an oblique tensile crack that penetrates the upper half of the BP, accompanied by a small amount of shear cracks. For rock with 30° angle, the failure mode is tensile-shear composite failure though BP. The rock first produces a small amount of shear and tensile cracks along the BP. With the further increase of the load, the lower half of the rock is connected into a diagonal main crack though the BP, and the shear cracks between the BPs are also significantly increased.

The failure modes of rocks with $\beta$=45° and 60° are tension-shear composite failure along the BP. The rock first produces cracks along the BP, and there are many shear cracks. This is because the shear strength of the BP is small. When the shear stress is greater than shear

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strength, more shear cracks are generated. As the load increases significantly, the two rocks slip along the BP. The 45° rock mainly forms an oblique tensile crack along the BP, while the 60° rock produces multiple tensile and shear cracks along the BP. The failure mode of rocks with $\beta$ =90° is mainly tensile failure along the BP. In the early stage of failure, multiple vertical tensile cracks are generated along the BP, and almost no shear cracks are generated. With further loading, the tensile cracks propagation and penetrate. covering the entire BP. Because the rock is affected by the bending moment, the buckling instability occurs, and the tensile cracks between the BPs are also connected and penetrated, forming two oblique tensile cracks. In summary, the failure modes of layered rocks are significantly different. With the increase of $\beta$ (0°→90°). The failure mode changes from tensile failure though BP (0°) to tensile-shear composite failure though BP (30°), then to tensile-shear composite failure along BP (45° and 60°), and finally to tensile failure along BP(90°).

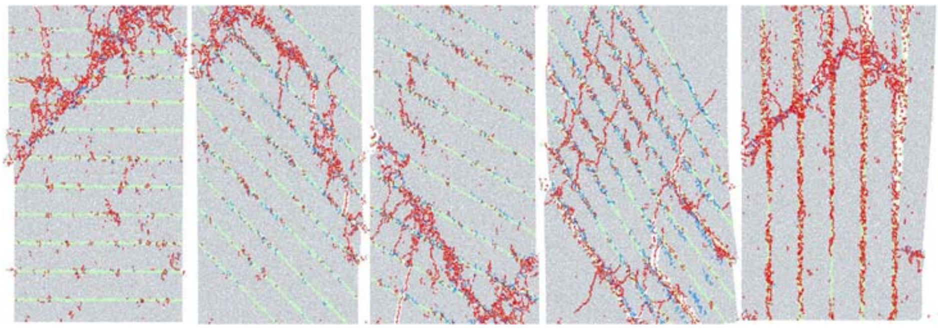

**Figure 5.** Crack propagation process of layered rock models: (a)0°; (b)30°; (c)45°; (d)60°; (e)90°

## 4. Conclusion

(1) With the increase of $\beta$, the peak stress and elastic modulus show a trend of decreasing first and then increasing, and the ratio of the maximum value to the minimum value is 2.65 and 1.29, respectively, indicating that the bedding effect of the rock model is obvious.

(2) When the $\beta$ increases from 0° to 90°, $k_{ci}$ decreases first, then increases and finally decreases, while $k_{cd}$ shows a trend of decreasing first and then increasing. The $k_{cd}$ of rock with 90° is the largest (0.95), indicating that the rock crack will be destroyed rapidly after unstable propagation, and the brittleness characteristics are the most obvious.

(3) The failure modes of layered rock are obviously different, which are mainly divided into tensile failure though BP (0°), tensile-shear composite failure though BP (30°), tensile-shear composite failure along BP (45°, 60°) and tensile failure along BP (90°).


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