Research Article

Numerical Analysis of the Mechanical Behavior and Failure Mode of Jointed Rock under Uniaxial Tensile Loading

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In the field of rock engineering, tensile failure is one of the most significant failure modes due to the presence of joints/fractures. However, due to the limitations of current laboratory testing, it is difficult to carry out direct tensile tests on jointed rock specimens in the laboratory. To study the effect of joints on the mechanical behavior and failure mode of jointed rock specimens, a three-point modeling method that can consider arbitrarily arranged rock joints is deduced and applied to discrete element simulation. The effects of different joint angles (the inclination angle \( \alpha \), rotation angle \( \beta \), and superimposed angle \( \gamma \) of \( \alpha \) and \( \beta \), where \( \gamma \) is the angle between the joint and horizontal plane), the density \( n \), and the rate of cutting area (RCA) of the specimen loading surface (LSS) on the tensile strength \( \sigma_t \), elastic modulus in tension \( E_t \), and failure mode of the specimens were analyzed. The results show that the joint angle (considering \( \alpha \), \( \beta \), and \( \gamma \)) and RCA have a significant effect on \( \sigma_t \) and failure mode, while \( n \) has a significant effect on \( E_t \). The failure mode of the specimen changes from tensile failure along the joint to direct tensile failure of the specimen as \( \gamma \) increases, and the mechanical behavior transitions from unstable to stable. In addition, the main influence of \( \gamma \) on the mechanical behavior of specimens is revealed, and the change process of the failure mode after the cutting of the LSS is analyzed. The present research can be utilized for multiple purposes, including the joint development of surrounding rock and failure dominated by tensile failure in underground engineering, especially for tunnels, roadways, chambers, and so forth.

1. Introduction

A rock mass is a geological body composed of many discontinuities with different scales and different occurrences, and rock masses are cut by these discontinuities into different shapes and sizes [1–3]. Sedimentary strata are significantly affected by geological structures such as folds and faults and weak structural planes such as joints, bedding, and fissures [4, 5], while the original defects and joint structures are internal characteristics of rock and have an essential impact on their fracture characteristics [6, 7]. The mechanical behavior of jointed rocks is very important in engineering applications [8], especially in recent years, with the vigorous development of resource mining, energy development, infrastructure construction, and so forth. It has become particularly important to obtain the mechanical properties of jointed rocks.

Most rocks in actual engineering are under compression, but because \( \sigma_t \) is much smaller than the compressive strength, in many cases, failure during rock engineering starts from local tensile failure of the rock [9]. Recently, more comprehensive explorations of rock compression tests have been performed by scholars. For example, Xin et al. [10] and Yoshinaka et al. [11] studied the scale effect of the
strength of a jointed rock mass and the effect of a jointed rock mass on the joint connectivity by uniaxial compression testing. Liu and Prudencio [12, 13] analyzed the fracture form and mechanical behavior of rocks under biaxial compression. Nguyen and Le [14] and Tiwari and Rao [15] conducted triaxial tests on different types of rocks. At present, the Brazilian test is the main method used to determine $\sigma_t$ in an indirect manner [16, 17]. As early as 1959, Hondros [18] established an analytical method for analyzing $\sigma_t$ based on the Brazilian test, and many scholars then carried out a considerable amount of research on $\sigma_t$ through Brazilian testing. For instance, based on the dynamic Brazilian test, Zhao and Feng Quang [19] developed a new empirical equation to describe the dynamic effect of the indirect tensile strength of the sandstone. Tavallali and Vervoort [20] analyzed the influence of joint orientation on $\sigma_t$ from the macroscale by the Brazilian test. Covioli and Gong et al. [21–23] indicated that $\sigma_t$ obtained by the Brazilian test is the same as the direct tension, but the Brazilian test cannot obtain $E_t$, and simulate the failure mode of the specimen under direct tension, especially for jointed rock. It remains quite challenging to conduct direct uniaxial tensile tests on intact rock specimens in laboratories due to the difficulties in avoiding (1) unfavorable stress concentration over the grip and (2) bending moments due to noncoaxial gripping and curvature of the specimen. Various attempts have been made in this regard [24, 25]. Whether considering a split test or a direct tensile test, a specimen taken from a layered rock mass generally has several densely arranged parallel persistent joints [26–28]. Thus, it is difficult to analyze the effect of one or more of the joints on the specimen, and it is difficult to repeat a test on a specimen with a more complicated joint structure to reduce uncertainty.

Based on the above situation, numerical testing is undoubtedly a more ideal testing method. With the development of underground engineering, the requirements for calculation accuracy and calculation workload have increased, and numerical tests are becoming increasingly recognized and widely used in various fields. For example, Lianchiong et al. [29] prepared the analysis software RFPA3D to simulate the rock failure process and used this software to study rock damage and fracture. Zhang [30] analyzed the jointed rocks under various loads through the particle flow numerical simulation software PFC and proved the reliability of a numerical test compared with a physical laboratory test. Han et al. [31] used the numerical manifold method (NMM) to analyze the effects of joint dip angle, joint spacing, and confining pressure on rock mass strength. However, the mechanical behavior and failure mode of rocks with persistent joints, especially those under uniaxial tension, have rarely been studied.

The spatial characteristics of rock joints are very complicated in actual engineering, and joints with different spatial distribution characteristics have a considerable impact on the mechanical behavior of rocks. However, the mechanical behavior and failure mode of jointed rocks under uniaxial tension are difficult to analyze through laboratory tests. The present study comprehensively analyzes the effect of multiple factors (angle, $n$, and the position of the cutting LSS) on the mechanical behavior (in terms of $\sigma_t$ and $E_t$) of a rock specimen with 3DEC (a three-dimensional distinct element code by Itasca), providing fundamental results for the further study of complex jointed rocks and the estimation of jointed rock mechanical properties.

2. Numerical Model and Control Conditions

2.1. Models and Parameters. The numerical model is constructed by means of 3DEC, which is a three-dimensional numerical program employing the distinct element method for discontinuum modeling. In this paper, under the guidance of Euclidean geometry [32], a three-point modeling method that can arbitrarily change the spatial characteristics of rock joints is deduced and applied to 3DEC. The method is as follows:

1. Define three noncollinear points $A$, $B$, and $C$ to determine the spatial characteristics of the rock joint. The three points move along three straight lines parallel to the $z$-axis. $A$ and $B$ are the long-axis endpoints of the elliptical joint plane, symmetrical about $E$ (the center of the specimen body), which are used to control the joint inclination angles ($\alpha$). The initial position of $C$ is at the same level as $E$, which is used to control the joint rotation angle ($\beta$), as shown in Figure 1.

2. Fix point $C$ and then move $A$ and $B$ up and down according to the magnitude of $\alpha$. After adjusting, the vertical distances $d_{AE}$ and $d_{BE}$ between $A$, $B$, and $E$ are as follows:

$$d_{AE} = d_{BE} = \frac{1}{2}D \cdot \tan \alpha,$$

where $D$ is the radius of the cylinder.

3. After determining the magnitude of $\alpha$, first fix the two points $A$ and $B$ and then move $C$ according to the magnitude of $\beta$ to $C'$. After adjustment, the vertical distance $d_{CC'}$ between $C'$ and $E$ is as follows:

$$d_{CC'} = D \cdot \frac{\tan \beta}{\sin \alpha}$$

This study mainly focused on how the spatial characteristics of rock joints ($n$, $\alpha$, $\beta$, and the cutting positions of LSS) affect the mechanical behavior of the specimen (in terms of $\sigma_t$, $E_t$, and failure mode). The specimen model was a cylinder that is 50 mm in diameter and 100 mm in height, as suggested by the International Society for Rock Mechanics [33–36]. All joints were considered to cut through the specimen. A constant rate of 0.005 mm/step was applied to the upper and lower boundaries of the model to simulate the uniaxial tensile load [36, 37]. After a specimen failed in tension, 1000 extra time steps were calculated to capture the after-peak behavior. With the stress-strain curves obtained under the different joint conditions, $\sigma_t$ and $E_t$ were
To study the effect of the joints’ spatial characteristics on the mechanical behavior of the specimens taken from layered rock, the joints in the model were persistent joints. In addition, $\alpha$ and $\beta$ were taken as $0^\circ$, $10^\circ$, $20^\circ$, $30^\circ$, $40^\circ$, and $50^\circ$. Moreover, $n$ was taken as 2, 3, 4, and 5. In this study, the rock parameters were selected with reference to the roof sandstone samples of Zhaogu No. 2 Coal Mine [39]. The mechanical parameters of the rock and joint are shown in Tables 1 and 2, respectively. In the tables, JKN stands for joint normal stiffness, and JKS stands for joint shear stiffness.

2.2. Numerical Model Verification. In the following sections, the reliability of the numerical model is verified by comparing the uniaxial compression stress-strain curves of a sandstone sample (taken from the roof of Zhaogu No. 2 Coal Mine) and the corresponding numerical simulation. The numerical model is further verified by comparing the $\sigma_t$ results determined from numerical simulation and Brazilian testing in the present paper.

2.2.1. Overview of the Test. The uniaxial compression testing and the Brazilian testing were completed on an RMT-150B rock mechanics servo testing machine. The average naturally dried density of the processed specimens is 1435 kg/m$^3$, and the P-wave velocity is 1903 m/s. The sandstone sample and the testing machine are shown in Figure 2. The test used displacement loading, and the loading rate was controlled to 0.05 mm/s. In addition, the loading was carried out under servo control until the sample failed.

2.2.2. Comparison of the Test Results. Figure 3 compares the uniaxial compressive stress-strain curves obtained by numerical simulation and laboratory testing. Because the sandstone samples were relatively dense and there were fewer internal cracks, the test curve entered the elastic stage after a short sag in the early stage, and the stress increased linearly until it reached the peak strength. The specimen failed, and the stress-strain curve dropped rapidly. It can be seen in Figure 3 that the curve obtained by numerical simulation is in good agreement with the trend of the laboratory test, and the maximum strain was approximately $3 \times 10^{-2}$ when failure occurred.

In the numerical simulation of uniaxial tension, the load was applied from the upper surface to the complete specimen. Since the specimen body in the model was a uniform continuous medium, the load was transmitted uniformly downward from the LSS along the direction of the specimen axis. With the continuous application of the load, the internal stress of the specimen increased accordingly, and the final specimen body failed from the loading end, as shown in Figure 4 (the specimen deformation is magnified 100 times), so the stress-strain curve dropped at that point. The $\sigma_t$ value of the numerical simulation was close to that of the laboratory data, as shown in Table 3. Numerical simulation data show good agreement with test data and thus support the reliability of the numerical simulation.

3. Effect of the Joint Angle on the Mechanical Behavior of Specimens with Single Joints

To study the effect of a single persistent joint on the mechanical behavior of rock under the superposition of different values of $\alpha$ and $\beta$, $\alpha$ was fixed at $0^\circ$, $10^\circ$, $20^\circ$, $30^\circ$, $40^\circ$, and $50^\circ$. The changing patterns of $\sigma_t$ and $E_t$ were studied by changing $\beta$. The angle change between $\alpha$ and $\beta$ is shown in Figure 5.

From the variation curve of $\sigma_t$, it can be seen that $\sigma_t$ was positively correlated with $\alpha$ and $\beta$, as shown in Figure 6(a), which is consistent with the findings of Shu et al. [37]. There was a smooth section in the stress-strain curves of all the studied inclination angles $\alpha$, and this section had a tendency to move forward with the increase in $\alpha$. Although the change in $\beta$ was the same, the smooth section range of the curve when $\alpha = 20^\circ$ and $\alpha = 30^\circ$ was larger than the others in the analysis of tension strength curves. This was probably because $\sigma_t$ tended to be stable when $\gamma$, the angle after the superimposition of $\alpha$ and $\beta$, was approximately $30^\circ$. When $\alpha$ was $0^\circ$, $10^\circ$, $20^\circ$, $30^\circ$, and $40^\circ$, the maximum change in $\sigma_t$ caused by $\beta$ was $40^\circ$ to $50^\circ$ (i.e., the sensitive range of $\sigma_t$ was $40^\circ$ to $50^\circ$ of $\beta$), and the increases were 12.4%, 12.8%, 14.3%, 16.1%, and 17.7%, respectively. It can be seen that the
increasing rate also had an obvious accelerating trend. However, when \( \alpha \) reached 50°, the rate of increase in \( \sigma_t \) decreased to 7.8%, which may have been caused by the edge of the upper and lower surfaces of the specimen (ULSS) being cut by the joint.

Through the analysis of the \( E_i \) change curve (Figure 6(b)) under a single joint, it can be seen that the increase in \( \alpha \) and \( \beta \) increased \( E_i \), but the range was very small, and the average increase in \( E_i \) was 0.10%, 0.18%, 0.22%, 0.31%, and 0.43% when \( \alpha \) was 0°, 10°, 20°, 30°, and 40°, respectively. However, when \( \alpha \) reached 50°, \( \sigma_t \) and the strain of the specimen during failure were reduced due to the joint cutting the ULSS, and the reduction in strain was greater than that in stress. Therefore, \( E_i \) increased greatly at \( \beta = 50° \), with an increase of 3.8%.

For \( \sigma_t \), the effect of the angle \( \gamma \) was great, especially when the LSS was not cut, and the rate of increase in \( \sigma_t \) was positively correlated with \( \gamma \), while the effect of \( \gamma \) on

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**Table 1: Mechanical parameters of the rock.**

| Lithology  | Density (kg/m³) | Bulk modulus \( K \) (GPa) | Shear modulus \( G \) (GPa) | Cohesion \( C \) (MPa) | Internal friction angle \( \varphi \) (°) | Tensile strength (MPa) |
|-----------|----------------|---------------------------|---------------------------|----------------------|--------------------------------------|----------------------|
| Sandstone | 2884           | 10.52                     | 4.86                      | 24.7                 | 30                                   | 8.79                 |

**Table 2: Mechanical parameters of the joint.**

| Lithology  | Cohesion \( C \) (MPa) | Friction angle (°) | JKN (GPa/M) | JKS (GPa/M) | Tensile strength (MPa) |
|-----------|-------------------------|-------------------|-------------|-------------|----------------------|
| Sandstone | 3.67                    | 26.8              | 32.5        | 19.3        | 3.88                 |

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![Figure 2](image1.png) **Figure 2:** Test equipment and rock samples. (a) Test equipment. (b) Sandstone sample.

![Figure 3](image2.png) **Figure 3:** Comparison of the uniaxial compression curves from the numerical simulation and laboratory testing.
$E_t$ was relatively small. However, when the joint was tangential to the edge of the LSS, $E_t$ increased obviously, and the increase in $\sigma_t$ slowed obviously. Thus, the angle and the cutting position of the joint had a very important effect on the mechanical behavior of the rock specimen.

4. Effect of the Joint Angle on the Mechanical Behavior of Specimens with Different Joint Densities

To further explore the effect of rock mechanical behavior by the superimposition of $\alpha$ and $\beta$ under different $n$, fixed $\alpha$ was assumed to be 0°, 10°, 20°, 30°, 40°, and 50°. The change patterns of $\sigma_t$ and $E_t$ were studied by changing the number of joint strips ($n = 2, 3, 4,$ and 5) and the rotation angle ($\beta = 0°, 10°, 20°, 30°,$ and 40°). The joint interval ($d = 5$ mm) was uniform from the center of the specimen body to both ends, as shown in Figure 7.

By comparing the $\sigma_t$ change curves under different $n$ (Figure 8), it can be found that when $\alpha \leq 30°$, $\sigma_t$ was hardly affected by $n$. However, when $\alpha = 40°$, the $\sigma_t$ curve of the specimen with $n \geq 4$ began to drop from $\beta = 40°$, and the drop range increased with increasing $n$. When $\alpha$ reached 50°, the $\sigma_t$ curve of the specimen with $n = 3$ exhibited a greater drop than that with $n = 2$, the $\sigma_t$ curve of the specimen with $n \geq 4$ tended to drop from $\beta = 30°$, and the drop range tended to increase as $n$ increased. The drop in the $\sigma_t$ curve of specimens with multiple joints and the slow increase in $\sigma_t$ in specimens with a single joint were related to the cutting features of the ULSS. However, whether the change in the $\sigma_t$ curve drop was due to $n$ or the area of joint cutting on the ULSS remains to be discussed.

To explore the reasons for the change in the drop range of the $\sigma_t$ curve, the first cut of the LSS with a persistent joint was set to 0%, 10%, 20%, 30%, 40%, and 50%. When RCA $\geq 20\%$ ($\gamma \geq 72.3\%$), $\sigma_t$ and $E_t$ tended to be stable, and the stability value of $\sigma_t$ was close to that of the complete specimen, which agrees with the results of the Brazilian test performed by Liu et al. [25]. Since the tensile strength of a jointed rock mass is anisotropic, the ratio of the tensile strength $\sigma_t$ at different $\gamma$ values to the tensile strength $\sigma_0$ at $\gamma = 0°$ has been defined as the angle...
anisotropy coefficient. When $RCA \geq 20\%$, the angle anisotropy coefficient is stable at 2.2, which is close to the anisotropy coefficient of sandstone under the Brazilian test [16]. $E_t$ suddenly increased between 0% and 10% of the RCA, but the increase in $\sigma_t$ became slow in this range.

The range of 0% to 10% of the RCA is further divided in this section, and every 1% of the RCA corresponds to a numerical simulation. Therefore, the curves of the change in $\sigma_t$ and $E_t$ with RCA are obtained, as shown in Figure 11. The changes in $\sigma_t$ and $E_t$ in the range of 0% to 10% of the RCA tend to be unstable, but the drop sections are in the middle of the range. In particular, when $RCA = 8\%$, $\sigma_t$ decreases to 6.01 MPa, and the ratio of $\sigma_t$ to the complete specimen is only 0.68. Through the above analysis, it can be found that when the RCA is between 0% and 10%, $\sigma_t$ fluctuates greatly, but the fluctuation in $E_t$ is relatively small and does not increase significantly until $RCA = 9\%$.

In the range of 0% to 10% of the RCA, $\sigma_t$ decreases with increasing $n$, but the decline range is relatively small. The maximum decline range is 0.208 MPa between $n = 1$ and $n = 2$, and the minimal decline range is 0.090 MPa between $n = 4$ and $n = 5$. In addition, in this range, the change in $E_t$ with respect to $n$ tends to be unstable, as does the change in $E_t$ with RCA. The numerical simulation results in the range of 20% to 50% of the RCA show that the change in $n$ in this range has little effect on the mechanical behavior of the rock specimen. Moreover, $\sigma_t$ in this range is close to that of complete specimens, which is basically consistent with the effect of the RCA in this range.

The change in $n$ has no obvious effect on $\sigma_t$ before cutting the LSS, and the effect of $n$ after cutting the LSS is actually caused by the change in the RCA. With increasing RCA, $E_t$ is greatly improved at $RCA = 9\%$ and then becomes stable. Moreover, it can be clearly seen that the range of sudden

![Figure 6: Variation in mechanical behavior of specimens with joint angles. (a) $\sigma_t$. (b) $E_t$.](image)

![Figure 7: Several joints in a rock specimen model.](image)
changes in $E_t$ and $\sigma_t$ occurs when approximately 8% of the RCA is reached.

5. Analysis of the Numerical Simulation Results

5.1. Stress State of the Specimens with Joints. Due to the existence of the joint, the stress distribution inside the specimen is not uniform. However, as shown in Figure 12, when any microblock close to the joint is considered, the stress $p_i$ on the joint can be decomposed into the stress $\sigma_{\gamma}$ perpendicular to the joint direction and the stress $\sigma_t$ along the joint direction [40].

$\sigma_i$ is the normal stress on microblock $i$ and $\gamma$ is the angle between the joint and the center plane located at the specimen center and parallel to the end surface ($0^\circ \leq \gamma \leq 90^\circ$).

According to Figure 12, the stress $p_i$ on the joint is
\[ p_i = \sigma_i \cdot \cos \gamma. \]  

The stress \( p_i \) on the joint can be further decomposed into the stress \( \sigma_y \) perpendicular to the joint direction and the stress \( \tau_y \) along the joint direction:

\[ \sigma_y = p_i \cdot \cos \gamma, \]  
\[ \tau_y = p_i \cdot \sin \gamma. \]  

Substituting equation (3) into equations (4) and (5), respectively, yields

\[ \sigma_y = \sigma_i \cdot \cos^2 \gamma = \frac{\sigma_i}{2} (1 + \cos 2\gamma), \]  
\[ \tau_y = \sigma_i \cdot \cos \gamma \sin \gamma = \frac{\sigma_i}{2} \sin 2\gamma. \]  

According to equations (6) and (7), the trend of the variation in \( \sigma_y \) and \( \tau_y \) with \( \gamma \) is shown in Figure 13.

It can be seen in Figure 13 that \( \sigma_y \) is negatively correlated with \( \gamma \), while \( \tau_y \) is positively correlated with \( \gamma \) when \( 0^\circ \leq \gamma \leq 45^\circ \) and negatively correlated with \( \gamma \) when \( 45^\circ \leq \gamma \leq 90^\circ \).

There are three main types of failure observed for specimens with joints under tensile stress: tensile failure along the joint, shear failure along the joint, and tensile failure of the specimen material.

\[ \begin{align*} 
\sigma_y & \geq \sigma', \\
\tau_y & \geq c' + \sigma_y \tan \varphi', \\
\sigma_i & \geq \sigma_{00}, 
\end{align*} \]
where \( \sigma' \) is the tensile strength of the joint; \( \sigma_{00} \) is the tensile strength of the material; \( c' \) is the cohesive force of the joint; and \( \varphi' \) is the internal friction angle of the joint.

Therefore, to cause the tensile failure of microblock \( i \), the curve of its normal stress \( \sigma_i \) with \( c' \) is shown in Figure 14.

5.2. Variation in the Specimen Failure Mode with the Joint State. When the LSS is not cut, the failure of the specimen is mainly tensile failure along the joints, and it can be seen in Figure 14 that if tensile failure occurs along a joint, with the increase in \( \gamma \), the normal stress \( \sigma_i \) increases correspondingly, and the growth rate continues to accelerate. Therefore, when LSS is not cut, \( \sigma_i \) and \( \gamma \) are positively correlated, the growth
rate tends to accelerate greatly, and the smooth section of the 
$\sigma_i$ curve corresponds to the smoother section in Figure 14.

When $\gamma$ is small, the failure of the specimen is tensile failure along the joint, as shown in Figure 15(a); however, Figure 14 indicates that when $\gamma$ is larger, tensile failure along the joint will occur, and the increase in normal stress $\sigma_i$ at these values of $\gamma$ is several times greater than that at smaller values of $\gamma$. However, due to the existence of the joint cohesion $c'$, the increasing normal stress $\sigma_i$ acts on the specimen block, and a part of the specimen block suffers tensile failure, as shown in Figure 15(b).

The uniaxial tensile strength of the specimen under direct tension is calculated as follows [41]:

$$\sigma = \frac{F}{A},$$

(9)

where $\sigma$ is the tensile strength of the specimen, $F$ is the axial peak load, and $A$ is the cross-sectional area of the specimen.

When the joint cuts the LSS, the axial load is divided into two parts from the load to the fixed end, so $F$ can be divided into two parts:

$$F = F_1 + 2F_2,$$

(10)

where $F_1$ is the axial load acting on the joint and $F_2$ is the axial load acting on the cut part of the LSS.

Due to the uneven distribution of stress during the loading process, the block on the loading side near the joint and the cut part of the LSS can be divided into $n$ microblocks and $m$ microblocks, respectively, and $F_1$ and $F_2$ are as follows:

$$F_1 = \sum_{i=1}^{n} \sigma_i,$$

$$F_2 = \sum_{j=1}^{m} \sigma_j,$$

(11)

where $\sigma_i$ is the stress of the microblocks on the loading side of the joint, $\sigma_i \leq \sigma_0$, $\sigma_j$ is the stress of the microblocks in the cut part of LSS, and $\sigma_j \leq \sigma_0$.

When RCA is relatively small, the rising section of the stress-strain curve is straight and slightly concave, and the steepness of the falling section of the curve decreases. This observation of the stress-strain curves is basically consistent with that of Dai et al. [42] for specimens with both structural face failure and rock tensile failure, as shown in Figure 16(b). $\sigma_i$ is determined by the load of $F_1$ which is transmitted by the joint at this time. Taking 2% of the RCA as an example, originally, when the stress rises to 80% of $\sigma_n$, the ULSS fails along the cut part initially under the action of $F_2$, and as loading continues, the stress-strain curve continues to rise to $\sigma_n$, as shown in Figure 16(a). Moreover, under the action of $F_1$, stress concentration and failure occur on both ends of the joint, which is close to the ULSS. With the continuity of loading, the stress-strain curve continues to fall, and the tensile failure zone expands from both ends of the joint to the middle until the specimen completely fails.

When RCA rises to 30%, the magnitude of $\sigma_i$ is determined by $F_2$. When the stress reaches 80% of $\sigma_n$, stress concentration occurs at both ends of the joint in the beginning under the action of $F_1$, and the block fails by tension, as shown in Figure 17. When the stress reaches $\sigma_n$, the cut part of the ULSS fails under the action of $F_2$. After continuous loading, the tensile failure zone does not extend to the middle along either end of the joint but extends from the cut part along the ULSS until the ULSS completely fails.

According to the above analysis, it can be seen that as the RCA increases, the load $F_1$ transmitted by the joint continues decreasing, while the load $F_2$ transmitted by the block continues increasing, and the critical load that affects $\sigma_i$ also transitions from $F_1$ to $F_2$. When RCA = 8%, it is just near the transition zone. At this time, $F_1$ and $F_2$ are approximately equal, and the critical load is to the minimum, so $\sigma_i$ is the smallest. When RCA = 8%, it can be seen clearly from the stress-strain curve that the peak appears with the continuous concentration of stress. However, the failure of the cut blocks does not cause the curve to fall. After continuous loading, tensile failure appears on the blocks at both ends of the joint, and the failure zone expands from both ends to the middle along the joint as the loading continues, and the curve falls quickly.

The effect of joints on $\sigma_i$ is actually the effect of joints on the overall bearing capacity of rock specimens [3]. With the increase in $\gamma$, the failure mode of rock specimens gradually changes from failure along the joint to direct failure of the specimen blocks; this phenomenon is also reflected in the Brazilian test [20, 25, 28].

6. Discussion

As the most common engineering material, the study of the mechanical behavior of rock has always been a very important subject. In addition, because the failure of rock engineering in most cases starts from tensile failure, $\sigma_t$ as one of the basic mechanical property parameters in rock materials, plays an irreplaceable role in rock mechanics research and practical applications of engineering rock masses [24]. Compared with the Brazilian test, the direct tensile test has a higher degree of confidence in obtaining $\sigma_t$. 

![Figure 15: Tension failure area slice (\(\gamma = 30^\circ\) and \(\gamma = 50^\circ\)). (a) \(\gamma = 30^\circ\). (b) \(\gamma = 50^\circ\).](image-url)
However, due to the limited conditions, it is difficult to carry out direct tensile tests of rock in the laboratory; thus, determining how to accurately obtain the rock $\sigma_t$ is key. Because of the complex formation conditions, the rock mass will produce a large number of weak structural planes that will have a dominant effect on the overall strength of the rock mass. The spatial characteristics of weak structural planes such as joints also have a large effect on the overall strength of the rock mass. In actual engineering rock mass, as long as the mechanical behavior of the rock block and the spatial characteristics of the weak structural plane can be well understood, the mechanical behavior of the rock mass as a whole can be predicted. However, in the field sampling process, due to limited conditions, the spatial characteristics of the joint structure in the sample will be different from the site, and the stress conditions of the rock mass at different positions in the actual engineering rock mass will also differ. In addition, restoring the mechanical characteristics of the rock mass through laboratory tests is challenging.

7. Conclusion

In this paper, a three-point modeling method was proposed and applied to 3DEC to realize the simulation of a jointed specimen. With this approach, the spatial characteristics of rock joints can be changed arbitrarily, and the change patterns of the mechanical behavior of the jointed rocks are determined by combining the results of different joint structures.
This study analyzed the effect of the joint’s spatial characteristics on the mechanical behavior of rock specimens under numerical simulation and revealed the effect pattern of the RCA on the overall mechanical behavior of the specimen. In addition, the effect of the specimen’s failure mode and force on the change in γ was examined, and the transition zone was identified, which will provide a basis for the prediction of jointed rock mechanical behavior and the inversion of the rock mechanical parameters in the future.

(1) For jointed rocks, σ1 is positively related to the joint angle (described by α, β, and γ), but Et is hardly influenced by the joint angle, while n is negatively related.

(2) When 0% ≤ RCA ≤ 10%, both σ1 and Et of the joint specimen tend to be unstable with the change in RCA, especially near RCA = 8%, and both σt and Et of the joint specimen undergo sudden changes. However, when RCA ≥ 20%, both σ1 and Et of the joint specimen tend to be stable with the increase in RCA and are close to that of the complete specimen.

(3) Through the analysis of the numerical simulation results, it was found that the main reason why σ1 of the jointed rocks increased with the increase in γ is the fact that the specimen is less likely to produce tensile failure along the joint as γ increases. Therefore, under uniaxial tensile stress, the change from tensile failure along the joint to direct tensile failure of the specimen blocks occurs with increasing γ.

(4) During the change from tensile failure along the joint to direct tensile failure of the intact parts of the specimen, a transition zone appears. The joint more greatly weakens the overall strength of the specimen when γ corresponds to this transition zone.

Data Availability
All underlying data supporting the results of this study can be found in the manuscript.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

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References
[1] B. H. G. Brady and E. T. Brown, *Rock Mechanics for Underground Mining*, Allen & Unwin, Crows Nest, Australia, 2004.
[2] Q. Wu, X. Li, L. Weng, Q. Li, Y. Zhu, and R. Luo, "Experimental investigation of the dynamic response of prestressed rockbolt by using an SHPB-based rockbolt test system," *Tunnelling and Underground Space Technology*, vol. 93, Article ID 103088, 2019.
[3] Q. Wu, L. Chen, B. Shen, B. Dlamini, S. Li, and Y. Zhu, "Experimental investigation on rockbolt performance under the tension load," *Rock Mechanics and Rock Engineering*, vol. 52, no. 11, pp. 4605–4618, 2019.
[4] L. Jiang, P. Zhang, L. Chen et al., "Numerical approach for goaf-side entry layout and yield pillar design in fractured ground conditions," *Rock Mechanics and Rock Engineering*, vol. 50, no. 11, pp. 3049–3071, 2017.
[5] Z. Zhang, M. Deng, X. Wang, W. Yu, F. Zhang, and V. D. Dao, "Field and numerical investigations on the lower coal seam entry failure analysis under the remnant pillar," *Engineering Failure Analysis*, vol. 115, Article ID 104638, 2020.
[6] A. Baghbanan and L. Jing, "Stress effects on permeability in a fractured rock mass with correlated fracture length and aperture," *International Journal of Rock Mechanics and Mining Sciences*, vol. 45, no. 8, pp. 1320–1334, 2008.
[7] C. Zhang, Q. Bai, and Y. Chen, "Using stress path-dependent permeability law to evaluate permeability enhancement and coalbed methane flow in protected coal seam: a case study," *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*, vol. 6, no. 3, pp. 1–25, 2020.
[8] Q. Bai and S. Tu, "A general review on longwall mining-induced fractures in near-face regions," *Geofluids*, vol. 2019, no. 19, 22 pages, Article ID 3089292, 2019.
[9] Y. Zhang, H. Deng, J. Deng et al., "Peridynamic simulation of crackpropagation of non-homogeneous brittle rock-like materials," *Theoretical and Applied Fracture Mechanics*, vol. 106, Article ID 102438, 2020.
[10] C. Xin, Z. Liao, and D. Li, "Experimental study of effects of joint inclination angle and connectivity rate on strength and deformation properties of rock masses under uniaxial compression," *Chinese Journal of Rock Mechanics and Engineering*, vol. 30, no. 4, pp. 781–789, 2011.
[11] R. Yoshinaka, M. Osada, H. Park, T. Sasaki, and K. Sasaki, “Practical determination of mechanical design parameters of intact rock considering scale effect,” *Engineering Geology*, vol. 96, no. 3-4, pp. 173–186, 2008.
[12] A. Bobet and H. H. Einstein, “Fracture coalescence in rock-type materials under uniaxial and biaxial compression,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 35, no. 7, pp. 863–888, 1998.
[13] M. Prudencio and M. Van Sint Jan, “Strength and failure modes of rock mass models with non-persistent joints,” *International Journal of Rock Mechanics and Mining Sciences*, vol. 44, no. 6, pp. 890–902, 2007.
[14] T. S. Nguyen and A. D. Le, “Development of a constitutive model for a bedded argillaceous rock from triaxial and true triaxial tests,” *Canadian Geotechnical Journal*, vol. 51, no. 10, pp. 1139–1150, 2015.
[15] R. P. Tiwari and K. S. Rao, “Post failure behaviour of a rock mass under the influence of triaxial and true triaxial confinement,” *Engineering Geology*, vol. 84, no. 3-4, pp. 112–129, 2006.
[16] H. Deng, X. Zhang, and H. Zhang, "Analysis and discussion on Brazilian tests on layered rock tensile strength," Rock and Soil Mechanics, vol. 37, no. 2, pp. 309–315, 2016.
[17] S. Okubo, K. Fukui, and Q. Qingxin, "Uniaxial compression and tension tests of anthracite and loading rate dependence of peak strength," International Journal of Coal Geology, vol. 68, no. 3-4, pp. 196–204, 2006.
[18] G. Hondros, "The evaluation of poissens ratio and the modulus of materials of a low tensile resistance by the Brazilian (indirect tensile) test with a particular reference to concrete," Australian Journal of Applied Science, vol. 10, no. 3, pp. 243–268, 1995.
[19] G. Feng-Qiang and G.-F. Zhao, "Dynamic indirect tensile strength of sandstone under different loading rates," Rock Mechanics and Rock Engineering, vol. 47, no. 6, pp. 2271–2278, 2014.
[20] A. Tavallali and A. Vervoort, "Effect of layer orientation on the failure of layered sandstone under Brazilian test conditions," International Journal of Rock Mechanics and Mining Sciences, vol. 47, no. 2, pp. 313–322, 2010.
[21] A. Coviiello, R. Lagioia, and R. Nova, "On the measurement of the tensile strength of soft rocks," Rock Mechanics and Rock Engineering, vol. 38, no. 4, pp. 251–273, 2005.
[22] F. Gong, G. Zhao, Q. Zhang, and W. Wu, "Dynamic failure characteristics and behavior of rock materials," Advances in Civil Engineering, vol. 2019, Article ID 6260351, 2 pages, 2019.
[23] K. Raj and R. Pedram, "Correlations between direct and indirect strength test methods," International Journal of Mining Ence and Technology, vol. 25, no. 3, pp. 355–360, 2015.
[24] Y. S. Wang, J. H. Deng, L. R. Li, and Z. H. Zhang, "Micro-failure analysis of direct and flat loading brazilian tensile tests," Rock Mechanics and Rock Engineering, vol. 52, no. 11, pp. 4175–4187, 2019.
[25] Y. Liu, H. Fu, and Y. Wu, "Study on Brazilian splitting test for slate based on single weak plane theory," Journal of China Coal Society, vol. 38, no. 10, pp. 1775–1780, 2019.
[26] Y.-Y. Zhou, X.-T. Feng, D.-P. Xu, and Q.-X. Fan, "An enhanced equivalent continuum model for layered rock mass incorporating bedding structure and stress dependence," International Journal of Rock Mechanics and Mining Sciences, vol. 97, pp. 75–98, 2017.
[27] B. Debecker and A. Vervoort, "Experimental observation of fracture patterns in layered slate," International Journal of Fracture, vol. 159, no. 1, pp. 51–62, 2009.
[28] Y. Zhao, G.-F. Zhao, Y. Jiang, D. Elsworth, and Y. Huang, "Effects of bedding on the dynamic indirect tensile strength of coal: laboratory experiments and numerical simulation," International Journal of Coal Geology, vol. 132, pp. 81–93, 2014.
[29] L. Lianchong, Y. Tianhong, L. Zhenghao, Z. Wancheng, and T. Chun, "Numerical investigation of groundwater outbursts near faults in underground coal mines," International Journal of Coal Geology, vol. 85, no. 3–4, pp. 276–288, 2011.
[30] Z. Zhang, Methods of Determining the Strength of Jointed Rock Mass and the Anisotropic Characters, Beijing Jiaotong University, Beijing, China, 2007.
[31] Z. M. Han, C. S. Qiao, and J. Zhu, "Analysis of strength and failure characteristics of rock mass with two sets of cross-persistent joints," Yantu Lixue/rock and Soil Mechanics, vol. 39, no. 7, pp. 2451–2460, 2018.
[32] T. L. Heath, The Thirteen Books of Euclid’s Elements, Cambridge University Press, Cambridge, UK, 1926.
[33] C. A. Tang, L. G. Tham, S. H. Wang, H. Liu, and W. H. Li, "A numerical study of the influence of heterogeneity on the strength characterization of rock under uniaxial tension," Mechanics of Materials, vol. 39, no. 4, pp. 326–339, 2007.