Numerical study on size effect and anisotropy of columnar jointed basalts under uniaxial compression

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Abstract: Under uniaxial loading, the heterogeneity of rock mass, the change of mechanical properties of joints and the progressive fracture process of rock mass significantly affect the size effect and anisotropy of columnar jointed basalts (CJBs). To reveal the fracture features and failure mechanisms of CJBs influenced by the size effect and anisotropy, the digital image correlation (DIC), meso-damage mechanics, statistical strength theory and continuum mechanics were combined (the DIC-improved RFPA), the digital images of CJBs specimens were processed to establish the inhomogeneous numerical models and a series of numerical tests were therefore conducted. The gradual fracture processes and macro failure patterns of CJBs orthogonal and parallel to column axis under uniaxial compression were studied, and the effects of various factors on the size effect and anisotropic mechanical properties of CJBs were further analyzed. The results show that model size, column dip angle, rock heterogeneity, column diameter, elastic modulus of joints, residual strength coefficient of joints, ratio of shift distance of joints, irregularity degrees of columns, model boundaries have remarkable and complex effects on the mechanical behaviors of CJBs. The results greatly improve our understanding of the non-linear deformation and failure behaviors of CJBs and provide theorical basis for engineering construction in the areas of CJBs.

Keywords: size effect; anisotropy; columnar jointed basalts; uniaxial compression; numerical simulation

List of symbols		**Abbreviations**	
σ	Stress (***MPa***)	CJRMs	Columnar jointed rock masses
f_{cr}	Residual compressive strength	CJBs	Columnar jointed basalts
f_{tr}	Residual tensile strength	UCS	Uniaxial compressive strength
f_{c0}	Uniaxial compressive strength	EDM	Equivalent deformation modulus
f_{t0}	Uniaxial tensile strength	TACUCS	Transverse anisotropy coefficient of uniaxial compressive strength
ε	Strain	TACEDM	Transverse anisotropy coefficient of equivalent deformation modulus
ε_{c0}	Strain at f_{c0}		
ε_{t0}	Strain at f_{t0}		
ε_{tu}	Ultimate tensile strain		

1. Introduction

Columnar joints are generally tensile fracture structures formed by cooling and contraction during basalt eruption or overflow. They belong to primary joints, by which rock masses are cut into regular or irregular prisms. Some studies tried to reveal the origin of columnar jointed basalts (CJBs), such as Xu (1995), Müller (1998a, b), Toramaru and Matsumoto (2004). Meanwhile, the U.S. Department of Energy organized Lawrence Berkeley National Laboratory, Itasca company and Columbia University in the 1980s to conduct many large-scale in-situ tests on columnar jointed rock masses (CJRMs) during the burial of nuclear waste in basalts, and evaluated the deformation modulus and strength parameters of CJBs. In recent decades, some large-scale hydropower stations have been built or are under construction in Southwest China. Especially, the CJRMs were encountered in several projects including the Baihetan, Xiluodu, and Tongjiezi stations. **Fig. 1** displays some representative field photographs of CJRMs (Weinberger and Burg 2019; Guy 2010; Goehring 2013; Xiang et al. 2020).

A few investigations have assessed the size effect and anisotropy of CJBs or CJRMs by physical experiment or numerical simulation (Liu et al., 2010; Xiao et al., 2014, 2015; Ke et al., 2019; Ji et al., 2017; Cui et al., 2016; Jiang et al., 2013). For physical experiment, the main difficulties lie in building models and setting the mechanical properties of joints, etc., while for numerical simulation, it is generally difficult to comprehensively consider the rock heterogeneity, irregularity degree of columns, size effect of rock mass, etc., and reproduce the progressive fracture process of CJRM. Liu et al. (2010) conducted experimental research of CJBs with a true triaxial apparatus at the Baihetan Hydropower Station. The stress-strain relationship, strength characteristics and failure mechanism of composite columnar rock mass under different unloading/loading stress paths were studied. However, the columnar joint surface in the test was relatively straight, and the influence of mechanical properties of joint surface was not considered. Through uniaxial and triaxial compression tests, Xiao et al. (2014, 2015) obtained the deformation modulus and uniaxial compressive strength (UCS) of CJRMs with different dip angles of columns, and then analyzed their anisotropic characteristics. However, the influence mechanism of cement layer on the strength and deformation of jointed rock specimens is still different from that of natural columnar joints on CJRMs. Through uniaxial compression tests, Ke et al. (2019) studied the influence of column dip angle and transverse joint on anisotropic mechanical properties and failure mechanism of CJRMs. Uniaxial compression tests were also conducted by Ji et al. (2017) on artificial CJRM specimens with geological structure characteristics similar with the actual CJRM. Jiang et al. (2013) conducted the experimental study on anisotropic characteristics of CJBs.

Besides, Cui et al. (2016) used joint network finite element method to study the influence of structural characterization parameters on equivalent deformation modulus (EDM) of CJRMs. Ni et al. (2015) conducted research on the size effect of EDM of CJRMs based on discrete element method. Zheng et al. (2010) established a three-dimensional discrete element numerical model of CJBs using the deformable discrete element method. Through numerical simulation of bearing plate tests of different sizes, the influence of size effect and anisotropy on the test results was discussed. Zhu et al. (2009) conducted research on anisotropic characteristics and size effect of CJRMs. Yan et al. (2012) established three-dimensional discrete element models of CJRMs and carried out triaxial compression simulation to study the size effect of macroscopic equivalent elastic modulus of CJRMs. A acceptable method of reconstructing the structure of irregular CJRMs using 3D printing was suggested by Xia et al. (2020) and their uniaxial compression results of the reconstructed CJRM specimens were compared with the in-situ tests.

However, most of the previous studies did not consider the influence of heterogeneity of rock mass, mechanical property variation of joints, or the progressive fracture processes of specimens. The CJBs are of significant discontinuity, inhomogeneity and anisotropy. In this study, with the aim of discussing the size effect and anisotropic properties of CJBs, the digital image correlation (DIC), meso-damage mechanics, statistical strength theory and continuum mechanics were combined (the DIC-improved RFPA), and then the digital images of CJBs specimens were processed to generate inhomogeneous finite element models. Meanwhile, a series of numerical tests were conducted under uniaxial compression. The simulated results were compared with the laboratory physical test results to verify the method rationality and reliability. Under uniaxial compression, the progressive fracture processes and failure patterns of CJBs were systematically studied. Furthermore, the effects of various factors on the size effect and anisotropic mechanical properties of CJBs were analyzed.

2. Numerical Modeling

2.1 Rationale of the DIC-improved RFPA method

The main advances of the rock failure process analysis (RFPA) method lie in modelling the progressive failure process without assuming when and where the new cracks will generate and how they will propagate and connect with each other (Tang 1997; Tang et al. 1998; Li et al. 2011; Yu et al. 2015; Liang 2005). The RFPA method has been widely used for evaluating the anisotropic behavior of jointed rock samples (Tang and Kou 1998; Tang et al. 2001; Xu et al. 2013). Also, RFPA has been applied in investigating the instability (Li et al. 2009), scale effect (Zhou et al. 2018) and anisotropy (Yang et al. 2015a, b) of jointed rock masses at different scales.

The digital image correlation (DIC) is combined with the RFPA method to improve the model building capability. Clearly, the image import, gray threshold segmentation and pixel processing are added into the RFPA method. In order to build the numerical models, it is necessary to transform the information on digital images into the vectorized data. A digital image is composed of square pixels, as shown in **Fig.2 (a)**. In 3D space, if an image is considered to have a certain thickness t, each pixel can be regarded as a finite element mesh. The corner coordinates of each pixel can be transformed into the corresponding physical positions in vector space (the thickness of each pixel is t and the side length is one unit). According to the gray value of each pixel, it is classified into joint or rock material and given corresponding material parameters. Based on these principles, the transformed finite element mesh model is shown in **Fig.2 (b)**. Elastic-brittle damage constitutive law of an element under uniaxial stress (Tang 1997, 2000; Tang et al. 1998; Li et al.2011; Lang 2018; Lang et al. 2019; Yu et al. 2015; Liang 2005) is shown in **Fig.2 (c)**. According to the method of extending the one-dimensional constitutive law under uniaxial stress to the three-dimensional constitutive law under complex stress conditions, which was proposed by Mazars and Pijaudier-Cabot (1989), we can easily extend the constitutive law described above to a three-dimensional stress state. The calculation flow diagram of the DIC-improved RFPA method is shown in **Fig.3**.

2.2 Validation of the numerical modeling

The laboratory physical experiments can be used to verify the numerical method. Xiao et al.

(2014) used the rock mass specimen with columnar joints made from the mixture of gypsum, cement and water according to the mass ratio of 3:1:3.2. The specimens were cylindrical specimens with a diameter of 50 ***mm*** and a height of 100 ***mm***. The diameter of the hexagonal prism inside the specimen was 20 ***mm***. The dip angles of $\boldsymbol{\beta}$ = 0 °, 15 °, 30 °, 45 °, 60 °, 75 ° and 90 ° were considered. The uniaxial compression tests of rock mass with columnar joints were carried out by the MTS815 rock test system. Firstly, the axial force was applied on the top of the model with the loading rate of 0.5 ***kN***/***min***. When the axial force reached 1 ***kN***, the loading mode was changed to the displacement loading mode with a load rate of 0.1 ***mm***/***min***.

Ji et al. (2017) used cement, fine sand, water and water reducer to make regular hexagonal prisms according to the mass ratio of 1:0.5:0.35:0.002, and then used white cement slurry to bond the prisms to form columnar jointed rock mass specimens. The specimens were cylindrical specimens with a diameter of 50 ***mm*** and a height of 100 ***mm***. The diameter of the hexagonal prism inside the specimen was 10 ***mm***. The dip angles of $\boldsymbol{\beta}$ = 0 °~ 90 ° were considered. Uniaxial compression tests of rock mass with columnar joints were carried out by the triaxial rheological test system. The loading mode was axial stress control with a loading rate of 0.6 ***MPa***/***min***.

In this paper, the specimens used for numerical verification were rectangular specimens with a width of 50 ***mm*** and a height of 100 ***mm*** as a plane strain case. The diameter of the hexagonal prism inside the specimen was 10 ***mm***. The directions I and II orthogonal column axis and the direction parallel to column axis ($\boldsymbol{\beta}$=0° to 90° with interval of 15°) were considered, as shown in Table 1. The digital images were converted into the finite element mesh models, as shown in Table 2. The mechanical parameters used in simulation are shown in Table 3, which is referred to the relevant literatures of CJBs. The displacement-controlled loading was used and the loading rate was 0.005 ***mm***/***step*** until failure of specimen occurred.

The comparison of normalized UCS coefficients between laboratory physical tests and numerical tests is shown in **Fig.4**. In terms of laboratory physical tests, the normalized UCS coefficients of Xiao et al. (2014) were presented with an approximately symmetrical U-shaped distribution with the increase of column dip angle. The normalized UCS coefficients of Ji et al. (2017) showed a U-shaped distribution with the characteristics of the high left side and the low right side. The lower values of both laboratory physical tests were mainly distributed in the range of dip angle $\boldsymbol{\beta}$ = 30°~45°. The results of laboratory physical tests showed that the strength anisotropy of CJRMs was obvious. The numerical simulation results also show an obvious U-shaped distribution. Simultaneously, the lower values of the normalized UCS coefficients of the numerical tests are also mainly distributed in the range of column dip angle $\boldsymbol{\beta}$ = 30°~45°. Table 4 displays the comparison of failure patterns between numerical tests and laboratory physical tests. It can be seen that the numerical test results are in good agreement with the laboratory physical test results.

2.3 Numerical configuration

In this study, the finite element numerical specimens are sourced from the CJBs of the Baihetan Hydropower Station in China with the column length of 0.5~3 ***m***, and the diameter of 13~25 ***cm***. In terms of the size effect of CJBs, the specimens are square models but owns different sizes of 0.5 ***m***, 1 ***m***, 2 ***m***, 3 ***m*** and 4 ***m***, respectively. Meanwhile, the column diameters are 20 ***cm***, 40 ***cm***, 60 ***cm*** and 80 ***cm***, respectively. As shown in Table 5, the heterogeneity index of column is 5, 10, 20 and 200, respectively. The elastic modulus of joints is 3.75 ***GPa***, 7.5 ***GPa***, 15 ***GPa***, 22.5 ***GPa*** and 30 ***GPa***, respectively, as shown in **Fig.5 (a)**. The residual strength coefficient of joints is taken as 0.1, 0.5, 0.75 and 1, respectively, which reflects the gradual transformation of the mechanical constitutive law of joints from brittleness to plasticity, as shown in **Fig.5 (b)**. Three kinds of model boundaries are considered when calculating the size effect, i.e., the case of plane stress, the case between plane stress and plane strain and the case of plane strain.

In the aspect of anisotropy of CJBs, the column dip angles are 0 °, 15 °, 30 °, 45 °, 60 °, 75 °

and 90 °, respectively. As shown in Table 6, the ratios of shift distance of the secondary joint set are 0%, 20%, 40% and 50%, respectively. The irregularity degrees of columns are considered as completely regular columns, approximately regular columns, moderately regular columns and irregular columns, respectively, cited from the examples of Cui et al. (2016). Three kinds of model boundaries (the case of plane stress, the case between plane stress and plane strain, the case of plane strain) are also considered during calculating.

In the numerical tests, the element size of each model keeps same. Taking 3-***m*** specimen as an example, the number of elements is 608,400. **Figs.6 (a)~(h)** show the typical setup and boundary conditions of numerical tests of the CJBs. For **Fig.6 (f)**, the hinge support constraints are set on two faces along two normal directions of the model, which means that normal displacements along two normal directions are constrained; for **Fig.6 (g)**, the hinge support constraint is set on one face along one normal direction of the model, which means that the normal displacement along one normal direction is constrained and the other normal displacement is free; for **Fig.6 (h)**, there is no hinge support constraint set on the faces along the normal directions of the model, which means that normal displacements along the normal directions are free. For each test, the left and right sides of the model are free, and the hinge support constraint is set at the bottom of the model, i.e., the vertical displacement at the bottom is constrained. A load is applied onto the top of each model along the normal direction in the displacement-controlled mode. The loading ratio is 0.017 ***mm*** per step until the model failure.

Generally, the mechanical parameters of joints are lower than intact rock (Gui and Zhao 2015). The parameter selection of joints would influence the magnitude of the deformation modulus and UCS (Sun et al. 2012). However, the ratios of mechanical properties between joints and intact rock have not been reported yet. Based on the above numerical verification and related literatures of CJBs, the mechanical parameters of joints are determined and listed in Table 7.

3 Results and Analysis

3.1 The size effect of CJBs under uniaxial compression

3.1.1 Progressive failure process and failure pattern along the direction I orthogonal to column axis

Fig. 7 shows the stress-strain curve of 3-***m*** specimen along the direction I orthogonal to the column axis under uniaxial compression, and the minimum principal stress contours at Points A, B, C, D, E and F corresponding to the stress-strain curve, which describes the process of crack initiation, propagation and fracture of the specimen during loading. The red area in the minimum principal stress contour represents the stress concentration.

Comparing **Figs.7 (a) & (c)**, it can be seen that at Points A and B, the stress concentration area gradually transfers from the top and the lower left and right sides of the specimen to the top of the specimen with the loading keeps growing. The joints at the upper part of the specimen gets cracked and cracks then developed downwards. From the minimum principal stress contour of Point B, it can be seen that with the cracking of the joints, the columns at the upper part of the specimen show obvious stress concentration. With the loading increasing, the joints at the lower part of the specimen do not get cracked further, and the stress concentration area does not develop downward, but the columns at the upper middle part of the specimen and individual columns get fractured. At the same time, the stress concentration degree of other columns is weakened, as shown in the minimum principal stress contour at Point C. When the stress reaches the peak point D, the fracturing of columns at the upper part of the specimen becomes more obvious, in which most of the fracture points originate in these column centers. Then the load continues to increase, and the stress drops to Point E. At this time, the fracturing of more columns at the upper part of the specimen intensifies, the cracking of joints becomes more obvious, which developed downward. When the stress reaches Point F, the specimen reaches the residual strength, columns at the upper part of the specimen are obviously broken, and the crack propagation of the joints stops to the lower end of the specimen. In brief, under uniaxial loading, the joints of the specimen get cracked and cracks gradually develops into the inner rocks, which leads to the material damage and strength decrease of the specimen.

3.1.2 Progressive failure process and failure pattern along the direction II orthogonal to column axis

Fig. 8 shows the stress-strain curve of 3-***m*** specimen along the direction II orthogonal to the column axis under uniaxial compression, and the minimum principal stress contours at Points A, B, C, D, E and F corresponding to the stress-strain curve, which describes the process of crack initiation, propagation and fracture of the specimen during loading. The red area in the minimum principal stress contour represents the stress concentration area.

According to **Figs.8 (a) & (c)**, at Points A & B of the loading curve, the tensile stress concentration mainly appears at the vertical joints between the columns. With the loading increasing, the vertical joints at the upper part of the specimen are cracked, and the stress concentrations are transferred to the oblique joints at the upper part of the specimen. This kind of phenomenon gradually develops to the lower part of the specimen. From the minimum principal stress contour of Point B, it can be seen that the cracking of vertical joints forms a V-shaped region. In addition, the cracking of vertical joints and the stress concentration of oblique joints also appear at the bottom left and right sides of the specimen. With the loading growing, other vertical joints in the specimen also get cracked, even in the middle of the upper part of the specimen and the lower left and right sides of the specimen, the stress concentrations of the oblique joints result in the crack initiations near the oblique joints. At this time, the stress concentration areas are mainly distributed at the crack tips near the oblique joints, as shown in the minimum principal stress contour of the peak Point C. Then the load continues to increase, the stress begins to drop to Point

D, the cracks originally initiated further develop, and the stress concentrations gradually appear in other oblique joints inside the specimen. When the stress further decreases to Point E, the fracturing at the upper middle part and the lower left and right sides of the specimen becomes more obvious, and the stress concentration at other parts of the specimen weakens. Then, the load continues to increase, the stress drops to Point F, and the specimen reaches the residual strength. It can be seen that in the breakage region with an inverted V-shape distribution of the specimen, the columns have been broken intensely, and the sporadic stress concentrations appear at the left and right sides of the specimen. To sum up, the mechanical behavior and stress state of the specimen at the beginning of uniaxial loading include the cracking of vertical joints and the stress concentration of oblique joints, forming a V-shaped region. As the load continues to increase, the fracturing at the middle of the upper part and the lower left and right sides of the specimen becomes more obvious, and the breakage region with an inverted V-shape distribution is formed, which makes the material damage of the CJBs specimen and leads to the strength decrease of the specimen.

In terms of failure patterns of CJBs with different sizes along the direction I orthogonal to column axis, according to **Figs.9 (a)~(e)**, for the specimen sizes of 0.5 ***m*** ~ 2 ***m***, there are fractured columns at the upper and lower parts of the specimens. For the specimen sizes of 3 ***m***~4 ***m***, the fractured columns are mainly at the upper part of the specimens. It shows that when the specimen size increases to a certain extent, the specimen contains more columns, which forms a structure for bearing load. There is a structure effect in these specimens borne with the uniaxial displacement load.

In terms of failure patterns of CJBs with different sizes along the direction II orthogonal to column axis, according to **Figs. 9 (f)~(j)**, for the specimen sizes of 0.5 ***m***~2 ***m***, most of the vertical joints at the upper and lower parts of specimens get cracked, and the stress concentrations appear at the oblique joints, and even crack initiation and propagation appear near some oblique joints. For the specimen size of 3 ***m***, in the middle of the upper part and the lower left and right sides of the specimen, the stress concentrations at oblique joints result in the crack initiation and propagation near oblique joints. For the specimen size of 4 ***m***, there are roughly two inverted V-shaped stress concentration regions at the upper part of the specimen. In these regions, the stress concentrations at oblique joints result in the crack initiation and propagation near oblique joints. In most of the lower part of the specimen, the vertical joints are presented with weak tensile stress concentration, but most of them are not cracked. The above results show that when the specimen size increases to a certain extent, the specimen contains more columns, forming a structure to bear loading. Under uniaxial loading, with the increase of specimen size, the stress transfer mechanism changes, and the loaded specimen shows obvious structure effect.

3.1.3 Influence of rock heterogeneity on size effect of CJBs under uniaxial compression

In this paper, the UCS is defined as the peak point of the stress-strain curve of the uniaxial compression test, and the EDM is defined as the slope from the origin to the peak point of the stress-strain curve. According to **Fig.10 (a)**, for the direction I orthogonal to column axis, in terms of UCS, when the heterogeneity index is 5, 10 and 20, the UCS firstly increases and then decreases with the increase of size, and the decreasing trend of UCS becomes slower with the increase of heterogeneity index. When the heterogeneity index is 200, the UCS of the specimens decreases in a fluctuating way. As shown in **Fig.10 (b)**, for the direction II orthogonal to column axis, when the heterogeneity index is 5, the UCS fluctuates with the increase of size; when the heterogeneity index is 10, the UCS gradually increases; when the heterogeneity index is 20 and 200, the UCS shows a trend of low left and high right with the increase of size.

3.1.4 Influence of column diameter on size effect of CJBs under uniaxial compression

According to **Fig.10 (c)**, in the aspect of UCS along the direction I orthogonal to column axis, when column diameter is 20 ***cm***, the UCS firstly increases and then decreases with the increase of specimen size; when the column diameter is 40 ***cm*** and 60 ***cm***, the UCS shows the trend of decreasing then slow changing; when the column diameter increases to 80 ***cm***, the UCS decreases, increases and then decreases. It can be seen from **Fig.10 (d)** that for the direction II orthogonal to column axis, when the column diameter is 20 ***cm***, the UCS shows a fluctuating trend with the increase of specimen size; when the column diameter is 40 ***cm***, the UCS decreases and then slowly changes; when the column diameter is 60 ***cm***, the UCS grows then shows a decreasing trend; when column the diameter is 80 ***cm***, the UCS decreases rapidly and then slowly.

3.1.5 Influence of elastic modulus of joints on size effect of CJBs under uniaxial compression

As shown in **Fig.11 (a)**, in terms of UCS along the direction I orthogonal to column axis, when the elastic modulus of joints is 3.75 ***GPa***, the UCS shows a fluctuating trend with the increase of specimen size; when the elastic modulus of joints is 7.5 ***GPa***, 15 ***GPa***, 22.5 ***GPa*** and 30 ***GPa***, the UCS increases rapidly and then decreases with the increase of specimen size. In the direction I, when the specimen size is larger, such as 4 ***m***, the influence of elastic modulus of joints on UCS is with a critical value. When the elastic modulus of joints is greater than 15 ***GPa***, the increase of elastic modulus of joints has limited effect on the growth of UCS.

As can be seen from **Fig.11 (b)** that for the direction II orthogonal to column axis, when the elastic modulus of joints is 3.75 ***GPa***, the UCS fluctuates with the growth of specimen size; when the elastic modulus of joints is 7.5 ***GPa*** and 15 ***GPa***, the UCS increases with the growth of specimen size; when the elastic modulus of joints is 22.5 ***GPa***, the UCS decreases firstly then increases; when the elastic modulus of joints is 30 ***GPa***, the UCS shows a fluctuating trend. For the direction II, when the specimen size is larger, such as 4 ***m***, there is a critical value for the influence of elastic modulus of joints on UCS. When the elastic modulus of joints is higher than 22.5 ***GPa***, the growth of UCS is limited with the increase of elastic modulus of joints.

3.1.6 Influence of residual strength coefficient of joints on size effect of CJBs under uniaxial compression

It can be seen from **Fig.11 (c)** that in terms of UCS along the direction I, when the residual strength coefficient of joints is 0.1, the UCS increases with the increase of specimen size, then changes slowly and then increases again. When the residual strength coefficient of joints is 0.5, the UCS firstly increases and then changes gently with the increase of specimen size. When the residual strength coefficient of columnar joint is 0.75, the UCS firstly increases and then decreases gradually with the increase of specimen size. When the residual strength coefficient of joints is 1, the UCS firstly increases and then decreases with the increase of specimen size. When the specimen size is larger, such as 4 ***m***, there is a critical value for the influence of residual strength coefficient of joints on UCS. When the residual strength coefficient of joints is greater than 0.5, the increase of residual strength coefficient of joints has limited effect on the growth of UCS.

As presented in **Fig.11 (d)**, in the aspect of UCS along the direction II, for the cases of residual strength coefficients of 0.1, 0.5, 0.75, 1 of joints, the relationship curves between UCS and specimen size show similar variation law. When the residual strength coefficient of joints is 0.1 and 0.5, the UCS firstly decreases and then changes slowly. When the residual strength coefficient of joints is 0.75, the UCS firstly decreases and then grows slowly. When the residual strength coefficient of joints is 1, the UCS shows the trend of decreasing firstly then increasing and then decreasing.

3.1.7 Influence of model boundaries on size effect of CJBs under uniaxial compression

It can be seen from **Fig.12 (a)** that in terms of UCS along the direction I, when the model boundary is in the case of plane stress, with the increase of specimen size, the UCS firstly increases then decreases, and then increases slightly; when the model boundary is in the case between plane stress and plane strain, the UCS shows the trend of firstly increasing then decreasing, and then changing slowly with the increase of specimen size; when the model boundary is in the case of plane strain, the UCS firstly increases and then decreases with the increase of specimen size. Compared with the other model boundaries, the UCS in the case of plane strain is obviously improved.

As depicted in **Fig.12 (b),** for the direction II orthogonal to column axis, when the model boundaries are in the case of plane stress and the case between plane stress and plane strain, the UCS shows the trend of decreasing firstly then changing slowly and then decreasing; when the model boundaries are in the case of plane strain, the UCS fluctuates with the increase of specimen size.

3.1.8 Fluctuation range of transverse anisotropy coefficients of UCS and EDM of CJBs under uniaxial compression

In this paper, the transverse anisotropy coefficient of uniaxial compressive strength (TACUCS) is defined as the UCS along the direction I divided by the UCS along the direction II. According to **Fig. 13 (a)~(e)**, in terms of TACUCS, for the CJBs with different model sizes and rock heterogeneity indexes of 5, 10, 20 and 200, the fluctuation range of TACUCS is 0.85~1.25. For the CJBs with column diameters of 20 ***cm***, 40 ***cm***, 60 ***cm*** and 80 ***cm***, the TACUCS is between 0.55~1.10. For the CJBs with elastic moduli of 3.75 ***GPa***, 15 ***GPa*** and 30 ***GPa*** of joints, the TACUCS is between 0.85~1.20. For the CJBs with residual strength coefficients of 0.1, 0.5, 0.75 and 1 of joints, the TACUCS is between 0.85~1.40. For the CJBs with model boundaries of the case of plane stress, the case between plane stress and plane strain, the case of plane strain, the TACUCS is between 0.85~1.15. Thus, the conclusion can be drawn that according to the sensitivity of TACUCS to influencing factors, the sensitivity order from large to small is column diameter (and residual strength coefficient of joints), rock heterogeneity index, elastic modulus of joints, model boundaries, respectively; for the CJBs with different sizes and various factors under uniaxial compression, they can be roughly approximated as transverse isotropy of UCS, that is, the TACUCS is approximately 1.

The transverse anisotropy coefficient of equivalent deformation modulus (TACEDM) is the EDM along the direction I divided by the EDM along the direction II. In the aspect of TACEDM, for the CJBs with different model sizes and rock heterogeneity indexes of 5, 10, 20 and 200, the fluctuation range of TACEDM is 0.85~1.10. For the CJBs with column diameters of 20 ***cm***, 40 ***cm***, 60 ***cm*** and 80 ***cm***, the TACEDM is between 0.8~1.05. For the CJBs with elastic moduli of 3.75 ***GPa***, 15 ***GPa*** and 30 ***GPa*** of joints, the TACEDM is between 0.85~1.25. For the CJBs with residual strength coefficients of 0.1, 0.5, 0.75 and 1 of joints, the TACEDM is between0.75~1.15. For the CJBs with model boundaries of the case of plane stress, the case between plane stress and plane strain, the case of plane strain, the TACEDM is between 0.85~1.05. Thus, the conclusion can be drawn that according to the sensitivity of TACEDM to influencing factors, the sensitivity order from large to small is elastic modulus of joints (and residual strength coefficient of joints), rock heterogeneity index (and column diameter), model boundaries, respectively; for the CJBs with different sizes and various factors under uniaxial compression, they can be roughly approximated as transverse isotropy of EDM, that is, the TACEDM is approximately 1.

3.2 The anisotropy of CJBs under uniaxial compression

3.2.1 Progressive failure process and failure pattern along the direction parallel to column axis

Fig. 14 shows the minimum principal stress contours corresponding to Points A, B, C, D and E of the stress-strain curve, which describes the process of specimen from compression shear, tension, slip, to crack initiation and propagation during loading. The red areas of minimum principal stress contours represent the stress concentration areas.

Combined with **Figs. 14 (a)&(c)**, it can be seen that at Point A, with the progress of loading, the stress concentration appears in the columnar joints inside the specimen. In addition, there is a certain degree of stress concentration at the top of the specimen. When the stress reaches the point B near the peak point, it can be seen from the minimum principal stress contour of Point B that the columnar joints in the specimen get cracked, especially at the upper part of the specimen. With the loading increasing, the stress drops to Point C, the cracking of columnar joints at the upper part of the specimen further develops to the lower part of the specimen, and the cracking of columnar joints on the left and right sides of the lower part of the specimen is also obvious. The original stress concentration of columnar joints dissipates, and the new stress concentration appears in the local area of the specimen top. When the stress point continues to drop to Point D, under the action of uniaxial displacement loading, due to the influence of column dip angle, tensile damages develop at the edges of several columns, and stress concentrations appear, as shown in the minimum principal stress contour at Point D. When the stress reaches Point E, the crack initiations and propagations occur at or near the original stress concentration positions of the edges of the columns, and the specimen reaches the residual strength. In conclusion, under uniaxial loading, the stress concentration appears in columnar joints of the specimen, columnar joints get cracked and cracks gradually develop into the inner rock. Moreover, the cracking of columnar joints on the left and right sides of the lower part of the specimen is also obvious. Besieds, stress concentrations occur at the edges of several columns, and cracks initiate and propagate, resulting in material damage and strength reduction of the CJBs.

For failure patterns of CJBs with different column dip angles along the direction parallel to column axis, according to **Fig. 15**, when the column dip angle is $\boldsymbol{\beta}$ = 0°, splitting tensile failure occurs along columnar joints in the specimen, and then compression shear damage and fracture of the material in columns develop. In the case of $\boldsymbol{\beta}$ =15°~45°, under uniaxial compression, stress concentration appears in columnar joints, and then columnar joints get cracked and cracking propagates downward. Due to the influence of column dip angle, then the stress concentration occurs at the edges of several columns, and the cracks initiate and propagate. In the case of $\boldsymbol{\beta}$ =60°~75°, there is still the influence of column dip angle. Under uniaxial compression, columnar joints of the specimens do not get cracked, and there are the strip stress concentration and the strip fracture in the specimens. In the case of $\boldsymbol{\beta}$ = 90°, there is no influence of column dip angle. Under uniaxial compression, the upper part of specimen is damaged and fractured under the action of compression shear and tension, and strip fractures appear, which then develops downwards to the middle of the specimen.

3.2.2 Influence of rock heterogeneity on anisotropy of CJBs under uniaxial compression

It can be seen from **Fig. 16 (a)** that in terms of UCS along the direction parallel to column axis, when the heterogeneity index is 5, 10, 20 and 200, the UCS of specimen shows a U-shaped trend with the increase of column dip angle. In the case of $\boldsymbol{\beta}$ = 30°, the UCS of specimen reaches the minimum value. When the heterogeneity index is 5, the change of UCS is gentle in the range of column dip angle $\boldsymbol{\beta}$ = 60°~90°; when the heterogeneity index increases to 10, the UCS of specimen increases obviously with the increase of heterogeneity index in the range of $\boldsymbol{\beta}$ = 0° and $\boldsymbol{\beta}$ = 60°~90°; when the heterogeneity index increases to 20 and 200, in the range of column dip angle $\boldsymbol{\beta}$ = 60°~75°, the growth of UCS is limited with the increase of heterogeneity index, while the growth of UCS is still obvious when $\boldsymbol{\beta}$ = 0° and $\boldsymbol{\beta}$ = 90°. In addition, when $\boldsymbol{\beta}$ = 15°~45°, the growth of specimen is not sensitive to the change of heterogeneity index.

As shown in **Fig. 16 (b)**, in the aspect of EDM, for the cases of heterogeneity indexes of 5, 10, 20 and 200, the relationship curves between EDM and column dip angle are with similar variation characteristics of decreasing firstly then increasing and then decreasing slightly, in which the EDM reaches the minimum value at $\boldsymbol{\beta}$ = 60°.

3.2.3 Influence of column diameter on anisotropy of CJBs under uniaxial compression

According to **Fig.16 (c)**, in terms of UCS along the direction parallel to column axis, when the column diameter is 20 ***cm***, 40 ***cm***, 60 ***cm*** and 80 ***cm***, the UCS of specimen shows a U-shaped trend with the increase of column dip angle, in which the UCS reaches the minimum value at β = 30°. When the column diameter is 20 ***cm***, the UCS changes gently in the range of β = 60°~90°; when the column diameter is 20 ***cm***~40 ***cm***, the UCS grows obviously with the increase of column diameter in the range of β = 60°~90°; when column diameter is 40 ***cm***~80 ***cm***, the increase of UCS is limited with the increase of column diameter in the range of β = 60°~90°. In addition, the UCS is not sensitive to the change of column diameter when β = 0°~45°.

As presented in **Fig.16 (d)**, in the aspect of EDM, there is a critical value for the influence of column diameter on EDM. When the column diameter is smaller than 60 ***cm***, the EDM increases obviously with the increase of column diameter; when the column diameter is larger than 60 ***cm***, the growth of the EDM is limited with that. For the cases of column diameters of 20 ***cm***, 40 ***cm***, 60 ***cm*** and 80 ***cm***, the relationship curves between EDM and column dip angle are with roughly similar characteristics of decreasing firstly then increasing (or changing slightly).

3.2.4 Influence of elastic modulus of joints on anisotropy of CJBs under uniaxial compression

According to **Fig.17 (a)**, when the elastic modulus of joints is 3.75 ***GPa***, 7.5 ***GPa***, 15 ***GPa***, 22.5 ***GPa*** and 30 ***GPa***, the UCS of specimen shows a U-shaped trend with the increase of column dip angle, in which the UCS reaches the minimum value at β = 30°. For the column dip angle of β = 0°, the UCS changes slightly with the increase of elastic modulus of joints, while the UCS grows relatively obviously with that for the column dip angles of 15°~90°. As depicted in **Fig.17 (b)**, except for the slight change of EDM at β = 0°, the growth of EDM is apparent at β = 15°~90° with the increase of the elastic modulus of joints. However, when the elastic modulus of joints is larger than 22.5 ***GPa***, the influence of elastic modulus of joints on the growth of EDM is limited.

3.2.5 Influence of residual strength coefficient of joints on anisotropy of CJBs under uniaxial compression

It can be seen from **Fig. 17 (c)** that in terms of UCS, when the residual strength coefficient of joints is 0.1, 0.5, 0.75 and 1, the UCS of specimen shows a U-shaped trend with the increase of column dip angle, in which the UCS reaches the minimum value at $\boldsymbol{\beta}$ = 30°. With the increase of residual strength coefficient of joints, the UCS changes not obviously at $\boldsymbol{\beta}$ = 0° and $\boldsymbol{\beta}$ = 75°~90°; the UCS grows relatively obviously at $\boldsymbol{\beta}$ = 15°~45°; the UCS increases most obviously at $\boldsymbol{\beta}$ = 60°. As presented in **Fig. 17 (d)**, for different residual strength coefficients of joints, the relationship curves between the EDM and column dip angle are closely at $\boldsymbol{\beta}$ = 0°~45° and $\boldsymbol{\beta}$ = 75°~90° except for at $\boldsymbol{\beta}$ = 60°, which indicates that the residual strength coefficient of joints has limited effect on the EDM at $\boldsymbol{\beta}$ = 0°~45° and $\boldsymbol{\beta}$ = 75°~90° but relatively obvious effect on the EDM at $\boldsymbol{\beta}$ = 60°.

3.2.6 Influence of ratio of shift distance of the second joint set on anisotropy of CJBs under uniaxial compression

Fig. 18 (a)&(b) shows the uniaxial compressive stress-strain curves of CJBs with different ratios of shift distance of the second joint set. It can be seen that the stress-strain curves of the CJBs with different ratios of shift distance and column dip angles show elastic-brittle failure characteristics.

As depicted in **Fig. 18 (c)**, in terms of UCS, when the ratio of shift distance of the secondary joint set is 0%, 20%, 40% and 50%, the UCS of specimen shows a U-shaped change trend with the increase of column dip angle, in which the UCS of specimen reaches the minimum value at $\boldsymbol{\beta}$ = 30°. When the ratio of shift distance increases from 0% to 20%, the UCS of specimen with column dip angle of 60°~75° increases obviously, while the UCS of specimens with the other column dip angles changes slightly. When the ratio of shift distance continues to increase to 40%, 50%, the change of UCS of specimen with column dip angle of $\boldsymbol{\beta}$ = 60°~75° is small.

As shown in **Fig. 18 (d)**, in the aspect of EDM, for different ratios of shift distance of the secondary joint set, the relationship curves between the EDM and column dip angle are closely at $\boldsymbol{\beta}$ = 0°~60° and $\boldsymbol{\beta}$ = 90° except for at $\boldsymbol{\beta}$ = 75°, which implies that the ratio of shift distance of the secondary joint set has limited effect on the EDM at $\boldsymbol{\beta}$ = 0°~60° and $\boldsymbol{\beta}$ = 90° but relatively obvious effect on the EDM at $\boldsymbol{\beta}$ = 75°. For column dip angle of $\boldsymbol{\beta}$ = 75°, when the ratio of shift distance increases from 0% to 20%, the growth of the EDM is larger, while that continues to increase to 40%, 50%, the variation of the EDM is less.

In terms of failure patterns of the CJBs with the ratios of 0 % and 50 % of shift distance of the secondary joint set, according to **Fig. 19** and **Fig. 20**, in the case of column dip angle of $\boldsymbol{\beta}$ = 0°, splitting tensile failure occurs along columnar joints in the specimen, and the stress concentrations of columns near the crack tips are obvious, and then compression shear damage and fracture of material in columns develop. In the case of $\boldsymbol{\beta}$ = 15°~45°, under uniaxial compression, stress concentrations occur in columnar joints, and then columnar joints get cracked, which then propagates downwards. Due to the influence of column dip angle, stress concentrations and crack initiation and propagation appear at the secondary joint set and the edges of several columns. In the case of $\boldsymbol{\beta}$ = 60°~75°, the influence of column dip angle still exists. Under uniaxial compression, the columnar joints of specimen do not get cracked. For the specimens with the ratio of 0% of shift distance, the secondary joint set gets cracked through, and for the specimens with the ratio of 50% of shift distance, the secondary joint set in the specimens gets cracked, and there are obvious stress concentrations nearby. In the case of $\boldsymbol{\beta}$ = 90°, there is no influence of column dip angle. Under uniaxial compression, the secondary joint set in the upper part of specimen gets cracked, and the upper part of specimen is subjected to compression shear and tension, resulting in damages and strip fractures, which develops downwards to the middle of specimen.

3.2.7 Influence of irregularity degrees of columns on anisotropy of CJBs under uniaxial compression

Figs. 21 (a)&(b) show the uniaxial compressive stress-strain curves of the CJBs specimens with different irregularity degrees of columns along the direction I orthogonal to column axis. It can be seen that the stress-strain curves of CJBs with different irregularity degrees of columns and column diameters are with elastic-brittle failure characteristics.

It can be seen from **Fig. 21 (c)** that in terms of the UCS along the direction I orthogonal to column axis, when the CJBs varies from with completely regular columns to with approximately regular columns, the change of the UCS is small. However, when the CJBs varies from with approximately regular columns to with moderately regular columns, irregular columns, the UCS decreases greatly. As presented in **Fig. 21 (d)**, for the UCS along the direction II, when the CJBs varies from with regular columns to with approximately regular columns, moderately regular columns, irregular columns, respectively, the UCS decreases gradually.

According to **Figs. 21 (e)&(f)**, in the aspect of the EDM along the direction I & II, for the CJBs with completely regular columns, approximately regular columns, moderately regular columns, the EDM shows the trend of increasing firstly then changing slowly (or decreasing slightly) with the increase of column diameter. For the CJBs with irregular columns, the EDM fluctuates in a large variation range with the increase of column diameter.

As shown in **Fig. 21 (g)**, in terms of UCS parallel to column axis, for the CJBs with completely regular columns, approximately regular columns, moderately regular and irregular columns, the UCS of specimen shows a U-shaped trend with the increase of column dip angle, in which the UCS of specimen reaches the minimum value at $\boldsymbol{\beta}$ = 30°. In addition, the irregularity degree of columns has a certain influence on the UCS of specimen at $\boldsymbol{\beta}$ = 45°, while that has little influence on the UCS of specimen at the other column dip angles.

As presented in **Fig. 21 (h)**, in the aspect of the EDM parallel to column axis, for different irregularity degrees of columns, the relationship curves between the EDM and column dip angle are closely at β = 0°~15°, 45° and 75°~90° except for at β = 30° and 60°, which indicates that the irregularity degree of columns has limited effect on the EDM at β = 0°~15°, 45° and 75°~90° but relatively obvious effect on the EDM at β = 30° and 60°.

In terms of failure patterns of the CJBs with irregular columns along the direction orthogonal to column axis, as depicted in **Figs. 21 (i)~(l)**, for the column diameter of 20 ***cm***, most of vertical joints get cracked, stress concentrations mainly occur at the column centers. For the column diameter of 40 ***cm***, several stress concentrations appear at the columns, and damaged fractures initiate at the edges of columns. For the column diameter of 60 ***cm***, there is crack initiation and propagation along the joints, with stress concentrations at crack tips. For the column diameter of 80 ***cm***, there are stress concentrations at crack tips and some column centers.

3.2.8 Influence of model boundaries on anisotropy of CJBs under uniaxial compression

It can be seen from **Fig. 22 (a)** that in terms of UCS, when the model boundary is in the case of plane stress, the case between plane stress and plane strain, and the case of plane strain, respectively, the UCS of specimen shows a U-shaped trend with the increase of column dip angle, in which the UCS of specimen reaches the minimum value at β = 30°. For the column dip angles of β = 0°~60°, the UCS of specimen in the case of plane stress is almost consistent with the case between plane stress and plane strain. For β = 75°~90°, the UCS of specimen in the case of plane stress is slightly lower than the case between plane stress and plane strain. Compared with the case of plane stress, the case between plane stress and plane strain, for β = 60°~90°, the UCS of specimen in the case of plane strain is higher.

As depicted in **Fig. 22 (b)**, in the aspect of the EDM, for the three kinds of model boundaries, the EDM shows the trend of decreasing firstly then increasing and then changing (or decreasing) slowly, in which the EDM reaches the minimum value at $\boldsymbol{\beta} = 60°$. Compared with the case of plane stress, the case between plane stress and plane strain, the EDM in the case of plane strain is larger.

4 Discussion

4.1 Influence of constitutive law of columnar joints on size effect and anisotropy of CJBs specimen

When the residual strength coefficient of joints is 0.1, 0.5, 0.75 and 1, respectively, the mechanical property of joint material is transformed from elastic-brittle mechanical behavior to elastic-plastic mechanical behavior, and then the influence on the size effect and anisotropy of CJBs is studied.

Take the square specimens along the direction I orthogonal to column axis as an example. In terms of UCS, when the residual strength coefficient of joints is 0.1, the UCS increases with the increase of specimen size, then changes slowly and grows again. When the residual strength coefficient of joints is 0.5, the UCS firstly increases and then changes gently with the increase of specimen size. When the residual strength coefficient of joints is 0.75 and 1, the UCS firstly increases and then decreases gradually with the increase of specimen size.

It can be seen from **Fig. 4** that in the numerical simulation verification, compared with the laboratory test results of Xiao et al. (2014) and Ji et al. (2017), the normalized UCS coefficient in this paper is higher at the column dip angle of $\boldsymbol{\beta} = 60°$. As presented in **Fig.17 (c)**, this may be related to the high value of residual strength coefficient of joints. **Fig.17 (c)** shows that for the column dip angle of $\boldsymbol{\beta} =60°$, when the residual strength coefficient of joints decreases from 1 to 0.1, the UCS of specimen decreases gradually.

4.2 Influence of elastic modulus of columnar joints on size effect and anisotropy of CJBs specimen

The elastic modulus of columnar joint in this paper is 3.75 ***GPa***, 7.5 ***GPa***, 15 ***GPa***, 22.5 ***GPa*** and 30 ***GPa***, respectively. The physical meaning of the increase of this joint material parameter is that the greater stress is required for elastic deformation of joint material. Further, the influence of that on the size effect and anisotropy of CJBs is studied.

Take the square specimens along the direction I orthogonal to column axis as an example. In terms of UCS, when the elastic modulus of joints is 3.75 ***GPa***, the UCS increases, then decreases and then increases with the increase of specimen size. When the elastic modulus of joints is 7.5 ***GPa***, 15 ***GPa***, 22.5 ***GPa*** and 30 ***GPa***, the UCS increases and then decreases with the increase of specimen size.

It can be seen from **Fig.4** that in the numerical simulation verification, compared with the laboratory test results of Ji et al. (2017), the normalized UCS coefficient in this paper is obviously higher at column dip angle of $\boldsymbol{\beta}$ = 60°,75° and 90°. Then, according to **Fig.17 (a)**, this may be related to the high value of elastic modulus of joints. **Fig. 17 (a)** shows that for the column dip angles of $\boldsymbol{\beta}$ = 60°, 75° and 90°, when the elastic modulus of joints decreases gradually from 30 ***GPa*** to 3.75 ***GPa***, the UCS of specimen decreases gradually.

4.3 Influence of the second joint set on strength anisotropy of CJBs specimen

As depicted in **Fig. 18 (c)**, in terms of UCS, when the ratio of shift distance of the secondary joint set is 0%, 20%, 40% and 50%, the UCS of specimen shows a U-shaped change trend with the increase of column dip angle, in which the UCS of specimen reaches the minimum value at $\boldsymbol{\beta}$ = 30°. When the ratio of shift distance increases from 0% to 20%, the UCS of specimen with column dip angle of $\boldsymbol{\beta}$ = 60°~75° increases obviously. When the ratio of shift distance continues to increase to 40%, 50%, the change of UCS of specimen with column dip angle of $\boldsymbol{\beta}$ = 60°~75° is small.

The numerical test results in this paper are compared with the laboratory test results of Ke et al. (2019), as shown in **Fig. 23**. It can be seen that for the ratio of 50% of shift distance of the second joint set, the variation trend of the normalized UCS coefficient of specimen in this paper is approximately consistent with the laboratory test results of Ke et al. (2019).

4.4 Influence of irregularity degrees of columns on deformation anisotropy of CJBs specimen

Take the square specimens along the direction I orthogonal to column axis as an example. In terms of the fluctuation range of EDM, under uniaxial compression, with the increase of column diameter, the fluctuation range of EDM of the CJBs with irregular columns along the direction I is largest. In the aspect of the magnitude of EDM, for the column diameter of 20 ***cm***, 60 ***cm*** and 80 ***cm***, compared with other irregularity degrees of columns, the EDM magnitude of the CJBs with irregular columns is highest, which is approximately consistent with that in the research results of Cui et al. (2016), that is, the EDM of irregular columns is largest. In addition, taking the square specimens along the direction II orthogonal to column axis as an example, for the column diameter of 20 ***cm*** and 40 ***cm***, the EDM of the CJBs with irregular columns is larger than that with other relatively regular columns.

5 Conclusions

Under uniaxial loading, the heterogeneity of rock mass, the change of mechanical properties of joints and the model boundaries significantly affect the size effect and anisotropy of CJBs specimen. At present, many experiments or numerical simulations have not reflected these characteristics. To reveal the fracture features and failure mechanisms of CJBs influenced by the size effect and anisotropy, the digital image correlation (DIC), meso-damage mechanics, statistical strength theory and continuum mechanics were combined (the DIC-improved RFPA), the digital images of CJBs specimens were processed to establish the inhomogeneous numerical models and a series of numerical tests were therefore conducted. The progressive fracture processes and failure patterns of CJBs orthogonal and parallel to column axis under uniaxial compression were studied, and the effects of various factors on size effect and anisotropic mechanical properties of CJBs were further analyzed.

(1) The fracture mechanism of the CJBs along the direction orthogonal to column axis. ① For the CJBs along the direction I orthogonal to column axis, under uniaxial loading, the joints of the specimen get cracked, the cracks gradually develop into the inner rocks, and the columns at the upper part of the specimen show obvious stress concentration, which leads to the material damage and strength decrease of the specimen. ② For the CJBs along the direction II, at the beginning of uniaxial loading, the cracking of vertical joints and the stress concentration of oblique joints appear, forming a V-shaped region. With the load increasing, the fracturing at the middle of the upper part and the lower left and right sides of the specimen becomes more obvious, and the breakage region with an inverted V-shape distribution is formed, which causes the material damage and strength decrease of the specimen.

(2) The failure patterns of CJBs with different sizes along the direction II, for the specimen sizes of 0.5 ***m***~2 ***m***, most of the vertical joints at the upper and lower parts of specimens get cracked, and the stress concentrations appear at the oblique joints. Meanwhile, crack initiation and propagation appear near some oblique joints. For the specimen size of 3 ***m***, in the middle of the upper part and the lower left and right sides of the specimen, the stress concentrations at oblique joints result in the crack initiation and propagation near oblique joints. For the specimen size of 4 ***m***, there are roughly two inverted V-shaped stress concentration regions at the upper part of the specimen.

(3) Fluctuation range of transverse anisotropy coefficients of UCS and EDM for CJBs with different model sizes and various factors under uniaxial compression. ① According to the sensitivity of TACUCS to influencing factors, the order from large to small is column diameter

(and residual strength coefficient of joints), rock heterogeneity index, elastic modulus of joints, model boundaries, respectively; for the CJBs with different sizes and various factors under uniaxial compression, they can be roughly approximated as transverse isotropy of UCS, that is, the TACUCS is approximately 1. ② According to the sensitivity of TACEDM to influencing factors, the order from large to small is elastic modulus of joints (and residual strength coefficient of joints), rock heterogeneity index (and column diameter), model boundaries, respectively; for the CJBs with different sizes and various factors under uniaxial compression, they can be roughly approximated as transverse isotropy of EDM, that is, the TACEDM is approximately 1.

(4) The fracture mechanism of the CJBs along the direction parallel to column axis. Under uniaxial loading, the stress concentration appears in columnar joints of the specimen, columnar joints get cracked, the cracks gradually develop into the inner rocks, and the cracking of columnar joints on the left and right sides of the lower part of the specimen is also obvious. Then, stress concentrations occur at the edges of several columns, and cracks initiate and propagate, resulting in material damage and strength reduction of the CJBs.

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