Numerical Investigation on the Triaxial Compression Behavior of Large-Scale Jointed Coal

Xiaoqing Wang

China Coal Technology and Engineering Group Corp China Coal Research Institute

Fuqiang Gao (✉ fuqgao@gmail.com)

China Coal Research Institute <https://orcid.org/0000-0001-6530-9787>

Research

Keywords: jointed coal, triaxial compression, synthetic rock mass, failure mode

Posted Date: April 21st, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-408317/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

Accurate estimation of the triaxial compression behavior of coal mass is essential for coal mining. In this study, a numerical synthetic rock mass method was used to study the triaxial compression behavior of coal mass. The jointed-coal specimens were constructed based on in-situ joint measurements and microparameter calibration against laboratory tested data. A series of triaxial compression tests on jointed-coal specimens with different loading orientations and confining pressures were performed to obtain joint and confining-pressure effects and to reveal the related failure mechanism. The results suggest that jointed coal has a strong joint effect and confining-pressure effect. Joints weaken the strength and elastic modulus, reduce the lateral deformation, and affect the geometries of the shear-rupture surface. With increase in the confining pressure, the peak strength and residual strength increase but the elastic modulus remains stable; the lateral strain decreases, especially at low confining pressure; the mechanical behavior transitions from brittleness to ductility; the failure mode transitions from shear-rupture surface to plastic flow; and the joint effect diminishes and even disappears. The shear-rupture surface is formed by the combined effect of shear stress and joints at low confining pressure, and the contribution of joints decreases with increase in confining pressure.

1. Introduction

As weak discontinuities, coal joints have a significant influence on the stability, recoverability, and gas flow of coalbeds. The literature on coal joints has been reported since the early nineteenth century[1]. Most current investigations on coal joints focus on the development of coalbed methane. Coal joints are always classified into three categories: bedding planes, endogenetic joints, and exogenetic joints [2]. Bedding planes are the most common coal joints and tend to cause roof separation of roadways in coal mining[3]. Exogenetic joints result from tectonic movements and always exist in groups. Endogenetic joints are formed during the coalification stage by tensile forces that are induced by coal-matrix shrinkage, tectonic stress and fluid pressure[4,5]. Cleats, which is the common term for endogenetic joints[6], usually occur in two sets: face cleats and butt cleats. In most instances, the two sets of cleats are perpendicular and perpendicular to the bedding planes. The butt cleat is always located between adjacent face cleats, and the face cleat is more continuous and larger. Laubach et al.[4] provide a schematic illustration of the coal-cleat geometry (see Fig. 1). Owing to their intersection and termination, cleats along with bedding planes always cut jointed coal into cube-shaped blocks [4,5].

Coal masses always occur under three-dimensional stress in coal mining. Roadways are excavated, and working faces are advanced in a huge rock medium subjected to a three-dimensional stress. In addition, the surrounding rock in a reinforced roadway can be considered to be in triaxial compression state, which results in a better stability response to mining disturbance than in the uniaxial compression state[7]. As a bearing body in a coal pillar, the pillar core is also in the triaxial compression state, which helps to maintain the coal-pillar stability[8]. Hence, it is essential to estimate the triaxial compression behavior of coal mass accurately. The Hoek–Brown failure criterion based on rock-mass classification is commonly used to estimate the rock-mass properties[9,10]. However, rock-mass classification methods, including the

Q Index [11], the RMR system[12], and the geological strength index [13], may be subjective and have poor operability. Laboratory and field tests are used widely, however, they suffer from limitations caused by jointed-specimen preparation, high expenses, and complicated operation. Because of the lack of preparation ability for complicated jointed specimens, specimens that contain a single joint or a simple layout of joints are always prepared in laboratory tests, which do not represent the real rock mass with complicated joints completely [14-16]. This difficulty has been alleviated, but not resolved because of the application of 3D printing technology in the preparation of complicated jointed specimens [17-19]. Field tests of uniaxial compression on coal mass have been conducted by Bieniawski [20,21], Cook et al. [22] and Van Heerden [23] to optimize the coal-pillars. However, field tests have rarely been used thus far because of their high expense and complicated operation.

The numerical simulation method is becoming widely used with a vast improvement in desktop computing power. In the continuum approach, the rock mass is assumed as an equivalent continuum, which must be given, and follows the constitutive law. In a discrete approach, the rupture behavior of rock mass can be simulated by block-based codes, including UDEC, 3DEC, and DDA, and particle-based codes, such as PFC, EDEM, and Yade. The synthetic rock mass (SRM) approach based on PFC appeared in 2007 as a step forward in the parametric research of rock mass [24]. The SRM approach integrates bonded-particle model (BPM), which represents intact rock, with the discrete-fracture network (DFN), which represents the joint geometry, to represent the real jointed rock mass, and thus, can simulate initiation, propagation, and coalescence of fractures, and slip along and the opening of joints. Compared with block-based discrete methods, the model in the SRM approach is more representative of rock and iterates based on relatively simple particle-contact laws rather than more complex constitutive laws [25], which is better to investigate the rupture mechanism of intact and jointed rock. Zhou et al. [26] used the SRM approach to investigate the failure mechanism, anisotropy, and size effects of rock mass by performing a series of triaxial compression tests with different joint dips and confining pressures. Huang et al. [27] conducted a series of triaxial compression tests on specimens that contained two unparallel fissures using the SRM approach. The numerical properties and failure types agreed well with the experimental tests.

Although many studies have been reported on the triaxial compression behavior of jointed rock using laboratory tests and the SRM approach, most were limited to a simplified rock mass with only a single joint or small numbers of arranged points. Few reports exist in literature triaxial compression behavior for real complicated jointed rock mass, especially at a large scale. Therefore, we constructed jointed-coal specimens that contain a real complicated layout of joints based on an in-situ joint measurement and microparameter calibration against laboratory experiments using the SRM approach. We conducted a series of triaxial compression tests under different loading orientations and confining pressures numerically on SRM specimens with a REV size to obtain joint and confining-pressure effects on the triaxial compression behavior of jointed coal. We revealed the formation mechanism of a shear-rupture surface for jointed coal subjected to triaxial compression. This study is expected to improve the understanding of triaxial behavior of jointed coal and provide a reference for investigation of other jointed rock.

2. Preparation Of Srm Specimen For Jointed Coal

2.1. DFN construction based on joint in-situ measurement

The DFN model should be constructed first when using the SRM approach. The DFN model is always generated using a Monte Carlo simulation based on joint data from outcrop mapping and calibrated against a borehole logging. To collect adequate joint data, a joint-sampling campaign was performed at the Sihecoal mine, Shanxi, China. According to a detailed survey, 3# coal seam was cut mainly by three orthogonal sets of joints: bedding planes, butt cleats, and face cleats, which is why 3# coal seam tends to rupture into regular blocks when in failure. To cover all sets of joints, five scanlines and one scan window were set up on the two side surfaces and the top surface in a 4m×4m×4m drilling field (see Fig. 2). Limited by the poor environment underground and the indistinct color difference between the coal matrix and the joints, laser scanning and photogrammetry do not work for joint measurement. Hence, a geological compass and steel tape was used to measure the orientations, traces, and joint spacings. With a rectangular shape, two joint sides should be considered when measuring the traces. A total of 119 joints, including 28 bedding planes, 51 butt cleats, and 40 face cleats were mapped, with 3% of the measured joints classified as random or artificial joints. The dip, dip direction, size, and spacing were analyzed statistically for each set, as given in Table 1.

In PFC3D, joints must be simulated as circular disks, which does not depict the rectangular shape of joints accurately jointed coal. Here, the coal DFN was generated first in code FracMan and then imported into PFC3D by a series of data processing. The constructed coal DFN in PFC3D is presented in Fig. 3A. Two random layers were extracted for clear display of the spatial distribution of bedding planes, face cleats, and butt cleats (see Fig. 3C and D), which agrees well with what is depicted in the coal mass[4,5]. Calibration must be followed by a comparison of the measured and numerical RQDs for two boreholes, termed I and II, respectively. As illustrated in Figs 2 and 3, practical and numerical boreholes have the same locations, diameters (130 mm), and lengths (4.0 m). The numerical RQD is obtained by calculating the lengths of borehole segmentations cut by the DFN and by counting the sum of the lengths of borehole segmentations that are longer than 10 cm with respect to the entire borehole length in a developed Fish program. The comparison is presented in Fig. 4. The core-length distribution and RQD values of the two methods are similar (89.2% vs. 88.8% for borehole I, and 85.2% vs. 82.0% for borehole II), which indicates that the generated DFN can represent the real joint geometry in jointed coal.

2.2. REV determination based on the constructed coal DFN

The coal mass exhibits a strong scale effect, whereby the strength decreases with sample size until the REV is reached [20,21]. The REV can be estimated by evaluating the variety of joint intensity. P_{32} and P_{31} are always used as joint-intensity indexes, which refer to the joint area and joint number in the unit rock-mass volume, respectively. Here, P_{32} and P_{31} are calculated with different sizes of sub-DFNs based on a cuboid with an aspect ratio of 2:1 by developing a PFC3D Fish program. The different sizes of the sub-DFNs are shown in Fig. 5. In the Fish program, the sub-DFNs are intercepted randomly five times for each

size in the jointed-coal DFN to reduce the discretization, and an average value is calculated for P_{32} and P_{31} . The varieties of P_{32} and P_{31} with the size of sub-DFNs are shown in Fig.6. P_{32} and P_{31} tend to be steady when the sub-DFN size increases to 1.0 m×1.0 m×2.0 m, the size of which is identified as the REV for jointed coal. The REV of jointed coal is consistent with the field observation where the REV of coal is 1–1.5m [20,21].

2.3. Jointed-coal SRM specimen preparation and its calibration

After the generation of DFN, BPM should be constructed. It has been proven that the parallel-bond model(PBM)provided in PFC can produce a more realistic representation of rock mass [28], therefore, the PBM was chosen to construct the coal BPM. The smooth-joint model(SJM) [25] in PFC is used to define the interaction between BMP and DFN in the SRM approach, whereby the SJMs are assigned to all contacts (originally bonded by PBMs) between particles on opposite sides of the DFN. If SJMs are considered, the particle size should be sufficiently small to reproduce slip along joints and rock-bridge breakage [29], and more than five articles should exist between adjacent joints [30]. The particle diameter for coal BPM is determined as 1.6–2.0 cm because the minimum spacing between joints in constructed DFN is 10.0 cm. To increase the construction efficiency of coal BPM, the 0.5-m cubic periodic brick [25] was generated first and then assembled into the REV-sized BPM. The REV-sized APM consists of 518,432 particles bonded by PBMs, which is a huge number for particle-based DEM simulation and needs a lot of time spent on calculation. The BPM is inserted into the DFN at any position, which creates SRM specimens with different joint geometries. After insertion, the SJMs are assigned to all contacts intercepted by the DFN to substitute the PBMs. The construction of jointed-coalSRM specimens is presented in Fig.7.

According to the construction of SRM specimens, the SRM model iterates based on PBMs and SJMs. Therefore, calibration of microparameters for the PBMs and SJMs is needed prior to numerical analysis. For PBM calibration, some uniaxial compression laboratory tests on intact coal specimens were conducted to obtain macro properties. A cylindrical BPM was constructed in PFC3D and used to produce the targeted macro properties from the laboratory tests with selecting microparameters by trial and error. To calibrate the SJM, a series of direct shear laboratory tests on coal specimens with a single-through joint under different normal stresses was undertaken to obtain the coal joint macro properties. The same numerical model was generated and used to conduct direct shear numerical tests to achieve the same macro properties from the laboratory tests. The detailed calibration for PBMs and SJMs in jointed-coal SRM specimen can be referred to Wang et al. [31]. The calibrated microparameters for balls, PBMs, and SJMs in jointed-coal SRM specimens are listed in Table 2.

3. Numerical Triaxial Compression Tests Of Jointed Coal

3.1. Numerical model set-up and its rupture-analysis method

A schematic of a triaxial test on the SRM specimen under a constant confining pressure is presented in Fig.8. The top and bottom walls act as loading plates, and the lateral walls are used to maintain a constant confining pressure using a servo-control mechanism [25]. All walls are 0.2 times larger than the SRM specimen. All sides of the SRM specimen are loaded first into the targeted confining pressure using a servo-control mechanism. Then a velocity of 0.1 m/s is applied to the loading walls to initiate the triaxial test, while the lateral confining pressures kept constant through servo-control walls during the test. Sensitivity studies have shown that this loading rate is sufficiently slow to ensure that the specimen remains in quasi-static equilibrium. The axial stress is obtained by dividing the average recorded reaction force on the loading walls by the cross-sectional area of the SRM specimen. The axial strain is calculated as the ratio of the sum of the displacement of both loading walls to the initial height of the SRM specimen. The lateral strain has a similar calculation method.

BPM damage is represented by shear and tension breakage of bonds that results in microcracks, which can be classified into shear and tension microcracks. The initiation, propagation, and coalescence of these microcracks form macro-matrix fractures, which are either of a tension or shear mechanism. A discrimination method for the macroscopic formation mechanism of matrix fractures was proposed, which differ from a comparison of velocity or displacement vectors of particles on the sides of a matrix fracture by Bewick et al.[32]. If a matrix fracture is composed of only tension microcracks and opens with a large gap, the macro formation mechanism is considered as tension. If a matrix-fracture is composed of tension and shear microcracks and closes, the macro formation mechanism can be judged as shear, because shear always occurs between two conterminous objects accompanied by tension breakage of asperities[33]. For SRM specimens, activated joints that result from the activation of pre-existing joints must be considered in rupture analysis. Fractures in the SRM specimen are always composed of activated joints and matrix fractures. With a large gap, the open fractures can be displayed easily and clearly by means of cut planes. However, cut planes do not display closed fractures, because the gap is very small. Microcracks can be used to depict the geometry of closed fractures, but they are inadequate when the fractures are complicated in spatial distribution. Particles on opposite sides of the closed fracture contact each other and form linear-contact models in the sliding process, thus the linear-contact models can be used to extract and display the closed shear fracture that results from triaxial compression on the jointed-coal SRM specimen.

All triaxial compression numerical tests were conducted by using code PFC3D5.0 on a 64-bit, two 2.30 GHz Intel(R) Xeon(R) processor computer with 64.0 GB RAM. Each case took 2–15 days to complete the calculations because of the large number of particles used (518,432 particles). The calculation time increases sharply with confining pressure because many microcracks grow and adjust their locations and orientations in the calculation under a high confining pressure.

3.2. Numerical triaxial compression tests for different loading orientations

3.2.1. Numerical triaxial compression test on intact coal with REV size

The triaxial compression numerical model for coal BPM with a REV size is shown in Fig.9A, with the microparameters listed in Table 2. After triaxial compression under a 1-MPa confining pressure, the specimen retains integrity, except for some microcrack bands along the surface (Fig. 9B). As illustrated in the cut planes (Fig. 9F, G, and H) at the $Y = 0$ position, the microcrack bands form a cut-through fracture that is labeled by a red dotted line, which is closed and composed of tension and shear microcracks. According to the rupture-analysis method in Section 3.1, the fracture is a shear-rupture surface for intact coal that is subjected to triaxial compression. For a clear display, the shear-rupture surface that is denoted by linear-contact models is extracted and rotated twice (Fig. 9C, D, and E). The shear-rupture surface is of an approximate parallelogram with a missing corner. The total number of microcracks is 1,225,010, of which 1,072,842 are tensile microcracks and 152,168 are shear microcracks.

The curves of axial stress difference, confining pressure, and lateral strain against axial strain are plotted in Fig.10. The confining pressures that are imposed on the lateral sides fluctuate around 1 MPa, which indicates a good servo control on the lateral walls. The stress difference refers to the difference between the monitored axial stress and the targeted confining pressure. The pre-peak curve of stress difference remains relatively straight, and the post-peak curve drops rapidly to a steady condition, with an elastic modulus of 2.36 GPa, a triaxial compression strength (TCS) of 33.7 MPa, and residual strength of 10.3 MPa. The lateral strain increases sharply after the peak strength, stabilizes briefly at the residual strength stage, and shows a rapidly increasing trend, with a Poisson's ratio of 0.23.

3.2.2. Numerical test on jointed coal with loading direction perpendicular to bedding planes

The SRM specimens of jointed coal to be loaded perpendicular to the bedding planes are presented in Fig.11A (joints geometry) and B (contact models). After the triaxial test, no fractures with a visible gap grow but an inclined band that consists of tension and shear microcracks cut through the specimen (Fig. 11E and F). A same inclined band of the linear-contact model that corresponds to the microcrack band also appears in the final contact models (Fig. 11C), which is shown in Fig. 11D. According to the rupture-analysis method, the inclined band is the shear fracture surface, which is a parallelogram.

The curves of microcrack number, axial stress difference, confining pressure, and lateral strain against axial strain are plotted in Fig.12. The confining pressures fluctuate around 1 MPa, which indicates a good servo control on lateral walls. In the pre-peak stage, the specimen transits gradually from elasticity to plasticity with the increase in axial stress, which produces the yield point. The sharp increase zone of the microcrack curves ranged from the yield point to the lowest point, where the coal matrix breaks heavily and results in a rapid growth of microcrack number. In the post-peak stage, the number of microcracks does not increase, but the lateral strain still increases, which indicates that the lateral deformation of the specimen originates from the increase in the gap of the existing fractures, rather than the formation of new fractures. The TCS, elastic modulus, Poisson's ratio, and residual strength are 26.6 MPa, 1.78 GPa, 0.20, and 4.0 MPa, respectively.

3.2.3. Numerical test on jointed coal with loading direction perpendicular to face cleats

The SRM specimen of jointed coal to be compressed triaxially perpendicular to the face cleats is presented in Fig. 13A. The corresponding contact model geometry is displayed in Fig. 13B. After the test, some linear-contact models were added to the specimen (Fig. 13C), which are extracted for a clear display in Fig. 13D. The distribution of microcracks agrees well with the linear-contact models (Fig. 13E and F). The combination bands of tension and shear microcracks represent closed fractures that result from triaxial compression. According to the rupture-analysis method for SRM specimens, bands of the linear-contact model are a shear-rupture surface. The geometry of shear-rupture surface differs from that under triaxial compression that is perpendicular to the bedding planes and is composed of the main fracture and a secondary fracture (Fig. 13D).

The curves of stress, strain, and microcrack number are plotted in Fig.14. The steady confining pressures also indicate a good servo control on the lateral walls. The TCS is 26.8 MPa at a confining pressure of 1 MPa, with an elastic modulus of 1.75GPa and a Poisson's ratio of 0.18. The sharp increase of microcrack number ranges from the yield point to the lowest point in the curve of the axial stress difference, where the coal matrix breaks heavily. In the residual strength stage, the axial stress is stable, but the lateral strain increases sharply. The microcrack number shows an increasing trend, which means that the lateral deformation results mainly from the increase in the gap of the existing fractures, and the formation of new fractures also provides some contribution. The residual strength is 7.9 MPa.

3.2.4. Numerical test on jointed coal with a loading direction perpendicular to butt cleats

The joint geometry in the SRM specimen to be triaxially compressed perpendicular to the butt cleats is shown in Fig. 15A and the corresponding contact model geometry is presented in Fig. 15B. After the test, some microcrack bands that consisted of tension and shear microcracks crossed through the specimen surface (Fig. 15E and F). This situation is the same as the two situations above, and many linear-contact models appear in the contact model geometry (Fig. 15C). These linear-contact models depict the geometry of the shear-rupture surface, which is extracted for clear display (Fig. 15D). The shear-rupture surface approximate diamond.

The numerical results are shown in Fig.16. Similar to the situation with triaxial compression perpendicular to the bedding planes and face cleats, the sharp increase in microcrack number ranges from the yield point to the lowest point in the curve of axial stress difference. The lateral deformation still increases significantly in the residual strength stage. The TCS, elastic modulus, Poisson's ratio, and residual strength are 26.1 MPa, 1.89 GPa, 0.21 and 8.5 MPa, respectively.

3.3. Numerical triaxial compression tests under different confining pressures

A series of numerical triaxial compression tests on jointed coal under different confining pressures were performed to investigate the confining-pressure effect. Based on the jointed-coal SRM specimen with loading perpendicular to the butt cleats, four magnitudes of confining pressure: 0, 1, 5, and 10 MPa were involved.

The fracture geometries under different confining pressures are shown in Fig. 17. Without a confining pressure, the loading is a uniaxial compression test. After the uniaxial compression test, fractures initiated and propagated along the joints parallel to the loading direction (Fig. 17A). The fractures resulted from inactivation, and their formation was dominated by the joints. If confining pressure is imposed, the interaction of confining pressure and axial loading stress will result in shear stress in the specimen, which will lead to the formation of shear fracture. When the confining pressure increases to 1 MPa, the shear-rupture surface approximates a rhombus (Fig. 17B). Joints parallel to the loading direction can be activated partially and affect the local geometry of the shear-rupture surface under low confining pressure. When the confining pressure continues to increase to 5 MPa, joint activation becomes more difficult and the joints will have a weak effect on the shear fracture. The shear-rupture surface is of a regular rhombus shape under a middle confining pressure (Fig. 17C). Therefore, the formation of a shear-rupture surface is dominated by shear stress and joints for jointed coal at low and middle confining pressures, but the influence of the joints weakens with the confining pressure. Many microcracks exist over the specimen at a 10-MPa confining pressure, which indicates that the jointed-coal specimen ruptured by plastic flow (Fig. 17D). Fracture formation is dominated only by shear stress and is independent of the joints for jointed coal under high confining pressure.

The numerical results for jointed coal that is subjected to triaxial compression with different confining pressures are shown in Fig. 18. As illustrated in Fig. 18A, the TCS is low and the residual strength is close to 0 without a confining pressure. When the confining pressure increases to 1 MPa, the TCS and residual strength increase significantly, but the axial stress drops sharply in the post-peak stage, which indicates a brittle behavior for jointed coal. When the confining pressure increases to 5 MPa, the TCS and residual strength also increase. The peak zone becomes smooth and wide, and the axial stress decreases gently, which shows a transition from brittleness to ductility for jointed coal at a 5-MPa confining pressure. When the confining pressure increases to 10 MPa, the TCS continues to increase but the peak zone disappears. After the TCS has been reached, the axial stress tends to be stable despite the axial strain increasing with loading. As shown in Fig. 17D, the specimen is in a plastic-flow state at a 10-MPa confining pressure. The estimated transiting pressure of brittleness to ductility for jointed coal in this study is 10 MPa. The elastic limit increases, but the elastic modulus remains stable with an increase in confining pressure, which means that the confining pressure has no effect on the elastic modulus, and the elastic modulus is an intrinsic property of jointed coal. As shown in Fig. 18B, the lateral deformation without confining pressure is severe and is far larger than that with confining pressure. The jointed-coal deformation is infinitely sensitive to a low confining pressure. The number of microcracks tends to be steady at the post-peak stage when the confining pressure is 0, 1, and 5 MPa, whereas the microcrack number keeps growing at a high rate during the entire stage under a 10-MPa confining pressure, which verifies that the specimen is in plastic-flow failure under a 10-MPa confining pressure. The number ratio of shear microcracks to tension microcracks increases with confining pressure, which shows that a transition from tension to shear for the macro rupture mechanism of the coal matrix occurs.

4. Discussion

4.1. Joint effect on triaxial compression behavior of jointed coal

The numerical results of the intact coal and jointed coal with a REV size under different triaxial loading orientations with a 1-MPa confining pressure are compared using histograms (see Fig.19). As illustrated in Fig.19, the properties of the jointed coal differ from those of the intact coal, which indicates a strong joint effect on the triaxial compression behavior of coal mass. The joint effect can be summarized as follows:

- (1) Joints weaken the peak strength, elastic modulus, and residual strength of the jointed coal under triaxial compression loading. Compared with loading on intact coal, the peak strength, elastic modulus, and residual strength of the jointed coal under different loading orientations decrease remarkably (Fig. 19A, B and C). The peak strengths and elastic moduli are similar for jointed coal with different joint geometries, respectively (Fig. 19A and B), whereas the residual strengths differ (Fig. 19C). The joint geometry has a significant influence on the post-peak behavior but little effect on the pre-peak behavior at low confining pressure.
- (2) Joints reduce the lateral deformation of jointed coal under triaxial compression loading. The Poisson's ratios of jointed coal are lower than those of intact coal (Fig. 19D), and the lateral strain at the same axial strain of 2.0% (Fig. 19E). This trend is distinctly different from that under uniaxial compression[34], where the lateral deformation of jointed coal is significantly larger than that of intact coal but is consistent with that under direct shear loading[31]. This may occur because the dilation of a matrix fracture under normal stress is larger than an activated joint. The Poisson's ratios of jointed coal with different joint geometries are similar.
- (3) Joints affect the geometries of shear-rupture surface for jointed coal under triaxial compression loading. The geometries of the shear-rupture surface differ for intact coal and jointed coal under different loading orientations (Figs.9, 11, 13 and 15), which indicates that the formation of a shear-rupture surface is affected by the joint distribution.
- (4) Joint effects on the triaxial compression behavior of jointed coal decrease with confining pressure. The properties, including the TCS, elastic modulus, and Poisson's ratio, are almost the same under different loading orientations at a 1-MPa confining pressure, as shown in Fig.19A, B, and D, which means that the confining pressure weakens the joint's effect on the triaxial compression behavior of jointed coal.

4.2. Confining-pressure effect on triaxial compression behavior of jointed coal

The strengths of intact coal and jointed coal with a REV size without and with a 1-MPa confining pressure are compared in Table 3. Without a confining pressure, the average strength of the jointed coal is 13.1 MPa less than that of intact coal, but the strength difference decreases to 7.2 MPa when the confining pressure increases to 1 MPa. It can be inferred that the strength difference will decrease further with an increase in confining pressure. Therefore, the influence of joints on the triaxial compression behavior of jointed coal will decrease and even disappear with confining pressure.

According to an analysis of the numerical triaxial-compression results for jointed coal under different confining pressures in Section 3.3, the triaxial compression behavior of jointed coal also has a strong confining-pressure effect. As the confining pressure increases, the following responses of jointed coal are observed: (1) the peak strength and residual strength increase significantly (Fig. 18A), (2) the elastic limit increases sharply but the elastic modulus remains stable (Fig. 18A), (3) the decrease of stress in the post-peak stage decreases and even disappears (Fig. 18A), (4) the mechanical behavior transits from brittleness to ductility (Fig. 18A), (5) the lateral strain decreases, especially at a low confining pressure (Fig. 18B), (6) the failure mode transitions from shear-rupture surface to plastic flow (Fig. 17), (7) the influence of joints on the triaxial compression behavior decreases and even disappears (Fig. 17, 19 and Table 3).

4.3. Rupture mechanism of jointed coal subjected to triaxial compression

In the triaxial compression tests, the interaction of confining pressure and axial loading stress will result in shear stress in the specimen. For ideal intact rock, the shear stress distributes symmetrically, which may cause an X-type conjugated incline-plane shear failure. The intact rock always ruptures by a single incline-plane shear failure (Fig. 20A) because the actual intact rock is not homogeneous and the confining pressures are not consistent on both sides.

For jointed rock, joints parallel to the loading direction can be activated easily by shear sliding and dilation without confining pressure. However, joint activation becomes more difficult with an increase in confining pressure. Joints parallel to the loading direction only can be activated partially to small-size fractures under low confining pressure. The distribution of these activated joints will affect the geometry of the shear-rupture surface significantly, which is controlled mainly by the shear stress (see Fig. 20B). Situations of triaxial compression on jointed coal under a 1-MPa confining pressure belong to this rupture mechanism. The cut planes of fractures and joint geometries for jointed coal under different loading orientations with a 1-MPa confining pressure are shown in Fig. 21. As illustrated in Fig. 21, joints parallel to the loading direction are activated partially (circled by the red dotted line) and the activated joints affect the geometries of the shear-rupture surface significantly. In Fig. 21A, the shear-rupture surface propagates along the X-axis direction, which is affected by the activated face cleats in the Y-Z plane. In Fig. 21B, the geometry of the shear-rupture surface agrees well with the distribution of butt cleats in the X-Y plane. In Fig. 21C, the face cleats in the X-Y plane have a distinct effect on the geometry of the shear-rupture surface. When the confining pressure increases to a middle level, joint activation becomes more difficult than that at low confining pressure, thus the joints have a minor effect on the shear-rupture-surface geometry (Fig. 20C). This can be verified by the regular rhombus shape of the shear-rupture surface under a 5-MPa confining pressure (Fig. 17C), which is almost unaffected by the joints. All four triaxial compression situations at a 1- and 5-MPa confining pressure prove that the shear-rupture surface is formed by the combined effect of shear stress and joints at low and middle confining pressure.

Under high confining pressure, shear microcracks grow all over the rock particles, which means that plastic-flow failure occurs (Fig. 20D). This failure mechanism is applicable to interpret the triaxial loading

of jointed coal under a 10-MPa confining pressure (Fig. 17D). The value to distinguish a high confining pressure is dependent on the rock mass itself, especially on the joint geometry, and is obtained by a series of tests under different confining pressures.

5. Conclusions

The investigation focused on a deep understanding of the triaxial compression behavior of large-scale jointed coal with areal DFN geometry using the SRM approach. Jointed-coal specimens with a REV size were constructed based on joint in-situ measurement and laboratory calibration experiments. A series of triaxial compression tests at different loading orientations and confining pressures were conducted numerically to obtain the joint and confining-pressure effects and to reveal the rupture mechanism. The major findings are summarized as follows:

(1) Joint effect on the triaxial compression behavior of jointed coal: (i) joints weaken the peak strength, elastic modulus, and residual strength; (ii) joints reduce the lateral deformation; (iii) joints affect shear-rupture-surface geometries; (iv) Joint effect diminishes and even disappears with confining pressure.

(2) Confining-pressure effect on the triaxial compression behavior of jointed coal: as the confining pressure increases, (i) the peak strength and residual strength increase significantly; (ii) the elastic limit increases sharply but the elastic modulus remains stable; (iii) the decrease of stress in the post-peak stage decreases and even disappears; (iv) the mechanical behavior transits from brittleness to ductility; (v) the lateral strain decreases, especially at a low confining pressure; (vi) the failure mode transitions from shear-rupture surface to plastic flow; (vii) the influence of joints on triaxial compression behavior decreases and even disappears.

(3) The formation mechanism of shear-rupture surface: (i) at low confining pressure, joints parallel to the loading direction can be activated partially to small fractures. The activated joints will affect the geometry of the shear-rupture surface significantly, which is controlled mainly by the shear stress. (ii) at a middle confining pressure, joint activation becomes more difficult and the joints have a minor effect on the formation of a shear-rupture surface. (iii) at a high confining pressure, the influence of the joints disappears and plastic-flow failure occurs. Values to distinguish low, middle, and high confining pressures are dependent on the rock mass itself.

Declarations

Acknowledgments

This work has been supported by the National Nature Science Foundation of China (grant no. 51774185), and China Coal Technology & Engineering Group funding (grant no. 2018QN017).

References

1. Kendall PE, Briggs H (1933) The formation of rock joints and the cleat of coal. *Proc R Soc Edinburgh* 53:164–187
2. Kang TH, Jin ZM, Zhao YS (1994) Study of the structural features and the distribution rules of the cracks in coal mass. *J Xi'an Min Inst* 14(4):318–323
3. Wang XQ, Kang HP, Zhao K et al (2016) Numerical analysis of bonding stiffness for support effectiveness of pre-stressed bolts. *J Chin Coal Soc* 41(12):2000–2007
4. Laubach SE, Marrett RA, Olson JE et al (1998) Characteristics and origins of coal cleat: a review. *Int J Coal Geol* 35:175–207
5. Su X, Feng Y, Chen J et al (2001) The characteristics and origins of cleat in coal from Western North China. *Int J Coal Geol* 47(1):51–62
6. Dron RW (1925) Notes on cleat in the Scottish coalfield. *Trans Inst Min Eng* 70:115–117
7. Kang HP (2016) Sixty years development and prospects of rock bolting technology for underground coal mine roadway in China. *J Chin Univ Min Techno* 45(6):1071–1081
8. Jaiswal A, Shrivastva BK (2009) Numerical simulation of coal pillar strength. *Int J Rock Mech Min Sci* 46(4):779–788
9. Hoek E, Brown ET (1980) Empirical strength criterion for rock masses. *J Geotech Geoenviron* 106:1013–1035
10. Hoek E, Brown ET (1997) Practical estimates of rock mass strength. *Int J Rock Mech Min Sci* 34(8):1165–1186
11. Barton N, Lien R, Lunde J (1974) Engineering classification of rock masses for the design of tunnel support. *Rock Mech* 6(4):189–239
12. Bieniawski ZT (1973) Engineering classification of jointed rock masses. *Civil Eng South Africa* 15(12):335–343
13. Hoek E (1994) Strength of rock and rock masses. *ISRM News J* 2(2):4–16
14. Xiao W, Deng R, Fu X et al (2015) Experimental study of deformation and strength properties of simulated columnar jointed rock masses under conventional triaxial compression. *Chin J Rock Mech Eng* 34(Supp. 1):2817–2826
15. Yang S, Lu J, Tian W et al (2018) Experimental study of mechanical behavior of rock specimens with different joint roughness coefficient under conventional triaxial compression. *Rock Soil Mech* 39(Supp. 1):21–32
16. Walton G, Alejano LR, Arzua J et al. Crack Damage Parameters and Dilatancy of Artificially Jointed Granite Samples Under Triaxial Compression. *Rock Mech Rock Eng* 2018. <https://doi.org/10.1007/s00603-018-1433-1>
17. Head D, Vanorio T (2016) Effects of changes in rock microstructures on permeability: 3D printing investigation. *Geophys Res Lett* 43(14):7494–7502
18. Jiang C, Zhao G, Zhu J et al (2016) Investigation of dynamic crack coalescence using a gypsum-like 3D printing material. *Rock Mech Rock Eng* 49(10):1–16

19. Jiang Q, Song L (2018) Application and prospect of 3D printing technology to physical modeling in rock mechanics. *Chin J Rock Mech Eng* 37(1):23–36
20. Bieniawski ZT (1968) The effect of specimen size on compressive strength of coal. *IntJ Rock Mech Min Sci* 5:325–335
21. Bieniawski ZT (1968) In situ strength and deformation characteristics of coal. *EngGeol* 2(5):325–340
22. Cook NGW, Hodgson K, Hojem JPM (1971) A 100 MN jacking system for testing coal pillars underground. *J S Afr Inst Min Metall* 71:215–224
23. Van Heerden WL (1975) In situ complete stress–strain characteristics of large coal specimens. *J S Afr Inst Min Metall* 75:207–217
24. Pierce M, Cundall P, Potyondy D et al. A synthetic rock mass model for jointed rock. In: *Rock mechanics: meeting society's challenges and demands*, 1st Canada-US rock mechanics symposium, Vancouver, Canada; 2007. p. 341–349
25. Itasca Consulting Group Inc (2016) PFC3D (Particle Flow Code in 3 Dimensions), version 5.0. Itasca, Minneapolis
26. Zhou Y, Wu S, Gao Y et al (2014) Macro and meso analysis of jointed rock mass triaxial compression test by using equivalent rock mass (ERM) technique. *J Cent South Univ* 21(3):1125–1135
27. Huang Y, Yang S, Zhao J (2016) Three-Dimensional Numerical Simulation on Triaxial Failure Mechanical Behavior of Rock-Like Specimen Containing Two Unparallel Fissures. *Rock Mech Rock Eng* 49(12):4711–4729
28. Potyondy DO, Cundall PA (2004) A bonded-particle model for rock. *Inter J Rock Mech Min Sci* 41:1329–1364
29. Ivars DM, Pierce M, Darcel C et al (2011) The synthetic rock mass approach for jointed rock mass modelling. *Int J Rock Mech Min Sci* 48:219–244
30. Gao F, Stead D, Kang H (2014) Numerical investigation of the scale effect and anisotropy in the strength and deformability of coal. *Int J Coal Geol* 136:25–37
31. Wang X, Kang H, Gao F (2019) Numerical investigation on the shear behavior of jointed coal mass. *Comput Geotech* 106:274–285
32. Bewick R, Kaiser P, Bawden W et al (2014) DEM simulation of direct shear: 1. Rupture under constant normal stress boundary conditions. *Rock Mech Rock Eng* 47:1647–1671
33. Bahaaddini M, Sharrock G, Hebblewhite BK (2013) Numerical direct shear tests to model the shear behaviour of rock joints. *Comput Geotech* 51:101–115
34. Wang X, Kang H, Gao F et al (2018) DEM simulation of mechanical behavior of jointed coal in large scale under uniaxial compression. *J China Coal Soc* 43(11):3088–3097

Tables

Table 1: Statistical results of coal-joint data used for DFN generation.

Jointset	Distribution(mean value / standard deviation)			
	Dip	Dip direction	Trace	Spacing
Bedding planes	N/A	N/A	N/A	NE (0.14/0.14)
Butt cleats	Normal (90/0.30)	Normal (90/0.20)	NE (0.28/0.28)	Log-normal (0.11/0.24)
Face cleats	Normal (90/0.30)	Normal (180/0.20)	Normal (2.80/0.20)	Log-normal (0.16/0.59)

Note: (1) NE means negative exponential, (2) trace for butt cleats and faces cleats only refer to length trace, with width trace equivalent to the spacing of bedding planes.

Table 2: Calibrated microparameters for BPM and SJM in the jointed-coal specimen.

Ball parameters		PBM parameters		SJM parameters	
Density(kg/m ³)	2500	Cohesion (MPa)	8.0	Normal stiffne(GPa/m/m)	30
R_{min} (cm)	0.8	S.D. Cohesion (MPa)	1.5	Shear stiffness(GPa/m/m)	6
R_{max} (cm)	1.0	Tensile strength (MPa)	9.0	Coefficient of friction	0.577
porosity	0.2	S.D. Tensile strength (MPa)	1.5	Tensile strength (MPa)	0
Coefficient of friction(μ)	0.7	Angle of internal friction(°)	0	Cohesion (MPa)	0
	5.0		5.0		
E_c (GPa)	1.8	(GPa)	1.8		

S.D.: Standard deviation

Table 3: Strength comparison between intact coal and jointed coal without and with 1-MPa confining pressure.

Confining pressure/MPa	Strength of intact coal/MPa	Strength of jointed coal with loading perpendicular to/MPa				Difference in strengths
		Bedding planes	Face cleats	Butt cleats	average	
0	23.1	15.3	7.7	7.1	10.0	13.1
1	33.7	26.6	26.8	26.1	26.5	7.2

Note: Difference in strengths refers to the strength difference between intact coal and jointed coal. The numerical results of coal without confining pressure are cited from Wang et al. [34].

Figures

Figure 1

Schematic illustration of coal-cleat geometry (Modified from Laubach et al.[4]).

Figure 2

Lay out of scanlines and scan window for coal-joint sampling at Sihe coal mine.

Figure 3

Coal DFN constructed in PFC3D: (A) coal DFN, (B) borehole geometry, translation from DFN for clear display, (C) and (D): two random layers.

Figure 4

Comparison of measured and numerical RQDs for boreholes I and II.

Figure 5

Seven different volumes of sub-DFNs centered at the origin of the coordinates.

Figure 6

Varieties of P_{32} and P_{31} with the size of sub-DFNs: (A) P_{32} calculation, (B) P_{31} calculation.

Figure 7

Construction of jointed-coal SRM specimen: (A) intact coal BPM, (B) 4m×4m×4m coal DFN, (C) inserting BPM into DFN, (D) jointed-coal SRM specimen with REV size.

Figure 8

Schematic of triaxial compression numerical model.

Figure 9

Fracture geometry and composition of intact coal with REV size after numerical triaxial compression test.

Figure 10

Stress and strain of intact coal with REV size after numerical triaxial compression test.

Figure 11

Fracture geometries and composition of jointed coal with REV size subjected to numerical triaxial compression with loading perpendicular to bedding planes.

Figure 12

Stress and strain of jointed coal with REV size after numerical triaxial compression perpendicular to bedding planes. Y-d and X-d refer to the Y- and X-directions, respectively.

Figure 13

Fracture geometry and composition of jointed coal with REV size subjected to numerical triaxial compression with loading perpendicular to face cleats.

Figure 14

Stress and strain of jointed coal with REV size after numerical triaxial compression perpendicular to face cleats. X-d and Z-d refer to the X- and Z-directions, respectively.

Figure 15

Joint geometry and rupture surface of jointed coal with REV size subjected to numerical triaxial compression with loading perpendicular to butt cleats.

Figure 16

Stress and strain of jointed coal with REV size after numerical triaxial compression perpendicular to butt cleats. Y-d and Z-d refer to the Y- and Z-directions, respectively.

	Fracture geometry	Fracture description	Rupture mechanism
0		Fractures correspond to the joints parallel to the loading direction and result from the activated joints.	Dominated by joints
1		The shear-rupture surface approximates a rhombus. The local geometry is affected by joints.	Dominated by the combined effect of shear stress and joints
5		The shear-rupture surface is of a regular rhombus shape.	
10		Microcracks grow all over the rock particles. Plastic-flow failure occurs in the specimen.	Dominated by shear stress

Figure 17

Fracture geometries and rupture mechanism for jointed coal with REV size under four magnitudes of confining pressure. The numerical result without confining pressure is cited from Wang et al. [34].

Figure 18

Numerical results of jointed coal subjected to triaxial compression with different confining pressures.

Figure 19

Numerical results of intact coal and jointed coal with REV size under different triaxial loading orientations with 1-MPa confining pressure. RS refers to residual strength, ν refers to Poisson's ratio, L_s refers to lateral strain.

Figure 20

Diagrams of rupture mechanism under triaxial compression for intact rock (A) and jointed coal with low (B), middle (C), and high (D) confining pressures. LS refers to the loading stress, CP refers to the confining pressure, LCP, MCP, and HCP refer to low, middle, and high confining pressures, respectively.

Figure 21

Cut planes of fractures and joint geometries for jointed coal subjected to triaxial loading perpendicular to bedding planes (A), face cleats (B), and butt cleats (C) with 1-MPa confining pressure.