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Abstract

To gain deeper insight into the influence of double circular holes on the mechanical properties and crack propagation processes in rock, a uniaxial compression model of rock-like specimens containing dual circular holes was developed using the particle flow code PFC2D. The validity and rationality of the numerical model were verified by comparing the macroscopic mechanical parameters obtained from experiments and simulations. Subsequently, the crack propagation process in specimens with double circular holes and the evolution of the stress field around the circular holes were analyzed. The results demonstrate that the numerical simulations agree well with the experimental results. Initial tensile cracks first nucleate at the top and bottom ends of the circular holes. As the axial stress increases, structurally weak zones typically form on the left and right sides of the hole walls. The initiation direction of these initial tensile cracks is always along the axial loading direction, independent of the bridge angle α, whereas the specimen strength and failure pattern are significantly influenced by α. The initial tensile cracks nucleate within tensile stress concentration zones. As these cracks propagate, the tensile stress concentration regions at the top and bottom ends of the circular holes correspondingly shift and dissipate. The compressive stress concentration zone of the stress component σyy is located on the left and right sides of the circular holes, while a "fusiform" compressive stress shielding zone forms at the top and bottom ends of the holes. The shielding effect becomes stronger and the compressive stress becomes smaller with decreasing distance to the vertical centerline of the circular hole.

Full Text

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Study on the Failure Mechanism of Rock-like Materials Containing Two Circular Holes under Uniaxial Compression

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Abstract: To gain an in-depth understanding of the influence of two circular holes on the mechanical properties of rock and the process of crack propagation, the particle flow code PFC^{2D} was used to construct a uniaxial compression model of a rock-like specimen containing two circular holes. The correctness and rationality of the numerical model were verified by comparison of the macroscopic mechanical parameters obtained from experiments and simulations. Then, the crack propagation process of the specimen containing two circular holes and the evolution of the stress field around the circular holes were analyzed. The results show that the numerical simulation agrees well with the experimental results; initial tensile cracks first initiate at the upper and lower ends of the circular holes, and as the axial stress increases, structurally weak zones are usually formed on the left and right sides of the hole walls. The initiation direction of the initial tensile cracks is along the axial loading direction and is independent of the bridge angle α, but the strength and failure mode of the specimen are affected by the bridge angle α. The initial tensile cracks initiate in the tensile-stress concentration zone. As the initial tensile cracks propagate, the tensile-stress concentration zones at the upper and lower ends of the circular holes move and dissipate accordingly. The compression-stress concentration zone of the stress component σ_{yy} is located on the left and right sides of the circular holes, whereas at the upper and lower ends of the circular holes a "spindle-shaped" compressive-stress concentration shielding zone is formed; moreover, the closer it is to the vertical centerline of the circular holes, the stronger the shielding effect and the smaller the compressive stress.

Keywords: rock mechanics; two circular holes; uniaxial compression; particle flow code; crack propagation; stress field

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Study on the damage mechanism of rock-like materials containing bicircular holes under uniaxial compression

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Abstract: To study the effect of double circular holes on the mechanical properties of rocks and the crack extension process, a uniaxial compression model for rock specimens containing double circular holes was constructed, and the correctness and rationality of the numerical model were verified based on the comparison of the macroscopic mechanical parameters obtained from experiments and simulations. In addition, the crack extension process of specimens containing double circular holes and the evolution of the stress field around the circular holes were analyzed. The results show that the numerical simulation results are in good agreement with the experimental results; the initial tensile crack first sprouts at the upper and lower ends of the circular hole, and with the increase of axial stress, structural weak zones are usually formed at the left and right sides of the hole wall. The sprouting direction of the initial tensile crack is in the axial load-

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ing direction, independent of the orientation angle α, but the damage pattern of the specimen is influenced by the orientation angle α. The initial tensile crack is generated in the tensile stress concentration area; the tensile stress concentration area at the upper and lower ends of the circular hole moves and dissipates accordingly with the expansion of the initial tensile crack. The compressive stress concentration area of the stress component σ_{yy} is located on the left and right sides of the circular hole, while a shielding area of compressive stress is formed at the upper and lower ends of the circular hole, and the smaller the distance from the vertical center line of the circular hole, the stronger the shielding effect and the weaker the compressive stress.

Key words: rock mechanics; bicircular hole; single-axis compression; granular flow procedure; crack extension; stress field

Rocks widely existing in nature are important media in such engineering works as tunnels, underground spaces, and water conservancy and hydropower projects. Under various geological actions, various forms and scales of cracks, holes, and other geological defects may exist inside rock-like materials, causing a reduction in their mechanical strength and the manifestation of complex failure characteristics, thereby directly affecting engineering stability[^1-^4]. Therefore, studying the initiation, propagation, and coalescence of cracks in rocks and rock-like materials containing prefabricated holes is of great significance.

In recent years, extensive research has been carried out on the mechanical and failure characteristics of rocks and rock-like specimens containing prefabricated holes. DZIK et al.[^5] conducted uniaxial compression tests on granite specimens containing a single circular hole with a radius of 2.5–50 mm. The results showed that when the radius of the circular hole was less than 20 mm, tensile cracks propagated stably, whereas when the radius of the circular hole was greater than 40 mm, the propagation of tensile cracks was unstable. Li Zhengyi et al.[^6] studied sandstone specimens with different hole diameters and different numbers of holes; the results showed that the presence of holes led to significant deterioration of the mechanical parameters of the specimens. LIU et al.[^7] investigated the influence of the distribution of multiple holes on crack coalescence and failure behavior in granite. Their results indicated that the interaction between vertically and horizontally arranged circular holes was weaker than that between diagonally arranged circular holes. Li Yinping et al.[^8] studied the crack coalescence mechanism of marble containing prefabricated holes under uniaxial compression. Wang Tao et al.[^9] used a non-contact strain measurement method based on digital image correlation to analyze the damage and failure process of coal containing a single hole under asymmetric loading and uniaxial compression. In addition, numerical simulation—such as the particle flow code (PFC)—has been widely applied in research on rocks and rock-like materials because it can reveal, at the mesoscopic scale, the mechanisms of crack propagation in rocks and rock-like materials. Feng Fan et al.[^10] used numerical simulation to study the laws of crack propagation around the hole in a single-hole specimen, finding that tensile cracks first appeared at the upper and lower ends of the circular hole; as axial stress increased, shear cracks successively initiated on both sides of the hole and gradually penetrated through. Nong Hongzheng et al.[^11] carried out uniaxial compression numerical simulations on multi-hole rock specimens with different hole inclination angles. The results showed that the bearing capacity and deformation-failure characteristics of specimens containing hole defects were closely related to the hole inclination angle. LI et al.[^12] used PFC^{2D} to explore the influence of the distribution of multiple holes on the mechanical properties of brittle materials. WONG et al.[^13] studied, through numerical simulation, the strength and failure morphology of rock specimens with different hole diameters and specimen widths. TANG et al.[^14] and WONG et al.[^15] used numerical simulation methods to further investigate the effects of the number, diameter, bridge angle, and spacing of holes on crack coalescence and failure modes in granite specimens. The above studies have improved the understanding of the mechanical and failure behaviors of rocks and rock-like materials containing prefabricated holes. However, to date, there have been relatively few studies on rock-like specimens containing two circular holes. When tunnels are constructed in karst areas, cavities may exist in adjacent regions[^16]; in underground structures, holes may be reserved due to structural requirements such as pipeline installation. In these situations, a double-circular-hole structure may be formed, and the interaction between the two circular holes will greatly affect the mechanical behavior of the material. It is therefore necessary to study the fracture mechanism of specimens containing two circular holes. In addition, the stress distribution around holes is essentially a key factor leading to crack initiation and propagation and hence to rock failure. Therefore, it is necessary to obtain the stress distribution of specimens containing two circular holes. However, in laboratory tests, stress-field information can be obtained only with the aid of complex testing systems[^17], whereas PFC can obtain stress-distribution data relatively easily through programming.

Based on the above issues, this study adopts PFC^{2D} to establish a numerical model of a rock-like specimen containing two circular holes. First, according to the laboratory test results for intact specimens, the mesoscopic parameters of the numerical specimen are calibrated, and rock-like specimens containing circular holes under uniaxial compression are simulated. Next, the crack prop-

Diagram of the parallel bonding model

Figure 1: Diagram of the parallel bonding model

agation process of specimens containing two circular holes is analyzed in detail. Finally, the evolution process of the stress field around the circular holes is analyzed. This study improves the understanding of the failure mechanism of rock-like materials containing two circular holes and provides a theoretical basis for ensuring the safety and stability of related rock engineering projects.

1 Discrete Element Modeling Method

1.1 Microscopic Model

The discrete element method (DEM) is

a numerical simulation method based on interactions between rigid particles; it treats various media as assemblies of discrete rigid particles. In the DEM, the parallel bonding model (PBM) is suitable for simulating cemented materials[18]. Particles are connected by parallel bonds, which can be regarded as a group of springs uniformly distributed over the contact surface. They can bind the rigid particles in mutual contact together to form aggregates of arbitrary shape, and forces and moments can be transmitted between particles[19-20]. When the maximum tensile stress exceeds the tensile strength or the maximum shear stress exceeds the shear strength, the parallel bond breaks; at this point, the associated forces, moments, and stiffness are removed, and the model degenerates into a linear model. The breakage of parallel bonds between contacting particles can be regarded as the initiation and propagation of microcracks in the aggregate, allowing the initiation and expansion process of cracks to be represented intuitively. After the parallel bonds break, damage is formed and further expands into a rupture surface that causes specimen failure, which is consistent with the development of damage in actual rock-like materials. The parallel bonding model is shown in Fig. 1[21].

图 1　平行黏结模型图[21]

Fig. 1　Diagram of the parallel bonding model[21]

1.2　Construction of the numerical model

In the preceding laboratory tests of this research group, the rock-like specimens were prepared from cement mortar, with cement mortar made by mixing cement:sand:aggregate:water at a mass ratio of 2:3.4:7:11, and cast into rectangular thin-plate specimens[22] (height 200 mm, width 150 mm, thickness 30 mm). The focus of this study is crack propagation, and PFC^{2D} can more clearly represent the crack propagation pattern; therefore, this study carried out numerical simulation of the specimens using a two-dimensional plane-stress model[23].

Complete numerical specimen IS generated in PFC2D

Figure 2: Complete numerical specimen IS generated in PFC2D

Samples with round holes

Figure 3: Samples with round holes

PFC^{2D} was used to establish a complete specimen as shown in Fig. 2, denoted by IS. The dimensions of the numerical specimen were the same as those of the laboratory-test specimen, namely width 150 mm and height 200 mm. To neglect the effect of particle-size effects in the model, the dimensionless parameter characteristic length ratio L/R (the ratio of the model height L to the mean particle radius R) must be sufficiently large. Studies have shown[24] that when $L/R \geq 200$, the particle size has little influence on the overall distribution of various mechanical parameters and on the failure mode of the model. Therefore, in this study the particle-size range in the specimen was selected as 0.3–0.9 mm, and the particle sizes followed a uniform distribution. In laboratory tests, specimens containing circular holes were prepared by placing cement mortar into special molds with circular steel tubes[22]. In this study, specimens containing prefabricated circular holes were created by deleting spherical particles. To investigate in detail the effects of the distribution pattern of the holes on specimen strength, deformation characteristics, and crack-propagation behavior, the hole-distribution forms shown in Fig. 3 were designed: the specimen with only one hole is defined as specimen OS, where r denotes the radius of the circular hole; specimens containing two circular holes of radius r are called specimens TS, S denotes the distance between crack and crack , and the bridge angle α denotes the included angle between the line connecting the centers of the two circular holes and the horizontal direction. As α varies, the specimens containing two circular holes are defined as TS-0, TS-30, TS-60, and TS-90, respectively.

图 2 PFC^{2D} 中生成的完整数值试样 IS

Fig. 2 Complete numerical specimen IS generated in PFC^{2D}

(a) Specimen OS (b) Specimen TS-0 (c) Specimen TS-30 (d) Specimen TS-60 (e) Specimen TS-90

图 3 含有圆形孔洞的数值试样

Fig. 3 Samples with round holes

1.3 Simulation process

Loading is achieved through the axial movement of the upper and lower loading plates. To ensure that the specimen remains in quasi-static equilibrium throughout the entire simulation process, a sufficiently low loading rate must be applied. Some scholars have used PFC2D to analyze in detail the effect of loading rate on the cracking behavior of specimens containing fissures under uniaxial compression

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. The results show that, even for different fissure inclination angles, when the loading rate increases from 0.005 m/s to 0.08 m/s, the crack-initiation stress and uniaxial compressive strength remain basically constant. Therefore, in this study, a loading rate of 0.01 m/s was adopted, and loading was stopped when the axial stress decreased to 80% of the peak strength. According to the numerical results for specimens containing circular holes under uniaxial compression, the crack evolution process in the specimens and the stress field around the pre-existing holes can be analyzed in detail.

2 Calibration of microscopic parameters

In PFC2D, the macroscopic basic physical and mechanical parameters of real specimens cannot be used directly to establish the model; the microscopic parameters must be calibrated

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. In this study, the microscopic parameters were calibrated according to the macroscopic behavior of the complete specimen IS obtained from laboratory tests. Based on the results of sensitivity analysis of the parallel-bond model parameters

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, the particle modulus (E_{ball}), bond modulus (E_{bond}), particle stiffness ratio (k_{ball}), and bond stiffness ratio (k_{bond}) were first adjusted so that the elastic modulus reached the measured value from the laboratory test. Then the parallel-bond normal strength (σ_{bond}), parallel-bond shear strength (τ_{bond}), and interparticle friction coefficient (μ) were continuously adjusted until good agreement with the experimental results was achieved. Table 1 lists the microscopic parameters calibrated in this study.

Table 1 Microscopic parameters used for the specimens

Tab. 1 Microscopic parameters used for the specimens

Microscopic parameter	Value
Minimum particle radius/mm	0.3
Ratio of maximum to minimum particle radius	3
Particle contact modulus/GPa	2
Particle contact stiffness ratio	1.5
Parallel-bond elastic modulus/GPa	2
Parallel-bond stiffness ratio	1.5
Parallel-bond normal strength/MPa	12
Parallel-bond shear strength/MPa	16.7
Interparticle friction coefficient	0.1

Fig. 4 Comparison of experimental and simulated stress-strain curves for complete specimens IS

Figure 4: Fig. 4 Comparison of experimental and simulated stress-strain curves for complete specimens IS

Microscopic parameter	Value
Friction coefficient between particles and walls	0

Fig. 4 shows the experimental and simulated stress–strain curves of specimen IS under uniaxial compression. It can be seen from Fig. 4 that the simulated curve agrees well with the laboratory test curve, including the elastic deformation stage, the crack-initiation and growth stage before peak strength, and the unstable failure stage after peak strength. However, because of the closure of some initial cracks and voids in the rock, the experimental stress–strain curve shows an initial pore-compaction stage with downward concavity at the early loading stage; this was not observed in the numerical specimen, resulting in a relatively large difference between the simulated and experimental peak strains ε_{p}. This is because, in PFC2D, the contacts between particles are relatively tight, and each particle is in contact with no fewer than three other particles, so the initial pore-compaction stage that occurs in the laboratory compression test is not reproduced

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. The calculated uniaxial compressive strength σ_{p} and elastic modulus E of the simulated IS specimen are 26.71 MPa and 3.07 GPa, respectively, whereas the experimentally obtained σ_{p} and E are 27.15 MPa and 3.20 GPa, respectively. The two are basically consistent, indicating that the microscopic parameters in Table 1 are reasonable and can be used in the subsequent computational analysis.

Fig. 4 Comparison of experimental and simulated stress-strain curves for complete specimens IS

3 Numerical simulation results for specimens containing circular holes

3.1 Strength and deformation behavior of specimens containing circular holes

Figure 5 shows a comparison of the strength and deformation parameters between the tests and simulations for specimens containing circular holes. From the two black curves in Fig. 5(a), it can be seen that the simulated peak compressive strength σ_{p} shows the same trend as the experimental results, namely, it first decreases and then increases. It is worth noting that the σ_{p} value of

Fig. 5 Strength and distortion parameter comparison between test and simulation of specimens containing holes

Figure 5: Fig. 5 Strength and distortion parameter comparison between test and simulation of specimens containing holes

specimen TS-90 containing two circular holes is greater than that of specimen OS containing only one hole, whereas specimen TS-60 has the smallest σ_p value

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. This indicates that the mechanical properties of the specimens depend not only on the number of holes, but also on the distribution of the holes. Moreover, from the two red curves in Fig. 5(a), it can be observed that, under the same hole distribution conditions, the ···

Under these conditions, the elastic modulus obtained by numerical simulation is very close to that obtained from the laboratory test. Figure 5(b) shows a comparison of the peak strains obtained from numerical simulation and laboratory testing. It can be seen that, under the same hole-distribution conditions, the peak strain of the specimen in the test (black curve) is higher than that obtained from the simulation (red curve). This is mainly caused by the initial nonlinear deformation of the real specimen. If the initial nonlinear deformation is taken into account, the peak strain ε_p of the specimen containing circular holes in the simulation can be corrected by adding an initial strain value (the difference between the OS simulation and the experimental ε_p, about 3.9×10^{-3}). It can be seen that the corrected simulation curve (blue curve) agrees well with the experimental ε_p.

Fig. 5 Strength and distortion parameter comparison between test and simulation of specimens containing holes

3.2 Crack propagation in specimens containing two circular holes

Figure 6 shows the influence of the bridge angle α on the ultimate failure mode of specimens containing two circular holes under uniaxial compression in both tests and simulations. It can be seen that, although there are some differences between the simulations and the tests, these differences can be explained as follows: on the one hand, the numerical-simulation specimens are composed of many standard circular particles, which differs from the real specimens; on the other hand, the heterogeneity of the tested material and the inherent randomness of the numerical simulation also have an influence

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. Nevertheless, the overall ultimate failure characteristics obtained from the simulation are basically the same as those in the tests, and the coalescence

Fig. 6 Test of specimen with bicircular hole and simulated damage mode

Figure 6: Fig. 6 Test of specimen with bicircular hole and simulated damage mode

Fig. 7 Stress-strain-microcrack curve for specimens containing holes under uniaxial compression

Figure 7: Fig. 7 Stress-strain-microcrack curve for specimens containing holes under uniaxial compression

pattern between the two holes agrees well. This indicates that PFC^{2D} can be used to simulate the cracking characteristics of rock-like materials.

Fig. 6 Test of specimen with bicircular hole
and simulated damage mode

Taking the representative specimens TS-0, TS-60, and TS-90 as examples, Figures 7-10 present the crack-propagation processes of the three specimens, so as to study the influence of the bridge angle α on the crack-propagation process of the specimens. From Figures 7-10, it can be seen that the cracks in the specimens evolve gradually. Most microcracks initiate after the peak strength and grow exponentially with increasing strain.

For the convenience of subsequent research, in this study the state at which the strain of each specimen reaches 3×10^{-3} is defined as the initial compression state, as shown in Figure 7; at this time, no microcracks have initiated. In Figures 7-10, point a corresponds to the axial stress at crack initiation. The definition of crack-initiation stress varies among different studies

[30–32]

. In this study, when the number of cracks in the specimen reaches approximately 10% of the total number of cracks at peak strength, the corresponding stress is defined as the crack-initiation stress. For specimens containing two circular holes under uniaxial compression, the process of crack coalescence can be analyzed in detail from Figures 7-10. It should be noted that the letters in Figure 7 correspond to the letters listed in Figures 8-10.

Figure 8 gives the crack-propagation process of specimen TS-0. The numbers in the figure indicate the sequence of crack propagation, and the superscripts of the numbers indicate cracks at different positions at the same time. When the specimen is loaded to point a (Fig. 8a), initial tensile cracks 1^a-1^c occur at the upper and lower edges of hole and at the upper edge of hole . The initiation directions of initial tensile cracks 1^a-1^c are all in the axial loading direction. This is because, under uniaxial compression, stress concentration occurs around the holes, and the tensile stress along the vertical centerline of the holes is usually much higher than the tensile stress elsewhere.

Fig. 8 Crack extension in TS-0 specimens under uniaxial compression

Figure 8: Fig. 8 Crack extension in TS-0 specimens under uniaxial compression

Fig. 7 Stress-strain-microcrack curve for specimens containing holes under uniaxial compression

Fig. 8 Crack extension in TS-0 specimens under uniaxial compression

With the increase in axial stress (Fig. 8b), collapse failure occurred in the right wall of hole under the action of high compressive stress, forming a structurally weak zone

, from which crack 2^a was generated. Meanwhile, tensile–shear mixed crack 2^b initiated in the upper half of the specimen. When the load reached the peak stress (Fig. 8c), crack 2^b propagated rapidly along the axial direction. In the lower half of the specimen, a tensile–shear mixed crack 3^b, almost equal in length to crack 2^b, also formed. Tensile crack 3^c initiated at the lower edge of hole . Subsequently, collapse failure also occurred at the left wall of hole , generating crack 3^a. With further increase in axial deformation (Fig. 8d), crack 3^a rapidly propagated toward the upper left of the specimen. Collapse failure also occurred at the right wall of hole , producing a new crack 4^c. In addition, two far-field cracks 4^a and 4^b were observed in the upper-left and lower-right parts of the specimen, respectively. After the specimen was loaded to point e (Fig. 8e), shear crack 5^a generated in the specimen caused cracks 4^c and 4^b to coalesce. Crack 3^a further extended and intersected with crack 4^a. Eventually, the specimen was completely destroyed by the penetration of mixed cracks 2^b and 3^b. It is worth noting that after crack 2^a was generated, it propagated obliquely upward and finally intersected with 2^b in the upper-middle part of the circular hole; the two did not directly connect the two circular holes.

The crack extension process of specimen TS-60 is shown in Fig. 9. It can be seen that when the specimen was loaded to point a (Fig. 9a), the crack-initiation stress was reached, and four initial tensile cracks $1^a \sim 1^d$ initiated from the upper and lower edges of the two circular holes and developed along the axial-stress direction. When the axial stress reached point b (Fig. 9b), collapse failure occurred simultaneously at the left and right walls of hole , and cracks 2^a and 2^b then initiated in the two weak zones. When the axial stress reached point c (Fig. 9c), collapse failure also occurred at the right edge of hole , forming crack 3^b. Two far-field cracks 3^a and 3^c also formed in the upper-left and lower-right corners of the specimen. Initial tensile cracks 1^a and 1^d developed along the axial-stress direction. In addition, crack 2^b extended to the upper-left boundary of hole , but the specimen as a whole still retained a certain bearing capacity. When the axial stress dropped to point d (Fig. 9d), initial tensile cracks 1^a and 1^d extended only slightly, which may be due to the constraint of the specimen boundary; shear crack 4^a also formed at this time and coalesced with cracks

Fig. 9 Crack extension in TS-60 specimens under uniaxial compression

Figure 9: Fig. 9 Crack extension in TS-60 specimens under uniaxial compression

Fig. 10

Figure 10: Fig. 10

3^b and 3^c. When the specimen was loaded to point e (Fig. 9e), initial tensile crack 1^a extended to the upper edge of the specimen, and the newly initiated shear crack 5^a developed rapidly and coalesced with cracks 2^a and 3^a; at this point the specimen completely lost its bearing capacity. It is worth noting that, in the TS-60 specimen, through-going failure occurred in the vertical direction between the two circular holes.

Fig. 9 Crack extension in TS-60 specimens under uniaxial compression

Figure 10 presents the crack extension process of specimen TS-90 under uniaxial compression. It can be seen that when the specimen reached the crack-initiation stress at point a (Fig. 10a), initial tensile cracks 1^a and 1^b were generated at the upper edge of hole and the lower edge of hole , respectively, and the initiation directions of both initial tensile cracks 1^a and 1^b were along the axial loading direction. As the axial stress of the specimen increased to point b (Fig. 10b), cracks 2^a and 2^b began to initiate at the upper edge and the right side of hole , respectively. When the load reached the peak stress at point c (Fig. 10c), collapse failure occurred on both sides of the wall of hole and on the left side of the wall of hole , generating cracks $3^a \sim 3^c$; crack 3^b propagated obliquely downward and coalesced with crack 2^b, while crack 3^d formed on the left side of hole and coalesced with crack 3^c. In addition, as in the TS-60 specimen, far-field cracks 3^e and 3^f were generated in the upper-left and lower-right corners of the specimen, respectively. After the peak, the axial stress dropped to point d.

(Fig. 10d), the initiated shear crack 4^a converges with cracks 2^b and 3^f, causing hole to become connected with the specimen edge. It is worth noting that crack 3^d extends upward and converges with crack 3^a, and crack 2^b extends to the right wall of hole , so that hole and hole are both penetrated on the left and right sides of the hole walls. When the specimen is loaded to point e (Fig. 10e), crack 3^a extends to the upper surface of the specimen, and the specimen is completely damaged. Unlike specimen TS-60, the initial tensile crack initiated on the crack centerline almost no longer extends after loading to point c, and therefore does not propagate to the specimen edge.

图 10 单轴压缩下 TS-90 试样裂纹扩展过程
Fig. 10 Crack extension in TS-90 specimens under uniaxial compression

Fig. 11

Figure 11: Fig. 11

3.3 Force-chain field analysis of specimens containing two circular holes

A force chain is a concept proposed to describe the contact forces between densely packed particles; it can represent the changes and transmission process of interparticle contact forces. From the experimental point of view, this is almost impossible to obtain. Taking specimen TS-60 as an example, Fig. 11 shows the force-chain distribution between particles before and after crack initiation in the specimen. In the figure, red denotes microcracks, black line segments denote compressive force chains of parallel bonds, green line segments denote tensile force chains of parallel bonds, and the thickness of the line segments denotes the magnitude of the force.

It can be seen from Fig. 11 that, as the specimens containing two circular holes are loaded, during crack initiation and propagation, the bonding forces between particles continuously evolve. In the initial compression stage, tensile force-chain concentration zones are generated above and below the two circular holes, whereas compressive force-chain concentration zones are generated on the left and right sides, indicating that stress concentration occurs in these regions. As loading proceeds (point a), initial tensile cracks $1^a \sim 1^d$ initiate in the tensile force-chain concentration zones. When the axial stress reaches point b, the initial tensile cracks further propagate, the region of tensile force-chain concentration dissipates and becomes smaller, and shifts to the tips of the initial cracks. Meanwhile, cracks 2^a and 2^b initiate respectively in the compressive force-chain concentration zones (on the left and right sides of hole). This is because the tensile strength of the rock-like material is lower than its compressive strength, and failure of the specimen begins with tensile failure. When loading reaches point c, crack 3^b initiates and propagates in the compressive force-chain concentration zone on the right side of hole , whereas the compressive force-chain concentration zones originally located on the right side of hole and on the left side of hole dissipate because of the penetration between the two holes. Continued loading to point d, with the increase of tensile and shear microcracks, the left side of hole and the right side of hole are still in compressive force-chain concentration zones. In the final unstable failure state of the specimen (point e), compressive force-chain concentration zones appear at both ends of crack 5^a, and the compressive force-chain concentration zones on the left and right sides of the holes dissipate; at this time, the force-chain distribution in the specimen changes from a relatively uniform distribution to an irregular distribution.

图 11 单轴压缩下 TS-60 试样力链场分布
Fig. 11 Force chain field distribution of TS-60 specimen under uniaxial compression

Fig. 12

Figure 12: Fig. 12

Fig. 13 Stress component σ_{xx} around the hole at different loading stages with different orientation angle

Figure 13: Fig. 13 Stress component σ_{xx} around the hole at different loading stages with different orientation angle

3.4 Analysis of the crack-evolution mechanism of specimens containing two circular holes

The stress distribution around the holes is essentially the key factor leading to crack initiation and propagation and thus to specimen failure. To obtain a deeper understanding of the crack-evolution mechanism of the specimens, this section investigates the distribution and evolution process of the stress field around the circular holes. As shown in Fig. 12, the stress distribution around the circular holes is measured by arranging multiple measurement circles around the prefabricated circular holes. Each measurement circle contains 8–10 particles. After the average stress is measured, the corresponding stress-distribution cloud map can be plotted.

图 12 预制圆孔周围的测量圆分布

Fig. 12 Distribution of measurement circles around prefabricated round holes

This study measured the stress distributions around the circular holes for bridge angles α of 0°, 60°, and 90°, respectively, during the initial compression stage, stage a (when the axial stress reaches point a), and stage b (when the axial stress reaches point b). The corresponding stress-cloud diagrams of σ_{xx} and σ_{yy} were generated. As shown in Figs. 13–14, the stress-cloud diagrams adopt the local coordinate system of the circular holes; the coordinate origin is located at the midpoint of the centerline of the two prefabricated circular holes, and the x- and y-coordinate values have both been nondimensionalized (except for the diameter $2r$ of the circular holes). Under compression, the stress value is negative; under tension, it is positive.

Fig. 13 Stress component σ_{xx} around the hole at different loading stages with different orientation angle

Figure 13 shows the distribution of the circumferential stress component σ_{xx} around the circular holes at each stage under different bridge angles α. In the initial compression stage, it can be observed that relatively large compressive-stress concentration zones (blue regions) appear at the left and right edges of the circular holes, while tensile-stress concentration zones (orange-red regions) appear at the upper and lower edges of the circular holes; these are also the regions where the initial tensile cracks initiate. The reason for this phenomenon should be that axial compression tends to close the circular holes. At this time,

Fig. 14 Stress component σ_{yy} around the hole at different loading stages with different orientation angle

Figure 14: Fig. 14 Stress component σ_{yy} around the hole at different loading stages with different orientation angle

the relatively large compressive strain on the left and right sides of the circular holes causes tensile strain on the upper and lower sides of the holes, thereby generating tensile stress around the circular holes.

When $\alpha = 0°$, the compressive stresses on the right side of hole and the left side of hole merge with each other. As α increases, the distance between the compressive stresses on the right side of hole and the left side of hole gradually increases. At the same time, the tensile stresses below hole and above hole gradually approach each other. As the axial stress increases, the initial tensile cracks initiate in stage a. Comparing this with the crack-initiation process shown in Figs. 8-10, it can be observed that the initial tensile cracks initiate in the tensile-stress concentration zones and release tensile stress in those zones. As the initial tensile cracks propagate, the compressive-stress concentration zones (blue regions) are basically unaffected, but the tensile-stress concentration zones originally located at the edges of the circular holes are affected.

the tensile-stress concentration zone had moved to the tip of the initial tensile crack (orange-red region). When the axial stress reached point b, as the crack continued to propagate, the tensile-stress concentration zone further shifted and dissipated.

The distribution of the stress component σ_{yy} around the circular holes is shown in Fig. 14. The stress distributions around the two holes are relatively similar. Under uniaxial compression, the stress component σ_{yy} around the holes is negative. It can be seen from the figure that the compressive-stress concentration zones (blue regions) are located on the left and right sides of the circular holes, causing crushing failure on the left and right sides of the hole walls. At the upper and lower ends of the circular holes, a "fusiform" compressive-stress concentration shielding zone (red region) appears. The smaller the distance from the vertical centerline of the circular hole, the stronger the shielding effect and the lower the compressive stress. It is noteworthy that when $\alpha = 90°$, the compressive-stress concentration shielding zones between the two circular holes intersect with each other, indicating that the region between the two circular holes is not subjected to high compressive stress.

图 14 不同桥角下不同加载阶段预制孔洞周围的应力分量 σ_{yy} 分布

Fig. 14 Stress component σ_{yy} around the hole at different loading stages with different orientation angle

4 Conclusions

In this study, PFC^{2D} was used to construct rock-like specimens containing circular holes, and uniaxial compression tests were carried out on them. In addition, the crack propagation process, the evolution of the force-chain field around the circular holes, and the evolution of the stress field for specimens with each pair of circular holes were analyzed. The following main conclusions were obtained.

1) Based on the laboratory test results of intact specimens, the mesoscopic parameters of the numerical model of the rock-like specimens were calibrated. Then, specimens containing circular holes under uniaxial compression were simulated. The comparison of the macroscopic mechanical parameters obtained from the tests and simulations verified the correctness and rationality of the numerical model. Through quantitative comparison between the simulation results and the test results, it was found that the numerical simulation results were in good agreement with the experimental results.

2) Most microscopic cracks initiated after the peak strength and ⋯

increases exponentially with increasing axial strain. When the axial stress reaches the crack-initiation stress, initial tensile cracks first initiate at the upper and lower ends of the circular holes. As the axial stress increases, structurally weak zones usually form on the left and right sides of the circular holes. The initiation direction of the initial tensile cracks is the axial loading direction and is independent of the bridge angle α; however, the strength and failure morphology of the specimen are affected by the bridge angle α.

3) The initial tensile cracks initiate in the tensile-stress concentration zone. As the initial tensile cracks propagate, the tensile-stress concentration regions at the upper and lower ends of the circular holes correspondingly shift and dissipate. The compressive-stress concentration zone of the stress component σ_{yy} is located on the left and right sides of the circular holes, while an "oval" -shaped compressive-stress concentration shielding zone forms at the upper and lower ends of the circular holes. The closer the distance to the vertical centerline of the circular holes, the stronger the shielding effect and the smaller the compressive stress.

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Note: Figure translations are in progress. See original paper for figures.