Study on the Effects of Joint Inclination and Size Effect on the Failure Process of Rock-like Materials

Dong tao, Cao ping, Liu Zhizhen, Wang fei

School of Resources and Safety Engineering, Central South University, Changsha Hunan 410083, China

Corresponding author’s e-mail: pcao_csu@163.com(P.Cao)

Abstract. To explore the effects of joint inclination angle and the size on the mechanical properties and failure process of rock-like specimens, a series of uniaxial compression tests were carried out on rock-like specimens. The specimens are consist of two sizes and contain three parallel joints with various inclination angles. During testing, the variation characteristics of apparent strain field of specimens is recorded by digital image correlation (DIC) system. Testing results reveal the uniaxial compression strength of the specimen decreases gradually with the joint inclination increases from 0° to 60°, while increasing gradually with the joint inclination increases from 60° to 90°. In addition, the peak compression strength of the large-size specimens is obviously lower than that of the small-size specimen when the joint inclination angle is 0°~30°. By contrast, the peak compression strength of the large-size specimens is the same as that of the small-size specimen when the angle is 30°~60°, approximately. But, the peak compression strength of large-size specimen is obviously higher than that of small-size specimen when the joint inclination angle is between 60° and 90°. Finally, five different types of cracks are observed in this work, i.e., tensile crack, airfoil tension crack, pull-shear mixing crack, secondary crack and far field tensile crack.

1. Introduction

As a natural complex heterogeneous medium, the rock mass contains various kinds of joint cracks, pores and other defects at the beginning of its formation. The interaction between the primary joints and the fractures has a great influence on the mechanical properties of the rock mass [1]. The failure of the rock mass is closely related to the expansion and penetration of the primary joint fractures. Therefore, studying the crack propagation behavior and the damage strength is especially important for understanding the failure mechanism of rock and preventing disasters in rock engineering. Based on fracture mechanics and damage mechanics, scholars have established a complete theoretical system for studying the development of rock joint fissures [2,3]. Park et al [4] analyzed the crack propagation process of closed and open cracks, and proposed eight crack penetration modes. Fan Xiang et al [5] found that the rock bridge dip angle contains two the peak compression strength and cracking stress of the fracture specimen have a great influence. Chen Xin et al. [6] studied the jointed rock mass by analyzing the digital image of the test piece during the test. Han Zhiming et al [7] proposed a strength prediction model suitable for rock mass with a set of joint joints after comprehensive consideration of confining pressure. Liu Hongyan et al [8] proposed a simultaneous the calculation method of rock damage variable considering the influence of joint strength and geometric parameters on the mechanical properties of rock mass is studied. He Manchao et al [9] proposed the theory of engineering rock mass continuity to study the size effect of
engineering rock mass mechanical parameters. Yang Shengqi et al [10] established a statistical model of rock damage considering the size effect under uniaxial compression. Chen Yu et al [11] performed uniaxial compression tests on columnar rock samples with different aspect ratios. Liang Zhengzhao et al [12] proposed a multi-scale rock engineering calculation method from micro to macro. The above scholars' research reveals that the factors such as joints and test size have an important influence on the stability of rock mass, but there are relatively few studies combining the fracture development process is studied from a dynamic perspective. To this end, the author designed two kinds of rock specimens with different joint inclination angles, tested the specimens with servo machine, and The effects of dip and size effects on the apparent strain field of rock materials were studied by high-precision digital image correlation (DIC).

2. Test piece production and test process

2.1. Test piece production

The cement mortar is used to make test pieces. The cement mortar is mixed with fine sand, white cement and water in a volume ratio of 1:2:1. Make two sizes specimen, specimen size (height × width × thickness) were 100 × 100 × 30 and 150 × 150 × 30. The joint cracks in the test piece were made by interposing mica sheets with a thickness of 0.6 mm. The lengths of the joint cracks were 2 mm and 3 mm. The specific distribution of parameters and joint cracks is shown in Figure 1.

Make samples as described above. Each test piece is grouped and numbered as S - α (S represents the size of the test piece, respectively 100 and 150; α represents joint inclination ). After 24 hours of curing, the mold was conserved in a standard curing room with a temperature of 20 ± 2 ° C and a humidity of 95% for 28 days. The test piece is shown in Figure 2a. The finished test piece is sprayed with speckle on one side of the test piece as shown in Figure 2b.

![Figure 1. Specimen geometry and joint distribution](image1)

![Figure 2. Test specimen](image2)

2.2. Experimental procedure

The test adopts the uniaxial loading test mode. The loading test device consists of the DCS-200 loading control system and the new SANS electro-hydraulic servo rigid testing machine. The test adopts the force-controlled loading mode with a loading rate of 200N/S. In the whole process of the experiment, the high-definition camera was used to record the whole process of the damage of the test piece, and the high-precision digital image correlation (DIC) was used to dynamically capture the evolution process of the surface strain field of the test piece with time. The schematic diagram of the test device is shown in Figure 3. The basic physical and mechanical parameters of the test piece materials are shown in Table 1.
3. Influence of joint inclination and specimen size on the strength of rock mass

The influence of joint inclination and size effect on the peak compression strength of the specimen is shown in Fig. 4. With the increase of the joint inclination angle, the peak compression strength of the two specimens decreases first and then increases. Reaches minimum when the joint angle is $60^\circ$. The equivalent peak intensity $\sigma_e/\sigma_c$ was introduced to study the effect of joint dip and size on the peak compression strength of rock-like materials. The ratio of the peak compression strength of the joint-containing fractured specimen to the peak compression strength of the intact specimen of the same size is defined as the equivalent peak strength. It can be seen from Fig. 5 that the ratio of all the test pieces is less than 1, but the ratio varies from 0.90 to 0.45, indicating that the degree of the crack of the joint crack and the size of the test piece have different degrees of weakening of the peak compression strength of the test piece. In the case of the same joint inclination angle, when the joint crack angle range is from $0^\circ$ to $30^\circ$, the large-sized test piece is affected by the size effect, and the peak compression strength is weakened greatly; when the joint crack angle range is from $30^\circ$ to $60^\circ$ the size effect has similar effects on the peak compression strength. When the joint crack angle ranges from $75^\circ$ to $90^\circ$, the small-sized specimens are affected by the size effect, and the peak compression strength is weakened.

4. Failure mode and crack expansion analysis

4.1. Crack propagation mode

According to the development form of the crack before the final failure of the test piece, combined with the comprehensive analysis of the literature [14], the crack types of this test are mainly divided into: tensile crack (I), airfoil tensile crack (II), tensile shear mixed crack (III), secondary crack (IV), far field tensile crack (V).
4.1.1. **Mode one.** Fig. 7 is a graph showing the final destruction result of the test piece 100-0, the crack type is mainly type I, and there are a small number of V-shaped cracks. The crack propagation process is as follows: Firstly, a vertical upward I-shaped crack appears at the center of the No. 1 joint; as the loading continues, the vertical direction appears near the middle and the tip of the No. 2 and No. 3 joints. The type I crack developed, and a V-shaped crack appeared in the upper right corner of the test piece. The type I crack and the V-shaped crack of joint No. 2 are close to the lateral boundary. Since the lateral boundary of the test piece is not affected by force, the two cracks develop rapidly until the specimen undergoes macroscopic damage and loses the bearing capacity. There was no rock bridge lap joint in the final damage of the test piece, and the fractured specimen was less broken and the completion was high.

4.1.2. **Mode three.** As can be seen from Fig. 8, the crack types of the test pieces 100-60 are mainly type II and type III, and there are a small number of type IV and type V. The crack propagation process is specifically as follows: at the initial stage of loading, there is a obvious type II crack at the prefabricated joint. The type III crack has appeared at the rock bridge between the joints No. 2 and No. 3; the loading continues, significant V-shaped cracks appear in the upper left and lower right of the test piece. At the stage of later loading, the type III cracks between joints No. 2 and No. 3 develop fully, and the type IV cracks at the joint tip. Through repeatedly comparing the failure process of the same type of test piece and the final failure result map, it is concluded that the type III crack that appeared earlier in the middle of the rock bridge affects the development direction and length of the joint type IV crack. Eventually, the No. 2 and No. 3 joints converge with the rock bridge in the middle. The crack propagation mode of this type of test piece is complex, the cracks are interpenetrating and intertwined, and the final fracture of the test piece is high.
4.1.3. **Mode four**. The final damage results of the test pieces 150-90 are shown in Fig. 9. The crack types of the test pieces 100-90 are mainly type I and type V, and there are a small number of type II and type IV. The crack propagation process is specifically as follows: the type IV crack along the joint plane appears in the joint of No.1, and then the crack appears in the joint of No.3 joint; the loading continues, the type I crack appears on the left side of the test piece, and the expansion speed is faster, and the joint There is no obvious expansion of the crack at the place; in the early stage of the test piece, the type II crack appeared in the joint of No. 2, and the crack of the type IV crack appeared in other joints. The specimen was not near the pre-destruction, and there was still no large macro-crack, but the damage type I crack at the lower right of the test piece developed rapidly, and at the same time, the block collapsed in the lower part of the test piece, and similar rock bursts occurred in other test pieces of the same kind of joint inclination angle. When the test piece was finally destroyed, there was no rock bridge lap joint, and the boundary of the test piece was broken, but the overall fracture degree was general and the integrity was normal.

4.2. **Test piece failure mode**

According to the relationship between the crack and the pressure acting surface under uniaxial compression, the failure modes of the specimens in this test can be roughly divided into five types: tensile failure, airfoil tensile failure, tensile shear mixing failure, shear failure and overall splitting failure, select some representative specimens for failure mode analysis, and Figure 10 gives the test pieces (100-0, 100-45, 100-60, 150-75, 150-90) The ultimate destruction mode.

The results shown in Table 2 were obtained from the crack type, the penetration and the failure mode of all the test pieces. It is worth noting that when the joint inclination angle is 0° and 90°, the crack type, penetration and failure mode of the specimen are extremely similar, but the uniaxial compression strength is significantly different. When the joint inclination angle is 30°~75°, the crack type and failure mode of the test piece are different. Combined with the equivalent peak intensity analysis of the corresponding test pieces, the influence of the size effect of the different joint dip angle specimens on the peak compression strength was demonstrated again.
5. Conclusion

(1). With the increase of joint inclination angle, the compression strength of the two sizes of specimens showed a trend of decreasing first and then increasing, and the peak compression strength was the smallest at 60°.

(2). In the case of the same joint inclination angle, the peak compression strength of the large-size specimens is obviously lower than that of the small-size specimen when the joint inclination angle is 0°~30°. By contrast, the peak compression strength of the large-size specimens is the same as that of the small-size specimen when the angle is 30°~60°, approximately. But, the peak compression strength of large-size specimen is obviously higher than that of small-size specimen when the joint inclination angle is between 60° and 90°.

(3). The failure mode of the test piece mainly depends on the size of the joint inclination. According to the type of crack and the type of crack expansion, the failure mode of the test piece can be divided into five types: tensile failure when the inclination angle is 0°; airfoil tension when the inclination angle is 30° and 45°; pull-shear mixing failure or shear failure when the inclination angle is 60° and 75°; splitting failure when the inclination angle is 90°.

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