Analysis of shear failure process of jointed rock

Changren Ke, Tingting He and Qingwei Wen

College of civil architecture and environment, Hubei university of technology, Wuhan, Hubei province, 430068, China

*Corresponding author’s e-mail: longmanke@163.com

Abstract. Based on regular sawtooth joint specimens with four fluctuating angles, the shear tests under five normal stresses were carried out to get the test curve. The shear stress-shear displacement curves and different failure modes of joints were analyzed. The law of shear strength weakening stage was studied by using shear strength weakening ratio. It was concluded that when the normal stress is small and the undulation angle is large, the value of shear strength weakening ratio is larger, and it has a good linear relationship with the undulation angle.

1. Introduction

On the basis of analyzing the analysis of the cutting shear stress-displacement curve presents pre-peak hardening and post-peak softening, Tang Zhicheng and Xia caishu [1-2] proposed a full-volume shear-based structure model that considered hardening-softening, and used a single function to reflect the changing characteristics of the arbiting shear displacement curve. The model shows strong adaptability by different types of shear displacement curves. Li hongzhe [3] obtained two failure modes of jointed rock mass through triaxial loading test: slip along joint surface and failure of joint surface. In general, most of the theoretical achievements of domestic and foreign scholars [4-9] are mainly indoor and outdoor experimental studies on artificial joint surface or natural (rock) joint surface.

In this paper, the failure mode, shear strength, residual strength and weakening characteristics of joints in the shear process are studied through the shear tests of regularly serrated rock-like joints under normal stress at different undulating angles, and relevant conclusions are drawn.

2. Test materials and test plan

2.1. Sample preparation

This paper adopted cement mortar as the artificial jointed sample prepared for rock-like materials to conduct experiments. The cube joint sample with the side length of 150mm was made. The upper and lower parts of the sample block were poured separately. The mold size used was 150mm ×150mm ×75mm. Blade angle of 5°, 15°, 30° respectively, and 0° angles does not need to be pad plate, which formed the joint surfaces with different undulating angles. All mortar aggregates are made of standard sand. The mix proportion of the rock-like material sample is water: cement: sand = 1:2:3. The aggregate of mortar is all made of standard sand and the cement grade is 42.5R. After hardening, the uniaxial compressive strength is about 23.9 MPa measured by WAW-600C electro-hydraulic servo universal testing machine, as well as the internal friction angle is 36° measured by stress-controlled push shear testing machine, and that the cohesion force is 0.1 KPa.
2.2. Direct shear test equipment and method design
The direct shear test device for artificial joints was carried out by the RMT-150C rock mechanics test system of the State Key Laboratory of Geotechnical Mechanics and Engineering, Wuhan Branch of Chinese Academy of Sciences. A series of shear stress-shear deformation curves were obtained through experiments, for the purpose of analyzing the evolution law of mechanical parameters corresponding to different shear displacements in the stage of strength weakening.

In the test, the joint specimens with different undulating angles were tested under different normal stresses, and the normal stresses were 0.5 MPa, 1 MPa, 2 MPa, 3 MPa and 4 MPa, respectively. At the beginning of the test load, the hydraulic device of the starting system first applied the vertical load to the predetermined value at the rate of 1KN/s, and then applied the tangential load in the way of controlling displacement, with the increase rate of tangential load was 0.005 mm/s. During the whole test process, the servo machine automatically collects shear stress, shear deformation and other related parameters to obtain the corresponding shear stress-shear deformation curve.

3. Analysis of test results
Observing the specimens after shear test, the figure 1 is the specimens after the joint surface is damaged under normal stress with 0° undulation angle. There is no obvious form of destruction inside the specimen, but there are more obvious ring-shaped cracks on the surface of the upper and lower joint surfaces. Figure 2 is a specimen that it is destroyed under normal stress with 30°undulation angle. The joint surface of the whole specimen is highly destroyed, and the serrated teeth are completely cut off, leaving a large amount of rock debris. A large number of fine cracks can be found under the debris, and the direction of cracks is basically the same as that of shear. In the process of experiment, there will be a clear sound of the bump being cut, because the sawtooth with large fluctuation angle is the main body of bearing shear stress. Once it is destroyed, it reaches the peak shear strength of the joint surface. Figure 3 is a specimen that it is destroyed under normal stress with 5° undulation angle. It can be clearly seen that there are wear marks on the surface of the saw teeth. The sawtooth convex body becomes circular arc, and the height is lower than before, as well as the wear direction and shear direction are generally opposite. Under normal stress, the upper and lower joints are pressed together, and the shear force is mainly borne by the friction force on the sawtooth surface, so the shear strength after complete wear is its peak shear strength.

As shown in the figure 4 is the shear stress-displacement curves of 4 groups of joint samples under different normal stresses, which better reflects the shear deformation characteristics of joints under different normal stresses. It can be observed that the shear stress increases linearly with the displacement in the initial stage of loading, and the shear stiffness coefficient can be regarded as a fixed value in this stage. With the continuous increase of shear force, the shear displacement increases obviously, and the shear displacement curve shows a non-linear trend. The shear stiffness coefficient become to become smaller, and the test piece is asymptotically destroyed along the joint surface; With the continuous increase of shear load, there is no sharp softening after reaching the peak strength, but slowly into a relatively smooth transition period, and finally reach a certain degree of weakening its
slope tends to zero. At the same time, it can be observed that the displacement of the upper and lower joint planes is obviously staggered, the whole joint planes of the specimen are cut off, and the peak strength of the joint planes after shearing decreases continuously, which shows that the strength stress still exists when the final value reaches the residual strength, indicating that the jointed rock mass still has a certain degree of anti-shearing capacity. It can be seen from the graph that, during the whole process of this shear test, the shear stress and shear displacement do not always fluctuate within a stable range, but they often have intermittent changes. Hoskins and Jaeger[10] called it stick-slip phenomenon when they studied the sliding characteristics of the rock surface with different roughness. From the analysis of joint shear failure mechanism, on the one hand, after a small displacement of the joint, some other shear bumps will be chimed together to prevent the slide to continue, until the joint is cut again; On the other hand, in the process of shear, the contact area of joint surface decreases continuously, which causes its own friction resistance to drop suddenly and produces stick-slip.

![Figure 4](image)

**Figure 4.** Shear stress-displacement curves under different normal stresses.

### 4. Test weakening parameter analysis

| Undulation angle / ° | Normal stress /MPa |
|---------------------|--------------------|
|                     | 0.5                | 1      | 2      | 3      | 4      |
| 0                   | 1.09               | 1.30   | 1.03   | 1.08   | 1.04   |
| 5                   | 1.59               | 1.51   | 1.37   | 1.35   | 1.28   |
| 15                  | 2.29               | 1.69   | 1.86   | 1.89   | 1.84   |
| 30                  | 4.59               | 2.70   | 2.91   | 3.15   | 2.48   |

Joint rock mass under natural stress mainly is the destruction of the joint surface under the action of shear stress. However, in the joint plane after peak shear strength is destroyed, carrying capacity is
not completely did not have the strength, there will be residual strength, which many scholars have been verified by the experimental analysis. This paper introduce the concept of intensity attenuation ratio  \( \xi \), expressed as:

\[
\xi = \frac{\tau_f}{\tau_r}
\]

(1)

Where, \( \tau_f \) is peak shear strength and \( \tau_r \) is residual shear strength.

The value of \( \xi \) can reflect the weakening degree of joint interview piece in the shear process, and its value is greater than 1. The larger \( \xi \) is, the greater the degree of shear strength weakening in this environment is. The closer \( \xi \) is to 1, the less weakened it is. According to the data, the value of intensity weakening ratio \( \xi \) is calculated as shown in the table 1.

Figure 5 shows the variation trend of shear strength weakening ratio under different normal stress states with undulating angle of joint surface. The results show that the shear strength weakening ratio increases with the increase of undulation angle of joint surface under the action of 5 normal stresses, which indicates that the larger the undulation angle is, the greater the degree of shear strength weakening will be. And the magnitude of the shear strength weakening ratio is also different. Such as under 0.5 MPa, the undulation angle changes from 15° to 30° increase amplitude is the biggest of all.

Here, we adopt the weighted average method to eliminate the influence of normal stress, and apply the following formula to the data under various angles:

\[
\xi = \frac{\xi_1\sigma_1 + \xi_2\sigma_2 + \xi_3\sigma_3 + \xi_4\sigma_4 + \xi_5\sigma_5}{\sigma_1 + \sigma_2 + \sigma_3 + \sigma_4 + \sigma_5}
\]

(2)

It is obtained that: at 0° of undulating angle, shear strength weakening ratio is 1.08; At 5° of undulating angle, shear strength weakening ratio is 1.35; At 15° of undulating angle, shear strength weakening ratio is 1.87; At 30° of undulating angle, shear strength weakening ratio is 2.87. The average intensity weakening ratio under each fluctuation angle is drawn in figure 6, which shows that it conforms to a good linear relationship. The linear fitting formula can be obtained by fitting it, which has a good matching. The linear fitting formula is: \( y = 1.04786 + 0.05957x \), \( R^2 = 0.99408 \). It can be concluded that the intensity weakening ratio of joint components increases linearly with the fluctuation angle of joint surface. The larger the fluctuation angle is, the more obvious the intensity weakening will be in the shear process.

5. Conclusion

In this paper, the shear tests of saw-tooth joints with four undulating angles under five normal stresses were carried out. Due to the small number of test samples, the research content is limited. However, preliminary studies can be conducted on the mechanical properties and basic parameters of joints based on the results, and the following conclusions can be drawn:

(1) For the same joint sample, with the increase of normal stress and relief angle, the larger the peak shear strength value and residual strength value, the more significant the joint weakening.
phenomenon.

(2) The ratio between peak shear strength and residual shear strength is defined as the intensity weakening ratio. According to the data analysis, when the normal stress is small, the degree of weakening is large. When the undulation Angle increases, the weakening ratio also increases greatly. After eliminating the influence of normal stress, it can be known that the strength weakening ratio and the undulation Angle of joint surface present a good positive correlation linear relationship.

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