The closure behaviour of rock joints under impact loading

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Abstract: The dynamic properties of jointed rock and closure deformation behavior of rock joints under impact loading are of significant importance for a correct understanding of stress wave propagation or dynamic failure in the rock masses, so a serial of impact tests of the intact and joined samples was carried out based on a hammer-driven SHPB device. The cement mortar was used to make regular joint surface asperity for studying the effect of joint surface morphology on its deformation features and a dynamic B-B model was applied to describe closure curve characteristics. The test results demonstrate that the stress-strain curve of jointed rock is obviously influenced by joint roughness and the closure characteristic was affected by joint surface morphology. Specifically, the stress-strain curve of jointed rock exhibited some differences with the intact sample because of the existence of discontinuity and its roughness. The peak stress and elastic modulus of jointed rock were obviously low when compared to the intact samples. Rock joint under impact load exhibited hyperbolic deformation characteristics, and this behavior is not affected by joint surface morphologies. The dynamic initial stiffness increases and maximum allowance closure decrease with the increase of contact area ratio (CAR) and asperity inclination angle.

1 Introduction

Rock mass is inevitably encountered in engineering construction, and consists of many discontinuities, such as joints and fault, which affect the rock mechanical behavior and control the safety of rock engineering. While joint closure behaviors are a common phenomenon under dynamic loading, and this mechanical characteristic is very important to understand dynamic mechanical properties of jointed rock masses. This paper focuses on the closure deformation of joints under dynamic loading. Many theories and experiments have been developed in the field. Goodman carried out substantial laboratory experiments and suggested hyperbolic curve to describe the stress-closure behavior of joints. Bandis and Barton modified Goodman’s hyperbolic model and this had a better fit to trial data across the whole range of stress and closure values, known as BB model. BB model established some parameters such as maximum allowance closure and initial normal stiffness, which are used in practice[1-2]. A logarithmic model for joint closure was given [3-4], which provide a good fit at low stress levels. However, these models were obtained from experimental data in quasi-static loading; a
few studies have been conducted on dynamic closing behaviour of rock joint. Zhao [5] presented a dynamic BB model by taking loading-rate effect into account.

The joint closure behaviors not only were affected by the loading rate, but also by joint surface profiles. Joint roughness [6], the effective contact area [7], joint compressive strength and asperities parameters [8] were found to have a significant impact on joint initial stiffness.

The artificial joints have the following advantages in indoors rock mechanics tests: one is that it reduces the complexity of joint surface and simplifies joint model, the other is that this artificial joint morphology can be calibrated by quantitative parameters, such as asperity height, contact area and asperity inclination angle, which helps to quantitatively analyze the mechanical properties of the joints and deepen the understanding of joint dynamic properties. Therefore, in this study, the joint surface was are regular and artificial. The geometrical property of the joint surface is described by three parameters: contact area ratio, the inclination angle and asperity height. On the basis of test results, the closure behaviors of the joints under dynamic loading were discussed.

2 Experimental methodologies

2.1 Test Apparatus

All experiments reported in this study were performed using an SHPB apparatus driven by a pendulum hammer, which included an incident bar, a transmitted bar, a pendulum hammer, an absorbing bar, and a data acquisition system, as is shown in Figure 1. The diameters of the incident and the transmitted bars are the same, which are 0.05 m. The lengths of the two bars are 2.5 m and 2.0 m, respectively. The material of the bars is steel, whose density and Young’s modulus were measured as 7800 kg/m$^3$ and 210 GPa, respectively. The longitudinal wave velocity was 5188 m/s. The loading system is a pendulum hammer with a graduated board. The data acquisition system consists of a Tektronix mixed domain oscilloscope and Super-dynamic strain indicator and two strain gauges. The gauge signal of the two bars would be amplified by the strain indicator and then be displayed and recorded by the oscilloscope. The samples were sandwiched between two bars with good connection by applying Vaseline to the interface, as is shown in Figure 1.

![Figure 1. Schematic view for hammer-driven SHPB device](image)

2.2 Specimen Preparation

Testing specimens are made of cement mortar, which is mixed fine granite, cement and water in a weight ratio of 0.5:1:0.3. The mixture of cement and fine granites was shaken to make it sufficiently homogeneous and dense, and then is cured for at least 28 days to obtain the full strength of cement.
mortar. The contact area ratio was defined as the ratio of the area of the left specimen end surface $P'$ to the area of right specimens front surface $P$, as shown in Figure 2.

**Figure 2.** Arrangements of specimens with artificial joints **Figure 3.** The jointed rock samples

The specimens were divided into two series, A and B. Series A includes specimens A-1 to A-3 with three different contact area ratios, A-4 to A-5 with different inclination angles and the same asperity height of 2 mm; while series B consists of B-1 to B-5, which are the same as series A except that the asperity height is 3 mm (Fig.2; Tab.1). Besides the above mentioned 10 specimens, another two specimens, donated as A0-1 and A0-2, were used for the test, the set A0-1 was an intact cement mortar cube, and the other was comprised of two blocks with flat joints.

**Table 1.** Asperity parameters for the joints on specimens of series A.

| Series | Specimen no | A-1 | A-2 | A-3 | A-4 | A-5 |
|--------|-------------|-----|-----|-----|-----|-----|
| The contact width of ladder-tooth /a | 2mm | 3mm | 4mm | 2mm | 2mm |
| The asperity inclination angle | 60° | 60° | 60° | 75° | 90° |
| Distribution of asperities | symmetric | 4×4 |
| Number of asperities | 16 | 16 | 16 | 16 | 16 |
| Asperity height/ h | 2mm |
| Initial contact area ratio (CRA) | 5.2% | 11.8% | 20.9% | 5.2% | 5.2% |

Series B is the same with series A except the asperity height is 3 mm.

Prior to these impact tests, quasi-static test on intact specimens is carried out to determine the mechanical properties of cement mortar. The UCS is 67 MPa, the Poisson’s ratio is 0.24, the density is 2.29 g/cm³, and young’s module is 16 GPa.

The stress and strain of the specimens can be calculated by using typical methods. The impact velocity is small enough to assume that the rock only preforms linear elastic deformation when the joint preforms nonlinear deformation. Therefore, the joint normal closure can be calculated by the following equation:

$$\Delta V_j = \varepsilon L_j - \frac{\sigma (L_j - L_s)}{E}$$

Where $\Delta V_j$ represents the deformation of the joint, $\sigma$ and $\varepsilon$ is the stress and strain of the specimens, respectively. $E$ stands for the elastic modulus of the intact sample. $L_j$ and $L_s$ is the length of the specimen and joint, respectively. The loading rate is no significant effects in the elastic modulus of the material [8], hence the quasi-static value of elastic modulus can be used in the dynamic tests.

3 Test Results and Analysis
3.1 The stress-strain curve of the intact and jointed rock

To investigate the difference of dynamic properties of the intact and jointed rock, the stress-strain curve of the intact specimen (A0-1), jointed specimen with flat joint (A0-2) and roughness joint(A-1) under same impact velocity were plotted in the Figure 5. The loading rate ranges from 200 to 300 GPa/s. The stress-strain curve can be approximately divided into four stages characterized by the slope in the stress–strain response, i.e., compaction stage (OA) linear stage (AB), microcracking stage (BC) and unloading stage (CD). At compaction stage, whose slope is smaller than that in linear stage; at linear stage, the slope is nearly straight line, the specimen began to deform elastically; at microcracking stage, the small attenuation of Young’s modulus indicated that internal degradation happened, after reached the peak point, the curve comes to the unloading stage and has a negative slope. From the figure, we observed the intact sample exhibited no compaction stage and microcracking stage, the reason is that there are few internal defects in the intact rock or the stress level is relatively low. Meanwhile, it can be also observed that the maximum strain of specimen increased dramatically and the peak stress value decreased when the samples from the intact to the jointed samples and from the flat to roughness joint, which indicates that the joint and its roughness would increase the compression deformation amount of the samples.

![Stress-strain curves of different samples](image)

**Figure 4.** The stress-strain curves of different samples

3.2 The analysis of closure behavior

Based on Eq(1), the joint closure of these jointed specimens can be obtained. The joint closure-time curve of serial A and B were plotted in Figure 6. From this figure, the joint closure behavior shows the non-linear deformation with increasing of loading time. It can be observed that the peak value of joint closure decreases with the increasing of contact area ratio and the inclination angle. This suggests that the joints having large inclination angle and high contact area ratio become more stiffened and more difficult to deform. In addition, similar to the tendency of curves were also found in the samples of B serial, which indicated that the asperity height has little significant effects on joint nonlinear closing behavior subjected to this loading from the variation of stress and strain with time history. The peak values of joint closure of all samples are plotted in the Figure 6c. It can be found that the peak value decreases with the increasing asperity height (2 mm to 3 mm), however, the difference become smaller with the increasing of contact area ratio and inclination angle.
The hyperbolic model of joint normal behavior proposed by Bandis [1] is commonly used in rock mechanics and rock engineering, and is usually termed as static BB model. Zhao J [13] found that the loading rate significantly affected the values of dynamic initial stiffness and dynamic maximum allowable closure. So, the modified BB model when taking loading rate into account. It was expressed the following formula:

\[
\sigma_n = \frac{k_d^d \Delta V}{1 - \Delta V/\Delta V_m^d}
\]  

(2)

Where \( \Delta V_m^d \) represents the maximum allowable closure; \( k_d^d \) denotes initial stiffness increases, which describes the decremented ratio of dynamic joint maximum allowable closure. \( k_d^d \) and \( \Delta V_m^d \) can be determined from joint properties, such as joint wall compressive strength, joint roughness coefficient and average aperture thickness at zero normal stress, the loading rate. The present work, however, no attempt is made to develop functional relations between the joint closure parameters, and the mechanical properties and size distribution of the asperities. Figure 7 show dynamic normal closure curves at loading process for the specimens of B serial. It is found that the closure curves Figure 7 can be fitted very well with the hyperbolic function. Similar result for the specimens of A serial were also obtained.
Table 4 shows dynamic initial stiffness and dynamic maximum allowable closure obtained from these fitted curves. The test results of cement mortar samples indicated that a clear increase of initial stiffness and decrease of maximum allowable closure with increasing the inclination angle and contact area ratio. This suggests that the joints tend to be stiffened and to have small allowable deformation if subjected to dynamic loads with large inclination angles and high contact area ratio. The above results reveal that the inclination angle and contact area significantly affect the joint closure behaviour.

**Table 2. The fitted hyperbolic stress-joint closure curves**

| Specimen no | The inclination angle/θ | Initial contact area ratio (%) | Loading rate (GPa/s) | $k_a^d$ (GPa/m) | $\Delta V_m^d$ (μm) |
|-------------|--------------------------|-------------------------------|----------------------|-----------------|------------------|
| A-1         | 60°                      | 5.2%                          | 159.5                | 32.9            | 170.1            |
| A-2         | 60°                      | 11.8%                         | 137.8                | 93.07           | 142.2            |
| A-3         | 60°                      | 20.9%                         | 162.3                | 120             | 136.1            |
| A-4         | 75°                      | 5.2%                          | 150.2                | 42.5            | 136.8            |
| A-5         | 90°                      | 5.2%                          | 153.1                | 173.1           | 83.3             |
| B-1         | 60°                      | 5.2%                          | 173.7                | 9.3             | 362.3            |
| B-2         | 60°                      | 11.8%                         | 102.8                | 44.9            | 191.9            |
| B-3         | 60°                      | 20.9%                         | 161.9                | 175.9           | 183.1            |
| B-4         | 75°                      | 5.2%                          | 189.9                | 236.9           | 145.8            |
| B-5         | 90°                      | 5.2%                          | 158.8                | 315.8           | 133.3            |

3.3 The effect of contact area ratio and asperity inclination angle

To investigate the effect of contact area ratio (CAR) on joint closure behavior, these samples which have same the asperity inclination angle but different contact area ratio were selected from the Table 4 (A1, A2, A3 or B1, B2, B3). Then relations between CAR with the initial stiffness and maximum allowable joint closure were plotted in the Fig 8. It can be seen that the joint initial stiffness value generally increases with the joint contact area ratio, while maximum allowable joint closure shows the opposite trend. We can draw a conclusion that contact area ratio have important influence on joint closure properties. Similar results were observed by Li[12], who studied the dynamic response of granite samples with varying joint matching coefficients. When compared to the results of serial A and B, they showed a consistent variation in initial stiffness and some differences in maximum allowable closure. This indicated that the asperity height has little effect on joint initial stiffness but will increase
the amount of normal deformation.

These samples having same contact area ratio but different asperity inclination angles were selected from the Table 4 (A1, A4, A5 or B1, B4, B5) to study the influence of the asperity inclination angle. Then relations were plotted in the Figure 9. The initial stiffness increases while maximum allowance closure decreases with the increasing of the asperity inclination angle, which were similar with the results of CRA. That means a higher asperity inclination angle (or a flatter top of bump) would contribute to stiffer joint. When analyzing the effect of asperity height, the asperity height become more important in initial stiffness value.

![Figure 7. The effect of CAR](image1)
![Figure 9. The effect of the asperity inclination angle](image2)

4 Conclusions

Laboratory tests on the samples with artificial joint were carried out under impact loading to study the dynamic properties of jointed rock and the closure behaviors of the rock joint. The test results demonstrate that stress-strain curve of jointed rock is obviously influenced joint roughness and the closure characteristic was affected by joint surface morphology. From these experimental results, the following findings can be summarized as:

1. The stress-strain curve of jointed rock exhibited some differences with the intact sample under medium loading rate because of the joint and joint roughness. Specifically, the peak stress and elastic modulus of jointed rock were obviously low when compared to the intact samples.
2. Rock joint under impact load exhibited hyperbolic deformation characteristic, as likely static load, and this behavior is not affected by joint surface morphologies. The typical BB model can describe this deformation behavior.
3. The characteristics of closure deformation curve were affected by the joint surface morphologies. Specifically, the dynamic initial stiffness increases and maximum allowance closure decrease with the increasing of contact area ratio (CAR) and asperity inclination angle.

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