Experimental research on the shear-rate-dependent shear strength of rock-like joints

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Abstract. Shear strength is one of the most important strength parameters of rock joints, and it is also a primary parameter for the design and safety evaluation of rock mass structures. In view of the characteristic of variable deformation rates of rock joints subjected to dynamic disturbance, direct shear tests of rock-like joints under different shear displacement rates are carried out, and the law of shear strength changing with shear displacement rate is explored. The samples include planar and undulating joint samples and intact cubic samples, among which the undulation angles of undulating joints include 15° and 30°. The normal boundary of joints is a constant normal pressure. Shear displacement rates are set to 5 different values, including 2.3 mm/min, 7.6 mm/min, 13.1 mm/min, 22.2 mm/min and 47.2 mm/min. The experimental results show that the change of shear strength with shear displacement rate is related to the tangential deformation mode of joints. For planar joints and 15° undulating joints, the tangential deformation is dominated by sliding, and the shear strength decreases with the increase of shear displacement rate. While for 30° undulating joints and intact samples, the main characteristic of tangential deformation is slipping, which is caused by material failure, and the shear strength increases with the increase of the shear displacement rate. The mechanism may be that the shear strength of shear-sliding-type joints is derived from the inherent friction of the joint contact surfaces, while the shear strength of slipping-type joints is mainly dominated by the material strength of asperities. The inherent friction of contact surfaces decreases with shear displacement rate. However, the shear strength of material increases with increase of the shear displacement rate.

1. Introduction
Effect of shear rate on the shear strength of rock joints is an important issue in rock joint mechanics. In 1972, Dieterich firstly discovered that the time-dependent friction of rock fissures during the stick-slip process [1-2]. Crawford and Curran found that in different shear rate ranges, the variation trends of shear strength may be different [3]. While Barbero et al. concluded that the shear strength of planar rock joints was positively correlated with the shear loading rates [4]. Li et al. and Atapour et al. and Kleepmek et al. and Wang et al. and Qi et al. experimentally studied the relation between shear strength of artificial joints and shear rate [5-9], however, their research findings appeared to be conflicted. Several researches suggested that except for shear rate, normal loading rate also significantly affected the shear strength of planar joints [10-11]. Liu et al. explored the effect of shear rate on the shear strength of planar-filled joints, and found that the shear strength increased slightly...
with the increase in shear rate \cite{12}, Meng et al. found that both of the shear strength and residual shear strength of rough granite joints decreases with increasing shear rate \cite{13}.

Increase in normal pressure, undulation angle and roughness may lead to different failure modes of rock joints. For planar joints, the higher normal pressure, the more serious of joint surface abrasion. For undulating joints, with increasing undulation angle and normal pressure, the failure mode may transform from surface abrasion into snipping \cite{14-16}. For joints with random roughness, with increasing roughness and normal pressure, the failure mode may also transform from surface abrasion into snipping. Mechanisms of surface abrasion and snipping are different due to contribution of cohesion of material \cite{17-18}. Therefore, the transformation of failure mode of rock joints may be responsible for the conflicted results in literatures. However, differences of failure mode under various shear rate conditions are usually neglected.

In the present work, direct shear tests on planar joints, undulating joints and intact samples are carried out. Five different shear rates and constant normal loading (CNL) are applied in those tests. And then, the failure modes of tested samples are analyzed. Thirdly, the shear-rate-dependence of shear strengths is obtained. Finally, the macroscopic mechanism of shear-rate-dependence of shear strength is discussed.

2. Experimental schemes

2.1. Sample preparation
The rock-like joint samples are prepared using cement mortar. The mass ratio of water to cement was set to 1:2. The poured samples are cured for 28 days under standard curing conditions. The tested uniaxial compressive strength of the standard cylindrical sample is about 25 MPa, and the sample density is about 1.925 g/cm\(^3\). According to the discrepancy of joint profile, the samples can be divided into three types, namely planar joint, undulating joint and intact cubic sample. The undulation angles of undulating joint include 15\(^\circ\) and 30\(^\circ\). As shown in Fig. 1, an undulating joint sample consists of two blocks called upper block and lower block, respectively. For the convenience of mechanism analysis, only one trapezoidal asperity is contained in the joint profile. All the samples have an identical size of 100 mm in length, 100 mm in width and 103 mm in height. More detailed dimensions of the sample can be seen in Fig. 1.

![Figure 1. Schematic map of sample geometry and dimensions (Unit: mm). a 15\(^\circ\) undulating joint sample and b 30\(^\circ\) undulating joint sample.](image)

| Sample type          | Joint profile                  | Shear rate \(v\) (mm/min) | Normal pressure \(\sigma_0\) (MPa) |
|----------------------|--------------------------------|----------------------------|----------------------------------|
| Planar joint sample  | Plane                          | 1.0, 2.0, 3.0              |                                  |
| Undulating joint sample  | 15\(^\circ\) trapezoidal asperity | 0.5, 1.0                  |                                  |
| Undulating joint sample  | 30\(^\circ\) trapezoidal asperity | 2.3, 7.6, 13.1, 22.2, 47.2 | 0.5, 1.0                         |
| Intact cubic sample   | —                              | 1.0                       |                                  |

2.2. Loading schemes
All tests are conducted on an MST-600E type servo-controlled direct shear testing apparatus. The loading schemes are shown in Table 1. Considering the lower normal pressure, the constant normal
Load (CNL) boundary is adopted. The normal loading rate is set to 0.1 kN/s. The multi-stage shear programme [19] is applied for direct shear tests for planar joints, and the single shear programme is adopted to test undulating joint samples and intact cubic samples. The shear rates include 5 values ranging from 2.3 to 47.2 mm/min. Identical shear rate setting is adopted in tests for three types of samples.

3. Experimental results and analysis

3.1. Failure modes of joints

**Planar joints**

Figure 2 presents some typical shear stress-shear displacement curves of planar joints under different conditions. For planar joints, the deformation process can be divided into two main stages, namely stress-accumulation stage and stable-slip stage. Stable-slip is the most significant deformation stage during direct shear process. The failure mode of planar joint is shear-sliding. Its mechanism is the wear damage of small-scale asperities on joint surface.

Shear rate has no marked influence on the shear stress-shear displacement curve profiles. In another word, failure mode of planar joints is shear-rate-independent. In addition, with increasing normal pressure, slight stress fluctuation arises during stable-slip process. The reason lies in the failure of surface asperities.

**Undulating joints**

Shear stress-shear displacement curves of 15° undulating joints are plotted in Fig. 3. Deformation mode of 15° undulating joints is more similar with that of planar joints. It means that the failure mode of 15° undulating joints is shear-sliding. Moreover, under normal pressure 0.5 MPa and 1.0 MPa, the profiles of shear stress-shear displacement curves are some different. When normal pressure equals 1.0 MPa, the shear-softening is more apparent. Effect of shear rate on the failure mode of 15° undulating joints is not very apparent. This phenomenon may imply the potential in transformation of failure mode.

![Figure 2](image)

**Figure 2.** Shear stress-shear displacement curves of planar joints.

![Figure 3](image)

**Figure 3.** Shear stress-shear displacement curves of 15° undulating joints. a $\sigma_n$=0.5 MPa and b $\sigma_n$=1.0 MPa.
Figure 4 presents typical surface abrasion of 15° undulating joints. It is seen that at an identical shear rate, the higher normal pressure, the more serious surface abrasion. Due to the increase in normal pressure, the contacts between upper block and lower block become more and more tight, and the shear resistance of joint increases consequently. Thus, relative climbing movement between two contact surfaces is harder to develop, and the deformation degree of asperities may increase consequently. It can be inferred that once the normal pressure is high enough, the shear-sliding failure mode may transform into snipping failure mode.

Figure 4. Typical surface abrasion of 15° undulating joints.

Figure 5 presents the shear stress-shear displacement curves of 30° undulating joints. Remarkable discrepancy can be seen compared with those of planar joints and 15° undulating joints. Under most test conditions except for \( v=2.3 \) mm/min, \( 7.6 \) mm/min and \( \sigma_n=0.5 \) MPa, stress-drop phenomenon in the post of peak is obvious. When \( v=2.3 \) mm/min, \( 7.6 \) mm/min and \( \sigma_n=0.5 \) MPa, shear stress peak cannot be seen, but the stable-slip is apparent. These results imply that with the increase in shear rate, the shear-sliding failure mode transforms into snipping failure mode.

Figure 5. Shear stress-shear displacement curves of 30° undulating joints. a \( \sigma_n=0.5 \) MPa and b \( \sigma_n=1.0 \) MPa.

Figure 6. Typical asperity damage of 30° undulating joints.
Figure 6 plots the asperity damage of 30° undulating joints under some test conditions. When shear rate equals 2.3 mm/min, 7.6 mm/min and normal pressure equals 0.5 MPa, the completeness of the trapezoidal asperity is reserved while only surface abrasion of asperity can be observed. When shear rate and normal pressure is increased, the asperity is gradually destroyed. The serious asperity damage leads to stress drop in shear stress-shear displacement curve. Obviously, under lower shear rate and lower normal pressure, the failure mode of 30° undulating joints is shear sliding. With the increase of shear rate and normal pressure, the failure mode finally transforms into snipping. 

The shear resistance of 30° undulating joint mainly relies on the strength contribution of the trapezoidal asperity. Once the asperity is destroyed, the shear resistance would be reduced significantly. And then, the shear sliding will arise along the fresh rough surface. During the sliding phase, shear stress gradually decreases until the residual strength is reached.

![Image](image.png)

**Figure 7.** Shear stress-shear displacement curves of intact cubic samples.

**Intact cubic samples**
Shear stress-shear displacement curves of intact cubic samples are plotted in Fig. 7. Similar with those of 30° undulating joints, dramatic stress drop also arises in the post of peak. The stress drop is caused by shear failure of the intact sample. After the stress drop, shear stress may increase in a small amplitude, which is not observed in shearing process of 30° undulating joints. A larger scale fresh rough surface and higher roughness may be the reason for small-amplitude increase in shear stress. After the small-amplitude stress increase, shear-sliding process gradually evolutes.

Even though shear rate is altered, curve profiles of shear stress-shear displacement are not notably changed, whereas stress drop become more and more serious. It means that the snipping failure mode of intact samples is not affected by shear rate.

**Table 2.** Failure modes of samples under different conditions.

| Sample               | Shear rate (mm/min) | Normal pressure (MPa) | Failure mode  |
|----------------------|---------------------|-----------------------|--------------|
| Planar joint sample  | 2.3, 7.6, 13.1, 22.2, 47.2 | 1.0, 2.0, 3.0          | Shear sliding |
| 15° undulating joint | 2.3, 7.6, 13.1, 22.2, 47.2 | 0.5, 1.0              | Shear sliding |
| 30° undulating joint | 2.3, 7.6            | 0.5                   | Shear sliding |
|                      | 13.1, 22.2, 47.2     | 0.5                   | Snipping      |
|                      | 2.3, 7.6, 13.1, 22.2, 47.2 | 1.0                   | Snipping      |
| Intact cubic sample  | 2.3, 7.6, 13.1, 22.2, 47.2 | 1.0                   | Snipping      |

According to above results, it can be concluded that normal pressure, joint profile, and shear rate have an effect on the failure mode of rock-like joint samples. The general failure modes of samples under different conditions are summarized in Tab. 2.

3.2. Shear-rate-dependent shear strength
Figure 8 illustrates the relation between shear strength and shear rate for planar joints. It is noted that the horizontal axis denotes the logarithm of shear rate $v$. From Fig. 8, shear strength of planar joints negatively changes with logarithm of shear rate. Linear regression is adopted to quantify relation between shear strength and logarithm of shear rate, that is,

$$\tau_v = \tau_0 - A \ln v$$  \hspace{1cm} (1)
where $\tau_s$ denotes shear strength; $\tau_s$ and $A$ are unknown constants.

The fitted results are plotted in Fig. 8. It is seen that linear function can well describe the relation between shear strength and logarithm of shear rate. Values of parameter $A$ under three normal pressure levels are very close, and with increasing normal pressure, variation rates of shear strength present a small-amplitude increase. That means influence of normal pressure on variation rates of shear strength is weak.

As for undulating joints, variation trends of shear strength with shear rate show some different characteristics (as shown in Fig. 9). According to Fig. 9(a), for $15^\circ$ undulating joints, shear strength tends to decrease with the increase in shear rate. Similar results are obtained under normal pressure $0.5$ MPa and $1.0$ MPa. However, variation rate under normal pressure $0.5$ MPa is obviously slower than that under normal pressure $1.0$ MPa. The reason for this phenomenon has not been clearly understood yet.

However, under two normal pressure levels, shear strengths of $30^\circ$ undulating joints appear different variation trends as shown in Fig. 9(b). Under normal pressure $0.5$ MPa, with increasing shear rate, shear strength first decreases, and then increases inversely. While normal pressure equals $1.0$ MPa, shear strength keeps increasing as shear rate increases. This interesting finding has not been seen in previous research works. We think the reason for this result may lie in the discrepancy of deformation mode under different normal pressures levels. And that will be discussed in detail in Sec. 4.
As illustrated in Fig. 10, shear strength of intact cubic samples monotonously increases with the increase in shear rate. Relation between shear strength and logarithm of shear rate fits with linear function well. Compared with that of 30° undulating joints, variation rate of shear strength of intact sample is larger. This finding can be easily comprehended. According to previous research works, rate-strengthening is a common nature of rock, concrete and other geotechnical materials [20].

4. Discussion
Experimental results show that normal pressure and joint profile affect the shear-rate-dependent shear strength of joints. Moreover, lower shear rate, lower normal pressure and smaller undulation angle result in a negative relation between shear strength and shear rate. On the contrary, higher shear rate, higher normal pressure and larger undulation angle may lead to a positive relation between shear strength and shear rate. These seemingly conflicted findings may be related with the discrepancy of failure mode under different conditions. Some theoretical models may help to support this view.

Patton put forward the bilinear strength model through shear tests of saw-tooth joints [21], that is,

\[ \tau = \sigma_n \tan (\phi_b + i), \quad \sigma_n < \sigma_f \] (2)
\[ \tau = c + \sigma_n \tan (\phi_b + i), \quad \sigma_n \geq \sigma_f \] (3)

where \( \phi_b \) and \( \phi_r \) denote the basic friction angle and residual friction angle, respectively; \( i \) is the undulation angle; \( \sigma_f \) denotes the normal pressure threshold.

When normal pressure is lower than the threshold \( \sigma_f \), only shear sliding develops during shearing process. Only shear dilation and friction are believed to contribute to the shear strength of joints. For the very reason, Eq. (2) is widely called Patton’s shear dilation model. Once normal pressure exceeds the threshold \( \sigma_f \), snipping of large-scale asperities occurs, and the contribution of cohesion to joint shear strength has to be taken into account. Because the strength of asperities plays a more important role in the joint shear strength.

Based on the principle of conservation of energy, Ladanyi and Archambault proposed a strength criterion reflecting the failure characteristics of joints [22], that is,

\[ \tau = \frac{\sigma_n (1-a_s)(V + \tan \phi_b) + a_s \tau_R}{1 - (1-a_s)V \tan \phi_b} \] (4)

where \( a_s \) denotes the proportion of snipping-failure zone; \( V \) denotes shear dilation ratio; \( \tau_R \) is the shear strength of intact rock; \( \sigma_n \) is the uniaxial compression strength of intact rock.

When the joint is undamaged, \( a_s \) tends to be 0 and the shear dilatancy ratio \( V \) tends to be tan \( i \). In this case, Eq. (4) is consistent with Patton’s shear dilation model as Eq. (2). When snipping failure occurs to joint asperities, as gradually approaches 1. In this case, the joint shear strength gradually approaches that of the intact rock, that is, the strength of the material gradually plays a greater role.

In terms of shear-sliding-type joints, based on Patton’s shear dilation model, shear strength is proportional to normal pressure, dilatancy angle and friction angle. The experimental results show that shear strength of planar joints decreases as shear rate increases (as shown in Fig. 8). It means that the friction angle is negatively correlated with shear rate. Additionally, with the evolution of joint surface abrasion, the shear dilation angle tends to be smaller. All of these variation result in a negative correlation between shear strength and shear rate. For instance, the shear strength of 15° undulating joints decreases with increasing shear rate (see Fig. 9(a)). Moreover, under normal pressure 0.5 MPa, when shear rate increases from 2.3 mm/min to 7.6 mm/min, the failure modes of 30° undulating joints are shear sliding and have no change. As shown in Fig. 9(b), tested shear strength indeed decreases as shear rate increases.

As for snipping-type joints, according to Ladanyi & Archambault’s model, when the large-scale asperity snipping occurs, \( a_s \) gradually tends to approach 1, which means the shear strength of the large-scale asperity gradually plays a dominated role in the joint shear strength. According to the experimental results of intact cubic samples (as shown in Fig. 10), the shear strength is positively shear-rate-dependent. The shear strength of 30° undulating joints generally increases with shear rate
consequently. In addition, Patton’s bilinear strength model also implies that if snipping-failure of large-scale asperities occurs, cohesion will make an important contribution to the shear strength of joints.

5. Conclusions
Failure modes of joints is affected by shear rate, undulation angle and normal pressure. A smaller undulation angle, lower normal pressure and shear rate result in a shear-sliding failure of joints. With increasing shear rate, undulation angle and normal pressure, the shear-sliding failure may transform into snipping failure.

For planar joints and 15° undulating joints, shear strengths are negatively correlated with shear rate. For 30° undulating joints and intact cubic samples, shear strengths generally increase with increasing shear rates, even though shear strength of 30° undulating joints firstly decreases and then increases when normal pressure equals 0.5 MPa.

Whether shear strength is positively correlated with shear rate may be affected by failure mode of joints. When the shear sliding plays a dominated role in joint failure, the shear strength generally decreases with the increase in shear rate. On the contrary, if the joint failure is dominated by snipping of large-scale asperities, a positively shear-rate-dependent shear strength is obvious. The reason may be that the mechanism of shear-sliding mode is joint surface abrasion, while that of snipping failure is damage and failure of material. Friction dominates the shear-sliding mode and cohesion dominates the snipping mode.

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