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FRICTIONAL BEHAVIOR OF SANDSTONE FRACTURES UNDER PRE-PEAK CYCLIC LOADING CONDITIONS

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บทคัดย่อ

วัตถุประสงค์ของการศึกษาคือเพื่อหาผลกระทบของการให้แรงเฉือนแบบวัฏจักร โดยให้ค่าความกว้างของคลื่นต่ำกว่าค่ากำลังเฉือนสูงสุดของรอยแตกในหินทรายชุดพระวิหาร รอยแตกในหินถูกจำลองขึ้นในห้องปฏิบัติการด้วยวิธีการกดแนวเส้นซึ่งจะได้รอยแตกภายใต้แรงดึง รอยแตกถูกเฉือนแบบวัฏจักรในทิศทางไปข้างหน้าและดันกลับมาข้างหลังภายใต้ความเค้นกดมีค่าระหว่าง 1-4 เมกะปาสคาล การทดสอบการเฉือนแบบวัฏจักรมี 2 สภาวะ โดยใช้ตัวอย่างหินสองชุด คือ 1) ให้ความกว้างของคลื่นความเค้นคงที่ และ 2) ให้ความกว้างของคลื่นการเคลื่อนตัวคงที่ โดยดำเนินการภายใต้ 50 วัฏจักร ผลที่ได้ระบุว่าการเฉือนรอยแตกแบบวัฏจักรจะลดค่ากำลังเฉือนและความยืดหยุ่นของรอยแตกได้เล็กน้อยในทั้งสองสภาวะ ปรากฏการณ์นี้เป็นผลมาจากความขรุขระของผิวรอยแตกลำดับที่สองถูกเฉือนออกไป พลังงานที่ใช้ในการเฉือนรอยแตกจะเพิ่มขึ้นในแต่ละรอบสำหรับการทดสอบแบบความกว้างของคลื่นความเค้นคงที่ แต่จะลดลงสำหรับการทดสอบแบบความกว้างของคลื่นการเคลื่อนตัวคงที่ ค่ากำลังเฉือนของรอยแตกหลักจากถูกเฉือนแบบวัฏจักรแล้วจะมีค่าต่ำกว่าค่ากำลังเฉือนของรอยแตกที่ไม่ได้ถูกเฉือนแบบวัฏจักร

ABSTRACT

The objective of this study is to determine the effect of cyclic loading under pre-peak condition on shearing behavior of fractures in Phra Wihan sandstone. The fractures are artificially made in the laboratory by tension inducing method. Specimens are sheared cyclically under forward and fully backward loading paths with constant normal stresses of 1, 2, 3 and 4 MPa. Two cyclic loading conditions are performed on separate sets of specimens: constant stress amplitude and constant displacement amplitude. A total of 50 shear cycles are applied for both conditions. The results indicate that the pre-peak cyclic loading can slightly reduce shear strengths and stiffness of the sandstone fractures. The cyclic loading under both conditions can degrade the second order asperities of the fractures. The energy required to shear the fractures increases with loading cycles for constant stress amplitude testing, but decreases for constant displacement amplitude testing. The monotonic shear tests conducted after cyclic loading show the fracture peak shear strengths that are slightly lower than those of the identical fractures without cyclic loading.

KEYWORDS: Phra Wihan Sandstone, Asperity, Shear Amplitude, Cyclic Loading

1. Introduction

Joint shear strength is one of the key properties used in the stability analysis and design of engineering structures in rock mass, e.g. slopes, tunnels and foundations. The conventional method currently used to determine the joint shear strength is the direct shear testing [1]. The joint properties, such as roughness, strength, separation, gouge and even the spatial distributions make the behavior of jointed rock masses more complicated [2]. Most previous laboratory experiments on the mechanical properties of rock joints have been focused on determining the peak shear strength and shear displacement under unidirectional shear loading. Cyclic shearing due to seismic and earthquake loadings can however affect the shear strength. Hosseini et al. [3] state that small repetitive earthquakes may not make considerable movements, but because of their repetitive nature they may affect the shearing resistance of rock joints. The cyclic effect has been recognized by Hutson and Dowding [4], Jafari et al. [5], Mirzaghorbanali et al. [6] and Kamonphet et al. [7] who commonly conclude that the cyclic shear loading beyond the peak shear strength can reduce the friction of rock fractures to their residual shear strengths. The cyclic loading can degrade the first and second order asperities along the joint surface and hence reduce its shear strength.

Liu et al. [8] and Fathi et al. [9] investigate the shear fatigue damage in rock joints under pre-peak cyclic loading condition. They find that the peak shear strength of fracture decreases with increasing loading cycles. The shear strength of rock joints under cyclic loadings may be an important consideration for long-term stability of engineering structures in the areas where seismic activity and ground vibration occur. Even though the cyclic shear effect beyond the peak shear strength has long been recognized, data basis regarding the effect of the cyclic loading below the peak strength (pre-peak loading cycle) have rarely been produced. In particular, the previous testing has been performed by using one-directional cyclic loading path. Laboratory investigation on the cyclic loading effect under forward to fully backward loading paths has never been conducted. It is presumed in this study that such forward-backward loading path would occur on the rock blocks on mass of rock blocks under in-situ condition where seismic activity occurs.

The objective of this study is to assess the effects of cyclic loading on the frictional behavior of sandstone fractures. The effort primarily involves performing series of cyclic direct shear tests on tension-induced fractures. Two cyclic loading conditions are performed: constant shear stress amplitude and constant shear displacement amplitude. The pre-peak cyclic loading is applied in forward to fully backward manner for both conditions. The fracture shear strength and degradation of fracture asperities under the two cyclic loading conditions are of interest.

2. Rock Samples

Rock sample selected for this study is Phra Wihan sandstone. It is fine- to coarse-grained rock grayish white and composed mainly of quartz and feldspar with very few mica. The grains are uniform, well sorted and angular. The rock comprises 72% quartz (0.2-0.8 mm), 20% feldspar (0.1-0.8 mm), 3% mica (0.1-0.3 mm), 3% rock fragment (0.5-2 mm), and 2% other (0.5-1 mm). The block specimens are prepared to have nominal dimensions of 10×10×16 cm^3. Tested fractures are prepared by applying a line load at the mid-section of the specimen until splitting tensile failure occurs (tension-induced fracture). The nominal fracture area is 10×10 cm^2. Figure 1 shows example of laser scanned images of the fractures. The maximum asperity amplitudes are used to estimate the joint roughness coefficients (JRC) for each fracture based on Barton's chart [10]. The JRC values for all prepared fractures are in the range of 10-11. The rock density is determined based on ASTM standard practice [11] as 2.32 g/cc. The uniaxial compressive strength obtained from relevant studies [12] on the same sandstone is 68.6 MPa. A total of 28 sandstone fractures has been prepared.

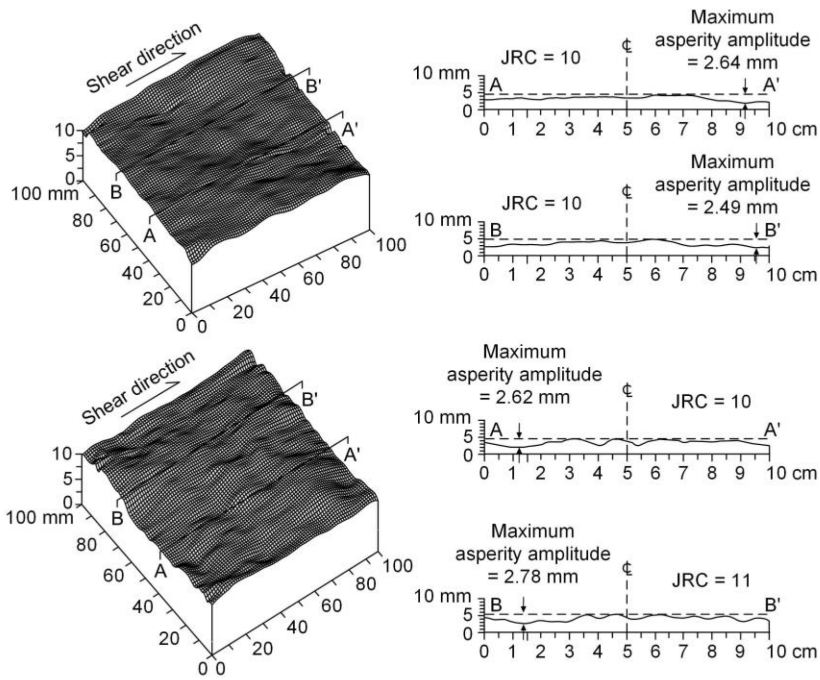

Figure 1 Some fracture images obtained from laser scanning

3. Test Apparatus and Method

The test method and calculation follow as much as practical the ASTM [1] standard practice, where applicable. Each specimen is sheared under a constant normal stress using a direct shear device (SBEL DR44) (Figure 2). The applied constant normal stresses are 1, 2, 3 and 4 MPa. The shear rate is maintained constant at 1 kN/s. A total of 50 shear cycles is performed. Two separate series of testing are conducted: constant shear stress amplitude and constant shear displacement amplitude. The shear amplitudes for both test series are set as 25, 50 and 75% of the peak shear strength (τ_p) and of the peak shear displacement (d_p). The applied shear forces and the corresponding shear displacements are monitored and recorded. Figure 3 shows the forward-backward cyclic loading path which is used for both constant stress and constant displacement conditions. One loading cycle is divided into four stages: forward (stage I) to reach the defined maximum stress or displacement; returning (stage II) the shear to original; backward (stage III) to reversely reach the maximum stress or displacement, and returning (stage IV) to original position. Due to the limitation of the available shear device, the cyclic frequency is relatively low, about 4 cycles/hour. The effect of cyclic frequency is not investigated in this study.

First, direct shear testing is performed under monotonic loading using a separate set of sandstone specimens with identical tension-induced fractures. The normal stresses used are 1, 2, 3 and 4 MPa. The fractures are sheared beyond their peak strength.

Figure 2 Direct shear device SBEL DR44 used in this study

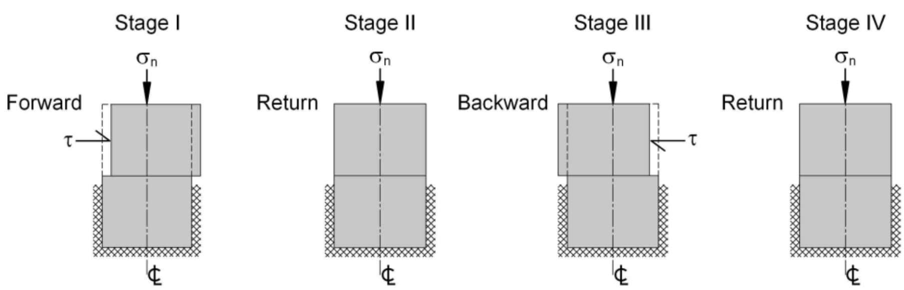

Figure 3 Shearing path for forward-backward cyclic loading in one cycle

This is primarily to obtain the peak shear strength and peak shear displacement under each normal stress. The results show the friction angle of 40 degrees with cohesion of 0.9 MPa. The peak strengths and displacements are used to define the shear stress and shear displacement amplitudes for the cyclic shear testing under constant stress and constant displacement conditions, as shown in Table 1.

After the cyclic loading test is completed for 50 cycles, the sheared fractures are again subjected to monotonic loading beyond the peak strength to assess the effect of cyclic loading of the two test conditions on the peak and residual strengths of the same fractures.

Table 1 Test variables for constant shear stress amplitude and constant shear displacement amplitude.

σ_n (MPa)	Monotonic loading		Cyclic loading	
	τ_p (MPa)	d_p (mm)	Constant shear stress amplitude (MPa)	Constant shear displacement amplitude (mm)
1	1.80	0.85	0.50 ($0.25\tau_p$)	0.23 ($0.25d_p$)
			1.00 ($0.50\tau_p$)	0.45 ($0.50d_p$)
			1.40 ($0.75\tau_p$)	0.68 ($0.75d_p$)
2	2.47	1.10	0.60 ($0.25\tau_p$)	0.28 ($0.25d_p$)
			1.20 ($0.50\tau_p$)	0.55 ($0.50d_p$)
			1.80 ($0.75\tau_p$)	0.83 ($0.75d_p$)
3	3.43	1.20	0.85 ($0.25\tau_p$)	0.30 ($0.25d_p$)
			1.70 ($0.50\tau_p$)	0.60 ($0.50d_p$)
			2.55 ($0.75\tau_p$)	0.90 ($0.75d_p$)
4	4.27	1.50	1.20 ($0.25\tau_p$)	0.38 ($0.25d_p$)
			3.00 ($0.50\tau_p$)	0.75 ($0.50d_p$)
			3.50 ($0.75\tau_p$)	1.13 ($0.75d_p$)

4. Test Results

Figure 4 shows shear stress (τ) as a function of shear displacement (d) for the constant shear stress amplitude with normal stresses of 1 and 4 MPa. All specimens show that the shear displacement for each cycle increases with increasing shear cycles, particularly under high shear stress amplitude (τ_A). After the first few cycles under high shear stress amplitude (τ_A = 1.4 MPa or 75% of peak strength, τ_p), the shear displacement progresses in the forward direction more than that in the backward direction. This may be due to that the sheared-off rock powder has accumulated in the fracture aperture. The larger number of shear cycles, the more rock powder has deposited in the aperture. This phenomenon has not been observed for the lower shear stress amplitude (τ_A = 0.5 MPa or 25% of peak strength) testing. The results also suggest that the cyclic loading with shear stress amplitudes from 25% to 75% of the peak strength has some impact on the fracture shear strength. This is evidenced by that the monotonic loading results of the identical fracture (no cyclic loading, solid lines in Figure 4) are slightly higher than those of the fractures after subjecting to the cyclic loading (dash line in Figure 4).

Figure 5 shows the cyclic loading results under constant shear displacement amplitude (d_A). The shear stress of each cycle decreases with increasing loading cycles, particularly under high normal stress and large displacement amplitude (d_A=1.13 mm or 75% of d_p). This may be because the second order asperities have been sheared-off during the first few loading cycles. Smaller shear stresses are therefore required for the subsequent cycles to reach the same displacement amplitude (d_A). This observation holds true for all normal stresses and all displacement amplitudes.

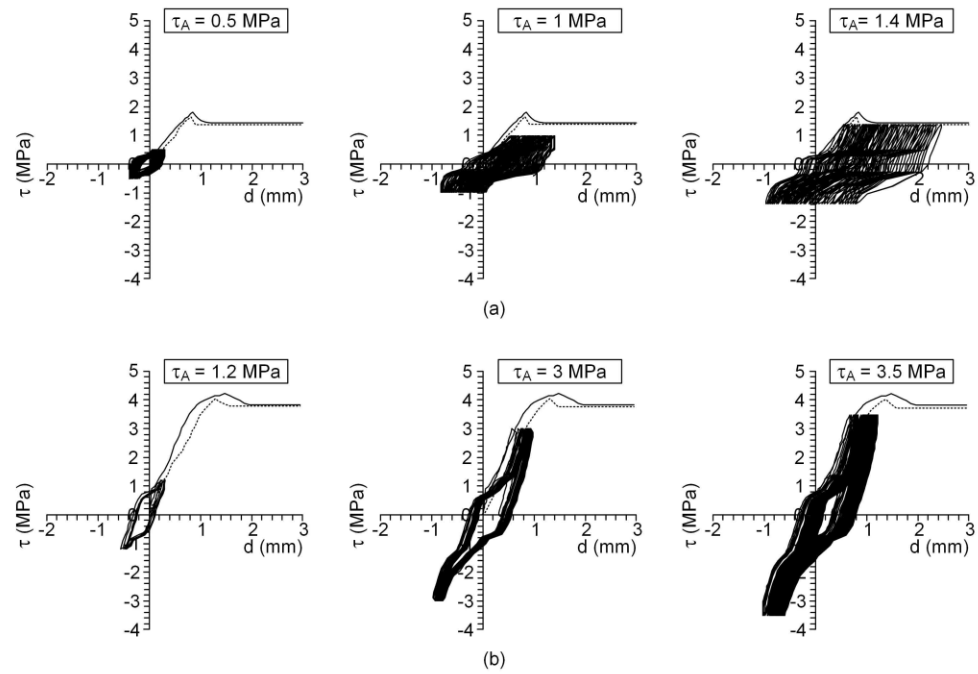

Figure 4 Shear stress-displacement curves for constant shear stress amplitude under normal stresses of 1 MPa (a) and 4 MPa (b). The cyclic shear results are compared with monotonic loading of identical fractures (solid lines). Dash lines are shear strengths of fractures after subjecting cyclic loading

Similar to the constant stress amplitude testing, the pre-peak cyclic loading under constant displacement amplitudes (d_A) also has some impact on the fracture shear strengths. The shearing resistances under monotonic loading for the original fractures (solid line in Figure 5) are slightly higher than those of the fractures after subjecting to 50 shear cycles (dash line in Figure 5). More discussions in the issues are given in the following sections.

5. Cyclic Loading Effect on Joint Shear Stiffness

The fracture shear stiffness (K_s) values for both cyclic test conditions are determined and compared with those of the monotonic loading on the original fractures and on the fractures after subjecting to cyclic loading. The results are shown in Figure 6 for normal stresses of 1 and 4 MPa. Both cyclic loading tests show rapid deceases of Ks within the first few cycles.

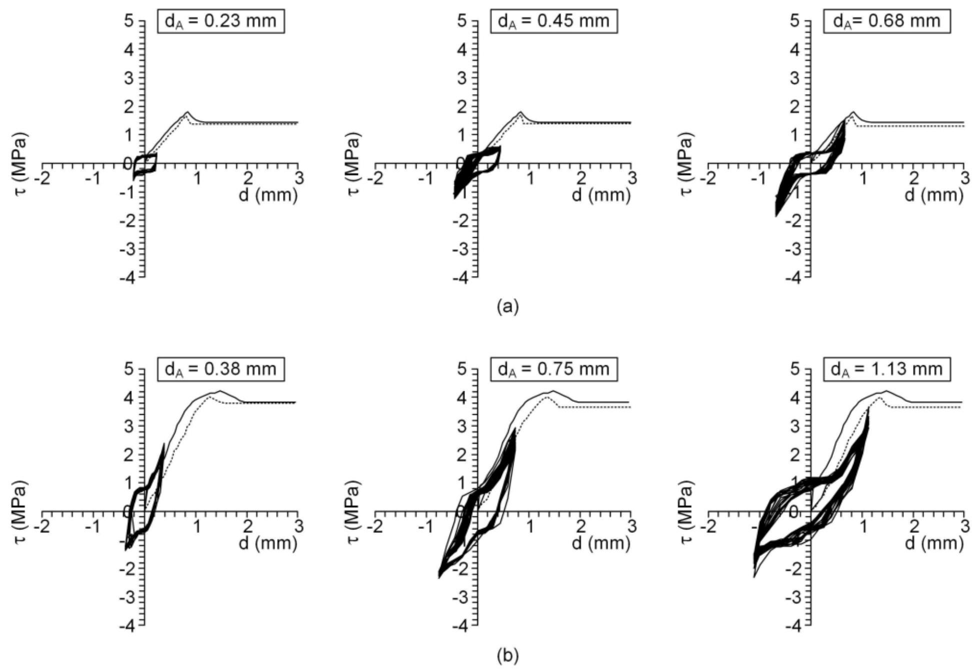

Figure 5 Shear stress-displacement curves for constant shear displacement amplitude under normal stresses of 1 MPa (a) and 4 MPa (b). Solid and dash lines are monotonic loading results of original fractures and of fractures after cyclic loading, respectively

This is probably due to the degradation of the second order fracture asperities. The stiffness tends to approach certain values after 10 to 20 loading cycles (N). Fractures under constant stress amplitudes (Figure 6b) tend to degrade more quickly than those under constant displacement amplitude (Figure 6a). The results also show that the fracture shear stiffness under monotonic loading ($K_{s,post}$) after subjecting to cyclic loading is slightly lower than those of the original fractures ($K_{s,pre}$). This supports the previous observations that the shear strengths of the original fractures are slightly higher than those of the fractures after subjecting to cyclic loading.

6. Shear Energy

An attempt is made here to analyze the fracture shear strengths and displacements under cyclic loading by simultaneously considering both shear stress and shear displacement. The shear energy principle proposed by Hutson and Dowding [3] is applied to the test results obtained here. The energy (U) required to shear a rock fracture can be calculated by:

$$U = \sigma_n \cdot d_n + \tau_A \cdot d \tag{1}$$

where σ_n is normal stress and is normal displacement (dilation). Figure 7 shows the energy (U) calculated for all loading cycles under normal stresses of 1 MPa and 4 MPa for both test conditions. The results indicate that the energy required to reach a constant shear stress amplitude tends to increase with loading cycles (Figure 7a). On the other hand, the energy required to reach a constant displacement amplitude tend to decrease with increasing the loading cycles (Figure 7b). This is primarily because the shear displacement for the constant stress amplitude testing progressively increases with the loading cycles (see Figure 4) while the shear stress for the constant displacement amplitude testing tends to decrease with increasing loading cycles (see Figure 5). The diagrams in Figure 7 also show that the energy required to monotonically shear the fracture through beyond the peak strength is higher than those required during cyclic loading. The monotonic shearing of the original fractures requires energy (U_{pre}) slightly higher than does the shearing of fractures after cyclic loading (U_{post}). This agrees with the previous observations on the fracture shear strength and shear stiffness given in the previous sections.

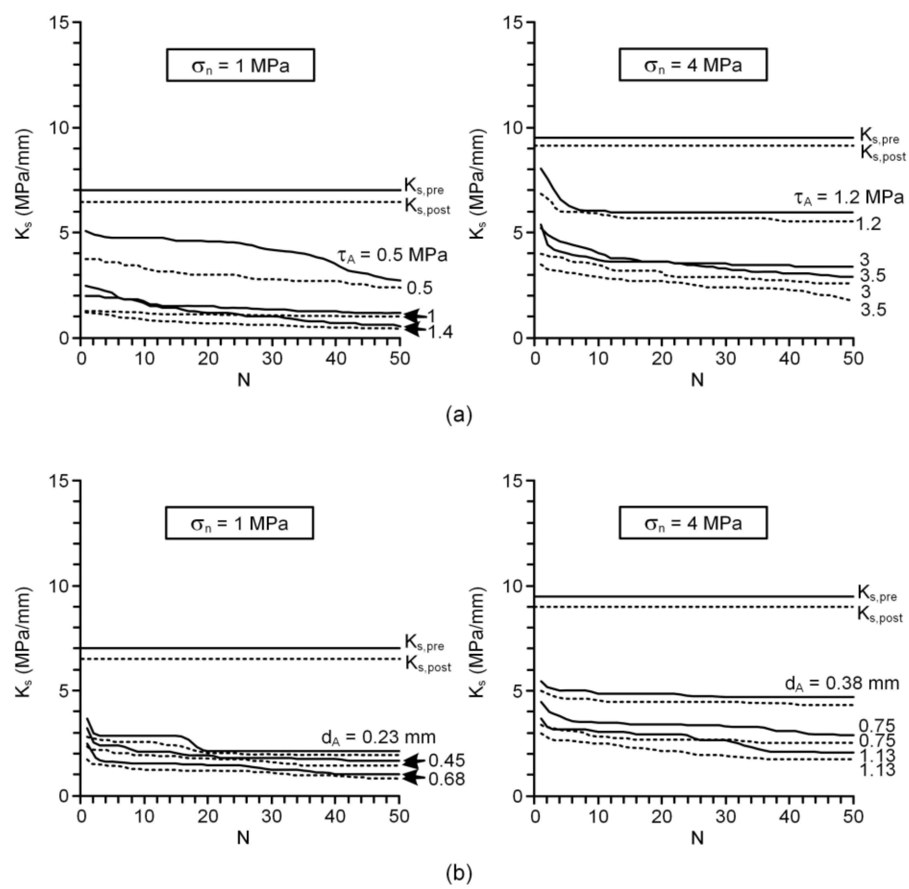

Figure 6 Fracture shear stiffness (K_s) as a function of number of cycles (N) for constant shear stress amplitudes (a) and constant shear displacement amplitudes (b). Solid and dash lines are monotonic loading results of original fractures and of fracture after cyclic loading, respectively

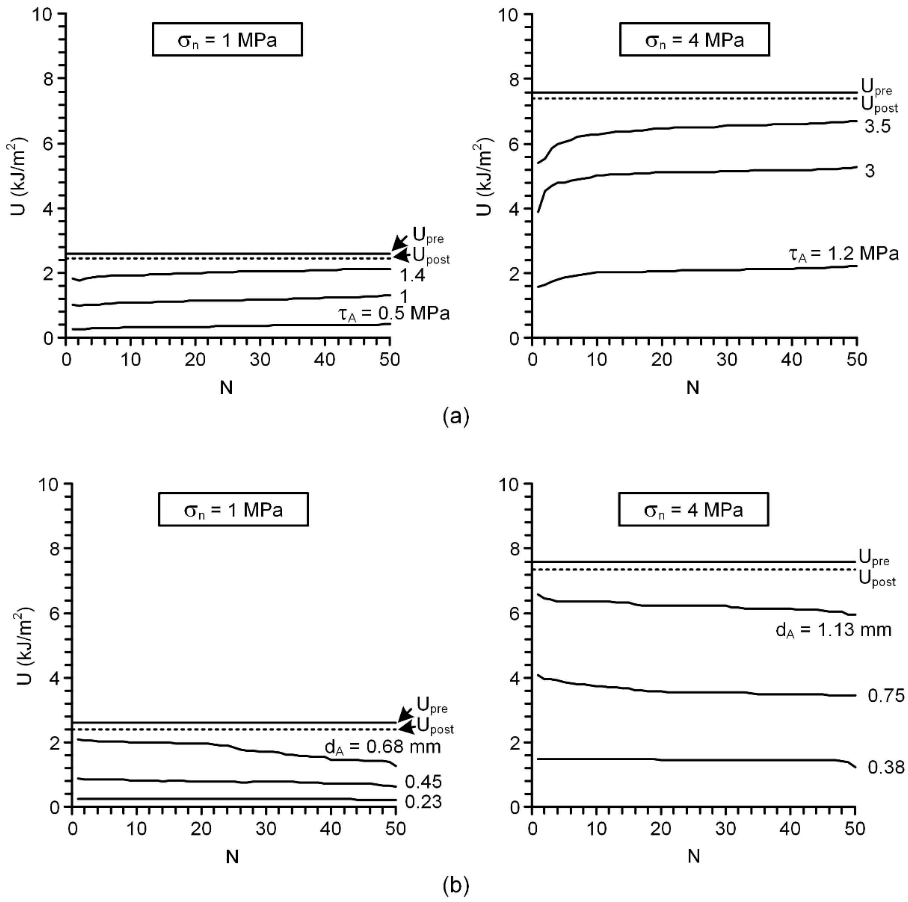

Figure 7 Energy (U) as a function of shear cycle (N) for constant shear stress amplitudes (a) and constant shear displacement amplitudes (b). Solid and dash lines are monotonic loading results of original fractures (U_{pre}) and of fracture after cyclic loading (U_{post}), respectively

7. Discussions and Conclusions

The 50 cycles of loading under both test conditions seem adequate to assess the effects of cyclic shearing on the fracture shear strength and stiffness. This is evidenced by the clear trends of the reduction or enhancement of the fracture shear stiffness (Figure 6) and of the energy required to displace the fractures under both test conditions. The results of forward-backward cyclic loading under constant stress amplitudes obtained here agree reasonably well with those of Liu et al. [8] and Fathi et al. [9]. These investigators use only forward loading, without backward loading. The forward-backward cyclic loading under constant stress amplitude and particularly under constant displacement amplitude has never been performed anywhere. Due to the complexity of the seismic responses of the rock blocks or mass of rock blocks under in-situ condition, it is believed that the actual movement of these blocks would be governed by the loading characteristics that lie within the two extreme conditions simulated in this study. A significance finding obtained here is that the pre-peak cyclic loading can reduce the rock fracture shear strengths. The shear strength reduction is however small as compared to those of the fractures that are subjected to the post-peak cyclic loading as previously performed by other investigators [2-5].

Admittedly the conclusions drawn above are limited to one rock type with relativity smooth fractures (JRC = 10-11). Obtaining test results on a variety of rock strengths and roughness would likely enhance the reliability of the conclusions drawn here or gain more understanding and knowledge on the fracture shearing behavior under pre-peak cyclic loading.

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