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Shear Behaviour of Rock Joints Under Cyclic Loading

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ABSTRACT

For the design of civil and mining engineering geo-structures, it is often necessary to investigate the behaviour and the role of discontinuities on the rock mass performance. In many cases, failure is governed by the shear behaviour of discontinuities in excavations. In this context, evaluation of the effects of small repetitive earthquakes on the shear strength parameters of rock joints especially in tunnels and dam foundations is also important. This paper presents the results of a systematic study carried out on the cyclic shear behaviour of artificial rock joints under constant normal stiffness (*CNS*) conditions, as many of the previous studies have been conducted under constant normal load (*CNL*) conditions. To understand the basic mechanisms involved, idealized joint samples were subjected to cyclic loading using a large scale direct shear apparatus for different stress amplitudes. The mechanisms behind the shearing under cyclic loading at low and high level of normal stresses have been investigated and compared with *CNL* conditions experiments. The results indicate that asperity sliding and shearing are the two main mechanisms governing the mechanical behaviour of joints under cyclic loading. Moreover, the joint cyclic dilation is overestimated under the *CNL* conditions.

Key word: Rock joints, cyclic shearing, shear strength, asperity degradation,

1 Introduction

It is well known that the mechanical behaviour of a rock mass is affected by the presence of rock joints within the mass. As a result a different joint behaviour will also result in a different rock mass behaviour. For a joint with a rough surface, the dilatancy phenomenon is observed with shear deformation. When this dilation is confined due to the stiffness of the surrounding rock mass the normal stress increases, i.e. *CNS* conditions, and the joint asperities are subjected to an increased damage upon additional shear displacement. The damage is even more pronounced if cyclic loading, e.g. from small repetitive earthquakes, is exerted onto the asperities under *CNS* conditions.

Although a considerable number of studies has been conducted on the shear behaviour of rock joints, the great majority are under monotonic conditions (Patton, 1966; Jaeger, 1971; Barton, 1973; Indararatna and Haque, 1997; Indraratna et al., 1998; Indraratna et al., 2010). Plesha (1987) studied the cyclic shear behaviour of rock joints by considering an exponential law for the degradation of asperity incorporating the rate of dilation. Hutson and Dowding (1990) performed laboratory tests and further verified the exponential form representing the decay of dilation rate. Lee et al. (2001) extended the original model of Plesha through forward and backward shear displacements to study in detail the asperity degradation and the implication on the joint shear behavior. Jafari et al. (2003) performed experimental studies to evaluate cyclic peak shear strength of rock joints under *CNL* conditions by considering different shear rate, stress amplitude, and number of loading cycles. However, these studies have often been conducted under *CNL* conditions. As a result, the effect of asperity degradation under *CNS* conditions is still not well understood.

In this study, the experimental results of cyclic shearing carried out on artificial rock joints under *CNS* conditions for different levels of normal stress are discussed and the results are compared with Jafari et al. (2003)'s experiments under *CNL* conditions.

2 Cyclic shear test definition

A cyclic shear displacement refers to the condition in which shear displacement changes repeatedly between the positive and negative maximum displacements (i.e. shearing period) over each cycle of operation. A typical cyclic shear test along with the change in the shear displacement over the elapsed time is depicted in Figure 1.

As shown in Figure 1, in a cyclic test the lower specimen moves from its initial fully mated position to a positive maximum shear displacement (Phase 1), followed by a shearing direction reversal in which the specimen reaches a negative maximum shear displacement in the opposite direction (Phase 2), returning to the fully mated condition in a complete cycle.

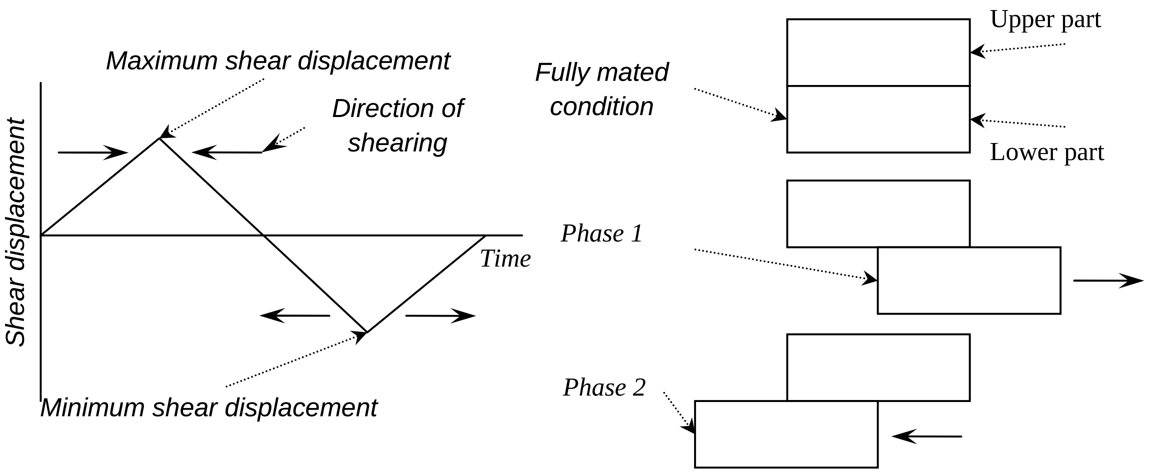

Figure 1. Cyclic shear displacement

3 Joint shape and sample preparation

The joint surface was prepared based on a regular triangular saw tooth shape with inclination angle equal to *26.5°* as shown in Figure 2. This artificial synthetic rock, allows for controlled repeatability of the initial roughness and the effect of asperity degradation under cyclic loading can be analyzed conveniently. The joint surface area for all the samples is *187.45* cm^2 (*250 x 75 mm*) with a total of *8* asperities *30 mm* long in the direction of shearing with an amplitude of *7.48 mm*.

In this study, Gypsum plaster ($CaSo_4.H_2O$ *hemihydrates, fraction of* $CaSo_4$ to H_2O *= 3.5:1)* was used to mould the artificial rock joints. This material can take any desired shape when mixed with water and the long term strength is independent of time once the chemical hydration is complete. The initial setting time of plaster is about *25* minutes. Furthermore, the cured plaster mix shows a repeatable uniaxial compressive strength in the range of *11 to 13 MPa* and a Young modulus of *1.9 to 2.3 GPa which are parameters comparable to many sedimentary rocks*. Testing on planar joints with the *Gypsum Plaster* showed a basic friction angle of approximately *35°*.

Figure 2. A close view of artificial joint prepared for testing

4 Cyclic shear apparatus for laboratory testing

In order to investigate the cyclic shear behaviour of rock/rock interface under cyclic loading a large scale direct shear apparatus was designed at *University of Wollongong* as shown in Figure 3. This apparatus can be used to apply cyclic shearing to the specimens under *CNS* conditions. The *CNS* shear apparatus consists of two boxes, one of size of *250* mm in length, *75* mm in width and *150* mm in height at the top, and the other of size *250×75×100* mm at the bottom. The bottom box is fixed on a rigid base by bearings and can only move horizontally. The top box can only move in the vertical direction with the normal stiffness kept constant by a set of spring simulating the normal stiffness of surrounding rocks. The desired initial normal stress is applied via a hydraulic jack located at the top of the apparatus where the applied load is measured via a calibrated load cell. The cyclic shear load is applied via a hydraulic actuator which is connected to the controller unit. The applied cyclic shear load also is measured via load cells. Finally, the desired rate of cyclic displacement can be set by the controller unit.

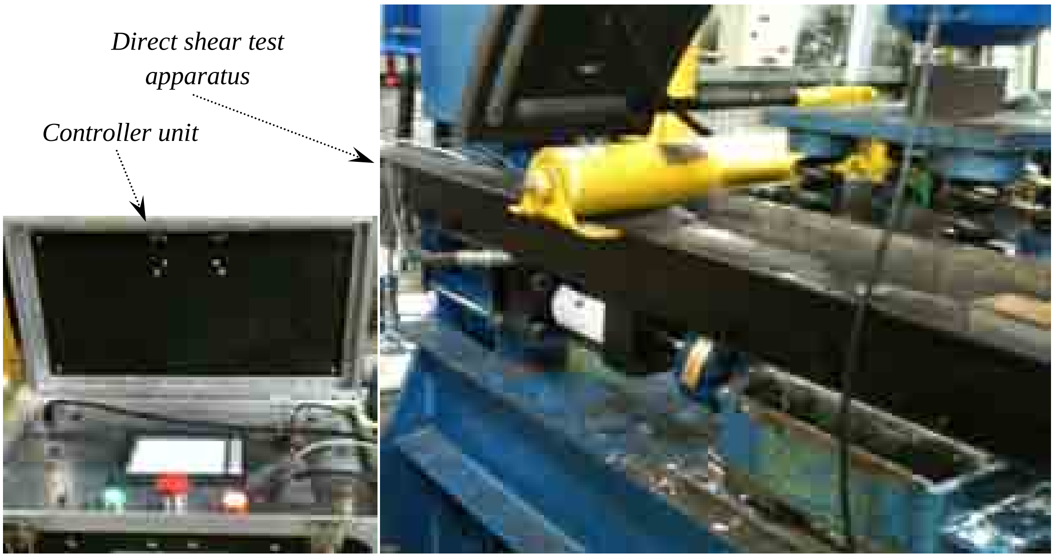

Figure 3. Cyclic direct shear apparatus

5 Experimental plan

Laboratory cyclic shear tests were conducted on the artificial saw tooth joints with initial asprity angle of *26.5º*. Initial normal stresses ranging from *0.16 to 2.64* MPa (*0.16, 0.3, 0.56, 1.1, 1.64, and 2.64* MPa) have been applied to the samples. All the specimens were sheared at a constant rate of *0.5 mm/min* and under a constant normal stiffness of approximately *7.3 KN/mm*.

6 Experimental results and analysis

As discussed above, the variation of cyclic shear strength under *CNS* condition at different levels of normal stresses have been investigated and the results are compared with the cyclic shear strength experiments under *CNL* conditions available on the literature. Tests have been conducted in two series of normal stresses, one level considered low for civil excavations (*0.16 to 0.56 MPa*) and one considered high (*1.1 to 2.64 MPa*) which are discussed in the following sections.

6.1 Cyclic shearing at low level of normal stresses

Figures 4 to 6 show the cyclic shear behaviour of the saw tooth joints under a low level of normal stress ranging from *0.16 to 0.56 MPa*. The test results indicate that, at this level of normal stresses, the shearing mechanism after the first cycle is mainly governed by a sliding mechanism with the less pronounced asperity degradation in the consecutive cycles. Nevertheless, asperity degradation is still observed, particularly in the first cycle, and the shear strength diminishes with increasing number of shear cycles. Asperity degradation is evident by the reduction of dilation with increasing shear cycles

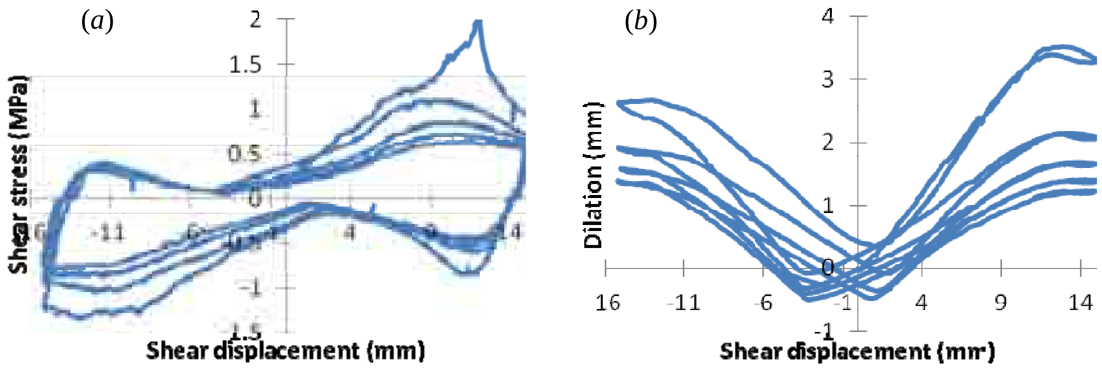

Figure 4. Cyclic shear behaviour of saw tooth profile under normal stress of 0.16 MPa (a) Shear stress-shear displacement (b) Dilation-shear displacement

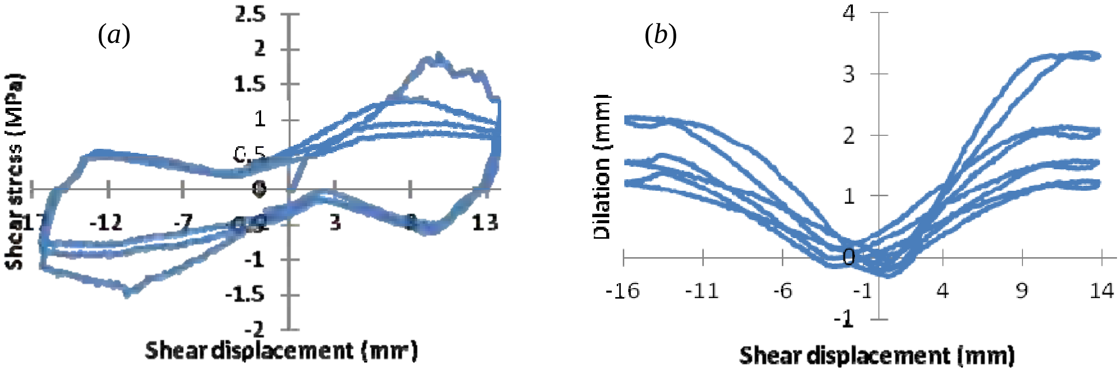

Figure 5. Cyclic shear behaviour of saw tooth profile under normal stress of 0.3 MPa (a) Shear stress-shear displacement (b) Dilation-shear displacement

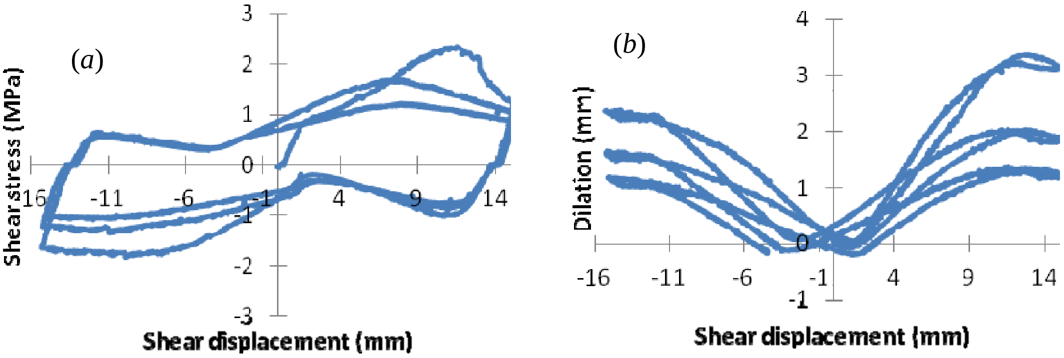

Figure 6. Cyclic shear behaviour of saw tooth profile under normal stress of 0.56 MPa (a) Shear stress-shear displacement (b) Dilation-shear displacement

6.2 Cyclic shearing at high level of normal stresses

The variation of shear strength of the idealized saw tooth joints with cyclic horizontal displacement at a high level of normal stress, ranging from *1.1 to 2.64 MPa*, is plotted in Figures 7 to 9. As expected, the results indicate more pronounced asperity degradation with the shearing mechanism transitioning from a combined sliding and shearing to mainly shearing with increasing normal stresses. This transition becomes evident in the dilation plots. Furthermore, by increasing the normal stress (Figure 9), contraction (seating) is observed rather than dilatancy behaviour.

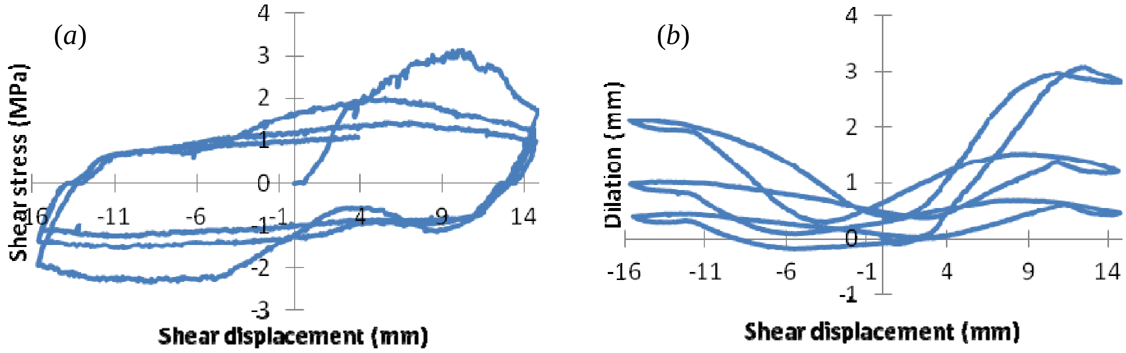

Figure 7. Cyclic shear behaviour of saw tooth profile under normal stress of 1.1 MPa (a) Shear stress-shear displacement (b) Dilation-shear displacement

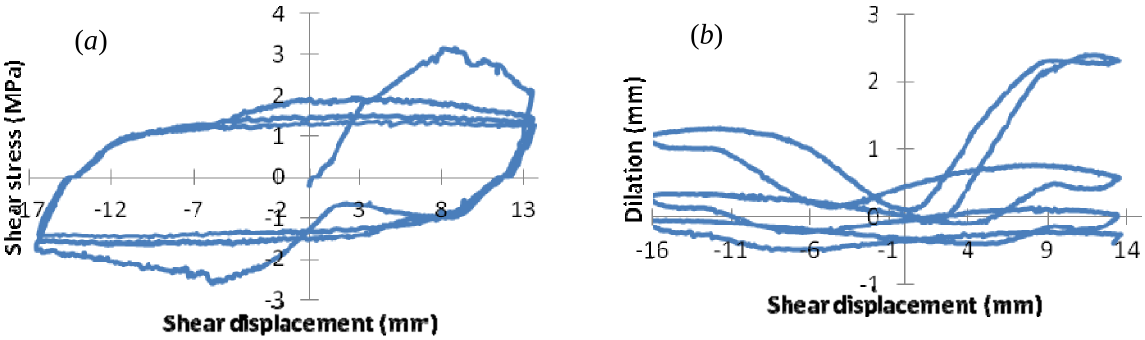

Figure 8. Cyclic shear behaviour of saw tooth profile under normal stress of 1.64 MPa (a) Shear stress-shear displacement (b) Dilation-shear displacement

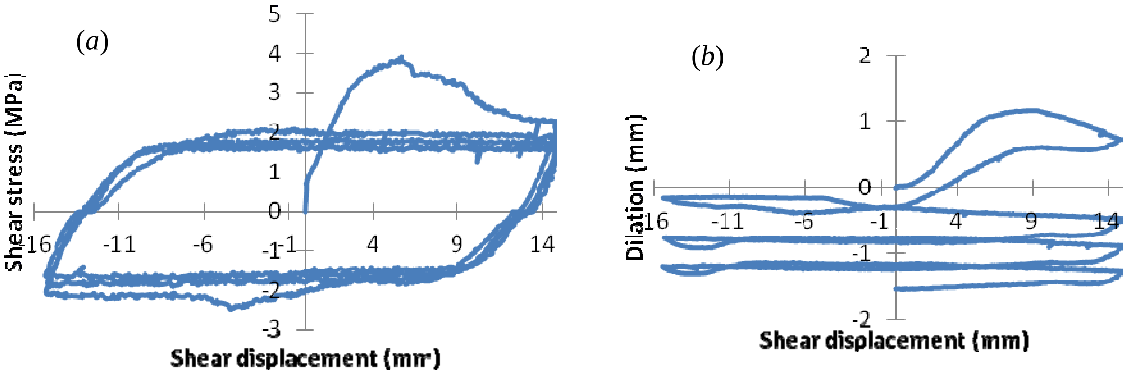

Figure 9. Cyclic shear behaviour of saw tooth profile under normal stress of *2.64 MPa* (*a*) Shear stress-shear displacement (*b*) Dilation-shear displacement

6.3 Comparison with the cyclic data under *CNL* conditions

Preliminary comparison with the cyclic experiments results reported by Jafari et al. (2003) (Figure 10) under *CNL* conditions, it is understood that the cyclic peak shear strength under *CNS* conditions is attained at greater cyclic shear displacements rather than that of *CNL* conditions. The above results indicate that the *CNL* condition may overestimate the joint cyclic dilation as greater asperity damage is observed under *CNS* condition reducing the overall friction angle (basic plus dilation angles). Further investigation is currently underway to better illustrate the main differences between these two conditions (*CNL* vs *CNS*) under cyclic conditions.

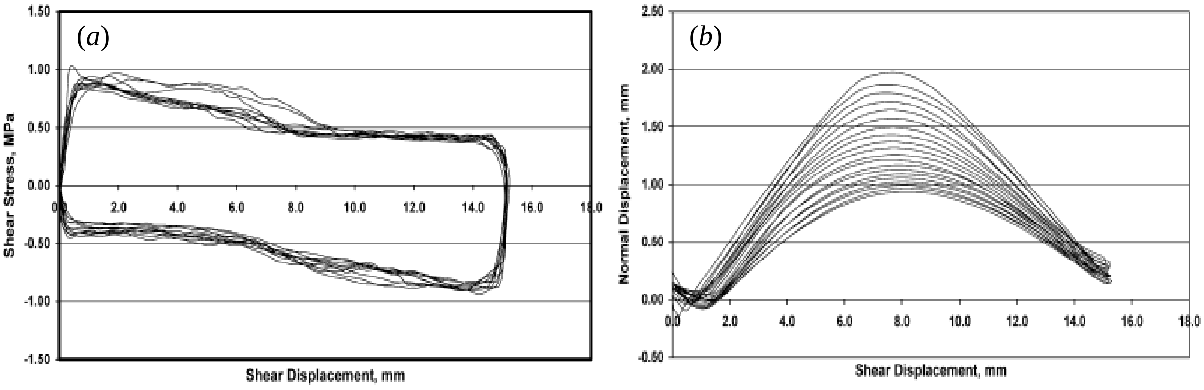

Figure 10. Cyclic shear behaviour of saw tooth profile under *CNL* conditions and normal stress of *1.2 MPa* (*a*) Shear stress-shear displacement (*b*) Dilation-shear displacement (initial asperity angle=*15°*) (Jafari et al. (2003))

7 Conclusion

This study presents a systematic laboratory investigation carried out on the cyclic shear behaviour of artificial rock joints under *CNS* conditions. The following preliminary conclusions are obtained based on this study:

1. Generally and as expected, cyclic shear behaviour of rock joints changes from asperity sliding to asperity shearing with increasing normal stress.
2. Due to the damage of asperities, the shear strength diminishes with increasing number of shear cycle.
3. Degradation of asperities mostly occurs at the initial cycles and attenuates with increasing number of shear cycles.
4. By increasing the applied normal stress and number of shear cycle, contraction (seating) may be observed rather than dilatancy behaviour.
5. Cyclic peak shear strength under *CNS* conditions is obtained at greater cyclic shear displacements rather than that of *CNL* conditions.
6. Testing under *CNL* condition may overestimate the joint cyclic dilation as higher damage is exerted to asperities under *CNS* conditions.

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