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A STUDY ON THE SHEAR BEHAVIOUR OF INFILLED ROCK JOINTS UNDER CYCLIC LOADING AND CONSTANT NORMAL STIFFNESS CONDITIONS

Ali Mirzaghorbanali, Jan Nemcik and Naj Aziz

ABSTRACT: Shear behaviour of infilled rock joints under cyclic loading and constant normal stiffness conditions were studied. The experiments were carried out in a cyclic loading direct shear apparatus. The laboratory studies were conducted using saw tooth shaped asperities cast in high strength gypsum plaster. Two types of triangular asperities inclined at 9.5° (Type I) and 18.5° (Type II) from the shearing direction were considered for testing. Clayey sand (75% fine sand and 25% Kaolinite) at initial moisture content of 12.5% was selected as the infill material. Profile of shear planes and strength envelopes for different conditions of infill thickness to asperity height ratio, initial normal stress, and initial asperity angle were investigated.

INTRODUCTION

Rock masses are heterogeneous and often contain joints and discontinuities, separating them into different blocks. When a rock mass is excavated, sliding along the joints may be experienced. The magnitude and direction of these movements is controlled by the shear behaviour of joints present within the rock mass. Depending on the origin of joints and mineralogy of the rock, joints may have planar (smooth) or rough surfaces. For planar joints, the shear strength is equal to the frictional resistance only as there are no asperities. In the case of rough joints, an additional shear resistance is generated by the roughness of the joint surface. Moreover, in circumstances where the dilation is confined by the surrounding rocks, the increase in the normal stress due to overriding of asperities increases the joint shear strength. During earthquakes and blasting, cyclic loading shearing degrades the joint roughness. The asperity degradation decreases the dilation magnitude and eventually reduces the friction angle and normal stress acting on the joint surface.

By representing joint shearing as an interaction between two media, Plesha (1987) introduced a softening cyclic loading model by assuming sliding mechanism along an inclined asperity angle degraded exponentially due to a portion of the plastic shear work. The analytical model of Plesha (1987) was further verified by Hutson and Dowding (1990) under Constant Normal Load (CNL) conditions in which the normal load remains constant during shearing. The original model of Plesha (1987) was later revised to represent sinusoidal asperities and to include the second order asperity effects (Qiu and Plesha 1991; Lee, *et al*., 2001). In another study, Jafari *et al*., (2003) performed a series of cyclic loading shear tests on undulated joints under CNL conditions for different applied normal stresses and suggested an empirical relationship for the variation of peak shear strength against the number of loading cycles. Other studies on cyclic loading shear behaviour of rock joints under CNL conditions were carried out by Aubry *et al*., (1990), Huang *et al*., (1993), Souley *et al*., (1995), Dong and Pan (1996), Fox *et al*., (1998), Stupkiewicz and Mróz (2001), and Puntel *et al*., (2006).

The studies mentioned above, focused on clean joints (unfilled) only. Recently, Mirzaghorbanali *et al.,* (2013) investigated the effects of cyclic loading on the shear behaviour of infilled rock joints under Constant Normal Stiffness (CNS) conditions. This paper is aimed studying the strength envelopes and profile of shear planes of infilled rock joints subjected to cyclic loading for different ratios of infill thickness (t) to asperity height (a), initial normal stresses (σ_{n0}), and initial asperity angles.

TEST APPARATUS, SPECIMENS, AND EXPERIMENTAL PLAN

Experiments were carried out at the Rock Mechanics Laboratory, University of Wollongong, NSW, Australia, using the large scale cyclic direct shear apparatus. The instrument consisted of two main parts, controller unit and mechanical section as shown in Figure 1. The digital controller was able to assign the cyclic displacement of the sample. The mechanical part had two steel shearing boxes, 250

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mm in length, 75 mm in width, and 150 mm and 100 mm in height of the top and bottom boxes respectively. A hydraulic jack located on top of the instrument was used to apply the initial normal load. A set of springs with stiffness of 8 kN/mm was incorporated to confine the joint dilation simulating the effect of surrounding rock mass. The lower box was only displaced laterally via a hydraulic actuator driven by the digital controller unit. The upper box moves only in a vertical direction on ball bearings such that any relative rotation of the joint surfaces is avoided. The shear and normal loads were measured by strain meters mounted on the load cells and the normal displacement was recorded using Linear Variable Differential Transformer (LVDT).

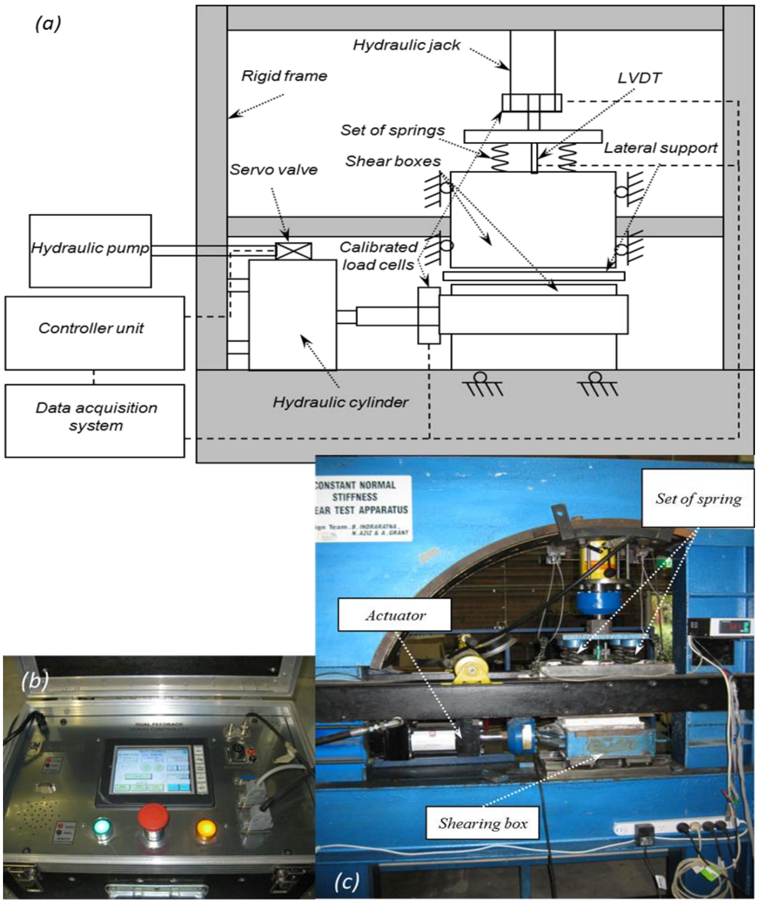

Figure 1 - (*a*) Schematic diagram of the CNS cyclic direct shear apparatus (*b*) controller unit (*c*) general view of the apparatus

Two different initial asperity angles 9.5° (Type I) and 18.5 ° (Type II) were selected to prepare triangular asperity moulds. The equivalent Joint Roughness Coefficient (JRC) values of 4.2 and 9 have been calculated for Types I and II asperity surfaces using the method suggested by Xie and Pariseau (1992). For each mould, a number of fully mated joints of high strength gypsum plaster (CaSo4.H2O hemihydrates) were cast using a mixing ratio of 3.5:1 by weight of plaster to water. The bottom block was prepared inside the bottom mould containing the required surface profile and left for two hours to cure. The matching specimen was then cast on the top of the bottom specimen to ensure the fully mated conditions and the whole assembly was left for two additional hours to satisfy the initial setting time. During sample preparation, mild vibration was applied to the mould externally to eliminate any entrapped air within the samples. The samples were then allowed to cure in an oven for 14 days at a constant temperature of 40°C. Prior to the cyclic shearing, the prepared samples were then acclimatised to room temperature. Clayey sand (75% fine sand and 25% Kaolinite) at initial moisture content of 12.5% was selected as infill material. After preparation of the infill material, it was kept inside a sealed container to ensure retention of the percentage of moisture. In order to prepare the infill surface, the cured bottom block was positioned inside the bottom shearing box in a way that allowed the surface profile to stay slightly above the edge of the bottom box. A closure over the specimen from the joint plane was provided by attaching an adjustable collar with the same shape as the surface profile on the top of the specimen. The collar was set to create the required infill thickness by precisely measuring the closure at four corner points. The infill material was then placed inside the collar and extended over the surface area using a spatula. Once, the collar was filled, the infill material was trimmed and compacted with a steel plate having the same triangular shape as the asperities. The collar was then removed and the bottom part of the sample was placed in the shear apparatus. The top shear box containing the upper sample was then mounted on top of the lower sample, thus sandwiching the infill layer between the two matching plaster surfaces. The smooth lateral confinement, on both sides of the sample, made from stainless steel was assembled to prevent loss of the infill material during cyclic shearing. A close view of artificial infilled joint (Type I asperity surface) with infill thickness to asperity height ratio equals to unity is shown in Figure 2.

Figure 2 - A close view of artificial infilled joint prepared for testing

More than 18 cyclic loading direct shear tests were carried out on the samples. Some of the tests were repeated to ensure the accuracy and precision of the measured data. The applied initial normal stresses (σ_{n0}) were 0.56, 1.64, and 2.4 MPa. Three different ratios 0.3, 0.6 and 1 of infill thickness (t) to asperity height (a) were tested. Infill joints were subjected to predetermined initial normal stress (σ_{n0}) for an hour before shearing. All samples were sheared for four consecutive cycles with total accumulated displacement of 240 mm and a shear rate of 0.5 mm/min to ensure a uniform drained condition of infilled joints. A constant normal stiffness of 8 kN/mm was applied to restrict the dilation. The maximum shear displacement was set to 15 mm.

RESULTS OF EXPERIMENTS

Figure 3 shows variations of the strength envelopes for infilled rock joints subjected to cyclic loading for different conditions of infill thickness to asperity height and initial asperity angles. At low infill thickness (t/a = 0.3) and Type I asperity surface, there is a slight difference in strength envelopes between the first and second shear cycles (Figure 3/left *a*). As the infill thickness to asperity height was increased to 1, the difference between the strength envelopes of consecutive shear cycles became marginal, verifying that, at high infill thickness to asperity height ratios, the shear behaviour is dominated by the infill material (Figure 3/left c). For t/a = 0.3 and Type II asperity surface, the strength envelope of the first cycle lies significantly above the later cycles (Figure 3/right *a*). As the number of loading cycles was increased, the strength envelopes under cyclic loading tended to become close to each other and approached that of infill material. It is deduced from strength envelopes of Type I and II asperity surfaces that the gap between the cyclic loading strength envelopes increases with increase in the asperity angle for the same infill thickness to asperity height ratio.

Figure 4 shows the profiles of shear planes for selected infilled joints at different initial normal stresses under cyclic loading. The cyclic loading shear planes were estimated from the measured normal displacement against the shear displacement data, and they are shown by dashed lines in Figure 4.

For t/a = 0.3 and 0.6, the shear planes pass through both infill and asperities (Figures 4 *a* and *b*). For t/a equals to unity, the shear planes for the first cycle pass slightly below the tips of asperities (Figure 4 *c*). As the number of loading cycles increases, for all the cases the shear planes pass always along a lower elevation as compared to the previous cycles, indicating either the asperity damage or deformation of infill material. The portion of the asperity surface that contributes to the shear planes, increases with the number of shear cycles. The difference between the elevations of shear planes decreases during cyclic loading. The reduction in the elevations of shear planes for the same values of infill thickness to asperity height and initial normal stress is greater for Type II asperity surfaces in comparison to Type I asperity surfaces. The gap between the shear planes of the first and last loading cycles of the joints with the same asperity type is higher for greater infill thickness to asperity height ratios and initial normal stresses.

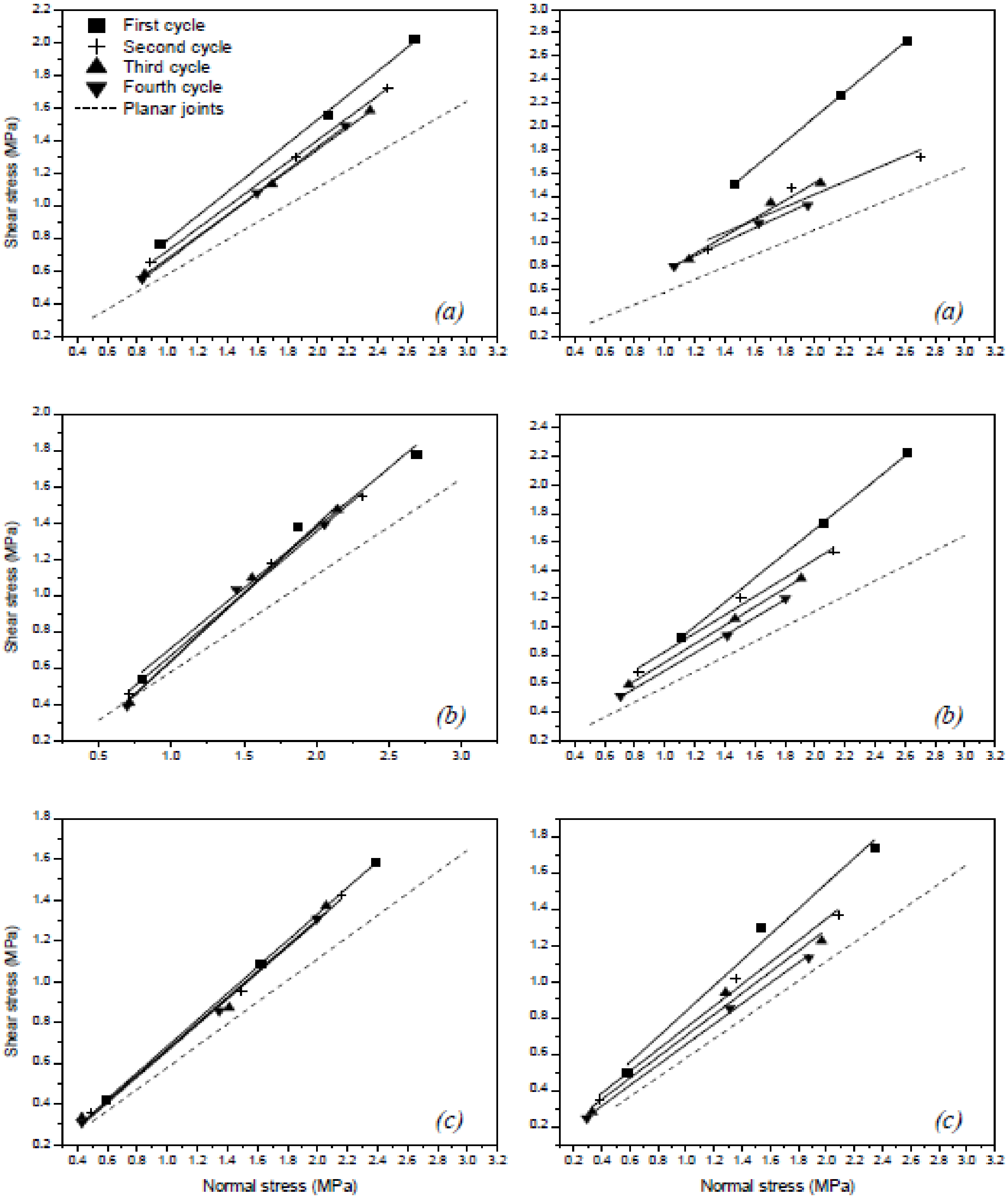

Figure 3 - Strength envelope under cyclic loading: [left] Type I asperity surface, [right] Type II asperity surface, (*a*) *t*/*a* =0.3, (*b*) *t*/*a*=0.6, (*c*) *t*/*a*=1

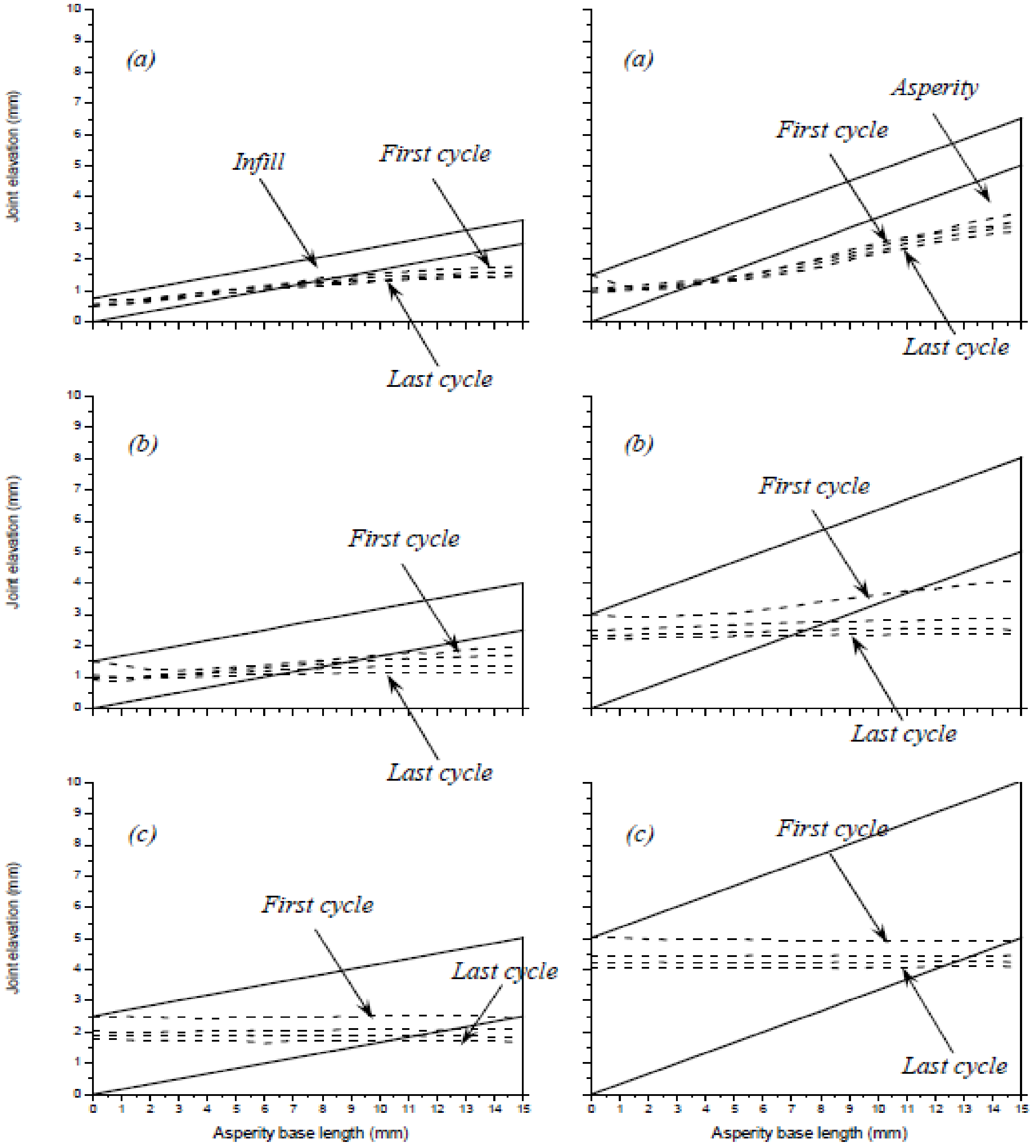

Figure 4 - Relative location of shear plane through infilled joints under cyclic loading, (dashed lines = shear planes): [left] Type I asperity surface, [right] Type II asperity surface, (*a*) t/a = 0.3 and σ_{n0} = 0.56 MPa, (*b*) t/a = 0.6 and σ_{n0} = 1.64 MPa, (*c*) t/a = 1 and σ_{n0} = 2.4 MPa

CONCLUSIONS

Strength envelope and profile of shear plane of infilled rock joints subjected to cyclic loading shearing under CNS conditions were studied. The following main conclusions can be drawn based on this investigation:

- There is a slight difference in strength envelopes between the first and second shear cycles at low infill thickness (t/a = 0.3) and Type I asperity surface.
- For t/a = 0.3 and Type II asperity surface, the strength envelope of the first cycle lies considerably above the later cycles.
- The difference between the strength envelopes of consecutive shear cycles became less pronounced as the infill thickness to asperity height was increased to 1.

- The shear planes always pass along a lower elevation in comparison to the previous cycles, implying either asperity damage or deformation of infill material.
- The gap between the elevations of shear planes decreased as the number of loading cycles increased.
- A higher portion of the asperity surface is sheared with increase in the number of loading cycles.

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