Laboratory Investigation on Shear Strength Variation of Joint Replicas Due to Low and High Amplitude Cyclic Displacements

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ABSTRACT: *The dynamic stability of shallow underground openings in jointed rock masses depends on several parameters that the most important of them for design engineers is the shear strength of rock joints. In this research in order to study the effects of cyclic loading on this parameter, about 50 joint replicas have been tested using triaxial and direct shear testing devices. The saw-tooth identical joint samples were prepared using silicon moulds and special mortar. The samples have been tested in different loading conditions to simulate the effects of small and large earthquakes. Variations of the shear strength with the parameters of cyclic loading and also degradation of asperities have been studied during the tests. The results show considerable changes of shear strength due to the rate of loading, number of cycles, frequency and amplitude of loading. Also the trends of wearing and asperity degradation have been studied in higher levels of cyclic displacement.*

Keywords: Shear strength; Roughness; First and second order asperities; Cyclic behaviour; Damage; Asperity degradation; Rate of loading; Number of cycles; Frequency and amplitude of loading

1. Introduction

Underground openings such as tunnels and caverns, were considered as safe places during earthquakes [1]. Some catastrophic collapses and severe damages to underground openings due to earthquake shakings during the recent years made the researchers to evaluate the seismic behaviour of underground openings more precisely. Several papers and reports are now available about the damages to under ground excavations in seismic areas due to the previous earthquakes [2, 3]. The results of these studies show that although underground openings are relatively more resistant to dynamic loading, but they are vulnerable to earthquake shaking specially when they are constructed in jointed rock masses. Up to now, few systematic researches regarding the effects of earthquakes on stability of underground excavation in jointed rocks have been done and most of them are on the basis of numerical modelling that should be calibrated by experimental data.

In jointed rock masses, joint surface properties such as roughness, separation, matedness, and gouge have considerable effects on shear strength specially in low levels of normal stresses. Shear displacements due to earthquake loadings can affect these parameters. During strong earthquakes one can expect considerable displacement along the joint surfaces in each event. Small repetitive earthquakes can not make considerable movement, but because of their repetitive nature they may affect the shear resistance of rock joints. Few researchers such as Hutson and Dowding [4], Huang et al [5], Boulon [6], Divoux et al [7] and Armand et al [8] have studied the effects of large displacements on shear strength of rock joints but there are not much studies about the effects of small earthquakes of rock joints properties [9].

In this paper the results of some experimental studies for both of the above mentioned conditions will be presented and some mathematical models will be proposed based on the obtained results.

2. Sample Preparation

2.1. Joints Shape

The selected joint shape for the replicas for all of the tests was saw-tooth shape with maximum inclination (i-value) of 15 degrees. Some small asperities are also made on the surface of the teeth to simulate the effects of second order asperities on shear strength of replicas. Schematic views of the samples are shown in Figure (1). This joint shape was chosen since it is relatively easy to analyse the variations of the teeth shapes before and after the tests. Also Hutson and Dowding [4] have shown that saw-tooth samples can respond in a manner similar to that occur at a field scale. The plan area of the joint surface was identical for all the samples equal to $30 cm^2$ for cylindrical and $50 cm^2$ for cubic samples. Each sample includes 5 main teeth with wave length about $1.5 cm$ and amplitude $0.2 cm$. Other geometrical parameters of the joint surfaces and samples are displayed in Figure (1).

2.2. Material of the Physical Model

The material used for making the replicas was a special kind of mortar called Rapidex made by Lafarge Company. The main advantage of this mortar is its strength after a few hours. Its uniaxial compression strength is about $55 MPa$ and its tensile strength (using Brazilian test) is about $8 MPa$ after about 24 hours. Also the basic friction angle and cohesion of this mortar (using triaxial tests in different confining pressure) are 40 degrees and $16.8 MPa$. For making homogenous mortar, a sieve of $0.5 mm$ has been used to remove the large particles of mortars and then it has been mixed with water in a weight ratio (5: mortar; 1: water) using a small vibrator.

2.3. Sample Preparation

All the samples were prepared using special moulds made by silicon rubber called Silastic (Rhone-Poulene Company). The external moulds for triaxial samples were *PVC* tubes and for direct shear samples were the testing cells. The internal silicon moulds of each side of the joint were put into the external moulds and then were filled with the prepared mortar. After 24 hours tests were performed on the samples and their uniaxial compression and tensile strength were measured using cylindrical samples prepared at the same time with the same materials. Figure (2) shows the internal silicon moulds, external moulds and some of the prepared samples.

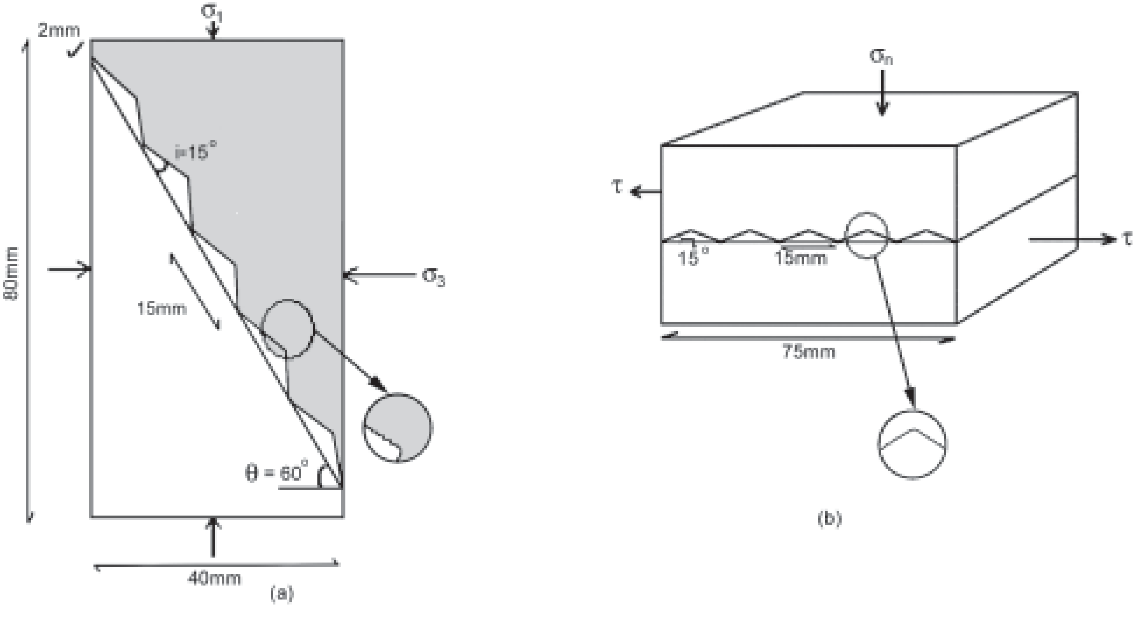
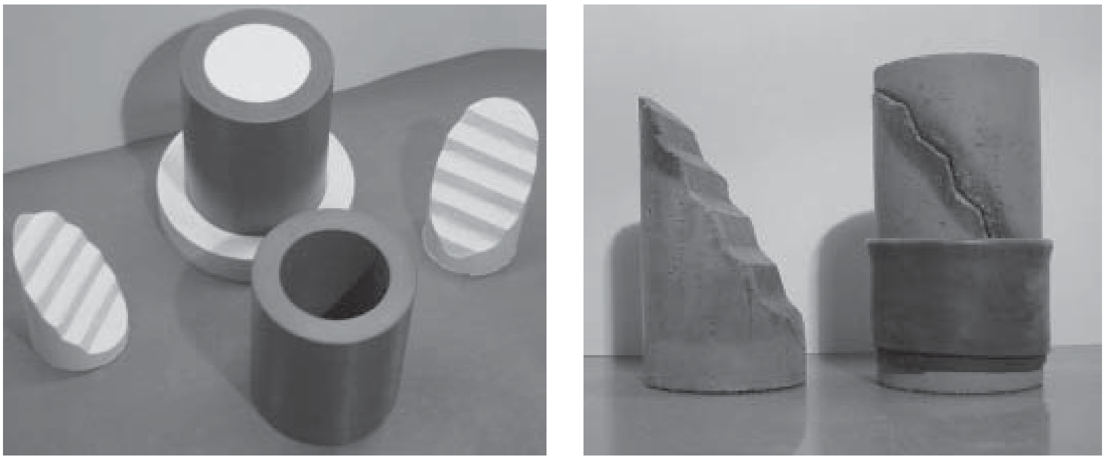
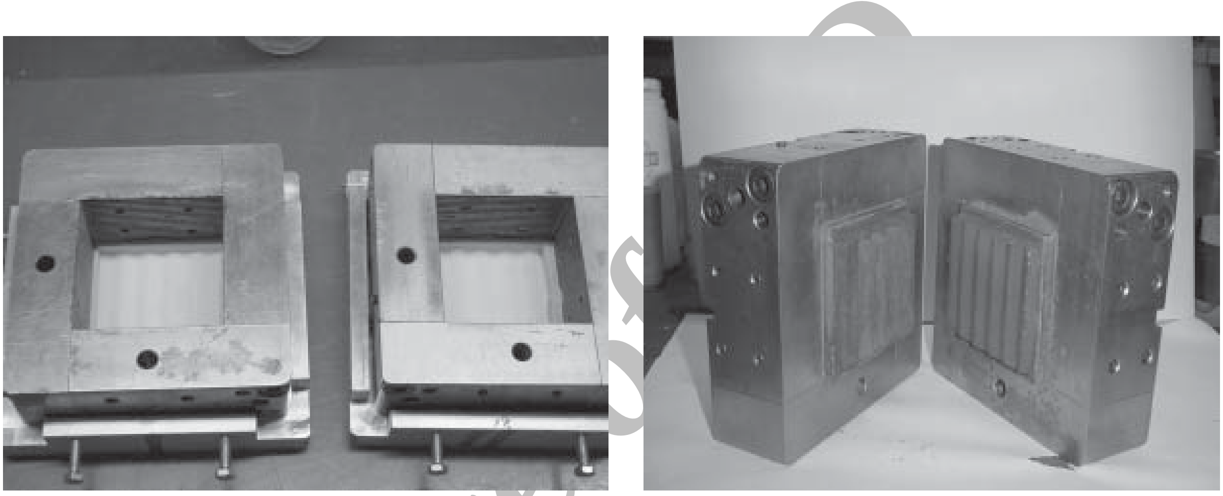


Figure 1. Schematic views of the samples used for cyclic tests; a) Cylindrical samples tests ; b) Cubic samples.



a) Triaxial samples.



b) Direct shear samples.

Figure 2. Internal and external moulds and saw-tooth samples.

3. Testing Devices

In order to perform the triaxial tests two devices have been used, one in the University of Joseph Fourier, Laboratory 3*S* (Lab. 3*S*), in Grenoble, France and the other in the Laboratory of Rock Mechanics (*LMR*) in Lausanne Institute of Technology (*EPFL*), Switzerland. For direct shear tests the shear machine in Lab. 3*S* called *BCR* 3*D* has been used.

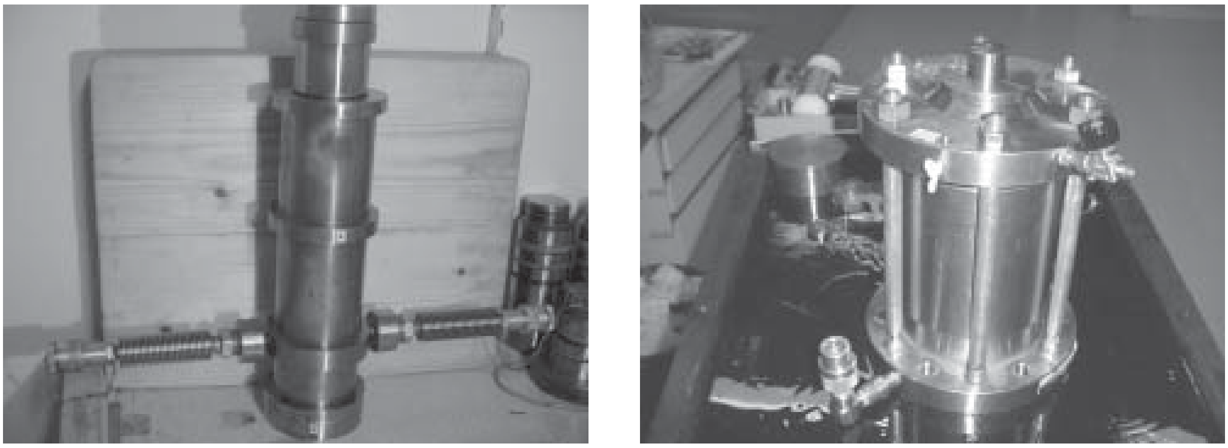
3.1. Testing Cells

Figure (3) shows the triaxial testing cells used in Lab. 3*S* and *LMR*. These cells have three main parts included base, hollow cylinder and upper piston. Cylindrical samples were covered with special membrane and put into the hollow cylinder. After filling the hollow cylinder with special oil, then the upper piston was pushed on the upper side of the hollow cylinder.

The testing cell for direct shear tests is consisted of four steel frames that used also as external moulds for preparation of samples, see Figure (2b).

3.2. Testing Devices and Data Acquisition Systems

For triaxial tests in both laboratories two separate systems for applying the axial loads and confining pressure are used. The total loading capacity of the axial hydraulic jack in Lab. 3*S* is 1000*kN* and in *LMR* is 2000*kN* and for confining pressure is about 100 *MPa* in Lab. 3*S* and 20*MPa* in *LMR*. All the systems have been equipped with a function generator to provide different kinds of voltages for applying cyclic loads. All the data such as displacements, force, confining pressure and time, are collected and recorded with *IBM PC* based systems with the adjustable sampling rates. Axial displacements have been measured using 4 vertical *LVDTs* simultaneously and the average of them have been used during analysis.



a) In Lab. 3S b) In LMR.

Figure 3. Testing cells for triaxial testing.

Direct shear tests were performed using a new device called *BCR 3D* developed by Boulon [6]. Maximum normal stress that can be applied by this device is about 60*MPa*. By using two similar brushless servo-motors, two walls of joint can move symmetrically, so no relative rotation would occur during the shearing displacement and the normal force would remain on the centre of active part of the joint surface at any time. Each jack is equipped with one load cell to measure loads during the tests. Shear and normal displacements are measured with 4 *LVDTs* in each direction. All the data are recorded using a standard computer and a high frequency data acquisition card. Figure (4) displays these testing devices.

4. Summary of the Experimental Results

In this research variations of shear strength due to cyclic loading have been taken into consideration. Some of the main parameters of loading that their effects on shear strength have been investigated in this research are rate of shearing velocity, number of small loading cycles and their frequencies, amplitude of cycles, and asperity degradation due to cyclic loading. Tables (1) and (2) present the results of some of these tests.

5. Effects of Small Shear Displacement on Shear Strength

As mentioned before cyclic behaviour of rock joints can be studied in two ranges of displacement. In order to simulate the effects of small cyclic loadings (such as small earthquakes), the effects of small cyclic displacements on shear strength should be taken into account. As it can be seen in the following parts, in such cases second order asperities of joint surface play the main role in shearing behaviour of rock-joint system.

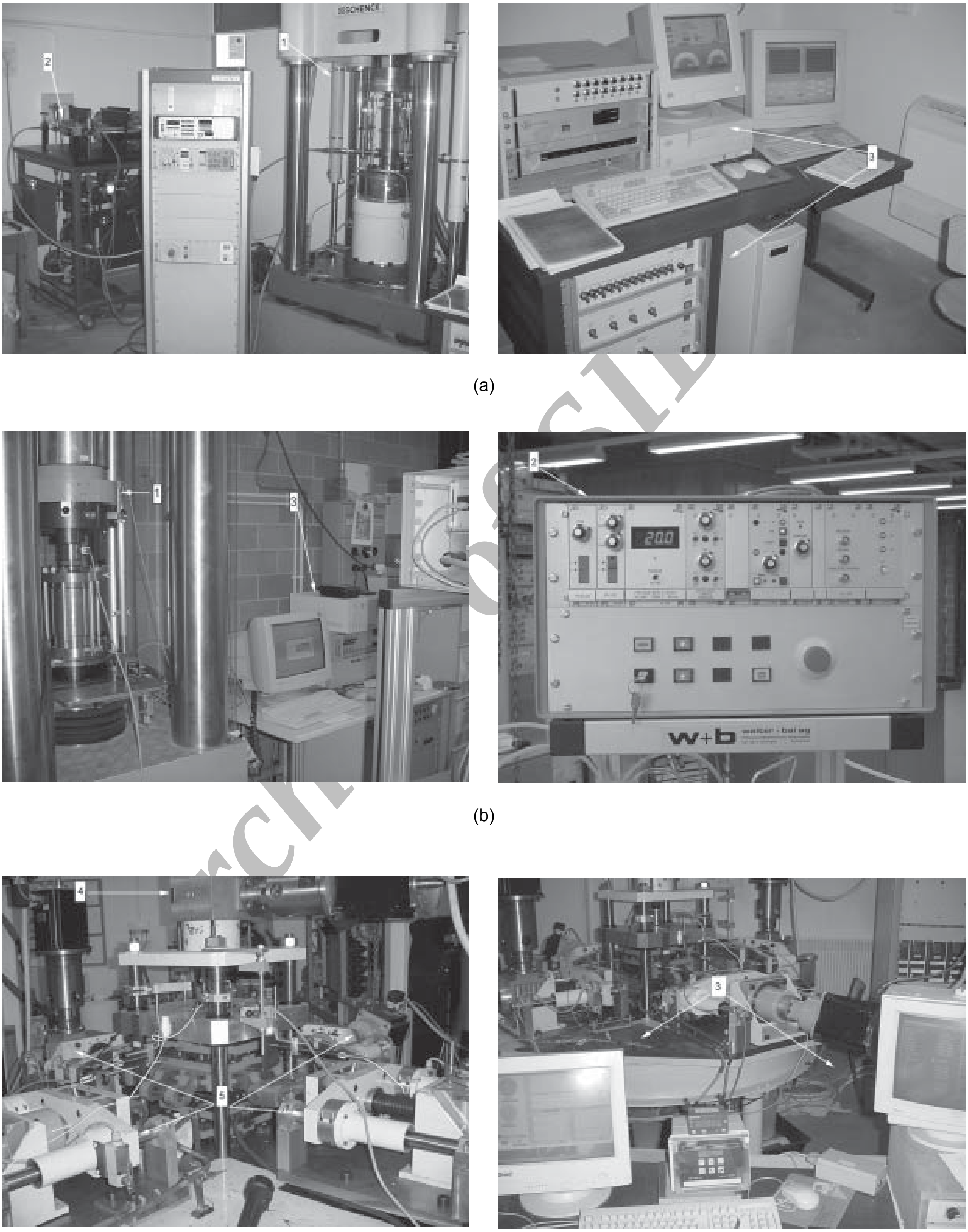
In order to study the effects of small cyclic displacements on shear strength, triaxial loading device is selected because of its abilities to apply high levels of cyclic loads in different frequencies and its accuracy for applying small displacement. In the performed tests only limited displacements (below 1*mm* in most of the cases) have been applied on the samples and shear strength variations due to different rates of velocity, number of cycles and their frequencies, and amplitude have been studied. It should be considered that in triaxial tests on jointed samples, it is not possible to apply large shear displacements due to limited resistance of membrane during the shear displacement.

5.1. Influences of Shearing Velocity on Shear Strength

For evaluating the effects of velocity on the shear strength of the prepared samples, some monotonic triaxial tests under 4*MPa* confining pressure in different velocity rates (between 0.05 to 0.4*mm*/*min*) have been performed. The results of some of these tests have been presented in Figure (5).

As it can be seen in this graph for most of the performed tests, there are pick and residual values for shear strength. Considering the small shear displacement applied in the tests, it can be concluded that the second order asperities are the only parameter that can make these variations. Figure (6) presents the normalized peak and residual shear strength (normalized by σ_3) for these tests.

As it can be seen in Figure (6), shear strengths decrease nearly logarithmically with increase of velocity rates. Also the differences between the peak and residual values become smaller in higher levels of velocity rate. It means that in higher rates of velocity second order asperities do not have much effects on shear strength of jointed samples.



(a)

(b)

(c)

Figure 4. Testing machines and data acquisition systems, a) Triaxial machine in 3S ; b) Triaxial machine in LMR ; c) Direct shear machine in 3S (1- axial jack, 2- confining pressure system, 3- data acquisition system, 4-axial brushless servo-motor, 5- shearing brushless servo-motor).

5.2. Effect of the Number of Cycles and Frequency of Small Loadings Cycles

In this section the effects of small cyclic loadings on shear strength of the tested joint replicas would be evaluated. This situation corresponds with a rock-joint system subjected to lots of the small earthquakes in different frequency levels. The most important controlling parameter of joint surface in this case is

Table 1. Some of the results of triaxial tests on saw-tooth samples.

Test No.	Changing Parameter	Axial Displacement at Peak Point (mm)	Peak Shear Stress MPa	Peak Normal Stress MPa	Mean Residual Shear Stress MPa	Shear Displacement at Peak Point mm
R1	Rate of Velocity (0.05 mm/min)	0.20	3.39	5.96	3.05	0.17
R2	Rate of Velocity (0.01 mm/min)	0.39	3.04	5.76	2.66	0.34
R3	Rate of Velocity (0.02 mm/min)	0.34	2.66	5.53	2.51	0.30
R4	Rate of Velocity (0.04 mm/min)	0.28	2.45	5.42	2.45	0.24
N1	Number of Cycles (25 Cycles)	0.09	3.30	5.91	2.94	0.08
N2	Number of Cycles (50 Cycles)	0.15	3.23	5.86	2.84	0.13
N3	Number of Cycles (100 Cycles)	0.27	3.15	5.82	2.75	0.23
N4	Number of Cycles (300 Cycles)	0.15	3.09	5.78	2.72	0.13
N5	Number of Cycles (500 Cycles)	0.11	3.04	5.75	2.68	0.09
N6	Number of Cycles (1000 Cycles)	0.08	3.00	5.74	2.64	0.07
N7	Number of Cycles (3000 Cycles)	0.11	2.99	5.73	2.63	0.10
F1	Frequency (1Hz)	0.27	3.15	5.82	2.75	0.23
F2	Frequency (0.5Hz)	0.50	3.26	5.88	2.88	0.43
F3	Frequency (0.2Hz)	0.15	3.34	5.93	2.94	0.13
A1	Amplitude (0.5 MPa)	0.42	2.93	5.69	2.93	0.36
A2	Amplitude (1.6 MPa)	0.23	2.65	5.52	2.65	0.20
A3	Amplitude (1.8 MPa)	0.15	2.32	4.83	2.32	0.13

the variations of second order asperities during cyclic loading. Due to number of cycles and their frequencies these asperities may change gradually and can affect the shear strength of jointed samples. In order to evaluate the effects of small cyclic loadings on shear strength, some cyclic-monotonic triaxial tests have been done on saw-tooth samples. The results of one of these tests are presented in Figure (7).

Table 2. Some of the results of direct shear tests on saw-tooth samples.

Cycle No.	Normal Stress (MPa)	Forward (i) Angle (Degrees)	Reverse (i) Angle (Degrees)	Forward Degradation (mm)	Reverse Degradation (mm)	Peak Forward Shear Stress (MPa)	Peak Reverse Shear Stress (MPa)
1-1	1.2	15	13.6	0.09	0.18	1.02	0.94
1-2	1.2	13.3	12.9	0.23	0.28	0.97	0.91
1-3	1.2	12.5	11.9	0.34	0.42	0.91	0.89
1-4	1.2	11.3	10.8	0.5	0.57	0.92	0.88
1-5	1.2	10.2	9.8	0.65	0.7	0.92	0.87
1-6	1.2	9.5	9.3	0.74	0.76	0.88	0.88
1-7	1.2	9.2	9.1	0.78	0.8	0.84	0.88
1-8	1.2	8.7	8.3	0.85	0.91	0.86	0.88
1-9	1.2	8	7.6	0.95	1	0.86	0.85
1-10	1.2	7.3	7	1.04	1.08	0.85	0.84
4-1	4.2	14.2	13.1	0.12	0.24	3.9	3.7
4-2	4.2	12	10.9	0.32	0.49	3.8	3.5
4-3	4.2	-9.5	-3.4	3.15	3.25	3.6	2.4
4-4	4.2	-5.7	-4.5	4.13	4.24	2.9	2.2
4-5	4.2	-5.3	-4.2	4.91	5.08	2.8	2.1
6-1	6.5	-8.1	-3.7	2.55	2.7	5.67	3.73
6-2	6.5	-7.1	-3.3	3.15	3.2	4	3.65
6-3	6.5	-6.1	-3.7	3.55	3.65	3.95	3.65
6-4	6.5	-5.3	-3.5	3.8	3.9	4	3.7
6-5	6.5	-4.7	-3.4	4.2	4.25	3.9	3.5
6-6	6.5	-4.5	-3.7	4.4	4.45	3.85	3.6
6-7	6.5	-4.3	-3.5	4.55	4.6	3.9	3.45
6-8	6.5	-4.1	-3.6	4.7	4.75	3.85	3.4
6-9	6.5	-3.9	-3.3	4.8	4.85	3.8	3.45
6-10	6.5	-3.7	-3.5	4.9	4.95	3.75	3.25

These tests have been performed in two successive stages, first stress control and then strain control. In the first part, see Figure (7a) loading cycles with amplitude about half of the maximum values of static shear strength were applied on the samples and in the second part it followed by monotonic loading, Figure (7b). It can be observed in Figure (7), that cyclic degradation will happen during the first loading cycles but it decreases after experiencing about 30-50 cycles. Figure (8) presents the results of some of the performed tests.

As it is shown in this figure, shear strength do not change considerably after experiencing about 300 small cyclic loads. It can be related to the cyclic

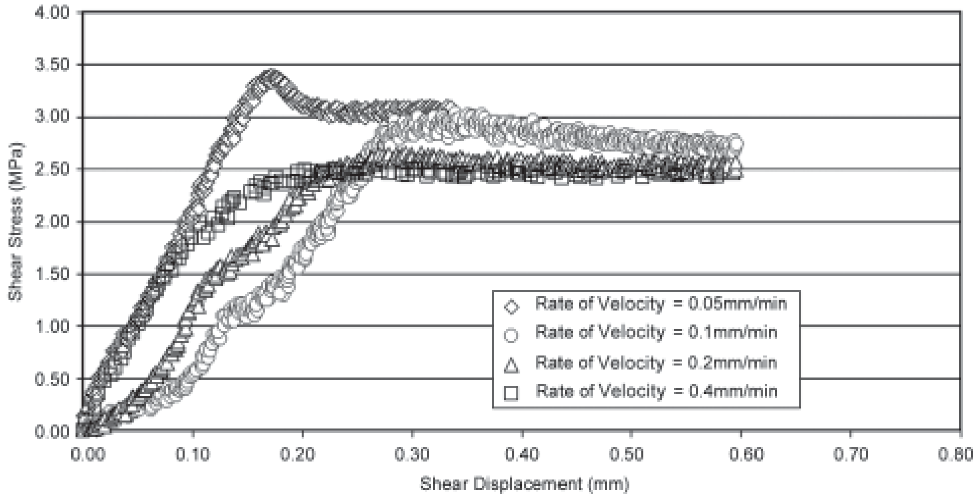
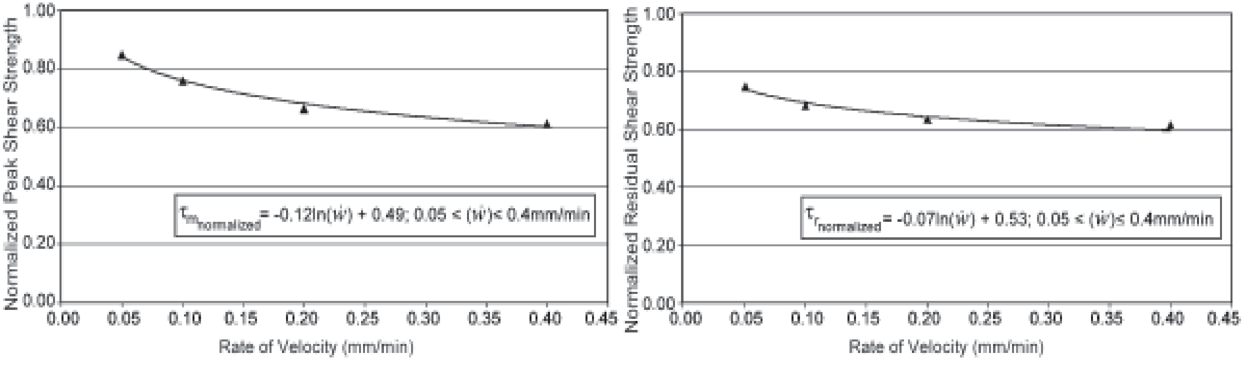
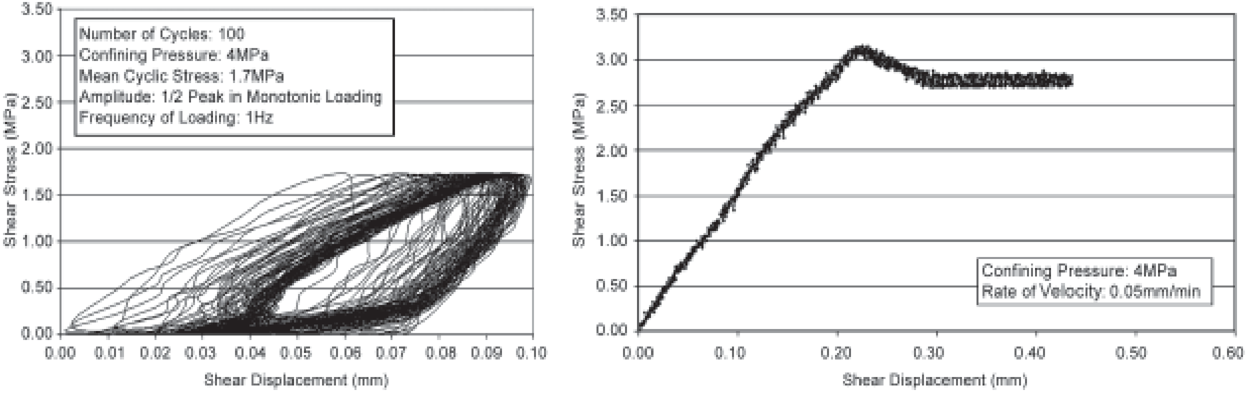


Figure 5. Shear stress – shear displacement curve for different rates of velocity.



(a) (b)

Figure 6. Logarithmic trends between the results of the tests in different rates of velocity; a) Maximum shear strength; b) Residual shear strength.



(a) (b)

Figure 7. The results of one of the cyclic tests on saw-tooth samples subjected to 100 cycles a) Stress control part; b) Strain control part.

degradation of the second order asperities on joint surface. When the shear stress-shear strength loops are overlapped completely, even with increasing the number of cycles, the values of peak and residual shear strength would be constant. Figure (8) also presents the trend of normalized shear strength with number of small cycles.

Frequency of these small cycles has also some effects on shear strength of rock joints. To study this effect, some triaxial tests on same samples in the same conditions, but in different frequencies have been performed. In each test 100 small loading cycles (with amplitude about 1.7*MPa*) in different frequencies have been applied on the saw-tooth samples and the new peak and residual shear strength after experiencing these cycles have been measured. Some of the results are presented in Figure (9).

In these figures shear strength has been normalized by σ_3. It was not possible to apply higher levels of frequency due to the mechanical limitations of the devices. As it can be seen in Figure (9), shear strength decreases with increase of loading frequency. This result is nearly similar to the effects of rate of loadings but it is necessary to perform more tests in higher frequency levels to see the possible changes of this trend.

5.3. Influence of Amplitude of Loading Cycles

The amplitude of the loading cycles in the previous mentioned tests was about 50% of maximum strength in monotonic testing. In order to study the effects of loading amplitude to shear strength, some triaxial tests have been performed. In these tests 100 cycles with frequency equal to 1Hertz in different levels of cyclic amplitudes (between 30% to 80% of maximum strength) have been applied on saw-tooth joint samples and then monotonic shear strength has been measured. The results of some of these tests are presented in Figure (10).

The results of these tests show the importance of amplitude of cycles on joint shear strength. In the performed tests shear strength decreases sharply by applying cyclic loads with amplitude more than 50% of static shear strength, but below this level there is no important effect of amplitude of cycles on shear strength. Other performed tests with higher levels of amplitude showed that during cyclic stage, shear strength decreases to its critical level and two

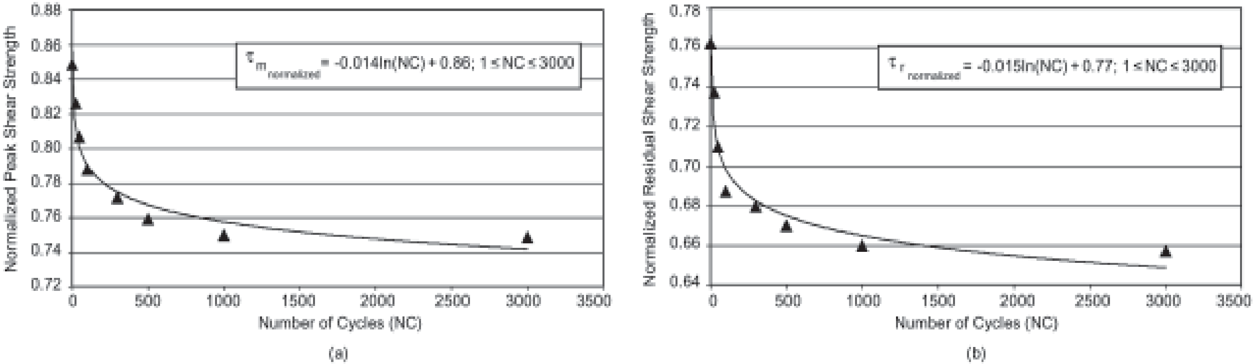


Figure 8. Logarithmic trends for decrease of normalized shear strength (normalized by σ_3) with number of cycles; a) Peak values ; b) Mean residual values.

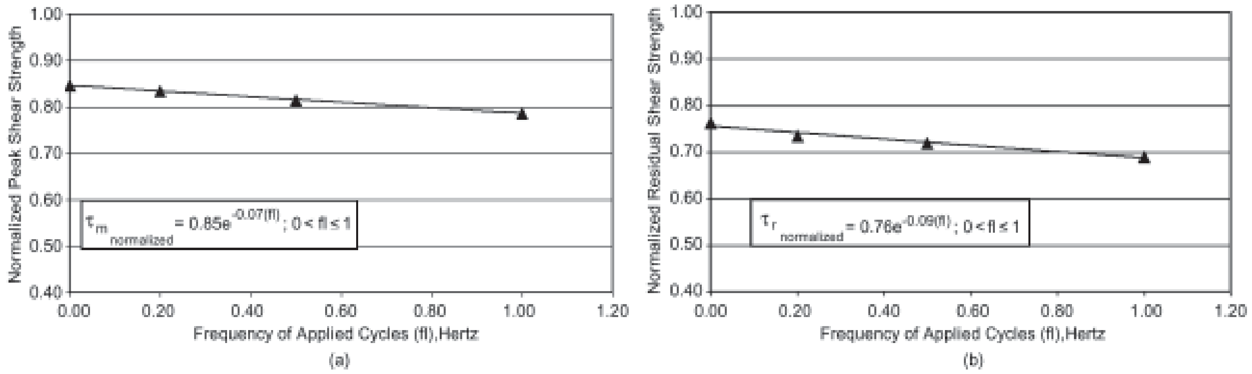


Figure 9. Variations of shear strength with frequency; a) Peak values; b) Residual values.

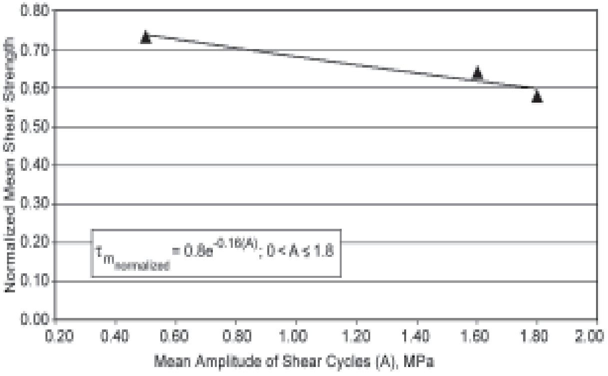


Figure 10. Sharp decrease of shear strength (normalized by σ_3) due to increase of loading amplitude.

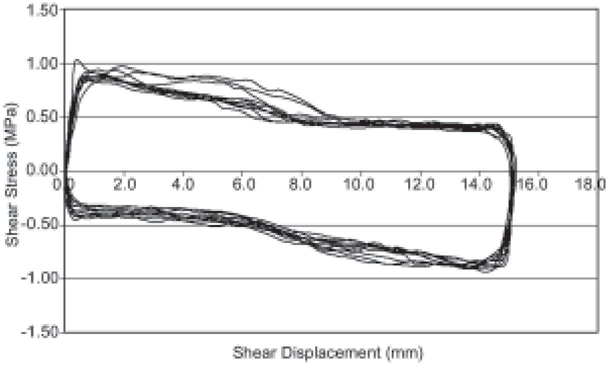


Figure 11. Shear stress –shear displacement curve for saw-tooth sample during 10 cycles in 1.2 MPa normal stress.

walls of the joint start to move on each other after a few cycles. So it can be concluded that the effects of second order asperities are more considerable in low amplitude of cyclic loadings and its influence on shear strength would decrease in higher amplitudes, for example during the strong earthquakes.

6. Effects of Large Shear Displacement on Shear Strength

In this research, variations of joint shear strength due to large displacements (for example during strong earthquakes) were also studied. Some direct shear tests using a modern device called *BCR*-3*D* have been performed on saw-tooth samples. In each test, two walls of the joints have been moved on each other simultaneously to a maximum value equal to 75*mm*. So the total maximum relative displacement in each test was about 150*mm*. Degradation of the asperities and their effects on shear strength have been studied during the tests. Some of the results of these tests will be presented in the following sections.

6.1. Shear Strength and Degradation of Asperities in Low Levels of Normal Stress

In low levels of normal stresses the dominant mechanism for shear displacement is sliding over the asperities and not much breakage occur along the main asperities. In cyclic loading although sliding over the asperities is still the main mechanism for shear displacement, but degradation of asperities take place in each cycle and it has considerable effects on shear strength of joint sample.

In this research some direct shear tests have been done on saw-tooth samples in order to evaluate the rate of cyclic degradation of the asperities and its effect on shear strength. Figure (11) presents the results of one of these tests that has been performed under 1.2*MPa* normal stress. In this figure the variations of shear stress with shear displacement for saw-tooth samples have been displayed. As it can be seen, the graph in the first cycle has a small peak that can be related to the effects of second order asperities, which have been disappeared during the other cycles. Also it can be observed that the shear strength in upward displacement along the teeth is much higher than the downward displacement. It is related to the components of normal and shear forces acting on joint surface.

Both first and second order asperities would be degraded during cyclic displacement, but in the first 2-3 displacement cycles, the effects of second order asperities would be diminished considerably and first order asperities can resist against shear displacement. As it can be observed in Figure (11) after the first 5-6 cycles, shear strength nearly decreases to a constant level that can be related to stabilizing of joint surface due to degradation and wearing.

Figure (12) presents the rate of asperity degradation of this test. It can be observed that degradation continues during cyclic displacement but its rate decreases with increase of number of cycles. It can be expected that this trend would be continued to smooth joint surface up to a constant level.

Figure (13) presents the variations of dilation angle with number of cycles. The trend of the data in Figure (13), explains why the shear strength decrease during cyclic displacements. As shear strength is in direct relation with dilation angle (i), so it reduces when the dilation angle decrease. Besides the dilation angle, there are some other important parameters such as wearing that should be considered for better evaluation of variation of shear strength due to cyclic displacement.

6.2. Shear Strength and Degradation of Asperities in High Levels of Normal Stress

In higher levels of normal stresses, cutting the asperities in shearing direction is the main mechanism for shearing. Not much dilation can be expected at high levels of normal stresses and even there are high possibilities for contraction due to breakage of the first order asperities. In this research in order to evaluate the variation of shear strength during cyclic displacement in high levels of normal stresses, some direct shear tests have been done on saw-tooth samples in 6.5*MPa* normal stress.

Results of one of these tests are presented in Figure (14). As it can be observed in this figure, in the first cycle of forward shearing, the teeth have been broken from their bases. The shear strengths for all other cycles are nearly the same and the little changes are due to small changes in joint surface during shear displacement.

Figure (15) presents the variation of dilation-contraction curves during cyclic shearing. Only in the first cycle small dilations can be observed and in all other cycles contraction is the main volumetric effects of shear displacement.

Although because of the breakages of the teeth, shear strength decreases suddenly, but due to wearing and compaction during shear displacement, the shear strength would be recovered to intermediate levels after a few cycles. Increasing number of cycles does not have much effects on shear strength after stabilizing the joint surface conditions.

6.3. Shear Strength and Degradation of Asperities in Intermediate Levels of Normal Stress

In the previous sections, two different conditions for cyclic shearing in low and high levels of normal stresses have been explained. In order to determine the transition behaviour (sliding to breaking) some cyclic direct shear tests have been done using *BCR 3D*. One of the results is presented in Figure (16).

The results of this test show the possibility of

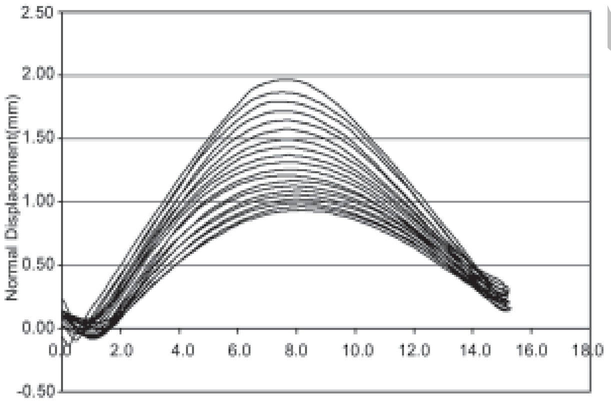


Figure 12. Asperities degradation due to cyclic displacement in low levels of normal stress (σ_n =1.2MPa).

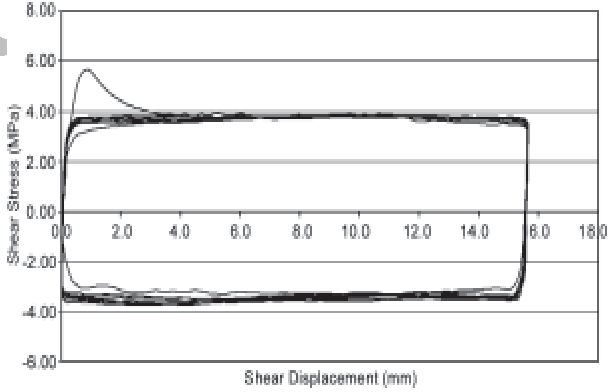


Figure 14. Shear stress-shear displacement curve for saw-tooth samples during 10 cycles in 6.5MPa normal stresses.

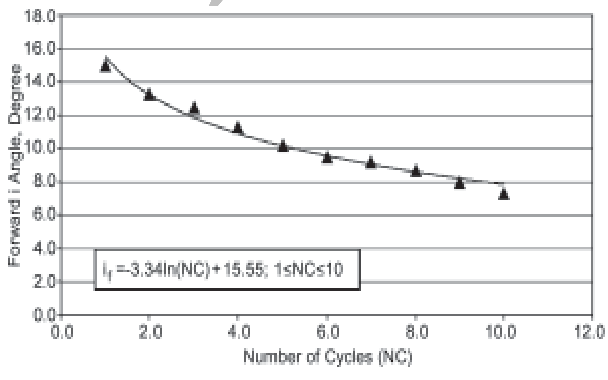


Figure 13. Variation of forward dilation angle with number of cycles in low levels of normal stress (σ_n =1.2MPa).

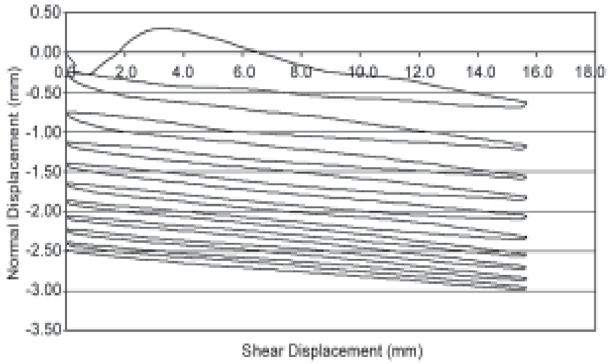


Figure 15. Contraction due to cyclic shear displacement in high level of normal stress (σ_n = 6.5MPa).

changing the behaviour of joint samples during cyclic displacements. As it can be seen in Figure (16), during the first two cycles, upper and lower walls of the joint slide on each other, but in the third cycle breaking of the teeth occurred and the behaviour has changed. Changing the behaviour during cyclic displacement is very important for evaluation of stability of under/above ground structures in jointed rock masses as in most cases designers use simple shear test results for determination of shear strength.

The changing of the behaviour can be observed more clearly in dilation– contraction curves as shown in Figure (17). It can be observed that in the first two cycles the behaviour of the sample is controlled by dilation angles. In these two cycles degradation of asperities occurs during cyclic displacement. In the third cycle, due to breaking the teeth, dilation changed to contraction and during the rest of the cycles the shearing conditions are in accordance with the behaviour discussed in section 6.2.

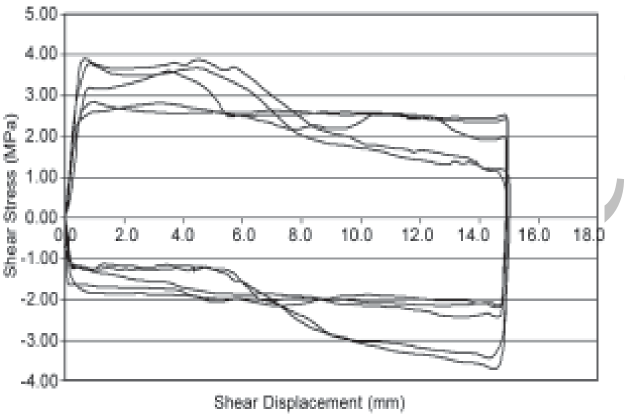


Figure 16. Shear stress-shear displacement curve for saw-tooth sample during 5 cycles in 4.2 MPa normal stress.

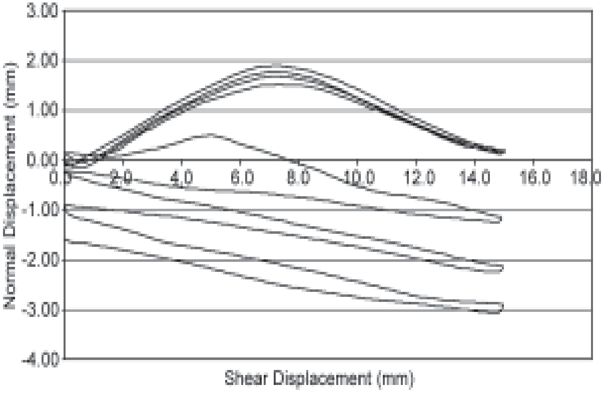


Figure 17. Dilation-contraction behaviour of joint replicas tested in intermediate levels of normal stresses (σ_n = 4.2MPa).

7. Conclusion

In this paper two different effects of cyclic loadings on shear strength of joint replicas were described. These situations can be used to simulate the behaviour of jointed rocks subjected to weak and strong earthquakes. The following conclusions can be presented:

- During small cyclic displacements, the degradation of second order asperities is the main geometrical feature that controls the shear strength of jointed rocks and the first order asperities do not have much effects on shearing resistance. On the other side during the large cyclic shear displacements degradation of first order asperities is the main controlling parameter for evaluation of shear strength. In such cases the second order asperities do not have much effects on shear resistance especially after experiencing a few cycles.
- When degradation and wearing of the joint surface have been stabilized in a constant level, shear strength does not change considerably even if more displacement or loading cycles apply on the jointed samples.
- During small cyclic loadings several parameters can affect the shear strength of jointed rocks. Increase of rate of loading or shearing velocity, number of loading cycles and their frequency and amplitude can decrease the shear strength considerably.
- Cyclic displacement may change the shearing behaviour of jointed samples from sliding to breaking.

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