13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 3070

SHEAR STRENGTH REDUCTION OF ROCK JOINTS DUE TO CYCLIC LOADING

Kambod Amini Hosseini[1]
Frederic Pellet[2]
Mohammad Kazem Jafari[3]
Marc Boulon[4]

SUMMARY

During strong earthquakes, relative large cyclic displacements may be occurred between the different walls of rock joints. These cyclic displacement degrade the first and second order asperities along the joint surface and reduce shear strength of rock joint.
In this experimental study, the variation of shear strength of rock joints during large cyclic displacement is investigated to simulate the effects of strong earthquakes on rock joints. Artificial Jointed samples have been prepared adopting a developed moulding method using special mortar and tested in direct shear apparatus under cyclic loading conditions. The tests have been performed in different levels of normal stresses to investigate the shearing behaviour of rock joints located at different depths from ground surface. In each test, several displacement cycles have been applied on the samples and the variation of shear strength; asperity degradation and wearing have been studied during each cycle.
Based on the results of this research, it was concluded that shear strength of rock joints is in close relation with number of loading cycles and rate of asperity degradation in all levels of applied normal stresses. In addition it was concluded that the level of normal stress will control the displacement and rupture mechanism of jointed rock. In high level of normal stresses during shear displacement the asperities will be cut from their bases while when applying lower levels of normal stress, the predominant displacement mechanism is sliding.
Finally, based on the evaluations of experimental results, a mathematical model has been developed for prediction of shear strength in large cyclic loading conditions.

---

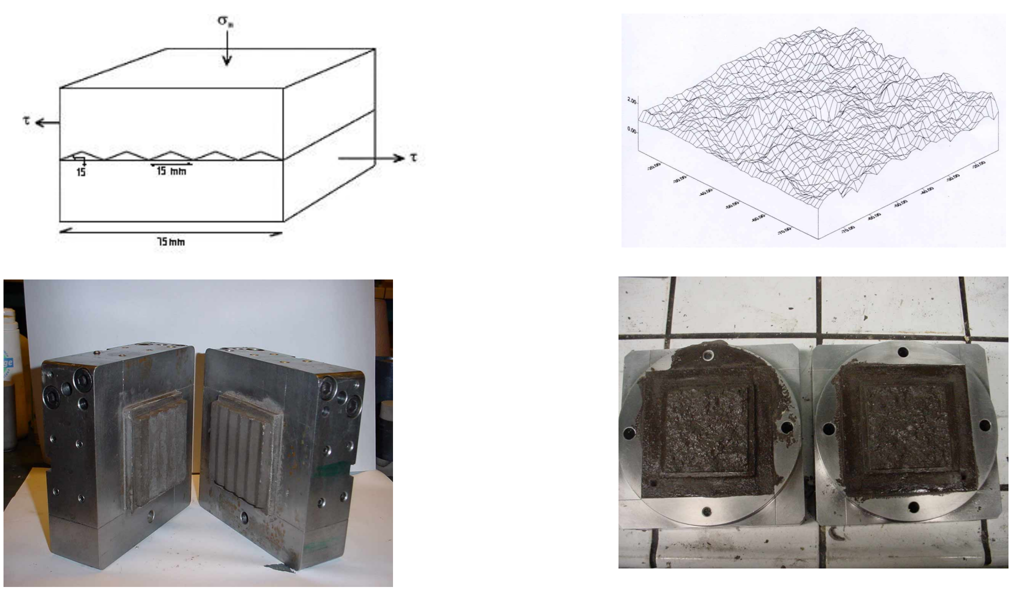
[1] Assistant professor, Geotechnical Eng. Research Center, International Institute of Earthquake Engineering and Seismology, Tehran Iran.
[2] Associate professor, Laboratoire 3S, Unversite Joseph Fourier, Grenoble, France
[3] Associate professor, Geotechnical Eng. Research Center, International Institute of Earthquake Engineering and Seismology, Tehran Iran.
[4] Professor, Laboratoire 3S, Unversite Joseph Fourier, Grenoble, France

INTRODUCTION

Among the geometrical parameters that affect the shear strength of unfilled rock joints during cyclic loading, roughness and dilation angle are the main ones. Due to cyclic displacement, these properties could change as a result of variations of first and second order asperities.
The previous studies have been generally focused on determining of the peak shear strength of rock joints under monotonic loading and their behaviour under cyclic loading condition has been rarely reported. Hutson and Dowding (1990) performed some cyclic tests on artificial joints with sinusoidal shape and presented a wear equation for joint asperity based on the experimental results. Huang et al (1993) have also performed cyclic tests on saw-tooth samples to evaluate the degradation law proposed by Plesha (1983). Divoux et al (1997) presented a mechanical constitutive model based on the results of cyclic shear tests. Armand et al (1998) have studied the frictional properties of the contacts between smooth Dionysos marble experimentally and numerically in different conditions. Kana et al (1996) introduced the importance of second order asperities in cyclic loading and suggested the interlock – friction model for dynamic shear response.
In this paper the results of a new experimental investigation on artificial joints will be presented. Cyclic displacements have been applied on the prepared identical samples, using direct shear testing machine, to simulate the effects of strong earthquakes. Based on the obtained results, a mathematical model has been developed for evaluation of cyclic shear strengths of rock joints.

TESTING PROGRAM

Two types of the joint surface have been prepared for all the tested replicas: saw-tooth and a real joint surface moulded from a fresh joint. Schematic views of these surfaces are shown in figure (1). All the samples were prepared using a special kind of mortar and a developed moulding method using special silicon rubber. The uniaxial compression strength of the samples was more than 55 MPa and its tensile strength (using Brazilian test) was about 8 MPa after 24 hours. Figure 2 shows some of the prepared samples by this method.



(a) *(b)*

Figure 1: a- *Saw-tooth samples;* ***b-*** *Real surface samples for direct shear tests*

All of the tests have been performed using a direct shear testing machine (figure 2) developed by Boulon (1995) called BCR 3D at Laboratory 3S (Lab. 3S) of the University of Joseph Fourier, in Grenoble, France. 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 active part of the joint at any time. Shear and normal displacements are measured by 4 LVDTs in each direction. All of the data are recorded using a standard computer and a high frequency data acquisition system.

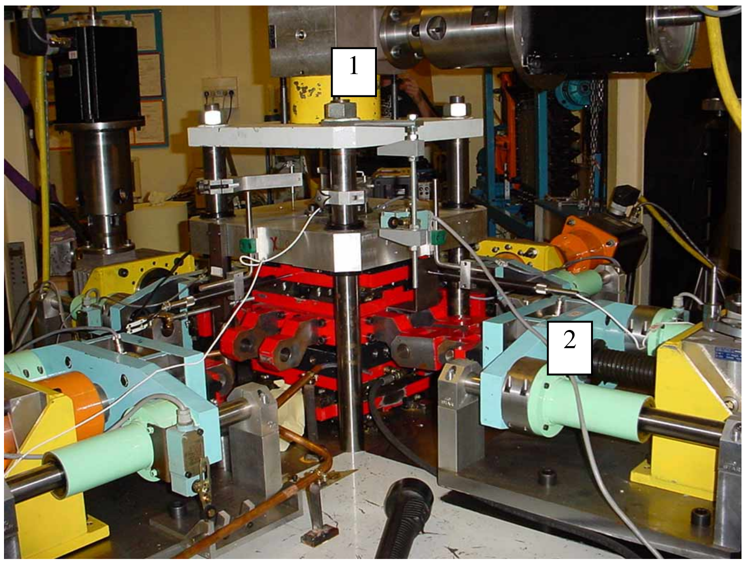


Figure 2: *Direct Shear testing machine (BCR 3d);*

1- *Axial brushless servo-motor ,* ***2****- Shearing Brushless servo-motor*

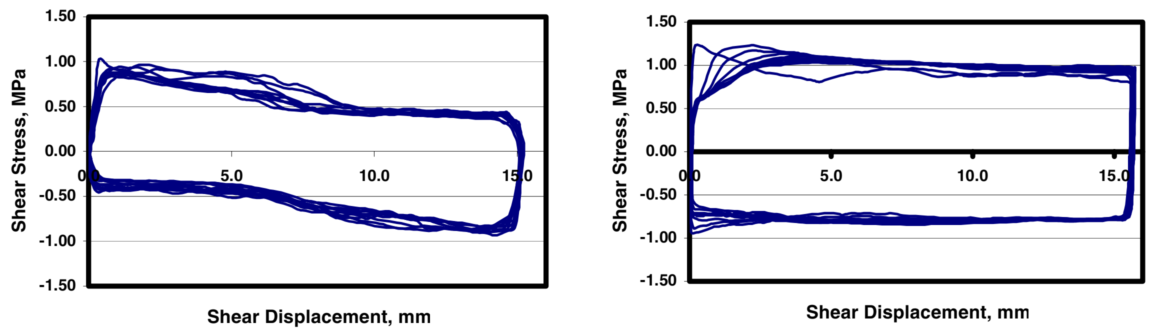
EXPERIMENTAL RESULTS

Two types of the joint surface have been prepared for all the tested replicas: saw-tooth and a real joint surface moulded from a fresh joint. Schematic views of these surfaces are shown in figure (1). All the samples were prepared using a special kind of mortar and a developed moulding method using special silicon rubber. The uniaxial compression strength of the samples was more than 55 MPa and its tensile strength (using Brazilian test) was about 8 MPa after 24 hours. Figure 2 shows some of the prepared samples by this method.

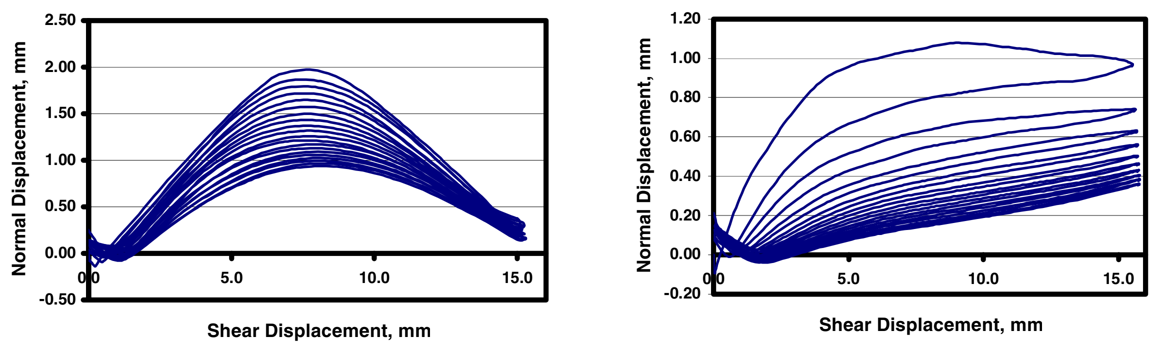
Degradation under low level of normal stresses

In low level of normal stresses the main shearing mechanism during cyclic displacement is sliding over the asperities. During sliding, degradation could occur in both second and first order asperities that may finally smooth the shearing surface. Shear strength of the joint samples reduces in each cycle to reach to a constant level after experiencing few cycles (5-6 in this investigation).
In figure (3-a) the results of some of the performed tests on saw-tooth and real surface models under 1.2 MPa normal stresses are presented. Although degradation of second and mainly first order asperities continue during cyclic displacement, but the second order asperities do not have considerable effects on shear behaviour of joint replicas as they diminish after few cycles.

The trend of degradation could be observed more clearly in figure (3-b). As the shear strength is in direct relation with dilation angle (i), therefore it will be reduced when the dilation angle decrease. In addition, the effects of wearing should be also considered for better evaluation of shear strength variations during cyclic displacement.



(a)



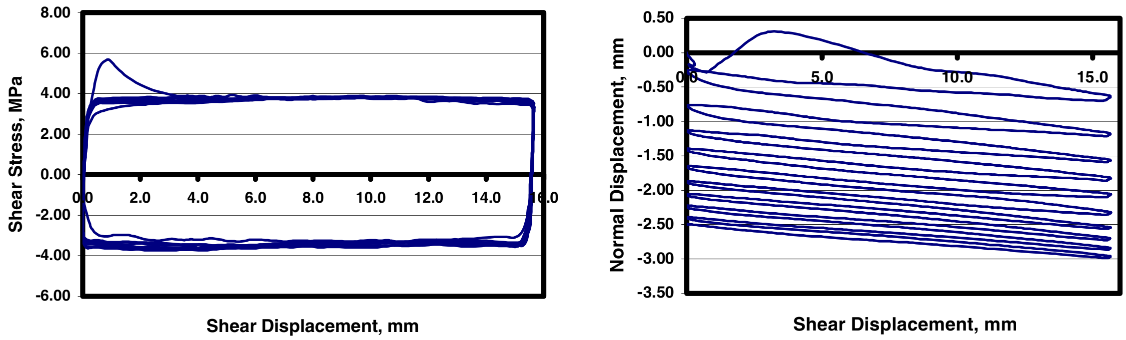
(b)

Figure 3: a- *Shear Stress- Shear Displacement curve for saw-tooth and real surface joint models during 10 cycle,* ***b-*** *Asperities degradation due to cyclic displacement (* $\sigma_n = 1.2 MPa$ *)*

Degradation under high level of normal stresses

In high level of normal stresses, the asperities would be broken during the shear displacement and no considerable dilation could be expected. Figure (4-a) shows the result of one of the performed tests on saw-tooth replicas under 6.5 MPa normal stresses. During forward shearing at the first cycle, all teeth have been cut and the shear strength for rest of the cycles is nearly constant.

The variation of dilation-contraction curves during cyclic shearing is shown in figure (4-b). Only in the first cycle and before breaking the teeth small dilations could be expected and in the other cycles, contraction would be the main observed behaviour in the tests.



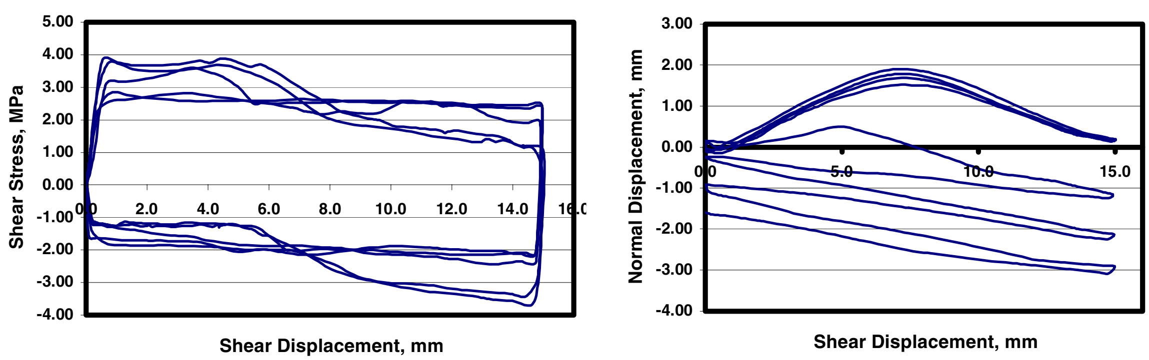
(a) *(b)*

Figure 4: a- *Shear Stress- Shear Displacement curve for saw-tooth joint models during 10 cycle, b- Contraction due to cyclic displacement (* $\sigma_n = 6.5MPa$ *)*

Degradation under intermediate level of normal stresses

In order to study the transition behaviour (sliding to breaking) of joint replicas during cyclic displacement, some direct shear tests have been performed on saw-tooth and real surface models of jointed samples. The results presented in figure (5-a) demonstrate this transitional behaviour. During the first two cycles the main controlling mechanism on the sample is sliding over the asperities, but in the third cycle teeth have been broken and the behaviour has been changed. In real conditions, this sharp transformation cannot be expected.

This phenomenon can be observed more clearly in dilation – contraction curves (figure 15-b). In sliding mechanism, dilation occurs during shearing while in breaking stage, the contraction of the sample is predominant.



(a) *(b)*

Figure 5: a- *Shear Stress- Shear Displacement curve for saw-tooth joint models during 5 cycles, b- Dilation- Contraction behaviour due to cyclic displacement (* $\sigma_n = 4.2MPa$ *)*

MATHEMATICAL MODEL

Based on the results of the performed tests and the trends of the data, the following mathematical model has been developed to evaluate the shear strength of the jointed samples during large cyclic shear displacement:

$$\frac{\tau}{\sigma_n} = \frac{b(NC)^p (i_n)^q + c}{1 + b(NC)^p (D_n)^q} \qquad (1)$$

Where:

τ is shear strength,

σ_n is normal stress,

NC is number of displacement cycles,

i_n is the normalized dilation angle (normalized by the maximum angle measured before the test)

D_n is normalized degradation (normalized by maximum value of asperities amplitude).

In this relation the parameters b, c, p and q could be obtained by model calibration as follows:

b = –0.33
c = 1.44
p = 0.12
q = 0.3

The parameters b and c are related to the mechanical properties of the tested sample such as friction angle (ϕ) and also geometrical features of the joint surface. Wearing and asperity degradation are functions of number of cycles, and may have important effects on shear strength of jointed samples.

Dilation angle and asperity degradation are also two related parameters that control the shear strength of rock joints during cyclic displacement. If asperity degradation increases, the dilation angle and the shear strength would decrease. In figure (6) some of the test results have been compared with the proposed model in which the good agreement is observed.

CONCLUSION

In this paper the variation of shear strength of joint replicas in different condition of cyclic loadings have been studied. Following main conclusions could be drawn from this investigation:

1- During cyclic shear displacement, degradation of both first and second order asperities will occur depending on the applied cyclic displacement and normal stress.

2- Dilation angle, degradation of asperities and wearing are three dependent main factors which affect the shear strength of rock joints during large cyclic displacement.

3- The shear behaviour of rock joints during sliding is in direct relation with the normal stress level and may change from sliding to breaking during cyclic displacement.

4- Presented model in this paper is based on the performed tests on artificial joints. In order to improve the proposed model, more investigations should be carried out on real joint samples in different condition.

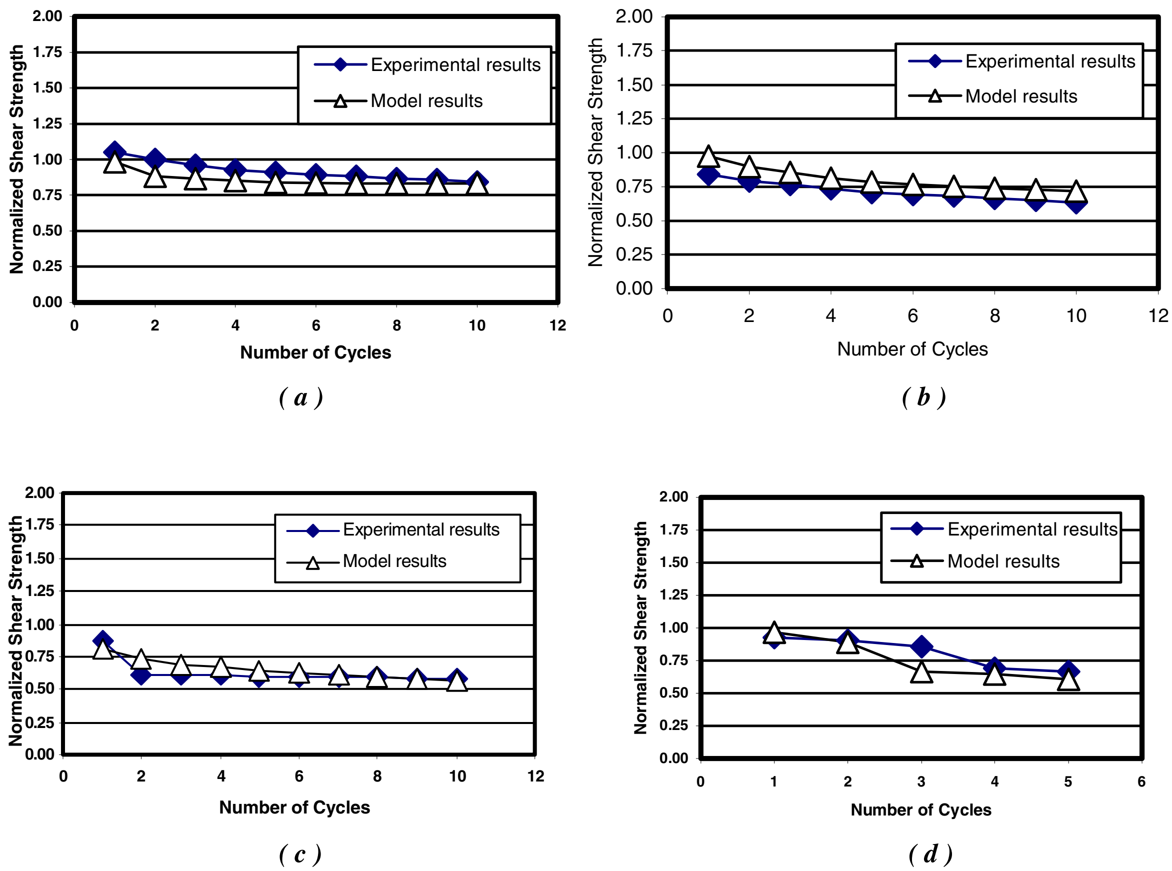


Figure 6: *Comparison of the measured and evaluated shear strength,*

a- *Real surface joint model at low levels of normal stress* $(\sigma_n = 1.2MPa)$;

b- *Saw-tooth joint surface at low levels of normal stress* $(\sigma_n = 1.2MPa)$;

c- *Saw-tooth joint surface at high levels of normal stress* $(\sigma_n = 6.5MPa)$;

d- *Saw-tooth joint surface at intermediate levels of normal stress* $(\sigma_n = 4.2MPa)$;

Shear Strength has been normalized by normal stress

REFERENCES

1. Armand, G., Boulon, M., Papadopoulos, C., Basanou, M.E. and Vardoulakis, I.P. (1998) Mechanical behaviour of Dionysos marble smooth joints: I. Experiments, *Proc. Mechanics of Jointed and Faulted Rock,* Rossmanith (ed.), 159-164.
2. Boulon, M. (1995) A 3D direct shear device for testing the mechanical behaviour and the hydraulic conductivity of rock joints, *Proc. Mech. of Jointed and Faulted rock,* Rossmanith (ed.), 407-413.

3. Divoux, P., Boulon, M. and Bourdarot, E. (1997) A mechanical constitutive model for rock and concrete joints under cyclic loading, *Proc. Damage and Failure of Interfaces*, Rossmanith (ed.), 443-450
4. Huang, X, Haimson, B. C., Plesha, M. E., and Qiu, X. (1993) An investigation of the mechanics of rock joints, *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, 30, 3, 257-269.
5. Hutson, R. W. and Dowding, C.H. (1990) Joint asperity degradation during cyclic shear, *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, 27, 2, 109-119.
6. Kana, D. D., Fox, D. J., Hsiung, S. M. (1996) Interlock/friction model for dynamic shear response in natural jointed rock, *Int. J. Rock Mech. Min. Sci.*, 33, 371-386.
7. Plesha, M. E. (1987) Constitutive models for rock discontinuities with dilatancy and surface degradation, *Int. J. Numer. Anal. Meth. Geomech.,* 11, 345-362.