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Evaluation of shear strength of rock joints subjected to cyclic loading

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Abstract

Variation of the shear strength of rock joints due to cyclic loadings is studied in the present paper. Identical joint surfaces were prepared using a developed moulding method with special mortar and shear tests were performed on these samples under both static and cyclic loading conditions. Different levels of shear displacement were applied on the samples to study joint behaviour before and during considerable relative shear displacement. It was found that the shear strength of joints is related to rate of displacement (shearing velocity), number of loading cycles and stress amplitude. Finally, based on the experimental results, mathematical models were developed for evaluation of shear strength in cyclic loading conditions.

Keywords: Shear strength; Roughness; Cyclic loading; Shearing velocity; Number of cycles; Stress amplitude

1. Introduction

The behaviour of rock joints under cyclic loading depends on their surface properties such as roughness, strength of asperities, separation, matedness, presence of gouge, etc. These properties may change as a result of variations in second-order asperities due to small cyclic loading, e.g. during weak earthquakes. Strong earthquakes in contrast affect mainly the first-order asperities. Previous studies have generally focused on determining the peak shear strength of rock joints under monotonic loading and their behaviour under cyclic loading conditions has been less reported. Few systematic studies are available concerning the effects of small repetitive earthquakes on the shear strength of rock joints. Hutson and Dowding [1] performed some cyclic tests on artificial sinusoidal joints and presented a wear equation for joint asperity based on the experimental results. Huang et al [2] also performed cyclic tests on saw-tooth samples to evaluate the degradation law proposed by Plesha [3]. Divoux et al [4] presented a mechanical constitutive model based on the results of cyclic shear tests. Armand et al [5] studied the frictional properties of the contacts between smooth Dionysos marble experimentally and numerically in different conditions. Kana et al [6] 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 an experimental investigation carried out on artificial joints will be presented. Two levels of cyclic displacement were applied on the identical prepared samples, using two types of testing machine, to simulate the effects of weak and strong earthquakes. Based on the results obtained, mathematical models were developed for evaluating the cyclic shear strength of rock joints.

2. Testing programme

Two types of 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 Fig. 1. The cylindrical samples (Fig. 1(a)) were prepared to evaluate the effects of small cyclic loads using a triaxial loading device, and the cubic samples (Fig. 1(b) and (c)) were designed for large displacement using a direct shear apparatus. All the samples were prepared using a special kind of mortar and a specially developed moulding method using silicone rubber. The uniaxial compression strength of the samples was more than 55 MPa and its tensile strength (determined by Brazilian tests) was about 8 MPa after 24 h. Fig. 2 shows some of the samples ready to be tested.

For the small cyclic displacement tests, two triaxial testing devices were used at the 3S Laboratory (Lab. 3S) of

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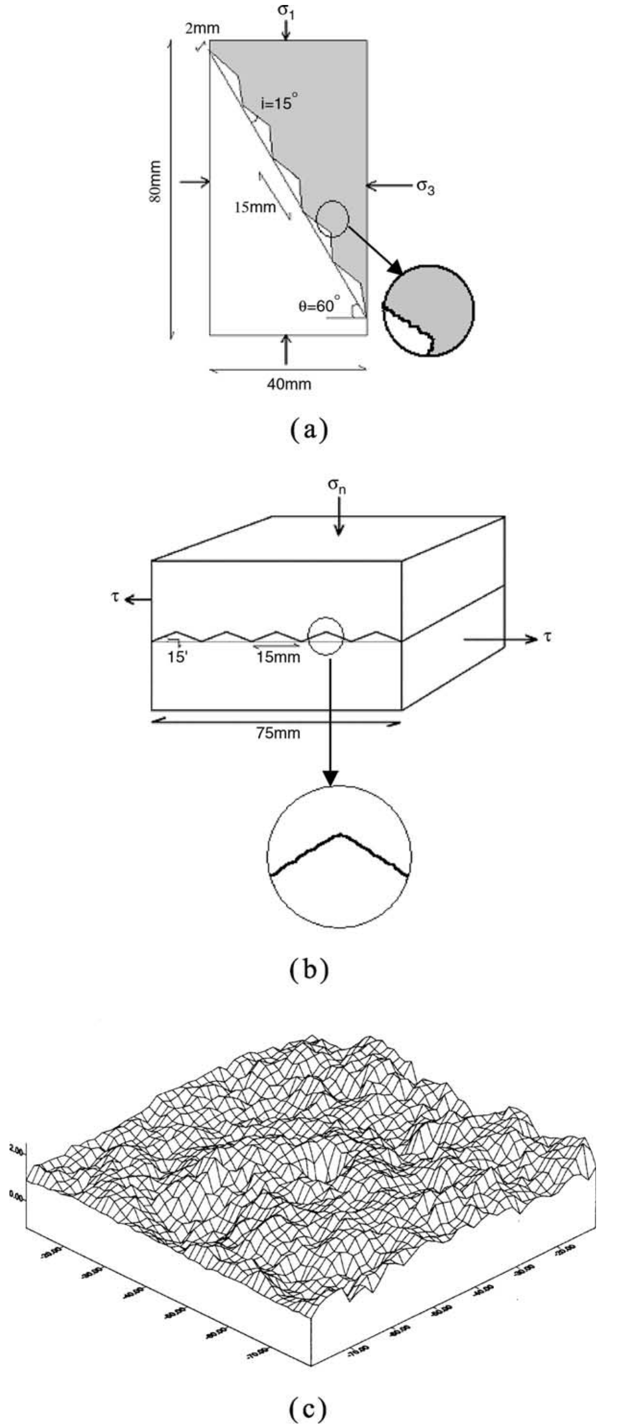


Fig. 1. (a) Saw-tooth samples for triaxial tests; (b) saw-tooth samples for direct shear tests; (c) real surface joint model for direct shear tests.

the University Joseph Fourier in Grenoble, France and at the Laboratory of Rock Mechanics (LMR) of the Swiss Institute of Technology (EPFL) in Lausanne, Switzerland. Two separate systems for applying the axial loads and confining pressure were used. All the systems were equipped with a function generator to provide different types of voltages for applying cyclic loads. All the data including displacements, forces, confining pressure and

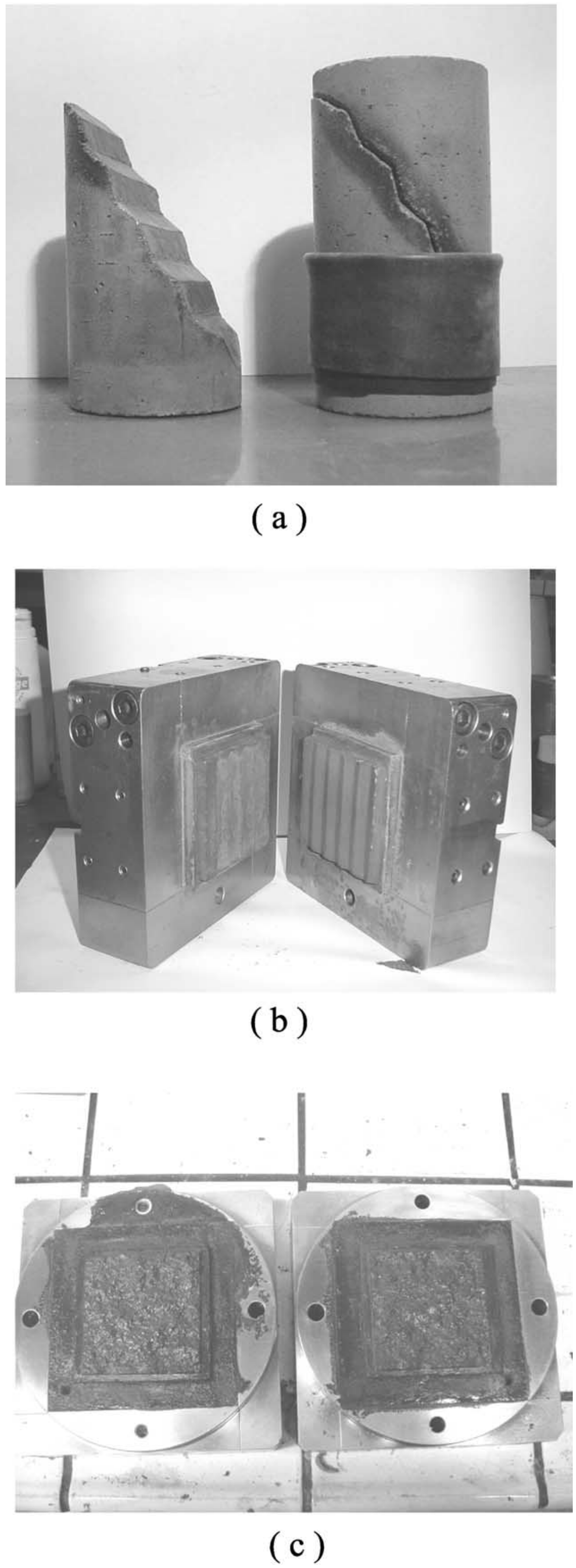
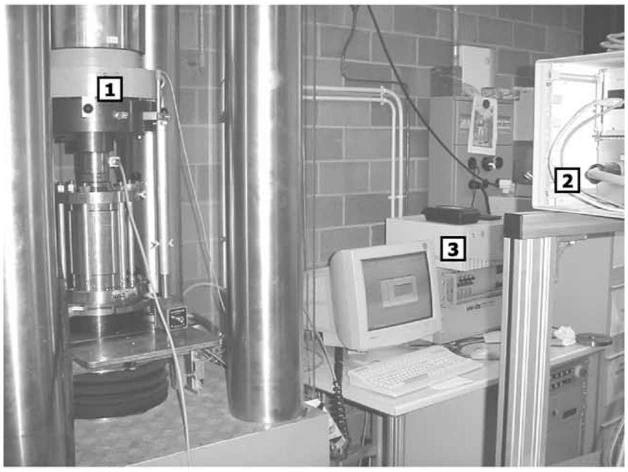
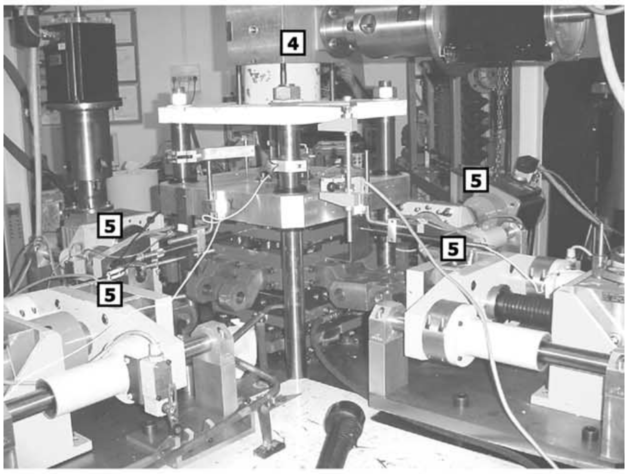


Fig. 2. Some of the prepared samples by using silicon moulds; (a) and (b) saw-tooth samples; (c) real joint surface sample.

(a)



(b)



(c)

Fig. 3. Testing machines and data acquisition systems, (a) triaxial machine at Lab. 3S; (b) triaxial machine at LMR; (c) direct shear machine at Lab 3S (1—axial jack, 2—confining pressure system, 3—data acquisition system, 4—axial brushless servo-motor, 5—shearing brushless servo-motor).

time were measured and recorded by personal computer with the adjustable sampling rates. Axial displacements were measured using 4 vertical LVDTs simultaneously and their average used for analysis.

All of the large cyclic displacement tests were performed using a new direct shear testing apparatus at Lab. 3S. called BCR 3D, developed by Boulon [7]. By using two similar brushless servo-motors, the two walls of a joint can move symmetrically, so no relative rotation occurs during the shearing displacement and the normal force remains centred on the active part of the joint at any given 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. Fig. 3 shows the testing devices.

3. Effects of small cyclic displacements on shear strength

3.1. Experimental results

The triaxial tests were performed to study the behaviour of the joint samples during small cyclic displacements. Variations in shear strength in monotonic and cyclic loading conditions under different shearing velocities, numbers of cycles, and stress amplitudes were studied. The results of some of the tests performed will be presented and discussed in this paper.

3.1.1. Effects of displacement rates

In order to study the effects of displacement rates (or shearing velocity) on shear strength, some monotonic tests were performed in different ranges of axial displacement in 4 MPa confining pressure from 0.05 to 0.4 mm/s. Some of the results have been presented in Fig. 4. The differences between the curves can be related to the effects of shear velocity on second-order asperities, as the total applied displacement is limited. It is observed that shear strength reduces with increasing shear velocity, approaching the same values for the peak and residual strength at higher shearing velocities.

3.1.2. Effects of number of cycles

To study the effects of the number of stress cycles on the shear strength of rock joints two different stages were defined. In the first stage several stress cycles (between 25 and 3000 cycles) were applied on the replicas (stress control) and in the second stage the monotonic loading (displacement control) was continued to reach the ultimate shear strength.

One of the results of the tests performed is presented in Fig. 5. In the first part (Fig. 5(a)) 100 stress cycles were applied on the sample and in the second part the test was followed by monotonic loading (Fig. 5(b)). As can be observed, degradation of asperities happens mainly during the first stress cycles, being attenuated in the higher stress cycles. Due to the limited level of the shear displacement applied, asperity degradation could be related to the second-order asperities.

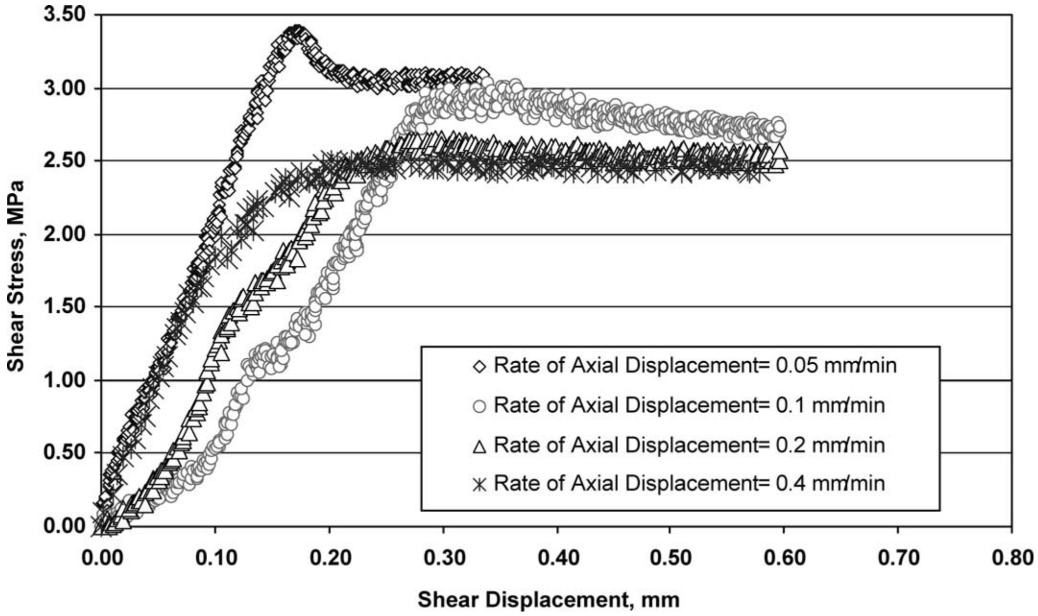
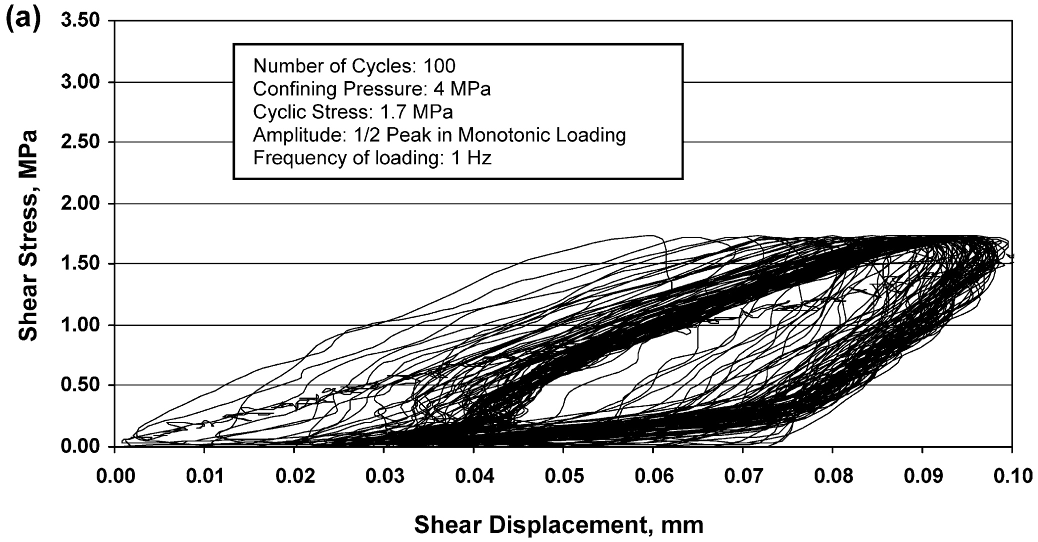


Fig. 4. Shear stress–shear displacement curve for different rates of axial displacement.



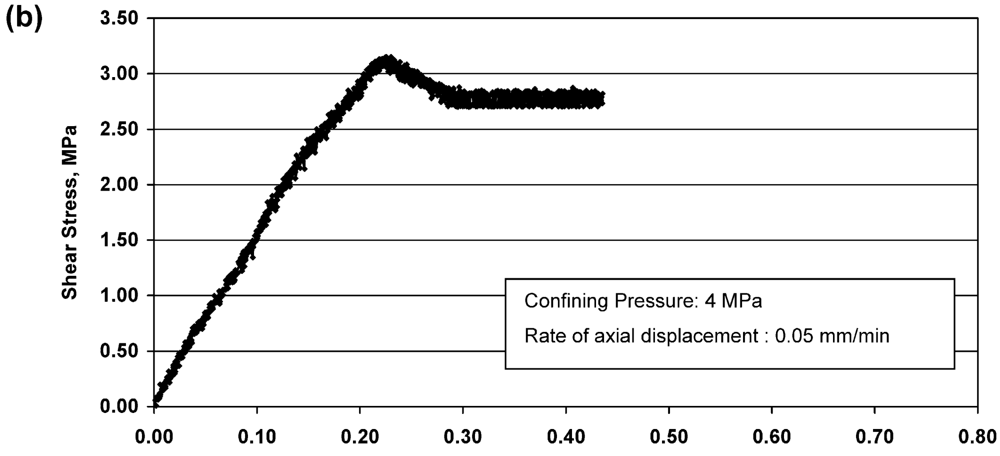


Fig. 5. The results of one of the cyclic tests on saw-tooth samples subjected to 100 loading cycles; (a) stress control part; (b) displacement control part.

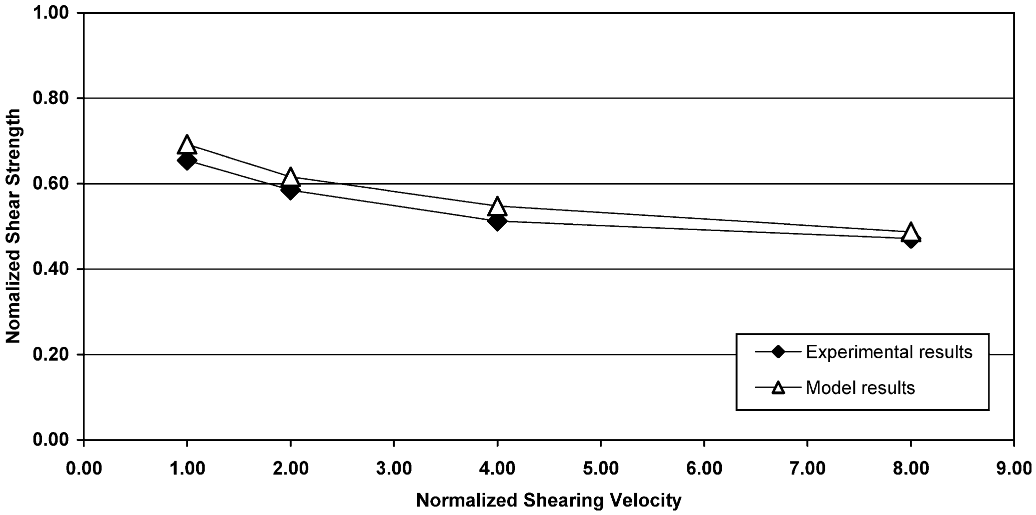


Fig. 6. Comparison of the measured and calculated shear strength at different shear velocities.

3.1.3. Effects of stress amplitude

The stress amplitude in the above-mentioned tests was selected as half of the maximum strength measured in monotonic loading. Some extra investigations were performed on the samples applying 100 stress cycles at different levels of stress amplitude (between 15 and 70% of maximum strength). The shear strength appears to decrease (for the same number of cycles) for higher levels of stress amplitude applied on the joint surface.

3.2. Mathematical modelling

Based on the test results the following relation could be proposed for evaluating shear strength under low amplitude cyclic loading

$$\frac{\tau}{\sigma_n} = \frac{a(NC_s)^m(\dot{\omega}_n A_n)^n}{1 + a(NC_s)^m(\dot{\omega}_n A_n)^n} \quad (1)$$

where τ is the shear strength, σ_n is the normal stress, NC_s is the number of stress cycles, $\dot{\omega}_n$ is the normalized shear velocity (normalized by the minimum shearing velocity during monotonic tests, in which the maximum shear strength exists), A_n is normalized stress amplitude (normalized by maximum shear strength).

Based on calibration with the results of the tests performed, the following model parameters are obtained

$a = 0.3, \ m = -0.045, \ n = -0.17.$

The parameter a is related to the mechanical properties of the joint sample (e.g. base friction angle, ϕ_b) and the geometrical features of joint surface. As the present investigations focused on artificial joint samples, more investigations on real rock joints with different conditions should be carried out to obtain a better evaluation of these parameters. The number of stress cycles, NC, has little effect on shear strength, represented by the small value for

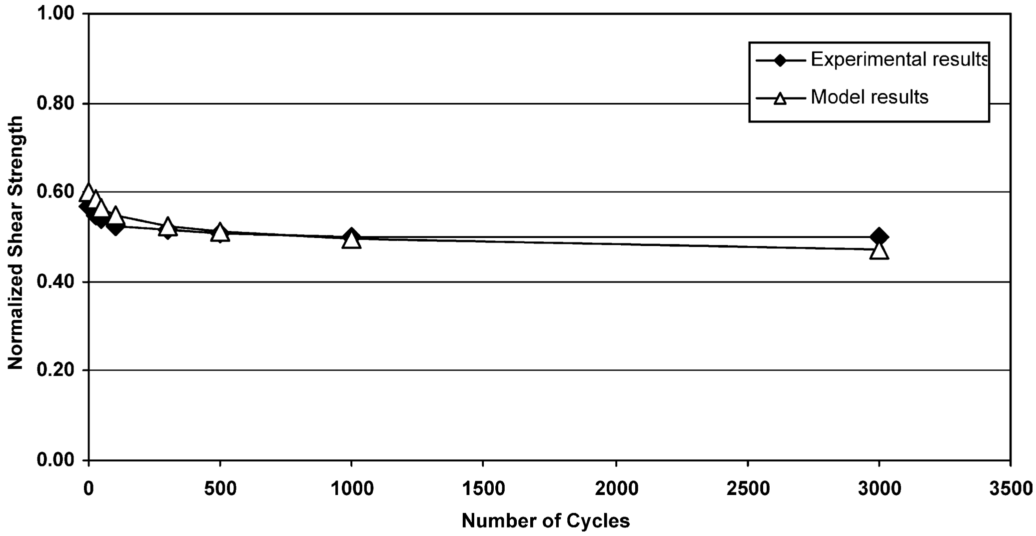


Fig. 7. Comparison of the measured and calculated shear strength for different numbers of stress cycles.

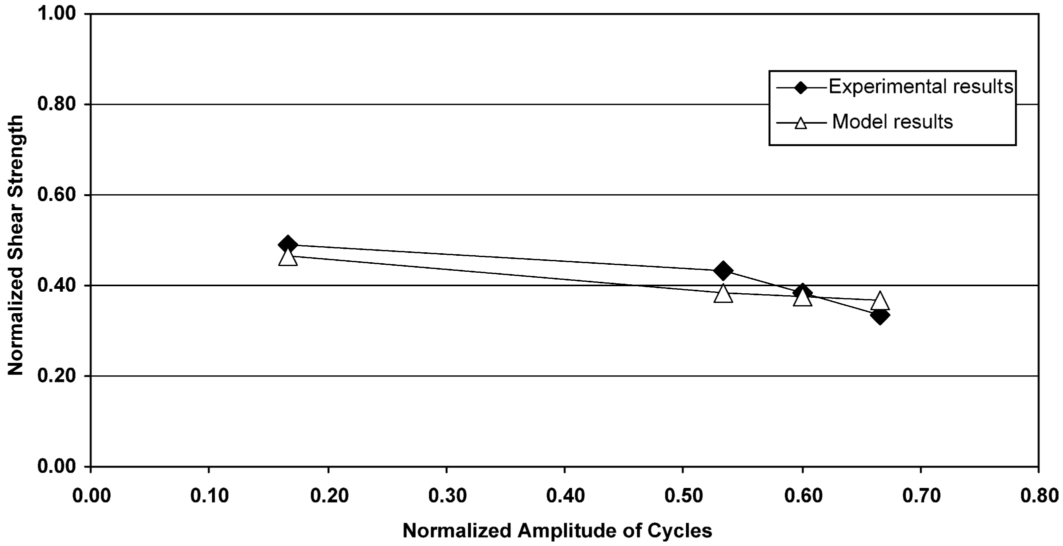


Fig. 8. Comparison of the measured and calculated results for different stress amplitudes.

the parameter *m*. In contrast, stress amplitude and shearing velocity have relatively large effects on shear strength due to the higher value for the parameter *n*. As can be observed in Figs. 6–8, the proposed model correctly simulates the experimental results with an acceptable level of precision.

4. Effects of large shear displacement on shear strength

4.1. Experimental results

In order to evaluate the shear strength of joint replicas during large cyclic displacements, direct shear tests using BCR-3D were performed on saw-tooth and real surface models of joint samples. The total relative displacement applied was 15 mm, in which each wall of the joints was moved 7.5 mm. The tests were performed at three different levels of normal stress and the variations in shear strength as well as the degradation of the asperities were studied.

4.1.1. Degradation at low levels of normal stress

At low levels of normal stress, the main shearing mechanism during cyclic displacement is sliding along the asperities. During sliding, degradation may occur in both second- and first-order asperities to smooth the shearing surface. The shear strength of the joint samples diminishes in each cycle to reach a constant level after experiencing a few cycles (5–6 in this investigation).

In Figs. 9 and 10 the results of some of these tests performed on saw-tooth and real surface models under 1.2 MPa normal stresses are presented. Degradation of second- and mainly first-order asperities continues during

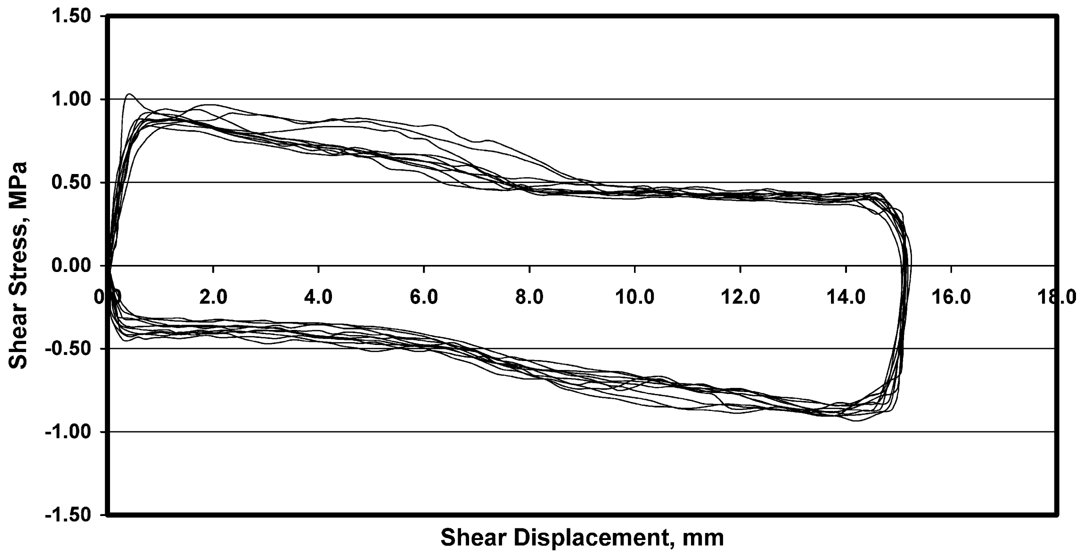


Fig. 9. Shear stress–shear displacement curve for saw-tooth samples during 10 cycles under 1.2 MPa normal stress.

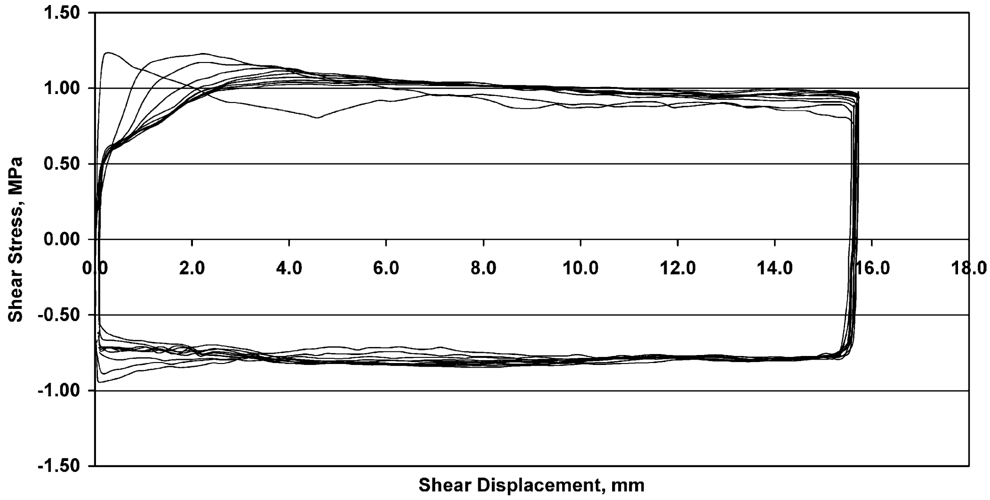


Fig. 10. Shear stress–shear displacement curve for real surface model during 10 cycles under 1.2 MPa normal stress.

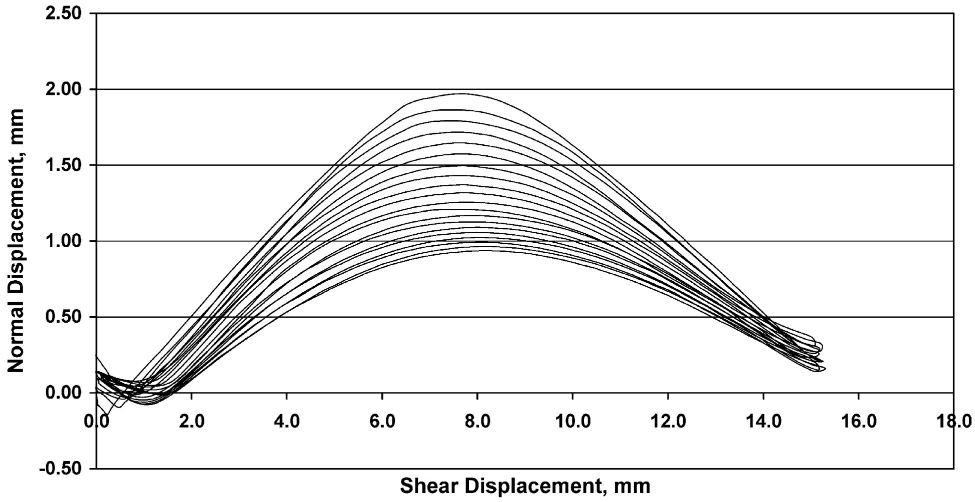


Fig. 11. Asperities degradation due to cyclic displacement at low levels of normal stress for saw-tooth samples during 10 cycles ($\sigma_n = 1.2$ MPa).

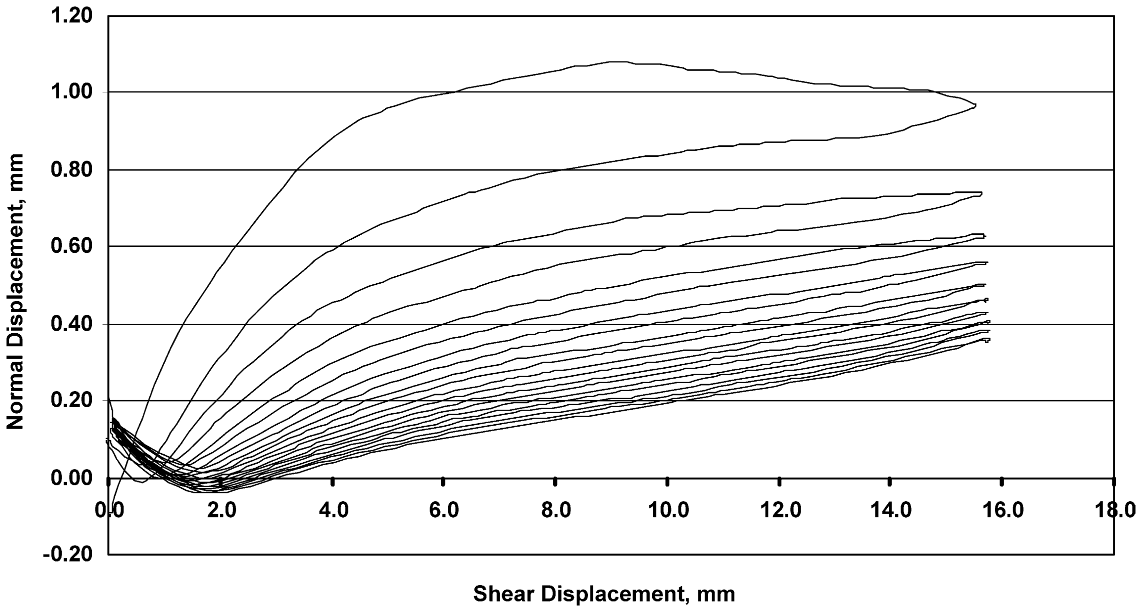


Fig. 12. Asperities degradation due to cyclic displacement at low levels of normal stress for real surface model during 10 cycles ($\sigma_n = 1.2$ MPa).

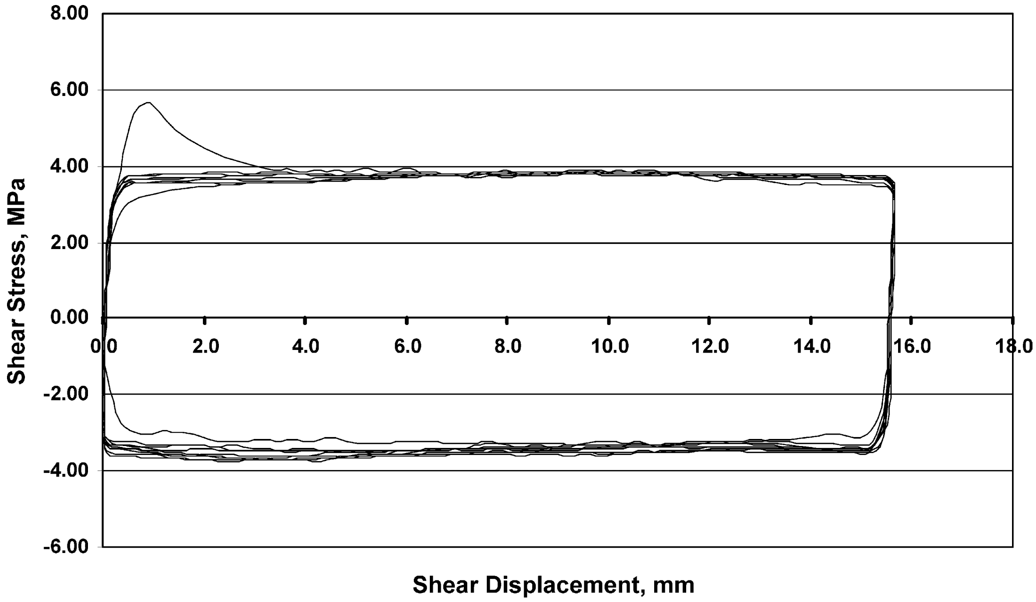


Fig. 13. Shear stress–shear displacement curve for saw-tooth samples during 10 cycles under 6.5 MPa normal stresses.

cyclic displacement, but the second-order asperities do not have any considerable effect on the shear behaviour of joint replicas as they diminish after a few cycles. The degradation trend can be observed more clearly in Figs. 11 and 12. As the shear strength is directly related to the dilation angle (i), it will be reduced when the dilation angle decreases. In addition, the effects of wearing should also be considered to obtain a better evaluation of shear strength variations during cyclic displacement.

4.1.2. Degradation under high levels of normal stress

At high levels of normal stress, asperities will be broken during shear displacement and no considerable dilation can be expected. Fig. 13 shows the results of one of the tests performed on saw-tooth replicas under 6.5 MPa normal stresses. During forward movement in the first cycle, all the teeth were cut and the shear strength for the rest of the cycles was nearly constant.

The variation in dilation–contraction curves during cyclic shearing is shown in Fig. 14. Only in the first cycle and before breaking of the teeth, some small dilation can be occurred and in the other cycles, contraction is the main mechanism observed in the tests.

4.1.3. Degradation under intermediate levels of normal stress

In order to study the transition between sliding and breaking of joint replicas during cyclic displacement, some direct shear tests were performed on saw-tooth and natural surface models of jointed samples. The results presented in

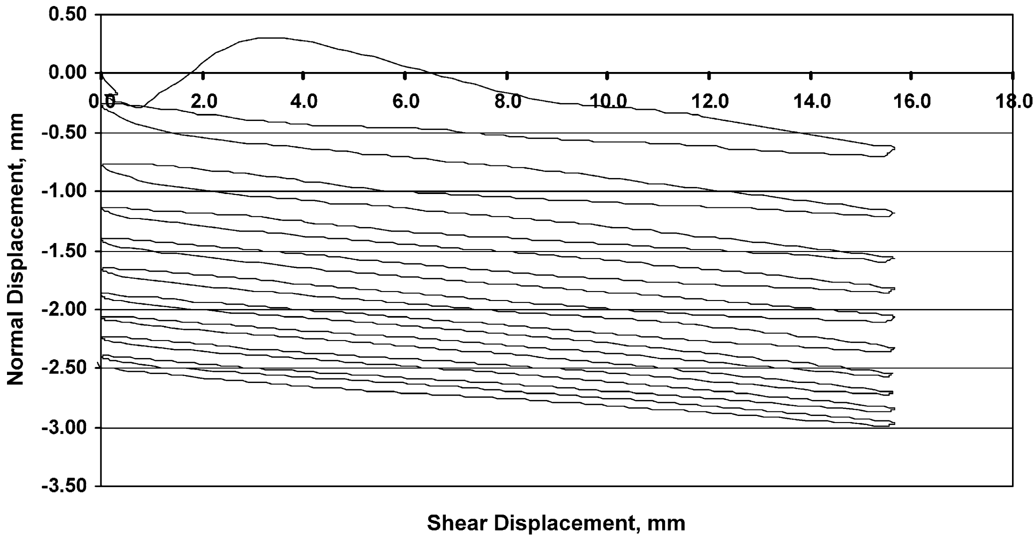


Fig. 14. Contraction due to cyclic shear displacement in high level of normal stress in saw-tooth samples ($\sigma_n = 6.5$ MPa).

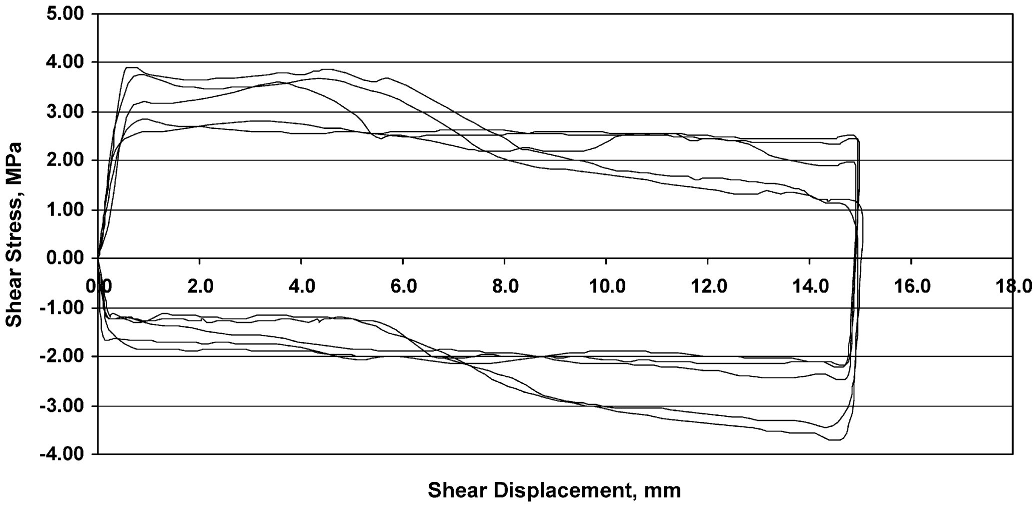


Fig. 15. Shear stress–shear displacement curve for saw-tooth sample during five cycles under 4.2 MPa normal stress.

Figs. 15 and 16 demonstrate this transitional behaviour. During the first two cycles (Fig. 15) the main controlling mechanism on the sample is sliding over the asperities, but in the third cycle teeth were broken and the behaviour has been changed. In real conditions (Fig. 16) this sharp transformation cannot be expected.

This phenomenon can be observed more clearly in dilation–contraction curves (Fig. 17). With a sliding mechanism, dilation occurs during shearing while at the breaking stage, the contraction of the sample is predominant.

4.2. Mathematical model

Based on the results of the tests performed and on the trends of the data in each group discussed, the following mathematical model was developed to evaluate the shear strength of the jointed samples during large cyclic shear displacement

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

Where τ is shear strength, σ_n is normal stress, $\mathrm{NC_d}$ 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 can 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 sample tested, such as friction angle (ϕ) and also the geometrical features of the joint surface. Wearing and asperity degradation are functions of the number of cycles, and may have important effects on

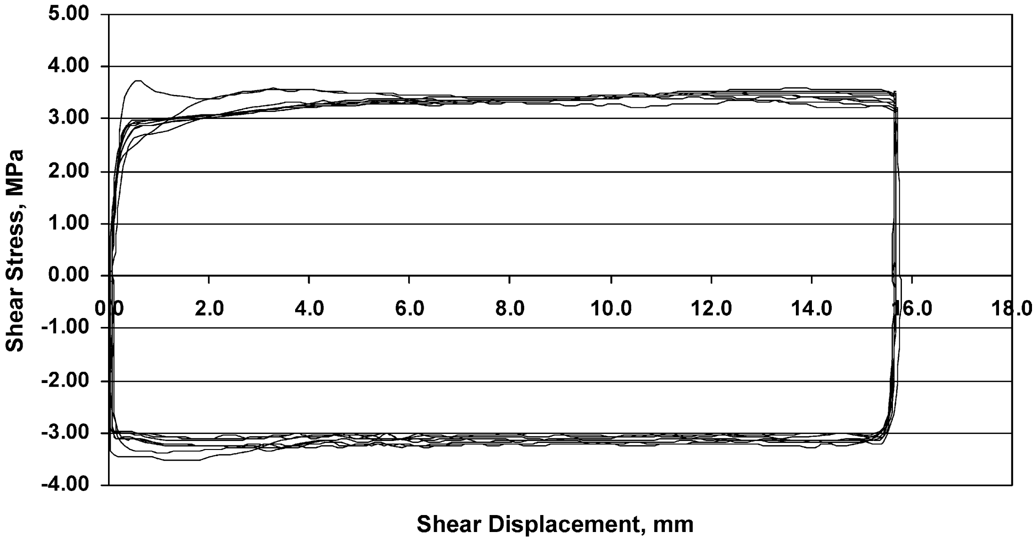


Fig. 16. Shear stress–shear displacement curve for real surface sample during 10 cycles under 4.2 MPa normal stress.

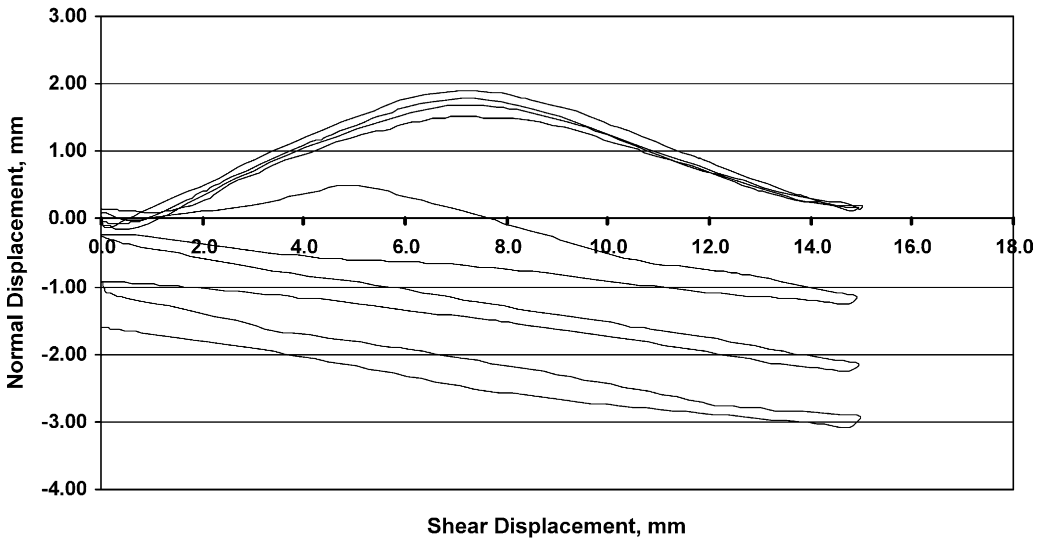


Fig. 17. Dilation–contraction behaviour of joint replicas for intermediate levels of normal stress ($\sigma_n = 4.2$ MPa).

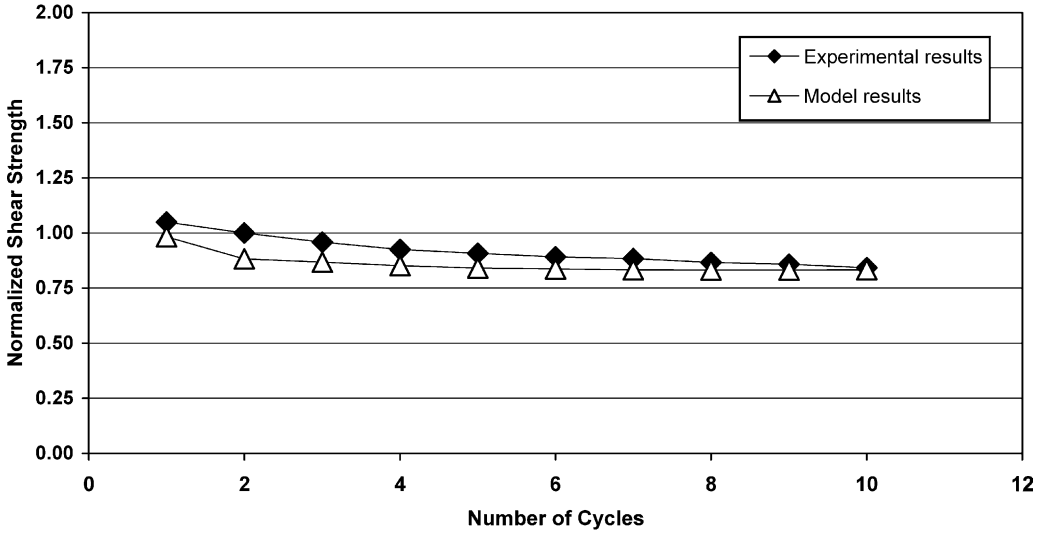


Fig. 18. Comparison of the measured and evaluated shear strength of real surface joint model at low levels of normal stress ($\sigma_n = 1.2$ MPa).

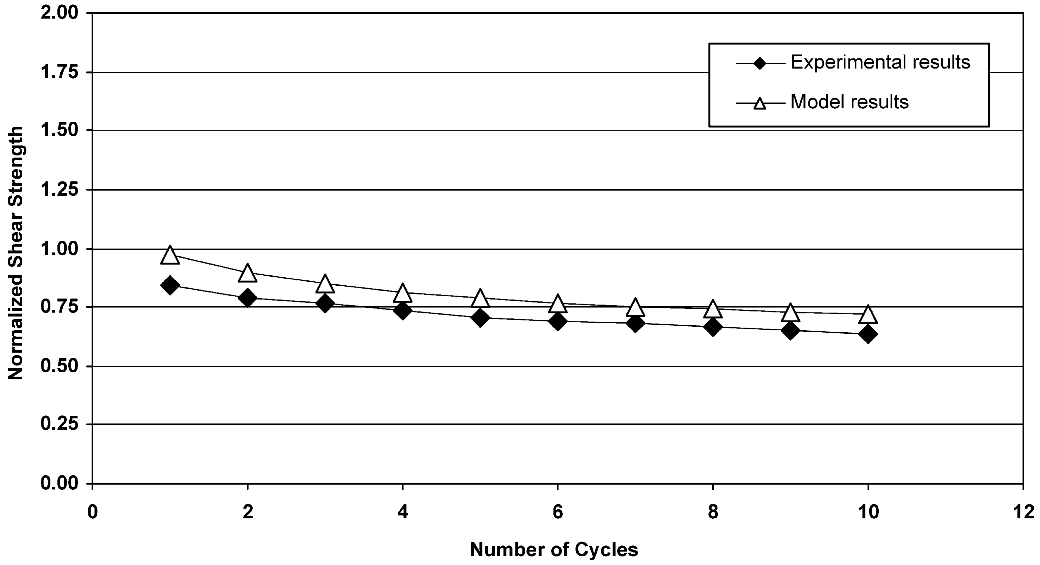


Fig. 19. Comparison of the measured and evaluated shear strength of saw-tooth joint model at low levels of normal stress ($\sigma_n = 1.2$ MPa).

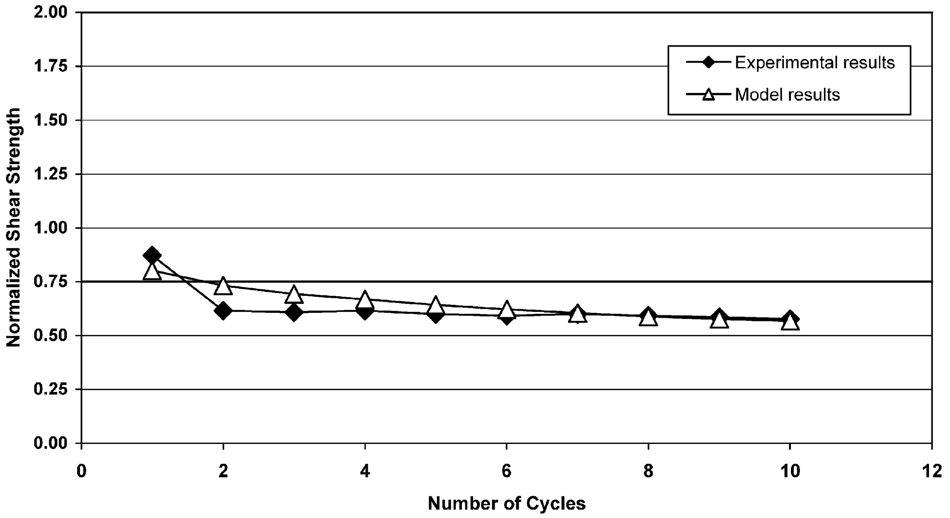


Fig. 20. Comparison of the measured and calculated shear strength of saw-tooth joint model at high levels of normal stress ($\sigma_n = 6.5$ MPa).

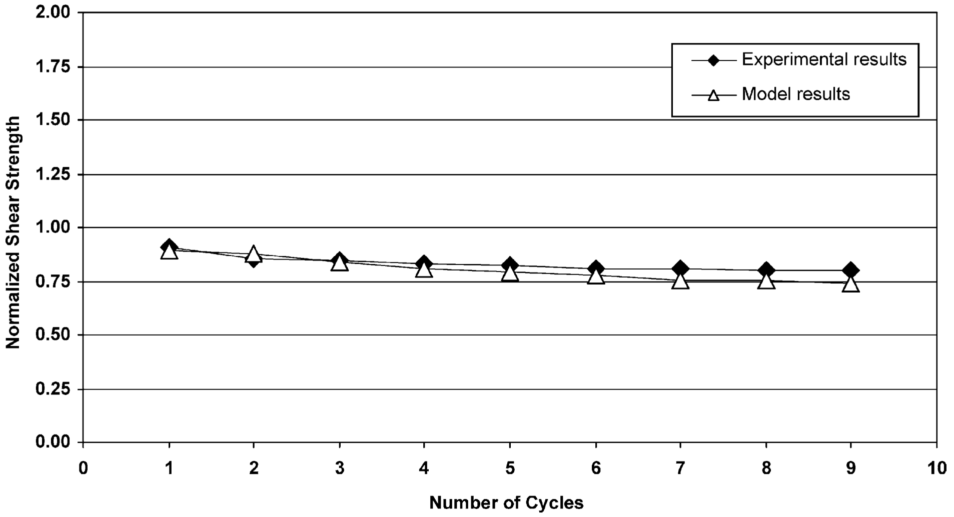


Fig. 21. Comparison of the measured and evaluated shear strength of real surface joint model at intermediate levels of normal stress ($\sigma_n = 4.2$ MPa).

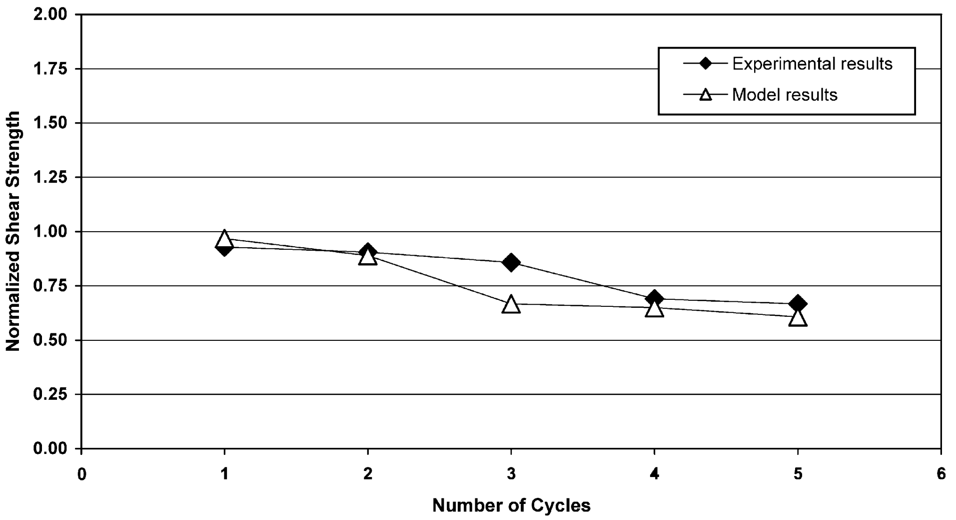


Fig. 22. Comparison of the measured and evaluated shear strength of saw-tooth joint model at intermediate levels of normal stress ($\sigma_n = 4.2$ MPa).

the 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 will decrease. For a better evaluation of these parameters it is necessary to perform similar tests on different kinds of real joint surfaces (especially different wall strengths).

In Figs. 18–22 some of the test results were compared with the proposed model, and good agreement is observed.

5. Conclusion

This paper discusses a study of the variation in shear strength of joint replicas in different cyclic loading conditions. The following main conclusions may be drawn from this investigation:

1. During cyclic shear displacement, degradation of both first- and second-order asperities will occur, depending on the cyclic displacement and normal stress applied. During small earthquakes and low amplitude dynamic loadings, second-order asperities will be mainly affected, but in strong earthquakes and high amplitude dynamic loadings, both first- and second-order asperities may be damaged.
2. The shear strength of joint replicas will be decreased during small repetitive cyclic loadings. The number of loading cycles and stress amplitude are two main parameters controlling the shearing behaviour of rock joints during cyclic loading.
3. Dilation angle, degradation of asperities and wearing are three main factors which affect the shear strength of rock joints during large cyclic displacement.
4. 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.
5. The models presented in this paper are based on tests carried out on artificial joints. In order to improve the models, more investigations should be carried out on real joint samples.

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