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Ali Mirzaghorbanali
University of Wollongong, amirzagh@uow.edu.au

Haleh Rasekh
University of Wollongong

Naj Aziz
University of Wollongong, naj@uow.edu.au

Jan Nemcik
University of Wollongong, jnemcik@uow.edu.au

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EFFECTS OF SHEARING DIRECTION ON SHEAR BEHAVIOUR OF ROCK JOINTS

Ali Mirzaghorbanali, Haleh Rasekh, Naj Aziz and Jan Nemcik

ABSTRACT: Effects of shearing direction on shear behaviour of rock joints were studied. Artificial triangular asperities with initial asperity angles of 9.5° (Type I) and 18.5° (Type II), inclined at 0°, 30°, and 60° from the direction perpendicular to the shearing movement were cast using high strength gypsum plaster. Samples were tested at different initial normal stress ranging from 0.56 MPa to 2.4 MPa under constant normal stiffness of 8 kN/mm. The measured data were analysed and accompanied by a mathematical model to describe the effects of shearing direction on shear strength of rock joints. The proposed model simulated reasonably the reduction in the shear strength of rock joints with increase in the angle of shearing direction.

INTRODUCTION

The effects of joints and discontinuities on the mechanical behaviour of rock mass and the stability of undergmound structures constructed in close proximity to jointed rock masses are a well understood topic. In this context, many researchers have investigated the shear behaviour of rock joints with different values of initial normal stress and initial asperity angle. Patton (1966) was among the first who studied the shear behaviour of rock joints by conducting direct shear tests on artificial triangular asperities under Constant Normal Load (CNL) conditions where the acting normal load remains unchanged during shearing. A failure criterion was also introduced by Patton (1966) to represent the sliding and breakage mechanisms captured through experiments. Barton (1973) performed direct shear tests on real joints and proposed an empirical shear strength model incorporating the concept of Joint Roughness Coefficient (JRC). Barton (1976) revised the concept of JRC and introduced the concept of mobilised Joint Roughness Coefficient (JRC_{mob}) to replicate the hardening and softening phenomena as a function of the normalised shear displacement. Seidel and Haberfield (1995) investigated the shear behaviour of rock joints under Constant Normal Stiffness (CNS) conditions where the normal load varies due to the joint's dilation and proposed a shear strength model based on the energy balance theory. Indrarata (2000) applied the Fourier series to describe the variation of normal displacement in relation of shear displacement under CNS conditions, extending the shear strength model proposed by Seidel and Haberfield (1995). Phien-wej *et al*. (1991) investigated the shear behaviour of infilled rock joints under CNL conditions and proposed an experimental model to quantify the shear strength of infilled rock joints. Other studies on shear behaviour of infilled rock joints have been carried out by Ladanyi and Archambault (1977), Papaliangas *et al*. (1990, 1993), de Toledo and de Freitas (1993), Indraratna *et al*. (1999, 2005), and Oliveira and Indraratna (2010) under CNL and CNS conditions.

No studies have been recorded in the literature on the effects of shearing direction on shear behaviour of rock joints under CNS conditions. A systematic experimental study was carried out using artificial rock joints for various initial normal stresses, asperity angles, and angles of shearing direction under CNS conditions. The experimental data were critically investigated and a revised shear strength criterion was proposed to describe the effects of shearing direction on shear strength of rock joints.

TEST APPARATUS, SAMPLE PREPARATION, AND EXPERIMENTAL PLAN

The large scale direct shear apparatus at the rock mechanics laboratory of University of Wollongong was used to perform the shear tests. The instrument had two main sections, a controller unit and a mechanical part as shown in Figure 1. The rate of shear displacement was set by the digital controller unit. The mechanical part consisted of two steel shearing boxes, 250 mm in length, 75 mm in width, and 150 mm and 100 mm in height of the top and bottom boxes respectively. The initial normal load was applied to the samples using a hydraulic jack located on the top of the instrument. The joint dilation was confined by a set of springs with stiffness of 8 kN/mm, simulating the effect of surrounding rock mass. A hydraulic actuator controlled by the digital controller unit, displaced the lower box laterally. The upper

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University of Wollongong, Wollongong, NSW, Australia, 2500. Email: am001@uowmail.edu.au. M: +61 448 859 037

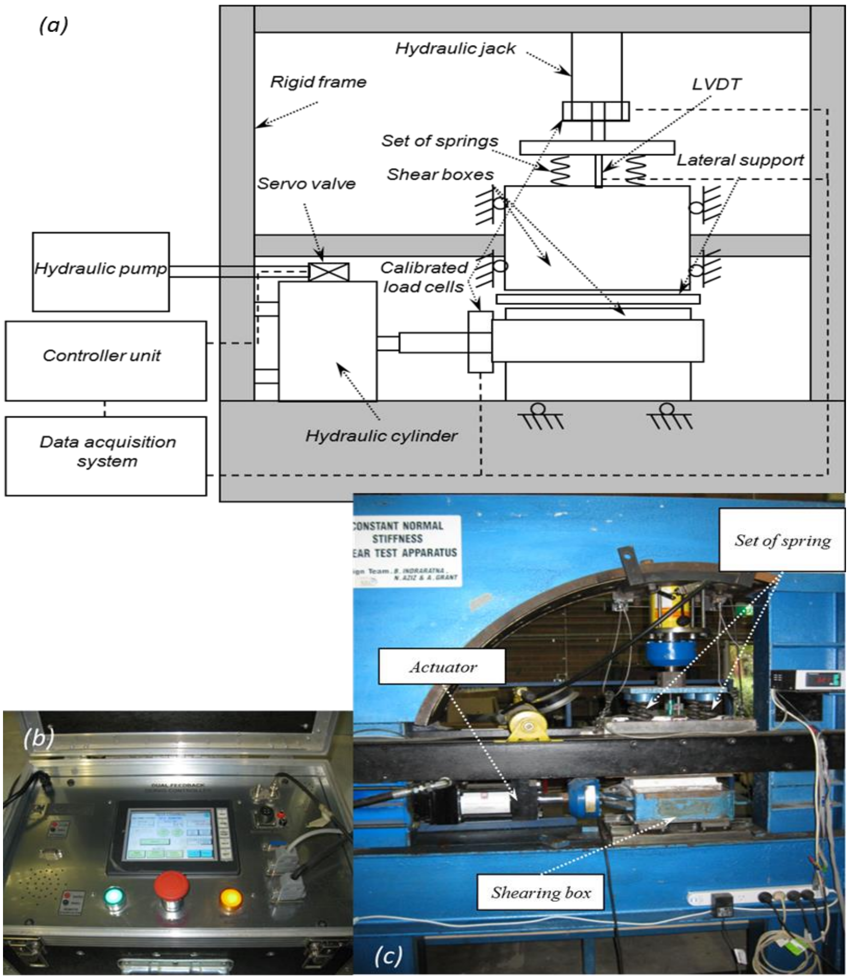

Figure 1 - (*a*) Schematic diagmam of the CNS cyclic direct shear apparatus, (*b*) Controller unit, (*c*) General view of the apparatus

box moved only in a vertical direction on ball bearings such that any relative rotation of the joint surfaces was avoided. The amounts of shear and normal loads were recorded by strain meters mounted on the load cells and the normal displacement was recorded using a Linear Variable Differential Transformer (LVDT).

Two initial asperity angles 9.5° (Type I) and 18.5° (Type II) representing low and high roughness of field joints were considered to prepare moulds. For each type, tooth shaped asperities were inclined at 0°, 30°, and 60° from the direction perpendicular to the shearing movement making six different asperity surfaces. High strength gypsum plaster ($CaSo_4.H_2O$ hemihydrates) with a mixing ratio of 3.5:1 by weight of plaster to water was used to prepare the samples. The amount of plaster and water were 2100 gm and 600 gm for bottom samples respectively, while these amounts were 4900 gm and 1400 gm for top samples. During sample preparation, mild vibration was applied to the mould externally to eliminate any entrapped air within the samples. The samples were then left for two hours to satisfy the initial setting time. They were then allowed to cure in an oven for 14 days at a constant temperature of 40°c. Subsequently, the samples were cooled down to room temperature. A close view of the selected prepared samples is shown in Figure 2. Appropriate tests performed on samples made from high strength gypsum plaster, indicated an average basic friction angle of 35° and uniaxial compressive strength of 60 MPa.

More than 18 direct shear tests were conducted on the samples. The values of initial normal stress were 0.56 MPa, 1.64 MPa, and 2.4 MPa while the rate of shear displacement was set to 0.5 mm/min. A constant normal stiffness of 8 kN/mm was incorporated to restrict the dilation. The values of shear load, normal load, and normal displacement were monitored against shear displacement during the whole length of each test.

TEST RESULTS AND ANALYSIS

The experimental results for different conditions of initial normal stress, asperity type, and angle of shearing direction are shown in Figures 3 to 5.

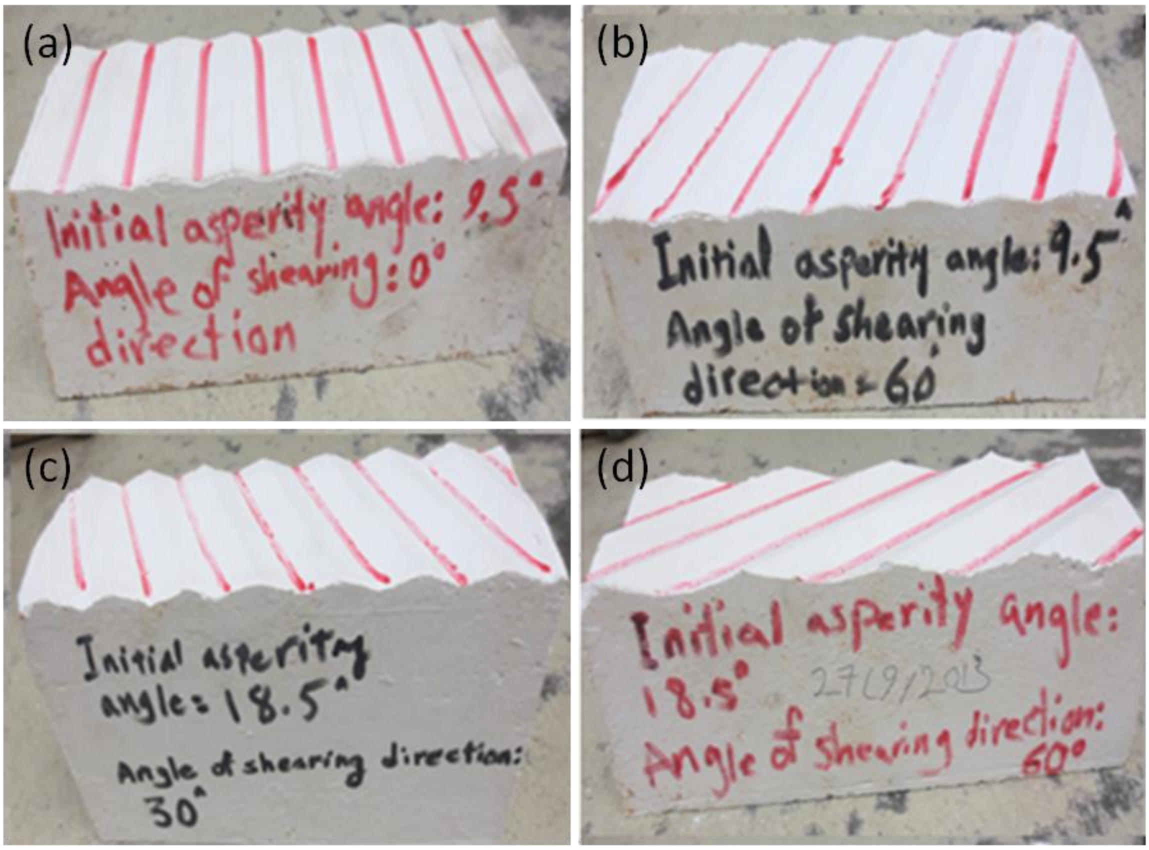

Figure 2 - Selected prepared samples; (*a*) Type I and 0° angle of shearing direction, (*b*) Type I and 60° angle of shearing direction, (*c*) Type II and 30° angle of shearing direction, (*d*) Type II and 60° angle of shearing direction

In general, it is observed that the shear strength decreased as the angle of shearing direction increased. For low values of initial normal stress (close to 0.56 MPa), the gap between the shear strength profiles with various angles of shearing direction, is more pronounced for the Type II asperity surface when compared to the Type I asperity surface. For the Type I asperity surface and 2.4 MPa of initial normal stress, the shear strength decreased 23 % by increasing the angle of shearing direction from 0° to 60°. This value was determined to be 29% for the Type II asperity surface.

The dilation behaviour of rock joints was decreased by increasing the angle of shearing direction. For instance, the maximum magnitude of dilation for the Type I asperity surface with 30° of shearing direction and 0.56 MPa of initial normal stress, was measured as 1.06 mm whereas this value was 0.32 mm for the 60° shearing direction. The dilation curves deviated from linearity to dome shaped with increase in the initial normal stress due to the asperity breakage mechanism.

As shearing was conducted under CNS conditions, the variations of normal stress showed similar trends with normal displacement, which affected the shear strength.

MATHEMATICAL MODELLING

The experimental studies showed that the shear strength decreases with increase in the angle of shearing direction. This can be described by the lower asperity contact angle resists against the shearing in comparison to the initial asperity angle as shown in Figure 6.

In Figure 6, N is the normal force, S is the shear force, i_0 is the initial asperity angle, β is the angle of shearing direction, and i is the asperity contact angle.

According to Figure 6, the relationship between the initial asperity angle and asperity contact angle is deduced as:

$$i = \tan^{-1}\left[\tan(i_0)\times\cos\beta\right] \tag{1}$$

The shear strength criterion for rock joints based on Newland and Alley (1957) is obtained as:

$$\tau = \sigma_n \tan(\phi_b + i) \tag{2}$$

where, τ is the shear strength, σ_n is the normal stress, and φ_b is the basic friction angle.

By introducing Equation (1) in Equation (2), the shear strength for rock joints oriented from thedirection of shearing is extended as:

$$\tau = \sigma_n \tan(\phi_b + \tan^{-1}\left[\tan(i_0)\times\cos\beta\right]) \tag{3}$$

The comparison between the model predicted results and experimental data is depicted in Figure 7.

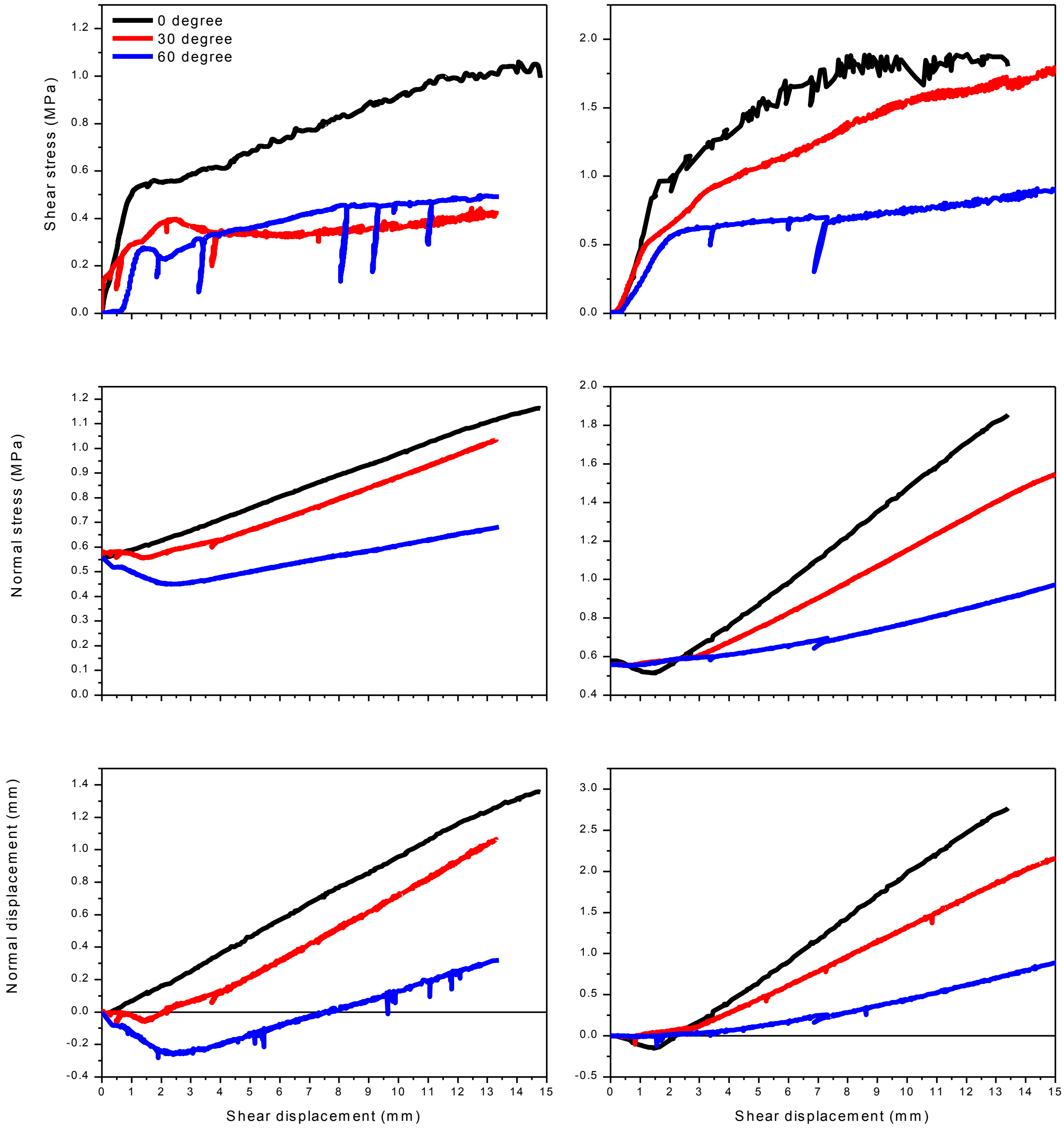

Figure 3 - Experimental results for 0.56 MPa of initial normal stress; (*left*) Type I asperity surface, (*right*) Type II asperity surface

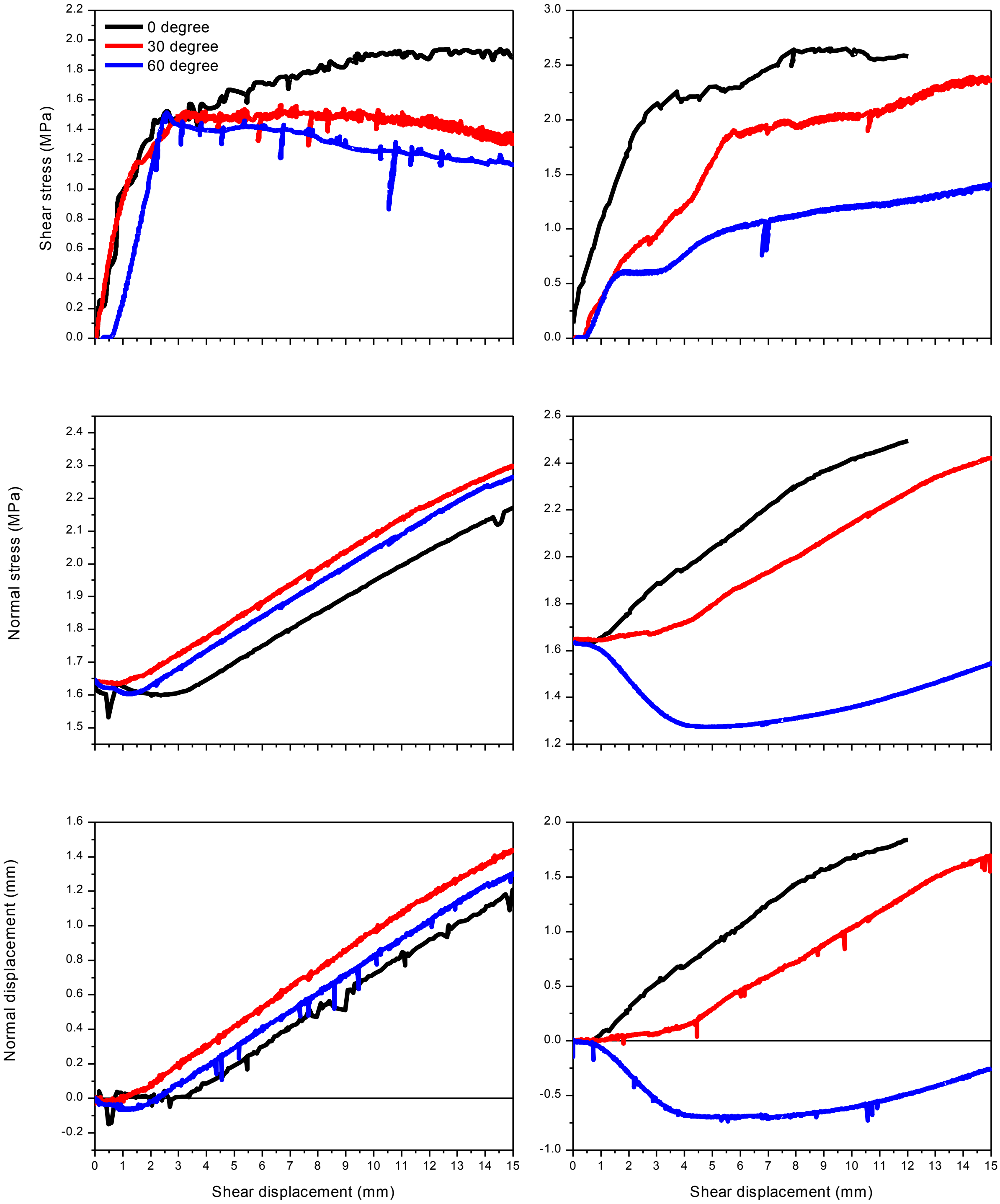

Figure 4 - Experimental results for 1.64 MPa of initial normal stress; (*left*) Type I asperity surface, (*right*) Type II asperity surface

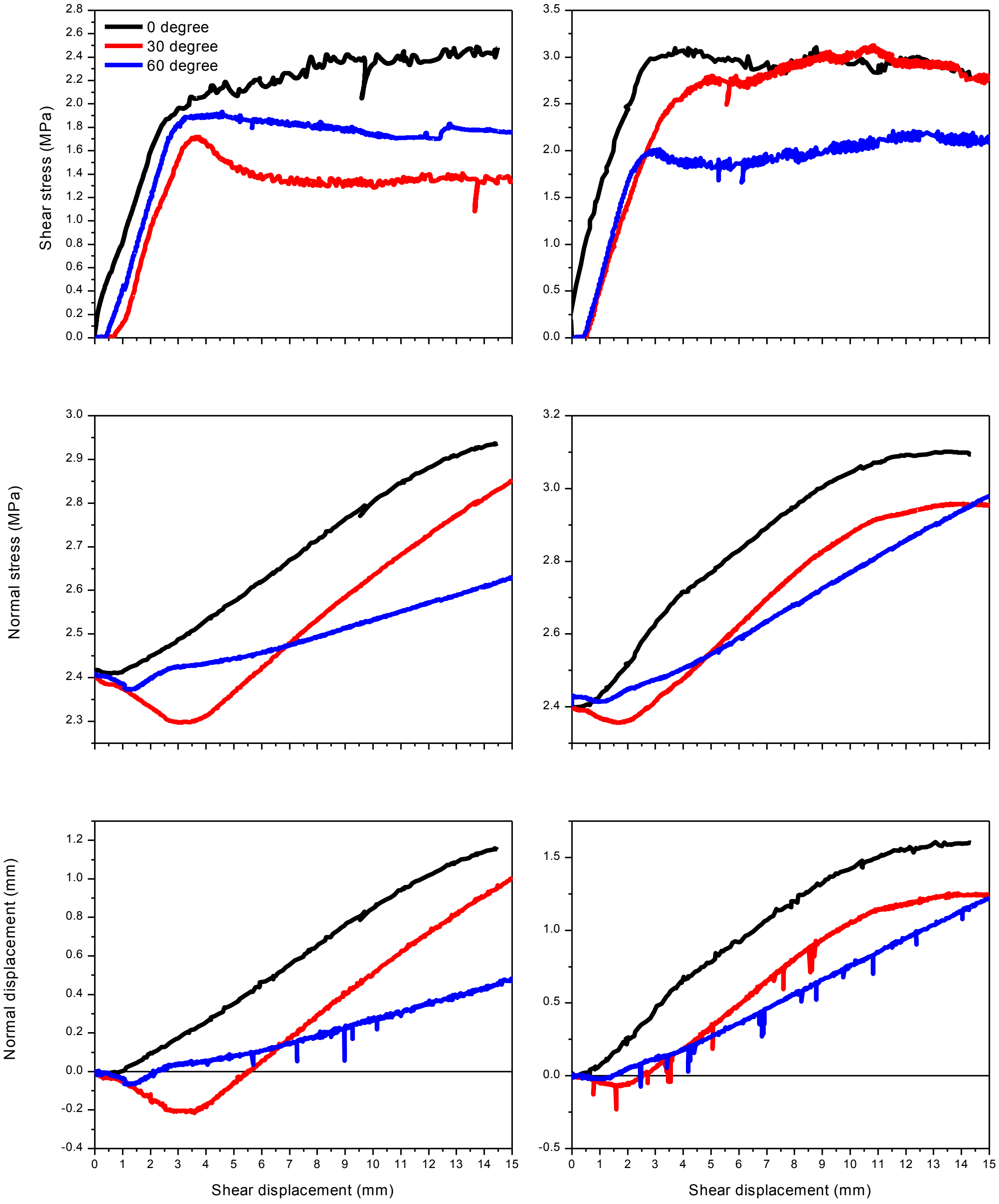

Figure 5 - Experimental results for 2.4 MPa of initial normal stress; (*left*) Type I asperity surface, (*right*) Type II asperity surface

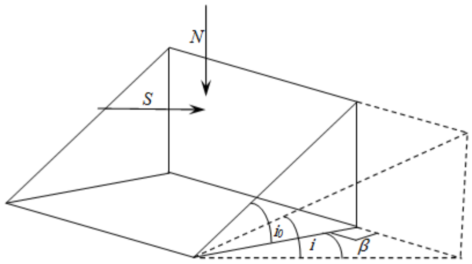

Figure 6 - Asperity shearing under shear and normal force

It is noted that the proposed model is able to replicate the reduction in the shear strength with increase in the angle of shearing direction. Generally, the results of simulation are closer to the measured data for the Type I asperity surface rather than the Type II asperity surface. Furthermore, the best agreement between the proposed model and experimental data is achieved for angle of shearing of 60° where the asperity damage is not significant. Nevertheless, discrepancies are observed between the proposed model and experimental results where the shearing mechanism is governed by the asperity breakage. This behaviour is expected for higher values of initial roughness and normal stress as the proposed model is based on the sliding mechanism.

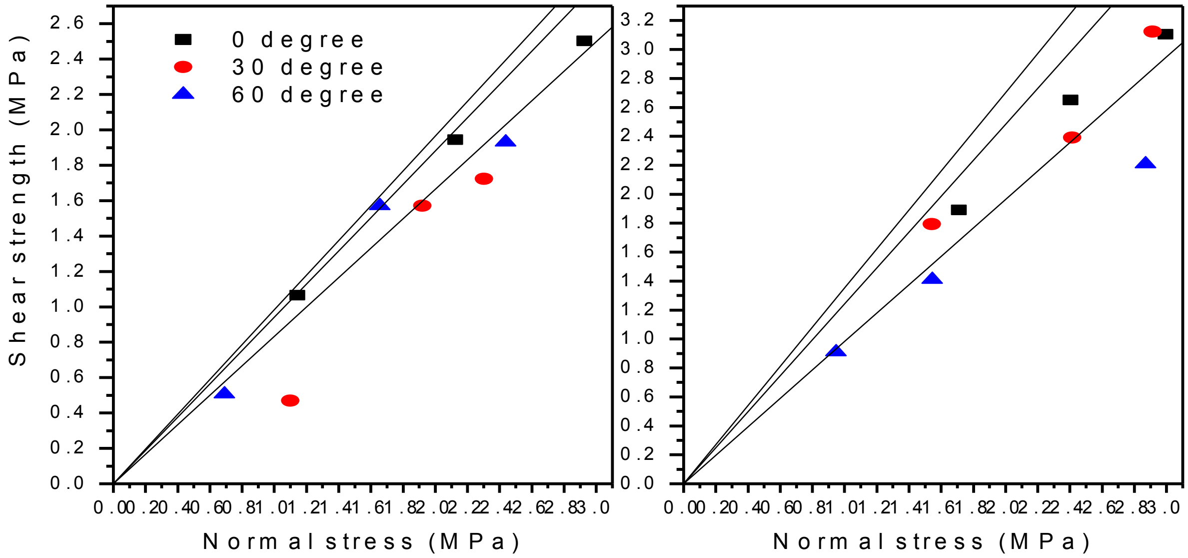

Figure 7 - Comparison between the proposed model and experimental data; (left) Type I asperity surface, (right) Type II asperity surface; (line) model predicted, and (symbols) experimental data

CONCLUSIONS

The results of the systematic experimental study conducted on the shear behaviour of rock joints oriented from shearing direction were presented in this paper. The following main conclusions were extracted based on this study:

- The shear strength of rock joints is significantly influenced by the angle of shearing direction. By changing the angle of shearing direction from 0° to 60°, the values of shear strength were observed to decrease.
- The magnitudes of dilation decreased as the angle of shearing direction increased due to a lower asperity contact angle.
- A revised shear strength criterion was proposed to describe the effects of shearing direction on shear strength of rock joints.
- The proposed model simulated the shear strength of rock joints fairly where the asperity damage was not significant. This is remarked for the tests carried out on the Type I asperity surface with 60° of shearing direction.

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