Friction and degradation of rock joint surfaces under shear loads

F. Homand*, T. Belem†, M. Souley

Laboratoire Environnement Géomécanique and Ouvrages, Ecole Nationale Supérieure de Géologie, B.P. 40, Vandoeuvre-les-Nancy Cedex, F-54501, France

SUMMARY

The morpho-mechanical behaviour of one artificial granite joint with hammered surfaces, one artificial regularly undulated joint and one natural schist joint was studied. The hammered granite joints underwent 5 cycles of direct shear under 3 normal stress levels ranging between 0.3 and 4 MPa. The regularly undulated joint underwent 10 cycles of shear under 6 normal stress levels ranging between 0.5 and 5 MPa and the natural schist replicas underwent a monotonic shear under 5 normal stress levels ranging between 0.4 and 2.4 MPa. These direct shear tests were performed using a new computer-controlled 3D-shear apparatus. To characterize the morphology evolution of the sheared joints, a laser sensor profilometer was used to perform surface data measurements prior to and after each shear test. Based on a new characterization of joint surface roughness viewed as a combination of primary and secondary roughness and termed by the joint surface roughness, $\text{SR}_\text{s}$, one parameter termed ‘joint surface degradation’, $D_\text{s}$, has been defined to quantify the degradation of the sheared joints. Examinations of $\text{SR}_\text{s}$ and $D_\text{s}$ prior to and after shearing indicate that the hammered surfaces are more damaged than the two other surfaces. The peak strength of hammered joint with zero-dilatancy, therefore, significantly differs from the classical formulation of dilatant joint strength. An attempt has been made to model the peak strength of hammered joint surfaces and dilatant joints with regard to their surface degradation in the course of shearing and two peak strength criteria are proposed. Input parameters are initial morphology and initial surface roughness. For the hammered surfaces, the degradation mechanism is dominant over the phenomenon of dilatancy, whereas for a dilatant joint both mechanisms are present. A comparison between the proposed models and the experimental results indicates a relatively good agreement. In particular, compared to the well-known shear strength criteria of Ladanyi and Archambault or Saeb, these classical criteria significantly underestimate and overestimate the observed peak strength, respectively, under low and high normal stress levels. In addition and based on our experimental investigations, we put forward a model to predict the evolution of joint morphology and the degree of degradation during the course of shearing. Degradations of the artificial undulated joint and the natural schist joint enable us to verify the proposed model with a relatively good agreement. Finally, the model of Ladanyi and Archambault dealing with the proportion of total joint area sheared through asperities, $a_c$, once again, tends to underestimate the observed degradation. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: sheared rock joints; joint degradation; rock joint surfaces; shear loads

*Correspondence to: F. Homand, Laboratoire Environnement Géomécanique and Ouvrages, Ecole Nationale Supérieure de Géologie, B.P. 40, Vandœuvre-les-Nancy Cedex, F-54501, France
†Presently at Université de Québec en Abitibi, 445, Bb de l’Université, Rouyn – Noranda, Què., Canada J9X5E4

Received 20 March 2000
Revised 19 February 2001
1. INTRODUCTION

For the purpose of elaborating a constitutive law for sheared rock joints explicitly taking into account the initial morphology evolution, it is necessary to understand better the exact role played by this morphology during the course of shearing. The degradation of joint walls has generally been approached in terms of direct quantification of joint wall wear, roughness evolution or in terms of dilatancy angle evolution [1–5]. However, to our knowledge, except for the ratio of the degraded asperities area, $a_s$, defined by Ladanyi and Archambault [6], there does not exist in the literature a parameter directly quantifying the wear or degradation of the joint walls during shearing. Degradation of surface roughness has also been investigated by Leong and Randolph [7] by using the wear theory. In their approach, degradation is viewed in terms of reduction in dilatancy and plough resistance due to ploughing of the surface by asperities and wear particles. No explicit formulation of degradation has been given in their shear constitutive model.

Over the last decade, several researchers have investigated the use of fractal analysis to measure rock fracture roughness with the aim for easily introducing scale-dependent parameters [8–16]. However, as indicated by a number of works in the literature, the occurrence of fractal dimension estimation depends on the asperity height measurement tools, the method used to derive the fractal dimension as well as the step length used to evaluate this dimension. For instance, fractal parameters calculated by the existing methods depend significantly on the input value used in the method (e.g. lag-distance in variogram method, bandwidth in spectral method, step size in line scaling method, etc.) as well as the stationary/non-stationary nature of profile or joint surface [10,12,13,17].

In the morphological characterization of rock joints including fractal analysis undertaken in our laboratory [8,9,15,16] correlation between fractal dimension and joint surface roughness prior to and after shearing as a function of normal stress has been investigated. Results showed a chaotic evolution of fractal dimension of studied morphologies. Thus, it has not been possible to detect a particular trend, characteristic of surface roughness evolution according to shearing sequences. Furthermore, fractal dimension is a qualitative parameter and somewhat inappropriate for a quantitative study of damage of fracture surface roughness. As a conclusion, the fractal dimension is properly a parameter describing the degree of irregularity (scaling properties of surface roughness), whereas this paper is mainly focused on the surface roughness parameters with the aim to quantify the amount of surface damage in the course of shearing. This added to the conclusions of Huang et al. [10]: the fractal dimensions describe the amount of interlocking between joint asperities, whereas the conventional rms (root mean square) variance is more closely related to shear strength or constitutive relations of rock joints.

Assuming that the asperity height measurement tools and the method used to derive the fractal dimension are appropriate with regard to the stationary/non-stationary nature of joint surfaces, it is possible to correlate certain joint strength parameters to the fractal dimension based on the evaluation of fractal dimension prior and after shear tests. As an example, Kulatilake et al. [11] extend the rock joint strength developed by Barton [18,19] to an anisotropic strength criterion based on the correlation between fractal dimension and Barton’s coefficient, JRC. The investigation reported by Kulatilake et al. [11] can thus be regarded as a start to the research on the topic, and authors suggest further experimental, theoretical and analytical research in order to improve their techniques for roughness characterization and anisotropic peak shear strength modelling of
natural rocks. This once more illustrates the relevant character of fractal dimension used to model the joint surface degradation, not only in terms of shear strength, but also during the shear sequence (e.g. from the mobilization of the asperities in pre-peak region to their total destruction in the residual region, while passing by the peak).

In this paper, we present some results of direct shear tests carried out in order to characterize the degradation of sheared joints walls directly. Three types of joints (granite joint with hammered surfaces, natural schist joint and an artificial regularly undulated joint) were sheared under various constant normal stress levels. Tests performed on the schist joint are monotonic, whereas both artificial hammered and undulated joints were sheared in a cyclic shear mode. In order to directly characterize the joint surface wear, the degradation degree, $D_w$, and the degradation coefficient, $W_{dc}$, of sheared joint walls are defined on the basis of actual joint wall area before and after shearing. In addition, and based on our experimental results, the evolution of initial joint roughness during the course of shearing is proposed. Hence, the parameters describing the proposed models are mainly angularity, anisotropy and degree of roughness. Finally, this study is essentially focused on the role played by the evolution of morphology on peak strength and dilatancy in terms of joint degradation.

2. EXPERIMENTAL PROCEDURES

2.1. Tested samples

For this study, three experimental series of direct shearing were carried out (Table I). The first series concerns the man-made Lanhelin granite joints. These are non-interlocked and non-mated joints with hammered surfaces (slight hammering the walls). The second series concerns the mortar replicas of a man-made regularly undulated surface. Finally, the third series concerns the mortar replicas of natural schist joint with rough and undulated surfaces. Three samples were sheared for series 1, six for series 2, and five samples for series 3.

All the man-made Lanhelin granite joints have the same dimensions of $150 \text{ mm} \times 150 \text{ mm}$, the same thickness of 40 mm and the same maximum surface amplitude of 1.742 mm. The mortar replicas have the same mean thickness of 40–45 mm, but a section of $135 \text{ mm} \times 145 \text{ mm}$ for the natural schist joint, and $100 \text{ mm} \times 145 \text{ mm}$ for the regularly undulated surface. The mechanical properties of these replicas are listed in Table II.

Figure 1(a) shows a three-dimensional representation of the lower wall surface of the hammered granite joints, whereas Figures 1(b) and 1(c) present initial morphology of the regularly undulated and natural schist joints.

<table>
<thead>
<tr>
<th>No. of series</th>
<th>Material</th>
<th>Joint shape</th>
<th>Section (mm$^2$)</th>
<th>No. of sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Granite</td>
<td>Hammered surfaces</td>
<td>$150 \times 150$</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>Mortar</td>
<td>Undulated$^*$</td>
<td>$100 \times 145$</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>Mortar</td>
<td>Rough undulated$^1$</td>
<td>$135 \times 145$</td>
<td>5</td>
</tr>
</tbody>
</table>

$^*$Regularly undulated with a period of 25 mm.

$^1$Natural schist joint replica.
Table II. Mechanical material properties*.

<table>
<thead>
<tr>
<th></th>
<th>Granite joint</th>
<th>Rough undulated joint</th>
<th>Undulated joint</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_c$ (MPa)</td>
<td>152</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>$\sigma_t$ (MPa)</td>
<td>10</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$\phi_b$ (degree)</td>
<td>25</td>
<td>34</td>
<td>34</td>
</tr>
</tbody>
</table>

* $\sigma_c$: uniaxial compressive strength, $\sigma_t$: tensile strength, $\phi_b$: basic friction angle

2.2. Direct shear test apparatus

Shear tests have been carried out with a new computer-controlled 3D-shear apparatus (CC-3DSM) providing constant normal load (CNL), constant normal stress (CNS), constant normal stiffness (CNK) and constant volume (CV) shear tests as well as uniaxial compression tests. This 3D-shear device is illustrated in Figure 2. Furthermore, shear tests under monotonic or cyclic shear mode can be performed in 2D-configuration along direction $x$ or $y$, or in a 3D-configuration following each direction in an $xy$ plane. This shear apparatus entirely designed by LAEGO-ENSG runs using electric micro motors whilst the 3D direct shear device for testing mechanical and hydraulic behaviour of rock joints designed by Boulon [20] uses hydraulic pumps to apply loadings. Appropriate filters are used in order to overcome problems of interference. Six degrees of freedom are allowed in this shear apparatus: two degrees in direction $x$, two degrees in direction $y$, one degree in direction $xy$ and one degree in direction $z$. The technical characteristics of CC-3DSM [8,20] are: (a) two shear boxes where the sample (constituted of two blocks) is placed: the two blocks can simultaneously (mode II) or independently (mode I) move with respect to the test type; (b) normal and shear forces are measured by 5 captors (4 in shear direction, and 1 in normal direction); (c) displacements are recorded by LVDT captors: 4 captors horizontally ($x$ and $y$ directions) and 4 vertically ($z$ direction) and (d) measurements are displayed on the notice board or on the computer screen where data are stored during the course of shear. The shear and normal loading capacity is about 120 kN.

2.3. Performed tests

Table III summarizes the different characteristics of shear tests performed in this study. All tests were carried out according to mode II with respect to a total shear displacement of about 200 mm (10 mm × 4 forward–reverse × 5 cycles) for the Lanhelin granite joints with hammered surfaces, 400 mm (10 mm × 4 × 10) for the artificial regularly undulated joint and 20 mm for the natural schist joint. Cyclic shear mode is assumed for both Lanhelin granite joints with hammered surfaces and the artificial regularly undulated ones, even though tests on the natural schist joint are performed in monotonic shear mode. All tests have been carried out under CSN conditions for different normal stress levels at a same constant shear rate of 0.5 mm/min. The three hammered joints underwent 5 cycles of direct shear under three normal stress levels ranging from 0.3 to 4 MPa. The six replicas of the man-made regularly undulated joint underwent 10 cycles of shear under six normal stress levels ranging from 0.5 to 5 MPa. Finally, the five replicas of the natural schist joint underwent a monotonous shear under five normal stress levels ranging from 0.4 to 2.4 MPa.

2.4. Topography data acquisition

In order to evaluate the contribution of morphology to the mechanical behaviour of sheared joints, topographical measurements were carried out prior to and after shear tests with a laser sensor profilometer. This equipment allows three-dimensional measurements of the joint wall surfaces ($x$, $y$, $z$ co-ordinates) to be taken. The measurement system uses the principle of laser triangulation between a laser plane and a CCD camera shifted with respect to the laser plane [15,18] (the laser and video camera unit being non-deformable). The topographic profile
corresponds to the intersection of the laser beam with the sample surface. The whole surface coordinates \((x, y, z)\) are stored. The laser profilometer is made up mainly of an optical sensor equipped with a CCD camera of a 50 \(\mu\)m resolution and with a He–Ne laser of 670 nm wavelength. The design features of the laser beam are: 40 mm in length; 50 \(\mu\)m thick; 50 \(\mu\)m of vertical resolution (z-axis); 73 \(\mu\)m of horizontal resolution (x- or y-axis according to the sensor position); 5 \(\mu\)m of standard deviation of white noise error due to mechanical vibrations. With 73 \(\mu\)m of horizontal resolution (e.g. pixel size), measurements along a 40 mm profile (e.g. length of laser beam) involve approximately 620 points. However, distance between two successive points cannot be controlled along an axis parallel to the laser beam. In the configuration where the laser beam is parallel to the x-axis and by fixing the sampling steps along the y-axis at 1 mm \((\Delta y = 1 \text{ mm})\) for example, the laser beam will record more than 180 000 points corresponding to

**Table III. Shear tests programme.**

<table>
<thead>
<tr>
<th>Joint types</th>
<th>Shear rate (mm/mn)</th>
<th>Normal stress (MPa)</th>
<th>Shear paths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammered surface</td>
<td>0.5</td>
<td>0.3</td>
<td>5 cycles</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1.2</td>
<td>5 cycles</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>4</td>
<td>5 cycles</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0.4</td>
<td>Monotonic</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0.8</td>
<td>Monotonic</td>
</tr>
<tr>
<td>Rough undulated</td>
<td>0.5</td>
<td>1.2</td>
<td>Monotonic</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1.8</td>
<td>Monotonic</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>2.4</td>
<td>Monotonic</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>0.5</td>
<td>10 cycles</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1</td>
<td>10 cycles</td>
</tr>
<tr>
<td>Regularly undulated</td>
<td>0.5</td>
<td>2</td>
<td>10 cycles</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>3</td>
<td>10 cycles</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>3</td>
<td>10 cycles</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>5</td>
<td>10 cycles</td>
</tr>
</tbody>
</table>

Figure 2. Computer-controlled 3D-shear apparatus.
100 profiles for a surface of about 100 mm × 100 mm. This number of points is reduced to 10 000 after data pre-treatment by adopting: Δx = 1 mm.

3. DIRECT CHARACTERIZATION OF SHEARED SURFACE DEGRADATION

From a practical point of view, it is very difficult to evaluate the ratio of the degraded asperities area, \(a_s\), used in the peak strength criterion developed by Ladanyi and Archambault [6] or the revised version reported by Saeb [21]. The peak shear stress, \(\tau_p\), and normal stress, \(\sigma_n\), in the revised criterion are related as follows:

\[
\tau_p = \sigma_n \tanh(\phi + i_p)(1 - a_s) + a_s S_R
\]

where \(S_R\) represents the shear strength of the asperities and is equal to the intact rock strength; \(\phi\) is the angle of friction for sliding along the asperities; \((1 - a_s)\) is the portion on which sliding occurs; \(i_p\), the dilatancy angle at the peak shear stress.

A recent study concerning the characterization of the degradation of sheared joint surfaces, reported by Riss et al. [22], identifies the wear areas (size, density and location) in relation to normal stress for a given relative tangential displacement by image processing (qualitative and quantitative analysis). From their studies, authors conclude that the total area of the whole damaged regions is an upper limit of the degraded surface.

The shear area ratio \(a_s\) appearing in Equation (1) represents the fraction of the surface on which shearing through asperities took place. One possible technique to evaluate the joint surface on which shearing through asperities took place is to entirely paint the joint walls prior to each shear test. After shearing, a trace of the joint surfaces enables the damaged regions to be delimited. Finally, the area of these damaged regions, \(A_s\), is computed using a planimeter [23,15].

As an initial approximation, the following empirical expression has been used by Ladanyi and Archambault [6] to express the probable variation of the shear area ratio, \(a_s\), as a function of normal stress, \(\sigma_n\):

\[
a_s \sim \frac{A_s}{A} \approx 1 - \left(1 - \frac{\sigma_n}{\sigma_T}\right)^{k_1}, \quad 0 \leq \sigma_n \leq \sigma_T
\]

where \(k_1\) is a constant depending on initial joint roughness (Ladanyi and Archambault [6] have suggested a value of 1.5) and \(\sigma_T\) is the transitional stress beyond which shearing through joint asperities is the dominant shear mechanism \((a_s = 1)\) and no dilatancy is possible \((i_p = 0)\).

The previous definition of \(a_s\), based on the ratio between \(A_s\) and \(A\) (the asperities are sheared off over the portion \(A_s\) of the total projected shear area \(A\)) implies that the shear area ratio can easily be derived when the actual joint wall area prior to and after shearing have been properly evaluated. In addition, since the actual joint wall area can be estimated elsewhere, it becomes possible to define parameters capable of quantifying the wear or degradation of the sheared joint walls.

3.1. Estimation of actual joint surface area, \(A_i\)

Based on the fracture surface triangulation shown in Figures 3 and 4, the actual area \(A_i\) of the fracture surface can be estimated by summing the triangular element areas \(A_i\) as:

\[
A_i = \sum_{\text{surface}} A_i
\]
By carrying out topographic measurements of profiles at small constant steps (e.g. $70 \mu m \leq \Delta x = \Delta y \leq 200 \mu m$) with a laser sensor profilometer or other apparatus, the actual area $A_t$ of the fracture surface can also be evaluated by the integral method. Assuming that the fracture surface is continuum and derivable, its actual area $A_t$, is mathematically given by the relationship:

$$A_t = \int_{\text{surface}} \sqrt{1 + \left( \frac{\partial z}{\partial x}(x,y) \right)^2 + \left( \frac{\partial z}{\partial y}(x,y) \right)^2} \, dx \, dy$$

(4)

The discrete form of $A_t$ can be approximated for very small sampling steps, $\Delta x$ and $\Delta y$ by

$$A_t \approx \Delta x \Delta y \sum_{i=1}^{N_x-1} \sum_{j=1}^{N_y-1} \sqrt{1 + \left( \frac{z_{i+1,j} - z_{i,j}}{\Delta x} \right)^2 + \left( \frac{z_{i,j+1} - z_{i,j}}{\Delta y} \right)^2}$$

(5)

Copyright © 2001 John Wiley & Sons, Ltd.

3.2. Formulation of degradation degree, $D_w$

Let $A_i$ be the actual joint surface area; $A_n$ be the nominal surface area (e.g. projection of joint wall surface onto the mean plane assumed to be horizontal); $A_{i0}$ be the actual joint surface area before shearing test, and $A_{i1}$ be the actual joint surface area after shearing test. Parameter $U_i$ ranged between 0 and 1 and given below quantifies the degree of relative degradation of a single joint wall (surface with respect to its initial state (e.g. prior to shearing).

$$U_i = \frac{A_{i1} - A_{i0}}{A_{i0}} = \frac{A_d}{A_{i0}}$$  \hspace{1cm} (6)

In Equation (6), $A_d$ represents the total degraded area of the joint wall surface after shearing ($A_d \neq A_i$). Parameter $U_i$ is comparable to $a_s$ (Equation (2)). However $U_i$ differs from $a_s$ or $(1-a_s)$ which are estimated from the projected wear surface areas onto the mean plane instead of the actual surface areas themselves (e.g. $a_s = A_s/A$; the asperities are sheared off over portion $A_s$ of the total projected shear area $A$).

When $U_i = 0$, either the joint wall is not degraded after shearing or the joint has not been sheared ($A_i = A_{i0}$). Values of the degree of relative degradation of surface, $U_i$, will never reach 1 because $A_i$ will never be null ($A_i \neq 0$) even when the surface has been entirely flattened after shearing ($A_i = A_{i0}$). The relative degradation degree of joint wall surface must be redefined with respect to a perfectly smooth and flat reference surface with zero roughness. For instance, this reference surface area is the nominal surface area, $A_n$ (Figure (4a)). By defining the degree of degradation of an upper or lower joint wall surface with respect to the joint mean plane (e.g. nominal surface of area $A_n$) Equation (6) becomes

$$U_i = \frac{A_{i1} - A_{i0}}{A_{i0} - A_n} = \frac{A_d}{A_{i1} - A_n} = 1 - \frac{A_{i0} - A_n}{A_{i1} - A_n}$$  \hspace{1cm} (7)

Equation (7) shows that when the joint wall surface is entirely flattened or smoothed after shearing ($A_i = A_{i1}$), the degree of degradation $U_i$ is equal to 1. When the joint wall is not degraded after shearing or the joint has not been sheared off, $U_i$ is null. However, this equation is valid only for the initially rough surfaces ($A_{i0} > A_n$).

Based on the results of numerous actual joint surface areas computed according to Equation (5) prior to and after different shear tests carried out on Lanhelin granite joints [5], Equation (7) can also produce negative values of $U_i$ indicating that shearing involves an increase in actual surface area, $A_d < 0$. For positive values of $A_d$ (reduction of the actual surface area $A_{i1}$ after shearing compared to the initial area $A_{i0}$) degradation corresponds to sense stricto wear, whereas for negative values of $A_d$, degradation is not associated with sense stricto wear. However, even if the wear of sheared joint wall surface is easily conceivable, the increase of the actual surface area after shearing could be explained by (i) the cleaning of the sheared surface before topographic data acquisition and (ii) morphological features including asperity distributions, inclination angles and geometry favouring a certain mode of asperity degradation such as wear by flaking within particular zones of the surface, or wrenching. Unfortunately, a true physical explanation for this negative wear has not been undertaken in this study.

Taking these observations into account, it is desirable to rewrite the degree of relative degradation \( D \) by introducing the notion of total degradation of the two joint walls subjected to shear, \( D_\text{w} \) (ranged between 0 and 1) for an initially rough joint and given by the following equation:

\[
D_\text{w}(\text{joint}) = \frac{|A^c_i - A^c_n|}{A^c_i - 2A_n} = \frac{|A^u_i|}{A^u_i - 2A_n} = \frac{|(A^u_i + A^u_n) - A^u_i + A^u_n|}{(A^u_i + A^u_n) - 2A_n}
\] (8)

where \( A^c_i \) and \( A^c_n \) are the actual composite surface areas prior to and after shear test, respectively and \( A^u \) is the actual composite area of sheared asperities. Exponents \( u \) and \( l \) refer to upper and lower joint walls, respectively, \( c \) refers to composite and represents the sum of lower and upper quantities.

This equation shows that \( D_\text{w} \) is null when the joint walls have not been degraded after shearing or when the joint has not been sheared. When all the joint asperities are sheared off at the base (flattened surface), then \( A^c_i = 2A_n \) and \( D_\text{w} = 1 \). The percentage of degradation, \( D_\text{w} \) (\%), is obtained by multiplying the value of \( D_\text{w} \) per 100.

For a single joint wall (e.g. upper or lower joint wall), the degradation degree can be calculated by assuming in Equation (8): \( A^u_i = A^u_i - A^u_i \) for lower wall and \( A^u_i = A^u_i - A^u_i \) for upper wall; the denominator remaining unchanged, as follows:

\[
D_\text{w}(\text{lower}) = \frac{|A^1_i - A^1_n|}{A^1_i - A^1_n},
\] (9)

\[
D_\text{w}(\text{upper}) = \frac{|A^u_i - A^u_n|}{A^u_i - A^u_n},
\] (10)

Let us remember that the previously defined degree of degradation \( D_\text{w}(\text{joint}) \), \( D_\text{w}(\text{upper}) \) and \( D_\text{w}(\text{lower}) \) range between 0 and 1.

### 3.3. Sheared joint degradation coefficient, \( W_{de} \)

Let us define the degradation coefficient, \( W_{de} \), which quantifies the degradation rate of joint wall surface with respect to its initial rough state by the following relation:

\[
W_{de}(\text{joint}) = \frac{A^c_i - A^c_n}{A^c_i + A^c_n} = \frac{A^u_i + A^u_n - 2A_n}{A^u_i + A^u_n - 2A_n} \quad 0 \leq W_{de}(\text{joint}) \leq 2.
\] (11)

The corresponding single lower or upper coefficient of degradation is:

\[
W_{de}(\text{lower}) = \frac{A^1_i - 2A_n}{A^1_i + A^1_n - 2A_n} \quad 0 \leq W_{de}(\text{lower}) \leq 2
\] (12)

\[
W_{de}(\text{upper}) = \frac{A^u_i - 2A_n}{A^u_i + A^u_n - 2A_n} \quad 0 \leq W_{de}(\text{upper}) \leq 2
\] (13)
By combining Equations (8) and (11), the degradation degree can be rewritten as a function of degradation coefficient as

$$D_w = |1 - W_{de}| = \begin{cases} 
1 - W_{de} & \text{with } 0 \leq W_{de} \leq 1, \\
W_{de} - 1 & \text{with } 1 < W_{de} \leq 2.
\end{cases}$$

(14)

Null value of $W_{de}$ is associated with joint wall surfaces having been entirely flattened after shearing (e.g. zero final roughness), when $W_d = 1$ joint surfaces have not been sheared or joint surfaces have not been degraded after shearing. Values of $W_{de}$ up to unity indicate that joint surfaces are degraded by increasing the initial surface area and then an amount of roughness termed negative wear. To summarize, when $0 < W_{de} < 1$, surfaces degrade by sensu stricto wear (e.g. positive wear), when $W_{de} > 1$, surfaces degrade by increasing their initial area or level of roughness (e.g. negative wear). Based on the above, it follows that a graphical plotting of $D_w$ as a function of $W_{de}$ allows us to distinguish the two previous modes of degradation, that henceforth disappeared in equation (8).

4. PARAMETERS QUANTIFYING ROUGHNESS

In this paper, joint surface morphology refers to primary asperities and high order asperities (or secondary asperities), as defined by Jing et al. [5] or used by Huang et al. [10]. The primary asperities have largest undulations (or wavelengths) compared with the dimension of sample. The secondary asperities are much smaller in size and are taken to be superimposed on the primary asperities. In other words, the secondary asperities were defined by the distribution heights of surface and include both profile and surface angularities, surface roughness coefficient and surface tortuosity, whereas the primary asperities refer to the global surface geometry and include real and apparent structural anisotropy of surface as well as its undularity.

In addition to the existing linear parameters $Z_2$, $R_s$ and $P_s$, and in order to characterize the roughness better, which includes morphological characteristics such as magnitude (surface point elevations), angularity (slopes and angles), undularity (periodicity), anisotropy, and in a less pronounced way curvature, numerous parameters have been defined and estimated. Details of the additional morphological parameters succintly summarized below should be consulted in Reference [24].

4.1. Profile mean angle, $\theta_p$

For a given topographic profile, the mean angle of profile inclinations, $\theta_p$, is computed along $x$ or $y$-axis by:

$$\theta_p = \tan^{-1}\left(\frac{1}{N_k - 1} \sum_{i=1}^{N_k - 1} \frac{|z_{i+1} - z_i|}{\Delta k}\right)$$

(15)

where $k$ denotes $x$- or $y$-axis, $z_i$ are the discrete algebraic values of heights along the profile, $(N_k - 1)$ the number of intervals used for slope calculation along $k$-axis and $\Delta k$ the sampling step along $k$-axis (Figure 5).

For the whole joint surface involving non-identical profile lengths, the pseudo-surficial mean angle, defined as the weighted average of the mean profile angles in $k$-direction, $\bar{\theta}_p$, is evaluated
Figure 5. Slopes and angles of a topographic profile along x-axis.

According to the following relation:

\[
\overline{\theta_p}_k = \tan^{-1} \left( \frac{1}{N_k^i - 1} \sum_{i=1}^{N_k^i-1} \frac{z_{i+1} - z_i}{\Delta k} \right)
\]

where \( M_k \) is the total number of profiles in \( k \)-direction (x or y); \( N_k^i \) the number of discrete points corresponding to the \( j \)th profile along \( k \)-axis and \( l_k^j \) length of the \( j \)th profile along \( k \)-axis.

Note that when all the surface profiles are of the same nominal length (e.g. identical \( l_k^j \) in \( k \)-direction), Equation (16) is reduced to an arithmetical mean. In this study, arithmetical means rather than circular means are assumed due to the directional dependency of certain morphological parameters related to the shear direction changes.

4.2. Three-dimensional mean angle, \( \theta_s \)

Consider that the joint wall surface is made up of an assembly of elementary flat surfaces defined by topographical data (x, y, z), spatial orientation of each elementary surface characterized by the azimuth and the inclination angle, \( z_k \), of its normal unit vector (Figure 4(b)). The three-dimensional mean angle is calculated from the \( z_k \) angles of the normal vectors of all the elementary mean planes according to

\[
\theta_s = \frac{1}{m} \sum_{i=1}^{m} z_i
\]

where \( m \) denotes the total number of elementary surfaces. \( \theta_s \) can be seen as the average slope of surface asperities.

4.3. Apparent anisotropy degree, \( k_a \)

According to the previous definition of \( \overline{\theta}_p \), the pseudo-surficial mean angle evaluated along both x and y directions can account for the apparent structural anisotropy of surfaces. This apparent anisotropy can be described on the basis of the mathematical definition of an ellipse in the xoy
co-ordinates system, with the half-axis $a$ and the half-axis $b$ (along $x$- or $y$-axis). The degree of anisotropy $k_a$ is defined by the relationships

$$ k_a = \frac{b}{a} = \frac{\min\{\theta_p, \theta_{p'}\}}{\max\{\theta_p, \theta_{p'}\}} \quad (0 \leq k_a \leq 1) $$

subscript $x$ or $y$ denotes, respectively, the direction for which the individual profiles mean angle $\theta_p$ have been computed.

Thus, when $0 \leq k_a < 1$, the surface is anisotropic ($k_a = 0$ corresponds to surfaces with saw teeth, undulated surfaces, etc.); when $k_a = 1$, the surface is isotropic.

4.4. Surface roughness coefficient, $R_s$

The surface roughness coefficient, $R_s$, has been defined for a single joint wall by El Soudani [25] as the ratio between the actual joint wall area, $A_t$, and the nominal surface area, $A_n$ (e.g. projection of joint wall surface onto the mean plane):

$$ R_s = \frac{A_t}{A_n} \quad (1 \leq R_s \leq 2) $$

The variation range of $R_s$ reported by El Soudani corresponds to brittle fractures without recovering. In order to model the evolution of joint roughness in the course of shearing, we assume that the variation of the roughness coefficient must range between 0 and 1; where a null value will correspond to an absence of roughness (e.g. joint walls are fully degraded), and values close to unity will indicate an approximately intact roughness (e.g. non-degraded joint walls). To respect these assumptions, a specific roughness coefficient, $SR_s$, has been introduced. For a single joint wall, the specific roughness coefficient has the following expression:

$$ SR_s = \frac{A_t - A_n}{A_n} = R_s - 1 \quad (0 \leq SR_s \leq 1). $$

Note that in this equation $SR_s$ is defined with respect to the nominal surface area, $A_n$. Finally we define the degree of surface roughness, $DR_s$, in order to relate the roughness to the initial fracture surface:

$$ DR_s = \frac{A_t - A_n}{A_n} = \frac{SR_s}{R_s} $$

As a reminder, the parameters defined in Equations (19)–(21) have been formulated for a single wall surface. Knowing that the lower and upper joint walls are in contact, it seems better to quantify the joint interface roughness. Joint interface is defined by composite topography or by ‘actual composite area’, $A_i^c$, which is the sum of the real areas of the lower and upper wall surfaces ($A_i^c = A_i^l + A_i^u$). The three previous parameters are then calculated from the composite area $A_i^c$ according to

$$ R_s(\text{joint}) = \frac{A_i^c}{A_n} = \frac{A_i^l + A_i^u}{2A_n} = \frac{1}{2} (R_s^l + R_s^u) $$

Copyright © 2001 John Wiley & Sons, Ltd.

In these equations, it was assumed that both upper and lower joint walls have the same nominal surface area $A_n$. Consequently, the composite nominal surface area $A_n$ is replaced by $2A_n$.

By combining Equations (22) and (14), the degradation degree of sheared joint surfaces can be rewritten as follows:

$$D_w(joint) = |1 - W_{de}(joint)| = \left| 1 - \frac{SR_n(joint)}{SR_n^0(joint)} \right| (0 \leq D_w(joint) \leq 1)$$

where exponents 0 and $s$ denote, respectively, prior to and following shearing.

5. MORPHO-MECHANICAL ANALYSIS OF DIRECT SHEAR TESTS

5.1. Shear behaviour of studied joints

5.1.1. Artificial joint with hammered surfaces. Figure 6 presents the first cycle of a shear test performed on the Lanhelin granite joints under 1.2 MPa of constant normal stress. For this type of joint and up to 0.8 mm of shear displacement, shear stress continuously increases with shear displacement. This typical behaviour where no clear peak can be identified is characteristic of the non-mated and non-interlocked joint walls. In addition, no veritable residual phase has been observed after 5 cycles. Examination of dilatancy curve (normal displacement vs shear displacement), not presented herein, suggests the non-dilatant nature of these joints.

Evolution of the morphological parameter $SR_n$ as a function of normal stress for the last cycle (e.g. cycle 5), is illustrated in Figure 7(a). A progressive decrease in surface roughness with a normal stress level can be noticed. In addition, a continuous decrease of surface roughness from
cycle 1 to cycle 5 for a given normal stress was observed. The percentage of degradation $D_w$ (per cent) increases with normal stress (Figure 7(b)). However, it seems that the low value of $D_w$ for the CNS shear test performed under 4 MPa compared to the test under 1.2 MPa, is the result of experimental problems such as the surpassing of the tangential motor capacity (e.g. going beyond the limit of tangential motors). For this type of joint (e.g. hammered granite joints) and in spite of the experimental problem encountered at 4 MPa, experimental results show that the hammered roughness favours a significant degradation under high normal stress as well as under low normal stress.

5.1.2. Replica of natural schist joint. Figure 8 presents the shear tests performed monotonically on the natural schist joint under CNS conditions for normal stress ranging between 0.4 and 2.4 MPa and a total shear displacement of about 20 mm. Both shear stress and dilatancy vs shear displacement are plotted in Figure 8. In spite of these tests having been carried out over a significant shear displacement (e.g. 20 mm), it should be noted that the residual phase has not yet been reached. In this case, the dilatancy curve clearly illustrates the dilatant nature of the schist joint. Globally, we observe that the specific joint roughness $SR_e$ slightly decreases when normal stress increases (Figure 9a). This reduction in $SR_e$ leads to a relative increase in the degradation percentage $D_w$ per cent as illustrated in Figure 9(b). However, values of $D_w$ (per cent) do not exceed a value of about 8. Visual examinations of joint walls after shearing indicate that degradation occurs mainly at the centre of the sample.

5.1.3. Artificial joint with undulated surfaces. Figure 10 displays the typical shear curves corresponding to 10 cycles of shear tests performed on the artificial joint with undulated surface under 1 and 4 MPa of constant normal stress. Both shear stress and dilatancy vs shear displacement are shown in this figure. Note an increase in shear stress until the peak is reached as well as a progressive decrease in shear stress beyond peak stress. It was also observed that, for a given normal stress level, the peak strength increases with the number of cycles in relation to an increase in contact area. These figures especially highlight a perfect elastoplastic behaviour from cycle 7 (e.g. residual phase is obtained after 7 cycles). For tests performed under constant normal stress levels beyond 5 MPa and not presented herein, the surfaces present significant degradation mainly due to the failure of mortar. Since this material is not a natural rock, the dominating effect...
of morphology on the shear behaviour has been prioritized. Finally, Figure 11(a) shows the evolution (a slight decrease) of $SR_c$ as a function of normal stress after 10 cycles. Consequently, low degradation can be induced (Figure 11(b)).
5.2. New failure criteria

Most joint failure criteria encountered in the literature generally attempt to predict the peak shear strength of initially mated and interlocked joints displaying a certain dilatant behaviour.
except the well-known Mohr–Coulomb criterion which is appropriated for smooth and flat joint or used as a first approximation (or for simplicity) for irregular joints. As a result, a higher degree of surface roughness is usually associated with higher friction and higher wear. As previously demonstrated from our experimental results, it seems that the hammered roughness (which is the secondary component of surface roughness and mainly governed by $\theta_s$ and $R$, while the apparent anisotropy $k_a$ as well as the surface undulation period express the primary component of surface roughness) [8,26] plays a certain role in joint shear behaviour. It was also proved that the degradation quantification reflects significant wear of hammered surfaces (Figure 7(b)). Failure of hammered roughness (e.g. roughness of artificial hard rock joints or soil–rock/structure interfaces) in relation to its degradation has not received much attention in the literature. Particular attention is paid to this subject in this section.

5.2.1. Failure criterion for non-dilatant joints. Values of morphological parameters corresponding to the Lanhelin granite joint after the last cycle of shear and summarized in Table IV indicate a reduction of surface roughness as a function of normal stress and number of cycles as reported by Belem [8]. The hammered joint was not initially interlocked and mated. Then, asperities degrade during the course of shearing by wear as well as by progressive collapse leading to an increase in contact area and interfacial friction. This type of behaviour differs from that of the well-known smooth and flat joint. Thus, a suitable peak strength criterion must integrate sliding component through asperities (generally termed by dilatancy rate for mated and interlocked rough joints) as well as a component that describes the contribution of asperity wear and accumulation of debris provided from the failure of asperities. This last component must also include the strength of the infilling material trapped between the surfaces of asperities that are approaching each other in shear. In other words, the resistance provided by static friction must be augmented by the asperity component of shear strength, since the asperities continue to flatten as reported by Xu and de Freitas [26]. Let $i_n$ be the additional strength component. The failure criterion written below attempts to integrate both hammered roughness and hammered degradation during the course of shearing in terms of resistances previously mentioned:

$$
\tau_p = \sigma_n (\phi_n + i_n)
$$

where $\phi_n$ is the base friction angle (e.g. friction angle for smooth non-damaged surfaces) differing by a few degrees from the interparticle friction angle, $\phi_p$; angle $i_n$ (index n denoting non-dilatant) relates the effect of morphology changes induced by asperity degradation. Both absence of dilatancy and the increase in shear strength are represented by a progressive increase of contact areas. The angle, $i_n$, appears to be influenced by asperity inclination, normal stress and deformation of material constituting the asperities, but in addition, $i_n$ is markedly dependent on the

<table>
<thead>
<tr>
<th>$\sigma_n$ (MPa)</th>
<th>Cycle 5 $\theta_s$ (°)</th>
<th>Cycle 5 SR $i$</th>
<th>Cycle 5 DR $i$</th>
<th>Cycle 5 $k_a$</th>
<th>Cycle 1 $\tau_p$ (MPa)</th>
<th>Cycle 1 $i_p$ (°)</th>
<th>Cycle 5 $\tau_p$ (MPa)</th>
<th>Cycle 5 $i_p$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>9.6</td>
<td>0.026</td>
<td>0.025</td>
<td>0.98</td>
<td>0.22</td>
<td>—</td>
<td>0.25</td>
<td>—</td>
</tr>
<tr>
<td>1.2</td>
<td>7.5</td>
<td>0.016</td>
<td>0.015</td>
<td>0.92</td>
<td>1.01</td>
<td>—</td>
<td>1.15</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>7.8</td>
<td>0.017</td>
<td>0.016</td>
<td>0.91</td>
<td>3.00</td>
<td>—</td>
<td>3.61</td>
<td>—</td>
</tr>
</tbody>
</table>

Table IV. Morpho-mechanical properties of Lanhelin granite joint.
thickness of debris resulting from asperities wear as reported by Xu and de Freitas [26] in their extension of Barton’s criteria to infilled joints.

From our experimental investigations, it was found that the $i_n$ is $\theta_i$ dependent according to the following form:

$$i_n = \theta_i^0 + S_n$$

where $\tan S_n = C \tan \theta_i^0 \ln \left( \frac{\sigma_k}{\sigma_n} \right)$  \hspace{1cm} (27)

where $C$ is a constant related to sheared surface degradation and $\theta_i^0$, the initial three-dimensional mean angle prior to shear process. $C$ is also dependent on the number of shear cycles, and then, on the accumulated maximum displacement, $u_{\text{max}}$. This constant depends on the initial morphology in terms of maximum surface height and the minimum surface height, on the initial coefficient of surface roughness, $\text{SR}_i^0$ related to the thickness of debris. In addition to hammered joint, the higher value of $a_0$ must be associated with an increase in debris accumulation and then, in a certain manner, with a reduction of $S_n$. Also for the hammered surfaces, it was experimentally observed that shear stress continuously increases with shear displacement, this indicates that $S_n$ increases with $u_0$ or the number of cycles $n$. Finally, from these considerations and based on the experimental results, the degradation constant $C$ is formulated as follows:

$$C = \frac{2}{k_n} \exp \left( -\frac{a_0}{u_0} \right) \text{SR}_i^0 \left( 1 - \frac{1}{4n - 3} \right)$$ \hspace{1cm} (28)

Finally, by integrating Equation (27) into Equation (26), the failure criterion, which takes into account the maximum distance of slip, is written as:

$$\tau_p = \sigma_n \tan \left( \phi_n + \theta_i^0 + a \tan \left[ C \tan \theta_i^0 \ln \left( \frac{\sigma_k}{\sigma_n} \right) \right] \right)$$ \hspace{1cm} (29)

Equation (29) allows us to predict the shear strength for the forward direction (see portion P1 in Figure 6a or Homand et al. [27] for more details) as a function of shear displacement level, $u_0$ (representing the maximum positive shear displacement in a forward direction) or $n$ the current number of cycles on the base of initial morphological characteristics.

Figure 12 presents the new failure criterion and experimental data corresponding to the Lanhelin hammered joint (cycles 1 and 5). The Mohr–Coulomb criterion is also represented. The values of input morphological parameters are summarized in Table V. The values of degradation constant $C$ evaluated based on equation (28) for cycles 1 and 5 are, respectively, 0 and 0.07. From this figure, good agreement between experiments and predictions can be observed. In addition, due to the fact that artificial undulated joints have exhibited a moderate dilatancy and a low degradation in relation to their morphological parameters (Table VI), the corresponding tests are used again to validate the new failure criterion. Both Equation (29) and the Mohr–Coulomb criterion, as well as experimental data after cycles 1 and 10, are plotted in Figure 13. Except for the test performed at 5 MPa of normal stress for which predictions tend to overestimate the peak strength, a relatively good agreement between experiments and predictions is noticed.

Finally, these figures display the ability of this new failure criterion to predict the shear strength of non-dilatant or moderately dilatant joints.
Figure 12. New shear strength criterion for non-dilatant rock joints compared to the Mohr-Coulomb criterion: case of Lanheling granite joint.

Table V. Initial morphological parameters.

<table>
<thead>
<tr>
<th></th>
<th>( \theta_s ) (°)</th>
<th>SR(_s)</th>
<th>DR(_r)</th>
<th>( k_a )</th>
<th>( a_0 ) (mm)</th>
<th>( u_0 ) (mm)</th>
<th>( u_{\text{max}} ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammered</td>
<td>12.7</td>
<td>0.045</td>
<td>0.043</td>
<td>0.98</td>
<td>1.74</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Undulated</td>
<td>10.3</td>
<td>0.047</td>
<td>0.045</td>
<td>0.43</td>
<td>8.10</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Rough</td>
<td>11.9</td>
<td>0.043</td>
<td>0.043</td>
<td>0.21</td>
<td>2.00</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 13. New shear strength criterion for non-dilatant rock joints compared to the Mohr-Coulomb criterion: case of artificial undulated joint.

5.2.2. Failure criterion for dilatant joints. Throughout the literature the prediction of dilatancy phenomenon of regular or irregular joints subjected to direct shear loading has been addressed by numerous authors, such as Patton [28], Ladanyi and Archambault [6], Jaeger [29], Barton [18,19], Saeb [21] or Homand et al. [27]. In addition, variations in dilatancy with normal stresses.
have been modelled by many authors: Ladanyi and Archambault [6], Jaeger [29], Barton [19], Leichnitz [30], Benjelloun [31], etc. It is well known that Patton [28] criterion is able and sufficient to describe failure of regular joints where geometry remains invariant during shearing, whilst the failure criteria developed by Ladanyi and Archambault, Barton or Saeb are more suitable to describe the shear strength of irregular joints. As a result, even if generally the shear surface had been regularly indented, at failure its geometrical regularity may be partially or completely lost. For instance according to Barton [18,19], the peak shear stress is related to both normal stress and peak dilatancy by the following equations:

\[ \tau_p = \sigma_n (\phi + i_p) \]  \hspace{1cm} (30)

where \( i_p \) denotes peak dilatancy depending on normal stress, the joint roughness coefficient (JRC) and the joint wall compressive strength (JCS) as follows:

\[ i_p = JRC \log_{10} \left( \frac{JCS}{\sigma_n} \right) \]  \hspace{1cm} (31)

In this study, we propose to define the evolution of the peak dilatancy angle, \( i_p \), as a function of different previously described roughness parameters. In the literature, numerous experimental studies have shown that peak dilatancy decreases non-linearly when normal stress increases. This is again demonstrated by our tests carried out on the schist joints or the artificial undulated joints. In addition, experimental results of the artificial undulated joints show that the peak dilatancy angle decreases progressively from cycle 1 to cycle 7. Beyond cycle 7, \( i_p \) remains more or less constant. By comparing the \( \theta_s \) values to those of \( i_p \) for the artificial undulated joint (Table VI) as well as for the schist joint (Table VII), it is to be noted that there is no trivial and simple relation between these two angles. The values of the peak dilatancy angle are systematically greater than the mean 3-D angle which is practically constant except for artificial undulated joints tested under normal stress beyond 5 MPa. For schist replicas exhibiting a well-marked dilatant behaviour, the peak dilatancy angle as a function of normal stress has been firstly predicted according to the following equation:

\[ i_p = i_0 \exp(-a\sigma_n) \]  \hspace{1cm} (32)

where \( i_0 \) represents the maximum inclination angle prior to shear process (e.g. under null normal stress) with respect to shear direction and approached by \( \theta_s^0 \); \( a \) is a constant dependent on the intact uniaxial compressive strength, \( \sigma_{uc} \), the initial roughness (SR\(_0\) or DR\(_0\)) and the apparent surface anisotropy, \( k_s \).

Table VI. Morpho-mechanical properties of undulated joint replica.

<table>
<thead>
<tr>
<th>( \sigma_n ) (MPa)</th>
<th>Cycle 10 ( \theta_s ) (°)</th>
<th>Cycle 10 SR</th>
<th>Cycle 10 DR</th>
<th>Cycle 10 ( k_s )</th>
<th>Cycle 1 ( \tau_p ) (MPa)</th>
<th>( i_p ) (°)</th>
<th>Cycle ( \tau_p ) (MPa)</th>
<th>( i_p ) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>10.2</td>
<td>0.021</td>
<td>0.021</td>
<td>0.19</td>
<td>0.40</td>
<td>17</td>
<td>0.40</td>
<td>16</td>
</tr>
<tr>
<td>1</td>
<td>10.4</td>
<td>0.022</td>
<td>0.022</td>
<td>0.25</td>
<td>1.00</td>
<td>15</td>
<td>1.20</td>
<td>13</td>
</tr>
<tr>
<td>2</td>
<td>10.2</td>
<td>0.021</td>
<td>0.020</td>
<td>0.22</td>
<td>2.30</td>
<td>17</td>
<td>2.30</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>10.2</td>
<td>0.021</td>
<td>0.020</td>
<td>0.25</td>
<td>3.00</td>
<td>16</td>
<td>3.50</td>
<td>11</td>
</tr>
<tr>
<td>4</td>
<td>10.0</td>
<td>0.022</td>
<td>0.021</td>
<td>0.27</td>
<td>3.90</td>
<td>15</td>
<td>4.40</td>
<td>9.9</td>
</tr>
<tr>
<td>5</td>
<td>9.4</td>
<td>0.020</td>
<td>0.019</td>
<td>0.32</td>
<td>4.50</td>
<td>16</td>
<td>5.30</td>
<td>9.1</td>
</tr>
</tbody>
</table>
Due to the previous equation that underestimates the experimental data, we believe that for a better prediction of experimental results, angle \( i_d \) which will integrate both dilatancy phenomena and degradation strength, must be greater than the observed peak dilatancy angle. Furthermore, when joint is subjected to a cyclic shear, the angle \( i_d \) of the last cycle must be greater than those of the first cycle. Consequently, the \( i_d \) angle differs from the peak dilatancy angle obtained experimentally. Angle \( i_d \) demonstrates the effect of dilatancy as well as the surface change due to asperity degradation which increases the contact area and hence friction and shear strengths. Based on our experimental observations, angle \( i_d \) can be modelled as follows:

\[
i_d = 20^0\exp(-b\sigma_n)
\]

where \( b \) is a constant depending on \( \sigma_c \), the initial roughness, \( DR^0 \), the apparent surface anisotropy \( k_s \) and the maximum shear displacement, \( u_{\text{max}} \) (or number of cycles). According to our observations, it was found that the constant \( b \) can be expressed as follows:

\[
b = \frac{1}{\sigma_c} \left( \frac{u_0^3}{a_0u_{\text{max}}} + \frac{k_s}{DR^0} \right)
\]

where \( a_0 \) is the maximum amplitude; \( u_0 \) is the maximum shear displacement in forward direction (or maximum displacement for monotonic shear displacement). For a monotonic shear, \( u_{\text{max}} = u_0 \). Finally, the shear strength criterion for dilatant joint whilst taking into account the influence of cycles in shear direction, has the following form:

\[
\tau_p = \sigma_n \tan(\phi_b + 20^0\exp[-b\sigma_n])
\]

where \( b \) appearing in this expression is for instance approached by Equation (34).

Figures 14 and 15 present a comparison between the existing failure criteria (Ladanyi and Archambault denoted by L & A; Saeb & Barton) and the proposed failure. Comparison concerns the two tested dilatant joints. Parameters needed for Ladanyi and Archambault, Saeb or Barton failure criteria are derived from our experimental data; \( \phi_b = \phi_f = 34^0; \sigma_T \approx \sigma_c = 75 \text{ MPa} \), and \( i_0 = \theta^0 \). Examination of these figures shows that the proposed failure criteria and Barton’s criterion are in good agreement with the experimental data. For these joints, results also demonstrate the Saeb failure criterion plots very close to the original model of Ladanyi and Archambault as reported by Saeb [21]. The Barton roughness parameters used to represent our experimental data are: JRC = 11 for the schist replicas and JRC = 7.5 for undulated joints. These roughness coefficient values have not been derived from our experimental data, but back-calculated in order to fit well with the experiment. Due to the proposed failure criterion directly
integrating morphological properties as well as shear characteristics, we consider that this criterion is appropriated to describe well the peak shear stress of dilatant joints.

In addition to the fact that the proposed failure criterion captures the contribution of dilatancy, and describes the mechanical behaviour of dilatant joints with a good agreement compared to experiments, the main advantage of this new criterion is: the morphological properties, which partly govern dilatancy phenomena, are directly incorporated.

6. FORMULATION OF SHEARED JOINTS DEGRADATION

6.1. Basic assumptions

In this section, we attempt to predict the morphology evolution during the course of shearing as a function of normal stress, $\sigma_n$. Previous experimental results suggest that joint degradation
during shearing depends, amongst other factors, upon (i) the initial morphology and particularly the degree of joint mismatching (or dislocating), (ii) the uniaxial compressive strength of intact rock material constituting the joint asperities, $\sigma_c$, (iii) the shear loading path (e.g. constant normal stress or stiffness, see Reference [27] for details), (iv) the dilatancy rate and (v) the maximum shear displacement and then the shear mode: monotonic or cyclic.

Equation (25) shows that, to predict the variation in degradation with respect to normal stress is equivalent to finding a law of evolution regarding the surface state, $\xi$, quantified by the specific joint roughness $SR_s$, for example. The main parameters to be taken into account are: $\sigma_c$, the anisotropy degree, $k_a$, the degree of surface roughness, $DR_s$, and the surface angularity, $\theta_s$; such as

$$\frac{d\xi}{d\sigma_n} = F(\sigma_c, k_a, DR_s, \theta_s)$$

(36)

Under a low normal stress level ($\sigma_n \approx 0$) the joint must remain undamaged ($SR_s = SR_s^0$), whereas under a high normal stress level ($\sigma_n \approx \sigma_c$) the joint must be fully degraded and exhibit null roughness ($SR_s = 0$) for a given maximum shear displacement, $u_{max}$.

6.2. Model formulation

From our tests performed on the granite, artificial undulated and natural schist joints, we have observed that the specific roughness coefficient decreases non-linearly with normal stress (Figures 7(a), 9(a) and 11(a)). In other words, the percentage of degradation $D_w$ (per cent) increases non-linearly with normal stress. Consequently, the instantaneous degradation rate of a joint surface for a given maximum displacement must be proportional to the surface state prior to shearing and inversely proportional to the dilatancy rate (or dilatancy power). We assume that the term $(1 - \sigma_n/\sigma_c)$ can quantify this power of dilatancy which should govern the contact areas during the course of shearing. This term decreases from 1 at $\sigma_n = 0$ (contact between joint walls is simply due to the sample installation) to 0 at $\sigma_n = \sigma_c$ (expressing maximum contact between joint walls, and no dilatancy is possible). From these observations and assumptions, the following relation is proposed:

$$\frac{d\xi}{d\sigma_n} = -n\xi + \frac{\xi}{\sigma_c(1 - \sigma_n/\sigma_c)} = \xi\left(-n + \frac{1}{\sigma_c(1 - \sigma_n/\sigma_c)}\right)$$

(37)

Integrating this equation leads to

$$\xi = \xi_0 \left(1 - \frac{\sigma_n}{\sigma_c}\right) \exp(-\sigma_n)$$

(38)

Substituting the surface state variable, $\xi$, by the specific roughness coefficient after shearing, $SR_s$, and the constant $\xi_0$ by the initial value of roughness coefficient prior to shear, $SR_s^0$; the previous equation can be written in a general form as:

$$SR_s = SR_s^0 \left(1 - \frac{\sigma_n}{\sigma_c}\right) \exp\left(-\frac{k_a \sigma_n}{B \sigma_c}\right)$$

(39)

where $B$ is a constant depending on the initial morphology. For instance, our experimental investigations show that $B$ can be approached by $2DR_s^0/k_a$. The specific roughness coefficient
then has the following final expression:

\[
SR_a = SR_a^0 \left(1 - \frac{\sigma_n}{\sigma_c}\right) \exp\left(-\frac{k_a^2 \sigma_n}{2DR^0 \sigma_c}\right) \text{ when } \sigma_n \leq \sigma_c
\]

\[
SR_a = 0 \text{ when } \sigma_n > \sigma_c
\]

Based upon the relationship between the specific roughness coefficient \(SR_a\) and the degradation degree \(D_w\) (Equation (25)), the following equation relates the variation of \(D_w\) as a function of normal stress ranged between 0 and \(\sigma_c\):

\[
D_w = 1 - \left(1 - \frac{\sigma_n}{\sigma_c}\right) \exp\left(-\frac{k_a \sigma_n}{B \sigma_c}\right) \text{ with } 0 \leq D_w \leq 1
\]  

(40)

or for the tested joints

\[
D_w = 1 - \left(1 - \frac{\sigma_n}{\sigma_c}\right) \exp\left(-\frac{k_a^2 \sigma_n}{2DR^0 \sigma_c}\right) \text{ with } 0 \leq D_w \leq 1
\]  

(41)

(42)

Beyond the uniaxial compressive strength, the degree of degradation remains equal to unity.

6.3. Model verification

Figure 16 shows the model prediction compared to the experimental data. A relatively good agreement can be found between degradation prediction of dilatant joints under low normal stress levels and experiments. The proportion of total joint area sheared through asperities as defined by Ladanyi and Archambault [6] is also plotted in Figure 16. It should be noted that the model of Ladanyi and Archambault tends to underestimate the degradation. A small quantity of tests carried out here does not allow us to prove the validity of our approach for high normal stress levels. However, other direct shear tests under high normal stress levels as well as under other shear paths (e.g. constant normal stiffness) and for different levels of shear displacement are

![Figure 16. New model of joint surfaces degradation compared to the well-known Ladanyi and Archambault coefficient, \(a_e\).](image-url)
needed to again prove the model performance in a large range of normal stress and under other stress paths as recently undertaken in Homand et al. [27].

7. CONCLUSION

Numerous monotonic and cyclic shear tests under constant normal stress levels were conducted on one artificial granite joint with hammered surfaces, one artificial regularly undulated joint and one natural schist joint in order to understand their morpho-mechanical behaviour. A laser sensor profilometer enables surface data measurements to be taken prior to and after each shear test, and afterwards to calculate joint surface roughness, $SR_w$, and joint surface degradation, $D_w$, presently defined. From our experimental observations, it was clearly illustrated that the peak strength of a hammered joint which is non-dilatant significantly differs from the classical formulation of dilatant joint strength. In addition, both dilatancy and joint surface degradation must be incorporated in the peak strength of dilatant joints. The prediction of the well-known criteria reported in the literature thus tends to underestimate or overestimate the observed peak strength. With regard to joint surface degradation, two new peak strength criteria have been developed. The first attempts to predict the peak strength of joints with an initial hammered roughness, whereas the second attempts to describe dilatant joint strength. The validity of this new peak strength criterion for hammered surfaces is successfully proven based on the experimental results of hammered joint and artificial undulated joint, whereas both results of tests performed on artificial undulated joint and natural schist joint provide a good verification of the new peak strength criterion for dilatant joints. The main advantage of these new criteria over the classical ones is that the input parameters are essentially governed by the initial morphology and that slide distance is fully incorporated.

Finally, we propose a model to predict the evolution of joint morphology and the degradation degree during the course of shearing. Degradations of the artificial undulated joint and the natural schist joint provide a verification of the proposed model with a very good agreement when compared to the prediction of the well-known model of Ladanyi and Archambault of joint surface degradation.

The next stage of this work is to extend the model of joint surface degradation after shear presented here to a continuous degradation model dependent both on current shear displacement and the boundary loading conditions (e.g. constant normal stress and stiffness) with a view to developing an elaborated constitutive model for rock joints.

REFERENCES

FRICTION AND DEGRADATION OF ROCK