Historical shear deformation of rock fractures derived from quantitative three-dimensional description of fracture surfaces on digital outcrop models (DOMs)

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Abstract

The initiation and development of fractures in rocks is the key part of many problems from academic to industrial, such as fracture network development, faulting, folding, rock mass characterization, reservoir characterization, etc. Conventional ways of evaluating the fracture mechanical origin and historical deformations depend on the geologists’ visual interpretation of the indicating structures such as offsets, plumose structures, fault striation and fault steps, and hence suffer from problems like subjectivity and the absence of obvious indicating structures. In this study, we propose a quantitative method to derive historical shear deformations of rock fractures based on the analysis of effects of indicating structures on the shear strength parameter $\theta_{\text{max}}^*/C$ (Grasselli et al., 2002) (the three-dimensional description) of the fracture surface. This method fit a model that combines effects of isotropic base shear strength and anisotropic shear deformations’ indicating structures to this shear strength parameter of the fracture. The amount of indicating structures and their occurrences are estimated, and the historical shear deformations can be inferred. The validity of the proposed method was proved by testing it on fracture surfaces with clear indicating structures. The application of this method on an example outcrop shows two different deformation patterns of rock mass with and without preexisting fractures and an intuitive idea of how the rock mass was deformed, and

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hence demonstrate the effectiveness and high potential utility of the proposed method.

**Keywords:**
Historical shear deformation; Quantitative method; Shear strength parameter; Quasi striations; Quasi steps; Digital outcrop models (DOMs);

### 1. Introduction

Rock fractures in the field usually have complex mechanical origin and deformation history. The complex relationships between fracture deformation, fracture network, faulting, folding, rock mass properties, reservoir production, geological CO$_2$ storage, and etc. make the fracture deformation data the key part of many problems from academic to industrial. However, to our knowledge, the fracture mechanical origin and historical deformations were mainly inferred from the geologists’ visual interpretation of the indicating structures – if they were very well shown – such as offsets, plumose structures, fault striation, fault steps, etc. Beside this method’s drawbacks of requiring large amount of labor and prone to subjectivity when the indicating structures are not so obvious for visual interpretation, quite commonly, the fracture doesn’t show any obvious indicating structures for visual interpretation at all.

The Digital Outcrop Model (DOM) (Bellian et al., 2005), which is usually acquired using techniques such as laser scanning, structure from motion or stereo vision, describes the outcrop surface in the form of a point cloud, a large number of 3D ($X,Y,Z$) points, and thereby contains morphological features indicating historical deformations of rock fractures. The 3D geometries of those indicating structures may vary wildly depending on the magnitude of the shear deformation, the properties of the rock, and so on. An important fact is that a certain type of indicating structure can have similar effects on the shear strength of a fracture. Thus it’s possible to estimate the existence and the amount of indicating structures, hence the historical shear deformations, by analyzing the effects of these indicating morphological fea-
tures on the shear strength of rock fractures. In doing so, the contribution of surface morphology on the shear strength of rock fractures should firstly be modeled. Efforts have been made in the literature to estimate the shear strength of rock fractures while trying to study the contribution of surface morphology. Among all the models (e.g., Ladanyi’s empirical model (Ladanyi and Archambault, 1969), Barton’s empirical model (Barton and Choubey, 1977), Amadei-Saeb’s analytical model (Amadei et al., 1998; Saeb and Amadei, 1992) and Plesha’s theoretical model (Plesha, 1987)), Barton’s morphological parameter known as the joint roughness coefficient (JRC) is the one that is mainly used in practice (ISRM, 1978). As shearing strictly depends on three-dimensional contact area location and distribution (Gentier et al., 2000), Grasselli et al. (2002) proposed a method for the quantitative three-dimensional description of a rough fracture surface, and based on this description, Grasselli and Egger (2003) proposed a constitutive criterion to model the shear strength of fractures and also to estimate the JRC value. This constitutive model was reported to be able to describe experimental shear tests conducted in the laboratory (Grasselli and Egger, 2003). Based on this three-dimensional description, which describes the contribution of surface morphology on the shear strength of rock fractures, the effects of indicating structures can be analyzed, since indicating structures are part of the surface morphology.

On the other hand, each individual fracture surface should be extracted from outcrop point clouds, and during the last 10 years, many methods have been developed because of the wide range of applications of the fracture data (Slob et al., 2005; Roncella et al., 2005; Voyat et al., 2006; Olariu et al., 2008; Lato et al., 2009; Ferrero et al., 2009; Gigli and Casagli, 2011; García-Sellés et al., 2011; Riquelme et al., 2014; Gomes et al., 2016; Wang et al., 2017). Among those methods, the region-growing approach proposed by Wang et al. (2017) is specially designed for the automatic extraction of the full extent of each individual fracture surface from the outcrop point cloud, unlike methods that do not extract the full extent of each individual fracture (Slob
et al., 2005; Olariu et al., 2008; Lato et al., 2009; Gomes et al., 2016) or methods that need human supervision (Ferrero et al., 2009; Gigli and Casagli, 2011; García-Sellés et al., 2011; Riquelme et al., 2014). And using the region-growing method, Wang et al. (2017) reported that automatically extracted fracture data are of the same or even better quality as the manually surveyed data.

Based on researches described above, this paper present a quantitative method to derive historical shear deformations of rock fractures from DOMs. Rock fracture examples with clear indicating structures were used to test this method. The results are consistent with human visual interpretations and therefore prove the validity of this method. The application of this quantitative method on an example outcrop show interesting and inspiring indications of how the rock mass was deformed and different patterns of deformations, and hence demonstrate the effectiveness and high potential utility of the proposed method.

2. Methodology

2.1. The extraction of individual fracture surfaces from outcrop point clouds

Using laser scanning instruments, an outcrop is scanned as point clouds (Fig. 1a). Rock fracture surfaces need to be extracted from outcrop point clouds before any analysis can be conducted. And in order to account for all features on the fracture surface, the full extent of individual fracture surfaces should be extracted. The region-growing approach (Wang et al., 2017) was specially designed for this purpose and was proven to be able to get high quality results, as shown in Fig. 1b, in which different fracture surfaces are shown by different colors.

2.2. The contribution of surface morphology on the shear strength of rock fractures

The indicating structures on fracture surfaces are in fact the results of historical shear deformations. Although the 3D geometries of those indicating structures may vary wildly depending on the magnitude of the shear deformation, the properties of
Figure 1: (a) The point cloud scanned from an outcrop and (b) the result of individual fracture surfaces extraction from the outcrop point cloud. Different fracture surfaces are shown by different colors.

the rock, and so on, a certain type of indicating structure can have similar effects on the shear strength of a fracture. For instance, the existence of fault steps would make it harder for the fracture to shear in the direction that faces the steps. Thus it’s possible and logically reliable to estimate the existence and the amount of indicating structures by deciphering the shear strength of fractures. Note that it’s not necessary to use the real shear strength of fractures to estimate the indicating structures, and the contribution of fracture surface morphology on the shear strength is sufficient as the indicating structures are themselves morphological structures.

The triangulated surfaces were reconstructed using a triangulation algorithm pro-
posed by Marton et al. (2009) on fracture point clouds in order to handle the “frac-
tal” structures of fracture surfaces (Fig. 2). The parameter $\theta_{max}/C$ that describes
the contribution of fracture surface morphology on the shear strength was proposed
by Grasselli et al. (2002). The parameter is able to capture and quantify the effect
of surface anisotropy on the shear strength of a fracture (Grasselli and Egger, 2003).

![Figure 2](image1.png)  
(a) The point cloud of a fracture surface and (b) the reconstructed fracture surface using
a triangulation algorithm proposed by Marton et al. (2009).

In the calculation of $\theta_{max}/C$, the potential contact area $A_{\theta^*}$, the sum of all areas in
contact or damaged during shearing, is very important as shearing strictly depends
on three-dimensional contact area location and distribution. With specific shear
direction $t$, for each triangle surface, the azimuth angle $\alpha$ is the angle between the
true dip vector projection on the shear plane $w$ and the shear vector $t$, measured
clockwise from $t$, the dip angle $\theta$ is the angle between the shear plane and the triangle,
the apparent dip angle $\theta^*$ describes the contribution of each triangle inclination, where

$$\tan \theta^* = - \tan \theta \cos \alpha.$$  \hspace{1cm} (1)

The identification of the potential damaged areas only requires to determine the
areas which face the shear direction and which, among them, are steep enough to be involved (Grasselli et al., 2002). In a simplified shearing mechanism (Grasselli et al., 2002), $A_{\theta^*}$ is the sum of all areas of the surface facing the shear direction, and steeper than a threshold apparent inclination (denoted as $\theta_{cr}^*$). To describe the relationship between the potential contact area $A_{\theta^*}$ and the corresponding minimum apparent dip angle $\theta^*$, the following equation (Grasselli et al., 2002) was adopted to fit the data:

$$A_{\theta^*} = A_0 \left( \frac{\theta_{max}^* - \theta^*}{\theta_{max}^*} \right)^C,$$

where $A_0$ is the maximum possible contact area in the shear direction, $\theta_{max}^*$ is the maximum apparent dip angle in the shear direction, and $C$ is a “roughness” parameter, calculated using a best-fit regression function, which characterizes the distribution of the apparent dip angles over the surface.

The ratio $\theta_{max}^*/C$ describes the change of angularity across the surface; low values indicate relatively few steeply inclined areas, which, therefore, corresponds to less shear strength. And the shear-strength-related parameter $\theta_{max}^*/C$ can be obtained for each shear direction on the fracture surface to capture and quantify the effect of surface anisotropy (such as the indicating structures) on the shear strength of a fracture. For instance, the values of $\theta_{max}^*/C$ were calculated for shear directions all around the average plane of the fracture shown in Fig. 2 in steps of $5^\circ$. The polar diagram of $\theta_{max}^*/C$ shows the anisotropic behavior in shear strength of this rock fracture (Fig. 3b).

2.3. Historical shear deformations of rock fractures

We assume that for the same rock type and similar normal load on the fracture, the amount of indicating structures is positively associated with the degree of historical shear deformations. And we know that the amount of indicating structures is positively associated with the degree of anisotropic behavior in shear strength of the rock fracture. So the problem becomes the estimation of the amount and the spacial occurrence of indicating structures from the polar diagram of $\theta_{max}^*/C$. 

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Figure 3: (a) The reconstructed fracture surface. (b) The polar diagram of $\theta_{\text{max}}^*/C$ calculated for shear directions all around the average plane of the reconstructed fracture surface in steps of 5°. Note the anisotropic distribution of values $\theta_{\text{max}}^*/C$ for the fracture surface.

Two kinds of indicating structures are discussed in this paper: fault striations and fault steps. Note that the “striations” and “steps” we are talking about here are not necessarily as obvious as what a geologist would have considered standard — they are estimated as long as they are causing anisotropic behavior in shear strength of the rock fracture. Here we call them quasi fault striations and quasi fault steps.

When considering the effects of quasi fault striations and quasi fault steps on the shear strength of rock fractures, it’s easy to understand that the quasi fault striations have “sinusoidal” effects — the shear strength is weakened in directions parallel to the quasi striations while strengthened in directions perpendicular to the quasi striations (Fig. 4b), and that the shear strength is strengthened in shear directions that face the quasi steps (Fig. 4c). On the other hand, if the quasi striations and quasi steps, hence their anisotropic effects, are removed, we have the isotropic “base” shear strength parameter of rock fractures (Fig. 4a).
Figure 4: The illustration of effects of indicating structures on the shear strength of rock fractures. (a) The isotropic “base” shear strength parameter without effects of anisotropic structures. (b) The “sinusoidal” effects of quasi striations. (c) The strengthening effects of quasi steps.

We can formulate the effects of quasi fault striations as:

\[ f(\phi) = M_f \sin \left( 2 \left( \phi - \left( \phi_f - \frac{3\pi}{4} \right) \right) \right), \]  

(3)

where \( M_f > 0 \) is the magnitude of the quasi striations’ effects and \( \phi_f \) is the direction.
that parallels to the quasi striations. The effects of quasi fault steps can be formulated as:

\[
g(\phi) = M_g \Pi \left( \frac{2(\phi - \phi_g)}{T} \right) \sin \left( \frac{2\pi}{T} \left( \phi - \left( \phi_g - \frac{T}{4} \right) \right) \right) \\
+ M_g \Pi \left( \frac{2(\phi - (\phi_g + 2\pi))}{T} \right) \sin \left( \frac{2\pi}{T} \left( \phi - \left( \phi_g + 2\pi - \frac{T}{4} \right) \right) \right),
\]

where \( M_g > 0 \) is the magnitude of the quasi steps’ effects, \( \Pi \) is the rectangular function defined as:

\[
\Pi(t) = \begin{cases} 
0, & \text{if } |t| > \frac{1}{2} \\
\frac{1}{2}, & \text{if } |t| = \frac{1}{2} \\
1, & \text{if } |t| < \frac{1}{2}
\end{cases}
\]

\( T \) is the period of the sine function, \( \phi_g \in (\frac{T}{4} - 2\pi, 2\pi - \frac{T}{4}) \) is the direction the quasi steps face. Due to the fact that quasi steps are usually not strictly facing the same direction, the range of \( \phi \) over which the quasi steps have effects, i.e., \( T/2 \), is larger than \( \pi/2 \). The value of \( T/2 \) is usually set in the range of \( (\pi/2, \pi) \) depending on the occurrence of the quasi steps.

Thus we have a model \( F(\phi) \) to describe the shear-strength-related parameter \( \theta_{\text{max}}^*/C \):

\[
F(\phi) = B + f(\phi) + g(\phi),
\]

where \( B \) is the base shear strength parameter of rock fractures. Fitting this model to the polar diagram of \( \theta_{\text{max}}^*/C \) obtained in Section 2.2, as shown in Fig. 5, we have the estimations of \( B, M_f, \phi_f, M_g \) and \( \phi_g \) for this fracture surface, i.e., we get the amount and the spacial occurrence of quasi striations and quasi steps on this fracture surface. For quasi striations, the amount is \( M_f/B \) and the spacial occurrence is \( \phi_f \), and for quasi steps, the amount is \( M_g/B \) and the spacial occurrence is \( \phi_g \).

3. Method validation

The proposed method was tested on outcrop fracture surfaces with obvious fault striations (Fig. 6a) and fault steps (Fig. 7a). The estimated spacial occurrence of
Figure 5: Model $F(\phi)$ fitted to the polar diagram of $\theta_{\text{max}}/C$.

quasi striations, which is shown as white stripes on the fracture surface (Fig. 6b), agrees well with the real occurrence of striations shown in Fig. 6a. The estimated quasi steps is shown as black stripes on the fracture surface (Fig. 7b), and the quasi steps face the direction in which the stripes’ color change gradually from black to normal colors. Again, the estimated spacial occurrence of quasi steps agrees well with the real occurrence of steps shown in Fig. 7c and Fig. 7d. Those two examples clearly demonstrate the effectiveness of the proposed method.

4. Applications and discussion

The quasi striations and quasi steps data that indicate historical shear deformations of rock fracture has great prospect of applications, and may play a very important role in a lot of research scenarios, such as fracture network development, faulting, folding, rock mass characterization, reservoir characterization, and so on. Here we first look at the applications on an outcrop (Fig. 8a). Fracture surfaces on the outcrop are colored based on the amount of quasi striations and quasi steps.
Figure 6: The validation of the occurrence of quasi striations. (a) The point cloud of the fracture surface with obvious fault striations and (b) the occurrence of quasi striations shown as white stripes on the fracture surface.

The occurrence of quasi striations is shown as white stripes on the fracture surface (Fig. 8b) and the occurrence of quasi steps is shown as black stripes on the fracture surface (Fig. 8c). The quasi steps face the direction in which the stripes’ color change gradually from black to normal colors as stated above.

The visualization of quasi striations and quasi steps data on the outcrop gives an intuitive idea of how the rock mass was deformed. For example, fractures with less shear deformation indicators (quasi striations and quasi steps) seem to be mostly facing left as shown in Fig. 8b — in other words, the rock blocks may have undergone tensile stress in this direction during the formation of those fractures, while fractures facing right may have undergone shear stress. From the occurrence of quasi striations and quasi steps we know that fractures with similar occurrences have similar shear deformation directions (though the amount of shear deformation indicators may vary), which is consistent with the relatively stable geological background stress. Combining the occurrence of quasi striations and quasi steps of fractures facing right,
we know the exact direction of the shear deformation on those fractures, and we know that there may be a shear component in the stress applied on fractures facing left.

In addition, the amount of quasi striations and quasi steps can be integrated into the pole density plot (Fig. 9). Both Fig. 9a and b indicate that the rock fractures can be grouped into two: group one consists of fractures whose stereographic plot poles are near the arc of the bedding and group two consists of fractures whose stereographic plot poles are relatively away from the arc of the bedding. Fractures of group one are more perpendicular to the bedding surface and are more sheared. Fractures of group two are more vertical and are less sheared. The story behind Fig. 9a and b may be that fractures of group one were formed as conjugated shear fractures when the bedding surfaces were still horizontal, then the strata were tilted and the geological stress was loaded on fractures of group one, which resulted in directional preference of local tensile stress (hence the preference of occurrence of tensile fractures) and the reactivation and formation of shear fractures roughly perpendicular to those tensile fractures. If the story is true, it demonstrates two different deformation patterns of rock mass with and without preexisting fractures.

The application of quasi striations and quasi steps data will improve our understanding of a lot of fracturing-related phenomena and even help us build models to predict more accurately. Further research should focus on the application of quasi striations and quasi steps data on more sophisticated problems such as fracture network development, faulting, folding, and so on.

5. Conclusions

A quantitative method to derive historical shear deformations of rock fractures from DOMs was proposed in this paper. After the extraction of individual fracture surfaces from outcrop point clouds, the fracture surfaces are reconstructed using a triangulation algorithm and the shear strength parameter $\theta_{max}/C$ is calculated for shear directions all around the fracture surface. A model that combines the effects
of “base” strength, quasi striations and quasi steps on the shear strength of rock fracture is fitted to the calculated $\theta_{max}/C$, thus the amount and occurrence of quasi striations and quasi steps are estimated, and the historical shear deformations can be inferred.

The validity of the proposed method was proved by testing it on fracture surfaces with clear indicating structures. The application of this method on an example outcrop shows two different deformation patterns of rock mass with and without preexisting fractures and an intuitive idea of how the rock mass was deformed.

There is great prospect of applications of the proposed method and the quasi striations and quasi steps data. Further research should focus on the application of this method on problems such as fracture network development, faulting, folding, etc.

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Figure 7: The validation of the occurrence of quasi steps. (a) The picture of the fracture surface with obvious fault steps. (b) The occurrence of quasi steps shown as black stripes on the fracture surface. The quasi steps face the direction in which the stripes’ color change gradually from black to normal colors. (c) and (d) Pictures showing the occurrence of fault steps.
Figure 8: (a) The outcrop point cloud. (b) The visualization of quasi striations. (c) The visualization of quasi steps. Fracture surfaces are colored based on the amount of quasi striations and quasi steps.
Figure 9: Pole density plot with the amount of (a) quasi striations and (b) quasi steps.