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Shear strengths of sandstone fractures under true triaxial stresses

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ABSTRACT

True triaxial shear tests have been performed to determine the peak shear strengths of tension-induced fractures in three Thai sandstones. A polyaxial load frame is used to apply mutually perpendicular lateral stresses (σ_p and σ_o) to the 76 × 76 × 126 mm rectangular block specimens. The normal to the fracture plane makes an angle of 59.1° with the axial (major principal) stress. Results indicate that the lateral stress that is parallel to the fracture plane (σ_p) can significantly reduce the peak shear strength of the fractures. Under the same normal stress (σ_n) the fractures under high σ_p dilate more than those under low σ_p. According to the Coulomb criterion, the friction angle decreases exponentially with increasing σ_p/σ_o ratio and the cohesion decreases with increasing σ_p. The lateral stress σ_p has insignificant effect on the basic friction angle of the smooth saw-cut surfaces. The fracture shear strengths under $\sigma_p = 0$ correlate well with those obtained from the direct shear tests. It is postulated that when the fractures are confined laterally by σ_p, their asperities are strained into the aperture, and are sheared off more easily compared to those under unconfined condition.

1. Introduction

Friction and movement of rock fractures are important in the understanding of natural geologic hazards such as earthquakes, faults and volcanic activities, and engineering applications such as mining, petroleum exploitation, and waste disposal in geologic media. Direct shear testing (e.g., ASTM D5607-08) is widely used to determine the peak and residual strengths of rock fractures. Its test configurations however pose some disadvantages; the magnitudes of the applied normal stress are limited by the uniaxial compressive strength of the rock and the fractures are sheared under unconfined conditions. The triaxial shear test method (Tisa and Kovari, 1984; Brady and Brown, 2006; Jaeger et al., 2007) has therefore been employed to simulate the frictional resistance of rock fractures under confinements. The cylindrical rock core containing an inclined fracture or weakness plane can be axially loaded in a triaxial pressure cell with a wide range of applied confining pressures. The normal stress at which the shear strengths are measured can be controlled by the applied axial stress and confining pressures (Lane and Heck, 1964; Rosso, 1976). The test provides the shear strengths of rock fractures under uniform lateral confining stresses ($\sigma_1 \neq \sigma_2 = \sigma_3$), which may not truly represent their actual in-situ conditions, where $\sigma_1 \neq \sigma_2 \neq \sigma_3$. It has long been recognized that the intermediate principal stress or the true triaxial stress condition can notably affect the intact rock strengths and deformability (e.g., Haimson and Rudnicki, 2010; Alexeev et al., 2008; Cai, 2008; Haimson, 2006; Colmenares and Zoback, 2002; Haimson and Chang, 2000). Rare attempt has however been made at determining the shear strengths of rock fractures under true triaxial stresses (Morris and Ferrill, 2009). A shear strength criterion for rock fractures that can incorporate the effect of the three-dimensional stress state has never been developed. Such knowledge could improve an understanding of the friction of rock fractures around deep underground structures and of the faulting behavior at crustal depth.

The objective of this study is to experimentally determine the shear resistance of fractures in sandstone specimens under true triaxial stresses. The effort involves performing true triaxial shear tests on tension-induced fractures and smooth saw-cut surfaces by using a polyaxial load frame. Conventional direct shear tests are also performed to compare their results with those of the true triaxial tests. Empirical equations representing the cohesion and friction angle as a function of the applied multi-axial stresses are derived and incorporated into the Coulomb criterion.

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2. Sample preparation

The specimens used for the true triaxial shear tests are prepared from the Phu Kradung, Phu Phan and Phra Wihan sandstones (hereafter designated as PKSS, PPSS and PWSS). They are cut to obtain rectangular blocks with nominal dimensions of $76 \times 76 \times 126\ \text{mm}^3$. These rocks are classified as fine-grained quartz sandstones with highly uniform texture and density. A line load is applied to obtain a tension-induced fracture diagonally across the sandstone block, as shown in Fig. 1. The normal to the fracture plane makes an angle of 59.1° with the major axis of the specimen. All fractures are clean and well mated. The asperity amplitudes on the fracture planes are measured from the laser-scanned profiles along the shear direction. The readings are made to the nearest 0.01 mm. The maximum amplitudes are used to estimate the joint roughness coefficients (JRC) of each fracture based on Barton's chart (Barton, 1982). The joint roughness coefficients are averaged as 8, 6 and 6 for PKSS, PPSS and PWSS, respectively. Fig. 2 shows examples of the laser-scanned profiles for the three sandstones. Some three-dimensional image profiles are shown in Fig. 3. For the specimens with the saw-cut surface, two sandstone blocks are used to form a complete pair of specimens primarily to avoid the effect of the groove caused by the cutting blade. Each block is cut diagonally, hence producing smooth fractures with the normal making an angle of 59.1° with the major axis of the specimen. All specimens are oven-dried before testing. For the direct shear test specimens a line load is applied to obtain a tension-induced fracture at the mid-section of the $100 \times 100 \times 160\ \text{mm}^3$ sandstone blocks. The fracture area is $100 \times 100\ \text{mm}^2$.

3. Polyaxial load frame

A polyaxial load frame (Fuenkajorn and Kenkhunthod, 2010; Fuenkajorn et al., 2012) is used to apply true triaxial stresses to the specimens (Fig. 4). One of the lateral stresses is parallel to the strike of the fracture plane and is designated as σ_p. The other is normal to the strike of the fracture plane and is designated as σ_o. They are applied by two pairs of 152 cm long cantilever beams set in mutually perpendicular directions. The outer end of each beam is pulled down by a dead weight placed on a lower steel bar linking the two opposite beams underneath. The beam inner end is hinged by a pin mounted between vertical bars on each side of the frame. During testing all beams are arranged nearly horizontally, and hence a lateral compressive load results on the specimen placed at the center of the frame. Using different

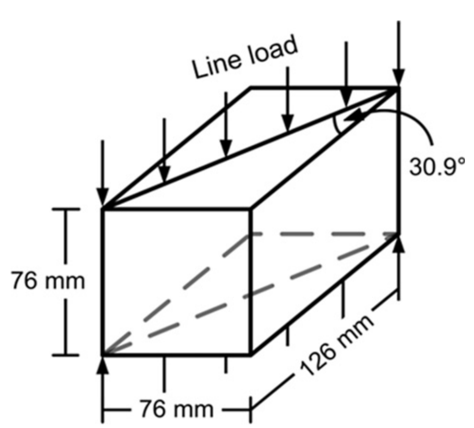

Fig. 1. Line load applied to obtain tension-induced fracture in sandstone specimen.

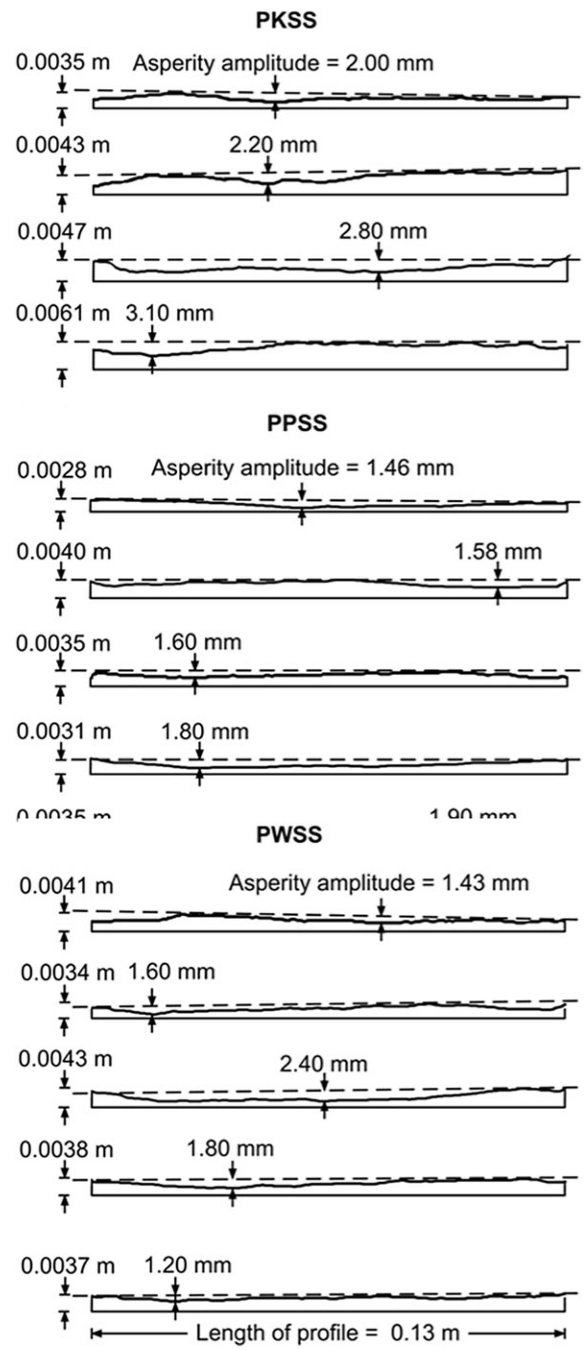

Fig. 2. Examples of laser-scanned profiles to measure the maximum asperity amplitude and to estimate the joint roughness coefficient (JRC).