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Behavior of microcontacts in rock joints under direct shear creep loading

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ABSTRACT

Two types of fractures were induced in sandstone by means of modified shear and indirect tension. The fractured rock samples were assembled following their initial formation and direct shear tests were performed under a constant normal force and stepwise increased shear creep loadings. Using computerized tomography (CT) and laser scanning, the micro-contact mechanism of the fractured rock surfaces were observed and measured before, during, and after the shear tests. Under a moderate normal force, dilation tends to occur in the shear fractured rocks; with the increase of normal force, the peak shear strength of tensile fractured rocks grows faster than that of shear fractured rocks and eventually gives rise to a higher value. A few micro-contact modes and fracture phenomena of the rough surfaces in contact are recognized through CT and laser scanning images, such as shear-off of micro-asperities, friction between macrowaved rough surfaces, migration of worn debris, propagation and healing up of hybrid cracks in subsurface. The long-term shear strength of fractured rocks is mainly composed of two mechanisms: one is the shear resistance raised from interlocked microasperities in the scale of *roughness* in tensile fractured rocks, the other is the frictional resistance produced between macroasperities in the scale of *waviness* on the shear fractured rocks. The microcontact configuration and contact area are observed and measured by *slice cutting* of the mated rough surfaces in contact. Two distinct patterns of contacts in rock joints are recognized, term as *coastline* pattern and *islands* pattern. The shear strength of fractured rocks is closely related to the maximum contact area and the surface roughness.

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1. Introduction

Joints, fractures in rock mass display a significant effect on the mechanical behavior, hydraulic conductivity and chemical transporting properties of rock mass. [1,2] The shear strength of jointed rocks is a key topic in rock engineering that has been investigated over many years. Byerlee [3] considered that the tips of asperities that are subjected to a normal force and lateral (shear) force are crushed to a certain extent under the action of applied forces when the induced tensile stress locally exceeds the tensile strength. Einstein et al. [4] investigated the influence of asperity and the phenomenon of interlocking in rock friction. Patton [5] systematically studied the influence of the inclination and the numbers of asperities on the phenomenon of friction and the failure modes of asperities.

Studies show that the mechanical properties and behavior of jointed rocks are closely related to the morphological characteristics under moderate normal stress level. [6-9] In Barton's empirical model, [7] the joint roughness coefficient (JRC) describes the influence of surface roughness on the shear strength of rock joints, and a set of 'standard profile of rock joints' with the JRC values from 0 to 20 is proposed as a reference to evaluate the surface roughness.

Since then, Barton's model has been discussed from different viewpoints, such as the subjective evaluation of JRC, the scale effect, and anisotropic discrepancy in shear of the profiles, [10–14] modification on the model has been made by consideration of the matching of the rough surfaces in contact. [15] In addition, the studies on the topography of fractured rock surface showed much complicated behavior, due to their scale effect and anisotropic features. [16,17] A variety of researches have been carried out to quantitatively describe the surface roughness of fractured surfaces, for instance, the statistics and fractal approaches, in attempt to relate the conventional geometric parameters or fractal dimensions of surface roughness with the mechanical behavior of rock joints. [18–22]

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Natural rock fractures in contact exhibit a variety of structural phenomena, contact configuration, and time dependence. Microscopic observation showed that frictional state dependence represents an increase of contact area with contact age. Transient changes of sliding resistance correlate with changes in contact area and arise from shifts of contact population age. [23] Wang and Xie [24,25] studied the degradation and evolution of surface roughness as described by fractal dimension due to the fracturing and wearing of asperities on rock surfaces in a shear process.

By making use of the photo-elastic method, the influence of surface roughness on the contact mechanical behavior of the joints has been studied, [26] which showed that the rough joints with high fractal dimensions will give rise to lower normal stiffness and higher shear stiffness. For a smooth joint with a relatively low fractal dimension, an increase in normal force will result in spreading the contact laterally to form a larger contact area, while the contact point numbers approach almost constant values under a high normal load. On the contrary, for a rougher joint the contact point numbers will significantly increase with the increase in normal and shear loads, and as a result, more contact points and a greater degree of interlocking of asperities are obtained. The shear stress developed around asperities increases with the increase of applied normal and shear loads. The position of high stress concentration is relatively fixed for a smooth joint but it mobilizes for a rough joint. It is interesting that the maximum shear stress will decrease in the subsurface of a rougher joint, implying that the increase in shear resistance for a rougher joint can be expected.

In view of the complexity of rock joints, the study of microstructure of the fractured rock surfaces in contact is significant for analysis of the mechanical behavior of rock mass. Although many methods have been proposed to describe the surface roughness of rock joints, they count mostly for one side of the rough surface. In fact, interlocking of asperities relates both sides of the rock joints. The effect of surface roughness on the mechanical behavior of fractured rocks should take into account the microcontacting state and interlocking characteristics of the rough surfaces in contact. In addition, anisotropic properties and scale effect arise from different fracture formations in rocks, a series of mechanical relationship regarding to the rough surfaces of rock joints had better regard the contact mechanics in the three dimensional space.

Because of the time-dependent property of fractured rocks in nature, the contacts of rough surfaces display irregular, local scattering and stochastic features under a normal and tangential force, and the contact state varies with the increase in loading and time. Advancing mechanical model of rock joint, based on the observation of micro-contact mechanism in shear creep loading and combined with the quantitative description of the rough surfaces in contact, will be great helpful in analysis and prediction on the behavior of rock joints.

2. The research objectives and scheme

In order to elaborate the comprehensive contact mechanism in relation to the shear strength of rock joints from microscopic point of view, the behavior and characteristics of rough surfaces in contact are investigated by direct shear creep test. For the purpose of study, two kinds of rock fractures were produced in shear and tensile formation respectively by modified shear and indirect tension. Direct shear tests were carried out for the fractured rocks under a constant normal force and stepwise increased shear creep forces. To manifest the creep behavior within a short period of time, the shear force was kept constant for 10–14 h at each level. In order to look inside the micro-contact configuration and to analyze the damage state of the rock surfaces, the industrial computerized tomography (CT) and laser scanning (LS) techniques were employed. The CT images manifest clearly the inner contact configuration and damage state of the fractured rock surfaces in contact in different loading stages. The morphological features of the rough surfaces and their variation subjected to shear creep loading were analyzed on the basis of the laser scanning data and fractal geometry.

Through the experimental investigation, some important mechanical relationship of the shear strength of rock joints and the contact configuration with respect to fracture formation is elaborated as follows: (a) The fractured rocks formed by shear and tension present distinct morphology and mechanical behavior; (b) The failure mode of fractured rocks under shear creep loading depends on the fracture formation; (c) Shear fracture and tensile fracture display a distinct contact configuration under shear creep loadings; (d) The shear strength of fractured rocks is closely related to the contact areas of the rough surfaces in contact.

3. Description of experiment

3.1. Preparation of the fractured rocks

The rock being tested is sandstone collected from Majialiang Colliery in Shanxi province, China. The basic mechanical properties of the rocks are as follows: uniaxial compressive strength $\sigma_C = 100.69$ MPa, tensile strength $\sigma_T = 3.61$ MPa; elastic modulus $E = 1717$ MPa, Poisson's ratio $= 0.107$, angle of internal friction $\varphi = 46.64°$, cohesion $c = 20.78$ MPa, and density $\rho = 25.13$ kN/m^3.

The fractures were induced in intact rock samples by modified shear and Brazilian split tests respectively as follows. First, the rock block was cut into cubic samples with the size of $50 \times 50 \times 50$ mm^3. The surfaces facing the loading plate were polished to make sure that the normal and shear forces could be evenly distributed over the sample surfaces. Shear fractures were then induced by a modified shear device. The device consists of two spherical seats and sample holders. The cubic sample was placed inside the holders, and afterwards the holders were installed between the seats. The spherical seats can be rotated to obtain different shear angle (the angle between shear plane and loading direction). The modified device with the cubic sample at a shear angle of 20° was placed between loading plates of a loading machine. Under the compressive loading, a relatively clean and waved shear fracture surface was produced.

Tensile fractures were produced following the Brazilian split mechanism. Two steel wires with a diameter of 2.5 mm were placed parallel respectively in the middle of two opposite sides of the cubic rock sample, and they were fixed on the rock surfaces using 502 glue. The compressive load was applied to the steel wires. Since the steel wires played a role of line indenters, with the increase in the applied load, a tensile stress perpendicular to the loading was developed in rock sample, and finally an indirect tensile fracture between the two steel wires was produced along the steel wires in the rock sample.

As shown in Fig. 1, the fractured surfaces in shear formation appear undulant with a few smooth macroasperities (Fig. 1a), whereas the fractured surfaces in tensile formation present relatively plain with numerous microasperities (Fig. 1b).

3.2. Procedure of the experiment

A number of engineering and literature works have shown that under a moderate loading condition creep deformation might continually develop in fractured rocks over a plenty period of time before instability brings about. To elaborate the creep behavior of fractured rocks in a relative short period, the *fast shear creep tests* were performed under a constant normal force, in which the

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