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Shear mechanism of rock joints under pre-peak cyclic loading condition

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ABSTRACT

Thirteen mortar replica specimens were made from natural unweathered granite joint. Shear tests were conducted through two consecutive steps; load-controlled and displacement-controlled. Load controlled shear tests were conducted under 5, 10, 20, 100, 500, and 1000 cycles of pre-peak loading with amplitudes of 30% and 50% of the maximum monotonic shear strength. Then tests were continued up to 10 mm shear displacement in the displacement-controlled manner. By defining a concept named 'tiny window', the geometric models of the joint surfaces were reconstructed and the distribution and size of just in-contact areas, in-contact damaged zones and not in-contact areas were identified. Two threshold angles were defined in the pre-peak stage of shearing: "in-contact threshold angle" as the boundary between not in-contact areas and just in-contact areas and "damaged threshold angle" as the boundary between just in-contact areas and in-contact damaged zones. The distribution and the geometric properties of contact areas in different stages of shearing were identified and degradation of the first and second order asperities was evaluated. The results of the pre-peak cyclic loading tests are compared with the results of a monotonic test to clarify the effect of the cyclic loading on the joint shear mechanism and the shear strength parameters. It was found that the steepest asperities that are facing the shear direction came into contact in shearing before peak in the monotonic test. Contraction occurred during low number of cycles and consequently the contact area and the shear strength parameters slightly increased. During larger number of cycles, degradation occurred on the second order asperities, therefore the shear strength parameters slowly decreased. It was also found that increasing or decreasing the number of cycles during pre-peak cyclic loading does not have a significant effect on the residual shear strength parameters of the tested specimens.

1. Introduction

One of the most important factors that can control the stability of geotechnical structures is discontinuities. The key to manage the destructive effect of discontinuities is the knowledge of the discontinuities' shear mechanism, which is strongly affected by the joint roughness and the loading conditions.[1–5] According to the field conditions, many of the shear loads to be considered in the study of discontinuities fall into two main categories: monotonic and cyclic. Cyclic loading can cause shear failure of the joints (e.g. strong earthquakes) or cause some degradation in pre-peak behavior of joints (e.g. weak earthquakes). From now on the latter is called pre-peak cyclic loading.

The shear mechanism of rock joints under monotonic loading conditions has been studied and several constitutive models have been proposed.[1,6–12] Most of the constitutive models developed for monotonic loading conditions are not suitable for taking into account the effect of the cyclic loading conditions on predicting the shear behavior of rock joints.[13,14]

Most of the initial research on the cyclic loading tests was focused on determining the stress-displacement relationship and the peak shear stress of the cyclic loading tests. Jing et al.,[15] Souley et al.,[16] Fox et al.,[17] Jafari et al.,[18] and Nemcik et al.[14] have proposed some models to predict the shear behavior of rock joints and Crawford and Curran,[19] Curran and Carvalho,[20] Hutson and Dowding,[21] Barbero et al.,[22] Homand-Etienne et al.,[23] Jafari et al.,[18] have studied the shear strength of rock joints subjected to cyclic loading conditions. These researchers reported that the shear strength is a function of joint roughness, number of cycles and, normal stress. Also, under low normal stress, the dynamic shear strength is greater than the corresponding static value and this effect decreases with increasing normal stresses.

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After the initial efforts to explain the effects of cyclic loading on predicting the peak shear stress and the shear behavior of rock joints, most of the research focused on studying the influence of the asperity degradation on the mechanical behavior of rock joints under cyclic loading conditions. Lee et al.[24] indicated that the mechanism governing the asperity degradation under constant normal stress (CNS) and cyclic shear loading would be different according to the shear direction (forward or backward shearing), the type of asperities and the strength of rock materials. Belem et al.[13,25] proposed experimental asperity degradation models that are function of the accumulated shear displacement by scanning and quantifying the surface damage after different shearing cycles under both constant normal stress (CNS) and constant normal stiffness (CNK) loading conditions. Chern et al.[26] studied the degradation mechanism of joint asperities and the variation in shear strength of joint replicas under cyclic loading conditions and constant normal load (CNL). Asperity degradation was found to be a function of joint roughness, normal stress, shearing displacement and the number of loading cycles. Mirzaghorbanali et al.[27] studied the variations of the shear strength of rock joints under cyclic loading and constant normal stiffness (CNK). They proposed a mathematical model to evaluate the shear strength of infilled rock joints. It was found that, for a particular normal stiffness, the shear strength is a function of the initial normal stress, initial asperity angle, joint surface friction angle, infill thickness, infill friction angle, loading direction and number of loading cycles.

Most of the research carried out so far has addressed the effect of the cyclic loading conditions on the prediction of shear strength parameters and the shear mechanism of rock joints; however, the comprehensive shear mechanism of rock joints under the pre-peak cyclic loading conditions has rarely been reported. According to the US Geological Survey National Earthquake Information Center, the number of small earthquakes is much higher than the number of large earthquakes (99% with a magnitude less than 4.9 and 90% with a magnitude less than 3.9). During each small earthquake, some small changes occur along the discontinuities and the accumulation of these changes can induce high stress concentrations at the discontinuities' asperities.[28,29] The small-displacement cyclic loading conditions mostly occur in the pre-peak stage of shearing. Shear and normal displacements, as well as the degradations in this stage of shearing are very small, and consequently measuring of changes are difficult.

Some researchers, such as Jafari et al.,[28] Ferrero et al.,[29] and Tsubota et al.,[30] have studied shear strength parameters of rock joints which were affected by pre-peak cyclic loading conditions. Jafari et al.[28] investigated the effect of the number, the frequency, and the stress amplitudes of the pre-peak (load controlled) cycles on the peak and the residual shear strength of rock joints. They tested some core replica joints using triaxial compression devices under constant confining pressure conditions. They reported that the shear strength increased with normal stress and decreased when either the number, frequency, or stress amplitudes of the cycles was increased. Ferrero et al.[29] evaluated rock joint damage after pre-peak (displacement controlled) cyclic loading tests under constant normal stress (CNS) loading conditions. They showed that progressive surface damage and, consequently, regressive shear strength are related to the cyclic frequency, the normal stress, the roughness, the surface compressive strength and the number of cycles. Tsubota et al.[30] showed that shear strength decreases when the number of cycles increases, and that the frequency of loading (0.1 and 1 Hz) has no significant impact on the shear strength. They also stated that the dynamic shear strength is equal or higher than the monotonic shear strength, which is the opposite of the results reported in Refs. 28,29.

2. Research significance

Although the aforementioned studies have provided some insight into shear strength parameters of rock joints under pre-peak cyclic loading conditions, the shear mechanism and the discrepancy between increasing and decreasing of the shear strength by cyclic loading are not fully understood. The quantitative evaluation of several driving parameters through experimental testing and theoretical development is imperative in an attempt to understand this complex mechanism. In order to overcome this complexity, the influence of the pre-peak cyclic loading conditions with different numbers of cycles on the shear mechanism of the joint replicas is assessed. For this purpose 5, 10, 20, 100, 500, and 1000 cycles of the pre-peak loading with amplitude of 30% (0.25 MPa) and 50% (0.42 MPa) of the maximum monotonic shear strength (0.84 MPa) were applied to assess the effect of different cycles on the shear mechanism of rock joints. Also, a new mathematical method, developed by Fathi et al.,[31] is used to characterize the replicas surfaces and track the changes of the role of in-contact asperities during pre-peak loading shear tests in order to provide a better explanation of their shear mechanism.

3. Experimental procedure

3.1. Specimen preparation

Rectangular-shaped joint replicas were prepared by pouring non-shrinking cement mortar on a fresh joint surface of an artificial split granite block in order to reproduce its roughness. One advantage of using joint replicas is that replicas allow studying the effect of one specific factor on the shear mechanism of the joints while the other factors do not change.

A rectangular wooden mold, with an internal dimension of $140 \times 140\ \text{mm}^2$ was fixed on the granite joint surface. After spraying a form release agent (to allow easy detachment of the replica), grout was poured into the mold and the first halves of the joint specimen was made. An appropriate mortar recipe (Water and SikaGrout 212 at a ratio of 0.18) was selected to fabricate the mortar specimens. The grain sizes of the mortar were small enough to reproduce the details of the granite surface roughness. The first fabricated replica was used as a reference for generating other replicas. A taller mold was made and the first half of the specimen was fixed within it and the second half of the specimen was cast by pouring mortar onto the surface of the first half. Based on this, it was assumed that upper and lower replica surfaces are completely matched at the initial stage of shearing and therefore the initial contact area was considered to be 100%. A total of thirteen specimens were made using this method. The roughness parameters were calculated for the granite joint and the upper halves of the specimens. The calculated parameters showed that the roughness of specimens were acceptably close to the roughness of the granite (Table 1). The uniaxial compressive strength and tensile of cylindrical specimens of the mortar were measured at 65 days (83 MPa and 4.4 MPa, respectively).

The shear tests were conducted using a Material Testing System (MTS) press at the Laboratory of Rock Mechanics, Université de Sherbrooke. The MTS press was servo-controlled and had a capacity of 2670 kN. The normal and shear loads were measured directly by the respective load cells. Normal and shear displacements were measured using four LVDTs and one extensometer repeatability.

A profilometer laser scanner (Kreon Zephyr© 25) was used to acquire 3D coordinate of the joint surfaces. The maximum resolution of the laser profilometer was 72 µm for the x and y axes, and 16 µm for the z axis. Scans were performed before and after