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An experimental investigation on the shear mechanism of fatigue damage in rock joints under pre-peak cyclic loading condition

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ABSTRACT

In this study, the shear mechanism of fatigue damage in rock joints with first-order and second-order triangular asperities under pre-peak cyclic loading conditions is investigated in laboratory. A monotonic shear test is firstly conducted to determine the shear strength in rock samples containing joints with different orders of asperities. Secondly, influence of the pre-peak cyclic loading conditions with various numbers of cycles on the shear mechanism of fatigue damage in rock joints is studied at constant normal stress. In the cyclic loading conditions, two consecutive steps, such as load-controlled and displacement-controlled, are applied in tests. The load-controlled step is used to achieve the cycles of pre-peak loading in shear tests, and the displacement-controlled step is then applied to realize the final failure of rock samples with constant rate of 0.5 mm/min. Moreover, the effects of shear loading rates, numbers of cycle and cyclic shear loading magnitude on fatigue damage, peak shear strength and residual shear strength of rock joints are researched. We found that fatigue damage occurs at the second-order asperities in the upper and lower blocks within low number of cycles, but the fatigue cracks initiated with initiation angle of 90° with respect to the first-order asperities in the upper and lower blocks coalesce with each other (or rock joints) within the high number of cycles. Meanwhile, the variations of peak shear strength and residual shear strength of rock joints within low number of cycles are also different from ones within the high number of cycles.

1. Introduction

Rock masses consist of different kinds of discontinuities, such as flaws, faults and joints, which play an important role in the stability of geotechnical structures [1–6]. Hencher [7] recommend classifying discontinuities as open, weak, moderate or strong, relative to the strength of the parent rock as an aid to categorizing rock mass quality and to overcome the dilemma imposed by thenarrow constraint of the ISRM definition [8]. In many cases, the progressive failure of rock masses around the cut or natural rock slopes and underground excavations is controlled by the stress conditions and shear strength of discontinuities. Based on the loading conditions, shear loads can be considered in the study of discontinuities to divide into two main kinds: monotonic and cyclic [9]. The cyclic loading conditions can cause shear failure of rock joints in strong earthquakes, which are mainly governed by the first-order asperities, and cyclic loads also can cause some degradations and fatigue damage in pre-peak behavior of rock joints in weak earthquakes, which are mainly controlled by the second-order asperities due to small cyclic loading [10]. Therefore, it is necessary to improve understanding of discontinuities' shear mechanism, which is strongly affected by the joint roughness and loading conditions [9–16].

In the past decades, some researchers have studied the shear mechanism of rock joints under monotonic loading conditions [9,17–29]. Wang et al. studied the characteristics of anisotropy and directionality of joints rock masses under the direct shear tests [25]. Hencher et al. [27] provided guidelines for characterizing sheeting joints and determining their shear strength. Hencher and Richards [28] proposed an approach to assessing shear strength of rock joints at project scale based on measurement and analysis, including dilation measurement and correction. In the shearing tests, shear and normal loads are converted to average engineering stresses dividing by the gross contact area of rock joints [28]. A general equation to calculate the area of contact in rock cores were proposed by Hencher and Richards [29]. Zhang et al. [26] investigated the shear behaviors of rock joints under the constant normal stress conditions through three groups of artificial joints in the laboratory. They found that the peak shear strength increases with increasing of applied normal stress when the rock joints have the same characteristics of roughness [26]. Whereas, for the same normal stress, the peak strength of rock joints increases as the roughness of joint surfaces grows. Some constitutive models and shear failure criteria in

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monotonic shear loading tests are also proposed [17,24,30–31]. However, the above proposed constitutive models and failure criteria for monotonic loading conditions are not suitable for ones under the cyclic shear loading conditions [32–34]. The results indicates the shear mechanism of rock joints subjected to cyclic shear loads are different from that under the monotonic shear loading conditions.

In the initial researches on the cyclic shear loading tests, scholars mainly forced on determining the stress-displacement relationship and the peak shear stress of the cyclic loading tests [10,33,35–43]. Experimental asperity degradation models, which are functions of the accumulated shear displacement, under both constant normal stress (CNS) and constant normal stiffness (CNK) loading conditions were proposed by Belem et al. [32,44]. The shear degradation mechanism of rock joints asperities and shear strength of rock joints under cyclic loading conditions and the constant normal stress (CNS) was investigated by Chern et al. [45]. The relationship between shear strength of rock joints and constant normal stiffness (CNK) under cyclic loading conditions are studied by Mirzagohobanali et al. [16]. They found that the shear strength of rock joints is related to the initial normal stress, initial asperity angle, joint surface friction angle, infill thickness, infill friction angle, loading direction and number of loading cycles. The previous studies were mainly focused on the effect of the cyclic loading conditions on the prediction of shear strength parameters and shear mechanism, however, only few investigations of shear mechanism of rock joints under the pre-peak cyclic loading conditions were conducted. Based on the previous studies [9,46–50], magnitudes in 99% of earthquakes are less than 4.9 degree and ones in 90% of earthquakes are smaller than 3.9 degree, which indicates that the occurring frequency of small earthquakes is higher than that of large earthquake. In the small earthquakes, some small variations happen along the discontinuities, i.e., rock joints, which induce high stress concentrations at discontinuities' asperities at the pre-peak stage of shearing under small displacement cyclic loading conditions [9,47–48,50]. The pre-peak cyclic shear loading behaviors of rock joints play important roles in weak earthquakes [9]. Therefore, the shear mechanism of fatigue damage in the pre-peak cyclic loading tests should be deeply studied and revealed.

Some researchers have studied the shear strength parameters of rock joints under the pre-peak cyclic loading conditions. The effects of the number, frequency and stress amplitudes of the pre-peak cycles on the peak shear strength and the residual shear strength of rock joints are experimentally studied by Jafari et al. [47]. In the triaxial compressive tests with constant confining pressures, the results revealed that shear strength of rock joints increases with increasing the normal stress, but that decreases as the number, frequency or stress amplitudes of cycles increases. The rock joint fatigue damage in the pre-peak cyclic loading conditions with constant normal stress (CNS) was evaluated by Ferrero et al. [48]. They found that the surface damage and regressive shear strength of rock joints are related to the number of cycles, cyclic frequency, normal stress, surface roughness and the uniaxial compressive strength. Tsubota et al. [49] found that shear strength of rock joints decreases as the number of cycles increases, and that the frequency of loads only slightly affects on the shear strength of rock joints. Fathi et al. studied the shear mechanism of asperities of rock joints in the pre-peak cyclic loading tests [9,50]. Two kinds of joint shear mechanism, i.e., contraction and degradation, are revealed in the pre-peak cyclic loading conditions [9].

Although the above studies have provided some insights into shear strength parameters of rock joints under the pre-peak cyclic loading conditions, the shear mechanism of fatigue damage in rocks and the relationship between cyclic loading conditions and rock shear strength are not fully understood. The relationships between peak shear strength of rock joints and the number of cycles, orders of asperities in joints, cyclic shear loading rate and amplitudes are rarely studied in the pre-peak cyclic loading tests. The asperity of a rough joint can occur on many scales. As early as 1966, Patton [17] classified the asperity of rough joints into first-order (waviness) and second-order (unevenness) categories, and reported that the shear behavior of rock joints was primarily controlled by second-order and first-order asperity during small and large displacements, respectively. Lee et al. [51] indicated that the mechanism governing the asperity degradation under CNS and cyclic shear loading would be related to the shear direction, types of asperities and the strength of rocks. The influence of rock joint roughness on the shear behaviors of rock joints was studied by Liu et al. [52]. An imaging processing technique developed by Gentier et al. [53] showed that the cyclic shear mechanical behaviors of rock joints is strongly linked to the geometrical of asperities. Grasselli and Egger [30] stated that degradation is more likely to happen in steeper asperities, where an effective contact area should be considered in the shearing process. Fathi et al. [50] studied the changes of role of asperities at different stages of cyclic shearing loading tests, and proposed a new methodology for the characterization of asperities in rock joints. Therefore, the influence of geometry of asperities on monotonic and cyclic shear strength of rock joints plays an important role in the shear mechanism of rock masses.

This study aims to investigate the shear mechanism of fatigue damage in rock joints with first-order and second-order triangular asperities under pre-peak cyclic loading tests. In rock samples, the distribution and geometric properties of contact areas in different stages are considered, and the shear mechanism of fatigue damage in the first- and second-order asperities is investigated in tests. First, a monotonic shear test is conducted to determine the shear strength in rock samples containing joints with different orders of asperities. Second, influence of the pre-peak cyclic loading conditions with various numbers of cycles on the shear mechanism of fatigue damage in rock joints is studied at constant normal stress. In the cyclic loading conditions, two consecutive steps, such as load-controlled and displacement-controlled, are applied in tests. The load-controlled step is used to achieve the cycles of pre-peak loading in shear tests, and the displacement-controlled step is then applied to realize the final failure of rock samples with constant rate of 0.5 mm/min.

For this purpose 20, 50, 100, 200 and 500 cycles of the pre-peak loading with different amplitudes of the maximum monotonic shear strength are applied to evaluate the effect of different cycles on the shear mechanisms of rock joints. Jafari et al. [47] concluded that if the applied cyclic stress amplitudes is lower than 50% of the peak strength in monotonic shear tests, the shear strength of rock masses would be nearly constant after experiencing a high number of cycles. Therefore, in order to obtain the obvious variations of shear strength in the pre-peak cyclic shear tests, the applied cyclic stress amplitudes are taken as 50% and 80% of the monotonic peak shear strength in this study. The results of the pre-peak cyclic loading tests are compared with the results of a monotonic loading test to illustrate the effect of the cyclic loading conditions on the shear mechanism of rock joints with different asperities and shear strength parameters. In addition, the effect of loading rate and loading amplitude on shear mechanism of rock joints are discussed in this study.

This paper is arranged as follows. The experimental study is described in Section 2. Mechanism of fatigue damage in rock joints is stated in Section 3. The effects of cyclic number, cyclic loading rate and cyclic loading amplitude on shear mechanism of rock joints are discussed in Section 4, and the conclusions are drawn in Section 5.

2. Experimental study

2.1. Rock sample preparations

The sandstone samples from the Three Gorges Reservoir Region, Chongqing City, China, are used in the experiments. The sandstone has crystalline and blocky features and an average unit weight of about 2780 kg/m^3. The prepared rectangular sandstone samples have dimensions of 120 mm in height, 160 mm in length and 120 mm in thickness, as