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Behaviour of rock joint reinforced by energy-absorbing rock bolt under cyclic shear loading condition

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ABSTRACT

Rock joints will undergo a sequence of cyclic shearing loadings during a seismic event. However, the effect of cyclic shear loading on the energy-absorbing rock bolts has never been studied before. Laboratory shear experiments were carried out to study the shear behaviour of rock joints reinforced by the energy-absorbing rock bolts under cyclic loading condition. The results illustrated that the support effect of the energy-absorbing rock bolts was very small after the first cycles in the cyclic shear experiments. In the case of small cyclic distances, the shear resistance of the energy-absorbing rock bolts will gradually recover after the shear displacement has exceeded the cyclic distance in the subsequent shear experiment after 5 cycles. In the case of large cyclic distances, no recovery of shear resistance was found in the subsequent shear experiment, indicating that the energy-absorbing rock bolts had completely lost its supporting role after cyclic shear loading. A new index of shear energy loss ratio (SELR) was proposed to evaluate the shear behaviour of energy-absorbing rock bolt and rock joint under cyclic shear loading condition. The results showed that the SELR of rock joints was commonly less than 20%. However, the SELR of rock bolts could reach nearly 100% when the cyclic distance was larger than 8 mm. When the cyclic distance was 4 mm or 6 mm, the SELR of the fully encapsulated rock bolts almost reached 100%. However, the SELR of the energy-absorbing rock bolts were located in the range of 50–80% for the same condition. The results indicated that the shear behaviour of a rock bolt inserted in a rock joint was strongly influenced by cyclic shear loading. The shear performance of the energy-absorbing rock bolts was better than the fully encapsulated rock bolts under cyclic shear loading conditions.

1. Introduction

Rock bolts are one of the most commonly used support equipment for fractured rock mass.[1] However, the conventional fully encapsulated rock bolts are easily damaged when subjected to shearing movement of rock mass.[2–4] Li proposed a concept of "energy-absorbing rock bolt", which is a promising way to improve the shear displacement of rock bolt inserted in the rock joints.[5]

The energy-absorbing rock bolts should not only have high strength to reinforce the rock mass, but also be deformable to adjust to the movement of rock mass. There are many types of energy-absorbing rock bolts. According to the yielding mechanism, they can be summarized as structural components sliding type and steel deformation type as shown in Fig. 1. The structural components sliding type mainly include Cone bolt,[6] Roofex, He-bolt[7] and Cold drawing bolt.[8] They were designed according to steel-rock or steel-steel interaction. However, the "energy-absorber" unit makes the bolt inherently cost expensive due to its complex structure. The steel deformation type includes a smooth segment which is free of grout, and D bolt is a typical representative of them. It is a smooth steel bar with a number of anchors along its length. The anchors are fixed in the borehole with either cement grout or resin, while the smooth sections of the bolt between the anchors can deform freely in response to rock movement.[9] Because of the simple structure and low cost, a lot of research has been done on the steel deformation type energy-absorbing rock bolts.

Many experiments have been conducted to study the behaviour of rock bolts in resisting the shear loading. However, most of the experiments was conducted on the fully encapsulated rock bolt.[10–17] Chen and Li conducted some experiments and confirmed that the behaviour of energy-absorbing rock bolt was much better than the conventional fully encapsulated rock bolt in resisting shear loading.[18,19] However, all these experiments were conducted under a direct shear loading

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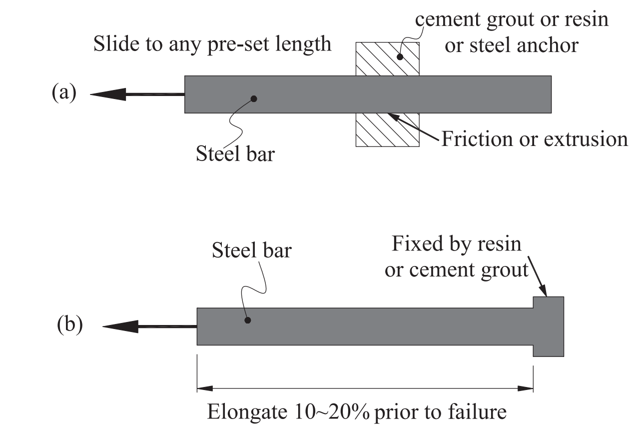

Fig. 1. Yielding mechanism of the energy-absorbing rock bolts. (a) structural components sliding type, (b) steel deformation type.

condition. Direct shear loading condition means that the shear load was applied in a single direction until the failure of rock bolt.

When a joint is subjected to loading and/or unloading during a seismic event, it will undergo a sequence of cyclic shearing loadings.[20] In engineering practice, the cyclic shear loading during earthquake activity could cause a great threat to the stability of the surrounding rock mass.[21,22] It is an important issue in terms of assessing the stability of reinforced slopes during and after earthquakes. It is inappropriate to ignore the effect of cyclic shear loading on the behaviour of rock bolts in support design where earthquakes may occur.

According to the experiment results by the authors for the fully encapsulated rock bolts, cyclic shear loading can cause a significant impact on their mechanical properties.[23] However, the effect of cyclic shear loading on the energy-absorbing rock bolts is still unknown. The effect of cyclic shear loading on the energy-absorbing rock bolts was investigated in this paper.

2. Experiment arrangement

Laboratory shear experiments were conducted to study the shear behaviour of rock joints reinforced by the energy-absorbing rock bolts (steel deformation type) under cyclic loading condition.

2.1. Experiment method

There are two methods of shear testing for rock bolt, single and double shear tests. The double shear testing used a three piece concrete block to simulate shear behaviour of rock bolts in rock.[12,13,16] However, there are two joint planes in this experimental model. If the rock bolts are not long enough, mutual influence will be inevitable. The single shear test method[10] was adopted in this study. Two simulated rock blocks with molded joint faces were used to simulate the rock joints. The biggest difference between conventional fully encapsulated rock bolt and the steel deformation type energy-absorbing rock bolts is the existence of smooth section on the bolt body. The smooth sections of the energy-absorbing rock bolts can deform freely in response to rock movement. Therefore, the energy-absorbing rock bolts were simulated by smooth rods. The smooth rods were inserted at the center of the rock joints to study their shear behaviour. The arrangement of the cyclic shear test is shown in Fig. 2. The tests were performed on a cyclic shear testing machine under constant normal load condition. During the test, the upper block was fixed, and a shear force was applied to the lower block. The shear displacement, shear stress, normal stress and normal displacement were recorded during testing. A 20 mm diameter hole was drilled at the center of the shear box to protect the bolt end when the normal stress was applied. A constant normal stress of 1 MPa was applied on the top of the upper shear box during the shear process, and the cyclic shear load was applied laterally on the lower shear box. In order to simulate a quasi-static condition, the shear rate was set to 3 mm/min.

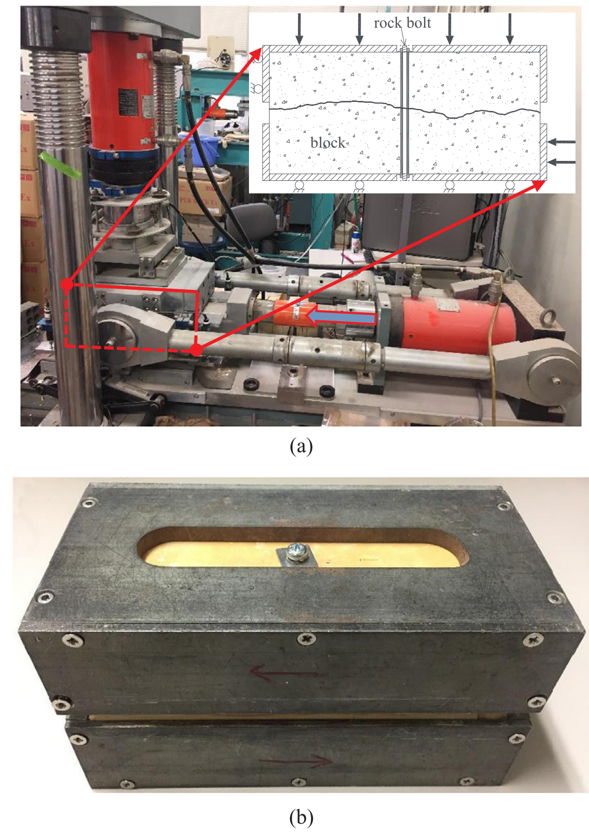

Fig. 2. Arrangement of the cyclic shear test: (1) test machine; (2) shear box.

2.2. Bolt and rock specimens

To conduct cyclic shear experiments with different cyclic distances, it was necessary to prepare identical samples using a moulding method. In order to be more consistent with engineering practice, two replicas of natural rough joints were made from granite joint planes. The roughness of two joints were measured by a laser profilometer and the results are shown in Fig. 3. The JRC values of the natural rough joints were evaluated via the comparison of measured profiles against the standard JRC profiles.[24] The mean JRC values were identified as 3.5 and 12.3, respectively.

Small samples had to be used due to the difficulty in manufacturing large-size natural rough joints and the space limitation of the cyclic shear testing machine. This was acceptable since the main aim of this research was to study the influence of cyclic shear loading on the behaviour of the energy-absorbing rock bolts. In any case, they provided a simplified basis for investigating the effects of cyclic loading on the shear behaviour of bolted rock joints. All the specimens used in the shear experiments were 100 mm in width, 200 mm in length and 100 mm in height. They were made of mixtures of plaster and water with a weight ratio of 1:0.2. The average uniaxial compressive strength of the prepared samples was approximately 50 MPa. The joint specimens used in the experiments is shown in Fig. 4.

The energy-absorbing rock bolt specimens used in this test were smooth bars made of iron. According to the shear experiments carried out with bolt diameters of 8, 10, and 40 mm by Spang and Egger,[10] the dimensionless values of the shear force and shear displacement were not dependent on the bolt diameters. The dimensionless values of the shear force were obtained through dividing maximum shear force by