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Reinforcement of rock mass with cross-flaws using rock bolt

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ABSTRACT

Rock bolting is one of the most effective and economical means of rock mass reinforcement. Existing studies of rock bolt reinforcement are mostly focused on rock masses without flaw, with a single flaw, or with parallel flaws. However in rock masses, cracks or flaws usually exist in the form of cross-flaws. In order to understand the impact of cross-flaws on rock bolt reinforcement and to further explore the differences of bolt reinforcement between rock mass with cross-flaws and rock mass with a single flaw, reinforced analog specimens with cross-flaws and with a single flaw were tested under uniaxial compressive condition. The experimental results show that the uniaxial compressive strength of the reinforced rock mass with cross-flaws in this research is higher than that of reinforced rock mass with a single flaw. This observation can be explained by the difference in the failure modes of reinforced specimens: the reinforced rock masses with a single flaw fail due to the formation of a shear crack while reinforced rock masses with cross-flaws fail as a result of a tensile fracture or interaction between tensile fracture and shear fracture.

1. Introduction

Rock bolting is one of the most effective and economical means of supporting in rock engineering applications such as rock tunneling. Understanding of the bolt reinforcement effect is essential for an optimal usage of rock bolts and thus for safety of rock engineering infrastructures (Grasselli, 2005).

Since the first application of rock bolt in 1913, researchers conducted a series of studies for a better understanding of the mechanics of rock bolting (Farmer, 1975; Littlejohn and Bruce, 1975; Aldorf and Exner, 1986; Endersbee, 1999; Kovári, 2003). Zou (2004) studied the in-situ rock bolt loading for a single crack in rock mass, and showed that the bolt tension may reach peak at any location. Aksoy and Onargan (2010) demonstrated that the ground settlements could be substantially decreased by limiting the tunnel face movement into the tunnel. Aksoy and Onragan's face bolting system created an umbrella arch around the tunnel face, thus enhancing the stability of the tunnel face. However, Aksoy and Onargan (2010) did not consider any flaws that also impact on rock mass reinforcement. Kang et al. (2013) investigated the mechanisms and factors resulting in bolt fracture failure through a close examination of bolts obtained from underground roadways, but they did not consider rock cracks or flaws in their investigation. As a matter of fact, the rock flaw was ignored in most of the in-situ rock bolt studies.

To carefully investigate the effect of flaws on rock bolting, researchers carried out bolt reinforcement tests with rock mass or rock analog material in laboratory. There was not a special term for the pre-existing crack in the beginning, and then gradually the term "flaw" has been used to describe an artificially created crack (Wong and Einstein, 2009). These pre-existing flaws can be either open or closed. Ge and Liu (1988) established a theory for rock bolt. They determined the optimal bolting angle based on shear tests of the rock mass with a single flaw. They found that the reinforced rock mass attains the highest shear strength when the bolt bar and the flaw was at an angle of $a_{opt} = 30° + \varphi$, where φ is the frictional angle of flaw surface. Guo and Ye (1992) found that when the angle between the bolt bar and the flaw was at 30–50°, the reinforced rock mass achieved the highest shear and compressive strength. Ferrero (1995) carried out experiments on different types of rocks reinforced by various elements. His experimental and numerical simulation results on reinforced rock mass with a single flaw showed two failure modes: the first type of failure was caused

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by a combination of shear and tensile stresses at the joint intersection for hard rock, while the second was due to a combination of tensile stresses and bending moments for weaker rock. Jeng and Huang (1999) studied the holding mechanism of under-reamed rock bolts, their results showed that the under-reamed end was blocked by the surrounding rock mass, resulting in a larger holding capacity than conventional rock bolts. They used the pull-out experiments to examine the holding mechanisms of under-reamed rock bolts. However, the influence of flaw in rock mass was not taken into consideration. Kılıc et al. (2002) studied the influence of grouting material on bolt reinforcement through pull-out test of rock bolt without considering the flaw. Their study showed that increasing the bolt diameter and length increased load bearing capacity of the bolt, and this increase was limited by the ultimate tensile strength of the bolt materials. Through large-scale shear tests on reinforced rock mass with two parallel flaws, Grasselli (2005) studied the different mechanical responses of the full steel bar and the frictional Swellex bar. Martín et al. (2013) presented a method to obtain the bolt-grout interface behavior of fully grouted rock bolts from laboratory experiments without considering the rock flaws.

Researchers also studied the bolt reinforcement of rock mass through theoretical analysis (Li and Stillborg, 1999; Cai et al., 2004; Guan et al., 2007; Osgoui and Ünal, 2009). Li et al. (2012) proposed a method to back calculate the grout cohesive strength and the grout friction angle based on the measured field pull-out force of rock bolt without considering the rock flaws. Maghous et al. (2012) described a three-dimensional theoretical and numerical model for the behavior of tunnels with reinforced bolts, and the elastoplastic constitutive equations for the reinforced rock were derived in the framework of homogenization method.

In rock mass, the pattern of cross-flaws is one of the most common flaw patterns. However the existing studies on the rock bolt reinforcement as discussed above focused on rock mass with no flaw/crack, a single flaw/crack or parallel flaws/cracks. It is thus the objective of this work to understand the rock bolt reinforcement of rock mass with cross-flaws. Using rock analog materials, specimens simulating rock mass with cross-flaws are fabricated. Bolted specimens are subjected to uniaxial compression with purpose to qualitatively demonstrate the bolt reinforcement effect. The angle between the main flaw and the loading direction, and the angle between the main flaw and the secondary flaw are considered. The strength of the bolted samples are measured and the failure modes are observed and discussed in the context of mechanism of reinforcement.

2. Specimen preparation and testing equipment

The rock analog specimens are made of cement mortar, with cement: sand: water = 1:3.58:0.73. The cement used in is #425 Portland cement, the diameter of sand is smaller than 0.9 mm, and the water used is tap water. The bolt bar is simulated with galvanized iron wires. Cross-flaws are made by cross plastic slices inserted in the mortar during casting. These flaws are thus between open and close flaws but can be considered as close flaws.

The dimension of the testing specimens is 70 mm in width, 70 mm in thickness and 140 mm in height. The main flaw of the cross-flaws is 30 mm in length, and the secondary flaw of the cross-flaws is 20 mm long. The plastic slice for making the cross-flaws is 0.2 mm thick. The cross-flaws are made through the thickness of the specimen, perpendicular to the 70 × 140 mm face. The bolt bar is 6.4 mm in diameter. The parameters of bolt bar material are as follows: the elastic modulus is 190 GPa, the yield strength is 190 MPa, and the ultimate strength is 420 MPa.

The mold used to cast specimen is composed of steel plates. There is no a steel plate on the top of the mold for pouring the cement mixture. The procedure used for specimen preparation is as follows. First the sand is poured into a sieve with 0.9 mm mesh to remove particles bigger than 0.9 mm. Secondly the cement, sand and water are weighted and mixed in a blender for 5 min. Thirdly the plastic slices to simulate the flaws are glued into the steel mold with a direction parallel to the thickness, and the bolt bar is placed in the steel mold (Fig. 1). At the last step the cement, sand, and water mixture is poured into the steel mold. The mold with the fresh cement mixture is then vibrated at a room temperature for 3 min. The specimens are taken out of the mold 24 h afterwards, for curing in the water at a constant temperature of 20 °C for 7 days. The photo of cured specimen is shown in Fig. 2.

The Loading is applied on specimens by displacement control at a rate of 0.02 mm/s with testing equipment (Fig. 3).

3. Experiments

3.1. The testing conditions

The angle between the main flaw and the secondary flaw as well as the angle between the bolt bar and the loading direction are taken as testing parameters. The angle between the main flaw and the loading direction is fixed at 45°. The reason to choose 45° angle as the main flaw angle is that 45° is a representative angle of I–II type mixed mode fracture. The testing specimen configuration is schematically shown in Fig. 4, where α is the angle between the main flaw and the loading direction, β is the angel between the main flaw and the secondary flaw, and γ is the angle between the bolt bar and the loading direction. The testing conditions are shown in Table 1, where the test specimen without β stands for the rock mass with a single flaw.

The specimens are loaded in a uniaxial compression condition until failure. The loading direction is parallel to the longitudinal direction of the specimen.

3.2. Experimental results and discussions

3.2.1. Stress–strain relation of rock mass reinforced by bolt

The stress–strain curve of testing condition c-0 without bolt and slice which represents the rock mass in-situ was plotted in Fig. 5. Stress–strain curves of reinforced rock masses are shown in Fig. 6, where c-1 to c-16 stand for the No. of the testing conditions.

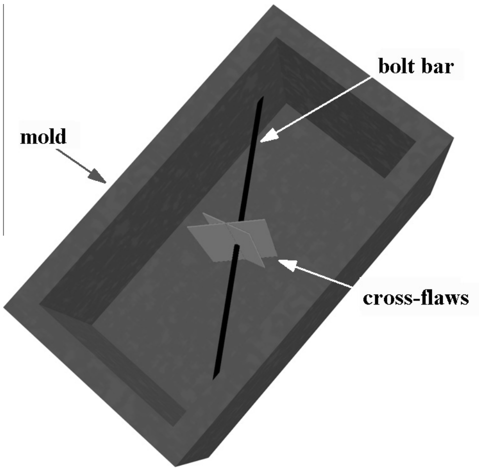

Fig. 1. The schematic diagram of steel mold with plastic slices and bolt bar.