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Mechanical performances and stress states of rock bolts under varying loading conditions

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ABSTRACT

A comprehensive study including laboratory tests and numerical modeling was performed to investigate factors of rock bolt fracture. Experimental tests were performed to evaluate the mechanical performances of bolt ends including the thread and adjacent. The effects of installation angle, pretension and accessories (plate, washer and nut) were evaluated. It is found that a bolt installed with an oblique angle to roadway surface suffers a complex stress combination of tensioning, bending and twisting on the bolt. This complex stress is much greater than the tensile stress, leading to cracking and growth at the location of bending causing the thread to fail even though the tensile stress is less than the yield strength. Bolt thread is more vulnerable to fracture than rebar.

1. Introduction

Rock bolting has been widely used in nearly 70% of Chinese coal mine roadways. The technique has been developed through stages of low-strength and high-strength to high-pretension and very high-strength (Kang et al., 2011).

With an increase in mining depth and growing complexity of geological and geotechnical conditions, conventional rock bolts with low strength (i.e. yield strength < 400 MPa, tensile strength < 600 MPa) and low pretension (20–30 kN) have been found insufficient in suppressing roadway deformation. A new type of high strength rock bolt has been developed in the Chinese coal mine industry. This type of rock bolt has a yield strength of 500–650 MPa and a tensile strength of 700–850 MPa. It has been found that this type of rock bolt, when installed with high pretension (30–50% of yield load), greatly inhibits roadway deformation and failure (Gao and Kang, 2008; Kang et al., 2009). However, a major issue with the use of these high-strength and high-pretension rock bolts is the resulting frequent observation of threaded rebar rupture in underground coal mine roadways, which causes a potential safety hazard (Kang et al., 2013). Threaded rebar rupture is related to stress distributions. Investigation of the stress states of rock bolts under varying loading conditions is critical to safety and structural stability.

Much research on the stress states of rock bolts has already been performed. Farmer (1975) carried out pull-out tests on rock bolts and argued that the axial stress of the bolt decreases exponentially from the point of loading to the far end of the bolt. Dunham (1976) examined the mechanism of anchorage failure through pull-out tests on specimen anchorages and presented a formula for calculating shear stress at the steel/resin interface. The influence of bolt profile, diameter, length and the mechanical properties of grouting materials on the pull-out load have also been scientifically examined (Karanam and Dasyapu, 2005; Kılıc et al., 2003, 2002). Freeman (1978) carried out field studies in the Kielder experimental tunnel to examine the performance of fully grouted rock bolts and stated the concepts of "neutral point", "pick-up length" and "anchor length". At the neutral point, the shear stress at the bolt-grout interface is zero, while the tensile axial load of the bolt is at peak value. Similar phenomenon was observed in Chinese underground coal mines (Sun, 1984). Further studies found that in jointed rock masses the opening of individual joints may result in not only one but several neutral points along the bolt (Björnfot and Stephansson, 1984).

Other researchers have studied the stress distribution along rock bolts under shear load and the reinforcement mechanics of rock bolts (Ferrero, 1995; Grasselli, 2005; Jalalifar et al., 2006; Pellet and Egger, 1996; Spang and Egger, 1990). Spang and Egger (1990) carried out 70 laboratory and field tests to study the behav-

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ior of fully-grouted, tensionless rock bolts in stratified and jointed rock masses. Formulae were developed by Spang and Egger to evaluate the bearing capacity of fully-grouted bolts. Pellet and Egger (1996) proposed an analytical model for the prediction of the contribution of bolts to the shear strength of a rock joint. Using this model, parameters such as bolt inclination, bolt mechanical properties, rock strength and joint friction angle were examined. Jalalifar et al. (2006) developed a double shearing apparatus to examine the shearing behavior of a bolt installed at a perpendicular angle across two joints and showed that bolt behavior subjected to shear load is influenced by bolt profile configuration, rock strength and bolt pretension. Grasselli (2005) carried out experimental tests and numerical simulations to study the mechanical behavior of fully grouted bolts and Swellex bolts under shear loading and showed that the two bolt types deform differently. Ferrero (1995) carried out experimental measurements and numerical modeling to study rock bolt failure and recognized two failure mechanism types. When a bolt is installed in a strong and stiff rock material, failure occurs at the joint intersection as a result of shear and tensile stresses. When a bolt is installed in a weaker rock, two symmetric plastic hinges may occur in the bar, causing a failure if either the tensile strength or the ultimate elongation of the reinforcement are reached.

In this study, a systematic study was carried out to investigate the stress states at the ends of threaded rebar that is vulnerable to failure. This was achieved through a combination of laboratory tests and numerical analyses. The influence of threaded rebar, plates, and domed washers was examined.

2. Laboratory experiments on mechanical performances of rock bolts under tensioning and bending

Laboratory tests were performed to analyze the mechanical performances of rock bolts under tensioning and bending.

2.1. Mechanical performances under tensioning

2.1.1. Tensioning tests on rebar

The performance of rebar under tensioning has been evaluated in a previous study by means of experimental tests on a 22-mm diameter bolt rebar of bolt hot-rolled ribbed bars with a yield strength of 500 MPa (BHRB500) and bolt hot-rolled ribbed bars with a yield strength of 600 MPa (BHRB600) (Kang et al., 2009). To evaluate the tensile strength of the thread a 700 mm long rebar was cut from the 22-mm diameter bolt of the BHRB500, and one end of the rebar was machined to M24 standard thread with a length of 130 mm; then the thread was cut off completely for the tensile test, and the remaining part of the rebar was cut to a tensile specimen 500 mm in length for a contrast test to the thread. A pair of specific sockets was made for the tensioning tests on the thread, as can be seen in Fig. 1a. The two ends of the thread (each 30 mm long) were screwed into the sockets, which were then settled on the loading apparatus to be tested. The results are given in Table 1, and a typical broken thread from the tensioning test is shown as Fig. 1b. From these results we can conclude that:

(1) The tensile load of the threads was over 90% of the rebar tensile load. A few samples exhibited an even higher load than the rebar. This was attributed to the hardening effect during thread machining.
(2) The average elongation rate of the threads was approximately 88.4% of that of the rebar. The elongation rate decreased during the thread rolling process due to the hardening effect.
(3) The average cross section shrinkage of the threads was approximately 32.3% less than that of the rebar. The brittleness of the threads was greatly prompted during the thread machining.

2.2. Mechanical performances under bending

The rebar can resist bending without any damage. But the thread cannot. To study the performance of thread subjected to bending, a total of nine thread specimens were cut from rock bolts, which were 220 mm long with standard M24 thread 150 mm long, sufficiently long for bending. Table 2 gives the test results and Fig. 2 details the fracture process of one of the specimens as it was being bent. The results are summarized as follows:

(1) Cracks were observed at the bending zone of all nine specimens at a bending angle of approximately 15–30°. This was likely due to surface damage incurred during thread machining.
(2) Specimens with high brittleness (Impact Energy Absorbing Efficient (IEAE) < 30 J), were likely to rupture suddenly at small angles (<60°) after a certain degree of cracking developed.
(3) For relatively ductile specimens (IEAE > 30 J), sudden rupture was usually not an occurrence at angles less than 60°. Several cracks appeared and their width increased (Fig. 2b and c) until a final rupture occurred at an angle greater than 60° (Fig. 2d).

3. Laboratory experiments on mechanical performances of rock bolts under complex stress states

Field observations and monitoring showed that most broken rock bolts were not just subjected to tension, but rather to complex stresses, including tensile, twisting and bending stresses, caused by inclined installation angles and rough excavation surfaces, see Fig. 3. This is a typical rock bolting condition experienced in Chinese coal mine practice. Designed fully-grouted rock bolts are generally not entirely grouted but with a certain length of free section, due to poor quantity control of resin capsules. This free rebar section together with threaded section is subjected to complex stresses and vulnerable to failure during bolt installation (Fig. 3b). To better understand the relevant mechanisms, the effects of the installation angle on the mechanical performance and stress states of rock bolts were evaluated with laboratory tests using an inclined surface loading system.

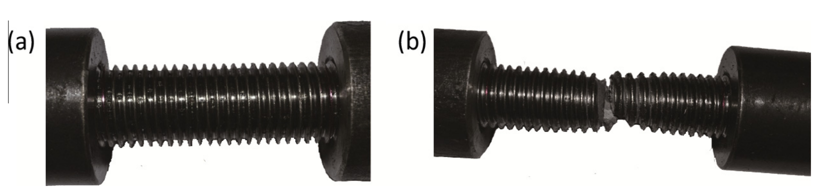

Fig. 1. Bolt thread before (a) and after (b) tensioning test. Bolt rebar is BHRB500 type, and thread is M24.