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Quasi-static laboratory testing of a new rock bolt for energy-absorbing applications

Gang Wang [a,b,*], Xuezhen Wu [a], Yujing Jiang [a], Na Huang [a], Shugang Wang [c]

[a] State Key Laboratory Breeding Base for Mining Disaster Prevention and Control, Shandong University of Science and Technology, Qingdao 266590, China
[b] Shandong Provincial Key Laboratory of Civil Engineering Disaster Prevention and Mitigation, Shandong University of Science and Technology, Qingdao 266590, China
[c] Department of Energy and Mineral Engineering, G3 Center and Energy Institute, The Pennsylvania State University, University Park, PA 16802, USA

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ABSTRACT

High stress in the surrounding rock mass can cause serious stability problems. The applied support system used under high in situ stress condition should be able to carry high loads and also to accommodate large deformation without experiencing serious damage. This paper presents a specifically designed rock bolt for energy-absorbing applications, which can provide support for squeezing and burst-prone rocks often encountered during underground excavation in the tunneling and mining community. The bolt mainly consists of a smooth steel bar with an anchor near the bottom end of its body. The anchor is firmly fixed within a borehole using either cement grout or resin, while the smooth section of the bolt inserted in the anchor can slide in response to rock deformation once the load exceeds the pre-set capability. Static pull tests on the new bolt show that it can elongate to any expected length at a high load level, thereby absorbing a large amount of energy to maintain the stability of surrounding rock.

1. Introduction

The increased demand for minerals over the past years has driven mine development to deeper levels and into regions that have previously been considered inaccessible and unstable. At the same time tunneling for transportation and energy recovery expands into more sensitive areas as the need for further infrastructure extension continues (Neugebauer, 2008). These extreme conditions greatly increase the difficulty of underground supporting, and puts towards a higher request on the underground support technology.

The major stability concern is rock falls under gravity at shallow depths. Loosened rock blocks are usually stabilized by installing rock bolts. In low stress conditions, the bolts are required to be strong enough to sustain the dead weight of the loosened block (Hoek, 2007). The strength of the bolt is therefore a crucial parameter in rock support design. As the most widely used rock bolt in geotechnical engineering, fully encapsulated rebar bolt is verified to be a satisfactory type of bolt for this purpose since it fully utilizes the strength of the bolt steel (steel reaches the ultimate tensile strength prior to failure(Li, 2012)).

Many mines around the world, for example those in China, Germany, Australia, and South Africa, are currently being operated at depths greater than 1000 m (Amusin, 1998; Li et al., 2012). The essential difference between rocks at greater depth and rocks at shallow depth is the significant increase in the in situ rock stresses. As a consequence of this increase in stresses, rock burst may occur in hard rocks, or large squeezing deformation may appear in soft and weak rocks (Ortlepp, 2001; Ansell, 2005; Li, 2010). It is observed that some of the conventional bolts fail when experiencing large shear and opening displacement at rock joints/fractures (Ortlepp, 2000; Li et al., 2011). The premature failure of the rebar bolts implies that rebar is too stiff to sustain rock dilations in high stress rock masses. The conventional support devices are thus not suitable for large deformation conditions and dynamic condition (Stillborg, 1994; Hoek et al., 1995).

Under high stress conditions, the loading for the support system is a displacement controlled process rather than a dead-weight controlled. Wall convergence can be induced by both rock squeezing and the dilation of fractures. The magnitude of rock displacement is influenced by the support system, which is usually composed of both internal and external support devices. The loading process is well described by the Ground Response Curve (GRC) (Carranza and Fairhurst, 2000). The more displacement allowed, the less the requirement for support pressure to stabilize the ground. This can be illustrated by the example of a “flexible support system” consisting of shotcrete linings with deformation slots together with rock bolts. Whilst the shotcrete lining is

* Corresponding author at: State Key Laboratory Breeding Base for Mining Disaster Prevention and Control, Shandong University of Science and Technology, Qingdao 266590, China. Tel.: +86 1595 4884373; fax: +86 0532 86057957.
E-mail address: wanggang1110@gmail.com (G. Wang).

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intentionally weakened (slotted) to sustain the high early loading without damage (Dalgıc, 2002), the accompanying rock bolts are not flexible enough. However, if the support resistance is not enough, the surrounding rock can experience large displacement, which is also very dangerous. The desired type of bolt for rock support in high stress rock masses should be not only strong, but also deformable, i.e., energy absorbent.

In this paper, we first review the history of energy-absorbing rock bolts. After that, we introduce a new rock bolt for energy-absorbing applications in details, including its layout and principle. This paper focuses on the static performance of the new bolt and its deformation characteristics are demonstrated by theoretical analysis and static pull tests.

2. A review of energy-absorbing rock bolts

Cook and Ortlepp (1968) first proposed the use of yielding support in the deep gold mines of South Africa. The applied support system used in deep mines should be able to carry high loads and also accommodate large deformations without experiencing serious damage; that is, they should be capable of absorbing a large amount of energy prior to failure. The energy-absorbing bolt has been studied over the 20 years around the world. Windsor and Thompson (1992) first proposed the concept of an ideal reinforcement device. The device should have the strength of rebar and the deformation capacity of Split Set bolts (Fig. 1), with the ability to be rapidly mobilized to a load level similar to the strength of the material. It should be capable of deforming over a long distance while the load remains high. This concept has been recognized early, but it has been difficult to technically manufacture such devices. Since 1980, extensive research and development work on yielding rock support has been conducted. Some energy-absorbing bolts have been successively developed and applied in mines. So far there have been dozens of energy-absorbing bolt types, and the yielding mechanism of them can be summarized as structural components sliding and steel deformation as shown in Fig. 2.

The first energy-absorbing rock bolt, the so-called cone bolt, was designed in South Africa (Jager, 1992). The cone bolt consists of a smooth steel bar with a flattened conical flaring forged onto one end. The bolt is fully encapsulated with either cement grout or resin in a borehole. The dilation of the rock between the cone and the bolt plate induces a pull load in the bolt shank. The cone is designed so that the conical end ploughs through the grout when the pull load exceeds a pre-defined value. Its energy absorbing capacity is the sum of compression of the grout and steel deformation. Its performance is closely controlled by the interaction between the cone and the grouting agents which in turn is significantly influenced by the properties of the grout material, the diameter of drill hole, the mixing efficiency and the encapsulation condition. In most cases these factors are not completely under control, the effect of a cone bolt (or modified cone bolt) therefore is less consistent and reliable (Gillerstedt, 1999).

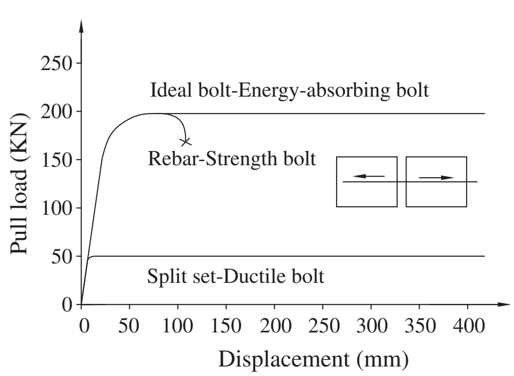

Fig. 1. Concept of the ideal bolt and definitions of strength, ductile and energy-absorbing rock bolts. All data sections are redrawn from Li CC [6].

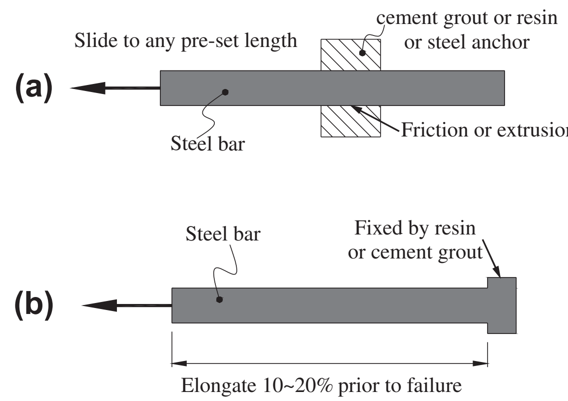

Fig. 2. Yielding mechanism of energy-absorbing rock bolt: (a) structural components sliding and (b) steel deformation.

D bolt is a steel deformation bolt designed based on the yielding mechanism (Li, 2010). It is a smooth steel bar with a number of anchors along its length. The anchors are firmly fixed within a borehole using either cement grout or resin, while the smooth sections of the bolt between the anchors can deform freely in response to rock dilation. Failure of one section does not affect the reinforcement performance of other sections. The bolt is designed to fully use both the strength and the deformation capacity of the bolt material along the entire length. The bolt has large load-bearing and deformation capacities. Static pull tests and dynamic drop tests show that the bolt length elongates by 14–20% at a load level equal to the strength of the bolt material, thereby absorbing a large amount of energy. While, filed measurements show that resin mixing is critical to ensure that the anchors do not move in extreme conditions underground, according to technical information data shifts by Chantale and Benoit (2012).

Roofex is another energy-absorbing bolt that was developed by Atlas Copco (Salzburg, 2009). The bolt is based on a steel-steel interaction with a high quality steel bar traveling through a energy absorbing element (energy absorber) fixed with resin or cement grout inside the borehole. The energy absorber receives a total of six cemented carbide slightly engraved into the steel bar and perform a cold rolling process, deforming the original round shape to a hexagonal shape, whilst the steel bar travels along its sliding path. Roofex is a rock bolt that can absorb movements with excellent performance and predictability for both yielding and rock burst prone grounds. However, the "energy-absorber" unit makes the bolt inherently cost expensive due to its complex structure. As cemented carbide pins are slightly engraved into the steel bar, structural damage of the bar was inevitable.

All the existing bolts have advantages and disadvantages, and there are more and more industrial requirements on developing a performance-reliable and cost-effective yielding rock support system.

3. Layout and principle of the new bolt

Since 2010, the authors have been conducting extensive research and testing to develop a new energy-absorbing rock bolt suitable for dynamic and/or large convergence ground conditions (Wang et al., 2012). The appearance of the new bolt is similar to Roofex, but the structure of the "energy-absorber" unit is simpler and more stable, which can provide a larger resistance (a load level