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Estimating the support effect of energy-absorbing rock bolts based on the mechanical work transfer ability

Xuezhen Wu[a,b], Yujing Jiang[b,c,*], Zhenchang Guan[a], Gang Wang[c]

[a] *College of Civil Engineering, Fuzhou University, Fuzhou 350108, China*
[b] *Graduate School of Engineering, Nagasaki University, Nagasaki 852-8521, Japan*
[c] *State Key Laboratory of Mining Disaster Prevention and Control, Shandong University of Science and Technology, Qingdao 266590, China*

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ABSTRACT

An interaction model is proposed to describe the interaction between the energy-absorbing rock bolt and the rock mass. Based on the plane-strain axial symmetry assumption and the incremental theory of plasticity, the equilibrium equations and compatibility equations of rock mass, as well as the response of the energy-absorbing rock bolt are deduced theoretically. The proposed method was programmed in a Visual Basic environment, and a semi-analytical solution for the coupling model was achieved. The reinforcement mechanism of the energy-absorbing rock bolt in conventional tunneling is clearly demonstrated through an illustrative case study. The reinforcement effect of the energy-absorbing rock bolt under different conditions was estimated quantitatively, and its mechanical work transfer ability is presented. In addition, the validity of the proposed method was verified through numerical simulations. Finally, a number of derivative cases were investigated to reveal the influence of the bolt and rock properties on the reinforcement effect and the bolt work transferred on the rock mass. In the case of higher in-situ stress or low-strength rock mass, the support effect of the energy-absorbing rock bolt is significantly improved, and the bolt absorbs more energy. Increasing the bolt installation density could always be helpful for the stabilization of the surrounding rock mass. However, additional rock-bolt length could hardly affect ground reinforcement because the bolt section embedded in the elastic region of the rock mass could barely help to constrain the elastic displacement release. The bolt should be installed no later than the stage of critical inner pressure, namely when the plastic region occurs.

1. Introduction

High stress in surrounding rock mass can cause severe stability problems, such as massive squeezing and rock burst.[1–4] It has been observed that numerous conventional rock bolts failed when experiencing large displacement of rock mass.[5,6] This phenomenon implies that they are too stiff to sustain large deformation and dynamic conditions.[7,8] The energy-absorbing bolt, which is also called the yielding rock bolt, has been widely used for rock reinforcement in mining and civil engineering under the aforementioned conditions.[9]

According to Windsor,[10] the types of rock bolts can be classified as: (1) continuously mechanically coupled (CMC), (2) continuously frictionally coupled (CFC), and (3) discretely mechanically or frictionally coupled (DMFC). Several analytical models have been proposed, such as those presented by Li and Stillborg,[11] Cai et al.,[12,13] Guan et al.,[14] Carranza-Torres.,[15] Tan,[16] and Farmer.[17] Most of them focused on the CMC and CFC rock bolts; however, the majority of the existing energy-absorbing rock bolts are of the DMFC bolt type.[18–22]

For the DMFC bolt, solutions are only obtained by treating the contribution of the rock bolt as two uniformly compressive distributed loads applied at both ends of the bolts.[15] However, the assumption of the smeared contribution of the rock bolt is acceptable only under the premise of small bolt spacing.[19] The errors increase as the rock-bolt spacing increases. On the other hand, the sudden jump in radial stress of rock mass that appears at the distal end of the bolt will probably not occur in practice. Therefore, no analytical model is available for the qualitative prediction of the reinforcement effect of energy-absorbing rock bolt.

The mechanism of the interaction between the energy-absorbing rock bolt and the rock mass is substantially complex because of the yielding deformation of the rock bolt.[19] The supporting design that employs the energy-absorbing rock bolt is still empirical or semi-empirical, and it is difficult to evaluate its performance quantitatively. The mechanical work that the energy-absorbing rock bolt can transfer on the rock mass is an important ability, which can be used to estimate its support effect. Some researchers studied the energy absorbing ability of

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[*] Corresponding author at: Graduate School of Engineering, Nagasaki University, Bunkyo Machi 1–14, Nagasaki 852–8521, Japan.
E-mail address: jiang@nagasaki-u.ac.jp (Y. Jiang).

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rock bolt by laboratory testing under dynamic loading condition, and the energy absorbing ability was evaluated by the energy released by impact hammer.[18,23] However, there is no published research work that is focused on the energy transfer of rock bolt and rockmass during their interaction process by theoretical methods. Therefore, it is imperative to develop a reasonable model to predict the mechanical work transfer ability of energy-absorbing rock bolts in practical engineering and to quantify their performance in the context of the supporting design.

This study is focused on estimating the quasi-static reinforcement effect of energy-absorbing rock bolts according to their mechanical work transfer ability using an analytical method. After a brief review of the mainstream energy-absorbing rock bolts, a coupling model will be proposed to describe the interaction between the energy-absorbing rock bolt and the rock mass, as well as the influence of the bolt and rock properties on the reinforcement effect; the mechanical work transfer ability will be highlighted through parameter studies.

2. A brief review of energy-absorbing rock bolts

Yielding support was first proposed and used in deep gold mines in South Africa by Cook and Ortlepp. The support system used in deep mines should be able to carry high loads and, in addition, accommodate large deformations of rock mass without experiencing serious damage in itself. Windsor and Thompson[10] were the first to propose the concept of the ideal rock bolt, which should have the strength of a rebar and the deformation capacity of a Split Set bolt, along with the ability to be rapidly mobilized to a load level similar to the strength of the bolt material.

Extensive research and development work on yielding rock support has been conducted in recent years. Certain energy-absorbing rock bolts have been successfully developed and applied in coal mines and gold mines. According to the yielding mechanism, they can be classified into two types: the type with sliding structural components and the steel-deformation type.

The type with sliding structural components mainly includes the Cone bolt,[20] the Roofex, the cold drawing bolt,[21] and the He bolt.[22] The Cone bolt consists of a smooth steel bar with a flattened conical flaring, which is designed to plough through the grout when the pull load exceeds a predefined value. The Roofex, the cold drawing bolt, and the He bolt are all based on steel–steel interactions with energy absorbing elements.

The typical representatives of steel-deformation energy-absorbing rock bolts are the bolts proposed by Ansell[23] and the D bolt.[18] Their typical characteristic is the existence of a smooth segment in the bolt, which can elongate by 14–22% at high-load levels. 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 dilation.

3. Reinforcement mechanism of the energy-absorbing rock bolt

3.1. Generalized model of the energy-absorbing rock bolt

Regardless of their different types, most energy-absorbing rock bolts can be represented through a generalized model. As shown in Fig. 1, the interaction mechanism between the energy-absorbing rock bolt and the rock mass is concisely illustrated. The total length of the bolt can be divided into three segments: the outer anchoring segment, the free-elongating segment, and the inner anchoring segment.[24–26]

After excavation, the surrounding rock mass will deform toward the excavation space. The outer anchoring segment of the energy-absorbing rock bolt will exert a stress on the rock mass to prevent its outward movement and transfer a positive work. In contrast, the stress of the inner anchoring segment points to the free surface, which results in a negative work.

With the increasing rock mass displacement, the axial force of the rock bolt will increase at an early stage. Once the pre-set sliding load is reached, the free-elongating segment starts to function and the bolt load will remain constant, thus preventing the self-destruction of the energy-absorbing rock bolt, whereas the work transferred by the rock bolt will increase continuously.

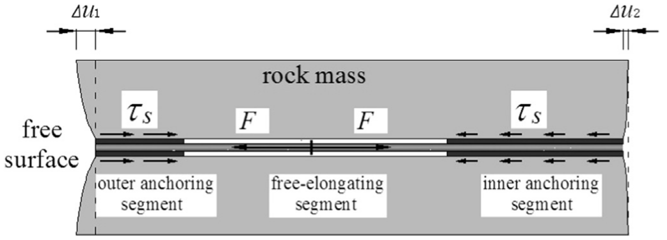

Fig. 1. The interaction mechanism between the energy-absorbing rock bolt and the rock mass.

3.2. The conventional spring-slider model

According to the pullout tests for passive bolts, the failure of the fully grouted bolts typically occurs at the bolt–grout interface, the grout–rock interface, the grout itself, and the rock matrix.[27] These four failure modes are generalized into conventional spring-slider model. The conventional spring–slider model can simulate the properties of CMC and CFC bolts, however, it not very suitable for energy-absorbing rock bolts, which are of the DMFC bolt type. On the other hand, there is no slider element in the bolt itself in the conventional model; therefore, the large deformation properties of energy-absorbing rock bolts cannot be expressed.

3.3. Interaction model of energy-absorbing rock bolt and rock mass

The energy-absorbing rock bolt is characterized by its large deformation properties, which means that the bolt can elongate to limit the axial load, and transfer more work on the rock mass. According to the characteristics of the energy-absorbing rock bolt, an interaction model is proposed, as shown in Fig. 2(a). The spring between the bolt and the anchor hole, which controls the interaction between the rock mass and the rock bolt, represents the shear stiffness of the anchoring agent. Its characteristic curve is shown in Fig. 2(b). Endpoint A signifies that the relative displacement and the shear stress between the rock

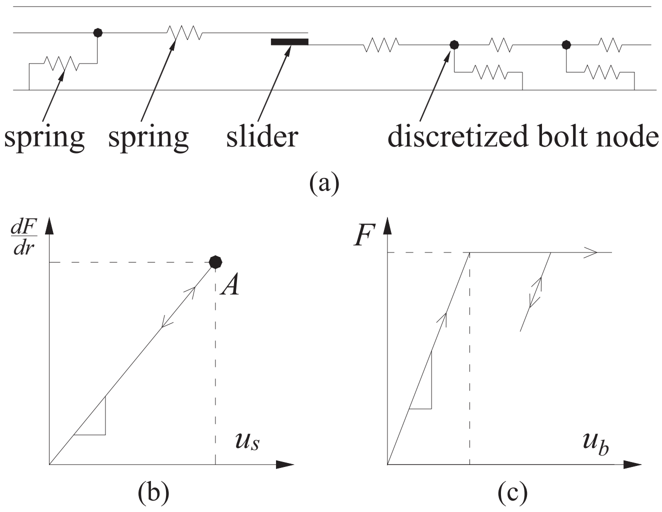

Fig. 2. The coupling model of energy-absorbing rock bolt and rock mass: (a) the overall structure model of energy-absorbing rock bolt; (b) the shear force per unit length versus relative shear displacement in anchoring segments; (c) the axial force versus displacement in free segment.