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A new analytical solution for calculation the displacement and shear stress of fully grouted rock bolts and numerical verifications

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A B S T R A C T

In presence of difficult conditions in coal mining roadways, an adequate stabilization of the excavation boundary is required to ensure a safe progress of the construction. The stabilization of the roadways can be improved by fully grouted rock bolt, offering properties optimal to the purpose and versatility in use. Investigations of load transfer between the bolt and grout indicate that the bolt profile shape and spacing play an important role in improving the shear strength between the bolt and the surrounding strata. This study proposes a new analytical solution for calculation displacement and shear stress in a fully encapsulated rock bolt in jointed rocks. The main characteristics of the analytical solution consider the bolt profile and jump plane under pull test conditions. The performance of the proposed analytical solution, for three types of different bolt profile configurations, is validated by ANSYS software. The results show there is a good agreement between analytical and numerical methods. Studies indicate that the rate of displacement and shear stress from the bolt to the rock exponentially decayed. This exponential reduction in displacement and shear stress are dependent on the bolt characteristics such as: rib height, rib spacing, rib width and grout thickness, material and joint properties.

1. Introduction

Steel bolts are an essential part of roadway support in coal mining roadways [1]. Fully grouted rock bolts are able to support tensile, compressive, shear and bending loads. The current study focuses on their tensile behavior because it is very often encountered and furthermore it allows studying the load transfer mechanism between the rock mass and the reinforcement element. Experience throughout the world has shown that under tensile solicitations failure often takes place by de-bonding at either the bolt-grout interface or at the grout-rock interface, depending on which one is weaker: in fact, if a bolted rock mass tries to move, a load will be progressively transferred to the rod and a shear stress will develop consequently along the embedded length. As the shear strength of the interface is progressively reached, de-bonding will occur [2]. The effectiveness of bolt reinforcement is a well-known and well researched subject; however, little has been done in optimizing the bolt profile that directly contributes to the load transfer between the bolt and the surrounding grout.

To improve bolt load transfer through the steel rebar design, it is essential to research the details of the bolt profile shape and configuration. Analytical studies, laboratory tests and numerical modeling provide the tools that enable a better understanding of the rebar profile role in increasing the shear resistance during the working life of bolts [1]. Investigations of load transfer between the bolt and grout indicate that the bolt profile shape and spacing play an important role in improving the shear strength between the bolt and the surrounding strata [3]. The short encapsulation pullout tests of rock bolt indicate significant variance of shear resistance for various bolt profile spacing, angle, shape and size [4,5]. Empirical studies can match the graphs of physical tests; however these methods cannot describe the exact reasoning why such behavior occurs [6]. Numerical modeling techniques are much better as they can mimic the physical tests in great detail, however, these methods depend on an accurate knowledge of the physical properties that must be incorporated or added into the model. The power of the numerical model rests on its ability to compare several models and to establish the optimum solution to the problem. The laboratory testing has its challenges as fabrication of minute differences in bolt profile in the workshop is difficult. Nevertheless the laboratory tests are important to calibrate all the empirical work and the numerical models. At present

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mathematical description of the bolt profile and its behavior during the bolt pull out test is under development to provide better understanding of the physical process that influences the shear strength of the loaded bolt [7,8]. The in situ pullout tests are commonly used to examine the shear capacity of rock bolts. Only a few researchers have conducted laboratory tests to study various bolt profile parameters and their influence on the bolt anchorage [2,9,10]. The work presented here extended the analytical solution in a fully grouted rock bolt based on bolt profile and movement joint. The analytical solution is to be validated by ANSYS software. Finally, comparisons between the analytical solution and the numerical modeling are shown and the results are discussed.

2. Analytical approach

A bolt installed in a deformable rock mass is subjected to an axial loading and it provides resistance to the movement of rock mass through shear stresses which developed axially in the bolt-grout interfaces [11]. All theoretical models are capable of determining the load transfer mechanism with one fracture, regardless of their bolt profile. Thus, in order to successfully determine essential, only a small part of the bolt-grout and jointed rock is modeled, as shown in Fig. 1. The new analytical model that is presented here is the extension of Cao et al. [8], Deb et al. [11] and Li and Stillborg [12].

In Fig. 1, $b\sin\theta$ is the rib height (mm), c the rib spacing (mm), θ the rib slope (°), a the profile width (mm), m the grout width (mm), L the failure length ($a + 2b\cos\theta + c$) (mm), L_j the length of the bolt up to at bolt intersect to the joint plane from the excavation face (mm), L_b the length of the bolt (mm), $\int \sigma_n dh$ the normal forces in the grout-rock interface (kN) and $\int \tau dh$ the shear forces in bolt-grout interfaces (kN).

Researchers presented new relationship to calculate the displacement and shear stress of the bolt, grout and jointed rock base on bolt profile and jump joint, which are presented as follows.

2.1. Displacement and shear stress in the grout

To investigate where the grout failure will occur, several potential planes of failure can be trilled. The Mohr-Coulomb criterion of failure was used to calculate the maximum pull out force needed for the assumed plane of failure. To draw a link between the load transfer system and the bolt profile configuration, a single spacing between two bolts ribs is examined. When the bolt is loaded, the load is applied to the grout boundary as shown in Fig. 2. The location of these loads is dependent on the bolt geometry while their magnitudes depend on the bolt geometry and the grout-bolt interface properties [8].

The normal and shear force, grout displacement and shear stress to the failure plane are determined by Eqs. (1)–(5).

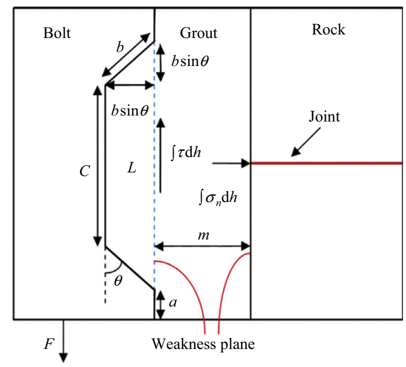

Fig. 2. Load transfer between the bolt, grout and jointed rock.

$$\int_n^\sigma dh = \frac{F}{\pi b\sin\theta}\left[\left(\frac{\pi}{2}-\theta\right)(a+2b\cos\theta+c) - (a+2b\cos\theta+c)\tan^{-1}\left(\frac{(a+c)\cos\theta+b\cos 2\theta}{m+(a+c)\sin\theta+b\sin 2\theta}\right) + (b\cos\theta-m\sin\theta)\left[\tan^{-1}\left(\frac{a+b\cos\theta+c+m\sin\theta}{b\sin\theta+m\cos\theta}\right) - \tan^{-1}\left(\frac{m\sin\theta-b\cos\theta}{b\sin\theta+m\cos\theta}\right)\right]\right] \tag{1}$$

$$\int \tau dh = \frac{F}{\pi}\left[\tan^{-1}\frac{a+b\cos\theta+c}{b\sin\theta}+\frac{\pi}{2}-\theta\right] \tag{2}$$

$$u_g = \frac{F}{\pi\cdot L\cdot K_{bond}}\left[\tan^{-1}\frac{a+b\cos\theta+c}{b\sin\theta}+\frac{\pi}{2}-\theta\right] \tag{3}$$

$$\tau = u_g\cdot L\cdot K_{bond}/A_{in} \tag{4}$$

Thus:

$$\tau = \frac{F}{\pi A_{in}}\left[\tan^{-1}\left(\frac{a+b\cos\theta+c}{b\sin\theta}\right)+\frac{\pi}{2}-\theta\right] \tag{5}$$

where u_g is the grout displacement (mm), τ the shear stress in the grout (MPa), F the axial bolt pull out force (kN), A_{in} the area interface bolt and grout (mm^2), and K_{bond} the bond shear stiffness (kg/mm^2).

2.2. Displacement and shear stress in jointed rock

In general, rock displacement is a monotonically decreasing function with radial distance x, measured from an excavation boundary. The form and rate of decrease of rock displacement u_r depend on the size and shape of the opening, presence of a joint plane, the strength and structure of the rock mass, loading

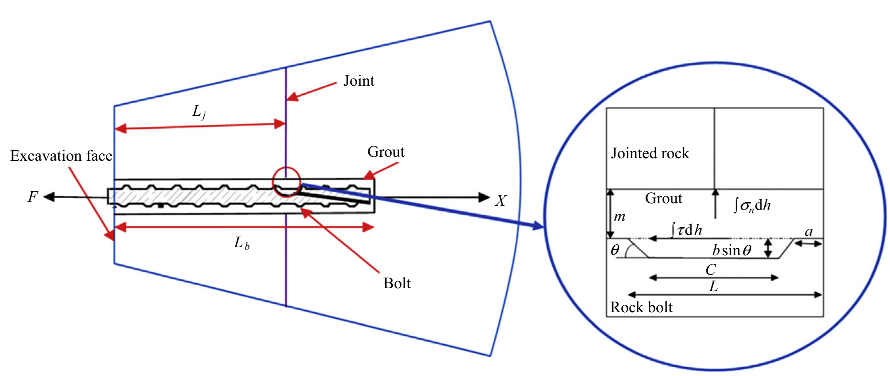

Fig. 1. Proposed research model.

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