International Journal of Rock Mechanics & Mining Sciences 71 (2014) 293–300

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

# Numerical modelling of failure propagation in fully grouted rock bolts subjected to tensile load

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ARTICLE INFO

Article history:
Received 8 October 2013
Received in revised form
8 July 2014
Accepted 9 July 2014

Keywords:
FLAC model
Rockbolt elements
Fully grouted rock bolts
Non-linear bond–slip relationship
Debonding failure process

ABSTRACT

Numerical modelling of fully grouted rock bolts loaded in tension is presented by implementing a non-linear bond–slip relationship of bolt–grout interface into a commercial finite difference rock mechanics code. The proposed model shows a close match with the experimental results and analytical predictions in terms of load–displacement relationship, rock bolt axial force distribution and interfacial shear stress distribution. A detailed debonding failure process is also presented, which includes five successive states: elastic state, elastic-softening state, elastic-softening-debonding state, softening-debonding state and debonding state.



## 1. Introduction

Rock bolts have become a popular technique for reinforcing rock masses all over the world. Rock bolts are installed to reinforce fractured rock mass by resisting dilation or shear movement along the fractures. Several rock bolts can create a reinforced zone in fractured rock mass to improve the self-supporting capacity of rock. Rock bolts usually undergo tensile and shear loading in the field. When the bolted rock mass deforms, load transfer occurs between the bolt and the rock. The purpose of this study is to provide a better understanding of the load transfer mechanism to optimise bolt design for ground support and improve rock mass reinforcement.

In the past few decades, a series of laboratory and in situ pull-out tests have been conducted to study the load transfer mechanism of bolts in tension [1–6]. Li and Stillborg [7] stated that when a fully encapsulated rock bolt is subjected to tensile load, failure may occur either at the grout–rock interface, in the grout medium or the bolt–grout interface, depending on which failure plane is the weakest. The dominant failure would often occur at the bolt–grout interface [8]. Therefore, to identify the shear stress distribution of the bolt–grout interface it is important to understand the debonding failure mechanism and then achieve the optimum design of the rock bolt.

### 1.1. Bond–slip models

Analytical research has also been carried out to examine the axial stress distribution in the rock bolt and shear stress distribution at the bolt–grout interface. Farmer [2] stated that the interfacial shear stress attenuates exponentially from the bolt loading end to the far end of the bolt before the debonding occurs. Li and Stillborg [7] presented an analytical approach by taking into account the debonding mechanism to predict the interfacial shear stress distribution along fully grouted rock bolts subjected to tensile force.

In addition, various bond–slip models have been introduced to study the axial behaviour of fully grouted rock bolts. Benmokrane et al. [9] developed an idealised tri-linear bond–slip model based on laboratory studies shown in Fig. 1. The parameters of $\tau 1$, $\tau 2$, $s1$ and $s2$ in Fig. 1 can be obtained from the pull-out tests. Initially the shear bond stress increases up to the peak stress at ($s1$, $\tau 1$) and then experiences a weakening trend down to ($s2$, $\tau 2$) followed by a horizontal line representing the non-zero residual strength $\tau 2$. Ren et al. [10] and Blanco Martín et al. [11] proposed their respective analytical models based on the tri-linear bond–slip relationship. Ma et al. [12] presented a non-linear bond–slip model to study the load transfer machanism of fully encapsulated rock bolts as illustrated in Fig. 1. These analytical models can provide reasonable predictions with respect to the axial stress distribution in the bolt, interfacial bolt–grout shear stress distribution and the overall load–displacement curve.

The non-linear bond–slip model of fully grouted rock bolts presented by Ma et al. [12] was used in this paper due to its

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http://dx.doi.org/10.1016/j.ijrmms.2014.07.007
1365-1609/

simplicity in predicting the bolt behaviour and capability of representing the complete decoupling of the bolt–grout interface. Fig. 2 schematically shows the fully grouted rock bolts when subjected to tensile load.

Based on the non-linear bond–slip model, the load–slip relationship, the axial load and the shear stress distribution of fully grouted rock bolt in tension can be expressed using the following equations [12]:

$$P(s) = \frac{E\pi d_b^2}{4}\frac{a}{b}[1 - e^{-(s/a)}] \quad (1)$$

where $d_b$ is the bolt diameter, $s$ is the loaded end slip, $E$ is Young's modulus of rock bolt rebar, $a$ and $b$ are coefficients determined from tests, and $P$ is the loading force at the loaded end. The axial load at a certain point $x$ along the bolt can be calculated by

$$p(x) = \frac{E\pi d_b^2}{4}\frac{a}{b}\frac{1}{[1+e^{-(x-x_o)/b}]} \quad (2)$$

where $p(x)$ is the bolt load at a distance $x$, and $x_o$ is a coefficient determined from tests. The interfacial shear stress distribution at the bolt–grout interface can be described by the following equation:

$$\tau(x) = \frac{Ed_b a}{4b^2}\frac{e^{-(x-x_o)/b}}{[1+e^{-(x-x_o)/b}]^2} \quad (3)$$

The coefficient $x_o$ can be expressed as

$$x_o = L + b\ \ln\left(\frac{aE\pi d_b^2}{4bP} - 1\right) \quad (4)$$

where $L$ is the total length of the grouted bolt.

### 1.2. Previous studies of rockbolt simulation

Bolt–grout bond–slip behaviour can be modelled using numerical modelling software. Up to date a limited amount of numerical modelling has been undertaken to simulate the behaviour of rock bolts and the bolt–grout bond–slip relationship. Li [13] modelled the interaction behaviour between concrete and steel bar (without considering grout) using a translator element in ABAQUS [14]. The translator element can simulate the interfacial bond behaviour between concrete and steel however, the user has to conduct the node-to-node connection with translator, which is not efficient especially when the model has a large number of nodes at the interface.

Li and Kaliakin [15] developed a four node zero-thickness interface element to simulate non-linear deformation of the interface between geological materials. Although this interface element is capable of simulating the non-linear axial stress distribution and interfacial shear distribution of a rock bolt, it can only be implemented in a 2-Dimentional model and cannot be extended to a 3-Dimensional model. Hence this interface element is not able to actually model the practical behaviour of in situ rock bolts for several reasons such as: the diameter of rock bolt cannot be simulated properly using the four node zero-thickness interface element and to correctly implement a given bond–slip relationship into this interface element is a challenge.

Ivanović Neilson [16] proposed a lumped parameter model in which the rockbolt system is represented by a number of spring/damper systems. The lumped parameter model is capable of simulating the trend of the axial force distribution, shear force distribution and the debonding mechanism of fully grouted rock bolts. However, the lumped parameter model is limited to the implementation of the bi-linear or tri-linear bond–slip model and the complexity in application makes it inconvenient to model the behaviour of fully grouted rock bolts installed underground.

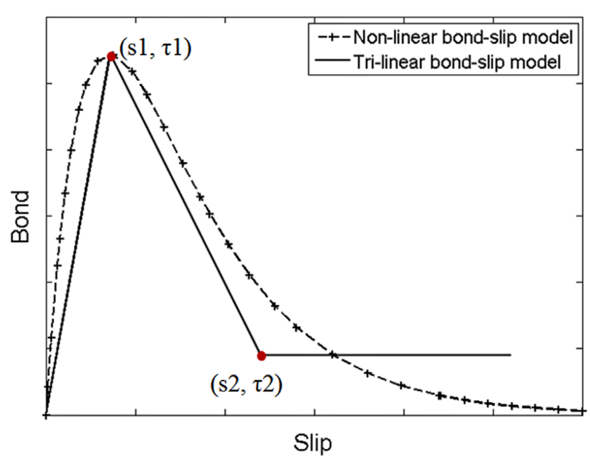


**Fig. 1.** Tri-linear bond–slip model [9] and non-linear bond–slip model [12].

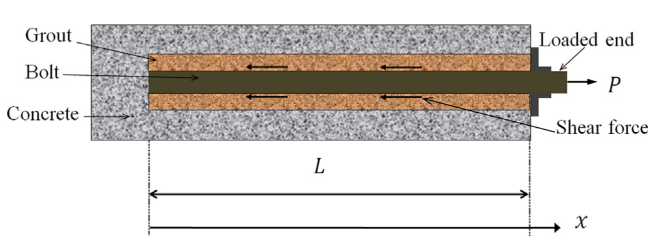


**Fig. 2.** Fully grouted rockbolt loaded in tension.

### 1.3. Scope of this paper

A two-dimensional explicit finite difference programme (FLAC2D), is used in this study to simulate the pull-out tests of fully grouted rock bolts as it appears that at this stage FLAC3D, 3DEC, ABAQUS and ANSYS do not seem to be suitable to model the bond–slip behaviour effectively. Although rockbolt elements or the cable elements provided by FLAC software are popular applications in modelling rock bolts in the field [17–21], they cannot simulate (without modification) the interfacial shear bond weakening mechanism between the bolt and the rock mass due to its linear elasto-plastic behaviour. Based on the analytical studies of Ren et al. [10], Blanco Martín et al. [11] and Ma et al. [12], the shear bond stress between the rockbolt element and the rock mass is expected to show a non-linear relationship with the relative displacement between the rockbolt node and the grid as shown in Fig. 1.

Hence, there is a need to modify the interfacial shear bond stress along the boltbolt element as a function of relative shear displacement. A new approach is proposed to implement the non-linear bond–slip relationship of rock bolt–grout interface into the FLAC model. This was achieved using FISH subroutine (a programming language embedded within FLAC). The obtained results are compared with a laboratory test and the analytical model. The comaprison of the rockbolt behaviour with and without modification is shown in Fig. 14.

## 2. Rockbolt element in FLAC2D

FLAC2D is commonly used in mining and civil engineering for simulating soil, rock, and structural behaviour [22]. FLAC2D is based on explicit finite difference formulation and provides structural elements representing the soil and rock support systems. FLAC have seven specified forms of structural support elements: beam elements, liner elements, cable elements, pile