Construction and Building Materials 57 (2014) 30–37

Contents lists available at ScienceDirect

Construction and Building Materials

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

Analytical model for rock bolts reaching free end slip

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HIGHLIGHTS

- An analytical model is proposed for fully grouted rock bolts under tension.
- The model takes into account free end slip of fully grouted rock bolts.
- The load displacements, the strain and shear stress distribution have been derived.
- The proposed model is in good agreement with the laboratory data.

ARTICLE INFO

Article history:
Received 16 October 2013
Received in revised form 13 January 2014
Accepted 15 January 2014
Available online 21 February 2014

Keywords:
Rock bolts with free end slip
Bond–slip relationship
Analytical model

ABSTRACT

This paper presents the difference of behaviour between fully grouted bolts with and without free end slip when loaded in tension. An analytical approach is proposed for fully encapsulated bolts when the free end of the bolt slips. This model is based on the existing bond–slip relationship of bolt–grout interface with no free end slip. The derived analytical solutions of load–slip relationship, slip distribution, the shear stress and strain distributions presented in this paper are all connected with free end slip. The analytical approach is validated by experimental results. Free end slip has a significant influence on rock bolt behaviour and should not be ignored.

1. Introduction

Rock bolts have found extensive application in tunnelling and mining engineering to reinforce the jointed rock mass or to support underground openings. Fu et al. [7] stated that anchor bolts could improve the peak strength, elastic modulus and shear strength of the bolted rock mass. The principal objective of the rock bolt reinforcement is to enhance the internal load bearing strength of rock mass to support itself [3]. Rock bolt performance depends on the type of rock bolt, anchorage system, strata lithology and other geological conditions. Accordingly, three fundamental mechanisms are proposed: suspension, beam building and keying. One or a combination of the three basic mechanisms takes place in the function of the bolt system [15]. Where dynamic loads are common, for example in hard rock mining, the point anchor rockbolts or bolts that can elongate in response to sudden loading are often used. In contrast, rockbolts installed in soft rock mostly experience gradual loading that require full encapsulation of the bolts to optimise their performance. Winsdor [21] divided the current reinforcement devices into three types: Continuous Mechanically Coupled (CMC), Continuous Frictionally Coupled (CFC) and Discretely Mechanically or Frictionally Coupled (DMFC). Accordingly, the fully grouted bolt system belongs to CMC.

In the field, rock bolts usually experience tensile and shear loading. When the reinforced rock mass deforms, a load transfer mechanism takes place between the bolt and the rock surface and transfers the applied tensile and shear load into the surrounding mass. The load transfer mechanism plays an important role in the reinforcing function of the rock bolt system. Better understanding of the load transfer is helpful in optimising bolt design for ground support. Throughout the last few decades, many *in situ* and laboratory pull tests have been carried out to study the load transfer capacity of the bolt under tension [5,1,18,11,10,12]. Li and Stillborg [13] stated that rock bolts may fail either at the grout–rock interface, in the grout medium or at the bolt–grout interface, depending on which failure plane is the weakest when fully grouted bolts are in tension. The dominant failure would mostly occur at the bolt–grout interface [9]. The identification of the shear stress distribution of the bolt–grout interface is of great importance for understanding the load transfer mechanism and the optimal design of the rock bolts.

Analytical approaches, regarding fully encapsulated bolts, have been significantly researched in the past several decades. Farmer [5] proposed a theoretical shear stress distribution along the grouted bolt and showed that the shear stress at the bolt–grout interface

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0950-0618/$ - see front matter
http://dx.doi.org/10.1016/j.conbuildmat.2014.01.057

would decrease exponentially from the loading point to the free end of the bolt before decoupling occurs. Li and Stillborg [13] presented an analytical approach to predict the shear stress distribution along a fully encapsulated rock bolt subjected to tensile force. This model introduced the decoupling mechanism and took into account the complete decoupling behaviour with zero shear stress. Ren et al. [17] proposed non-uniform axial stress and shear stress distribution relationships for five loading stages using a tri-linear bond–slip relationship of the interface between the rock bolt and grout. However, the existing analytical approaches proposed by Farmer [5], Li and Stillborg [13] and Ren et al. [17] only focused on rock bolts without free end slip. In all cases they ignored the slip of the bolt free end. In laboratory pull testing of bolts in extremely weak rock such as chalk, free end slip was observed for the bolt length ranging up to 700 mm [5]. For bolts with short encapsulation (100 mm) in a strong rock mass, the slip of the free bolt end was readily observed. In this study, it was found that bolt free end slip could significantly influence the load transfer mechanism. Neglecting the slip of the bolt free end could lead to incorrect predictions of the rock bolt behaviour.

Free end slip was taken into consideration in this paper. A shear bond–slip relationship of bolts without free end slip presented by Ma et al. [16] is given by:

$$\tau(s) = \frac{Ed_b}{4} \cdot \frac{a}{b^2} \cdot e^{-\frac{s}{a}}\left(1 - e^{-\frac{s}{a}}\right) \tag{1}$$

where E refers to Young's modulus of rock bolts, d_b defines the bolt diameter, a and b are experimental constants and s is the displacement of the loaded end.

Thus Eq. (1) is applicable to predicting the behaviour of bolts without free end slip under pull out load. The bond–slip relationship is independent of the occurrence of the slip of the bolt free end, due to the fact that it represents the inherent characteristic of the bolt–grout joint interface [4]. Shima and Chow [20] also pointed out that the bond–slip relationship essentially has nothing to do with the boundary conditions. Hence in this context, the bond–slip relationship for bolts with or without free end slip is assumed to be the same and Eq. (1) is therefore used in both cases.

2. Governing equation

Fig. 1 illustrates schematically the axial displacements (x), the strain distribution $\varepsilon(x)$ and the shear stress distribution along the bolt when the encapsulated rock bolt having free end slip is subjected to tensile force. L represents the bonded length. In this paper, loaded end refers to the bolt end being loaded whereas the free end/unloaded end means the bolt end without external loading as shown in Fig. 1.

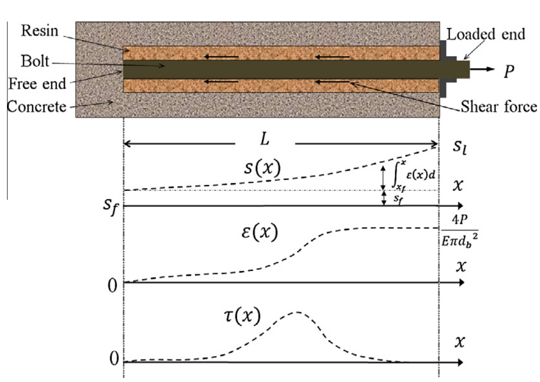

Fig. 1. Typical responses of a fully grouted bolt with free end slip.

$s(x)$ can be defined as an axial displacement at any point along the bolt equal to the sum of free end slip s_f and the integration of strain along the bolt as shown in Fig. 1.

$$s(x) = s_f + s_b(x) = s_f + \int_{x_f}^{x} \varepsilon(x)dx \tag{2a}$$

Differentiating Eq. (2a),

$$\varepsilon(x) = \frac{ds(x)}{dx} = s'(x) \tag{2b}$$

For the elementary length of dx in Fig. 2, the relationship between the shear stress in the bolt–resin interface and the axial tensile stress in the bolt can be deduced by the force equilibrium equation in the axial direction:

$$(\sigma_b(x) + d\sigma_b(x) - \sigma_b(x)) \cdot \pi \cdot \frac{d_b^2}{4} = \tau(x) \cdot \pi \cdot d_b \cdot dx \tag{2c}$$

and can be simplified:

$$\tau(x) = \frac{d_b}{4} \cdot \frac{d\sigma_b(x)}{dx} \tag{2d}$$

where $\sigma_b(x)$ denotes axial stress of bolt corresponding to point x.

In this study, the bolt is assumed to be in elastic deformation and accordingly, $\sigma_b(x)$ can be expressed by;

$$\sigma_b(x) = E \cdot \varepsilon(x) \tag{2e}$$

Substituting Eq. (2e) into Eq. (2d), leads to;

$$\tau(x) = \frac{Ed_b}{4} \cdot \frac{d\varepsilon(x)}{dx} = \frac{Ed_b}{4} \cdot s''(x) \tag{2f}$$

According to Eqs. (1) and (2f), the governing equation for a grouted bolt with or without free end slip can be derived as follows:

$$s''(x) = \frac{a}{b^2} \cdot e^{-\frac{s}{a}}\left(1 - e^{-\frac{s}{a}}\right) \tag{2g}$$

3. Load–displacement relationship

As shown in Fig. 1, P is the applied axial load to the rock bolt and s_l and s_f are displacements of the loaded end and free end respectively. When a fully grouted bolt with free end slip is subjected to tensile force, the corresponding boundary conditions can be expressed as

$$\begin{cases} s = s_f \\ \varepsilon = 0 \end{cases} \quad \text{when } x = 0 \tag{3a}$$

$$\begin{cases} s = s_l \\ \varepsilon = \frac{4P}{E\pi d_b^2} \end{cases} \quad \text{when } x = L \tag{3b}$$

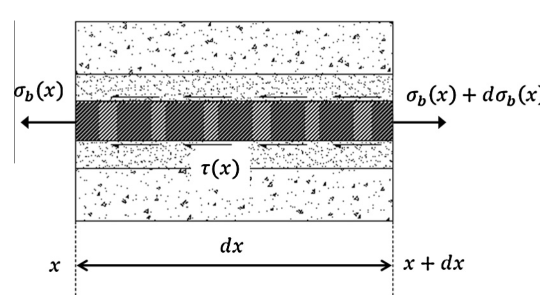

Fig. 2. Stress distribution in an elementary length dx of the test sample.