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An analytical analysis of the full-range behaviour of grouted rockbolts based on a tri-linear bond-slip model

F.F. Ren [a,b], Z.J. Yang [b,*], J.F. Chen [c], W.W. Chen [a]

[a] Key Laboratory of Mechanics on Disaster and Environment in Western China, Lanzhou University, Lanzhou 730000, China
[b] Department of Engineering, University of Liverpool, Liverpool L69 3GH, UK
[c] Institute for Infrastructure and Environment, School of Engineering, The University of Edinburgh, Edinburgh EH9 3JL, Scotland, UK

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ABSTRACT

This paper presents an analytical solution for predicting the full-range mechanical behaviour of grouted rockbolts in tension based on a realistic tri-linear bond-slip model with residual bond strength at the grout–bolt interface. The full-range behaviour consists of five consecutive stages: elastic stage, elastic–softening stage, elastic–softening–debonding stage, softening–debonding stage and debonding stage. For each stage, closed-form solutions for the load–displacement relationship, interfacial shear stress distribution and bolt axial stress distribution along the bond length were derived. The ultimate load and the effective anchor length were also obtained. The analytical model was calibrated and validated against two pullout experimental studies. The predicted load–displacement curves as well as the distributions of the interfacial shear stress and the bolt axial stress are in close agreement with test results. A parametric study is also presented, providing insights into the behaviour of the rockbolts.

1. Introduction

A rockbolt is a rod or a cable inserted into a borehole drilled in its surrounding rock or soil. Rockbolts are widely used in mining and tunnelling engineering to support underground excavation or to stabilise jointed rock mass. Rockbolts are usually under tension. They need to be appropriately anchored so that the applied tensile force can be effectively transferred into the surrounding mass. There are three widely-used anchoring techniques: mechanical apparatus, grouting with cement or resin, and friction. Among these, fully or partially grouting is most popular in practice due to its ease of installation, relatively low cost and versatility in applications [1]. This study is concerned with grouted rockbolts.

Since the 1970s, a large number of laboratory experiments and in situ tests have been conducted to investigate the mechanical behaviour of rockbolts under tension [2–15]. It has been found that the rockbolts often fail by debonding at either the bolt–grout interface or the grout–rock/soil interface. For such a debonding failure, the determination of the accurate distribution of the interface shear stress along the bonded length is crucial for predicting the ultimate bearing capacity and for achieving an optimal design. Many analytical studies have also been conducted. For example, Farmer [16], Aydan et al. [17], Hyett et al. [18] and Zhang and Tang [19] have shown that both the axial stress in the bolt and the bolt–grout interfacial shear stress (ISS) decrease exponentially from the loaded end to the embedded end. However, most existing analytical studies assumed that the ISS is linear to the shear slip and the interface debonding behaviour is neglected. Yazicit and Kaiser [1] proposed a conceptual model to predict the ultimate load capacity of fully-grouted cable bolts, assuming that the bearing capacity is primarily dependent on the friction related to the normal pressure at the bolt–grout interface and the interface cohesive strength is negligible. They concluded that the ultimate load increases with the rock-to-grout stiffness ratio, the strength of the grout, the friction coefficient between the bolt and the grout, and it decreases with the diameter of the borehole. Li and Stillborg [20] developed a solution for the ISS distribution along the bolt. They considered the elastic, softening and debonding stages but assumed that the ISS in the softening stage is linearly distributed along the bolt. Cai et al. [21,22] and Xiao and Chen [23] developed analytical solutions based on a bond-slip model with residual interfacial shear strength after debonding. They derived the equations for the ISS at both the elastic and the softening stages as well as for the bolt axial stress, but did not determine the ultimate load capacity. Xie [24] and Gao and Zhang [25] adopted a bond-slip model with the ISS decreasing exponentially in the softening stage, but their equations can only be solved using an iterative method so no closed-form solutions for the ISS and axial stress distributions are available. More recently, Ivanovic and Neilson [26] developed a non-linear bond model to analyse the dynamic behaviour of rockbolts with respect to the decrease in the first natural frequency. It

* Corresponding author. Tel.: +44 151 7944897.
E-mail address: zjyang@liv.ac.uk (Z.J. Yang).

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may be concluded, based on the best knowledge of the authors, that a closed-form solution capable of predicting the full-range non-linear behaviour of grouted rockbolts is not yet available.

This study develops such a closed-form solution for the prediction of the full-range mechanical behaviour of fully or partially-grouted rockbolts under tension. In this solution, a realistic tri-linear bond-slip model is used to accurately model the interfacial debonding mechanism between the grout and the bolt. Five stages are identified as the interfacial shear stress evolves: elastic, elastic–softening, elastic–softening–debonding, softening–debonding and debonding stages. Based on strain compatibility and force equilibrium, closed-form solutions are derived for the load–displacement relationships and the distributions of the interfacial shear stress and bolt axial stress at each stage, the ultimate load and the effective bond or anchor length. It should be noted that in deriving the analytical solutions, we closely followed the procedure detailed in Yuan et al.'s work [27], in which the full-range solutions for a bonded joint between the fibre reinforced polymer (FRP) composite and concrete were derived. However, in order to take the grout–bolt interface friction into account, this study uses a tri-linear bond-slip model, which consists of the conventional bilinear model plus a horizontal line representing the non-zero residual shear strength due to friction. As a result, deriving the analytical solutions becomes significantly more involved, and the solutions are more complicated. The procedure to calibrate the parameters in the solution is also different.

The following sections will first discuss the pullout tests and assumptions adopted in the analytical derivation, the tri-linear bond-slip model and the governing equations. The derivation of the analytical solutions for the five stages is then presented in detail. The calibration of parameters and the validation of the solutions are then carried out with respect to two pullout experiments of rockbolts. Finally, a parametric study of the key parameters is conducted.

2. The pullout tests and an idealized model

Both in situ tests and laboratory tests have been conducted to evaluate the load-carrying capacity of rockbolts in practice. Fig. 1a illustrates an in situ pullout test of a grouted rockbolt. The boundary of the surrounding rock is represented by the dashed lines symbolising the surrounding rock mass. The in situ tests are capable of evaluating the accurate load-carrying capacity of the tested rockbolts, but they are destructive and the testing conditions are difficult to control. The laboratory pullout tests are often used as alternatives. Fig. 1b illustrates a typical circular pullout specimen, in which a bolt is grouted into a steel tube [10]. If sufficiently stiff, the steel tube in the laboratory test can represent the surrounding rock in the in situ test. The diameter of the steel pipe is usually more than five times larger than that of the bolt [10,26] .

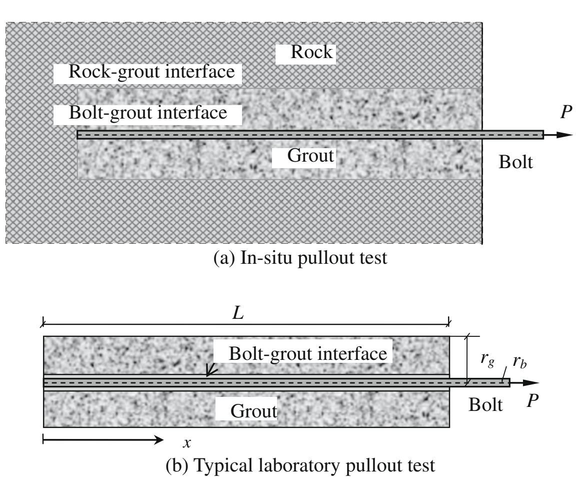

Fig. 1. Pullout tests of rockbolts. (a) In situ pullout test and (b) typical laboratory pullout test.

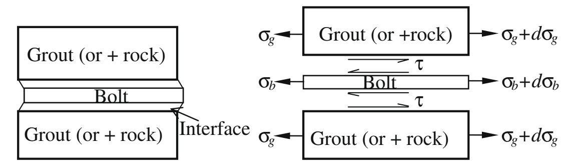

Fig. 2. Idealised model: deformation and stresses.

It is known that the ultimate failure of rockbolts may occur: (a) in the bolt, (b) in the grout, (c) in the rock, (d) at the bolt–grout interface, (e) at the grout–rock or steel tube interface and (f) a combination of these failure modes [2–14]. This paper is concerned with the very common debonding failure at the bolt–grout interface. Under the debonding failures, the deformation of the surrounding rock or grout is often negligible due to the massive volume and stiffness of the surrounding grout and rock (Fig. 1a) or the grout and steel tube (Fig. 1b). As a result, the bolt can be assumed to be under uniaxial tension and the bolt–grout interface layer under interfacial shear deformation only, leading to an idealised model as in Fig. 2 when the failure is debonding at the bolt–grout interface. If debonding occurs at the grout–rock or steel tube interface, the idealised model is still applicable, by treating the bolt and grout together as a "hybrid bolt" under uniaxial tension. It should be noted that the zero thickness interface represents the materials adjacent to the critical interface where debonding failure occurs. All deformations in the surrounding grout and rock outside the critical interface are lumped in the interface in this idealised model. It is also assumed that the pullout force P is horizontal so that the stress in the protruding length of the bolt is uniform.

3. Tri-linear bond-slip model

As mentioned early, this study follows the procedure used by Yuan et al. to derive the analytical solution for FRP-concrete joints [27]. However, two main differences exist between [27] and this study: (i) the present problem of grouted rockbolts is axi-symmetric but the FRP-concrete bonded joint is treated as a plane stress problem; (ii) once debonding is complete at the FRP-concrete interface, it is believed that no further shear resistance exists and thus a bilinear bond-slip model is suffice. This leads to a flat plateau on the predicted load–displacement curve in the elastic–softening–debonding stage [27]. This is however not the case in the grouted rockbolts. When the cement or resin is grouted to fill the gap between the bolt and the rock/soil mass, a pressure is usually applied, leading to a gripping force surrounding the bolt. Normal pressure on the bolt may also arise from expansion of the grout at failure, and from the gravity of rock mass if the rockbolt is not vertically installed in engineering practice. The normal pressure on the bolt results in surface friction after a complete debonding between the grout and the bolt. Consequently, no flat plateaus usually exist in the load–displacement curves of pullout tests of rockbolts.

To take the friction into account, this study adopts a tri-linear bond-slip model as shown in Fig. 3. It consists of a conventional bilinear model [27], which has an ascending branch up to the peak stress at (τ_f, δ_1) followed by a softening branch down to (τ_r, δ_f), and then a horizontal branch representing the non-zero residual frictional strength τ_r after complete debonding. The tri-linear bond-slip model is assumed as a material property and all the