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# An analytical model of fully grouted rock bolts subjected to tensile load

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## HIGHLIGHTS

- An analytical model is proposed for fully grouted rock bolts under tension.
- The model consists of the residual shear stress and the decoupling mechanisms.
- The axial bolt load, shear stress and load displacements have been derived.
- The proposed model agrees well with the laboratory and *in situ* data.

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## ABSTRACT

An analytical model for fully encapsulated rock bolts subjected to tensile load in pull-out tests is presented. This model is based on the bond–slip relationship describing the mechanical interaction at the bolt–grout interface. The model takes into account the residual shear stress in addition to the complete decoupling mechanisms. Formulations are also derived for the load–displacement curve, shear stress distribution at the bolt–joint interface and axial load distribution in the bolt. The model was validated with experimental results from both the laboratory experiments and *in situ* studies.

## 1. Introduction

Currently, rock bolts are used as a primary support to reinforce unstable strata underground and in surface mining, tunnelling, and various civil engineering excavations. The main purpose of the installed rock bolts is to clamp the weaker rock layers together to form stronger rock beam thus minimising sagging and separation of strata around excavation. Fundamentally, rock bolts provide a reinforced zone in fractured rock mass with the main objective to improve inherent strength of rock to become self-supporting. In order to optimise the rock mass support itself, effective load transfer between the bolt and the rock surface must take place during strata deformation. Windsor [20] introduced the bolt load transfer concept that has four principal elements: rock, the internal fixture, the external fixture and the reinforcing element. The reinforcing element and external fixture refer to the bolt, the face plate and nut, respectively. Coupling between the rock and the reinforcing element is via the internal fixture, which could be either cementitious or polymeric resin for grouted bolts, or a mechanical friction anchorage along the bolt–rock surface for frictionally coupled bolts. Accordingly, Windsor classified the current reinforcement devices into three fundamental groups: Continuous Mechanically Coupled (CMC), Continuous Frictionally Coupled (CFC) and Discretely Mechanically or Frictionally Coupled (DMFC) [20]. The fully grouted bolt system belongs to CMC, whereas expansion shell bolts belong to the DMFC system and Swellex rock bolts to the CFC system.

Due to the relatively simple installation procedure and economic factors, the grouted steel rebar is the most commonly used reinforcement system, using resin or cement grouts as an anchorage.

Better understanding of the bolt load transfer mechanism can lead to optimisation of the bolt profile design that can significantly improve the performance of the rock bolt reinforcement system. The load transfer capability in the bolt system has been widely studied over the past several decades [1,2,4,7,13,14,17]. Anchoring capacity of rock bolts is usually examined by pull-out tests. When a fully grouted bolt is subjected to a tensile load, the failure may occur either at the grout–rock interface, in the grout medium or at the bolt–grout interface, depending on which of the interfaces is the weakest [14]. From laboratory tests and field observations, Hoek and Wood [10] proposed that the most dominant failure mode was by shearing at the bolt–resin interface. The shear

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capacity of the bolt–resin interface consists of three components: adhesion, interlock mechanism and friction. Singer [19] pointed out that no adhesion exists in the bolt–resin interface and according to other studies of Aziz and Webb [2] and Yazici and Kaiser [21], adhesion strength has a small value which can be assumed to be negligible. Fig. 1 shows an example of weakly bonded bolt–resin interfaces. The load transfer capacity of a fully encapsulated rock bolt is dominated by mechanical interlocking between the bolt rib profiles and resin rather than the friction between them [16]. Accordingly, the terminology of bond in the rock bolt study case is equivalent to shear stress at the bolt–resin interface. The bolt–resin decoupling starts when the load reaches a critical value, which overcomes first the adhesive components, then the mechanical interlock and finally the frictional component Li and Stillborg [14].

Farmer [7] carried out fundamental work in studying the axial behaviour of the bolt subjected to tensile load and proposed a theoretical shear-stress distribution along the rock bolt. Farmer demonstrated that the shear stress at the bolt–grout interface would attenuate exponentially from the point of loading to the far end of the bolt before decoupling occurs. His theory was short of simulating the effect of de-bounding at the bolt–grout interface and was valid only when the bolt was subjected to low axial loading. Li and Stillborg [14] presented a model of the shear stress distribution along a fully encapsulated rock bolt in tension, which is shown in Fig. 2. In their model, the elastic, softening and de-bonding zones were taken into account, but with the limitation of linear behaviour within the softening zone. Ren et al. [17] proposed an analytical model for predicting the mechanical behaviour of grouted rock bolts subjected to pull load, based on a realistic tri-linear bond–slip model. They took into account the residual bond strength at the grout–bolt interface but did not consider the complete decoupling mechanism in the bolt–grout interface. In Ren et al.'s theory [17], non-uniform axial stress and shear stress distribution relationships were derived for five loading stages. Thus in order to compute the axial stress or shear stress along the bolt, the loading stages of the bolt has to be known resulting in complexities and inconvenience.

**Fig. 1.** Resin bolt separation after post-examination, after Aziz and Webb [2].

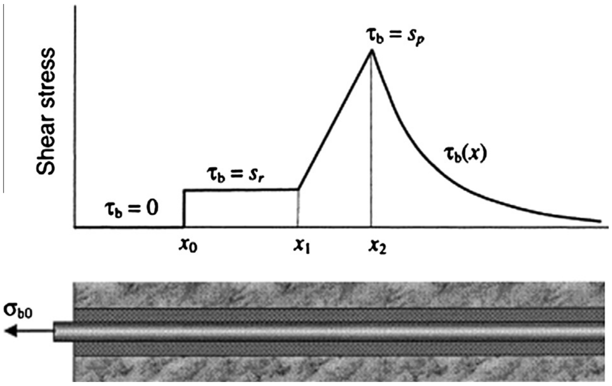

**Fig. 2.** Distribution of shear stress along a fully grouted rock bolt subjected to an axial load in coupled rock bolt, after Li and Stillborg [14].

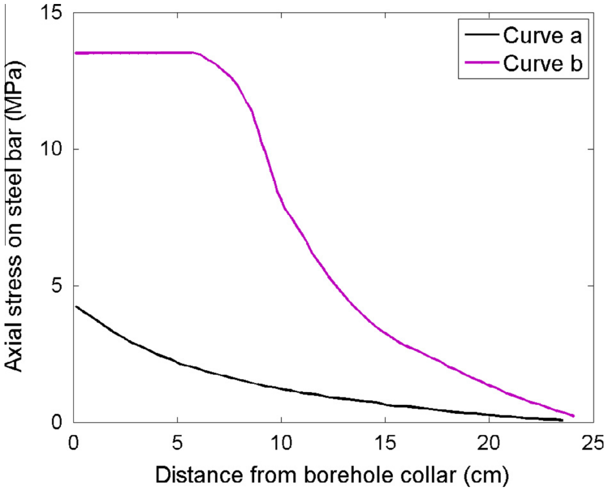

**Fig. 3.** Distribution of the axial stress along a grouted steel bar subjected to a pull load, after Hawkes and Evans [9].

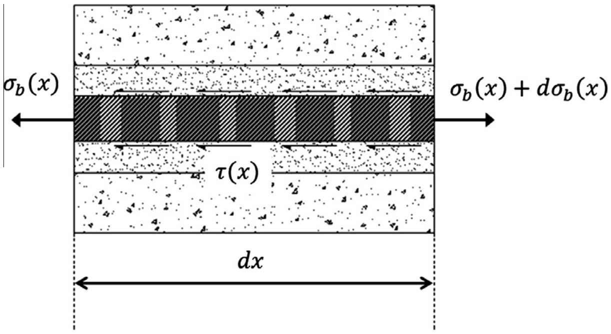

**Fig. 4.** Stress distribution in an elementary length *dx* of the test sample.

Fig. 3 shows the results of a typical pull-out test conducted by Hawkes and Evans [9] where curves *a* and *b* represent the axial stress distribution at both low and high applied loads respectively. For curve *b*, a complete decoupling mechanism has occurred.

According to Fig. 4, the relationship between the shear stress in the bolt–resin interface and the axial tensile stress in the bolt is given by the following expressions:

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