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Rock Bolt-Grout-Rock Interaction in Pullout Test and Determining Load-Displacement Curve of the Bolt Head

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ABSTRACT: The purpose of this paper is to investigate analytically the fully grouted rock bolt interaction with grout and rock in pullout test and to determine the load-displacement curve of the bolt head (beginning of the bonded section). Usually, the pullout test output is only the load-displacement curve. This paper discusses how to use this curve to determine the bolt-grout-rock interaction. For modeling bolt-grout interface behavior, coupling (complete bonding), partial decoupling, decoupling with the residual shear strength, and complete decoupling have been considered. With increasing the applied load, two possible cases including complete pullout and bolt shank yielding are considered. Based on experimental results, a model for the shear stress along a fully grouted bolt is assumed. According to this model, the distribution of axial stress in the bolt and displacement of the bolt head is determined. It is also assumed that the bolt is sufficiently long, which is usually used in underground excavations. Based on the presented analytical method, the bolt head load-displacement curve is determined by assuming input parameters. This curve is compared with a pullout test result.

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1. Introduction

A fully grouted rock bolt is commonly used in rock reinforcement and stabilization of underground and surface excavations. Understanding rock bolt-grout-rock interaction in pullout tests helps to design the rock bolt. When a load is applied on a fully grouted rock bolt, failure may occur at the bolt-grout interface, in the grout medium, at the grout-rock contact, or in the rock mass depending on which of them is the weakest [1]. Many researchers have studied this interaction. However, rarely have they have considered the bolt shank failure.

Farmer [2] was one of the first researchers who has developed a solution for determining the distribution of axial stress and displacement in grouted rock bolt and shear stress in bolt-grout contact. He proposed an exponential relationship for decreasing the stress besides rock bolt in the complete bonding and elastic condition. Signer presented fully grouted rock bolt pullout test results and discussed the load transfer mechanism [3]. Li and Stillborg [1] considered decoupling in the bolt-grout contact based on pullout experimental results. They presented an analytical model for the distribution of axial stress in the bolt and shear stress in the contact in pullout test, in the uniform displacement of rock mass, and a joint opening. They have not considered bolt shank failure. He et al. [4] used the same assumption by considering the bolt shank failure. They considered long and short rock bolt pullout tests, but they did not give a solution for the bolt head load-displacement curve. Instead, they presented a method for increasing load as a result of the joint opening. Benmokrane et al. [5] presented a tri-linear bond-slip model. Based on this model, some researchers such as Ren et al. and Martin et al. as well as Shuqi Ma et al. have presented a solution for determining the load-displacement curve of the bolt head [6-8]. The researchers have not used the load-displacement curve of the bolt head in pullout test for determining bond shear strength.

It is assumed that the bolt shank is a ribbed steel bar that is inserted in a drilled hole. Under a pull load, the bolt interacts with the surrounding rock via a grout (a cement based or resin grout). The rock and grout is considered elastic and failure may occur in the interfaces or bolt shank. The investigation is done in the grouted (bonded) part and the free length is not considered. In Fig. 1, the shear stress distribution along the bolt is shown (before and after bolt shank failure). In Fig. 2, simplified stress-strain curve of the bolt shank is given.

This paper uses the proposed model by Li and Stillborg and gives a solution for determining the load-displacement curve of the fully grouted rock bolt head by considering decoupling in bolt-grout or grout-rock contact and bolt shank yielding. The curve can be used to determine the bolt-grout shear strength parameters.

2. Bolt-grout-rock interaction in elastic condition

In the elastic condition and full bonding the bolt axial stress and displacement and contact shear stress distribution are as follow:

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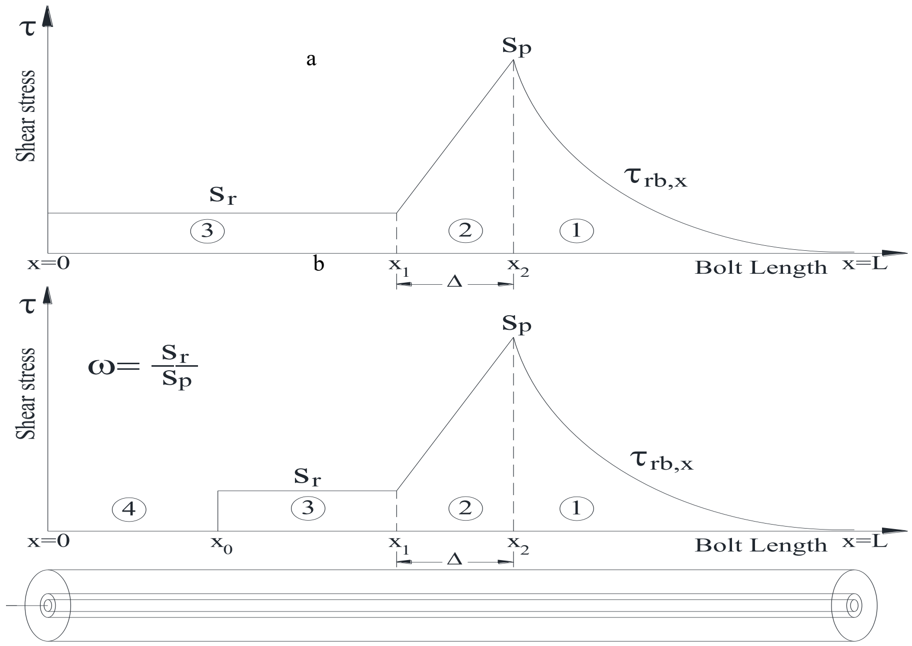

Fig. 1. Assumed interface shear stress distribution besides the rock bolt bond length: a) before steel bar yields, and b) after yielding of steel bar.

$$u_{bx}=\frac{d_b\sigma_0}{2E_b\alpha}e^{-2\alpha\frac{x}{d_b}}\ ,\ \sigma_{bx}=\sigma_0 e^{-2\alpha\frac{x}{d_b}}\ ,\ \tau_{rb,x}=\frac{\alpha\sigma_0}{2}e^{-2\alpha\frac{x}{d_b}} \qquad (1)$$

$$(\alpha)^2=\frac{2G_R G_g}{E_b\left[G_R\ln\left(\frac{d_h}{d_b}\right)+G_g\ln\left(\frac{d_o}{d_h}\right)\right]}$$

Where u_{bx},σ_{bx},$\tau_{(rb,x)}$ are the bolt axial displacement, axial stress, and the contact shear stress in a distance x from the bolt head, respectively. d_b is the bolt diameter, d_h is the hole diameter, h_o is the diameter of a circle in the rock outside which the influence of the bolt disappears, σ_0 is the axial stress of the bolt at the loading point (bolt head), E_{bis} the bolt elastic modulus, G_R,G_g are shear modulus of rock and grout, respectively.

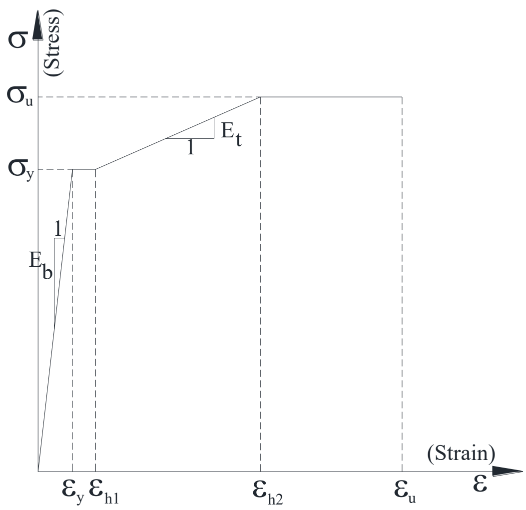

Fig. 2. Simplified stress-strain curve of bolt shank

3. Bolt-grout-rock interaction with yielding bar and decoupling in the contacts

By increasing the applied pull load on the bolt head, four stages are considered for the distribution of shear stresses along with the bolt as shown in Fig. 3.

In each stage, the displacement of the bolt head is calculated by:

$$\delta=\int_0^L \varepsilon dx=\frac{1}{E}\int_0^L \sigma_{bx}dx$$

So the displacement of bolt head in each stage is as:

Stage I:

$$\delta^I=\frac{1}{E}\int_0^L \sigma^I_{b,x}dx=\frac{d_b\sigma_0}{2E_b\alpha}=\frac{d_b p_0}{2A_b E_b\alpha}\Rightarrow p_0=\frac{2\alpha E_b A_b}{d_b}\delta^I \qquad (3)$$

Stage II:

$$\delta^{II}=\frac{1}{E_b}\left[\frac{4P_0}{\pi d_b^2}x_2^{II}-\frac{2S_p(x_2^{II})^2}{3d_b}\left(3-\frac{2(1-\omega)}{\Delta}x_2^{II}\right)\right]+\frac{S_p d_b}{E_b\alpha^2} \qquad (4)$$

Stage III:

$$\delta^{III}=\frac{1}{E_b}\left[\frac{4P_0}{\pi d_b^2}x_2-\frac{2\omega S_p}{d_b}(x_2-\Delta)^2-\frac{2S_p\Delta}{3d_b}\left[\Delta(1-4\omega)+6\omega x_2\right]\right]+\frac{S_p d_b}{E_b\alpha^2} \qquad (5)$$

Stage IV:

$$\delta^{IV}=\delta^{IV,1}+\delta^{IV,2}+\delta^{IV,3}+\delta^{IV,4} \qquad (6)$$

$$\begin{cases}\delta^{IV,1}=\dfrac{S_p d_b}{E_b\alpha^2} & x\in[x_2,L]\\ \delta^{IV,2}=\dfrac{1}{E_b}\left[\dfrac{4P_0}{\pi d_b^2}\Delta-\dfrac{2S_p\Delta}{3d_b}\left[\Delta(1-4\omega)+6\omega(x_2-x_0)\right]\right] & x\in[x_1,x_2]\\ \delta^{IV,3}=\dfrac{1}{E_b}\left[\dfrac{4P_0}{\pi d_b^2}(x_1-x_0)-\dfrac{2S_r}{d_b}(x_1^2-x_0^2)-\dfrac{4S_r}{d_b}x_0(x_1-x_0)\right] & x\in[x_0,x_1]\end{cases}$$

$$\delta^{IV,4}=\varepsilon x_0\Rightarrow\delta^{IV,4}=\varepsilon_{h1}x_0\ or\ \delta^{IV,4}=\varepsilon_{h2}x_0\ or\ \delta^{IV,4}=\varepsilon_u x_0$$

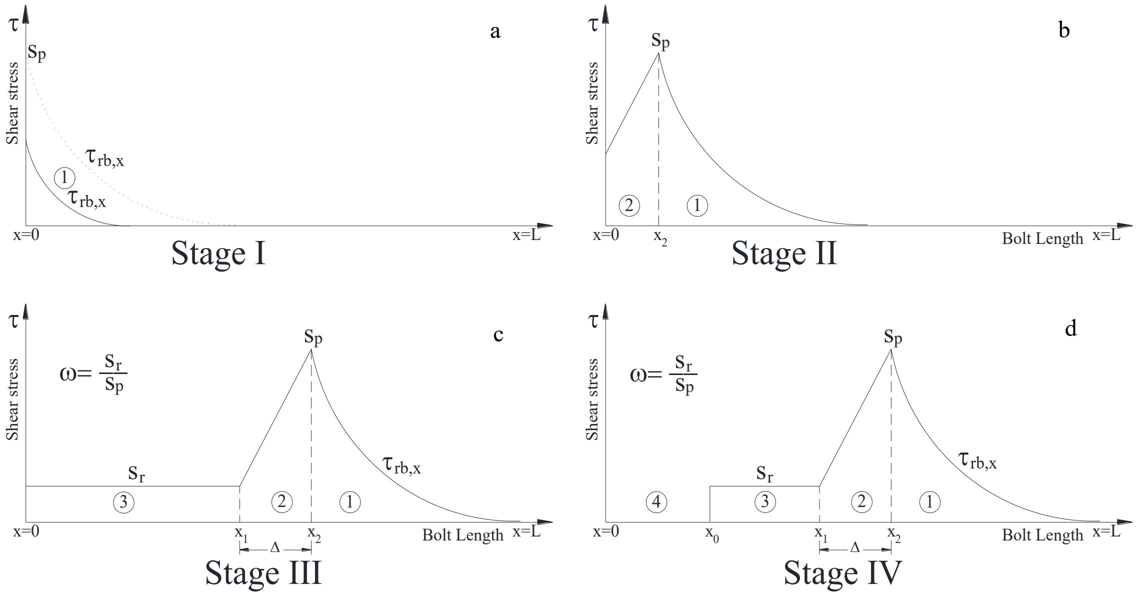

Fig. 3. Considered stages for shear stress distribution; a) Stage I: elastic bar and complete bonding, b) Stage II: elastic bar and partial de-bonding, c) Stage III: elastic bar and de-bonding with residual shear strength, d) Stage IV: elasto-plastic bar with complete de-bonding.

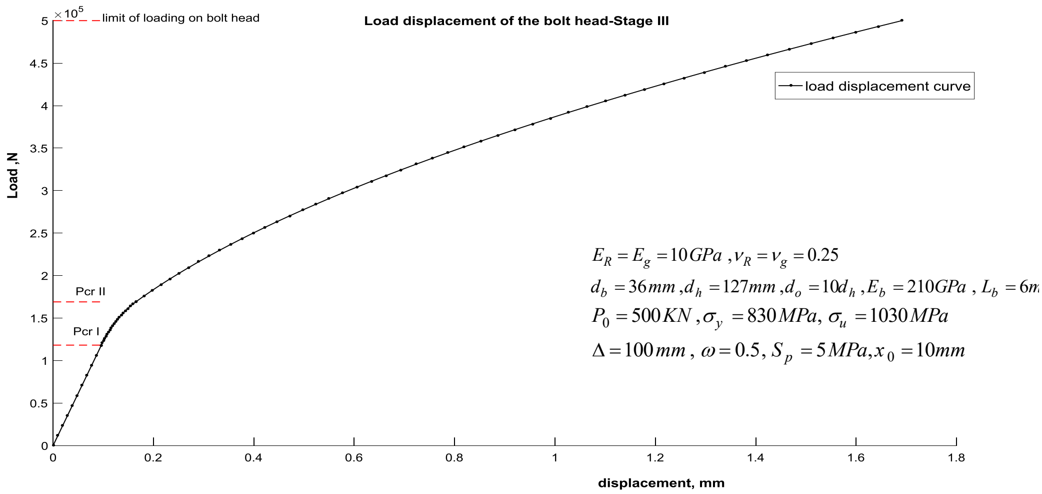

Fig. 4. Considered stages.

Parameters related to bolt, grout, rock, and applied load are known and the bond shear strength parameters Δ, x_0, ω, S_p are indeterminate, which can be defined. Using assumed parameters, the load-displacement curve of the rock bolt head is determined and presented in Fig. 4, in which Stages I, II, and III are clear.

4. Conclusions

This paper investigates the interaction mechanism and load transfer of a ribbed bar rock bolt with grout and rock mass under a pull load. Then the load-displacement curve of the rock bolt head is determined analytically. In this regard, bolt-grout interface failure and bolt shank failure is considered. Two possible failure is taken into account, bolt pullout completely and bolt shank failure.

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