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Modeling of grout crack of rockbolt grouted system

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ABSTRACT

This paper presents a numerical study on the pullout behavior of the rockbolt grouted system. Among the complicated failure modes of the rockbolt grouted system, the crack of the grout is concerned here. A tri-linear cohesive zone model (CZM) is used to simulate the interfacial behavior of rockbolt–grout interface; and a plastic damaged model is adopted for the grout materials. The feasibility of the numerical method is verified by comparing the calculated results with the test observations. The numerical results indicate that two types of cracks of the grout materials can be identified as the inclined crack and the horizontal crack. The inclined crack forms firstly and then the horizontal crack. Both cracks can reduce the interfacial shear stress and thus reduce the load transfer efficiency. Further analysis indicates that the crack of the gout material can induce the obvious drops of load capacity, which is not a safe failure mode. This study leads to a better understanding of the mechanism for rockbolt grouted system.

1. Introduction

Rockbolts have been widely adopted as the reinforced elements in the mining and tunneling engineering to control the deformation and stabilize jointed surrounding rock [1–4]. The rockbolt grouted system generally consists of a bar which is inserted in and anchored to a borehole by means of fixture. The borehole is drilled into the surrounding soil or surrounding rock. And the cementitious grout and resin are always adopted for the fixture. Correspondingly, the rockbolt support systems can be divided into three types: Continuous Mechanically Coupled (CMC) system, Continuous Frictionally Coupled (CFC) system and Discreetly Mechanical and Frictionally Coupled (DMFC) system [5]. Among these systems, the CMC system has become a popular support method due to its speed and simplicity, and the consequent lower labor and costs compared to other support techniques. The rockbolt cementitious grout system is the most common type of CMC.

Extensive field tests, laboratory experiments, numerical and analytical work have been conducted to investigate the pullout behavior of the rockbolt grouted system. Pells early studied the pullout behavior of the fully grouted system [6]. Freeman monitored the loading process of the bolts and the distribution of stresses along the fully grouted rockbolts in the Kielder tunnel [7]. Stillborg carried out a number of tests to investigate the interface failure process [8]. Hyett et al. carried out a series of tests to explore the major factors influencing the bond capacity of the grouted cable bolts [9,10]. From the existing tests, it could be concluded that the properties related to the grout between the rockbolt and surrounding rock play critical roles in the rockbolt grouted system by providing effective stress transfer from weaker rock zone to the stronger one. The shear-lag model (SLM) was earlier adopted to investigate the interaction between the rockbolts and surrounding rock [11,12]. Farmer analytically indicated that the axial load and the shear stress decrease exponentially from the loading point along the anchored length of the bolt [13]. Benmokrane et al. employed a tri-linear bond-slip model for the interaction between the bolt and the grout [14]. Recently, Ren et al. and Laura provided a full-range analytical analysis of the pullout behavior of rockbolt grouted system [15,16]. It should be noted that almost these analytical approaches are focused on the interfacial debonding failure, but the crack of grout is not involved.

Ivanovic et al. also investigated the rockbolt grouted system based on the lumped parameter model (LPM) [17]. Chang et al. studied the interface behavior based on an assumption of heterogeneity [18]. However, these numerical studies also concentrated on the interfacial debonding of the system.

The rockbolt grouted system is a complicated system composted of three kinds of materials and two types of interfaces. Therefore, the load distribution, load transfer mechanism and failure modes of a rockbolt grouted system must be clearly identified to optimize design in practices. The aforementioned test, analytical and numerical works focus on global behaviors of the system or establishing a constitutive relation between tractions acting on

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the surface. Those studies are fundamental and have contributed to a better understanding of the pullout behavior of the rockbolt grouted systems, which led to a higher quality design, a reduction in costs and an increase in safety. However, few of the existing works pay attention to the grout crack failure of grout between rockbolt and surrounding rock has limited the computational effort to deeply and completely understand the pullout behavior of the rockbolt grouted system. Therefore, a two-dimensional finite element model based on the ABAQUS/standard solver is conducted to explore the mechanical performance of cementitious grout material in this study.

2. Numerical model

2.1. Grout material

As mentioned above, the grout plays a critical role in transferring load from the rockbolt into the surrounding rock. Therefore, the properties of the grout material should be carefully modeled. The cementitious grout material is a mixture of sand, water and cement, which is similar to the composition of the concrete material. And thus a plastic damage model for concrete is used to model the grout materials. The equivalent uniaxial stress–strain relationship of grout is needed in this model. The widely accepted stress–strain model under compression condition proposed by Park and Paulay [19] is employed as the uniaxial stress–strain relationship, as shown in Fig. 1(a) and described as follows:

$$\sigma_c = f'\left[\frac{2\varepsilon_c}{\varepsilon_o} - \left(\frac{\varepsilon_c}{\varepsilon_o}\right)^2\right] \tag{1}$$

where f' is the cylinder compressive strength of grout. Strain ε_o, at which the maximum compressive stress is attained, is taken as 0.002. The ultimate strain is taken as 0.0038. The Poisson's ratio μ_c, in the elastic part of grout, usually ranges from 0.15 to 0.22 with a typical value of 0.19 [20]. This typical value is adopted here.

For grout under uniaxial tension, it is modeled as a linear material before the initial crack. And the corresponding strain at the initial crack can be described as:

$$\varepsilon^{cr} = \frac{f_t}{E_c} \tag{2}$$

According to Jendele and Cervenka [21], in the descending stage, the tension-softening model based on an extensive series of tensile tests of the concrete is adopted for the grout material.

$$\frac{\sigma_t}{f_t}\left[1 + \left(c_1\frac{w_t}{w_{cr}}\right)^3\right]e^{\left(-c_2\frac{w_t}{w_{cr}}\right)} - \frac{w_t}{w_{cr}}(1 + c_1^3)e^{-c_2} \tag{3}$$

$$w_{cr} = 5.14\frac{G_f}{f_t} \tag{4}$$

where w_t is the crack opening displacement, mm; w_{cr} the crack opening displacement at the complete release of stress or fracture energy, mm; σ_t the tensile stress normal to the crack direction, MPa; f_t the grout uniaxial tensile strength, MPa; and G_f the fracture energy required to create a stress-free crack over a unit area, N/m. Based on Chen et al. [22], c_1 and c_2 are 3.0 and 6.39, respectively.

The tensile strength of the grout is calculated from the compressive strength by CEB-FIP [23]:

$$f_t = 0.33\sqrt{f'} \tag{5}$$

And the fracture energy G_c is determined by Eq. (6)

$$G_f = \left(0.0469d_a^2 - 0.5d_a + 26\right)\left(\frac{f'}{10}\right)^{0.7} \tag{6}$$

where d_a is the maximum aggregate size for concrete, mm. In the paper, zero is adopted for the d_a since no coarse aggregate is used in the grout material.

If the specimen unloads from any point on the strain softening branch of the stress–strain curves, the unloading response is weakened and the elastic stiffness of the material appears to be damaged. Therefore, a damage variable (d) is employed to account for the progressive degradation of grout. For grout under compressive, the evolution of the compressive damage (d_c) is linked to the corresponding plastic strain $\left(\varepsilon_c^{pl}\right)$ and can be determined by the Eq. (7).

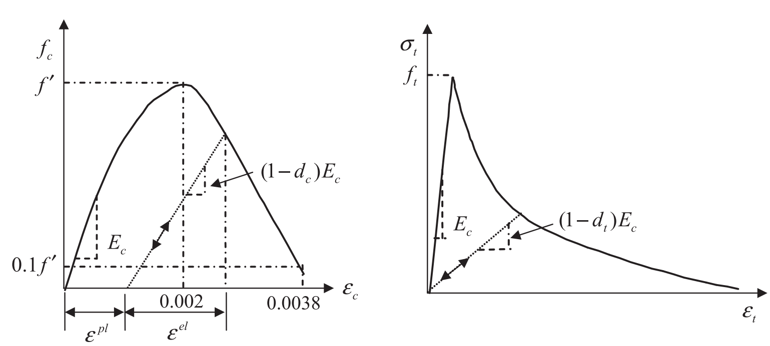
$$d_c = 1 - \frac{\sigma_c E_c^{-1}}{\varepsilon_c^{pl}(1/b_c - 1) + \sigma_c E_c^{-1}} \tag{7}$$

where a value of 0.7 for b_c fits well with the experimental data based on the tests by Sinha et al. [24].

For grout under tension, unloading returns almost back to the origin and leaves only a small residual strain [25]. Therefore, one simple method to define the tensile damage variable is to assume that the unloading path of the stress–strain passes through the origin of the coordinate system, as indicated in Fig. 1(b). And thus, the relationship among the stress (σ), the strain (ε) and the damage variable (d_t) can be described as follows:

$$\frac{\sigma_t}{\varepsilon_t} = E_c(1 - d_t) \tag{8}$$

According to Bazant and Planas [26], the relationship between the crack opening displacement (w_t) and the tensile strain (ε_t) can be described as:



(a) Grout in compression (b) Grout in tension

Fig. 1. Constitutive models.