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Explicit reinforcement models for fully-grouted rebar rock bolts

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ABSTRACT

This paper investigates the explicit use of rock reinforcement in a discontinuous stress analysis model. A series of numerical experiments was undertaken to evaluate the performance of local and global reinforcement models implemented in universal distinct element code (UDEC). This was made possible by calibrating the reinforcement models to the laboratory behavior of a fully-grouted rebar bolt tested under pure pull and pure shear loading conditions. The model calibration focuses on matching different loading stages of the force–displacement curve including the initial elastic response, the hardening behavior and the bolt rupture. The paper concludes with a discussion on the suitability of the different reinforcement models in UDEC including their advantages and limitations. Finally, it addresses the choice of input parameters required for a realistic simulation of fully-grouted rebar bolts.

1. Introduction

Reinforcement is a means of improving the overall properties of a rock mass by using stabilizing elements such as rock bolts, cable bolts and ground anchors. Rock reinforcement is often used as a primary support element, applied during or immediately after excavation, to stabilize the ground and ensure the safe working conditions during subsequent excavation.

The design of reinforcement for underground excavations in rock has not evolved considerably since the 1990s. Design is often based on empirical rules and rock mass classification schemes. This is somewhat surprising given the development and accessibility of sophisticated stress analysis tools. A potential reason for this may be the inherent limitations of how reinforcement is represented in stress analysis software packages. A further reason is related to the difficulties associated with calibrating the numerical models to gain confidence on the implemented reinforcement tools.

Numerical modeling is a valuable tool in the design of underground excavations. Continuum, discontinuum, and hybrid continuum–discontinuum codes are used to determine the resulting stresses and displacements following the introduction of an excavation in a rock mass. The design of reinforcement using numerical models can be either implicit or explicit. An implicit design process has been outlined by Wiles et al. (2004). In this approach, the results of a stress analysis can be used to qualify the ground response into "broken ground" and "cracked ground". The "broken ground" is a ground that has undergone stress-driven failure and represents the dead weight that has to be supported by the reinforcement. The "cracked ground" that is determined by a rock mass damage threshold criterion defines where the reinforcement anchoring begins.

An explicit design process implies that a representative reinforcement has been implemented in a stress analysis model and the results of the stress analysis process are accounting for the role and influence of reinforcement in the design. There are several challenges that have to be overcome in the explicit representation of rock reinforcement in stress analysis models. The first part is the choice of the type of model to be used that meets the objectives of the simulation and the problem definition. The next step is to specifically address how reinforcement is implemented in the stress analysis models. The final step, and the most important one, is how one can attain a successful level of calibration of stress analysis models that can be used with confidence for design problems.

This paper focuses on the explicit representation of reinforcement in a distinct element stress analysis model. The major objective is to critically and systematically evaluate two types of rock reinforcement models, i.e. local and global reinforcements. The

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theoretical basis for these reinforcement models is reviewed as well as a description of the required input parameters. The investigation was based on laboratory experiments of cement-grouted rebar bolts. The paper addresses calibration issues and investigates the behavior of fully-grouted rebar bolts under pure pull and pure shear loading conditions. An assessment of the advantages and limitations of the results obtained using these techniques can provide the basis for the selection of appropriate reinforcement models for a realistic simulation of rock reinforcement in jointed rock masses.

2. Laboratory tests on fully-grouted rebar

Rock bolts are the primary means of rock reinforcement for excavations in rock. Rock bolts reinforce the rock mass by one or more of the following methods: beam building, suspension of weak fractured ground to more competent layers, pressure arch, and support of discrete blocks (Hadjigeorgiou and Charette, 2001). The in situ behavior of rock bolts can best be captured by pull tests. This, however, is influenced by a multitude of parameters. A better understanding of the behavior of specific parameters can be obtained under controlled laboratory experiments. From a numerical perspective, it is convenient to investigate the representation of reinforcement models to well defined experimental data. This can be a prelude to modeling the in situ behavior of reinforcement.

Stjern (1995) conducted a series of laboratory tests to investigate the load–displacement behaviors of different types of rock bolts subjected to tensile (pull) and shear loading. Li et al. (2014) provided a comprehensive review of the performances of both conventional and energy-absorbing rock bolts based on the results of laboratory experiments conducted by Stjern (1995). The test rig used for this purpose consisted of two concrete blocks of a uniaxial compressive strength (UCS) of 65 MPa, which could be moved both laterally (for shear test) and normally (for pull test) to the joint. The sides of the concrete blocks were 0.95 m, which made testing of a full-sized rock bolt with standard anchorage element and bearing plate possible (Stjern, 1995). The pull and shear tests were conducted on fully-grouted rebar bolts, frictional bolts, cable bolts, and mechanical bolts. The complete load–displacement characteristics for the bolts were obtained during the tests using various instruments. The grout for the tests carried out on fully-grouted bolts had a water/cement ratio of 0.33. The bolts were installed according to normal field installation practice for each specific bolt type. To minimize the influence of joint shear resistance during shear tests, a 1 mm thick teflon film was attached to each joint surface.

More recently, Chen (2014) and Chen and Li (2015a, b) reported the results of similar laboratory tests and evaluated the anchorage performance of the rebar bolt and the D-Bolt under combined pull-shear loading condition. Chen (2014) investigated the influence of displacing angle (angle between the pull and the shear displacements), joint gap and host rock strength on the load–displacement behavior of the rebar bolt and the D-Bolt. Fig. 1a shows the front view of the test rig used by Stjern (1995) and Chen (2014), and Fig. 1b shows a sketch of the modified test rig (Chen, 2014).

Fig. 2a and b compares the results of pure pull and pure shear tests on 18 mm diameter fully-grouted rebar bolt conducted by Stjern (1995) and 20 mm diameter fully-grouted rebar bolt conducted by Chen (2014). The rebar bolt tested by Chen (2014) is relatively stronger than that tested by Stjern (1995) in both pull and shear tests. This could be due to the differences in the diameters of the rebar bolts used. However, their load–displacement curves are very similar in pull and shear loading conditions and both consist of three main loading stages. Under both pull and shear loading conditions, the bolts elongate elastically, then yield and harden until they reach the peak load. The bolts continue to elongate until

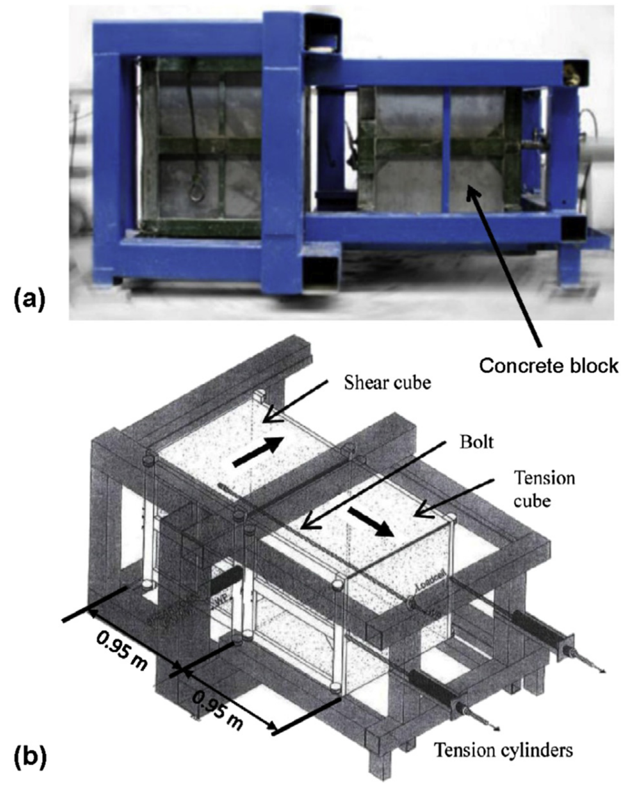

Fig. 1. The test rig for static pull, shear and combined pull-shear tests: (a) the front view of the test rig (after Chen, 2014); (b) an oblique sketch of the test rig (after Stjern, 1995).

rupture occurs. Table 1 compares the results of tests conducted by Stjern (1995) and Chen (2014) in terms of loading stages described above, including initial stiffness, yield load, peak load, displacement at the peak load, and rupture displacement. It is understood from this table and the load–displacement curves shown in Fig. 2 that the yield loads are about 86% and 47% of the peak loads under pull and shear loading conditions, respectively. In this paper, the results of laboratory tests on the fully-grouted rebar bolt reported by Stjern (1995) (i.e. blue curves in Fig. 2) are used for the evaluation of reinforcement models in universal distinct element code (UDEC).

3. Numerical modeling of rock reinforcement

Rock reinforcements can be simulated using either material models or structural elements. Both approaches have been demonstrated to be able to represent rock reinforcement behavior under different loading conditions. However, when simulating an underground excavation and support system, the approach based on material model is computationally intensive, as very fine mesh elements (or zones) are required to properly simulate rock reinforcement. Therefore, numerical representation of rock reinforcement using a material model is usually limited to the simulation of laboratory tests. Structural elements, however, can be used for the simulation of rock reinforcement under both laboratory and field conditions.

Examples of numerical representation of rock reinforcement, using material models, include those by Ferrero (1995), Grasselli (2005), Aziz and Jalalifar (2007), Chen and Li (2015c), and Tatone et al. (2015), who simulated laboratory tests on various types of rock bolts. Ferrero (1995) used a three-dimensional (3D) finite element code to simulate shear test on a rock joint system