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DEM simulation of mortar-bolt interface behaviour subjected to shearing

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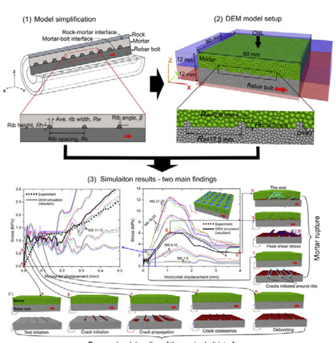
HIGHLIGHTS

- A DEM model was established to investigate the micro-macro behaviours of mortar-bolt interface subjected to shearing.
- This study allows detailed observations of mortar-bolt interface debonding and mortar rupture.
- The effects of particle size distribution and bolt profile configuration on simulation results were discussed.
- The simulation results were validated against experimental measurements.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, a 3D DEM model containing a mortar-bolt interface subjected to shearing was established in the context of the simplified rock bolt model (SRBM) proposed in a companion paper. The DEM model was calibrated against a series of laboratory experiments to reproduce the mechanical characteristics of a cement mortar with a uniaxial compressive strength of 30 MPa. The DEM simulation has led to a detailed observation and an in-depth understanding of the mode II progressive debonding of the mortar-bolt interface and subsequent mortar rupture (due to mechanical interlocking). In addition, the effects of particle size of mortar and profile configurations of rebar bolts (i.e., different rib spacings and rib heights) on simulation results were discussed. The numerical findings in the study were validated against laboratory measurements and a broad agreement was observed.

1. Introduction

Fully grouted rebar bolts have been widely used in the support of fractured rock masses in civil and mining engineering applications due to their proven efficacy and relatively low costs. The inherent strength of a fractured rock mass can be dramatically improved if a suitable rebar bolt is selected and properly installed [1]. Rock bolting has been of interest to practitioners and academics and has thus been studied for quite some time. It is well accepted that the supporting capacity of a fully grouted rebar bolt is largely dominated by its load transfer capacity, which relies on the shear strength of the mortar-bolt or mortar-rock interface and the mechanical interlocking between mortar and bolt ribs [2,3].

Laboratory and in-situ pull-out experiments are often conducted to understand the rock bolting mechanism [1,2,4–9]. It has been identified that debonding failure of the mortar-bolt interface often occurred for a fully grouted rock bolt, which is mainly due to the lower adhesive strength of the mortar-bolt interface in comparison with that of the mortar-rock interface.

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Fig. 1 presents a laboratory-reproduced example of the debonding failure of a mortar-bolt interface. Nevertheless, the progressive debonding process and subsequent mortar-bolt interactions which are not readily achievable and observable in current experimentation are still not well understood, although some attempts exist [5,10]. It is therefore imperative to investigate the micro-mechanism underlying the mortar-bolt interactions subjected to shearing.

In the past decades, some analytical models have been developed to investigate the mortar-bolt interactions, including the well-known bond strength model (BSM) [11], tri-linear bond-slip model (TLBSM) [12] and interfacial shear stress model (ISSM) [13]. Ren et al. [14] proposed a closed-form solution for a better understanding of the debonding mechanism of the mortar-bolt interface. Ma et al. [15] presented an analytical model for a further understanding of the mechanical interaction at the mortar-bolt interface. Cao et al. [2] analytically investigated two major failure modes (i.e., parallel shear failure and dilational slip failure) that often occurred at the mortar-bolt interface. Although those analytical studies have led to a deeper understanding of the rock bolting mechanism, they largely ignored the influence of profile configuration of rebar bolts, which is fundamentally important to the supporting capacity (in the sense of the mechanical interlocking) of a rock bolting system [2]. Additionally, the existing analytical models are unable to account for three-dimensional deformation of bonding materials (i.e., mortar), which is also important for a realistic understanding of the mortar-bolt interaction mechanism.

To date both continuum-based numerical methods [16–19] and discontinuum-based numerical methods [20–22] have been used in the numerical study of mortar-bolt interactions. For example, Li [23] investigated the interactions between steel bolt and concrete based on the finite element analysis, ABAQUS. He et al. [17] proposed and implemented a unified rock bolt model (URBM) into the two-dimensional discontinuous deformation analysis (DDA). The URBM can simulate the debonding process of the mortar-bolt and mortar-rock interfaces at large displacement although the accuracy is mesh-dependent due to the DDA code. Wang et al. [24] investigated the micro–macro failure mechanisms of a bolted joint using the Discrete Element Method (Particle Flow Code 2D). The continuum-based numerical methods have the limitation of investigating micromechanical behaviour of a rock or a solid material, thus the micro-mechanisms underlying the failure process cannot be known [25]. On the contrary, discontinuum-based numerical methods allow an explicit investigation and observation of the micro-crack initiation and propagation, which are more suitable for capturing the micromechanical behaviour of a rock bolting system.

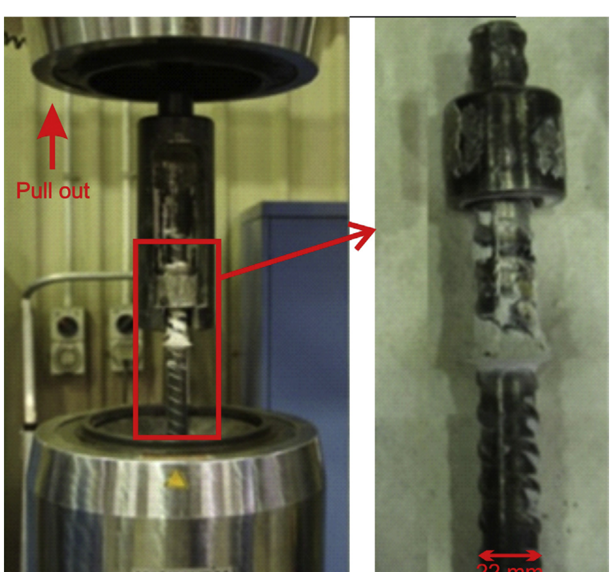

Fig. 1. Debonding failure of a mortar-bolt interface subjected to axial loading. Adapted from [15].

There exist several models which are based on the Discrete Element Method (DEM) for investigating the micro-macro behaviours of solid materials, for example the Universal Distinct Element Code (UDEC), the Particle Flow Code (PFC), and YADE. The DEM is a discontinuum-based numerical technique that defines solid materials as rigid blocks or particles. Comparing with the block-based DEM (such as UDEC), the particle-based DEM (such as PFC and YADE) discretizes solid materials as rigid particles through which the number of degrees of freedom can be decreased, thereby increasing the computational efficiency [26]. The PFC has some additional advantages over other particle-based DEM models. First, it can conveniently model fracture initiation and propagation; moreover it has resolved the intrinsic limitation of the particle-based DEM models (i.e., the low compression-to-tensile strength ratio due to the inadequate interlocking between spherical particles) by implementing the Flat Joint Contact Model (FJCM) which can provide efficient grain interlocking [26]. Furthermore, the PFC allows a detailed description of the interface/joint sliding behaviour by implementing the Smooth Joint Contact Model (SJCM). See a further discussion on this point in Section 3.1. Hitherto the PFC has been widely used in the investigation of the micro-macro failure mechanisms of solid materials, including anisotropic rocks [27], coal [28], porous concrete [29,30] and cement mortar [31,32]. As such, the PFC was used in the present study to investigate the mortar-bolt interface behaviour.

The primary aim of the study is to explore the micro-mechanisms underlying the mortar-bolt interactions. A DEM model was constructed based on three main assumptions: (1) the bond strength of mortar-rock interface is much stronger than that of mortar-bolt interface; (2) the possible chemical effect of the cement composition on the micro-structure of the steel bolt surface is ignored for simplification; and (3) the elongation and twisting of the rebar bolt are not considered (see detailed discussion on these assumptions in the Discussion section). The DEM model was calibrated against a series of laboratory experiments on a cement mortar to reproduce its mechanical characteristics. Simulated results based on the DEM model have been validated against laboratory measurements. This study allows a combined micro- and macro-scale observation of mode II progressive debonding of the mortar-bolt interface and subsequent rupture of the mortar (due to mechanical interlocking).

2. Laboratory experiment

A simplified rock bolt model (SRBM) was recently proposed by Yokota et al. [33] to investigate the mechanical and deformable behaviours of mortar-bolt interfaces in the laboratory. Fig. 2b shows a schematic diagram of the SRBM from a portion of a fully grouted rebar bolt. In the SRBM, the dark area on the bottom represents a small section of the rebar bolt (Fig. 2b), while the light area stands for the mortar. The terminologies for the profile configuration of the rebar bolt are included in Fig. 2b. In the experiment, the rebar bolt deformed along the direction as shown by the red arrows and the mortar was fixed. The simulation performed in this study is aimed at exploring a further understanding of the laboratory experiments performed on the SRBM in a direct shear configuration [33]. For clarification, in this section, the sample preparation and experimental setup procedures are briefly reviewed.