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EFFECT OF PRETENSION ON THE MECHANICAL BEHAVIOUR OF BOLTED ROCK

Mahdi Saadat[1] and Abbas Taheri[2]

ABSTRACT: A stepwise pull-and-shear test (SPST) scheme that numerically analyses the mechanical behaviour of bolted rock joints subjected to simultaneous pull-shear loading. The SPST scheme allows us to identify the optimum pretension stress magnitude at which the bolting system exhibits its ultimate shear capacity. The micro-mechanical properties of grout and bolt-grout interface were calibrated against the laboratory data. The micro-mechanical parameters of rock were calibrated against the laboratory data of coal and shale, and the micro-mechanical properties of rock joint interface were identified by reproducing the laboratory behaviour of coal-shale interface under the direct shear test. Then, the SPST scheme was employed to study the effect of pretension stress magnitude on the macroscopic behaviour of bolted coal. The numerical results revealed that at yield pretension stress magnitude (pull-out test) the rock bolting system could exhibit its ultimate shear performance.

INTRODUCTION

The natural discontinuities form unstable rock blocks, which control the safety and stability of underground coal mine structures. Any damage due to roof fall can hinder coal production and results in severe penalties being imposed on coal production companies. Therefore, reinforcement of unstable blocks is essential in providing a safe environment for mine personnel and promote sustainable coal production.

One of the most widely used reinforcement elements in coal mining is fully grouted rock bolts which are cost-effective and easy to install due to advancements in the bolting technology (He et al. 2018; Jin-feng and Peng-hao 2019). Fully grouted rock bolts form a self-supporting reinforcement system in rock mass through reinforcing unstable rock blocks and improve the shear resistance of bolted rock joints (Ma et al. 2017). The bolt-grout interface contributes to controlling the load transfer capacity of fully grouted rock bolts and the mechanical interlocking between the grout material, and rock bolt ribs enhance the axial strength of the bolting system (Li et al. 2019). The load transfer mechanism of fully grouted rock bolts can be identified using pull-out testing (Jin-feng and Peng-hao 2019). However, the field observations revealed that the failure of bolted rock joints occurs due to combined pull-out and shear forces (Li 2010). Therefore, understanding the failure mechanism and shear performance of fully grouted rock bolts under such mixed loading conditions is crucial for designing safe and stable support system in underground coal mining. Figure 1 illustrates the behaviour of a bolted rock joint in an underground coal mine subjected to combined pull-shear loads. Both pull-out and shear forces contribute to the failure of rock bolts. Figure 2 shows a failed rock bolt which was possibly broken due to combined pull-shear loads (Li 2010).

(Saadat and Taheri 2019b) proposed a SPST sheme to analyse the mechanical behaviour of fully grouted rock bolts subjected to combined pull-shear loads. The SPST scheme employs a discrete element method (DEM) framework augmented with a new cohesive contact model (Saadat and Taheri 2019c). The proposed SPST scheme is able to determine the mechanism involved in enhancing the shear strength of bolted rock joints and identify the pretension stress magnitude at which the rock bolting system exhibits its ultimate mechanical performance. This paper examines the application of the proposed SPST scheme in determining the optimum pretension stress magnitude at which the maximum shear resistance of a bolted coal specimen can be achieved.

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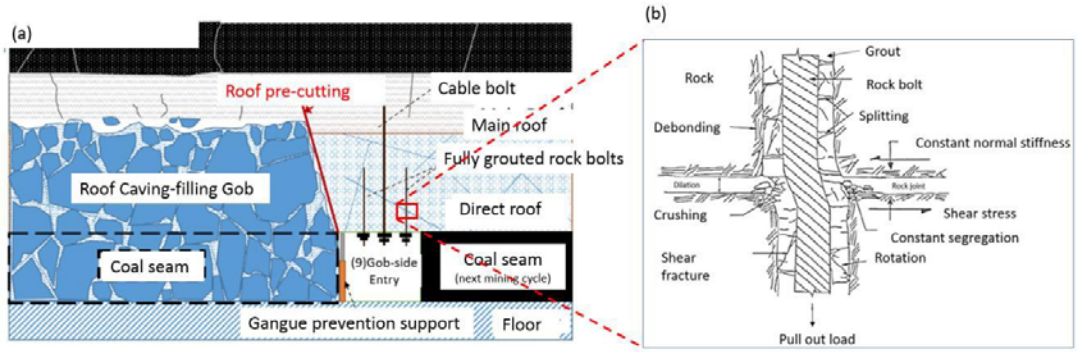

Figure 1: The reinforcement of coal layers in underground coal mining (longwall mining): (a) cross-section of the longwall mine at gob-side entry (modified from Zhu et al. (2018)), (b) mechanical behaviour of bolted rock joint subjected to combined pull-shear load (modified from Indraratna and Haque (2000)).

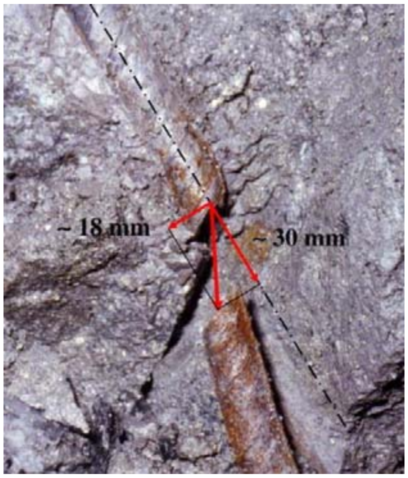

Figure 2: A failed rebar bolt subjected to both pull and shear loads (Li 2010)

COHESIVE CONTACT MODEL IN DEM

A DEM-based cohesive contact model that can be used for simulating geomaterials (e.g. rock, soil, and grout) and the interface between two materials (e.g. bolt-grout interface) (Saadat and Taheri 2019b). proposed model to facilitate the calibration procedure of the micromechanical parameters. In addition, a simplified contact model allows us to reduce the computational time which leads to performing of faster simulations. The details of model formulation and constitutive relationships can be found in the previous research (Saadat and Taheri 2019a, 2019c). Figure 3 illustrates the mechanical behaviour of cohesive DEM contacts in mode I (tension) and mode (II). The DEM model is called cohesive contact model (CCM) when it is used as a material model and the micro-properties of the model contained a subscript of CCM (e.g. C0CCM). When the model is employed as an interface model, which is called it cohesive smooth-joint model (CSJM) and the micro-properties of the model contained a subscript of CSJM (e.g. C0CSJM). it is clear that under the tensile model, the contact exhibits an elastic stage before reaching its maximum strength, which is shown in the graph by the value of initial cohesion (C0) divided by friction ratio (μ) of the DEM contact. Then, the contact experiences a gradual softening stage that is illustrated in Figure 3 as an exponential decay function. Similarly, under shear loading, the contact experience an initial elastic stage, a peak (C0), and finally a gradual softening stage. Notice that the maximum strength of the DEM contact during a shear failure is represented by the initial cohesion. Smooth-joint model (SJM) was used to reproduce the mechanical behaviour of rock joint. The details of SJM constitutive relationships can be found in Bahaaddini et al. (2013).

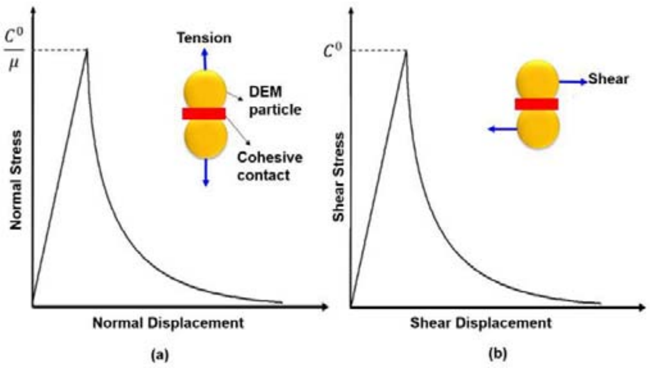

Figure 3: The behaviour of DEM-based cohesive contact model (Saadat and Taheri 2019c) in (a) tension and (b) shear.

MODEL CALIBRATION

The micro-properties of the proposed cohesive model have to be calibrated before employing the model for further parametric study of the bolted rock joints. In DEM analysis, calibration of micro-properties is the essential procedure since a unique set of DEM micro-properties can be regarded as a synthetic rock specimen representing a physical counterpart. The typical methodology for calibrating the micro-properties in PFC-DEM approach is to use the experimental observations of uniaxial compressive strength test and reproduce a similar macroscopic response by altering the micro-properties of the contact model (Bahaaddini et al. 2013; Saadat and Taheri 2019b). The experimental results obtained by Li et al. (2015) on coal and shale were used in the present work. Two different numerical specimens were generated with the dimension of 100 (mm)*50 (mm) and loaded uniaxially to reproduce the macroscopic response of the physical specimens. The details of the calibration procedure of the uniaxial compressive strength test can be found in the previous research of (Saadat and Taheri 2019b). Table 1 shows the micro-mechanical properties of the proposed model after completing the calibration procedure for both coal and shale. The macroscopic response of the numerical simulations, as well as their physical counterparts, are given in Table 2. You can see from Table 2 that the mechanical, macroscopic properties of the synthetic specimens are very close to the experimental specimens, thus the micro-properties in Table 1 represent the synthetic coal and shale specimens and can be used for further analysis of bolted rock joints.

Table 1: The micro-properties of the numerical coal and shale specimens

Micro-property	Symbol	Rock type	
		Coal	Shale
Young's modulus (GPa)	E^0_{CCM}	1.2	4.68
Normal to shear stiffness ratio	k^*_{CCM}	1.25	1.55
Initial cohesion (MPa)	C^0_{CCM}	2.2	32.5
Friction coefficient	μ_{CCM}	0.58	0.55
Dilation coefficient	β_{CCM}	0.25	0.25
Softening parameter (1/m)	κ_{CCM}	5.2e6	18.5e6

Table 2: The comparison between macroscopic properties of numerical specimens and experimental counterparts

Macroscopic property	Numerical values		Experimental values (Li et al. 2015)	
	Coal	Shale	Coal	Shale
Young's modulus (GPa)	1.1	4.8	1.08	4.85
Uniaxial compressive strength (MPa)	6.5	28.2	6.38	28.22
Poisson's ratio	0.28	0.25	0.32	0.26

Notice that the calibration of the coal-shale interface characteristics was needed before performing a direct shear test on the bolted specimen. This is because a set of interface micro-properties are required to accurately mimic the shear behaviour of the coal-shale interface as well as its asperity damage. Therefore, the direct shear test results of coal-shale interface obtained by Li et al. (2015) were used in order to identify the micro-properties of the DEM interface that represents the rock joint in numerical simulations. The details of the direct shear test setup in PFC-DEM can be found in the previous rock bolt investigation (Saadat and Taheri 2019b). The direct shear test was conducted under constant normal load (CNL) condition with a normal stress magnitude of 2 MPa. The smooth-joint model was assigned on the rock joint contacts that represent coal-shale interface, without infill material, in the physical specimen. The micro-properties of the SJM are normal, and shear stiffness and friction ratio (a micro-properties which controls the friction between DEM particles) which are identified as 150 GPa, 65 GPa, and 0.85, respectively. The complete shear stress-shear displacement of the numerical simulation and its experimental counterpart is illustrated in Figure 4. that the calibrated model successfully reproduced the macroscopic shear response of the coal-shale interface that is presented by close agreement between shear stress-displacement curves of numerical and experimental specimens (Figure 4a).

Figure 4b illustrates the asperity damage of the numerical model at different stages of shear loading. During elastic stage (point a) very few micro-cracks appeared in the specimen which is due to early bond-break in critical asperities. At peak shear stress (point b), the accumulation of micro-cracks is observed in the numerical specimen which is due to progressive bond failure of the cohesive contacts. In DEM simulations, the coalesce of micro-cracks form macroscopic fractures which demonstrate the damage propagation in the specimen. After reaching the peak shear stress, the numerical model exhibited a gradual softening response which is due to the incorporation of the softening parameter in the constitutive relationships of the contact model. This allows the contacts to release certain fracture energy which is not achievable in conventional contact models such as parallel bond model (PBM) or Flat-joint model (FJM). After softening response, the specimen exhibits a residual behaviour which is the result of significant asperity degradation (points c and d).

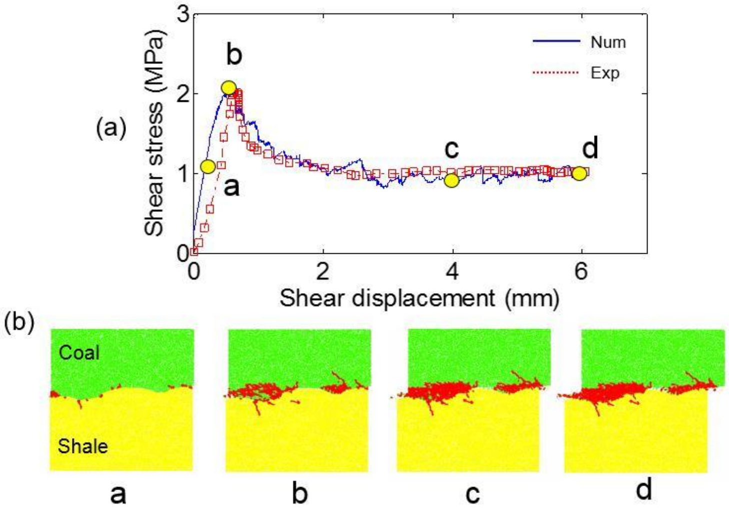

Figure 4: The results of numerical and experimental direct shear tests: (a) shear stress-displacement curves, (b) asperity damage at different stages of shearing in the numerical specimen. Experimental results are from Li et al. (2015).

The mechanical properties of the grout material and bolt-grout interface are calibrated against the laboratory data obtained by Shang et al. (2018) and the details of the calibration procedure, as well as the values of micro-properties of CCM and CSJM, are given in Saadat and Taheri (2019b).

NUMERICAL ANALYSIS OF BOLTED COAL

Figure 5 illustrates the schematic view of the proposed SPST scheme (Saadat and Taheri 2019b) that is followed in this study to conduct combined pull-shear load test on a fully grouted rock bolt. Three major elements are involved in the SPST test setup: rock joint, rock bolt, and grout. The proposed SPST scheme involves two main steps:

(1) Performing a pull-out test on the fully grouted rock bolt and achieving the axial stress-strain curve and damage response of grout material as well bolt-grout interface. At this step, the mechanical behaviour of fully grouted rock bolt is monitored stored at seven different points (i.e. points m, n, o, p, q, r, s in Figure 6) in various loading stages of axial stress-strain curve including linear elastic, pre-

hardening, peak, gradual softening, and residual stages. These seven points represent different pretension stress magnitudes during pull-out testing of the fully grouted rock bolt.

(2) Restoring the numerical files saved in the previous stage in order to conduct direct shear tests. At this stage, seven different direct shear tests are conducted on the bolted rock joints each of which has a different pretension stress magnitude. The macroscopic shear stress-displacement of the bolted rock joints is monitored during the shearing procedure, and the maximum value of peak shear strength is identified. This presents the point at which the fully grouted rock bolt exhibits its ultimate shear performance under combined pull-and-shear loading.

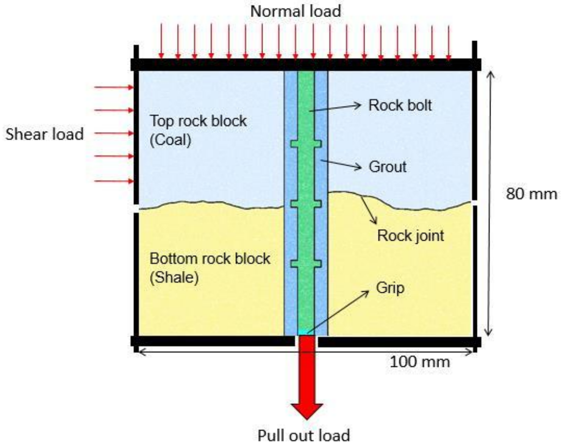

Figure 5: DEM test setup for conducting combined pull-shear load experiment based on SPST scheme.

Figure 6 illustrates the results of the pull-out test. Figure 6a shows the axial stress-displacement response of the fully grouted rock bolt. Figure 6b illustrates the magnitude of normal stress induced on the rock joint interface during the pull-out test. You can see that the stress-displacement curve consists of four different stages (I-IV). The first stage is a linear elastic stage (I) at which the bolting system perform elastically. The stress response of the system at two different points (points “m” and “n”) was monitored, which are equivalent to the pretension stress magnitude at the elastic stage. The stress-displacement curve then exhibits a non-linear response from point “o” to “p” resulting in a reduction in the axial stiffness of the bolting system (stage II). You can see that the rate of increase in the normal stress magnitude showed a significant drop during this stage. From point “p” to “r” the fully grouted rock bolt reproduced a gradual softening behaviour which was due to softening response of grout material and bolt-grout interface (stage III). Finally, from point “r” to point “s” the stress-displacement curve reached a plateau which was due to frictional response of the broken grout (stage IV). You can see that from point “o” the rate of increase in the magnitude of normal stress significantly reduced and this continued until the end of the pull-out procedure (Figure 6b).

Figure 7 illustrates the results of the numerical direct shear tests performed on the bolted rock joints. The rock blocks consist of coal and shale with their micro-mechanical properties were identified by conducting a UCS test (section 3). The micro-mechanical properties of grout and bolt-grout interface were calibrated against laboratory data (Saadat and Taheri 2019b). Figure 7a shows the shear stress-displacement graphs, and Figure 7b illustrates the damage response of the numerical specimens at the end of the shearing procedure. The pretension stress magnitudes that were stored in the previous step (Figure 6) are now restored and the direct shear tests were performed in order to observe at which pretension stress magnitude the rock bolting system exhibits its ultimate performance. You can see that specimen “o” exhibited the highest possible resistance against shearing which means that at the pretension stress magnitude prior to the peak axial strength (point “o” in Figure 6) the bolting system can produce its ultimate performance. It is interesting that although the magnitude of induced normal stress was higher during peak and post-peak stages of the pull-out process, the other pretension stresses from point “p” to “s” failed to return a higher peak shear stress than point “o” that represents the peak stress point during the pull-out test. This may be attributed to the fact that the compressive forces on the rock joint interface grew rapidly during post-peak (Figure 6) that encouraged the rock contacts to come closer to their yielding limits, and consequently the specimen with post-peak pretension stress magnitudes exhibited lower shear resistance with a more severe asperity degradation when compared to specimen at point “o”. The results of this numerical analysis show that the combined pull-shear load significantly affect the shear performance of fully grouted rock bolts and the SPST scheme is found to be an effective methodology in assessing the performance of rock bolting systems.

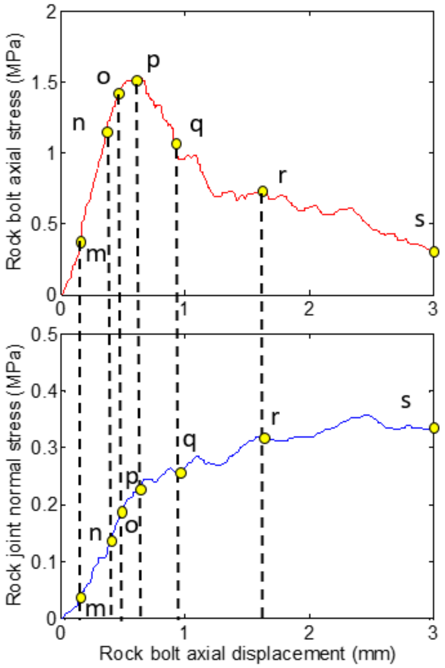

Figure 6: The results of the numerical pull-out test using he SPST scheme (Saadat and Taheri 2019b): (a) axial stress-displacement curve during the pull-out procedure, (b) induced normal stress on the rock joint interface versus axial displacement of the rock fully grouted rock bolt

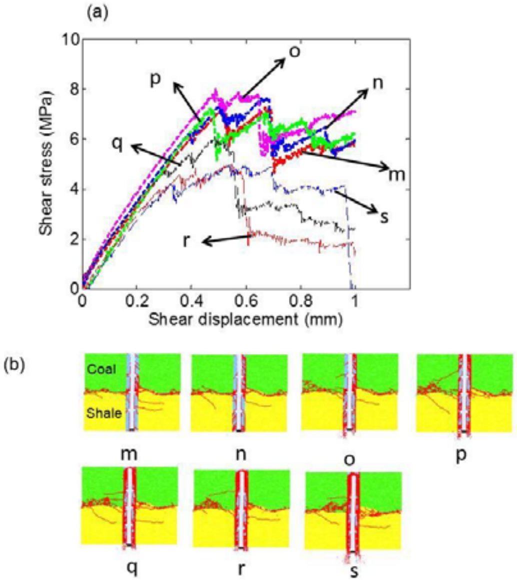

Figure 7: The results of combined pull-shear load tests using the SPST scheme: (a) shear stress-displacement curves, (b) failure of the specimen after completing the shearing process.

CONCLUSIONS

This paper presents the application of the SPST scheme in analysing the behaviour of bolted coal specimen subjected to different pretension stress magnitude. The SPST scheme enables us to conduct combined pull-shear loading tests on bolted coal specimens that is beneficial in identifying the hidden mechanisms involved in the failure of bolting systems in underground coal mining. It was observed that the fully grouted rock bolts experienced four different stages during the pull-out procedure, and the monitoring results revealed that the pull-out load (axial force applied on the fully grouted rock bolt) induces normal stress on the rock joint interface that shows an increasing trend during the pull-out procedure. With the failure of grout material and bolt-grout interface, the increasing trend slowed down but still showed an upward trend which was due to a transition from cohesive softening to the frictional softening response of grout material. The numerical analysis also revealed that the rock bolting system delivered its ultimate shear performance at yield pretension stress magnitude. The proposed SPST scheme has provided an efficient numerical framework that can be employed by mining engineers for carrying out realistic experiments (i.e. combined pull-shear loading test) to achieve new insights about the failure mechanism of rock bolting system. This promotes a reliable design outcome and increases the safety of mining operations.

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