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A new doubly enriched finite element for modelling grouted bolt crossed by rock joint

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ABSTRACT

A doubly enriched finite element (DEFE) procedure has been developed by introducing strong displacement discontinuities in the form of rock joints and reinforcement affect in the form of rock bolts. The proposed procedure extends the concept of extended finite element method (XFEM) and enriches the nodes of an element for determining displacements and stresses of bolt rod as well as displacement jumps and tractions of rock joint. The paper elaborates on the theoretical development of this procedure and derives stiffness matrix of a DEFE using variational approach. The stick-slip behaviour of joint, yielding of rock mass as well as grout material have also been implemented in the DEFE procedure. The paper also provides verifications of this procedure by solving two known examples, (i) direct shear test performed on a bolted joint sample-experimental verification, and (ii) reinforcement of a joint located in the vicinity of a circular tunnel-analytical verification.

1. Introduction

Rock bolts have been widely used as a primary support system to stabilize the rock mass around tunnels, underground mine galleries, slopes and others structure made in rock masses. The ability of rock bolts in reinforcing the rock mass is well known from laboratory tests as well as field experiments, however, modelling of its behaviour is complex if interaction mechanisms between rock, joint, grout and bolt are to be considered. In general, rock bolts reinforce rock masses through restraining deformation within rock masses [1] and reduces the yield region around the excavation boundary. During the last four decades, different types of rock bolts have been practiced, out of which fully grouted active/passive bolts were the most common types. For a fully grouted passive rock bolt installed in deformable rock masses, a neutral point exist on the bolt rod, where shear stress at the interface between the bolt and grout material vanishes. Based on these concepts, shear stresses and axial loads developed in a bolt rod are analytically formulated by many researchers who consider the effect of faceplate at the free end of the bolt [1,2]. Bolt grout interactions around a circular tunnel in Hoek and Brown medium have been formulated analytically considering a bolt density factor [3]. Considering different approaches to bolt performance Stille et al. [4] presented a closed form elastoplastic analytical solutions of grouted bolts. Based on shear lag model, Cai et al. [5] derived an analytical solution of rock bolts for describing the interaction behaviours of rock bolt, grout material and rock mass. In addition, recently, Carranza-Torres [6] presented closed form solution of elastic rock bolt in elastoplastic rock mass for grouted and anchored rock bolt. In his work, stiffness and strength of grout material are assumed to be infinitely high and hence, there is virtually no shear displacement in rock bolt interface. Osgoui and Oreste [7] presents an elastoplastic analytical solution of an axi-symmetrical problem for a circular tunnel reinforced by grouted bolts.

In numerical modelling context, Brady and Lorig [8] numerically analyzed the interactions of bolt grout in Mohr–Columb medium using finite difference method (FDM) and showed that radial displacement, peak tangential stress and yielded region would reduce due to the installation of grouted bolts around a circular tunnel. FDM technique has also been used for solving differential equation, which governs the interactions between rock bolt and grout material [2]. d'Avila et al. [9] proposed embedded finite element method for reinforcing curved layers and concrete structures, respectively. Feenstra and Borst [10] has proposed a numerical procedure for interaction of concrete and reinforcement (dowel action) considering trilinear bond behaviour. A three-dimensional elasto-viscoplastic constitutive model has been derived [11] to take special attention of bolts behaviour at a joint. Sadek and Shahrour [12] presents the formulation and verification

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of a 3D embedded beam element intended for numerical modelling of three dimensional problems in reinforced geomaterials.

The reinforcement effect of rock bolts depends not only on bolt axial and shear resistance, but also on the characteristics of rock mass. In the above mentioned literatures, rock bolts are mostly considered to be installed in continuous rock mass. In jointed rock mass where a discontinuity exists in the form of joint, fault or fracture plane, bolt may also behave like 'dowel' giving rise to bending resistance in addition to shear resistance. A fully-grouted un-tensioned bolt intersected by a joint or discontinuity could influence the shearing of a joint and also increase the bolt resistance. The increase in bolt resistance can occur due to (i) increase in axial and shear force in the bolt rod, and (ii) 'dowel' like behaviour of the bolt. The increase of the axial tensile force in the bolt is caused due to relative movement of the joint planes and the maximum value may occur right at the intersection point. The 'dowel' effect causes resistance to the shear movements of the joint and as a result bolt may penetrate into the surrounding grout. The bolt in turn experiences higher shear force and bending moments. Fig. 1 depicts a schematics of the dowel effect of bolt rod due to joint movement.

Several works have been published on this problem in the last twenty years and these works can be divided broadly into two groups, (i) determination of the maximal resistance provided by the bolt and (ii) understanding the mechanism of behaviour of the bolted joint from initial state to the failure of the bolt rod. The first group of works considers an equivalent material which behaves in

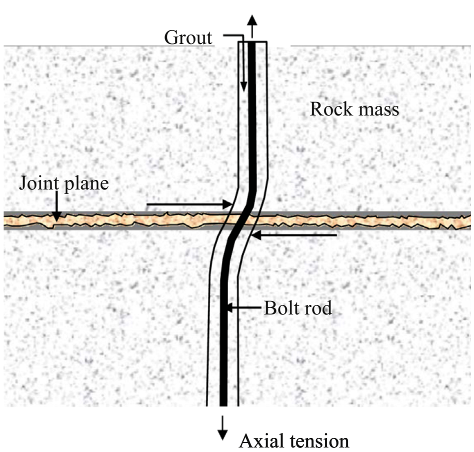

Fig. 1. Dowel action at shear joint in rock mass.

effectively the same way as the reinforcement of rock mass. Such an approach illustrated by Gerrard and Pande [13] for simple loading conditions, does not take into account of "dowel action" of the bolt. In most of the cases, only axial tension of the bolt is determined. In order to evaluate the dowel effect of bolt, Bijurstorm [14] has proposed a series of formulae to determine "dowel action" which takes care of a joint intersected a bolt perpendicularly. St. John and Van Dillen [15] developed a three-dimensional rock-bolt element considering tangential stiffness of the bolt and the grout. Brady and Lorig [8] suggested an element with two springs, one parallel to the local bolt axis and one to it's transverse direction. Aydan [16] has developed a special bolt joint element with special consideration for both the axial and the shear stiffness considering DOFs of rock mass and 2 additional DOFs representing the steel bolt. Since then, many researchers have modified and improved this type of rock-bolt in coupled form. Details of this rock-bolt element and some of its modifications can be found in [17]. Egger and Pellet [18] have defined an interface element based on the stiffness matrix of an interface element representing the rock joint introduced by Ghaboussi et al. [19]. In that case, the interface element thickness corresponds to the distance between two plastic hinges in the bolt. Marence and Swoboda [20] have introduced a Bolt Crossing Joint (BCJ) element by assigning different coordinates for the bolt nodes and the nodes of rock-grout interfaces, thus resulting in different displacements for the bolt and the rock at the bolt-joint intersection. In the numerical formulation, they have assumed that along the bolt length, rock mass cater constant transversal reaction force.

Extended finite element developed by [21–23] has been successfully applied in modeling rock joints [24,25]. This paper extends the concept of XFEM by incorporating elasto–plastic behaviour of rock bolt as a reinforcement element and joint as discontinuity plane. The bolt behaviour is modelled much like beam on solid foundation and hence, dowel action of bolt is included into the formulation. Nodes of an element is enriched twice for joint as well as for bolt and stiffness matrix of this doubly enriched finite element (DEFE) has been derived using variational approach. Elasto–plastic behaviour of rock as well as joint are implemented considering Mohr–Coulomb criterion. The efficiency of DEFE procedure has been performed by solving two known examples (i) experimental verification: direct shear test of a jointed rock sample with bolt reinforcement based on the work conducted by Spang and Eager, 1990 [26], and (ii) analytical verification: a circular tunnel constructed in rock mass where a discontinuity plane exists in the vicinity of a tunnel boundary and bolts are installed to reinforce it.

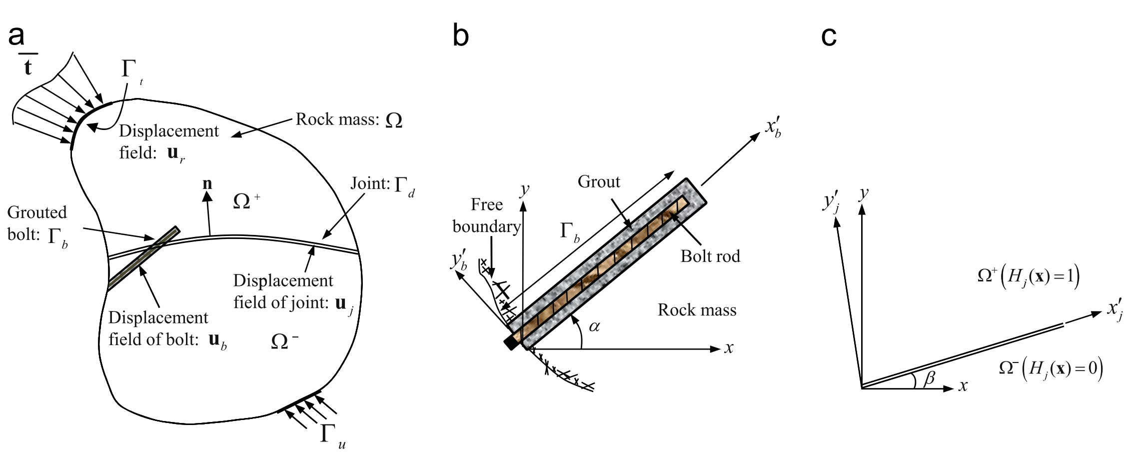

Fig. 2. Domain of definition and notation of (a) rock-bolt-joint, (b) bolt axis and (c) joint axis.