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A finite element framework for modeling internal frictional contact in three-dimensional fractured media using unstructured tetrahedral meshes

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Highlights

- Frictional contact of multiple interacting and intersecting 3D fractures is modeled.
- A square-root singular variation of the penalty parameter reduces traction error.
- Stress intensity factors for contacting cracks are validated against analytical solutions.

Abstract

This paper introduces a three-dimensional finite element (FE) formulation to accurately model the linear elastic deformation of fractured media under compressive loading. The presented method applies the classic Augmented Lagrangian(AL)-Uzawa method, to evaluate the growth of multiple interacting and intersecting discrete fractures. The volume and surfaces are discretized by unstructured quadratic triangle-tetrahedral meshes; quarter-point triangles and tetrahedra are placed around fracture tips. Frictional contact between crack faces for high contact precisions is modeled using isoparametric integration point-to-integration point contact discretization, and a gap-based augmentation procedure. Contact forces are updated by interpolating tractions over elements that are adjacent to fracture tips, and have boundaries that are excluded from the contact region. Stress intensity factors are computed numerically using the methods of displacement correlation and disk-shaped domain integral. A novel square-root singular variation of the penalty parameter near the crack front is proposed to accurately model the contact tractions near the crack front. Tractions and compressive stress intensity factors are validated against analytical solutions. Numerical examples of cubes containing one, two, twenty four and seventy interacting and intersecting fractures are presented.

Keywords: Frictional contact; Three-dimensional crack; Augmented Lagrangian method; Fracture network; Stress intensity factor; Domain integral

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1. Introduction

Understanding the mechanical behavior of heavily cracked materials under different mechanical and thermal loads is of vital importance and great interest to a variety of fields, including material science, geothermal energy

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production, mining engineering, oil and gas reservoir engineering, and structural and earthquake engineering. Geological formations are examples of fractured media at large scales, where rock joints have been shown to extend to lengths ranging from hundreds to thousands of meters [1]. Pre-existing natural fractures in rock masses act as local points of mechanical weakness, and as main flow pathways, and therefore control not only the deformation and strength behavior of the rock mass, but also its flow [2–4] and transport [5] properties. Experimental and numerical investigations show that normal closure and shear dilation can significantly change the fracture transmissivity [6,7]. Fluid flow in fractured rock masses is therefore strongly stress-dependent, with regards to the magnitude and orientation of principal permeabilities [8,9]. Accurate prediction of fluid pressure and solid deformation in fractured rocks, therefore, requires hydro-mechanically coupled models with the ability to resolve normal and shear components of contact tractions acting on the fractures [10].

An exact geometric representation of naturally fractured media is challenging for two main reasons. The first is related to the matter of scales and fracture size distribution. Observations suggest that fracture size is governed by power-law scaling models, spanning orders of magnitudes of length scales [1]. The second issue is fracture characterization, for which non-invasive methods to map fractures *in situ* have yet to be developed for more accurate fracture representations. Stochastic models are therefore required to investigate deformation/flow characteristics of fractured media. Stochastic models often use idealized fracture shapes [11,12], based on a statistical description of parameters such as distributions of size and orientation [13,14]. Models that rely on an explicit representation of fractures, as opposed to a continuum formulation, have been termed Discrete Fracture Network (DFN) models [15,16]. The concept of DFN was first introduced by Long et al. [17] for homogenizing complex fracture networks, and has been extensively used for flow/transport applications [8,18–21]. Nevertheless, despite great geometrical simplifications, this type of modeling approach is routinely applied to estimate effective values of engineering parameters relevant to fluid flow, e.g. permeability, [22] as well as mechanical deformation, e.g. Young's modulus [23–26].

The majority of numerical simulations of fracture networks have been conducted using discrete element method (DEM), whereas the use of the finite element method (FEM) has been limited to a few studies. DEM has also been very popular in simulating fracture growth and fragmentation of brittle solids, such as granular materials and rock and concrete [27–30]. DEM generally treats the fractured medium as the assemblage of separated blocks formed by connected fractures, solves the equation of motion for the blocks, and updates the contact between the block as a consequence of the motion and deformation of the blocks [31]. The distinct element method introduced by [32], with the commercial computer codes UDEC and 3DEC for 2- and 3-D problems [33,34], and the discontinuous deformation analysis (DDA) proposed by [35], have been the main approaches for analyzing the deformation and permeability of fractured rock masses [36,37,8,18]. DDA uses standard FEM meshes over blocks, and employs the penalty method for enforcing the contact constraint between blocks. A similar development to DDA is combined FEM/DEM, introduced by [38], which considers not only the block deformation but also fracturing and fragmentation of the rocks [39]. The application of DEM in modeling fracture growth and fragmentation entails the following difficulties: (1) Time-consuming and error-prone calibration of micro- to macro-properties must be performed for each material individually. Thus, elastic mechanical properties such as the Young's modulus and Poisson's ratio cannot be directly used to model elastic deformation. Moreover, the calibrated properties are scale- and mesh-size dependent [40]. (2) Fractures are not explicitly defined; in fact, they are modeled as the lack of cohesion between the particles in the material. (3) For fragmentation purposes, the materials often artificially behave as particulates or agglomerates. Therefore, 3D fragmentation simulations and qualitative pattern evaluation are scarce in relation to the maturity of DEM, possibly due to the lack of realism caused by the absence of a fracture mechanics-based crack growth models. The property calibration can be avoided by using an impulse-based method, which can be enriched with energy-conservative tracking to ensure energy conservation during contact [41,42]. Regarding the application of DEM in deformation and flow response of fractured networks, the following drawbacks are highlighted: (1) Isolated fractures are ignored when using DEM in modeling the fracture networks, and fractures are only modeled as the boundaries of isolated blocks; (2) The deformation inside blocks and the contact forces between the block are roughly approximated, as explicit methods are generally used to solve the balance equations. (3) The high stress gradients near the cracks cannot be captured accurately, and the variation of contact tractions over the contact surfaces is estimated roughly. The deformation of fracture surfaces, which controls the aperture change within fractures, is also only roughly estimated.

In contrast, the finite element method is able to capture the high gradient stress state near the crack, and can provide very accurate contact tractions based on implicit methods. Advantages of FEM for modeling fracture networks