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Finite element analysis of blast-induced fracture propagation in hard rocks

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ABSTRACT

This paper presents a numerical analysis based on the finite element method to simulate blast-induced hard rock fracture propagation. Three different approaches are compared: the extended finite element method, with a cohesive zone model to represent the growth of fractures; the conventional finite element method using a remeshing technique and based on the linear fracture mechanics; the element deletion method to simulate a rock fragmentation process. The rock mass is a sound granite that remains linear elastic right up the breakage. Two numerical examples are presented in order to discuss the advantages and limitations of each approach.

1. Introduction

Rock blasting is generally carried out by drilling into a rock mass, charging the blastholes and firing the igniters located in cylindrical charges. The detonation waves propagate with high velocities (between 2000 and 7000 m/s depending on the type of explosive), which justifies the assumption that the overpressure of the explosive gases begins to act on all points of the blasthole walls simultaneously. The energy released in the explosion is converted into two main forms that are responsible for rock fracturing, creating new cracks and widening the already existing ones: blast-induced stress waves (dynamic load) and the overpressure of the explosive gases (quasi-static load). There is no clear indication on how much energy is converted into stress wave energy, how much is available as high-pressure gases and how much is lost to other sources such as temperature increase, air blast and smoke. The energy partition will depend on the type of explosive, with TNT (trinitrotoluene) and like explosives classified as high in stress wave and low in gas production, while ANFO (ammonium nitrate/fuel oil) and others are considered high in gas production and low in stress wave energy [1].

The blast-induced P waves that travel out into the rock mass provoke sudden increases in the normal compressive stresses along the radial direction and normal tensile stresses in the tangential direction. Crushing of the rock adjacent to the blast hole occurs whenever the resulting compressive stresses exceed the rock compressive strength and a system of radial fractures, emanating from the drill hole, arises as consequence of the high tangential tensile stresses. Since the problem geometry is generally bounded by a free surface (a soil-air interface), compressive P waves reflect back from the free surface as tensile P waves, providing an important contribution to the rock fracturing, in addition to S waves generated by a modal conversion phenomenon [2]. These reflected waves, by their turn, will give rise to new S and P waves due to a multiple reflection mechanism that involves both the free surface and the surfaces of the growing fractures.

The region of dense radial fracturing around the blast hole extends to a distance that depends on the amplitudes of the stress waves, the mechanical properties of the rock and the characteristics of the explosive such as detonation velocity, type of contact between the charge and the blasthole walls. Reports in the literature [3–5] suggest that when ANFO explosive is used this region generally extends between 4 and 8 blasthole radiuses away. There is not practical interest in using high-intensity explosives that will generate very high pressures on the borehole walls. The crushing and the radial fracturing of the nearby rock will consume energy, but will only contribute with a very small volume of excavation, besides producing unnecessary damage to the rock surfaces and affecting the strength and stability of the remaining material.

Beyond the region of severe damage, some main fractures continue to grow around the blasthole perimeter. In the literature, there is no agreement about the number of dominant fractures but some numerical results [6,7] reported the existence of 8–12 dominant fractures around the blasthole when TNT explosive is employed. The number of dominant fractures depends on the char-

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acteristics of the explosive, represented by the shape and duration of the pressure pulse applied on the borehole walls [8].

The fracturing of rock masses can be numerically simulated by the conventional finite element method (FEM) but changes in the fracture topology with time will require remeshing of the entire domain, a severe limitation for situations of fracture propagation involving complex geometries. The use of adaptive remeshing schemes may also be awkward to implement because of the large computational burden and the consideration of multiple fractures will make remeshing almost intractable and inapplicable.

The extended finite element method [9] (XFEM) is an alternative approach that is particularly useful for the approximation of solutions with severe non-smooth characteristics in small parts of the domain. The finite element space is enriched with discontinuous functions that give a greater accuracy and computational efficiency to the numerical solution when compared to the conventional FEM applications. Furthermore, the mesh is not required to match the geometry of the fractures since they are not physically represented. XFEM is a very attractive and effective way to simulate the propagation of fractures along an arbitrary, solution-dependent path that eliminates the need for remeshing.

This paper investigates the dynamic fracturing of a sound rock mass, admitted as an isotropic and homogeneous material that remains linear elastic right up the moment of breakage. The behavior of hard rocks containing a large percentage of quartz closely corresponds to this material behavior, such as granite. Three methods are compared in this research: the extended finite element method (XFEM), the conventional finite element method (FEM) using a remeshing technique and the element deletion method that simulates the evolution of a rock fragmentation process.

Different types of numerical methods may be also useful to investigate the dynamic fracture propagation in solids. Among others, can be mentioned the molecular dynamic simulation [10], meshfree methods [11], the discrete particle method [12] and a version of the lattice model where a network of truss elements is used in the zone where the fracture process is expected to take place and a FEM element mesh may be considered in the surrounding areas [13].

The blasting effects on the rock immediately around the drill hole (crushed zone) are ignored and fracture propagation is considered due to the blast-induced stress waves only. The initial stresses existing near the blasthole are also neglected since the stress increments generated by the detonation are admitted much larger than the original stress state.

The elastodynamic problem is formulated under plane strain condition, an assumption that is approximately satisfied only at the plane normal to the longitudinal axis of the cylindrical blasthole passing through its mid-length; a true three-dimensional simulation would have been very complex, lengthy and expensive for the time being.

2. Extended finite element method

The main concept in XFEM is to enrich the usual finite element space with additional degrees of freedom that allow fractures to open and increase the accuracy of the approximation near the fracture tip. The functions in the XFEM space have the general form [14]:

$$u(x) = \sum_i u_i \varphi_i(x) + \sum_j b_j \varphi_j(x) H(x) + \sum_k \varphi_k(x) \left(\sum_{\ell=1}^{4} c_k^\ell F_\ell(r(x), \theta(x)) \right) \tag{1}$$

where $\{\varphi_i\}$ are the conventional interpolation functions, *H(x)* the Heaviside function associated to the current fracture geometry, $\{b_i\}$ the enrichment degrees of freedom associated with fracture separation away from the tip, $\{c_k^\ell\}$ the enrichment degrees of freedom associated with near-tip displacement and $\{F_\ell(r,\theta\}$ the asymptotic branch functions expressed in polar coordinates, from the fracture tip, as:

$$\{F_\ell(r,\theta\} = \{\sqrt{r}sin(\theta/2), \sqrt{r}cos(\theta/2), \sqrt{r}sin(\theta/2)\sin(\theta), \sqrt{r}cos(\theta/2)\sin(\theta)\} \tag{2}$$

The sum over i in Eq. (1) is taken considering all the nodes in the mesh while the set of nodes j over which the second sum is performed contains all the nodes belonging to an element entirely cut by the fracture. The set of nodes k is built in such a way that it contains all nodes located within a certain distance from the fracture tip [15,16].

XFEM requires additional degrees of freedom (enrichment) in order to allow fractures to open. In a region separated by a fracture into two pieces away from its tip, the enrichment is provided by a Heaviside function defined to be 1 on one side of the fracture and -1 on the other side. This technique is easy to implement in the case of a single straight fracture but it is more complicated as the geometry of the fracture becomes irregular. It has been shown [17,18] that the discontinuity in the displacement field with the Heaviside function is equivalent to the addition of an extra element on top of an existing one, a method that has become increasingly popular and is known as the phantom node method.

Consider an element with nodes n_1, n_2, n_3, n_4 (Fig. 1). The fracture Γ_c divides the element domain into two complementary subdomains, Ω_A and Ω_B. In the phantom node method, a discontinuity in the element displacement field is constructed by adding phantom nodes (here labeled $\tilde{n}_1$, $\tilde{n}_2$, $\tilde{n}_3$, $\tilde{n}_4$) on top of the existing nodes. The finite element is replaced by two new elements, referred to as elements *A* and *B*. The connectivity of the overlapping elements is $[\tilde{n}_1, \tilde{n}_2, n_3, n_4]$ for the new element *A* and $[n_1, n_2, \tilde{n}_3, \tilde{n}_4]$ for the new element *B*.

The elements do not shares nodes, and therefore have independent displacement fields. Both elements are only partially active; the active part of element *A* is denoted by Ω_A and the active part of element *B* by Ω_B. The displacement $u(x)$ of a point with coordinates x is computed with the standard finite element interpolation functions $\{\varphi(x)\}$ and the integrations are carried out considering either the subdomains Ω_A or Ω_B depending on the location of the point with respect to the fracture. Closure of the fracture tip is enforced when no phantom nodes are added on the element boundary that contains the tip; thus, the overlapping elements do share nodes and their displacement fields are not completely independent. Since the interpolation functions associated to the enriched elements are the same as for the intact elements, the phantom node method is easy to be implemented, being available in several commercial FEM solvers [20,21].

While XFEM is suitable for additional enrichment of the displacement field around the fracture tip to capture the singular field (third term of Eq. (1)), the method of phantom nodes is only applicable to model cohesive fractures, where the singularity in the stress field is removed due to the presence of a cohesive traction. The discontinuity generally grows elementwise, with the fracture tip located at an element boundary, although variations in the phantom element method may admit the tip inside the finite element [22].

In the cohesive zone model [23–25] the process region is admitted as an extension of the fracture length up to a point called fictitious fracture tip (or mathematical crack tip) in which a specific constitutive law is considered in order to relate stress decreases with increase in fracture opening. The real fracture tip (or physical fracture tip) is the point on the fracture surface where there is no stress and the normal opening is bigger than the critical opening.