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Finite element modeling of rock cutting and its fragmentation process

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ABSTRACT

Rock cutting is a challenging problem from a modeling perspective. The challenges come from the complexity of the physics from the tool–rock interaction to the fracture process and propagation of the quasibrittle rocks. This study was aimed at developing a finite element procedure that was capable of providing reasonable estimates of cutting forces and, at the same time, capturing the essential characteristics of the fragmentation process. Published laboratory rock scratch tests were used as modeling targets since these tests encompass all essential characteristics of rock cutting. Both shallow cuts and deep cuts from a rectangular cutter were analyzed first, followed by modeling of shallow cuts from a disc cutter. It was concluded that rock cutting could be reasonably modeled by using a plasticity-damage model, an element erosion scheme that removes an element when its energy release equals fracture energy, together with a proper selection of modeling parameters.

1. Introduction

Even though rock cutting is at the core of all construction activities involving rocks, it remains a very difficult and challenging problem from the analysis point of view. To remove rocks through cutting involves the tool–rock interaction, the fracture of rocks and the progression of fractures. The characteristics of a cutting tool, the mechanism of cutting, and the properties of the rock all impact on the process. With the limited applicability of simple analytical or approximate solutions,[1–4] numerical modeling is indispensable for gaining a better understanding of the mechanics of rock cutting, to the grasp the evolution of failure, and to the provision of meaningful guides for general application. This study presents a modeling framework within the Finite Element Method (FEM) that not only provides reasonable cutting force estimates, but also captures the associated fragmentation and its progression. FEM has been employed in analyzing diverse engineering problems, and has recently been successfully applied to rock cutting in two dimensional setups and yielded useful insights,[5,6] but it remains a challenging task as the problem in a general setting is complex and many contributing factors and their impacts remain not well understood for tackling rock cutting problems in a consistently credible manner.

The modeling difficulty can be attributed to the fact that from a modeling perspective, rock cutting poses a sequence of difficult problems: A contact problem first arises as a cutter advances and interacts with a target rock. This is followed by the problem of determining when and if the rock would fail. And if the rock does fail, a modeler is subsequently faced with the problem of how to initiate and continue on with the fragmentation process. This sequence of problems then repeats itself each step of the way until a cutting is completed. Moreover, a credible numerical model, first and foremost, should be capable of giving correct modes of failure without a *priori* knowledge. Depending upon the depth of cut, scratch tests, which embody the cutting action by cutters on drag bits, are known to induce two modes of failure on rocks.[7–9] When the depth of cut is shallow, the ductile mode of failure dominates and the material failure is strength govern in which cutting proceeds almost like grinding. Its cutting force exhibits a small level of fluctuation as if a rock undergoes a plastic flow. When the depth of cut is deep, the brittle mode of failure dominates and the material failure is fracture govern. Its cutting force fluctuates in large amplitudes as chips are formed and separated from the sample.

This study presents the construct of an FEM procedure in modeling rock cutting. The objectives of the study are to present a viable FEM modeling framework for general rock cutting analysis. In the process, the issues encountered are identified, and solutions presented. In the following, the rock cutting problem of the study is defined first. This is followed by a discussion on the FEM solution strategy. Decision on a proper way to model fracture and fragmentation is then presented. Salient features of the

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constitutive law adopted and how the calibration was carried out are further given. Details of FEM procedure then follows. Finally an assessment of the credence of the analysis is rendered and implications explored.

To initiate an FEM analysis, a decision first has to be made regarding how the deformation of the material is to be described. This is particularly important since a cutter induces a large deformation in rocks as it pushes through. One way to circumvent potential mesh distortion is to adopt the Euler formulation by "pushing" a material through a fixed mesh in space against a stationary cutter, and it has been shown to work for metal cutting.[10,11]. But this approach does not work for quasibrittle materials such as rocks: For fractures are not explicitly formed but are only identified via zones of lower densities; and that chip formation follows a flow pattern that does not resemble the fragmentation of brittle rocks. A combination of Euler with Lagrange approach, or arbitrary Lagrangian–Euler method, ALE,[12] also is hindered by similar problems. The study therefore adopts the updated Lagrange formulation which updates the geometry after each time step, including the new boundaries created by the use of element erosion. Also the erosion of element would cause the stiffness matrix to be singular, which is circumvented by the explicit solution scheme employed in LS-DYNA.

2. The rock cutting problem

The present study focuses on modeling linear orthogonal cutting of rocks as represented by laboratory rock scratch tests.[7,13] The selection of such a focus was decided based upon, first of all, the availability of test data. Secondly, the test encompasses all essential characteristics of general rock cutting. Thirdly, the simplicity of the test setup makes it a perfect setting for assessing the credence of an FEM analysis developed. Richard carried out extensive laboratory scratch tests on rocks and helped shed lights on the physics of cutting mechanics. In particular, he has carried out both deep cuts and shallow cuts, and obtained both the cutting forces and failure progression images. His data were employed as a basis for validation. However, Richard gave only the uniaxial compression strengths, σ_c, for rock properties and other crucial information needed for characterization was not reported. Fortunately, among the rocks he tested, the mechanical properties of Vosges sandstone were well documented,[14] which thus facilitated a detailed study of the subset of data involving Vosges sandstone. Fig. 1 depicts a typical scratch test set up: The cutter shown has a width of B and advances toward the sample at a fixed depth of cutting, d, slanted at a rake angle θ. A slab cut denotes a cutting setup that the cutter width is no less than the sample width, b, and the cutting width, w, thus equals the sample width, b, and, in such cutting, the problem geometrically is two dimensional. However, a two-dimensional analysis would not yield satisfactory results for modeling a slab cut, as it would become apparent from the discussions that follow.

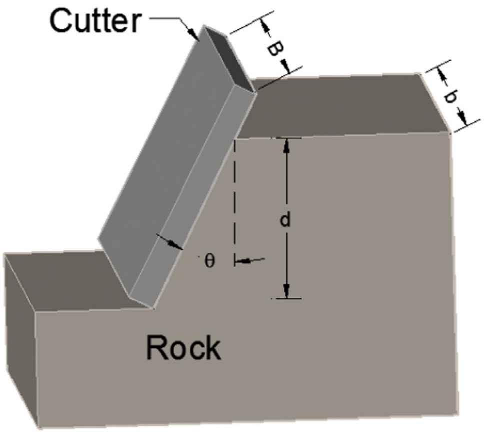

Fig. 1. Layout of a scratch test.

The mechanical specific energy, MSE, is defined as the mechanical energy or work required to remove a unit volume of rock. Not only that MSE is generally used to measure the efficiency of rock drilling and rock cutting, it is also an important measure in terms of the rock cutting modeling[15]:

$$\mathrm{MSE} = \frac{\text{Work by cutter}}{\text{Volume of cut}} \tag{1}$$

In a special case, when the depth of cut is fixed, only the horizontal component of the cutting force contributes to mechanical energy of cutting. With the cutter advancing horizontally over a distance x, the work done by the cutter to rock is $F_H x$, and if the cut volume is considered as the volume swept by the cutter, which is the multiplication of cutter width, w, cutting depth, d, and the travel distance, x. Thus

$$\mathrm{MSE} = \frac{F_H x}{w d x} = \frac{F_H}{w d} \tag{2}$$

where F_H is the average horizontal cutting force over the cutter advance distance x.

For this study, the above equation was applied to test data, while for the FEM analysis the denominator was replaced by actual volume of removal. It is clear that MSE has the unit of energy over volume such as MJ/m^3, but it can also be expressed in terms of stress unit, MPa, per Eq. (2). For a sharp cutter, which refers to cutters that do not have a wear flat section, the energy is completely spent in cutting rocks and MSE, under such a condition, is referred to as the intrinsic specific energy. Extensive tests using rectangular slab cutters have shown that the intrinsic energy serves as a good estimate of the uniaxial compressive strength, σ_c, of rocks.[16,17] This is also the reason why MSE is frequently expressed in the stress unit. The present study modeled sharp cutters in slab cuts first.

3. Fragmentation modeling

To capture the fracture of rocks, fracture mechanics based FEM modeling of rock cutting as a crack propagation problem has a long history.[18] As for the modeling of fragmentation, however, fragmentation involves not only crack formation, but also crack growth and chip formation. The application of fracture mechanics with explicit cracks does not work well for modeling fragmentation from rock cutting. This is mostly because the crack growth and crack interaction can easily become intractable under complex and persistent 3-dimensional loadings. Moreover, the uncertainty about the fracture process zone on the crack growth,[19] and what constitute appropriate crack growth criteria[20] together introduce too many unknowns for the conventional fracture mechanics based approach to be viable.

A simple alternative to explicit crack modeling is to introduce fracture into a plasticity based continuum model, together with an element removal scheme called element erosion in capturing the fracture initiation and growth. Within this framework, a damage index is employed to trace the level of strain softening of a quasibrittle material and determines when fracture occurs. We have investigated the use of several such models within LS-DYNA that included the Concrete Damage model, Johnson Holmquist Concrete model and the Continuous Surface Cap model,[21] CSCM. We have found that the CSCM, even though developed for concrete, works best among the models investigated for rock cutting