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CALCULATIONS OF CRATERING EXPERIMENTS WITH THE BEDDED CRACK MODEL

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The YAQUI/BCM stress wave code is being developed for the oil shale program. Its purpose is to characterize explosive fracture in a brittle, or quasi-brittle, material. YAQUI is a finite difference hydrodynamic code, based on the ALE¹ technique, which we have converted to a solid mechanics code. The BCM (bedded crack model) is the constitutive model. It is a statistical model that describes fracture in terms of the growth of microcracks present in the competent material.

In addition to computer modeling, there is an active program of large-scale field tests in oil shale. In this presentation, we will begin by describing the physical models upon which the BCM is based. Then we will describe calculations of a cratering event in the Colony Oil Shale mine in Colorado. Based on the computer simulations, we will outline the process of crater formation.

Current technology for extracting oil from the rock includes mining the rock, crushing it, and processing the fragments in a surface retort. For environmental as well as economic reasons, we are pursuing an alternate approach in which the rock is broken and retorted *in situ*.

In addition to stress wave propagation, it is crucial to correctly describe fragment size, porosity, and permeability of the fractured rock. Because of these requirements, we have chosen to model the microscopic process of fracture in terms of crack growth rather than to use a macroscopic model based on analogy with plasticity theory.² There are many advantages to this type of approach. The input to the model are physical quantities that can be determined by experiment. Also, by focusing on physical processes, the problem of scaling from laboratory tests to field tests does not arise. Finally, a detailed knowledge of crack statistics can provide a basis for calculating fragment size and permeability.

The approach is similar in concept to the BFRACT model developed at SRI by Seaman et al.³ However, the physical theory on which the BCM is constructed is different. There are three principal elements in this type of approach:

- 1) a criterion for crack growth,
- 2) elastic moduli reduction, and
- 3) a statistical description of the crack distribution as it evolves in time.

Crack growth in the BCM is described by a generalized Griffith criterion.⁴ The standard Griffith criterion⁵ is based on energy arguments and applies to two-dimensional slits in normal tension. We have extended Griffith's analysis to apply to penny shaped cracks in an arbitrary stress field. When the normal stress is tensile, a crack of radius c may grow if

$$\sigma_{zz}^2 + \left(\frac{2}{2-\nu}\right) \sigma_{rz}^2 \geq \frac{4\pi TE}{c} . \quad (1)$$

Here, T is the surface energy of the material, E is Young's modulus, and ν is Poisson's ratio.

What is new and different about our generalized criterion is that it predicts that a crack may grow in normal compression if the resolved shear is sufficiently large. In this case, the crack may grow if

$$\left(|\sigma_{rz}| - \tau\right) \left(|\sigma_{rz}| - 3\tau\right) \geq \left(\frac{4\pi TE}{c} \frac{2-\nu}{2}\right) . \quad (2)$$

Here, τ is the frictional stress between the crack faces, which we take as

$$\tau = \mu |\sigma_{zz}| ,$$

where μ is the coefficient of friction.

The presence of cracks alters the elastic moduli of the material. The effective moduli⁴ are found from static solutions for the displacement field for a body containing a statistical distribution of cracks, and subjected to a spatially uniform, but otherwise arbitrary stress field. The elastic moduli are the elements of a fourth order tensor

$$C_{ijkl} = \frac{\gamma_c}{\gamma} \frac{i \cdot j}{k \cdot l} . \quad (3)$$

For example, for a material containing cracks bedded parallel to the $x - y$ plane, the effective component of compliance

$$C_{zzzz} = \frac{C_{zzzz}^0}{1 + \gamma} . \quad (4)$$

Here C_{zzzz}^0 is the modulus of the material matrix and

$$\gamma = \frac{8}{3} (1 - \nu^2) \overline{Nc^3} . \quad (5)$$

The bar implies integration over the crack density distribution $N(c, t)$.

As the cracks grow, the distribution evolves, and so γ and the effective moduli vary in time. The constitutive relation takes the form

$$\frac{d}{dt} \frac{i \cdot j}{k \cdot l} = \frac{d}{dt} (C_{ijkl}^{-1} k \cdot l) , \quad (6)$$

or

$$\frac{d\sigma_{kl}}{dt} = (C^{-1})_{klij} \frac{dc_{ij}}{dt} - (C^{-1})_{klij} \dot{c}_{ijm,n} \sigma_{mn} . \quad (7)$$

Thus, the constitutive relation has the form of a Maxwell solid with a variable relaxation time.

The initial distribution of cracks is assumed to be exponential--the number of cracks with radius greater than c is

$$N_0 \exp \left(- \frac{c}{\bar{c}} \right) . \quad (8)$$

N_0 and $\bar{c}$ are material constants which are determined by measurement. This is the form assumed in BFRACT. However, the evolution of the distribution function in BCM differs in two essential features from BFRACT.

First, in BCM, only those cracks with radius greater than the critical radius, as determined by the generalized Griffith criterion, are allowed to grow. Thus, the distribution does not remain exponential. This is in contrast to BFRACT in which all cracks grow when the stress exceeds a threshold value.

Second, in the BCM, all cracks grow with the same speed, which is two-thirds of shear wave speed. This is an asymptotic approximation to Mott's result.⁶ The existence of a finite velocity for crack propagation makes strain rate effects an intrinsic feature of the model.

The principal restriction of our model lies in the assumption of bedded cracks. Oil shale is a bedded material, and we believe that we are modeling the wave propagation accurately. However, to predict fragment size and permeability, it will be necessary to allow for cracks of different orientations. We are currently generalizing the model in this regard.

We have simulated many actual cratering events with YAQUI/BCM. In a typical experiment, a 10 cm diameter cylindrical borehole is drilled vertically into the mine floor. The hole is partially filled with explosive, and the top of the hole is grouted. The explosive is bottom detonated, generating a shockwave that fractures the rock, and, depending on scaled depth of burial, usually produces a crater.

Figure 1 shows the initial configuration of a particular experiment, 78-1. The dotted line is the observed crater. The crater is roughly a truncated cone with an apex half-angle of 45°. In Fig. 2, the predicted region of fragmentation is shown with the observed crater superposed. One must distinguish between these profiles, for a fragment will be part of the crater only if it has sufficient vertical velocity for ejection.

The computer simulation predicts the width and general shape of the crater. Also, the YAQUI/BCM is in reasonable agreement with (limited) stress gauge and free surface velocity measurements made in several other cratering experiments. However, the inhomogeneity of the rock--that is, site specific geology,--leads to a large scatter in the data which makes detailed comparisons difficult.

The cratering process can be understood in the following manner. The propagating burn in the explosive produces a conical shock front in the rock. The angle of inclination to the horizontal is the arc tangent of the ratio of detonation velocity to sound speed in the rock. The wave is compressive, and so the fracture is due to shear (Equation 2). In the cratering event 78-1, these speeds are about equal, and so this shock front inclination is about 45° . The maximum shear acting on horizontally bedded cracks is found on a conical surface, also with an half angle of 45° .

The compressive wave produces a heart-shaped region of fracture around the charge (Fig. 3). The wave continues to the free surface where it reflects as a tensile relief wave. The tension produces a spall region of additional fracture. When the two regions overlap, a crater is produced.

In Fig. 4, we show a computer experiment in which the detonation velocity of the explosive is varied, keeping the total energy release fixed. The case with the larger detonation velocity is predicted to form a wider crater, with less damage above the borehole.

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Fig. 1. Initial configuration of cratering experiment 78-1 with final crater profile.

Fig. 2. Calculated fractured region of experiment 78-1. Dotted line shows the actual final crater profile.

Fig. 3. Calculated fractured region of experiment 79-2. The water is formed from a shear failed region and a tensile failed region.

Fig. 4. Computer comparison of fractured regions for two experiments in which only the detonation speed of the explosive varied. The under region corresponds to a higher detonation speed.