FRACTURE MECHANICS APPLICATIONS IN ROCK MECHANICS PROBLEMS

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ABSTRACT

The application of fracture mechanics principles to the solution of rock mechanics problems is the subject of discussion in this paper. Specifically, two examples relating to high energy gas fracturing and oil shale blasting are presented to illustrate the point. In high energy gas fracturing experiments, the way in which elastodynamic fracture mechanics can be used to design the pressure pulse shapes for multiple fracturing around the wellbore is given. In oil shale blasting, the strain rate effect can explicitly be treated in terms of fracture mechanics parameters. This treatment proves to be essential in the development of a damage model which has been used successfully in the evaluation of in situ oil shale retort blast designs.

INTRODUCTION

In many fossil and synthetic resource recovery processes, predictable rock fracturing behavior under rapidly applied loads is an essential ingredient toward their successful applications. The rapid rock

fracture process can be viewed as mainly a result of crack growth. Upon application of the load, existing cracks (e.g., faults, joints, voids and interfaces) are activated while new cracks are initiated. Further pressurization leads to the growth of these cracks to form crack network systems in the rock media. Additional available energy will eventually force the intersection of these systems to form rock fragments and complete the breakage process. The ability of fracture mechanics to account for the behavior of cracks makes it a suitable tool for dealing with rapid rock fracture problems. This has been recognized by researchers (e.g. [1-6]) in the field and various applications have been made.

The purpose of the present paper is to demonstrate the way in which fracture mechanics is used in solving rock mechanics problems. To accomplish this, two specific case studies will be presented. The first one involves high energy gas fracture experiments for enhanced gas recovery from unconventional reserves. This set of experiments is conducted to study the feasibility of using slow burning propellants to tailor pressure pulse shapes in a wellbore such that a prescribed fracture pattern around the wellbore can be achieved[6-8]. A brief discussion on the development of a fracture mechanics model and how it can be used to define pulse-shapes that will lead to desired fracture patterns in the rock is presented in the paper. Detailed description of the model has been given in [6] and interested readers are referred to [6] for further information. The second application is concerned with oil shale blasting in a cratering environment. Fracture mecha nics models with isolated cracks are used to define qualitatively the experimentally observed strain-rate dependent fracture behavior[5].

This observation leads to the development of a continuum damage model which is used to predict the extent of rock damage in oil shale crater blasting[9]. Only dynamic fracture mechanics treatment will be given in this paper. Details of the damage model development have been given elsewhere [9] and will not be repeated here.

HIGH ENERGY GAS FRACTURING

Because of the potential shortage of oil and gas, recovery methods which can enhance production from unconventional reserves are receiving increasing attention. Dynamic stimulation techniques that produce multiple fracturing in a wellbore are being investigated at Sandia National Laboratories [7,8] for enhanced gas recovery. Multiple fracturing appears to be especially promising for stimulating naturally-fractured reservoirs since this may be the most effective technique for connecting a wellbore to a pre-existing fracture network. The emphasis in this research work is on a tailored-pulse loading technique which uses propellants to control the borehole pressure-time behavior to minimize wellbore damage and maximize fracture growth by gas penetration.

Field experimental data in Nevada ash-fall tuff [7,8] indicated three different fracture patterns depending on the shape of the loading pulses. When the loading rate is "fast", rock near the wellbore is crushed by the high pressure such that the wellbore is permanently enlarged. During unloading, a compressive residual stress field is formed around the wellbore which prohibits communication

between the wellbore and the surrounding medium. This compressive stress field is referred to as the "explosive stress cage" and is undesirable for gas recovery purposes. When the loading rate is "slow", a single fracture is produced similar to that of hydraulic fracturing treatments. At the "intermediate" loading rates, no stress cages are formed while multiple fractures from the wellbore are produced. Obviously this is the most desirable situation for gas recovery in naturally-fractured reservoirs. Thus, it is important to determine the proper combination of loading parameters such that multiple fracturing can be consistently produced.

Toward this end, an analytical model has been developed [6] to understand the basic mechanisms which lead to the various rock fracture patterns. In the following, a brief description of the model as well as its application to the gas fracture problem will be presented.

1. Model Description

Fig. 1 shows the geometry of the model which consists of a circular hole embedded in a material of infinite extent. This geometry simulates that of a wellbore situated in a large rock mass. Radial cracks of various sizes are assumed to exist at the edge of the wellbore. In an attempt to show the dependence of the initiation of crack growth on crack sizes under pulse loads, the interactions between neighboring cracks are neglected in this study. Consequently, only two symmetric radial cracks exist in the model, Fig. 1. The radius of the hole is denoted by R while the crack length is given by a. By varying the a/R ratio, the effect of crack size can be isolated and its influence on the initiation of crack growth can be determined.

Fracture mechanics theory, namely the critical stress intensity factor criterion, was used to define the condition for crack propagation. Under a given pulse loading, the time at which crack growth initiates is recorded for each crack size. If smaller cracks are activated before the larger ones, the fracture pattern in the rock is said to be multiple radial fracturing. If the opposite is true, then hydraulic fracturing is said to have occurred. Because the stress cage behavior involves highly nonlinear response of the rock, this model is not suitable for differentiating the boundary between stress cage and multiple fracturing due to its elastodynamic nature. Consequently, the model will be used here only for defining the boundary between hydraulic and multiple fracturing behaviors.

2. Results and Discussions

Since a closed-form solution to the problem in Fig. 1 is not available, numerical solutions based on the finite element method have been obtained. The finite element code HONDO [10] was used to calculate the dynamic stress intensity factor associated with the crack. In order to compare analytical predictions with experimental data, ash-fall tuff properties, Table 1, were used in all calculations for the rock.

Table 1
Ash-Fall Tuff Material Properties [7]

Young's Modulus	5 GPa
Poisson's Ratio	0.26
Fracture Toughness	400 $KPa\sqrt{m}$
Density	1.8 gm/cm^3

Four loading cases corresponding to those of the Gas Frac experiments, Table 2, have been studied. Analytical predictions indicate that aside from GF 1 being a hydraulic fracturing case, the remaining three all have multiple fracturing patterns. As has been mentioned previously, the current model is not capable of predicting the explosive stress cage behavior and thus is not applicable to the GF 3 case. Otherwise, the model predictions agrees very well with the experimental observations for the remaining three cases.

Table 2
Results of Gas Fracture Experiments [7]

	GF 1 "SLOW"	GF 2 "INTERMEDIATE"	GF 3 "FAST"	GF 4 "INTERMEDIATE"
Loading Rate (KPa/μs)	0.6	140	10,000	430
Peak Pressure (MPa)	43	95	200	250
Time to Peak Pressure (ms)	72	0.68	0.02	0.58
Resulting Behavior	HYDRAULIC FRACTURE	MULTIPLE FRACTURE	EXPLOSIVE STRESS CAGE	MULTIPLE FRACTURE

Thus, the validity of the fracture mechanics model in predicting the fracture behavior in rock has been established. Additional calculations will define a design curve on the loading pulse shape for producing multiple fracturing patterns. Such a curve is given in Fig. 2.

The multiple and hydraulic fracturing boundary is given in terms of a band between 40 and 60 KPa/μsec pressure rate and this band is independent of the magnitude of the peak pressure. Note that on the right hand side of the figure there should be another band defining the boundary between multiple fracturing and explosive stress cage behavior. The current model is not capable of predicting this band and thus this boundary is left undefined on the figure. Also on the bottom of the figure, a line is drawn at peak pressure of 10 MPa. This line defines the minimum peak pressure which is capable of initiating the crack growth. This design curve is, of course, only valid for ash-fall tuff material. All available experimental data lend evidence to the validity of this curve. However, more experimental data are needed before this curve can be fully established.

In summary, the application of a fracture mechanics model to the prediction of rock fracture patterns in a pulse loading configuration has been presented. Model predictions compare favorably with experimental data. Further application of the model in design has also been given.

OIL SHALE BLASTING

Fracture and fragmentation of rock lies at the heart of suitable bed preparation for resource recovery techniques as applied to oil shale formations. Effective fracture and fragmentation may be accomplished by proper selection of explosive charges, geometry, and timing. To develop computational predictive capabilities, it is

necessary to incorporate essential physical features into the calculation model. One such feature involves the strain-rate dependence of oil shale under dynamic loading conditions. In spallation experiments, it is shown that the fracture stresses at strain rates of 10^4/s to 10^5/s is on the order of 100 MPa and is insensitive to orientation[11]. In contrast, the static fracture stress is on the order of 5-20 MPa (for competent material), and is quite sensitive to the loading orientation relative to the bedding planes[12]. Fracture stresses ranging from 30-50 MPa have been obtained at intermediate strain rates by torsional split Hopkinson bar techniques[13]. In addition, the size of the fragments have also been observed to be strain-rate dependent.

In an effort to understand the basic mechanisms that lead to the strain-rate dependence of oil shale, a dynamic fracture mechanics model which studies the response of an isolated crack subjected to the action of constant strain-rate tensile loads has been developed[5]. This model is justified since oil shale is known to have an existing flaw structure[14]. The response of an isolated crack forms the basis for statistical treatment of a distribution of flaws. In fact, this is the logical process in the development of a damage model at Sandia National Laboratories for the treatment on oil shale blasting in a cratering environment[15]. In the ensuing discussion, only the dynamic fracture mechanics treatment will be presented. Detailed development of the damage model has been summarized in [15] and interested readers are referred to [15] for further information.

1. The Dynamic Stress Intensity Factor

The strain-rate effect on the dynamic fracture strength of Anvil Points oil shale [14] is studied through the response of an isolated crack subjected to the action of constant strain-rate tensile loads. The impact response of an elastic solid containing a crack and subjected to tensile loading normal to the crack surface has been well characterized and is extensively discussed by Chen and Sih [16] in terms of the dynamic stress intensity factor. Specifically, if a Heaviside load of magnitude σ_o is applied to a crack with a characteristic dimension, a, the functional form of the stress intensity factor, K_1, at the crack tip is,

$$K_1(a,\ t) = \sigma_o \sqrt{a\pi}\, f(C_2 t/a) \qquad (1)$$

where C_2 is the shear wave velocity and t is the time. The response to an arbitrary stress loading function, $\sigma'(t)$, may then be expressed in terms of the convolution integral as

$$K_1(a,\ t) = \sqrt{a\pi}\int_0^t \sigma'(s) f(C_2(t - s)/a)ds \qquad (2)$$

For constant strain rate loading the stress rate is constant, $\sigma'(s) = \dot{\sigma}_o$, and equation (2) simplifies to

$$K_1(a,\ t) = \dot{\sigma}_o \sqrt{a\pi}\int_0^t f(C_2 s/a)ds \qquad (3)$$

through a change of variable. At some time, t_c, the stress intensity factor calculated by equation (3) may become large enough to exceed the critical stress intensity factor, K_{1c}, at which time crack growth initiates. At this critical time, t_c, the applied stress level will be the fracture stress σ_c with $\sigma_c = \dot{\sigma}_o t_c$.

Equation (3), when equal to K_{1c} at time t_c, is then written as

$$K_{1c} = \dot{\sigma}_o \sqrt{a\pi}\int_0^{\sigma_c/\dot{\sigma}_o} f(C_2 s/a)ds \qquad (4)$$

Equation (4) is now an implicit equation in the parameters a and σ_c, where K_{1c} and C_2 are material properties, and $\dot{\sigma}_o$ is the loading rate parameter. As an alternative, equation (4) could be considered an equation relating $\dot{\sigma}_o$ (or $\dot{\epsilon}_o$) and σ_c, in which, for constant crack size, a, the dependence of the fracture stress on strain rate is defined.

Using the functional form, $f(C_2 s/a)$, given in [16] for a penny-shaped crack, the fracture stress is plotted as a function of crack size for several representative strain rates in Fig. 3. The range of crack sizes is similar to that considered in previous characterizations of oil shale[14]. For reference, the static stress-crack radius relationship is also plotted in Fig. 3 ($\dot{\epsilon}_o = 0$). As the strain rate increases, the point of departure from the static solution moves toward smaller crack radii, and correspondingly higher fracture stress levels. For each strain rate (>0), it is observed that there is an intermediate crack length for which the fracture stress is a minimum, i.e., a preferential crack size. Although some particular intermediate crack size may have a slightly lower fracture stress, suggesting pulse tailoring to optimize the strain rate, the significant difference occurs between static and dynamic loading. When a solid with an array of cracks is loaded statically, the largest flaw will dominate the response of the solid, limiting the maximum load that can be applied. If a preferred orientation of the largest flaw exists, the material will also show an orientation dependence for the fracture stress. In the dynamic case, however, the largest crack no longer dominates; rather, cracks with a wide range of sizes are clearly activated nearly simultaneously, so failure occurs by fracturing the solid through multiple crack growth. Even with some preferred flaw orientation, the dynamic fracture stress tends to be independent of orientation.

The insensitivity of the fracture stress over a large range of crack sizes for constant strain-rate loading suggests that the inherent flaws in the rock are the basis for the strain-rate dependent fracture stress, i.e., it is a geometric and not a material effect. For crack radii larger than 2.0 mm (Fig. 3), the static fracture stress, which is governed by the largest flaw in the solid, is less than 20 MPa for the oil shale. The fracture stress is plotted as a function of strain rate for a crack size of 5.0 mm in Fig. 4 (solid line). A fracture stress of 100 MPa is calculated at strain rates in excess of 10^4/s. This dependence of fracture stress on strain rate is consistent with experimental results on oil shale [9] and holds over a large range of crack sizes.

2. Crack Shape Dependence

For the same material parameters, the fracture stress has been determined as a function of crack size for the plane crack. For the same strain rates as in Fig. 3 for the penny-shaped crack, the fracture stress-crack size dependence has been obtained. The general behavior is similar to that discussed for the penny-shaped crack,

including the shallow minimum indicating a preferential crack size at a given strain rate.

The results for the plane crack have been compared to those for the penny-shaped crack. It is observed that for static loading, a solid containing a penny-shaped crack has a larger fracture stress than one with a plane crack of the same characteristic dimension. As the strain rates become non-zero, it is noted that beyond some crack size, the fracture stresses for both the penny-shaped and plane cracks are identical. That is, beyond a certain crack size, the solid cannot discriminate the geometry of the flaw being loaded. This merging of fracture stress for the plane and penny-shaped cracks suggests that the crack front curvature is no longer important, and that for a characteristic dimension of crack, the shape is of no consequence to the constant strain-rate response.

3. Summary

Evidence has been presented for strain-rate dependent fracture response of an elastic solid containing a crack. Certainly, the analysis shows that the fracture initiation stress is a strong function of the strain rate for a given crack size. It is also observed that in dynamic loading, the fracture stress becomes independent of the crack geometry. These results appear to provide a good basis for explaining the strain-rate dependent fracture behavior of rocks with existing flaw distributions. Indeed, these results have been incorporated into a damange model which has been used in the prediction of the fracture and fragmentation of oil shale in crater blasting configurations[15].

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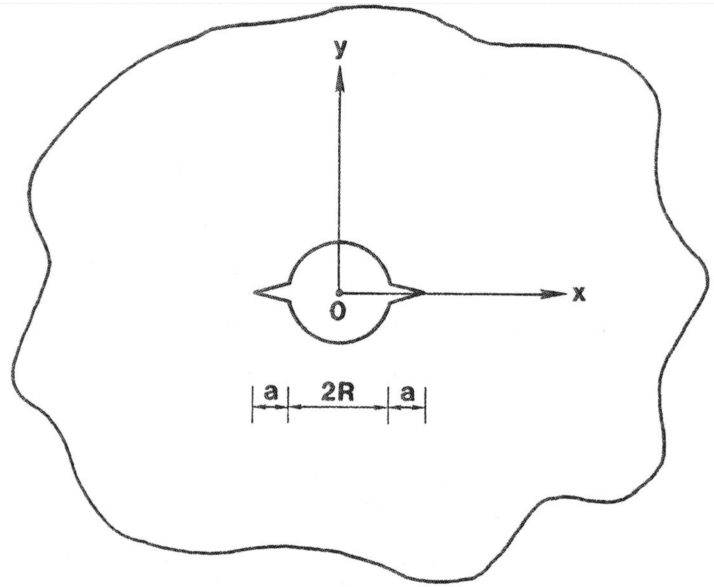

Figure 1. Radial Cracks in a Wellbore.

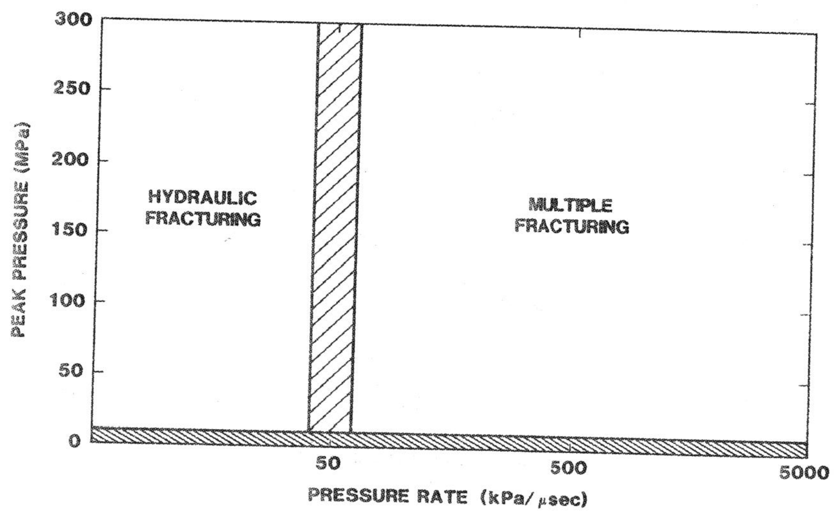

Figure 2. Peak Pressure vs. Pressure Rate Diagram.

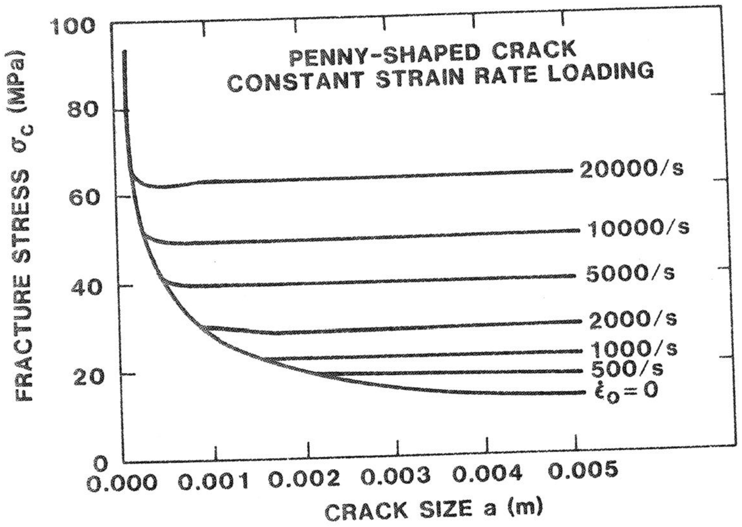

Figure 3. Fracture Stress vs. Crack Size at Constant Strain-Rate Loading (penny-shaped crack).

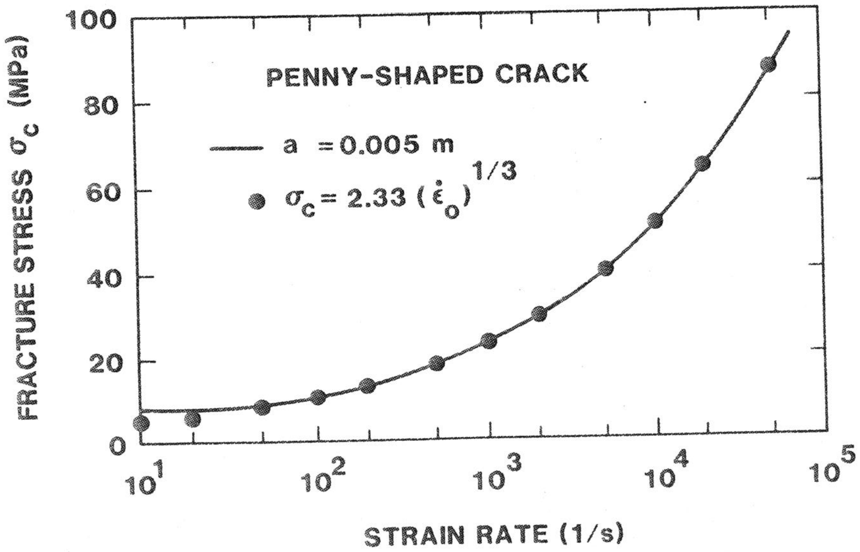

Figure 4. Fracture Stress vs. Strain Rate for Fixed Crack Radius.