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Modeling propellant-based stimulation of a borehole with peridynamics

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ABSTRACT

A non-local formulation of classical continuum mechanics theory known as *peridynamics* is used to study fracture initiation and growth from a wellbore penetrating the subsurface within the context of propellant-based stimulation. The principal objectives of this work are to analyze the influence of loading conditions on the resulting fracture pattern, to investigate the effect of in-situ stress anisotropy on fracture propagation, and to assess the suitability of peridynamics for modeling complex fracture formation.

It is shown that the loading rate significantly influences the number and extent of fractures initiated from a borehole. Results show that low loading rates produce fewer but longer fractures, whereas high loading rates produce numerous shorter fractures around the borehole. The numerical method is able to predict fracture growth patterns over a wide range of loading and stress conditions. Our results also show that fracture growth is attenuated with increasing in-situ confining stress, and, in the case of confining stress anisotropy, fracture extensions are largest in the direction perpendicular to the minimum compressive stress. Since the results are in broad qualitative agreement with experimental and numerical studies found in the literature, suggesting that peridynamics can be a powerful tool in the study of complex fracture network formation.

1. Introduction

Understanding fracture initiation and propagation in the subsurface is critical to the energy industry for improving productivity from reservoirs. In oil and gas reservoirs, production rates from wells may be enhanced through the process of hydraulic fracturing, a well-stimulation technique.[1] In hydraulic fracturing, fractures in the subsurface are created by pumping a mixture of fluid and sand into the borehole. Continuous pumping of the mixture increases the pressure inside the borehole up to the point when the fluid breaks into the formation and fractures the surrounding rock. As the mixture flows into the fractures, it induces continued growth and extension of the fractures away from the wellbore. Upon completion of the fracturing operation, the sand transported into the fractures keeps the fractures propped open to provide good flow conduits to the wellbore. A more detailed description may be found in 2. It is generally accepted that the orientation and geometry of the induced hydraulic fractures is controlled by the in-situ stress state, where initiation and growth occurs primarily in the direction perpendicular to the minimum confining stress in the rock. This results in a planar, bi-wing fracture geometry emanating from the wellbore. This type of stimulation greatly enhances the economics of producing so-called unconventional resources, including shale gas, tight gas and tight oil plays, where reservoir permeability is less than 1e-6 Darcy. As such resources represent a substantial portion of the industry's resource base, the continued development of well stimulation technology, as well as discovery and implementation of innovative and economical fracturing techniques is of increasing interest.

Propellant-based stimulation has also shown promise in enhancing connectivity between the wellbore and reservoir. In propellant-based stimulation, the ignition and controlled burning of a propellant generates a rapid increase in pressure in the wellbore due to the formation of gaseous combustion byproducts. The rate of increase and magnitude of the peak pressure can far exceed that encountered in hydraulic fracture operations. The loading conditions for the propellant fracturing technique are characterized by peak pressures in the range of 10,000 psi with a rise time on the scale of $\approx 1^{-2}$ s, or a loading rate of $\approx 10^{6}$ psi/s.

By contrast, hydraulic fracturing occurs at lower pressures, and the rate of loading is typically orders of magnitude slower. The principal effect of the high rate of loading in the propellant-based stimulation is that multiple fractures can initiate from the wellbore, in directions not necessarily aligned with the minimum in-situ confining stress.[3–6] By comparison, the pressure profile corresponding to a typical explosive pulse is also shown, where loading rates can reach 10^{12} psi/s. Here, the peak pressures and loading rates are so high that it results in pulverization of the rock near the wellbore instead of fracture exten-

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sion, not optimal for the goal of extending high conductivity pathways from the wellbore into the reservoir.

In propellant-based fracturing, it is generally accepted that two types of loading are in operation.[7,8] Early stage damage is driven by dynamic fracture processes. The detonation of the combustible material generates a stress wave that travels out from the borehole into the surrounding rock. This initially produces large compressive stresses that can exceed the rock strength, resulting in pulverization of the rock close to the borehole. As the stress wave moves further into the surrounding rock it induces a tensile hoop stress than can initiate and extend fractures radially out from the wellbore. The growth of some of these fractures may be attenuated by the competing growth process of nearby radial fractures. The selective extension of some subset of the initiated fractures is governed by a complex interaction of the local stress state near the fracture tips, material heterogeneity and the in-situ stress state in the rock.[8]

Following these dynamic processes, the fractures will be pressurized by the gas produced from the combustion process, which serves to further extend them from the wellbore. It is generally assumed that this process proceeds quasi-statically as the loading rates from the gas moving along the fracture is slow relative to stress wave velocities in the rock. The relative importance of each of these mechanisms in determining the final fracture pattern clearly depends on the in-situ stress state, and the rate and nature of the loading process, as has been demonstrated by several theoretical and experimental studies.[3,7–11]

Given the complexity of the mechanisms that may control fracture initiation and growth, there has been considerable effort applied to numerical modeling of the overall process. Many of these efforts have been motivated by rock blasting for mining applications, and have focused on either discrete element methods (DEM[7]) or continuum-based approaches such as finite element methods (FEM[12]).

In the DEM approach, elements are bonded to their neighbors with an interaction law that contains a suitable rupture criterion to represent fracture between the elements. The method is specifically designed to model problems where discontinuities such as fractures may form. A few representative applications to which DEM models have been applied include the investigation of the interaction of stress waves on initiation and propagation of radial fractures,[7] and wave propagation and fracture formation in rock under blasting conditions.[13] More recently, Fakhimi et al. 14 combined DEM with a Smooth Particle Hydrodynamics (SPH) model to examine the combined influence of the elastic stress wave and gas pressurization on rock blasting.

Finite element approaches have also been directly applied to problems of dynamic fracture. Like DEM, the models will assume fracture occurs on element boundaries, and utilizes a suitable interaction and rupture criterion to describe the fracture process. Cho and Kaneko 12 permit elements to crack based on a non-linear tensile stress threshold and a Mohr-Coulomb compressive fracture criterion. Ma and An 15 utilized the Johnson-Holmquist model, a continuum damage model for brittle materials, within the commercial FEM package LS-DYNA to simulate basting-induced rock fracture.

One of the difficulties that plague both DEM and FEM approaches is the need to prescribe the fracture plane of failure. When the failure planes are defined on element boundaries or at particle interfaces, the potential of mesh or particle size effects to influence simulation results becomes possible. Generalized or Extended Finite Element Methods[16] are capable of removing such mesh dependencies, but the techniques are limited to relatively simple fracture geometries, and usually cannot handle large scale initiation, branching and coalescence typified in dynamic fracture processes. Ideally, a numerical model for simulating dynamic fracture should be capable of accurately predicting aspects of fracture initiation, propagation, and bifurcation without an explicit reliance on the domain discretization to define the failure process.

A promising method that appears capable of overcoming some of these difficulties is peridynamics. Peridynamics[17] recasts classical continuum mechanics in a non-local framework, where points in a domain interact with its surrounding over a defined lengthscale. The conservation of momentum equation is reformulated so as to replace the traditional spatial derivatives with suitable integral counterparts. This greatly facilitates the description of discontinuities, and removes the requirement to explicity define fractures in terms of interfaces between a mesh or discrete particles.

The method has been shown to be particularly well suited for modeling dynamic fracture.[18] Many important features of dynamic fracture propagation have been validated against experiment with the technique, including crack path, propagation speeds, and bifurcation transitions.[19,20]. Early applications of the theory were restricted to simple brittle materials, but later extensions[21] enabled the development of a wide range of material models.[22,23]

The objective of this work is to investigate the effectiveness of peridynamics to model the influence of in-situ stress state and loading conditions on resultant fracture networks obtained from dynamic loading of a borehole. We restrict our attention to investigating the effect of the elastic stress waves on dynamic fracture patterns near the borehole. We begin with an overview of the peridynamic theory and methodology employed to model borehole fracture. We investigate a wide range of loading and in-situ stress conditions, looking at the influence of loading rate, peak loading and confining stress anisotropy on resulting fracture patterns. Finally, we compare some of our results to similar experimental and numerical studies published in the literature.

2. Model and methods

2.1. Peridynamics model

In the classical continuum solid mechanics, conservation of momentum for a body is given by

$$\rho_0(\mathbf{x})\ddot{\mathbf{u}}(\mathbf{x}, t) = \nabla \cdot \boldsymbol{\sigma} + \mathbf{b}(\mathbf{x}, t), \tag{1}$$

where $\mathbf{x}$ is a point in the body, $\mathbf{u}(\mathbf{x}, t)$ is the displacement of point $\mathbf{x}$ at time t, ρ_0 is the mass density in the undeformed body, and $\mathbf{b}$ is an external body force. Here, ∇ is the gradient operator taken with respect to the material coordinates and $\boldsymbol{\sigma}$ is the Cauchy stress. As spatial derivatives are not defined on fracture surfaces and other discontinuities, Eq. (1) cannot be directly evaluated at these points. In peridynamics, Eq. (1) is reformulated so as to replace the traditional spatial derivatives with suitable integral counterparts, as the integral equations of the peridynamic theory can be applied to fracture solutions without any mathematical difficulty. We provide a brief introduction to the peridynamic theory here; see[21,17,24] for additional details.

The peridynamic equation of motion is

$$\rho_0(\mathbf{x})\ddot{\mathbf{u}}(\mathbf{x}, t) = \int_{\mathcal{H}_{\mathbf{x}}} \mathbf{f}(\mathbf{x}', \mathbf{x}, t) dV_{\mathbf{x}'} + \mathbf{b}(\mathbf{x}, t). \tag{2}$$

Here, $\mathcal{H}_{\mathbf{x}}$ is a spherical region of radius δ centered at $\mathbf{x}$ and is the *family* of $\mathbf{x}$ and the vector valued function $\mathbf{f}$ is the force density per volume squared that $\mathbf{x}'$ exerts on $\mathbf{x}$. Referring to Fig. 1(a), Eq. (2) supposes that point $\mathbf{x}$ interacts directly with all points that lie within a distance δ of $\mathbf{x}$. In this paper, we refer to δ as the peridynamic *horizon*.

The vector between $\mathbf{x}$ and any other point in its family is called a bond, defined as $\boldsymbol{\xi} = \mathbf{x}' - \mathbf{x}$. Each bond has pairwise force density vector $\mathbf{f}(\mathbf{x}', \mathbf{x}, t)$ applied at both points. The force density is determined jointly by collective deformation of $\mathcal{H}_{\mathbf{x}}$ and collective deformation of $\mathcal{H}_{\mathbf{x}'}$. Bond forces are antisymmetric, meaning that $\mathbf{f}(\mathbf{x}', \mathbf{x}, t) = -\mathbf{f}(\mathbf{x}, \mathbf{x}', t)$.

Peridynamic material models are frequently written in terms of mathematical objects called *states*, which we briefly describe here. For the purposes of our discussion, states are operators that act on the family of a point $\mathbf{x}$. A *vector state* is an operator whose image is a vector, and may be viewed as a generalization of a second-rank tensor.