Mechanics of Materials 83 (2015) 17–29

Contents lists available at ScienceDirect

Mechanics of Materials

journal homepage: www.elsevier.com/locate/mechmat

Pore pressure cohesive zone modeling of hydraulic fracture in quasi-brittle rocks

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ARTICLE INFO

Article history:
Received 10 December 2014
Available online 31 December 2014

Keywords:
Hydraulic fracture
Pore pressure cohesive zone method
Finite element analysis
Experiment
Analytical asymptotic solutions

ABSTRACT

Hydraulic fracturing technology has been widely applied in the petroleum industry for both waste injection and unconventional gas production wells. The prevailing analytical solutions for hydraulic fracture mainly depend on linear elastic fracture mechanics. These methods can give reasonable prediction for hard rock, but are ineffective in predicting hydraulic fractures in quasi-brittle materials, such as ductile shale and sandstone. One of the reasons is that the fracture process zone ahead of the crack tip and the softening effect should not be neglected for quasi-brittle materials. In the current work, a set of chevron-notch three point bending tests were performed on sandstone samples from an oil field in Ordos Basin, Shaanxi province, China, and the results were compared with the cohesive zone method based on finite element analysis. The numerical results fit the experimental data well and it shows that the cohesive zone model and the Traction-Separation law used in the model are effective in modeling fracture nucleation and propagation in sandstone without considering the porous effect. A 3D pore pressure cohesive zone model was developed to predict nucleation and propagation of a penny-shaped fluid-driven fracture. The predictions were compared with the analytical asymptotic solutions and a field minifrac test from the literature; it shows that the proposed method can not only predict the length and aperture of hydraulic fracture well, but also predict the bottomhole pressure with reasonable accuracy. Based on analytical asymptotic and computational solutions, parametric studies were conducted to investigate the effects of different parameters on the fracture aperture and fracture length, fracture process zone and bottomhole pressure.
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1. Introduction

Hydraulic fracturing technology has been widely used in the petroleum industry to enhance oil and gas production. The fracturing fluid is pumped into the rock at high pressure, providing a path for oil and gas towards producing well, to be created. The advantage of hydraulic fracture technology is reflected in the production of an unconventional hydrocarbon source from shale, termed "shale gas". Because of the low permeability of shale, conventional technologies are neither commercial nor sufficient. Hydraulically fracturing rock around a wellbore to create extensive artificial fractures results in a significant increase in shale gas production. Hydraulic fracturing is also applied to determine in situ stress in rock (Bredehoeft et al., 1976) and underground disposal of toxic or radioactive waste (Weeren, 1966).

Over the years, several analytical solutions were proposed on modeling the nucleation and propagation of hydraulic fractures. The early research generally assumed simplified fracture geometries, such as the 2D plane strain,

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http://dx.doi.org/10.1016/j.mechmat.2014.12.010
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List of symbols

c_t, c_b	top and bottom Leak-off coefficient of ABAQUS
$C_L(C')$	leak-off coefficient of Carter's leak-off model (alternate form)
d	gap opening
$E(E')$	Young's modulus (plain strain modulus)
E_{eff}	cohesive layer stiffness
g	the volume of fluid leak-off per unit length of the fracture
G_{IC}	fracture energy
k_t	tangential permeability
K_{eff}	interfacial stiffness of cohesive layer
$K_{IC}(K')$	fracture toughness (alternate form)
M_k	dimensionless parameter
p	fluid net pressure
p_f	fluid pressure inside fracture
p_i	middle face pressure
∇p	pressure gradient along the cohesive element
q_t, q_b	flow rates into the top and bottom surface
Q_0	constant volumetric injection rate
t	time
t_n, t_s, t_t	Normal, the first, and the second shear stress components
t_*	timescale
T_0	original thickness of the cohesive element
γ	dimensionless fracture length
δ_n, δ_s, δ_t	normal, the first, and the second shear separations
ε	small parameter
ε_n, ε_s, ε_t	normal, the first, and the second shear components of nominal strain
κ	dimensionless toughness
$\mu\,(\mu')$	fluid dynamic viscosity (alternate form)
ν	Poisson's ratio
ξ	self-similar spatial coordinate
Π	dimensionless fluid net pressure
σ_0	constant far field stress
τ	dimensionless time
w	crack opening
Ω	dimensionless crack opening

Khristinaovic–Geertsma–de Klerk (KGD) and Perkins–Kern–Nordgren (PKN) models. They both assumed that the height of fracture is constant. KGD model was proposed by Geertsma and De Klerk (1969), and is suitable for fractures whose ratio of length to height is near unity or less. The KGD model assumes that the fracture is at a plane strain condition in the horizontal plane, and the fracture tip is a cusp-shaped tip (Barenblatt 1962). The PKN model which was proposed by Nordgren (1972) is suitable for fractures with large length/height ratio. The PKN model assumed that the fracture is at a plane strain condition in vertical plane, that the vertical fracture cross-section is elliptical, and that the fracture toughness does not affect the fracture geometry. A 3D penny shaped fracture model was proposed by Geertsma and de Klerk (1969), and the same problem was studied by Abe et al. (1976) with a rigorous treatment at the fracture tip. In recent years, a scaling and asymptotic framework was developed by Detournay (2004) and Mitchell et al. (2007), who assumed that the hydraulic fracture is governed by two competing energy dissipation and fluid storage mechanisms. The two energy dissipation mechanisms are associated with viscous flow and the creation of surface area in the solid material. The two fluid storage mechanisms correspond to the storage of fluid in the fracture and fluid leak-off into the permeable solid. Four limit conditions were studied in the paper, namely, storage-toughness dominated (K-Regime), storage-viscosity dominated (M-Regime), leak-off-toughness dominated ($\tilde{\text{K}}$-Regime) and leak-off-viscosity dominated ($\tilde{\text{M}}$-Regime). Various conditions were discussed for each regime.

On the other hand, with the development of computational technology, numerical models were employed to simulate fractures with more complex geometries. A pseudo-3D model was developed to predict the evolution of fracture geometry created by fluid injection (Settari and Cleary 1986). Dean and Schmidt (2009) developed a new geomechanical reservoir simulator (GMRS) which contains two separate criteria to model fracture propagation, one was based on critical stress intensity factors, and the other was based on a cohesive element incorporating strain-softening behavior. The simulator combined hydraulic fracture growth, multi-phase, Darcy/no-Darcy porous flow, heat convection and conduction, solids deposition, and poroelastic/poroplastic deformation in a single application.

Although several studies have been performed during the past few decades, the majority of these studies were based on linear elastic fracture mechanics (LEFM). They can give reasonable predictions for hard rock, when the nonlinear zone ahead of a fracture is small compared to structure size (Yao, 2012; Mokryakov, 2011). While in the oil and gas industry, especially for highly heterogeneous subsurface strata, such as ductile shale and other soft rocks, the nonlinear softening zone ahead of fracture is not negligible and dominates the fracture behavior, In this condition, LEFM-based methods will give conservative predictions, and cohesive fracture mechanics can be applied (Shet and Chandra, 2002; Yao, 2012).

The cohesive zone model was originally proposed by Barenblatt (1962) and Dugdale (1960). Roe and Siegmund (2003) incorporated a cohesive zone model into the finite element model. The fracture aperture at the crack tip was assumed to be zero in LEFM, and this non-linear degeneracy posed a considerable challenge for numerical modeling (Chen et al., 2009). During the development of cohesive zone method, a lot of studies have been conducted for hydraulic fracturing (Sarris and Papanastasiou, 2011;

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