Journal of Natural Gas Science and Engineering 33 (2016) 56–69

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Numerical simulation of hydraulic fracturing in orthotropic formation based on the extended finite element method

XiaoLong Wang [a], Fang Shi [a], He Liu [b], HengAn Wu [a, *]

[a] CAS Key Laboratory of Mechanical Behavior and Design of Materials, Department of Modern Mechanics, University of Science and Technology of China, Hefei, Anhui 230027, China
[b] PetroChina Research Institute of Petroleum Exploration & Development, 20 Xueyuan Road, Haidian District, Beijing 100083, China

ARTICLE INFO

Article history:
Received 21 January 2016
Received in revised form
29 April 2016
Accepted 1 May 2016
Available online 4 May 2016

Keywords:
Shale
Hydraulic fracturing
Orthotropy
Fracture deviation
XFEM

ABSTRACT

Shale shows remarkable anisotropy in terms of mechanical properties, and it can often be regarded as an orthogonal anisotropic linear elastic body. In this paper, we present a two-dimensional fluid-solid coupled numerical model based on the extended finite element method (XFEM) to simulate the propagation of hydraulic fracture in orthotropic formations. The interaction between rock deformation and fluid flow within fracture is taken into account. Special crack tip enrichment functions of XFEM are used to model fractures in orthotropic formations, and the maximum circumferential tensile stress criterion is modified to determine the fracture propagation direction. The simulation results show that the hydraulic fracture will deviate from its straight-ahead path if there is an angle (defined as the material angle) between the initial fracture direction and the material axes of orthotropy. The initial deviation angle of fracture changes with the variation of the material angle, and the extent of fracture deviation increases with the Young's Modulus ratio. The fracture deviation can be avoided only when the initial fracture is parallel to one of the material axes of orthotropy. In the case where the maximum and minimum horizontal stresses are not equal, the direction of fracture propagation is determined by the combined effects of in-situ stress and orthotropy of the material. These findings offer new insights into the hydraulic fracturing design in orthotropic formations, helping to improve the production rates in shale gas reservoirs.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

Shale gas reservoirs often require hydraulic stimulation for economical production due to their extremely low permeability. In recent years, a combination of horizontal drilling and multistage hydraulic fracturing has been proven to be a highly effective method for enhancing well production (Rahm, 2011; Wei and Sepehrnoori, 2013).

Because of the complexity of shale formations, it is challenging to predict the geometry and propagation behavior of hydraulic fracture in shale gas reservoirs. For example, the natural fractures in shale prevent the creation of a single transverse fracture and promote the formation of complex fracture networks (Guo et al., 2015a,b). The interaction between hydraulic fractures and pre-existing natural fractures has been extensively investigated using experiments in the laboratory and various numerical methods (Blanton, 1982; Dahi-Taleghani and Olson, 2011; Fu et al., 2013; Guo and Liu, 2014a,b; Meyer and Bazan, 2011; Nagel et al., 2012; Zhou et al., 2010). Both random natural fractures and differential in-situ stresses are thought to dominate the geometry and propagation of hydraulic fractures. Furthermore, the stress interference between transverse fractures also has a strong influence on the fracture propagation during multistage hydraulic fracturing (Morrill and Miskimins, 2012; Roussel and Sharma, 2011a,b). However, the anisotropy in the mechanical properties of shale formations, which has a significant influence on the propagation behavior of hydraulic fractures, was often neglected in the previous studies described above.

In fact, anisotropy is a common phenomenon in rocks and minerals, and isotropy is rare (Barton and Quadros, 2014; Stoeckhert et al., 2015). As a common feature of sedimentary rocks, shale shows different elastic properties in its vertical and horizontal planes (Franquet and Rodriguez, 2012). Thus, shale can often be regarded as an orthogonal anisotropic linear elastic body.

* Corresponding author.
E-mail address: wuha@ustc.edu.cn (H. Wu).

http://dx.doi.org/10.1016/j.jngse.2016.05.001
1875-5100/© 2016 Elsevier B.V. All rights reserved.

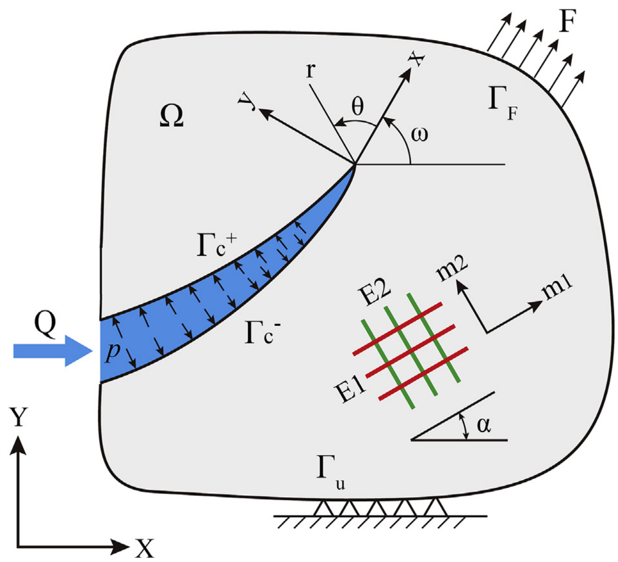

Fig. 1. Illustration of a 2D orthotropic formation containing an arbitrary hydraulic fracture with general boundary conditions.

The behavior of fracture propagation in orthotropic media is substantially different from that in isotropic media. Mixed-mode crack propagation in homogeneous orthotropic solids has been sufficiently investigated by various numerical methods (Aliabadi and Sollero, 1998; Saouma et al., 1987; Wang et al., 1980). In recent years, the XFEM has been widely utilized to model the crack in orthotropic materials by introducing new crack tip enrichment functions (Asadpoure and Mohammadi, 2007; Asadpoure et al., 2006a,b). XFEM allows cracks to propagate along an arbitrary path without explicit remeshing, and thus, the computational cost can be dramatically reduced in comparison with the traditional finite element method. However, all of the studies described above only investigated the fracture propagation in orthotropic materials under simple tension loading in which the fracture surfaces were stress-free. No hydraulically driven fracture propagation in orthotropic formations has been studied previously.

In this paper, an XFEM-based 2D fluid-solid coupled numerical model is established to simulate the hydraulic fracturing in orthotropic formations. Our main objective is to investigate the different fracture propagation behaviors in orthotropic formations compared with isotropic formations. Simulations are performed to illustrate the effects of the material angle and the Young's Modulus ratio of the orthotropic formation on fracture propagation. In addition, the combined effects of orthotropy of the material and in-situ stress on fracture propagation are studied.

2. Methodology

2.1. Governing equations of hydraulic fracturing problems

Note that our preliminary study is limited to 2D analyses. As illustrated in Fig. 1, consider a 2D homogeneous, orthotropic, linear elastic and impermeable medium Ω containing an arbitrary hydraulically driven fracture Γ_c. Prescribed tractions **F** and prescribed displacements are imposed on the boundaries Γ_F and Γ_u, respectively. An incompressible viscous fluid is pumped at the fracture inlet at a constant flow rate Q. The fracture propagation is assumed to be quasi-static, and no fluid lag is taken into account. Different coordinate systems are illustrated in Fig. 1.

The equilibrium equation of the structure and the boundary conditions can be expressed as

$$\nabla\cdot\boldsymbol{\sigma}+\mathbf{b}=0,\quad in\ \Omega \tag{1}$$

$$\begin{cases}\boldsymbol{\sigma}\cdot\mathbf{n}=\mathbf{F}, & on\ \Gamma_F\\ \boldsymbol{\sigma}\cdot\mathbf{n}^-=-\boldsymbol{\sigma}\cdot\mathbf{n}^+=\mathbf{p}^+=-\mathbf{p}^-=\mathbf{p}, & on\ \Gamma_c\\ \mathbf{u}=0, & on\ \Gamma_u\end{cases} \tag{2}$$

where $\boldsymbol{\sigma}$ and **b** are the stress and body force, respectively; **n** is the outward unit normal vector to the surface Γ_F; $\mathbf{n}^+$ and $\mathbf{n}^-$ are the outward unit normal vectors to the crack surfaces Γ_c^+ and Γ_c^-, respectively; $\mathbf{p}^+$ and $\mathbf{p}^-$ are the fluid pressure imposed on the crack surfaces Γ_c^+ and Γ_c^-, respectively. Strains are assumed to be small; thus, we can define $\mathbf{n}^+=\mathbf{n}^-=\mathbf{n}$, and $\mathbf{p}^+=\mathbf{p}^-=\mathbf{p}$.

2.2. Fracture mechanical for 2D orthotropic materials

The constitutive equation for 2D orthotropic materials can be written as (Kaw, 2005)

$$\begin{pmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{12}\end{pmatrix}=\begin{pmatrix}Q_{11} & Q_{12} & Q_{16}\\ Q_{12} & Q_{22} & Q_{26}\\ Q_{16} & Q_{26} & Q_{66}\end{pmatrix}\begin{pmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \gamma_{12}\end{pmatrix} \tag{3}$$

$$\begin{pmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \gamma_{12}\end{pmatrix}=\begin{pmatrix}S_{11} & S_{12} & S_{16}\\ S_{12} & S_{22} & S_{26}\\ S_{16} & S_{26} & S_{66}\end{pmatrix}\begin{pmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{12}\end{pmatrix} \tag{4}$$

where ε_{ij} and σ_{ij} are the strain and the stress components, respectively; Q_{ij} and S_{ij} are the stiffness coefficient and the flexibility coefficient, respectively.

Sih et al. (1965) have derived the displacement and stress fields in the crack-tip region for 2D orthotropic materials. The stress and displacement components for pure mode I can be described as follows:

$$\begin{cases}\sigma_{11}=\dfrac{K_I}{\sqrt{2\pi r}}\mathrm{Re}\left[\dfrac{s_1s_2}{s_1-s_2}\left\{\dfrac{s_2}{\sqrt{\cos\theta+s_2\sin\theta}}-\dfrac{s_1}{\sqrt{\cos\theta+s_1\sin\theta}}\right\}\right]\\ \sigma_{22}=\dfrac{K_I}{\sqrt{2\pi r}}\mathrm{Re}\left[\dfrac{1}{s_1-s_2}\left\{\dfrac{s_1}{\sqrt{\cos\theta+s_2\sin\theta}}-\dfrac{s_2}{\sqrt{\cos\theta+s_1\sin\theta}}\right\}\right]\\ \sigma_{12}=\dfrac{K_I}{\sqrt{2\pi r}}\mathrm{Re}\left[\dfrac{s_1s_2}{s_1-s_2}\left\{\dfrac{1}{\sqrt{\cos\theta+s_1\sin\theta}}-\dfrac{1}{\sqrt{\cos\theta+s_2\sin\theta}}\right\}\right]\end{cases} \tag{5}$$

$$\begin{cases}u_1=K_I\sqrt{\dfrac{2r}{\pi}}\mathrm{Re}\left[\dfrac{1}{s_1-s_2}\left\{s_1p_2\sqrt{\cos\theta+s_2\sin\theta}-s_2p_1\sqrt{\cos\theta+s_1\sin\theta}\right\}\right]\\ u_2=K_I\sqrt{\dfrac{2r}{\pi}}\mathrm{Re}\left[\dfrac{1}{s_1-s_2}\left\{s_1q_2\sqrt{\cos\theta+s_2\sin\theta}-s_2q_1\sqrt{\cos\theta+s_1\sin\theta}\right\}\right]\end{cases} \tag{6}$$

Download English Version:

https://daneshyari.com/en/article/1757049

Download Persian Version:

https://daneshyari.com/article/1757049

Daneshyari.com