MODELING HYDRAULIC FRACTURE INITIATION OF A NOTCH-FREE WELLBORE IN ANISOTROPIC ROCKS

Mahsa Sakha[1]*, Morteza Nejati[1], Laura De Lorenzis[2], and Thomas Driesner[1]

[1]Department of Earth Sciences, ETH Zurich, Switzerland, [2]Department of Mechanical and Process Engineering, ETH Zurich, Switzerland

** Presenting Author email: mahsa.sakha@erdw.ethz.ch*

Abstract

In this study, we address hydraulic fracture initiation from a notch-free wellbore subjected to compressive in-situ stresses, where the wellbore is situated in an anisotropic host rock with transversely isotropic properties. To capture the three unknown parameters, i.e. the initial crack length, orientation, and the fluid pressure at initiation in anisotropic formations, we extend the mixed criterion proposed for isotropic rock formations in the literature. The mixed criterion requires that both stress and energy conditions at the initiation point are met. To do so, we calculate the fracture energy through the displacement discontinuity method (DDM), where the kernel matrix appropriate to the geometry of the problem (i.e. an infinite plane with a circular hole) is adopted for a transversely isotropic formation. To evaluate the reliability of our formulation at any degree of material anisotropy, the crack emanating from the wellbore is simulated by the finite element method, and consequently the energy dissipated between the cracked and crack-free states is measured. While the two methods are in agreement, the results unravel the systematics of how the competition between the material anisotropy and the differential in-situ stresses determines the initiation parameters.

1. Introduction

Hydraulic fracturing is widely used in geotechnical applications to increase the permeability in shale oil and gas, mining, enhanced geothermal systems (EGS), carbon sequestration projects, wastewater injection plans etc. This process, generally, can provoke three different mechanisms: initiation of new fractures, fracture propagation, and shear-reactivation of existing fractures (Amann et al., 2018; Krietsch et al., 2020). Hydraulic fractures initiating at a wellbore wall are often assumed to emanate from an initial notch created by either perforation or pre-existing natural cracks (Zhang et al., 2011; Li et al., 2015; Sesetty and Ghassemi, 2018). In practice, however, hydraulic fractures may initiate from an unnotched wellbore wall and modeling this process requires the determination of the fluid pressure at initiation as well as the geometry of the initial crack. As the initial crack is considered to be a starting point for crack propagation, accurate knowledge of its geometry is pre-requisite to give a more realistic picture of rock fracturing. Particularly in a transversely isotropic formation, the geometry of the initial crack is described by its length and orientation. This communication therefore strives to give a rigorous analysis of hydraulic fracture initiation at a wellbore wall subjected to in-situ compressive stresses in a transversely isotropic rock.

2. Results

Hydraulic fractures at a notch-free wellbore instantaneously initiate once the fluid pressure exceeds the initiation pressure p_{b0}. At the instant of initiation, two symmetrical cracks radially emanate from the wellbore wall with the length of l_0 along the orientation θ_0. We restrict this analysis to transversely isotropic rocks where the wellbore lies within the isotropy plane of the rock formation (i.e. direction 1) and both of material principal directions lie within the plane perpendicular to the wellbore. The in-plane inclination of the rock isotropy plane β can influence hydraulic fracture initiation. The effect of the material anisotropy, however, can be more considerable for greater material anisotropy ratios $\xi = E/E'$ where E and E' are respectively the Young's moduli along principal directions 1 and 2. This study is also restricted to in-situ stress states which not only favor a 2D radial fracturing but also preclude the shear-reactivation around the wellbore. Accordingly, the stress anisotropy defined as $\lambda = \sigma_2/\sigma_3$ is set to

λ = 2, for which the in-situ compressive stresses are taken as positive values according to the widely-used geomechanics convention. Such a considerable stress anisotropy could drive the initial crack along the direction perpendicular to the minimum in-situ stress, σ_3 , in the absence of material anisotropy. The material anisotropy, however, competes with the loading effect to deviate the initial crack along the weakest material direction. This analysis therefore aims to explore how the material anisotropy can affect the initiation parameters. For the sake of simplicity, the initiation pressure and length are non-dimensionalized (Sakha et al., 2022).

In the analysis of hydraulic fracture initiation, it is often assumed that hydraulic fractures initiate once the wellbore pressure overcomes the tensile strength of the host rock. This model, or so-called "purely strength-based model", is however unable to give any information on the extent of the initial crack which instantaneously appears in the previously notch-free body. This drawback necessitates an auxiliary condition combined with the strength based model to fully capture the initiation parameters; the so-called mixed-criterion incorporates the fracture energy perspective, meaning that the energy released between the cracked and crack-free states must reach the critical energy release rate (fracture energy) of the material. Using the displacement discontinuity method (DDM) (Crouch and Starfield, 1983) as well as the finite element analysis, we can calculate the energy release rate of the yet to be initiated crack, where the induced stress field at its tip exceeds the material strength.

To implement the DDM, one needs to define the kernel matrix appropriate to the geometry in question, which can describe the stress induced by a unit edge dislocation. We therefore define the kernel matrix through the analytical relations derived by Wu (1992) for an edge dislocation interacting with a wellbore in an anisotropic medium. To validate the correctness of the kernel matrix, one can compare the results of the isotropic case given by Lecampion (2012) with the predictions obtained in the limit of $\mu_j \rightarrow i$ (j= 1, 2), where μ_1 and μ_2 are the complex roots of a characteristic polynomial describing the dependency of the elasticity solution on the material constants for the plane anisotropic body (see Sakha et al. (2022)). This comparison, however, cannot confirm whether the adopted kernel matrix can extensively describe the initial crack opening/shearing at any degree of material anisotropy, as the isotropic material is independent of β . To provide a more robust validation, we compare the initiation parameters calculated by DDM with the results simulated with finite element analysis. Fig. 1 illustrates that the results predicted by the DDM are well matched with the finite element predictions, and thus the correctness of the kernel matrix can be confirmed.

Fig. 1 presents the variations of the initiation parameters as functions of the material anisotropy orientation β for the different anisotropy ratios. According to Fig. 1, the initiation angle θ_0 tends to favor the material tendency with greater anisotropy ratios, meaning that the deviation of the initial crack from the weakest plane (i.e. $\theta_0 - \beta$) considerably drops as the material orientation approaches to 90° . The loading condition, however, becomes dominant at ξ = 3 as the θ_0 -curve becomes concave downward. Following the empirical relations describing the variation of the material fracture energy, a higher deviation from the isotropy plane can provoke a surge in energy required to form the initial crack; this clarifies why the longest cracks are initiated at the highest deviations for each anisotropy ratio. The surge in fracture energy also requires a higher fluid pressure at initiation. Nevertheless, it seems that the initiation pressure is more influenced by the orientation of the initial crack rather than its deviation from the isotropy plane. As shown in Fig. 1 for ξ = 4, although the crack initiates along the weakest plane at $\beta = 90^\circ$, an extremely high initiation pressure is required to open the crack faces where the stress field is highly compressive.

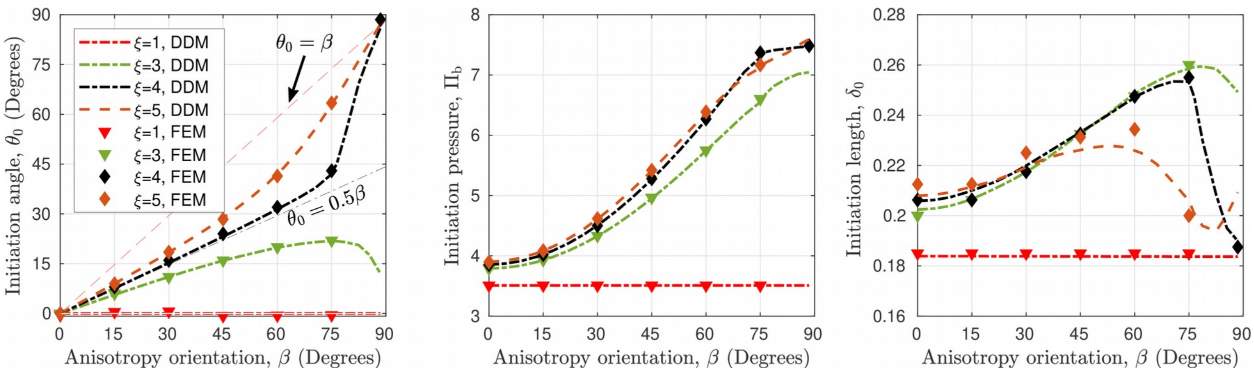

Fig.1 – Variations of initiation parameters as functions of the orientation β for different material ratios

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