International Journal of Rock Mechanics and Mining Sciences 103 (2018) 275–288

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics and Mining Sciences

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

Interaction analysis of propagating opening mode fractures with veins using the Discrete Element Method

Hunjoo P. Lee*, Jon E. Olson, Richard A. Schultz

Center for Petroleum and Geosystems Engineering, University of Texas at Austin, Austin, TX, USA

ARTICLE INFO

Keywords:
Fracture-Vein interaction
Fracture diversion distance
Discrete Element Method (DEM)
Semi-Circular Bend (SCB) test

ABSTRACT

Cemented natural fractures (veins) in shale formations generate mechanical heterogeneities which contribute to complex hydraulic fracture network development. Lee et al. (JGR, 2015) experimentally investigated the interaction of propagating tensile fractures with calcite-filled veins in Marcellus shale using Semi-Circular Bend (SCB) tests. In this study, we investigate those experimental results with three-dimensional Discrete Element Method (DEM) modeling to gain further insight in the fracture interaction processes that generate hydraulic fracture complexity. In addition, we quantified the length of fracture diversion distance to show the effect of vein properties, including approach angle, thickness, strength, stiffness, penetration length, on fracture diversion results.

The numerical results compared well with the laboratory fracture diversion results. There is a tendency towards fracture diversion as the approach angle becomes smaller and more oblique to the propagating fracture plane. As the stiffness of the vein increased, the microcrack-related damage increased and the bond breakages extended longer to either side of the main fracture path. Samples with thicker veins and increasing penetration length showed a weaker vein response; the induced fracture propagated for a longer distance in veins before kinking back into the rock matrix. In addition, the numerical model confirmed that the opening mode fracture initiated from the notch tip and the intergranular bond failure created microcracks within the vein before the approaching fracture intersected the vein. The failure mode of the bonds between discrete elements in the vein was predominantly tensile mode rather than shear.

1. Introduction

Hydraulic fracturing is a well-known stimulation technique that is required to enhance hydrocarbon recovery from tight (low-permeability) formations.[1] The classic description of hydraulic fracture is a single bi-wing planar feature. However, field observations, including micro-seismic monitoring in Barnett shale[2,3] and core observations from tight gas sandstones,[4] demonstrate that the hydraulic fracture growth in shale and naturally fractured formations is complex propagation of multi-stranded fracture networks. Natural fractures, which are ubiquitous geologic structures in these formations, are responsible for the development of these complex hydraulic fracture networks.[5,6]

Hydraulic fractures can interact with pre-existing natural fractures in various scenarios. The possible cases include fracture arrest, crossing, and diversion.[7] Previous studies mostly focused on the interaction between hydraulic fracture and frictional interfaces.[8–11] However, based on the structural characterization in shale formations, natural fractures range from frictional interfaces or open fractures to partially or fully cemented fractures.[6,12,13] The cemented natural fractures (i.e., veins) not only have shear resistance but also have tensile strength.[14] In addition, veins can have different mechanical properties than those of the host rock generating stress heterogeneities in the reservoir[15] that can disturb the hydraulic fracture trajectory. Recently, experimental and theoretical investigations on the interaction of hydraulic fractures with bonded preexisting discontinuities have been carried out.[1,16–19] Lee et al.[1] experimentally investigated the interaction of propagating opening mode fractures with calcite-filled veins in Marcellus shale using the set-up of Semi-Circular Bend (SCB) test. Their results showed that veins can contribute to fracture diversion depending on the approach angle and the critical strength of the vein which depends on both its fracture toughness and stiffness based on the energy release rate criterion.

A variety of numerical models have been proposed to generate practical deformation and failure behavior of rocks. Potyondy et al.[20] discussed two methods in modeling inelastic deformation and fracture of brittle materials including rocks. One is the indirect method,

---

* Correspondence to: University of Texas at Austin Department of Petroleum and Geosystems Engineering, 200 E. Dean Keeton St., Stop C0304, Austin, TX 78712-1585, USA.
E-mail address: hunjoo.lee@utexas.edu (H.P. Lee).

https://doi.org/10.1016/j.ijrmms.2018.01.005
Received 23 March 2017; Received in revised form 26 December 2017; Accepted 1 January 2018

continuum modeling, where damage is represented by constitutive laws. The other is the direct method, where damage is expressed by discrete cracks. One such direct model is the Discrete Element Method (DEM), also known as the Distinct Element Method. In this study, to better understand and interpret the experimental results from Lee et al.,[1] we numerically modeled the SCB test of samples containing veins using DEM.

The DEM has several advantages in modeling fractures in rock over the indirect method.[21] Particles in DEM interact with one another through contacts or bonds, and cracks are explicitly predicted when the applied stress exceeds the tensile or shear strength of the bonds. Fractures are created by the clustering of continuous bond breakages and furthermore multi-stranded fractures can propagate within a sample at the same time. Since DEM is based on microscopic mechanisms and the mode of failure is not predefined as in continuum methods, it is ideal for investigating complex macro-mechanical behavior in heterogeneous media.[22] Another important feature of DEM is that the fracture propagation process requires no special meshing. These capabilities of DEM contribute to understanding the micromechanical behavior of the interaction between propagating opening mode fractures with preexisting discontinuities. Virgo et al.[15] analyzed the impact of the approach angle and vein strength on fracture diversion, bifurcation, and failure nucleation in the vein with tension tests on notched samples using three-dimensional (3D) DEM models. In addition, Virgo et al.[23] showed that DEM can mimic the crack-seal mechanism of natural fractures. With 2D DEM model, Spence and Finch[24] studied fracture network development in reservoirs with chert nodules. They found that the mechanical stratigraphy has an impact on fracture propagation and generated complex fracture geometries similar to those found in outcrops.

In this study, we investigate the experimental results on Marcellus shale with calcite filled veins[1] with 3D DEM modeling to gain further insight in the micro-mechanical fracture interaction behavior that generate hydraulic fracture complexity. The influence of the approach angle, strength, stiffness, thickness, and penetration length of the vein on fracture diversion are assessed and interpreted through the numerical results. This study builds on earlier work by Lee[25] and Lee et al.[26]

2. Materials and methods

The Particle Flow Code in three-dimensions (PFC3D)[27] is a DEM model that uses three main constituents: particles, bonds, and walls. Particles consist of mass and volume, and they are used to represent grains, clusters of grains, or larger solid elements, as in this study. Adjacent particles are held together with bonds. PFC3D uses two types of bond models called parallel bonds and contact bonds. Parallel bonds are suitable for this study since they can resist moment or rotation, whereas contact bonds only resist normal forces. Particles and bonds work together to form a densely packed assembly, or a rock specimen. Walls act as the boundary for sample generation and as the loading surface for inducing deformation. The procedure for generating a sample assembly in PFC3D is outlined in Potyondy and Cundall[28] and Park et al.[21]

2.1. Microscopic parameter determination

The total number of particles in DEM governs the overall computational time. It is typically impractical to set a particle to express one grain and intractable to assume a grain size in shale of less than 0.004 mm in diameter because a substantial number of particles are required to describe a single SCB specimen of the Marcellus shale from Lee et al.[1] Therefore, to minimize the computational time, the particles in this study are discrete solid elements, representing clusters of grains, and these elements are bonded together to make the whole sample. A distribution of particle sizes is used to get a dense pack of elements, with the minimum particle diameter ($D_{\min}$) of 0.45 mm and $D_{\max}/D_{\min}$ of 1.65 for arbitrary isotropic packing.[28] The average diameter of particles (D_{avg}) is chosen to be small relative to sample size, on the order of a few percent or less of the specimen diameter. Further analysis on the effect of sample size in Section 3.7 shows that the assigned sample size and particle distribution provide representative values to evaluate the interaction between the propagating fracture and the vein.

To match the input microscopic properties of particles and bonds to the measured rock mechanical properties (e.g., Young's modulus, E; Poisson's ratio, ν; Unconfined Compressive Strength, UCS; Tensile strength, σ_T), it is necessary to carry out a trial-and-error process with conventional experimental tests in PFC3D, such as the SCB test, Brazilian test, the uniaxial and the triaxial compression test. Generally, Young's modulus and internal friction primarily constrain stiffness of the particles (k_n for normal, k_s for shear stiffness) and parallel bonds ($\overline{k_n}$ for normal, $\overline{k_s}$ for shear stiffness), while UCS and cohesion (S_o) constrain the parallel bond strengths ($\overline{\sigma}$ for normal, $\overline{\tau}$ for shear strength). Measured macroscopic mechanical properties of Marcellus core samples (E^{rock} of 8.9 GPa and UCS^{rock} of 53.4 MPa) from Lee et al.[1] are utilized to determine microscopic properties of the particles and parallel bonds. In PFC3D, Poisson's ratio is independent of particle size and only depends on the stiffness ratios of the particles (k_n/k_s) and the parallel bonds ($\overline{k_n}/\overline{k_s}$). Corresponding to $\nu^{rock} = 0.275$, based on the published log data (ν^{rock} of 0.25–0.3),[29,30] k_n/k_s and $\overline{k_n}/\overline{k_s}$ is set as 2.5. Both k_n/k_s and $\overline{k_n}/\overline{k_s}$ are set as equal to minimize the number of free parameters.[28] The parallel bond radius multiplier ($\overline{\lambda}$) is assumed to be 0.9 which corresponds to the porosity of 15%[31] that is within the range of the published porosity of Marcellus shale (0–18%).[32] The friction coefficient (μ) was assumed to be 0.75, a value within the range of μ for rocks, 0.6–0.85.[33] After the calibration, microscopic input parameters and macroscopic mechanical properties for the modeled rock are determined as listed in Tables 1 and 2.

The stress-strain curves of the UCS test and the load-displacement curves of the SCB test from both the numerically modeled assembly and the laboratory results from the Marcellus shale specimen are discussed in detail in Lee.[25] It should be noted that the PFC3D curves matched well with the laboratory UCS test, but the peak load for the SCB test was approximately 400 N greater resulting in greater fracture toughness.[25] The tensile strength (σ_T) of the sample assembly in PFC3D is measured from both the direct tension (DT) test and the Brazilian (BZ) test which is an indirect tensile test.[34] The tensile strength was measured as 11.3 MPa (${\sigma_T}^{DT}$) from the direct tension test and 16.4 MPa (${\sigma_T}^{BZ}$) from the Brazilian test. The ratio of 0.688 from the two tensile strengths (${\sigma_T}^{DT}/{\sigma_T}^{BZ}$) agrees with the value, 0.7, discussed in Perras and Diederichs[35]for sedimentary rocks.

The $|UCS/\sigma_T|$ ratios are approximately 4.1 ($|UCS/{\sigma_T}^{DT}|$) and 2.8 ($|UCS/{\sigma_T}^{BZ}|$) (Table 2). This is smaller than laboratory test results of rocks from other studies, where $|UCS/\sigma_T|$ ratio is generally between 10

Table 1
Micro-properties for the rock matrix in PFC3D.

Particle properties	
Modulus, E_p (GPa)	11.0
Normal/Shear Stiffness Ratio, k_n/k_s	2.5
Minimum Particle Diameter, $D_{\min}$ (mm)	0.45
Maximum/Minimum Diameter Ratio, $D_{\max}/D_{\min}$	1.65
Friction Coefficient, μ	0.75
Density, ρ (kg/m^3)	2650
Parallel bond properties	
Modulus, $\overline{E}$ (GPa)	11.0
Normal/Shear Stiffness Ratio, $\overline{k_n}/\overline{k_s}$	2.5
Normal Strength, $\overline{\sigma}$ (MPa)	45.0 ± 4.5
Shear Strength, $\overline{\tau}$ (MPa)	45.0 ± 4.5
Radius Multiplier, $\overline{\lambda}$	0.9