

Modeling Natural Fracture Activation Using a Poro-elastic Fracture Intersection Model

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Abstract: Pre-existing natural fractures in a hydrocarbon reservoir complicate the hydraulic fracture growth and consequently, the microseismic event interpretation. Due to the misalignment of the natural fractures with respect to the far-field principal stresses, shear slippage is introduced as a failure mode or microseismic source along natural fractures. This failure mode, however, leaves a concern about the connectivity of the induced fracture network in order to enhance hydrocarbon production. A poro-elastic fracture intersection and propagation model can rigorously address this concern.

Our numerical technique develops fracture intersections based on pore-pressure cohesive zone model (P-CZM) along both hydraulic and natural fractures. This model honors the fracture tip effects in quasi-brittle shale and introduces middle edge pore pressure nodes which are now hydraulically coupled at the intersection using additional simple governing equations. The model also provides a reasonable solution for the slit flow in fractures, which is fully coupled with continuum-based leak-off on the fracture walls along with poro-elastic effects within the porous media. Moreover, a user-defined stability function along the natural fracture(s) distinguishes the potential regions for the occurrence of microseisms.

Using this model, natural fracture opening and shear slippage are investigated depending on horizontal stress contrast, adjoining fissure conductivity, and hydraulic-natural fracture intersection angle. Modeling results demonstrate the complexities of hydraulic fracture growth through the intersection with natural fracture such as selective branching and throttling at the intersection. Our fracturing simulation results agree with the analytical criteria for fracture crossing or arrest at the intersection.

Keywords: Finite Element Method, Geomechanics, Poro-elasticity, Fully coupled pore pressure-stress analysis, Hydraulic fracture propagation, Pore pressure cohesive zone model, Naturally fractured shale formations, Microseismic monitoring, Fracture intersection, Stress shadowing effect, and Volumetric strain.

1. Introduction

Hydrocarbon reservoirs are buried geological formations which are capable of holding oil and gas in interconnected pore spaces known as porous media. The tectonic activities during millions of years in addition to the diagenetic processes leave natural fractures in the formation which get cemented by the flow of various minerals through the porous media. These natural fractures can occur in ultra-low permeable resources such as shale formations which can only be exploited through the recently improved technologies, horizontal drilling and multiple-stage hydraulic fracturing.

The investigation of these fracturing processes, however, requires the inclusion of natural fractures which are presumably cemented by weaker materials (e.g. calcite) compared to the adjoining media. Moreover, the evolution of the minimum horizontal stress alignment during geological times leads to a network of misaligned or intersecting natural fractures in addition to the propagation of the currently placed hydraulic fractures in directions not necessarily parallel to the pre-existing natural fractures. Therefore, the majority of hydraulic fractures inevitably intersect natural fractures in various angles which may not be known a priori. These intersections have been indirectly confirmed using microseismic monitoring during the field fracturing practices (Fisher et al., 2004; Warpinski, 2013).

The hydraulic-natural fracture (H-NF) intersection patterns can be classified as the following: (1) full natural fracture crossing without natural fracture de-bonding; (2) hydraulic fracture arrest at the intersection and subsequent natural fracture opening; (3) temporary hydraulic fracture arrest, partial de-bonding of natural fracture, and offset growth of hydraulic fracture; (4) natural fracture crossing and delayed de-bonding of natural fracture. The first three patterns have been observed experimentally (Fu et al., 2015) whereas the possibility of the last one has been demonstrated using numerical experiments (Haddad et al., 2016). These patterns may occur depending on the horizontal stress contrast (the difference between the minimum and maximum horizontal stresses or $S_{H,max} - S_{H,min}$), the absolute value of the horizontal stresses (Haddad et al., 2016), the fracture properties of the intact rock as well as the natural fracture cement, the injection rate, the fracturing fluid viscosity, and the intersection angle.

This work mainly focuses on the role of the intersection angle on the natural fracture activation and the subsequent hydraulic and natural fracture complexities as well as left signatures in the injection pressure and injection point aperture (fracture opening). For this purpose, the fracture intersection is included in a fully coupled pore pressure-stress analysis using a recently proposed model by Haddad et al. (2016). This model is based on pore pressure (hydraulic pressure) coupling at intersection and pore pressure-cohesive zone model (P-CZM) for the fracture space in Abaqus (Abaqus Analysis User's Guide, 2016). The generated conceptual models use the material properties, horizontal stresses, and pore pressure close to those for a shallow shale formation.

2. Method

Pore-pressure Cohesive Zone Model (P-CZM) in Abaqus/Standard has been extensively employed for hydraulic fracturing simulation, for instance in the works done by Searles et al. (2016), and Haddad and Sepehrnoori (2015). In these works, fractures are modeled by non-intersecting pre-defined cohesive layers which can cross multiple geological formations. The advantages of these models can be exemplified as thorough investigation of fracture height growth, stress interference of multiple hydraulic fractures, and mixed-mode fracture nucleation, coalescence, and propagation.

However, the inclusion of hydraulic and natural fracture intersections may need special treatment for the hydraulic coupling of intersecting fractures exactly at the intersection. This coupling can be implemented using the additional governing equations between the middle-edge pore pressure nodes at the intersection (Haddad et al., 2016). This approach assumes that one cohesive layer models a hydraulic fracture growth in the intact rock and the other intersecting cohesive layer models a natural fracture re-opening or dilation as shown Figure 1. The keyword ***EQUATION** in

Abaqus can couple the pore pressure degree of freedom of any pairs of middle-edge nodes; for instance, the following command in the input file equates the pore pressure value in Node 1 to the pore pressure value in Node 2:

***EQUATION**

2

1, 8, 1.0e0, 2, 8, -1.0e0

This coupling must be imposed for three pairs of middle-edge nodes leaving ultimately a single pore pressure degree of freedom at the intersection. For 2D cases, these equations can be manually added to the input file; however, 3D cases require a search algorithm to find the coupling nodes at the intersection and to generate an include file for ***EQUATION** commands (Haddad et al., 2016). Moreover, in order not to limit the fluid acceptance in multiple intersection legs, the damage value of the cohesive elements adjacent to the intersection is initialized as 1.0 as shown in Figure 1.

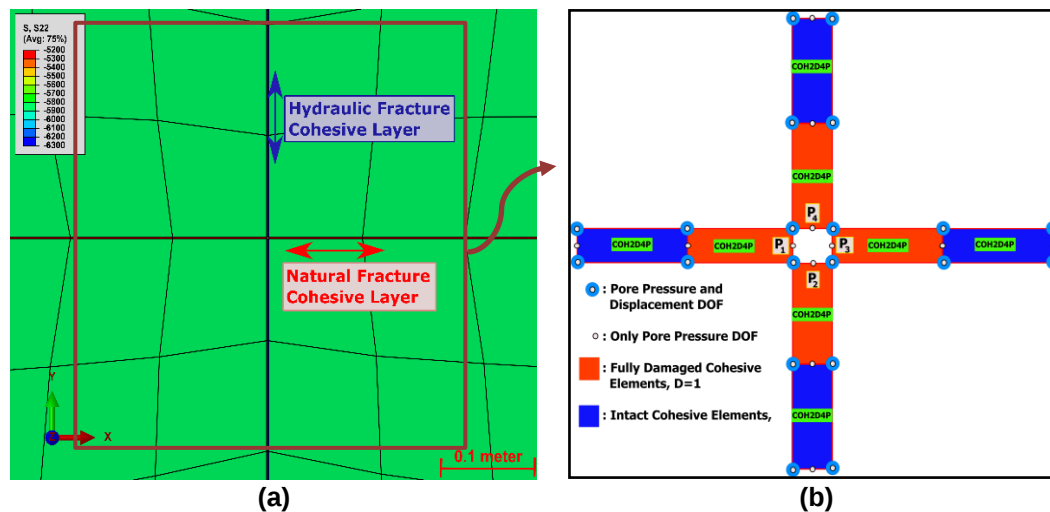


Figure 1. H-NF intersection model, Figure (a), and schematic of cohesive layer intersection configuration, Figure (b) (Haddad et al., 2016).

This approach requires special treatment for unique node numbering of the middle-edge nodes of the cohesive elements at intersection considering that Abaqus uses offset technique for the middle-edge node numbering. Defining clockwise or counter-clockwise sweep paths directions can guarantee this unique node numbering. For instance, for a double intersection case, sweep paths should be defined in opposite directions for the left and right intersections in order not to create repetitive middle node numbers at the intersections as shown in Figure 2.

Furthermore, due to the nonlinear nature of this problem, correct stress initialization for the matrix as well as the cohesive elements is of crucial importance for the initial solution convergence and the validity of the final results. The stress initialization simply follows the boundary loading conditions for the poro-elastic solid elements; however, it requires the calculation of shear and

normal stresses for the intersecting cohesive layers with intersecting angle of θ using slightly more complicated equations as Equations 1 and 2:

$$\tau = \frac{1}{2} \sin(2\theta) (S_{H,max,eff} - S_{h,min,eff}), \quad (1)$$

$$N = S_{H,max,eff} \sin^2 \theta + S_{h,min,eff} \cos^2 \theta, \quad (2)$$

where τ and N represent the shear and normal stresses on a cohesive layer making an angle of θ with the direction of the effective maximum horizontal stress, $S_{H,max,eff}$. Also, $S_{h,min,eff}$ denotes the effective minimum horizontal stress and perpendicular to the maximum horizontal stress. For instance, a purely tensile fracture propagation occurs at $\theta=0$ and hence, $N=S_{h,min,eff}$.

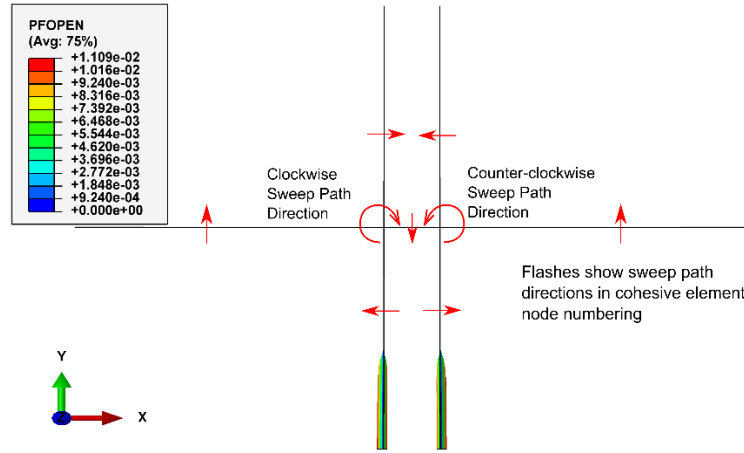


Figure 2. Top view of the cohesive layers in a double-stage hydraulic fracturing model containing two intersections with a horizontal natural fracture.

Natural fractures are usually cemented with weaker materials compared to the adjoining porous media due to different mineralogy and grain size distribution. Therefore, the material properties associated with an intact rock fracture may vary from the material properties of a fracture which re-opens a cemented natural fracture. This variation in the fracture properties can be reflected in the cohesive traction-separation response of intersecting cohesive layers using a weakening constant, WF , which proportionally scales down the fracture initiation stress, energy release rate, and elastic stiffness of the natural fracture from those of the hydraulic fracture, Figure 3. In this work, WF is assumed equal to 0.1.

Moreover, as stated before, the intersection of fractures occurs when the principal stresses, the minimum and maximum horizontal stresses, evolve with geological time due to the tectonic activities. In contrast to an idealized infinitely thin natural fracture, these stress evolutions create a joint zone also called gouges with contractional or dilational configurations expanding from a few millimeters up to tens of meters (Myers and Aydin, 2004; Committee on Fracture Characterization and Fluid Flow, 1996). This joint zone is likely characterized with more fluid conduits or barriers and therefore, enhanced or reduced permeability compared to the adjoining porous media. In order

to include this permeability alteration, we defined the porous media's material properties based on a field variable with a step-wise definition. This field variable is equal to 1.0 if the material node's distance from the natural fracture is less than a constant (e.g. a typical value of 0.1 meters), and equal to 0.0 for farther distances. We assigned this field variable to the material points using **UFIELD** user subroutine. In this work, we assumed that the joint zone permeability and the leakoff coefficient are enhanced by 2 times with respect to those outside the joint zone.

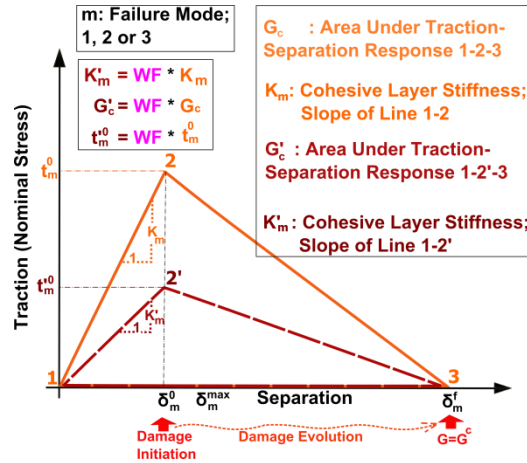


Figure 3. Traction-separation response for cohesive layers associated with the hydraulic and natural fractures shown with orange and red lines, respectively. Natural fracture properties are weakened by a factor of WF with respect to the hydraulic fracture properties (Haddad et al., 2016).

3. Results and Discussion

Figure 4 shows a typical computational domain in the current work, e.g. for the H-NF intersection angle equal to 30 degrees. The hydraulic fracture's cohesive layer is placed perpendicular to S_{xx} which is commonly assumed as the minimum horizontal stress and the natural fracture's cohesive layer makes an angle of θ with the hydraulic fracture. This angle takes values equal to 30°, 45°, 60°, and 90° for the sensitivity study on the intersection angle. Moreover, the horizontal wellbore is placed ideally in the x-direction and 25 meters far from the H-NF intersection point. In order to adequately refine the mesh around the cohesive elements, we used “Quad, Free, and Advancing front” mesh controls for the porous rock domain, and “Quad, Sweep” mesh controls for the cohesive elements.

Furthermore, the numerical values of the model parameters can be found in Table 1. The area under the traction separation response or the energy release rate is calculated using Irwin's plane-strain equation, $G_f^c = K_{Ic}^2 (1 - \nu^2) / E$, where K_{Ic} , E , and ν denote the fracture toughness, Young's modulus, and Poisson's ratio, respectively, and are given in Table 1. $S_{yy, threshold}$ in this table denotes the far-field stress component S_{yy} below which the natural fracture starts to open upon the hydraulic fracture arrival at the intersection. This stress threshold was obtained during multiple

attempts on this stress for every H-NF intersection angle, θ . As Table 2 shows, $S_{yy, \text{threshold}}$ reduces as the intersection angle increases.

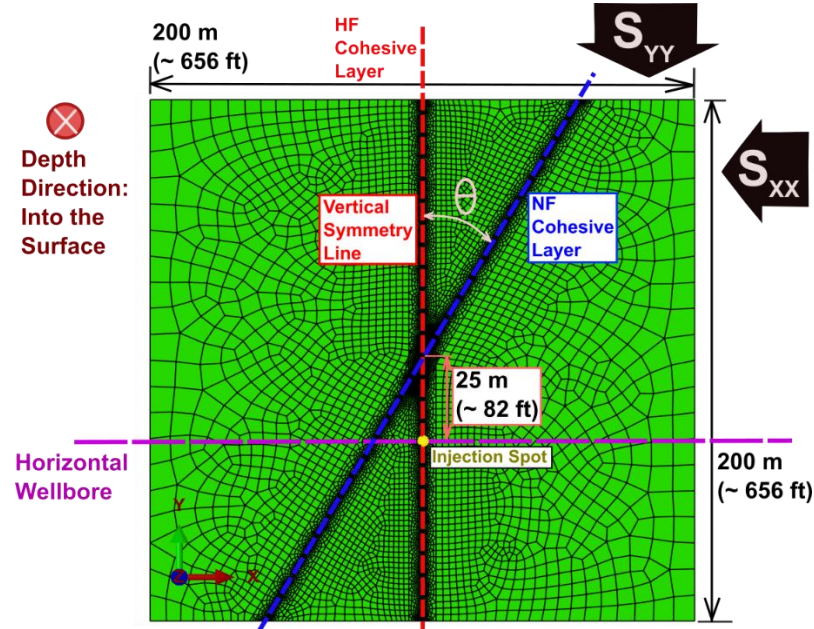


Figure 4. 2D Reservoir model consisting of 942 COH2D4P and 11865 CPE4P elements for the fracture and porous rock domains, respectively. HF and NF denote hydraulic and natural fracture planes, respectively.

Table 1. Parameters for the 2D intersection model

Properties	Value
Formation Thickness [m]	61
$S_{xx, \text{far-field}}$ [kPa]	6900
$S_{yy, \text{far-field}} = S_{yy, \text{threshold}}$ [kPa]	5904 (@ $\theta = 90^\circ$), 6346 (@ $\theta = 60^\circ$), 6456 (@ $\theta = 45^\circ$), 6677 (@ $\theta = 30^\circ$)
Initial Reservoir Pore Pressure [kPa]	690
Initial Porosity, ϕ [] (at zero pore pressure, stress, and zero strain)	0.14
Initial Effective Permeability [mD] (variable with porosity) at initial porosity	0.5
Poisson's Ratio, ν []	0.23
Young's Modulus, E [MPa]	20.7
Fracture Toughness [kPa. $\sqrt{\text{m}}$]	1756
Mode-I and -II Damage Initiation Stresses, t_0 [kPa]	1104, 68975
Leak-off Coefficient ($\text{m}^3/\text{kPa.s}$)	5.879E-10
Regularization Viscosity	0.035
Injection Amplitude Curve	Ramp up linearly in the first 100 seconds
Injection Time [sec]	2500
Injection Rate [m^3/s]	8.7E-4
Injection Fluid Density [kg/m^3]	1000
Viscosity [cp]	5

Figure 5 shows the stress components, S_{22} and S_{12} , on the left and right figures at various H-NF intersection angles and after 462 seconds of injection. Cohesive elements are removed in these figures in order to better show the hydraulic and natural fracture spaces. All these figures show throttling of the hydraulic fracture close to the intersection point and significant opening of the natural fracture as a result of fracturing fluid discharge into the natural fracture and its consequent activation. These exact patterns are associated with the threshold horizontal stress contrasts above which the hydraulic fracture completely crosses the natural fracture without any natural fracture activation.

Furthermore, the left natural fracture wing does not open as long as the right wing in the cases where the hydraulic and natural fractures are not perpendicular to each other. This asymmetric natural fracture growth results from different induced stresses on the natural fracture plane due to the hydraulic fracture growth. In 30° , 45° , and 60° intersection angles, the left wing carries higher induced compressional stresses compared to the right wing; this causes more resistance for the natural fracture to open on the left wing.

Figure 6 displays the dependence of the threshold horizontal stress contrast on the H-NF intersection angle. As shown in this figure, the natural fracture dilation requires negative horizontal stress contrasts or $S_{yy, \text{far-field}}$ smaller than $S_{xx, \text{far-field}}$. Also, higher intersection angles require more negative threshold horizontal stress contrast. This trend can be justified considering the stronger stress shadowing effect of the hydraulic fracture on both wings of the natural fracture at higher angles, and consequently, more resistance to the natural fracture opening.

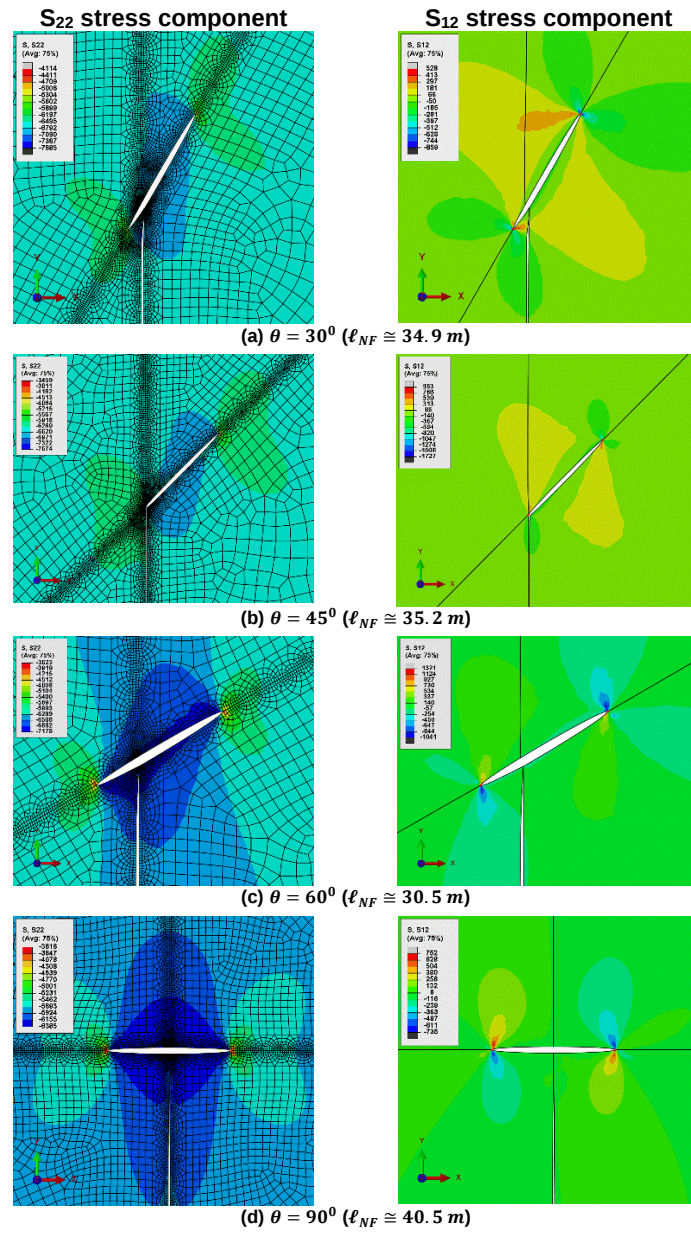


Figure 5. S_{22} and S_{12} stress component contours, left and right figures, on a zoomed area around the intersection at various H-NF intersection angles after 462 seconds of injection. ℓ_{NF} denotes tip-to-tip distance along the natural fracture. Displacements are magnified 1000 times.

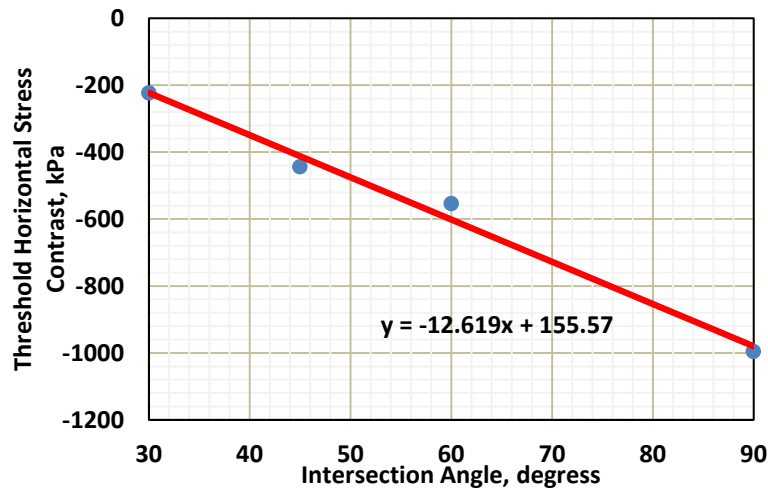


Figure 6. Threshold horizontal stress contrast to activate the natural fracture depending on intersection angle.

In order to better understand the natural fracture opening trends, we plotted the volumetric strain contours in Figure 7. The volumetric strain was calculated using **UVARM** subroutine by calling **GETVRM** subroutine for the “LE” strain components, and using the equation $LE_1 + LE_2$ where LE_1 and LE_2 denote the first and second logarithmic strain components. Notably, due to the finite strain analyses in this work, logarithmic strains are calculated instead of infinitesimal strains.

As Figure 7 shows, the cases at 30° and 45° intersection angles contain significant volumetric strains around the natural fracture majorly due to the natural fracture opening displacements not the hydraulic fracture growth. In contrast, cases at 60° and 90° intersection angles cause the region of high volumetric strains around the hydraulic fracture to overlap with that around the natural fracture. In these cases, the natural fracture opens harder as a result of more compressive volumetric strains. Therefore, the required horizontal stress contrast to open the natural fracture should reduce as stated in Figure 6.

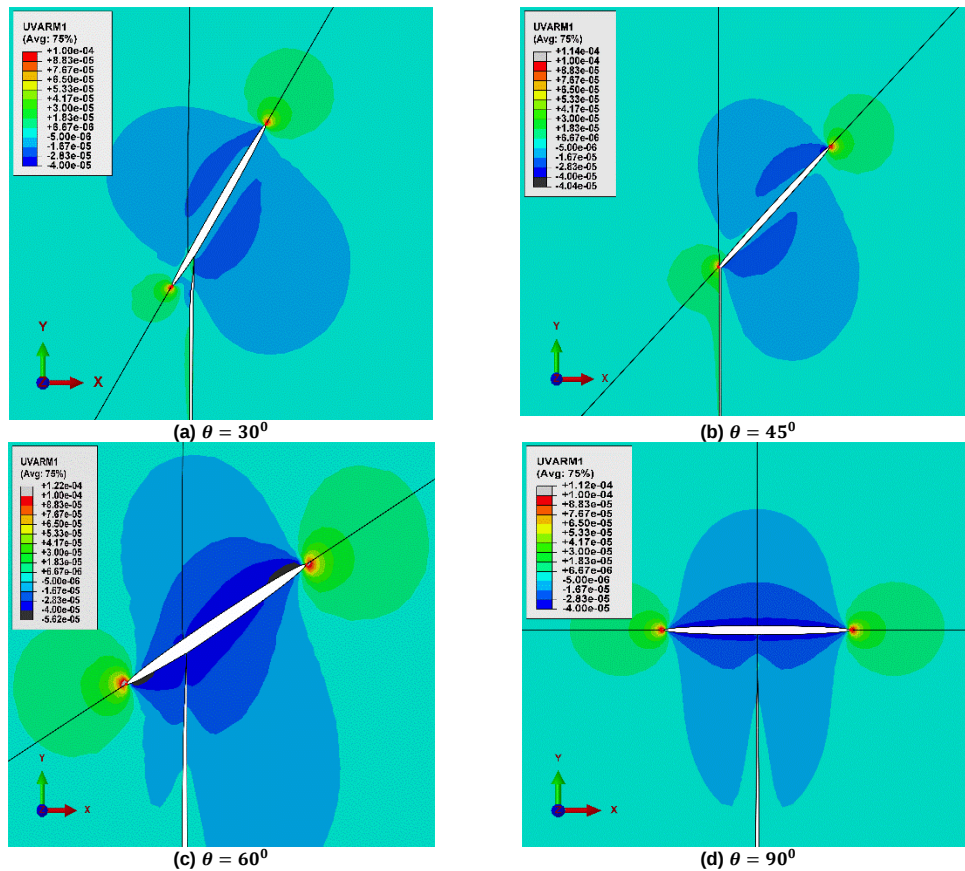


Figure 7. Volumetric strain contours on a zoomed area around the intersection at various H-NF intersection angles after 462 seconds of injection. Displacements are magnified 1000 times.

Figure 8 shows the fracturing fluid pressure at the injection point through time and far-field horizontal stress. The high spike in the injection pressure is consistent with the extremely high injection pressure at very early times in KGD model for plane-strain fracture propagation (Khristianovic and Zheltov, 1955; Geertsma and De Klerk, 1969). Also, early-time high injection pressures have been frequently reported during the fracturing operations in the oil and gas reservoirs. The abrupt injection pressure reduction coincides with the arrival of the hydraulic fracture tip to the H-NF intersection point and subsequent natural fracture opening. This natural fracture opening for the cases of 60° and 90° intersection angles occurred around 300 seconds later than that for the other two cases. This delay can be referred to the prior arrival of the lower hydraulic fracture wing to the lower boundary. As expected, all injection pressure profiles tend to converge to the far-field horizontal stress as the confining pressure on the hydraulic fracture.

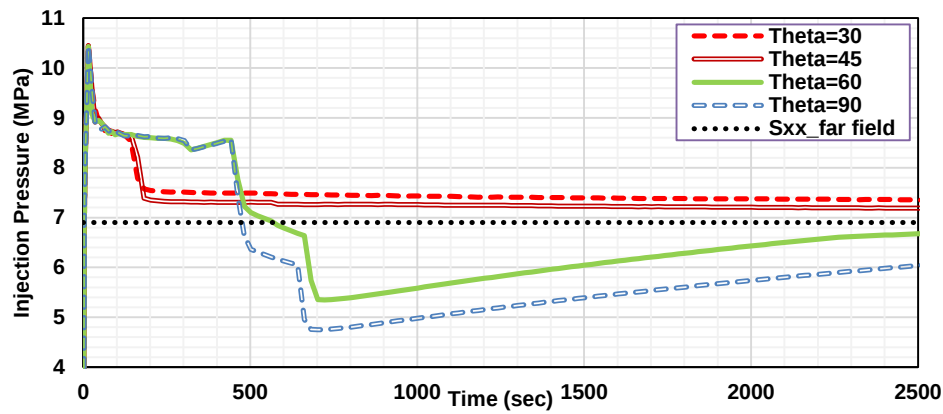


Figure 8. Injection pressure through time for different intersection angles, θ).

Figure 9 compares fracture opening at the injection point for different intersection angles. The trends shown in this figure are completely consistent with those in Figure 8. The early-time increasing injection pressure causes monotonic fracture opening at the injection point. This is followed by the abrupt injection point opening reduction due to the significant fluid invasion from the hydraulic fracture into the natural fracture. Also, as shown in Figure 6, this fluid invasion causes the closure of the hydraulic fracture close to the intersection point. Moreover, the hydraulic fracture closure at the injection point or close to the intersection point is more unfavorable in cases with 60° and 90° intersection angles, which may cause problems during proppant transport, e.g. proppant bridging, crushing and embedment, or during maintaining the H-NF connection.

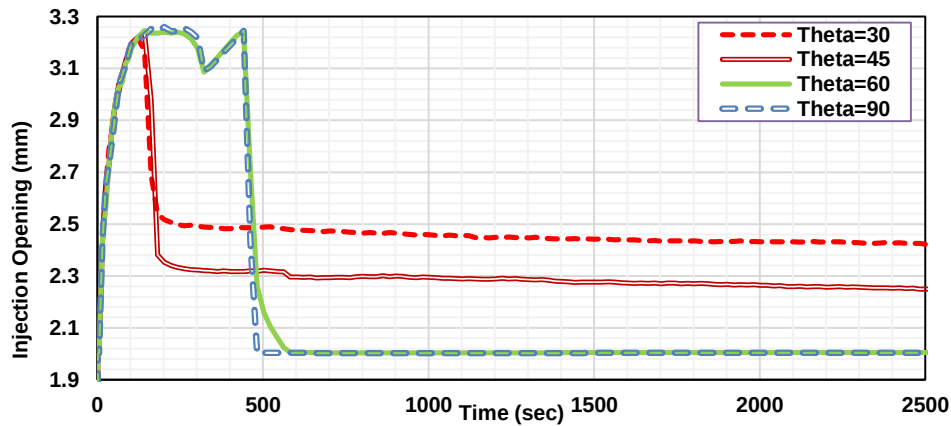


Figure 9. Injection fracture opening through time for different intersection angles, θ).

4. Future work

We accomplished this work through the following input file modifications in Abaqus 6.14-2: 1) addition of pore pressure degrees of freedom to the cohesive elements that we defined in Abaqus/CAE; 2) definition of concentrated flow, `*cflow`, in the step definition; 3) coupling pore pressure degrees of freedom at the intersection using `*EQUATION` keyword; and 4) parameterization of the material properties, and boundary and initial conditions.

However, the latest improvements in Abaqus/CAE 2016, provide access to the pore pressure cohesive elements and the corresponding concentrated flow boundary condition. Moreover, a recently developed group of pore pressure cohesive elements, e.g. `COD2D4P`, supports the transition of Darcy flow to Poiseuille flow within the fracture, fluid flow continuity at intersecting cohesive layers, and gravity-induced fluid flux. In order to increase the model accuracy and simplify the model generation, we are going to extend the current work using the aforementioned improvements in the new version of Abaqus.

5. Summary and Conclusions

In this work, we developed hydraulic fracturing models including the H-NF intersection at various intersection angles, enhanced joint zone permeability and stable weakening behavior of natural fracture. Our intersection model is based on coupling of the middle-edge pore pressure degrees of freedom for the cohesive element edges at the intersection.

Our results show almost a linear relationship between the threshold horizontal stress contrast for natural fracture dilation and the intersection angle; at a constant horizontal stress, increasing the intersection angle requires more reduction of the vertical stress in order to dilate the natural fracture upon the hydraulic fracture arrival to the intersection. These results are strongly influenced by the stress shadowing effect at large matrix deformations or finite strains during hydraulic fracture growth. Furthermore, natural fractures dilate asymmetrically at angles other than 90° ; this asymmetric dilation contributes to the lower magnitudes of the horizontal stress contrast required for the natural fracture opening at the smaller intersection angles.

6. References

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