Progressive Fracturing Simulations: Transition from Non-Intersecting Fractures to Intersections*

Mahdi Haddad[1]

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[1]University of Texas at Austin, Austin, TX, USA (mahdi.haddad@utexas.edu)

Abstract

The Cohesive Zone Model (CZM) engages the plastic zone and softening effects at the fracture tip in a quasi-brittle rock, e.g. shale, which concludes a more precise fracture geometry and pumping pressure compared to those from Linear Elastic Fracture Mechanics. Nevertheless, this model, namely planar CZM, assumes a predefined surface on which the fractures propagate and therefore, restricts the fracture propagation direction. Notably, this direction depends on the stress interactions between closely spaced fractures and can be acquired integrating CZM as the segmental contact interaction model with a fully coupled pore pressure-displacement, extended finite element model (XFEM). This later model simulates the fracture initiation and propagation along an arbitrary, solution-dependent path.

In this work, using XFEM-based CZM in Abaqus, we modeled four-stage 3D hydraulic fracturing in a triple-layer, quasi-brittle shale formation including slit flow and poro-elasticity for fracture and matrix spaces, respectively. We implemented a new method to connect our model to the infinite surrounding rock layers by replacing the horizontal stress boundary conditions with infinite elements around the solution domain of interest. Moreover, we characterized the cohesive segments by refining the stiffness, fracture initiation stress, and energy release rate using three geometric and accuracy criteria. Furthermore, we partitioned only the stimulation region into multiple XFEM enrichment zones to simulate multiple-stage fracture propagation, reduce computational expenses, and avoid unrealistic fracture growths around sharp edges.

We demonstrated the significance of operational parameters, rock mechanical properties, and loaded or fixed boundary conditions in fracture aperture and propagation direction in sequential and simultaneous four-stage fracturing cases. Also, having compared the multiple-stage fracturing results from planar CZM with those from XFEM-based CZM, we found that the stress shadowing effect of hydraulic fractures on each other can cause these fractures to rationally propagate out of plane. We investigated the effect of this arbitrary propagation direction on not only the fractures' height, length, aperture, and the required injection pressure, but also fractures' connection to the wellbore. This connection can be disrupted due to the near-wellbore fracture closure, which may embed proppant grains on the fracture wall, or screen out the fracture at early times.

Our results verified that the near-wellbore fracture closure strongly depends on three remarks: 1) the implemented model, planar or XFEM-based CZM; 2) the fracturing scenario, sequential or simultaneous; and 3) the fracture spacing. Ultimately, we proposed the best fracturing scenario and spacing to maintain the fractures connected to the wellbore for better proppant placement and subsequent production.

Selected References

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Progressive Fracturing Simulations: Transition from Non-intersecting Fractures to Intersections

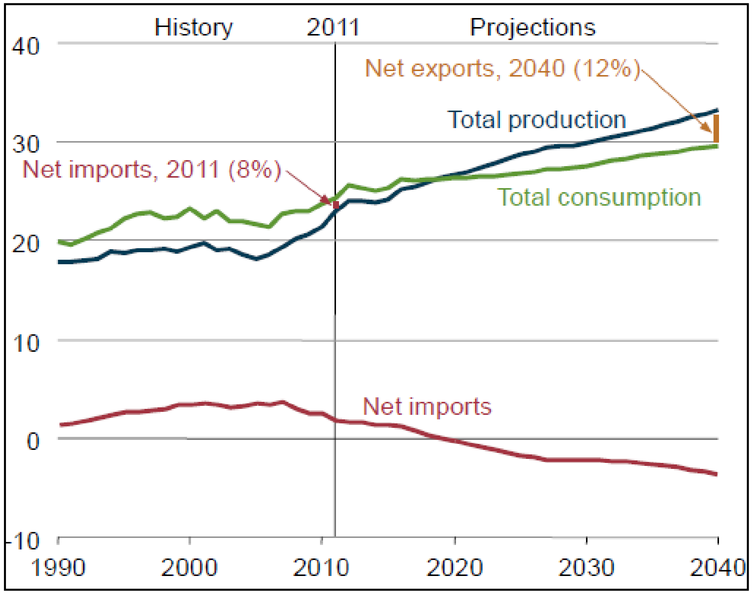
Mahdi Haddad
University of Texas at Austin

Outlines

- Problem Description
- Step 1: Planar Cohesive Zone Model
  - Method
  - Model Construction
  - Results
- Step 2: eXtended Finite Element Method (XFEM)
  - Method
  - Model Construction
  - Results
- Step 3: Fracture Intersection
  - Primary results
- Summary and Conclusion

Problem Description

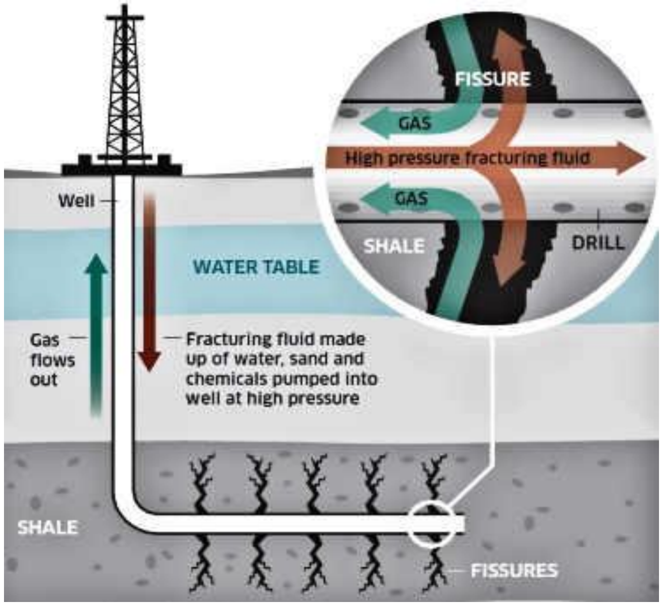
- Shale gas resources are organic-rich formations and will shift the U.S. from natural gas importer to exporter by 2019 (EIA 2013)



- Gas desorption by pressure depletion is one of the producing mechanisms in shale reservoirs, which requires complex network of fractures
- Due to ultra-low shale permeability, economic production is only possible by horizontal drilling and hydraulic fracturing
- Variety of shale formations and lack of data are the motivations for employing numerical optimizing tools per field

Problem Description: HF Concerns and Complexities

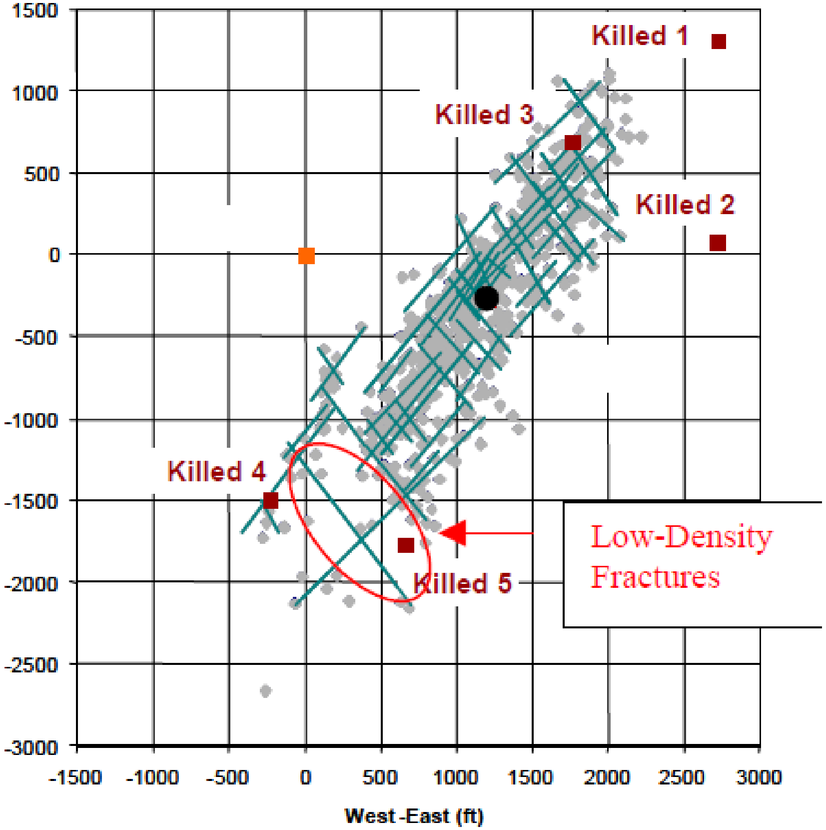
- Cap rock at the same place as reservoir – Controlled extension to upper or lower layers – Less environmental effects
- Demand for more trustworthy long term production estimate



- A multi-physics simulation problem coupling fluid mechanics with fracture mechanics; a fully coupled porous solid-fluid interaction problem
- More complexities due to stress shadowing effect
- Disapproval of bi-wing planar fracture models by micro-seismic monitoring in shale formations (Weng et al. 2011)

Problem Description

- Strong stress interaction of closely-spaced fractures.
- More complicated considering the natural fracture network.
- Observation using tilt-mapping in Barnett Shale (Fisher et al. 2002):
  - The extension of cross-cutting fractures along natural fractures perpendicular to the major hydraulic fracture propagation direction.
  - 45% of the injected volume invaded into these cross-cutting fractures.

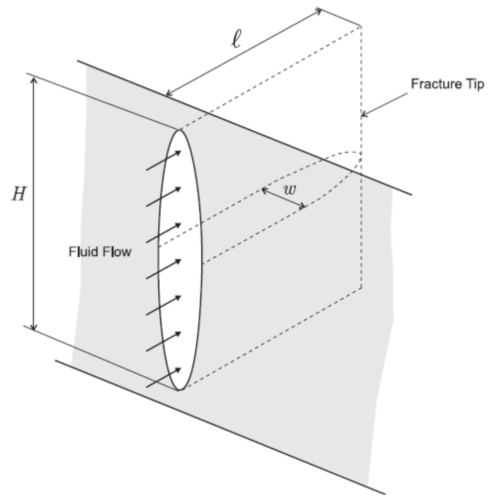


- Objective: The optimum fracture design considering NF's and intersections.

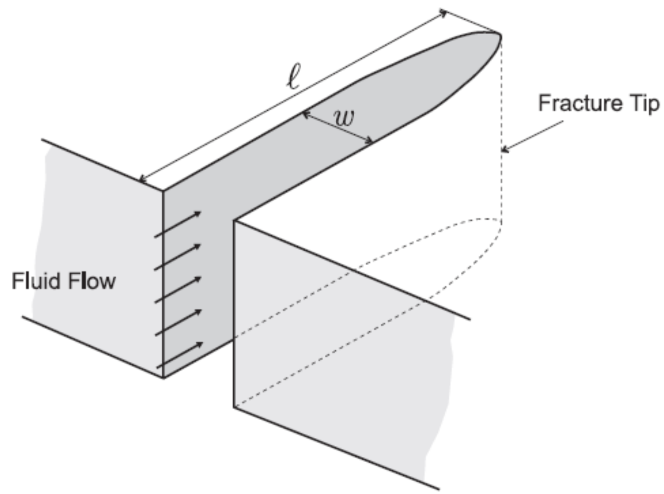
Primary Models

- Three most well-known 2D analytical models:

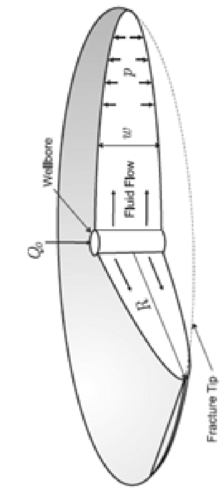
  PKN (Nordgren 1972), KGD (Daneshy 1973), and penny-shaped (Abe et al. 1976)



Schematic showing PKN fracture geometry



Schematic showing KGD fracture geometry



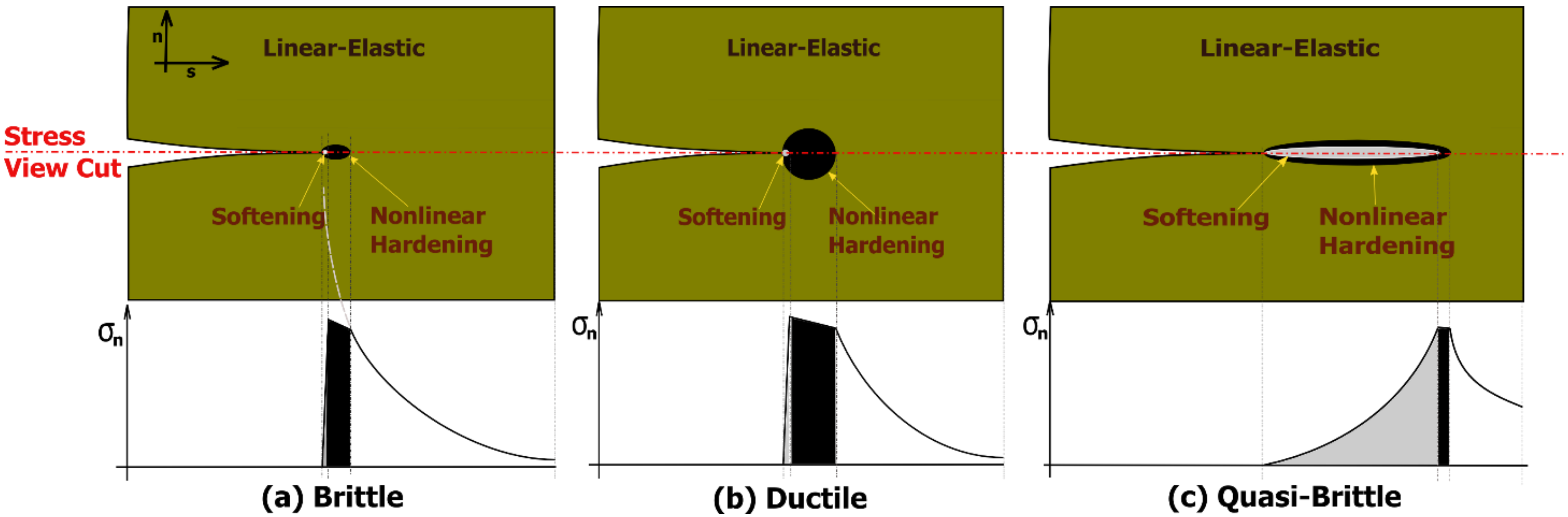
Schematic showing penny-shaped fracture geometry

Ref.: Adachi, et al. 2006

Step 1: Planar Fracture Propagation Using Cohesive Zone Model (CZM)

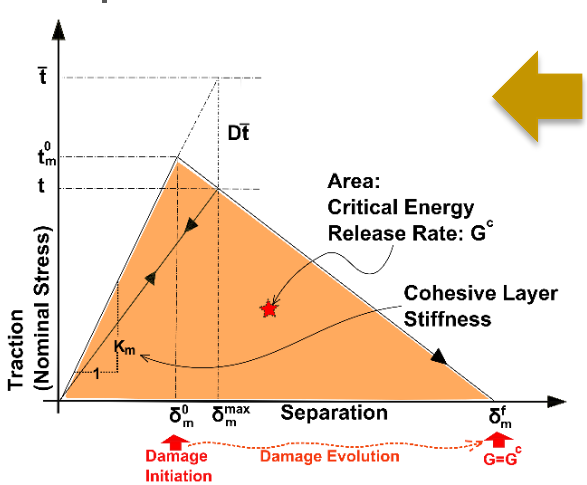
Method: Models and Restrictions on Material

- **The prevailing design tools in hydraulic fracturing applications:** Empirical methods and LEFM-based numerical techniques –good for brittle rocks, conservative results for ductile or quasi-brittle rocks; e.g. shales due to neglecting fracture process zone
- Progressive damage in the fracture process zone in quasi-brittle materials. Elastic response abruptly transitions to damage (Bazant and Planas 1998).



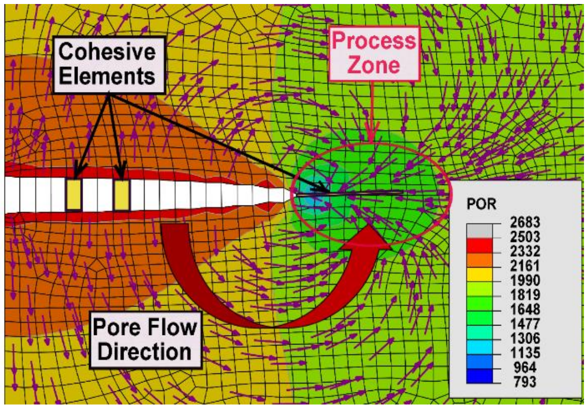
Method: 1-Cohesive Zone Model; a better material model for quasi-brittle rocks

- Cohesive behavior: a better treatment for HF simulations in shales.
- The concept of cohesive zones was applied to fracture modeling for the first time after Dugdale (1960) and Barenblatt (1962)
- Cohesive elements are attractive when interface strengths are relatively weak compared to the adjoining materials (cement in a natural fracture)
- CZM idealizes complex fracture mechanisms with a macroscopic "cohesive law". Planar CZM with a pre-defined fracture path as the right picture.



Typical cohesive traction-separation law

Typical fully coupled pore pressure-stress analysis using CZM; non-linear porous flow



Method: Geometrical Restriction for Fractures using Planar CZM

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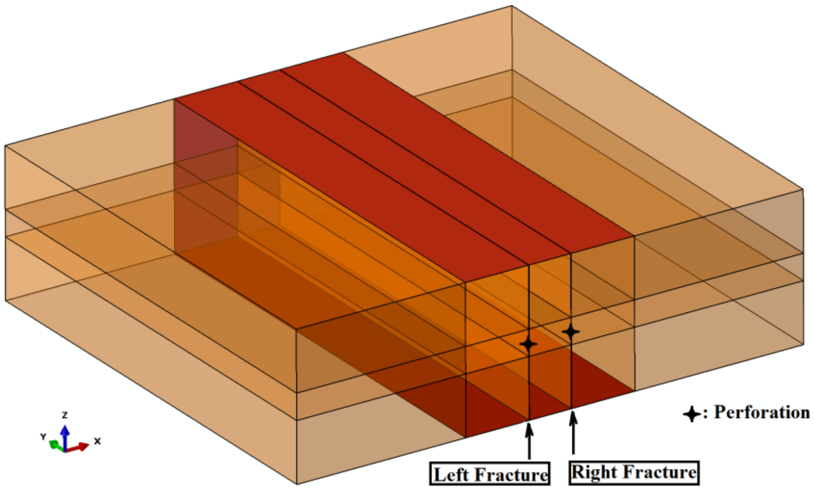
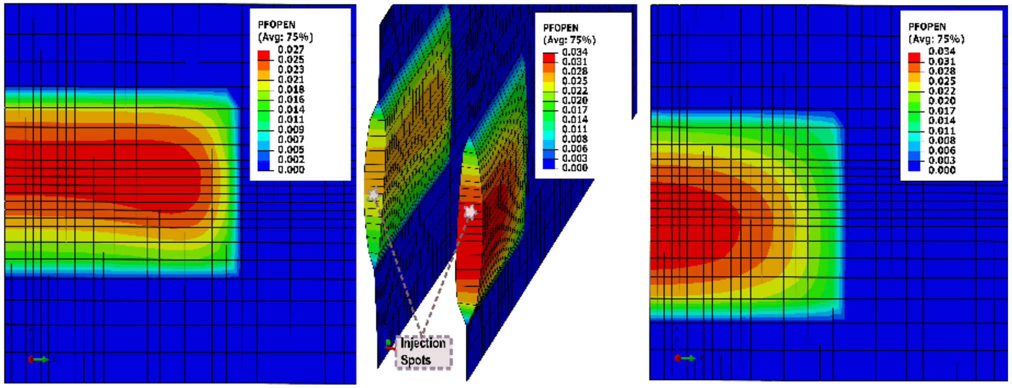
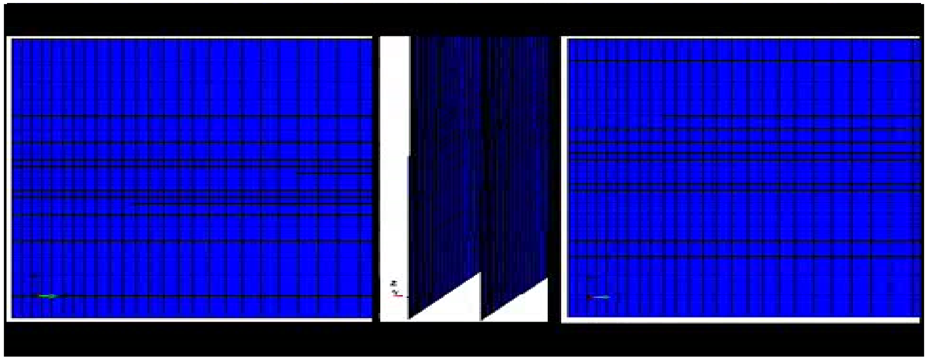




(a) Left fracture (b) Interaction (c) Right fracture

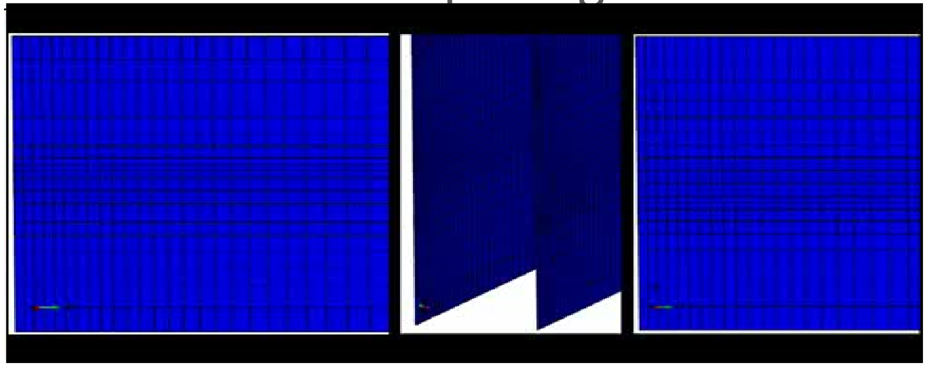
Animation 1: Opening contours



33-ft Spacing and sequential fracturing

Click Animation to Activate

Animation 2: Opening contours

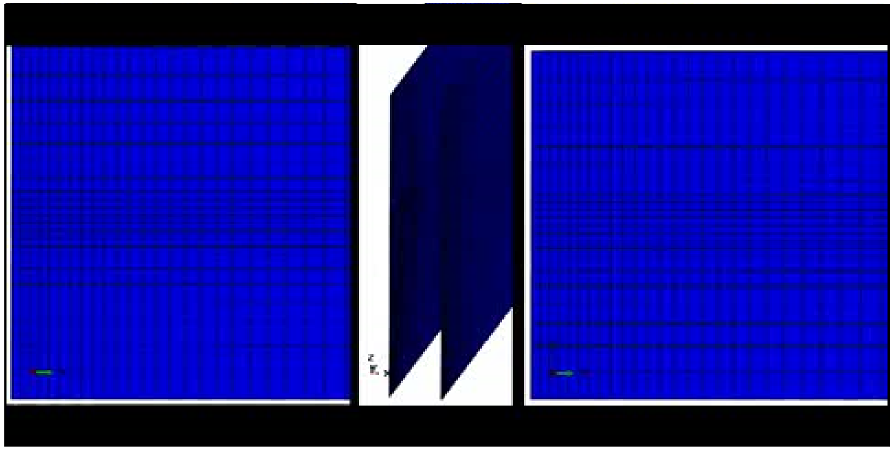


66-ft Spacing and sequential fracturing

Click Animation to Activate

Method: Geometrical Restriction for Fractures using Planar CZM: Simultaneous Double Stage Fracturing

Animation 3: Opening contours
33-ft Spacing



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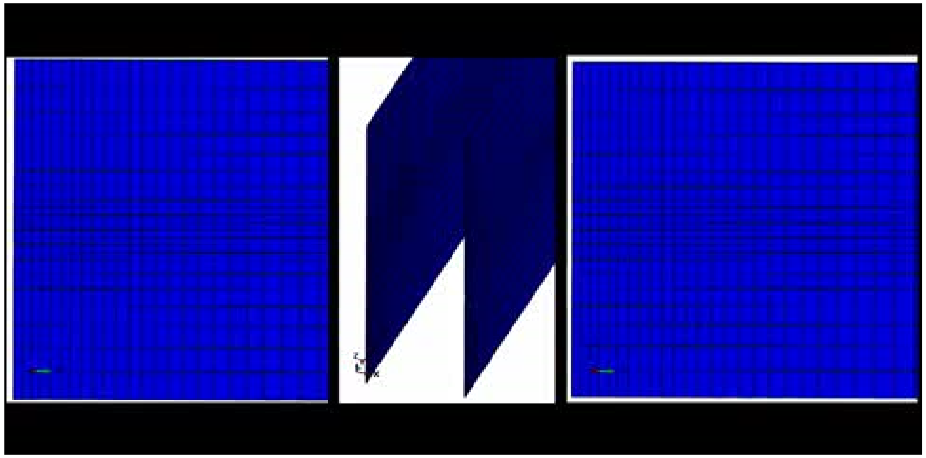
Animation 4: Opening contours
66-ft Spacing



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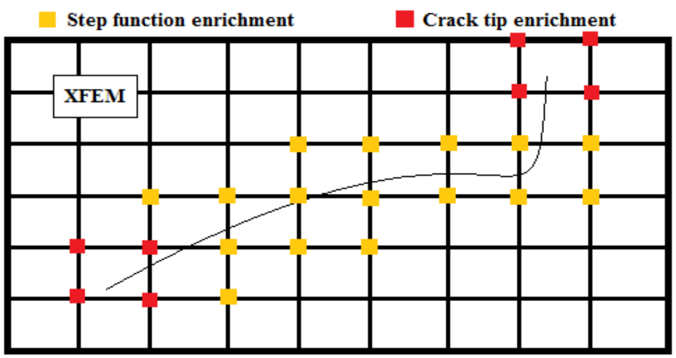
Step 2: Non-planar Fracture Propagation Using eXtended Finite Element Method (XFEM)

Method: 2-XFEM-based CZM; a better geometrical model

- XFEM simulates fracture propagation along arbitrary paths independent of the mesh.
- It uses edge and corner phantom nodes for frac. fluid flow and cohesive behavior.
- XFEM includes a priori knowledge of partial differential equation behavior into finite element space (singularities and discontinuities).

$$u^h(x) = \sum_{I \epsilon N} N_I(x) \left[u_I + H(x) a_I + \sum_{\alpha=1}^{4} F_\alpha(x) b_I^\alpha \right],$$

$$\{F_\alpha(r,\theta)\}_{\alpha=1,2,3,4} = \left\{ \sqrt{r}\sin\frac{\theta}{2}, \sqrt{r}\cos\frac{\theta}{2}, \sqrt{r}\sin\frac{\theta}{2}\sin\theta, \sqrt{r}\cos\frac{\theta}{2}\sin\theta \right\}$$



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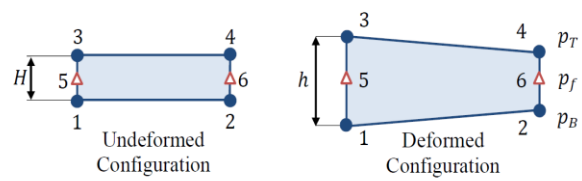
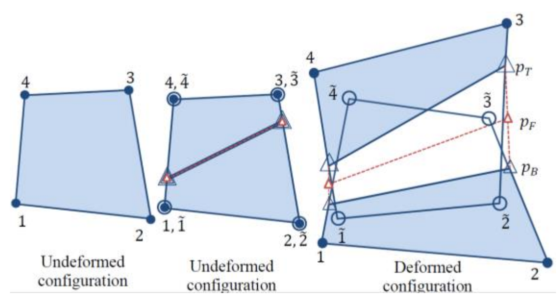


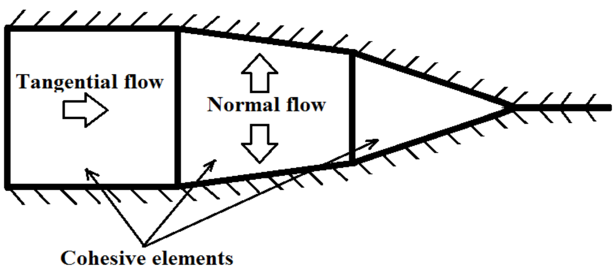
Cohesive elements in CZM



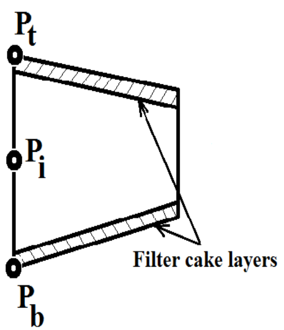
Corner and edge phantom nodes in XFEM-based CZM (Zielonka et al. 2014)

Method: Flow Model

- **Leak-off:** Historically assumed uncoupled from the fluid pressure and restricted to linear, 1D flow regimes. However, Cohesive Element Flow Model treats leak-off as a fluid component (fully coupled with the other unknowns) calculated from Darcy's or Forchheimer's law based on fluid speed.
- **Fracture, filter cake, and matrix flow:** Reynolds', filter cake, and matrix permeabilities for gap, leak-off, and matrix flows.



Tangential and normal flows in pore pressure cohesive elements



$$q_t = c_t \left(p_i - p_t \right)$$

$$q_b = c_b \left(p_i - p_b \right)$$

Normal flow or leak-off flow across gap surfaces

- No Proppant Transport

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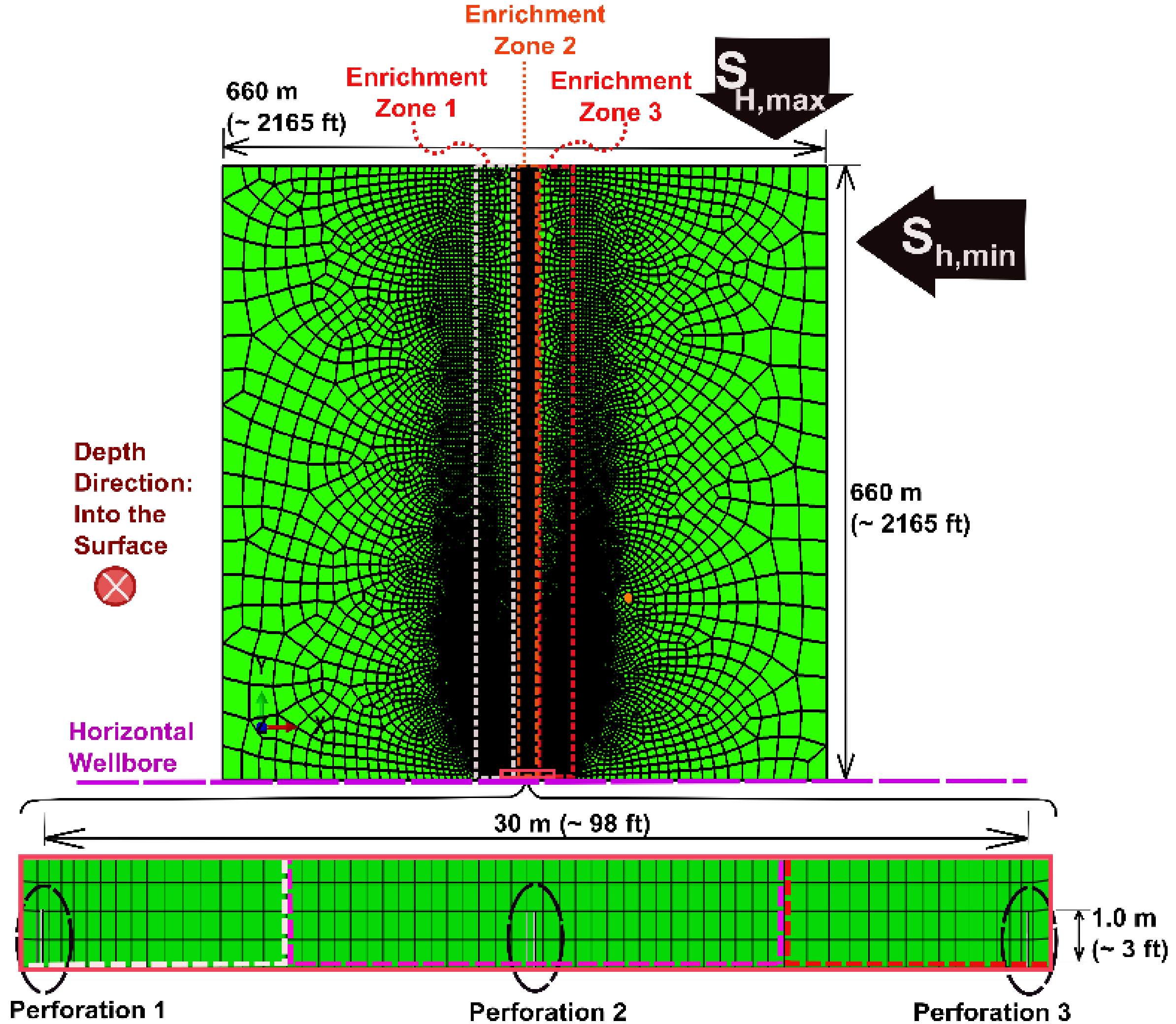
Model Construction: XFEM-based CZM; 1 Stage & 3 Clusters



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Model Construction: Properties

Properties	Value
Formation Thickness [ft]	137
$S_{h,min,total}$ [psi]	8000
$S_{H,max,total}$ [psi]	8200
Initial Reservoir Pore Pressure [psi]	5000
Initial Porosity, [] (at zero pore pressure, stress, and zero strain)	0.12
Initial Effective Permeability [microD] (variable with porosity)	80
Poisson's Ratio, []	0.23
Young's Modulus, E [10^6 psi]	3
Fracture Toughness [psi.in^0.5]	1600
Damage Initiation Stress, t^0 [psi]	80
Leak-off Coefficient (m^3/kPa.s)	5.879E-20
Stabilization Parameter	0.03

Parameter	Value
Max. Pump Rate [bbl/min]	20
Injection Amplitude Curve	Ramp up linearly in the first 10 seconds starting with half rate
Injection Time [sec]	500, 1500
Number of Perforations (clusters per stage)	2, 3
Cluster Spacing [ft]	50, 100
Injection Fluid Density [kg/m^3]	1000
Viscosity [cp]	1
Fracturing Fluid Power Law Exponent	1 (Newtonian)

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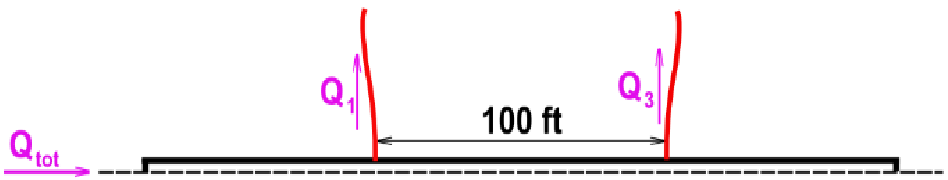
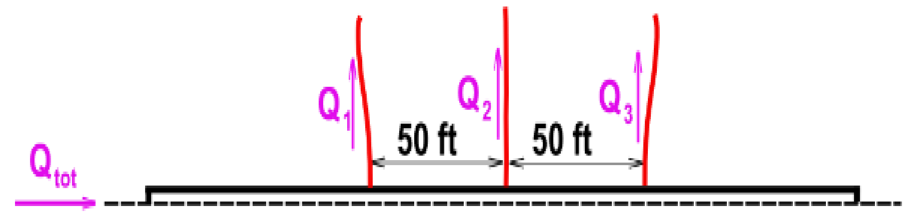
Model Construction: Properties



$0.5Q_{tot} = Q_1 + Q_3$

$Q_1 = Q_3 = 20$ bbl/min

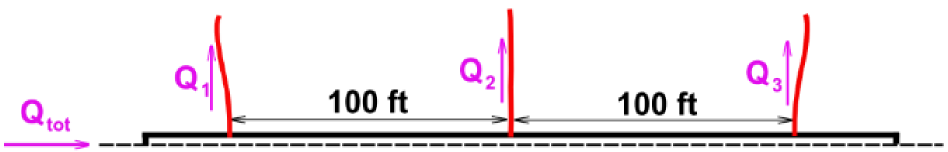
Case 1



$0.5Q_{tot} = Q_1 + Q_2 + Q_3$

$Q_1 = Q_2 = Q_3 = 20$ bbl/min

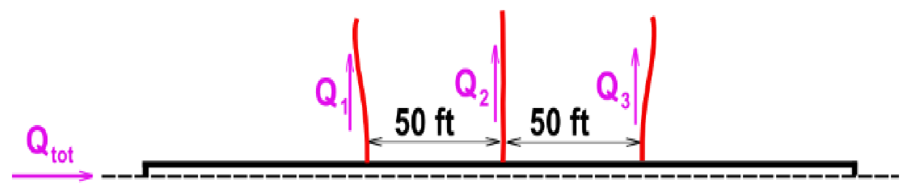
Case 2



$0.5Q_{tot} = Q_1 + Q_2 + Q_3$

$Q_1 = Q_2 = Q_3 = 20$ bbl/min

Case 3

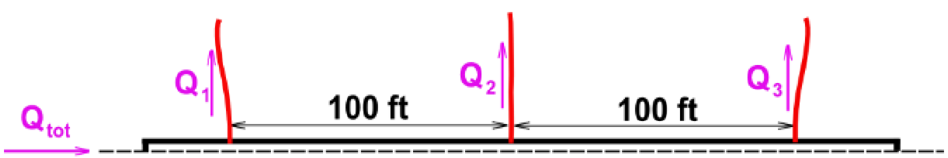


$0.5Q_{tot} = Q_1 + Q_2 + Q_3$

$Q_1 = Q_3 = 27$ bbl/min

$Q_2 = 6$ bbl/min

Case 4



$0.5Q_{tot} = Q_1 + Q_2 + Q_3$

$Q_1 = Q_3 = 27$ bbl/min

$Q_2 = 6$ bbl/min

Case 5

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Results: Case 1: Double Fracture with 100-ft Spacing and Equal Injection Rate in All Clusters

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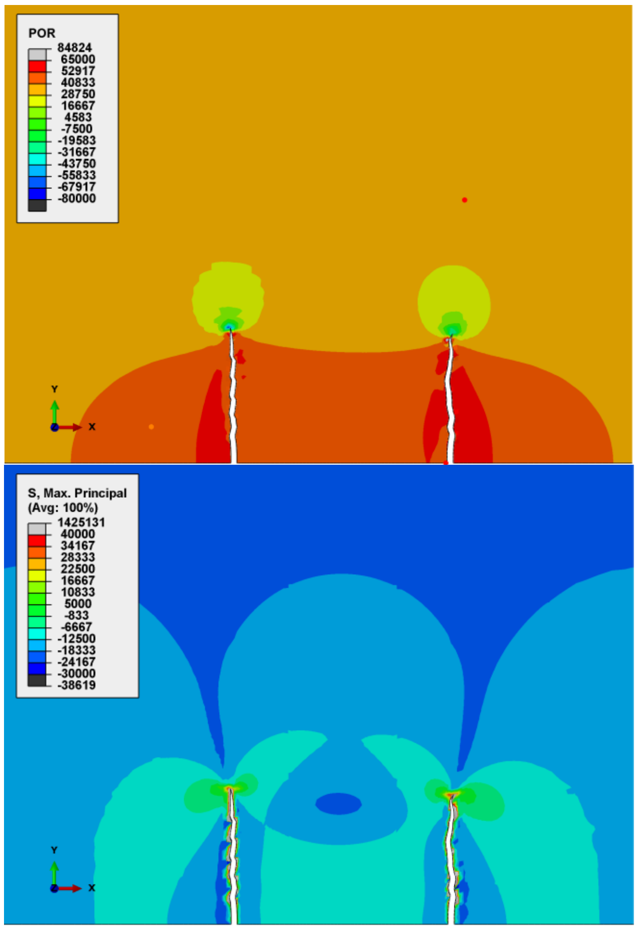

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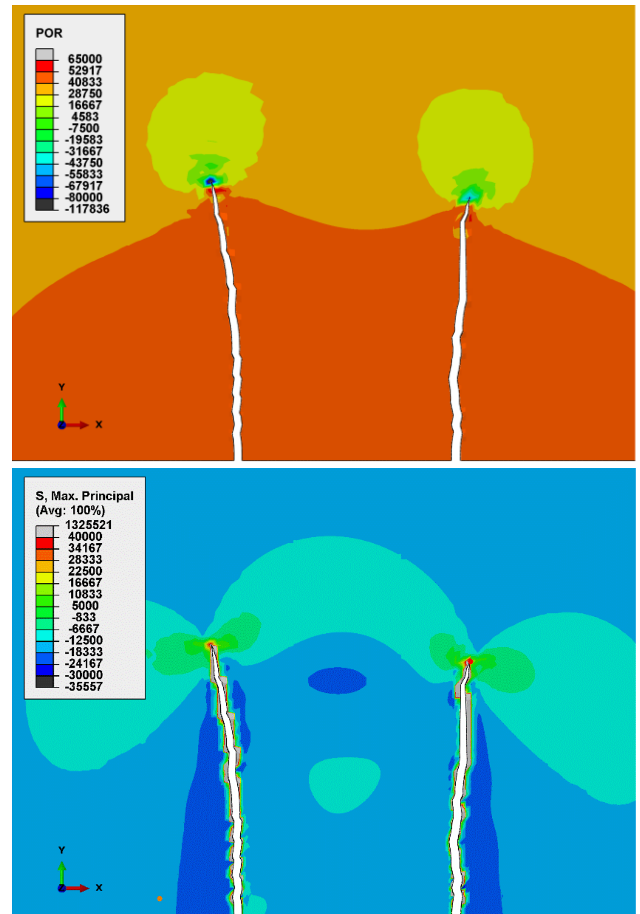

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Results: Case 3: Triple Fracture with 100-ft Spacing and Equal Injection Rate in All Clusters

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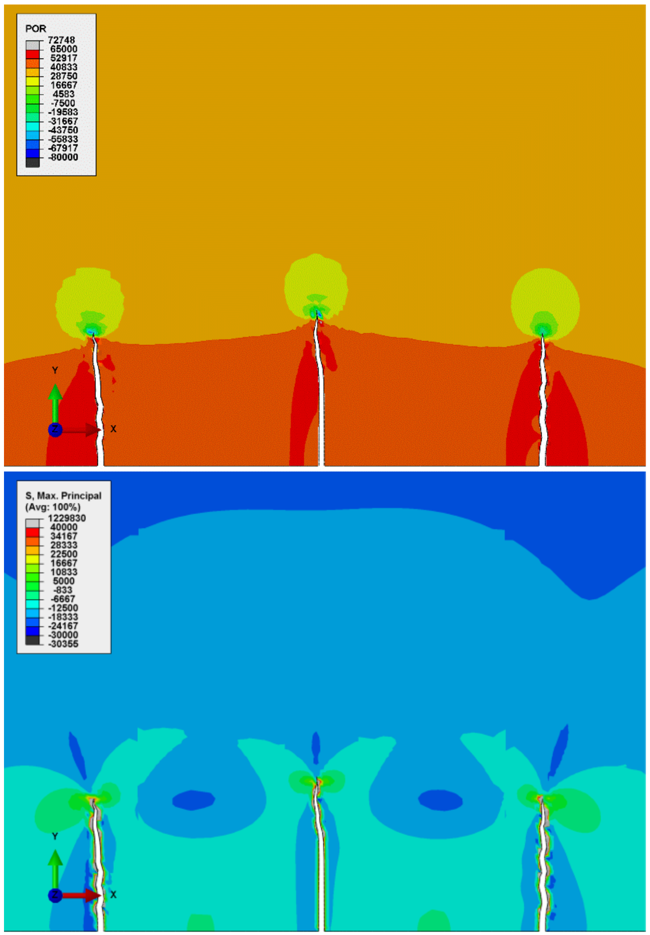

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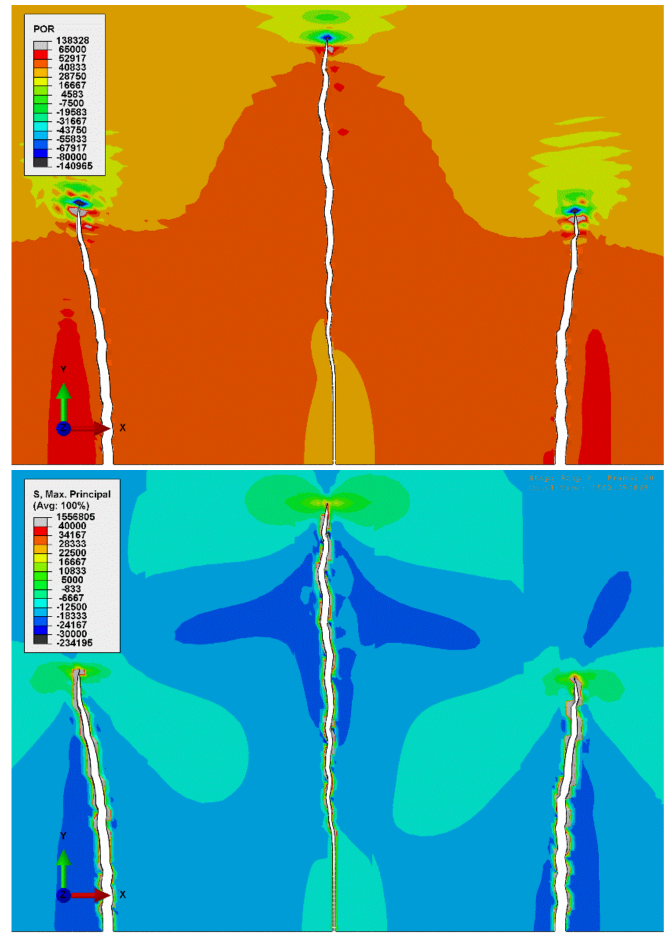

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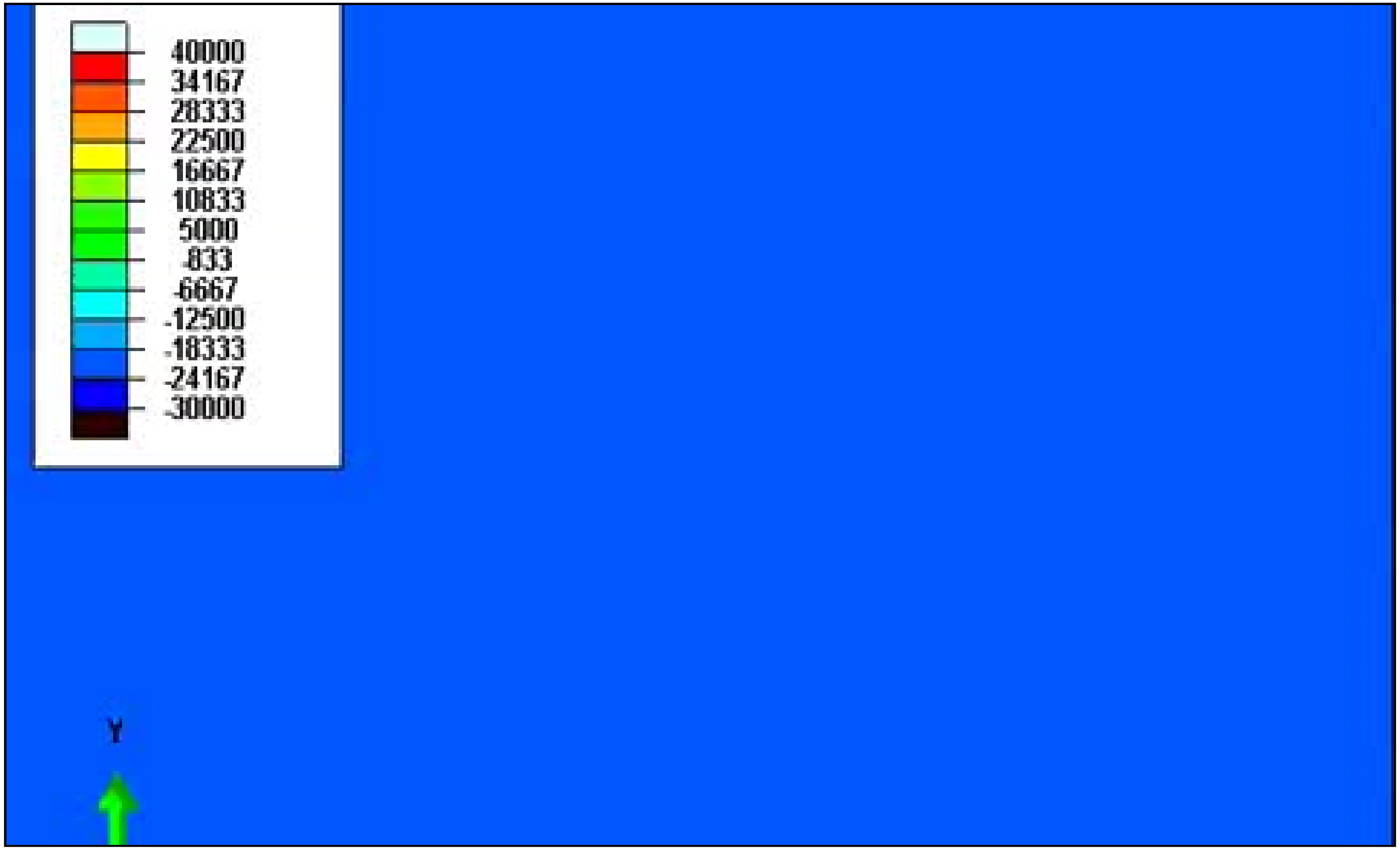
Results: Triple Fracture with 50-ft Spacing

Animation 5

Click Animation to Activate



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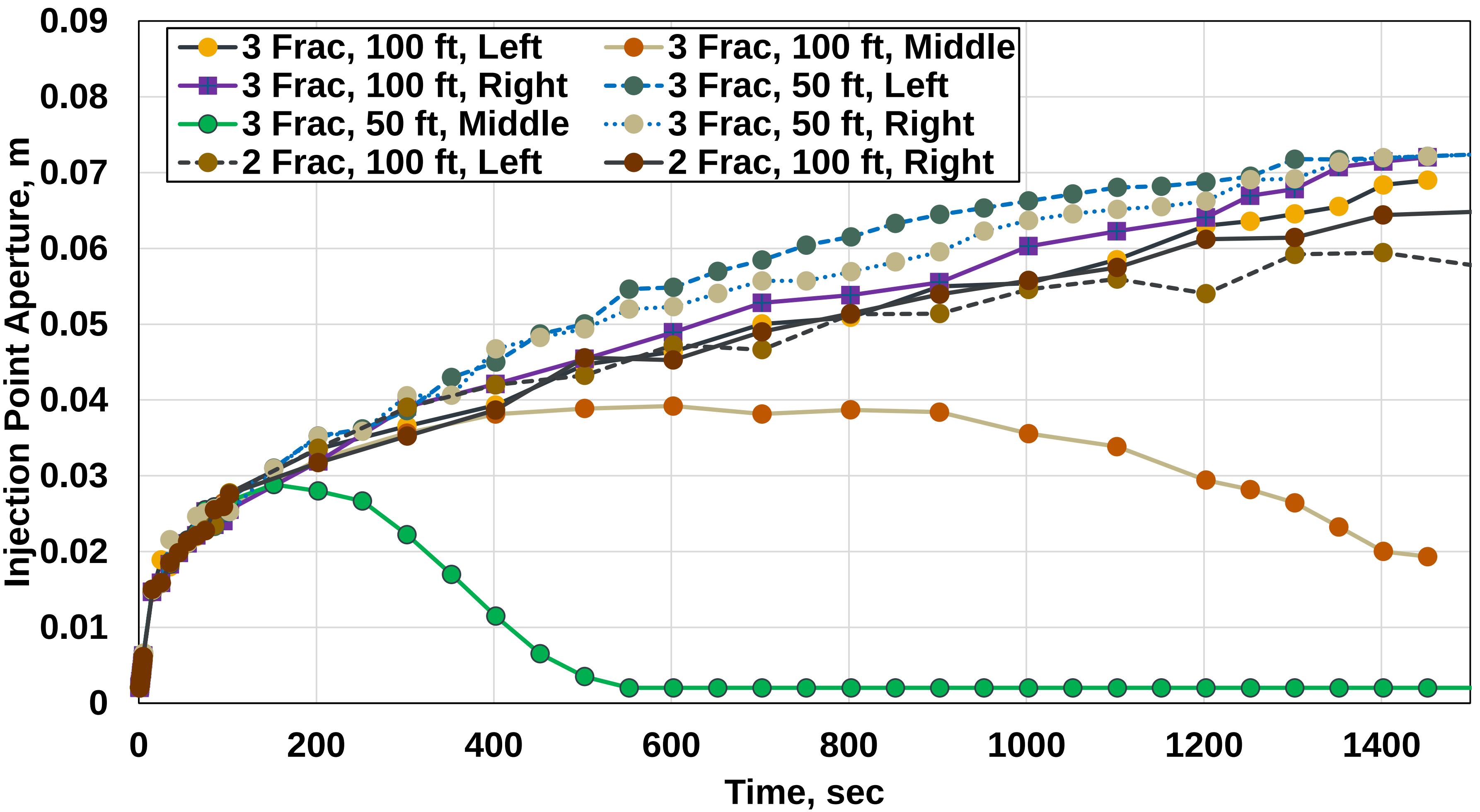
Comparison: Fracture Aperture at Injection Point



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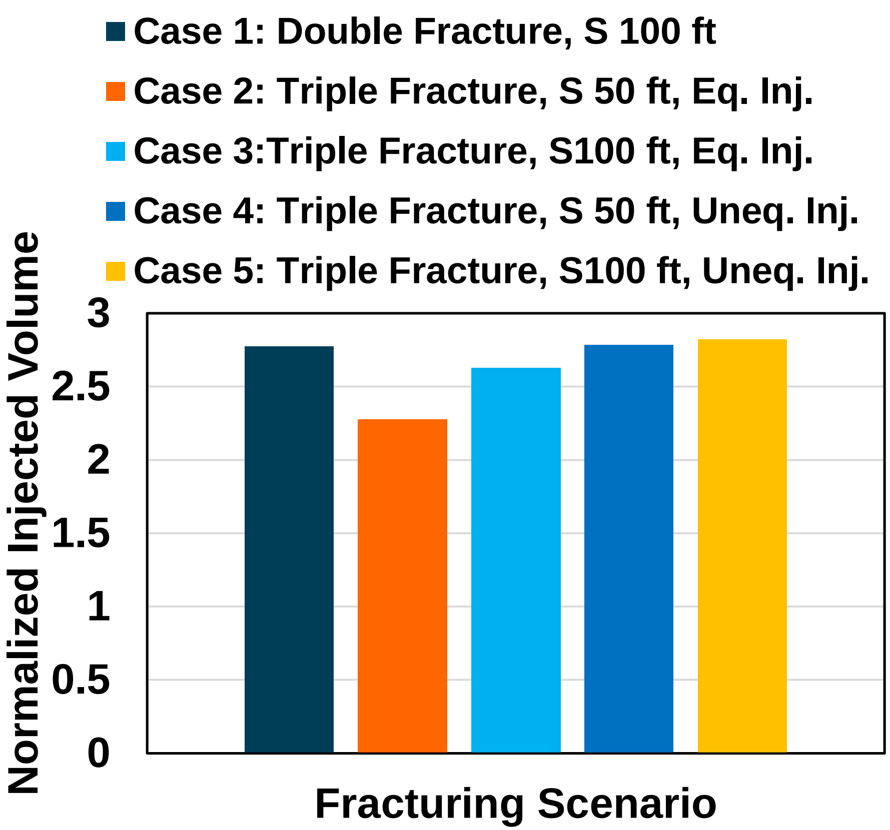
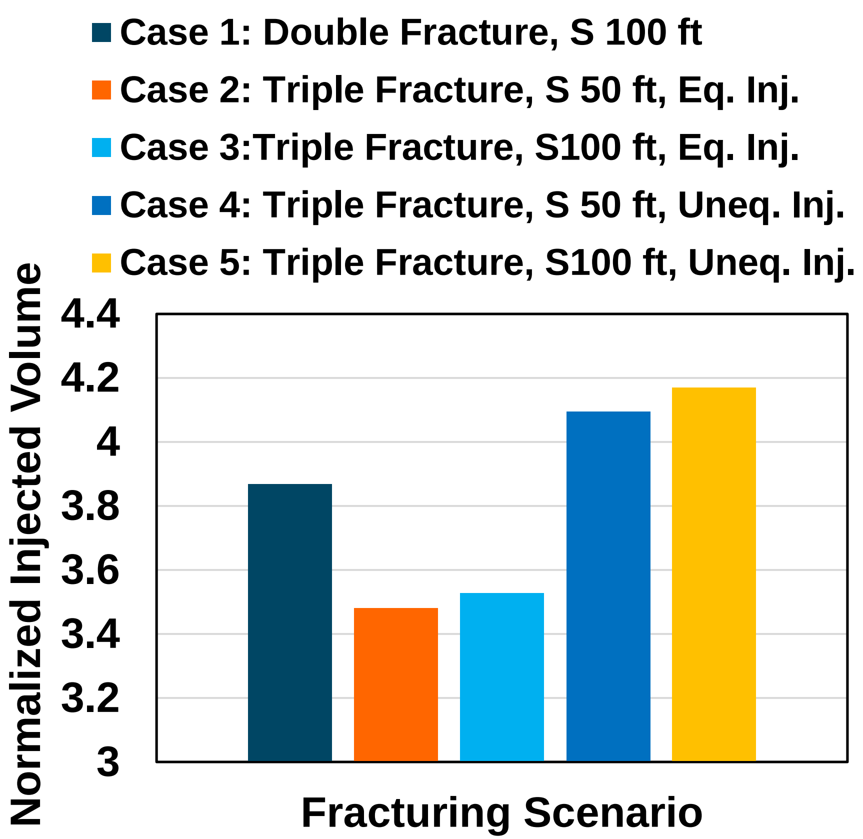
Comparison: Normalized Injected Volume

$$\text{Normalized Injected Volume} = V_{\text{inj,tot}} \Big/ \sum_{i=1}^{NHF} \ell_i$$





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Vertical Fracture Opening at Vertical Wellbore in a Real Case

Video Clip 1

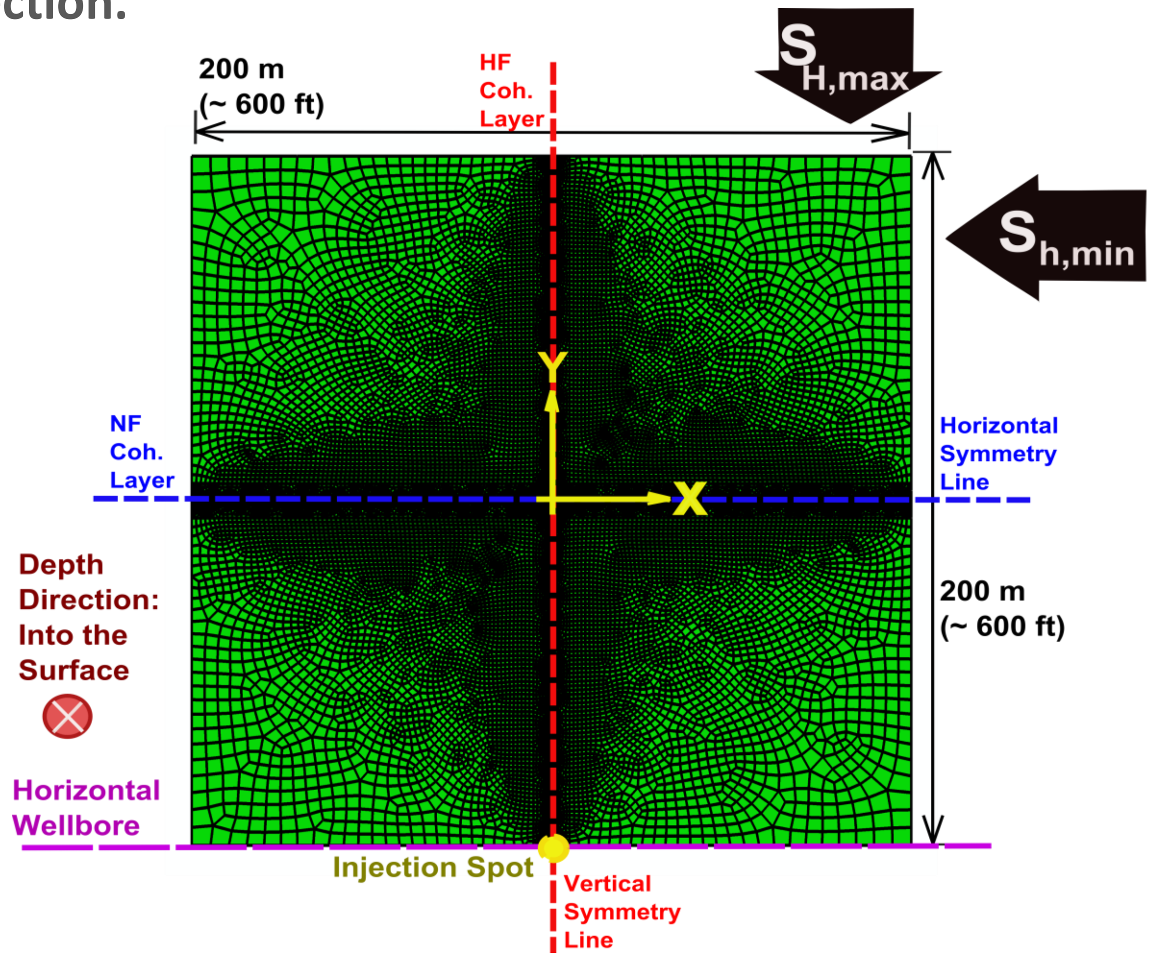
Click Animation to Activate

Hydraulic Fracturing Design and Treatment SPE Workshop, Smith and Montgomery (2015)

Step 3: Fracture Intersection

2D Fracture Intersection in Abaqus: Model Description

The intersection of hydraulic and natural fractures is modeled using two perpendicular layers of cohesive elements with additional governing equations for the intersection.



Results: Fracture Intersection

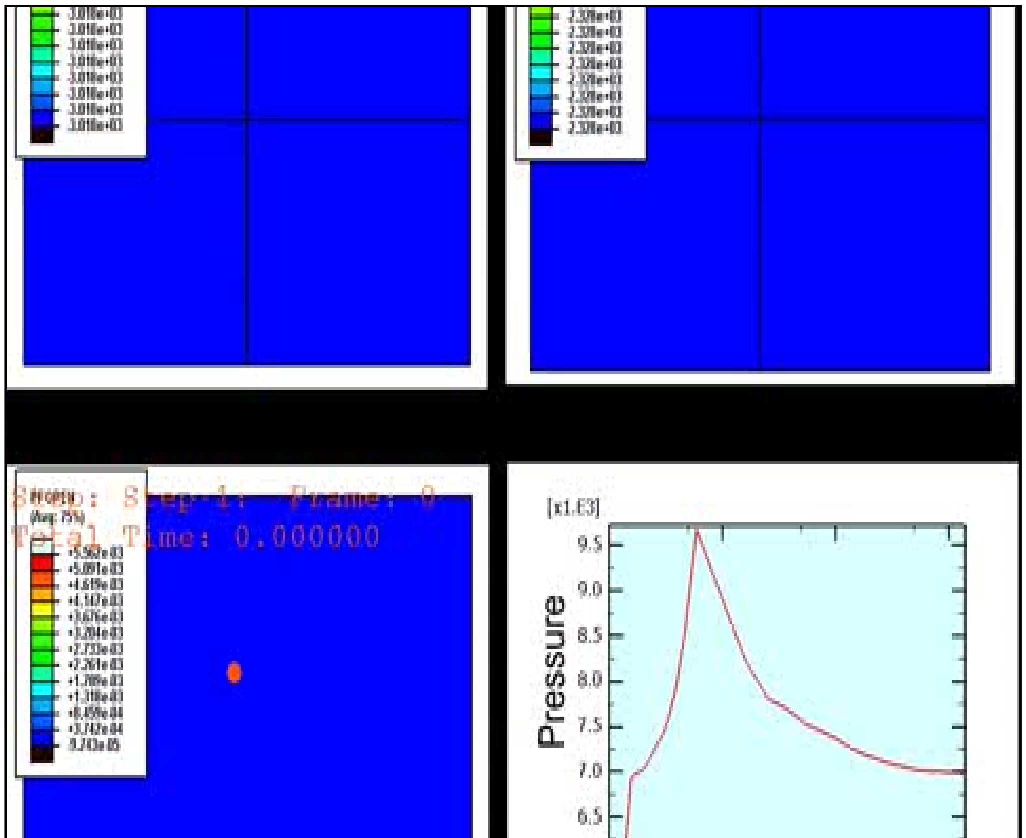
The hydraulic fracture turn was observed at S_{22} at least 100 psi less than S_{11}.

Animation 6

Click Animation to Activate

S11 Stress component

S22 Stress component



Fracture Opening

Injection Pressure

Summary and Conclusion

- **Step 1: Planar CZM**
  - ❑ We showed the benefits of modeling multiple-stage fracturing using our numerical method, FEM, demonstrating the stress shadowing effect of pre-existing or simultaneously growing fractures on the others.
  - ❑ Nevertheless, CZM provides the optimum fracturing scenario, simultaneous and 66-ft spacing, considering height growth.
- **Step 2: XFEM-based CZM**
  - ❑ Using a fully coupled pore pressure-stress analysis, we solved 3D triple-stage hydraulic fracturing problems using XFEM-based CZM, advantageous compared to LEFM for quasibrittle rocks.
  - ❑ XFEM-based CZM gives arbitrary solution-dependent path in contrast to CZM which gives growth on a pre-defined plane.

Summary and Conclusion

- Mechanical interactions or stress shadowing effects of closely spaced hydraulic fractures may lead to the following:
  - Coalescence, and outward deviation of side fractures in XFEM.
  - Closure of the middle fracture at injection point in XFEM depending on spacing.
  - Time-dependent
- Building a model and grid dependence analysis using XFEM-based CZM are easier than CZM due to the element type, initialization and element crossing.

- Step 3: Fracture Intersection
  - Modeling fracture intersections is feasible using CZM.
  - Multiple complications regarding branching, fracture capture, etc., are under investigation.

Acknowledgements

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- SIMULIA for providing ABAQUS license

Thanks for your attention!

Questions?

The University of Texas at Austin
Cockrell School of Engineering