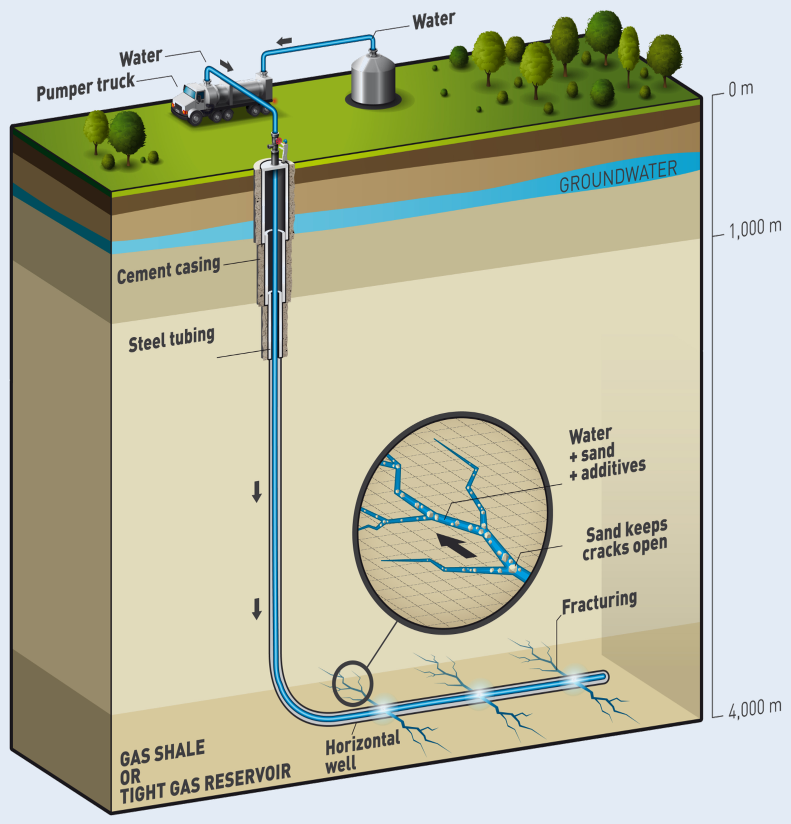
Coupled Fluid-Flow/Mechanical/Fracture Simulations of Hydraulic Fracture Propagation

Piyush Gupta, C. Armando Duarte

Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign

Introduction

Hydraulic fracturing is the propagation of fractures in a rock layer, as a result of the action of a pressurized fluid. It is the technique of choice for enhancing permeability in reservoirs for extraction of petroleum, natural gases etc.

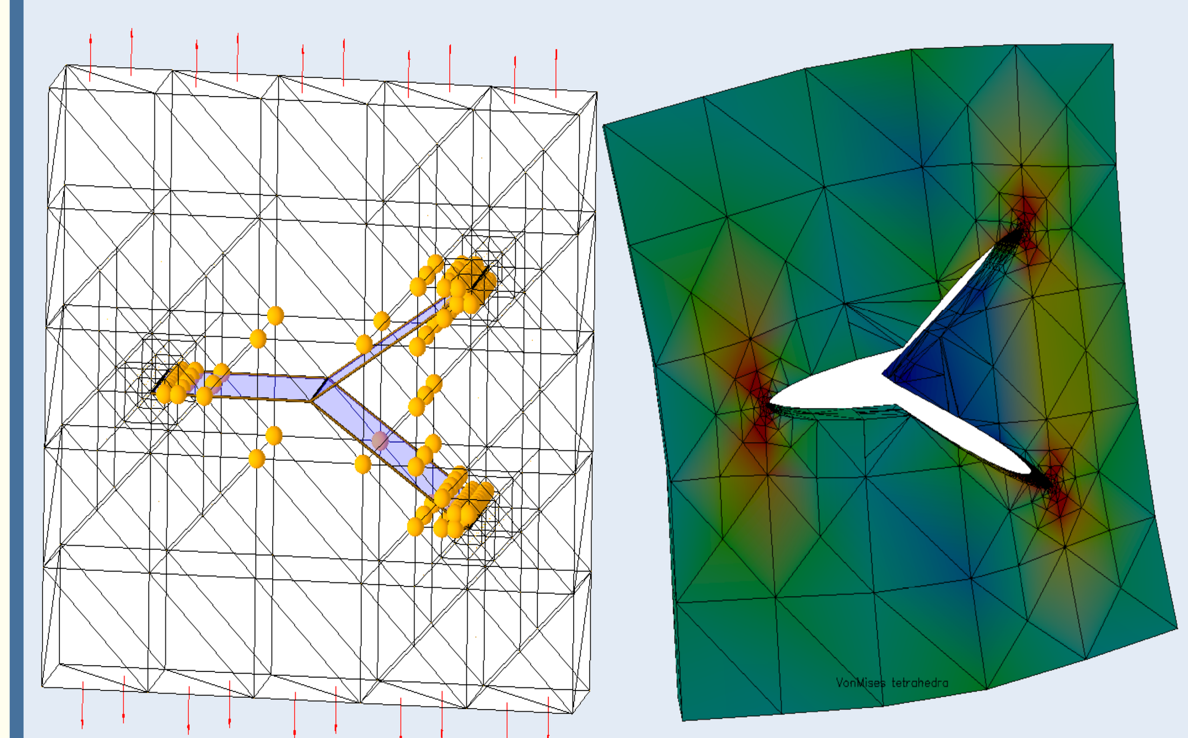


Objectives

- Fully coupled formulation for non-planar three dimensional hydraulic fracturing
- Coupling for fracture propagation criterion with mechanical deformation and fluid-flow in the fracture
- Computationally efficient techniques for time marching of the solution

Generalized FEM

- GFEM can be interpreted as FEM with shape functions built using concept of Partition of Unity
- GFEM shape function = FEM shape fn * enrichment



Salient Features

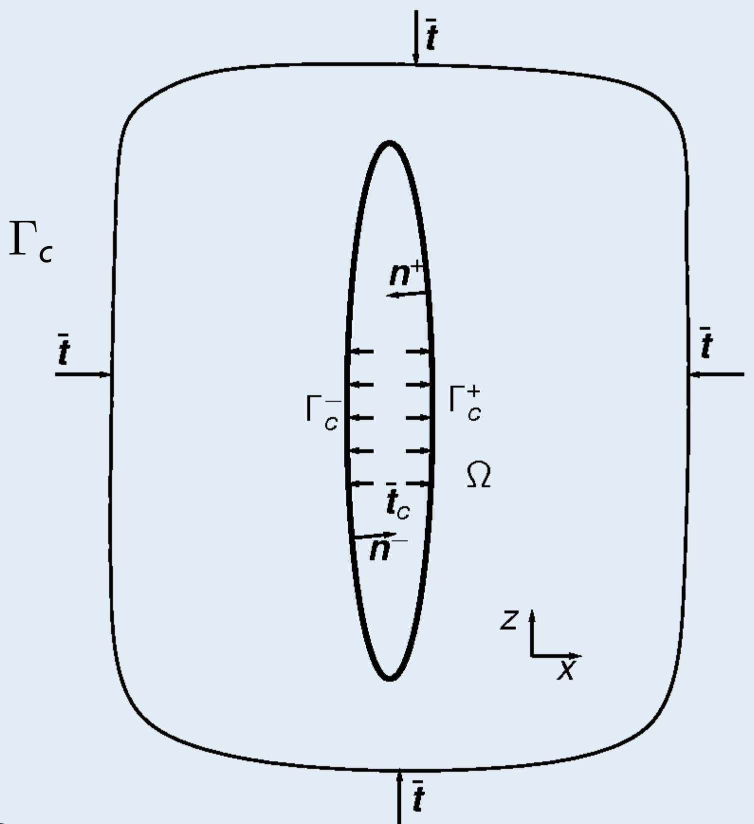
- Discontinuity and singularity along the crack front modeled via enrichment functions. No need for fracture mesh to conform to crack surfaces
- Fracture surface represented explicitly independent of volume mesh
- Adaptive volume mesh refinement along the crack front and crack surface

Coupled Hydro-Mechanical Formulation

Governing Equations for Porous Medium

$$\int_{\Omega} \nabla_s \delta u : \boldsymbol{\sigma}(u) d\Omega = \int_{\partial\Omega} \bar{t} \cdot \delta u d\Gamma + \int_{\Gamma_c^+} \bar{t}_c^+ \cdot [\![\delta u]\!] d\Gamma_c$$

where $[\![\delta u]\!]$ is the virtual displacement jump across the crack surface Γ_c



Governing Equations for Fluid-Flow in Fracture

Reynold's Lubrication Equation: $\nabla_{\bar{x}} \cdot q + \frac{\partial w}{\partial t} = Q_I - Q_L$

Poiseuille's cubic law: $q = \frac{w^3}{12\mu} \nabla p$

$$\int_{\Gamma_c} \frac{w^3}{12\mu} \nabla_{\bar{x}} \delta p \cdot \nabla_{\bar{x}} p \, d\Gamma_c = \int_{\Gamma_c} \delta p \left[Q_I - Q_L - \frac{\partial w}{\partial t} \right] d\Gamma_c + \int_{\partial\Gamma_c} \bar{q}(s) \, \delta p \, ds$$

Coupling Conditions

$$\bar{t}_c^+ = -p n^+$$

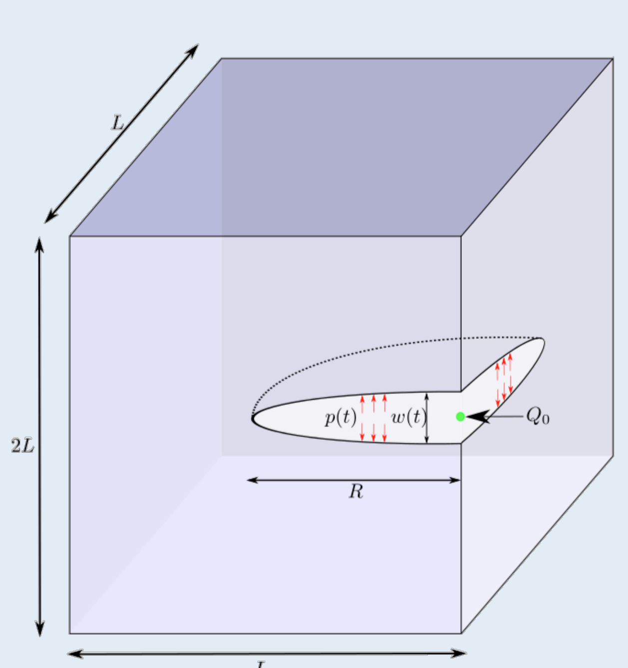
$$w = [\![u]\!] \cdot n^-$$

System of Equations

$$\begin{bmatrix} K_u^{n+1} & -\left(K_c^{n+1}\right)^T \\ K_c^{n+1} & \Delta t K_p^{n+1} \end{bmatrix} \begin{bmatrix} \hat{u}^{n+1} \\ \hat{p}^{n+1} \end{bmatrix} = \begin{bmatrix} t_u^{n+1} \\ \left(K_c^{n+1,n}\right) \hat{u}^n + \Delta t Q_p^{n+1} + \Delta t \bar{q}_p^{n+1} \end{bmatrix}$$

Verification Example

Planar Penny Shaped Fracture



$L = 5\,m \quad R = 0.5\,m$

Incomp. Newtonian fluid with viscosity

$\mu = 0.1$ cPoise

Injection rate at center of fracture

$Q = 0.001\, m^3/s$

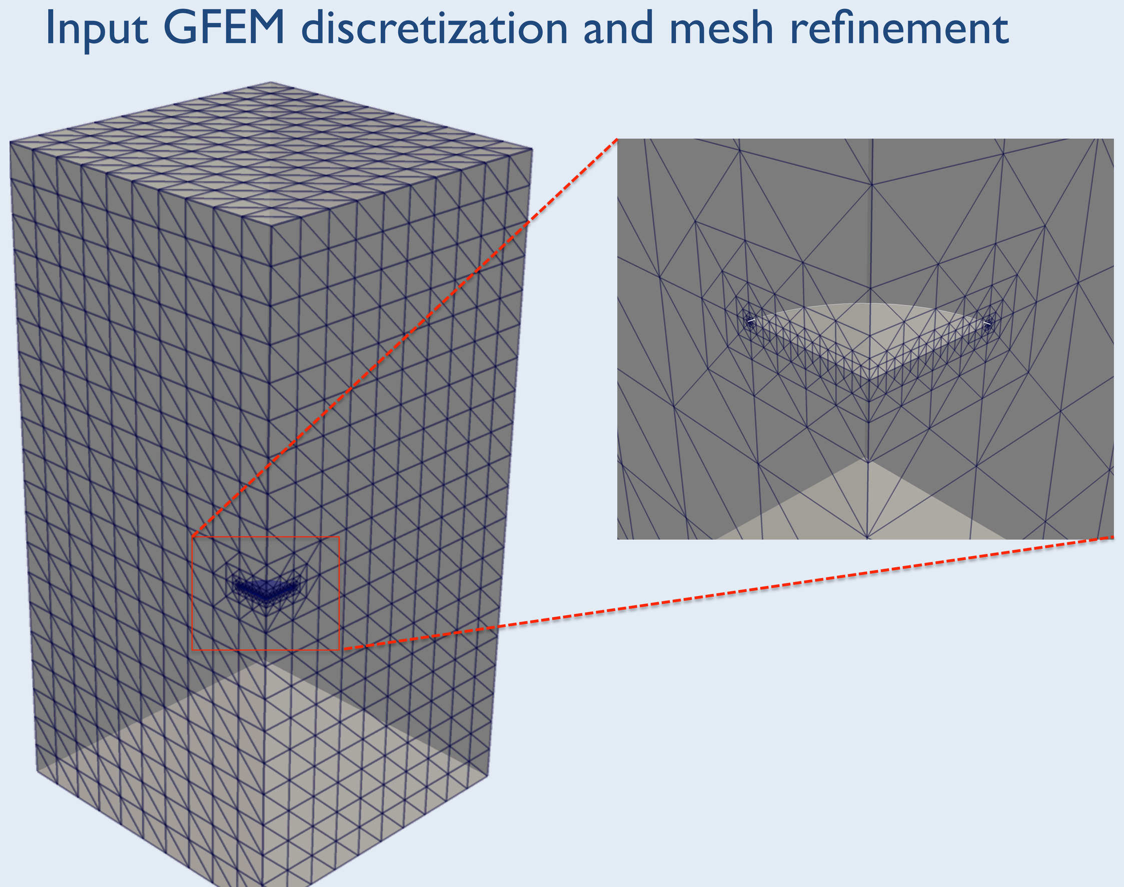
$E = 17$ GPa

$\nu = 0.2$

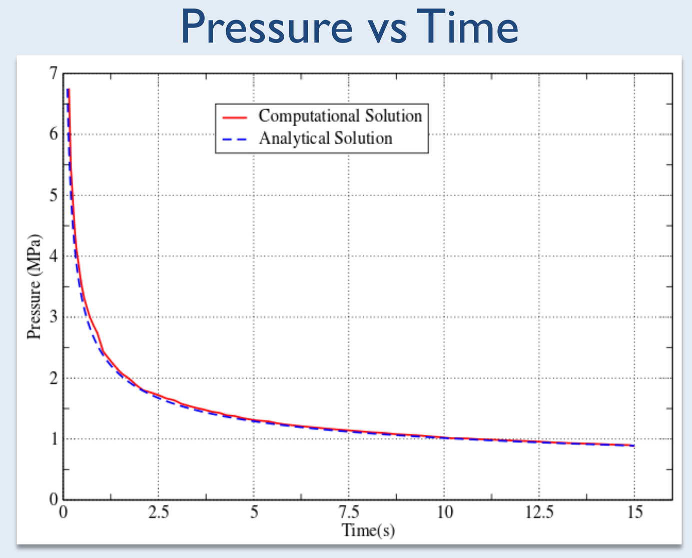
$K_{Ic} = 1.46$ MPa$\sqrt{m}$

$\Delta a_{max} = 0.05m$

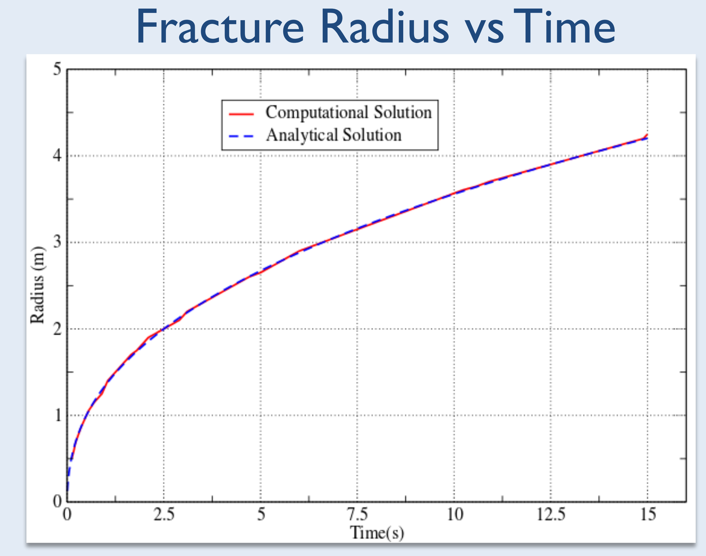
Input GFEM discretization and mesh refinement



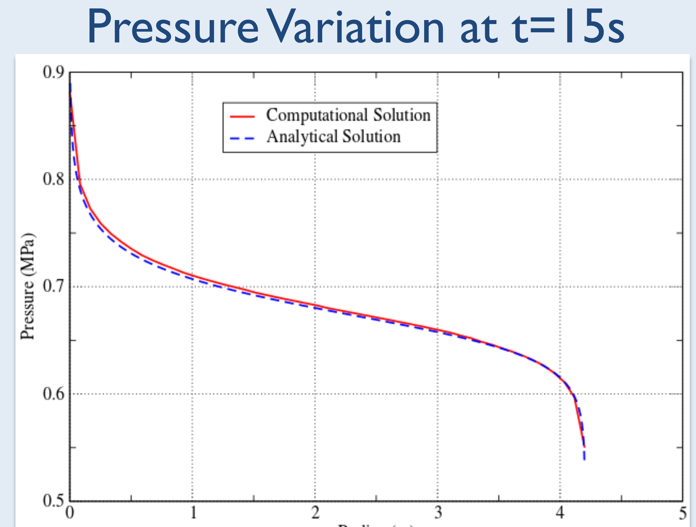
Pressure vs Time



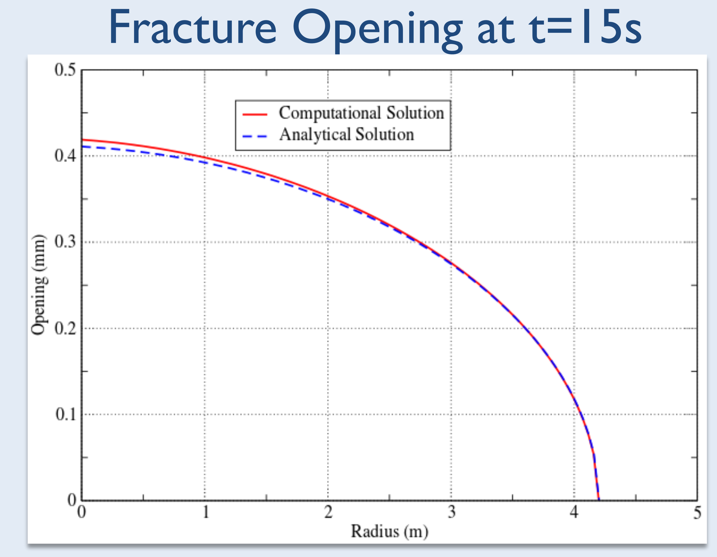
Fracture Radius vs Time



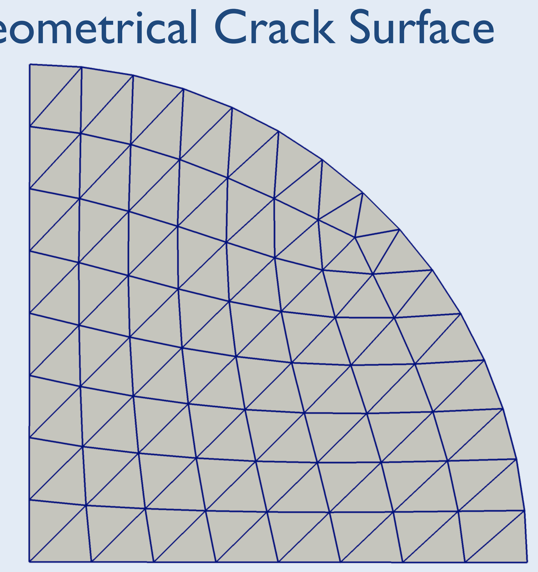
Pressure Variation at t=15s



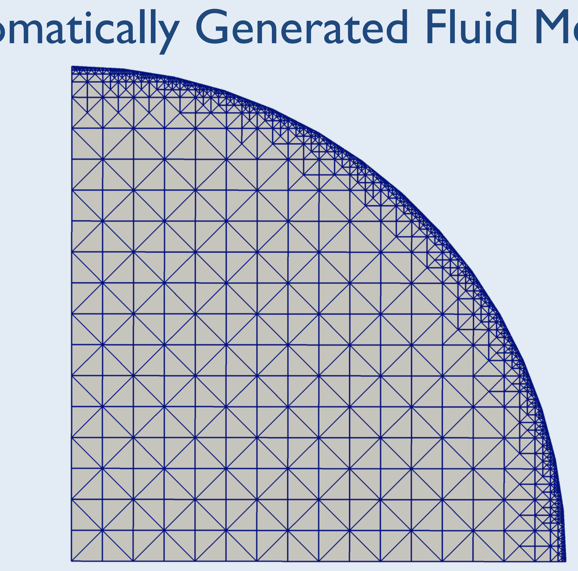
Fracture Opening at t=15s



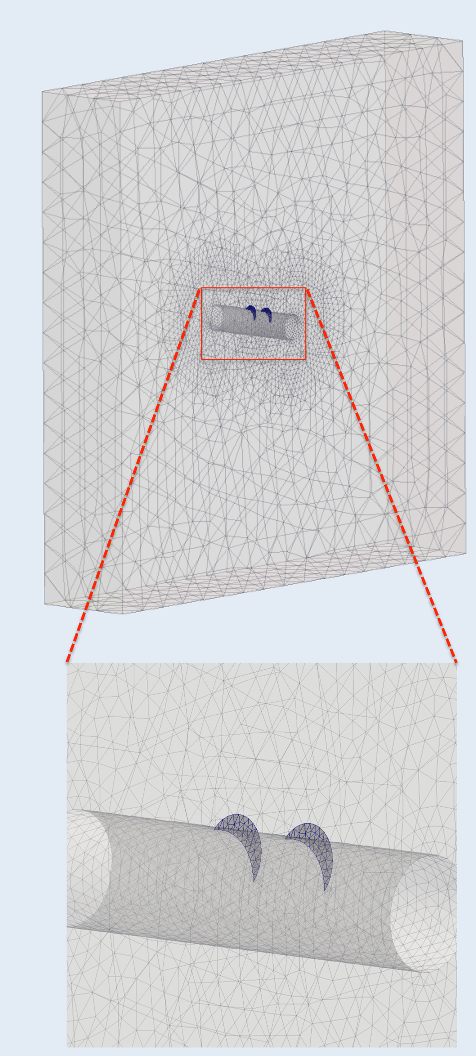
Geometrical Crack Surface



Automatically Generated Fluid Mesh



Fracture Interaction

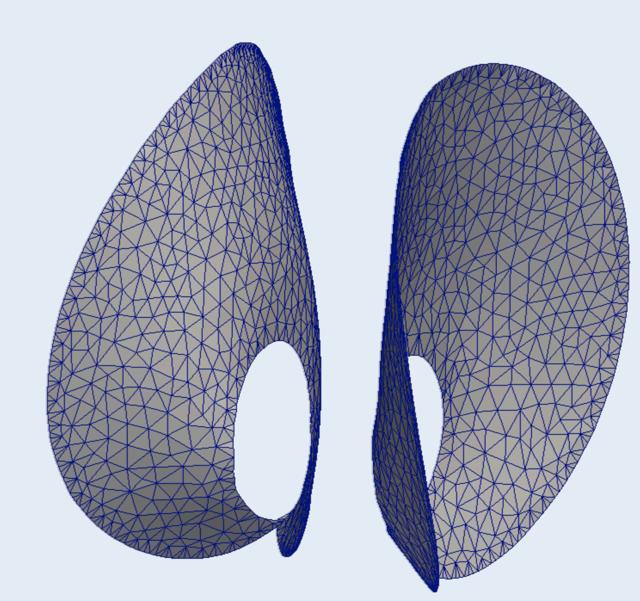


$\sigma_h = \sigma_H = 1.0 MPa$ and $\sigma_v = 2.5 MPa$

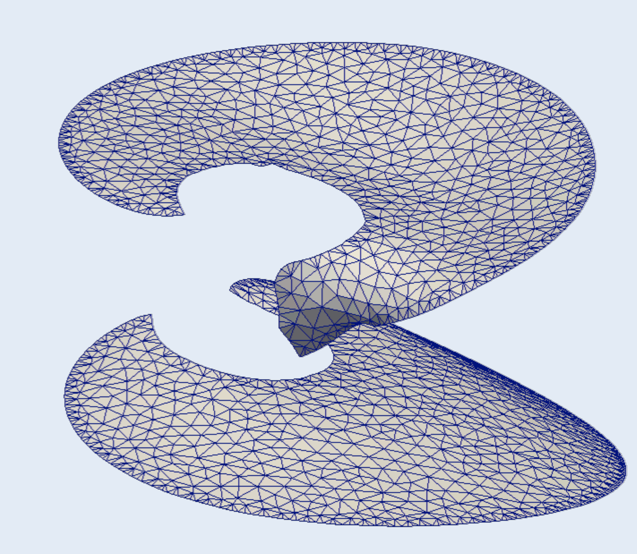
$E = 5GPa$, $\nu = 0.2$ and $K_{IC} = 0.1 MPa\sqrt{m}$

Pressure applied, $p = 3.0 MPa$

Different Interaction Scenarios



$d = 0.2m$
$Angle = 0°$



$d = 0.2m$
$Angle = 45°$

Conclusions and References

Conclusions

- Novel formulation using a GFEM for coupling of solid deformation and fluid flow inside a fracture
- No assumptions about geometry of the domain or fracture surface
- 3-D fracture interaction can capture near-wellbore tortuosity

References

- Savitski and Detournay, Propagation of a penny shaped fluid-driven fracture in an impermeable rock: asymptotic solutions, IJSS, 2002
- Gupta and Duarte, Coupled Formulation and Algorithms for Simulation of Non-Planar 3-D Hydraulic Fractures using the GFEM, Submitted

Contact email: gupta61@illinois.edu
Web: http://piyushgupta.info