Three-dimensional Modeling of Fracture Clusters in Geothermal Reservoirs

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EGS Component R&D › Stimulation Prediction Models

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Overview

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- **Timeline**
  - Project Established: October, 2009
  - Project End: December, 2011
  - Percent Completed: 25-30%
- **Budget**
  - Total project funding: $1,017,984
  - DOE share: $685,141
  - Awardee share: $171,285
  - Funding received in FY 09: $275K, funding for FY10: $685K
- **Barriers**: Site/Well Characterization: Accurate Prediction of Reservoir's Response to Stimulation
- **Partners**: AltaRock Energy, Inc., Sandia National Laboratory

Relevance/Impact of Research

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- The objective of this is to develop a 3-D numerical model for simulating mode I, II, and III (tensile, shear, and tearing) propagation of multiple fractures using the virtual multi-dimensional internal bond (VMIB), to predict geothermal reservoir stimulation

- **First year targets**:

  – Elaborate the three-dimensional multiple internal bond method; study WARP3D for consideration of implementing VMIB

  – implement VMIB in 3D FEM and compare model with lab results, conduct verification simulations and add hydraulic fracture routines

Relevance/Impact of Research

- **By helping remove barriers to reservoir design, the project will help increase reserves and lower costs**

- Permeable zones have to be created by stimulation, a process that involves fracture initiation and propagation in the presence of natural fractures

- Fracture propagation is a 3D problem and can be driven by hydraulic pressure and thermal stress, etc.

- Fracture can propagate in modes other than tensile
  - Reservoir creation and control

Scientific/Technical Approach

- Physical processes considered
  - Fully-coupled poro-thermoelastic constitutive equations
  - Non-linear rock deformation
  - Rock heterogeneity
  - Modes I, II, III
    - Pressurization and cooling
    - Pore pressure effects
    - Fracture interactions
- Calibration using lab and field data such as stress-strain behavior and pressure-time record

Scientific/Technical Approach

- Poro-thermoelastic Constitutive Equations

$$\dot{\sigma}_{ij} = 2G\dot{\varepsilon}_{ij} + \left(K - \frac{2G}{3}\right)\dot{\varepsilon}_{kk}\delta_{ij} + \alpha\,\dot{p}\delta_{ij} + \gamma_1\dot{T}\delta_{ij}$$

$$\dot{\zeta} = -\alpha\,\dot{\varepsilon}_{ii} + \beta\,\dot{p} - \gamma_2\dot{T}$$

$$\gamma_1 = K\alpha_m \qquad \beta = \frac{\alpha - \varphi}{K_s} + \frac{\varphi}{K_f}$$

$$\gamma_2 = \alpha\,\alpha_m + \left(\alpha_f - \alpha_m\right)\phi$$

- Virtual Internal Bond (VIB)

-Material consists of particles Interacting (in the micro scale) through a network of virtual internal bonds (Kline, Gao, 98)

-The macro constitutive relation is derived directly from the cohesive law between material particles

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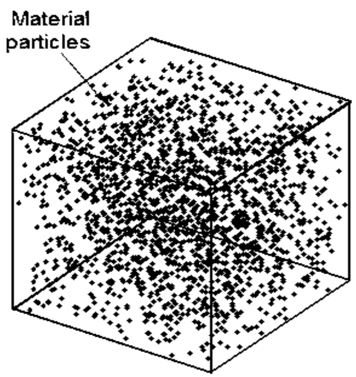
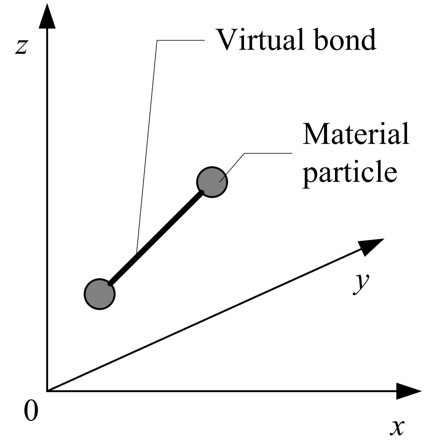
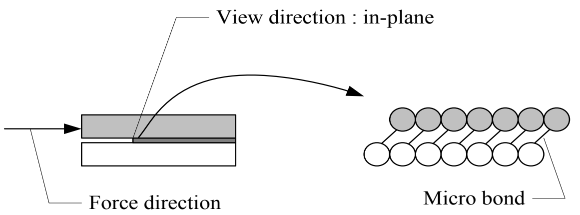




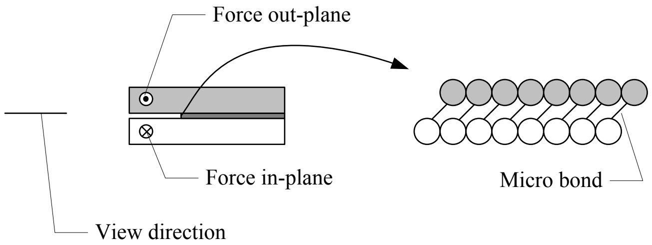
Scientific/Technical Approach

- Virtual Multiple Internal Bond (VIB)

Fracture criterion is implicitly incorporated into the constitutive relation by cohesive law. It is not necessary to employ a separate fracture criterion



Shear effect is considered in the interaction of material particles



By developing a suitable bond evolution function, the VMIB can successfully simulate fracture initiation and propagation.

Bond density function

$$\Phi = \int_0^{2\pi}\int_0^{\pi} U_L D(\theta,\phi)\sin(\theta)\,d\theta d\phi + \int_0^{2\pi}\int_0^{\pi}\left(U_{R1}+U_{R2}+U_{R3}\right)D(\theta,\phi)\sin(\theta)\,d\theta d\phi$$

Contributed by Normal stiffness

Contributed by Shear stiffness

Significance & Impact of Research

- Model 3D fracture propagation in multiple modes
  - Consider rock heterogeneity
  - 3D stress state
  - Fracture-natural fracture interaction
  - Pore pressure and thermal stress
  - Multiple cracks
  - Needs no re-meshing
  - No explicit fracture criterion

Scientific/Technical Approach

- Phase 1: Model development
  - Elaborate the three-dimensional multiple internal bond method
  - implement VMIB in 3D FEM and compare model with lab results, conduct verification simulations and add hydraulic fracture routines.
  - Implement in a 3D FEM; also use FEAP3D

Scientific/Technical Approach

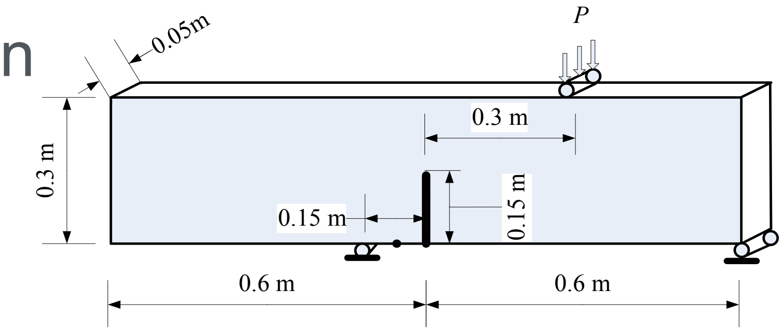
- Future work
  - Continue to develop the 3-D VMIB numerical model for propagation of multiple fractures in mixed mode (tensile, shear, and tearing) to aid in geothermal reservoir stimulation design
  - Continue with code development and consider combined poro-thermoelastic effects in 3D multiple fracture propagation
  - Develop special algorithms to improve accuracy and to enable fracture-natural fracture interaction in 3D

Accomplishments, Expected Outcomes and Progress

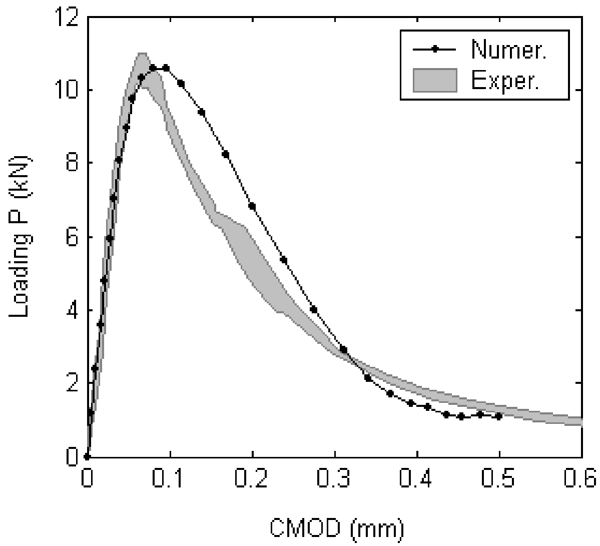
3D finite element model with VMIB has been developed

- Preliminary results show good agreement with lab data
- VMIB has been combined with pore pressure & poroelastic stress
- Routines for fracture-natural facture coalescence has been developed
- Rock heterogeneity can be considered

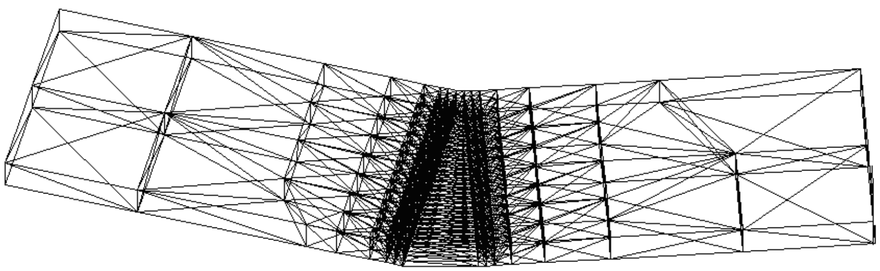
Simulation of Fracture Propagation



1) **Mixed mode (I-II) crack test problem**:
Young's modulus E=38.4GPa,
Poisson ratio = 0.12, Tensile strength= 3.2 MPa.



Test geometry for mixed mode fracture propagation .

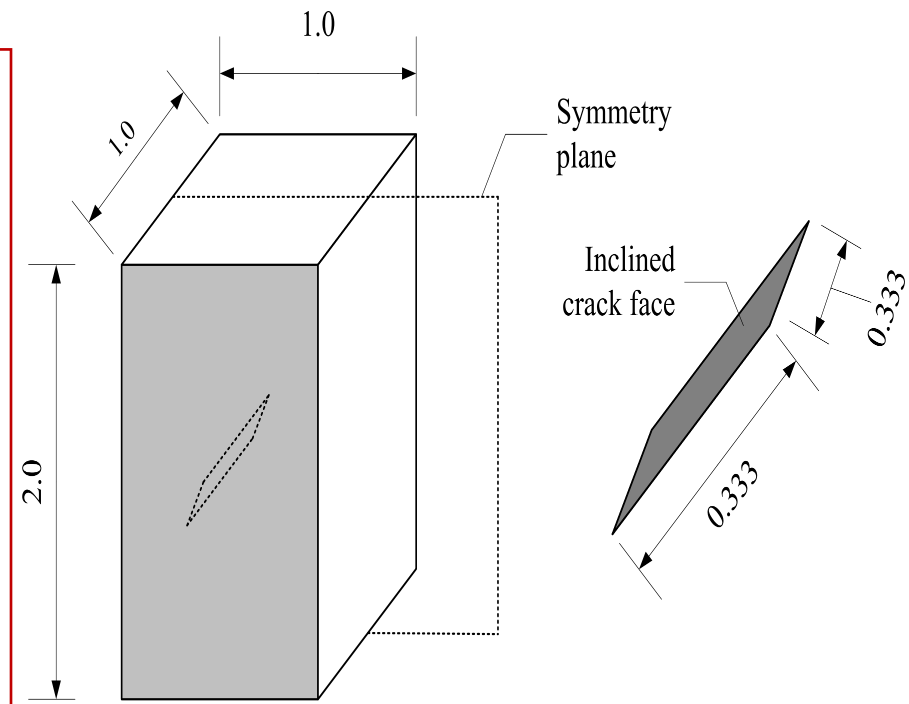


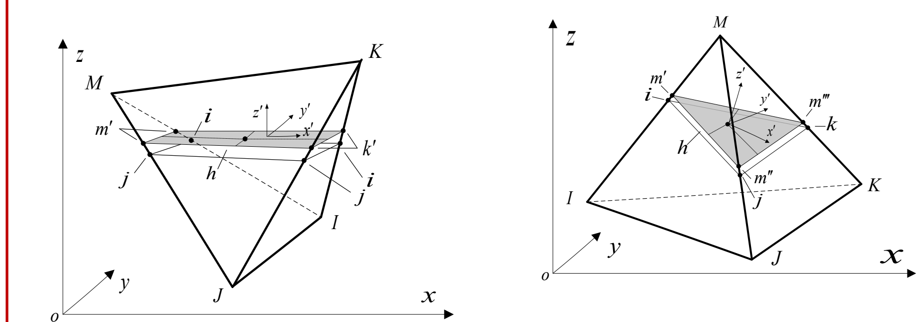
Comparison between simulated and experimentally measured P-CMOD crack mouth opening displacement

2) Mixed mode (I-III) test problem:

Planar crack embedded in rock subjected to compressive stress with same properties as before

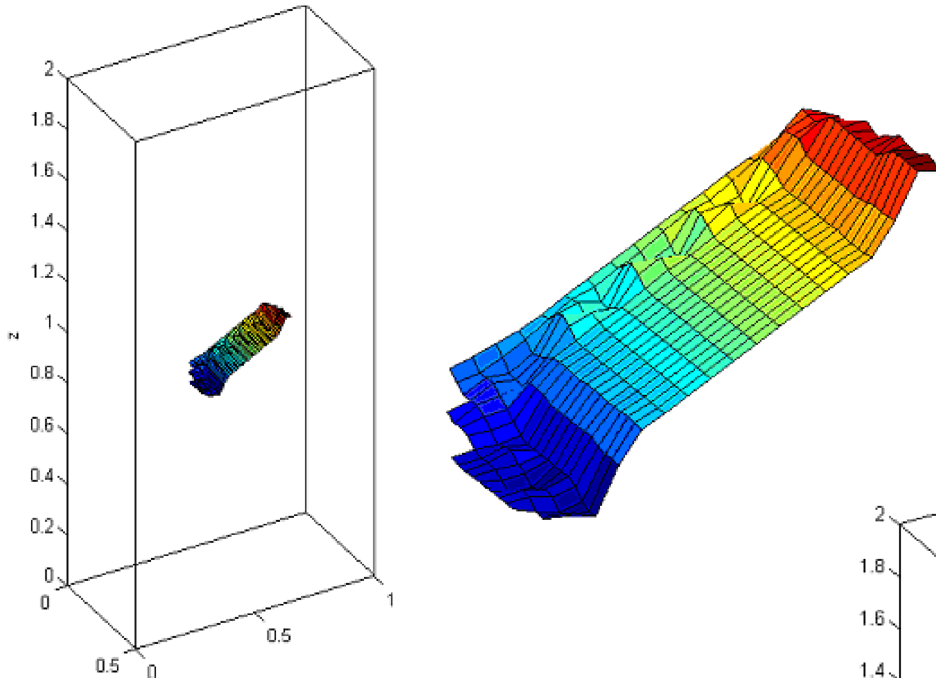
The fracture process simultaneously involves mode I and III which cannot be simulated by a 2D model.



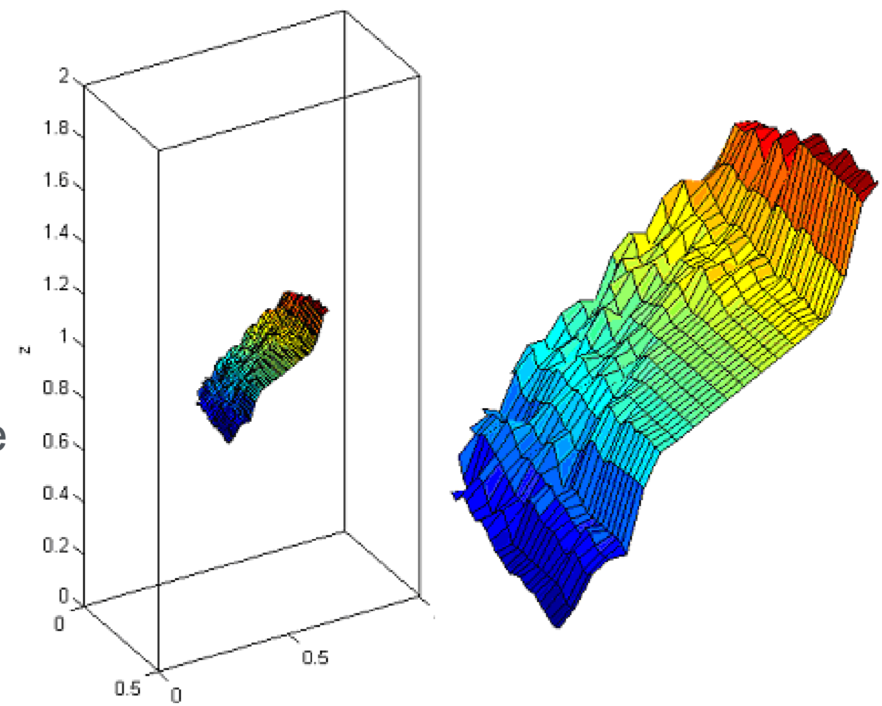


Partition modes of tetrahedron element: (a) type I: triangular fracture area; (b) type II: quadrangular fracture area

Embedded Fracture in Compression



Propagation is in tensile mode at the “tips”, but then proceeds in the lateral direction in tearing mode due to the relative slip between fracture faces



Poroelastic VMIB Model

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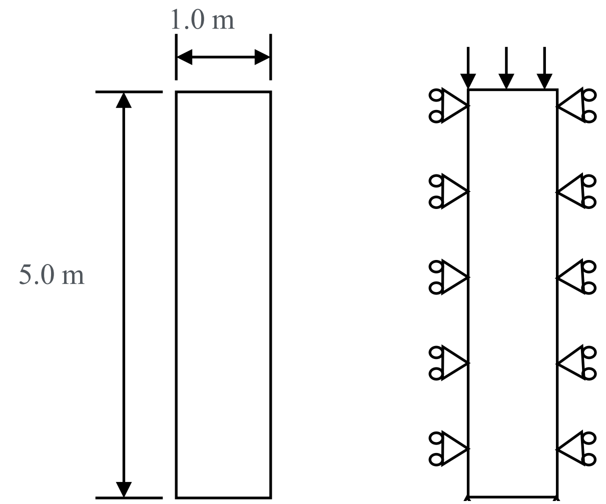
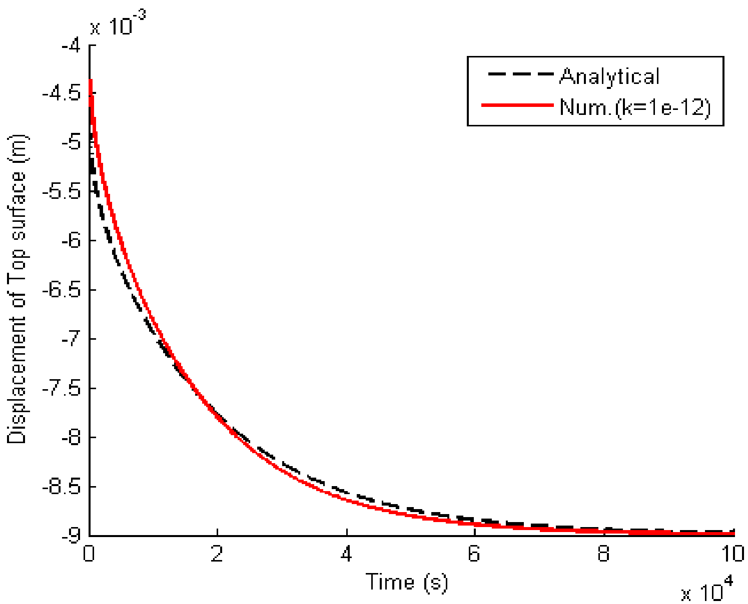
3) Test problem for poroelastic VMIB:

Compression of a poroelastic column of rock and calculation of the ensuing displacements and pore pressure

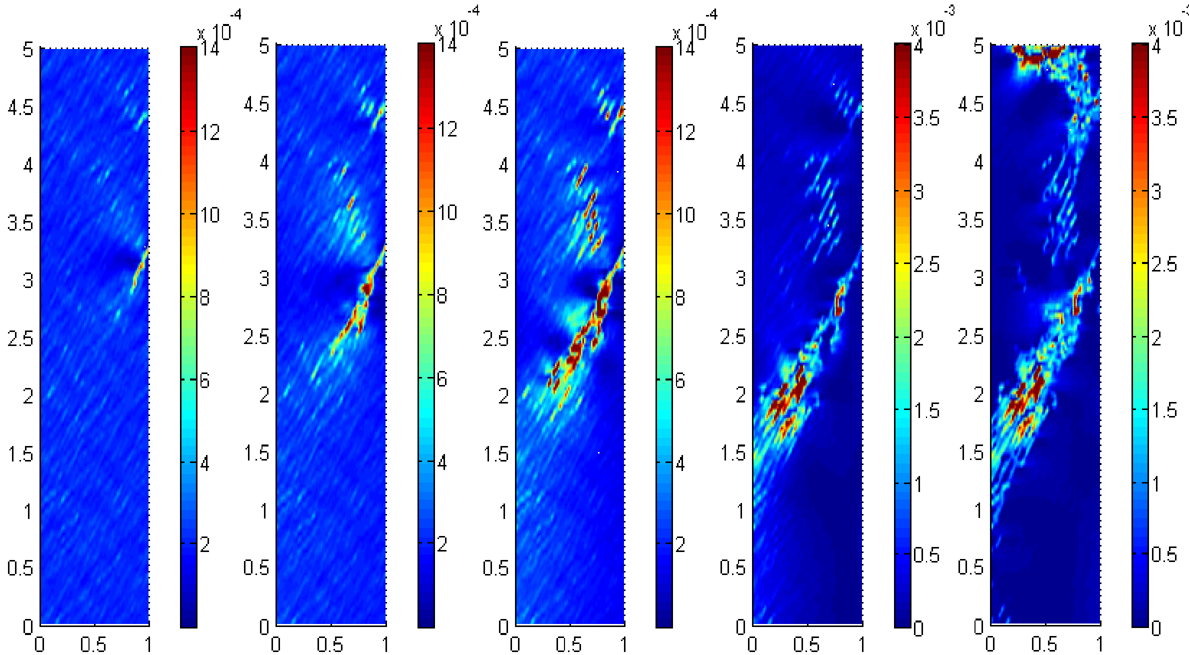


Comparison of the numerical and analytical results for displacement of the top surface is shown. The numerical results are in good agreement with the analytical solution.



Rock Deformation and Failure

4) Rock Failure in uniaxial compression



(a) t=1s (b) t=200s (c) t=3000s (d) t=3400s (e) t=3420s

E=10 Gpa
Poisson ratio = 0.2

Failure simulation using the poroelastic VMIB has a form similar to those in other works with similar failure plane orientation.

Project Management/Coordination

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- Work will continue on schedule
- Bulk of work done by graduate students, Post-Doc
- Will explore attracting funds from petroleum industry- Crisman Institute
- This project integrated with other projects through workshops; demonstration projects
- Exchange of ideas during visit by scientist from Sandia

Future Directions

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- The goal is to have a 3D fracture model to help predict reservoir stimulation
- The model will be applied to interpretation hydraulic fracture experiment published and planned by AltaRock
- Future work includes
  - Continue to develop the 3-D VMIB numerical model for propagation of multiple fractures in mixed mode (tensile, shear, and tearing)
  - Code development to consider combined poro-thermoelastic effects and multiple fracture propagation in 3D.
  - We will develop special algorithms to improve accuracy and to enable fracture-natural fracture interaction in 3D
  - comparison with laboratory compression tests

Mandatory Summary Slide

- We have developed the VMIB method for 3D fracture propagation in rock
- Numerical algorithms have been developed to allow element partitioning, application of hydraulic pressure, and consideration of heterogeneity
- A 3D elastic fracture propagation model has been developed and verified against experimental results. The model has successfully predicted mode I and mode III fracture growth in compression
- A 2D poroelastic VMIB model has been fully developed first and applied to show the potential of the approach

Related Publications

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

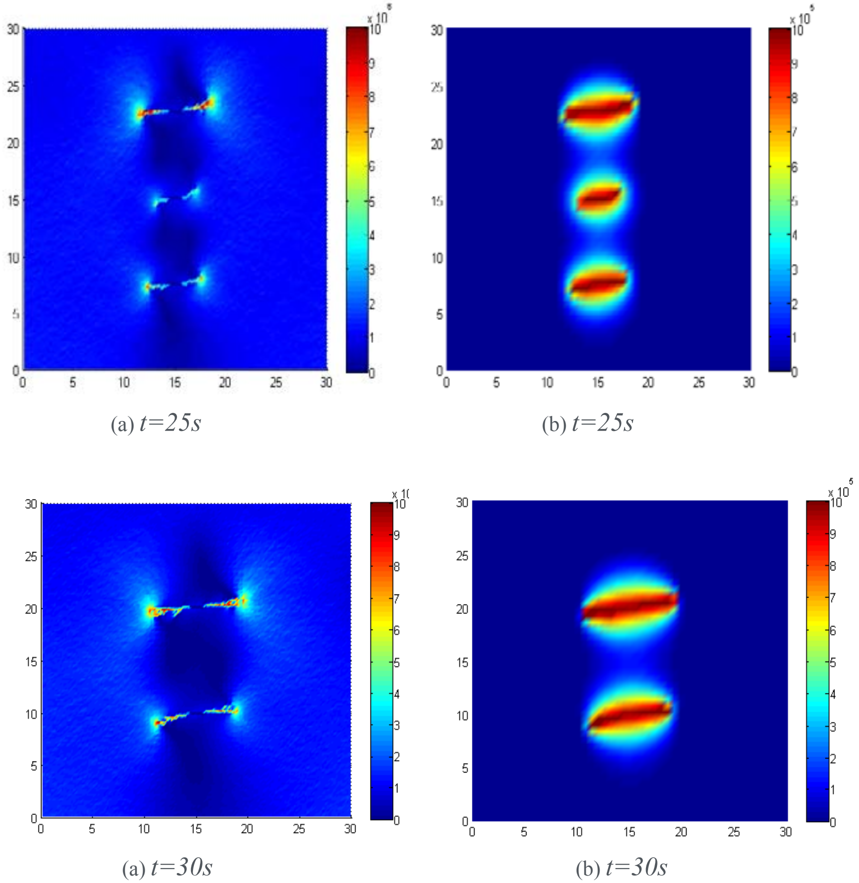
- Zhang, Z. Ghassemi, A. 2010. “Simulation of Hydraulic Fracture Propagation near a Natural Fracture Using Virtual Multidimensional Internal Bonds.” Int. J. Num. Anal. Methods. Geomech. DOI: 10.1002/nag.914.

- Min, K.S., Zhang, Z., and Ghassemi, A. 2010. “Hydraulic fracturing propagation in heterogeneous rock using the VMIB method.” Proc. 35th Workshop on Geothermal Reservoir Engrg. Stanford University, Ca.

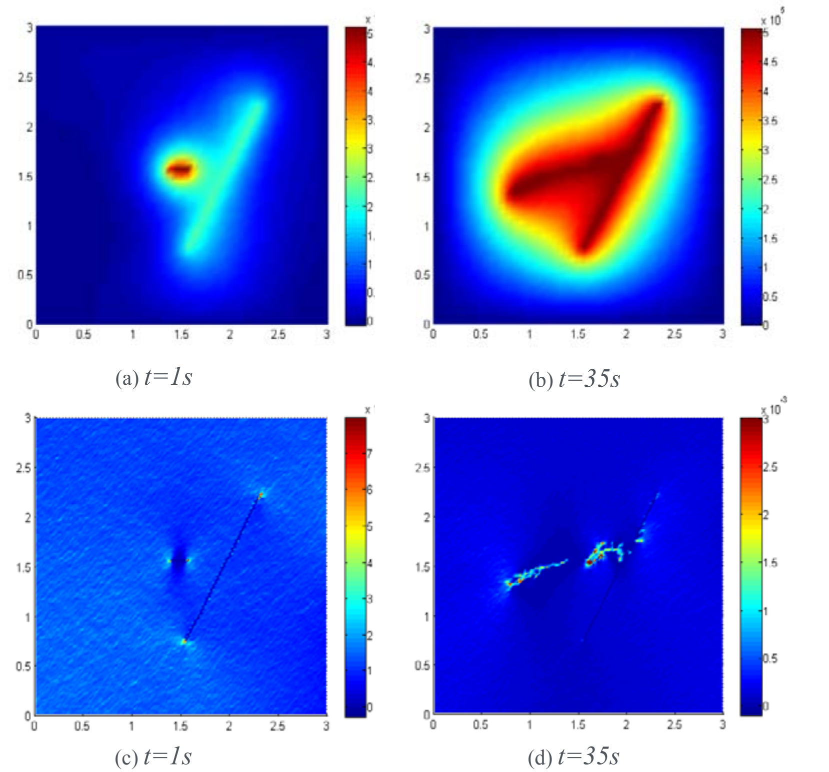
- Zhang, Z., Ghassemi, A. 2010. “Three-dimensional fracture simulation using virtual multidimensional internal bond.” 44th US Rock Mechanics Symposium and 5th U.S.-Canada Rock Mechanics Symposium, held in Salt Lake City, UT June 27–30, 2010.

- Zhang, Z., Ghassemi, A. 2010. “Numerical simulation for hydraulic fracture propagation in poroelastic rock using virtual multidimensional internal bond model.” (Will submit to Int. J. Rock Mech.).

Supplemental Multiple Fractures

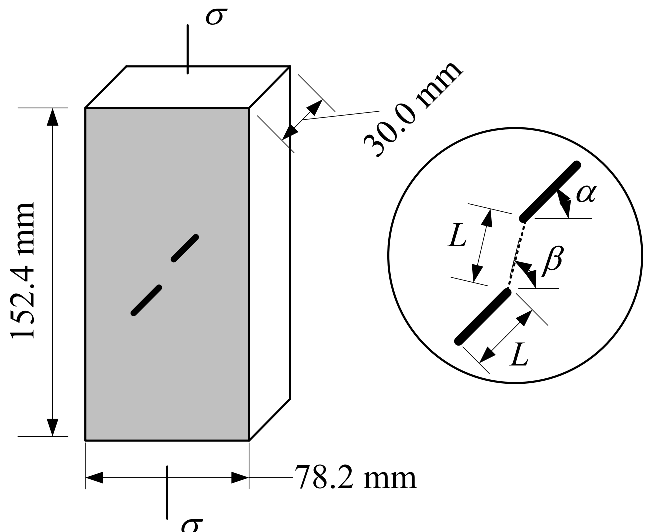


Multiple hydraulic fracturing; σ_x=1MPa, σ_y=0.5MPa; effective stress (a) and pore pressure (b) distribution at time 30s.



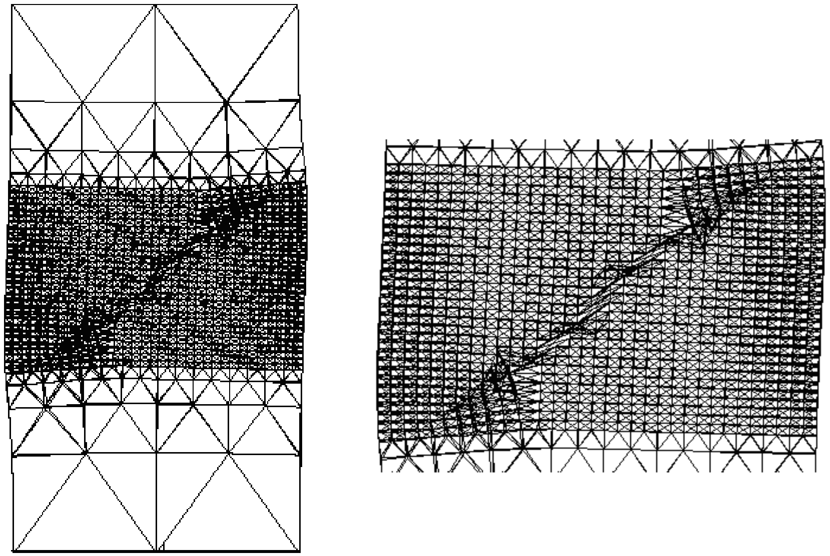
Hydraulic fracturing in heterogeneous rock; σ_x=1, σ_y=0.5MPa effective stress (a) and pore pressure (b) distribution at time 25s.

Supplemental



Simulated specimen for compressive fracture, Shen et al., 1995..

$$L = 12.7 \qquad \alpha = 45^{\circ} \qquad \beta = 45^{\circ}$$



(a) deformed mesh configuration ;(b) detail s of the middle part.
(b) (displacements are magnified 100 times).