SPE GCS Geomechanics Congress
"Recent Advancement in Petroleum Geomechanics"

Anisotropic Damage Mechanics for Modeling Hydraulic Fracturing in a Layered Naturally Fractured Reservoir

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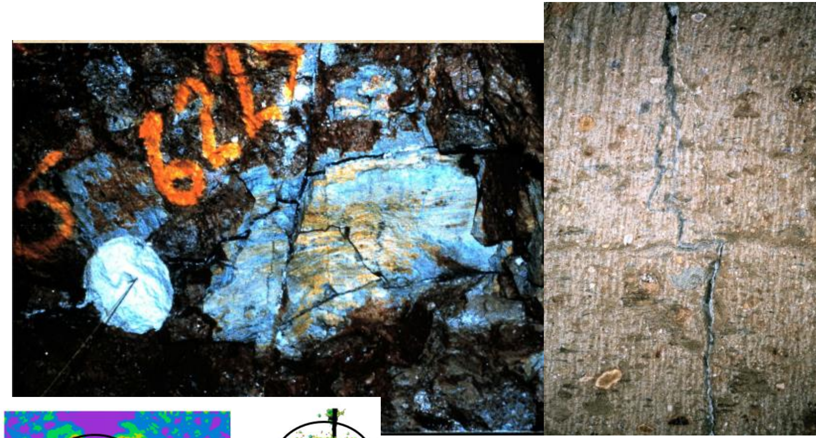
FracGeo
The Future of Shale Management, Today

18th April 2018
Houston, Texas

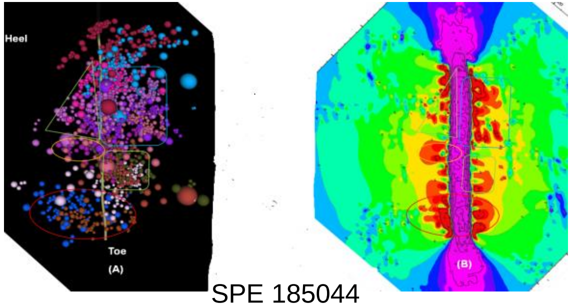
Society of Petroleum Engineers

Hydraulic – Natural Fracture Interaction

- Fundamental phenomenon needed for a better understanding of unconventional wells
- Very complex physics to model ➔ multiple methods are available
- Limited data to validate models ➔ Microseismic is the only volumetric field data that helps validate SOME aspects of this physics



Mineback experiments



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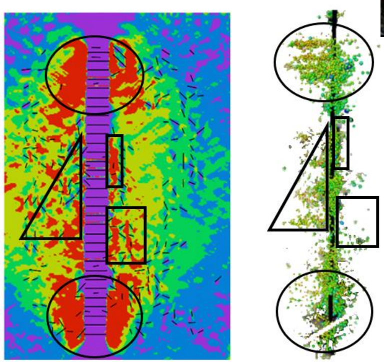
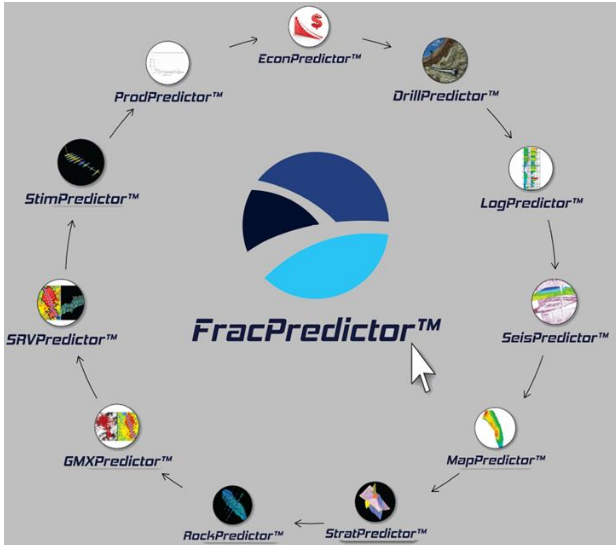


URTeC 2173459

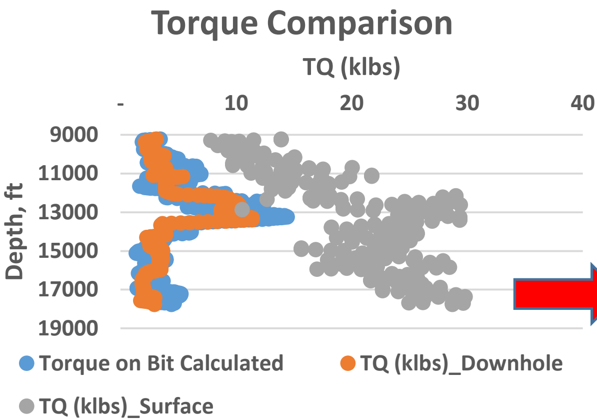
FracGeo's Approach to Modeling HF-NF

- Use continuum mechanics augmented with discontinuities' modeling to describe the HF-NF interaction
- Use the particle based method Material Point Method (MPM) to resolve the computational challenges.
- Use the Continuous Fracture Modeling (CFM) approach to describe the distribution of natural fractures in the reservoir
- Validate (NOT CALIBRATE) every geomechanical result with available field data (drilling, microseismic, pressure treatment, production, etc.)



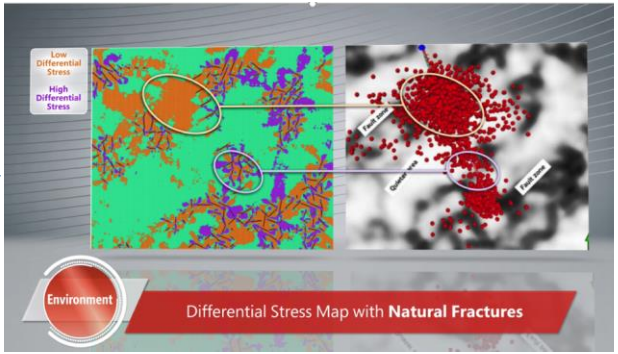
SPE International Gulf Coast Section

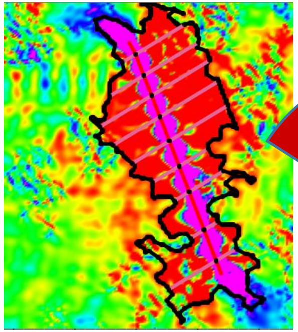
Removing Geomechanics from its silos: GMX from drilling to well interference optimization



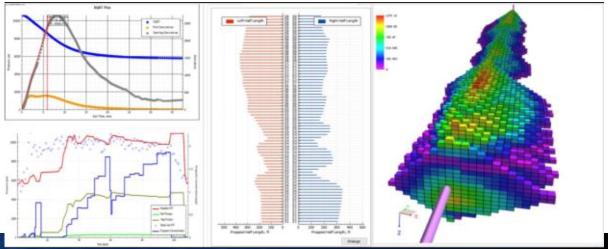
Geomechanical properties, pore pressure, stresses and natural fractures predicted from surface drilling data and **CMSE**

Reservoir **differential stress** and **strain** validated with microseismic data

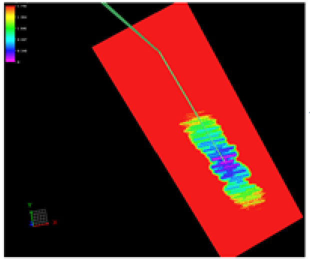




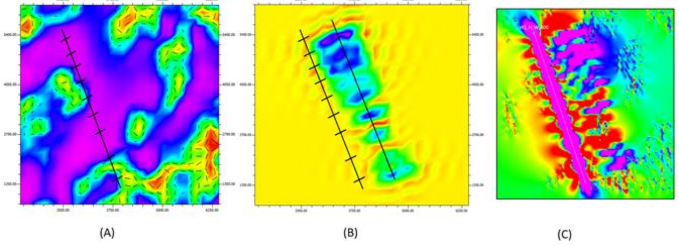
Geomechanically constrained **3D planar Frac simulator**



Fully coupled **Fast Marching Method** (FMM) flow simulator for **pressure depletion**



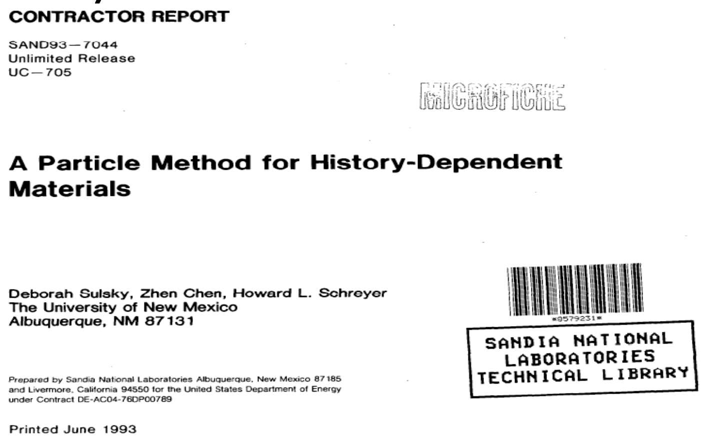
Poroelasticity for well interference optimization



The Future of Shale Management, Today

Material Point Method (MPM)

- MPM Originated from University of New Mexico & Sandia National Lab
- MPM is a powerful computational technique for solving solid dynamic problems;


CONTRACTOR REPORT

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MICROFICHE

A Particle Method for History-Dependent Materials

Deborah Sulsky, Zhen Chen, Howard L. Schreyer
The University of New Mexico
Albuquerque, NM 87131

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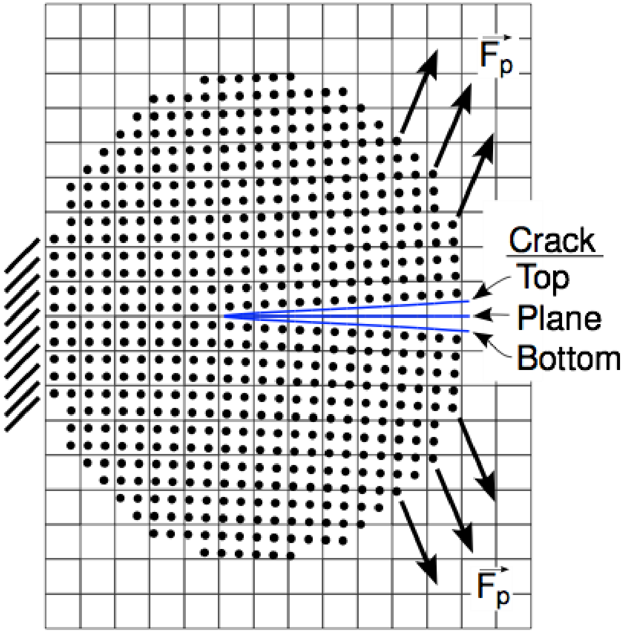
Prepared by Sandia National Laboratories Albuquerque, New Mexico 87185 and Livermore, California 94550 for the United States Department of Energy under Contract DE-AC04-76DP00789

Printed June 1993

- Used by Disney in Frozen and other movies

Material Point Method (MPM)

- Powerful tool developed for solid dynamics problems (Sulsky, Chen & Schreyer, 1994)
- Particle method: discretization into points, called particles
- Particles handle all material information
- Background grid associated with the particles, composed of elements.
- At each time step, particles information are extrapolated to the background grid to solve the equations of motion



MPM Application to HF-NF Interaction

- Explicit Fractures using Fracture Mechanics (FM)
  - CRAMP algorithm for explicit fracture modeling (Nairn, 2003)
  - J-Integral calculation
  - Cohesive zone model

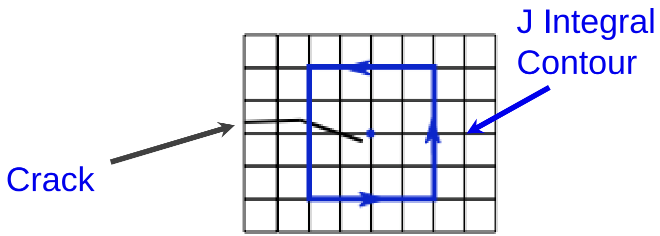
➔ The Continuous Fracture Model (CFM) provides the **explicit** description of the fractures at different scales

- Continuum Damage Mechanics
  - Anisotropic damage mechanics (ADaM) model (Nairn, Hammerquist, Aimene, 2017)
  - Augments a constitutive law
  - Uses the forth rank damage tensor by Chaboche (1979)

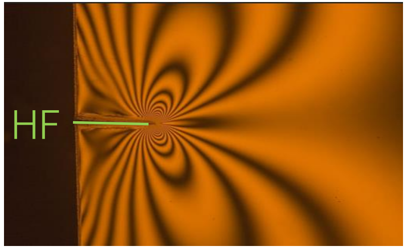
➔ The CFM models and seismic attributes provide the necessary Anisotropic Damage

Explicit Fracture in MPM

- J-Integral for fracture front parameters
  - J integral calculate the energy release rate and fracture-tip stress intensity factors

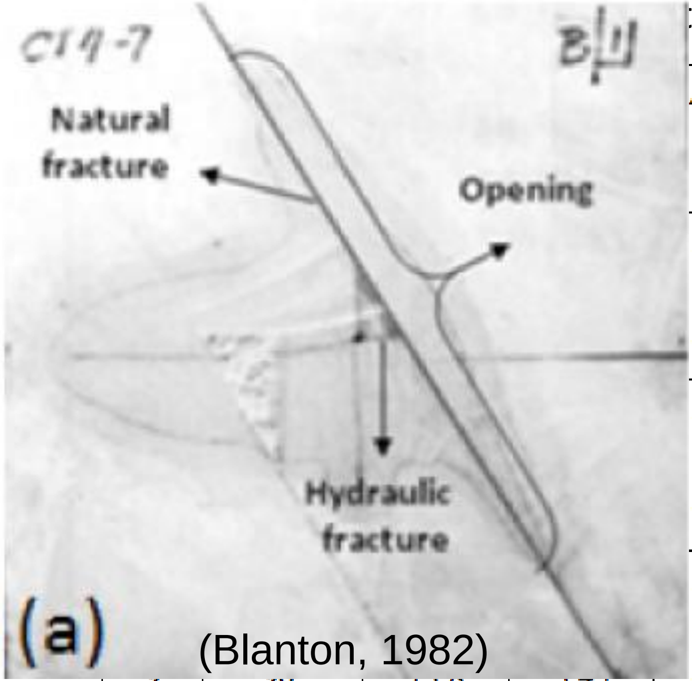


  - fracture tip parameters used to predict fracture initiation & propagation direction



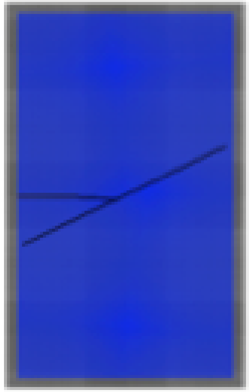
Stress field around fracture tip

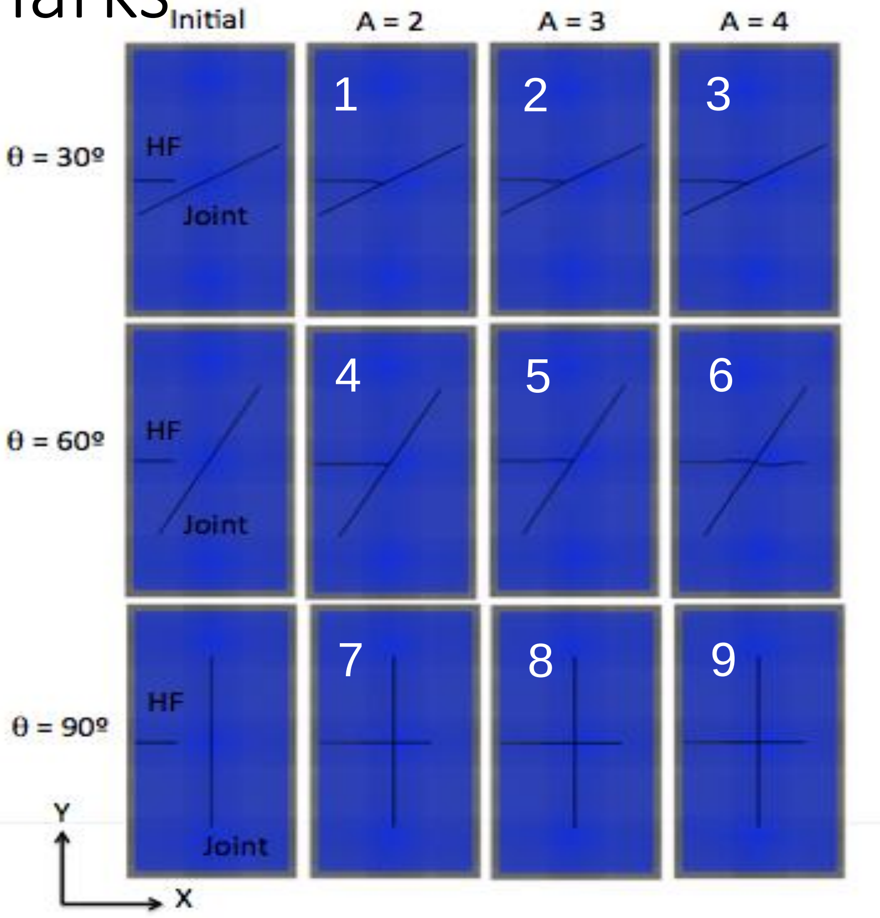
Hydraulic fracturing benchmarks



(Blanton, 1982)

A	Result
2	
3	
4	
2	
3	
4	Crossed joint
2	Dilated joint
3	Crossed joint
4	Crossed joint





Hydraulic fracturing benchmarks

- Fracture propagation path re-orientation to follow the maximum stress direction

Rock elastic properties

E = 8.4 GPa

ν = 0.23

ρ = 2.5 g/cm^3

Material toughness

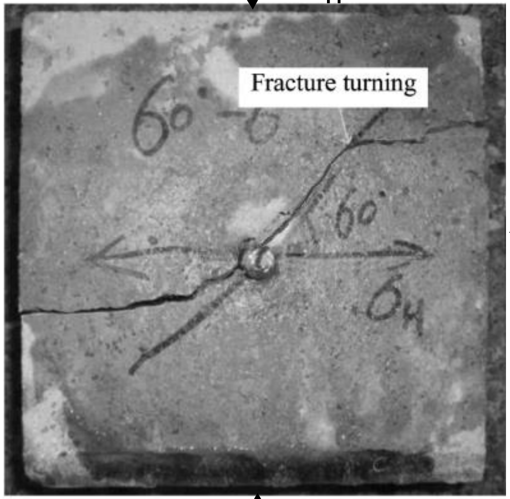
G_c = 2.55 J/m2

Initiation & propagation

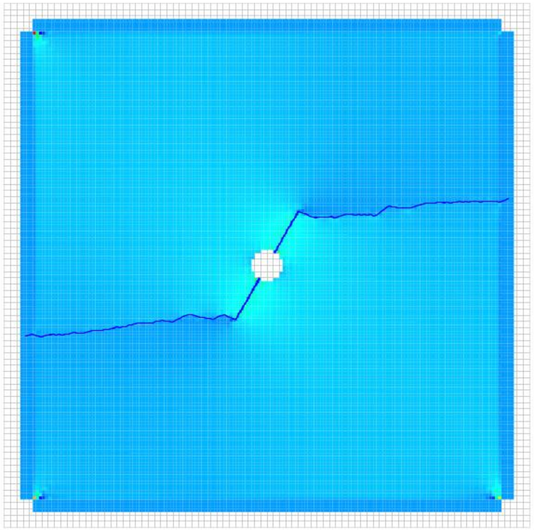
Maximum energy release rate & maximum hoop stress

σ_h = 4 MPa

σ_H = 4 MPa



Experimental fracture path from Chen et al. 2010.



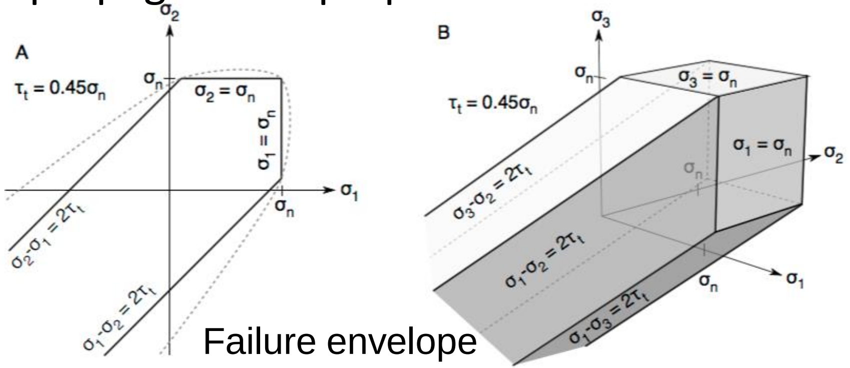
Fracture path from MPM simulation

Anisotropic Damage Mechanics Model (ADaM)

- The material constitutive law is augmented by an anisotropic damage tensor ***D*** (Chaboche, 1979):

$$\boldsymbol{\sigma} = (\mathrm{I} - \boldsymbol{D})\boldsymbol{C}_0\,\boldsymbol{\varepsilon}$$

- ***D*** depends on 3 damage variables (d_n, d_{xy}, d_{xz})
- Damage initiation is controlled by "damage initiation laws" attached to the material & damage propagation is perpendicular to the failure envelope



Failure envelope

Damage initiation and propagation

- The damage evolution is determined by three softening laws

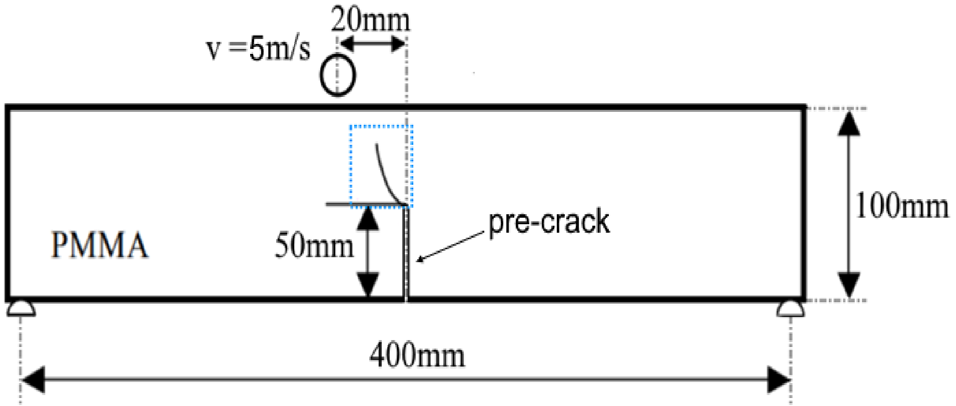
$$T_n = \sigma_n f_n(\delta_n) \qquad T_{xy} = \tau_t f_t(\delta_{xy}) \qquad T_{xz} = \tau_t f_t(\delta_{xz})$$

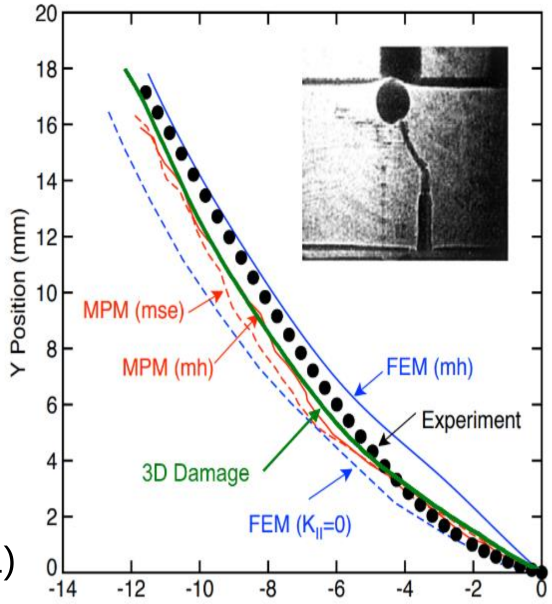
- The area under these softening laws are connected to tensile and shear energies released by propagation of damage.

- Summary
  - Damage parameters are strengths and toughness, along with failure envelop shape.
  - The damage model honors thermodynamics conditions for energy dissipation and have direct correspondence to fracture mechanics of an explicit fracture.

ADaM on general benchmarks tests

- Pre-cracked three-point bending specimen subject to dynamic impact with the eccentricity of e =*20 mm*

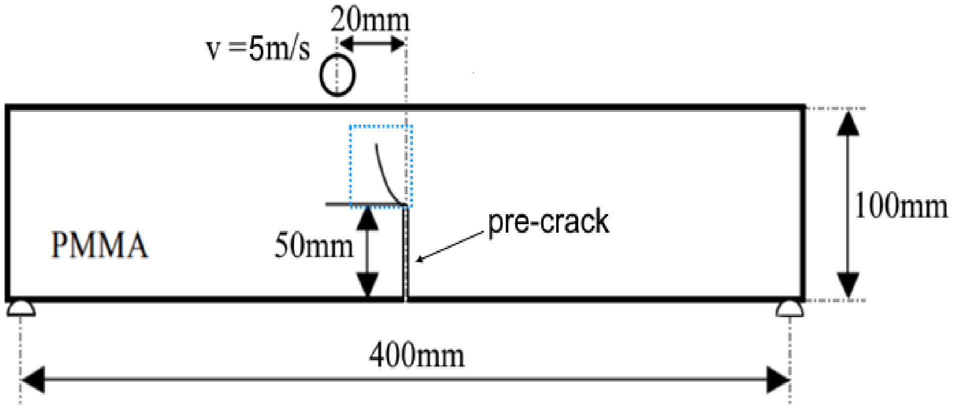


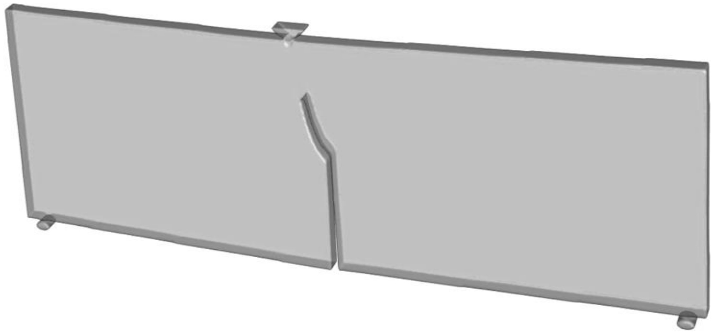


Experimental results and FEM predictions (Nishioka et al., 2001)

ADaM on general benchmarks tests

- Pre-cracked three-point bending beam specimen subject to dynamic impact.





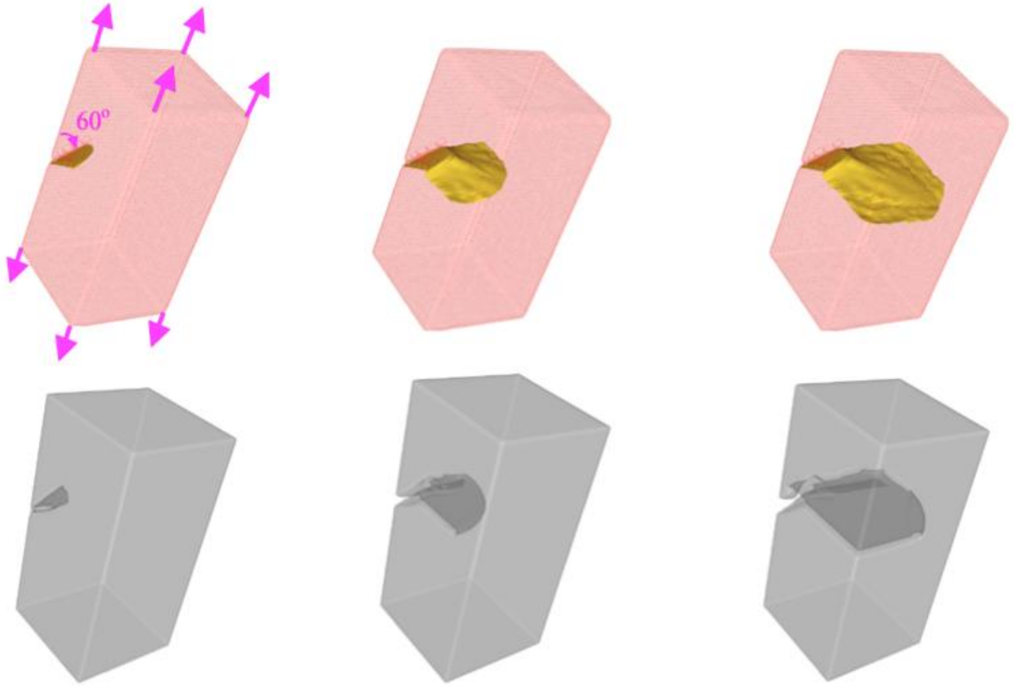
ADaM results capture well the mixed mode

ADaM vs. FM on general benchmarks tests

- Square rod with an initial fracture at 60º loaded in tension .

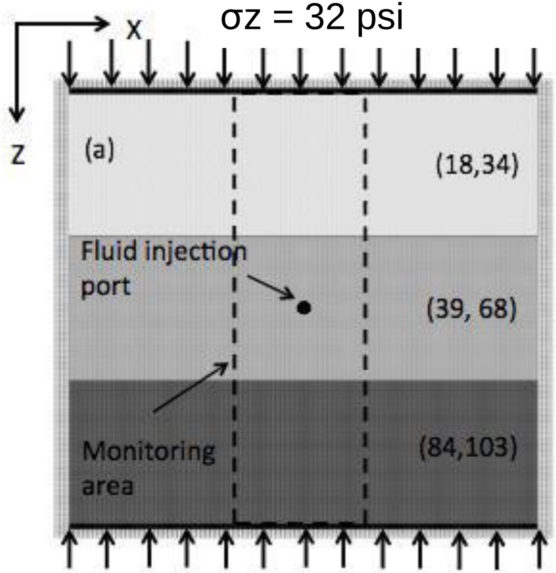
3D explicit fracture in MPM
from Guo and Nairn, 2018

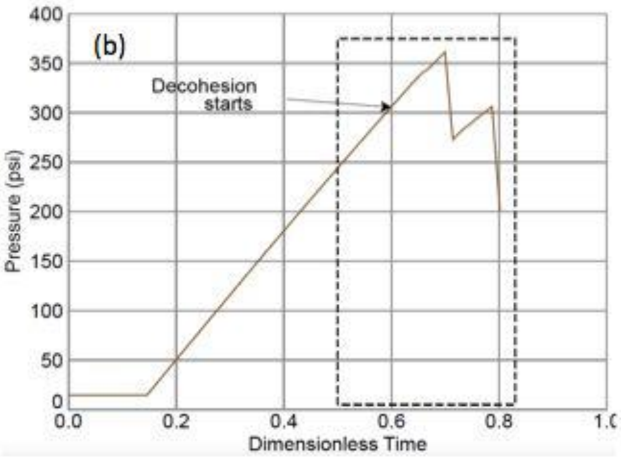
3D damage mechanics in MPM

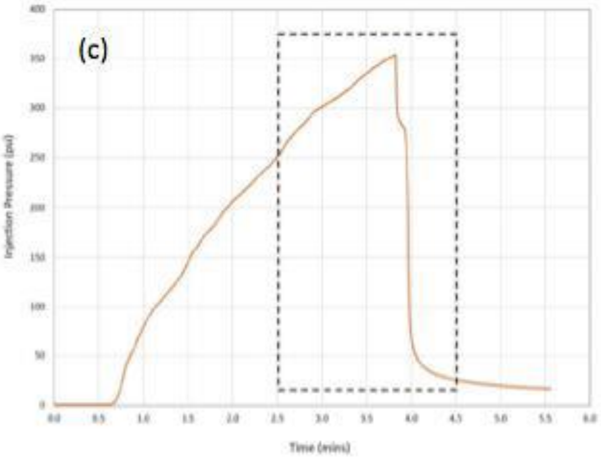


ADaM on a Layered Rock (Oreo Models)

- Numerical settings
  - Test 11 in AlTammar and Sharma (2017)
  - Perfect interface to match the well-bonded interfaces.





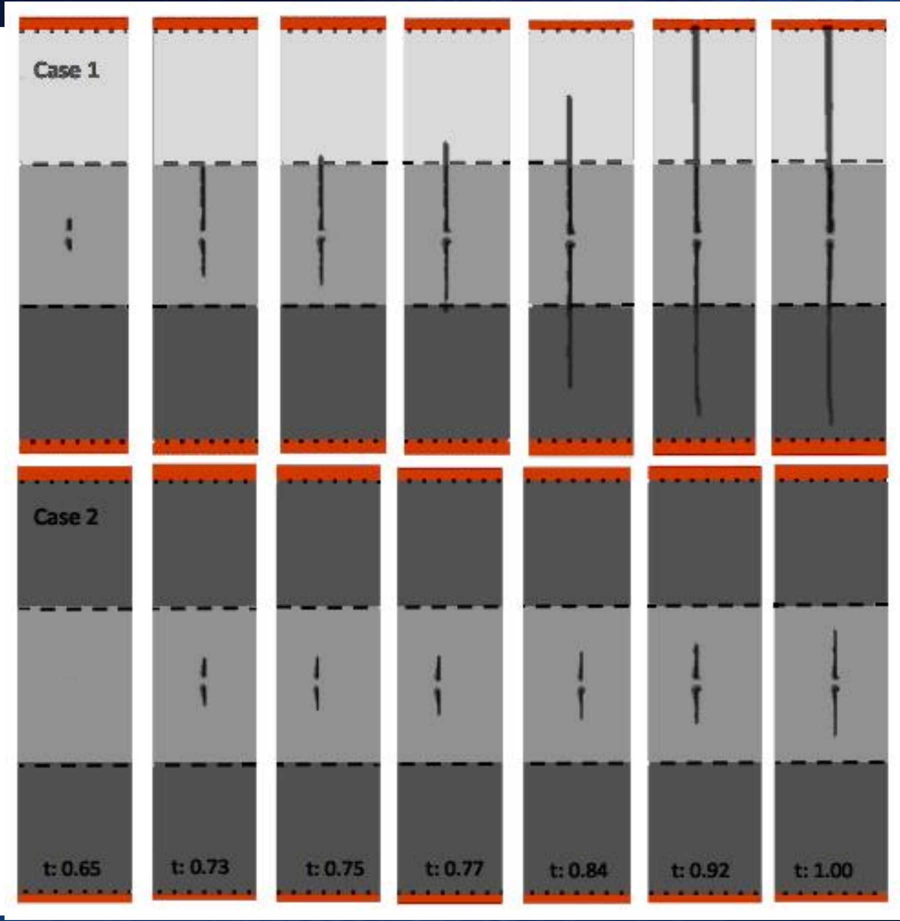


Average fluid particles vs. experimental monitoring injection pressure

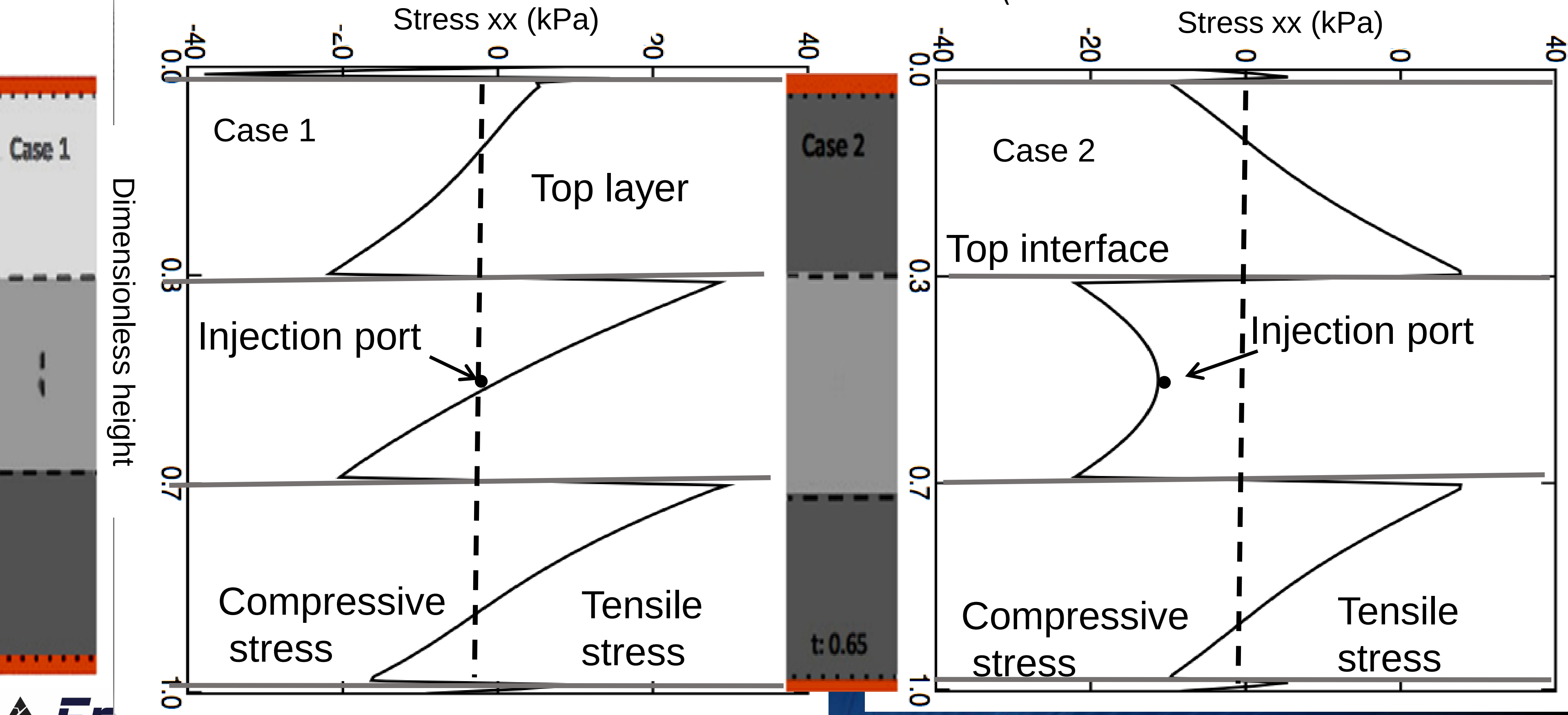
Isotropic "Oreos"

- Asymmetric height
- Early propagation

- Symmetric height
- Contained fracture

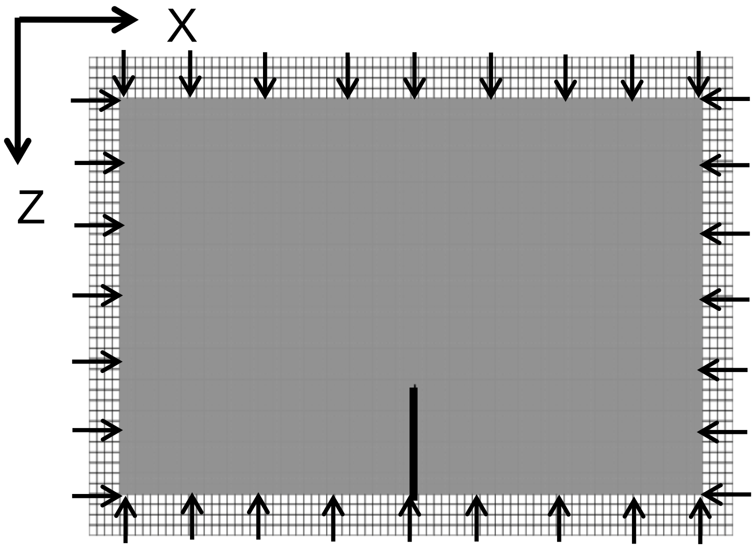


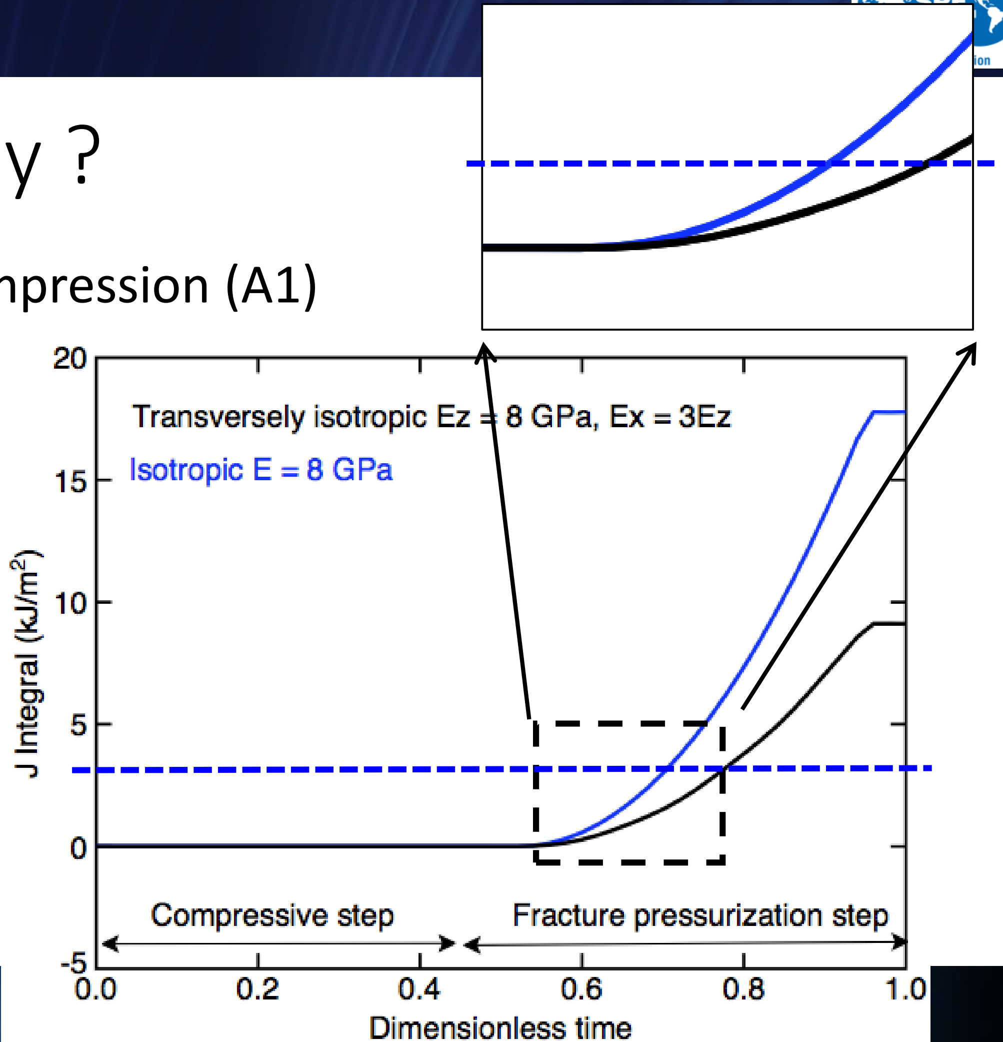
Stress Profiles due to interfaces (no Shmin)



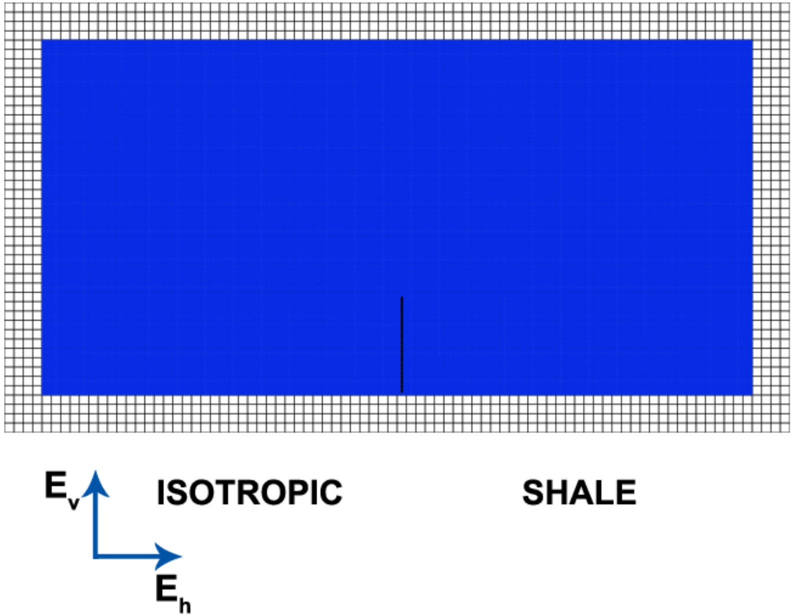
How about anisotropy ?

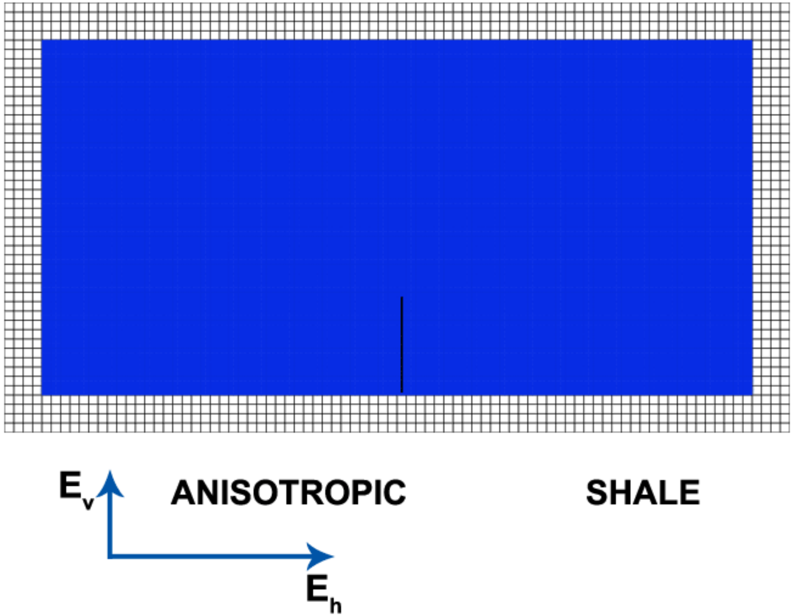
- Single notched edge test in compression (A1)





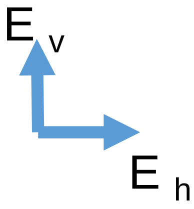
Anisotropy and Fracture Propagation



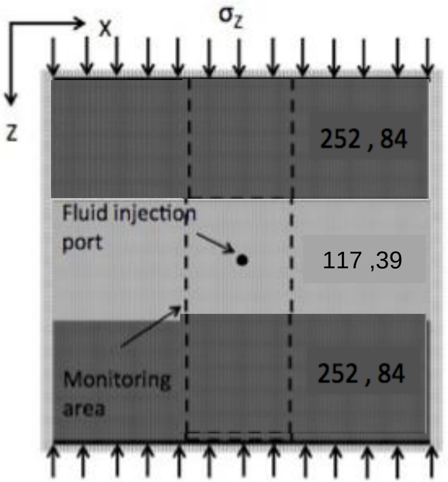


Major contrast between Horizontal and Vertical Young's Modulus

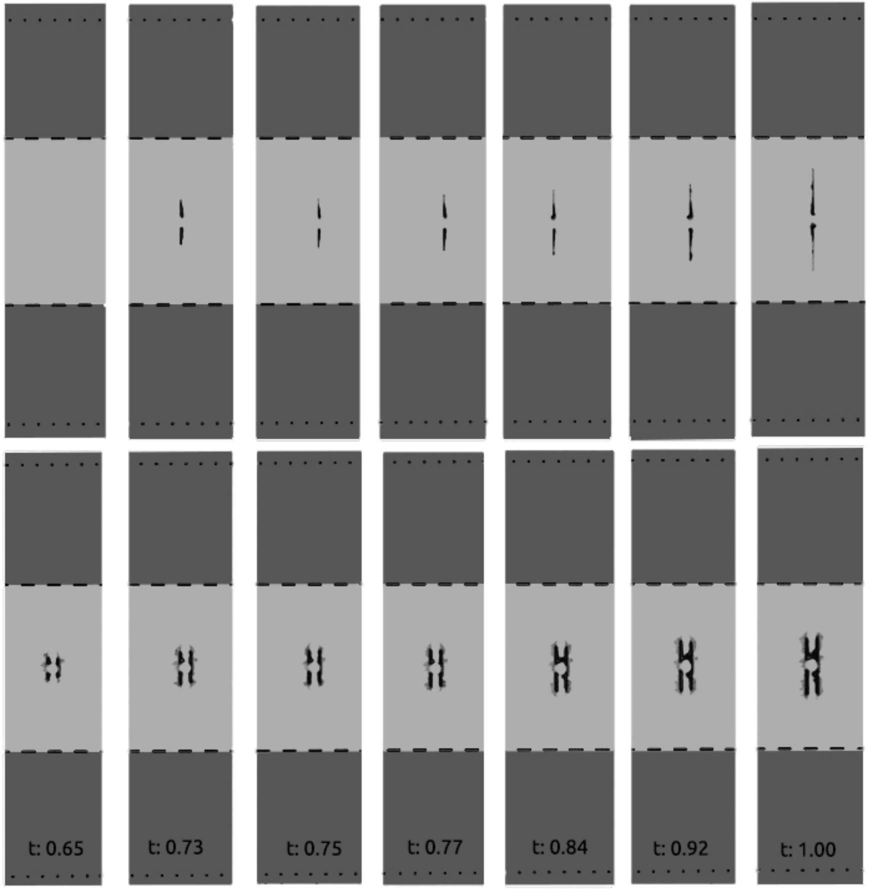
Anisotropy



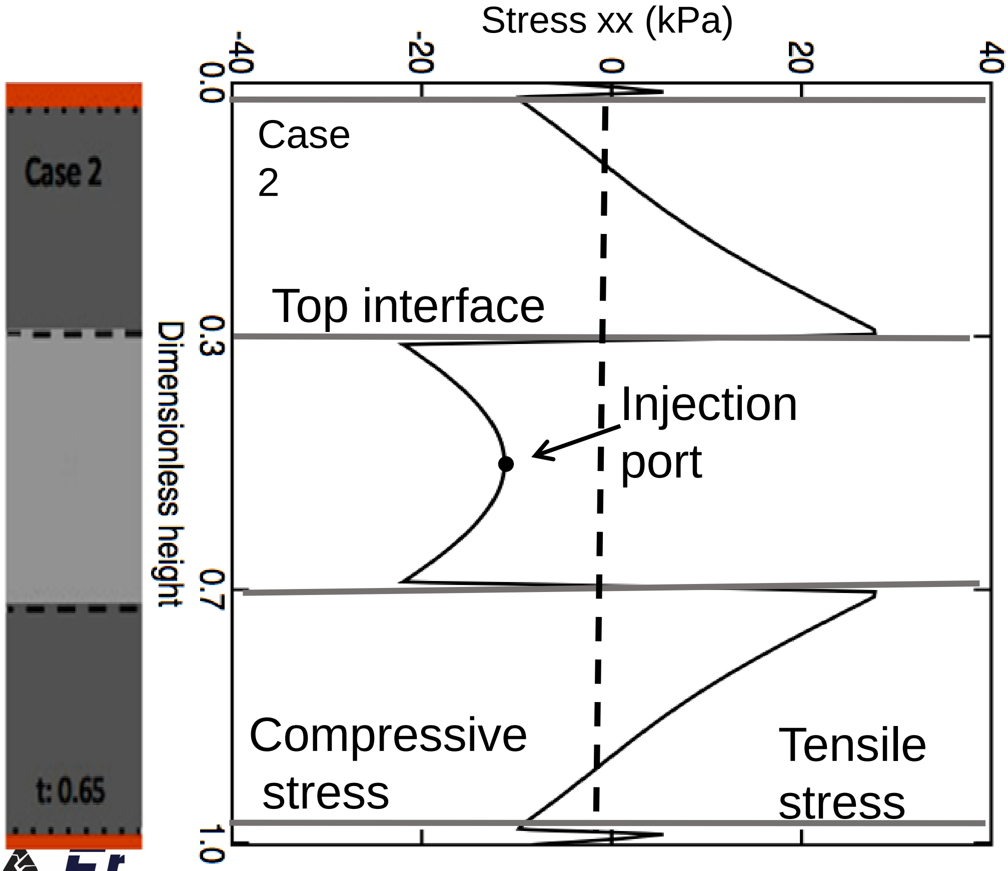
Isotropic Case 2

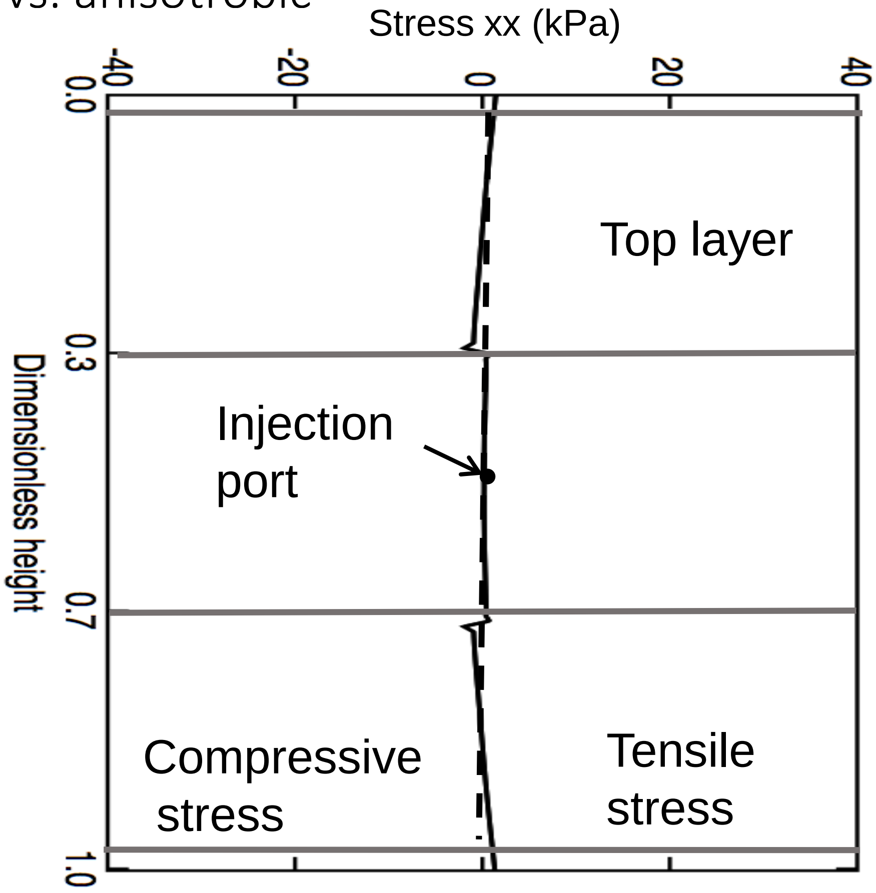


Anisotropic Case 2



Stress Profiles (no Shmin) : isotropic vs. anisotropic





Fracture Mechanics vs. Damage Mechanics

- Damage mechanics model can start without initial fracture. In fracture mechanics, an initial fracture is needed
- Connection between energy dissipated in ADaM and critical energy release rate in FM makes ADaM equivalent to FM.
- Most failure proceeds by coalescence of damage into a fracture that causes the material to become anisotropic.

$$\mathbf{D} = \begin{bmatrix} d_n & 0 & 0 & 0 & 0 & 0 \\ \frac{\nu}{1-\nu} d_n & 0 & 0 & 0 & 0 & 0 \\ \frac{\nu}{1-\nu} d_n & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & d_{xz} & 0 \\ 0 & 0 & 0 & 0 & 0 & d_{xy} \end{bmatrix}$$

Thank you

For more information, check out FracGeo's publications

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