SAND2015-7007C

Discrete fracture and flow modeling using general polyhedral grids and cohesive fracture models

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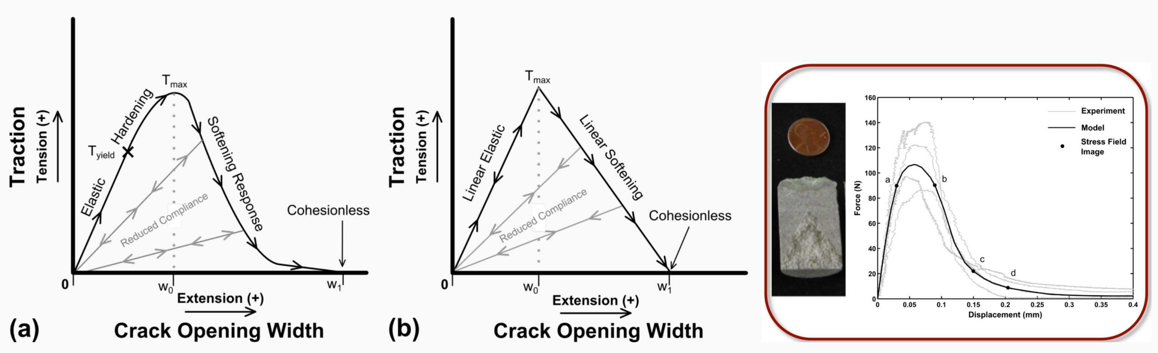
Introduction

The understanding of fracture phenomenon, both critical and subcritical, is important for the assessment of caprock integrity for CO2 sequestration. A computational method is presented for modeling the coupled flow and solid mechanical response of both single fractures and fracture networks. The meshing of the domain is facilitated by the use of general polyhedral grids, for both the solid mechanics and fluid mechanics. A simple hexahedral grid is used to mesh the overall domain. A cut-cell paradigm is used to generate explicit fracture surfaces. Each cut hexahedral cell becomes a polyhedral cell. A mimetic formulation is used for the flow physics, while a displacement-based finite-element formulation is used for the solid mechanics. The explicit fracture representation is advantageous for modeling coupled fluid-flow within the fracture network. Flow within the fractures is modeled using a full dimensional polyhedral mesh that conaturally resolves non-planar as well as intersecting fractures. Flow in the fracture is coupled with flow in the surrounding matrix through boundary conditions and forcing terms. A cohesive model is used at each fracture tip to represent the subscale damage and energy dissipated during fracture opening and growth.

Cohesive Fracture Modeling

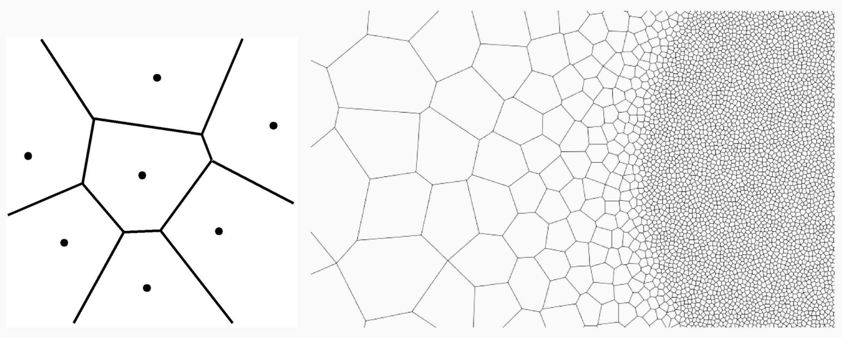
Cohesive Fracture Models (CFM) lump the inelastic processes occurring during fracture propagation into a thin zone between elastic subdomains. CFM assumes that the cohesive zone initially deforms elastically to a maximum tensile stress and then softens linearly from the crack opening width to zero stress at a critical crack opening width [6].

$$\nabla \cdot \mathrm{P} + \rho \mathrm{g} = 0$$

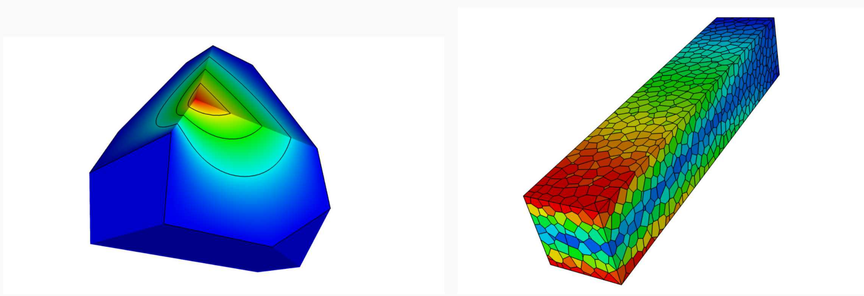


Polyhedral Finite Elements

The cohesive fracture model can be applied to both standard hexahedral element meshes as well polygonal meshes (including Voronoi) using harmonic basis function [2]:

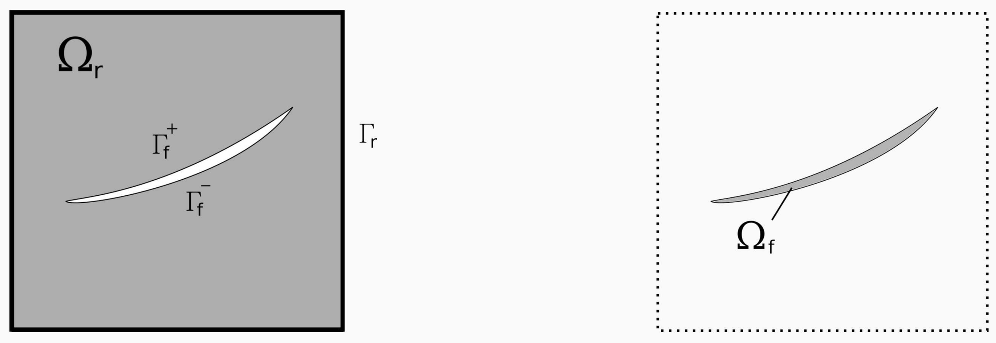


- Models can be used to assess geologic fracture initiation and propagation, or reactivation of existing fracture networks, in various lithologies and lithostatic stress-states.



Mimetic Finite Differences

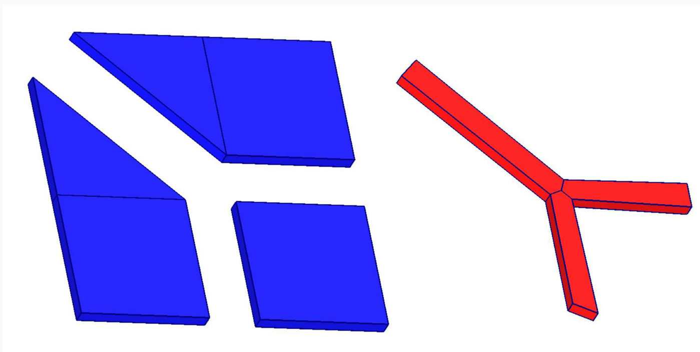
The Mimetic Finite Difference method [4] solves flow problems over a general set of polyhedral elements, which includes Voronoi grids.
For fracture flow calculations, the problem is divided over two separate domains, one for the fracture and one for the matrix. The two problems are then coupled using boundary conditions and source terms [1]:



$$-\nabla \cdot K_r \nabla p_r = f \quad \text{in } \Omega_r \qquad -\nabla \cdot K_f \nabla p_f = Q_l - Q_L \quad \text{in } \Omega_f$$
$$p_r = p_f \quad \text{on } \Gamma_f^{\{+,-\}} \qquad K_f \nabla p_f \cdot n = 0 \quad \text{on } \partial\Omega_f$$

Unlike other methods that define the fracture problem over a lower-dimensional manifold, we represent the fracture domain in the same dimension as the matrix domain. Doing so has some important advantages:

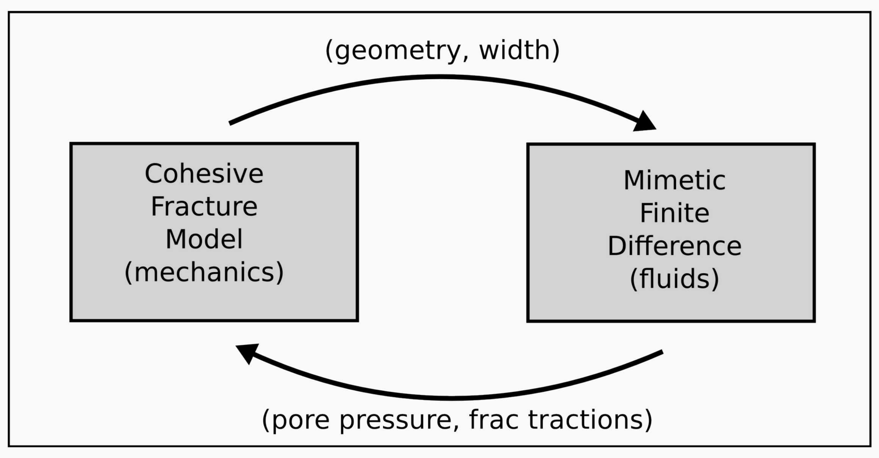
- Code reusability: we are using the exact same code for the both the fracture and matrix solution.
- Simple intersections: intersecting fractures are naturally represented in the full dimensional space.
- Fracture geometry: we can fully represent fracture aperture and curvature directly using the mesh.



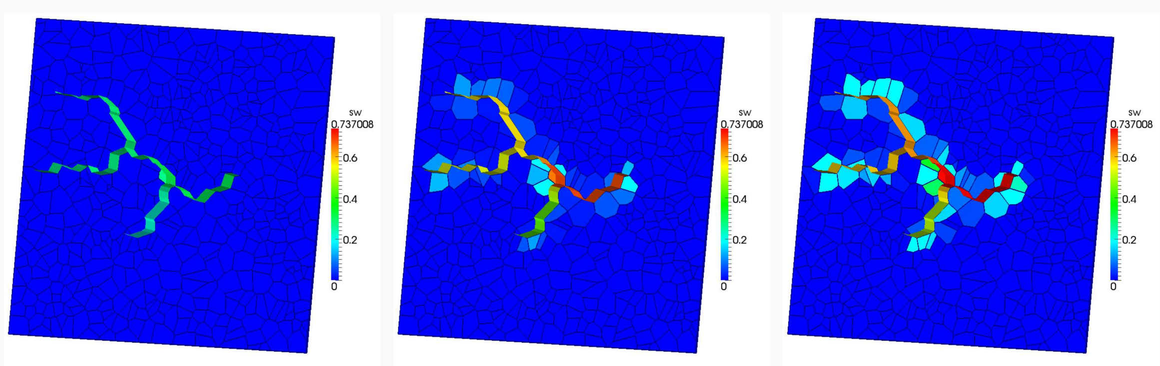
Putting it all together

Coupling mechanics and flow is a challenging problem. Typically, mechanics meshes are very different from the ones used in Flow. Since both the MFD method and a cohesive fracture modeling can be applied over the same meshes. a natural path for coupling the two methods is possible. We plan to couple the two methods over three stages:

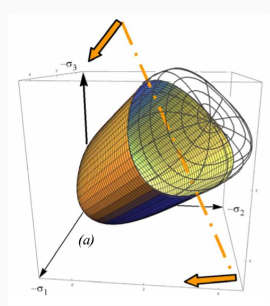
1. Sequential use: Run a full simulation of mechanics, and then use the final fracture geometry for flow.
2. Iterative coupling: In a singel simulation, iterate between the two models until convergence is reached.
3. Fully coupled: Solve for both systems simultaneously using a single jacobian matrix.



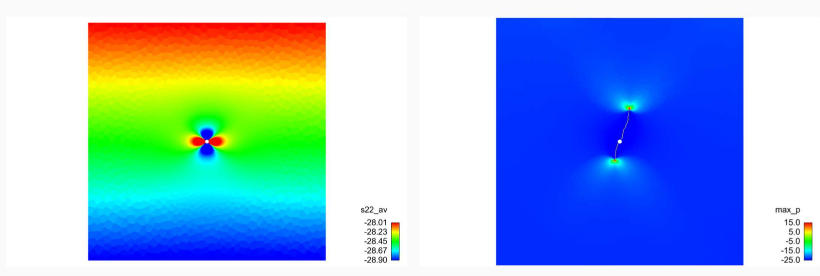
Numerical Results



Multiphase flow solutions through fracture network embedded in a Voronoi mesh using the MFD method.



Cohesive fracture model (comparison with experiment) and solid mecheanics plasticity model (Kayenta) [5, 6].



Initial lithostatic stress state around horizontal wellbore. Fluid-pressure induced fracture propagation from wellbore [3].

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