Modelling planar 3D hydraulic fracture propagation in materials with anisotropic fracture toughness

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Sedimentary rocks at the metric often exhibit an intrinsic transverse isotropy due to fine scale layering. The influence of such anisotropy on hydraulic fracture propagation needs to be better understood and predicted in order to improve well stimulation. In this study, we present an extension to the Implicit Level Set Algorithm (Peirce & Detournay 2008) to numerically investigate the influence of fracture toughness anisotropy on hydraulic fracture propagation. The elastic behaviour is assumed to be isotropic here.

Problem formulation

We consider a fluid driven planar fracture propagating in an impermeable rock with a pre-existing compressive state of stress. The properties of the medium are assumed be uniform and homogeneous and its behaviour modelled in the framework of linear elastic fracture mechanics (LEFM). The fluid is injected from a point source at a constant rate and is assumed to follow a Newtonian rheology. Fluid flow inside the fracture is assumed to be in lubrication conditions. Mathematically, the model combines width averaged mass and momentum conservation for fluid flow across the fracture width with the elastic deformation of the fractured solid expressed via a boundary integral equation relating fracture width to the normal tractions. The fracture toughness of the material is taken to be a function of the local propagation direction in the material principal direction.

Accounting for toughness anisotropy

An important feature of the implicit level set scheme is that it utilizes the tip asymptotic solution of a steadily propagating hydraulic fracture (Garagash et al. 2011) to locate the position of the propagating front. This is done by inverting the tip asymptote to get the distance of the front from a set of survey points just inside the fracture front, where the fracture width is known. To do this, local material and fluid properties such as the fracture toughness, leak off coefficient, viscosity of the fluid etc. are used to obtain the local closest distance to the front and local propagation velocity. The challenge, in the case of an anisotropic toughness is that while inverting this tip asymptote, the local fracture toughness is a-priori unknown as the local propagation direction may vary along the perimeter of the fracture. This propagation direction is implicit in the front position, which will only be available after the tip asymptote is inverted and the front is reconstructed. To solve for such an additional nonlinearity, we have added an additional iterative step to the original implicit level set algorithm in order to converge to the correct local toughness all along the fracture front (see Zia et al. 2018 for details). In this iteration, projections are drawn on to the front from the survey points to get the local propagation direction, giving, in turn, the appropriate value of toughness for a particular survey point.

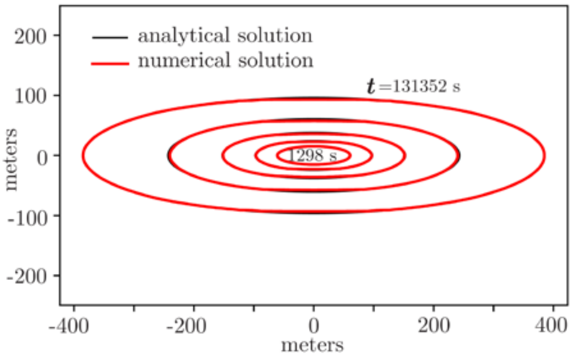

Fig. 1: Footprint of the fracture evaluated analytically and numerically at selected times.

Results

Toughness dominated elliptical HF benchmark:

To validate the scheme, we first analytically derived a specific toughness vs. propagation direction function that would impose an elliptical shape on the propagating fracture. A simulation was run with toughness evaluated with this analytically derived function to test if the scheme is able to produce a fracture that maintains elliptical shape as it propagates. Results show that the fracture indeed propagates with an elliptical shape, closely matching the derived analytical solution (see Fig. 1 for comparison of the evaluated footprints at selected times).

Fracture shape evolution from viscosity to toughness dominated propagation

The previous test case dealt with a fracture propagating in a purely toughness dominated regime to validate the scheme against an analytically derived solution. We also investigated how the transition from viscosity dominated propagation at early time to toughness dominated propagation at large time is influenced by the anisotropy of toughness. Results show that as time progresses, the hydraulic fracture, initially propagating as a radial fracture in the viscosity-dominated regime, becomes dominated by toughness dissipation, first in the direction where the material toughness is the largest, while still being dominated by viscous dissipation in other directions. Finally, at large time, the propagation becomes toughness dominated in all directions, and the fracture attained an elliptical shape corresponding to the specific form of the toughness anisotropy variation.

Large time/toughness dominated fracture shape as a function of the direction dependent toughness function

We also investigated the influence of the exact variation of toughness with propagation direction on the final shape of a planar 3D hydraulic fracture, driven from a point injection. A number of functions with a monotonic increase of toughness between the two material principal axes are tested. Results show that different toughness functions produces significantly different final shapes, as can be seen in Fig. 2.

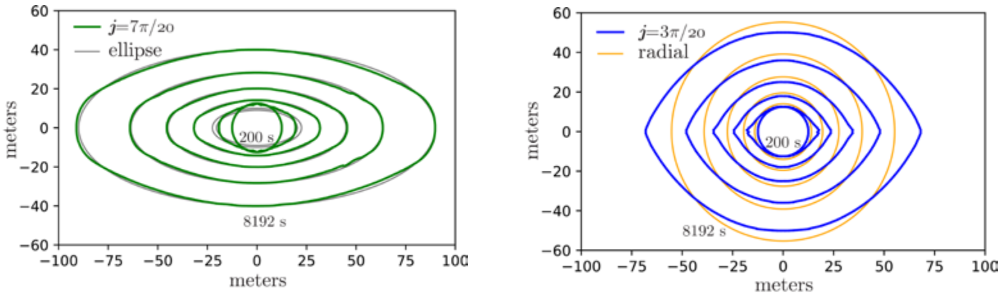

Fig. 2: Fracture footprints at selected times for the cases where the toughness transitions from low to high at the angle of $7\pi/20$(left) and $3\pi/20$ (right). The radial and elliptical shapes are also shown for reference.

References

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