A lattice based code for simulation of hydraulic fracturing - logic overview and applications

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HF Simulator

A 3D code developed by Itasca to simulate propagation of hydraulic fractures in naturally fractured reservoirs

Fluid injection/production from multiple boreholes and multiple clusters
Pre-existing joints derived from a user-specified Discrete Fracture Network (DFN)
Hydraulic Fracture propagation modeled as intact-rock failure in tension and slip and opening on joints
Lattice model of rock

- **3D lattice** representation of discontinuum rock

\[
\begin{align*}
\dot{u}^{(t+\Delta t/2)}_i &= \dot{u}^{(t-\Delta t/2)}_i + \sum F_i^{(t)} \Delta t / m \\
u^{(t+\Delta t)}_i &= u^{(t)}_i + \dot{u}^{(t+\Delta t/2)}_i \Delta t \\
\omega^{(t+\Delta t/2)}_i &= \omega^{(t-\Delta t/2)}_i + \frac{\sum M_i^{(t)}}{I} \Delta t \\
F^N &\leftarrow F^N + \dot{u}^N k^N \Delta t \\
F^S &\leftarrow F^S + \dot{u}^S k^S \Delta t
\end{align*}
\]

- Quasi-random assembly of point masses connected by springs that may break
Fracture propagation

• Springs break in tension when tensile limit $T$ is reached
  – Spring tensile limit $T$ representative of rock strength
• Broken springs interpreted as ‘microcracks’
• Microcracks connected by fluid pipes represent hydraulic fracture
Pipe Network for Fracture Flow

- Fluid nodes on broken springs (microcracks)
- Pipes connecting fluid nodes
- Connectivity at lattice resolution
- Continuous update of fluid network

\[
q = \beta \frac{a^3}{12\mu} [\Delta p + \rho_w g \Delta z]
\]

\[
\Delta p = \frac{Q}{V} K_F \Delta t_f
\]
Fluid-Mechanical Coupling

• Mechanical contribution:
  \[ \Delta P = k_R \frac{\Delta u}{A} \]
  \[ \Delta F = k_R \Delta u \]

• Fluid contribution:
  \[ \Delta P = \bar{K}_F \frac{\Delta u_F}{a} \]
  \[ \Delta u_F = \frac{Q_{in} - Q_{out}}{A} \Delta t \]
  \[ \Delta F = k_R \Delta u_F \]
  \[ \bar{K}_F = \frac{a}{A} k_R \]

• Explicit time step:
  \[ \Delta t \propto \frac{R}{K_R} \]
  \[ \Delta t = \frac{\lambda^3}{k' K_R} \]
  \[ \lambda = \frac{R}{a} \]
  \[ k' = \frac{1}{12 \mu} \]
Explicit Time Marching Formulation - a

- Newton second law to compute the motion of nodes; damping added for quasi-static solutions
- Force-displacement for each spring
- Update nodal forces, fluid pressure from spring deformation
- Use the lubrication equation to update fluid pressures and fluxes
- Update nodal forces from fluid pressure change
- Detection of new ‘microcracks’
- Update of fracture network at each time step
Explicit Time Marching Formulation - b

Uniform density scaling is applied
  – fluid multi-stepping is used
  – mechanical and (macro) fluid time steps are set equal

• Lattice spring carries the total force, which affects force balance and motion
• Effective stress is considered for joint slip or opening
Lattice Properties

• Link between lattice parameters and rock properties based on numerical testing
• Spring stiffness to match target rock elasticity
• Spring tensile limit, $T$, adjusted to represent rock toughness: $T \equiv K_{ic}/\sqrt{R}$
• Built in calibration factors based on lattice resolution
Additional code features

- Non-steady matrix flow
- Newtonian or power-law fluid
- Fluid can contain proppant
- Arbitrary initial stress by layer
- **Heat** propagation and associated rock deformation and damage
- Generation of microseismicity data associated with formation of microcracks and slipping on pre-existing joints
DEMONSTRATION EXAMPLES
Simultaneous injection in 2 clusters

(a) Homogeneous medium

(b) Medium with pre-existing joints
a – Homogeneous Medium
b - Fractured Medium
Flow pipe network

Fluid pressure at flow nodes
FRACTURE INTERACTION
Single pre-existing fracture -a
Single pre-existing fracture - b
APPLICATION EXAMPLES
Borehole and injection clusters

Injection rate specified at well head

Hydraulic fractures initiated from injection clusters
SIMULTANEOUS INJECTION
Simultaneous injection

1000 sec

30 m

70 m
Two, three clusters

30 m

15 m

30 m
Four, five, six clusters
Six clusters interaction

1000 sec

70m

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SEQUENTIAL INJECTION
Sequential Injection - a
Results from FLAC axisymmetric runs for 2-crack problem

Horizontal stress = 3 MPa

Horizontal stress = 6 MPa
Sequential Injection - c
STRESS BARRIER
Stress Barrier
FRACTURE INITIATION
CONCLUSIONS
Lattice approach for HF

- 3D lattice based approach, for simulation of hydraulic fracturing
- Capability to simulate both fracture of intact brittle rock and sliding and opening of pre-existing joints
- Overcomes some of the limitations of conventional methods
Thank you!