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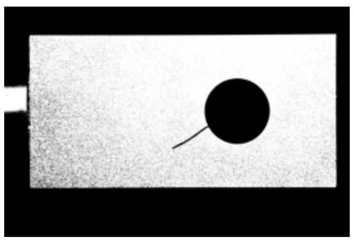

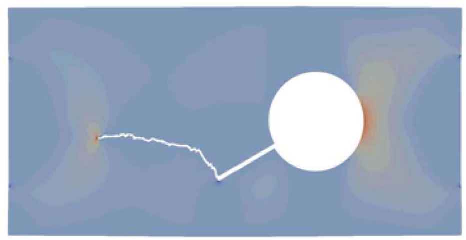

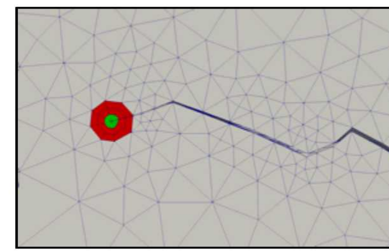

Sandia Fracture Models for Mixed-Mode Brittle Fracture

A. Stershic, M. Stender, S. Grutzik

Sandia National Laboratories

CFRAC 2019; Braunschweig, DE; June 12-14, 2019

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Overview

- Sandia fracture modeling capabilities in SIERRA
- Preliminary work
  - Geometry
  - Model Parametrization
- Element Death
- Phase Field
- SIERRA / FRANC3D Coupling

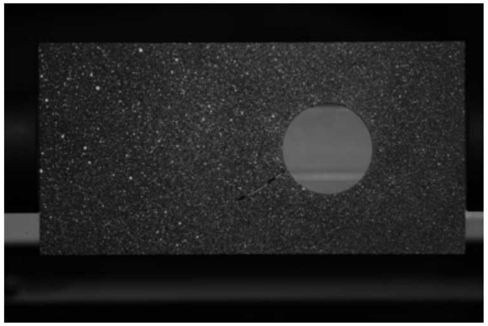
Sandia Capabilities

- SIERRA finite element code (Sandia National Laboratories)
  - Implicit & explicit integration
  - Fully parallelized for clusters, HPC
  - Finite strain formulation
  - Robust explicit & implicit contact
  - Verification & Validation
  - Multiphysics solutions
- Brittle Failure Strategies in SIERRA:

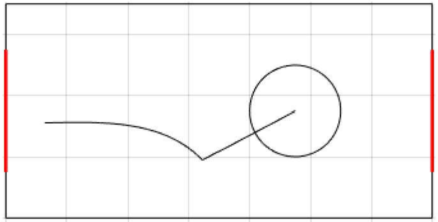
	Capability	Status
→	Element Death	Production
	XFEM	Production / Development
	Peridynamics	Research
	RKPM	Research
	Cohesive Elements	Production
	Localization Elements	Production
→	Phase Field	Research
→	FRANC3D Coupling	Production

Geometry

- Geometry:
  - Nominal geometry
    - Use nominal dimensions:
      - Specimen: 140 mm x 70 mm x 10 mm
      - Hole: 30 mm diameter, 25 mm off-center
      - Notch: 35 mm long from hole center, 30° from X axis
    - Use provided imagery:
      - Threshold at at critical gray value
      - Measure notch width: estimated 1mm wide
  - Sculpted geometry
    - SCULPT (Sandia) – meshes voxelized imagery
    - Input: thresholded image, background mesh(without hole, crack)
    - More expensive, but more accurate
  - Meshing
    - Several mesh densities of each
- Boundary conditions:
  - Left – fixed X, fixed Y
  - Right – prescribed displacement X (0.1 mm/min), fixed Y
  - Back (symmetry) – fixed Z



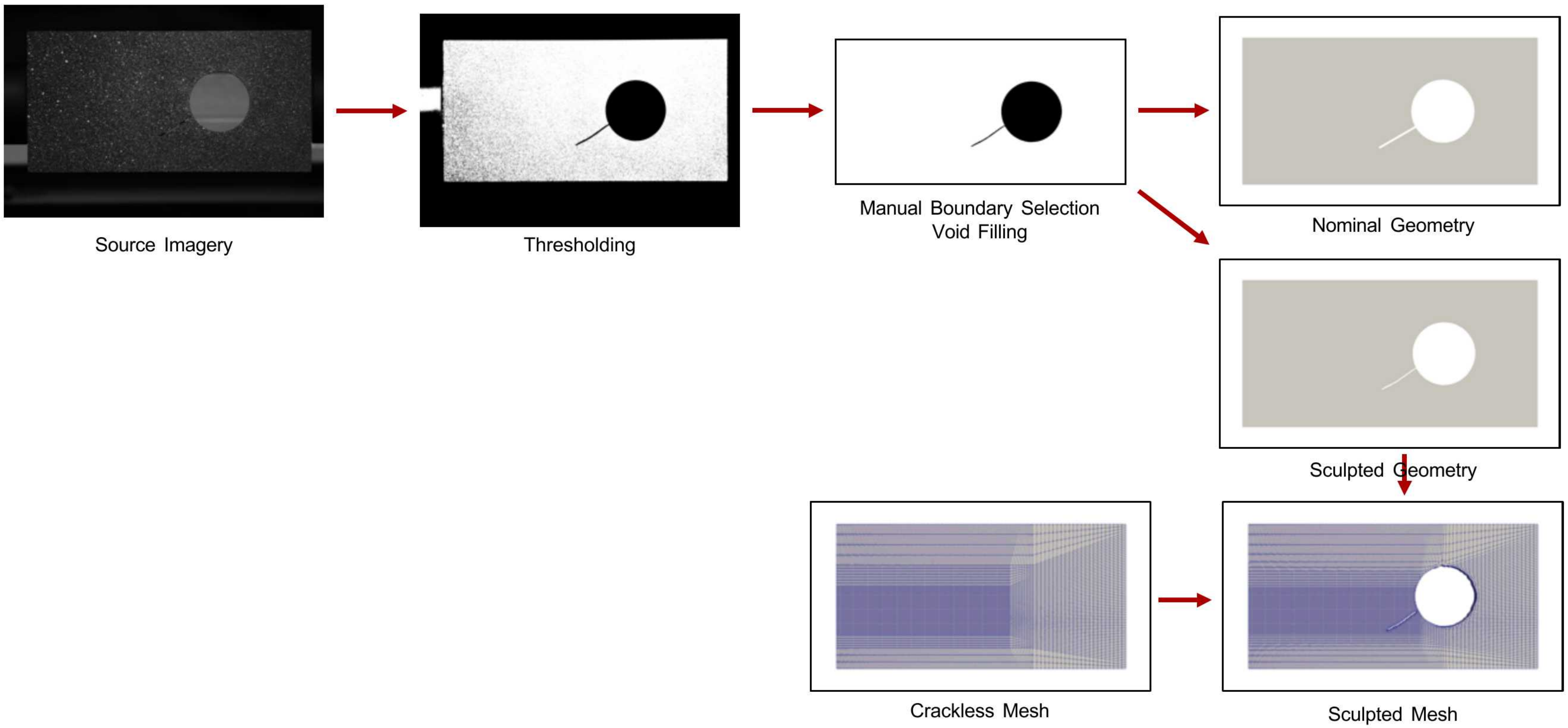
Source Imagery



Nominal Geometry, BCs highlighted

Geometry

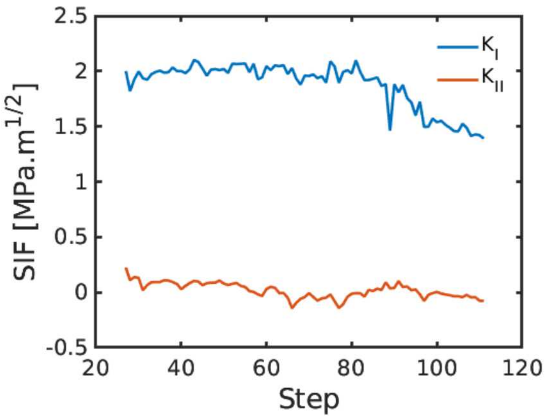
- Geometry:
  - Processing flow-chart:

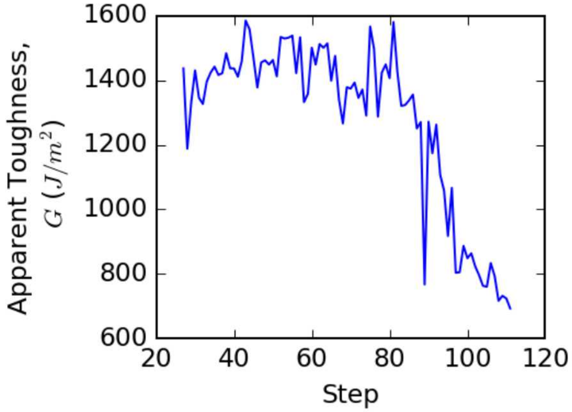


Model Parametrization

- Model parametrization
  - Provided data from benchmark specification (Young's modulus, Poisson's ratio)
  - Online references (density, fracture strength)
  - Post-processing of provided data (toughness / fracture energy G_c)

$$G = \frac{K_I^2}{E'} + \frac{K_{II}^2}{E'} \quad \text{where} \quad E' = \frac{E}{1-\nu^2}$$





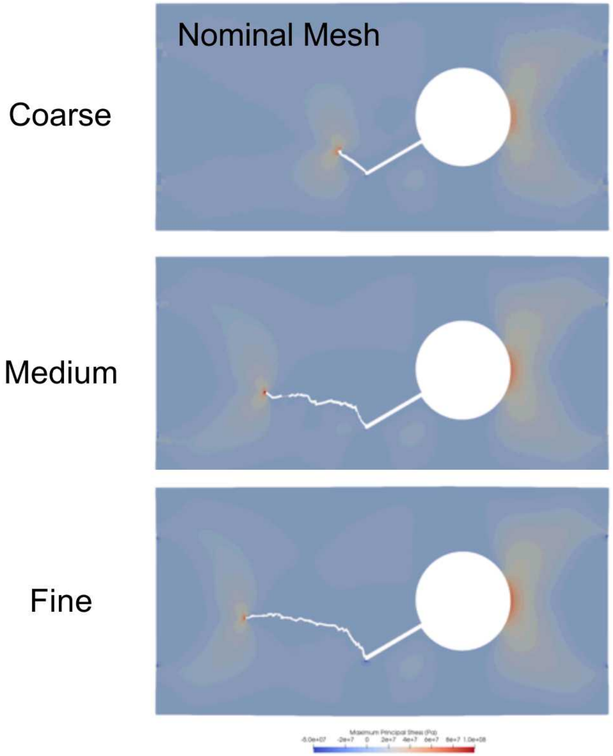
→ Estimate $G_c \approx 1400\ J/m^2$

ELEMENT DEATH

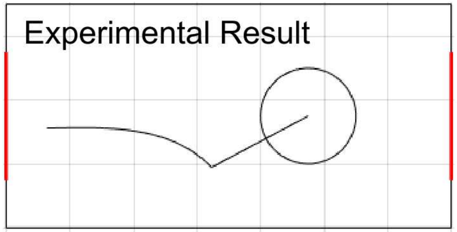
Andrew Stershic

Element Death

- Approach:
  - Kill elements when maximum principal stress exceeds critical value: $\sigma_I > \sigma_c$
- Concerns:
  - Mesh sensitivity: crack propagation length & direction, energy dissipation, stability



- Results:
  - Element death does decently at capturing the crack path
  - Still evidence of mesh dependence in crack length & direction
  - Perhaps the global stability of the problem (monotonic F/D even with crack) assists here



PHASE FIELD

Andrew Stershic

Michael Stender

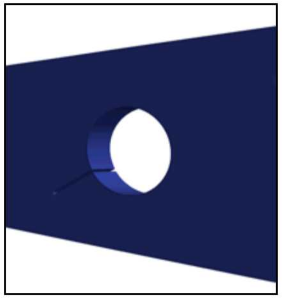
Brandon Talamini

Phase Field

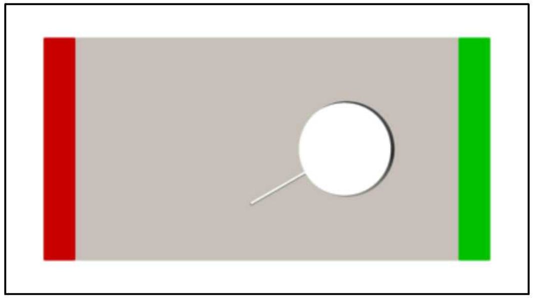
- Overview of approach:
  - Solve fracture problem by minimizing global energy functional
  - Approximate surficial fracture energy with volumetric energy

$$\Psi = \int_\Omega \psi \, d\Omega = \int_\Omega \tilde{\psi}^{e}(\varepsilon^e) d\Omega + \int_\Gamma G_c d\Gamma \rightarrow \int_\Omega g(c)\tilde{\psi}^{e}(\varepsilon^e) + f(c, \nabla c, l) G_c \, d\Omega$$

  - Γ-convergent: expressions equivalent in limit $l \to 0^+$
  - Similar formulation to gradient-damage model



Damage caused by stress conc. at BC



Geometry for phase field model with unbreakable blocks

- Details:
  - Phase field fracture model:
    - Threshold model, "AT-1": $\psi_{frac} = 2\psi_{crit}\left((1-c) + l^2|\nabla c|^2\right), \psi_{crit} = \frac{3G_c}{16l}$
  - Model parametrization
    - Set ψ_{crit} & l based on tensile failure strength ($\sigma_c \approx 50 \; MPa$): $\psi_{crit} = \frac{\sigma_c^2}{2E} \to l = \frac{3G_c E}{8\sigma_c^2}$
  - Inserting "unbreakable" blocks at boundary conditions
    - Prevents damage that arises due to idealization of boundary conditions

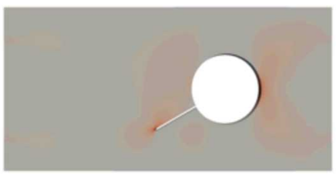
Phase Field

- Details (continued):
  - Mixed-mode fracture – only want tensile components to contribute to damage
    - Typically, full strain energy considered: $\tilde{\psi} = \frac{1}{2}\sigma_{ij}\varepsilon_{ij} = \frac{\lambda}{2}tr(\varepsilon)^2 + \mu\, tr(\varepsilon^2)$
    - Consider other energy decompositions: $\Psi = \int_\Omega g(c)\tilde{\psi}_{act} + \tilde{\psi}_{pas} + f(c, \nabla c, l)G_c\, d\Omega$
    - Other energy decompositions implemented for this benchmark

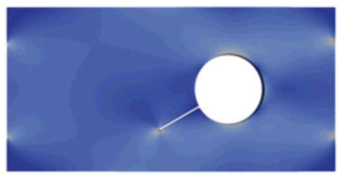
	Decomposition	$\tilde{\psi}_{act}$	$\tilde{\psi}_{pas}$	σ
	Full	$\frac{\lambda}{2}tr(\varepsilon)^2 + \mu\, tr(\varepsilon^2)$	0	$g(c)(\lambda tr(\varepsilon)I + 2\mu\varepsilon)$
→	Spectral	$\frac{\lambda}{2}tr(\varepsilon_+)^2 + \mu\, tr(\varepsilon_+{}^2)$	$\frac{\lambda}{2}tr(\varepsilon_-)^2 + \mu\, tr(\varepsilon_-{}^2)$	$g(c)(\lambda tr(\varepsilon_+)I + 2\mu\varepsilon_+) + (\lambda tr(\varepsilon_-)I + 2\mu\varepsilon_-)$
	Volumetric/ Deviatoric	$\frac{\lambda}{2}tr\left(\varepsilon_{vol,+}\right)^2 + \mu\, tr(\varepsilon_{dev}{}^2)$	$\frac{\lambda}{2}tr\left(\varepsilon_{vol,-}\right)^2$	$g(c)\left(\lambda tr\left(\varepsilon_{vol,+}\right)I + 2\mu\varepsilon_{dev}\right) + \lambda tr\left(\varepsilon_{vol,-}\right)I$
→	Volumetric/ Deviatoric Spectral	$\frac{\lambda}{2}tr\left(\varepsilon_{vol,+}\right)^2 + \mu\, tr(\varepsilon_{dev,+}{}^2)$	$\frac{\lambda}{2}tr\left(\varepsilon_{vol,-}\right)^2 + \mu\, tr(\varepsilon_{dev,-}{}^2)$	$g(c)\left(\lambda tr\left(\varepsilon_{vol,+}\right)I + 2\mu\varepsilon_{dev,+}\right)$ $+ \left(\lambda tr\left(\varepsilon_{vol,-}\right)I + 2\mu\varepsilon_{dev,-}\right)$

Phase Field

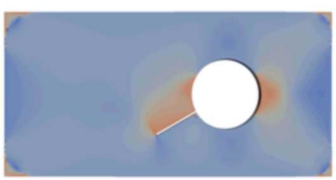
- Preliminary results:
  - Full energy does not crack in correct direction (expected)
  - Spectral decompositions crack in correct direction (expected)



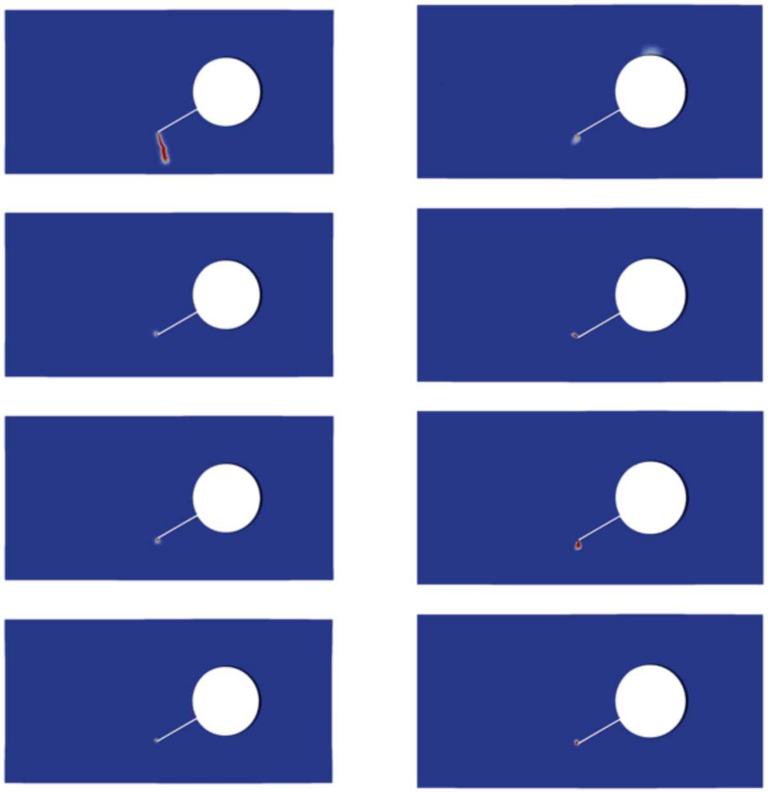
Max. Principal Stress



Von Mises Stress



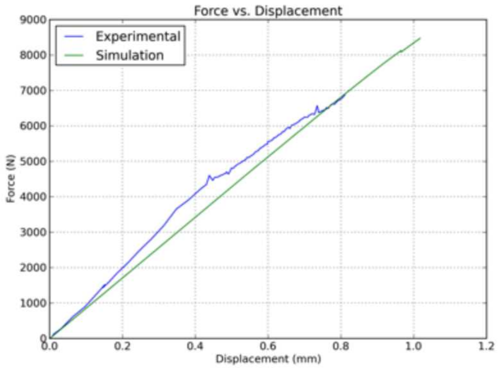
Triaxiality

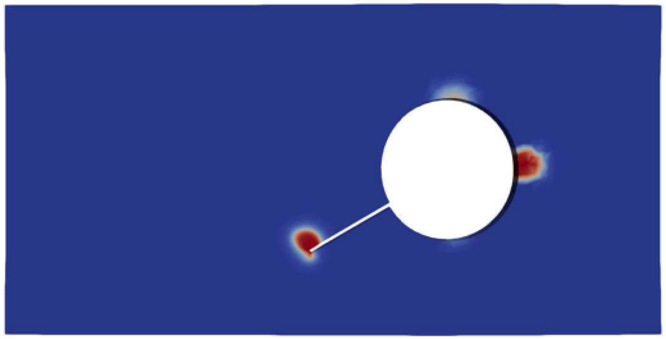


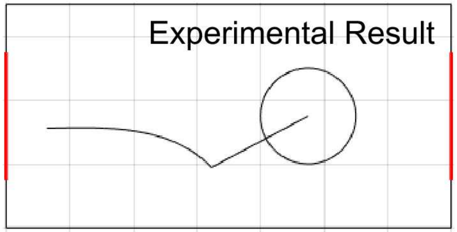
  - Performed qualitative verification by comparing to MOOSE framework
    - Same trends for all energy decompositions
    - Results do differ slightly in magnitude:
      - SIERRA & MOOSE have different solution schemes: staggered vs. monolithic

Phase Field

- Results:
  - Best answer (volumetric/deviatoric spectral, overloaded)
    - Predicts tensile crack development, but also has cracks growing from hole
    - Notched crack grows in correct direction, but not far enough
    - Force/displacement plot much more linear
      - Stiffness does decrease with damage growth, but much later







- Takeaways:
  - More work needed!
  - Alternative selection of length scale?
  - Eager to learn best practices

SIERRA / FRANC3D

Scott Grutzik

John Emery

http://www.fracanalysis.com (FRANC3D)

SIERRA / FRANC3D

- Overview of approach:
  - Discrete fracture representation
  - Coupling of SIERRA (Sandia) & FRANC3D (Fracture Analysis Consultants, Inc.)
    - SIERRA handles solid mechanics solve
    - FRANC3D performs mesh cutting & remeshing
    - FRANC3D uses “M-integral” calculate stress intensity factors
    - FRANC3D uses SIFs to compute crack extension distance & direction
- Details:
  - Solution in multiple steps. In each:
    - Compute physics (*entire displacement*)
    - Compute SIFs
    - Update geometry
  - Fatigue-like formulation
    - Solved in linear fashion
    - Crack growth proportional to SIF magnitudes: $\Delta a \sim K_I^2$
    - SIF ratios → crack growth direction
    - No concept of K_{IC}; no effort to ensure that $K_i \leq K_{ic}$ at all points (nonlinear)

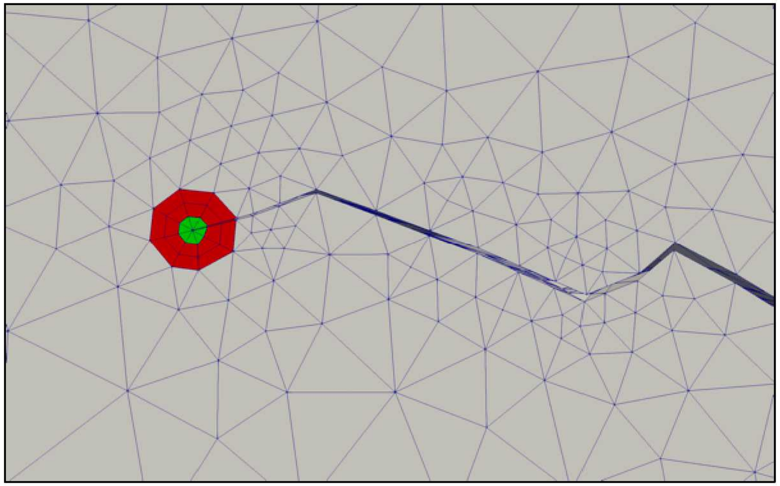
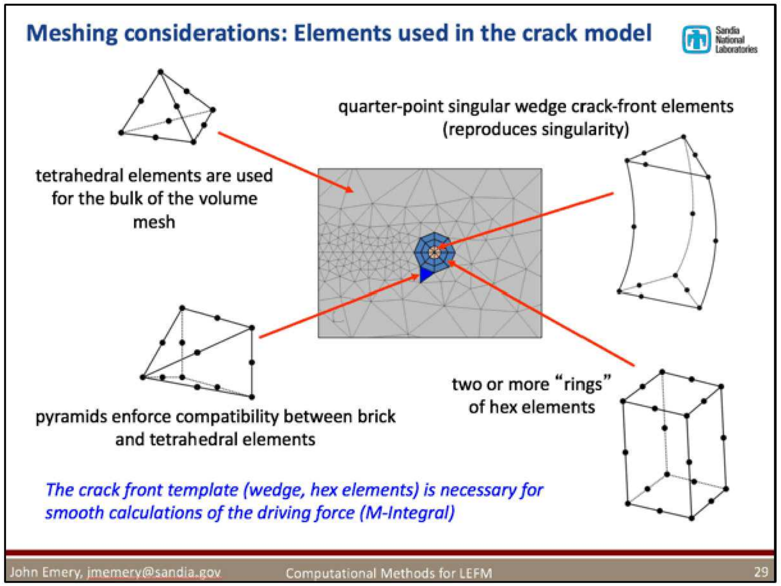


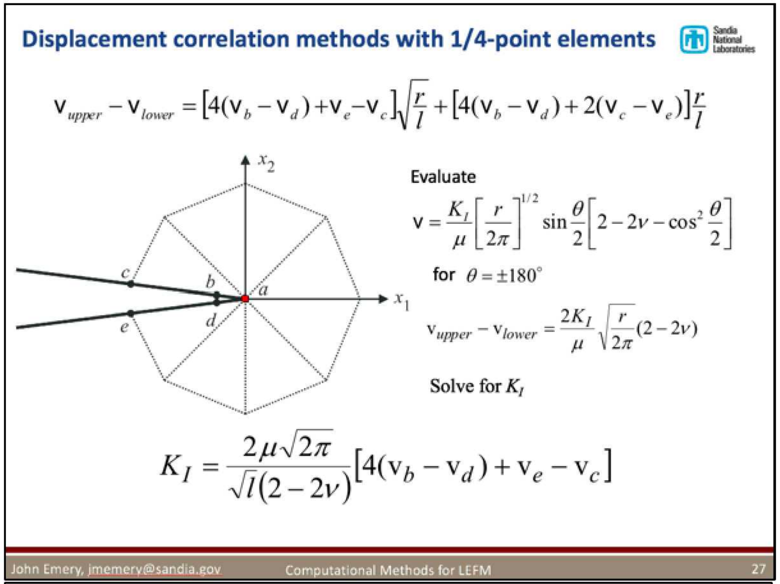
Illustration of FRANC3D mesh template placed at crack tip

SIERRA / FRANC3D

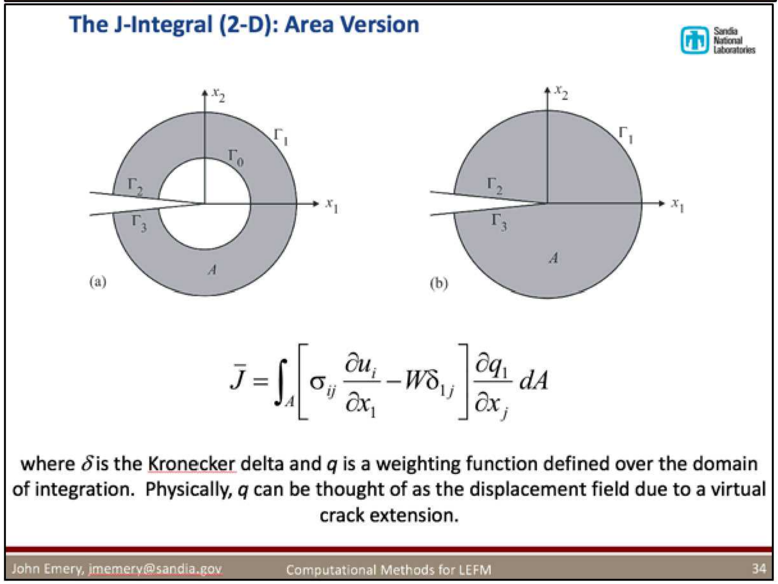
- Overview of approach:
  - Details of mesh template & SIF calculation



Option 1

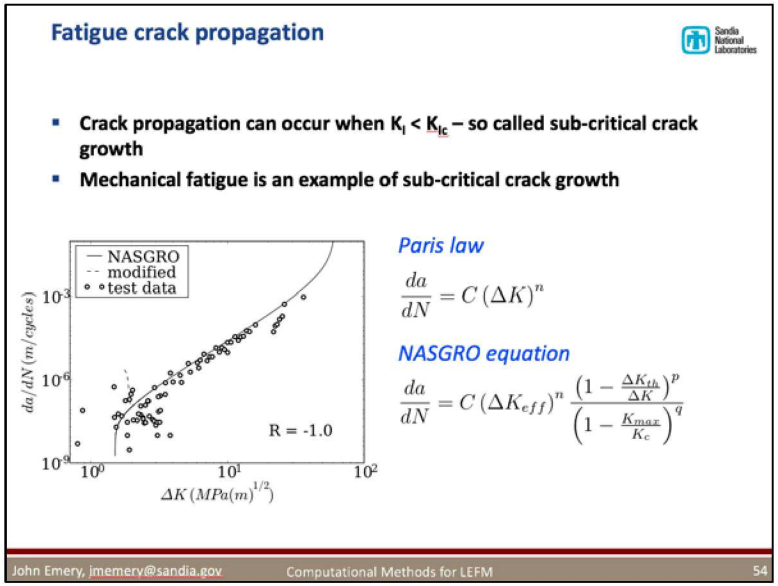


Option 2

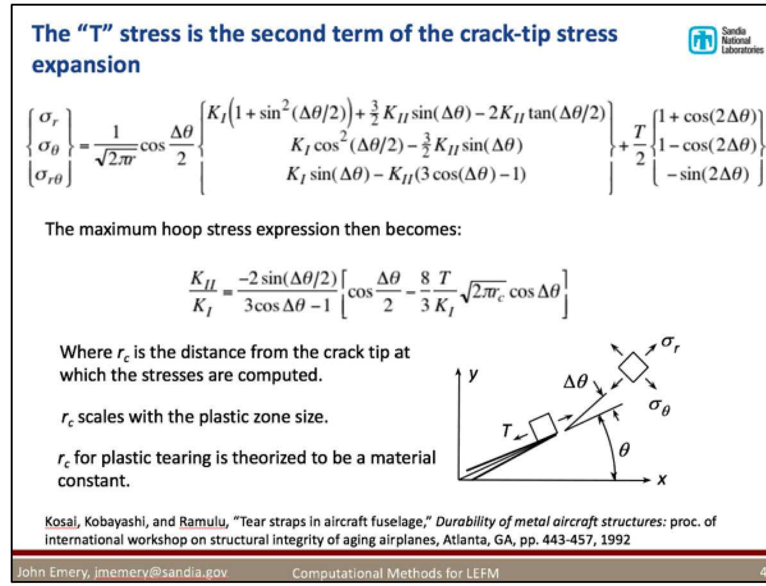


SIERRA / FRANC3D

- Overview of approach:
  - Details of crack extension & direction calculation:



Crack extension compute as fatigue crack

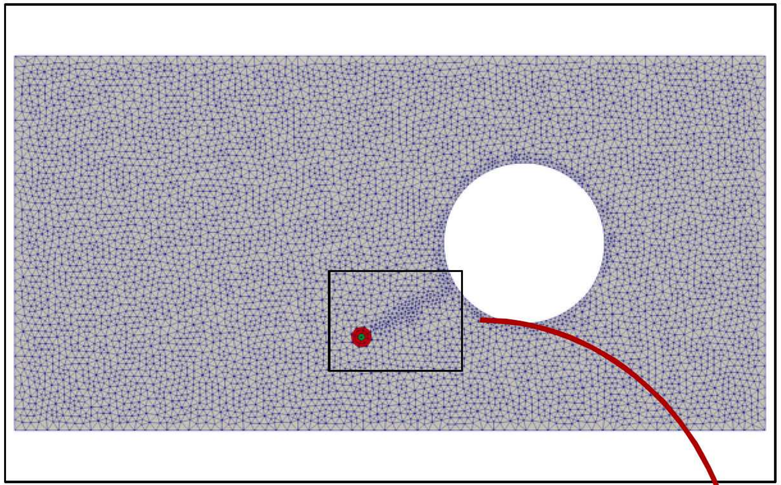


Crack direction determined by minimizing hoop stress σ_θ: $\frac{\partial \sigma_\theta}{\partial \theta} = \sigma_{r\theta} = 0$

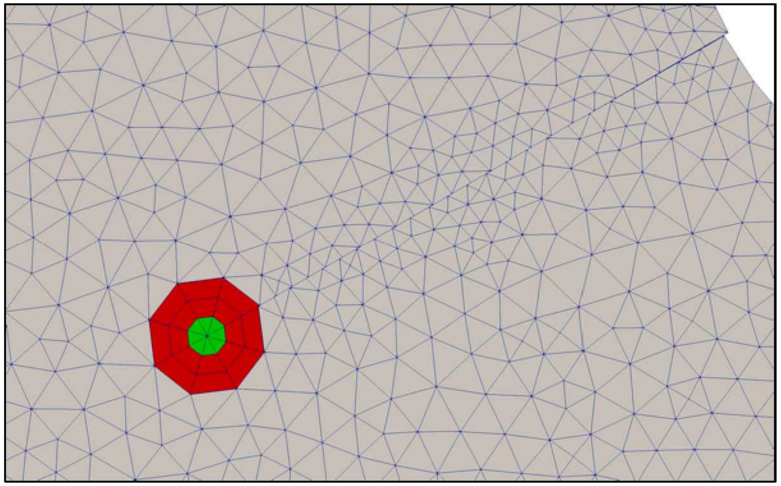
SIERRA / FRANC3D

- Strategy:
  - Geometry:
    - Nominal geometry & zero-thickness pre-crack
  - Analysis:
    - Total Lagrange quadratic Tet10 elements
    - Apply quasistatic displacement of 1 mm
    - Analyze over many steps, until crack extension becomes “sufficiently small”
    - 13 steps in this case, could go further
  - Post-Processing:
    - K_{Ic} correction:
      - σ & K_i linear functions of applied displacement
      - Assume that the crack extends at $K_I = K_{Ic}$
      - Scale simulation displacement (1 mm) by $\frac{K_{Ic}}{K_I}$ ratio to estimate actual displacement required to reach $K_I = K_{Ic}$

$$u_{actual} = \frac{K_{Ic}}{K_{I,simulation}} u_{simulation}$$



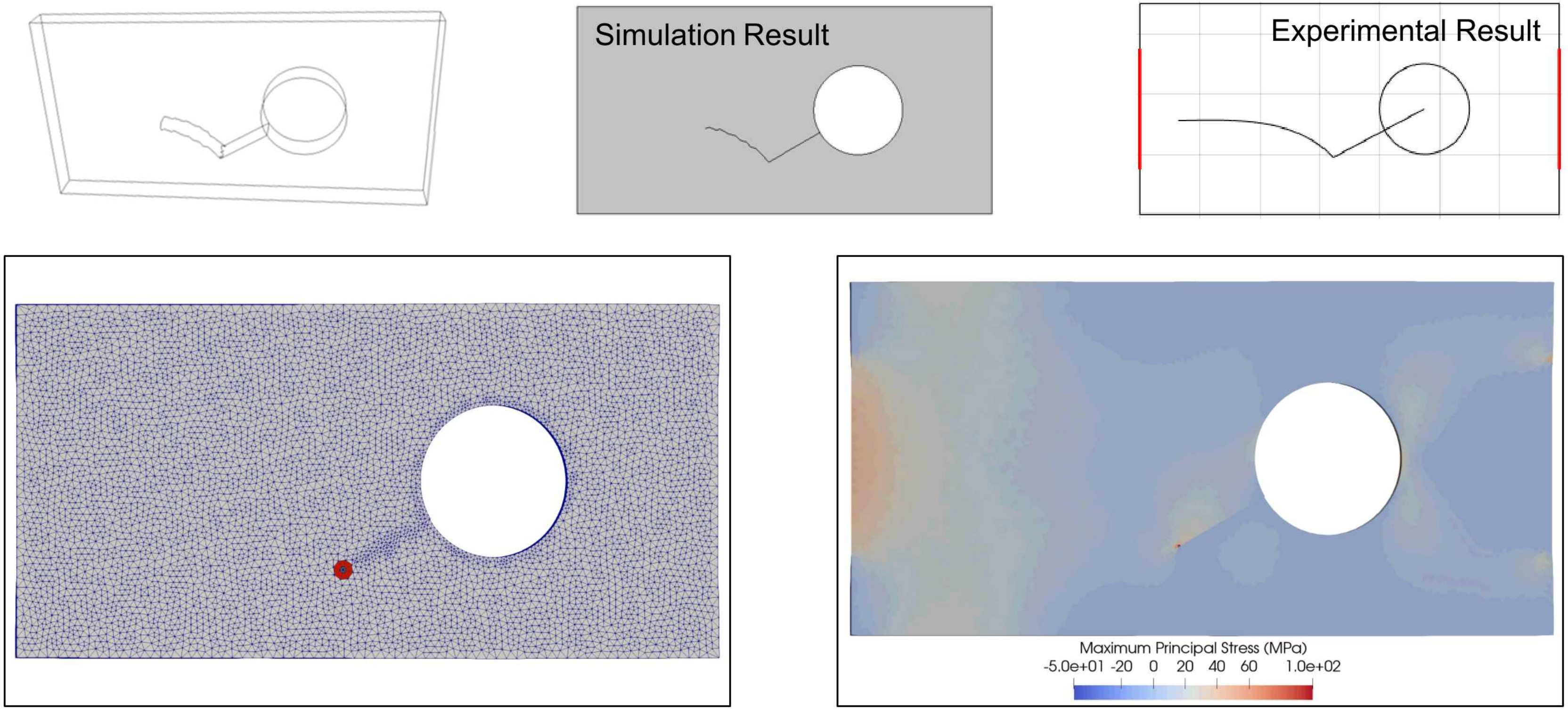
Initial Mesh – nominal geometry with zero-thickness crack



Initial Mesh – close-up of zero-thickness crack and crack tip mesh template

SIERRA / FRANC3D

- Results:



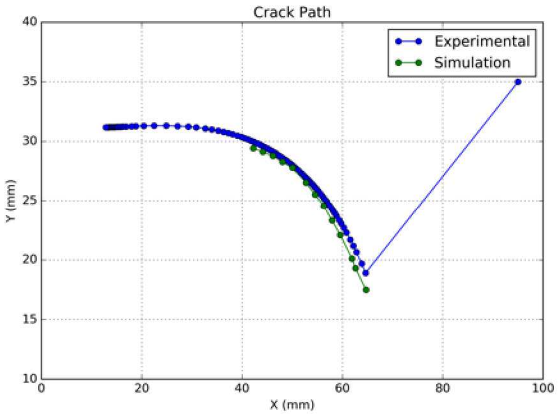
Mesh Evolution

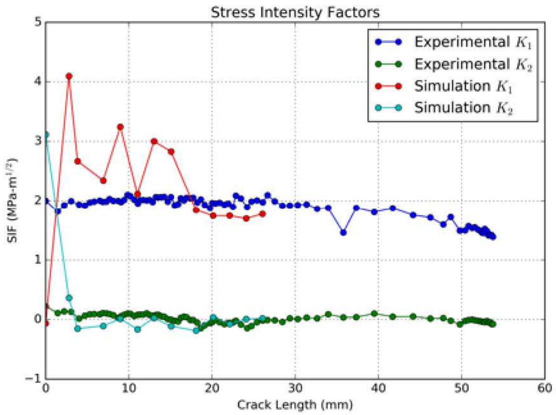
Maximum Principal Stress Evolution

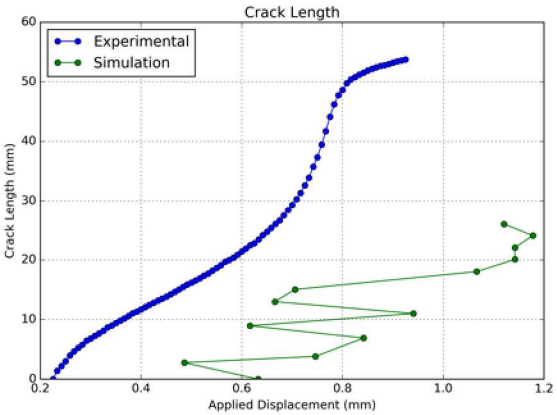
- FRANC3D does well at capturing experimental crack path
- Might get even better result with smaller steps, additional steps, and mesh refinement

SIERRA / FRANC3D

- Results:
  - Quantitative comparisons to experimental data, post-processed







*estimated using $\frac{K_{Ic}}{K_I}$ scaling

  - FRANC3D does well at capturing experimental crack path
  - Stress intensity factors are similar
  - Crack length vs. applied displacement matches less well, but this is based on post-processing ($\frac{K_{Ic}}{K_I}$ scaling)
  - Force/displacement comparison not (yet) available
  - Might get even better result with smaller steps, additional steps, and mesh refinement

Thank you!

Thanks to conference & benchmark organizers!

Andrew Stershic, PhD PE
Sandia National Laboratories
Multi-Physics Modeling & Simulation
Livermore, CA
ajsters@sandia.gov