QUEST RELIABILITY

Asset Longevity | Plant Performance

FEA-Crack Software

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March 7, 2007

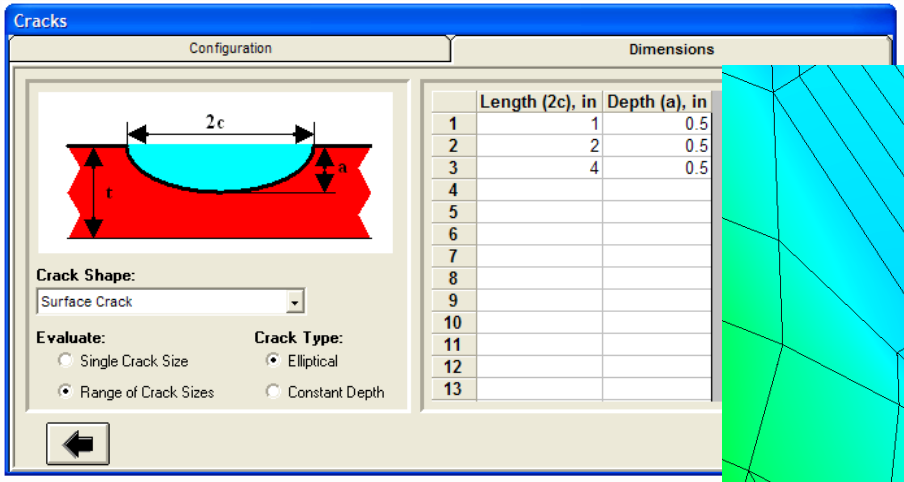
Company Overview

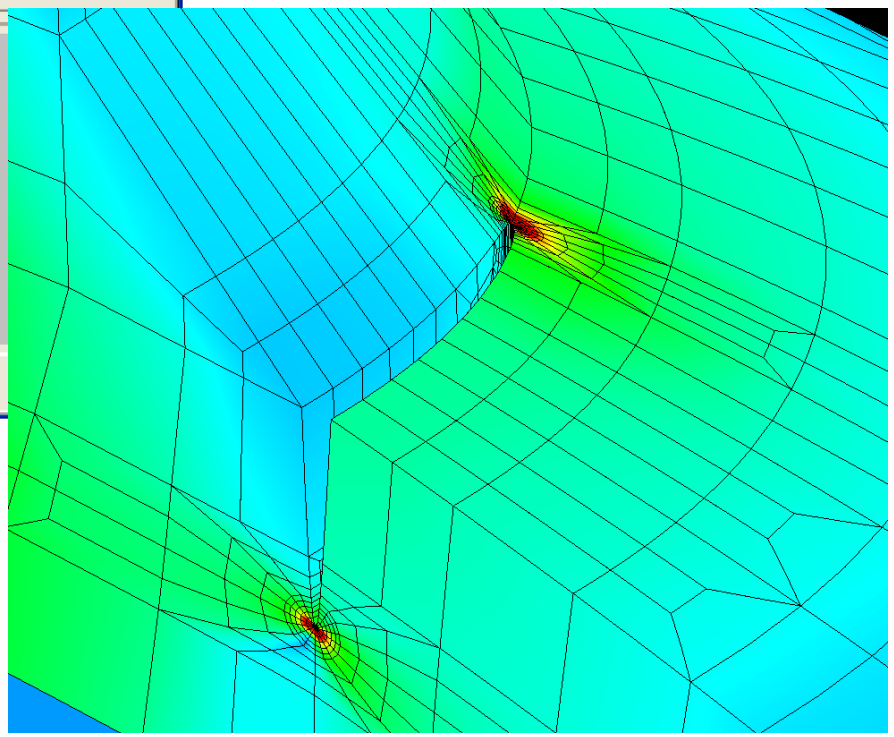
- Structural Reliability Technology (SRT) founded in 1995.
- SRT acquired by Quest Reliability, LLC on January 1, 2007.
- Approximately 50 engineers worldwide, including 15 with Ph.D. degrees.
- Office locations:
  - Boulder, CO
  - Houston, TX
  - Wellington, New Zealand
  - Brisbane, Australia

Company Overview (cont.)

- Broad range of services:
  - Fitness-for-service & fracture mechanics
  - Stress analysis
  - Failure analysis
  - Software development
- Diverse group of clients
  - Power
  - Chemical, petroleum, petrochemical
  - Pipeline
  - Rail transportation
  - Defense
  - Aerospace

FEACrack





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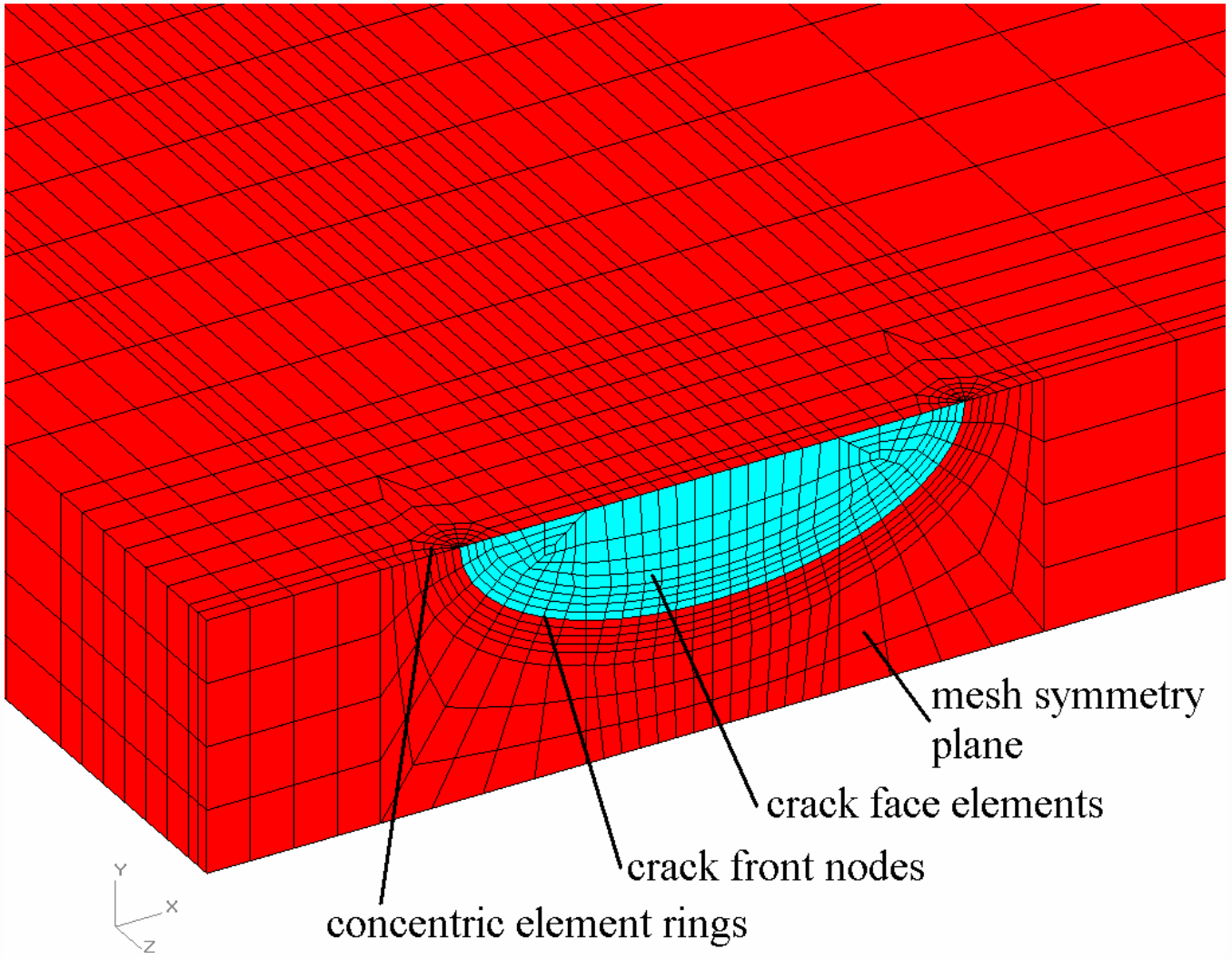
FEA-Crack Overview

- Pre- and post-processor for 3D crack problems.
- Front end to Abaqus, ANSYS, and Warp3D.
- Drop-down list of component/geometry choices (20 & counting).
- User-defined geometry option for cases not covered in list.
- Crack growth modeling
  - Re-meshing
  - Element deletion
  - Node release
  - Cohesive elements

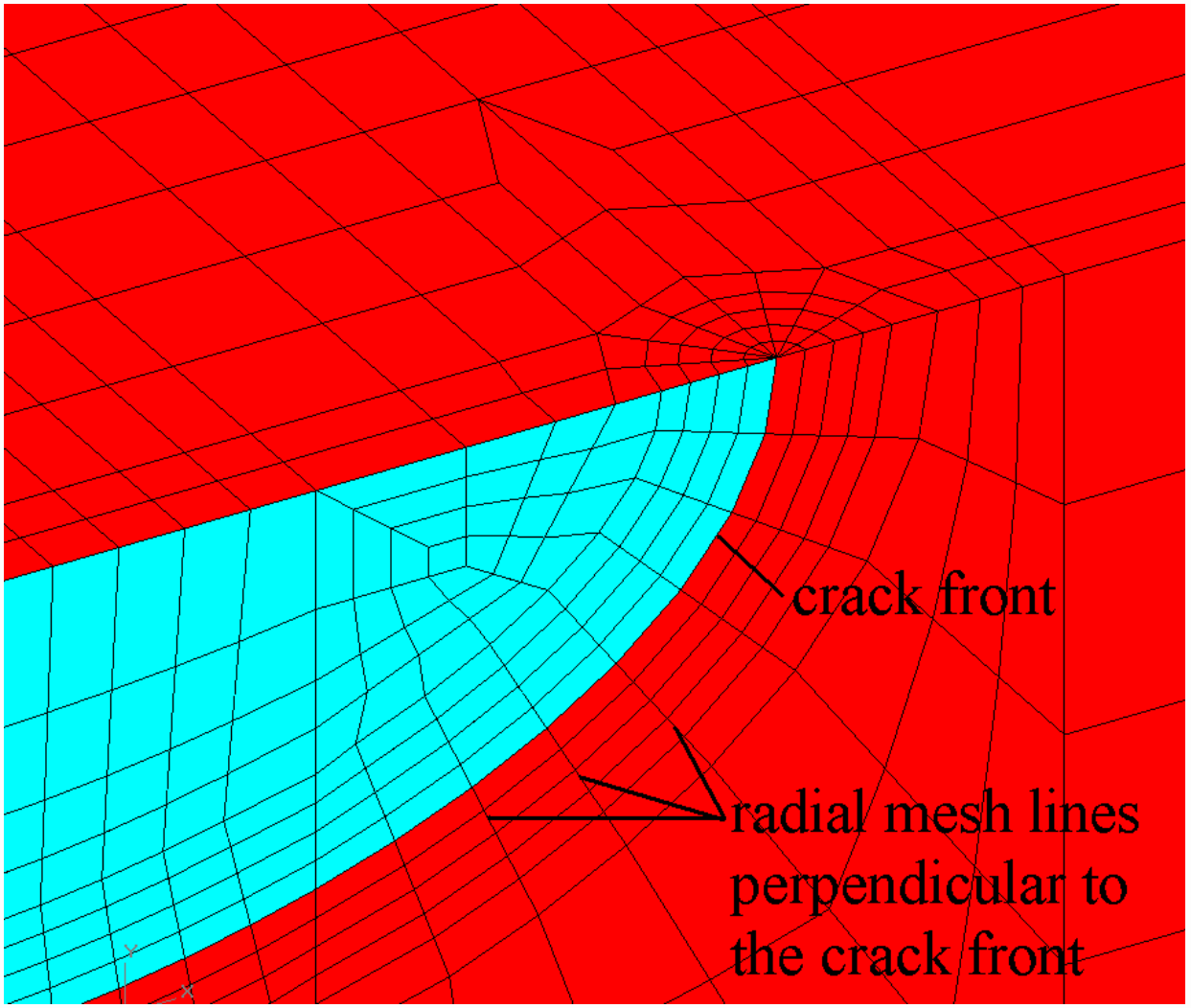
Partial List of FEA-Crack Customers

- NASA Marshall Space Flight Center
- Los Alamos National Laboratory
- ExxonMobil
- Shell
- BP
- Chevron
- Westinghouse
- Southwest Research Institute
- Rolls Royce
- Boeing
- Dominion Engineering

Crack Meshing



Crack Tip Region



FEACrack

File Edit View Tools Navigate Window Help

Main

Home

Geometry

Boundary Conditions

Material Properties

Build Mesh

Run FEA

FEA Results

Geometry

Configuration

Dimensions

Crack

C:\Program Files\SRT\FEACrack\Examples\Nozzle\nozzle.elt

View Type:

Isometric

Rotation:

X Axis 30

Y Axis 30

Z Axis 0

Free Rotate

Zoom:

Fit to Window

Zoom In

Zoom Out

Custom Zoom...

22267 Nodes
4662 Elements

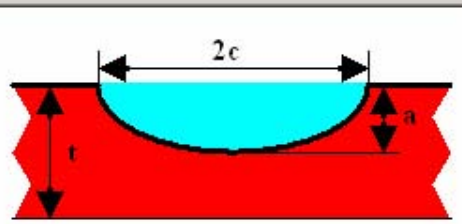
Displacement Scale:

Result Type:

No Results

Cracks

Configuration | **Dimensions**



Crack Shape:

Surface Crack

Evaluate:

- Single Crack Size
- Range of Crack Sizes

Crack Type:

- Eliptical
- Constant Depth

	Length (2c), in	Depth (a), in
1	1	0.4
2	2	0.4
3	4	0.4
4	6	0.4
5	8	0.4
6	1	0.6
7	2	0.6
8	4	0.6
9	6	0.6
10	8	0.6
11		
12		
13		

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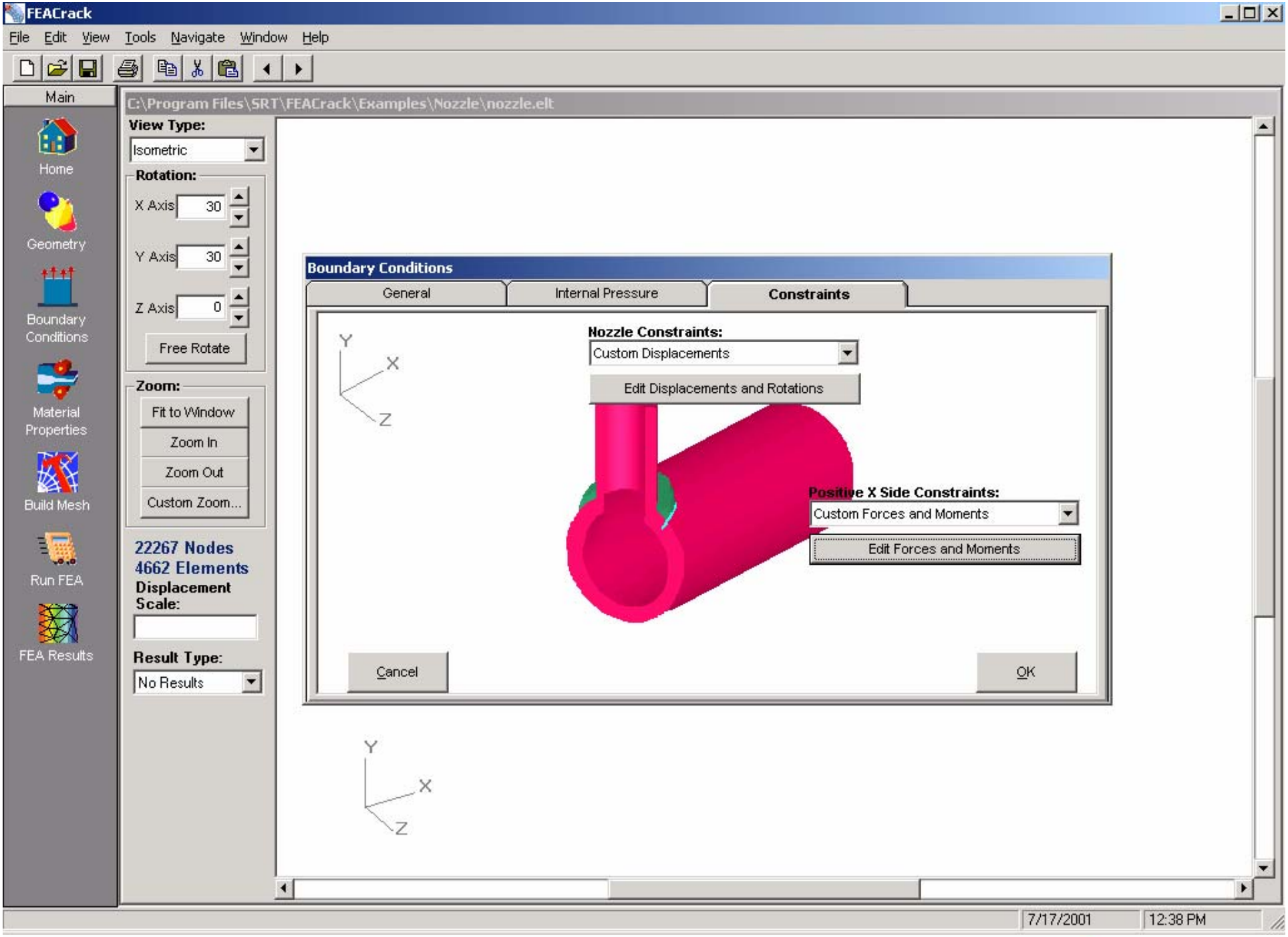
FEACrack
File Edit View Tools Navigate Window Help
Main
Home
Geometry
Boundary Conditions
Material Properties
Build Mesh
Run FEA
FEA Results
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View Type:
Isometric
Rotation:
X Axis 30
Y Axis 30
Z Axis 0
Free Rotate
Zoom:
Fit to Window
Zoom In
Zoom Out
Custom Zoom...
22267 Nodes
4662 Elements
Displacement Scale:
Result Type:
No Results
Boundary Conditions
General
Internal Pressure
Constraints
Nozzle Constraints:
Custom Displacements
Edit Displacements and Rotations
Positive X Side Constraints:
Custom Forces and Moments
Edit Forces and Moments
Cancel
OK
Y
X
Z
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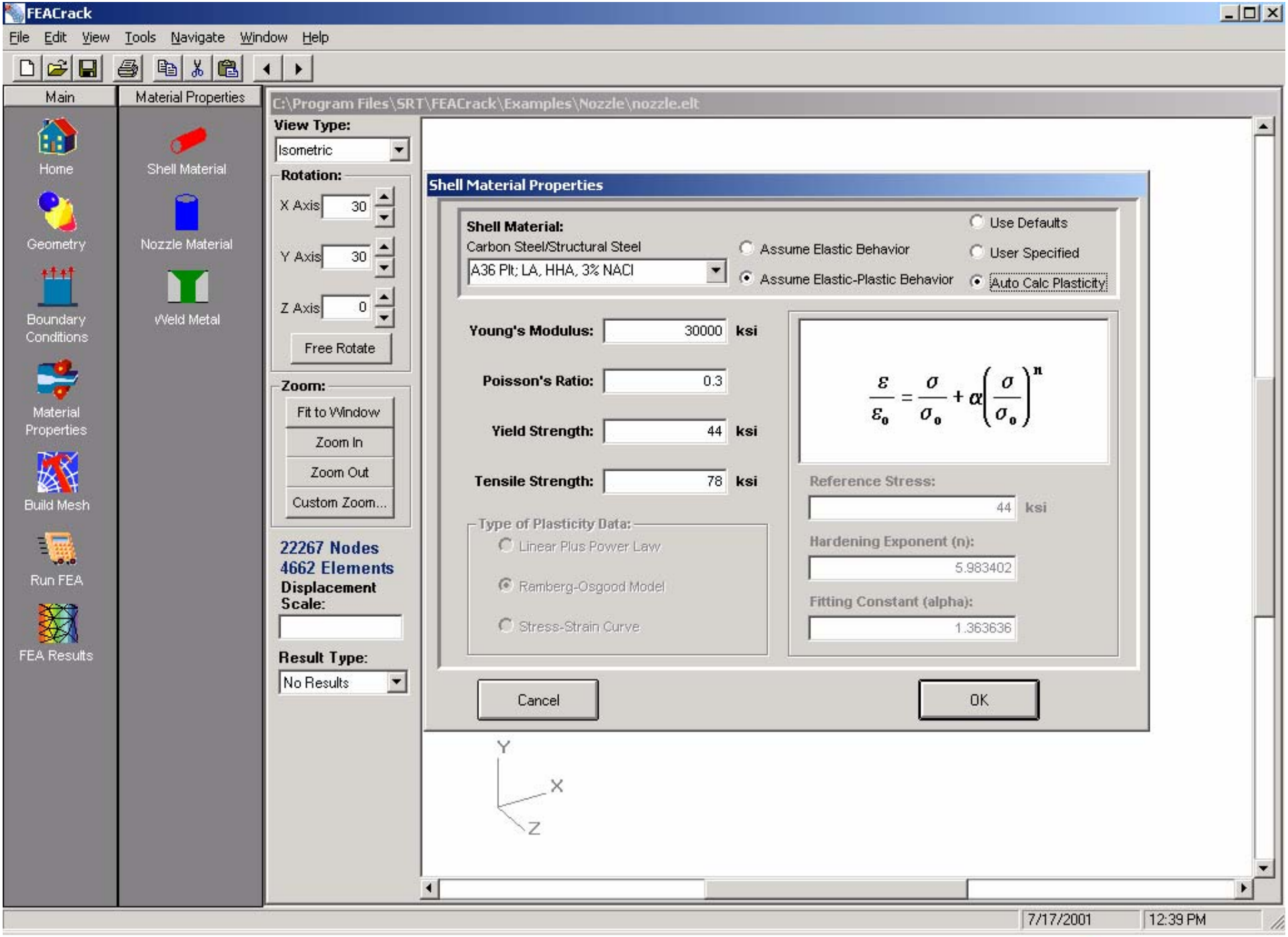
FEACrack
File Edit View Tools Navigate Window Help
Main
Material Properties
Home
Geometry
Boundary Conditions
Material Properties
Build Mesh
Run FEA
FEA Results
Shell Material
Nozzle Material
Weld Metal
C:\Program Files\SRT\FEACrack\Examples\Nozzle\nozzle.elt
View Type:
Isometric
Rotation:
X Axis 30
Y Axis 30
Z Axis 0
Free Rotate
Zoom:
Fit to Window
Zoom In
Zoom Out
Custom Zoom...
22267 Nodes
4662 Elements
Displacement Scale:
Result Type:
No Results
Shell Material Properties
Shell Material:
Carbon Steel/Structural Steel
A36 Plt; LA, HHA, 3% NACl
Assume Elastic Behavior
Assume Elastic-Plastic Behavior
Use Defaults
User Specified
Auto Calc Plasticity
Young's Modulus: 30000 ksi
Poisson's Ratio: 0.3
Yield Strength: 44 ksi
Tensile Strength: 78 ksi
Type of Plasticity Data:
Linear Plus Power Law
Ramberg-Osgood Model
Stress-Strain Curve
Reference Stress: 44 ksi
Hardening Exponent (n): 5.983402
Fitting Constant (alpha): 1.363636
Cancel
OK
Y
X
Z
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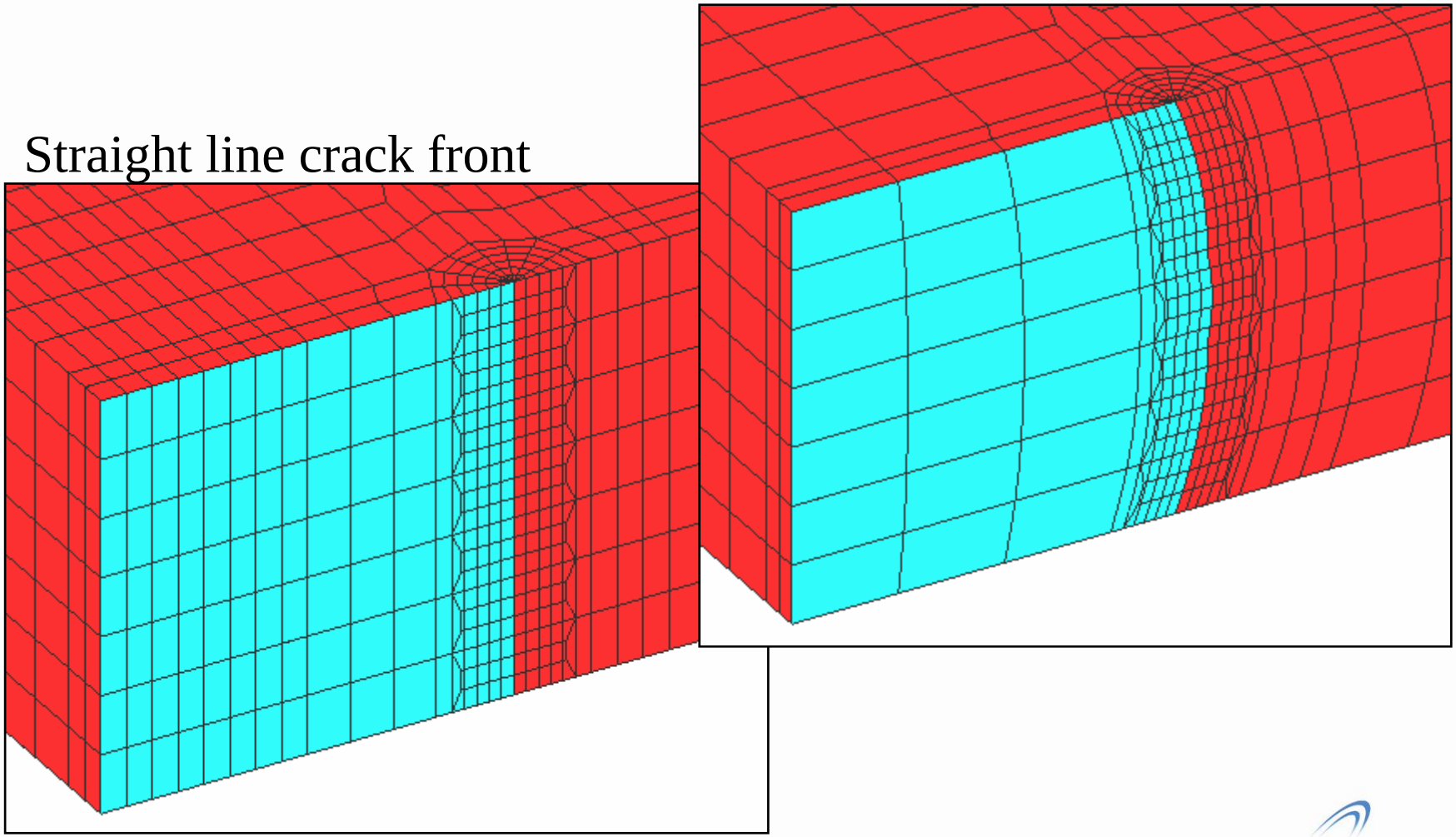
Crack Front Profile

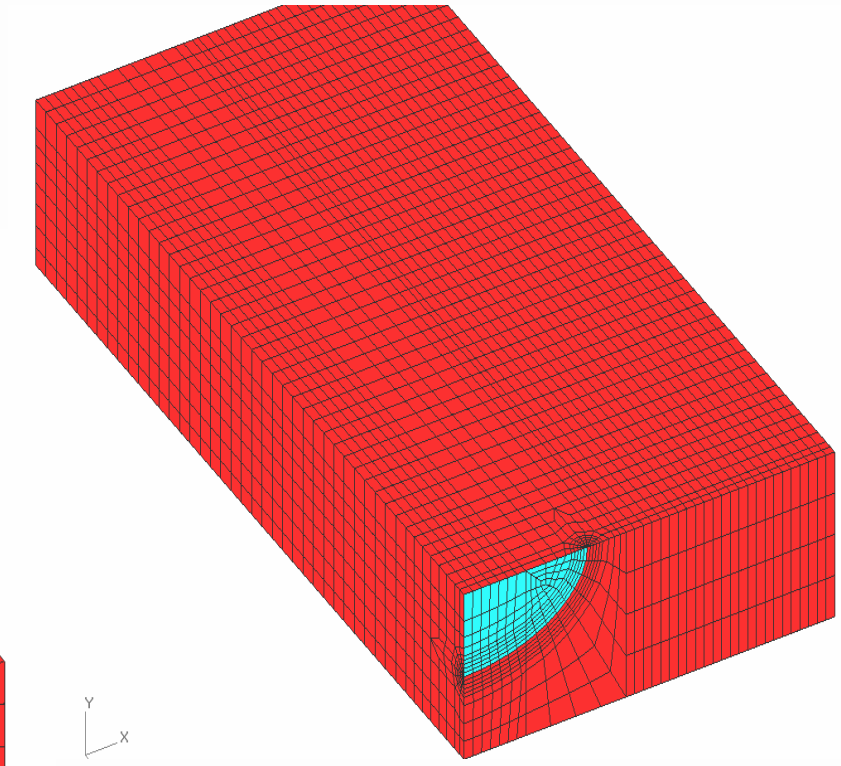
“Thumbnail” custom crack front

Straight line crack front

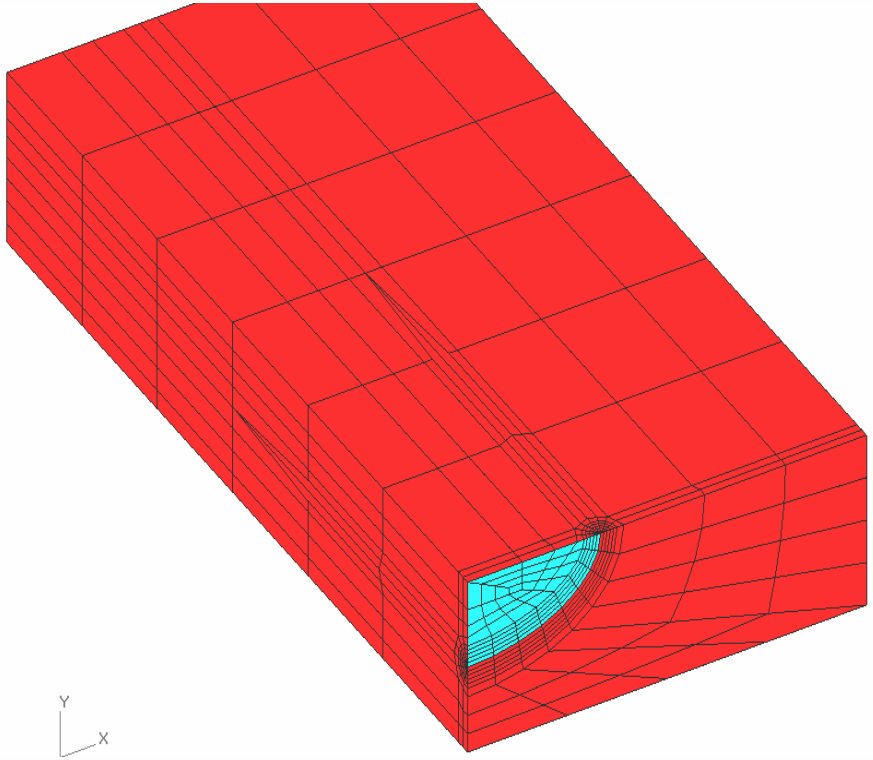


Meshing Controls

Refined Mesh



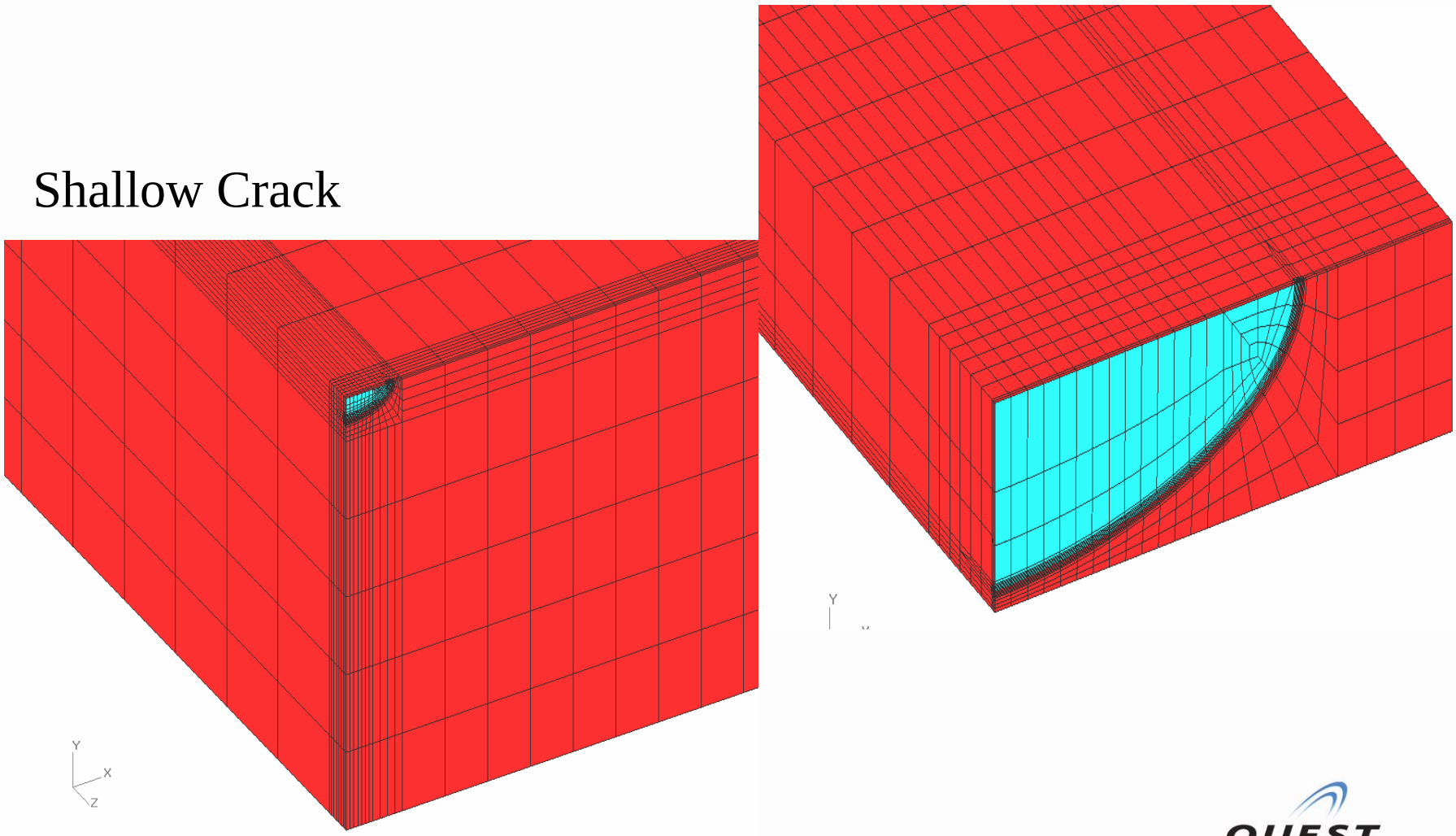
Coarse mesh



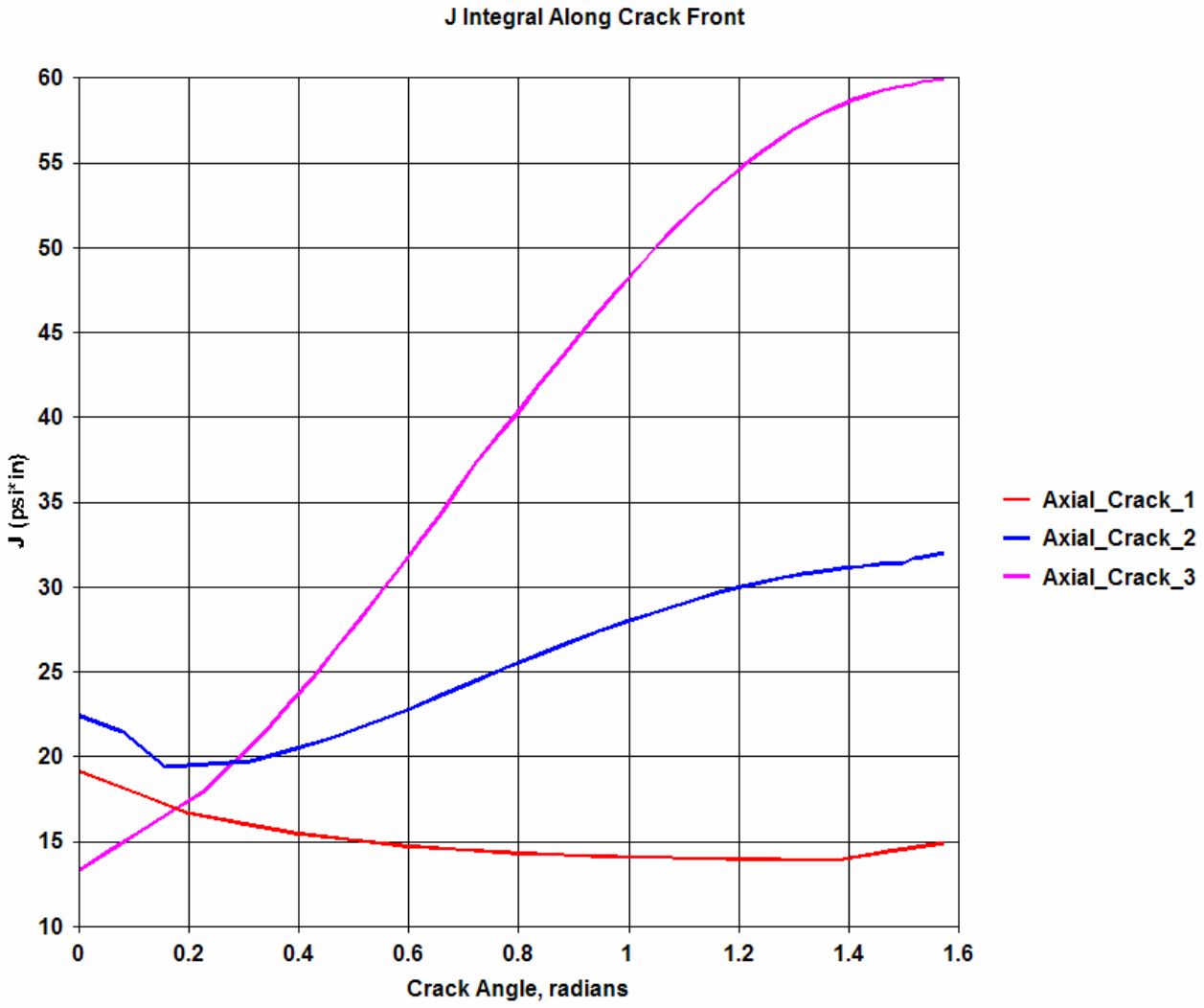
Variable Crack Dimensions

Deep Crack

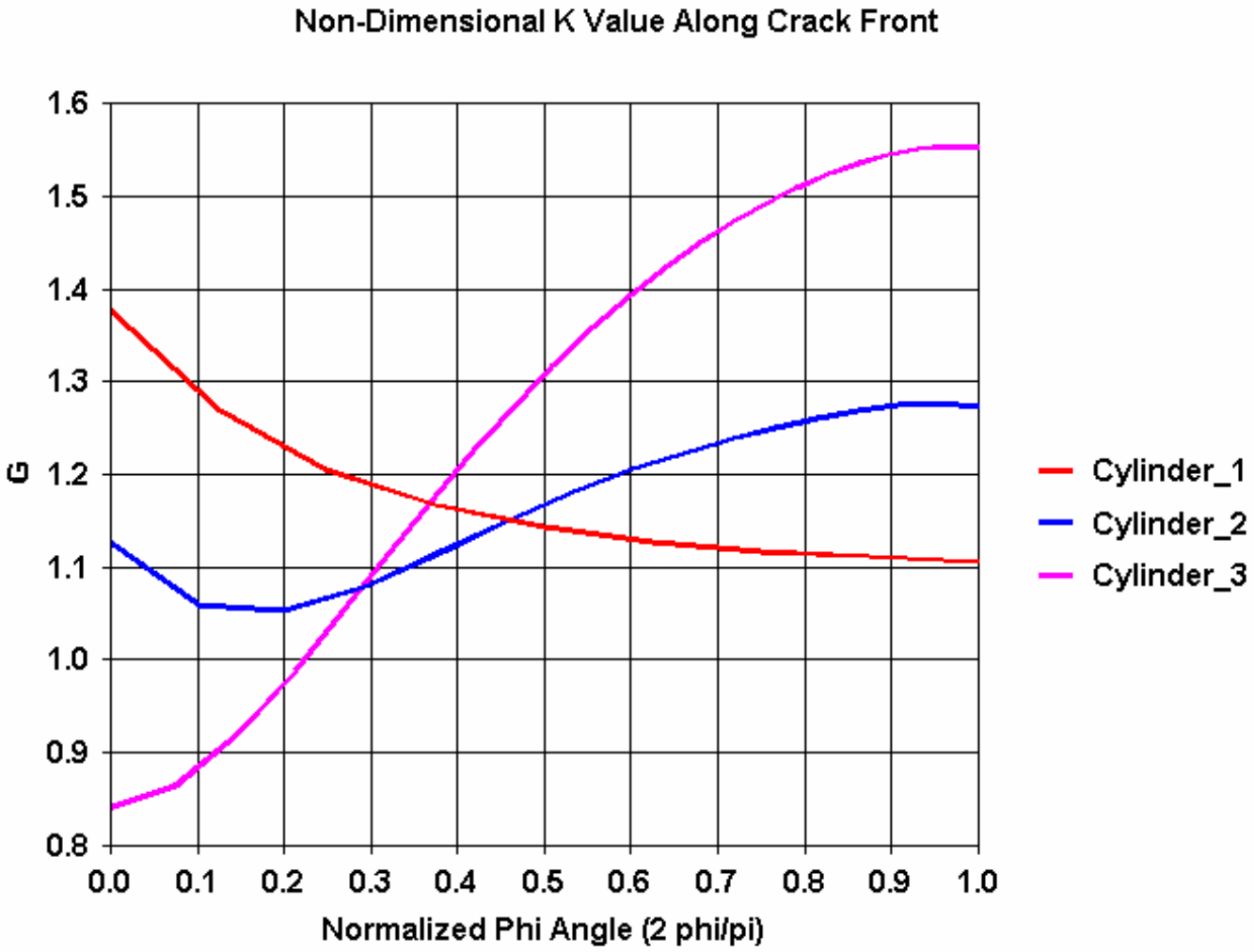
Shallow Crack



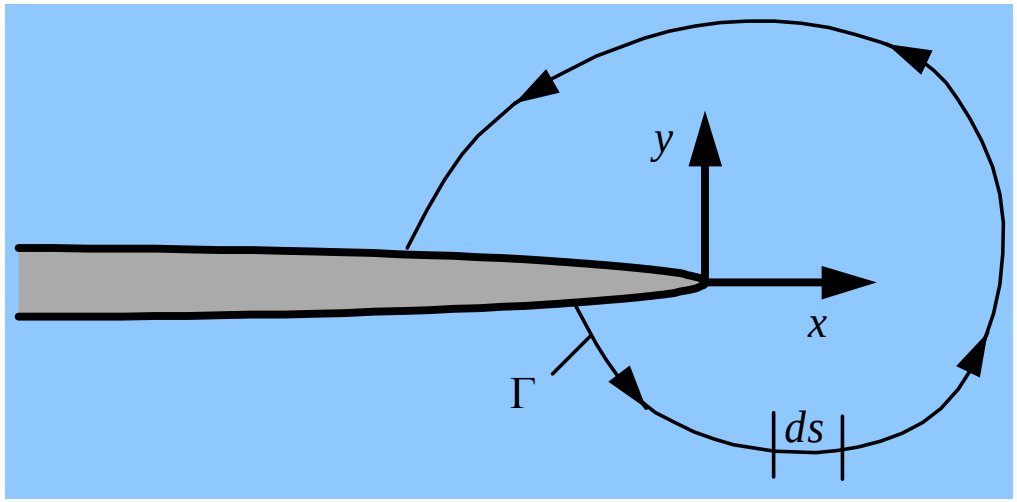
Post Processing
J-Integral Plot



Post Processing
Stress Intensity Results



The J-Integral
Path-Independent Line Integral



$$J = \int_{\Gamma} \left(w dy - T_i \frac{\partial u_i}{\partial x} ds \right)$$

Where Γ is an arbitrary counter-clockwise path around the crack tip and:

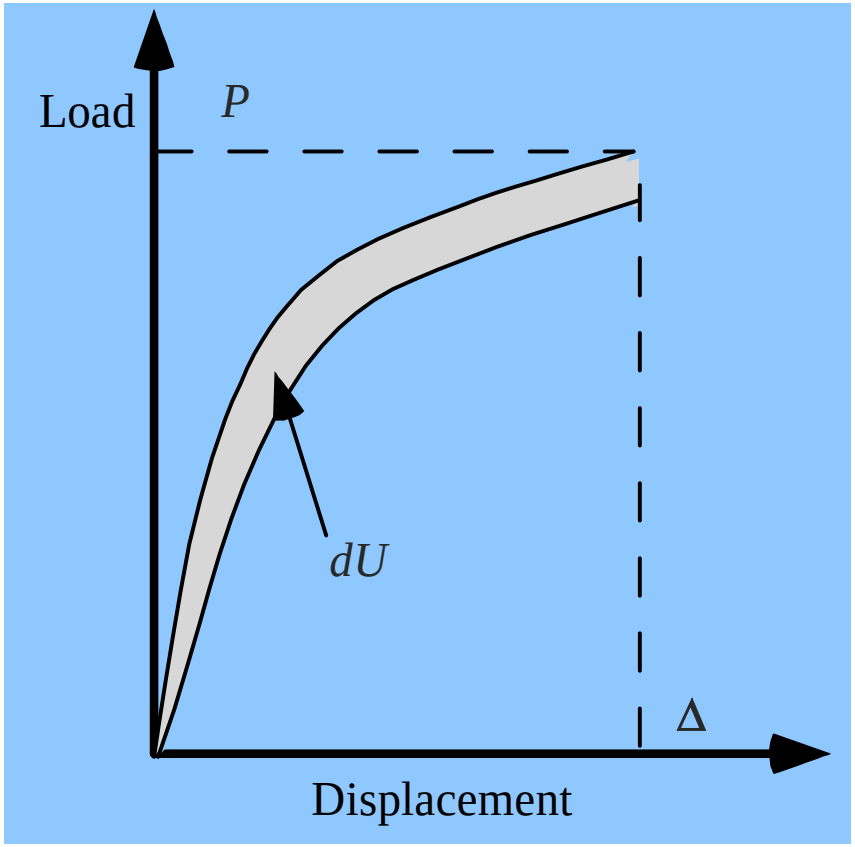
$$w = \int_0^{\varepsilon_{ij}} \sigma_{ij} d\varepsilon_{ij}$$

$$T_i = \sigma_{ij} n_j$$

For 2D problems, the line integral can be converted to an area integral for evaluation with finite element analysis.

In 3D, a surface integral is converted to a volume integral.

The J-Integral
Nonlinear Energy Release Rate



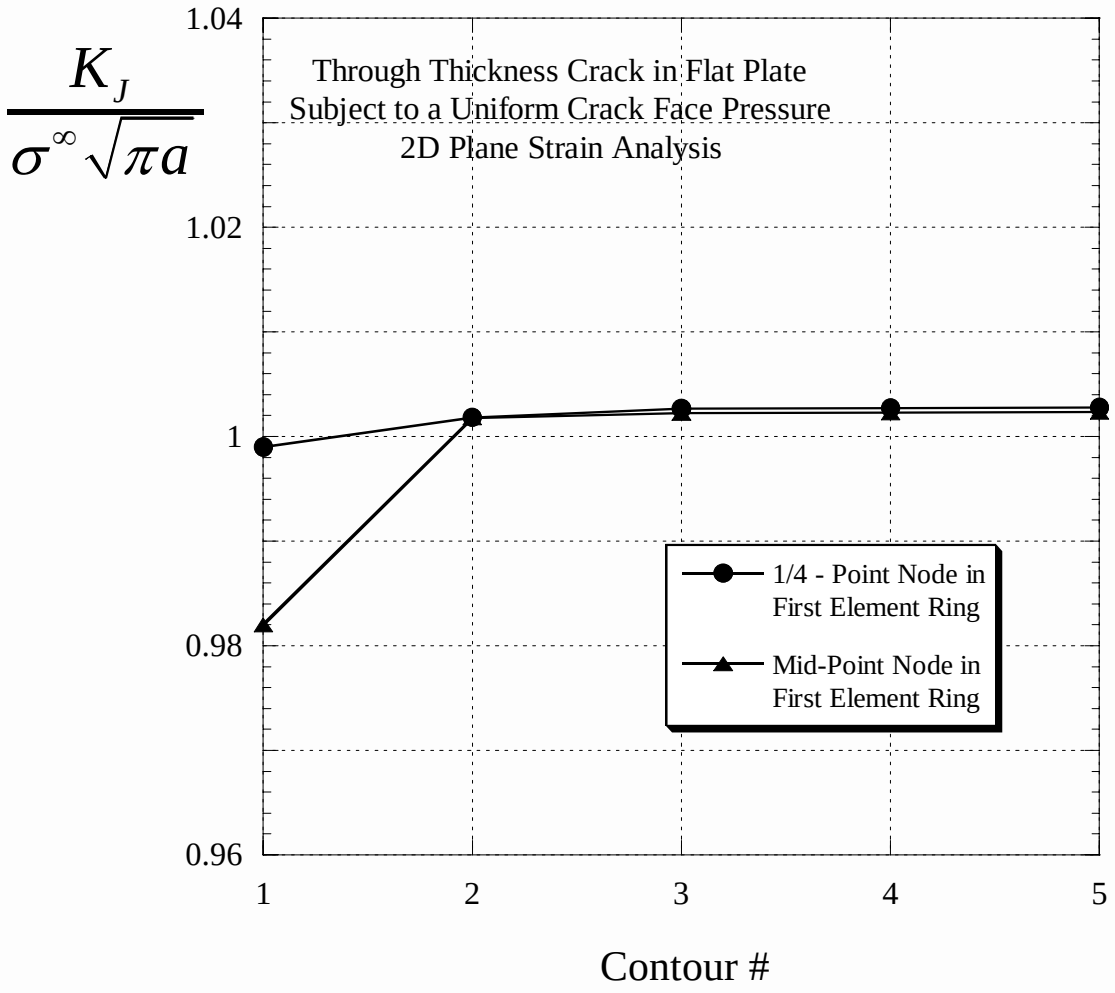
$$J = -\frac{1}{B}\left(\frac{dU}{da}\right)_{\Delta}$$

In the limit of linear elastic material behavior, $J = \mathcal{G}$ and:

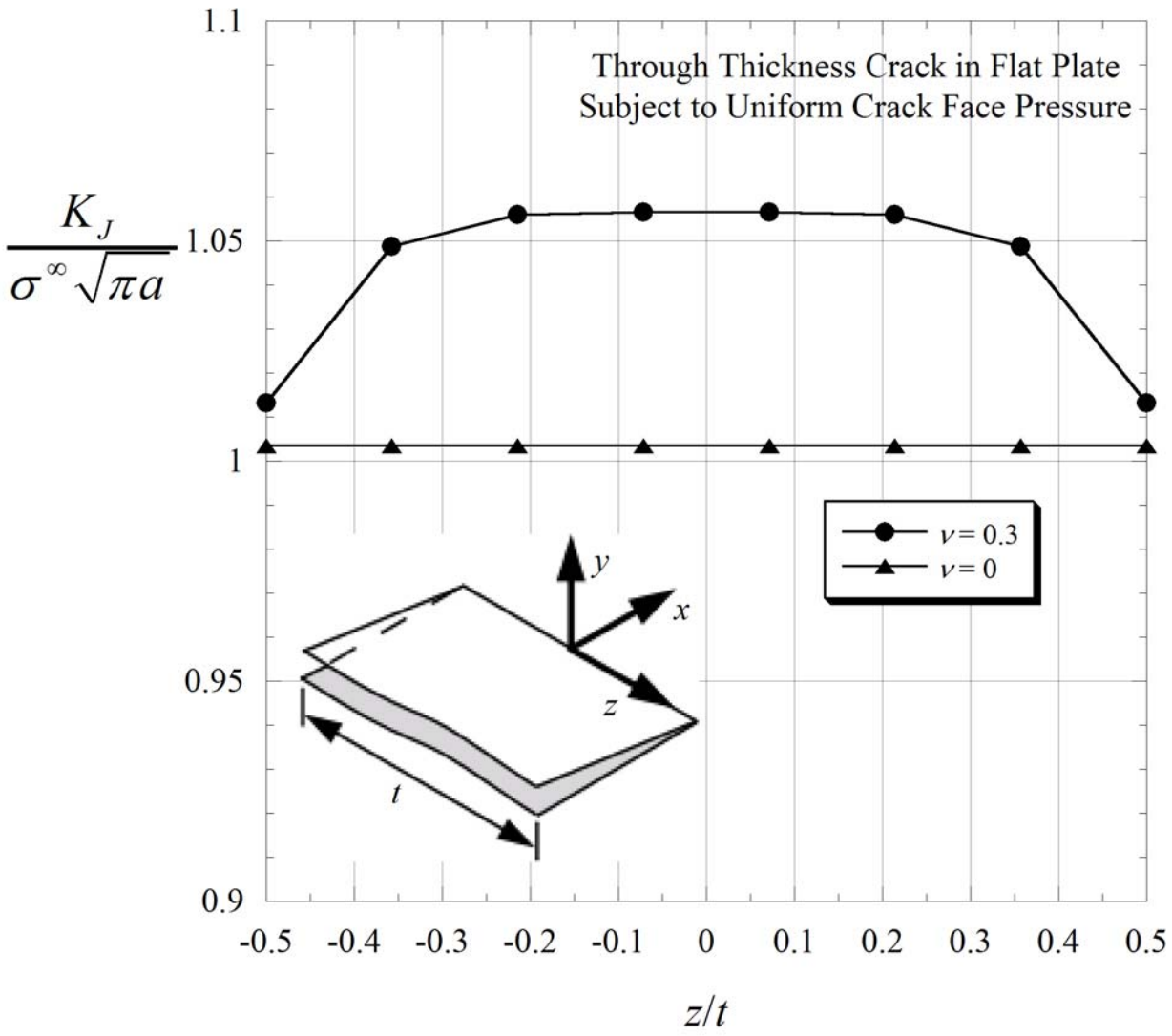
$$J = \frac{K_I\left(1-\nu^2\right)}{E}$$

assuming plane strain conditions.

K_I from J Example 1
Griffith Plate

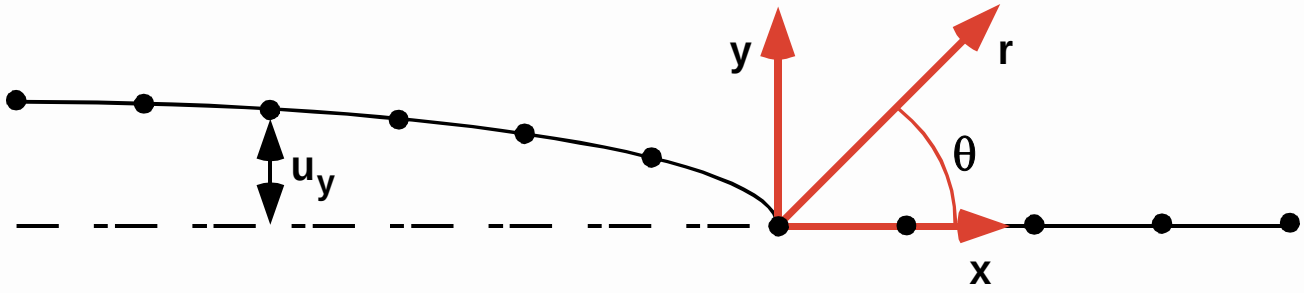


K_I from J Example 2
3D Griffith Plate



K_I from Crack Opening Displacement

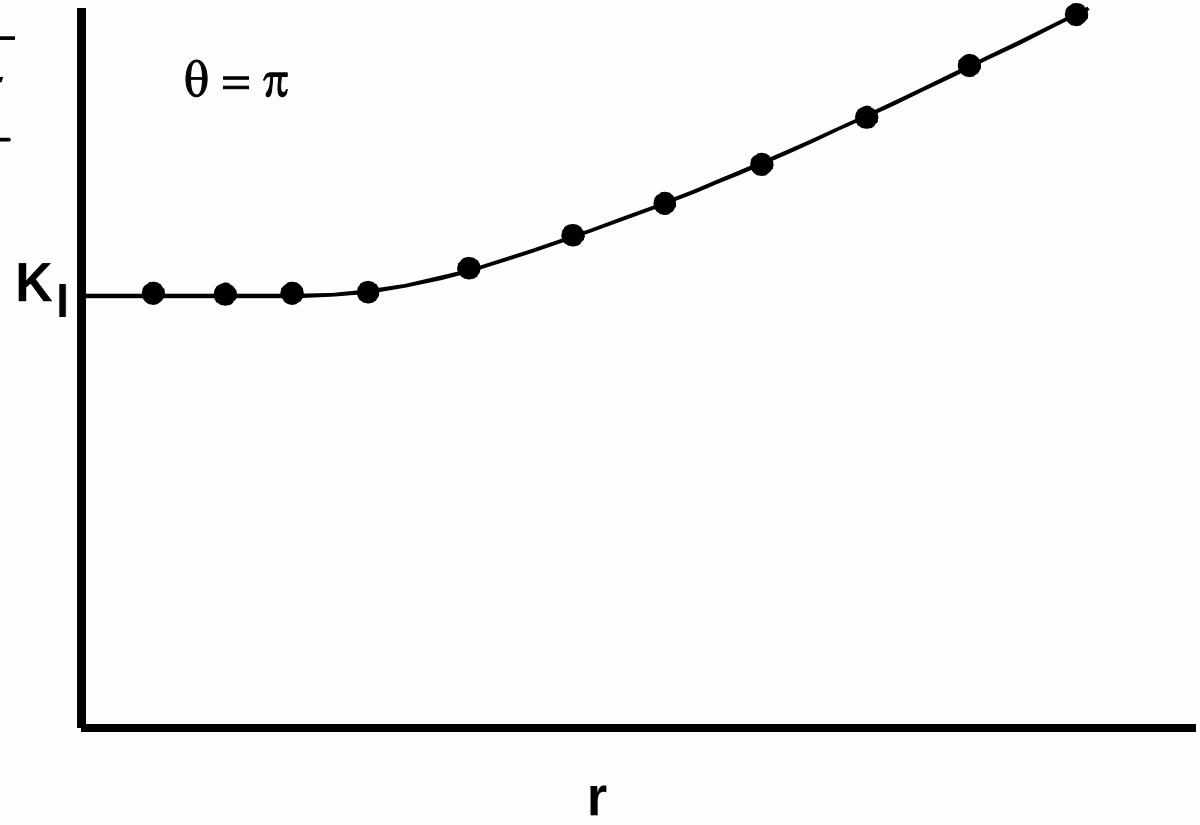
$$K_I = \frac{E}{1-\nu^2} \lim_{r \to 0} \left[u_y \sqrt{\frac{2\pi}{r}} \right] \qquad (\theta = \pi)$$



- Similar expressions exist for Modes II and II

Displacement Extrapolation

$$\frac{Eu_y}{1-\nu^2}\sqrt{\frac{2\pi}{r}}$$



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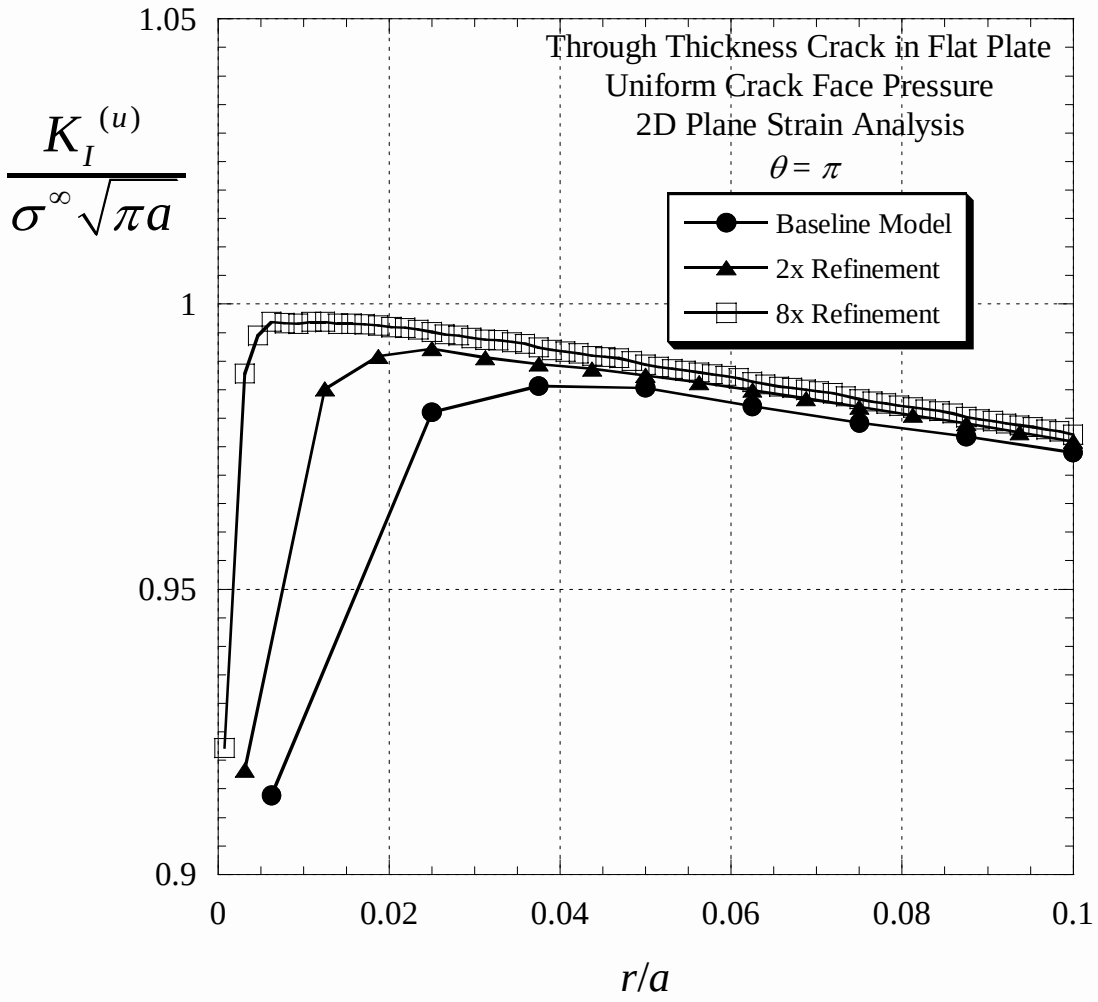
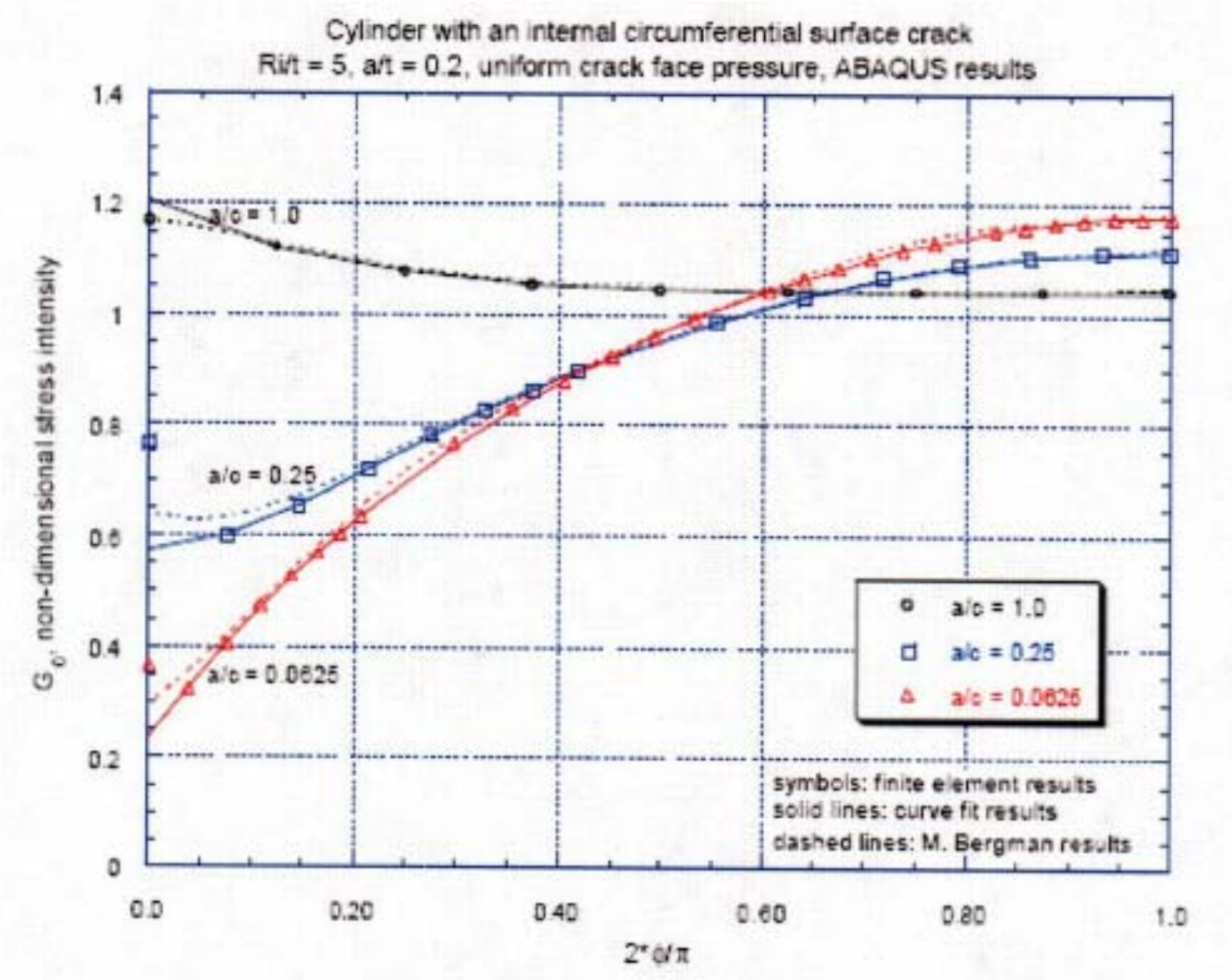
Displacement Method Example
Griffith Plate



FEA-Crack Validation Methods

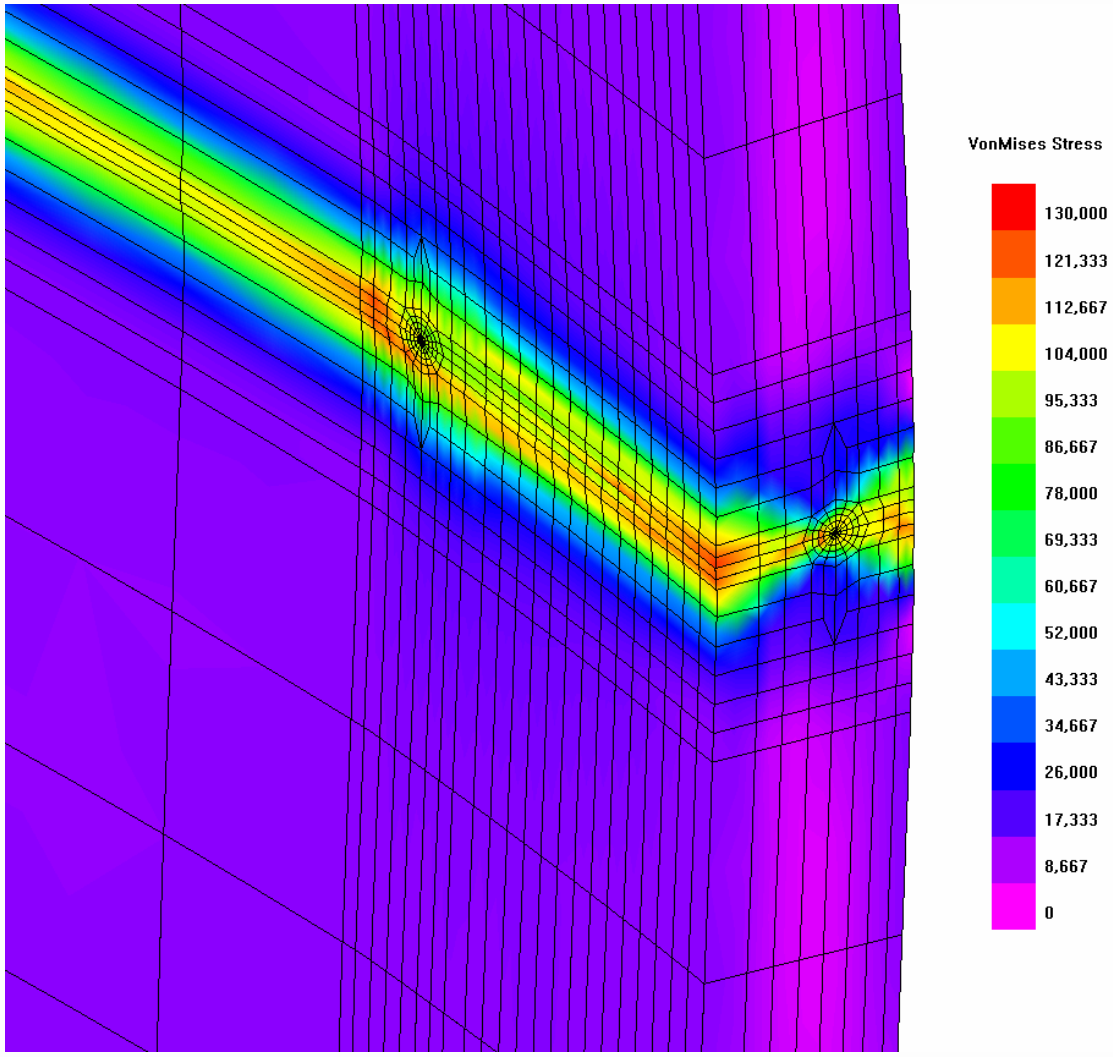
- Compare results to known cases (e.g. buried crack in infinite solid).
- Compare results from 2 different methods (e.g. K from J versus K from displacement).
- Compare results with published solutions.
- Compare results from different finite element solvers (e.g. Abaqus versus ANSYS).
- Perform mesh refinement convergence study.

Benchmark Example

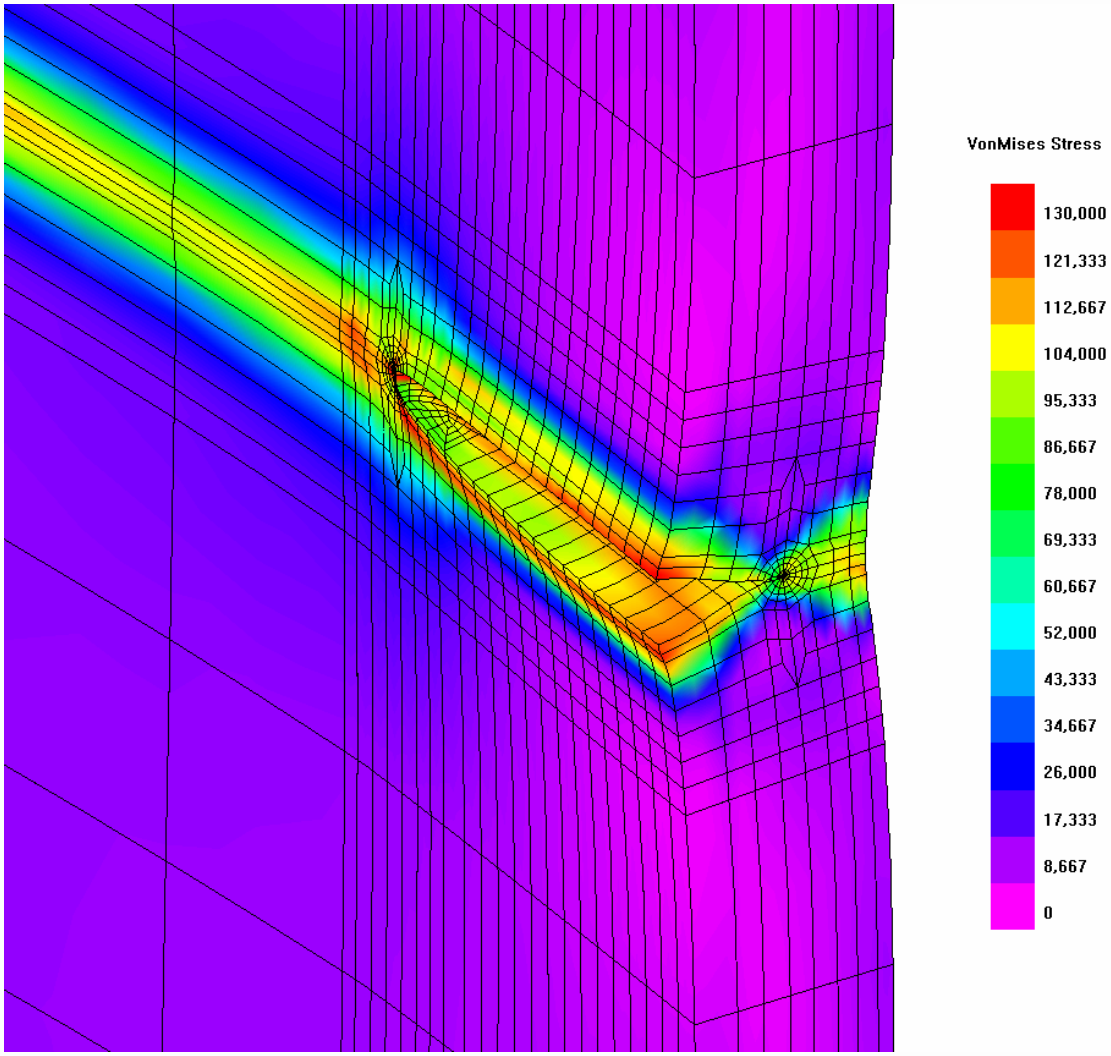


Incorporation of Weld Residual Stresses

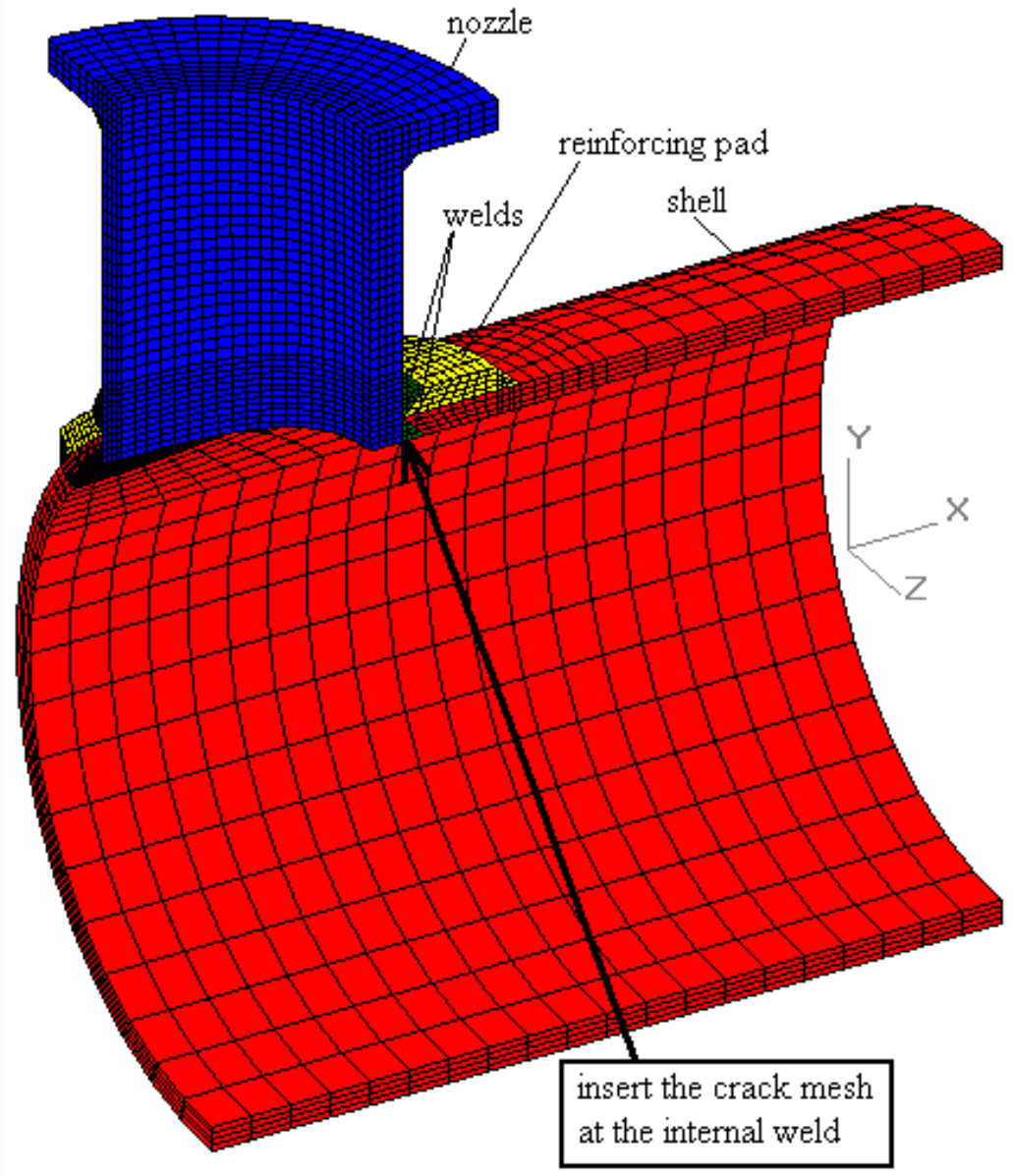
Map Residual Stresses with Crack Closed



Incorporating Weld Residual Stresses
Allow Crack to Open

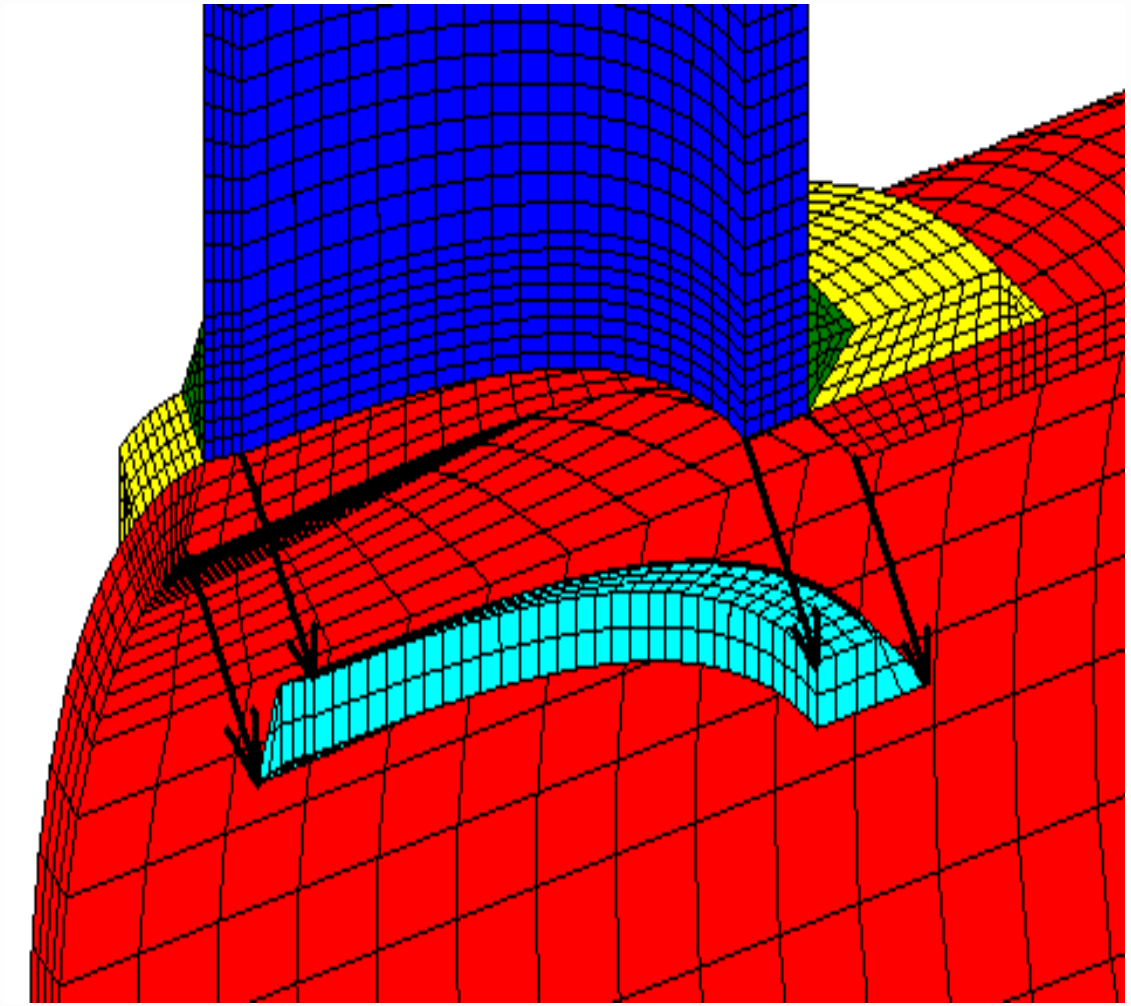


User-Defined Geometry
Initial Uncracked Mesh



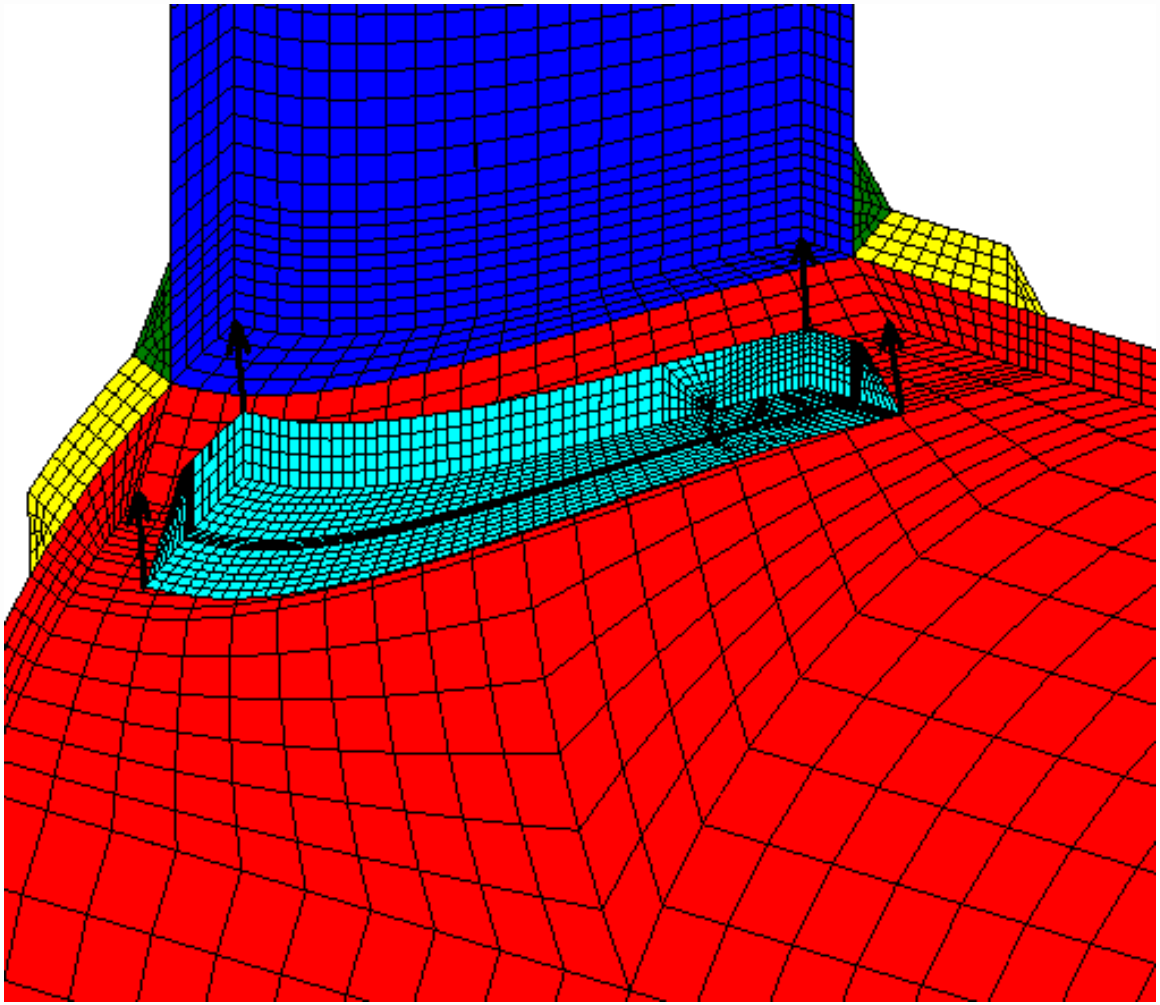
User-Defined Geometry

Remove 6-Sided Primitive

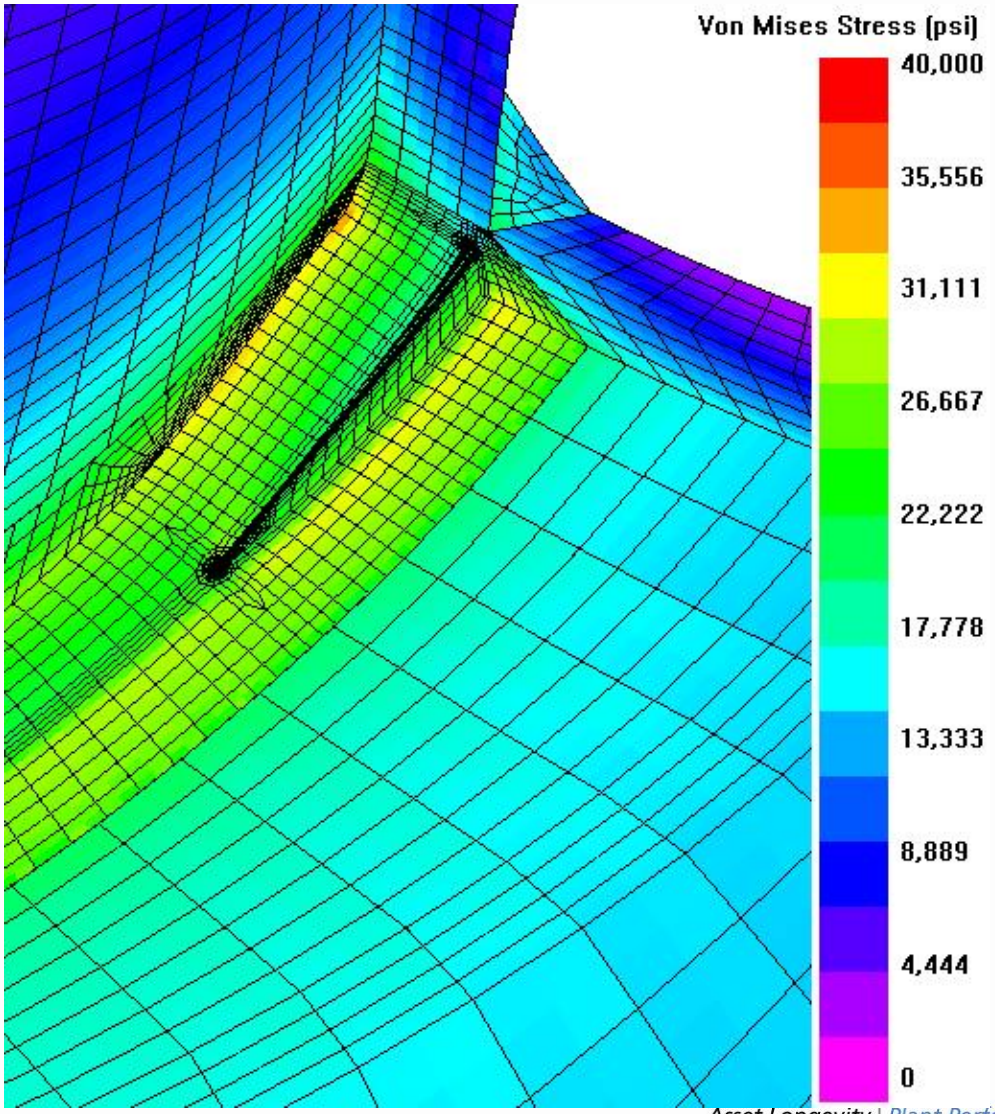


User-Defined Geometry

Insert New 6-Sided Primitive with Crack



User-Defined Geometry
FEA Results



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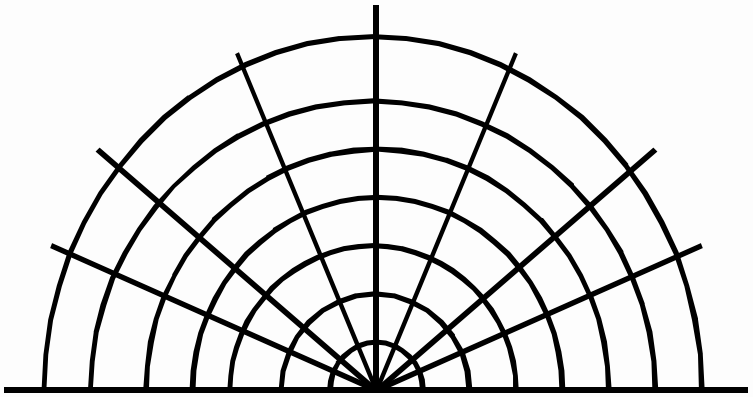
Crack Growth in a Finite Element Model

Examples of Available Methods

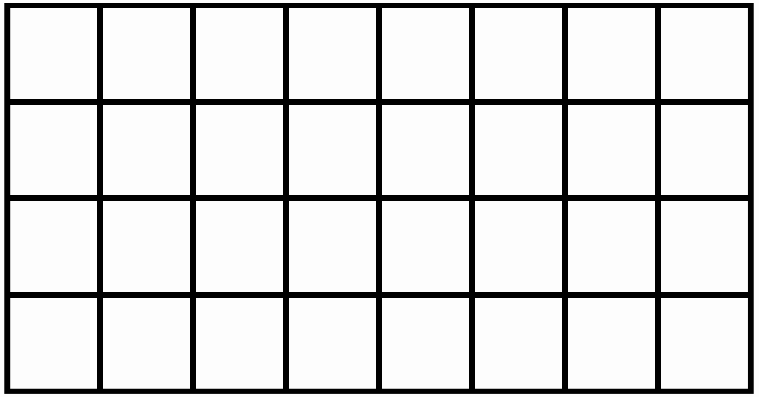
- Re-Meshing (Elastic Only)
- Element Deletion (e.g. Gurson-Tvergaard Plasticity)
- Node Release
- Cohesive Elements

Crack Growth in a Finite Element Model

Mesh Types



- Focused Mesh
  - Remeshing



- Cell Mesh
  - Element Deletion
  - Node Release
  - Cohesive Elements

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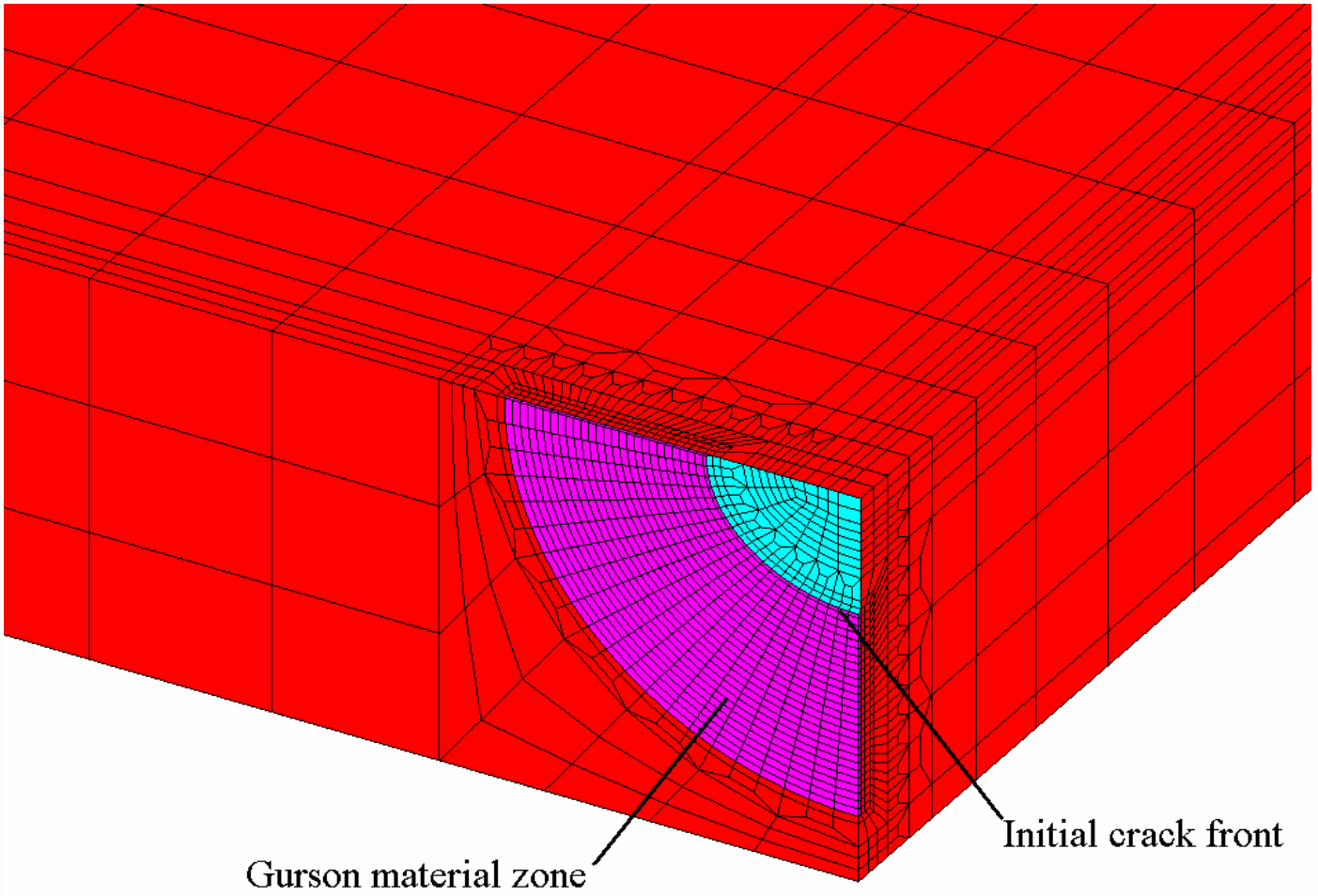
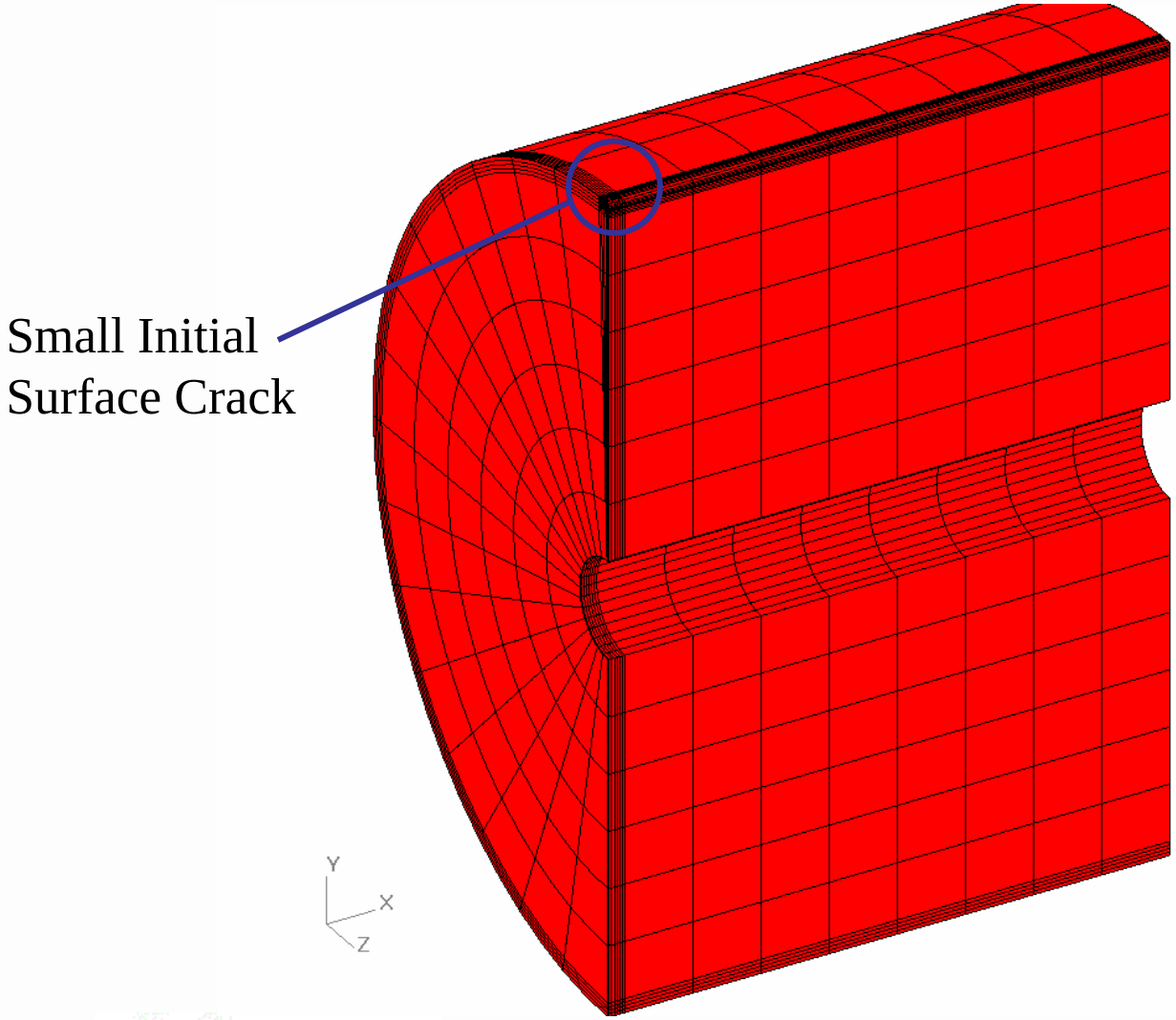
Cell Mesh for Crack Growth Analysis



Remeshing Example

Surface Crack in Wind Turbine Rotor



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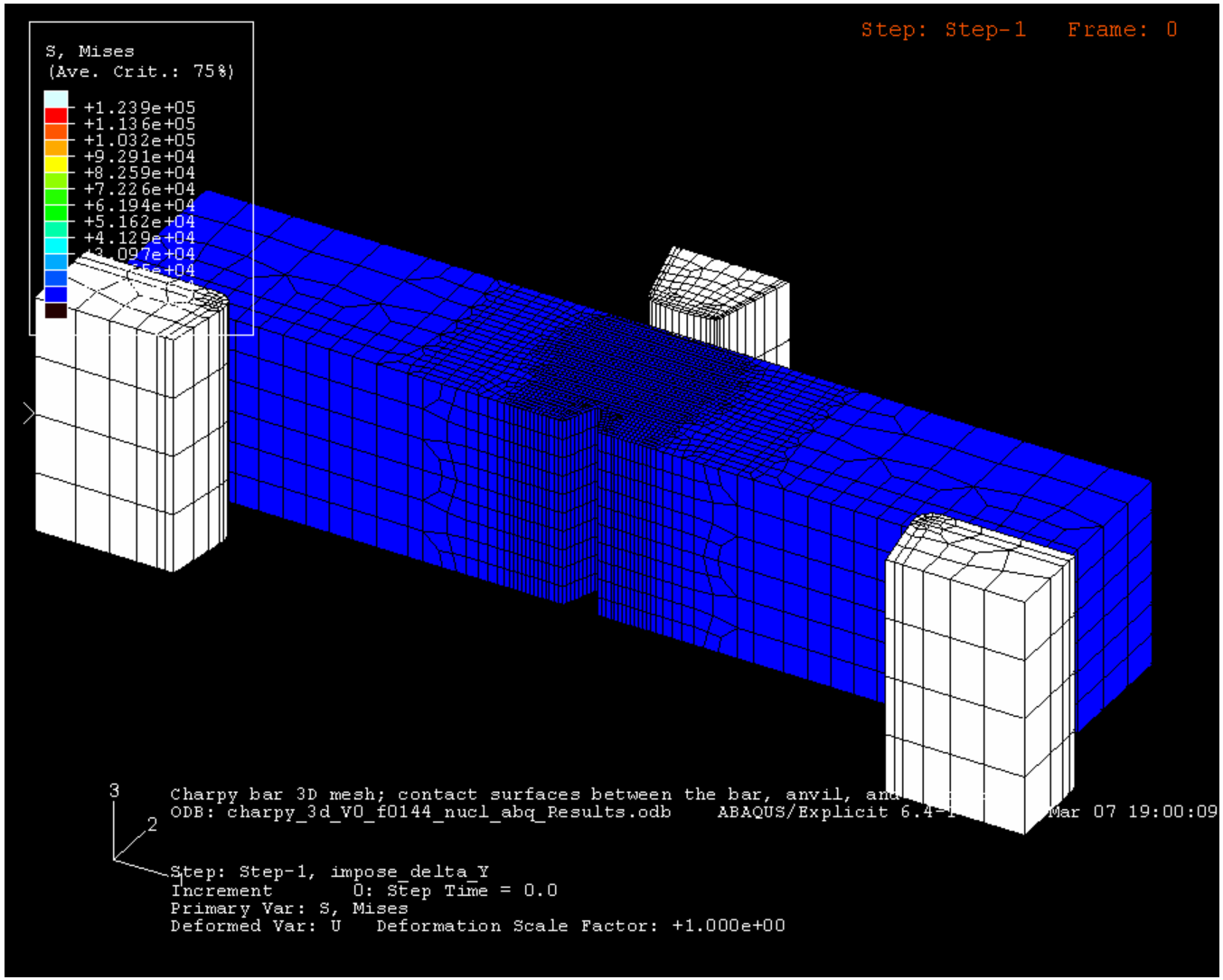
Dynamic Simulation of Charpy Test



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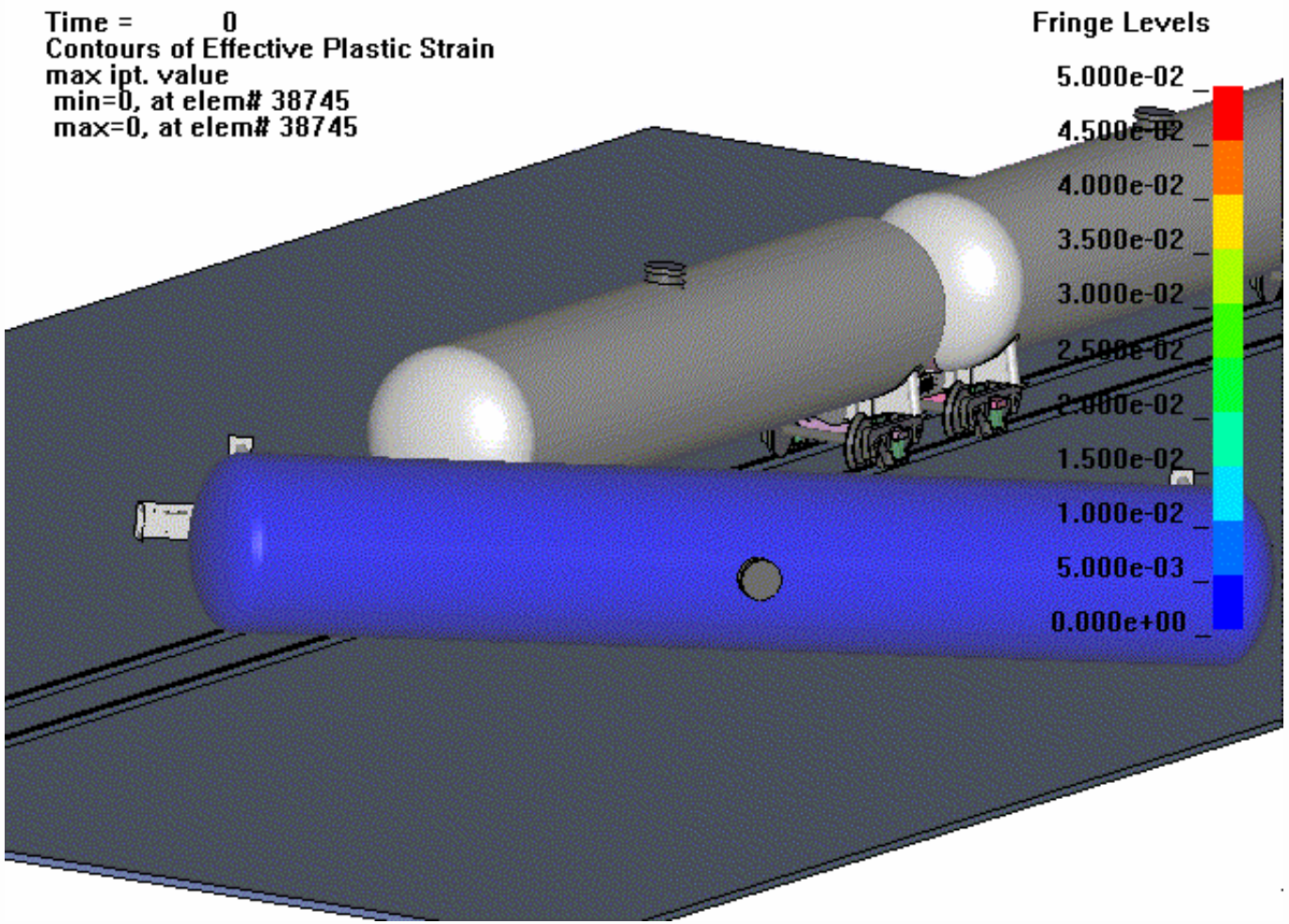
Collision/Fracture Simulation



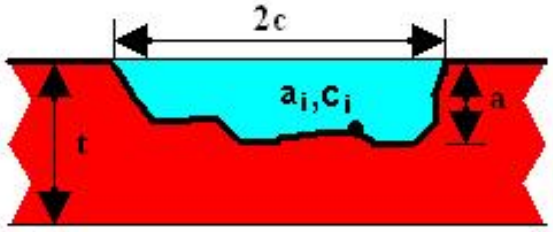
New FEA-Crack Development
Funded by EPRI

- Add custom-shape surface crack with K-driven crack growth,where *da*/*dt* (or *da*/*dN*) is computed at each node point along the crack front.
- Impose non-uniform temperature distribution in weld to mimic residual stresses.
- Add rigid contact surface to crack symmetry plane to model crack closure.
- Add additional functionality to custom through crack.
- Add “nozzle to safe end” geometry to drop-down list.

Custom Surface Crack Input

Cracks

Configuration | **Dimensions** | PRO Mesh | Advanced Mesh



Crack Shape:

Surface Crack

Evaluate:

- (•) Single Crack Size
- ( ) Range of Crack Sizes

Crack Type:

- ( ) Elliptical
- ( ) Constant Depth
- (•) User Defined

Number of Cracks: 1

i	Length Pos (c), in	Depth Pos (a), in
1	0.5	0
2	0.4980935	-4.36E-02
3	0.4923887	-8.69E-02
4	0.482929	-0.129536
5	0.4697866	-0.1711741
6	0.4530616	-0.2115068
7	0.4328817	-0.2502267
8	0.4094008	-0.2870384
9	0.3827977	-0.3216611
10	0.3532756	-0.353831
11	0.3210594	-0.3833025

Custom Surface Crack Mesh