Benchmarking Problems in Fatigue Crack Growth Analyses

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HILL ENGINEERING
Predict. Test. Perform.

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Overview/Outline

- Overview of Software Programs and Features
  - BAMF
  - BEASY
  - FRANC3D
- Benchmark Cases
  - Overview
  - Approach
  - Comparison Goals
- Discussion of Results
- Future Plans

BAMF Features

- **Broad Application for Modeling Failure (BAMF)**
- **Overview:**
  - USAF organically developed plug-in coupling FEA stress intensity calculations (StressCheck) with crack growth engine (AFGROW)
  - StressCheck
    - P-element finite element code
- **Key Features:**
  - 2-D planar growth
  - Full suite of AFGROW capabilities
    - Materials, spectra, retardation, etc.
  - Multiple crack front support
  - Surface based application of crack face traction
- **Current Limitations:**
  - Planar growth

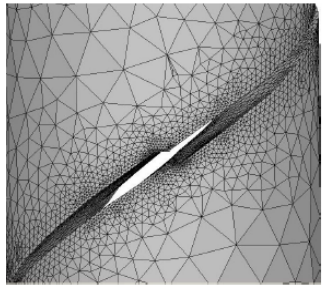
BEASY Features

- **Overview:**
  - COTS software with integrated Boundary Element code and crack growth engine
- **Key Features:**
  - 3D non-planar growth
  - Load spectrum support
  - NASGRO library support
  - Tabulated material data support
  - Retardation Models (GW and MGW)
  - Multiple crack front support
  - Mesh based application of crack face traction
- **Current Limitations**
  - Symmetry at crack face

FRANC3D Features

- **Overview**
  - COTS software with integrated Finite Element code (previously boundary element) and crack growth engine
    - H-element FE code
- **Key Features:**
  - Mesh based application of crack face traction
  - 3D non-planar growth
  - Load spectrum support
  - NASGRO library support
  - Tabulated material data support
  - GW Retardation Model
  - Crack front smoothing/fitting
  - Multiple crack front support
  - Python API for automation
  - Global/Local mesh segregation
  - Use of symmetry BCs
- **Current Limitation:**
  - MGW Retardation Model

FRANC3D



Evaluation Plan

- General approach
  - Define benchmark problems
  - Slowly increase the complexity of the problems
    - Allowed for basic validation of the software (e.g., handbook solutions)
    - Created a gradual learning curve for the software itself
    - Made identification of problematic analysis components easy since they are added piecemeal
  - Compared to complicated scenarios typically encountered with this type of analysis, the test cases remain quite simple. However, these relatively simple cases test a wide range of functionality in ways that allowed for easy comparisons.

Evaluation Test Matrix

Test ID	NASGRO ID	Geometry	Analysis Goals
FT01	TC02	Edge Cracked Plate	Comparison of SIF values to benchmark for 3D and 2D (plane strain) cases
FT02	TC01	Center Cracked Plate	Comparison of SIF values to benchmark for 3D and 2D (plane strain) cases and use of symmetry BCs (FRANC3D & BAMF only).
FT03	TC01	Center Cracked Plate	Use of NASGRO material model in a crack growth simulation with constant amplitude loading.
FT04	CC01	Corner Cracked Plate	Use of tabular material data, localized remeshing, and spectrum loading in a FCG simulation.
FT05	TC02	Edge Cracked Plate	Demonstration of applying crack face traction interpolated from an arbitrary mesh.

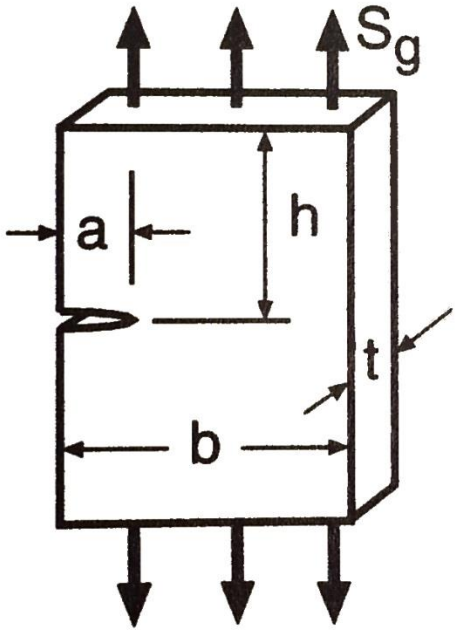
FT01: Basic Overview

- **FT01 Demonstration Goals:**
  - Duplication of benchmark case provided in FRANC3D documentation
  - Comparison of 3D and 2D plane strain SIF results

FT01/TC02 Geometry

Dimensions
h = 5
b = 5
a = 0.5
t = 5

Material: E = 3.0e7, v = 0.30
Loading: Uniform unit stress

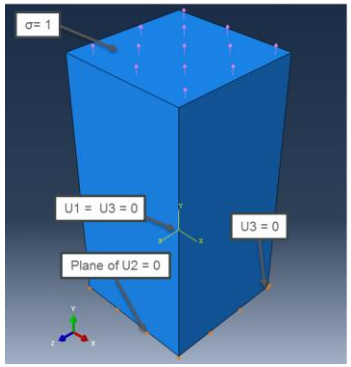


FT01: Loading and Mesh

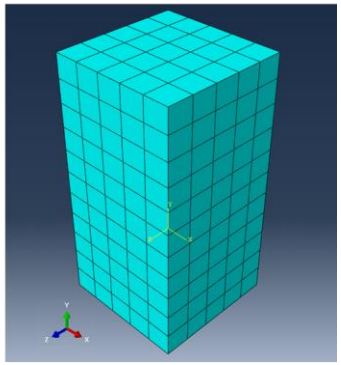
- Geometry, loading, and boundary conditions are as shown below

FRANC3D
Initial mesh = 275 C3D20R Elements

Geometry and Loading

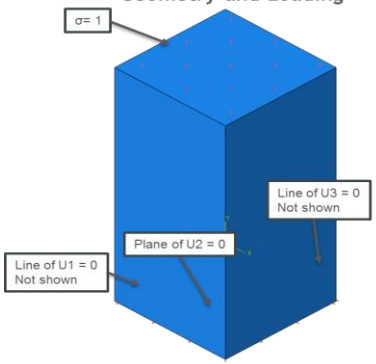


Initial Mesh

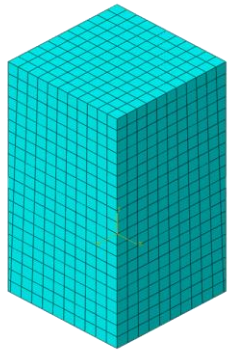


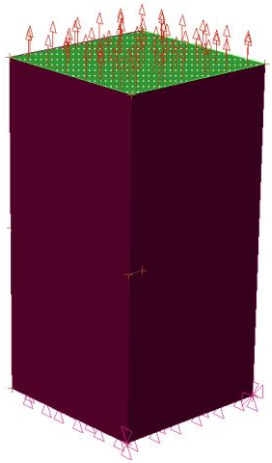
BEASY
Initial mesh = 1122 S4R shell elements

Geometry and Loading

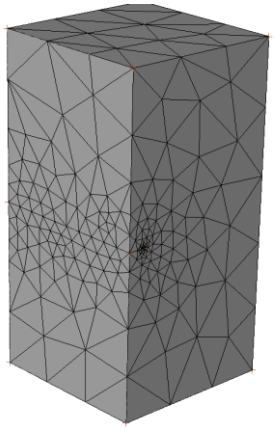


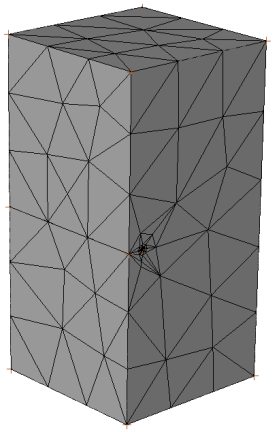
Initial Mesh





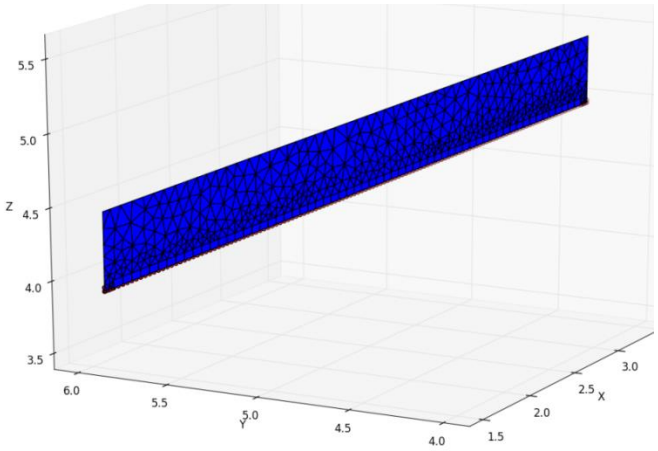
StressCheck
Mesh = 9245 tetrahedral elements
Mesh = 1764 tetrahedral elements



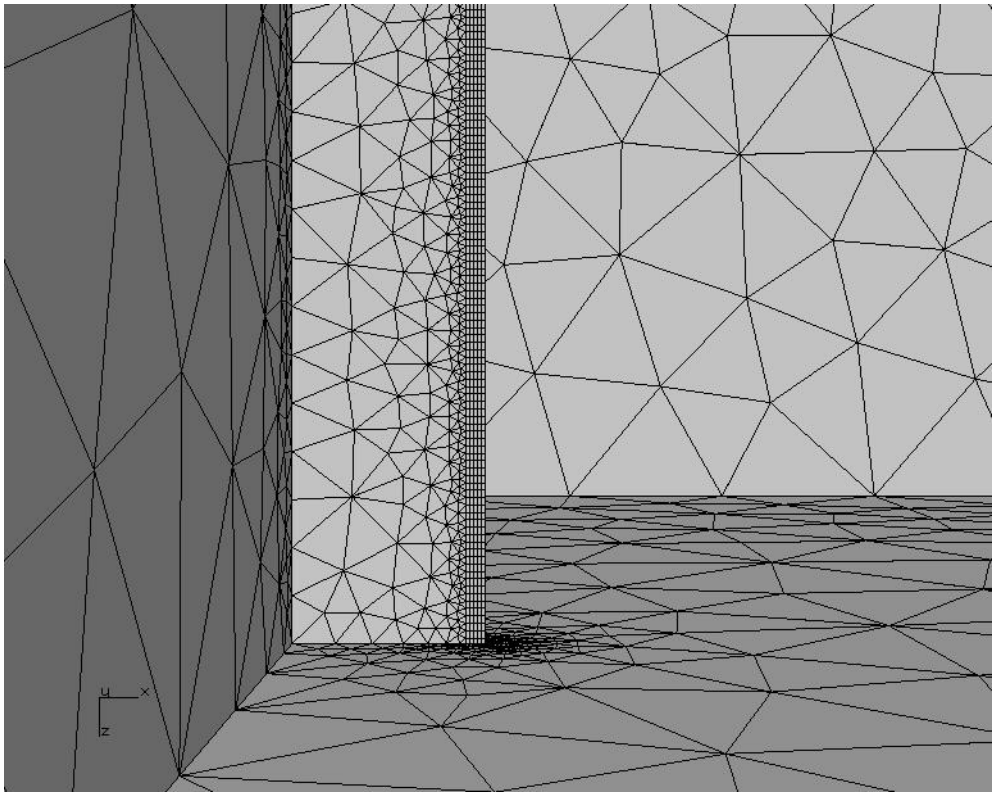


FT01: Crack Geometry: BEASY, FRANC3D

- **FRANC3D Crack Settings**
  - Crack length was 0.5
  - Template radius was 0.05
  - Volume Meshing was done with ABAQUS
  - Crack front template used 5 integration rings with 8 elements per ring.



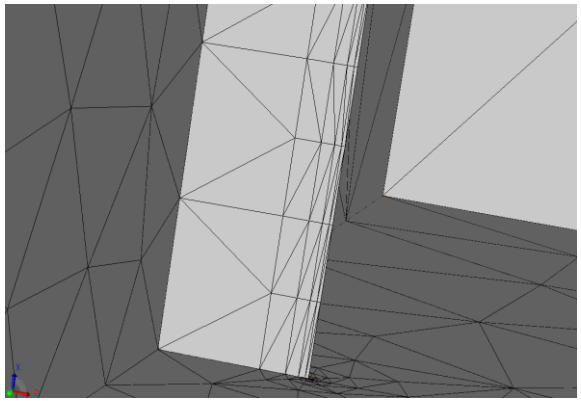
Beasy Crack Mesh

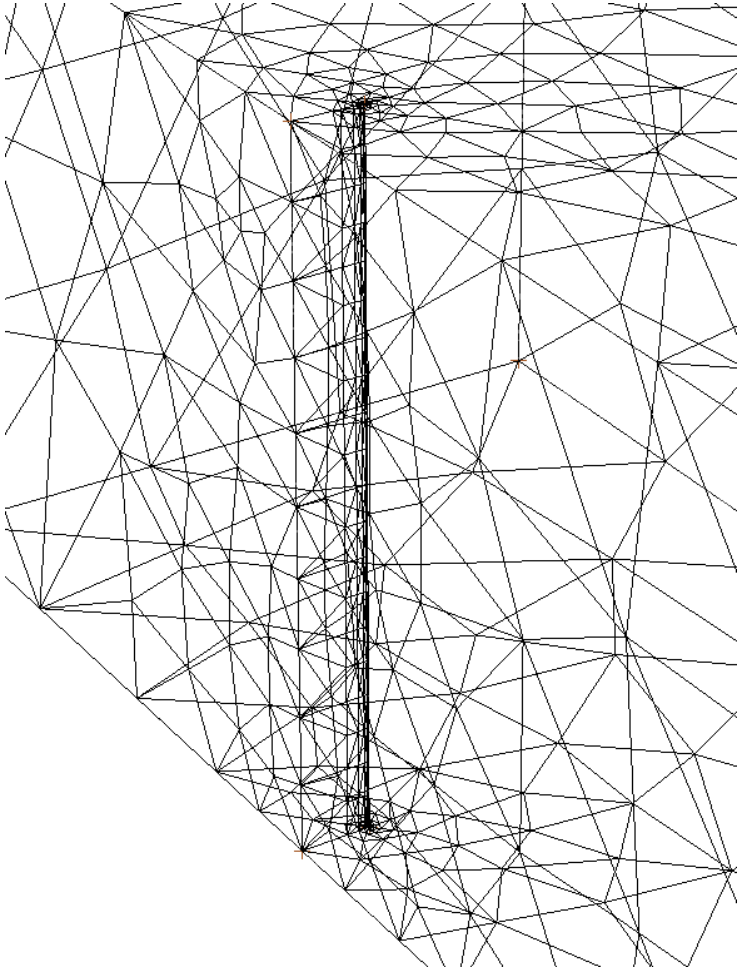


FRANC3D Crack Mesh/Geometry

FT01: Crack Geometry: StressCheck

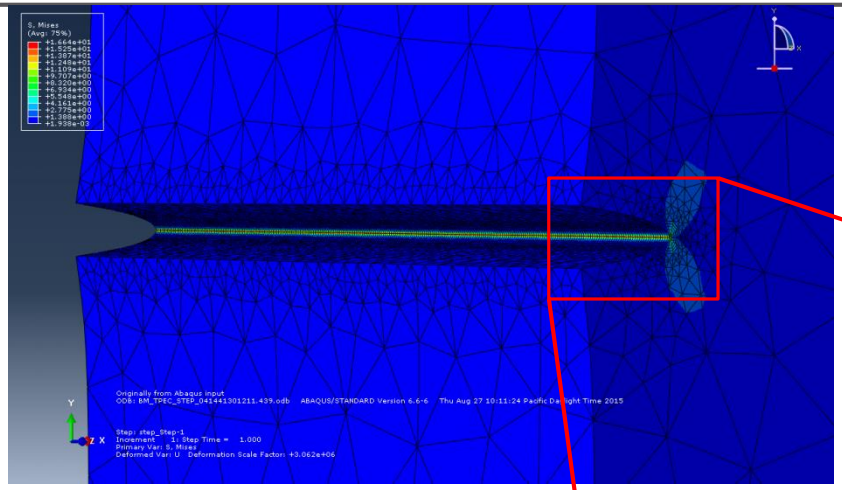
- **StressCheck Crack Settings**
  - Crack length was 0.5
  - Volume Meshing with tetrahedral automesher
  - Crack front used 4 layers of controlled mesh
    - First layer sacrificial
      - Isolate singularity
    - Integration through center of second layer

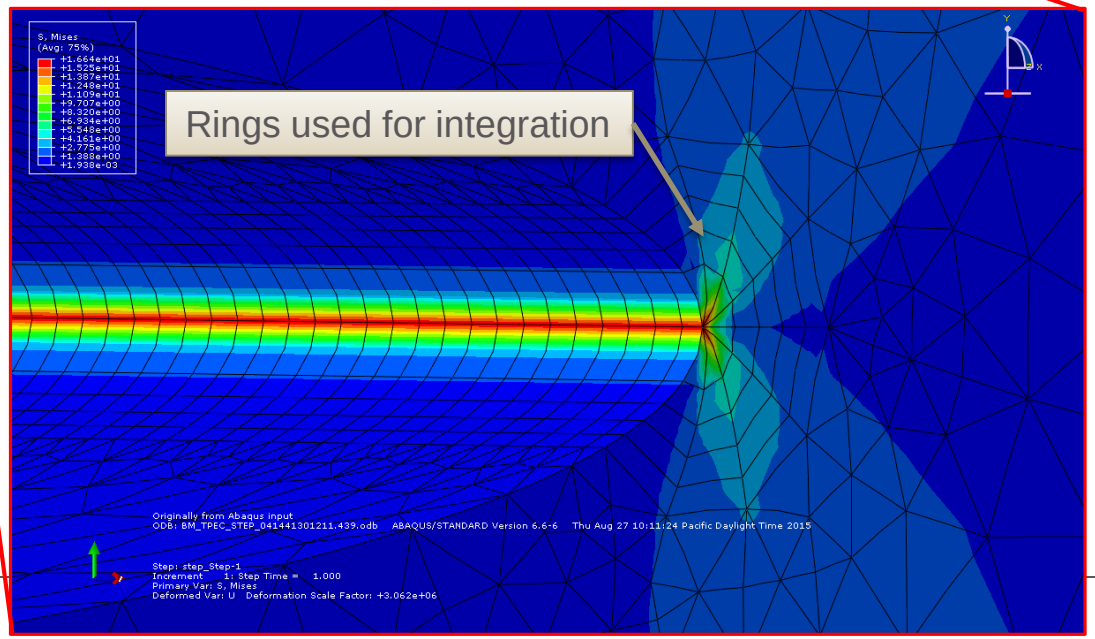




BAMF Crack Mesh/Geometry

FT01: FRANC3D SIF Results



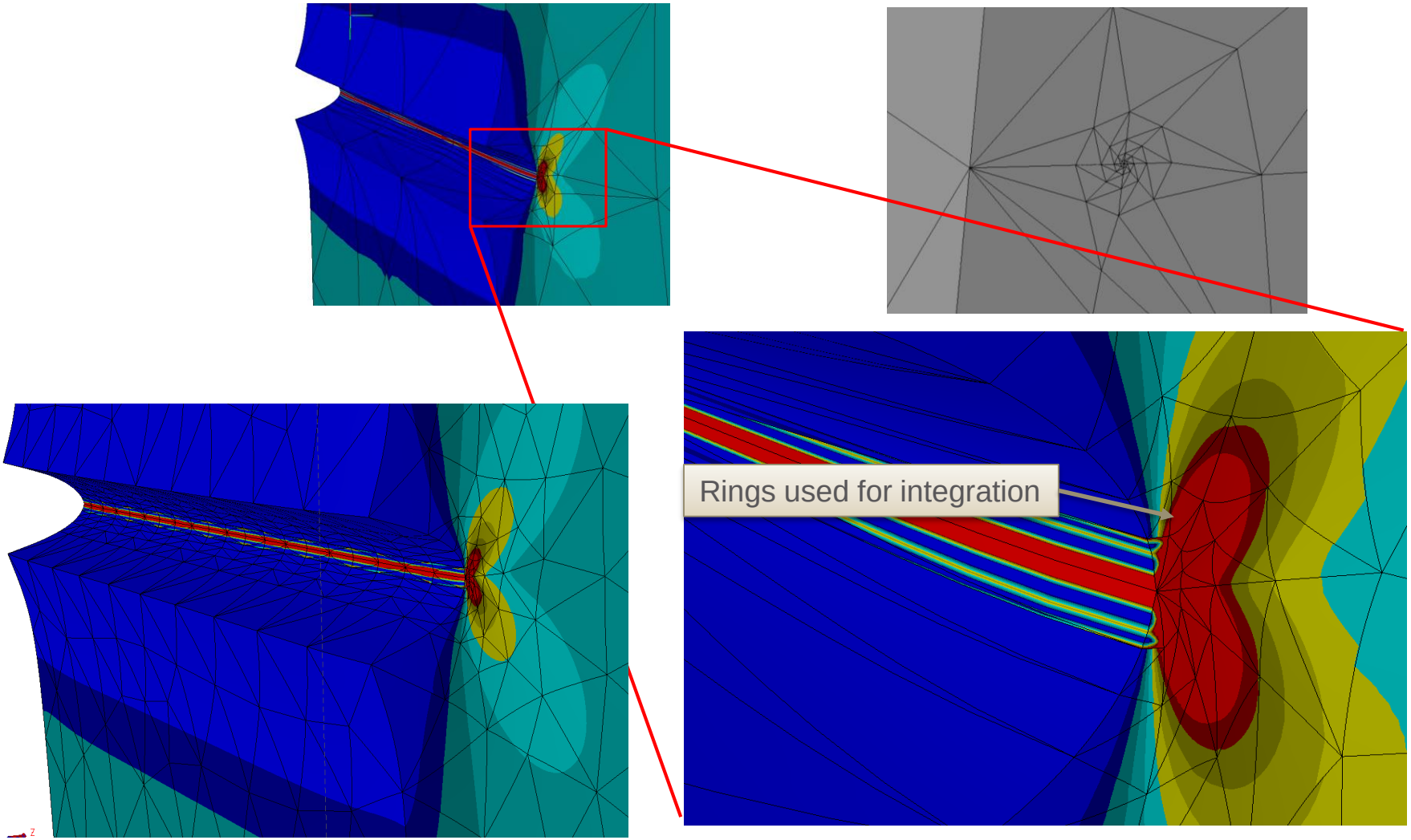


Note that the first ring is made up of wedge elements with the remaining rings using brick elements.

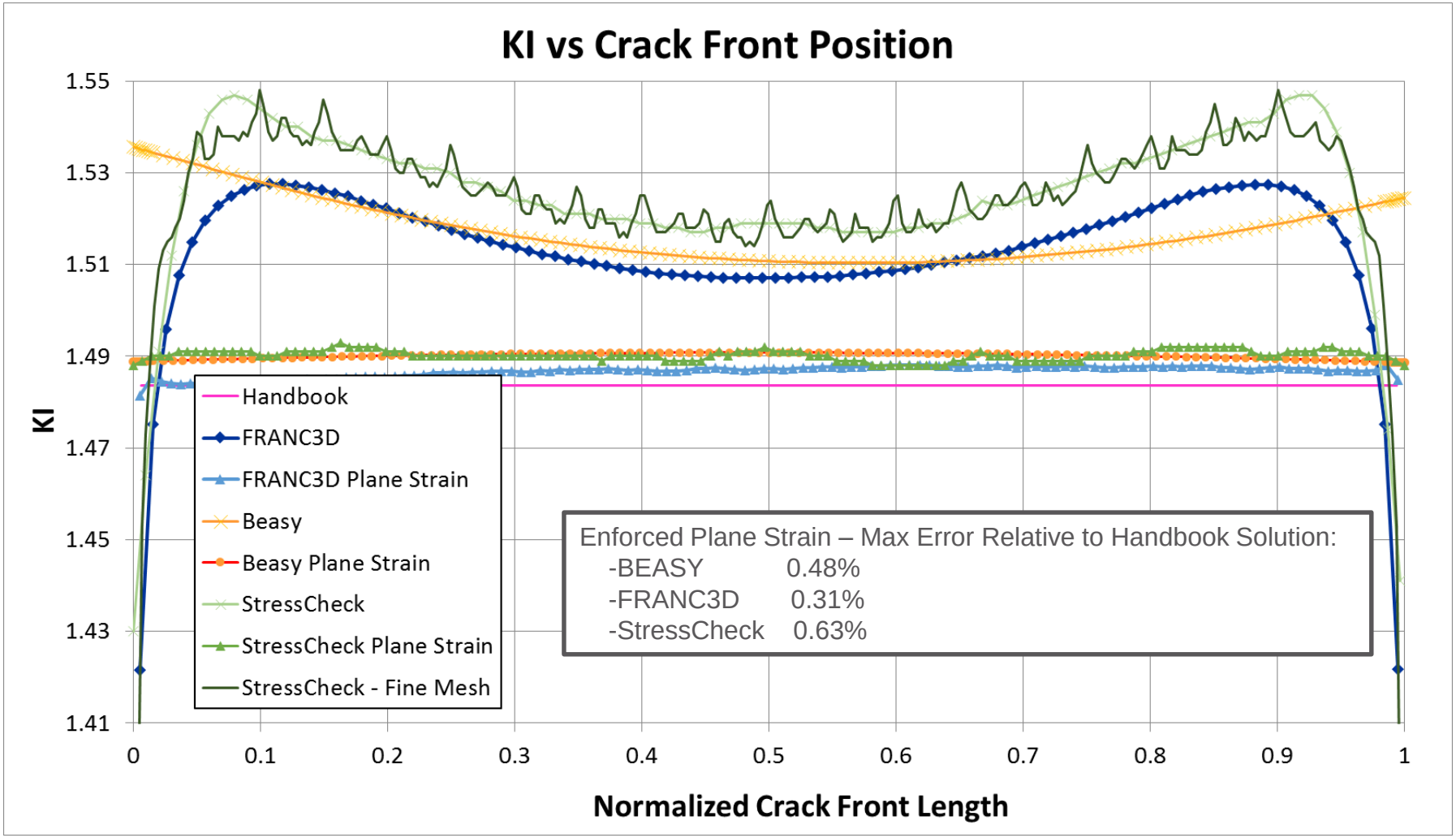
The volume is meshed using tetrahedral elements.

Note: Deformations are scaled by 3e6

FT01: StressCheck SIF Results



FT01: K1 2D and 3D Handbook Comparison



FT02: Basic Overview

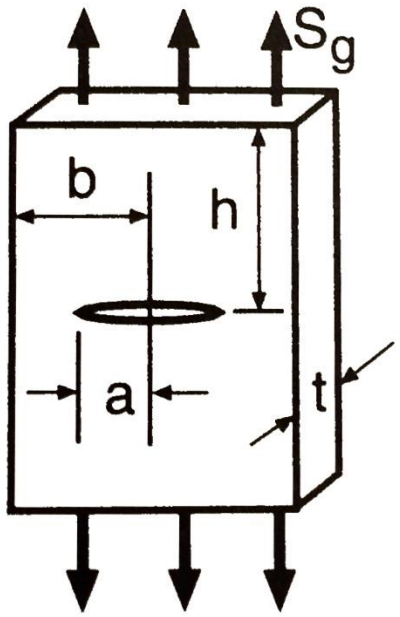
- **FT02 Demonstration Goals:**
  - Duplication of benchmark case provided in FRANC3D documentation
  - Comparison of 3D and 2D plane strain SIF results
  - Use of symmetry boundary conditions in StressCheck and FRANC3D for mesh size reduction (a feature BEASY doesn't support)

Dimensions

h = 5
b = 5
a = 0.5
t = 5

Material: E = 3.0e7, v = 0.30
Loading: Uniform unit stress

FT02/TC01 Geometry

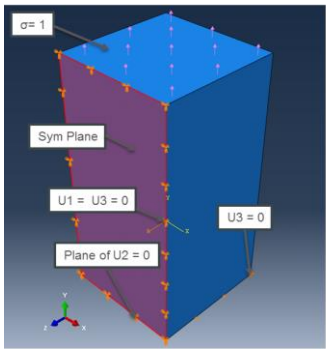


FT02: Loading and Mesh

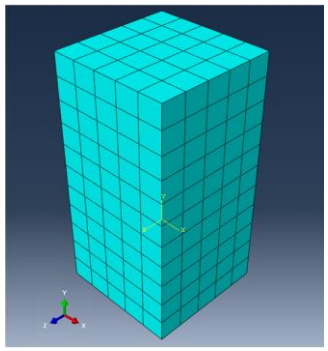
- Geometry, loading, and boundary conditions are as shown below

FRANC3D

Geometry and Loading

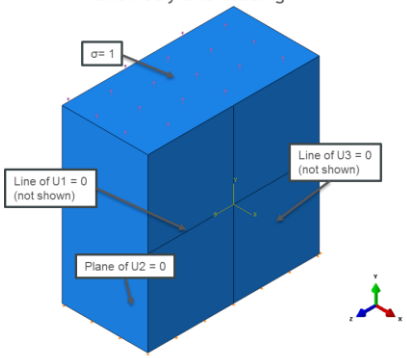


Initial Mesh

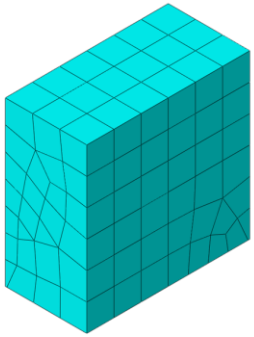


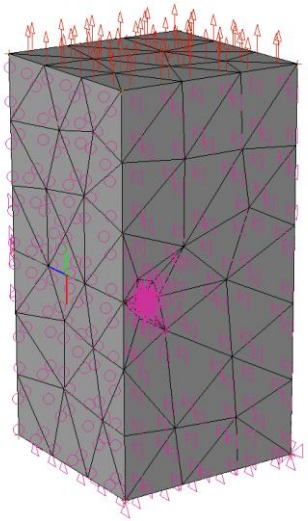
BEASY

Geometry and Loading

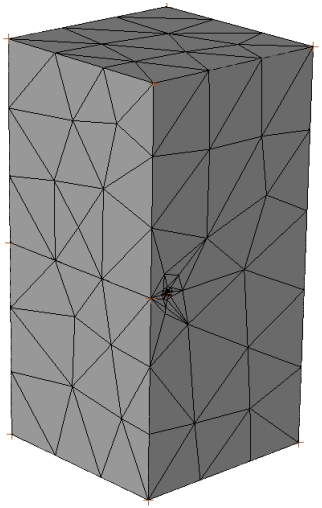


Initial Mesh

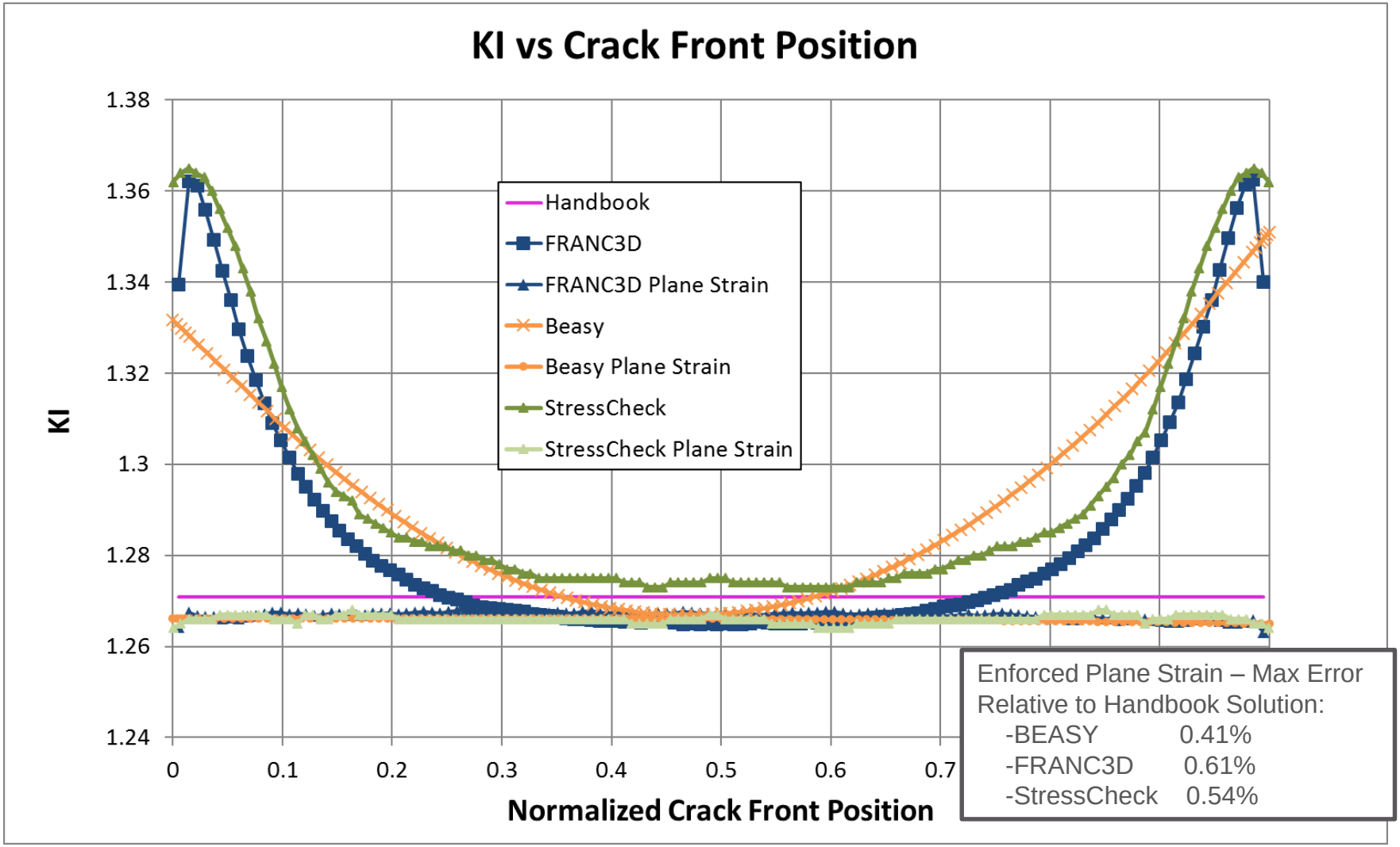




StressCheck



FT02: K1 2D and 3D Handbook Comparison



FT03: Basic Overview

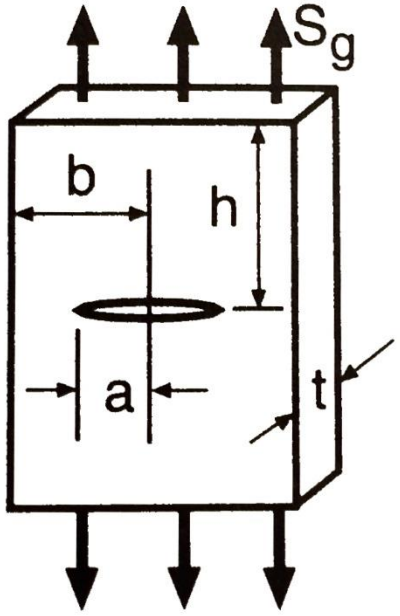
- **FT03 Demonstration Goals:**
  - Crack growth under constant amplitude (R = 0) loading
  - Basic use of NASGRO materials
  - Comparison and validation of SIF results with a handbook solution
  - Comparison and validation of lifing results with NASGRO TC01

FT03/TC01 Geometry

Dimensions (in)

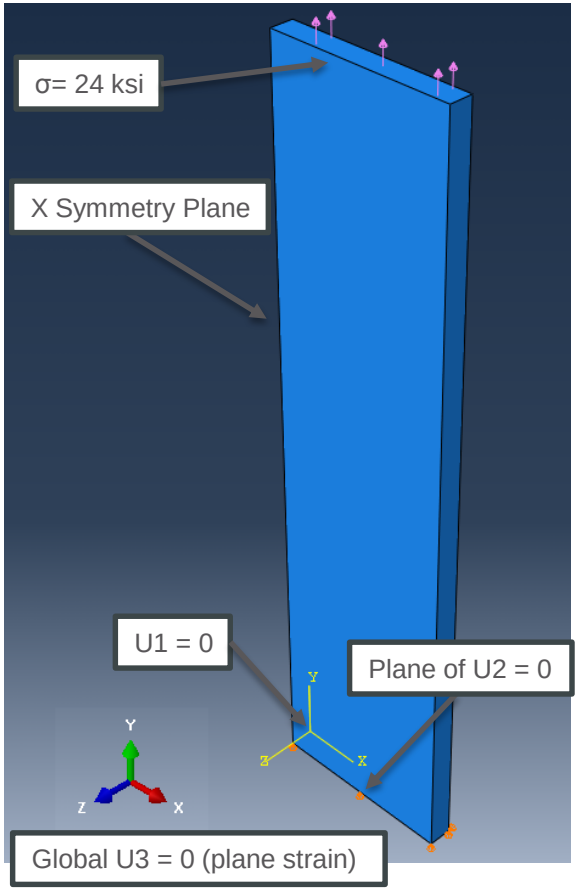
h = 2
b = 1
a = 0.05
t = 0.125

Material: 7075-T651 (11AB1)
Loading: 24 ksi (R = 0)



FT03: FRANC3D Geometry, Loading, and Mesh

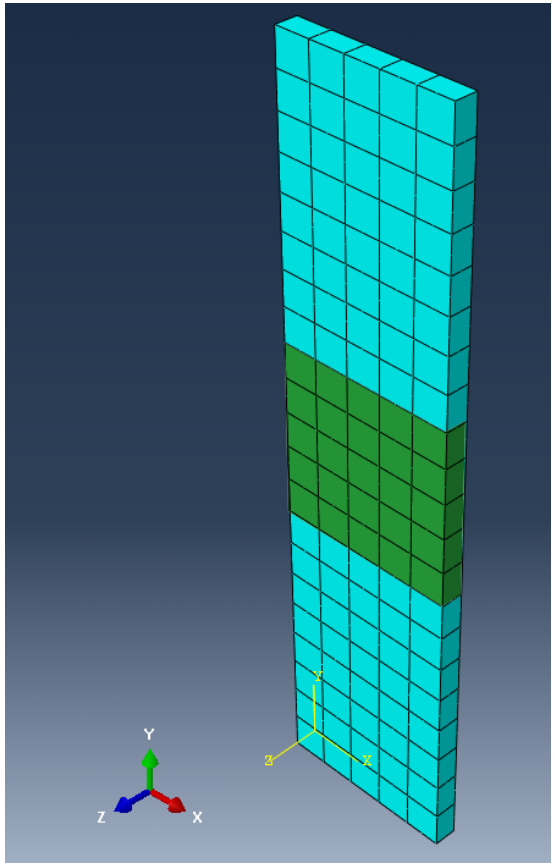
ABAQUS Geometry and Loading



Mesh

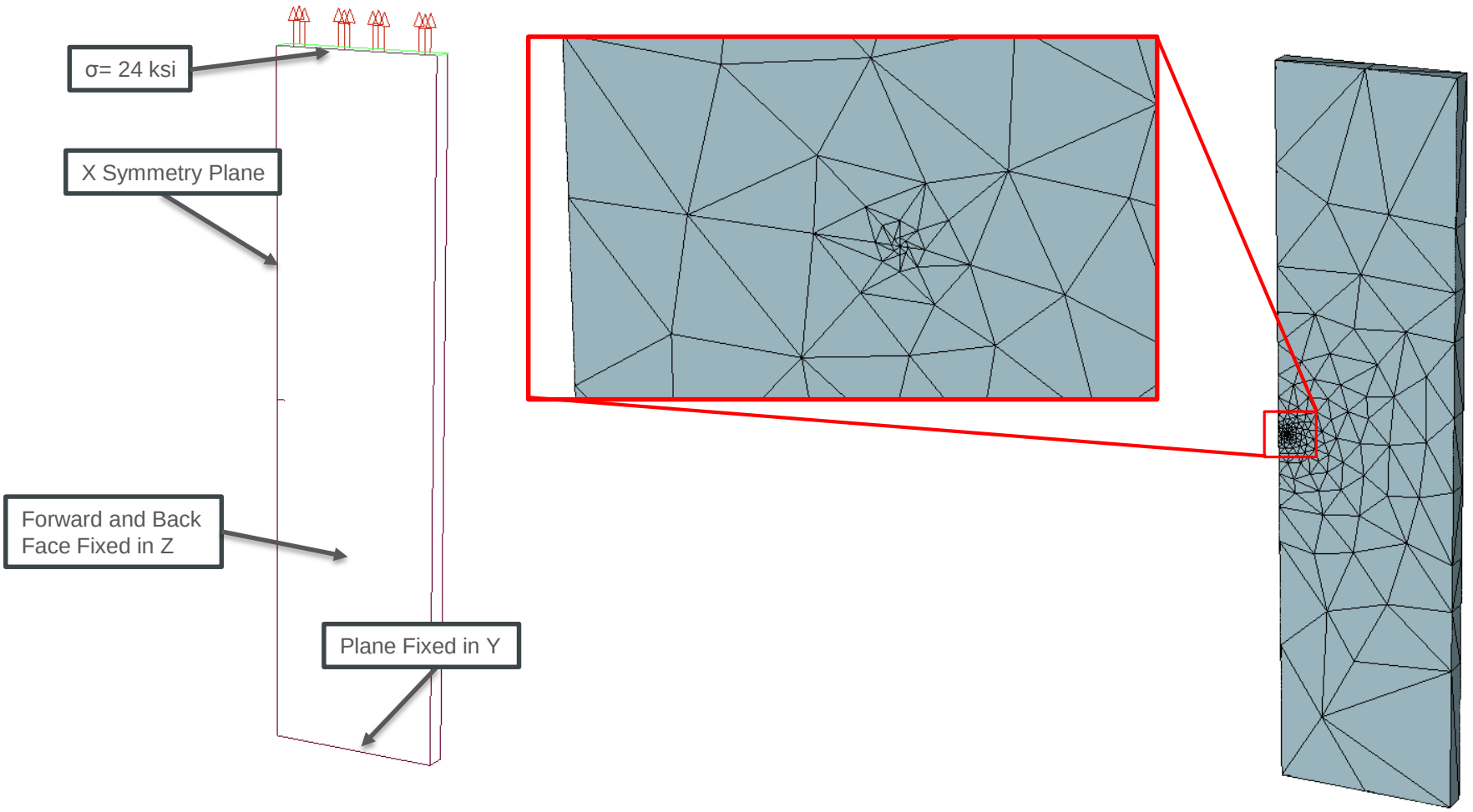
Global Mesh

FRANC3D Remeshing Region



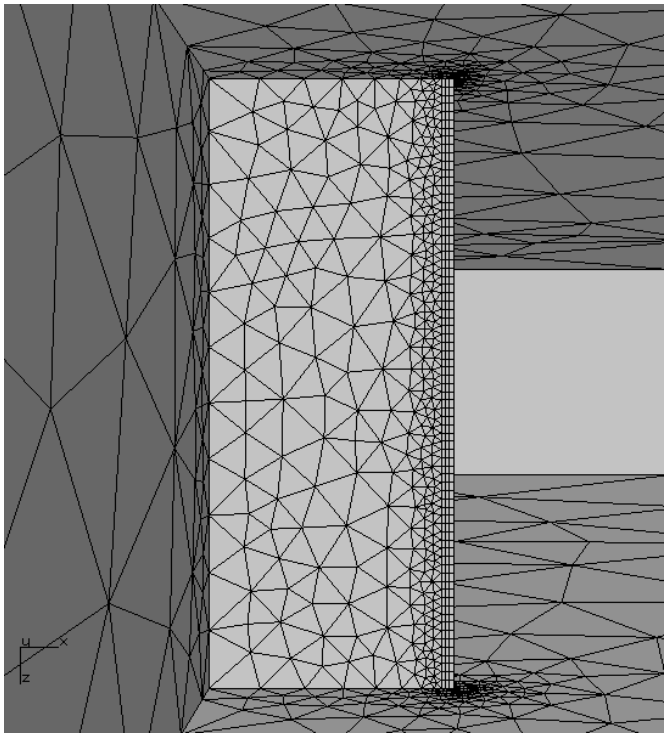
- Element Type is C3D20R
- 105 elements in total
- Symmetry is used to reduce model size and runtime
- Mesh is split into two regions: A global region that remains unchanged during the simulation and a local region that FRANC3D remeshing for each crack growth step

FT03: BAMF Geometry, Loading, and Mesh



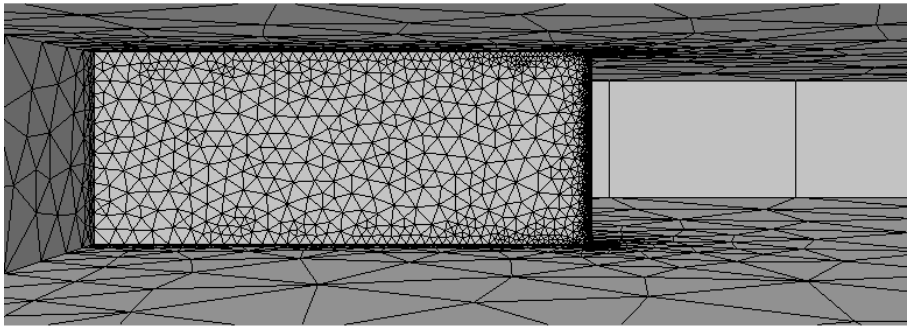
FT03: FRANC3D Crack Geometry

Initial Crack Geometry: a = 0.05 in

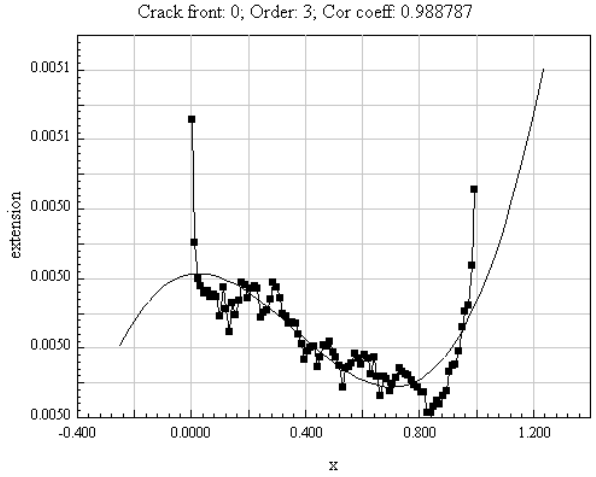


Template Radius: 0.0025
Number of Rings: 3
Elements per Ring: 8

Final Crack Geometry: a = 0.327 in

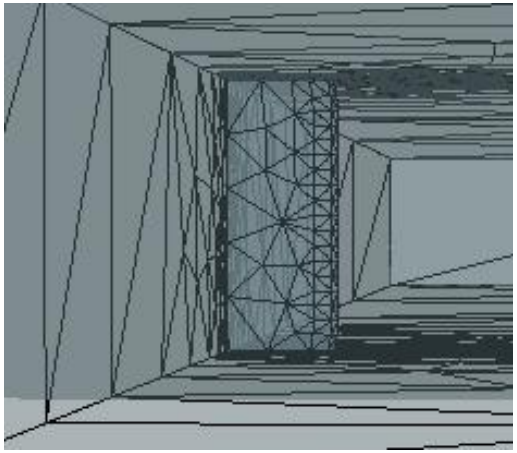


After 56 steps, the crack front remains undistorted thanks in part to crack front smoothing (as shown below).

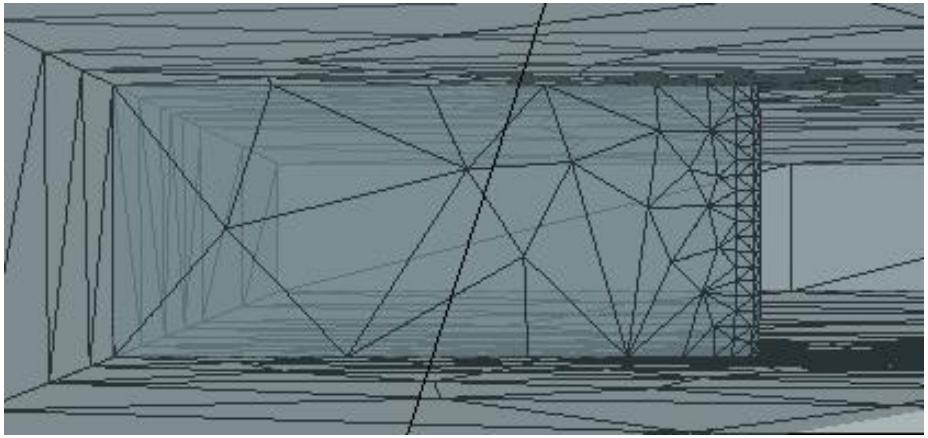


FT03: BAMF Crack Geometry

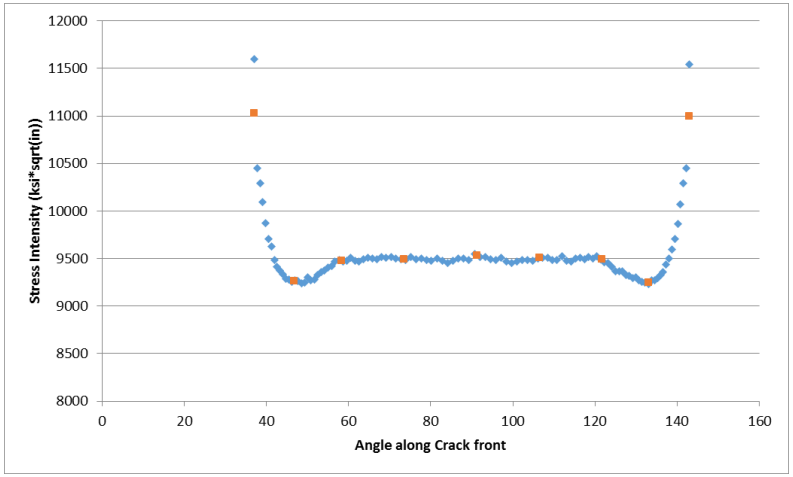
Initial Crack Geometry: a = 0.05 in

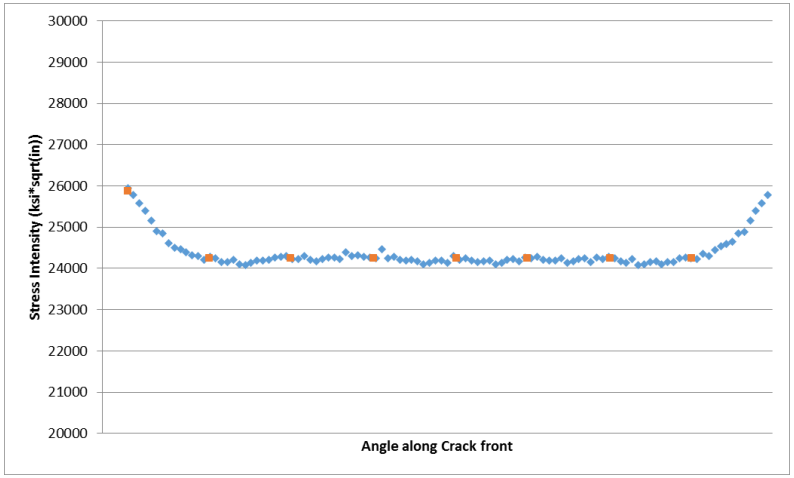


Final Crack Geometry: a = 0.297 in



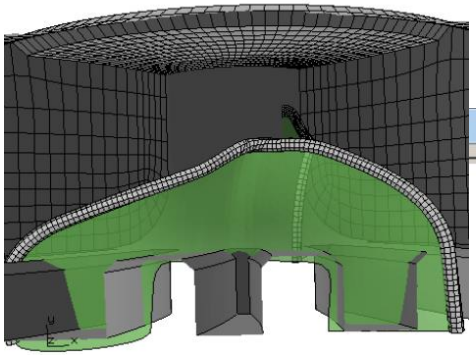
Layers of Mesh Refinement: 2

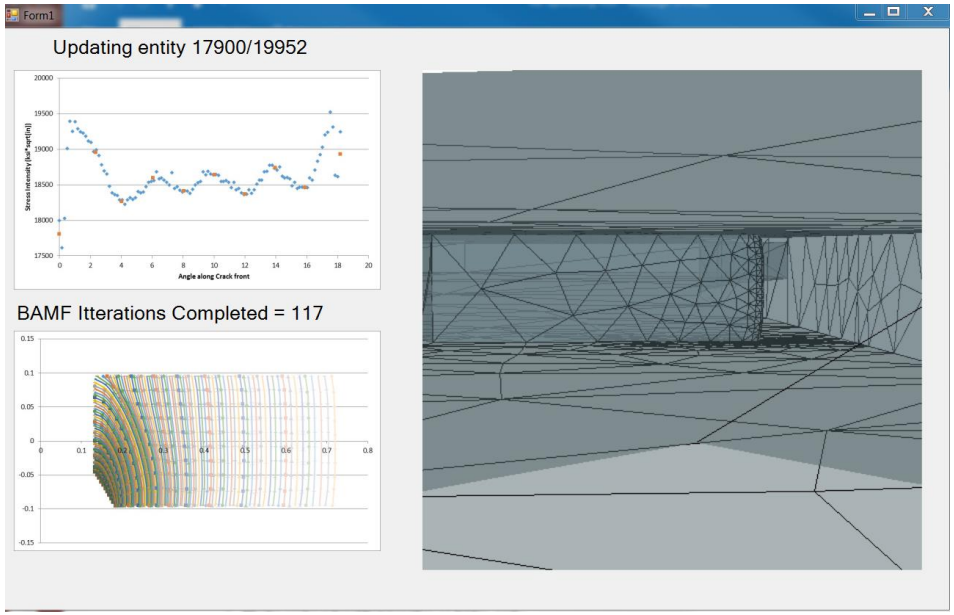




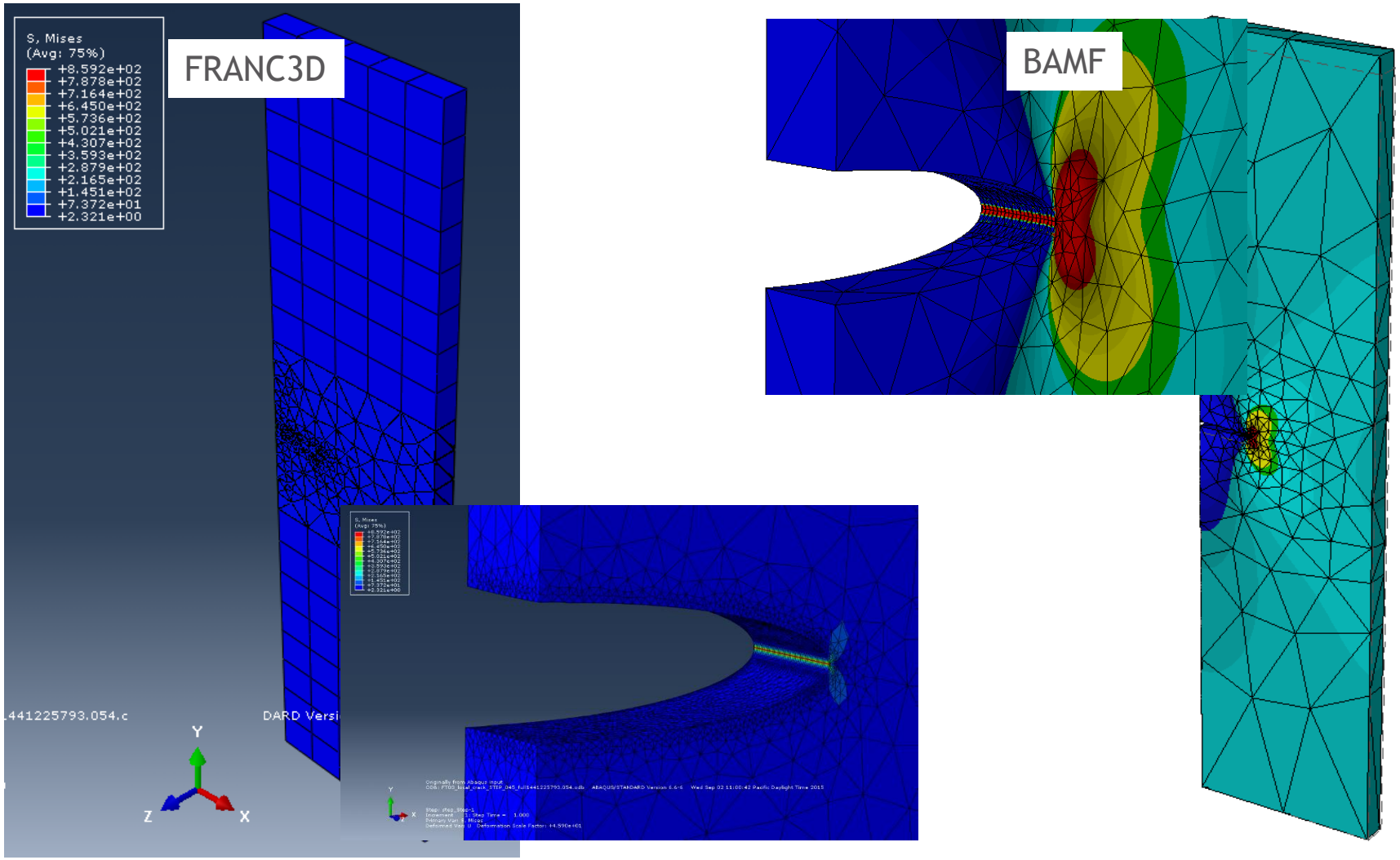
FT03: Note on Smoothing

- **Crack Front Smoothing**
  - FRANC3D smooths crack front
  - BEASY smooths SIF values
  - BAMF smooths crack front and SIF values

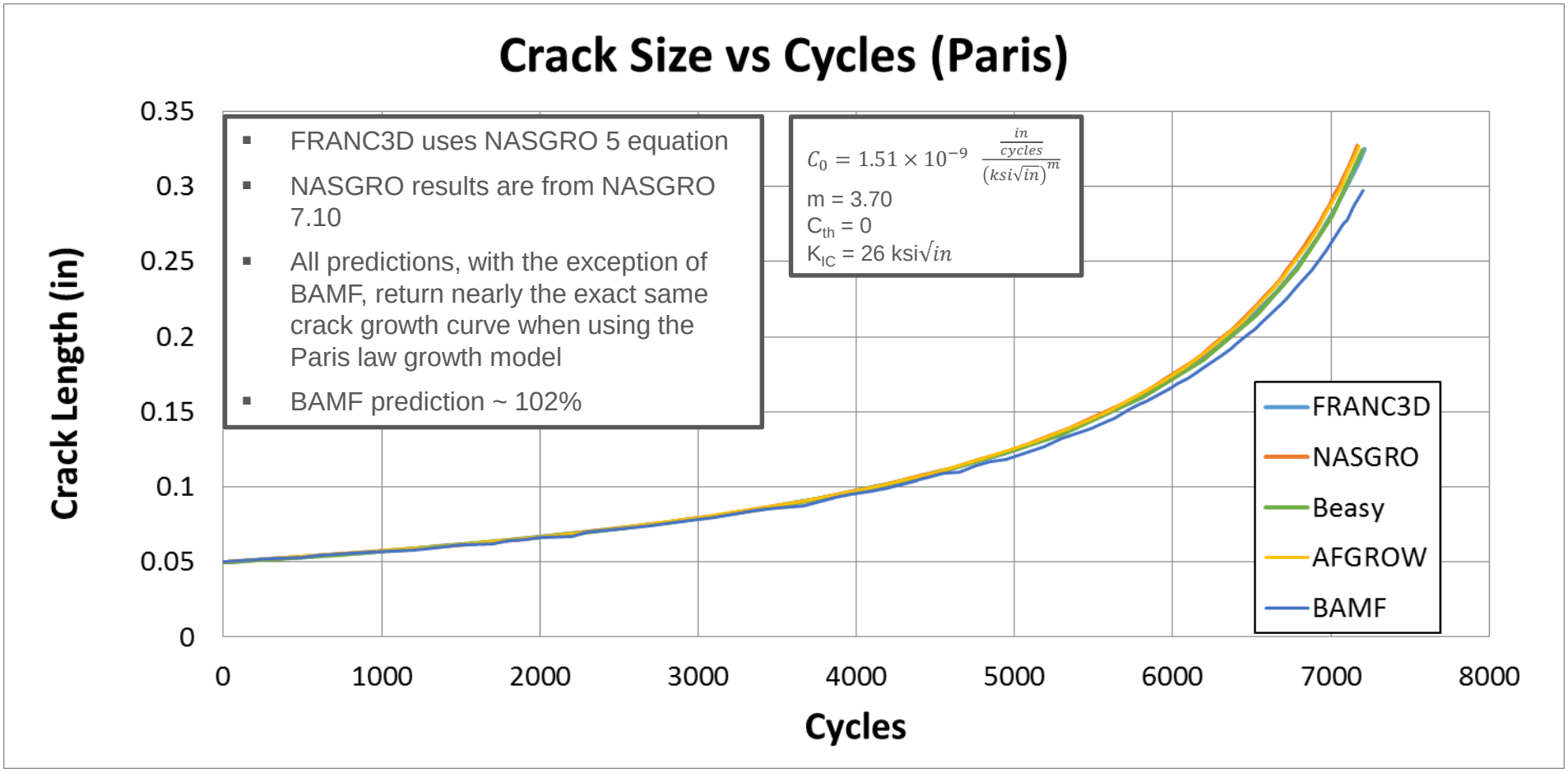




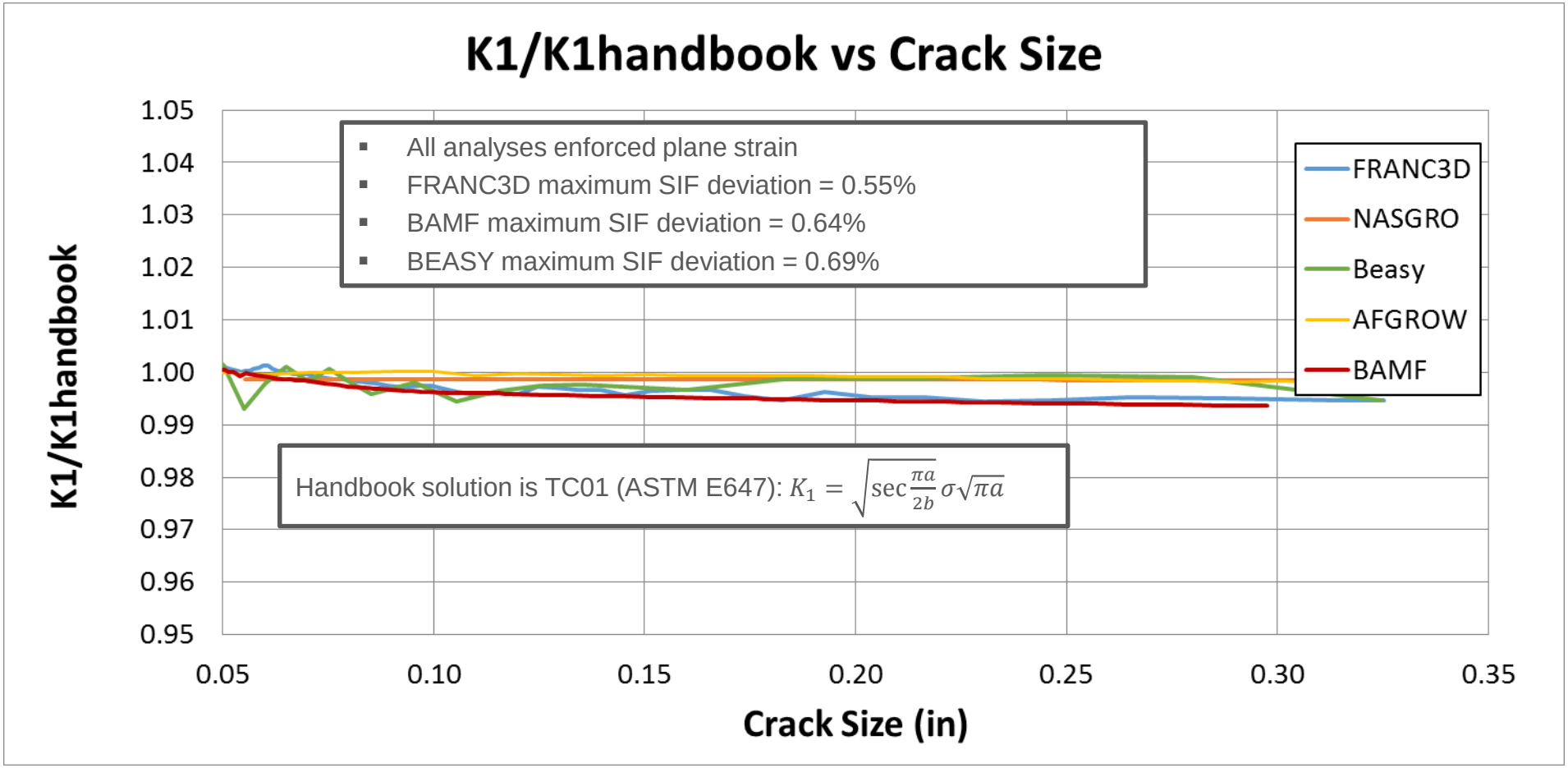
FT03: Example Stress and Displacement Results



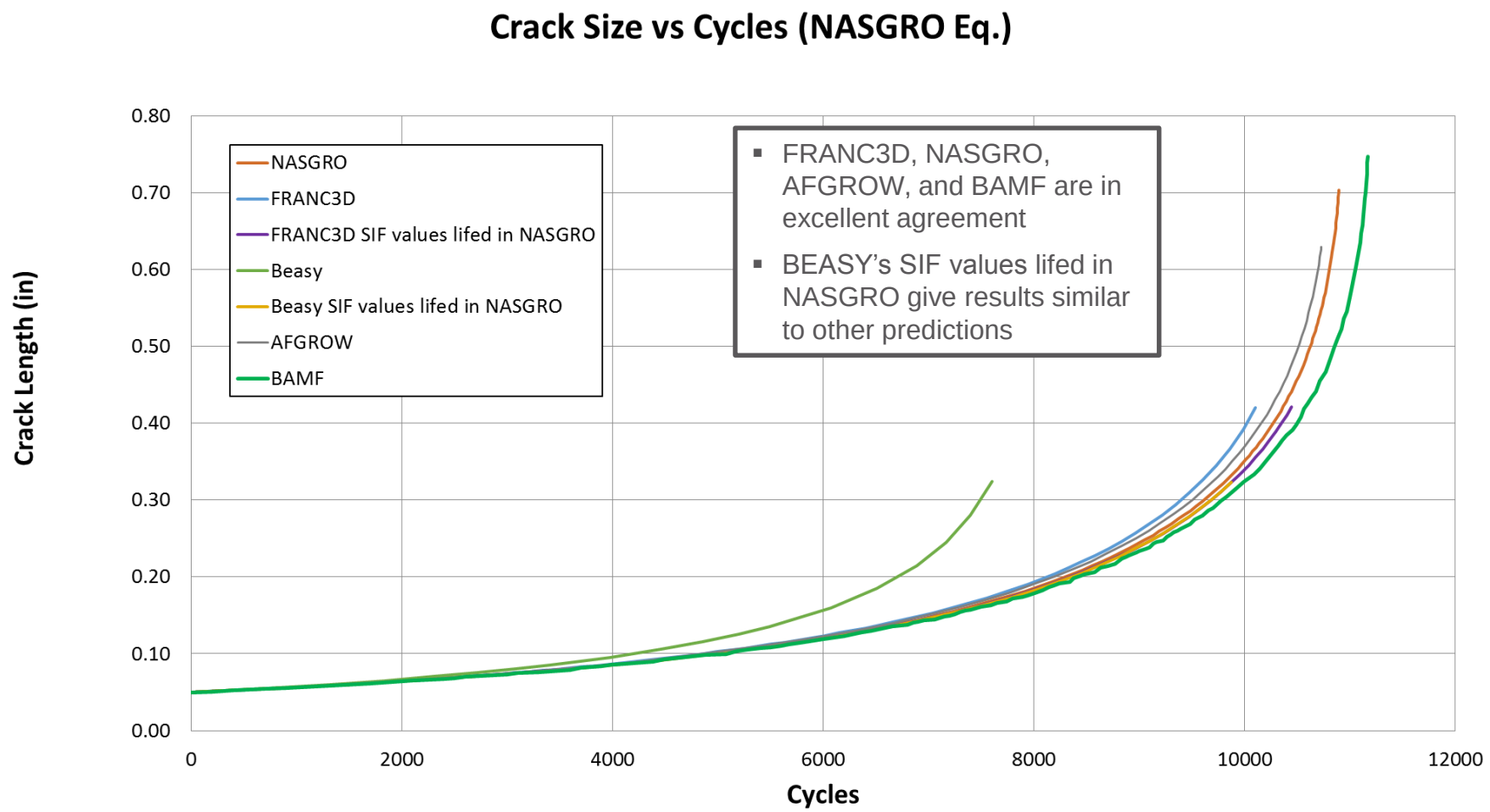
FT03: Paris Law Crack Life Results



FT03: KI Comparison



FT03: NASGRO Equation Crack Life Results



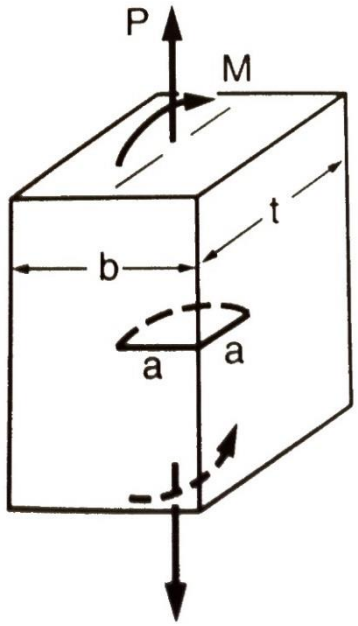
FT04: Basic Overview

- **FT04 Demonstration Goals:**
  - Localized re-meshing
  - Variable amplitude loading with both compressive and tensile loads
  - Tabular material data
  - Comparison and validation of FRANC3D lifing results with NASGRO CC01

FT06/CC01 Geometry

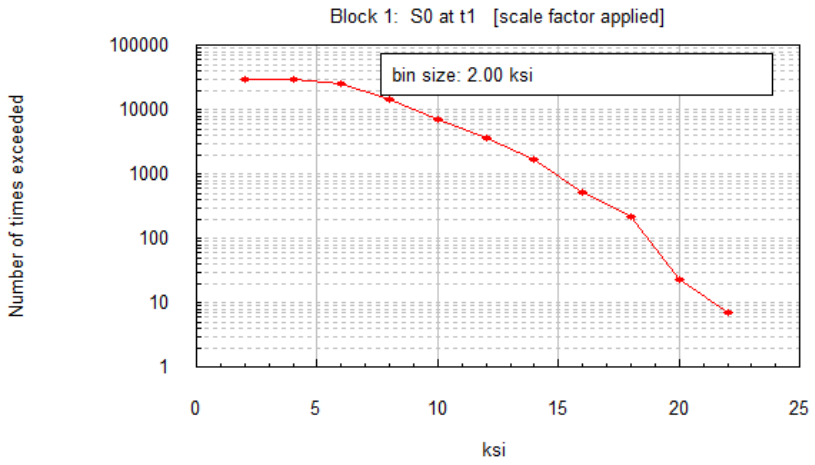
Dimensions (in)

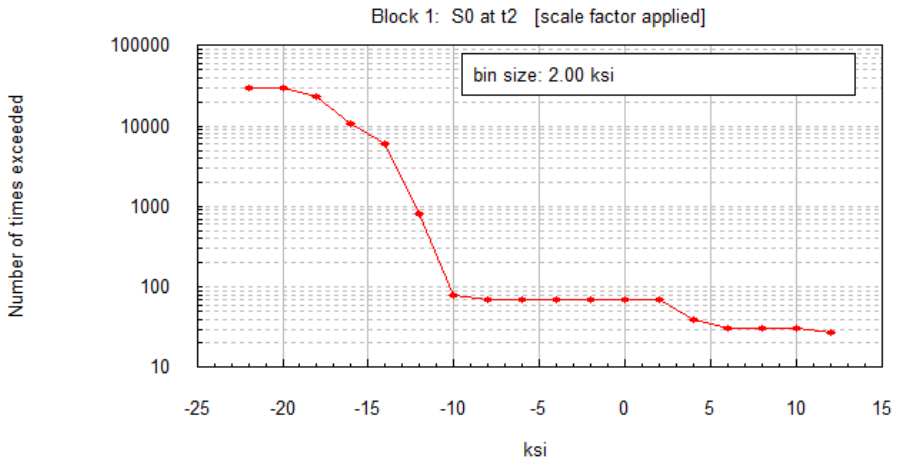
h = 9
b = 4
t = 6
a = 0.05

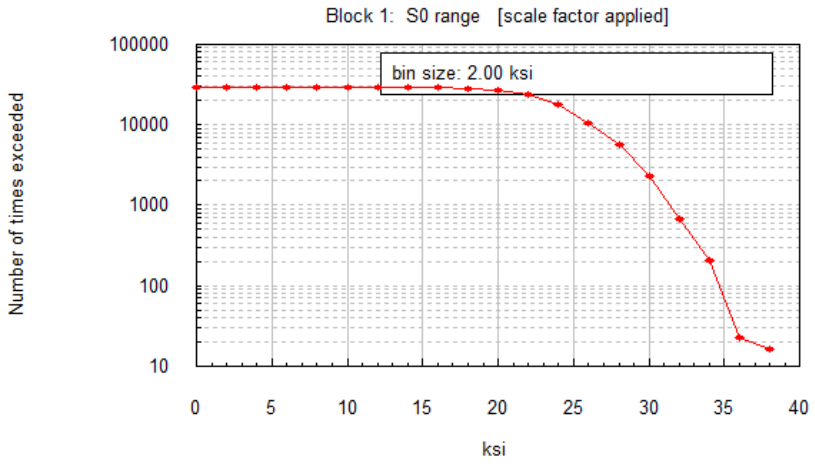


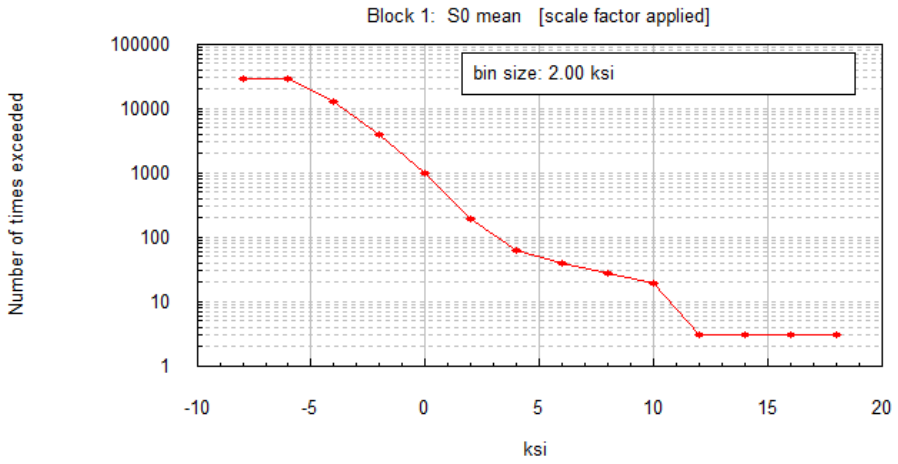
Material: Tabulated 7050 (M7GQ11AB1)
Loading: Variable with $|S_{max}| = 24$ ksi

FT04: Spectrum

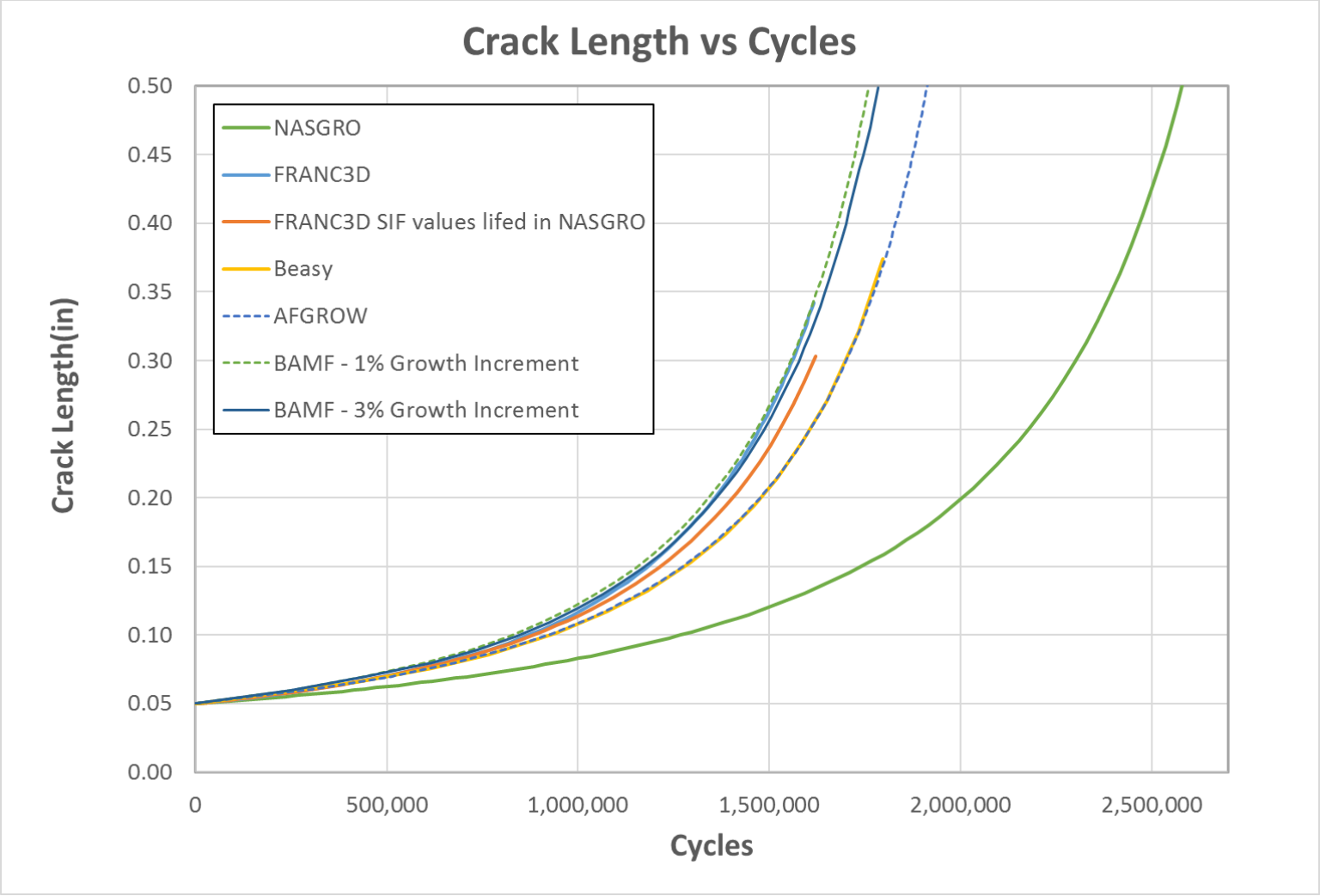




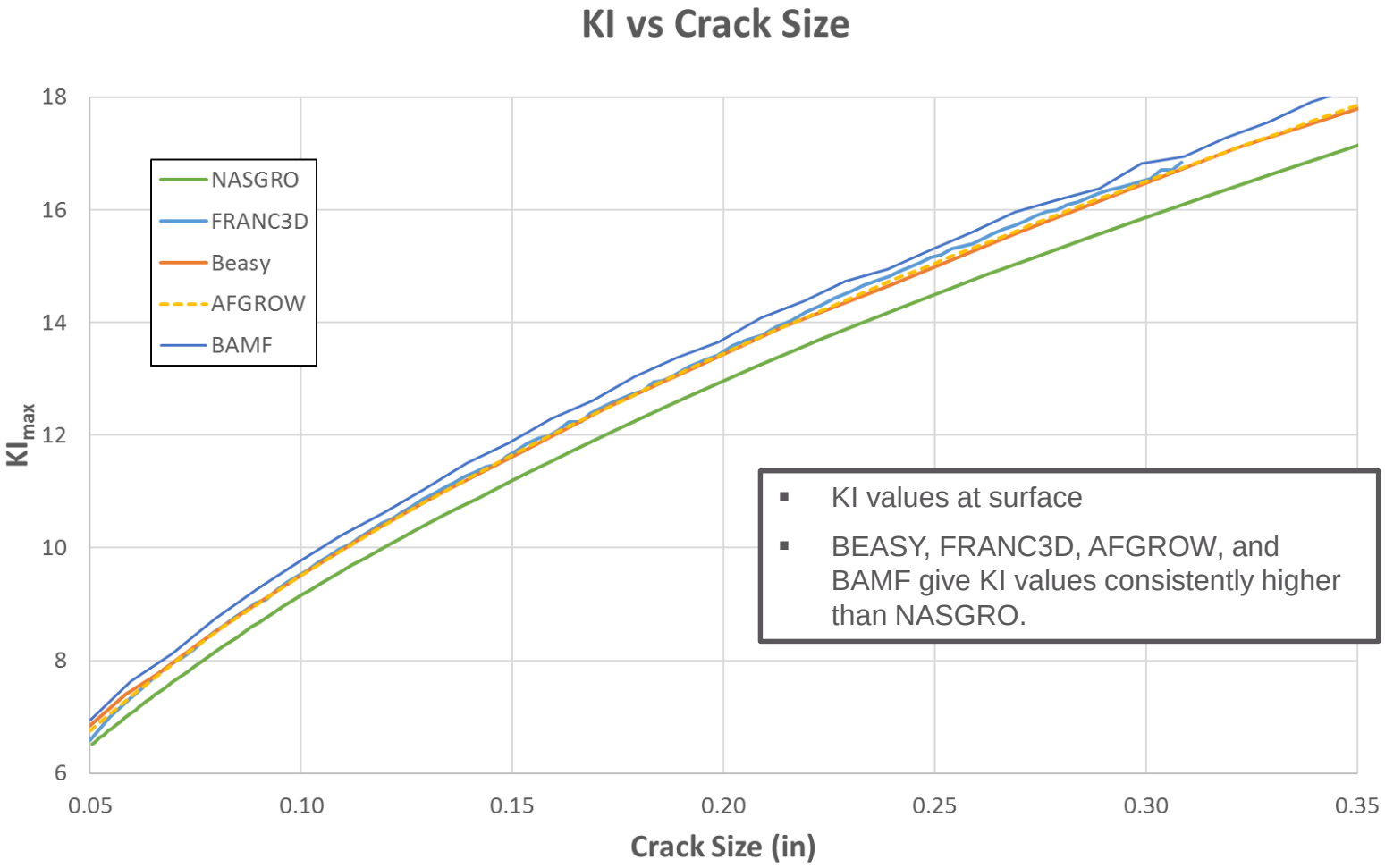




FT04: Crack Growth Results



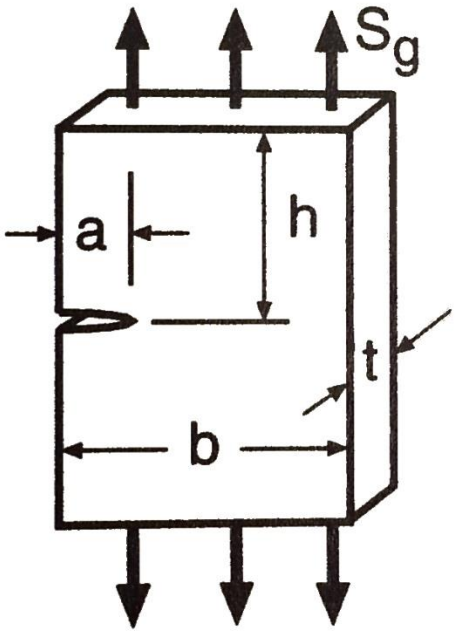
FT04: KI Results



FT05: Basic Overview

- **FT05 Demonstration Goals:**
  - Far field vs. crack face traction
  - Should result in same SIF

FT05/TC01 Geometry



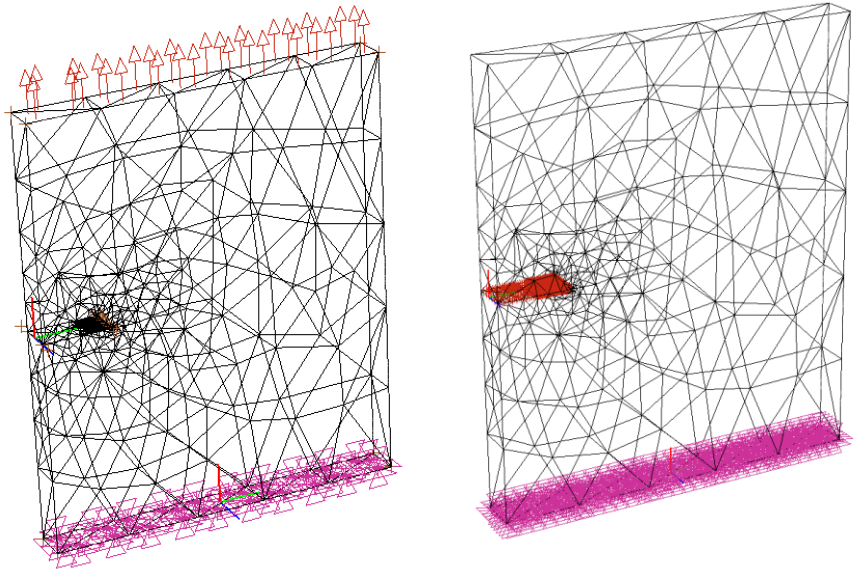
Dimensions

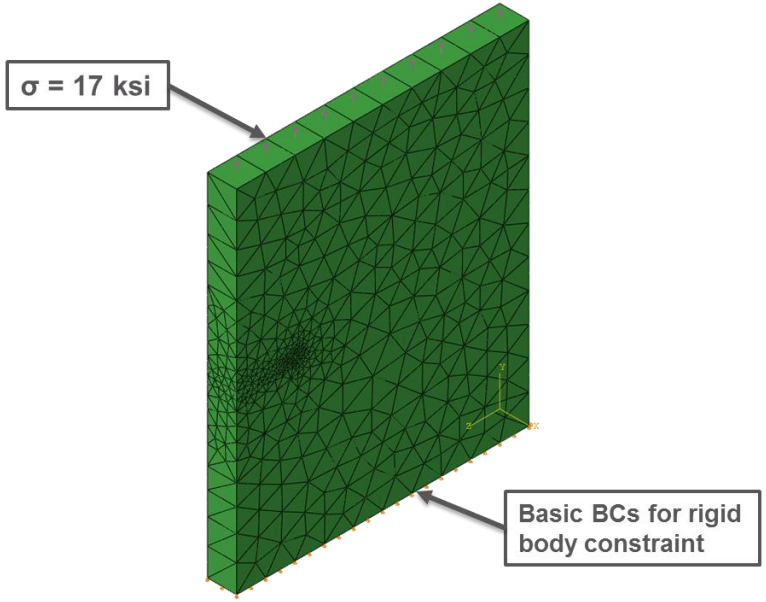
h = 0.75
b = 1.25
a = 0.25
t = 0.125

Material: E = 10.4 ksi, v = 0.33
Loading: 17 ksi tensile load

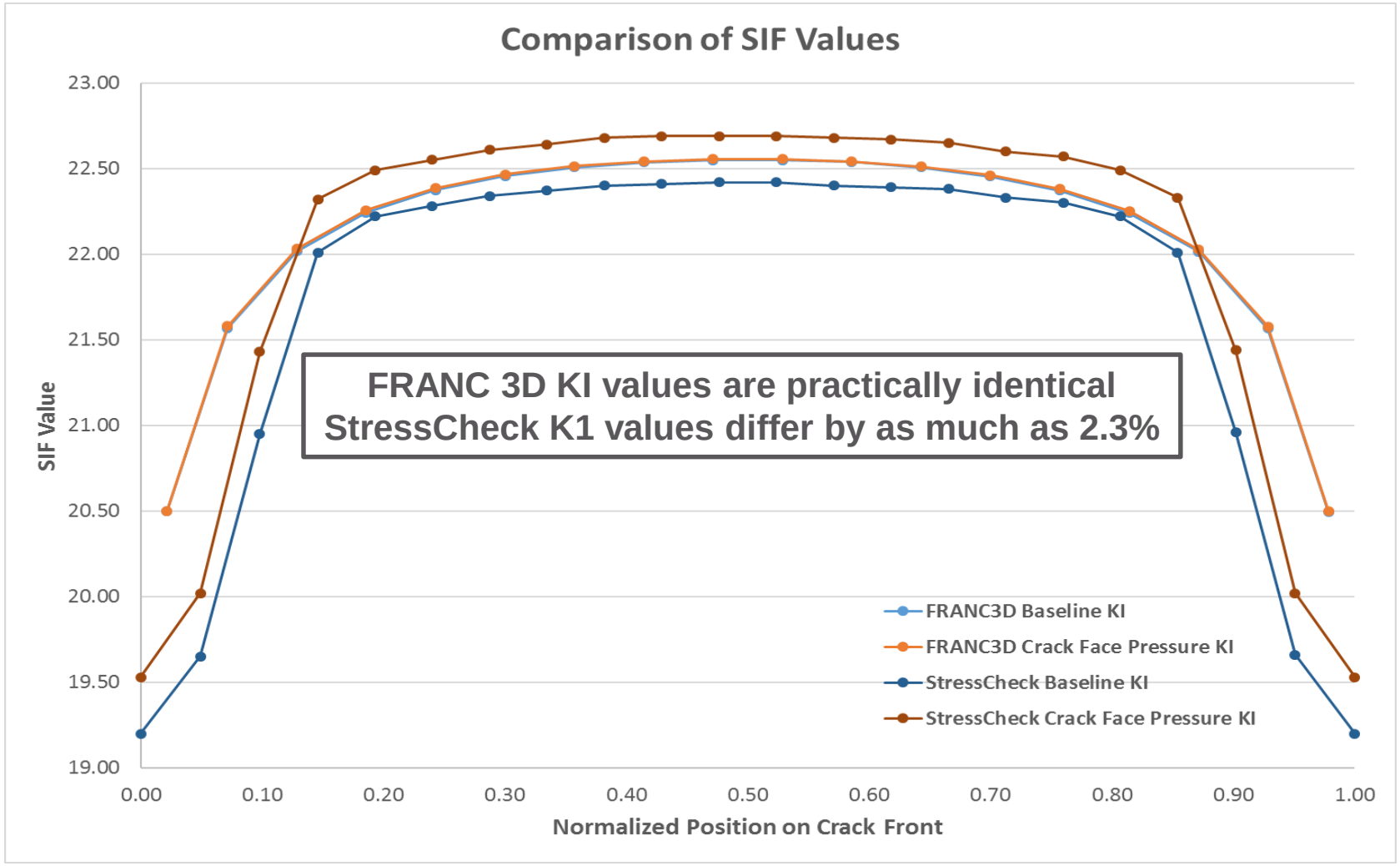
FT05: Mesh and Load

- **Baseline Case:**
  - The model/mesh shown to the right was subject to a 17 ksi tensile load
  - The SIF results for KI were calculated
  - StressCheck requires crack face traction to be input as formulae





FT05: KI Results

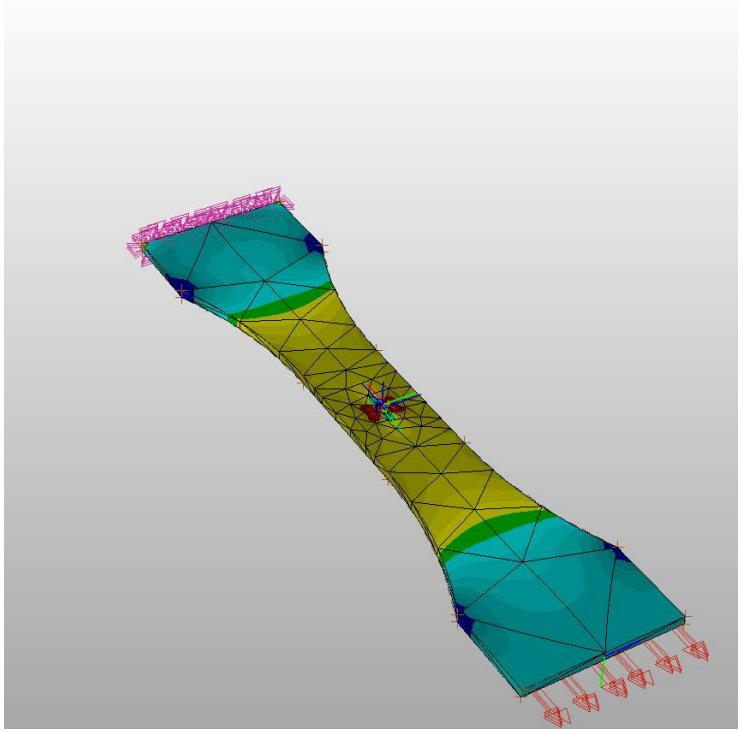


Summary

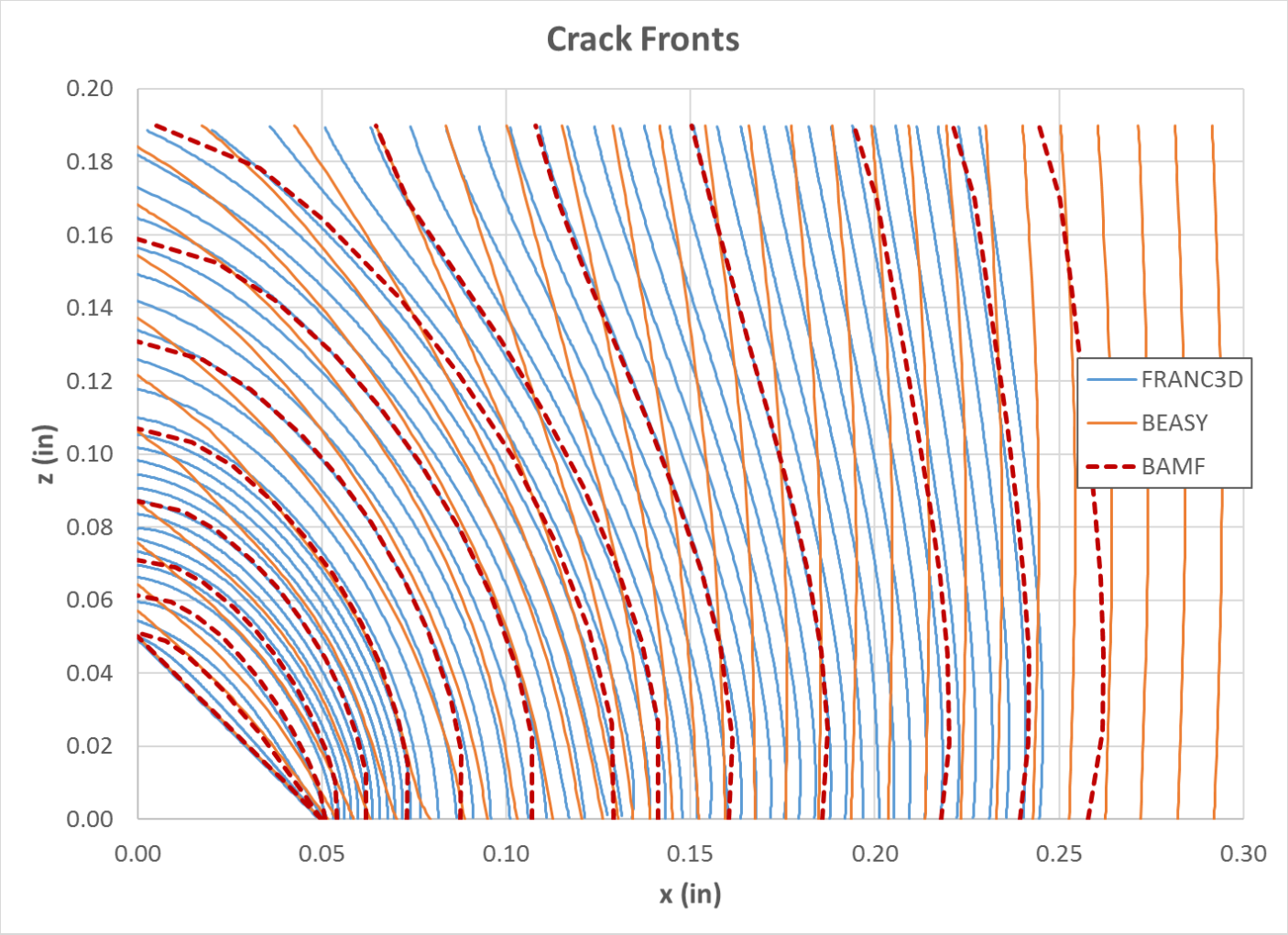
- Multiple Benchmarks Completed between Three Different Software Suites
  - BAMF – StressCheck P-element based Finite Element, AFGROW
  - BEASY - Boundary Element, Internal Crack Growth
  - FRANC3D – H-element based Finite Element, Internal Crack Growth
- Stress Intensity Comparisons to Handbook Solutions Demonstrated Accuracy within ~0.5%
- Different Methods are Employed to Smooth Crack Front and/or Stress Intensities
- Overall, Consistent Crack Growth Predictions are Observed with Some Noted Differences
- Far Field vs. Crack Face Traction Comparisons were Completed with Mixed Results

Future Plans

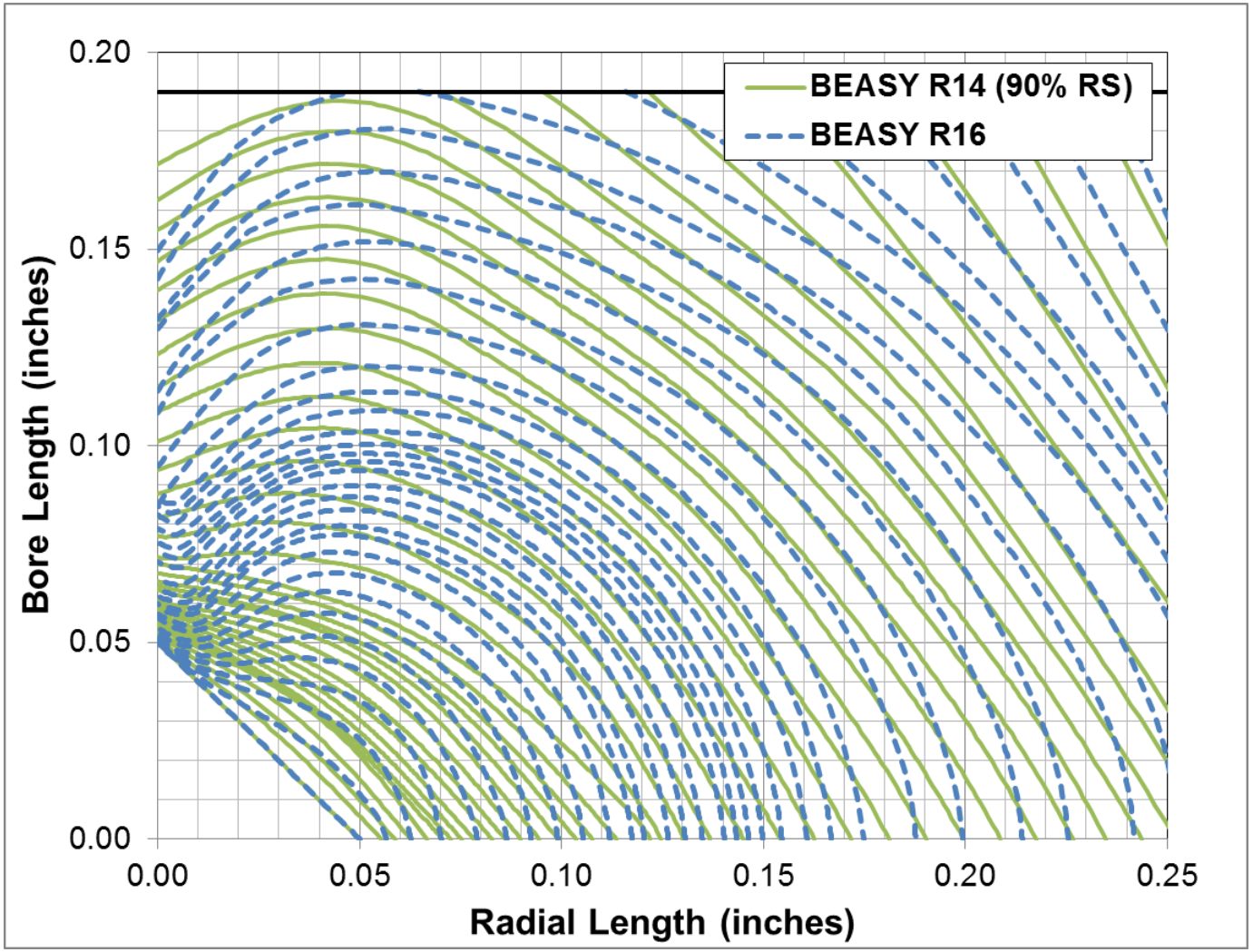
- **Investigate Differences Noted in Benchmark Cases Completed**
  - Engage in discussions with focals for each software suite
- **Additional Benchmarks:**
  - Open Hole in a Plate (non-coldworked)
  - Open Hole in a Plate (coldworked)
  - Complex Geometry
  - Complex Geometry with Residual Stress
- **Compare:**
  - Life Prediction
  - Crack Shape Evolution
  - Additional Features:
    - Retardation
    - Complex loading
    - Multiple crack fronts



Future Plans



Future Plans



Questions?

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