Implementation of Commercially Available MPFM Codes Within Existing Crack Growth Analysis Toolsets

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September 14, 2022

Agenda

- Overview
- Background
- Implementation
- Results Comparison
- Conclusions

Overview

- NG-11 program objective is to validate and assess capability of commercial off-the-shelf and proprietary multi-point fracture mechanics codes as applied to the linear elastic fracture mechanics (LEFM) analysis of cold-expanded (Cx) holes.

- Multi-Point Fracture Mechanics (MPFM) is an enabling technology that can reduce conservatism in component life assessments at cold-expanded (Cx) fastener holes that drive durability and damage tolerance (DaDT) analyses, to the benefit of the aerospace design and sustainment community.

- NG-11 aims to foster adoption of MPFM by implementing commercially available MPFM software using existing, common crack-growth-analysis toolsets, would allow broader adoption of these methodologies by increasing compatible crack-growth-analysis engines.

Background
NG-11 Program Summary

- NG-11: Verification, Validation, and Demonstration of commercially available Multi-Point Fracture Modeling software is the analytical portion of concurrent testing and analysis efforts.
  - The testing effort, led by the Air Force Research Laboratory, consists of a series of fatigue tests that increase in complexity in a building block fashion.
  - The analytical effort, NG-11, seeks to perform blind predictions to these tests.

- In combination these efforts comprise an approach to perform verification and validation (V&V) of multi-point fracture mechanics (MPFM) analysis methods in a manner consistent with incorporation on USAF weapons systems.
  - Analytical effort led by Northrop Grumman Aeronautics Systems (NGAS) supported by Hill Engineering LLC and Fracture Analysis Consultants Inc.

Background
NG-11 Program Team

NG-11 is being performed as part of the Metals Affordability Initiative (MAI) and is being performed cooperatively with a team of government and industry participants.

Team:

AFRL: Dr. Eric Burba, Dr. T. J. Spradlin, Dr. Reji John
NGC: Adam Morgan, Juan Perez-Narvaez, Cassidy Fitzpatrick
HE: Renan Riberio, Josh Hodges, Dr. Adrian Dewald, Dr. Mike Hill, Robert Pilarczyk
FAC: Dr. Paul 'Wash' Wawrzynek, Dr. Bruce Carter

Background
Multi-Point Fracture Modeling

MPFM is an enabling technology that explicitly models arbitrary cracks, under arbitrary loads, in arbitrary bodies.

- Reduces assumptions (and conservatism) characteristic of legacy crack growth analysis methods.
- Has been a major factor in demonstrating fleet viability in the face of groundings in the past.
- Has been identified as a key technology on the path to fully exploit the benefit from residual stresses in fleet management and sustainment.

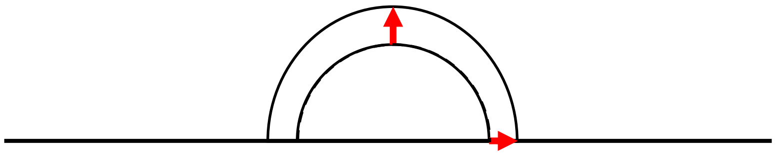
Background
Multi-Point Fracture Modeling

- Utilizes multiple points along a crack front in a finite element model to assess the crack driving force and the resulting increase in crack length.

TRADITIONAL

$$K_a = f(a, c)$$

$$\Delta_a = f(\Delta K_a)$$



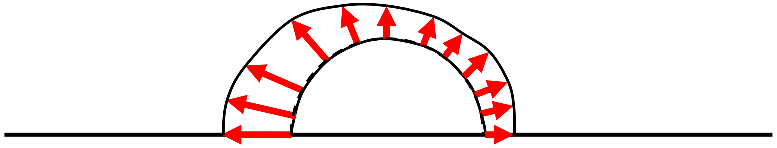
$$\Delta_c = f(\Delta K_c)$$

$$K_c = f(a, c)$$

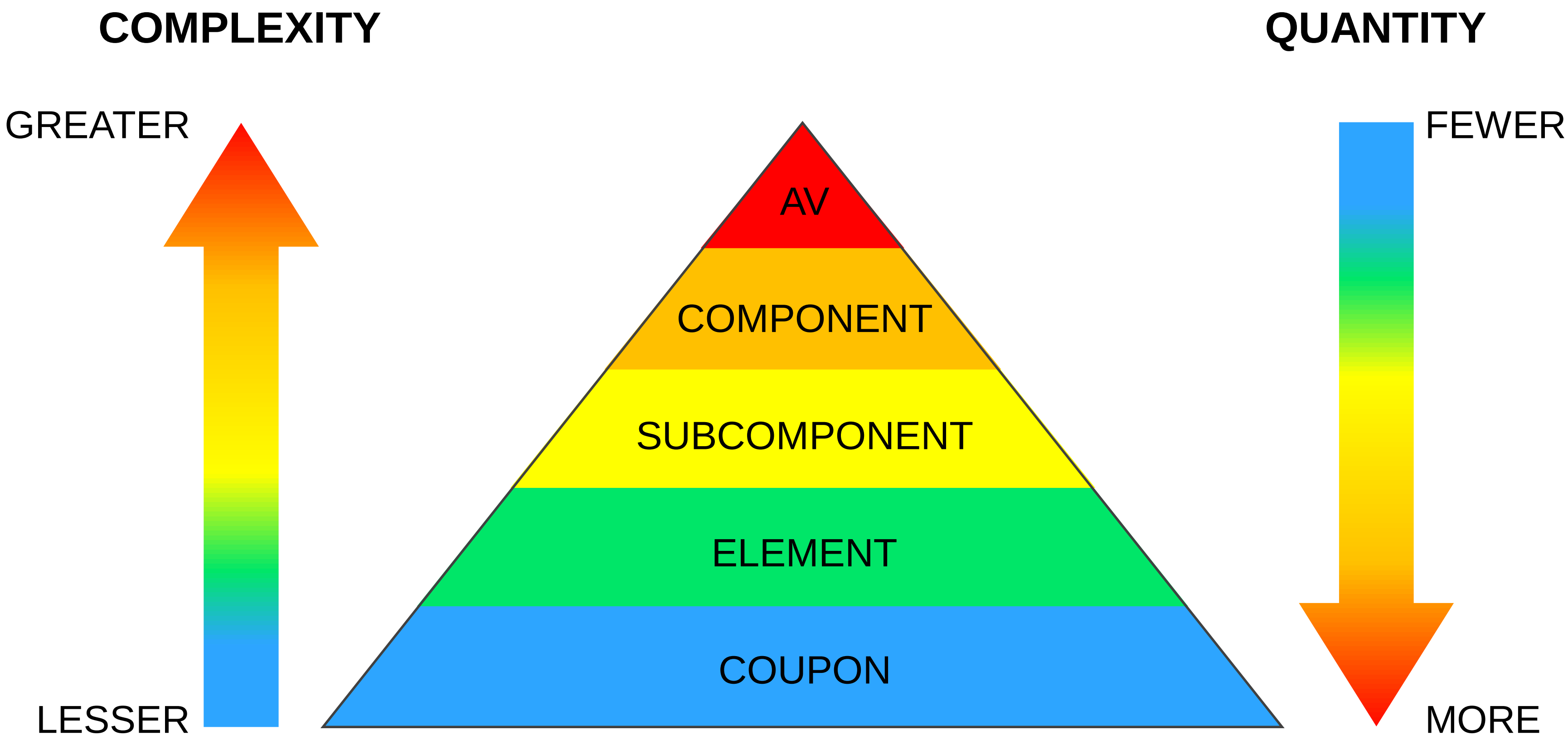
MPFM

$$K_n = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$\Delta_n = f(\Delta K_n)$$

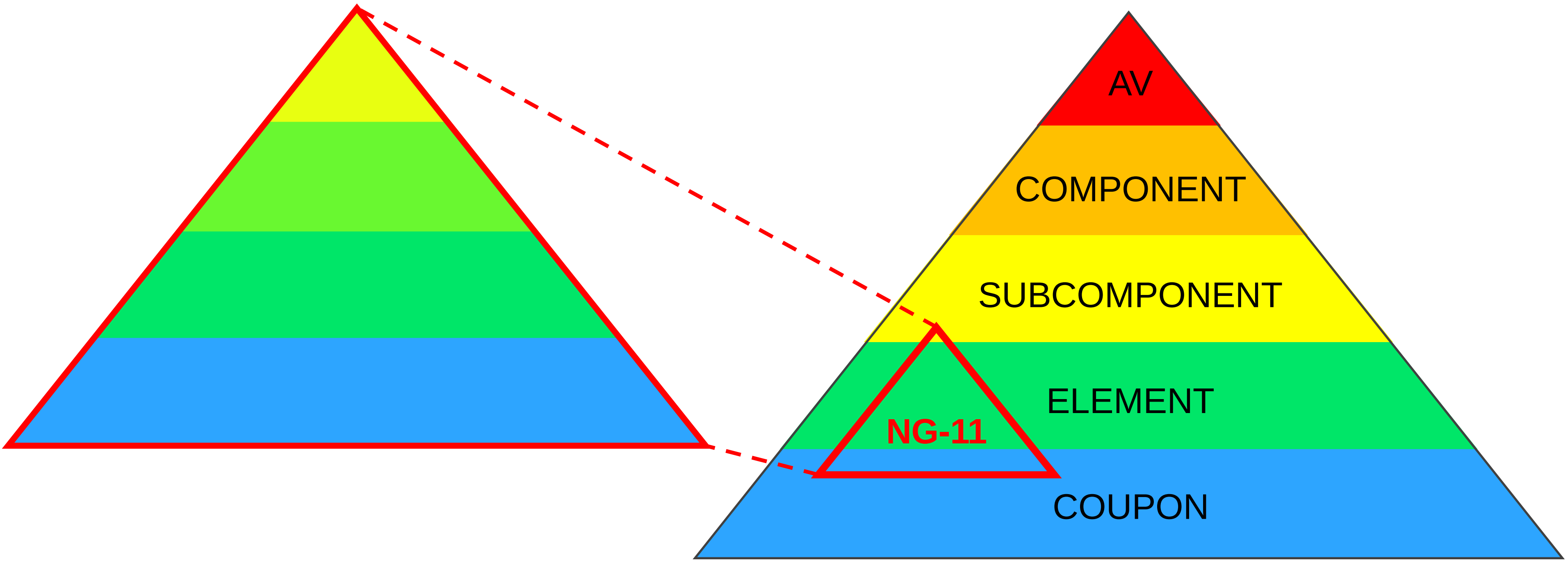


Background
Building Block Approach



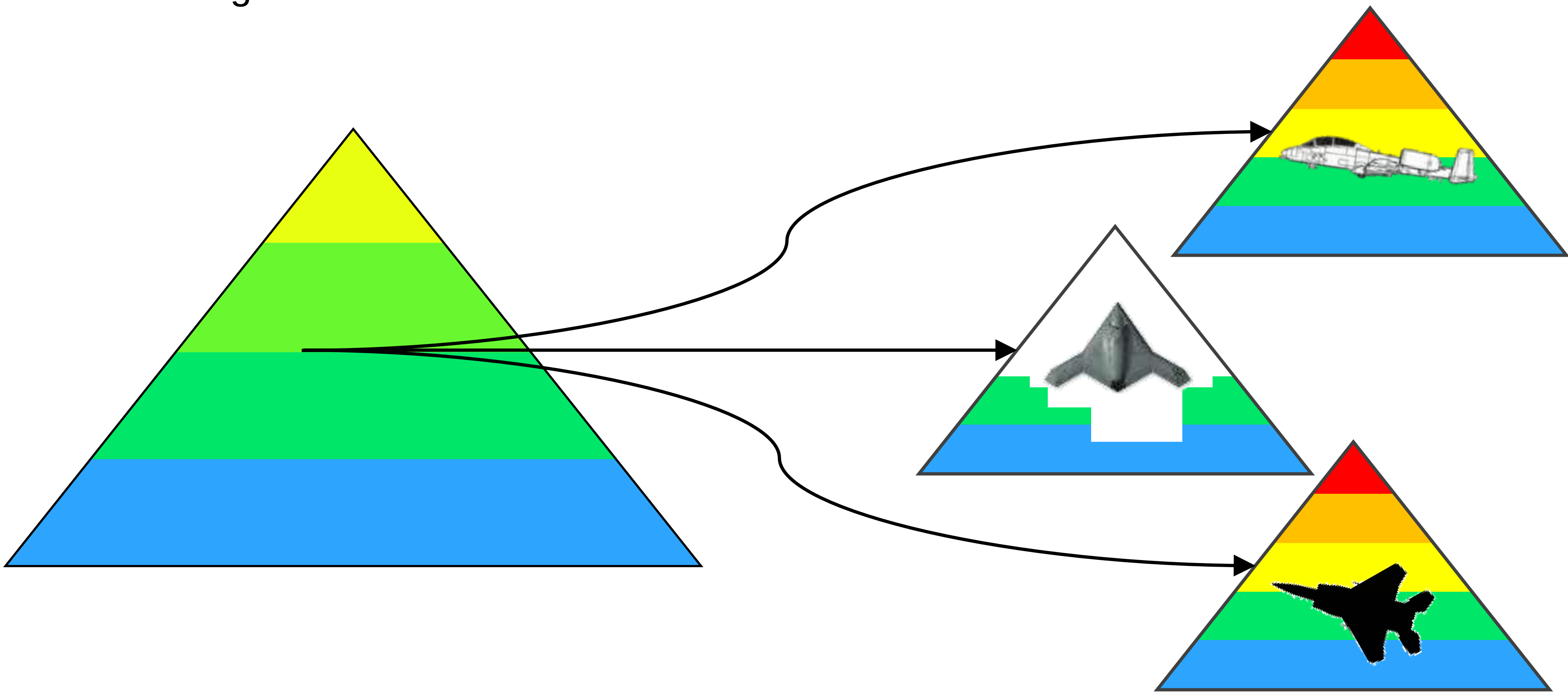
Background
Building Block Approach

- NG-11 is primarily element-level tests (of increasing complexity) with limited coupon-level test.



Background
Building Block Approach

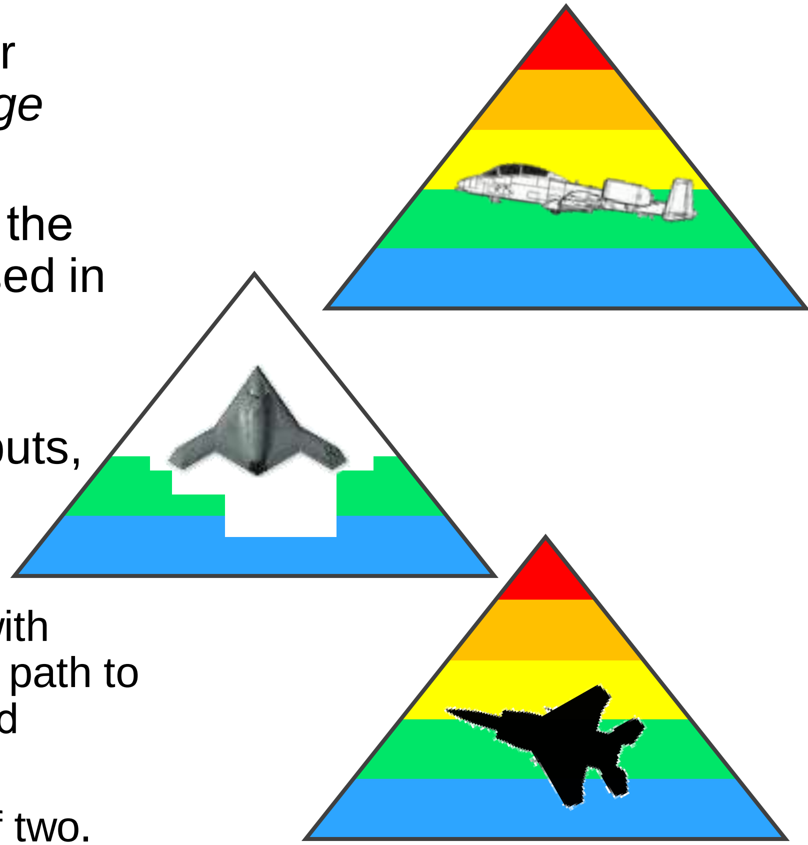
- NG-11 can be used as an integral part of existing and/or future program Building Block activities.



Background
Building Block Approach

ASIP managed programs *should* be using and/or developing "*validated analysis models for damage growth*", [MIL-STD-1530D].

- "*Validated analysis model*" can be considered the collection of inputs, tools, and assumptions used in crack growth analysis.
- Ideally, stress intensities from MPFM can be integrated into these existing collections of inputs, tools, and assumptions.
  - Many program unique challenges exist.
  - Demonstrating the integration of MPFM codes with external crack growth analysis codes provides a path to incorporating MPFM as part of existing "validated analysis models."
  - Maintain one set of tools/assumptions instead of two.



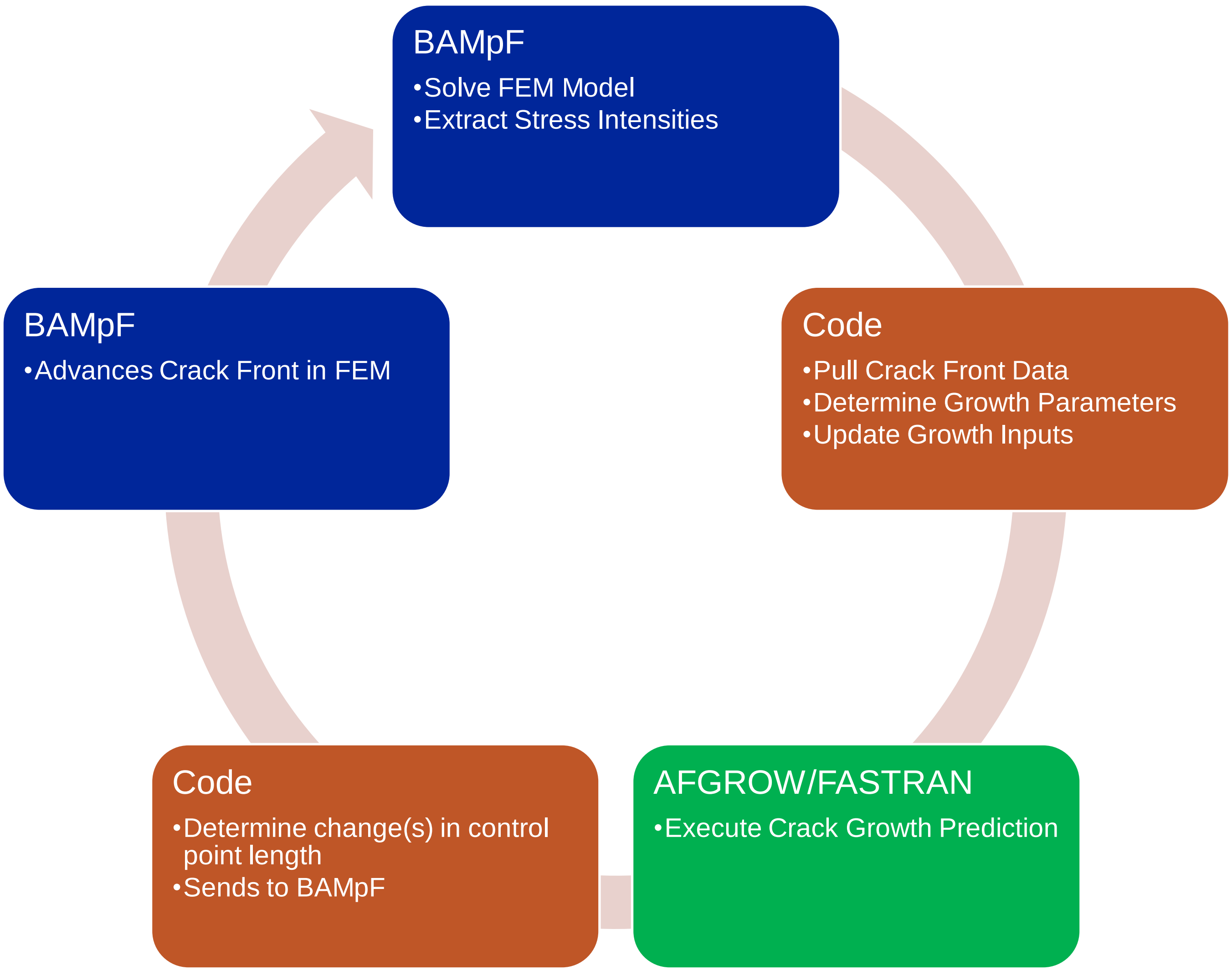
Background
Software Used

- <u>Crack Growth Solvers:</u>
  - AFGROW
  - FASTRAN
- <u>Multi-Point Fracture Modeling (MPFM) Codes:</u>
  - BAMpF w/ StressCheck
  - FRANC3D w/ NX NASTRAN
- <u>Other Software:</u>
  - Excel (VBA)
  - Python v3.9
    - Pywin32(-303) for AFGROW COM usage

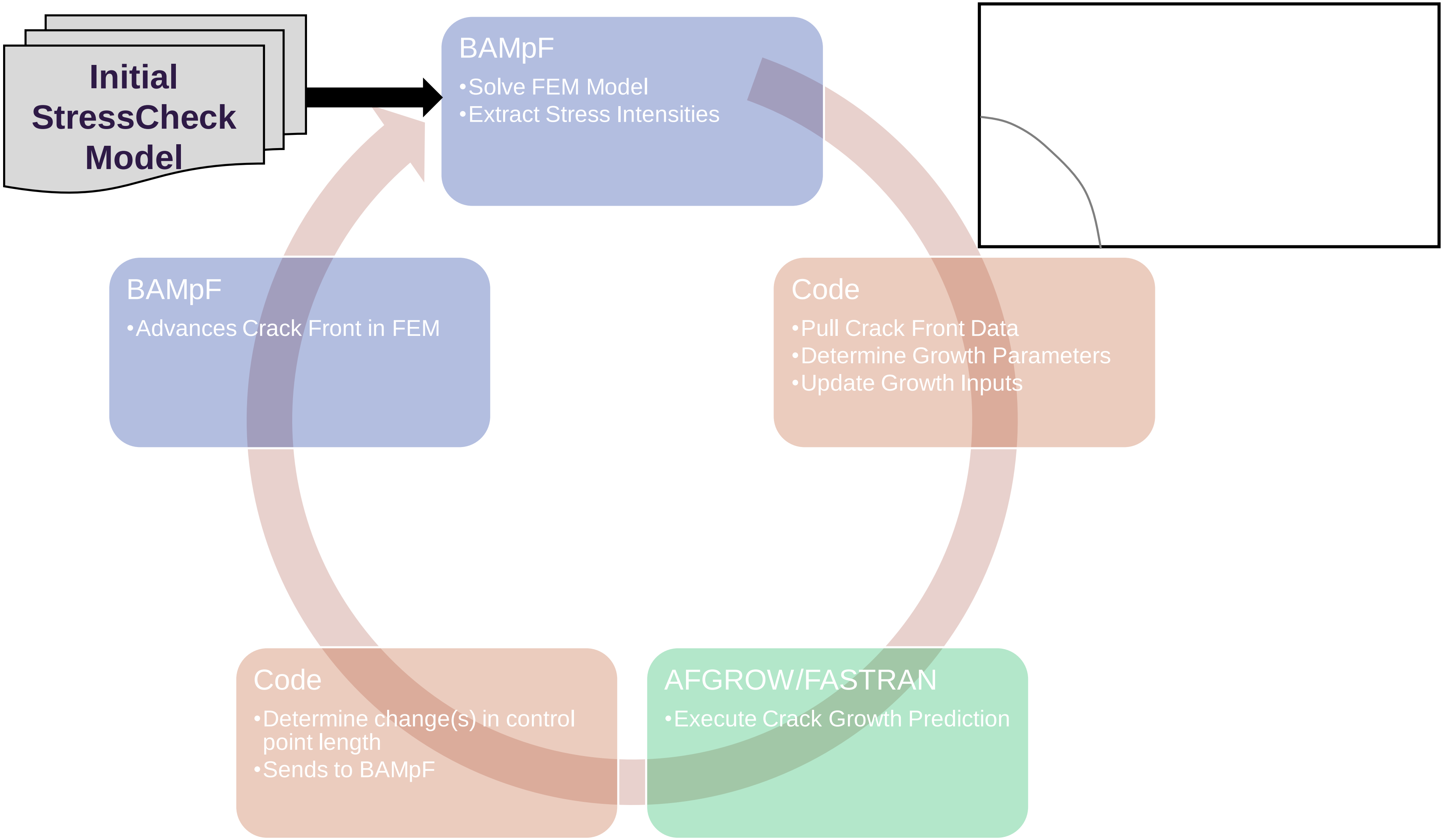
Implementation
BAMpF

- Provides an interface that enables crack growth analysis for complex geometry and loading using MPFM.
  - Supports FE codes: ESRD StressCheck
- Allows for planar growth of cracks and can link up multiple cracks on model.
- Residual stresses can be included in crack growth assessments in a straightforward manner.
- Interfaces with ESRD StressCheck to get stress intensity factors for specific geometry and loading.
- Interfaces with AFGROW for crack growth life predictions.
- COM API for automation capability.

Implementation
BAMpF Com Interface Code Diagram



Implementation
BAMpF Com Interface Code Diagram



Implementation
BAMpF Com Interface Code Diagram

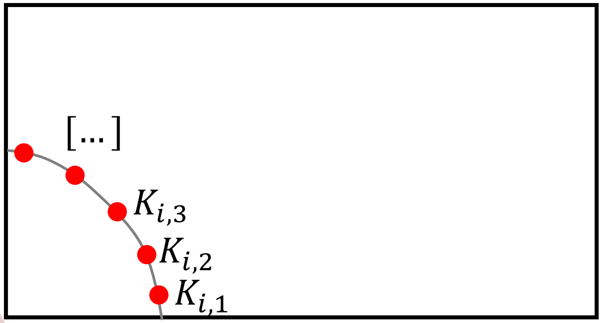
BAMpF
- Solve FEM Model
- Extract Stress Intensities

Code
- Pull Crack Front Data
- Determine Growth Parameters
- Update Growth Inputs

AFGROW/FASTRAN
- Execute Crack Growth Prediction

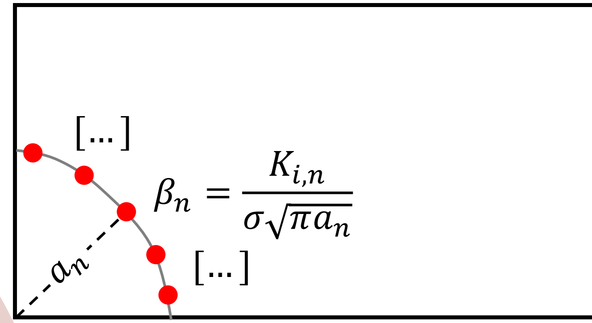
Code
- Determine change(s) in control point length
- Sends to BAMpF

BAMpF
- Advances Crack Front in FEM



Implementation

BAMpF Com Interface Code Diagram



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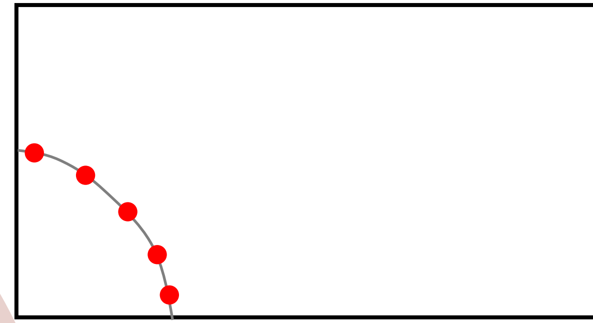

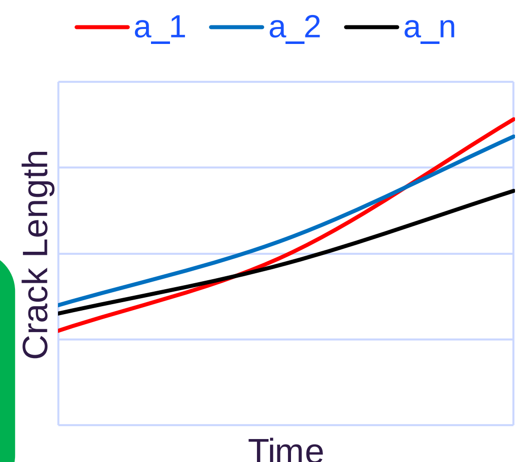

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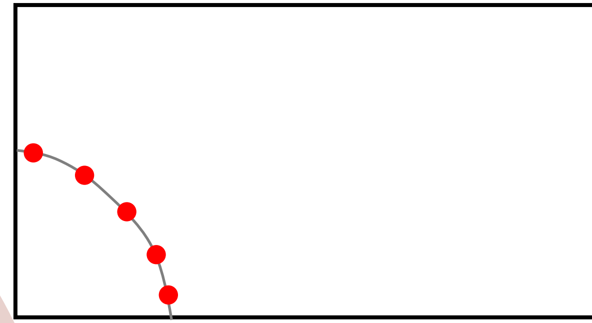
- Extract Stress Intensities



Code
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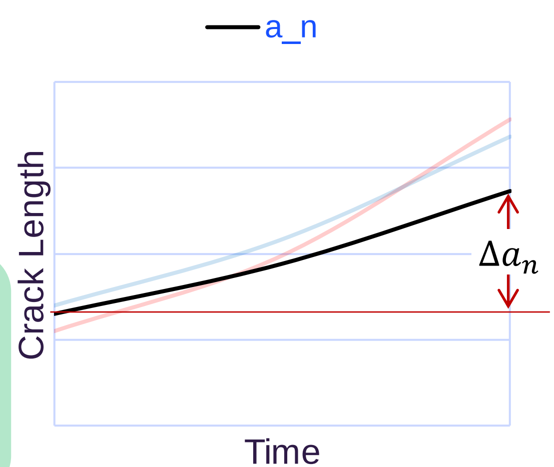
- Determine Growth Parameters
- Update Growth Inputs

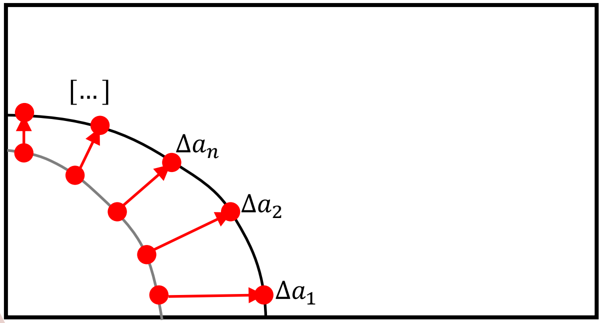


AFGROW/FASTRAN
- Execute Crack Growth Prediction

Code
- Determine change(s) in each control point's length
- Sends to BAMpF

BAMpF
- Advances Crack Front in FEM

Implementation
BAMpF Com Interface Code Diagram



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AFGROW/FASTRAN
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Code
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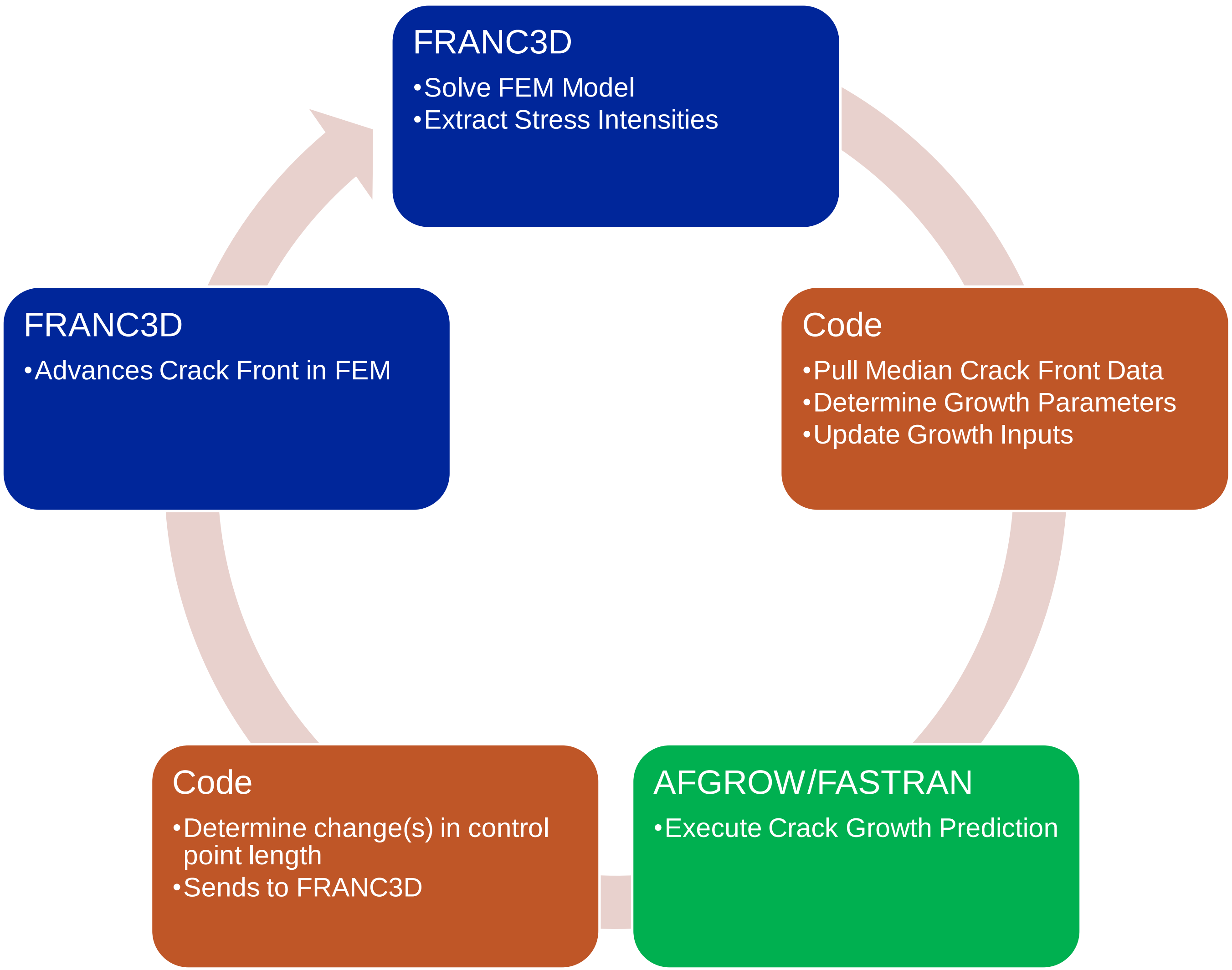
- Sends to BAMpF

BAMpF
- Advances Crack Front in FEM

Implementation
FRANC3D

- Internal crack growth and life prediction software that integrates linear and non-linear fracture mechanics with finite element methods.
  - Supports FE codes: ANSYS, ABAQUS, and NASTRAN
- Advanced geometry and mesh model representations with automatic mesh generation.
  - Global/Local mesh segregation
- 3D non-planar growth and multiple crack front support
  - Crack front smoothing/fitting
  - Multiple load step options: Cyclic, Temperature, Static, Residual stress
  - NASGRO library and tabular material data support
- Provides users with the stress intensity factors on the crack fronts
  - M-Integral, VCCT, Displacement Correlation
- Python API for automation capable

Implementation
FRANC3D Com Interface Code Diagram



Implementation
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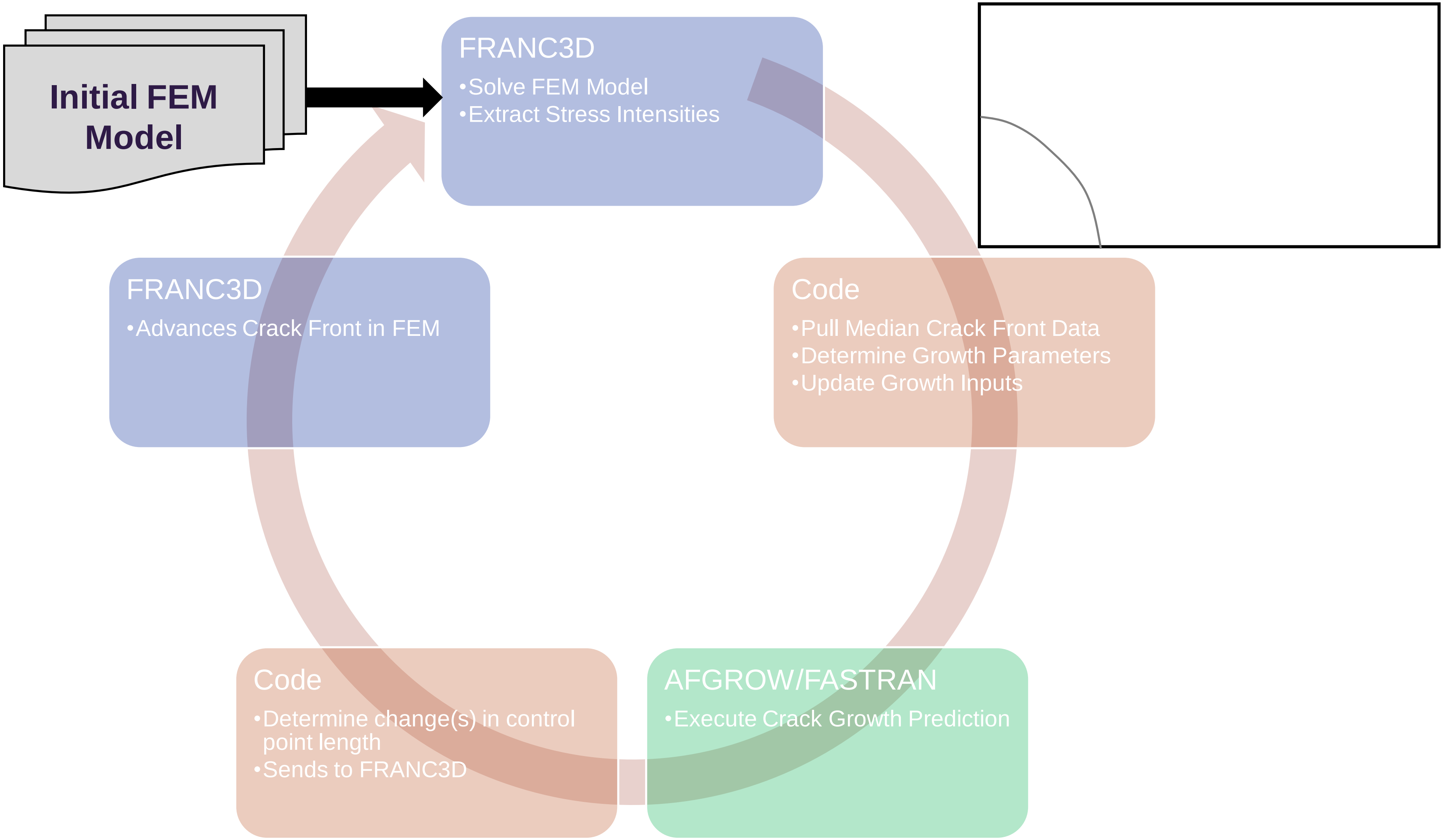
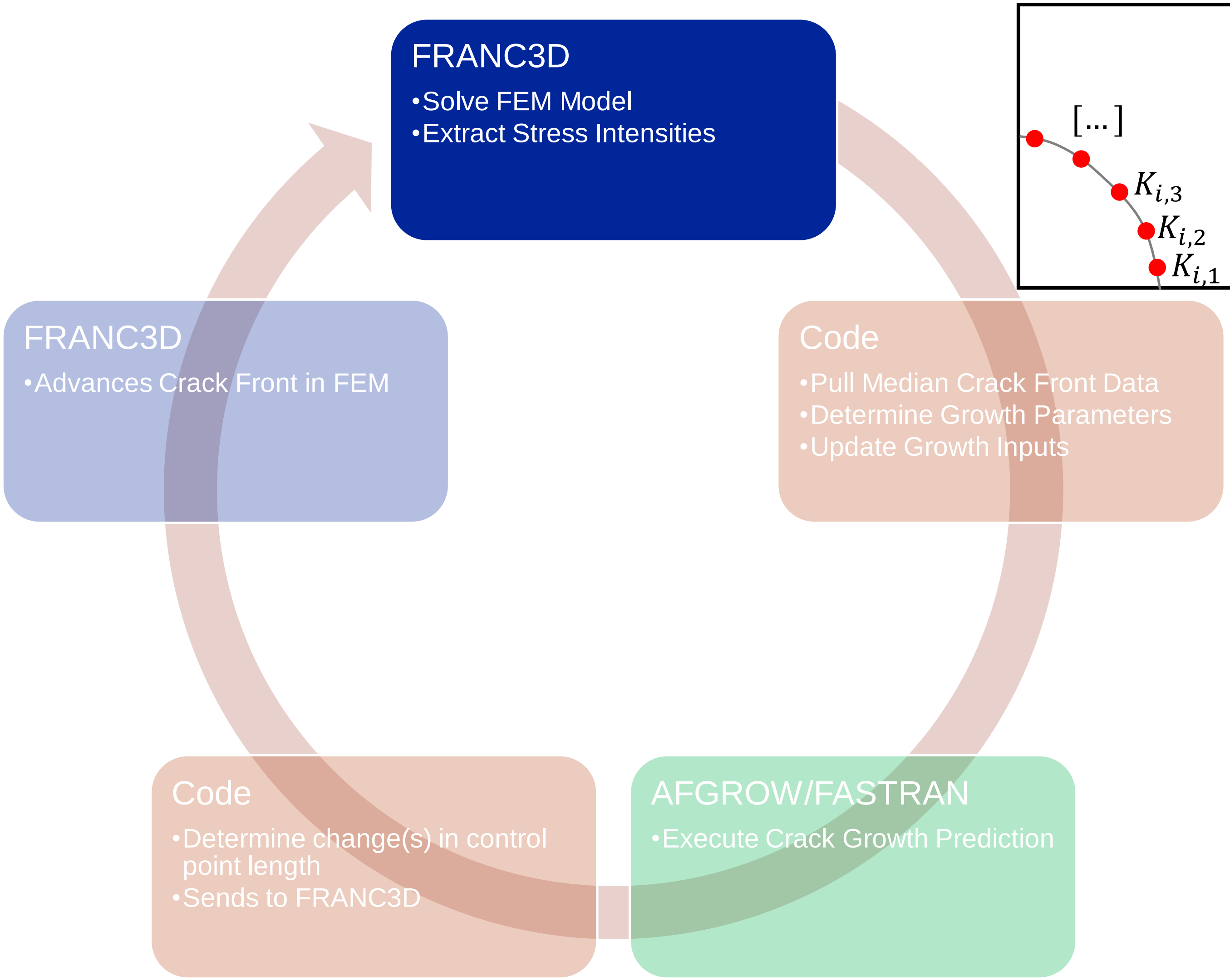
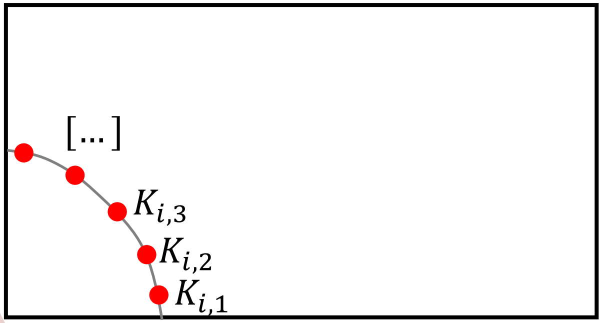


Implementation

FRANC3D Com Interface Code Diagram





Implementation
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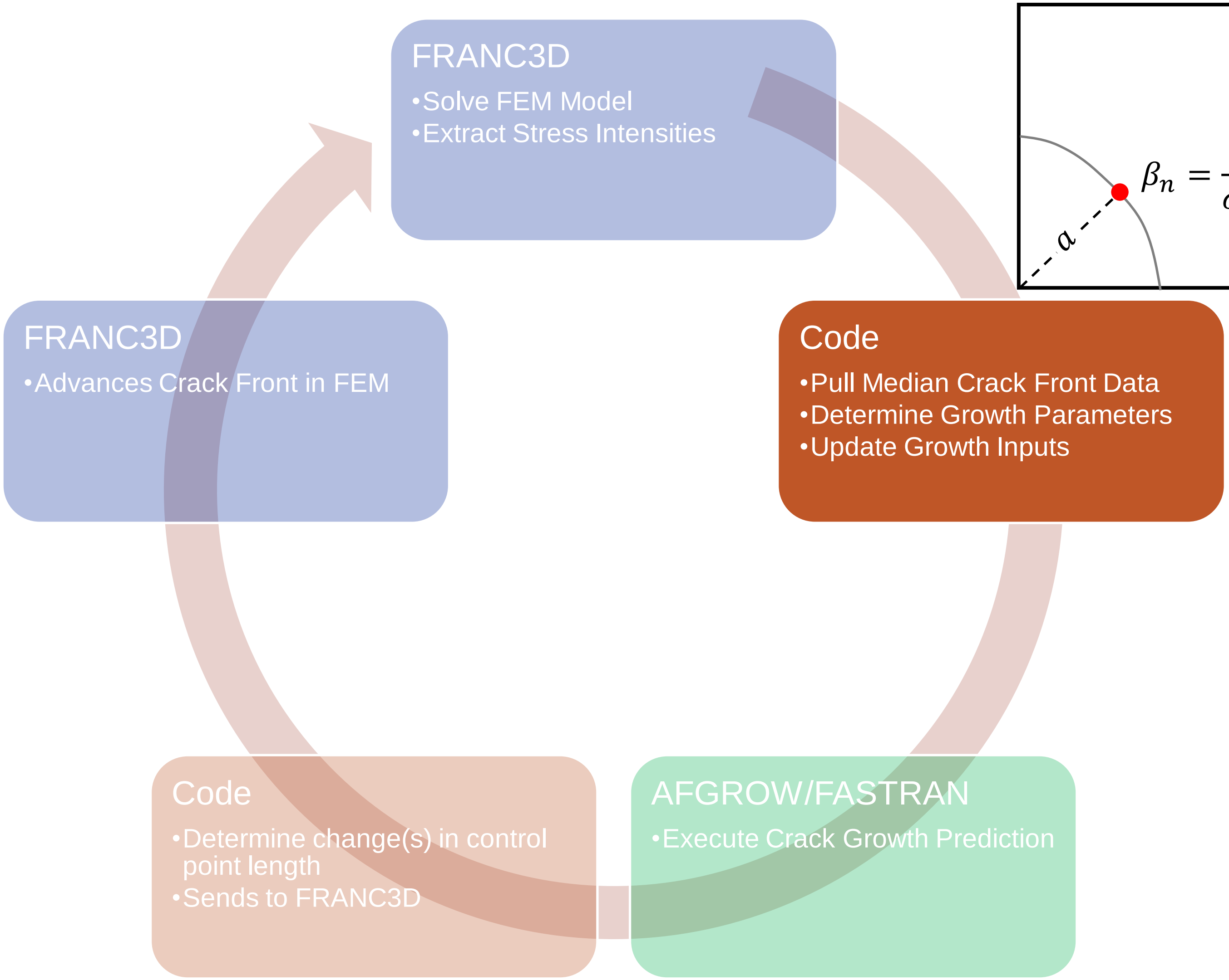
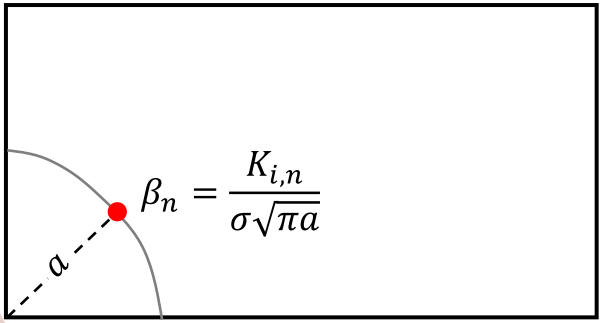




Implementation
FRANC3D Com Interface Code Diagram

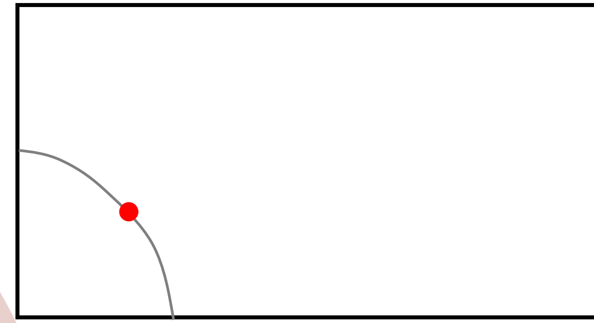
FRANC3D
- Solve FEM Model
- Extract Stress Intensities

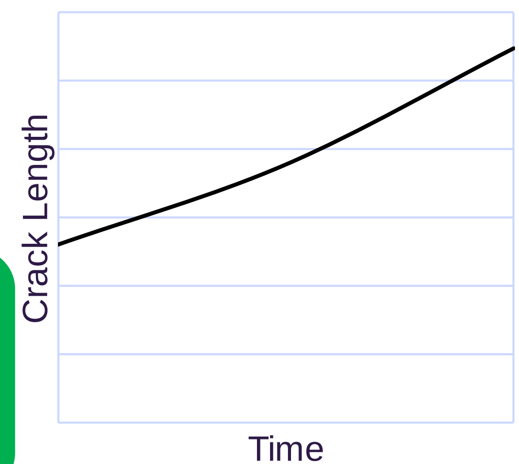
Code
- Pull Median Crack Front Data
- Determine Growth Parameters
- Update Growth Inputs

AFGROW/FASTRAN
- Execute Crack Growth Prediction

Code
- Determine change(s) in control point length
- Sends to FRANC3D

FRANC3D
- Advances Crack Front in FEM





Implementation
FRANC3D Com Interface Code Diagram

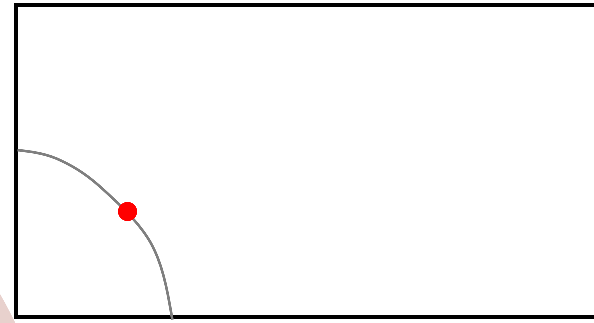
FRANC3D
- Solve FEM Model
- Extract Stress Intensities

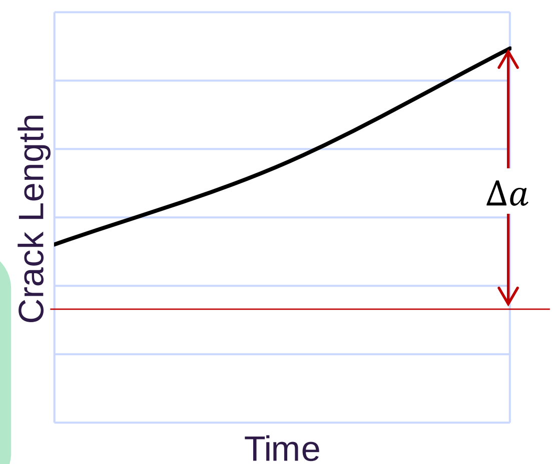
Code
- Pull Median Crack Front Data
- Determine Growth Parameters
- Update Growth Inputs

AFGROW/FASTRAN
- Execute Crack Growth Prediction

Code
- Determine change in median point's length
- Sends to FRANC3D

FRANC3D
- Advances Crack Front in FEM





Implementation

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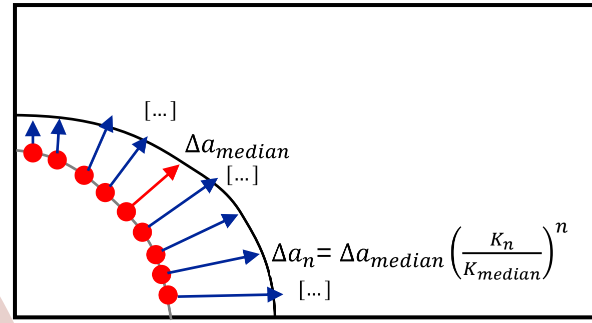


FRANC3D
- Solve FEM Model
- Extract Stress Intensities

Code
- Pull Median Crack Front Data
- Determine Growth Parameters
- Update Growth Inputs

AFGROW/FASTRAN
- Execute Crack Growth Prediction

Code
- Determine change(s) in each control point's length
- Sends to FRANC3D

FRANC3D
- Determines Other Control Point Extensions
- Fits equation to crack front extension
- Advances Crack Front in FEM

Implementation
Code Comparison

MPFM Software

- BAMpF
  - Solver: ESRD StressCheck
  - Crack Front
    - Consistent amount of extraction points throughout iterations
  - Solve time
    - Finishes predictions slower
    - ~10-12 hrs

- FRANC3D
  - Solver: NASTRAN
  - Crack Front
    - Amount of extraction points varies throughout iterations
  - Solve time
    - Finishes predictions faster
    - ~1-3 hrs

Crack Growth Solvers

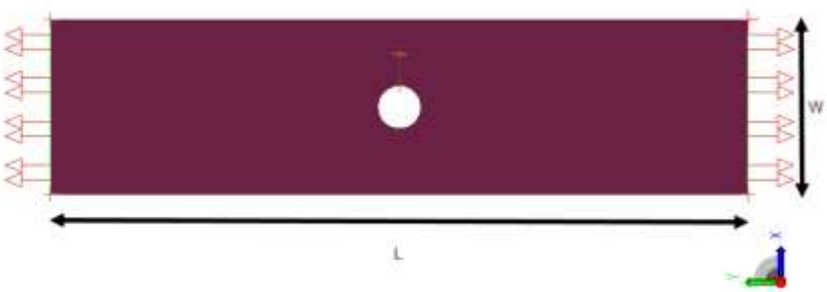
- AFGROW
  - Used VBA/Python for COM interface already incorporated within AFGROW
  - Created a base template model using Model 2000 User Defined Beta solution

  - Modified crack size and user defined betas after each iteration on the template file.

- FASTRAN
  - Modified text input files through VBA/Python after each iteration.
    - Modified crack size and user defined betas after each iteration in text file.
  - Ran FASTRAN using shell commands through cmd.exe
  - Extracted results from output text files.
  - Solutions 99 and -99 used.
    - Sol99 – User Defined Edge Crack
    - Sol-99 – User Defined Edge Crack at a Hole

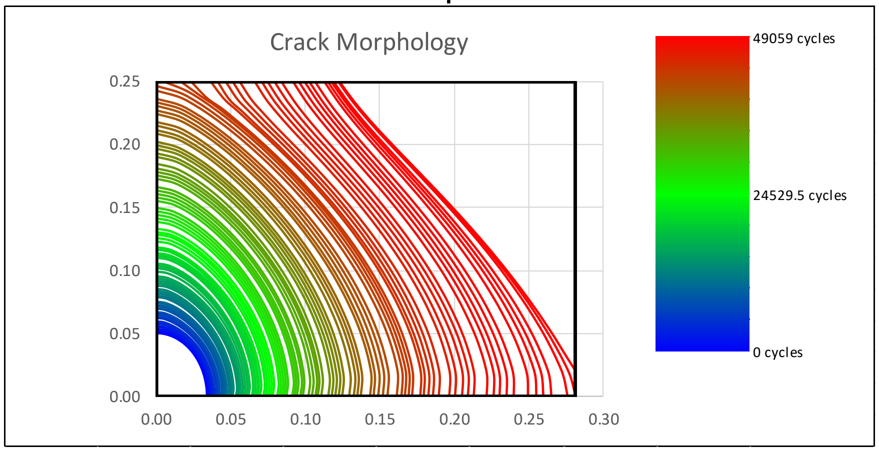
Results
Model Inputs

- Nominal Dimensions
  - Width (W) = 0.750”
  - Edge Distance (e) = 0.375” (centered hole)
  - Hole Diameter (D) = 0.1875” (3/16”)
  - Thickness (T) = 0.250”
  - Length (L) = 3.2”
  - Initial crack (a x c) = 0.05” x 0.034”
- Material
  - 7050-T7451 per AMS 4050
    - Young’s Modulus (E) = 10,300,000 psi
    - Poisson’s Ratio (v) = 0.33
- Loading
  - Constant Amplitude (CA): 15 ksi (Max Stress)
    - R=0.1
  - Variable Amplitude (VA): 20 ksi (Max Stress)

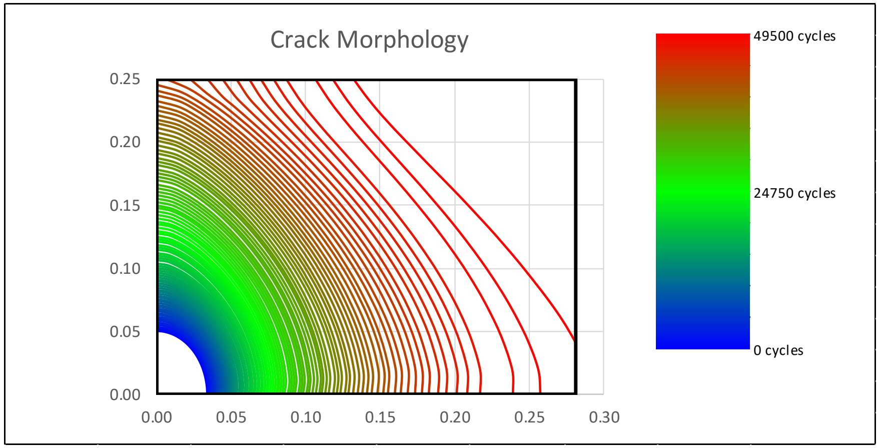


Results
BAMpF with AFGROW and FASTRAN (CA)

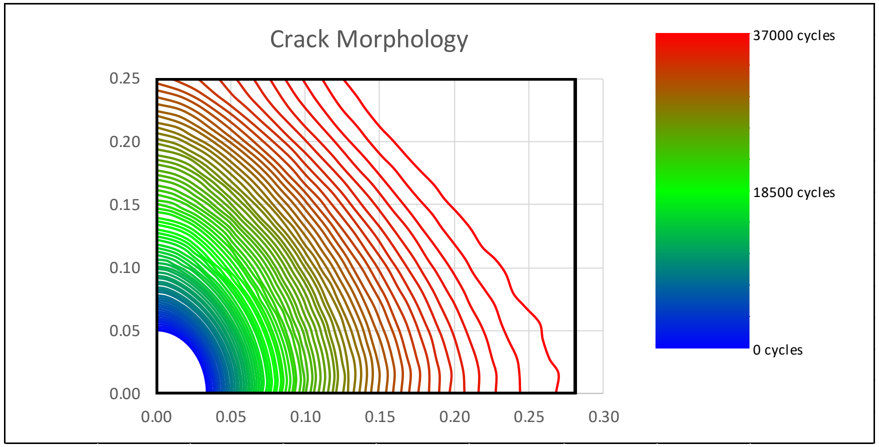
BAMpF



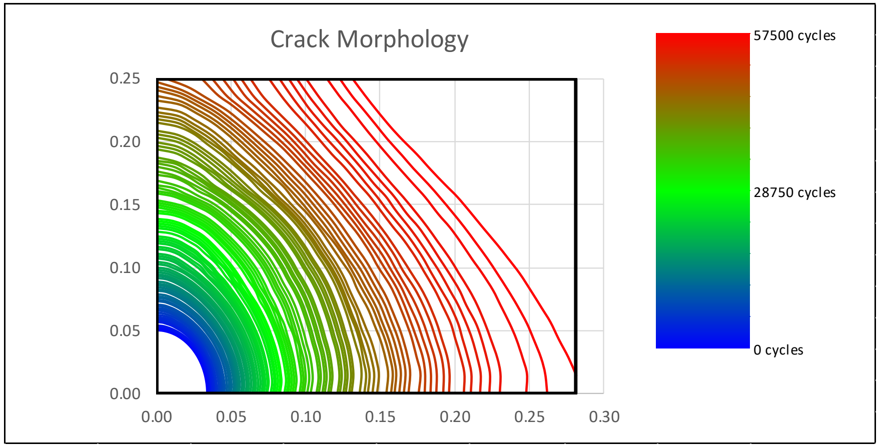
BAMpF_AFGROW



BAMpF_FASTRAN_SOL+99

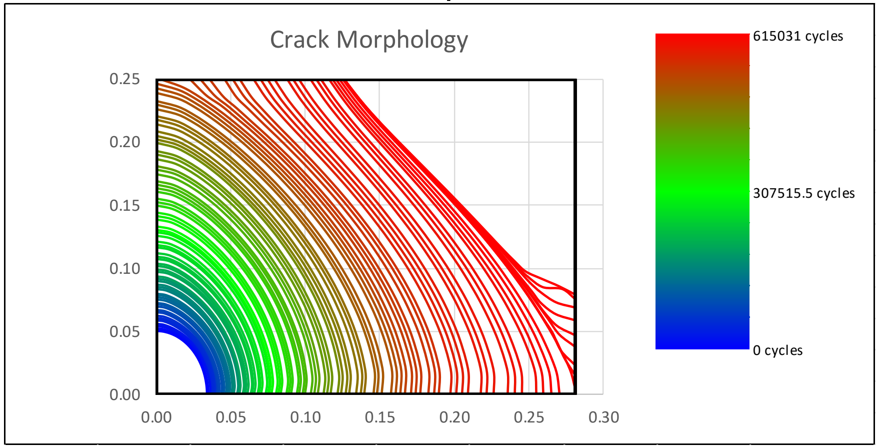


BAMpF_FASTRAN_SOL-99

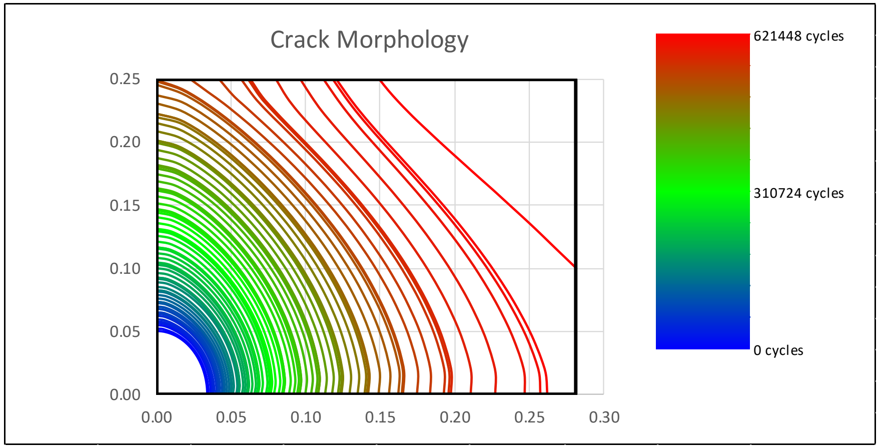


Results
BAMpF with AFGROW and FASTRAN (VA)

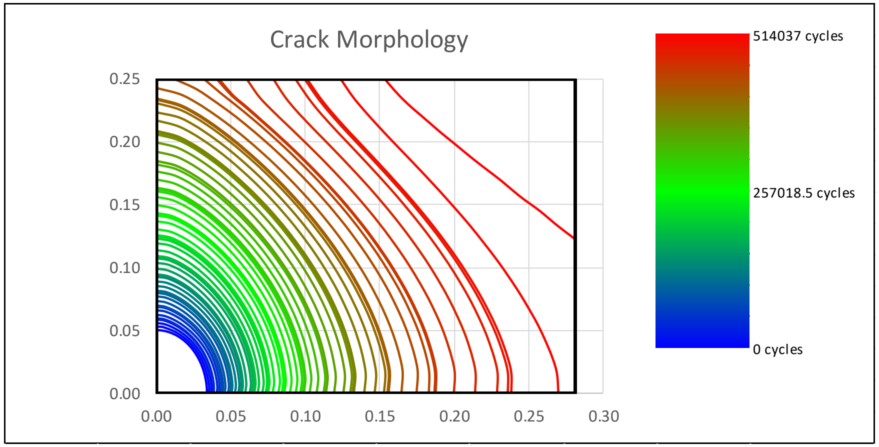
BAMpF



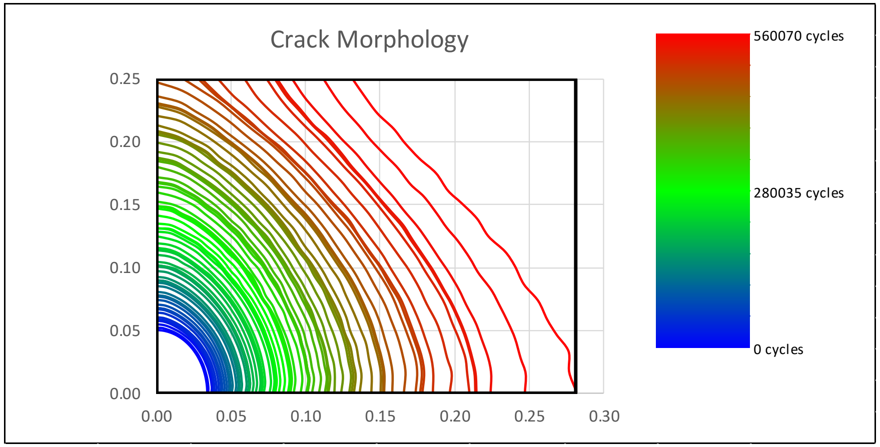
BAMpF_AFGROW



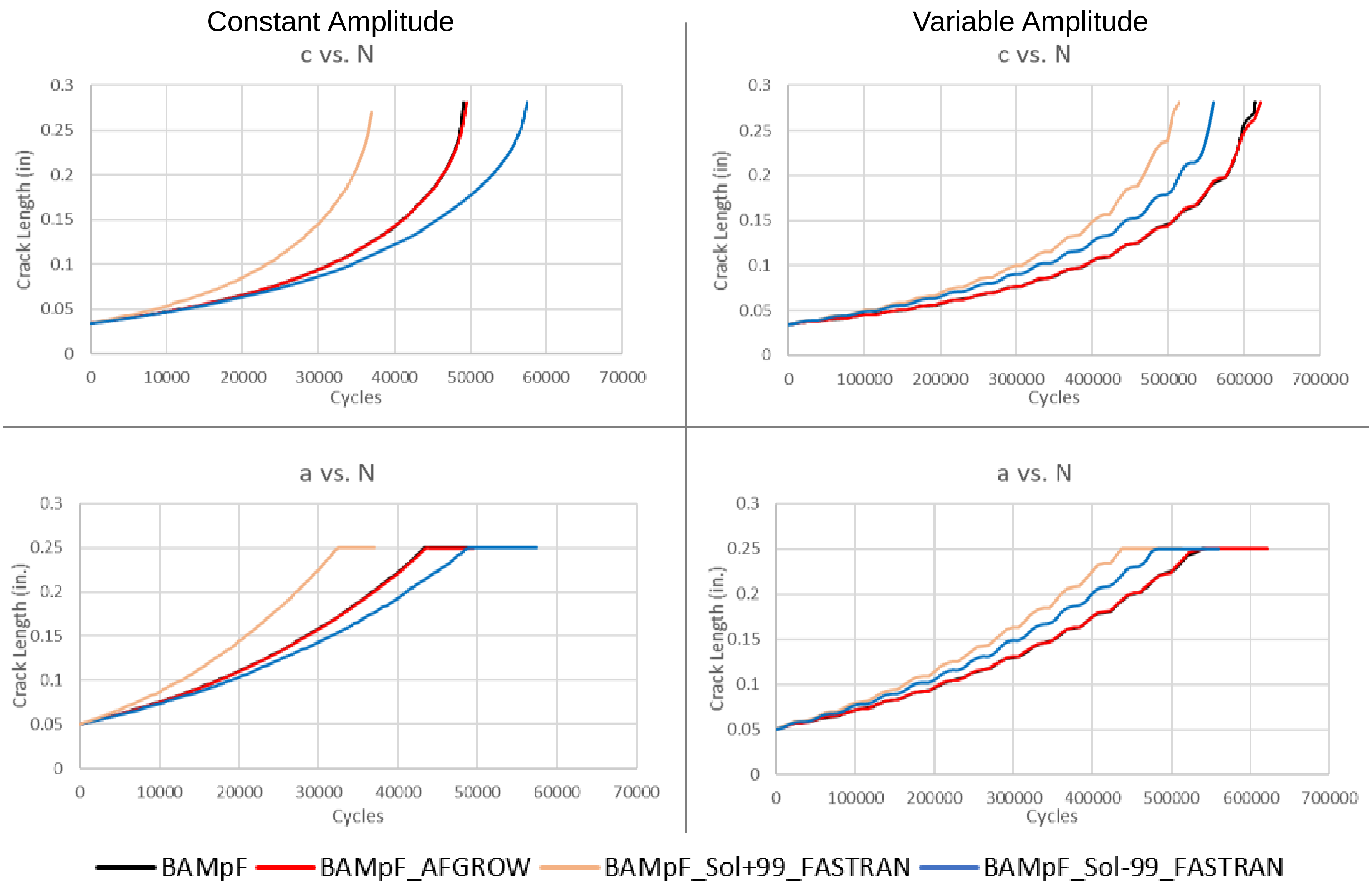
BAMpF_FASTRAN_SOL+99



BAMpF_FASTRAN_SOL-99

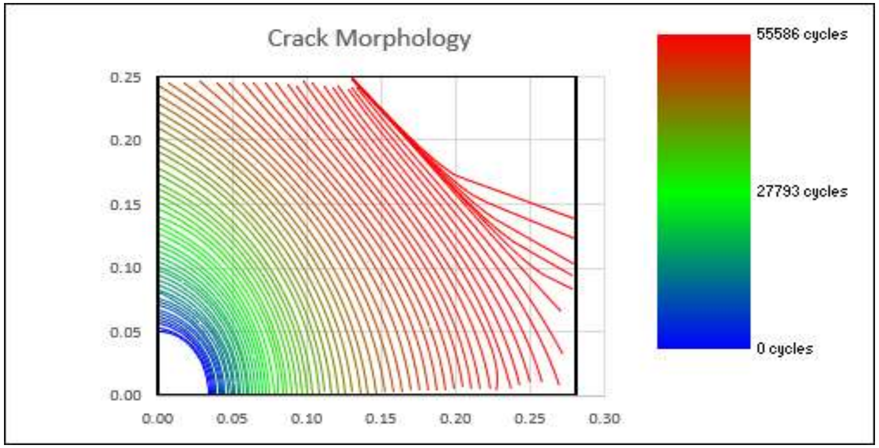


Results
BAMpF with AFGROW and FASTRAN

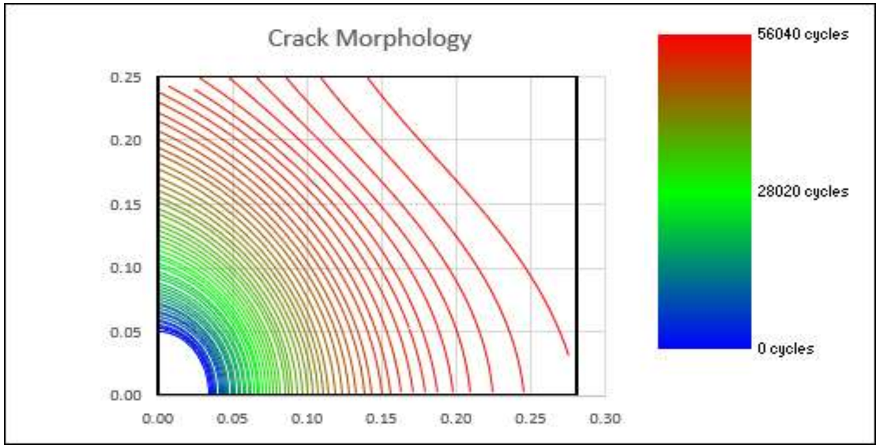


Results
FRANC3D with AFGROW and FASTRAN (CA)

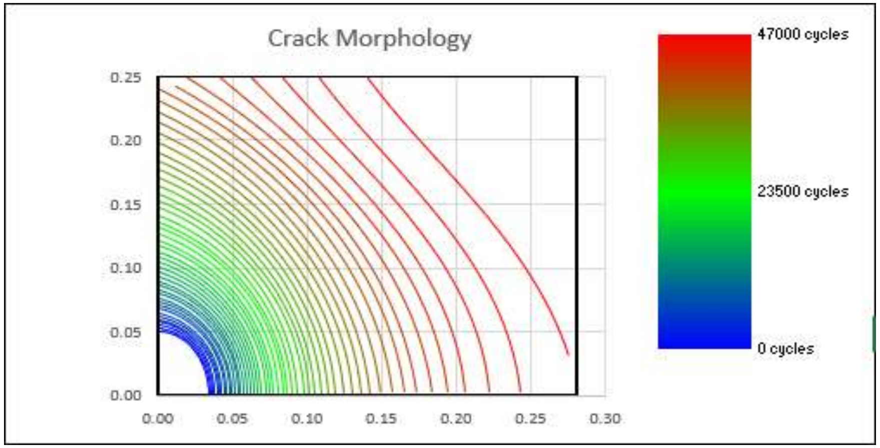
FRANC3D



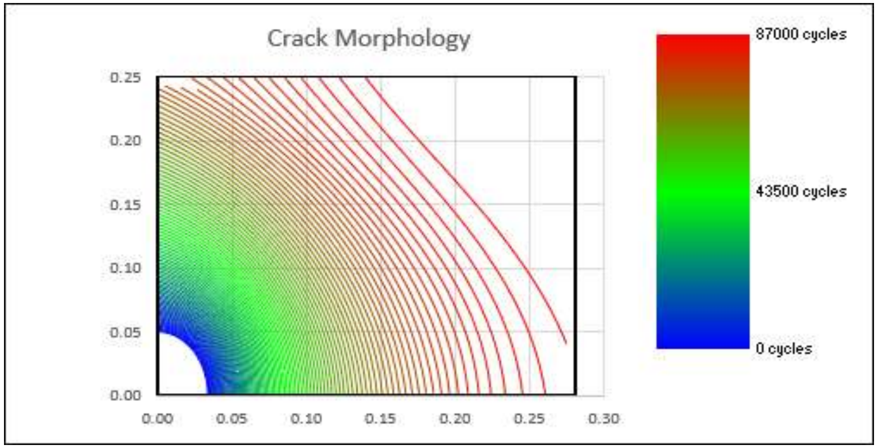
FRANC3D_AFGROW



FRANC3D_FASTRAN_SOL+99

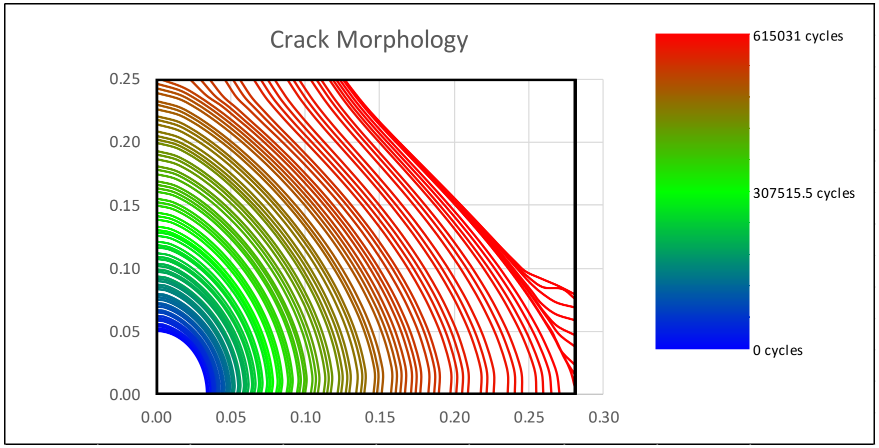


FRANC3D_FASTRAN_SOL-99

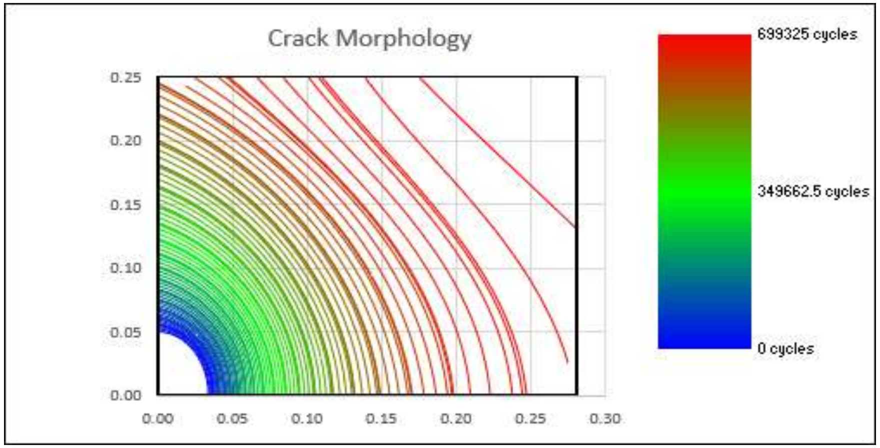


Results
FRANC3D with AFGROW and FASTRAN (VA)

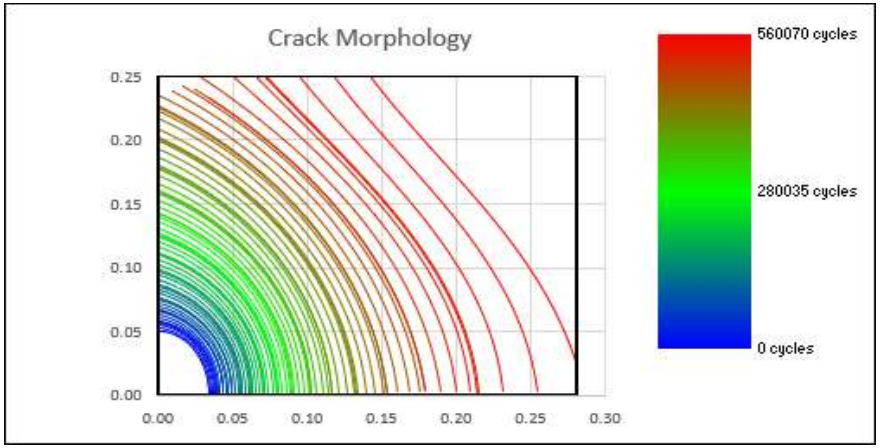
FRANC3D



FRANC3D_AFGROW



FRANC3D_FASTRAN_SOL+99



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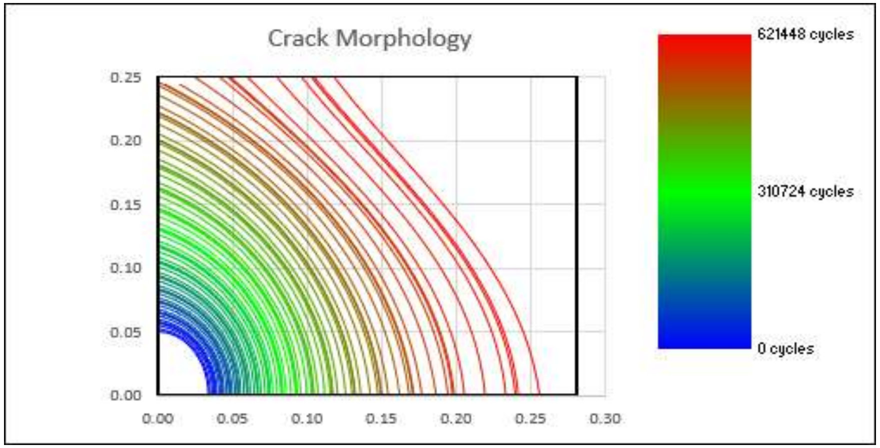
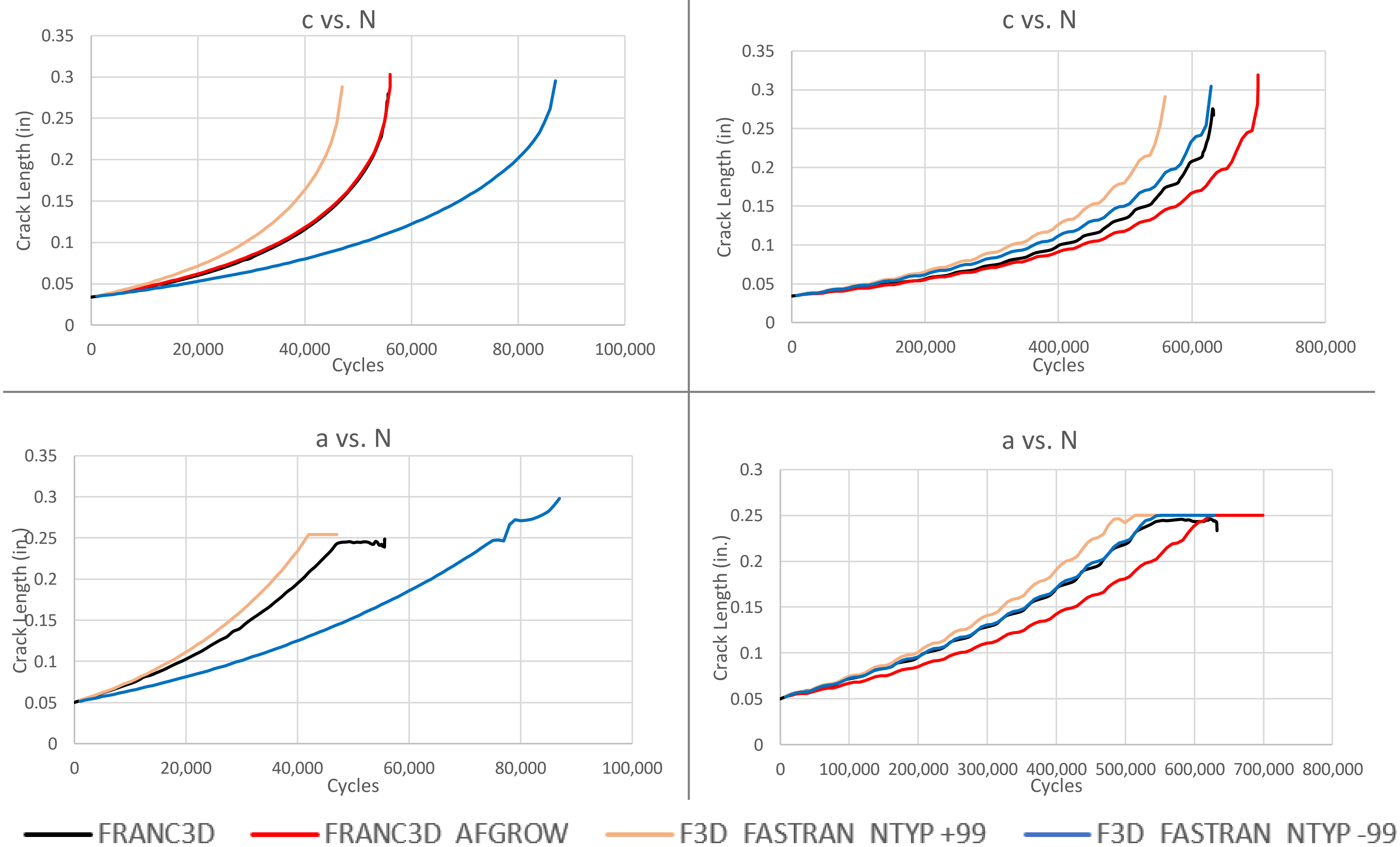


Results
FRANC3D with AFGROW and FASTRAN

Constant Amplitude

Variable Amplitude



Conclusions

- Successfully implemented commercially available MPFM codes within existing crack growth analysis toolsets.

- Crack growth results are comparable to the native MPFM analysis predictions.
  - Morphologies are consistent between BAMpF and FRANCD.
  - Run times are quite different.

- Differences shown when using FASTRAN are most likely due to dissimilar assumptions between the crack growth solvers. Further investigation is required to confirm the same assumptions are taken between toolsets and enable a more direct comparison.

- Future work for implementing external crack solvers with MPFM software:
  - Preferences such as retardation and crack closure included in the analysis predictions.
  - More robust features encompassed in the developed scripts.