Building Block Testing As Applied to Crack Growth Methods

An Application of Early Testing to Select Tools and Settings

Juan Perez-Narvaez
Principal Engineer, DaDT

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Agenda

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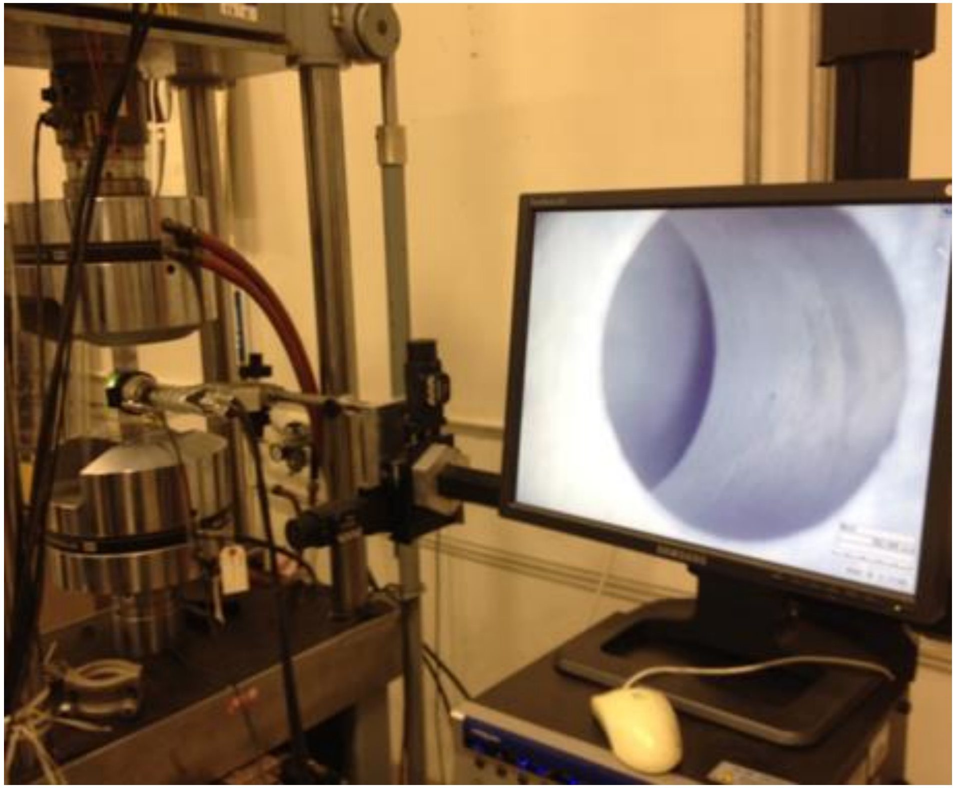
Agenda

- **B**ottom **L**ine **U**p **F**ront
- Background
  - Building Block Approach
  - Overview of Testing
  - Parameters Considered
- Parameter Selection
  - Method & Example Application
- Applicability to MPFM
  - Correlation of BAMF
- Acknowledgements



Bottom Line Up Front

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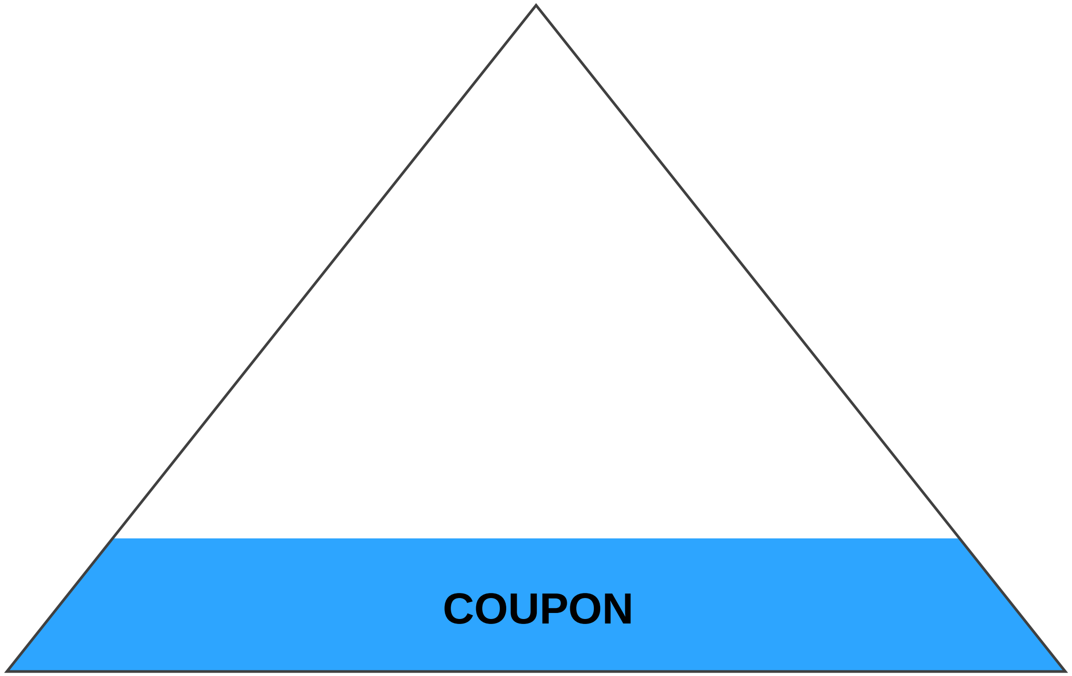
BLUF

- Building Block testing is an important aspect in selecting an appropriate combination of analysis tools, settings, and assumptions.
  - This effort is indicative of EARLY testing.
- In this presentation, technical considerations are examined but in practice external factors are also considered.
  - (Cost, Ease of Use, Availability of Training, Software interfaces, Automation)
- This effort focused on finding a combination of tools & settings (referred to as a methodology) that are suitably predictive for primary structure on an air vehicle platform.
  - Minimal consideration was given to the 'correctness' of various settings and instead emphasis was placed on the resulting predictions relative to test data (validation over verification).
- Emphasis on…
  - Life prediction from durability crack growth (a≈0.01") and damage tolerance (a≈0.05") initial flaw sizes.
  - Ability to predict influence of truncation.
  - Consistency of Load Interaction Model settings.
  - Consistency in shape of a vs. N curve.

Any reasonable tool setting '*could*' provide valid and useful results

Background

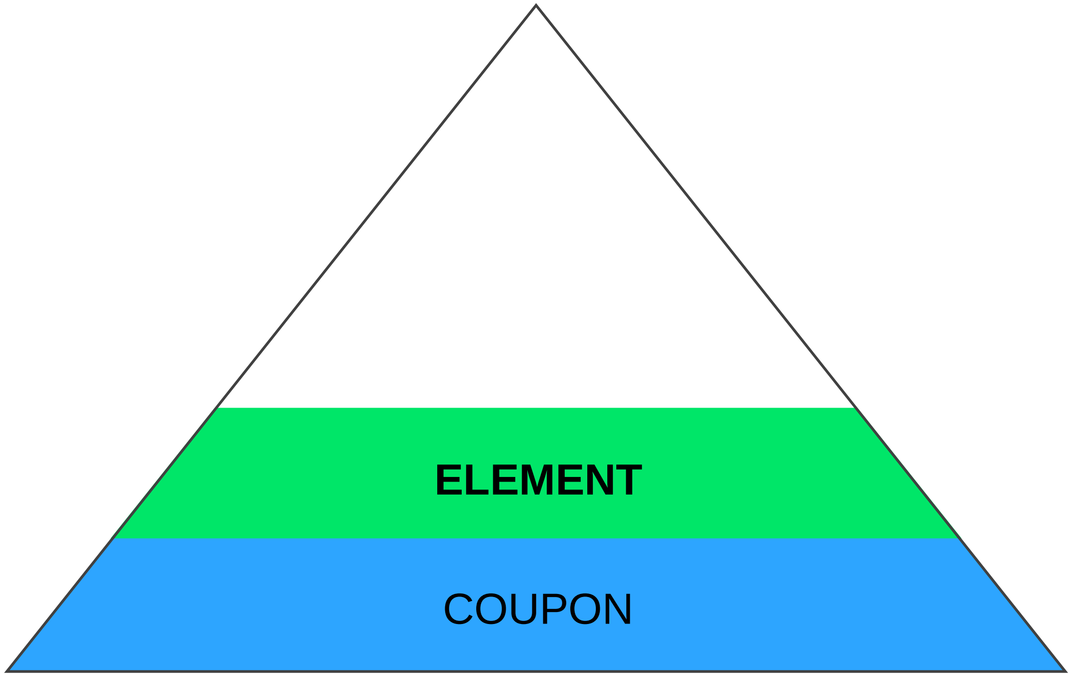
Background
Building Block Approach



- **Coupon-level test**
  - Main Use(s)
    - Material Characterization/Allowables

Background

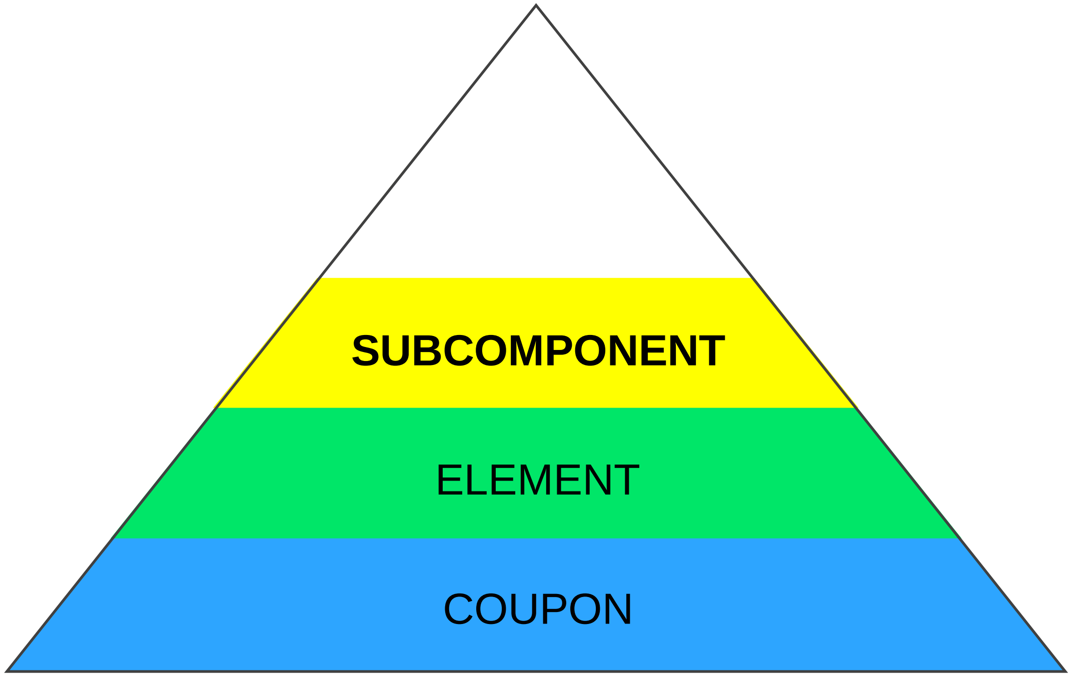
Building Block Approach



- **Element-level test**
  - Structural test of generic element.
  - Main Use(s)
    - Allowables
    - Analysis Calibration
    - Analysis Validation

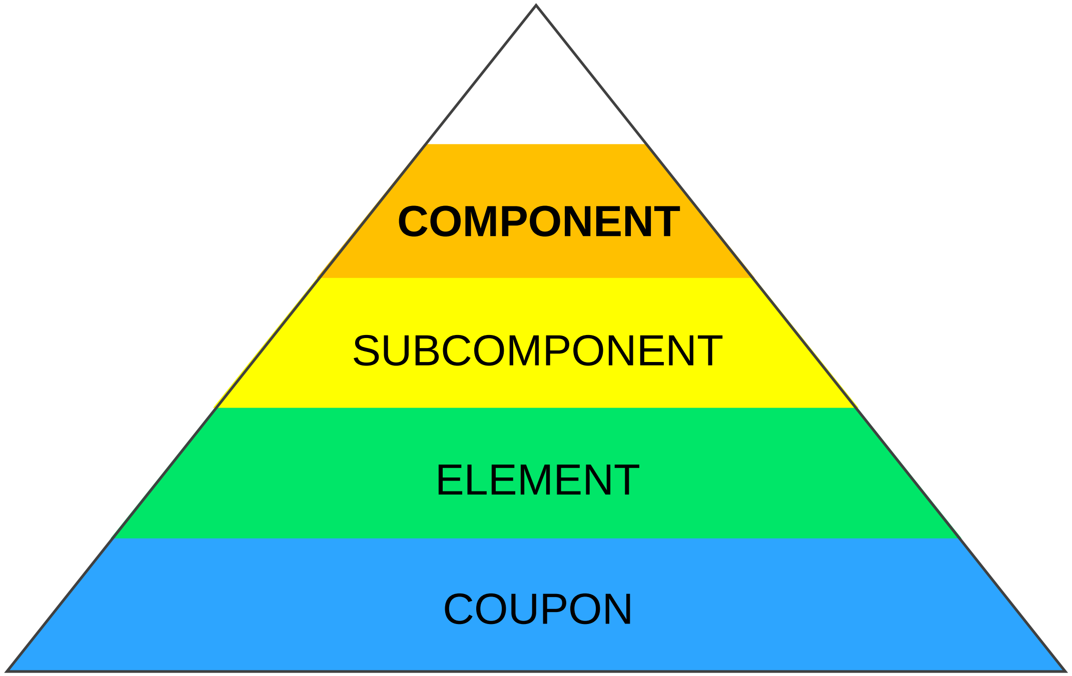
Background

Building Block Approach



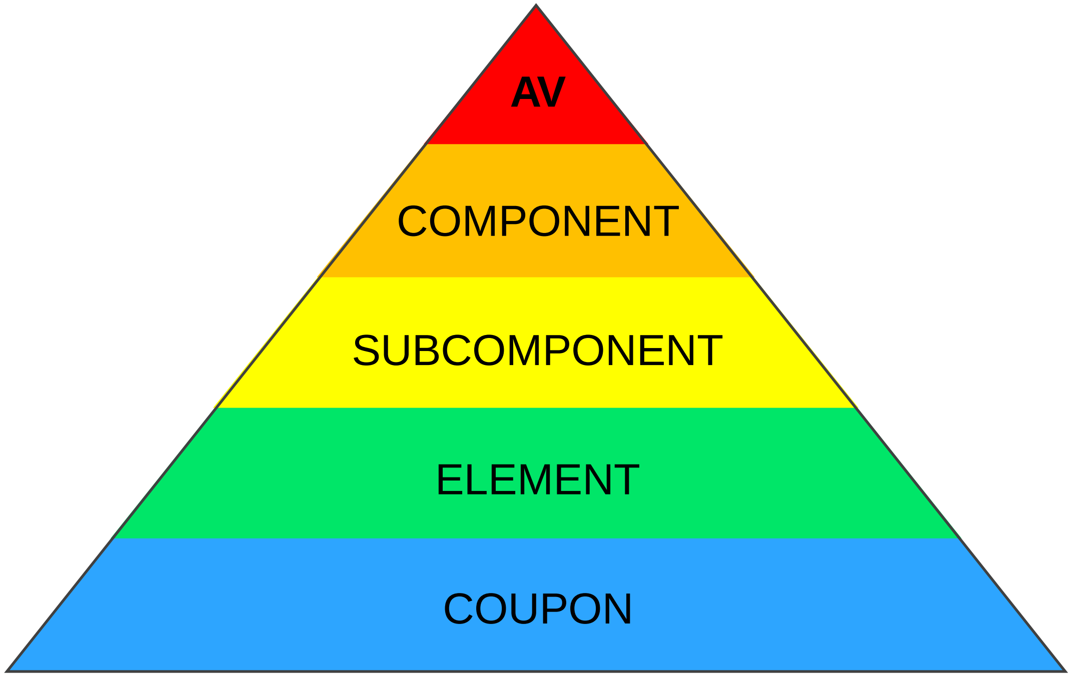
- **Subcomponent-level test**
  - More complex than element-level but not a standalone component. Intended to be structurally representative and often incorporate the interaction of multiple load components
  - Main Use(s)
    - Analysis Calibration
    - Analysis Validation
    - Risk Reduction
    - Certification

Background
Building Block Approach



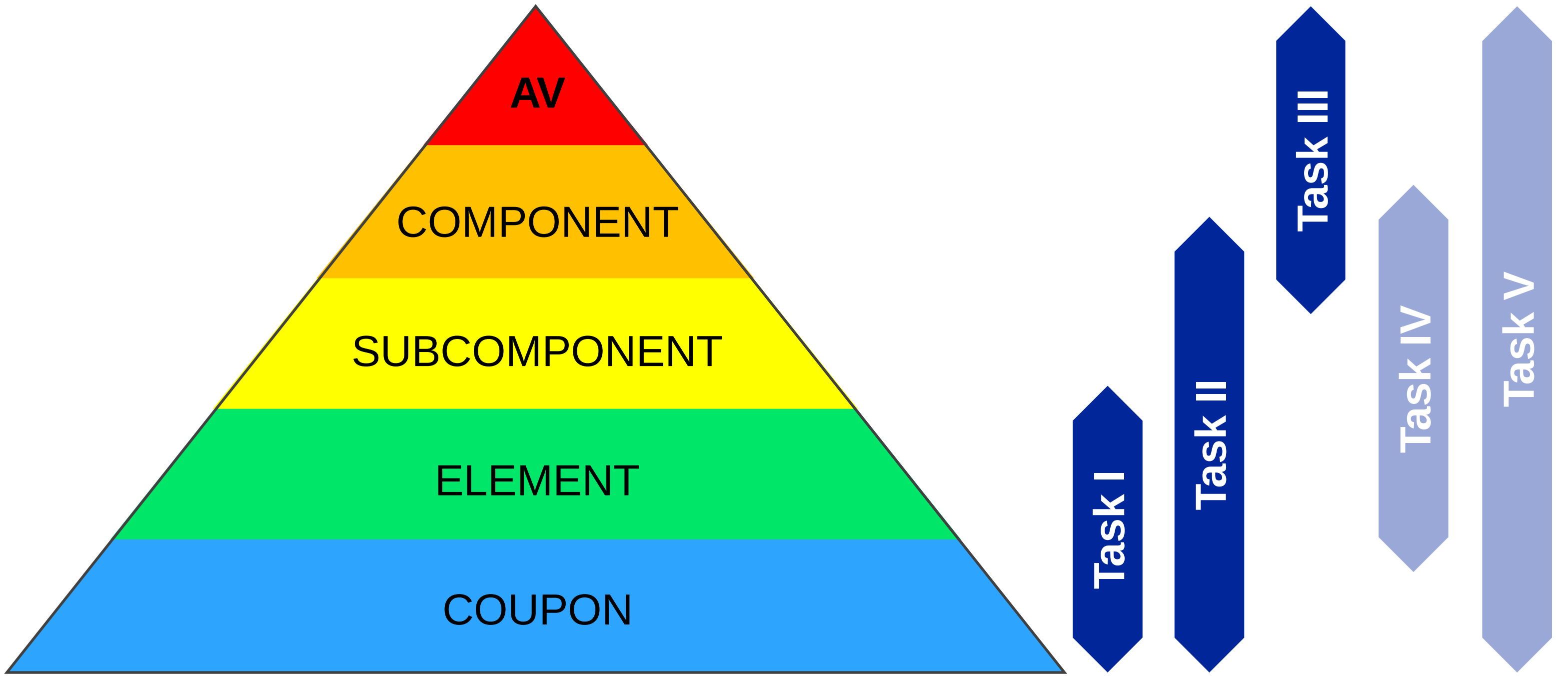
- **Component-level test**
  - Structural test of a full-scale airframe component/assembly
  - Main Use(s)
    - Certification
    - Analysis Validation

Background
Building Block Approach



- **Air Vehicle-level test**
  - Structural test of a full-scale airframe
  - Main Use(s)
    - Certification
    - Analysis Validation

Background
Building Block Approach

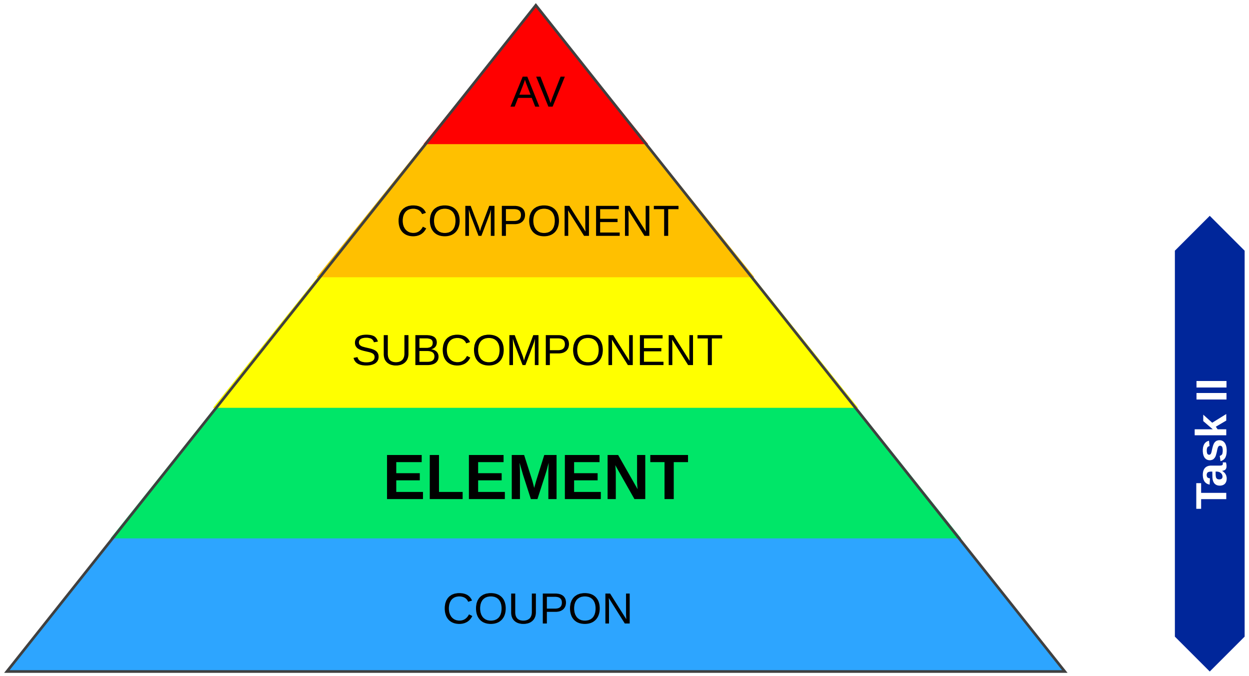


- **Required by MIL-STD-1530**

  5.2.14 Design development tests.

  Design development tests shall be conducted to establish material, process, and joint allowables; to verify analysis methods and procedures; to obtain early evaluation of allowable stress levels, material selection, fastener systems, and the effect of the design chemical/thermal environment spectra; to establish aeroelastic and loads characteristics through wind tunnel tests; and to obtain early evaluation of the strength, durability, fatigue (sonic and vibratory), and damage tolerance capabilities of critical structural components and assemblies…

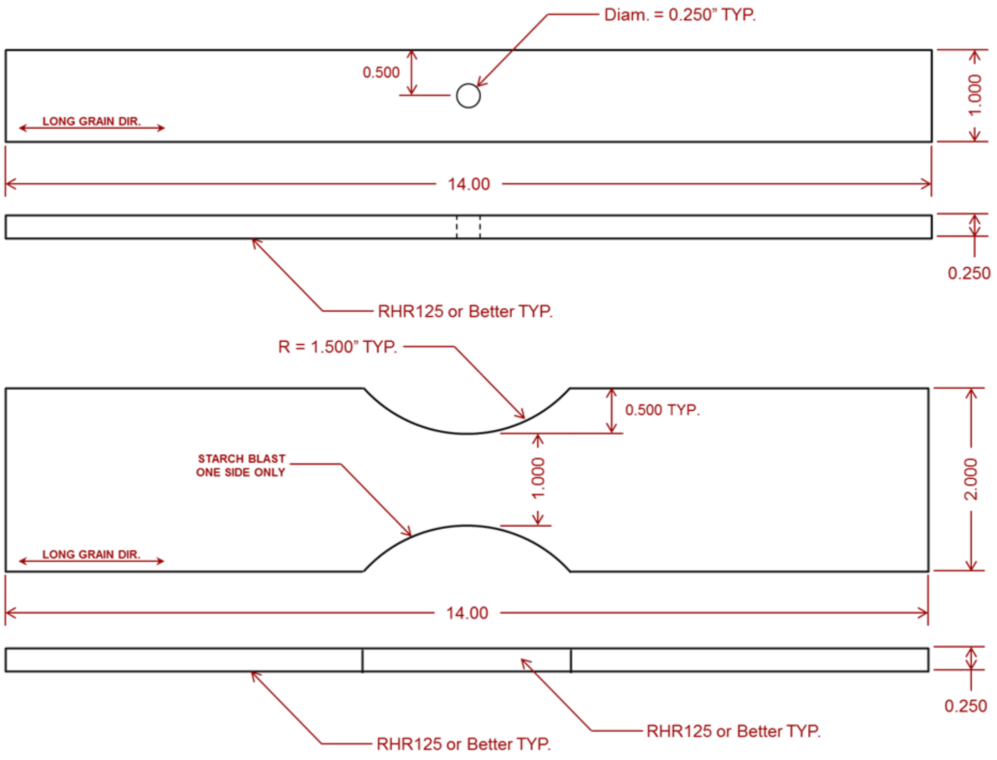
Background
Building Block Approach



This effort used simple element coupon indicative of early Task II

Background
Overview of Testing

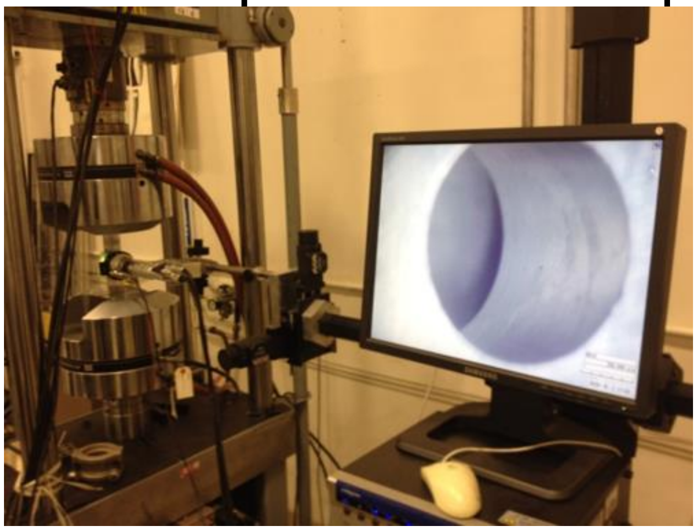
- Testing looked at:
  - Three materials
    - Aluminum
    - Titanium
    - CRES
  - Four Specimen Configurations
    - Open Hole – Pristine
    - Open Hole – With a Manufacture Flaw
    - Low Kt – Pristine
    - Low Kt – With a Manufactured Flaw
  - Seven Spectra Permutations
    - Five Control Points
    - One at three (3) levels of truncation



A reasonable level of testing to answer initial methods questions but not exhaustive

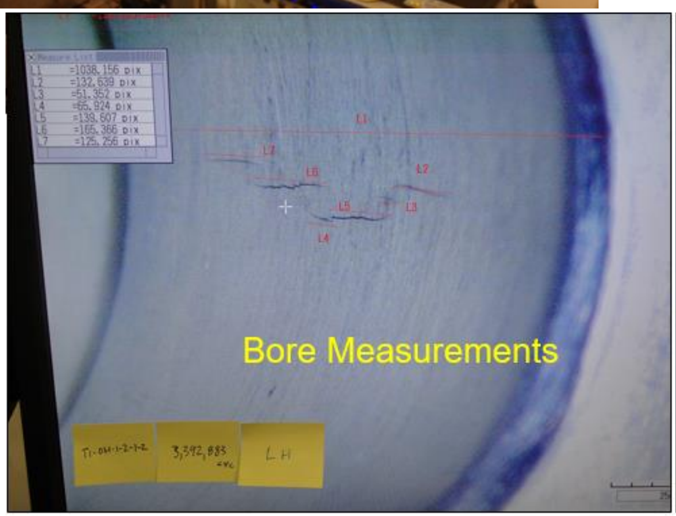
Background
Overview of Testing

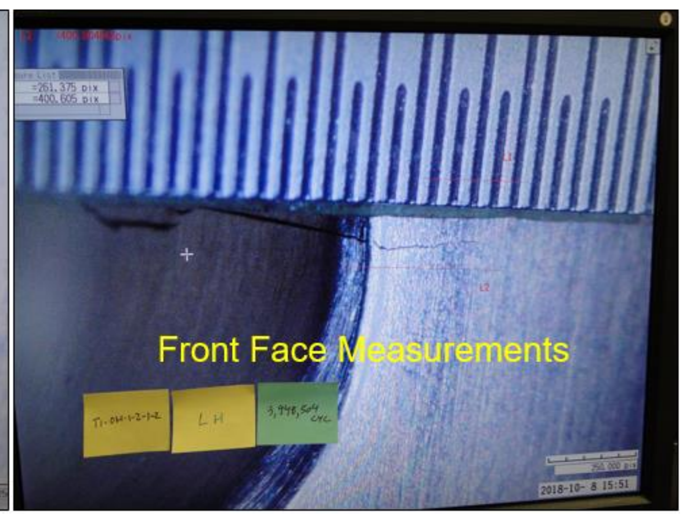
- HIROX Optical Microscope



Measurements in the bore
- With HIROX
- Both sides of hole
- All visible individual cracks
- As small as 0.004”
- Initiation taken as 2a=0.02” captured

Measurements on faces
- With HIROX & scale on front faces
- With scale on rear faces
- 4 faces
- To failure





Background
Parameters Considered

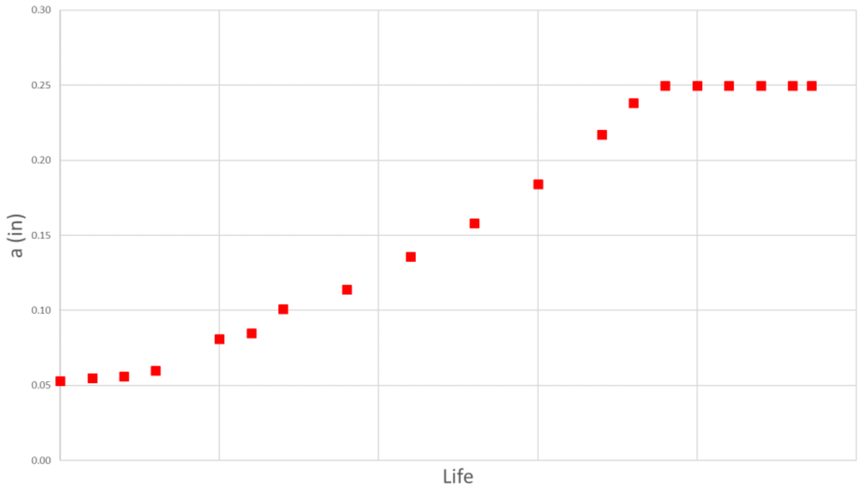
- Software:
  - **AFGROW**, FASTRAN, NASGRO, Internal Codes
- Material Model/Data Processing:
  - Harter-T Database
  - NASGRO Database
  - Available Test Data
    - Fit to raw test data vs. collapsed ΔK_{eff} (FASTRAN's dkeff13 code)
    - Mk. 1000 Eyeball vs. Regression Techniques
      - User-to-user comparisons
- Load Interaction Models:
  - Generalized Willenborg
  - Constant Closure
- SIF Solutions:
  - Classic Models
    - Phi Angles
    - Oblique Transition
  - Advanced Models
  - Weight Functions
  - User Defined SIFs
    - Results from other tools used to compare apples-to-apples
    - FEM based solutions
    - Proprietary solutions
  - Closure Correction Factor, β_r
  - Fixed Aspect Ratio vs. 'Free'

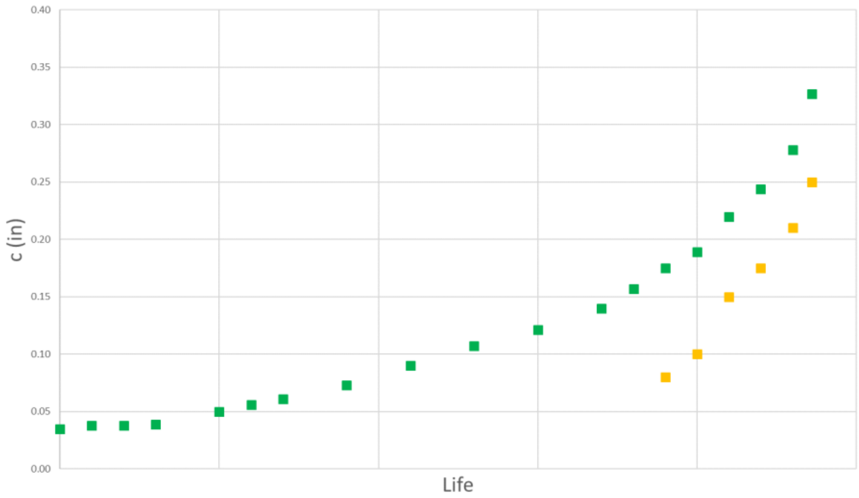
Parameter Selection
Method

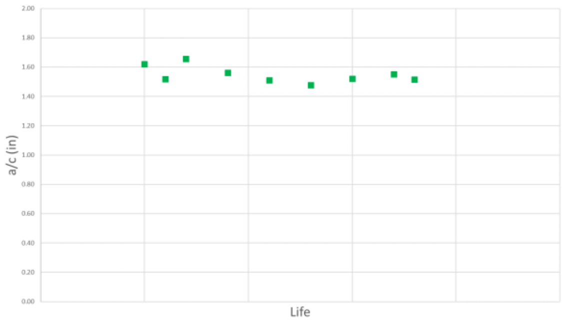
- Each test coupon results is first considered individually.
  - A Combination of Tool, Material Model, SIF solution, and Load Interaction Model (CG Method) are applied to a prediction using the measured initial flaw and specimen dimensions.
  - Parameters for load interaction model are varied to obtain an approximate match to the time to failure (either from the initial flaw or from crack initiation)

Parameter Selection
Example Application

- An individual coupons test data is examined.

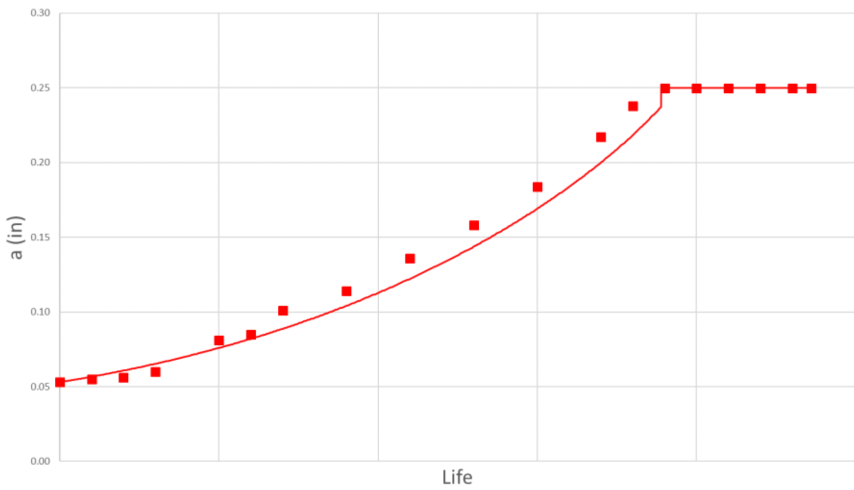


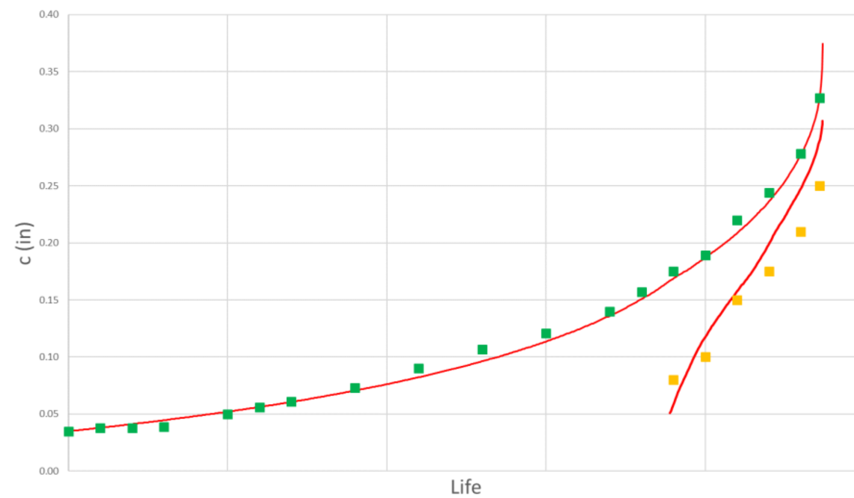


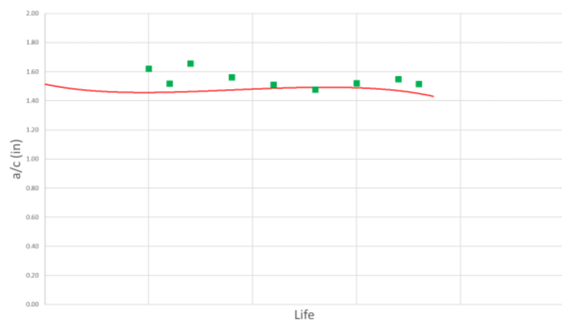


Parameter Selection
Example Application

- A load interaction parameter is determined to match the test data.







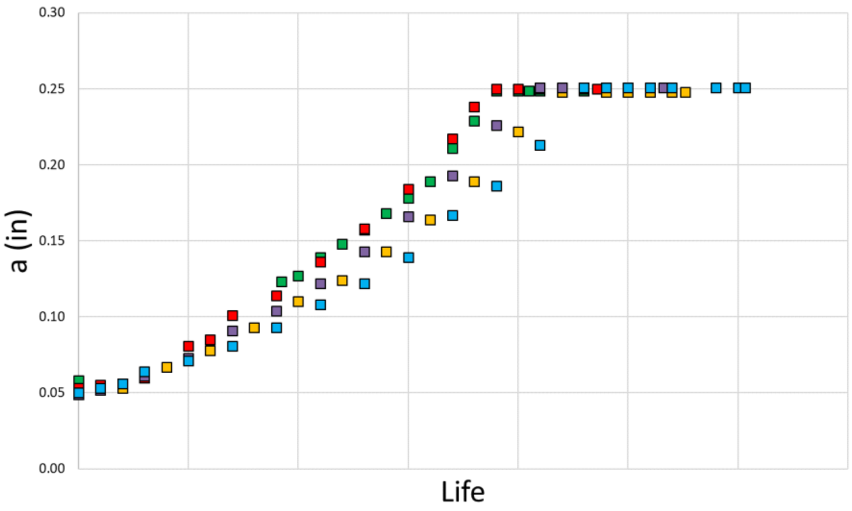
Prediction made using specimen specific geometry.

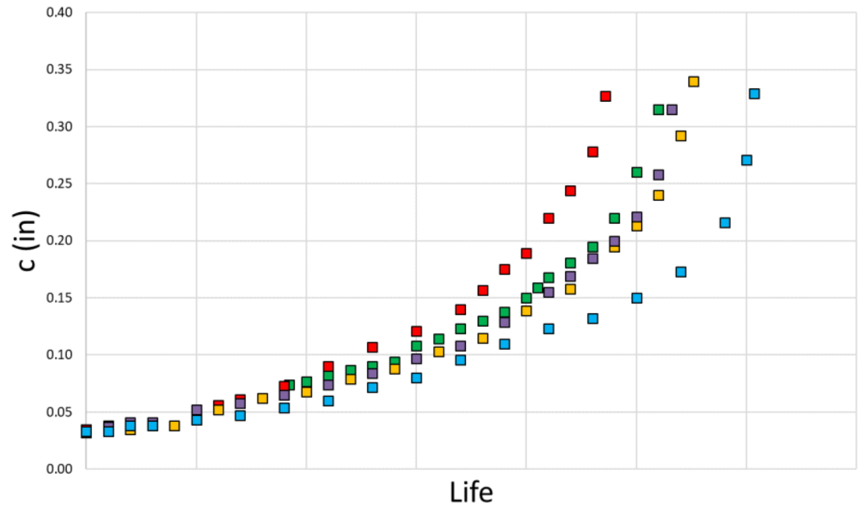
Parameter Selection
Method

- Replicates are pooled together to compare to a prediction from an ‘average’ initial flaw with ‘average’ parameters for load interaction.
  - CG Methods that result in inconsistent load interaction model parameters between specimens/spectra are eliminated.
  - CG Methods that don’t well follow the c vs. N curves are eliminated.
    - Deviation from the c vs. N curve indicates a lack of predictability from a range of initial flaws and indicates the method is unreliable for recurrent inspections.

Parameter Selection
Example Application

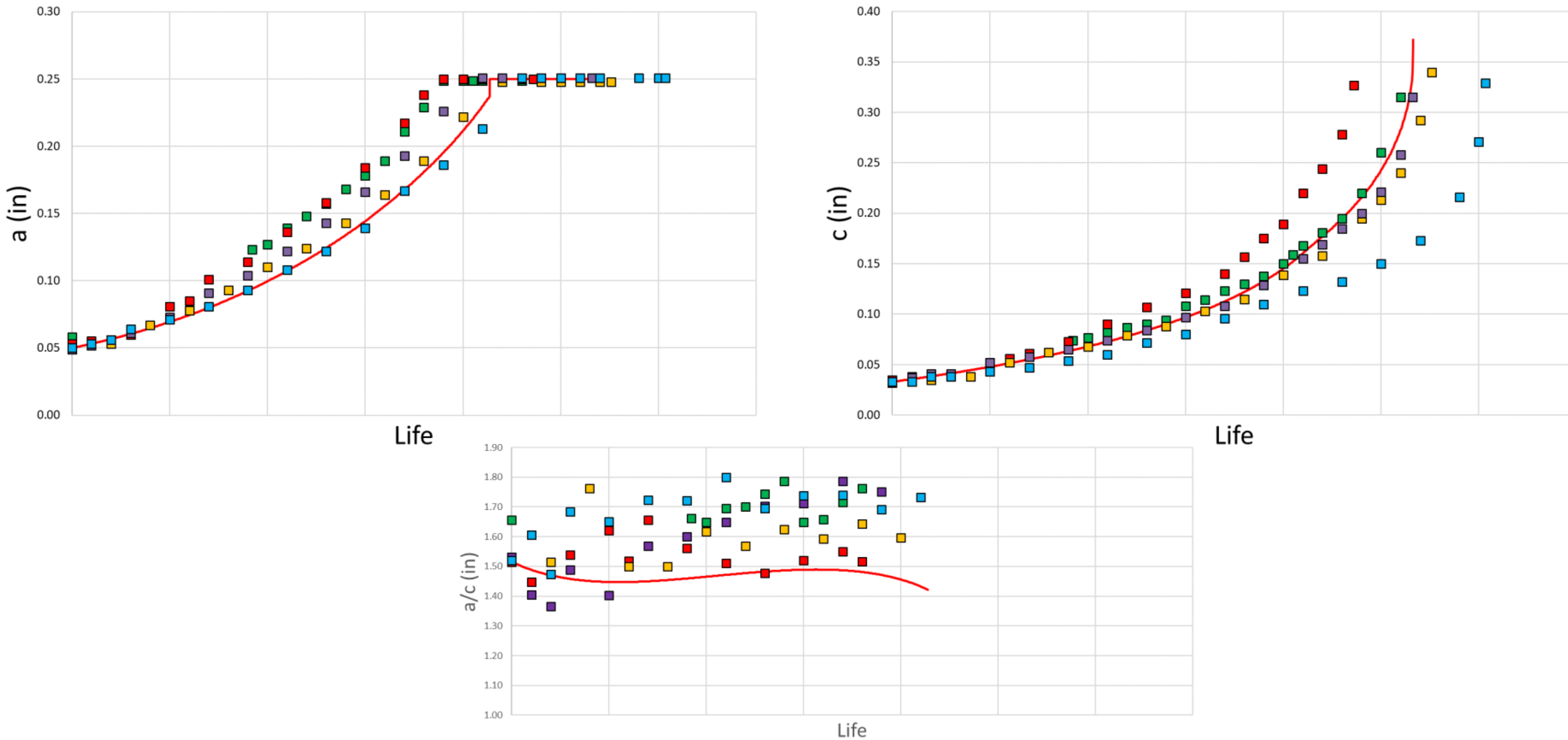
- All replicate data is examined.





Parameter Selection
Example Application

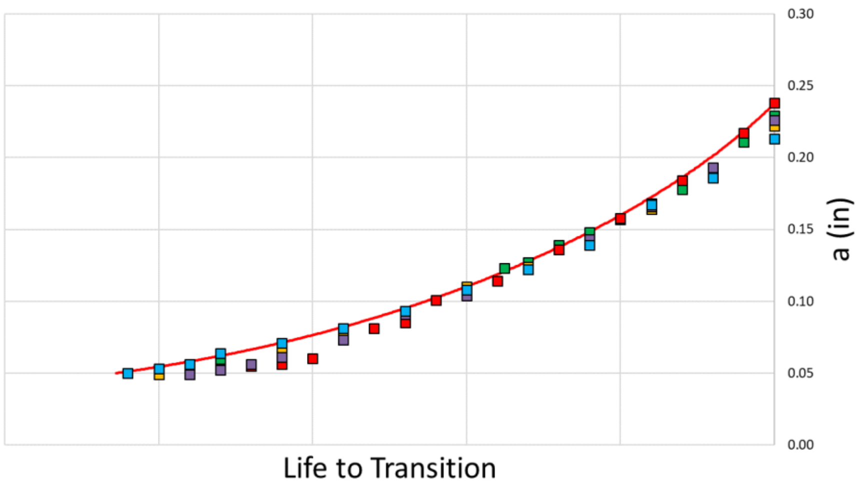
- And a prediction made using average load interaction parameters.

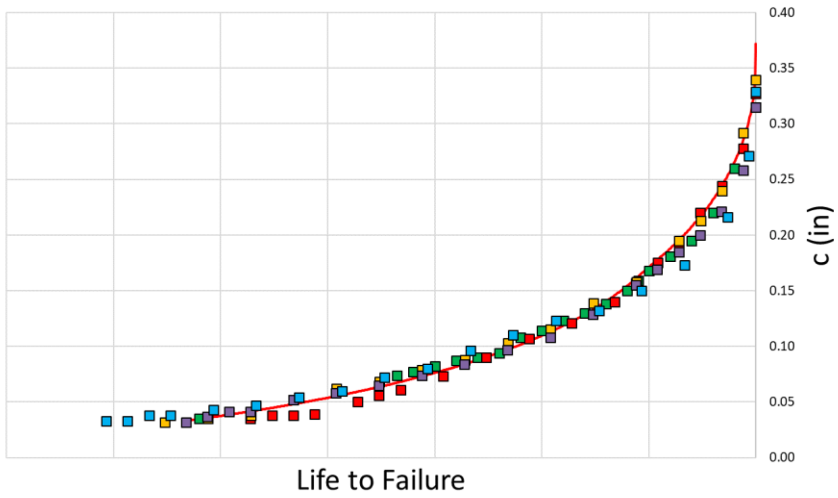


Prediction made using nominal geometry and an average initial flaw size.

Parameter Selection
Example Application

- Plots of time to failure/transition used to better assess shape of curves.





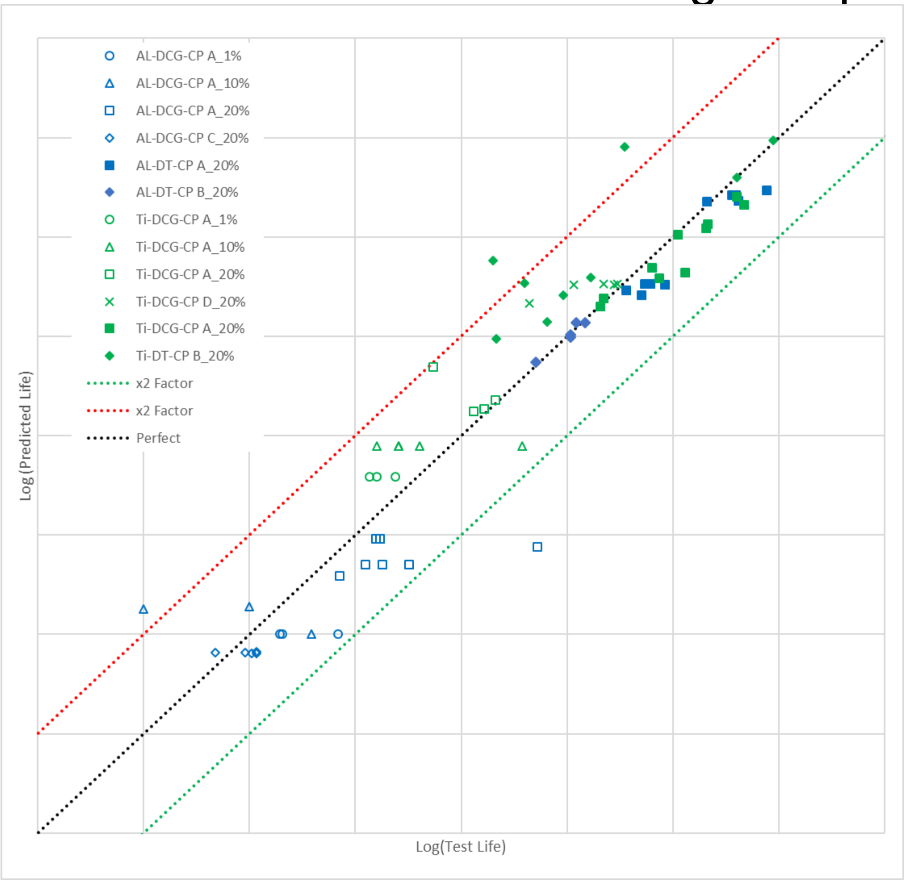
Plotting time to failure is often preferable.

Parameter Selection
Method

- Load interaction model parameters are examined across spectra.
  - A Design-To parameter is selected ‘sufficiently’ above the values encountered. (Conservative)

Parameter Selection
Example Application

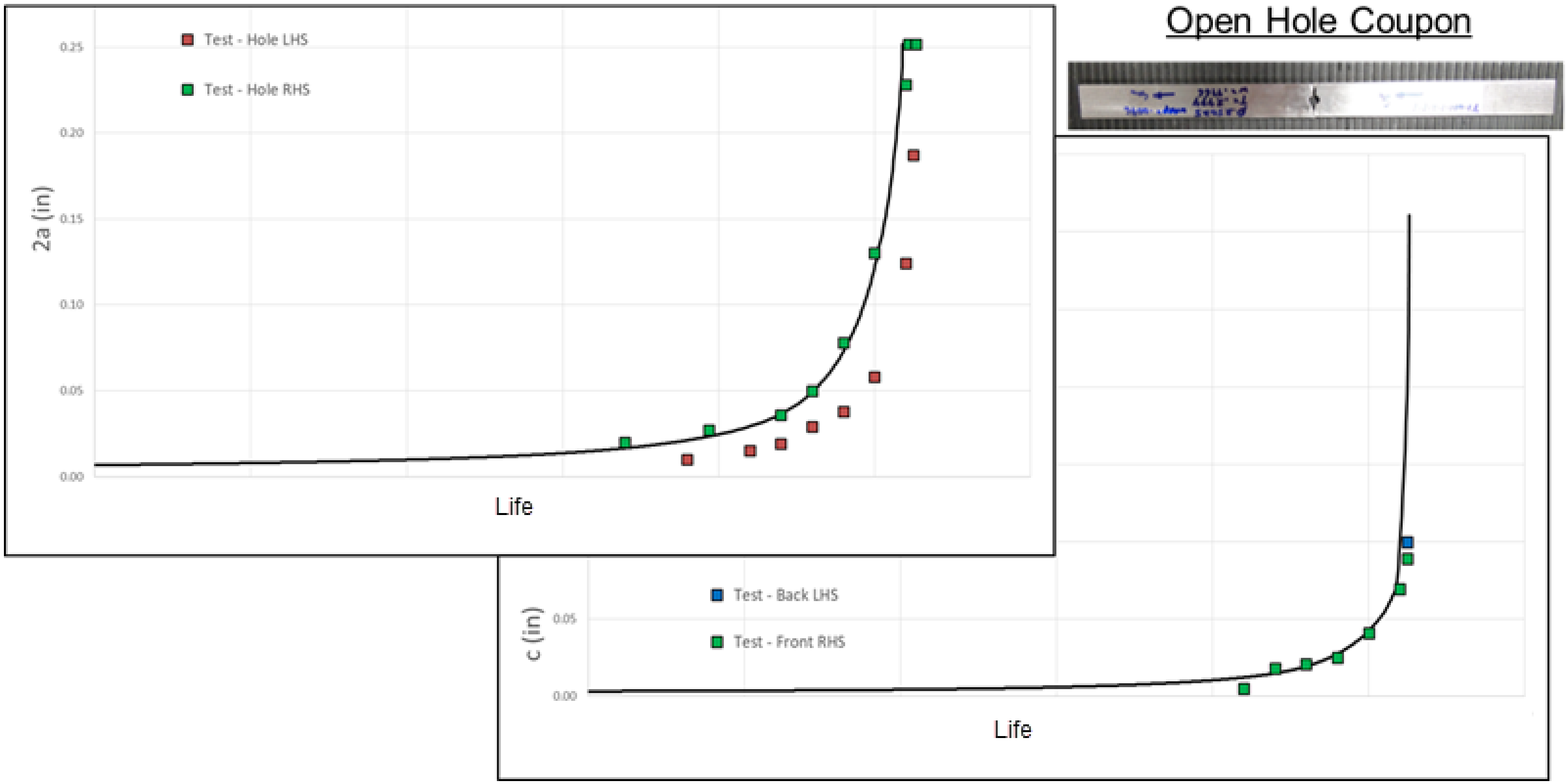
- Final correlation provided reasonable results across spectra, load levels, initial flaw sizes based on Design-To parameters.



Issues with Titanium material model identified and addressed via refined material characterization.

Parameter Selection
Method

- Once a CG Method is selected, the total life of the pristine specimens is used to develop EIDS distributions to support



Same dataset feeds risk analysis.

SIF Solution Substitution

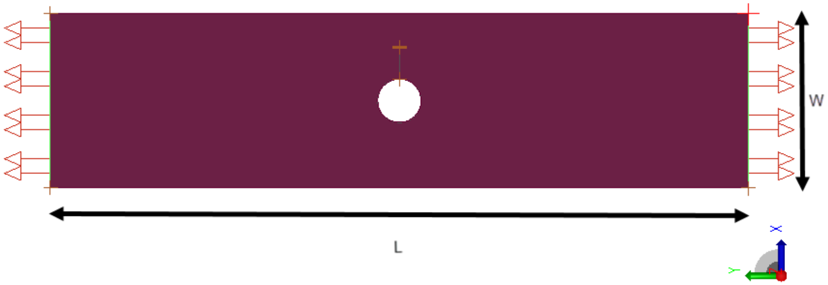
Multi-Point Fracture Modeling (MPFM)

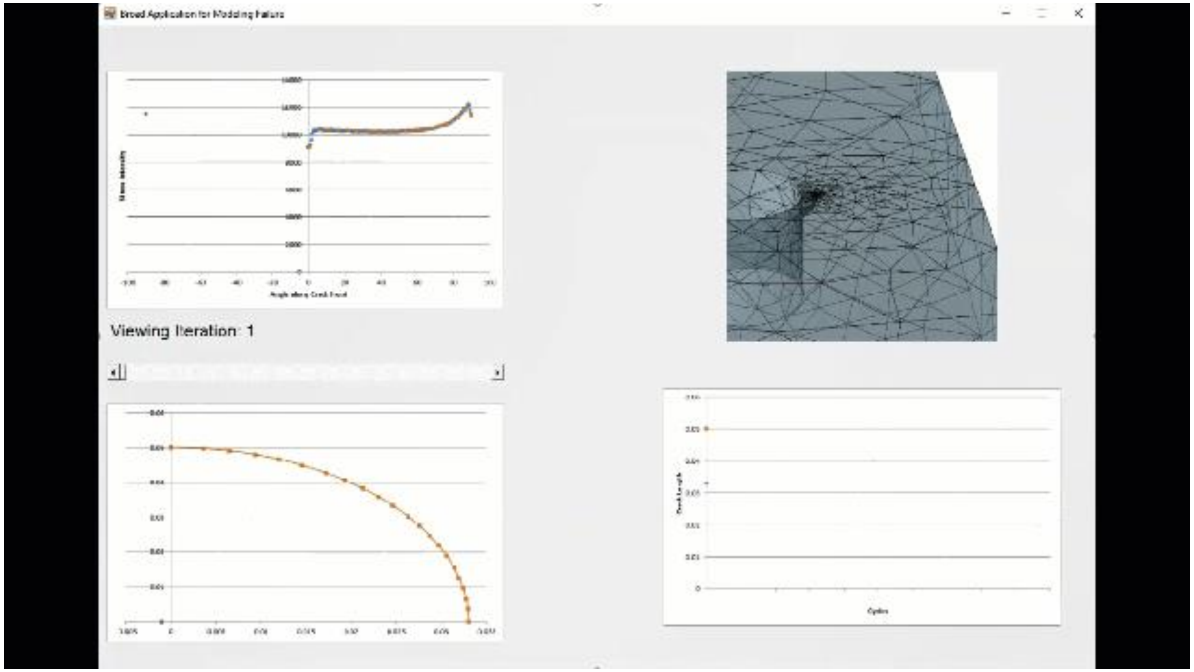
- Applicability of ‘canned’ solutions is limited to specific geometries and loading.
- Application to practical design conditions requires approximations/simplifications which are often conservative.
- Applicability of CG method (software, material model, load interaction) to a FEM based tool needs to be assessed.
  - Applicability to both manual (2 pt.) and automated (MPFM) approaches were assessed.
  - StressCheck was used for primary detail stress modeling tool and used with parametric elliptical flaws for manual growth.
  - BAMF V7 utilized for MPFM

BAMF proved to be quicker and more reliable than manual 2 pt. method.

Multi-Point Fracture Modeling (MPFM)

- BAMF Model:
  - Specimen Configuration
    - Open Hole – With average initial flaw size
  - Geometry
    - Aluminum
  - Geometry
    - $W = 1.0\ in$
    - $L = 4 * W = 4.0\ in$
    - $D = 0.25\ in$
  - SOLR
    - Average load interaction parameter





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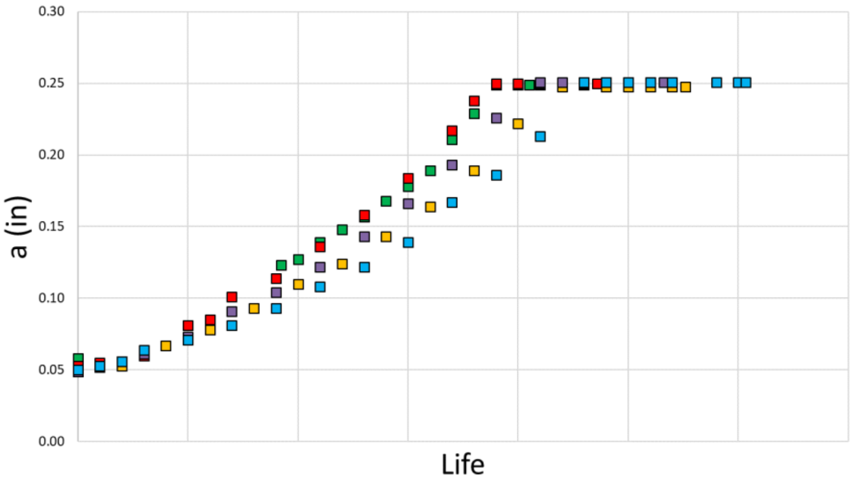
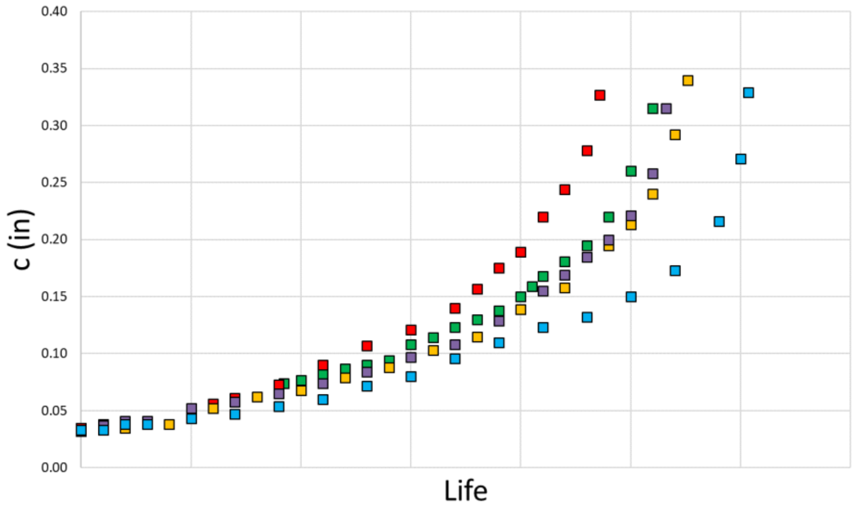
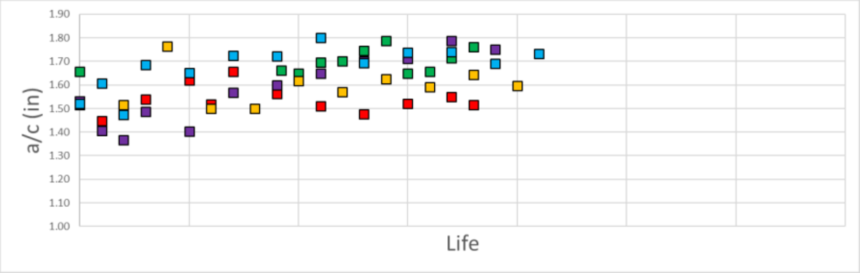
Correlation to BAMF

- Higher stress level testing

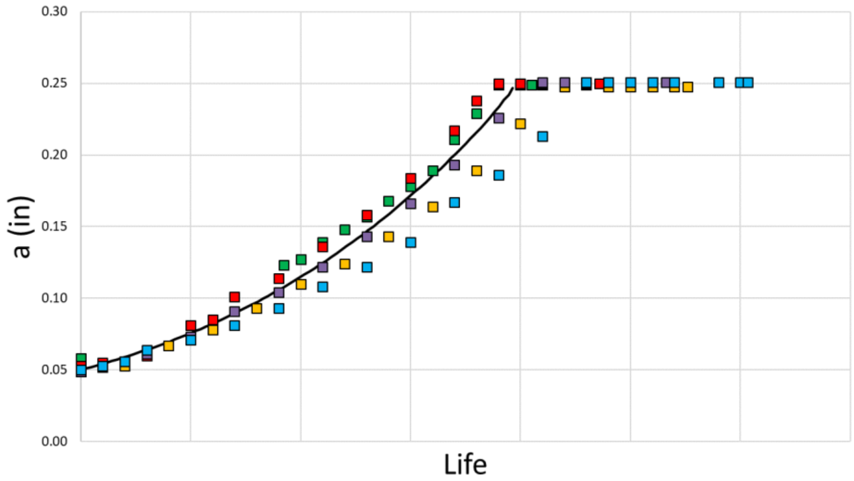


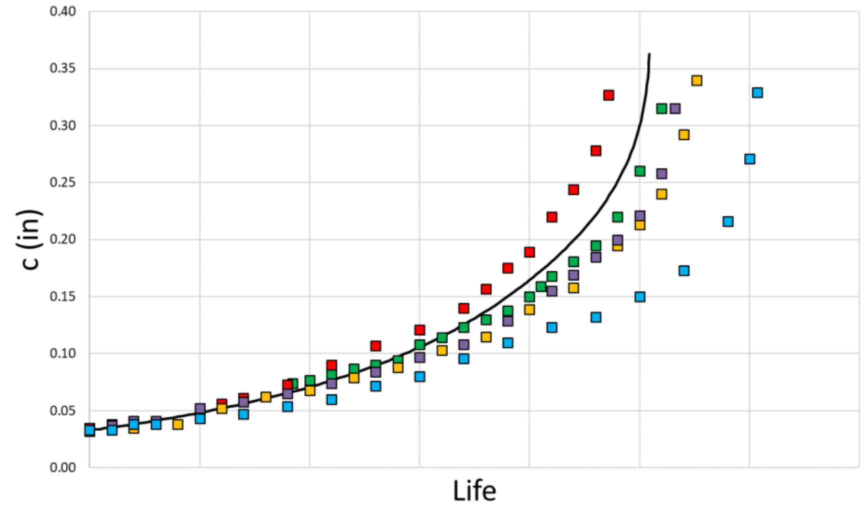


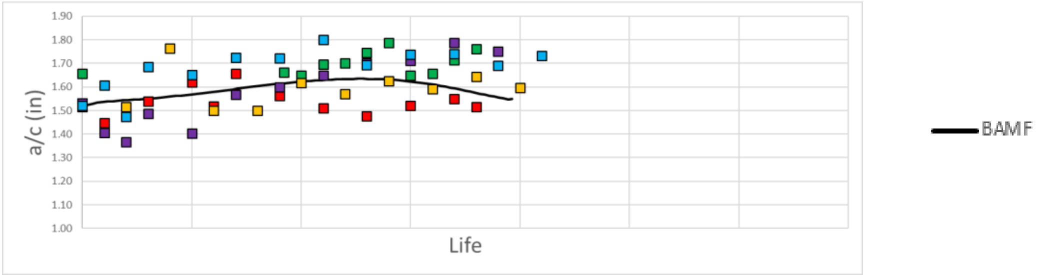


Correlation to BAMF

- BAMF prediction made using average load interaction parameters, nominal geometry, and average initial flaw size.

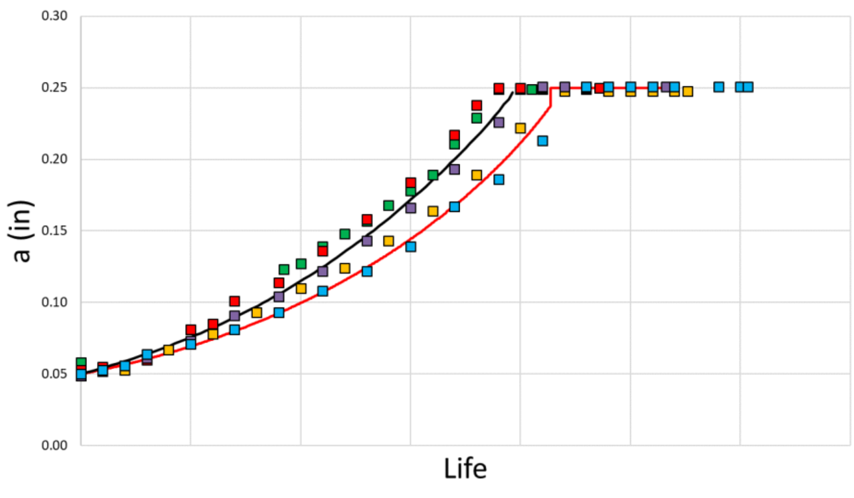


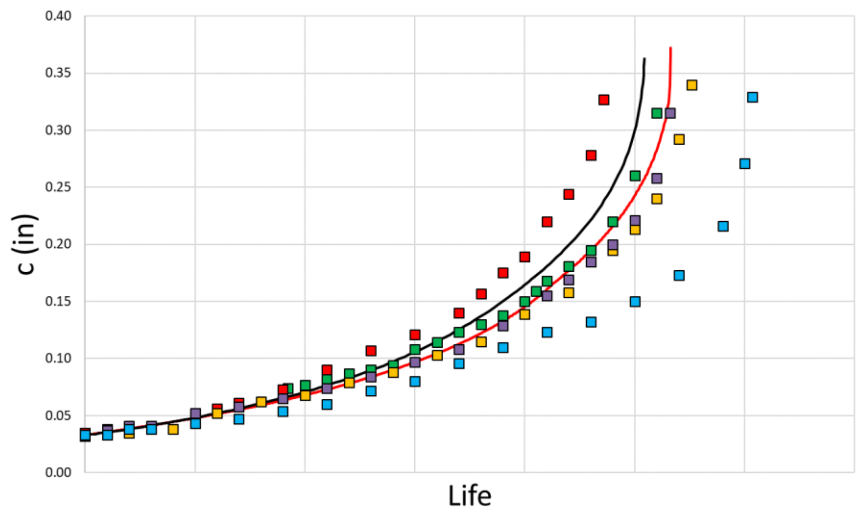


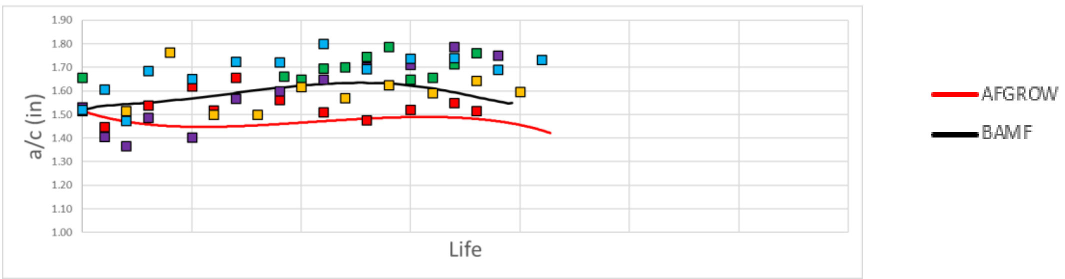


Correlation to BAMF

- BAMF prediction compared to AFGROW.

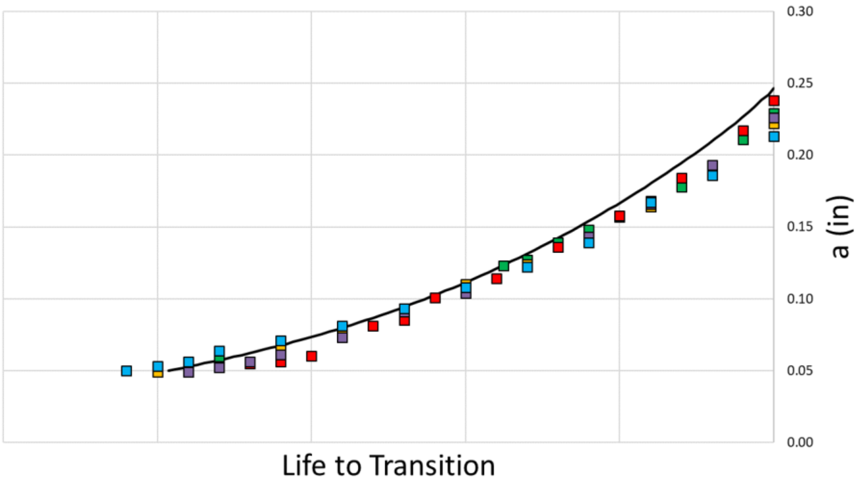


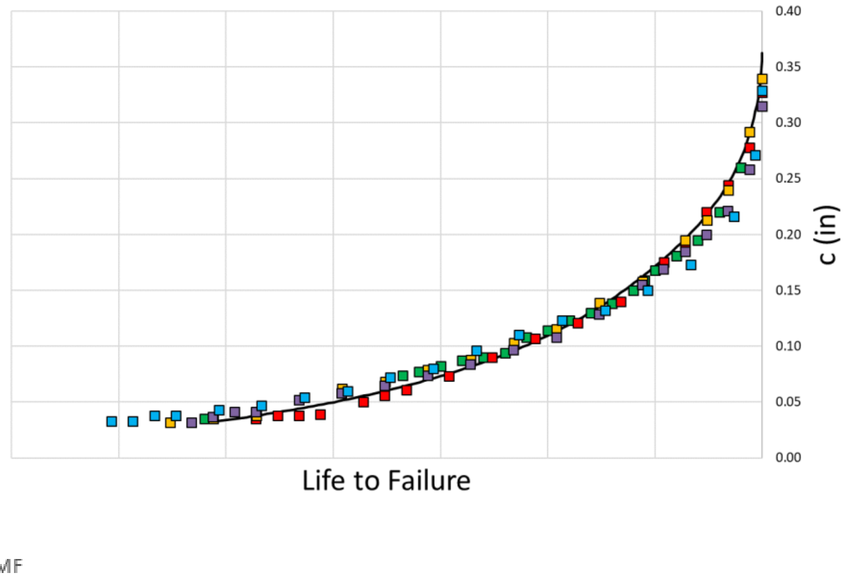




Correlation to BAMF

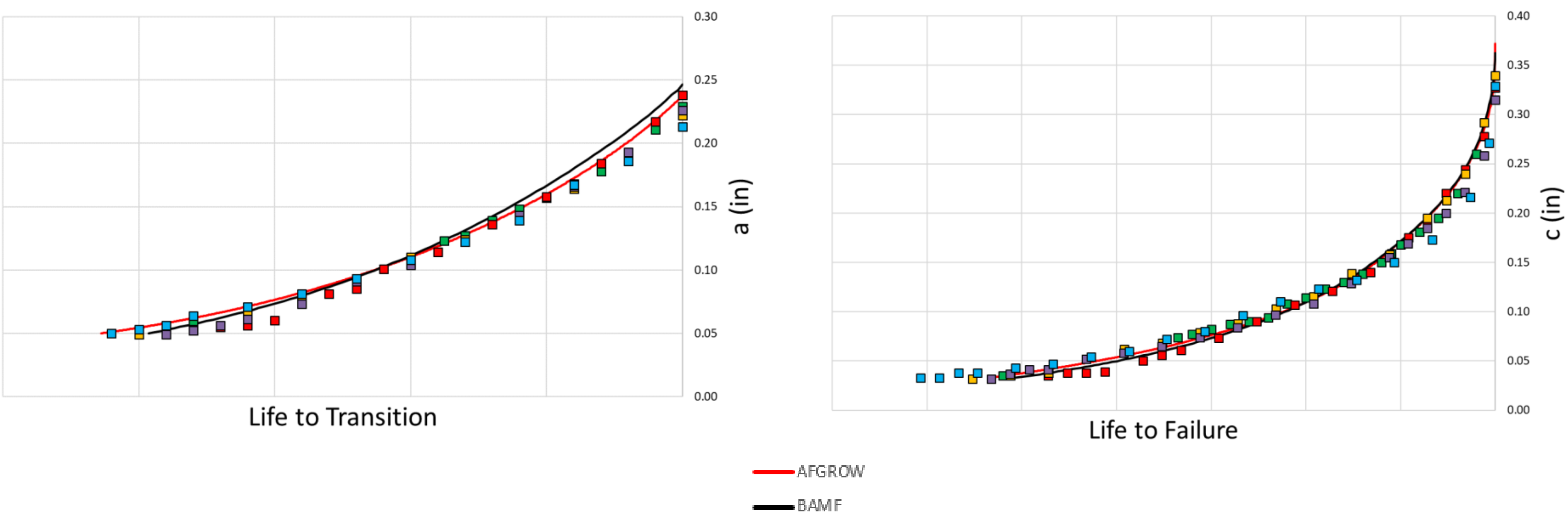
- Plots of time to failure/transition vs BAMF run.





Correlation to BAMF

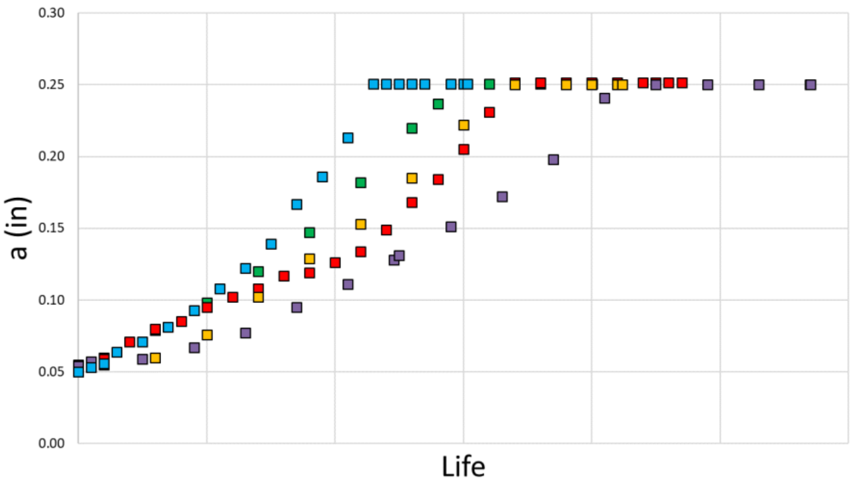
- Plots of time to failure/transition vs BAMF & AFGROW runs.

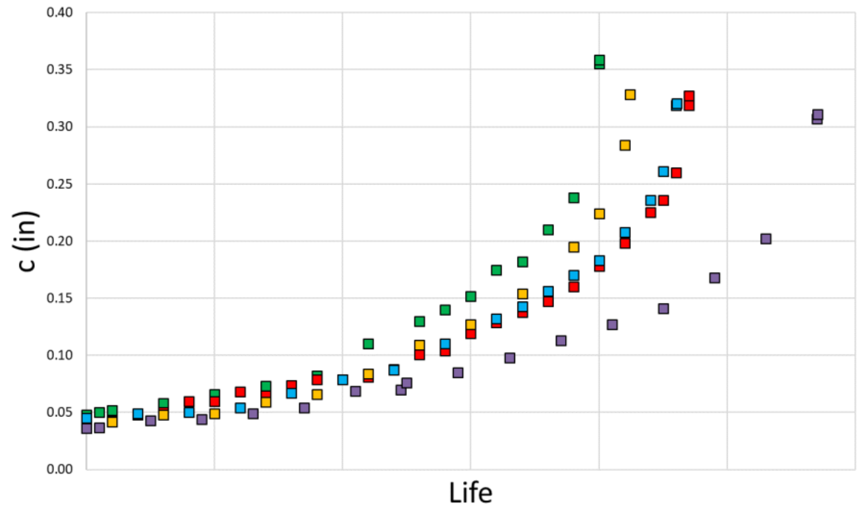


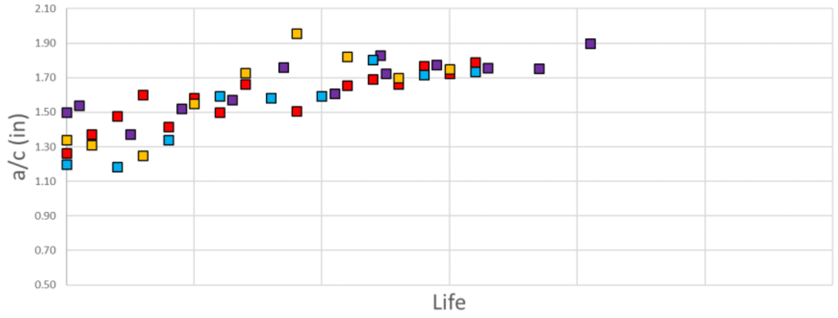
AFGROW life prediction was off by less than 1% on life while BAMF was off by 5% on life compared to test data.

Correlation to BAMF

- Lower stress level testing

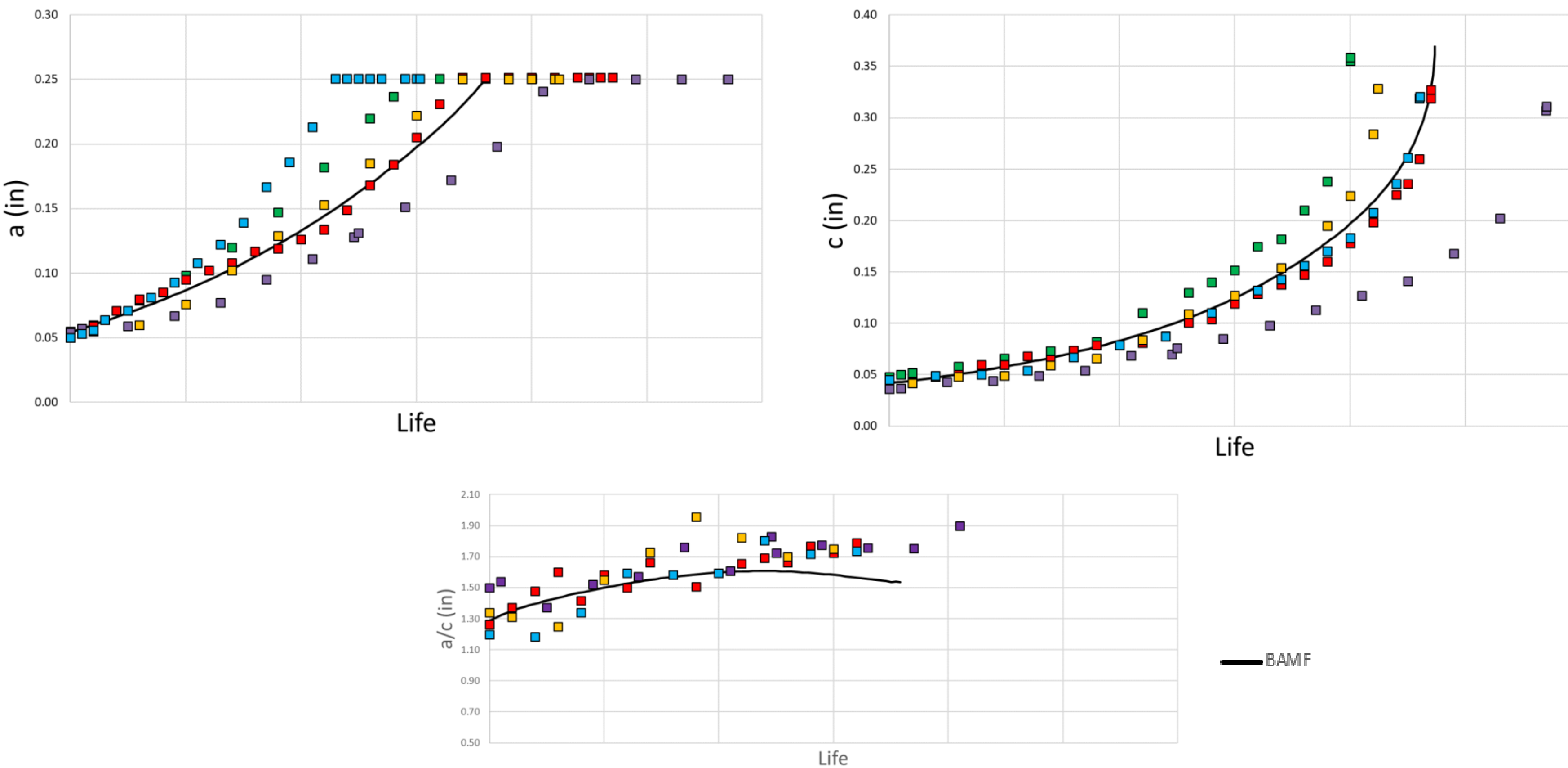






Correlation to BAMF

- BAMF prediction made using average load interaction parameters.



Correlation to BAMF

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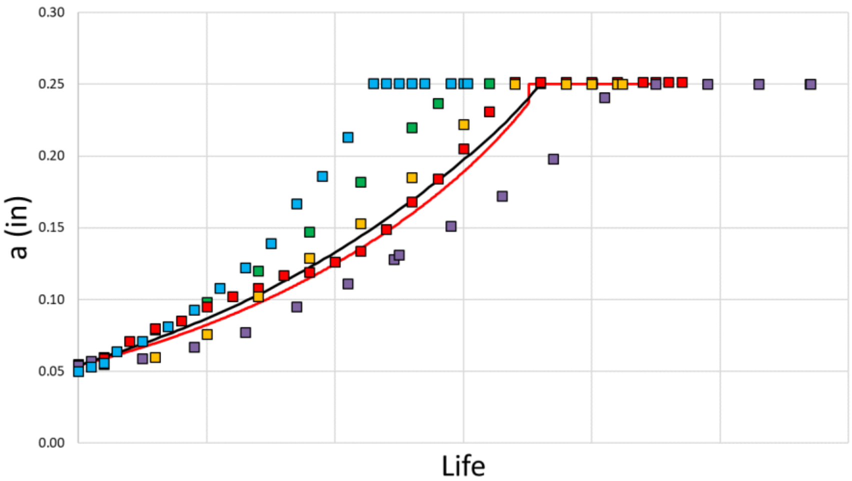
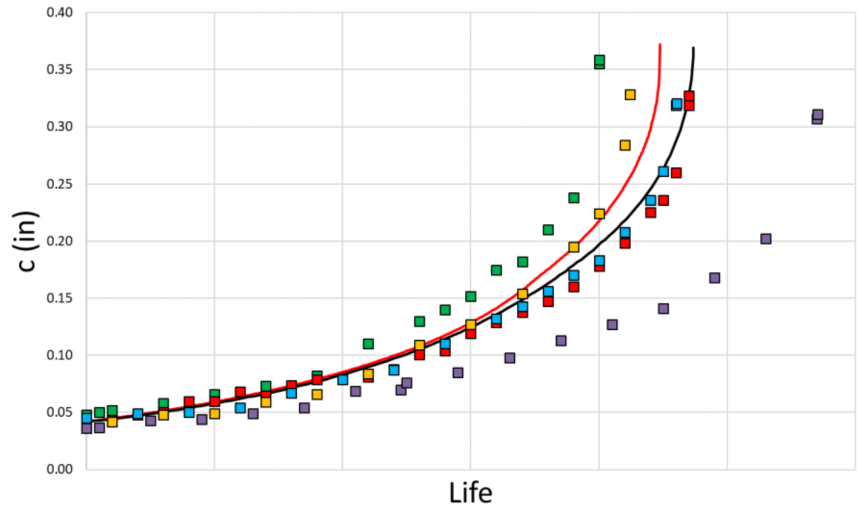
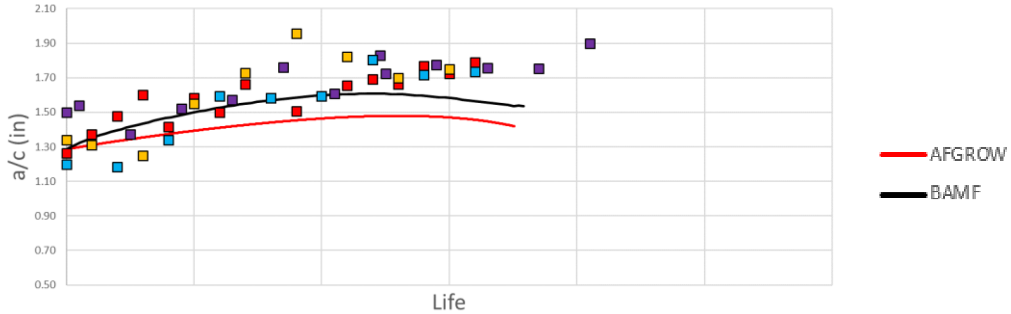
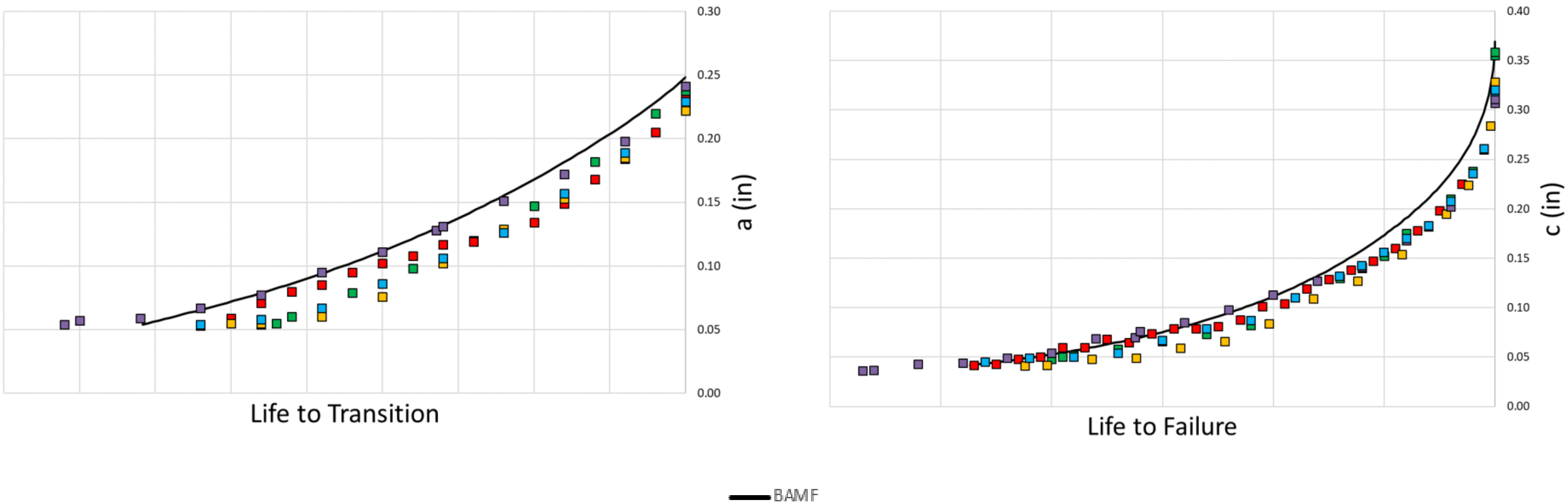






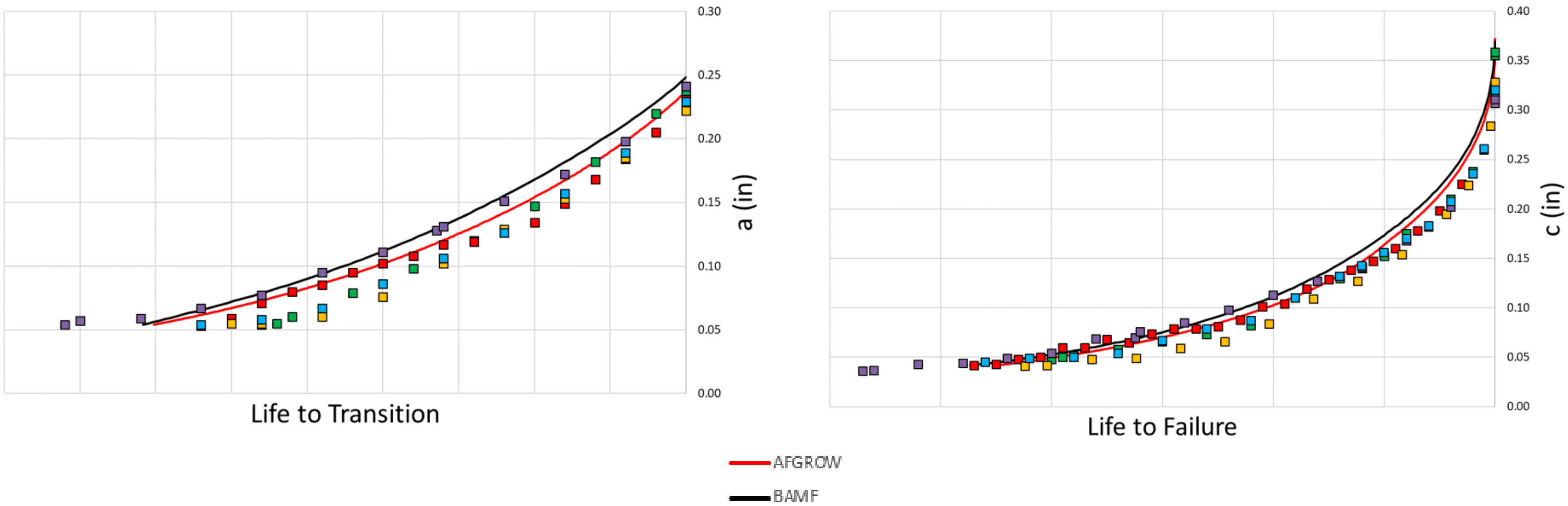
Correlation to BAMF

- Plots of time to failure/transition vs BAMF run.



Correlation to BAMF

- Plots of time to failure/transition vs BAMF & AFGROW runs.



AFGROW life prediction was off by less than 9% on life while BAMF was off by 3% on life compared to test data.

Conclusions

- Through a building block effort, a CG Method was found which allowed accurate crack growth predictions.
  - There are numerous parameters that can be combined in numerous permutations. The validity of these combinations must be determined.
- By using the same load interaction model with MPFM we were able to match testing results with small error.
  - Impact of closure correction factor on MPFM still needs to be assessed.
  - Adds confidence in applying MPFM in cases not covered by legacy solutions.
- Additional testing is required to assess and validate methods for other materials and specific applications.

Acknowledgements

- Northrop Grumman Aeronautics Systems:
  - Dr. Elias L. Anagnostou
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  - James Delea
- Mississippi State University:
  - Dr. James C. Newman, Jr.

Thank you