Analytical Methods & Testing Committee: Breakout Session

Engineered Residual Stress Implementation Group

Robert Pilarczyk
Group Lead – Structural Integrity
Hill Engineering, LLC

Jacob Warner
A-10 ASIP Engineering
USAF

Agenda

- Round Robin Efforts
  - Round Robin #1 (Pilarczyk)
  - Round Robin #2 (Warner)
- Modeling Efforts
  - Cyclic Redistribution (Pilarczyk, Mills)
  - Multi-Point MAI Program (Spradlin, Morgan)
  - AFGROW Advanced Model Predictions (Prost-Domasky)
  - Surface Corrections for Multi-Point Analyses (Hodges, Pilarczyk)
  - FCG Testing of Complex Coupons with Quench Induced Residual Stress (Ribeiro)
  - 7075 Prediction Comparisons (Pilarczyk)
- Validation Testing
  - Closure Images (Ross)
- Weapon System Applications
  - B-1 Taper-Lok Analysis & Testing (Pilarczyk, Lee, Smith)
- Misc. Other
  - Kt Free Coupons (Warner, Greer)
  - USAF Draft Structures Bulletin (Andrew, Warner, Spradlin)
  - Literature Review (Pilarczyk)

ROUND ROBIN EFFORTS

Round Robin #1 Wrap-up

- Follow-on efforts
  - Collaborating with Jim Newman, Kevin Walker, Jim Harter, and others to understand SIF comparisons for RR cases
- Publications
  - Presented at 19th International ASTM/ESIS Symposium on Fatigue and Fracture Mechanics (42nd National Symposium on Fatigue and Fracture Mechanics), May 2019
  - Presented at the 2019 USAF ASIP Conference
  - Published in Special Issue on Fatigue and Fracture Mechanics for Materials Performance and Characterization

ASTM INTERNATIONAL

Materials Performance and Characterization

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Successful Round Robin Analyses Resulting from the Engineered Residual Stress Implementation Working Group

Acknowledgements

- Co-Authors
  - Ricardo Actis, Engineering Software Research & Development Inc, St. Louis, MO, USA
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  - Scott Carlson, Lockheed Martin - Aeronautics, Ft. Worth, TX, USA
  - James Harter, LexTech Inc, Dayton, OH, USA
  - Joshua Hodges, Hill Engineering LLC, Rancho Cordova, CA, USA
  - Millard Kwan, Aviation Engineers Pty Ltd, Arundel, QLD, Australia
  - Scott Prost-Domasky, Analytical Processes/Engineered Solutions Inc, St. Louis, MO, USA
  - Guillaume Renaud, National Research Council Canada, Ottawa, Ontario, Canada
- Engineered Residual Stress Implementation (ERSI) Working Group

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

INTERFERENCE FIT FASTENER ANALYTICAL ROUND ROBIN

A-10 ASIP

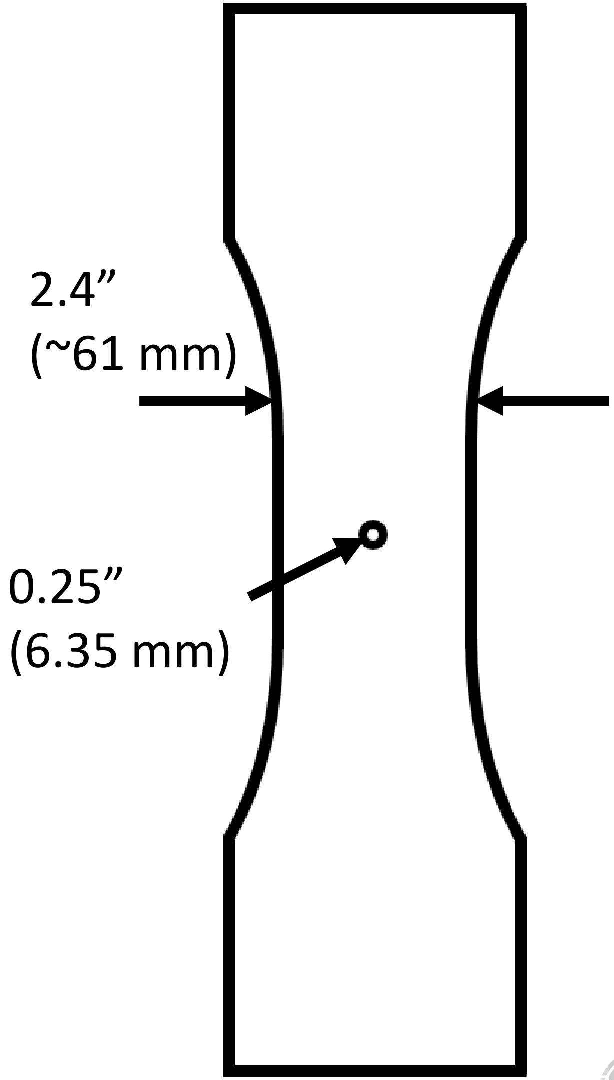
Jake Warner

LOADING AND GEOMETRY

- Constant amplitude, R = 0.1, 27.9 ksi (192.4 Mpa)
- 7075-T651, 0.25" (6.35 mm) thick
- 0.027" (~0.69 mm) precrack
- Hi-Lok (steel) fastener, target 0.4% interference

- Two (2) conditions tested
  - Open hole
  - 0.4% interference Hi-Lok (not torqued)

- Three (3) conditions predicted
  - Open hole
  - 0.4% interference
  - 0.6% interference



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ENGINEERED RESIDUAL STRESS IMPLEMENTATION

SUBMISSION DIVERSITY

- 12 Participants
- 13 Submissions
- Crack Growth Engine
  - 6 AFGROW
  - 3 FASTRAN
  - 4 Others
- Stress Intensity Solution
  - 7 StressCheck
  - 3 FASTRAN
  - 3 Others

	Crack Growth Engine	FEA Tool
P-61 Black Widow	AFGROW	MSC Marc 2019
U-2 Dragon Lady	AFGROW	StressCheck
KC-46 Pegasus	AFGROW	StressCheck
B-1 Lancer	AFGROW/ MS Excel	StressCheck
F-111 Aardvark	AFGROW	StressCheck
F-22 Raptor	AFGROW	StressCheck
SR-71 Blackbird	CPAT	StressCheck
F-16 Fighting Falcon	LifeWorks	StressCheck
A-10 Thunderbolt II	FASTRAN v 5.70	N/A
F-4 Phantom	FASTRAN v 5.70	N/A
B-21 Raider	FASTRAN v 5.42	N/A
B-2 Spirit	NASGRO	NASTRAN
F-15 Strike Eagle	SimModeler Crack	ANSYS

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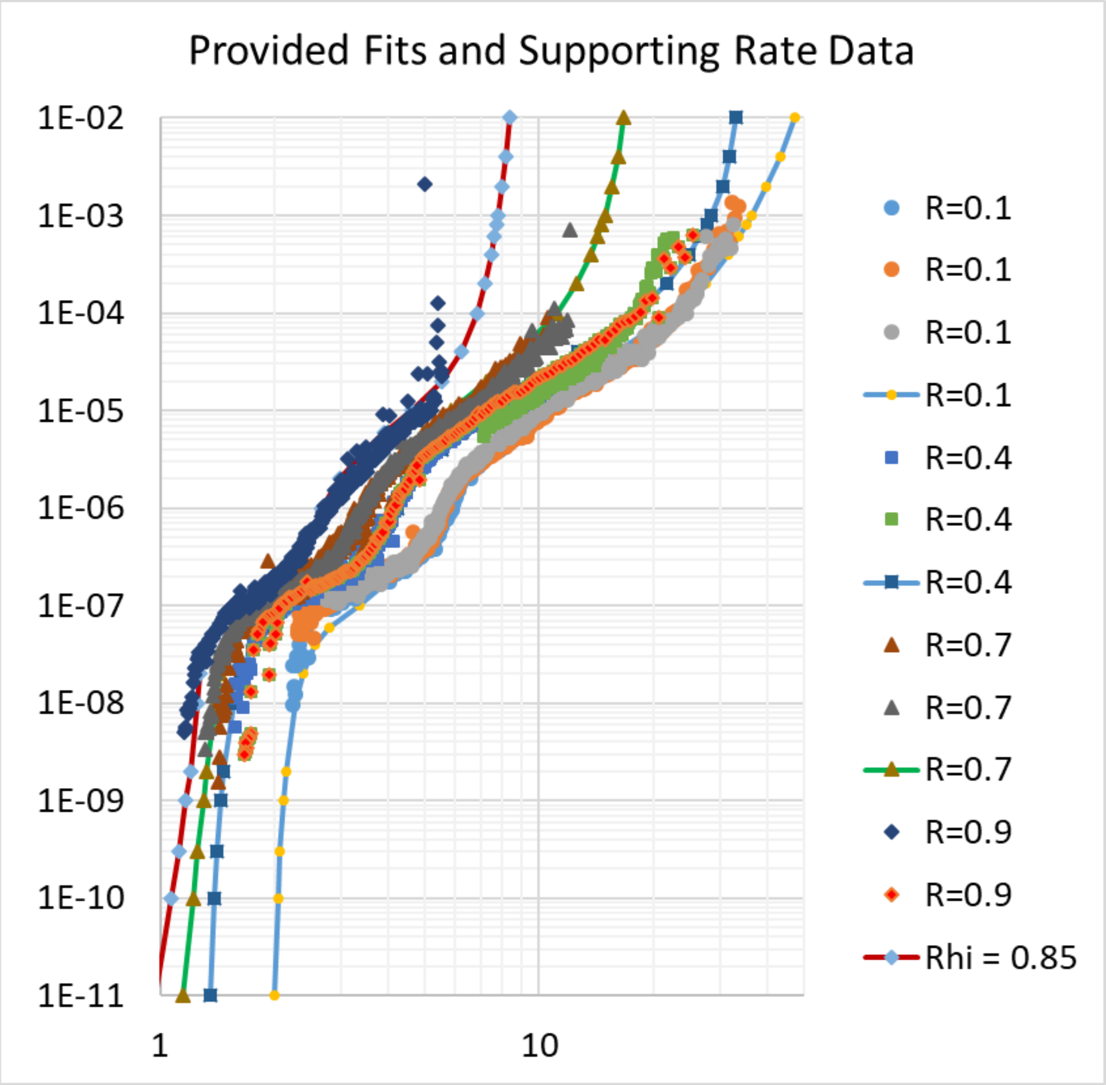
ENGINEERED RESIDUAL
STRESS IMPLEMENTATION

PROVIDED RATE DATA

- Material lookup file provided
  - Based on tests from multiple (4+) entities, material lots and timeframes
  - Good agreement across test data
  - Rate data *not* generated from same lot as test specimens
  - Rate data provided for 6 stress ratios
  - R = -0.15, 0.02, 0.1, 0.4, 0.7, 0.85



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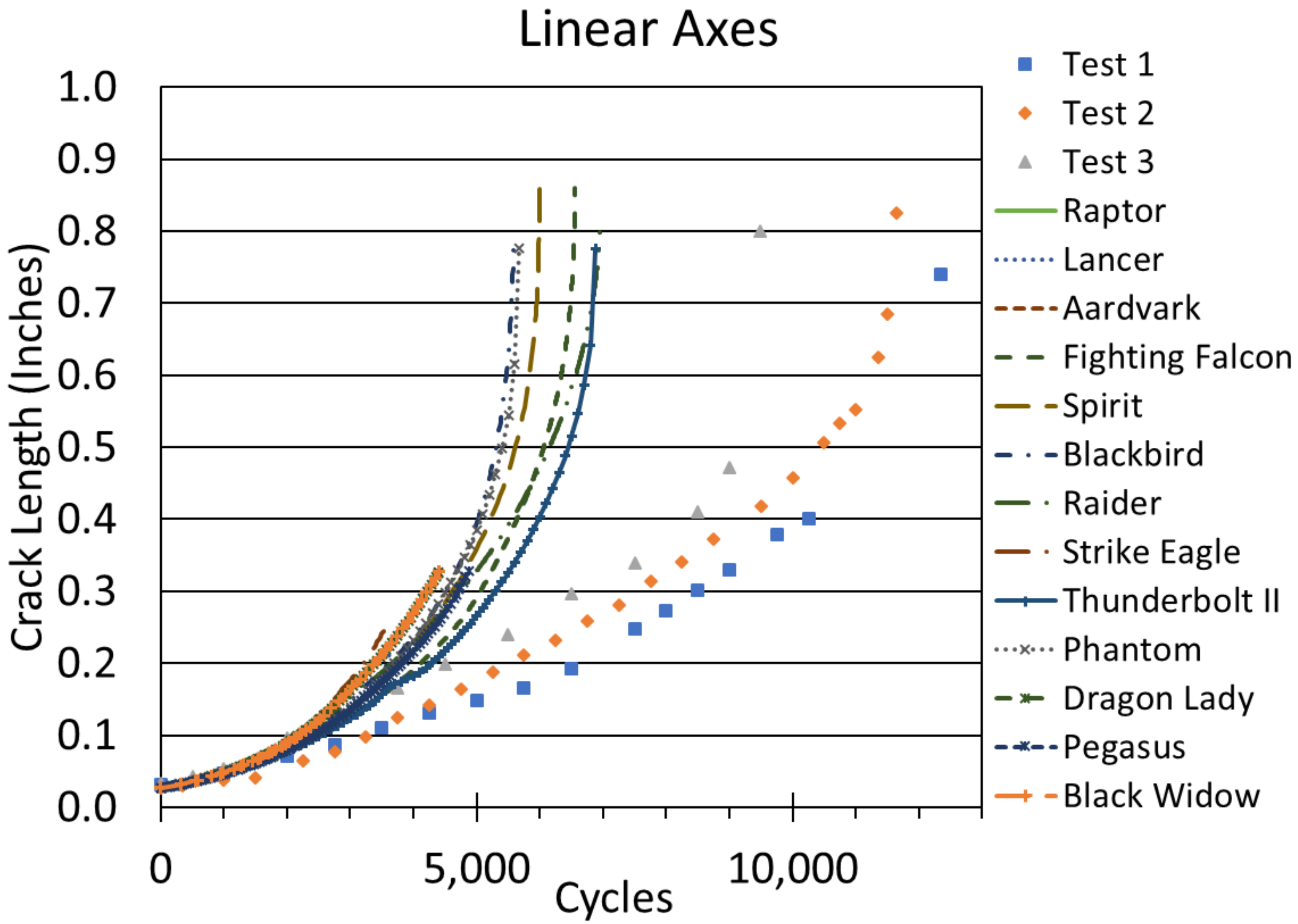
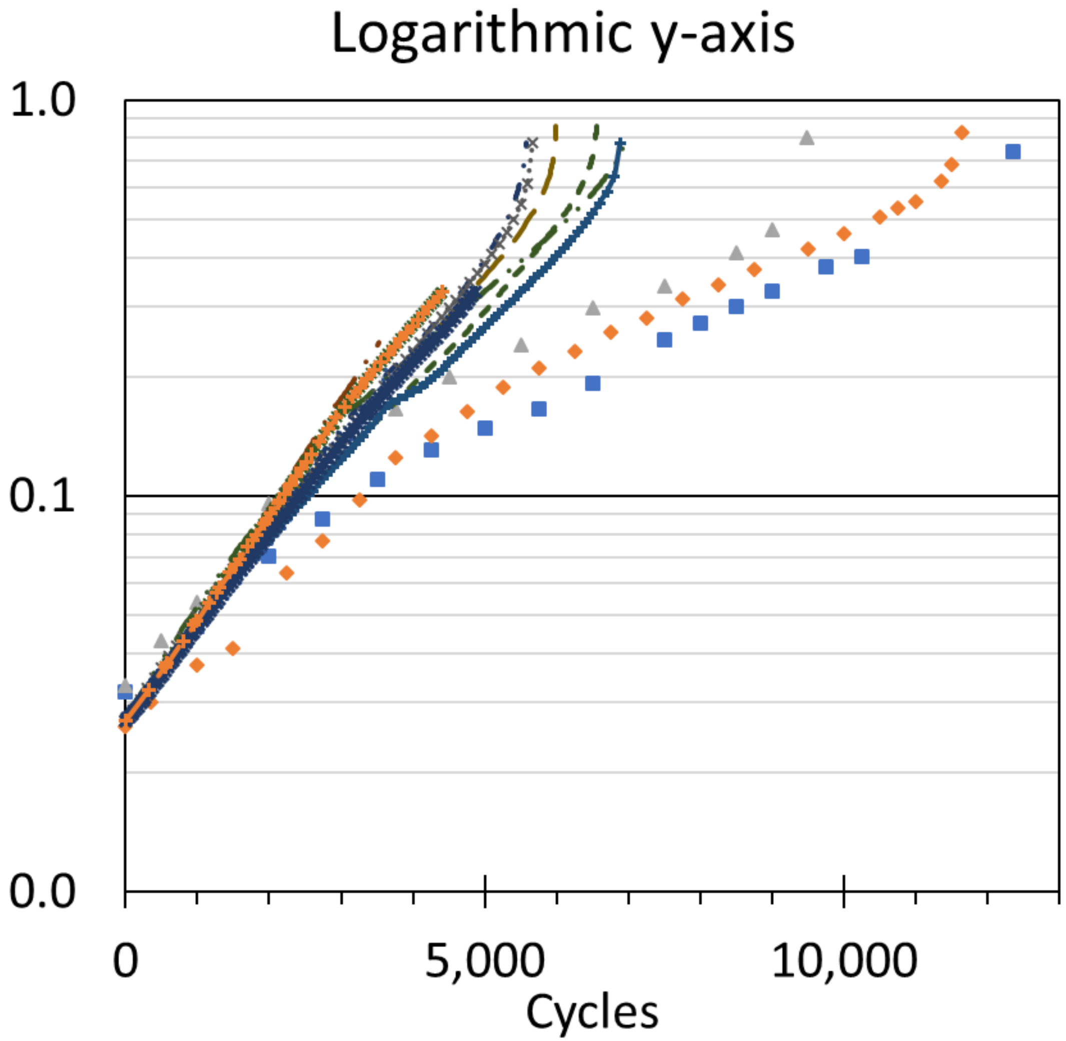
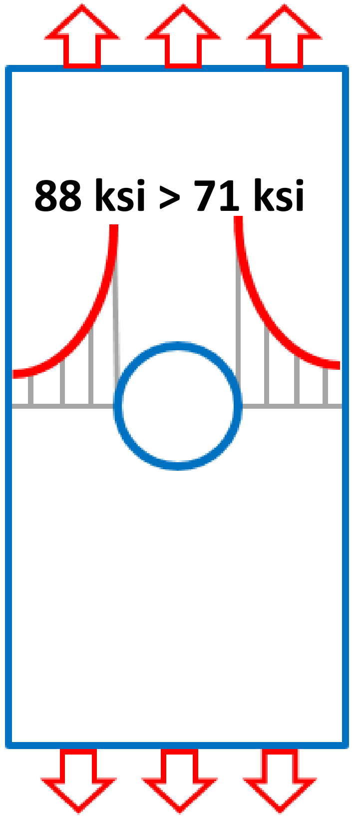
OPEN HOLE RESULTS SURFACE CRACK



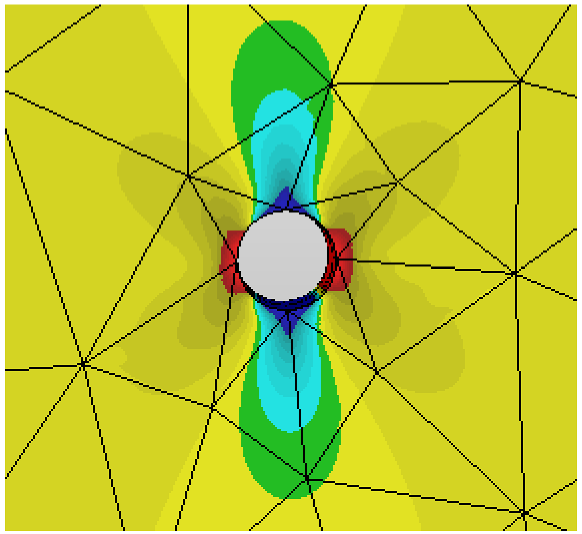


SPECIMEN YIELDING

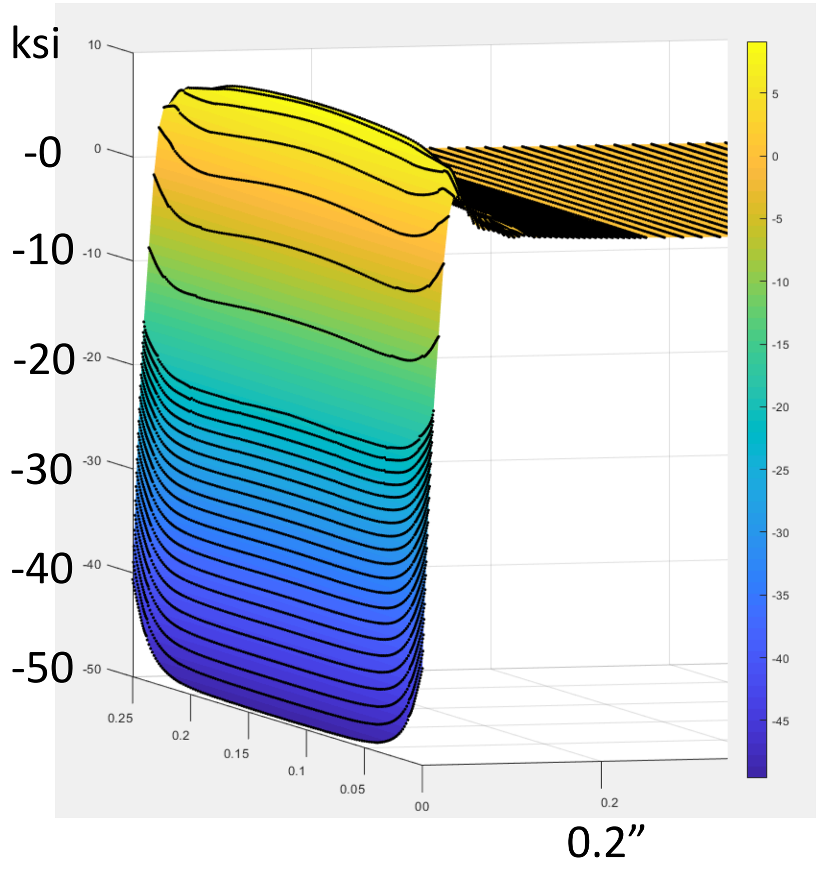
- Yield strength = 71 ksi (Reference MMPDS-15)



Yielding at hole edge

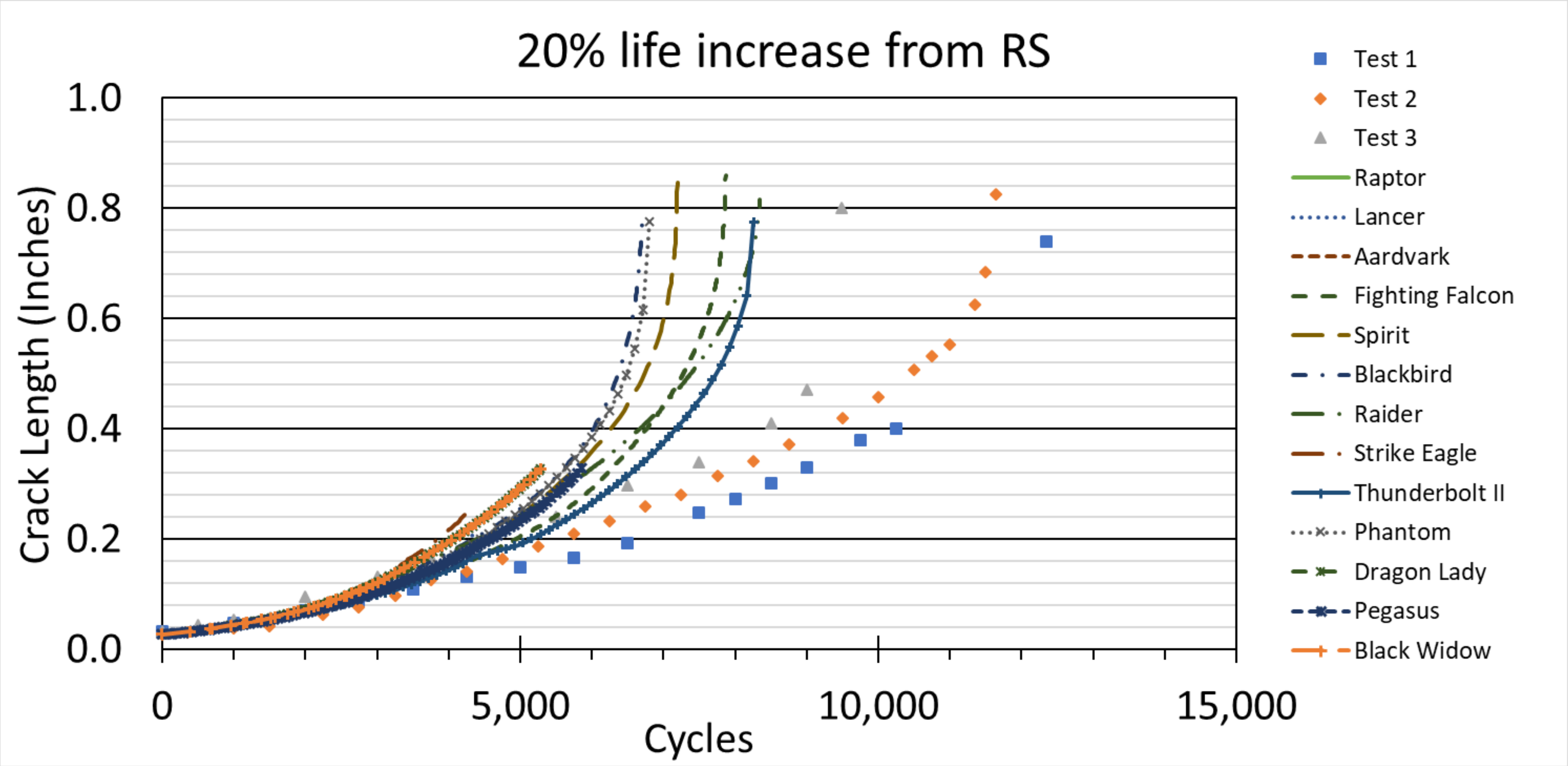


Residual stress from yielding



SPECIMEN YIELD RS INFLUENCE

- Residual Stress from yield provided ~20% life increase
- Applying a 20% life increase to all predictions appears encouraging



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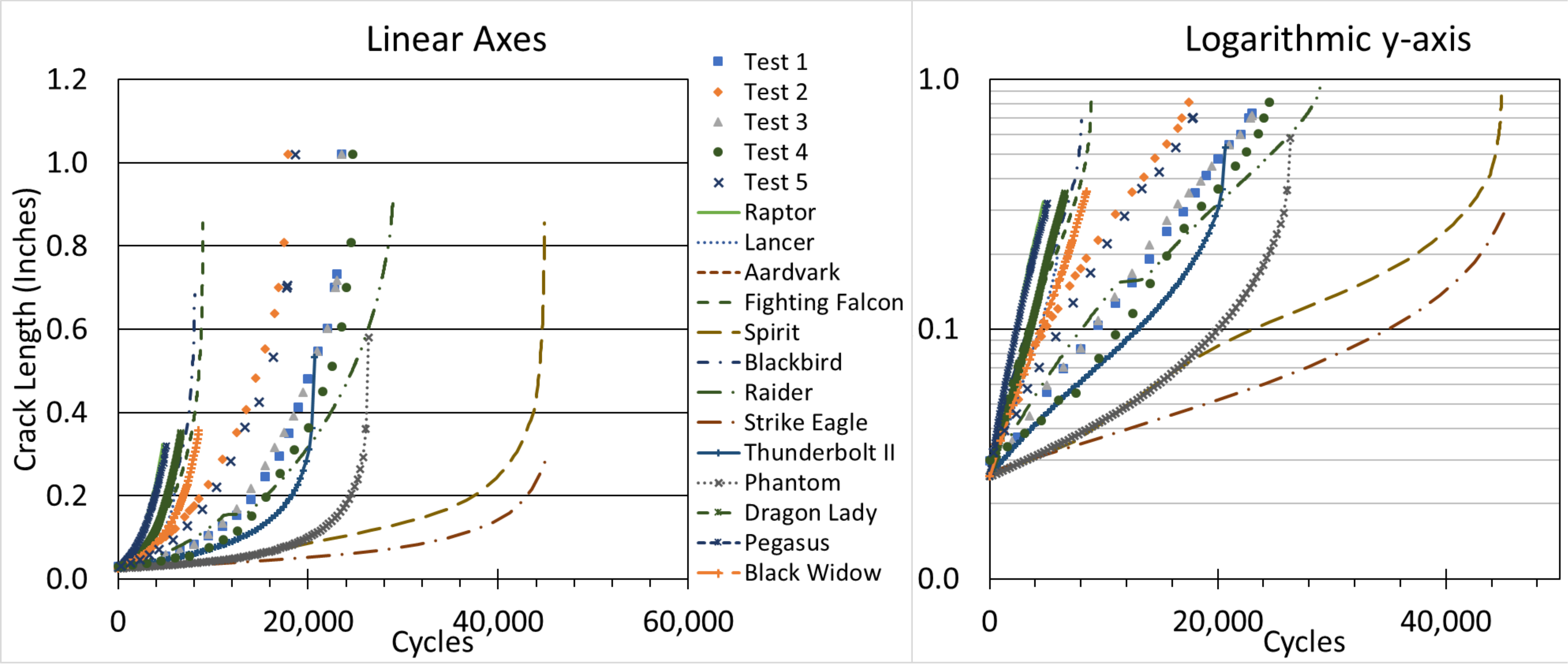
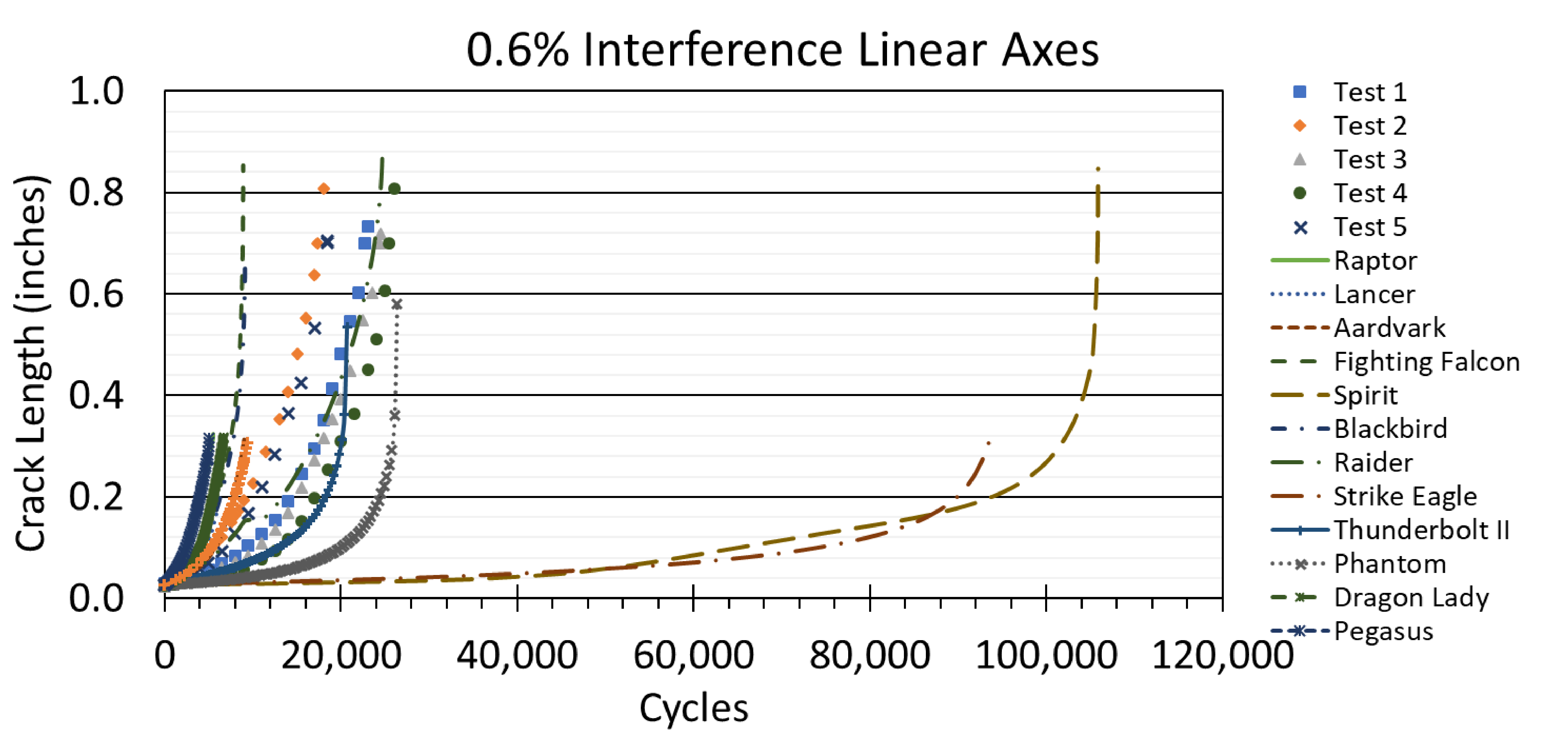
0.4% INTERFERENCE SURFACE CRACK GROWTH



0.6% INTERFERENCE SURFACE CRACK GROWTH



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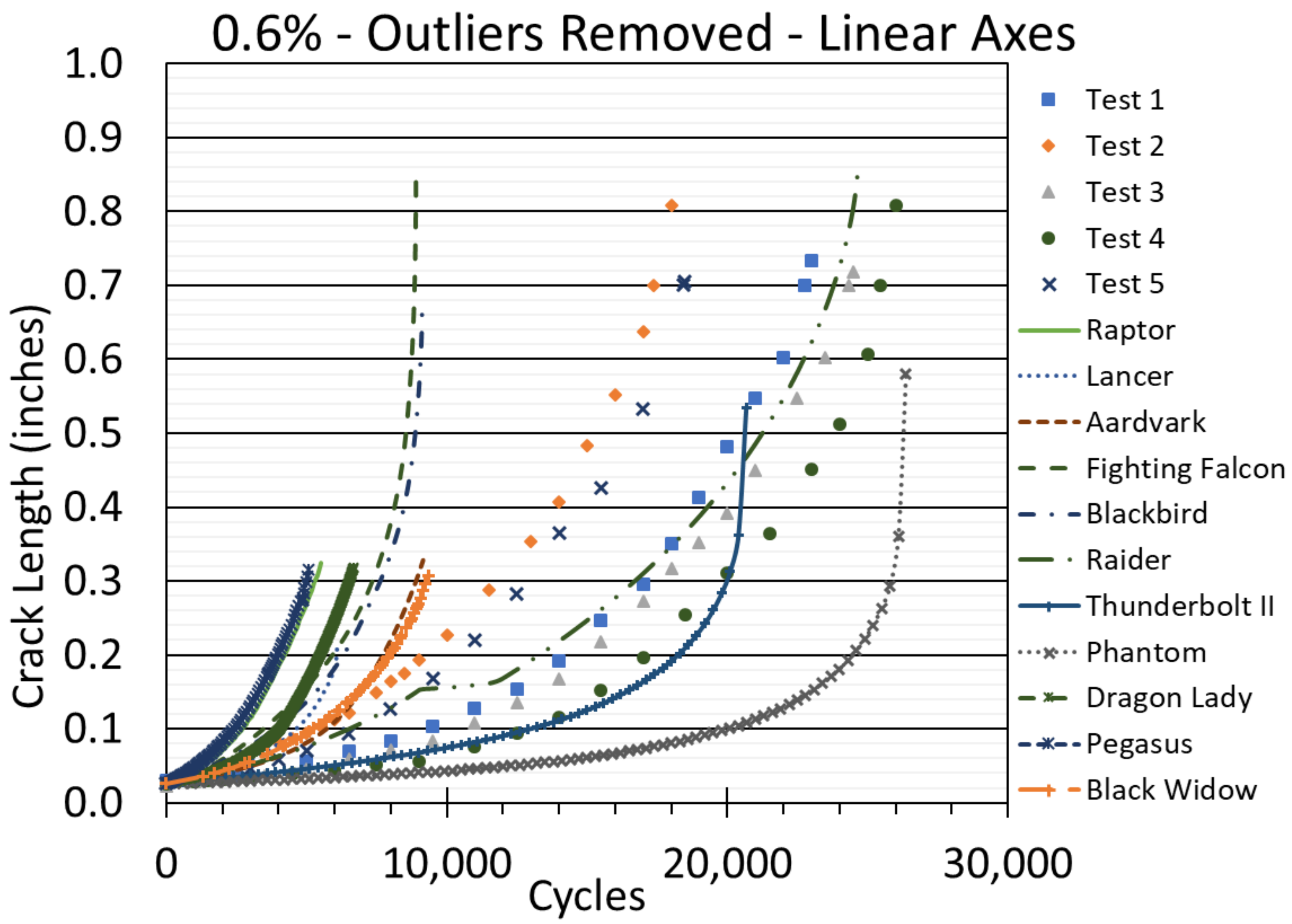
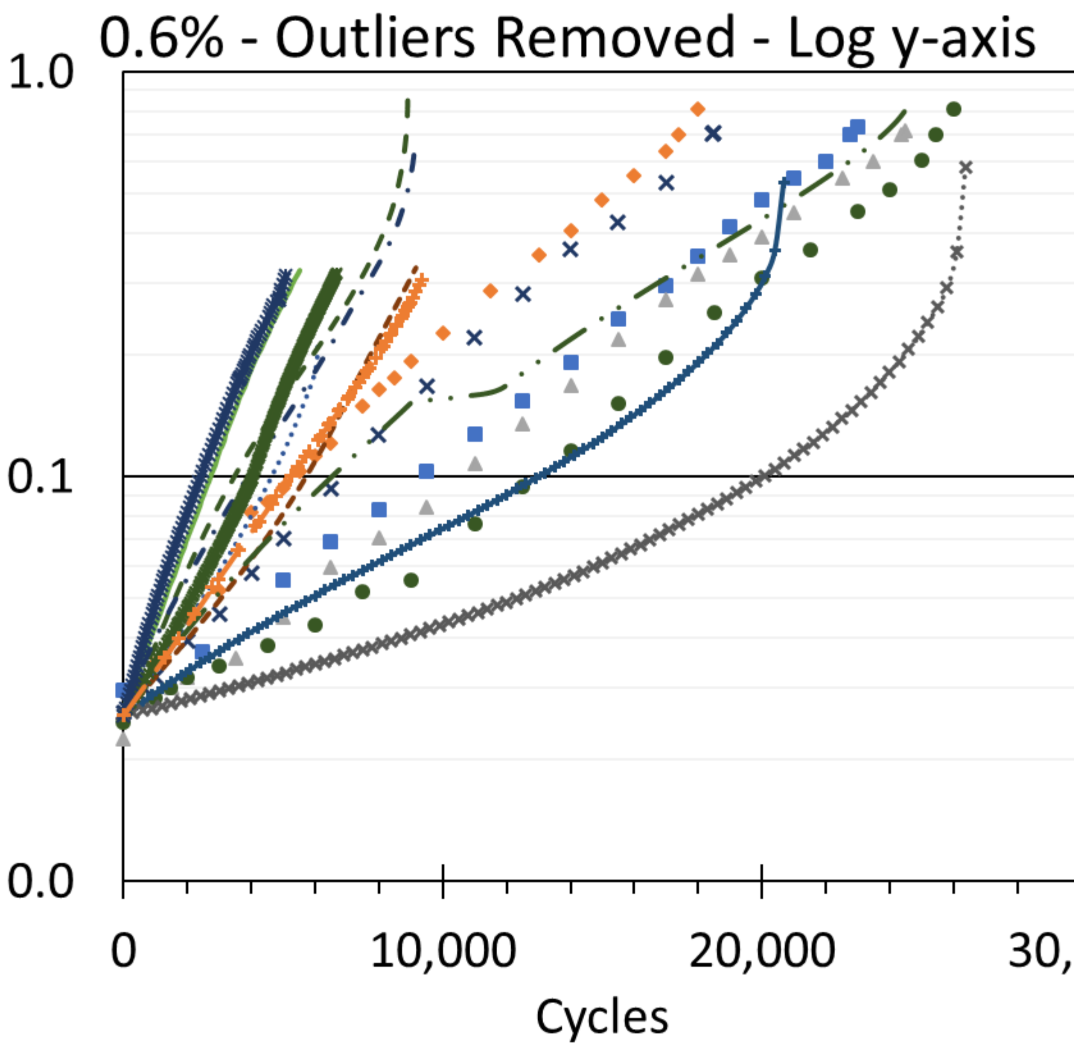
0.6% INTERFERENCE SURFACE CRACK GROWTH





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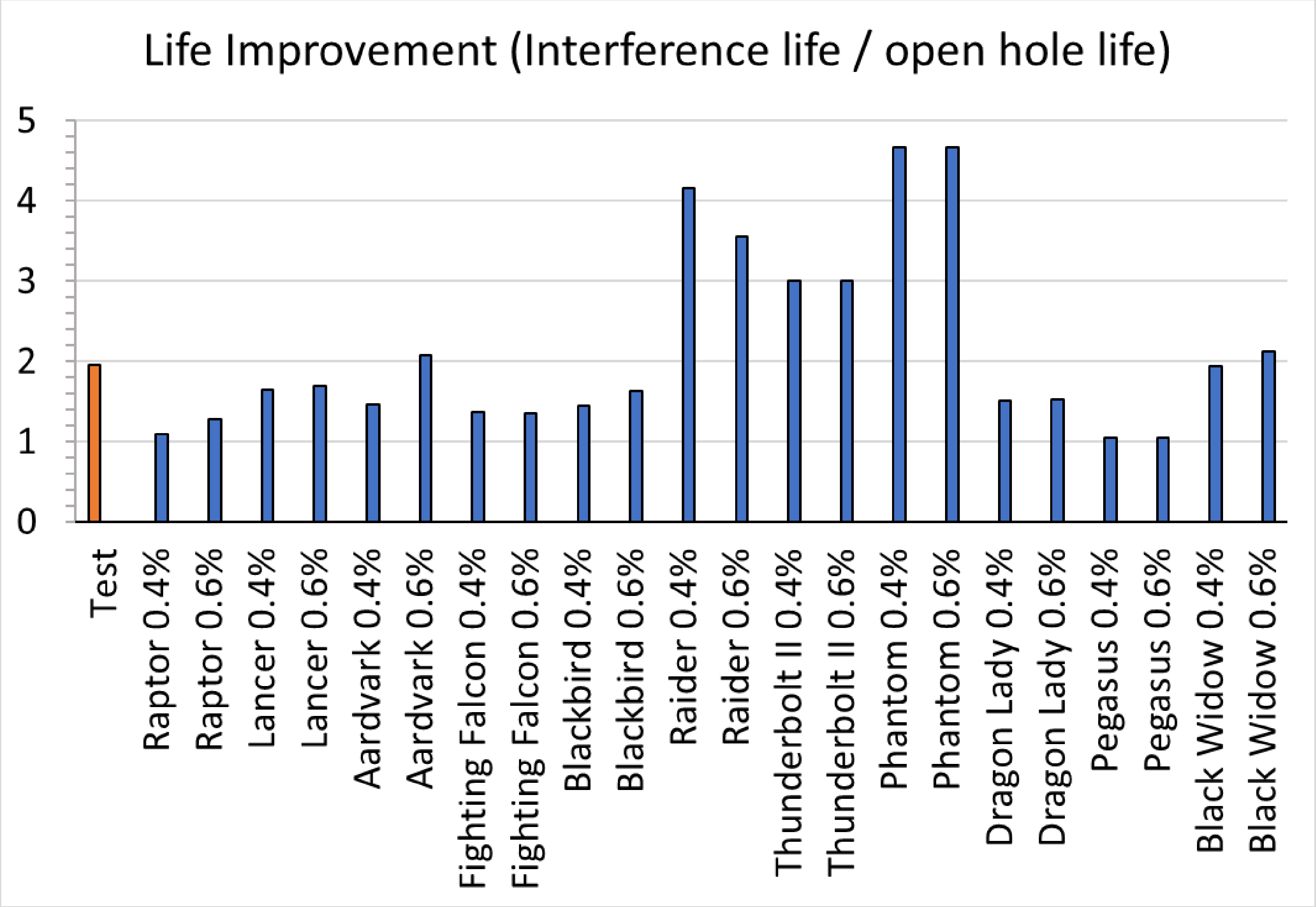
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

INTERFERENCE FIT LIFE IMPROVEMENT

- Test life improvement = 1.96
- Average predicted life improvement = 2.15 (Outliers removed)
- 3 submissions over predict life improvement (5 with outliers)
- 8 submissions under predict life improvement
- Black Widow submission has life improvement nearest to test data



CONCLUSIONS

- Need to understand disparity between open hole predictions and test results
  - Residual stress from overload appears promising
  - Are other plasticity effects compounding issue?
- Factor of two (2) life improvement despite high stress scenario
- Most submissions under predicted life improvement
- Loading scenarios that avoid yielding should be evaluated
- Generally small difference between 0.4% and 0.6% predictions

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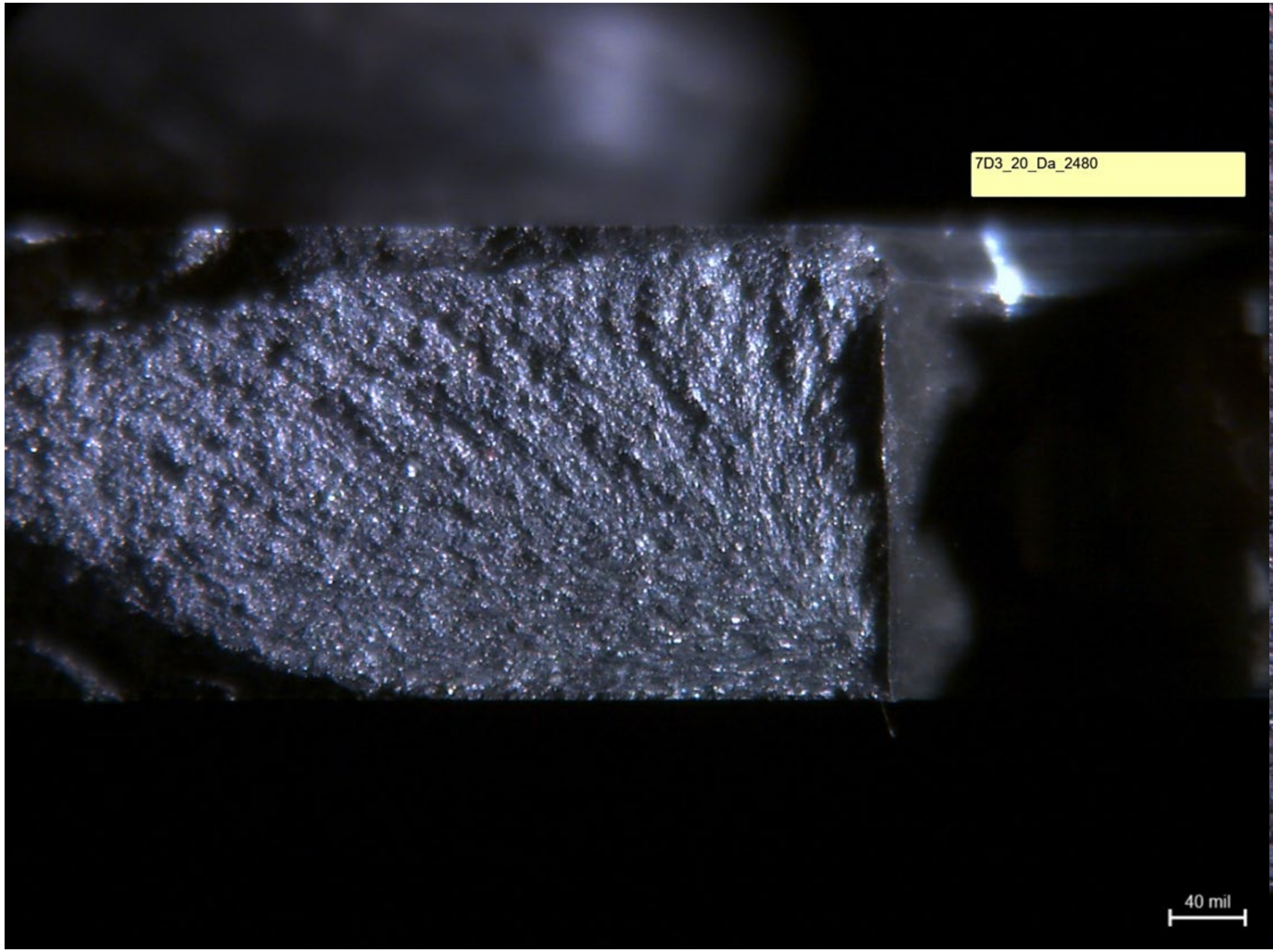
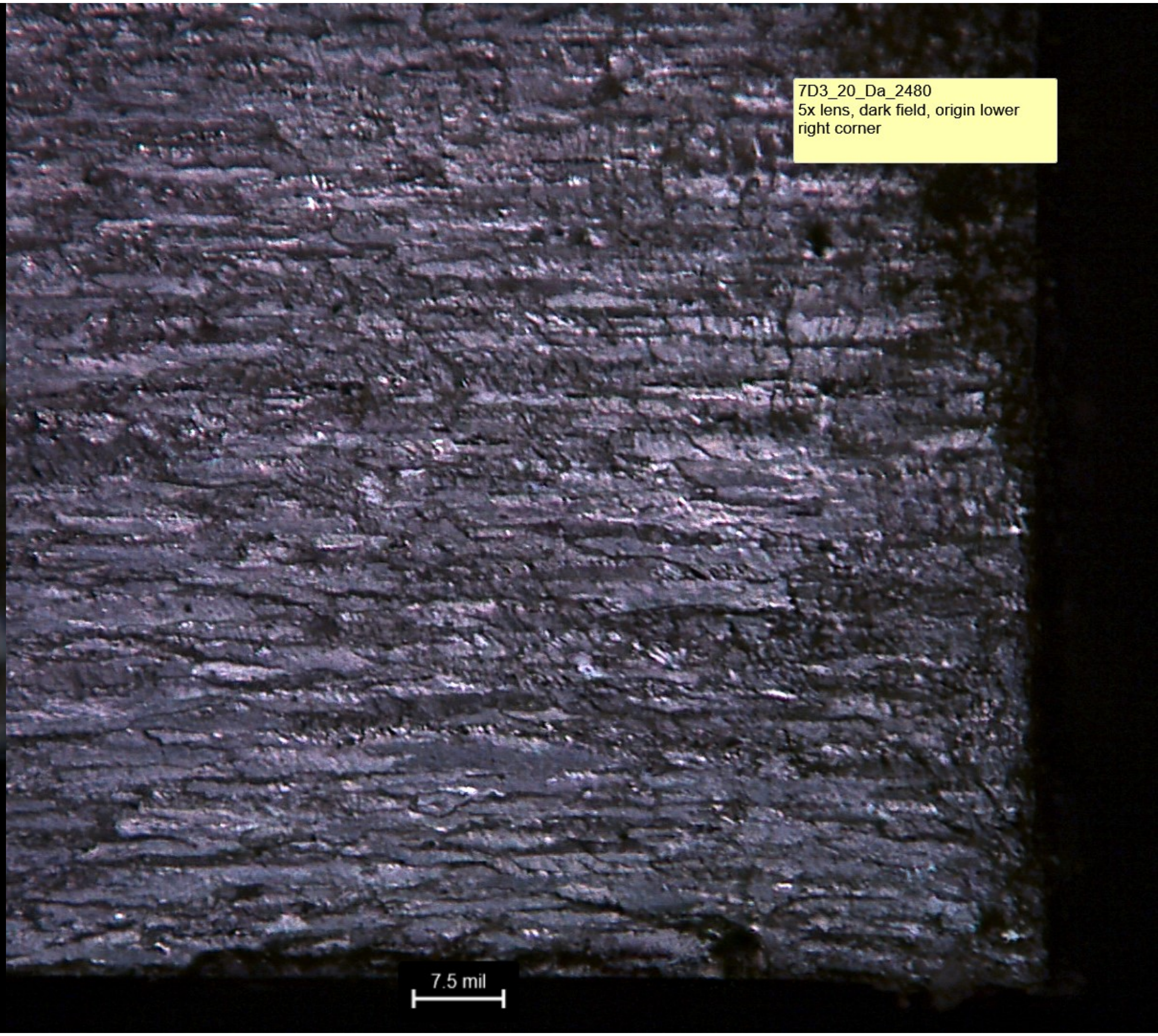
ENGINEERED RESIDUAL
STRESS IMPLEMENTATION

QUESTIONS?



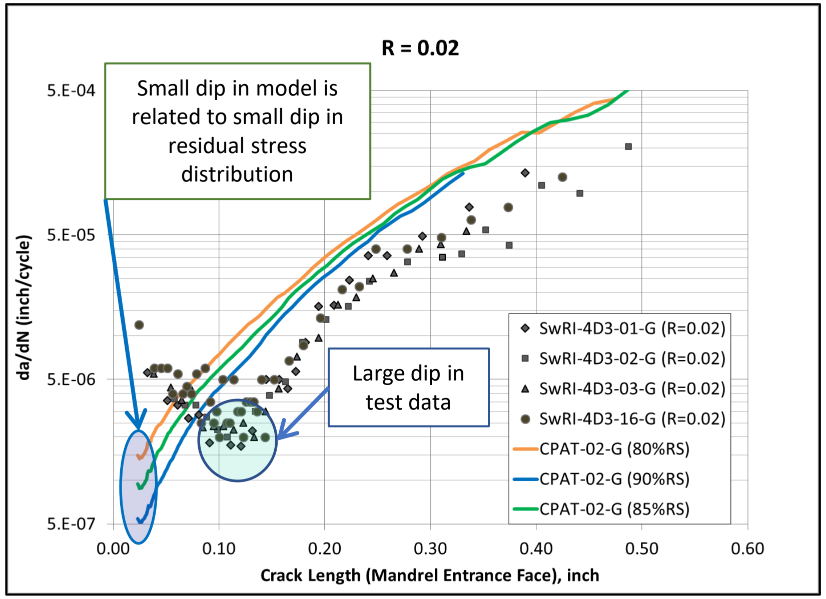


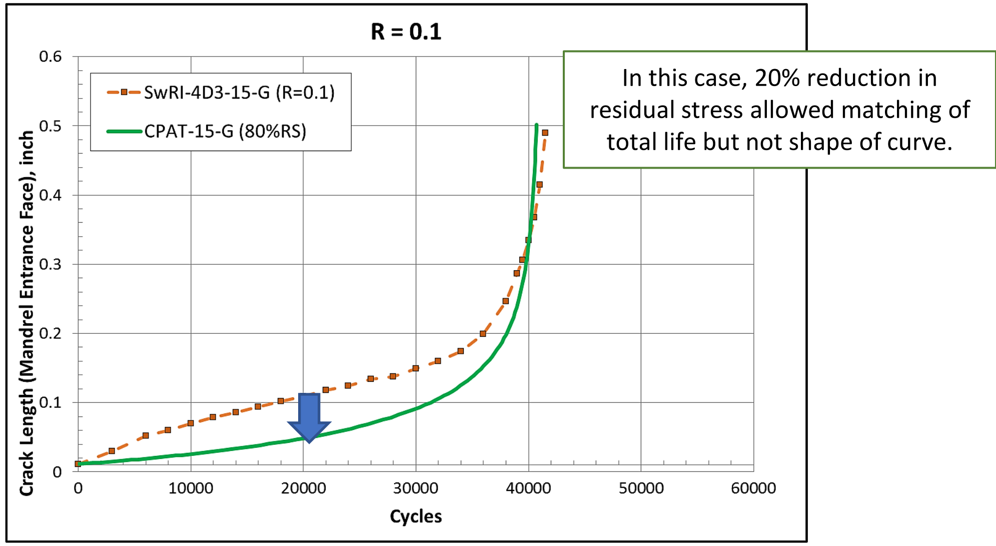
MODELING EFFORTS

Cyclic Redistribution

Refresher from 2018: Key Observations

- Most fatigue crack growth testing at CX holes has traditionally focused on lower stress ratios (e.g. applied R = 0.1)
- These data sets show a **characteristic dip** in crack growth rates
  - Crack propagation modeling efforts of the last several years do not capture this behavior
- Dip only occurs when $R_{tot} < 0$
  - Hypothesis of crack closure
- Dip leads to inaccuracy in modeling solutions





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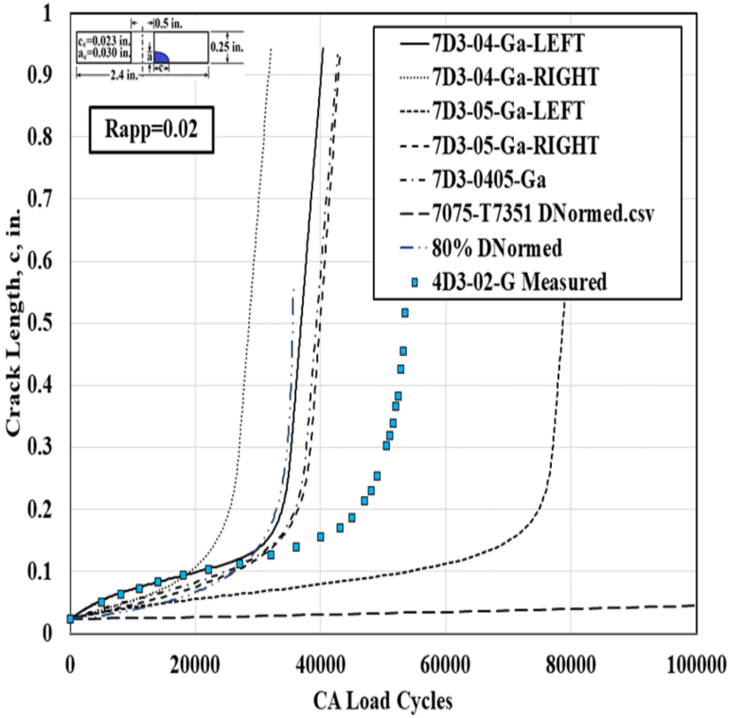
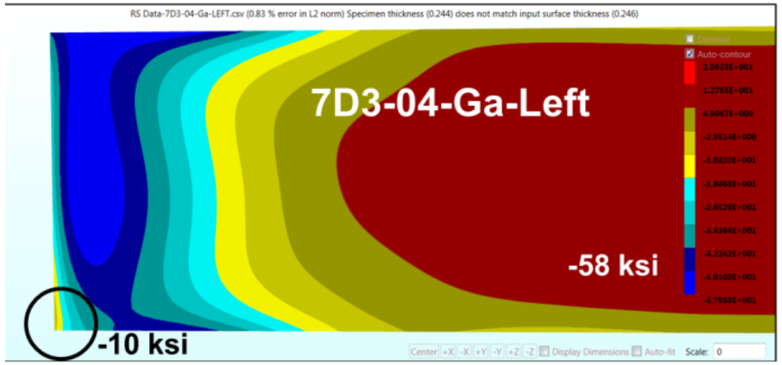
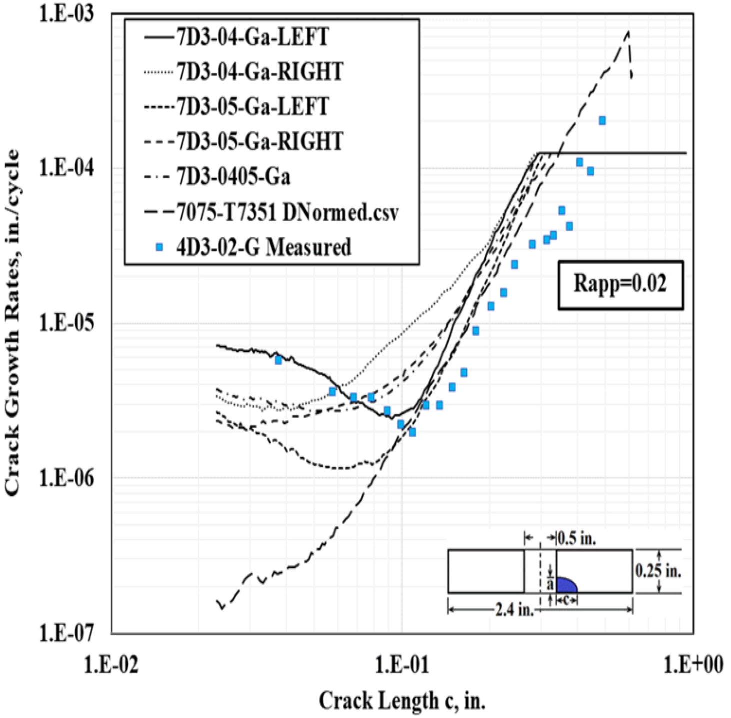
Redistributed Residual Stress Leads to Improved Modeling

- Open hole CX specimens pre-cycled 2000 cycles at test stress
  - “shakedown” of RS
- Results in much less compression at the bore surface than in past data that was not pre-cycled







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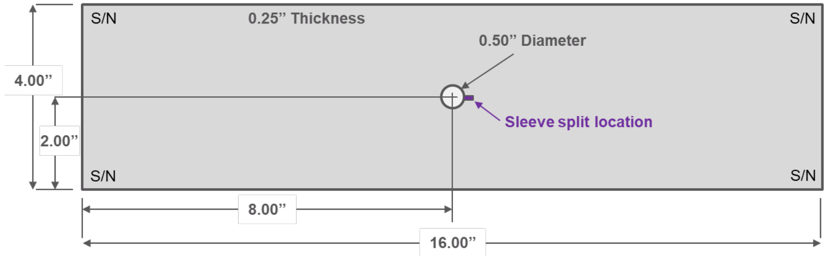
Cyclic Redistribution

- New Program to Investigate Behavior
- Approach
  - Investigate differences between:
    - non-cycled coupons
    - open hole cycled coupons
    - filled hole cycled coupons
- Scope
  - Coupon configurations (18 total)
  - Material: 2024-T351 and 7075-T651
  - Diameter: 0.50-inch
  - Hole Offset: centered
  - Thickness: 0.25-inch
  - Applied expansion: mean



Condition	Material	Thickness (in)	Width (in)	Hole Edge Margin	Pre-Cx Ream Diameter (in)	Applied Expansion	Post-Cx Ream Diameter (in)	Replicates
Non-Cycled	2024-T351	0.25	4.00	Centered	0.4755+/-0.0005	Mid	0.4960-0.4985	3
Open Hole Cycled								3
Filled Hole Cycled								3
Non-Cycled	7075-T651							3
Open Hole Cycled								3
Filled Hole Cycled								3

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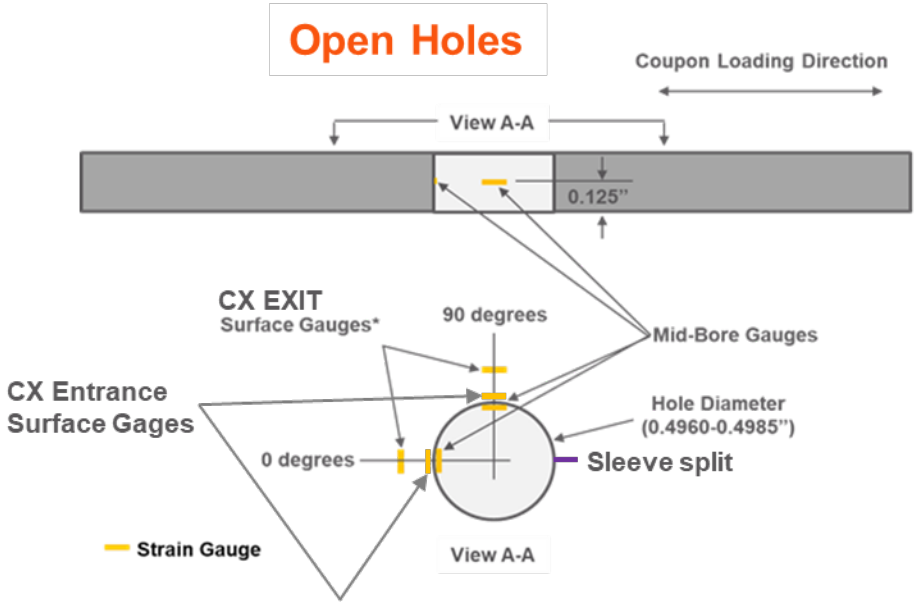
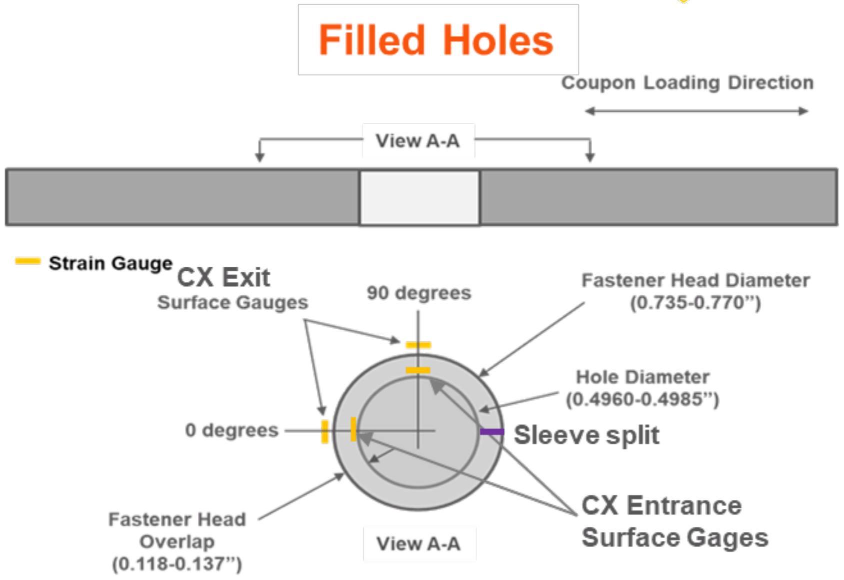
Cyclic Redistribution

- Pre-cycling
  - Strain gauging of (1) coupon per condition

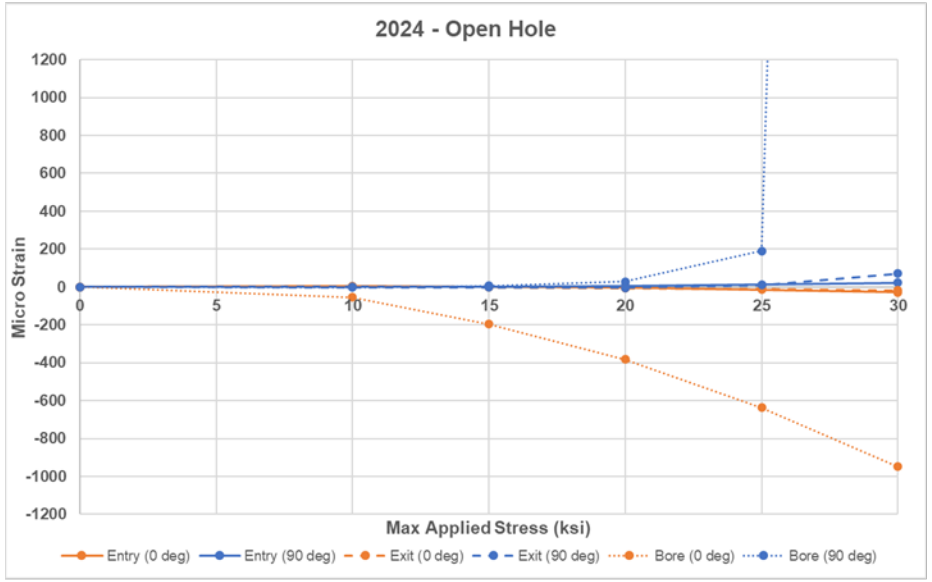


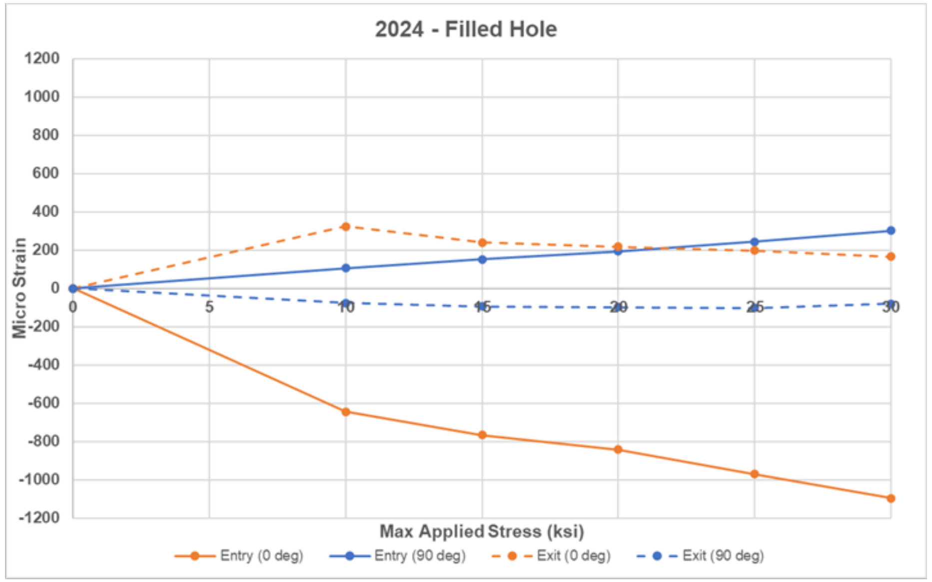


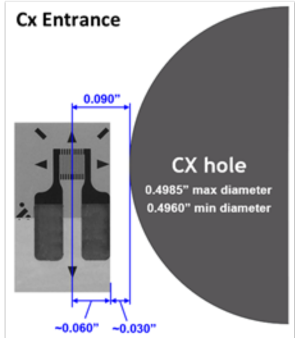
Condition	Loading	Strain Monitoring	Gauge Location	Max Stress (ksi)	Cycles	Replicates (each material)
Open Hole Cycled	CA R=0.1	Yes	Bore & Surface	10, 15, 20, 25, 30	2000/each	1
		No	N/A	30	2000	2
Filled Hole Cycled		Yes	Surface	10, 15, 20, 25, 30	2000/each	1
		No	N/A	30	2000	2

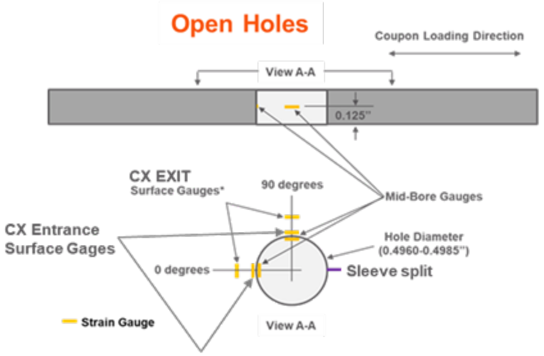
Cyclic Redistribution

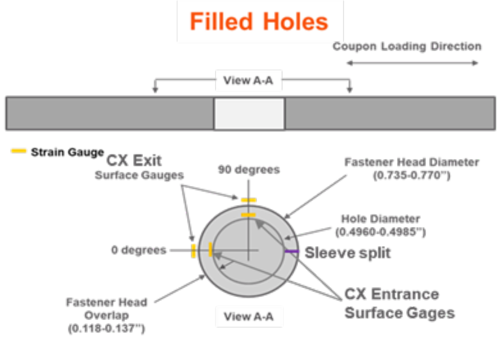
- 2024 strain gauge results
  - 100 microstrain ~ 1ksi

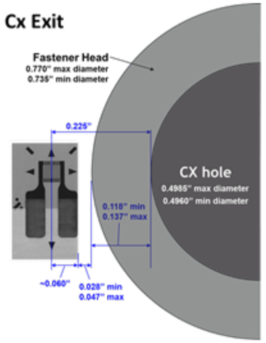












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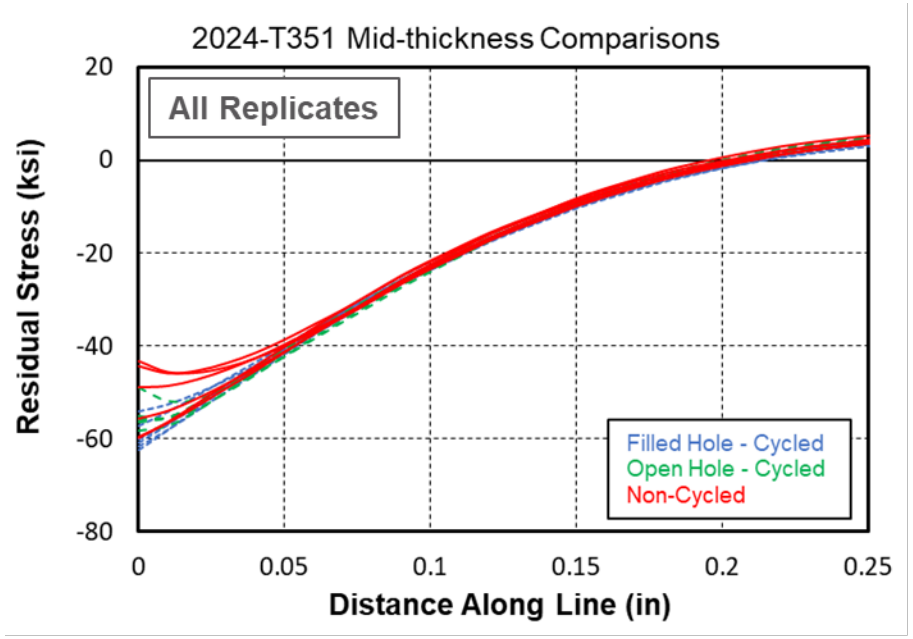
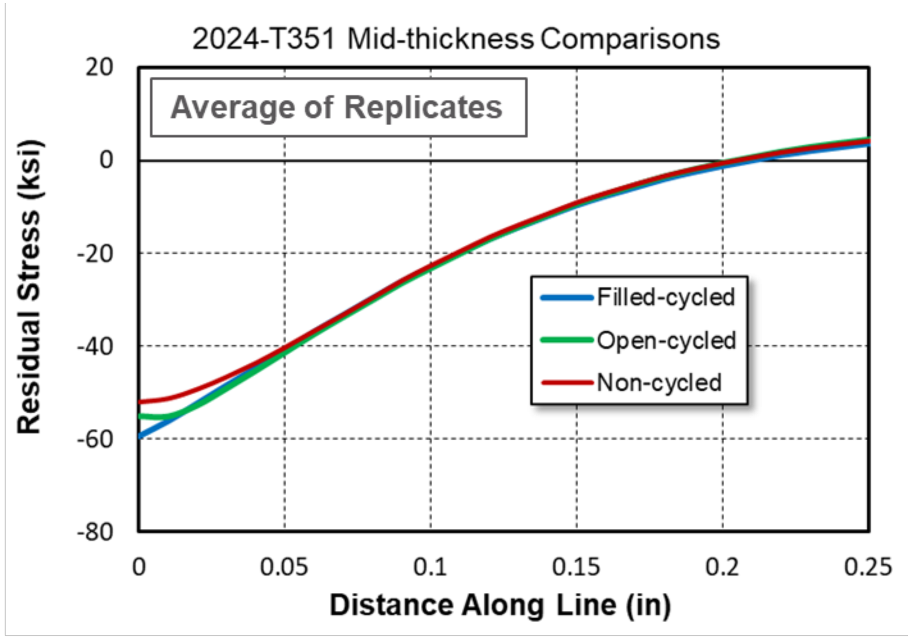
Cyclic Redistribution

- Residual stress measurements – 2024 comparisons





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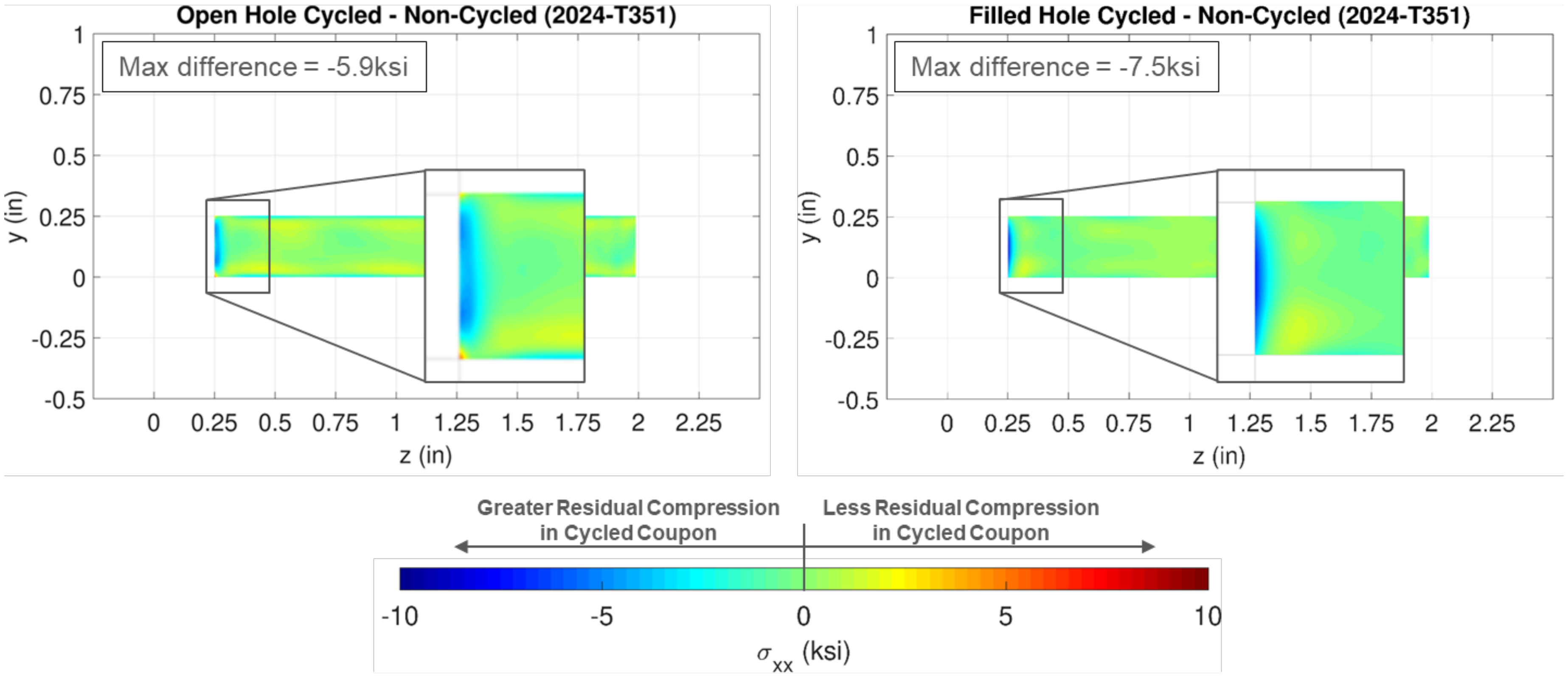
Cyclic Redistribution

- Residual stress measurements – 2024 comparisons



Cyclic Redistribution

- Summary & conclusions
  - Pre-cycled open and filled hole coupons did not result in appreciable changes in surface strains or residual stress relative to non-cycled coupons
  - Surface and bore strain gauges were generally within 400 microstrain
  - Residual stress changes were within 8ksi
    - Typically higher for cycles coupons near the bore
  - Redistribution of stress, as observed by APES in 7D3-04-Ga coupons, was not evident in measurement results
  - Still reviewing data, however, additional investigation is necessary to understand details for 7D3-04-Ga coupons and any underlying keys to resulting residual stresses

Multi-Point MAI Program

MAI III
NG-11 Program Overview

Verification, Validation, and Demonstration of Multi-Point Fracture Modeling (MPFM) Codes

Adam Morgan
Senior Principal Engineer

8th December, 2020

Program Team

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

Air Force Research Laboratory

ATI ADVANCED TECHNOLOGY INTERNATIONAL

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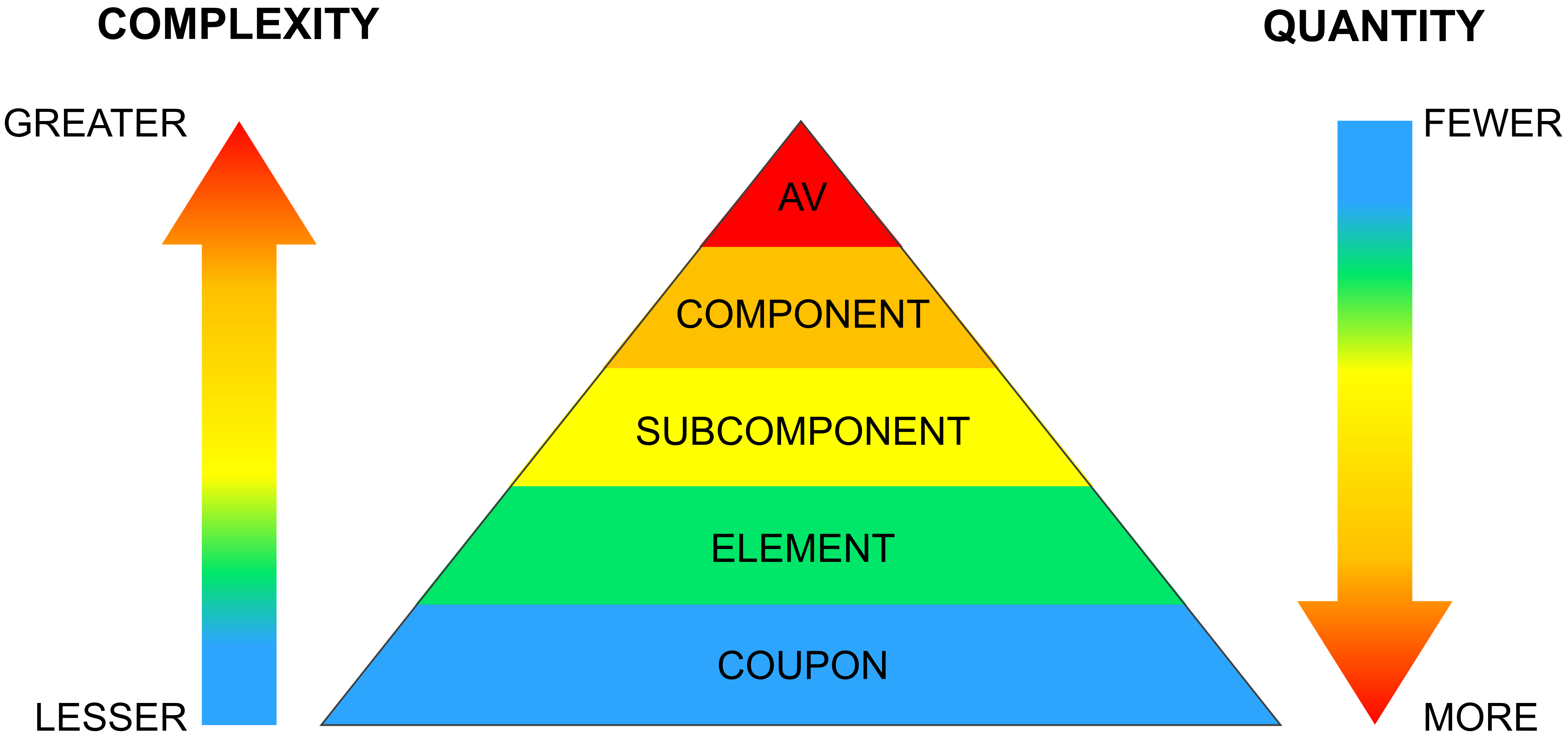
Fracture Analysis Consultants, Inc

Overall Program Objectives

"*Validate and assess capability of commercial off-the-shelf (COTS) and proprietary multi-point fracture mechanics (MPFM) codes as applied to the linear elastic fracture mechanics (LEFM) analysis of cold-expanded (Cx) holes.*"

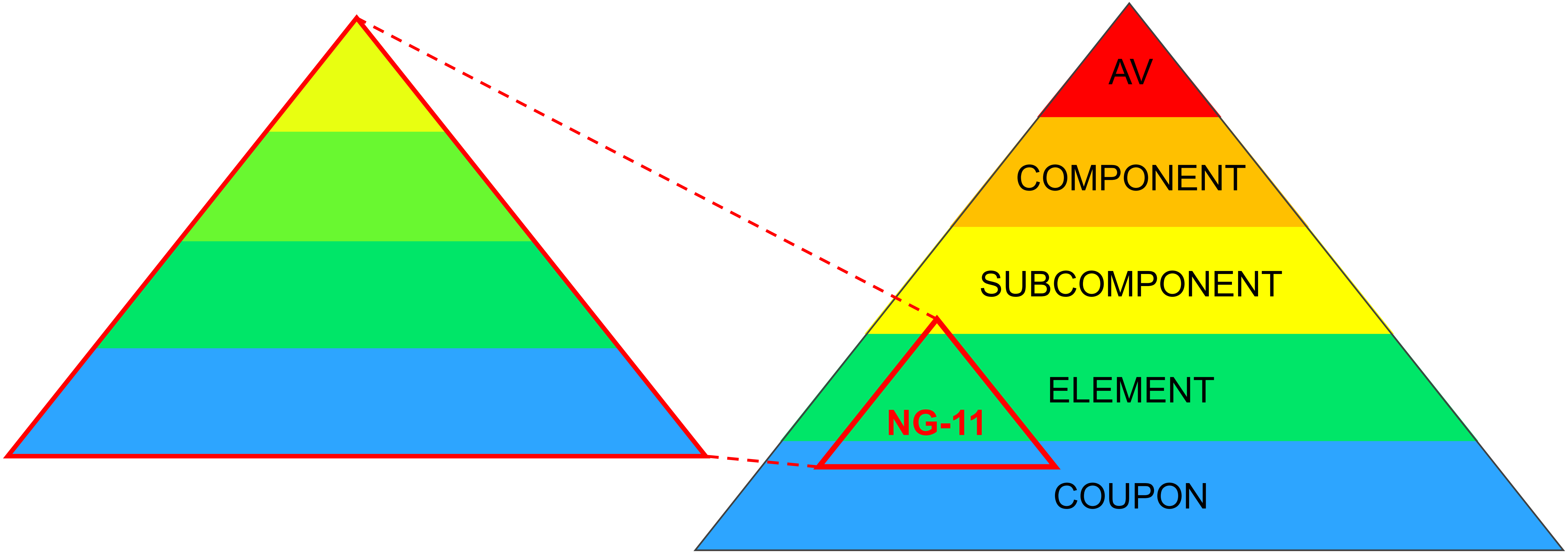
- Task 3 – V&V of MPFM against analytical solutions and test data
  - Building Block Approach
  - '*Blind*' Predictions
- Task 4 – Demonstrate MPFM on Defense Aerospace Application
- Task 5 – Document and Out Brief

Building Block Approach



Building Block Approach

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



Building Block Approach

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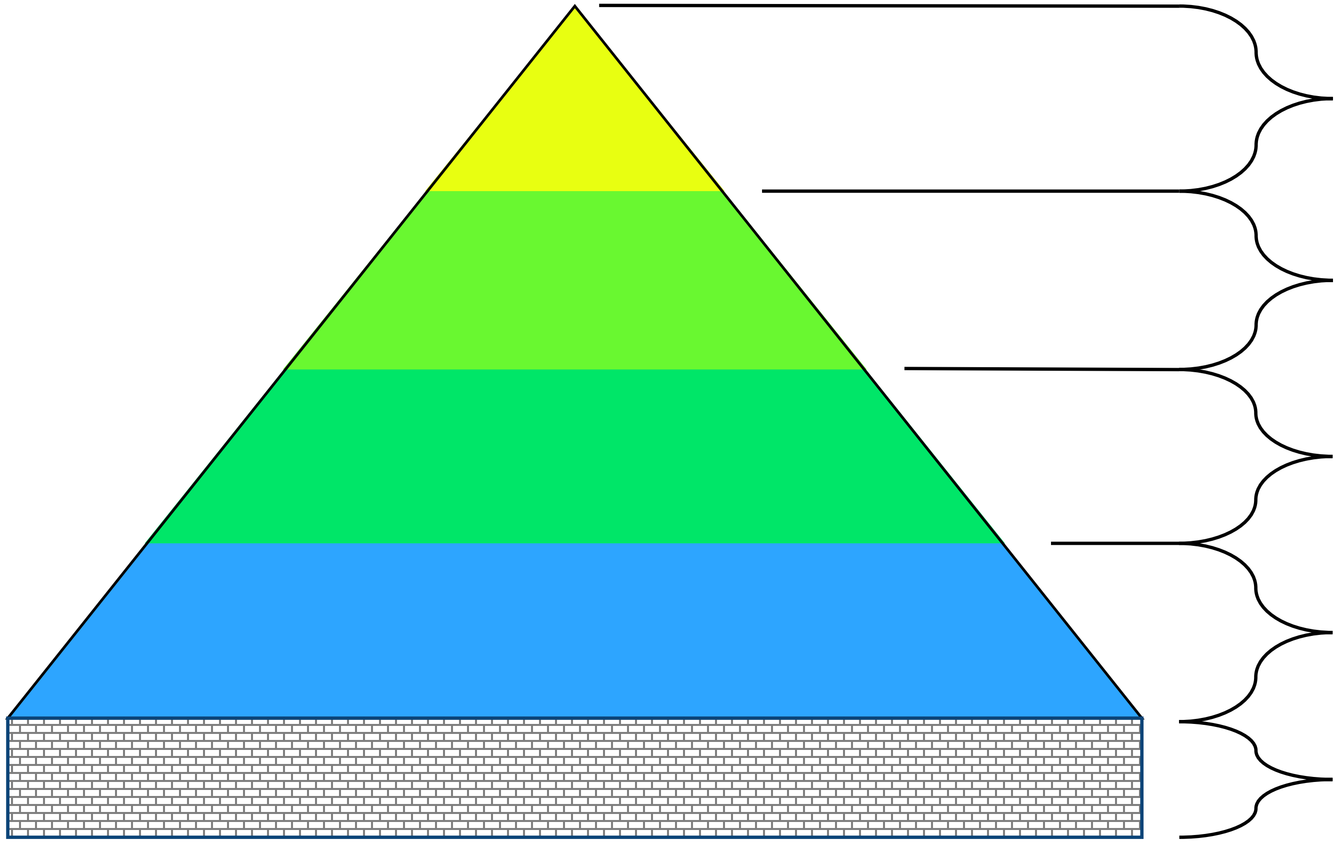

Element-to-Subcomponent Level – FCL *(Task 4)*
- AFRL Supplied
- Demonstrate on participating platform

Element Level *(Task 3.3)*
- AFRL Supplied – With residual stresses
- AFRL Supplied – With complex load
- Validate MPFM to level beyond traditional DTA methods

Element Level *(Task 3.2)*
- AFRL Supplied – No residual stresses
- Validate MPFM to level comparable to traditional DTA methods

Coupon Level *(Task 3.1 Continued)*
- *NG Legacy Data – Basis for material model*
- *Additional AFRL Data – Modify material models*
- Simulate to validate SIF + Analysis Code integration

Analytical Benchmark Case *(Task 3.1)*
- Verification of MPFM Solution
- Validation of modeling procedure/practices

MPFM Codes

Three (3) Multi-Point Fracture Modeling Codes to be utilized:

1. Broad Application for Modeling Failure (BAMF)
   - COM interface to be developed by Hill Engineering LLC
     - Integrate with AFGROW through COM interface
     - Integrate with FASTRAN through scripting
2. Fracture Analysis Code 3D (FRANC3D)
   - Allows for development of Python based extensions
     - Integrate with AFGROW through COM interface
     - Integrate with FASTRAN through scripting
3. BEASY
   - BEM and MPFM capabilities already integrated

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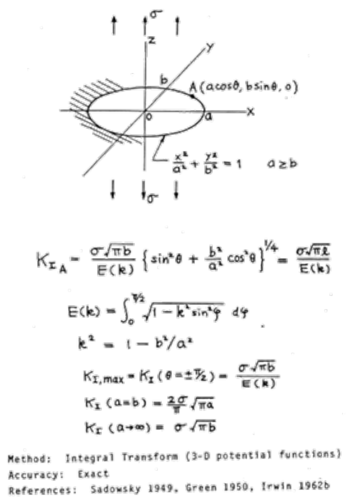
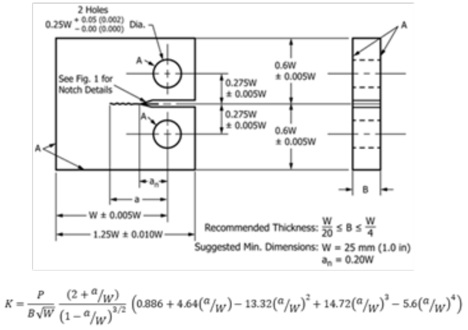
Benchmark-to-Sub-Component Analyses

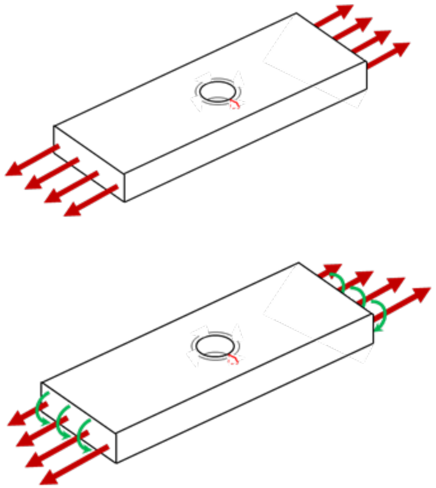
Analytical Benchmark



Basic Coupon Level



Element Level



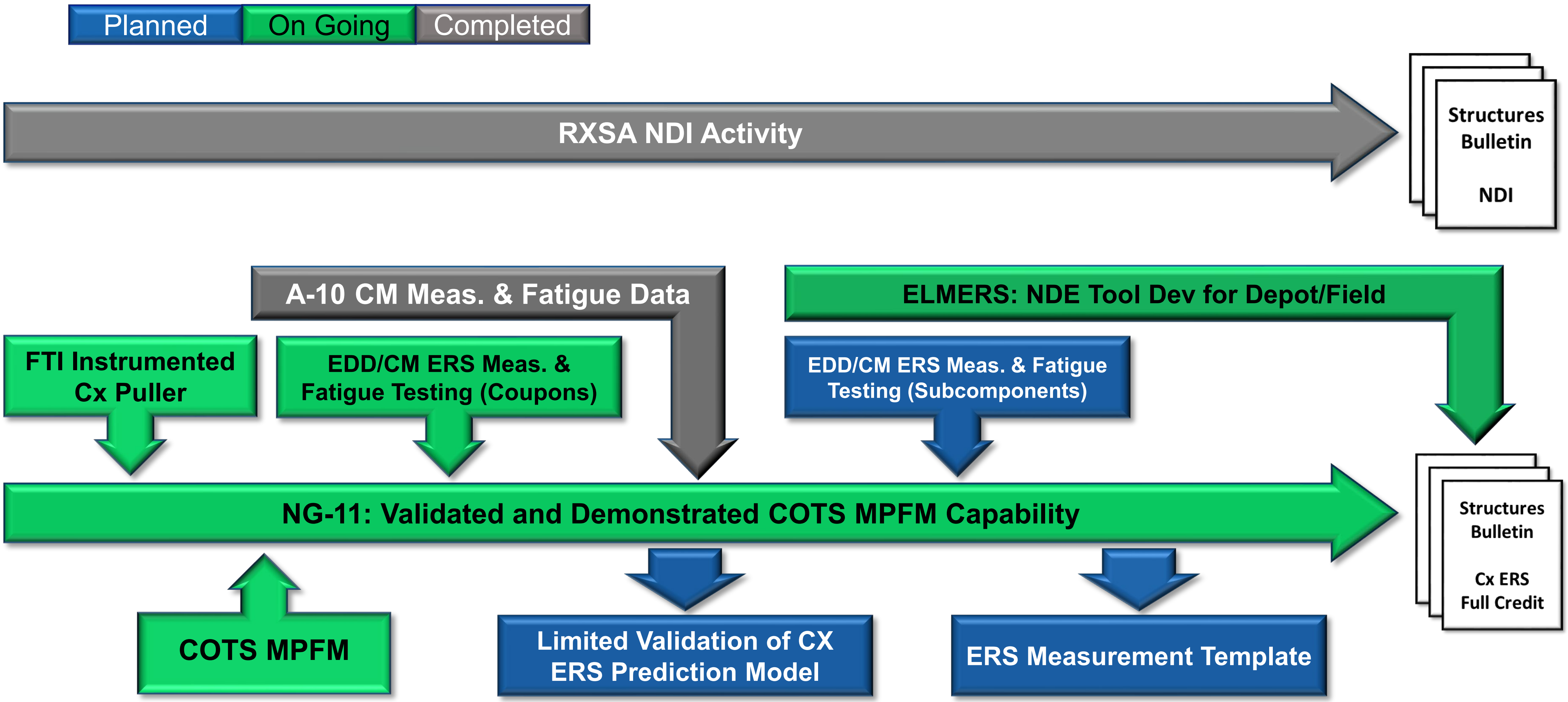
Sub-Component Level

Fatigue Critical Location on Partner Weapons Platform *(AFRL to Define)*

Summary

Description	Analysis Configurations
Task 3.1 - Baseline Verification Specimens	
Analytical – Embedded Ellipse	2
Empirical – Compact Tension C(t)	1
Task 3.2 - Validation to level commensurate with traditional DTA methods	
Corner Crack at an Open Hole - Axial	4
Task 3.3 - Validation to level beyond traditional DTA methods	
Corner Crack at a Cold Worked Open Hole – Axial Load	8
Corner Crack at an Open Hole – Complex Load	2
Corner Crack at a Cold Worked Open Hole – Complex Load	2
Task 4 - Demonstration	
Fatigue Critical Location	1

MAI NG-11: Interrelated Activities



AFGROW Advanced Model Predictions

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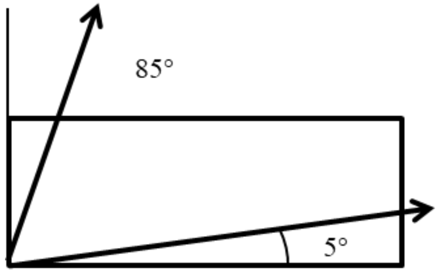
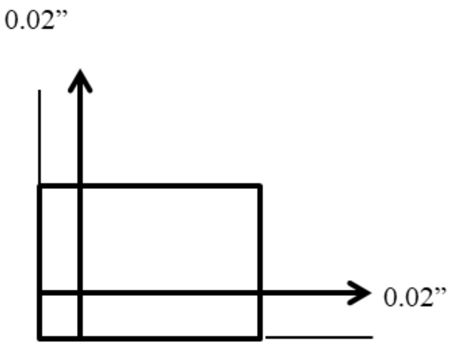
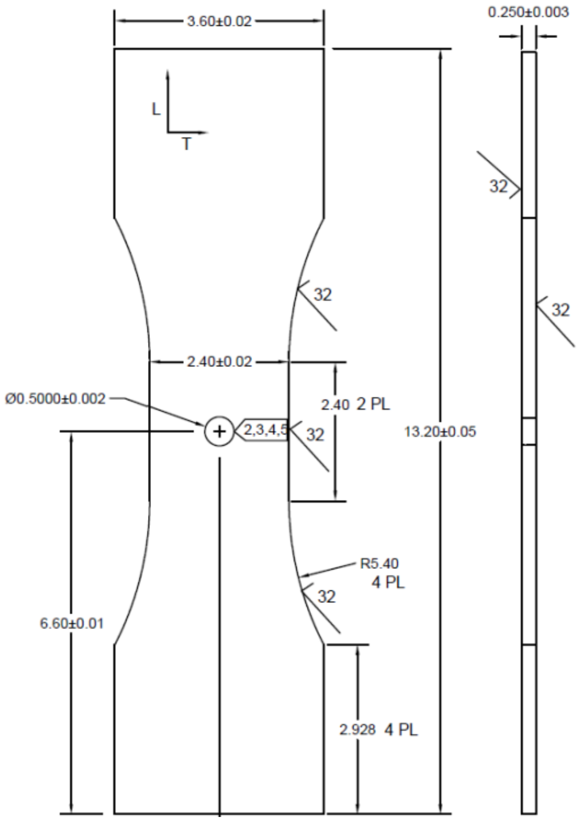
AFGROW Advanced Model Predictions

- Methods
  - AFGROW Advanced Models
  - Inputs
    - Materials (2): 7075-T7351, 2024-T3
    - Coupon Geometry: Central hole
    - Constant amplitude
    - AFGROW Residual stress "vectors"-1 vector each for adjusting "c" and "a" crack SIFs







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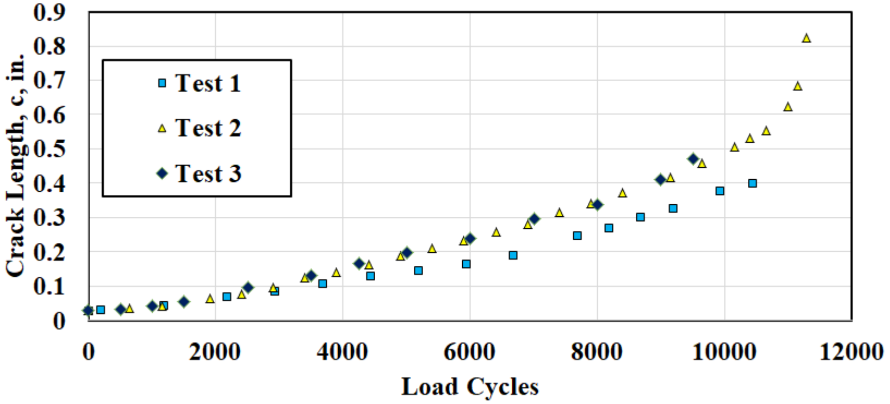
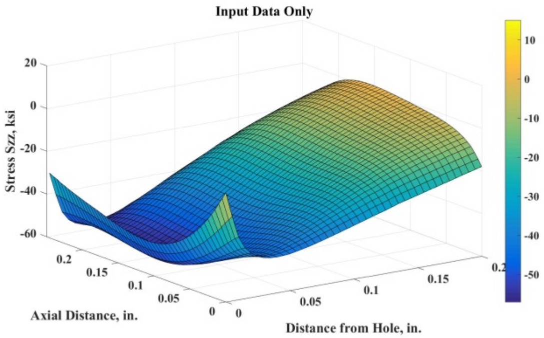
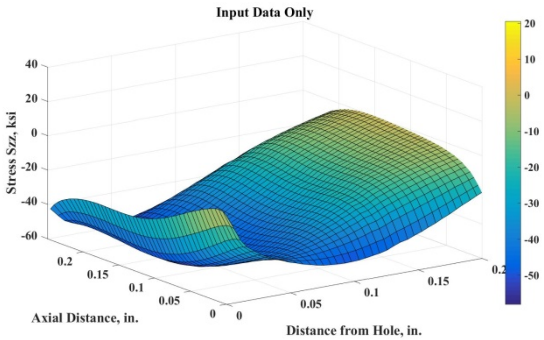
AFGROW Advanced Model Predictions

- Available Data for Validation
  - Experimental crack growth measurements



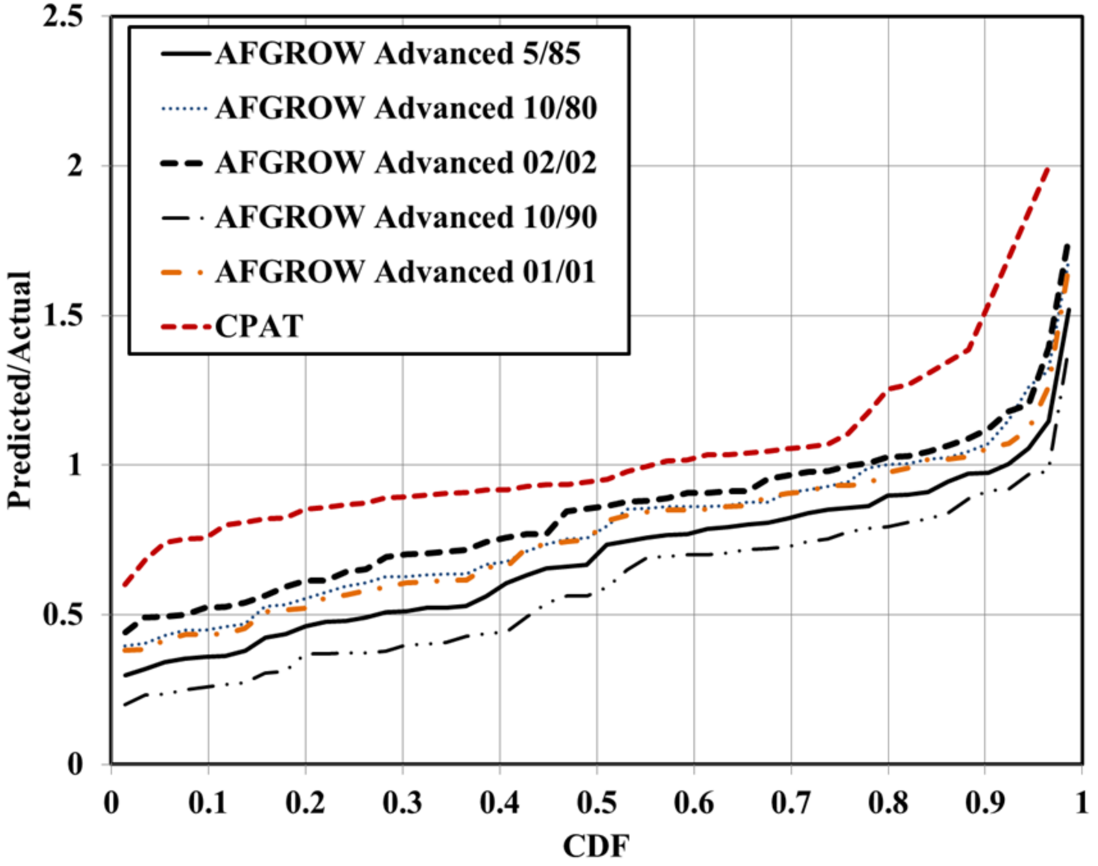
  - Residual stress measurements





AFGROW Advanced Model Predictions

- Summary of Predictions – 7075-T7351



Ranking

1. CPAT (Best)
2. 02/02
3. 10/80
4. 01/01
5. 5/85
6. 10/90

Initial cracks are as-measured pre-crack. References (Actuals) are measured fatigue lives.

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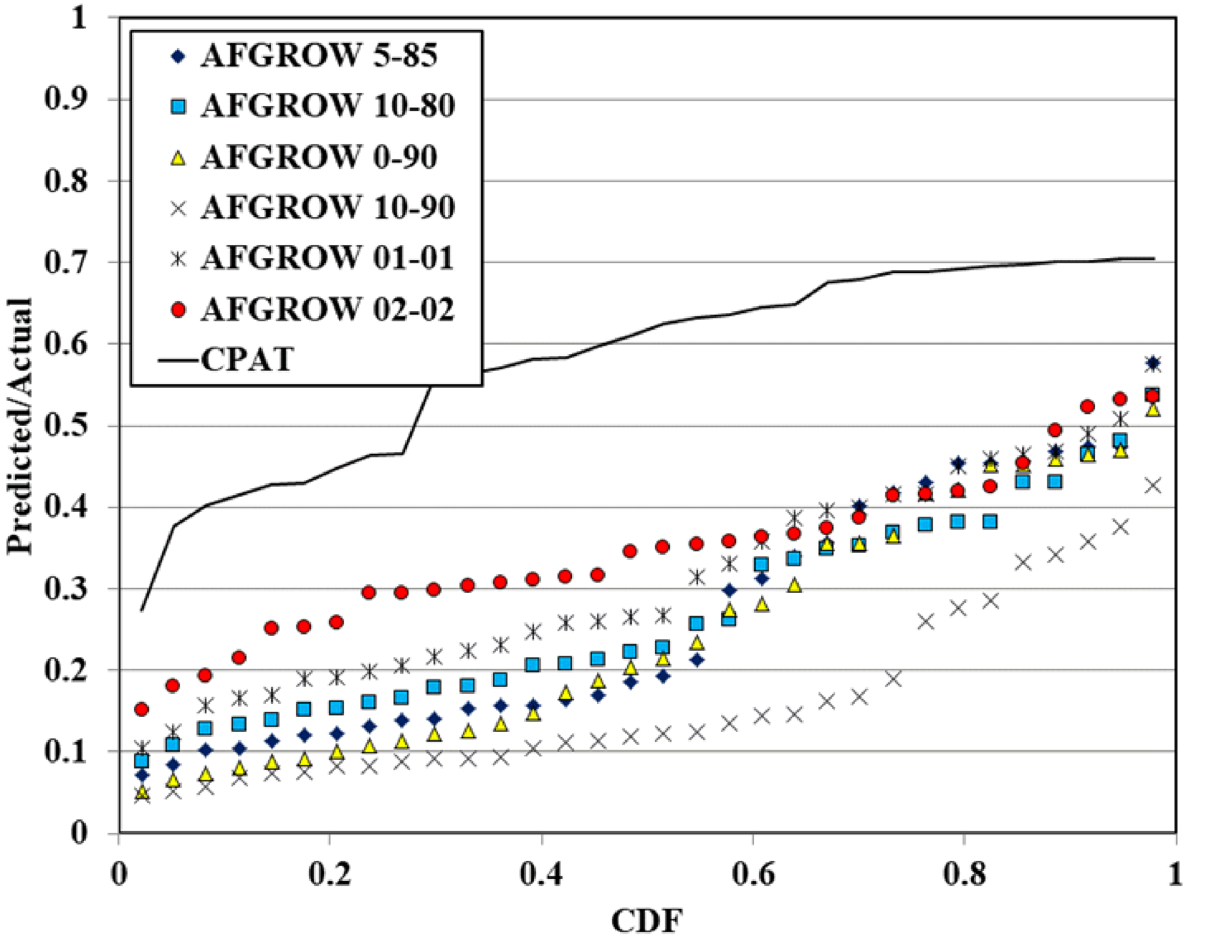
AFGROW Advanced Model Predictions

- Summary of Predictions – 2024-T3 Central Hole



Ranking
1. CPAT (Best)
2. 02/02
3. 01/01
4. 10/80
5. 5/85
6. 0/90
7. 10/90

Initial cracks are as-measured pre-cracks. References (Actuals) are measured fatigue lives.

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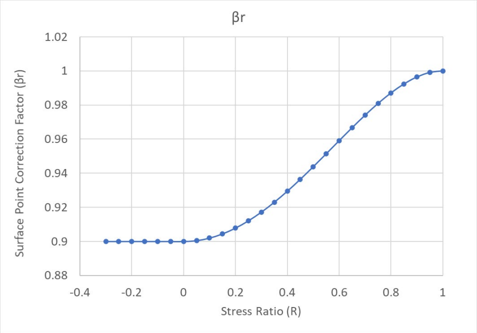
Surface Correction for Multi-Point Analysis

Crack Closure

- SwRI investigated the AFGROW implementation of crack closure and its impacts on typical A-10 control point analysis
  - Surface crack growth showed moderate life improvements (2-6%) and decrease in a/c (2-5%)
  - Corner crack growth shows increased analytical predictions (2-37%) but very little change in aspect ratio
  - Crack closure factor not recommended for current A-10 Methods
    - Minimal difference from current method
    - Concerns of potential conservatism due to location of K extraction
    - Concerns of potential conservatism due to constraint variation with large and small load cycles
  - Methods utilizing multi-point analysis should consider investigating effects of closure factor
    - Recommend performance of analytical study to compare multi-point growth with and without beta corrections at the free surfaces of the crack face

$$\beta_R = 0.9 + 0.2\,R^2 - 0.1R^4 \; for\; R > 0$$
$$\beta_R = 0.9 \; for\; R \leq 0$$



Note: this implementation still forces an assumed elliptical crack shape

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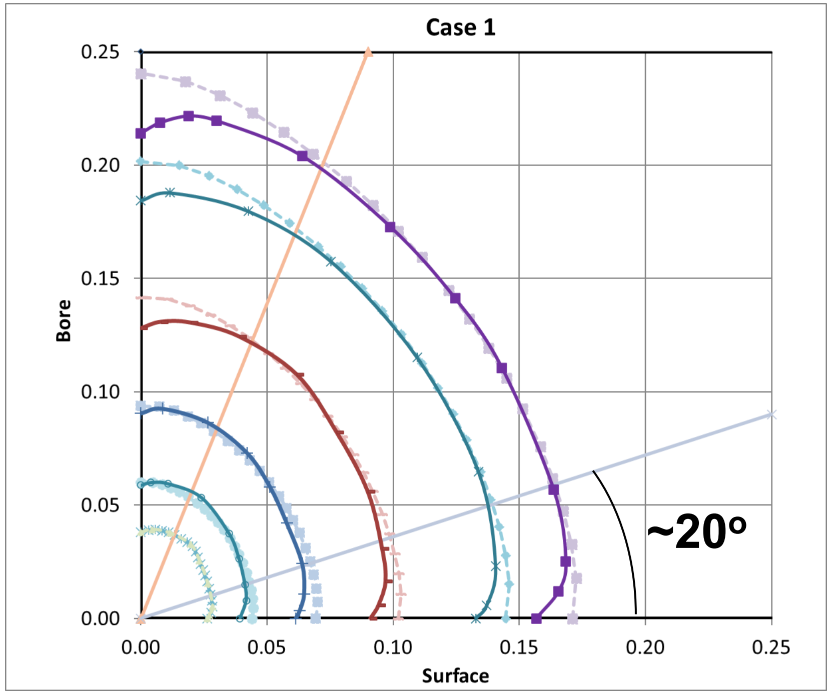
A-10 ASIP FIDUCIA NON SUPERBIA

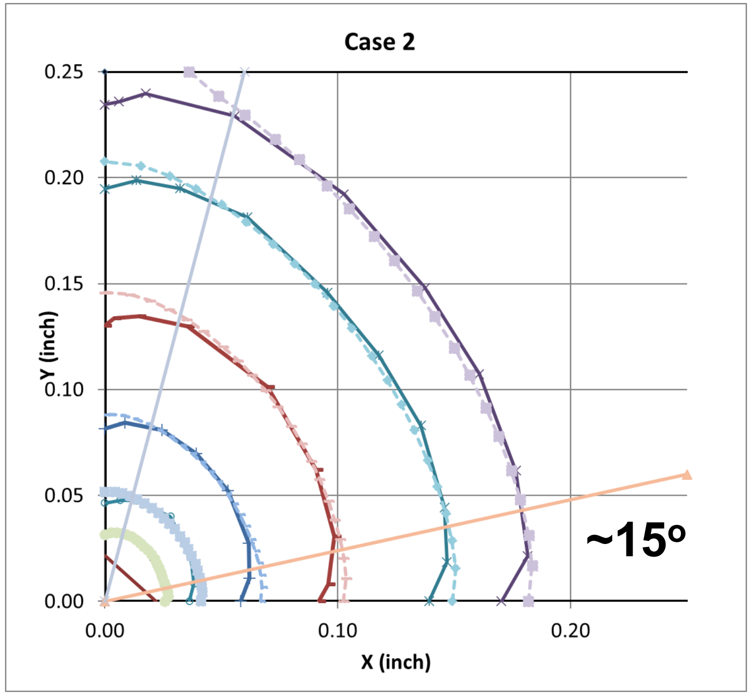
Approach

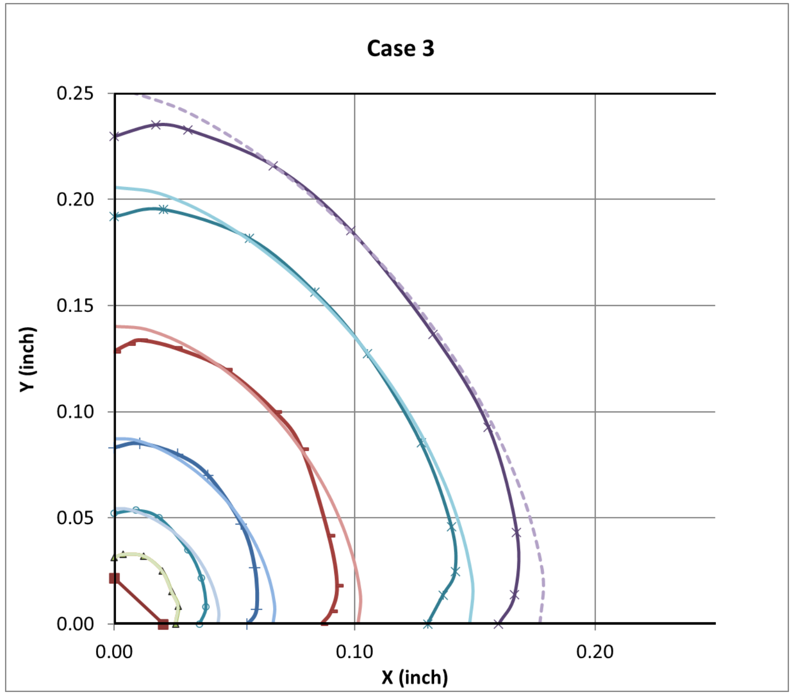
- Investigate differences in crack shape evolution from predicted shape
- Investigate effects modifying surface points have on crack shape
- Incorporate updates into BAMpF
- Complete predictions for defined conditions
  - AFGROW round robin
  - Other available data with good markerband and test correlation

AFGROW Round Robin – BAMpF Comparisons

- BAMpF vs. markerband comparisons







BAMpF Initial Implementation

- Initial approach
  - Implement function to modify K_{app} with a correction factor and an angle for both the surface and the bore
    - Implement capability to adjust angle utilizing BAMpF parameter features
  - Utilize an equation based on differences in crack growth profiles to determine correction factor and angle
    - Linearly interpolate correction factor from surface to defined angle
  - Utilize new functionality to determine effects the correction factor and angle have on life and crack shape

```
2 references
Public Function SPCFEquation(ByVal PointAngle As Double, ByVal MaxAngle As Double) As Double

    Return 0 * PointAngle ^ 2 + (0.2 / MaxAngle) * PointAngle + 0.8


End Function
```

$$\beta_{surface\ correction} = \frac{(1 - CF)}{Max_{angle}} \phi + CF$$

CF= Correction factor
Max Angle= Maximum angle the correction factor acts over
Φ=Angle from surface

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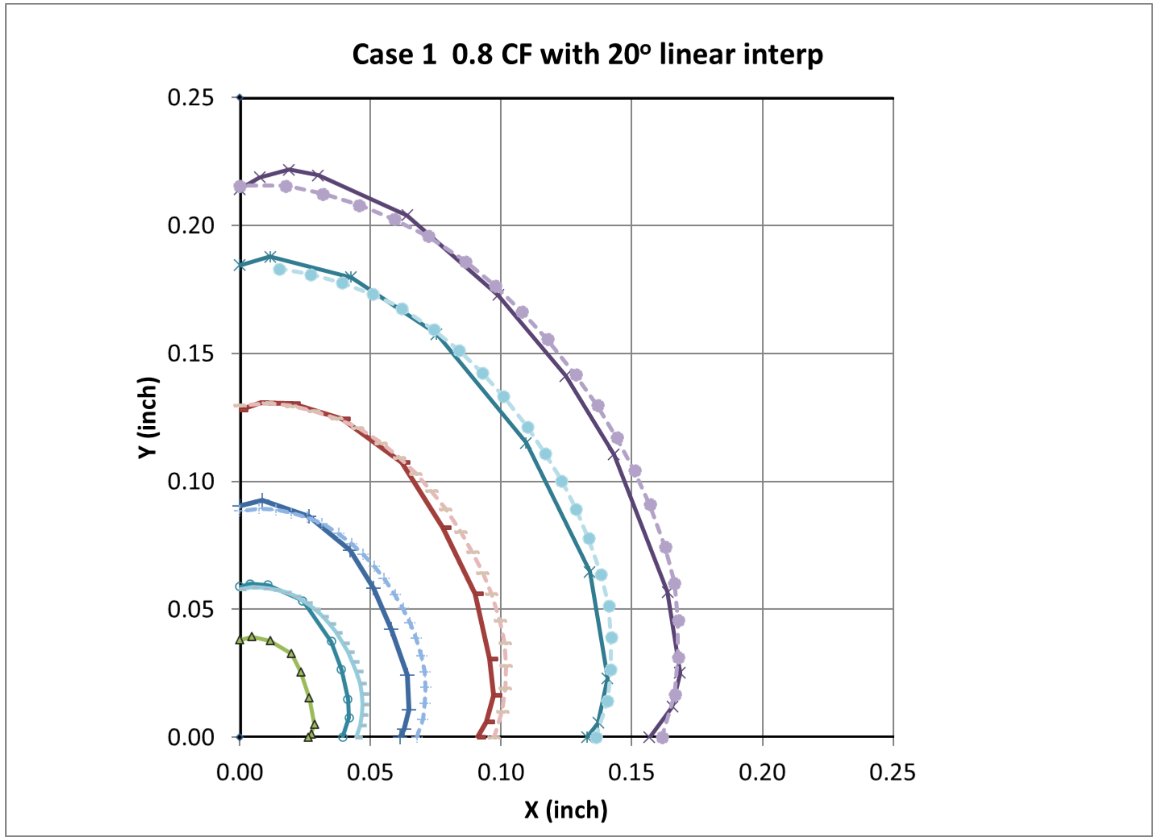
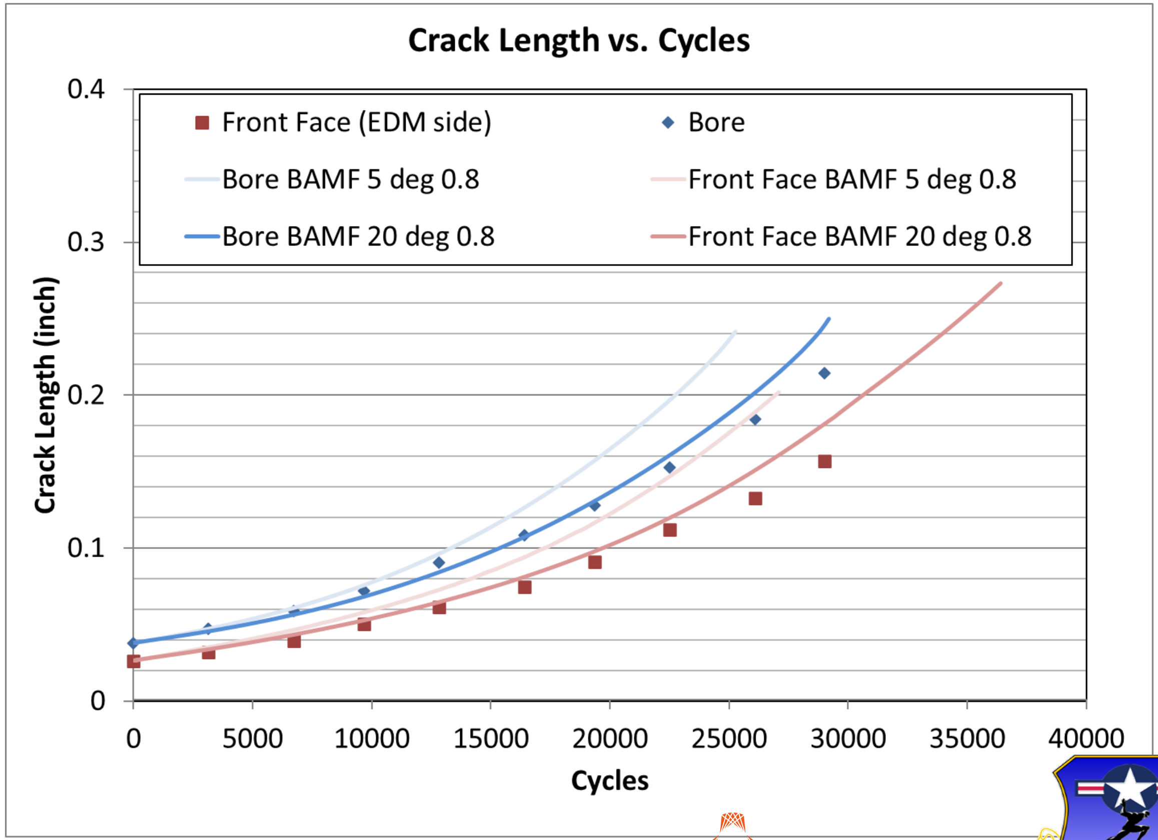
BAMpF Predictions - AFGROW Round Robin with Updated Angle

- AFGROW RR Case 1
  - Updated AFGROW RR results with 0.8 CF and 20^{o} max angle
  - Shape and life predictions are very consistent with test data

Markerbands
Predicted Shape





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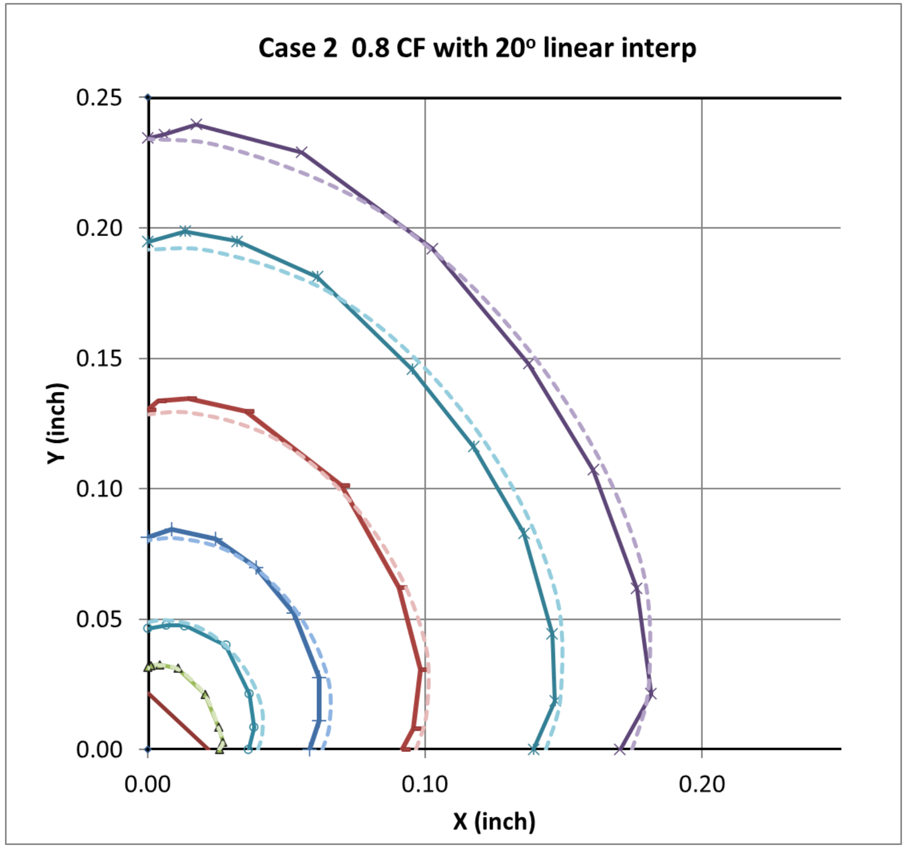
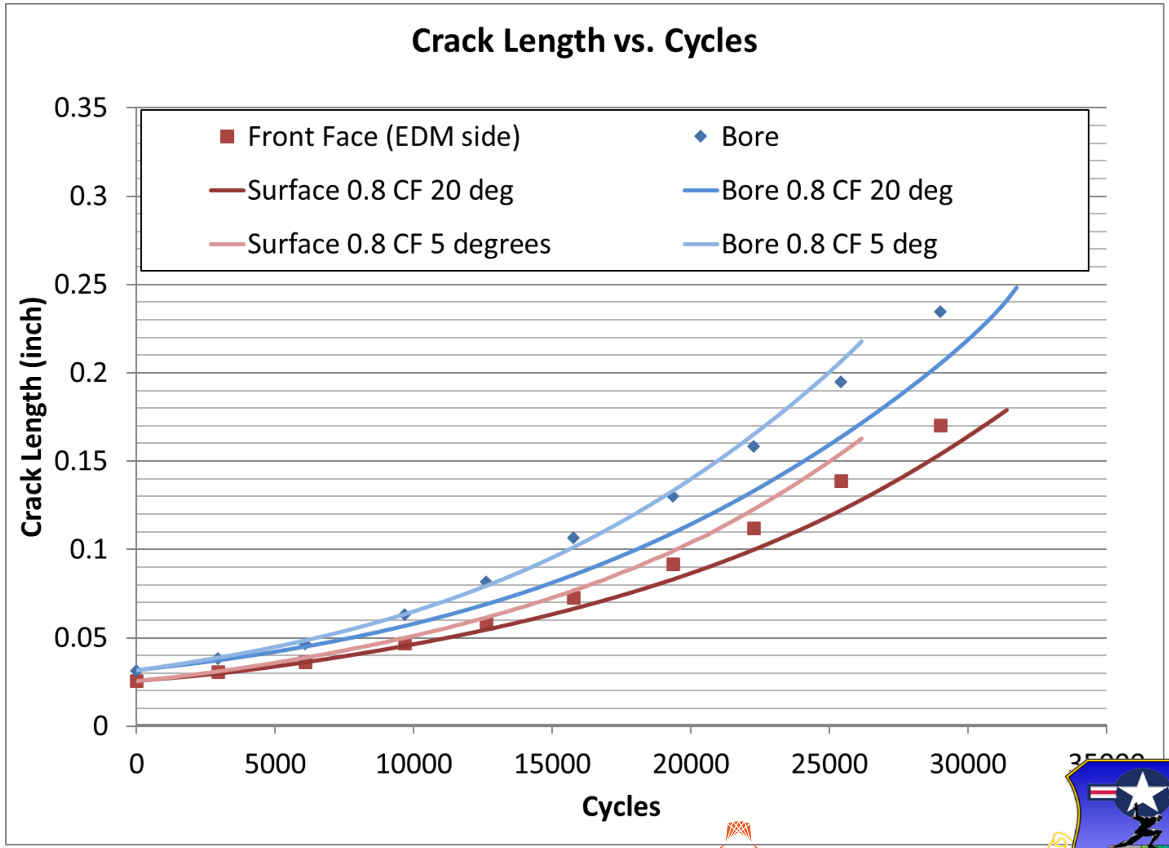
BAMpF Predictions - AFGROW Round Robin with Updated Angle

- AFGROW RR Case 2
  - Updated AFGROW RR results with 0.8 CF and 20º max angle
  - Life is slightly long (5% slower in prediction)

Markerbands
Predicted Shape





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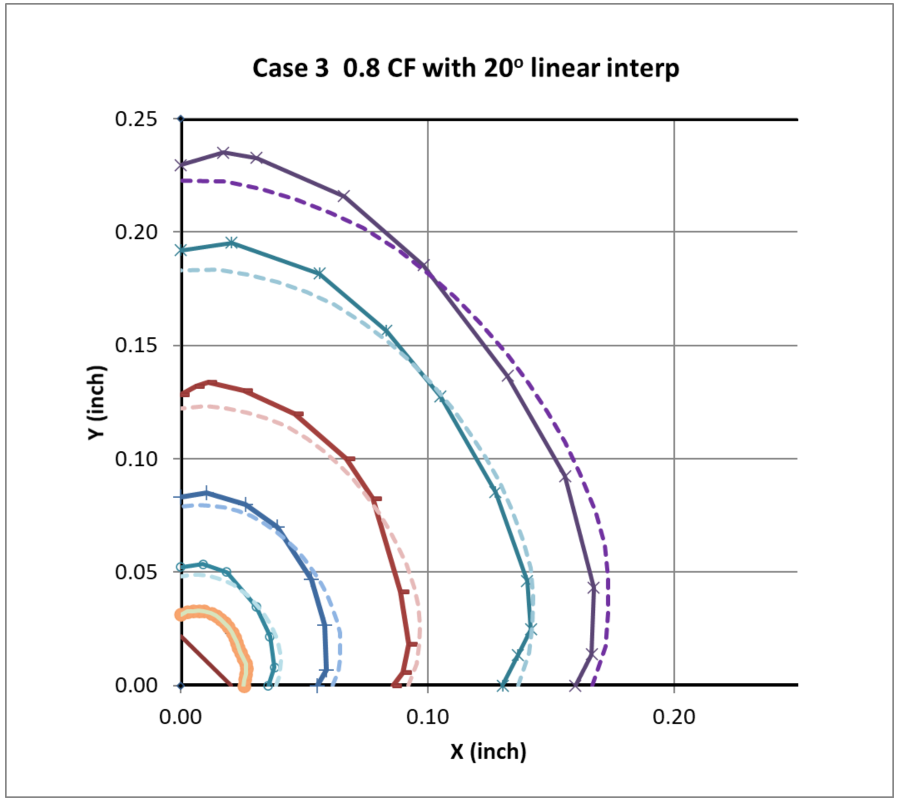
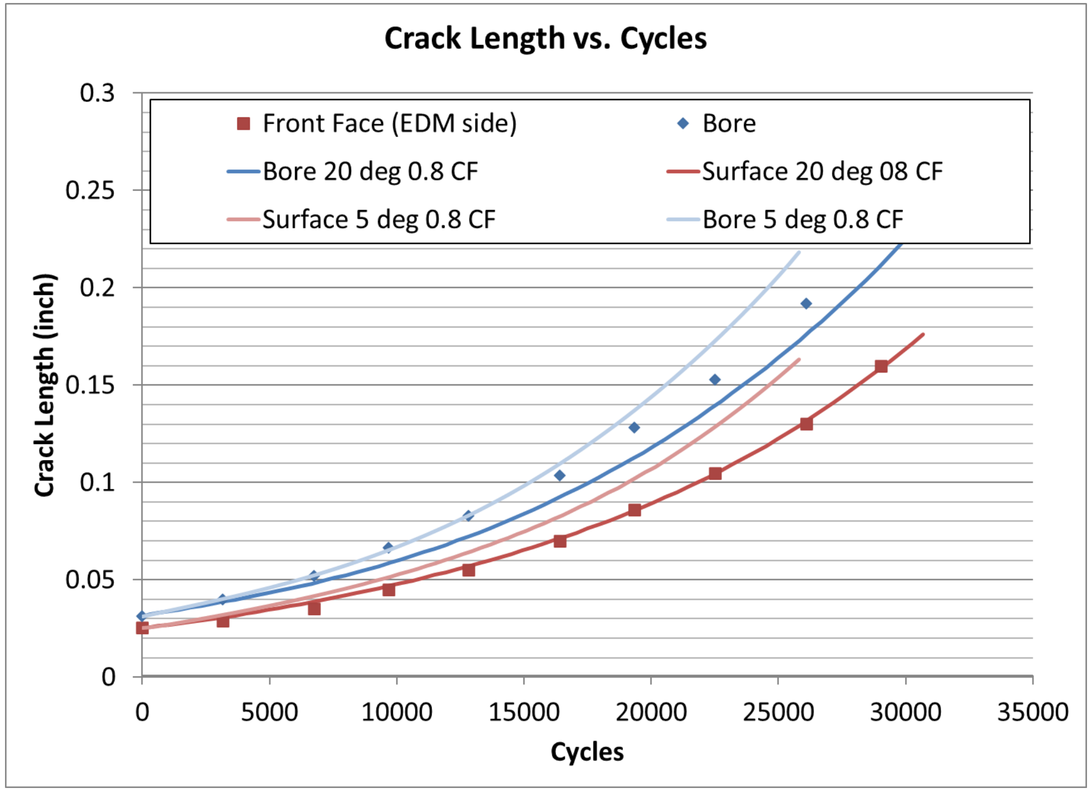
BAMpF Predictions - AFGROW Round Robin with Updated Angle

- AFGROW RR Case 3
  - Updated AFGROW RR results with 0.8 CF and 20° max angle
  - Life looks pretty good! Crack shape isn't bad (bore grows faster in test)





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Conclusions

- Method developed to implement surface corrections into BAMpF using a max angle and CF
  - Initial predictions indicate a correction factor of 0.8 and a max angle of 20 degrees correlates best to test data
  - Corrections appear to work for crack shapes in both CA and VA testing
  - Corrections resulted in good life correction for CA tests, however, VA tests showed life that was longer than test
  - Additional predictions completed for other conditions, materials, etc. with very good agreement
- So far, this is just experimentation to understand if we can consistently match observed test behavior
  - How do we move forward from here to understand the physics of the behavior and ensure the implementation isn't just a tuning knob (no self-licking ice cream cones)?
  - What is the correct implementation approach?
  - What data can we utilize to guide the approach?

FCG Testing of Complex Coupons with Quench Induced Residual Stress

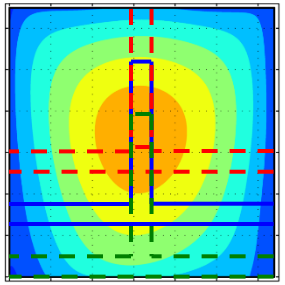
Renan Ribeiro – Hill Engineering

FCG in Coupons with Quench Residual Stress

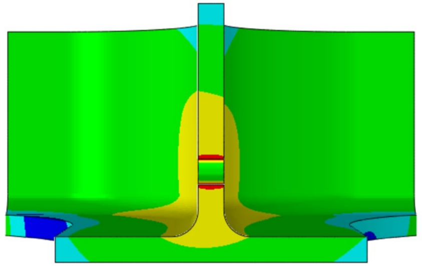
- Motivation:
  - Residual stress from quench is inherent in the production of key high-strength aluminum alloys (typical post-quench stress level 50% S_y)
  - Residual stress relief processes leave some residual stress behind
    - Stretched plate can have very low peak stress levels (≈ 2% to 4% S_y)
    - Compressed die forgings can have higher peak stress (≈ 5% to 20% S_y)
  - Fatigue performance of finished parts is affected by residual stress
  - Finished parts have different residual stress than does parent stock

Renan L. Ribeiro, UC Davis

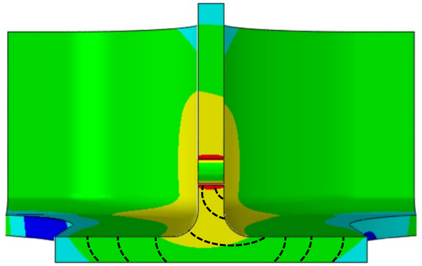
- Research questions:
  - Can residual stress from raw stock be used to predict stress in finished parts?
  - Can predicted residual stress improve prediction of fatigue crack growth in finished parts?



Measure RS in Raw Product Form



Predict RS in Part Cut from Raw Product Form



Predict Fatigue Performance Including RS

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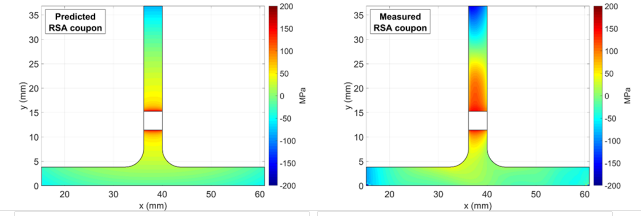
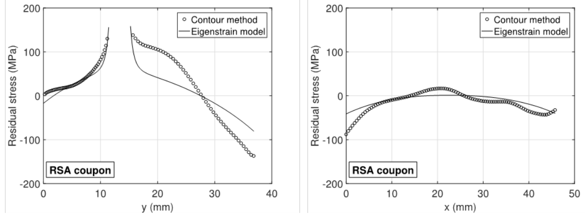
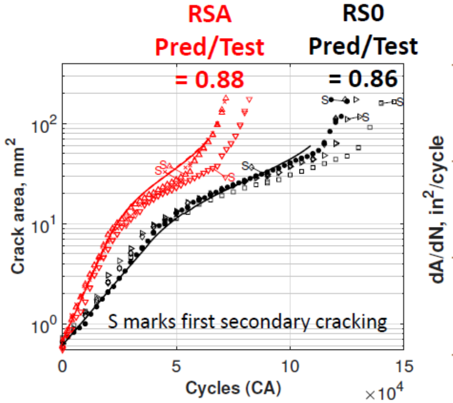
FCG in Coupons with Quench Residual Stress

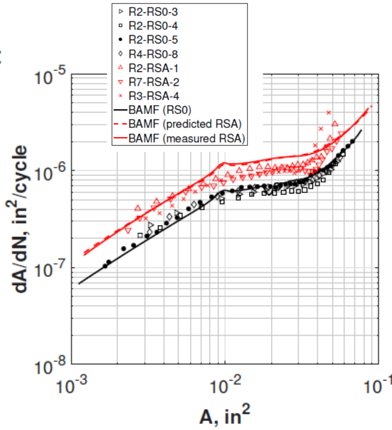
- Methods
  - Coupons manufactured from rectangular quenched bars (representative of airframe detail)
  - Eigenstrain method for prediction of residual stress based on raw stock measurements
  - Contour method for measurements of residual stress for validation
  - Fatigue crack growth testing
    - Pull-pull configuration, DCPD, marker banding, quantitative fractography, digital photogrammetry
  - Fatigue crack growth modeling
    - Multi-point fracture mechanics analysis (BAMpF)
    - Residual stress (predicted and measured) included

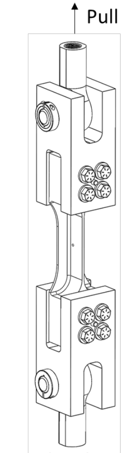


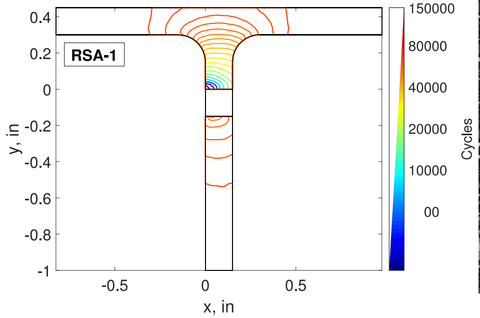


- Results
  - Can residual stress from raw stock be used to predict stress in finished parts? **(Journal paper 1 in progress)**
    - Yes, but with some discrepancy
    - This study showed point-wise accuracy to better than 70 MPa
  - Can predicted residual stress improve prediction of fatigue crack growth in finished parts? **(Journal paper 2 in progress)**
    - Yes, with good fidelity (better than 20% on crack growth life)
    - This study showed
      - Ignoring tensile RS caused anticonservative error of about 1.5X on life
      - Accuracy of crack growth prediction for RS bearing material (RSA) was comparable to that for low RS material (RS0)









Acknowledgements
Helpful advice from Dale Ball (LM Aero), TJ Spradlin (AFRL), and Kevin Walker (DST Group)
MPFM analyses with BAMpF by Josh Hodges (Hill Engineering, LLC)
Technical interchange with Jim Newman, Jr (MS State)
Prior collaborations with Mark James (Arconic)

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7075-T651 Predictions

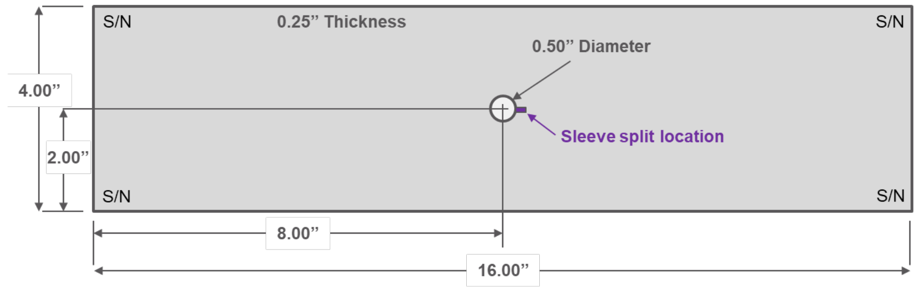
Robert Pilarczyk – Hill Engineering

Classic 0.005-inch IFS Comparisons

- Background
  - Reduced IFS has been and currently is the established method for Cx credit, recently referred to as "partial credit"
  - "Full credit" approaches would explicitly incorporate residual stress in the DTA
  - Comparisons between these approaches for 2024-T351 were completed during the A-10 Cx Teardown program and presented at the ASIP conference in 2018 and 2019
    - These results were directly compared to Warner's thesis and demonstrated reasonable correlation between predictions and experimental results
- Current effort
  - Repeat comparisons, however, focus on 7075-T651 aluminum as well as constant and variable amplitude loading
  - Compare to available experimental results as well as life improvement factors for 2024-T351

Classic 0.005-inch IFS Comparisons

- Approach
  - Maintain consistency with Pilarczyk's thesis
  - Inputs:
    - Geometry:
      - Width: 4-inch
      - Thickness: 0.250-inch
      - Hole diameter: 0.500-inch
      - Hole Offset: Centered hole
      - Applied expansion: mid
    - Loading:
      - Constant Amplitude, R=0.1
        - Peak stress: 20, 25, 30, 35ksi
      - Spectrum, A-10 RPDS DTRCP7
        - Peak spectrum stress: 20, 25, 30, 35ksi
    - Spectrum retardation:
      - Constant amplitude predictions: N/A
      - Reduced IFS predictions: A-10 ground rules for 7075-T6
      - Explicit residual stress predictions: No retardation
    - Residual stress:
      - Average of OY2 varying thickness coupons (0.250-inch thick) was utilized for residual stress



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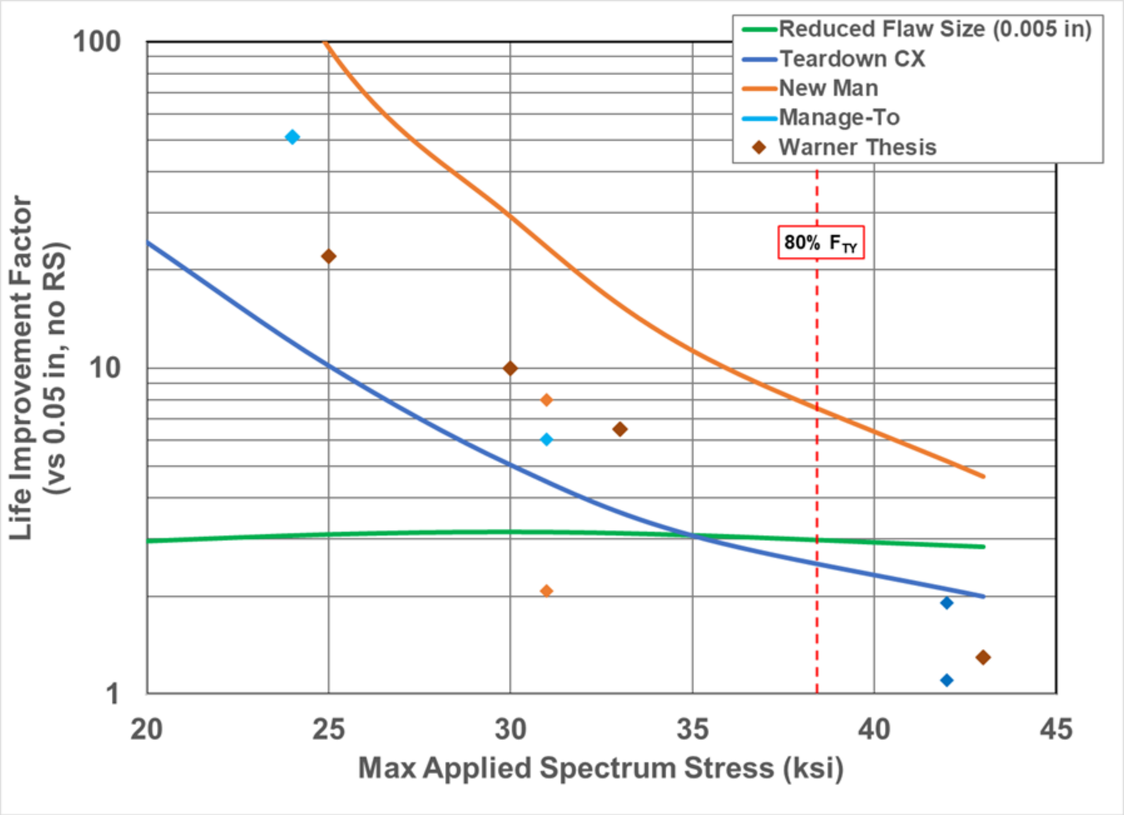
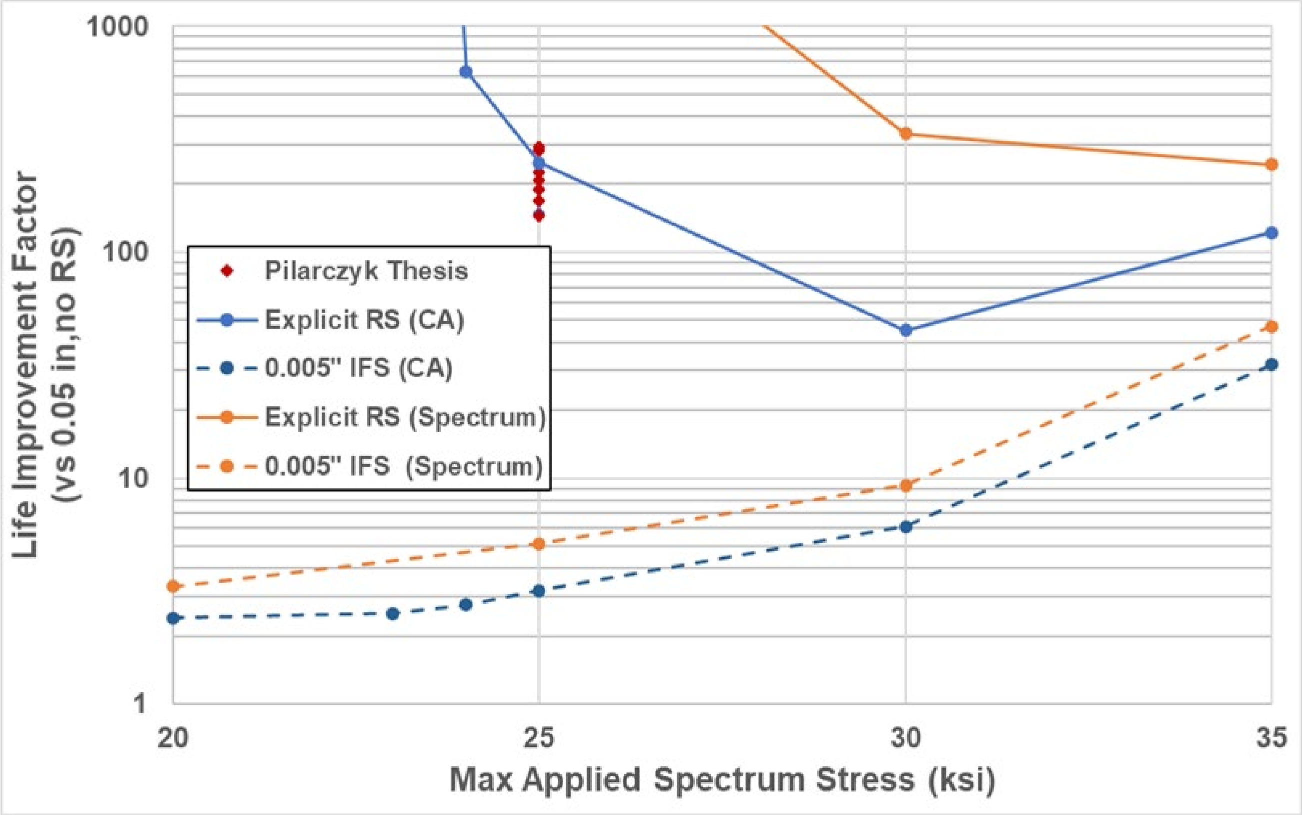
Classic 0.005-inch IFS Comparisons

Previous 2024-T351 Comparisons



New 7075-T651 Comparisons



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Classic 0.005-inch IFS Comparisons

- Summary & conclusions
  - Significant life improvements were observed for “full credit” analyses for 7075-T651, with the minimum improvement of 45x
    - Appreciably higher improvements relative to 2024, however, additional test data is necessary to validate trend
  - Comparable life improvement was observed for experimental results and predictions at 25ksi peak stress
  - Similar improvements were observed for constant and variable amplitude
  - Life improvements above 30ksi are somewhat skewed due to limited baseline life (less than 500 cycles and 2000 hours for constant and variable amplitude loading, respectively)
  - Overall, results indicate “full credit” analyses for Cx would result in a terminating action (no follow-on inspections) for 7075-T651 aluminum
- Recommendations
  - Complete additional validation testing to substantiate life improvement for Cx in 7075 aluminum

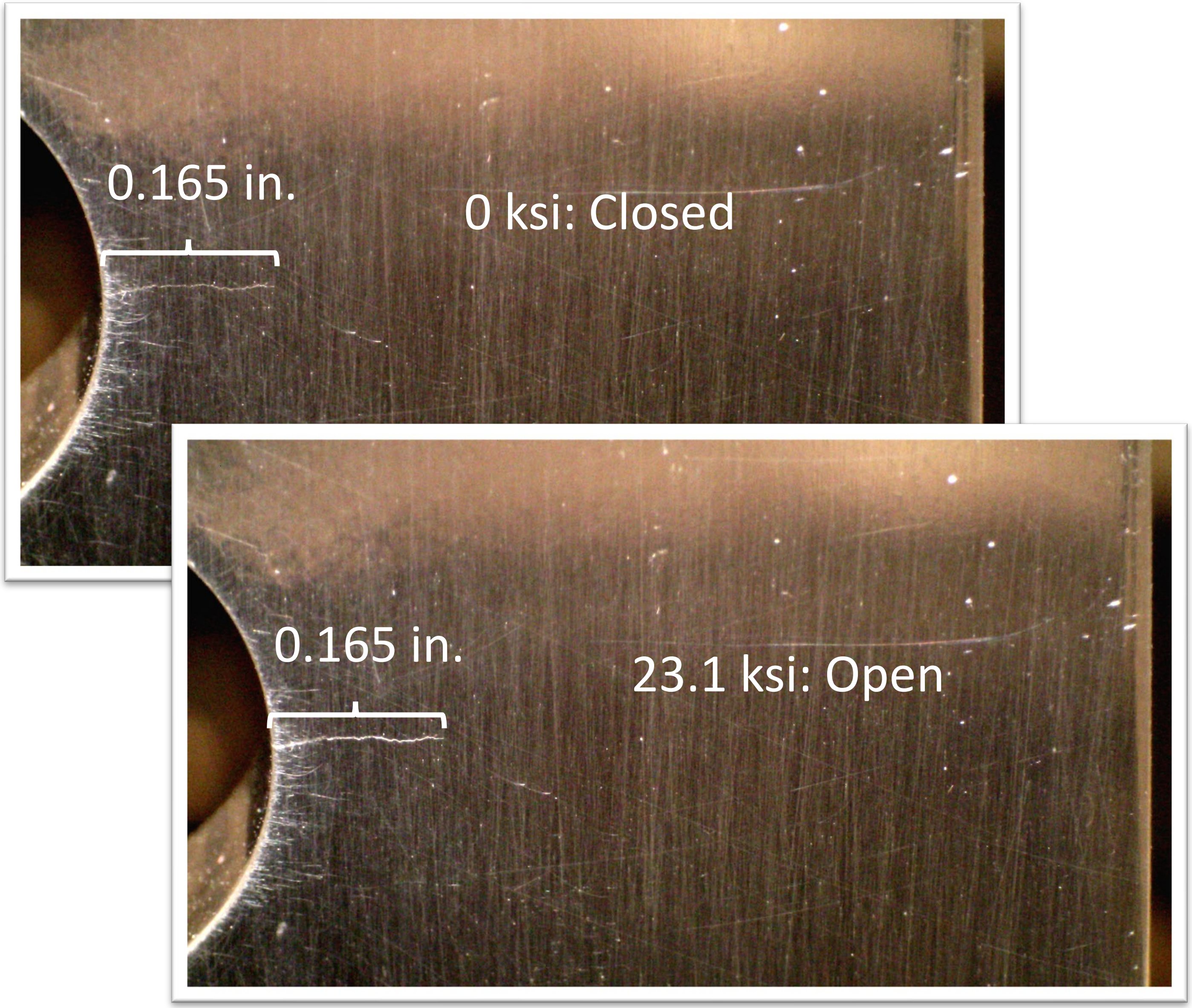
VALIDATION TESTING

Closure Images

Evan Ross - USAF

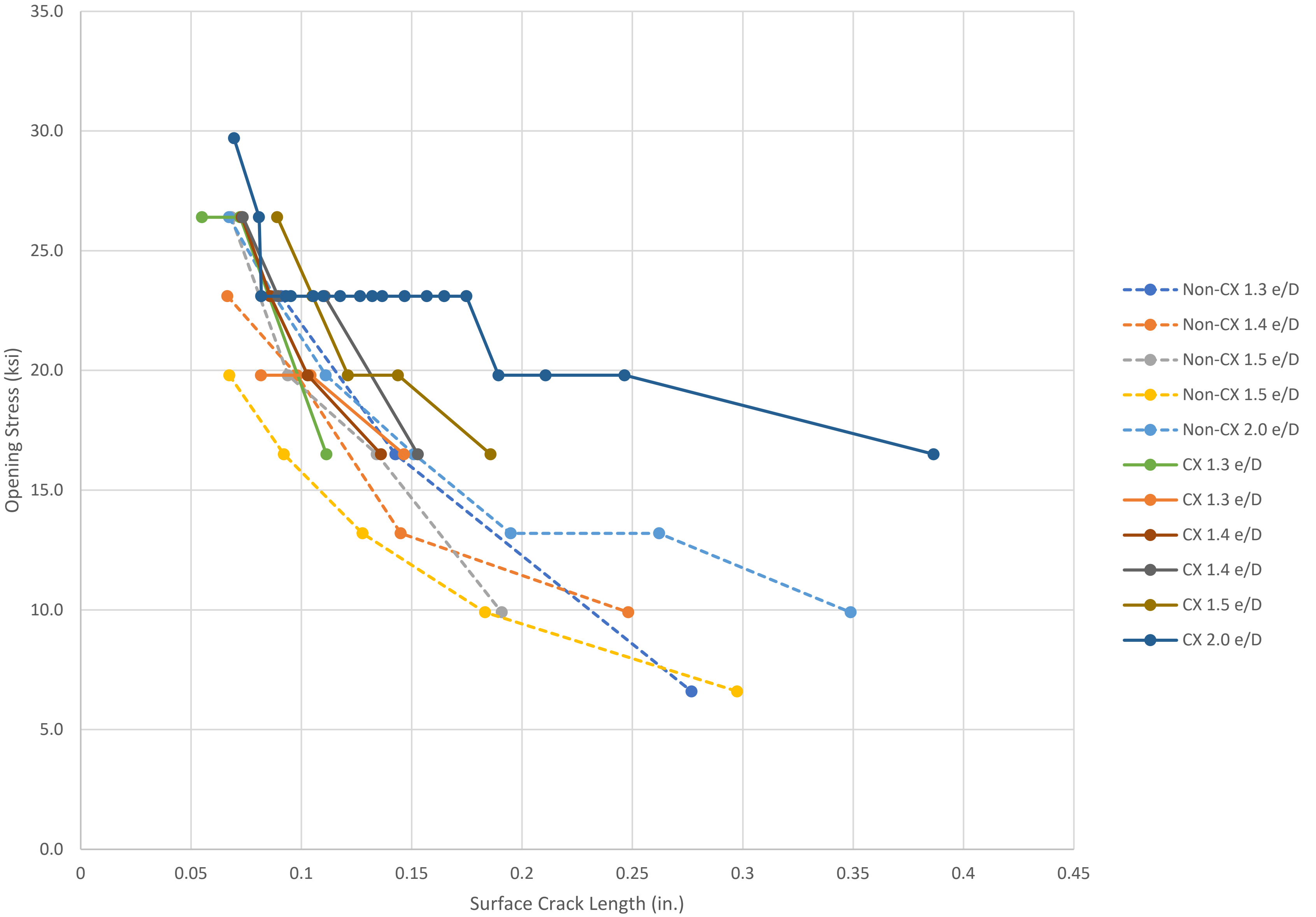
Crack Closure Imaging

- Cracks in 2024-T351 plate from 0.5” holes with short e/D (1.3, 1.4, 1.5, 2.0)
- Various crack lengths
- Images at 0 to 33 ksi with 3.3 ksi increments



Crack Closure Imaging

- Crack length vs opening stress
- Combined Non-CX (dashed) and CX (solid) holes
- All e/D



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WEAPON SYSTEM APPLICATIONS

B-1 Taper-Lok Analysis & Testing

B-1 Taper-Lok Background

- Taper-Lok Fasteners
  - Taper-Lok fasteners are known to produce high levels of interference and residual stress within the host material. As a result, details with Taper-Lok fasteners display increased fatigue and damage tolerance lives.
  - Limited methods exist to quantify the benefit of Taper-Lok installations
    - All require testing and coupons unique to the detail geometry being analyzed
    - These methods are known as partial-credit because they do not capture the full benefit
  - Currently, an analytical methodology does not exist to quantify the benefit of Taper-Lok installations

- B-1 Taper-Lok Locations
  - Common to wing rear spar structure (Al material)
  - Common to wing carry through structure (Ti material)

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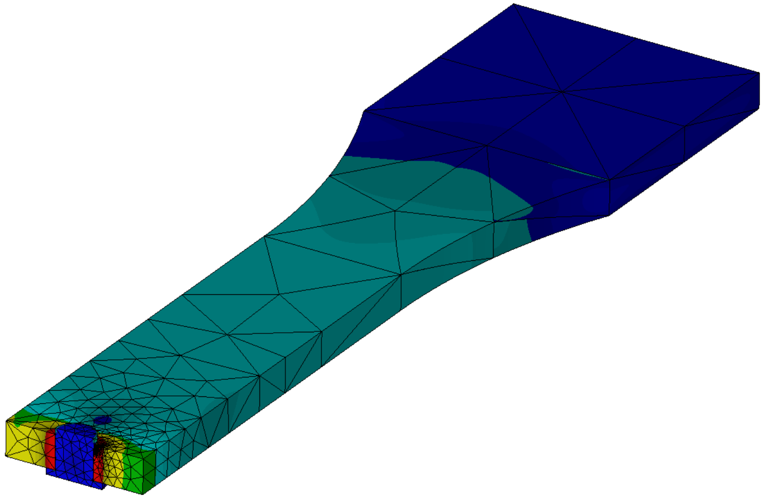
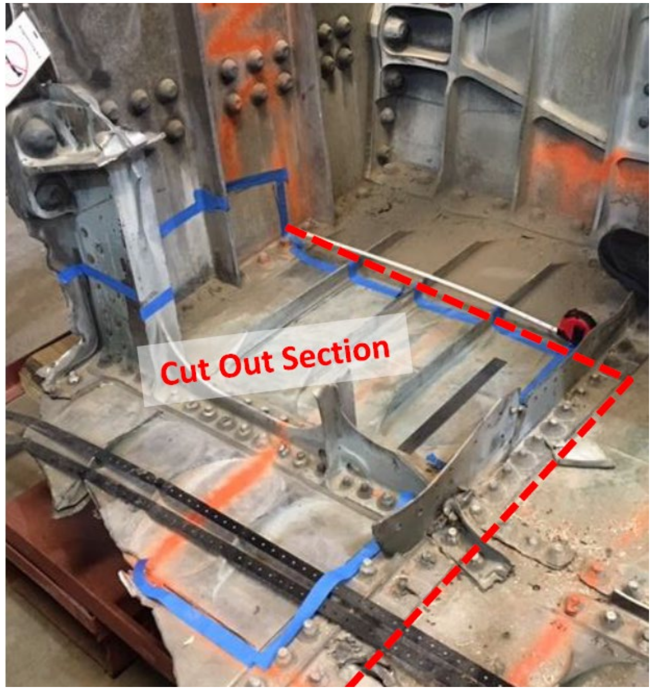
Program Objectives

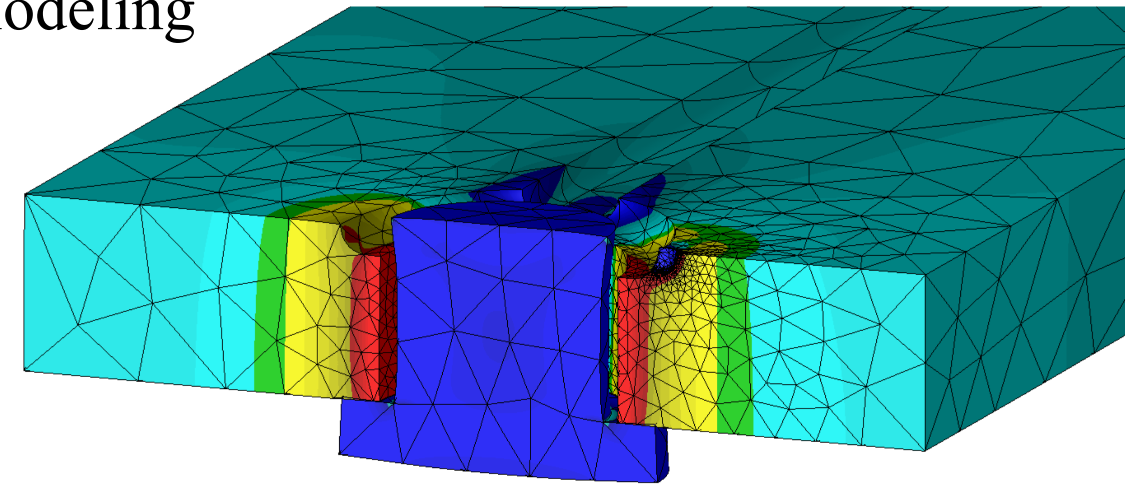
- Develop a robust analytical approach to predict the damage tolerance life at B-1 Taper-Lok fastener holes
- Perform measurements to quantify interference and residual stress at Taper-Lok fastener holes
- Perform fatigue tests for representative Taper-Lok fastener hole conditions
  - Representative coupon and excised component tests
- Perform fatigue crack growth analyses for representative Taper-Lok fastener hole conditions
- Perform damage tolerance assessments and assess inspection requirements for B-1 Taper-Lok fastener hole locations

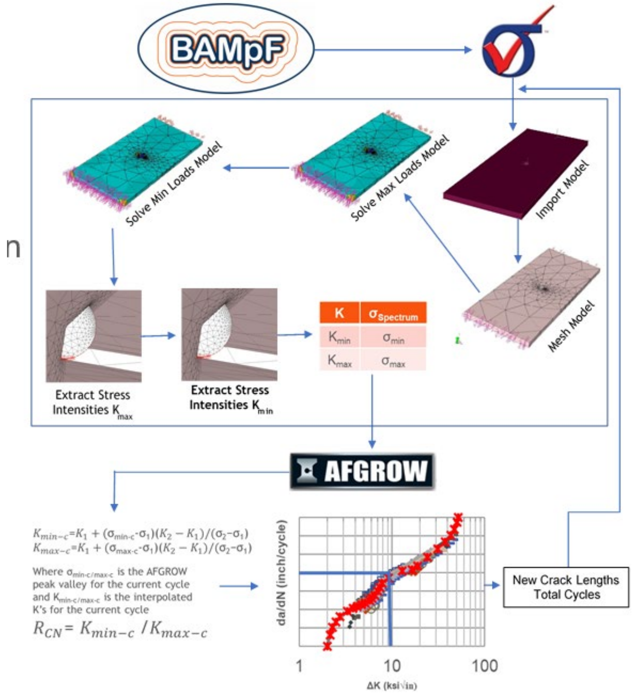




Analytical Approach

- Investigate Key Factors for Explicit Taper-Lok Modeling
  - Hole propping/interference and residual stress
- Modeling Approach
  - Multi-point fracture mechanics
    - Explicit model geometry, loading, etc.
    - Enables natural crack shape evolution
  - Fastener hole propping/interference
    - Multi-body contact
  - Residual stress
    - Crack face traction
  - Explicit modeling of fastener interference and residual stresses
- Sensitivity Studies
  - Investigate variations in key factors and their influence on damage tolerant life
- Tool Updates
  - Incorporated ability to pass tabular lookup (SIF vs. remote applied stress) instead of alpha to AFGROW from BAMpF to address non-linearity of SIFs from interference





Preliminary Results

- Combination of Process Simulations and Residual Stress Measurements
  - Comparisons between model predictions and measurements look good and promising
- Validation Testing for Baseline and Taper-Lok Conditions
  - Results look consistent
- Analysis vs. Test Comparisons
  - Wing process model prediction results show very well with test measurements, including baseline open hole and Taper-Lok configurations
- Extracted WCT Structure Test Specimens
  - Completed residual interference, protrusion measurements, fastener & hole diameter measurements and residual stress characterizations
  - Fatigue test pending

Remaining Effort

- Fatigue Testing
  - Coupon fatigue testing
  - Component fatigue testing
- Residual Stress Measurements
  - Non-cycled coupons
- Test vs. Analysis Comparisons
- Best Practices and Lessons Learned
- Updated B-1 DTAs

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MISC. OTHER

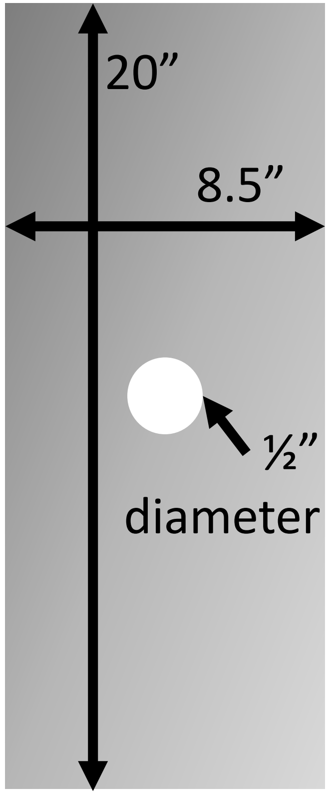
K_t-Free Coupons

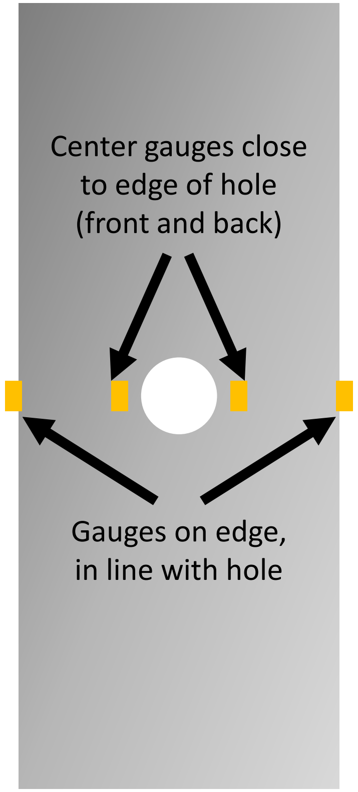
Jacob Warner, James Greer - USAF

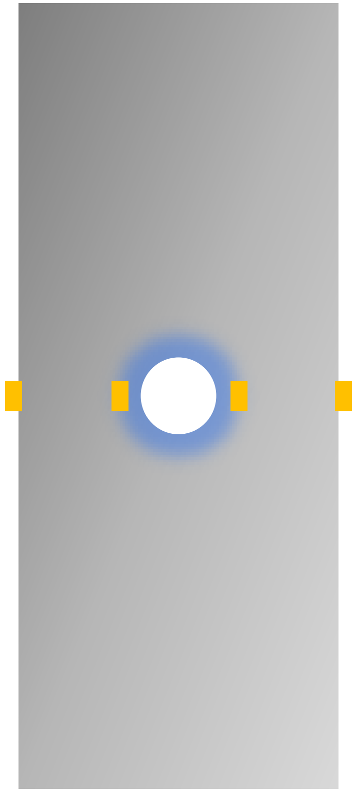
Coupon Development

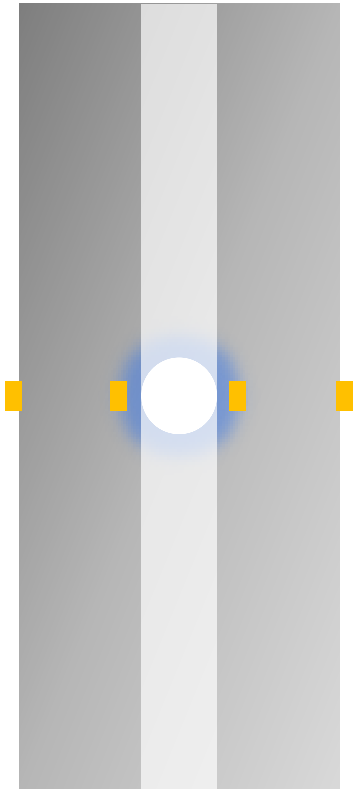
- Objective: Eliminate the effect of the hole K_t while preserving the RS field created by Cx

1. Machine ¼” thick Specimen
2. Install Strain Gauges (6)
3. CX Hole (record strain from CX) and final ream
4. Cut Specimen into two bars (measure strain to determine stress relaxation – next slide)









Cutting Process (step 4 of previous slide)

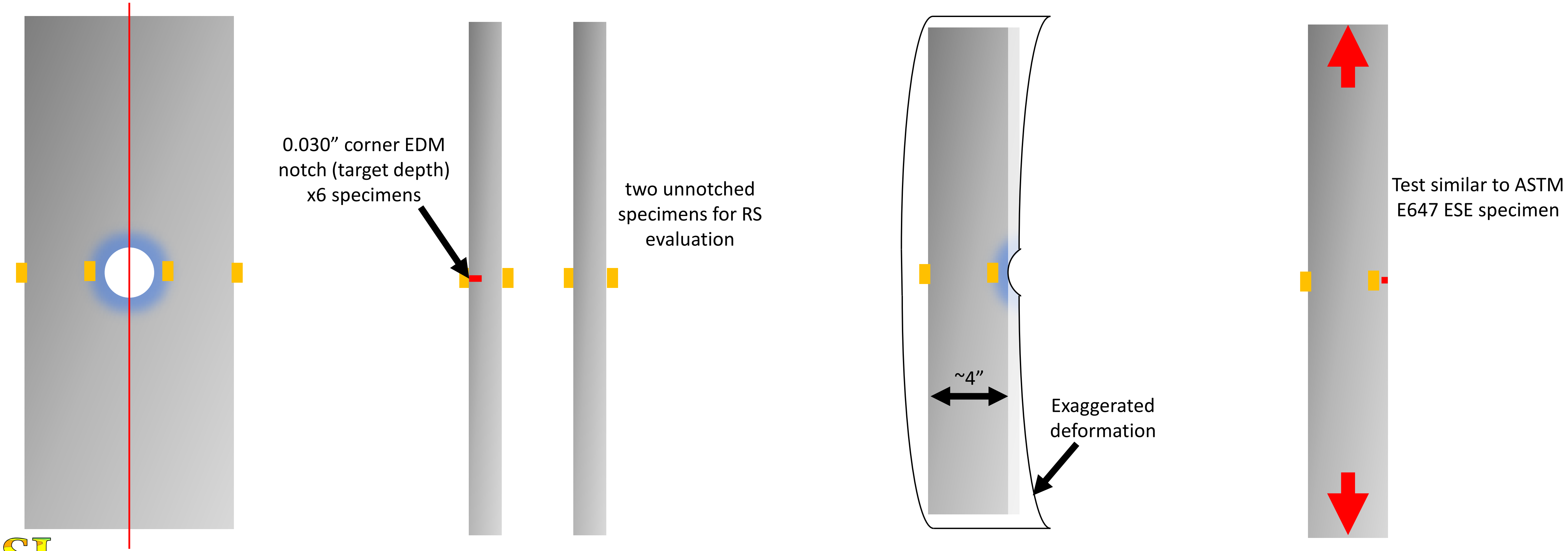
- Record strain at each step (either during process or before/after)

4a. After Cx and ream, bisect specimen with EDM

4b. EDM notch at hole corner (view rotated 90^o)

4c. Measure bow before and after milling square to tangency

4d. Precrack specimen to 0.050” corner crack from notch



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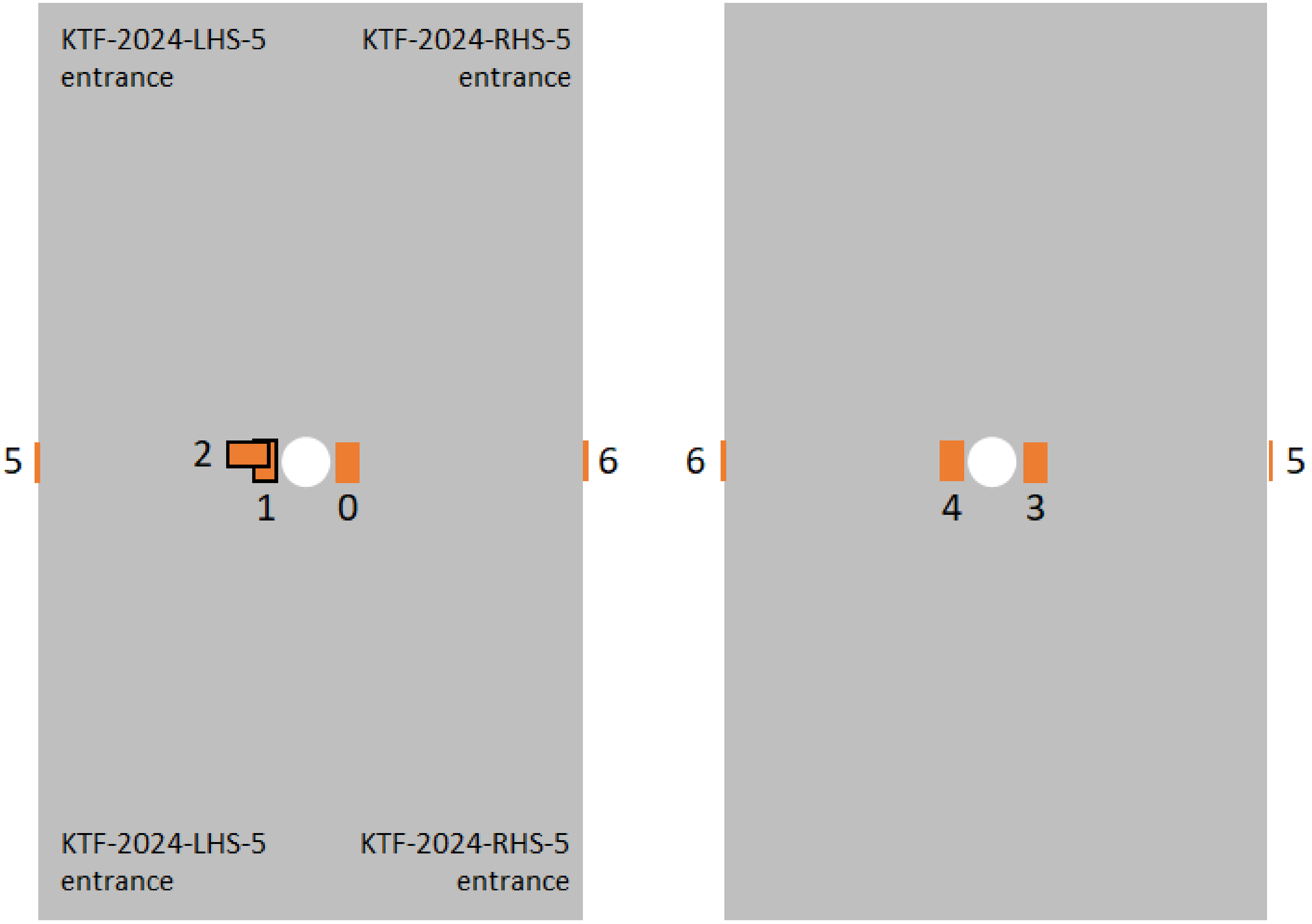
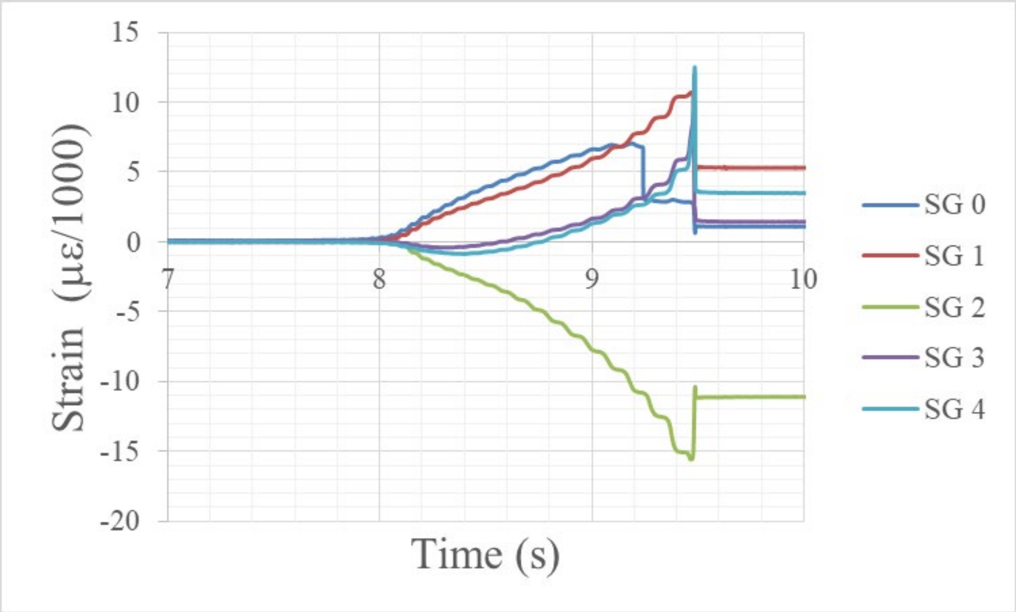
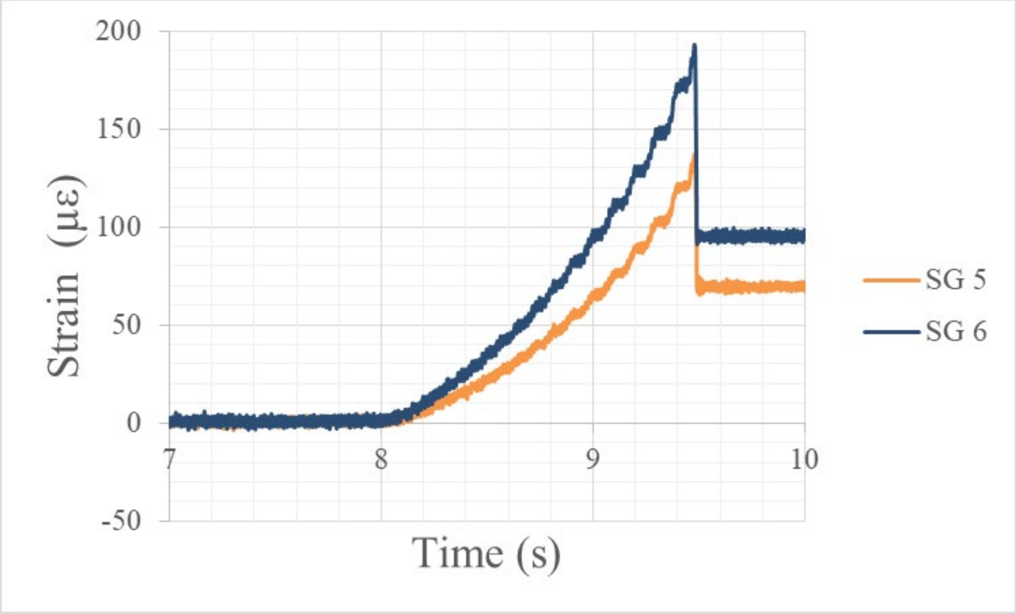
Strain Gage Data During Cx Mandrel Pull

Sample Data



PANEL KTF-2024-XXX-5





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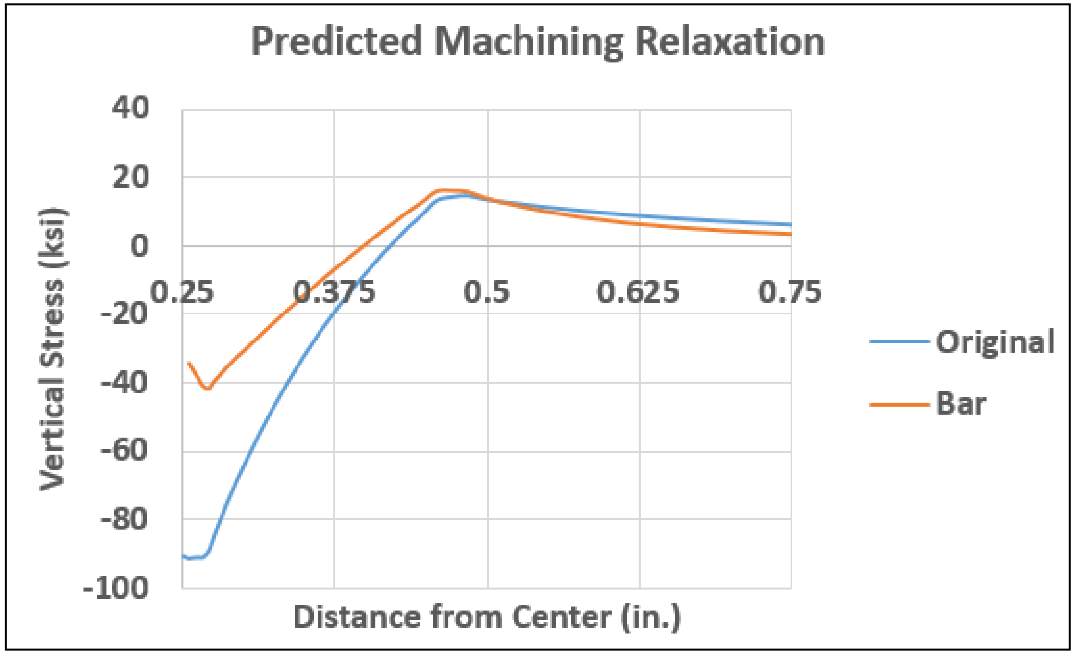
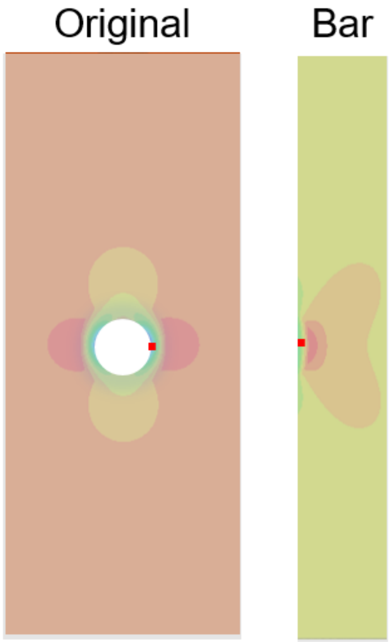
Summary

- FEA prediction indicates specimen with hole removed (“bar”) has an RS stress field with the same characteristic shape as the specimen with the Cx hole.
  - Will be verified with RS analysis.
- Fatigue crack growth (FCG) behavior will be compared to existing FCG data for Cx hole coupons.





- Status
  - Specimen preparation complete
  - Testing of FCG specimens (x6) and RS analysis specimens (x2) to follow

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USAF Draft Structures Bulletin

(Andrew, Warner, Spradlin)

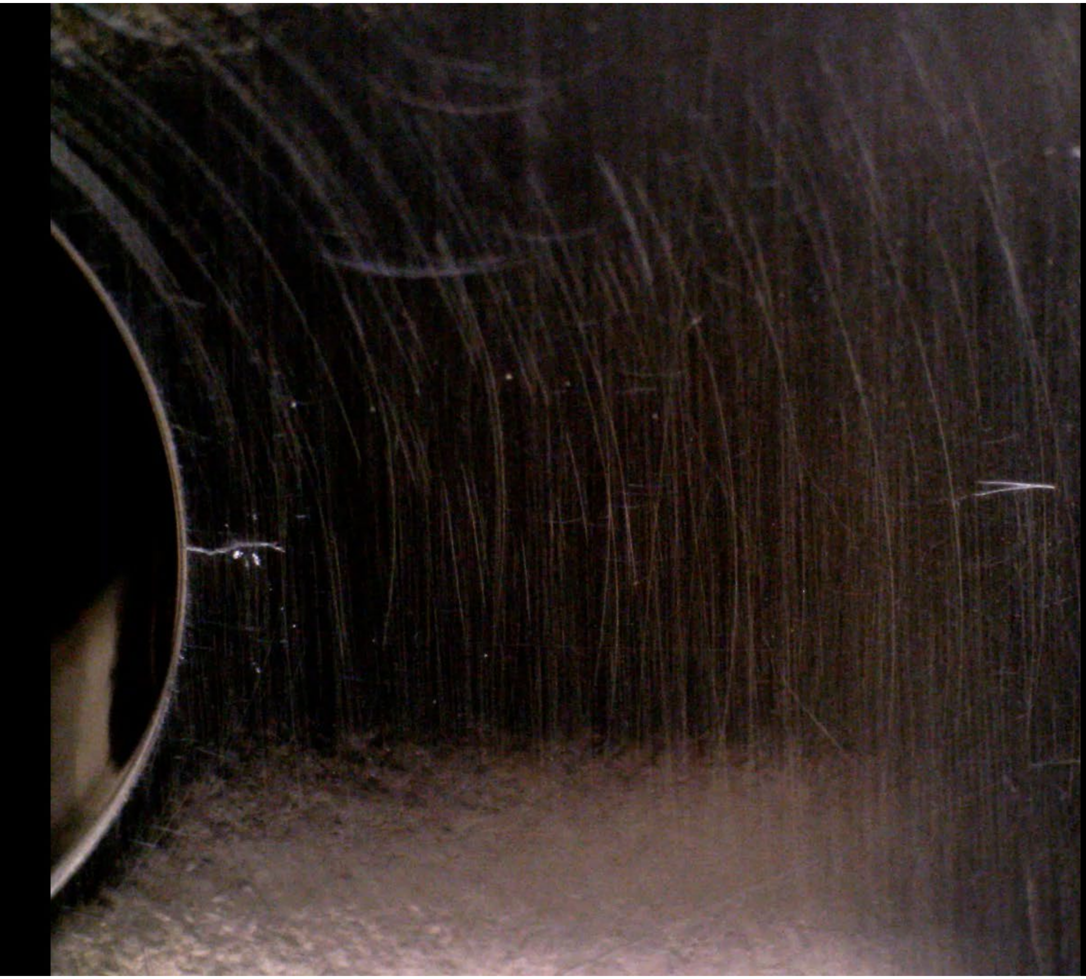
CX IN ANALYSIS IMPLEMENTATION

A-10 ASIP

Jake Warner

WHY CX

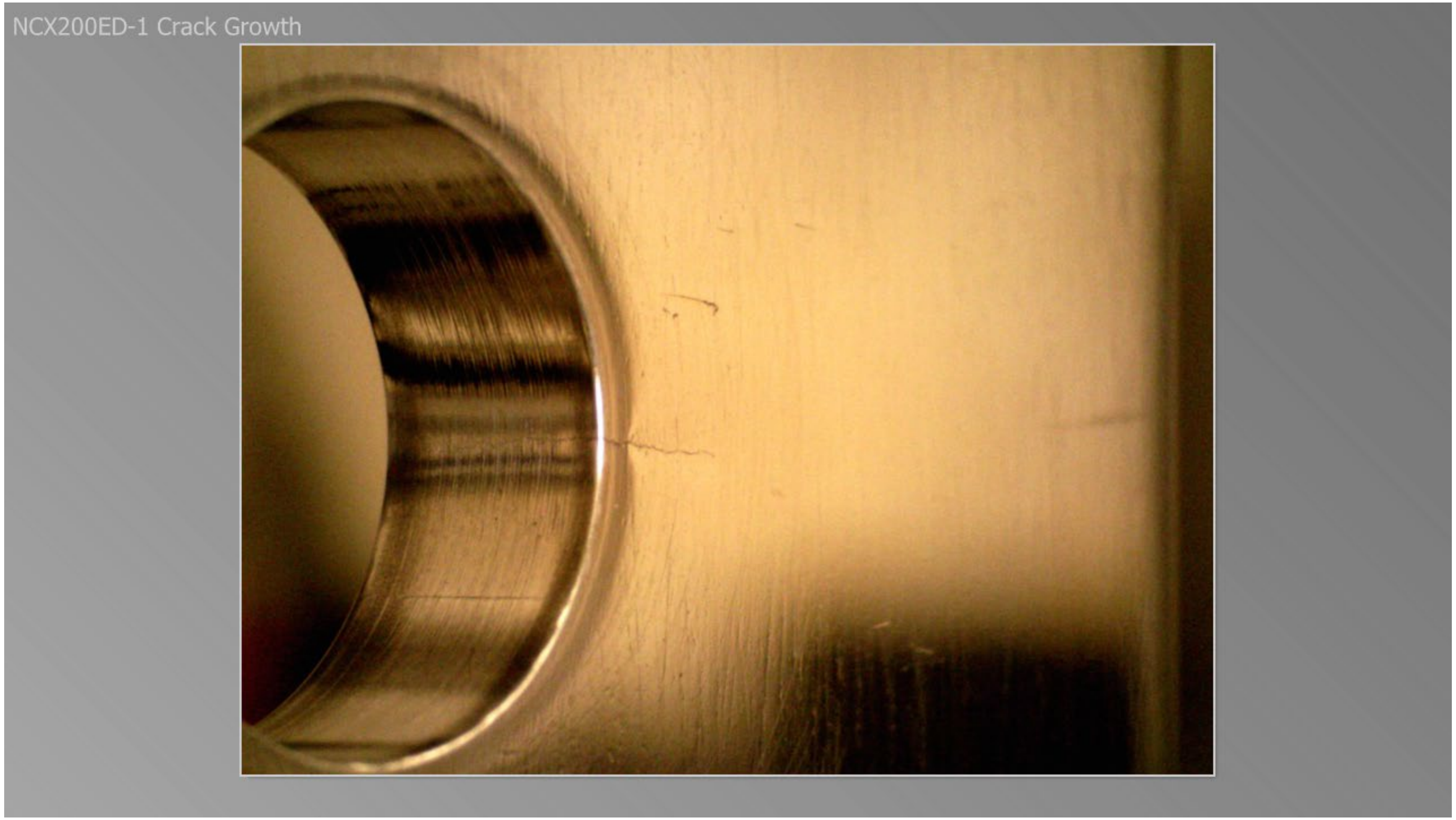
CX



Non CX

RECENT EXAMPLE
SHORT EDGE MARGIN TESTS

- Spectrum loaded – 33 ksi (227 Mpa) max spectrum stress
- e/D = 1.3, 1.4, 1.5, 2.0



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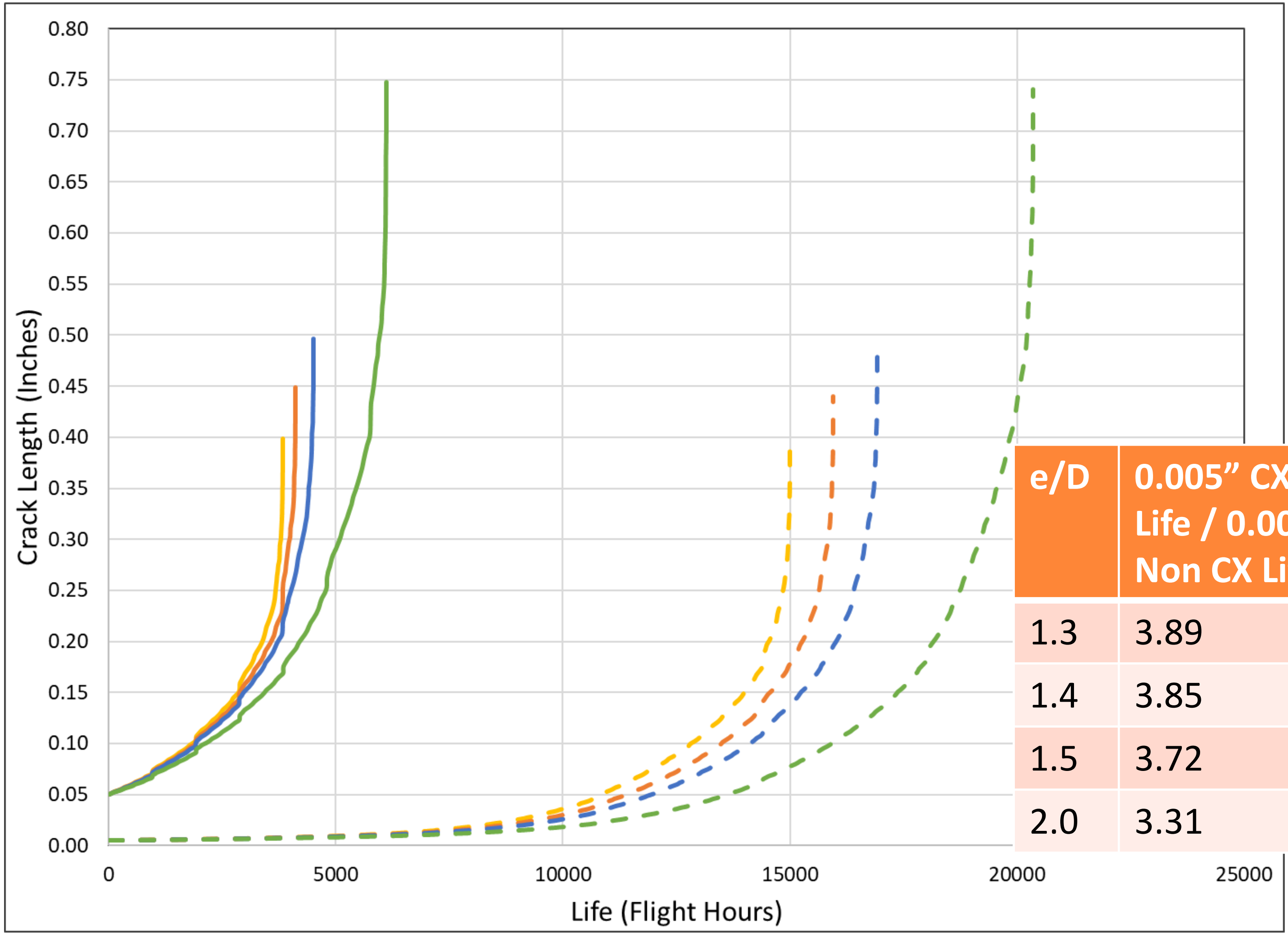
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

SHORT EDGE MARGIN TESTS 0.005" COMPARISONS



e/D	0.005" CX Life / 0.005" Non CX Life	Test CX Life / Test Non CX Life
1.3	3.89	3.44
1.4	3.85	4.3
1.5	3.72	4.39
2.0	3.31	8.22

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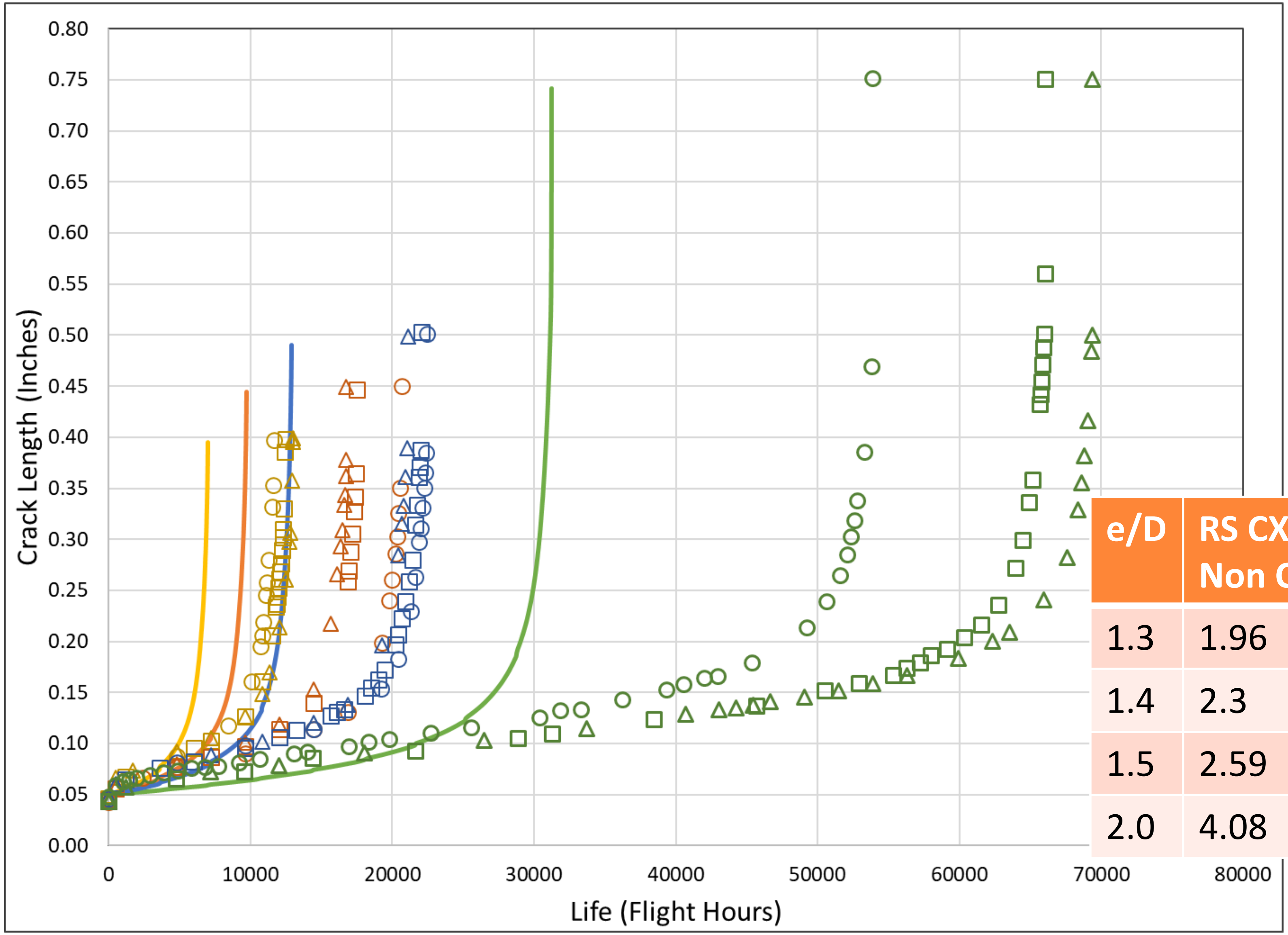
SHORT EDGE MARGIN TESTS BLIND EXPLICIT RS PREDICTIONS



e/D	RS CX Life / RS Non CX Life	Test CX Life / Test Non CX Life
1.3	1.96	3.44
1.4	2.3	4.3
1.5	2.59	4.39
2.0	4.08	8.22

AIR FORCE

STRUCTURES

Structures Bulletin

AFLCMC/EZ
Bldg. 28, 2145 Monohan Way
WPAFB, OH 45433-7101
Phone 937-255-5312

Number: EZ-SB-19-YYY

Date: TBD

Subject: Analytical Methods, Validation Testing, and Process Compliance Record Requirements for Explicit Utilization of Residual Stresses at Cold Expanded Fastener Holes in the Damage Tolerance Analysis of Metallic Structure

ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

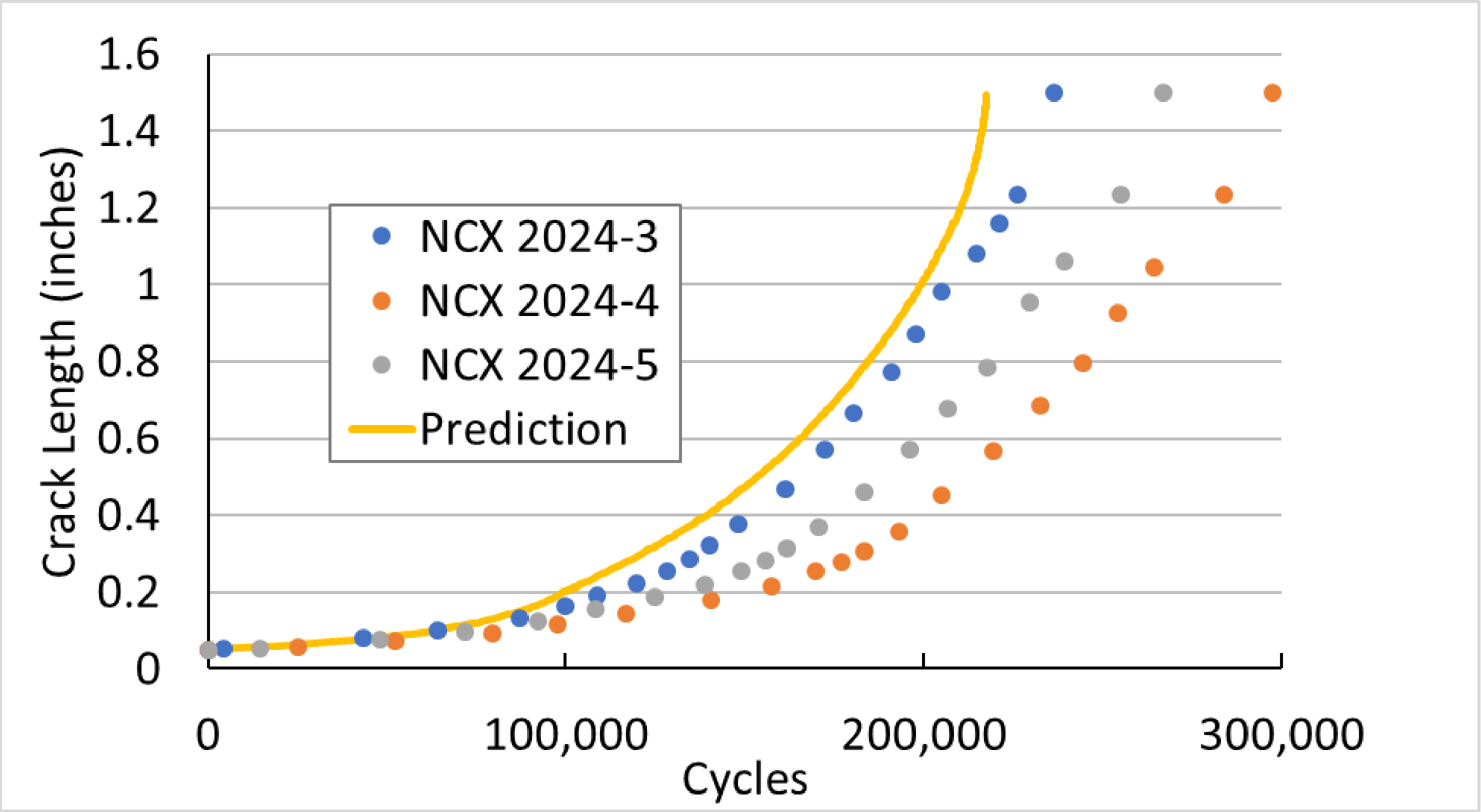
DEFINING SUCCESS CRITERIA

1. Define Requirements
2. Offer Recommendations

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

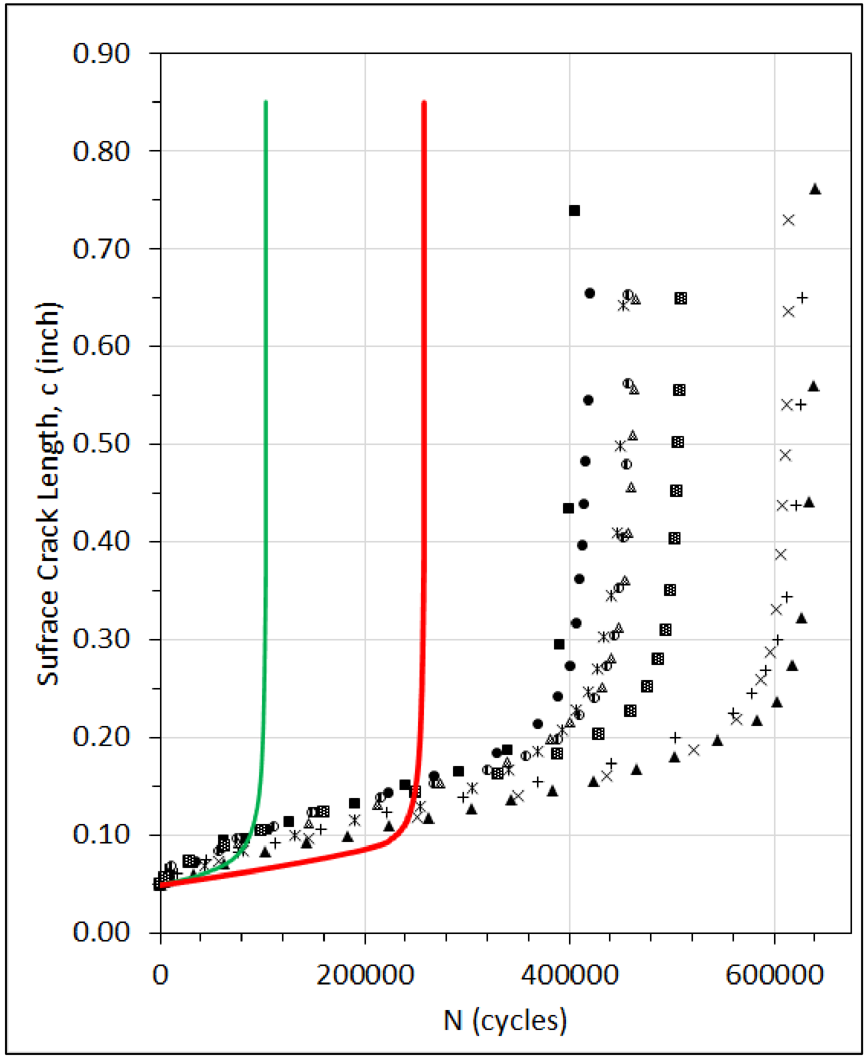
REQUIREMENT: CORRELATION TO TEST

- Require correlation to both CX and Non CX tests
  - Non CX
    - 3 test minimum
    - Prediction matches test average within 20%
    - Prediction matches each test within 50%



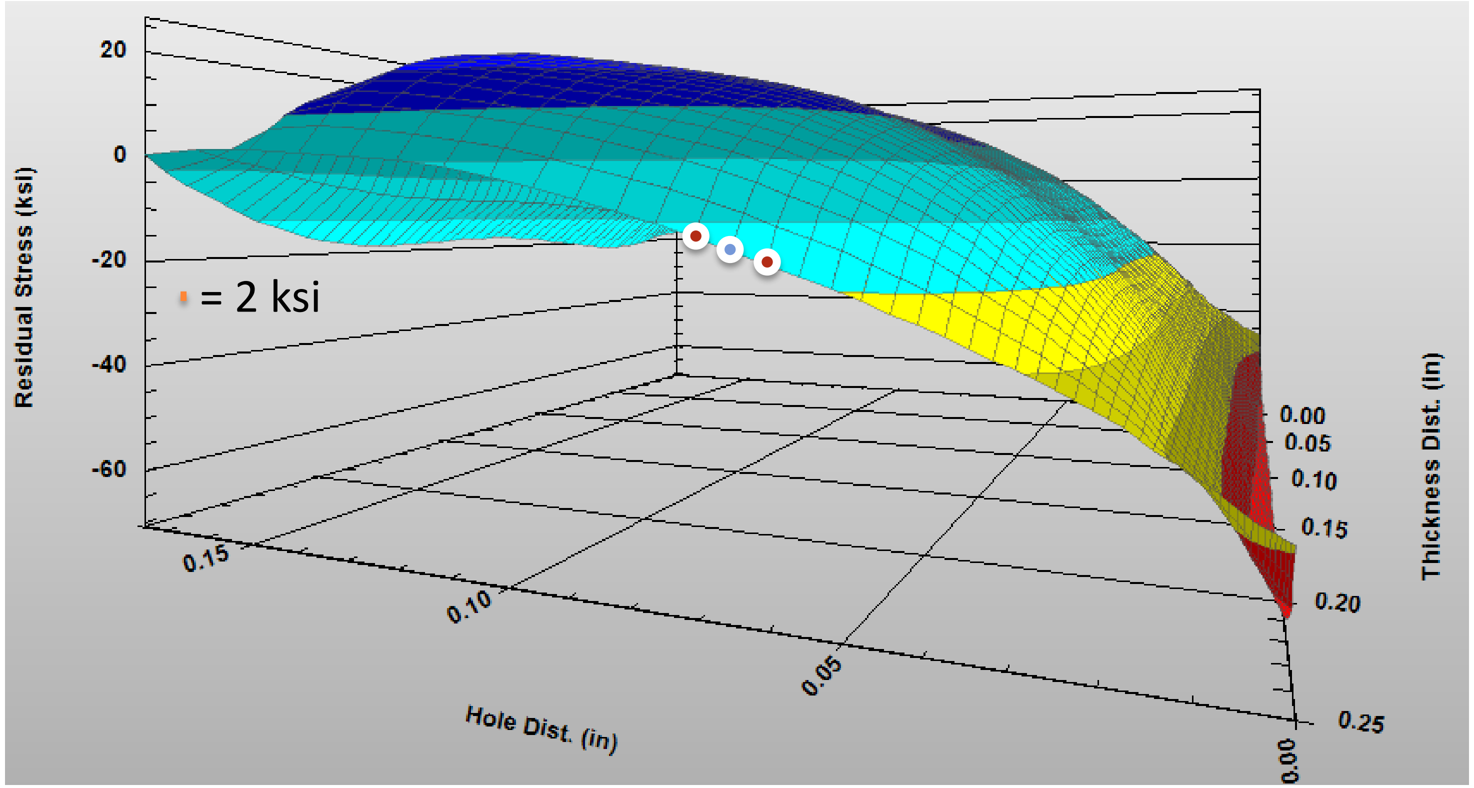
REQUIREMENT: CORRELATION TO TEST

- Require correlation to both CX and Non CX tests
  - Non CX
    - 3 test minimum
    - Prediction matches test average within 20%
    - Prediction matches each test within 50%
  - CX
    - 5 test minimum
    - Two predictions required
      - Mean expected life
        - 0.5 * Test Average < Prediction < 1.2 * Test Average
      - Min expected life
        - Prediction < 0.8 * Test min



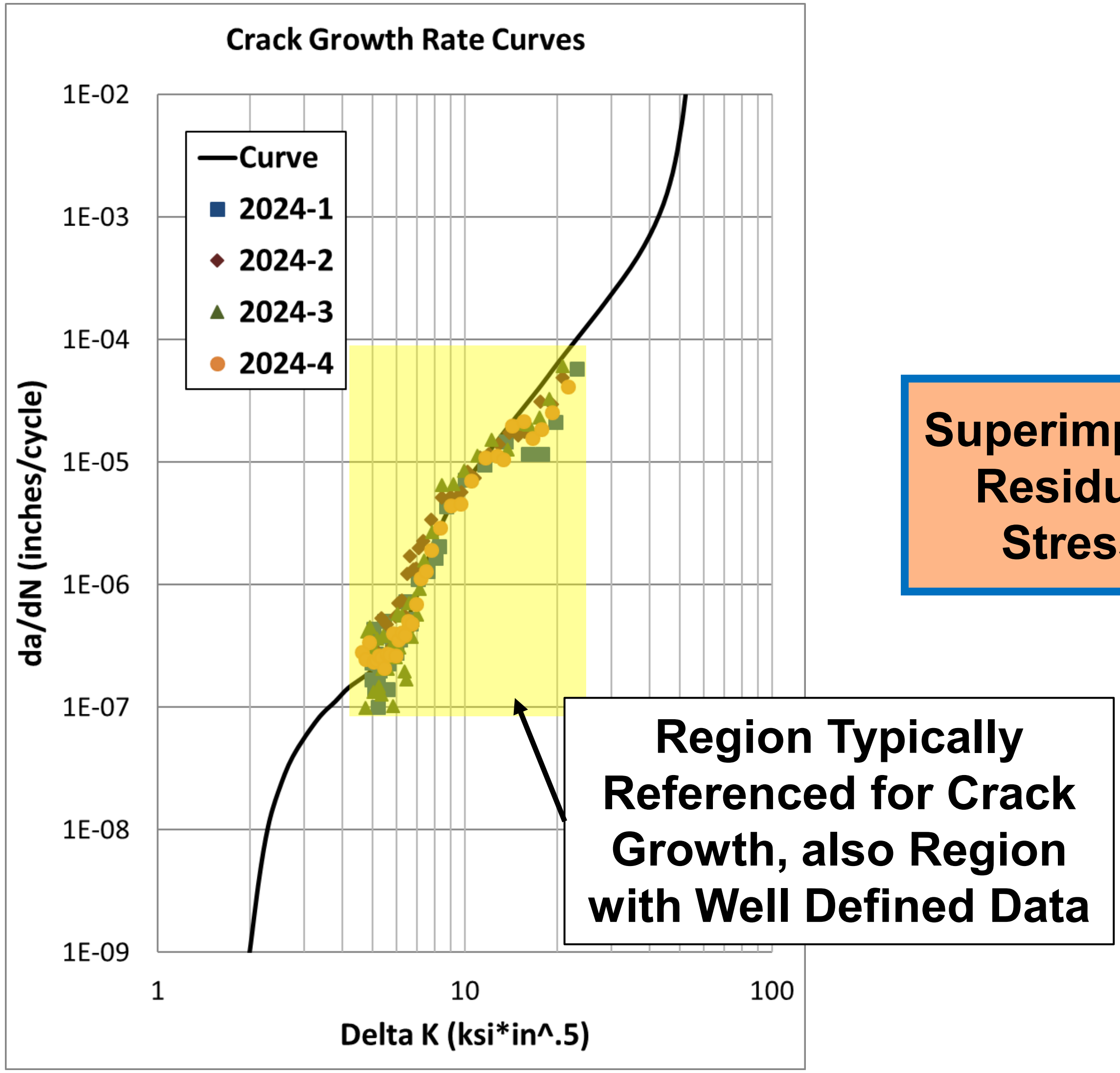
RECOMMENDATION: SPATIAL RESOLUTION

- Correlation to test is *requirement*
- *Recommendation* to resolve residual stress field within ~2-5 ksi (14-35 Mpa)

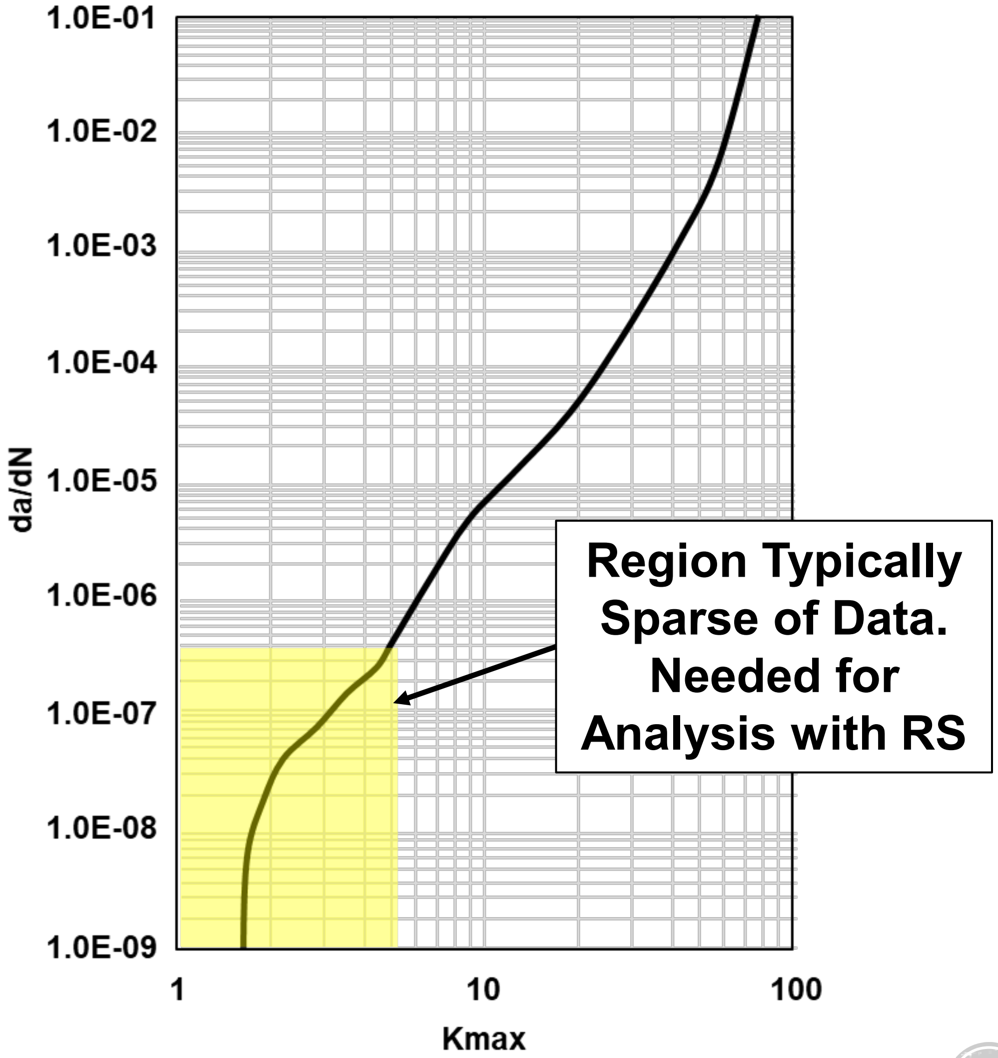


2024-T351
e/D = 1.2
D = 0.25
t = 0.25
3% CX

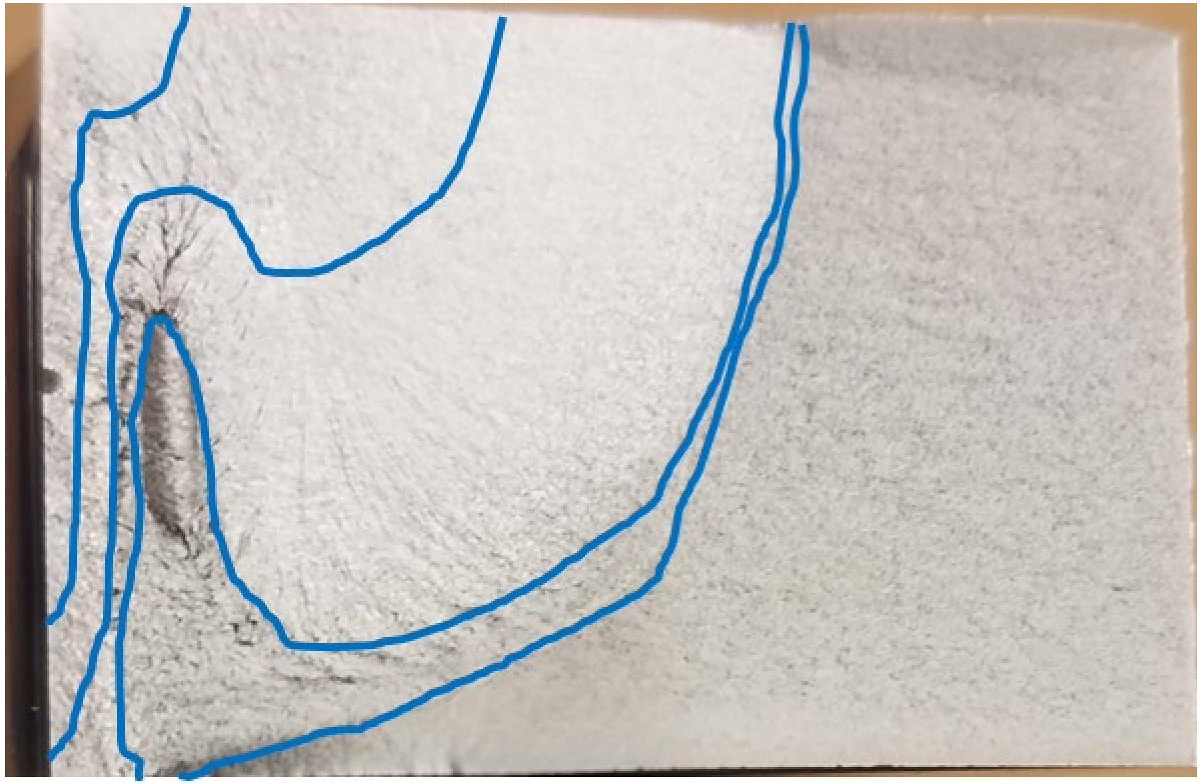
RECOMMENDATION: RATE DATA EVALUATION

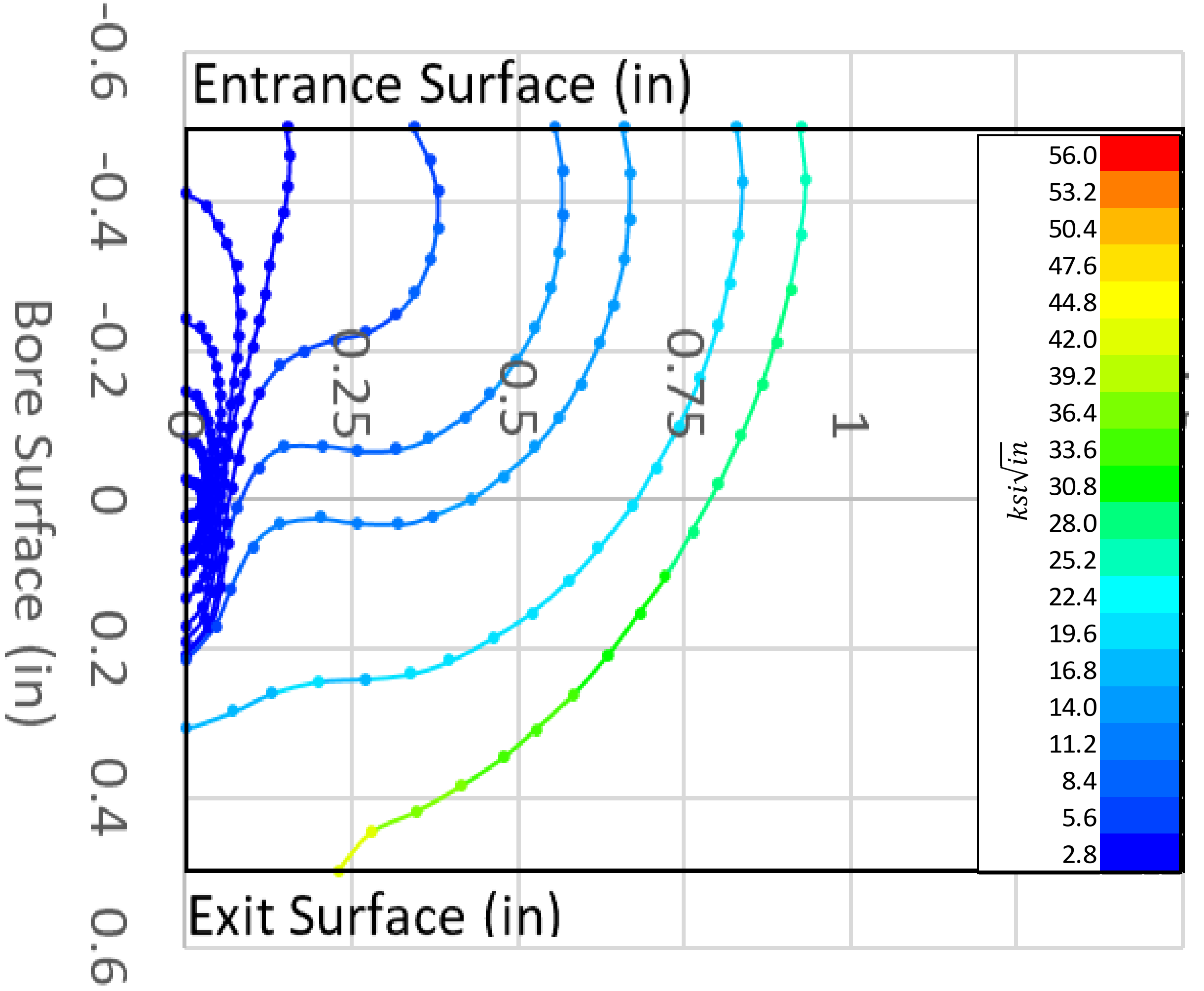


Superimpose Residual Stress



RECOMMENDATION: POINTS ALONG CRACK FRONT





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ENGINEERED RESIDUAL STRESS IMPLEMENTATION

CONCLUSIONS

- *Requirement* is correlation to test
- *Recommendations* can help meet the requirement

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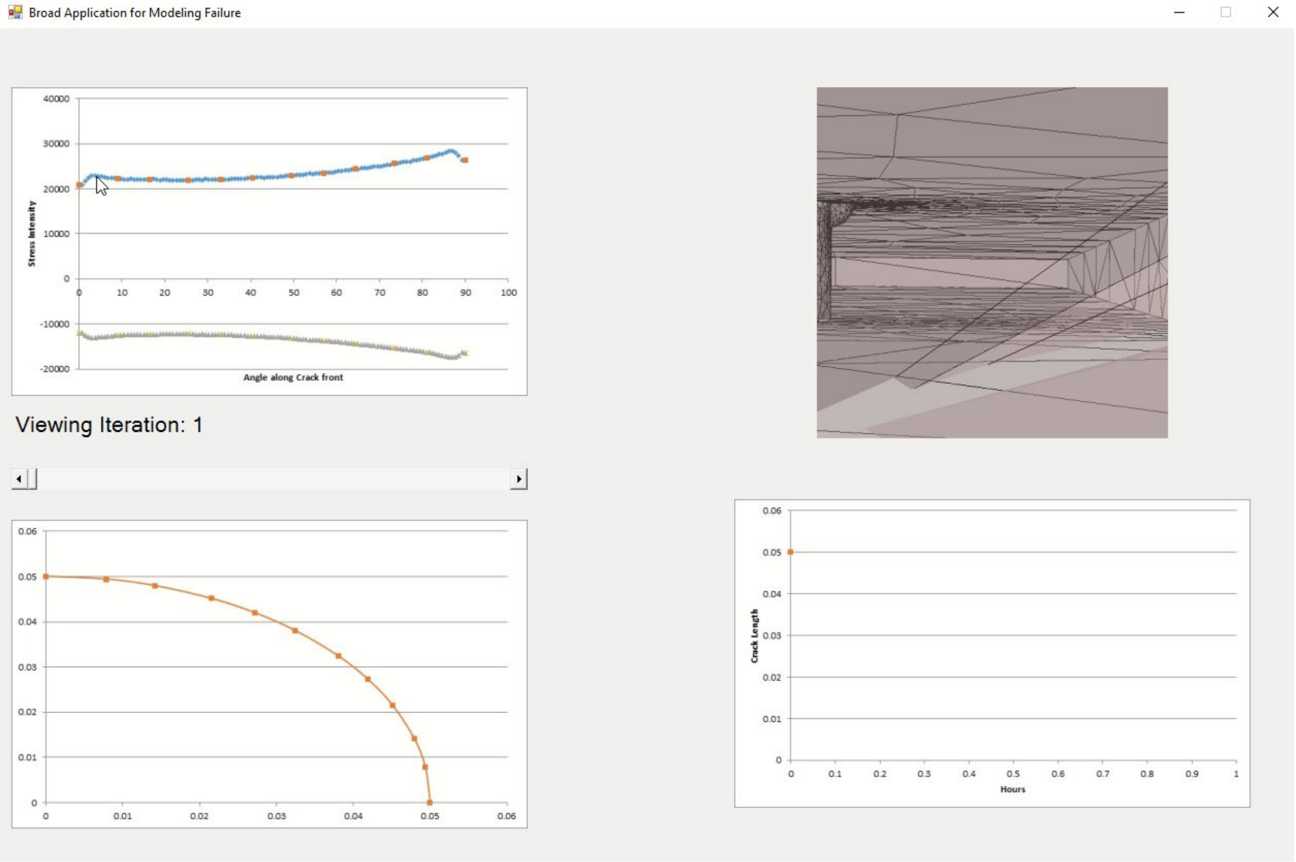

Literature Review

Literature Review

- Objective
  - Develop a consolidated summary of Cx references for the community
  - Increase visibility of existing Cx references
- Status
  - Developed a template to identify key parameters
  - Divvied out responsibility to populate amongst community

Source Information						Scope			Geometric Details					Cx Details				Testing Details	
Title	Source	Date published	Author	DOI link	Reference POC	Goal/Abstract Summary	Type of data (Analysis/Testing)	Compare to reduced IFS approach?	Material/s	Final Hole Diameter	Edge Margin (e/D)	Hole (Straight/Csk)	Hole Fill (Open/Filled/Interference)	Cx Level	Cx Order (Before/After Crack)	Final Ream (Y/N)	Residual Stress Measurement Data?	Loading (CA/VA)	Crack Formation (Natural/Notched)
Experimentally derived beta corrections to predict fatigue crack growth at cold expanded holes in 7075-T651 aluminum alloy	MS Thesis; University of Utah	Aug-08	Pilarczyk		Pilarczyk	Quantify life benefit of CX and derive beta corrections to accurately model life in 7075-T651	Both	Y	7075-T651	0.5	Center	Straight	Open	Nom	After	Y	N	CA	Notched
Experimentally derived beta corrections to accurately model the fatigue crack growth behavior at cold expanded holes in 2024-T351 aluminum alloys	MS Thesis; University of Utah	Aug-08	Carlson		Carlson	Quantify life benefit of CX and derive beta corrections to accurately model life in 2024-T351	Both	Y	2024-T351	0.5	Center	Straight	Open	Nom	After	Y	N	CA	Notched
Investigation of cold expansion of short edge margin holes with preexisting cracks in 2024-T351 aluminum alloy	MS Thesis; University of Utah	Dec-11	Andrew		Andrew	Quantify life benefit of short edge margin (e/D=1.2) CX holes under constant amplitude and fighter wing root bending spectrum loading	Both	Y	2024-T351	0.5	1.2	Straight	Open	Nom	Both	Y	N	Both	Notched
Cold Expansion Effects on Cracked Fastener Holes under Constant Amplitude and Spectrum Loading in the 2024-T351 Aluminum Alloy	MS Thesis; University of Utah	May-12	Warner		Warner	Quantify life benefit of precracked CX hole and compare to 0.005" IFS for fighter wing root bending spectrum at multiple stress levels	Both	Y	2024-T351	0.5	Center	Straight	Open	Nom	Before	Y	N	Both	Notched
Integrating Residual Stress Analysis of Critical Fastener holes into USAF depot maintenance	Rapid Innovation Fund	Feb-14	Mills		Mills	Quantify residual stress field and benefit at CX process tolerance extremes as well as nominal conditions	Both	Y	7075-T6 7075-T651 7075-T7351 2024-T3 2024-T351	0.25 0.375 0.5	Center	Straight	Open	High Middle Low	Both	Y	Y	Both	
Cold Expanded Hole Testing Summary	USAF Contract F34601-88-C-0392	Sep-90	Boeing		Warner	Summarize CX test data for CX application recommendations on B-52 and KC-135	Testing	N	7075-T411 7178-T651 7079-T6 7075-T6	0.375 0.5 0.875	Center 2.0 1.5 1.25 1.2 1.0	Both	Open	Nom	Both	Y	N	VA	Notched
Effects of Variations in Coldworking Repair Procedures on Flaw Growth and Structural Life (AFWAL-TR-82-3030)	AFWAL	Apr-84	J. M. Pearson-Smith, Lt		Warner	Quantify CX benefit in light of a final or starting hole diameter larger than permitted by CX process	Testing	N	7075-T651	0.25	Center	Straight	Open	Low	After	Both	Y	VA	Natural
Stress Analysis of Coldworked Fastener Holes (AFML-TR-74-44)	AFML	Jul-74	William F. Adler		Warner	Quantify residual stress/strain from CX and redistribution from tensile overloads analytically and experimentally	Both	N/A	7075-T6	0.25	Center	Straight	Open	Nom	N/A	Y	Y	N/A	N/A

Timeline of Research Efforts Related to the Application of Residual Stresses into Damage Tolerance Analysis for USAF weapon systems

U.S. AIR FORCE

Conclusions/Summary

- Incrementally, we are making progress within the Analysis Methods and Validation Testing Committees
  - Thanks to those individuals that have contributed
- We must continue to push forward with a focus on refining our analytical capability and addressing technical gaps

Historical

Residual Stress is considered a problem or used as a *band-aid* to address design deficiencies

Emerging

Residual Stress Engineering is a *conventional technology* that assures performance

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Questions?