Analytical Methods & Testing Committee: Overview of Recent Efforts

Engineered Residual Stress Implementation Workshop 2019

September 12, 2019

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USAF

ERSI

Acknowledgements

- USAF Structural Integrity Teams
- Air Force Research Lab
- Analysis Methods & Testing Committee Participants
- ERSI Working Group

Historical

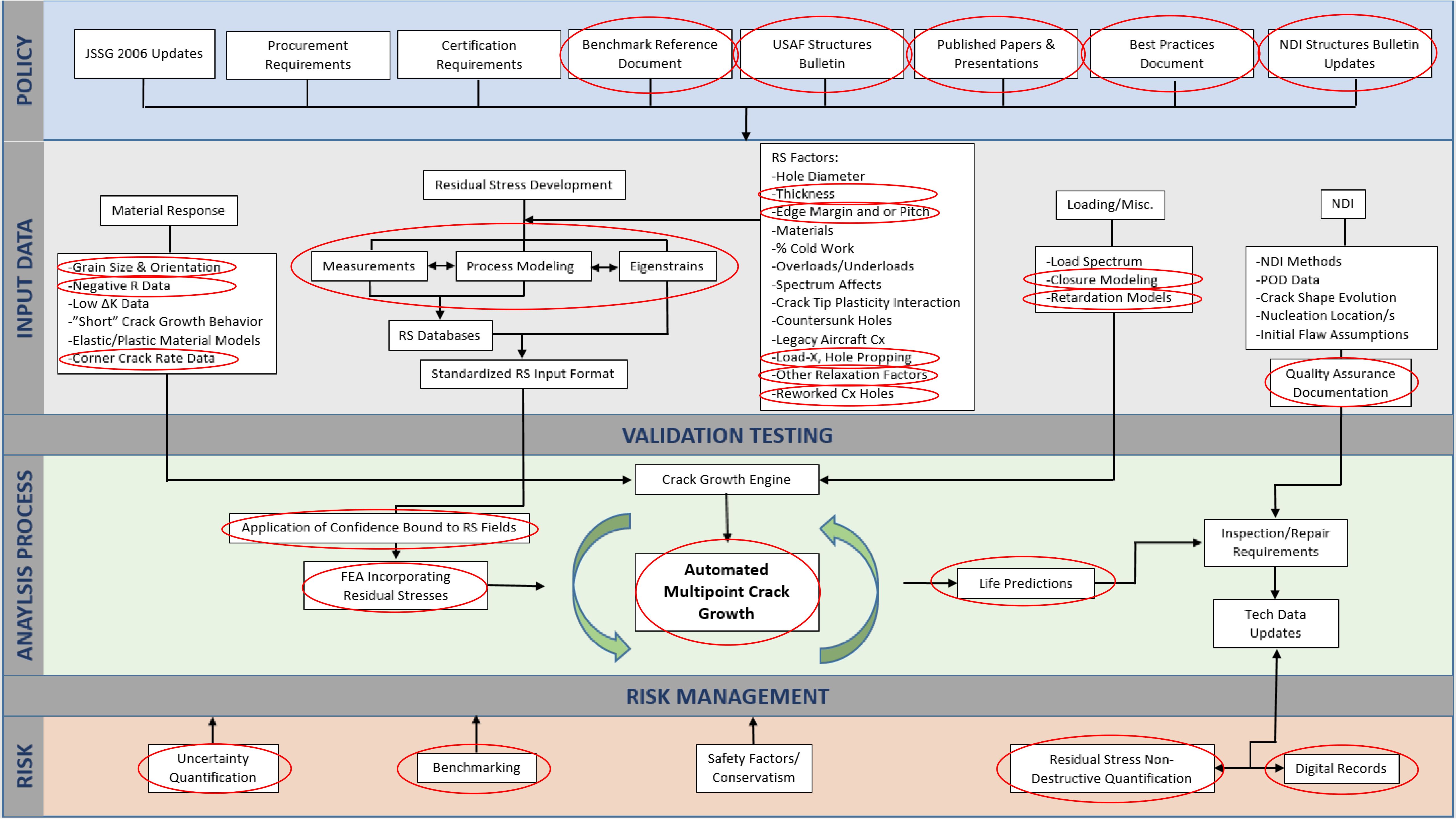
Residual Stress is considered a problem or used as a *band-aid* to address design deficiencies

Emerging

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

Agenda

- Round Robin Efforts
  - Round Robin Wrap-Up (Pilarczyk)
  - Round Robin #2 Plan (Warner)
- Modeling Efforts
  - Residual Stress Source Comparisons w/ Test Data (Carlson)
  - Multi-directional material properties (Pilarczyk)
  - Closure Modeling (Mills)
  - Closure Images (Ross)
  - Shakedown (Mills, Pilarczyk)
  - Notch Plasticity (Keller)
  - FCG Testing of Complex Coupons with Quench Induced Residual Stress (Hill)
  - Fatigue Life Variability (Warner, Mills)
- Validation Testing
  - Short Edge Margin Evaluation (Ross)
  - Geometrically Large Coupons (Warner)
- Weapon System Applications
  - F-18 Wing Root Shear Tie Analyses (Walker)
  - A-10 Control Point Predictions (Pilarczyk, Warner)
  - B-1 Taper-Lok Analysis (Pilarczyk)
- Misc. Other
  - USAF Draft Structures Bulletin
  - Literature Review (Pilarczyk)



POLICY
JSSG 2006 Updates
Procurement Requirements
Certification Requirements
Benchmark Reference Document
USAF Structures Bulletin
Published Papers & Presentations
Best Practices Document
NDI Structures Bulletin Updates
INPUT DATA
Material Response
-Grain Size & Orientation
-Negative R Data
-Low ΔK Data
-"Short" Crack Growth Behavior
-Elastic/Plastic Material Models
-Corner Crack Rate Data
Residual Stress Development
Measurements
Process Modeling
Eigenstrains
RS Databases
Standardized RS Input Format
RS Factors:
-Hole Diameter
-Thickness
-Edge Margin and or Pitch
-Materials
-% Cold Work
-Overloads/Underloads
-Spectrum Affects
-Crack Tip Plasticity Interaction
-Countersunk Holes
-Legacy Aircraft Cx
-Load-X, Hole Propping
-Other Relaxation Factors
-Reworked Cx Holes
Loading/Misc.
-Load Spectrum
-Closure Modeling
-Retardation Models
NDI
-NDI Methods
-POD Data
-Crack Shape Evolution
-Nucleation Location/s
-Initial Flaw Assumptions
Quality Assurance Documentation
VALIDATION TESTING
ANAYLSIS PROCESS
Crack Growth Engine
Application of Confidence Bound to RS Fields
FEA Incorporating Residual Stresses
Automated Multipoint Crack Growth
Life Predictions
Inspection/Repair Requirements
Tech Data Updates
RISK MANAGEMENT
RISK
Uncertainty Quantification
Benchmarking
Safety Factors/ Conservatism
Residual Stress Non-Destructive Quantification
Digital Records

Round Robin Efforts

Round Robin #1 Wrap-up

- Follow-up Efforts
  - Replicate variance and its impact on life predictions
- Publications
  - Presented at 19th International ASTM/ESIS Symposium on Fatigue and Fracture Mechanics (42nd National Symposium on Fatigue and Fracture Mechanics), May 2019
  - Publication in upcoming Special Issue on Fatigue and Fracture Mechanics for Materials Performance and Characterization

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Round Robin #2 Planning

- Background
  - Initial Round Robin effort proved to be quite fruitful and facilitated collaboration amongst committee
  - Follow-on Round Robins should focus on investigating other areas of the analysis process to <u>gain confidence in analysis methods, gather lessons learned, and define best practices</u>
- Approach
  - Investigate available datasets to identify candidates
  - Smaller subcommittee review data to determine best case for next Round Robin

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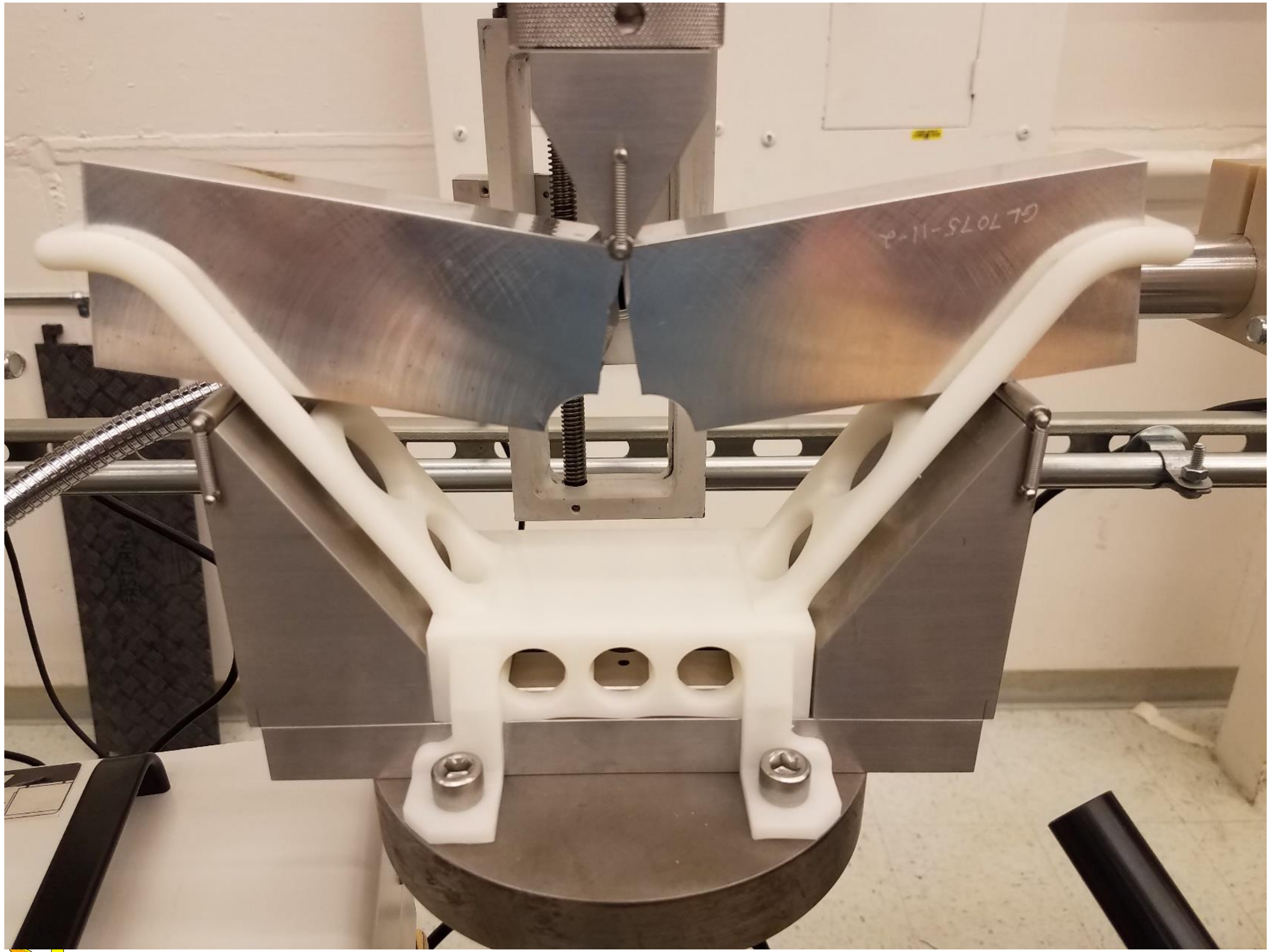
Round Robin 2 - Option 1



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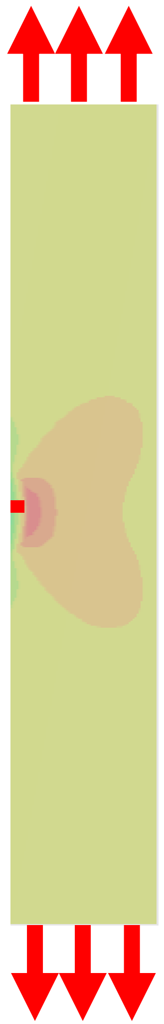
Round Robin 2 - Options 2 and 3

- SEN(T) specimen with residual stress field
  - Pros:
    - RS prediction without stress concentration
    - Focus on crack growth fundamentals
  - Cons:
    - No practical application
    - Test data not yet generated
- Interference fit fastener in a plate
  - Pros:
    - Typically far broader application than CX
    - One step closer to aircraft structure from open hole
  - Cons:
    - Different life improvement mechanism than RS, though still relevant

SEN(T)



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Round Robin 2

- Are there other relevant datasets to consider??
- Bring your ideas to our breakout session.

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Modeling Efforts

Assessing the State-of-the-Art Residual Stress Input Methods for Crack Growth Prediction vs. Test

Engineered Residual Stress Implementation Workshop 2019

September 12, 2019

Scott Carlson – LM-Aero

Marcias Martinez & Craig Merrett – Clarkson University

Keith Hitchman – FTI

Caleb Morrison – Hill Engineering, CA

Joshua Hodges – Hill Engineering, UT

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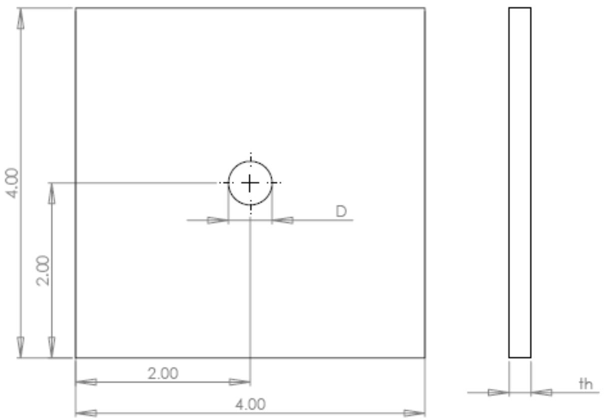
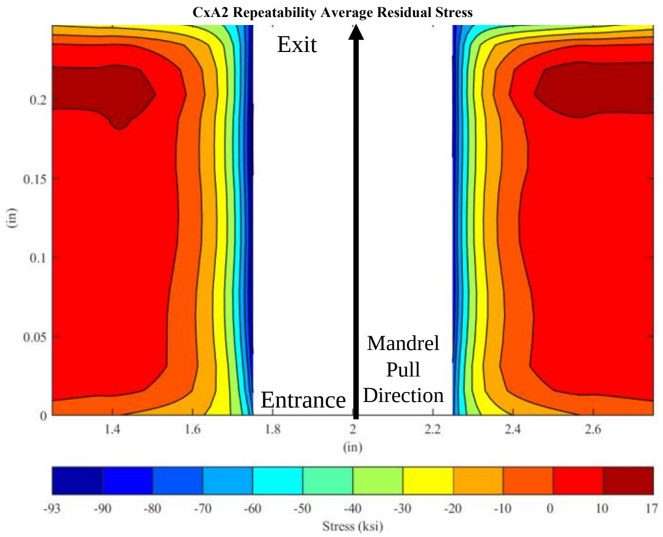
Problem Statement

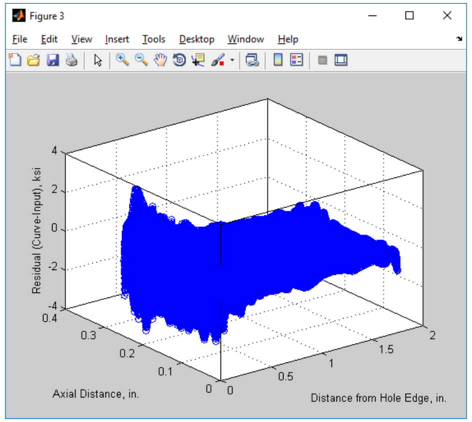
- Utilize Current State of the Art Residual Stress Inputs into a Crack Growth Prediction
  - Start with "simple" condition, 2024-T351
    - 0.25inch thick x 4inch wide with a "Low" applied expansion 0.5inch dia. hole
  - Residual stress inputs include
    - Contour method (Carlson)
    - Elastic-plastic process simulation (Hitchman)
    - Closed-form solution (Ball/Martinez/Merrett)
    - Eigenstrain fit (Morrison)
  - Include residual stresses into two crack growth engines
    - BAMF – multi-point FEA/LEFM tool
      - Residual stress included as a function
    - CGRO – LM's 2-point LEFM tool
      - Residual stress included as a point-wise cloud
- Predict Life from a 0.03x0.03inch Initial Crack – Compare to Test

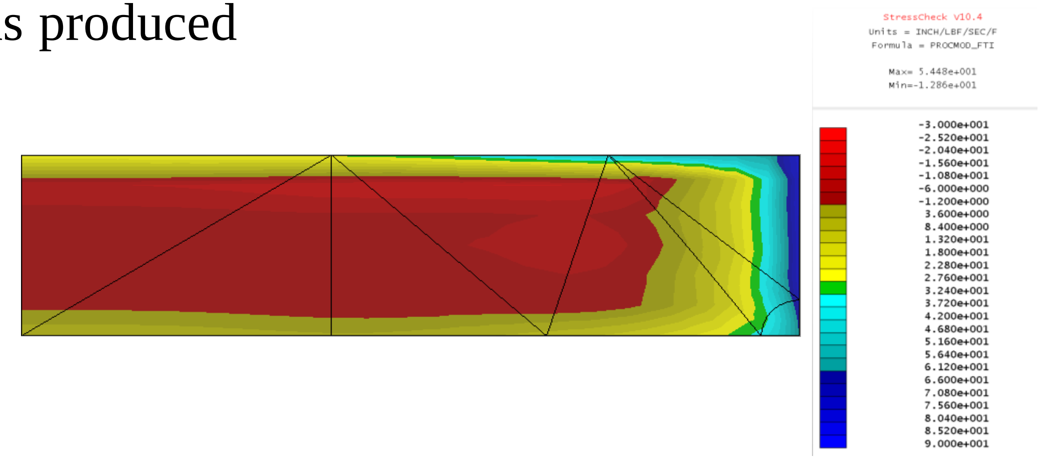
Residual Stress Input – Contour Method

- Contour Method for Determining Residual Stresses[1]
  - 5 Replicates were produced for the "Low" applied Cx
    - The "low" applied expansion represents 3.14-3.19%
    - Initial hole diameter = 0.4772-0.4774in
    - Mandrel diameter = 0.4684in with sleeve thickness = 0.0120in
    - Avg. post Cx diameter = 0.48783-0.48835inch
    - Residual expansion = 2.33%-2.34%
  - Average of left side of hole for all 5 replicates
  - Data was re-grid to a 0.001x0.001inch grid spacing
  - Data was fit using a 15th order polynomial for inclusion in BAMF
    - Residuals of fit to data was produced



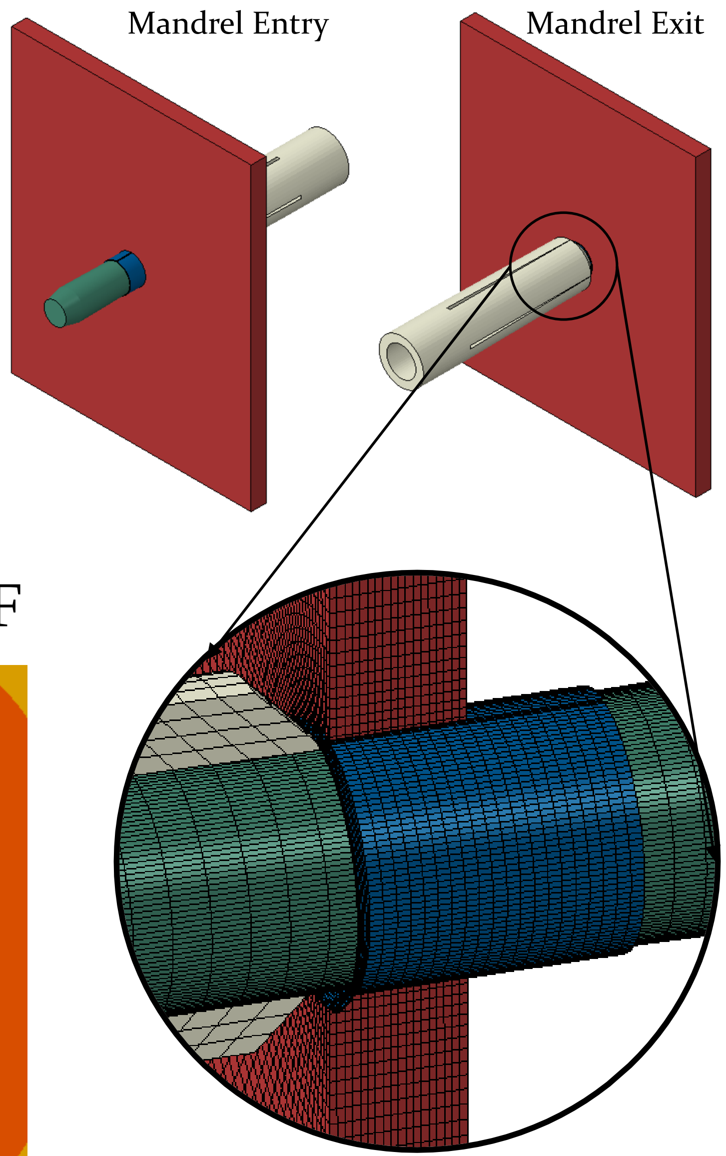


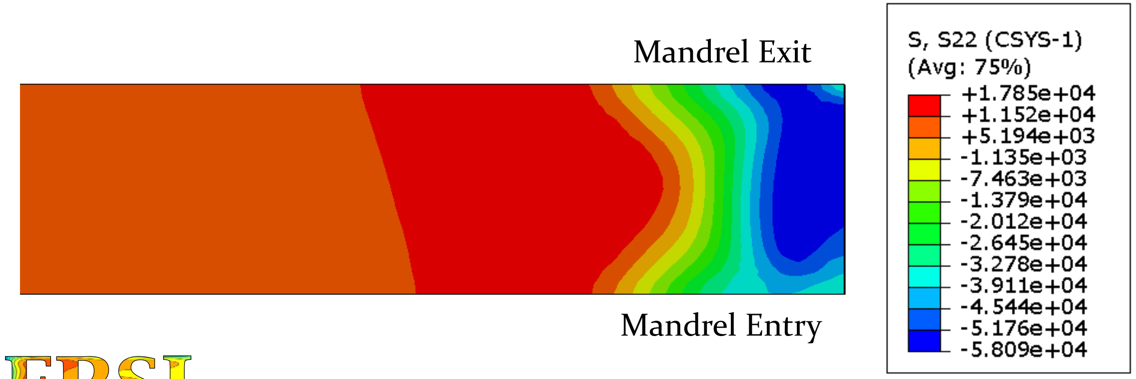




Residual Stress Input – Elastic-Plastic FEA

- Finite Element Analysis using ABAQUS[2]
  - 3D, mandrel pull through
  - Reduced integration elements (.017” x .011” x .014” near hole)
  - Penalty Contact with appropriate friction for sleeve, etc.
  - Combined hardening material model (others evaluated)
  - Post-Cx Ream via element removal (results shown)
  - Data was re-grid to a 0.001x0.001inch grid spacing
  - Data was fit using a 15th order polynomial for inclusion in BAMF
    - Residuals of fit to data was produced





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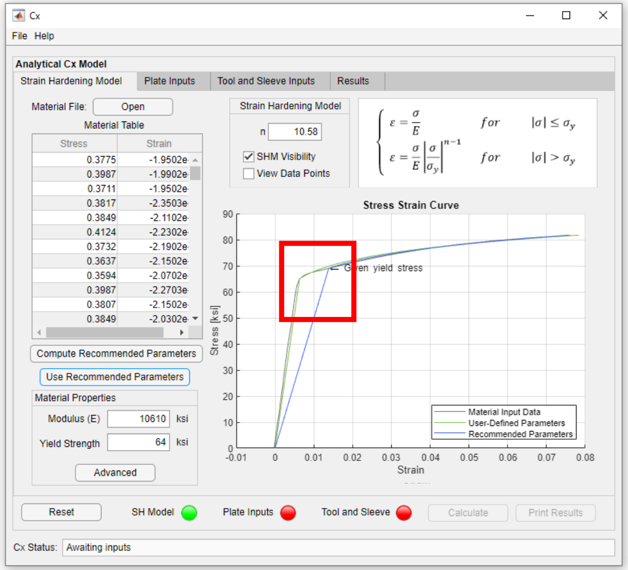
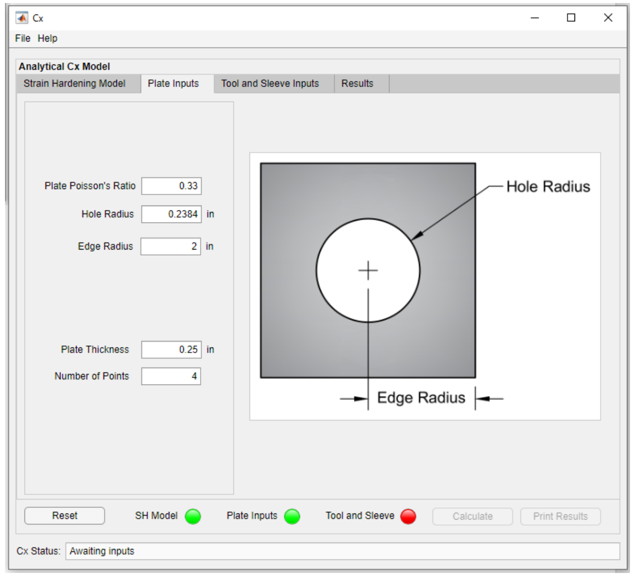
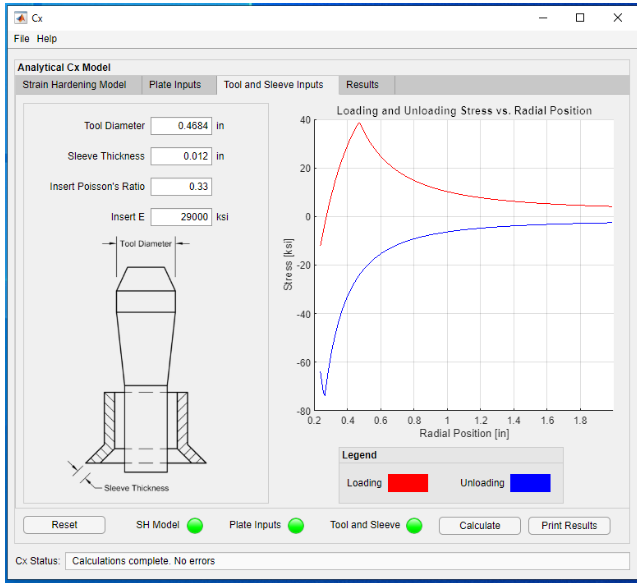
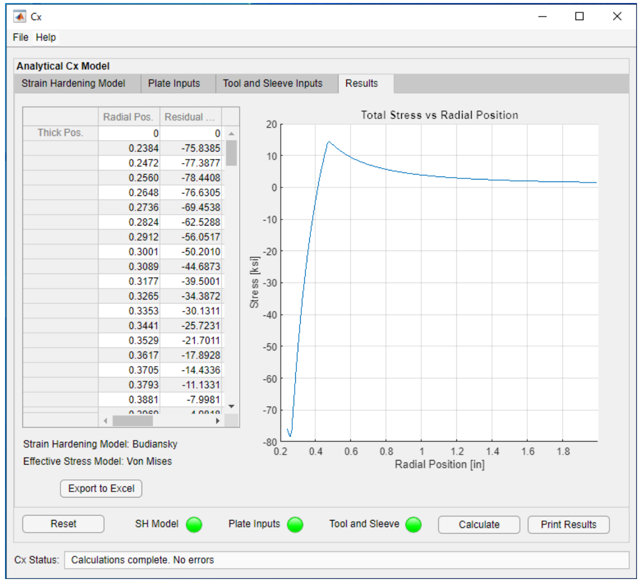
Closed Form Solution

- The closed form solution based on Dr. Ball's paper[3]
- Assumptions:
  - Radial expansion (no difference through material thickness)
  - Budiansky, elastic-plastic material model
  - Determination of elastic-plastic region based on an effective von Misses Stress
  - Process assumed to be quasi-static.
  - No strain rate dependencies included in the model
  - Isotropic material behavior
- Data was re-grid to a 0.001x0.001inch grid spacing
- Data was fit using a 15th order polynomial for inclusion in BAMF



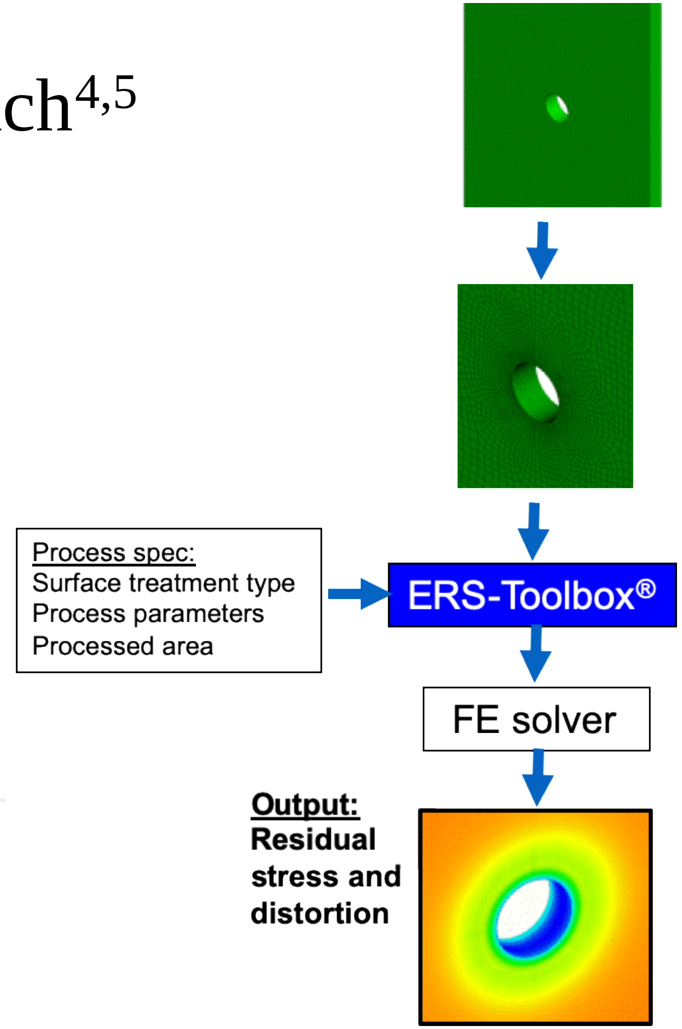




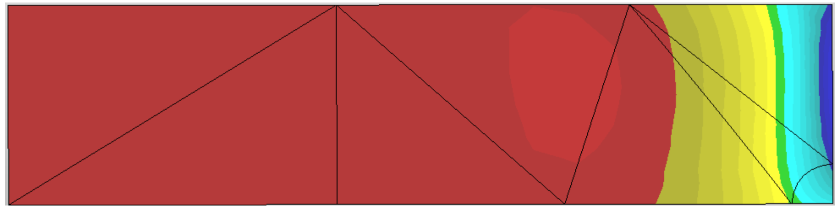


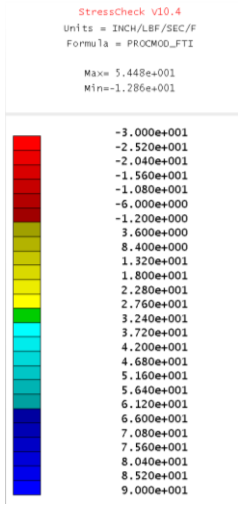
Residual Stress Input – Eigenstrain

- ERS-toolbox® software estimates full field residual stress and part distortion and implements the eigenstrain approach[4,5]
- Specifics of this case
  - Eigenstrain based on residual stress data for similar condition
    - Five coupons with CX spanning 3.14% to 3.23%
      - Coupon IDs are A2-1 to A2-5 from A-10 Mod III program
    - Eigenstrain model based on average of all coupon measurements
  - Residual stress output was interpolated on a 0.001x0.001inch grid
  - Fit to a 15th order polynomial for inclusion in BAMF



Residual stress input into BAMF





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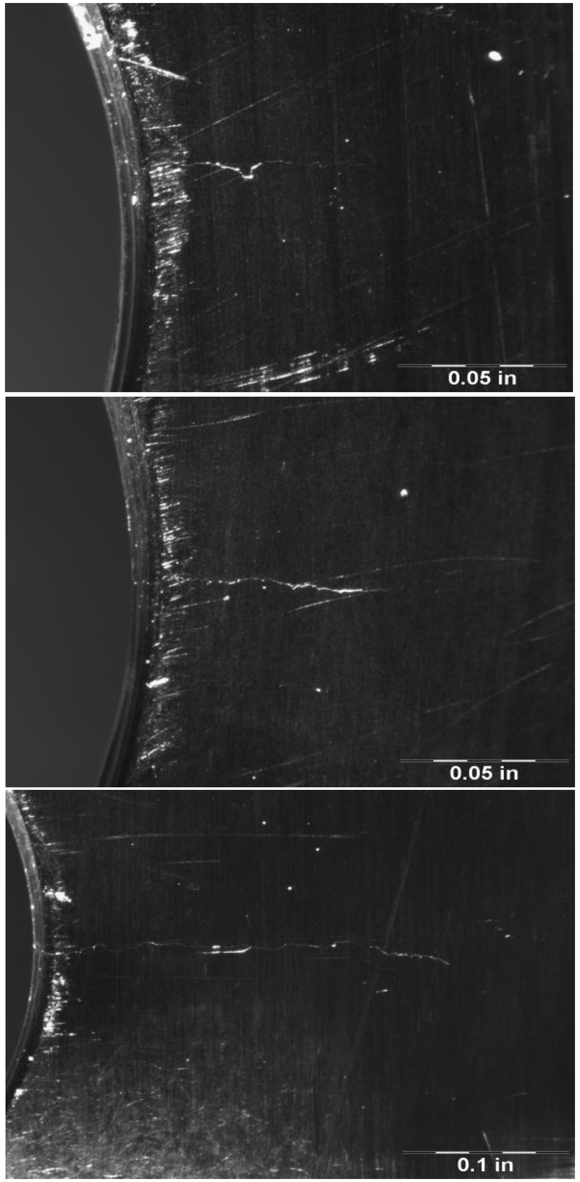
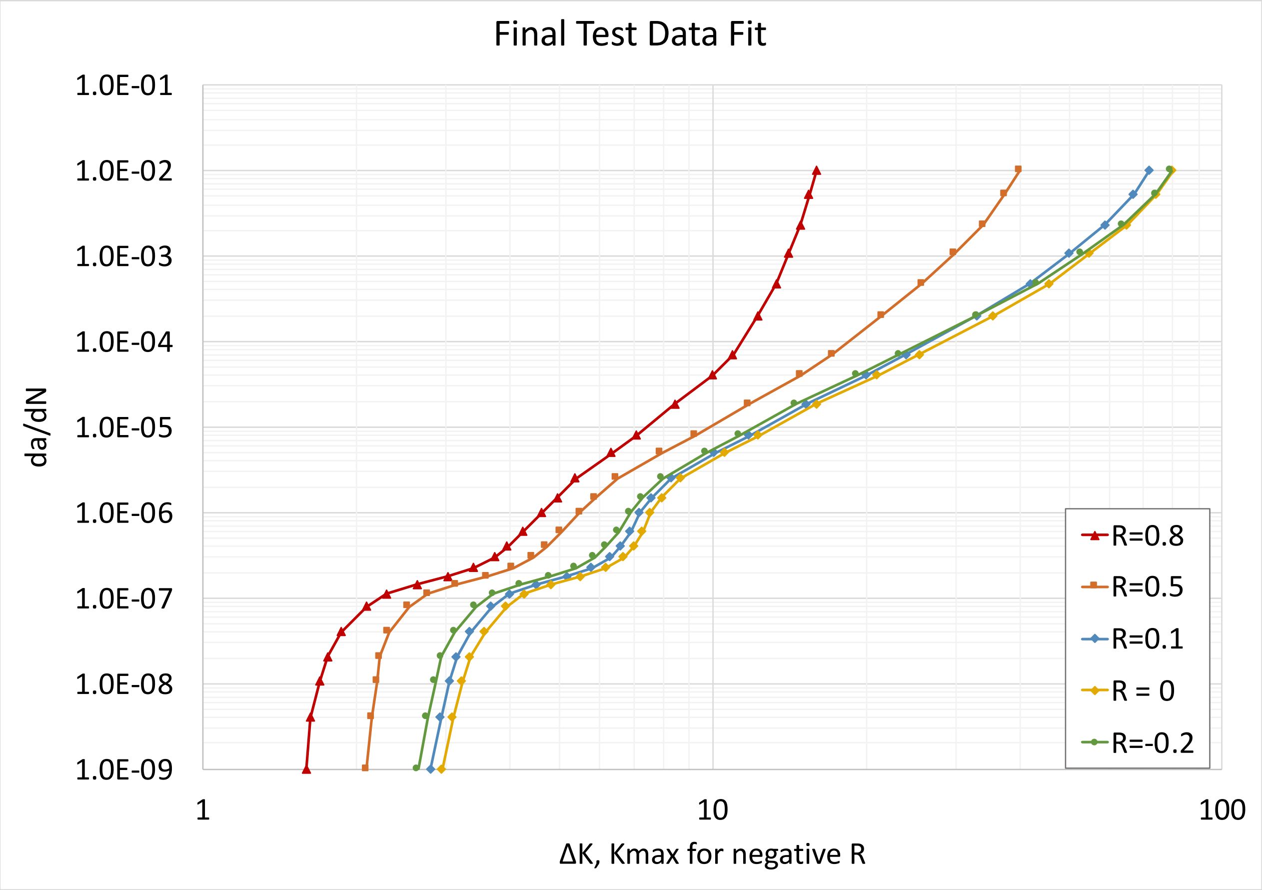
Fatigue Test Condition

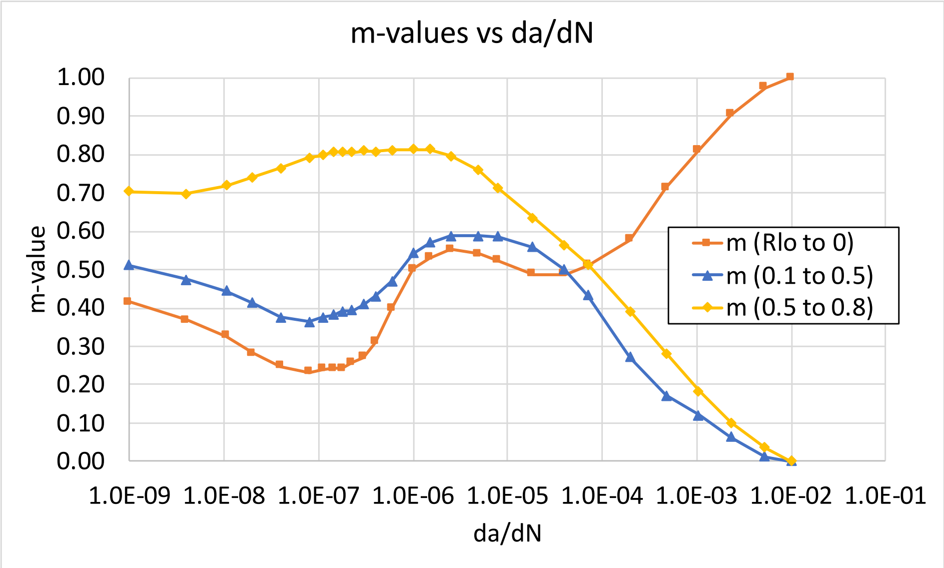
- Fatigue Test Coupon Configuration
  - 4inch wide x 0.25inch thick x 16inch long
  - Avg. initial ream diameter = 0.4770inch
  - Std on initial ream = 0.0001inch
  - Applied expansion avg = 3.24%
  - Avg final ream = 0.4992inch
  - Std on final ream = 0.0006inch
- Testing Spectrum – Constant Amplitude
  - Max stress = 25ksi
  - Stress Ratio (R) = 0.1
  - Marker banding with 15% overload
- Fatigue Testing Performed at APES
  - Surface crack length measured via traveling microscopes



BAMF Predictions

- Material File Input[6]
  - Material file same as ERSI Cx hole round robin and AFGROW round robin
  - 2024-T351, 4 Stress Ratios (R)
  - Material fit performed by Hill Eng. UT





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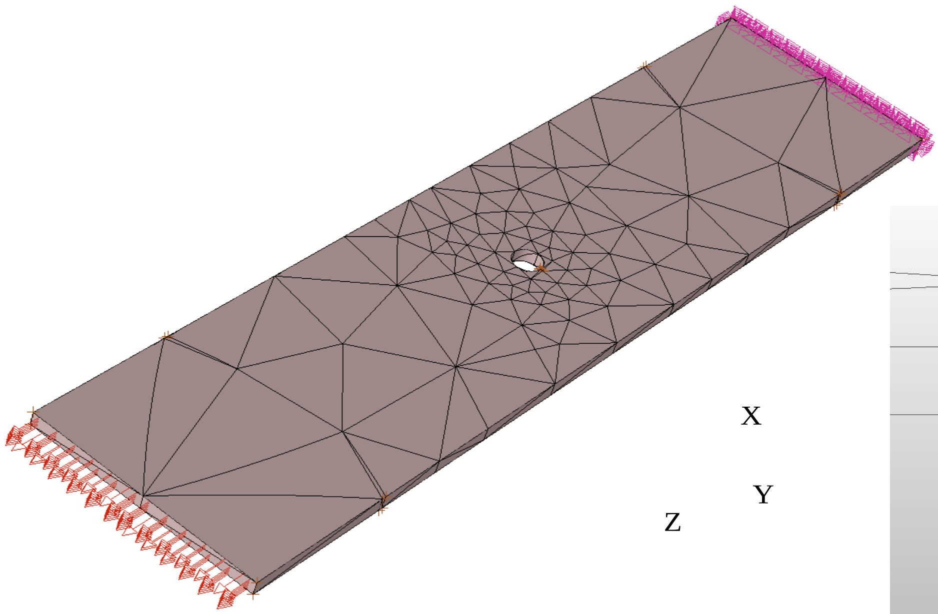
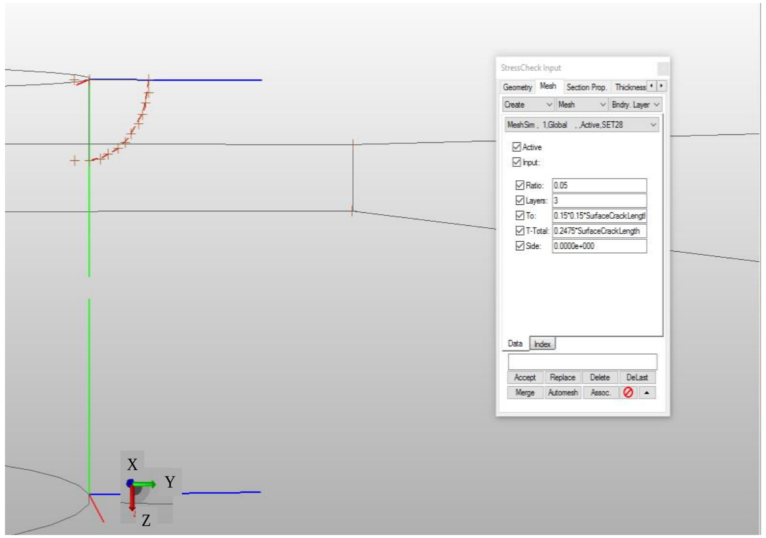
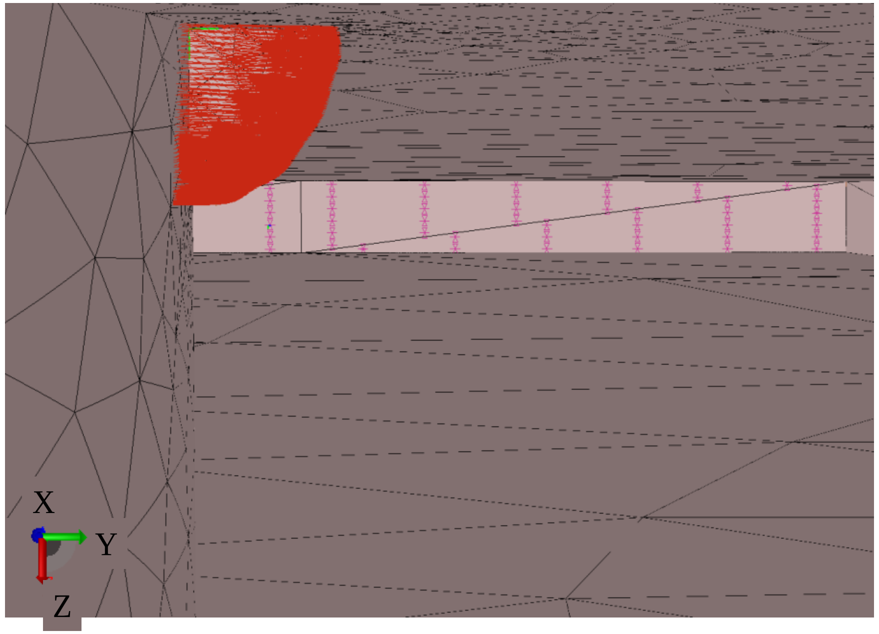
BAMF Predictions

- BAMF Set-up and Model Definition[7]
  - Size of initial crack in model = 0.03x0.03inch quarter elliptical
    - Size based on avg. initial crack size from marker banded coupons
  - Residual stress applied as crack-face traction
  - K_{total} solved at P-level = 5 with convergence checked



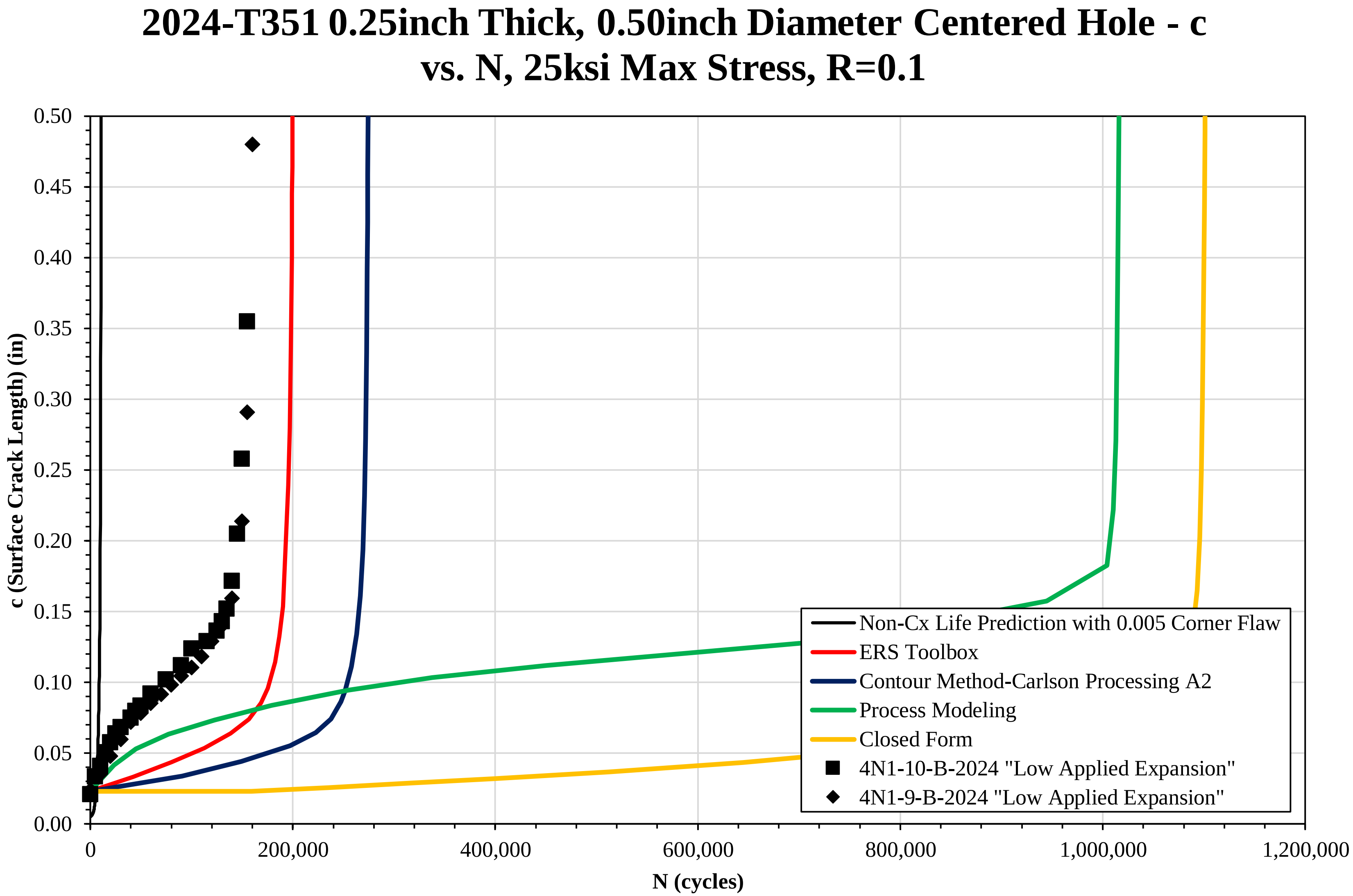




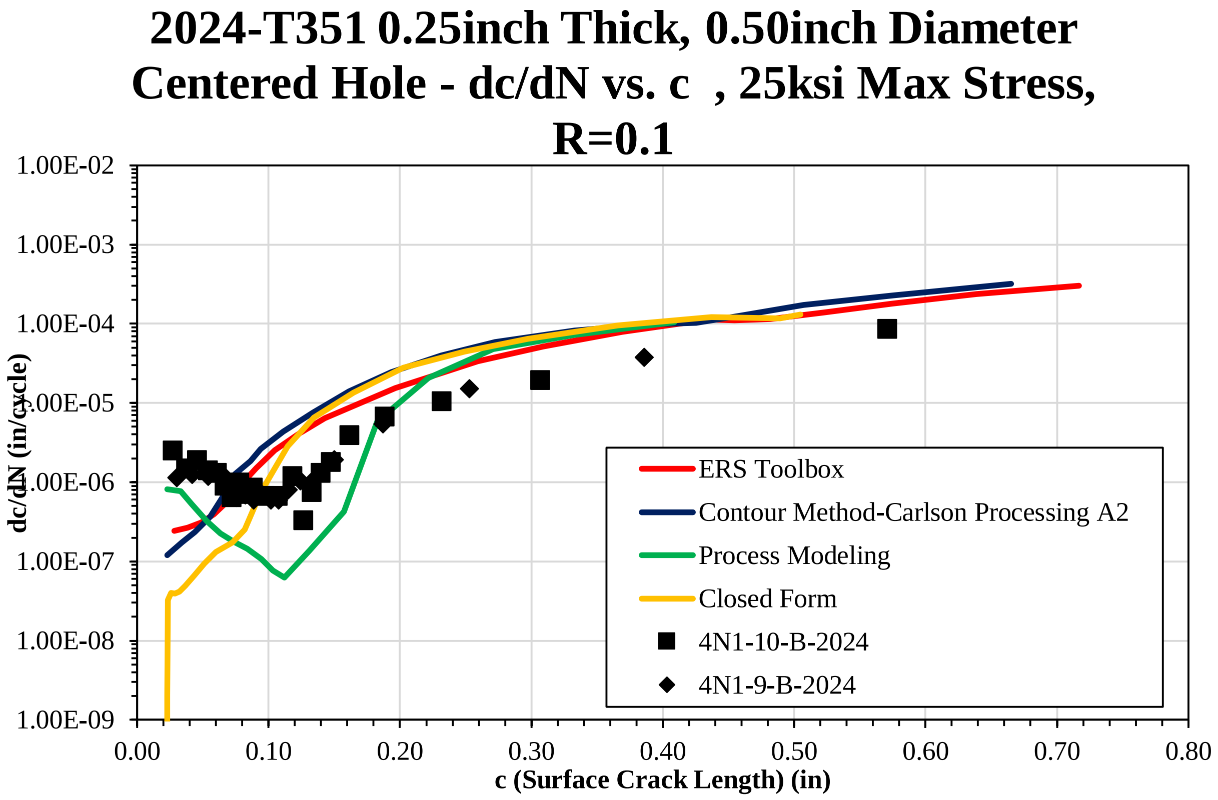
BAMF Predictions

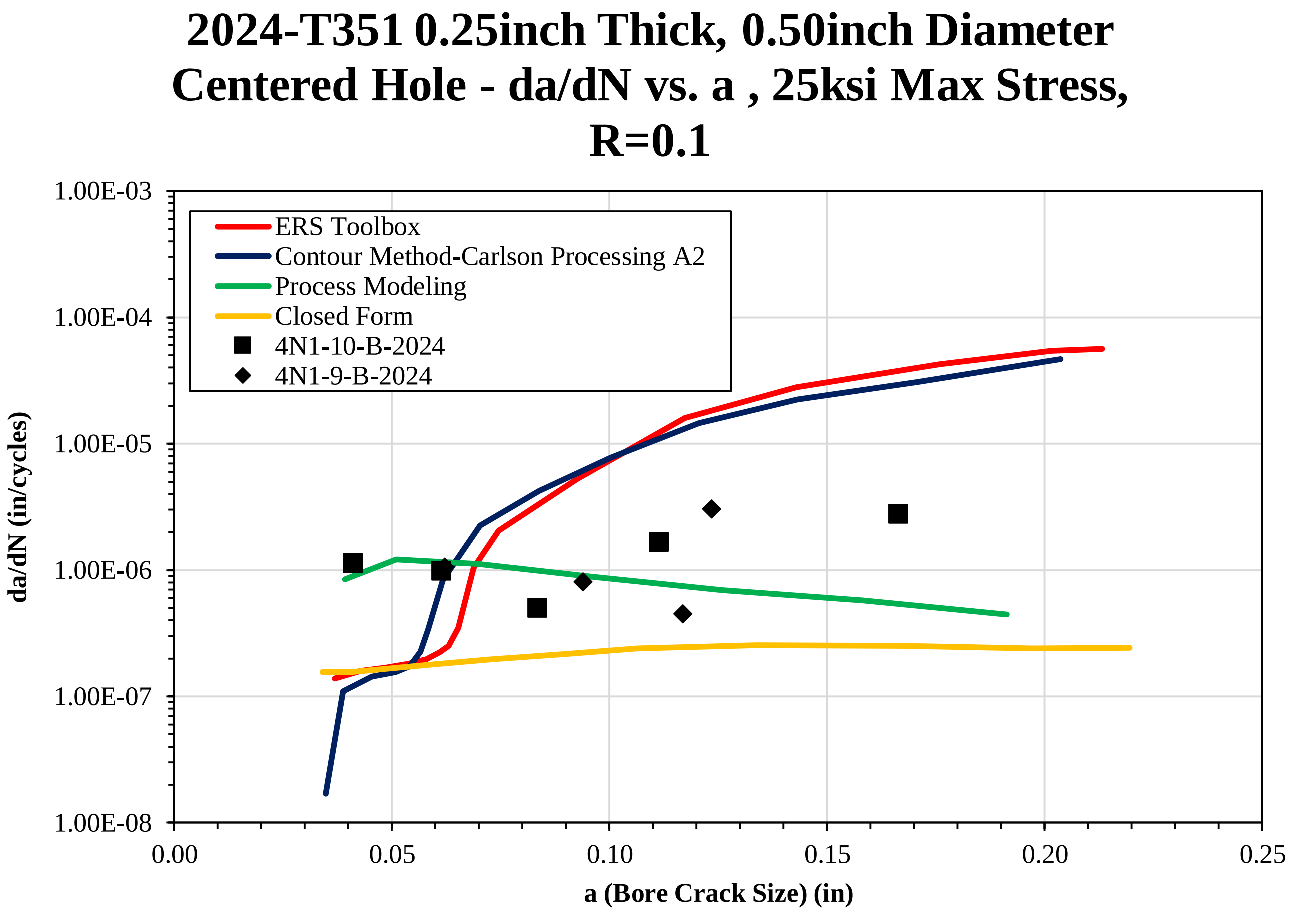
- Life Predictions with Assessed Residual Stress Fields

Residual Stress Input	Life Predicted	Test Life Avg.
0.005x0.005 IFS Assumption	10,900	160,000
Contour Method	275,500	
Eigenstrain	201,000	
Process Simulation	1,017,000	
Closed Form	1,102,000	



BAMF Predictions





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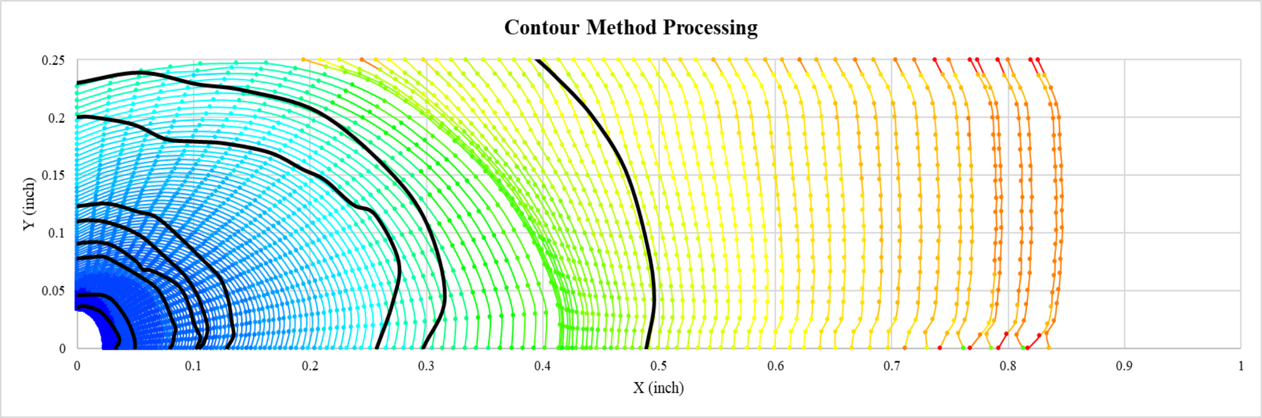
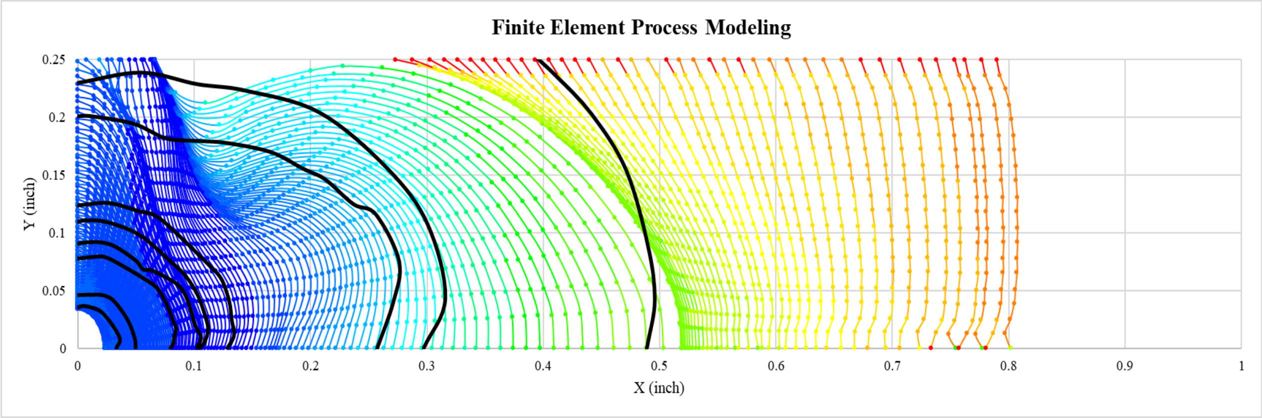
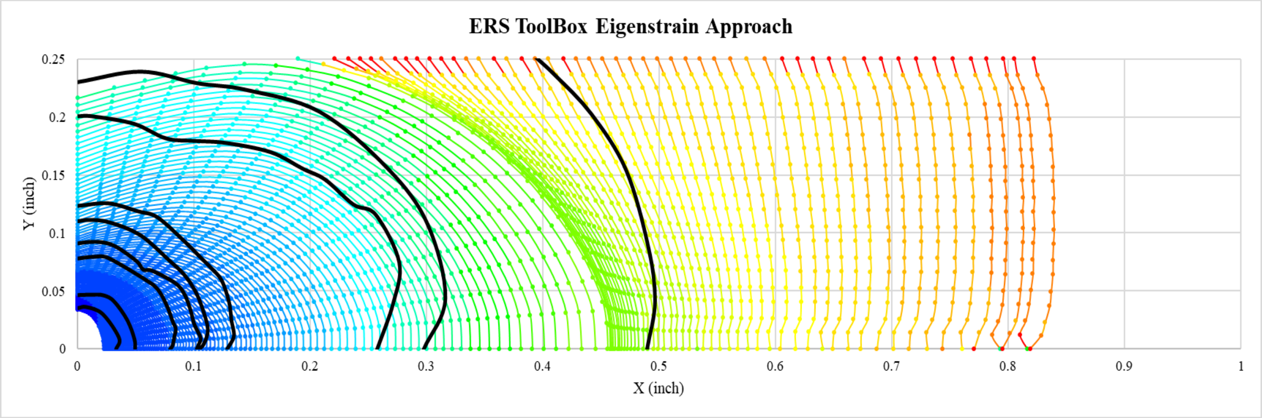
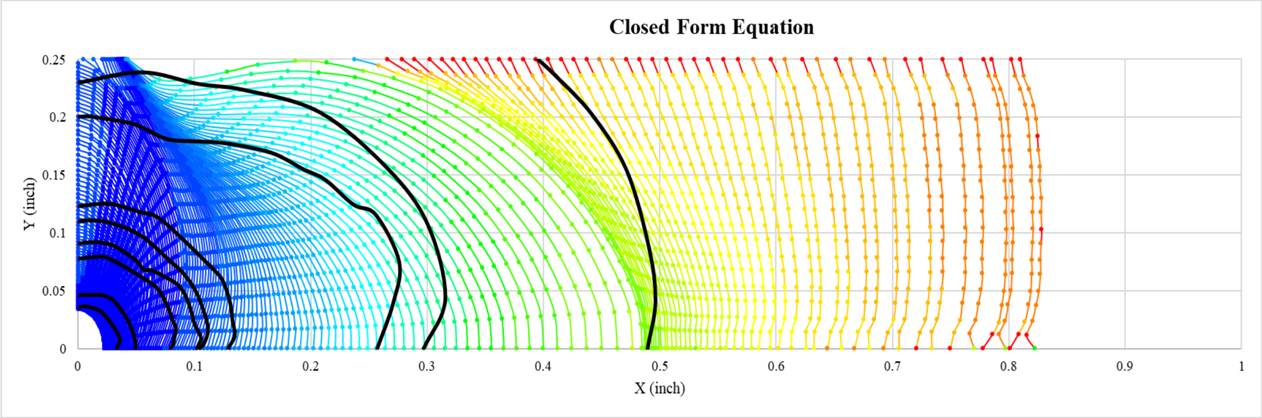
BAMF Predictions

- Predictions of Fatigue Crack Growth Shape vs. Test Marker Bands









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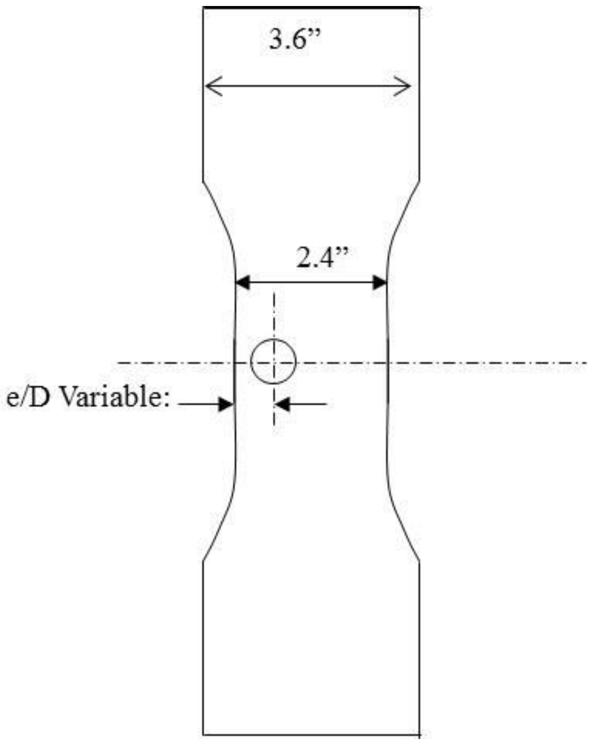
Phase II – ”Short” Edge Margin Hole

- Phase II
  - Move from a “centered” hole to a “short” edge margin hole (e/D = 1.8)
  - Material = 2024-T351
    - Thickness = 0.314inch
    - Final hole diameter = 0.375inch
  - Down select residual stress input from Phase I
    - Contour method
    - Eigenstrain-based ERS Toolbox®
  - Fatigue testing performed for condition via RIF Report[5]
    - Max stress = 22ksi
    - Stress ratio (R) = 0.1
    - Marker banding sequence = 15% overload
  - Perform crack growth prediction using BAMF and LM crack growth code



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References

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2. Kunnavakkam, R., Hitchman, K., (2017), Cold Expansion Process Modeling and Lessons Learned, Proceedings of the 2017 HOLSIP Workshop, Salt Lake City, UT, USA.
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Multi-Directional Material Properties

- Background
  - Inability to predict corner crack aspect ratio behavior has prompted recent interest to characterize FCG material properties in different orientations
  - SwRI has been generating data for the past few years
  - Analysis tools must be capably of handling FCG material properties in different orientations
- Approach
  - Incorporate multi-directional material property capability into multi-point fracture mechanics analyses (BAMF)
  - Develop routines (initial investigation) to interpolate between different directions
  - Evaluate new capability with comparisons to benchmarks

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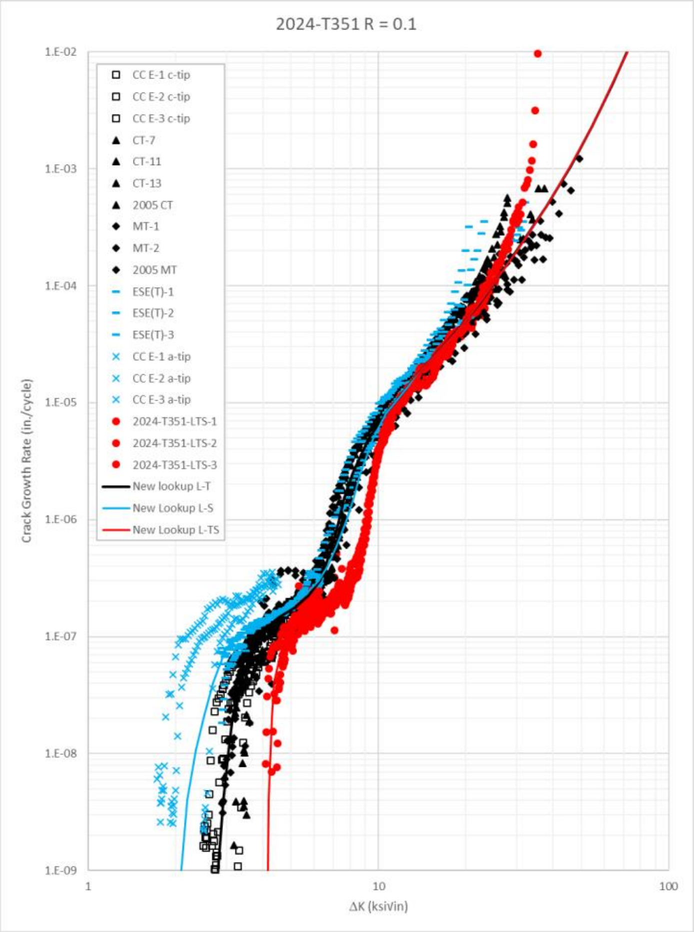
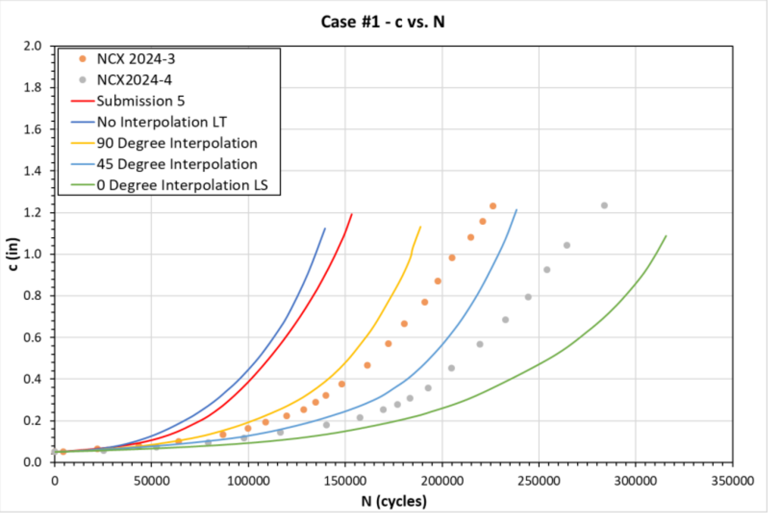
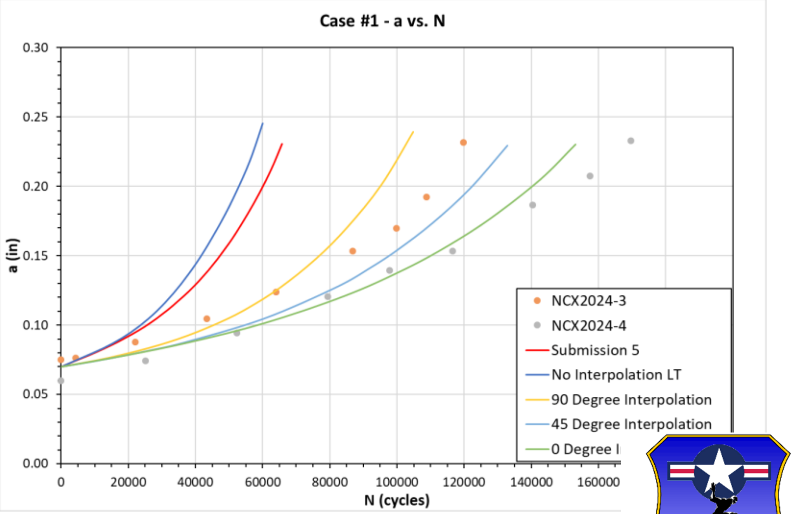
Multi-Directional Material Properties

- Results
  - Baseline analyses w/o Cx
    - AFGROW and ERSI Round Robins
  - Improved a/c trends
  - Mixed impacts for life prediction
- Next Steps
  - Investigate interpolation routines
  - Continue investigating and developing test data
  - New capability in upcoming release of BAMF







We're learning as we go…

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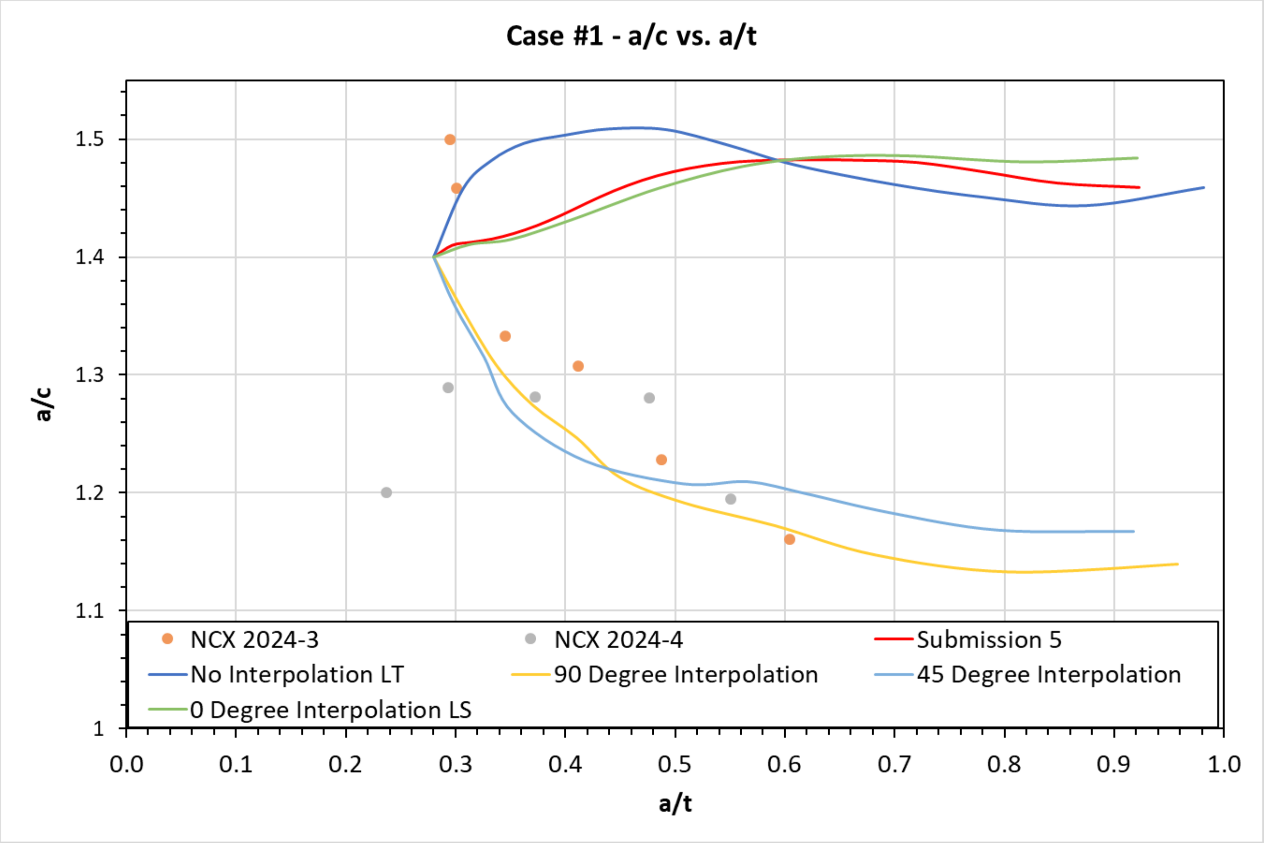
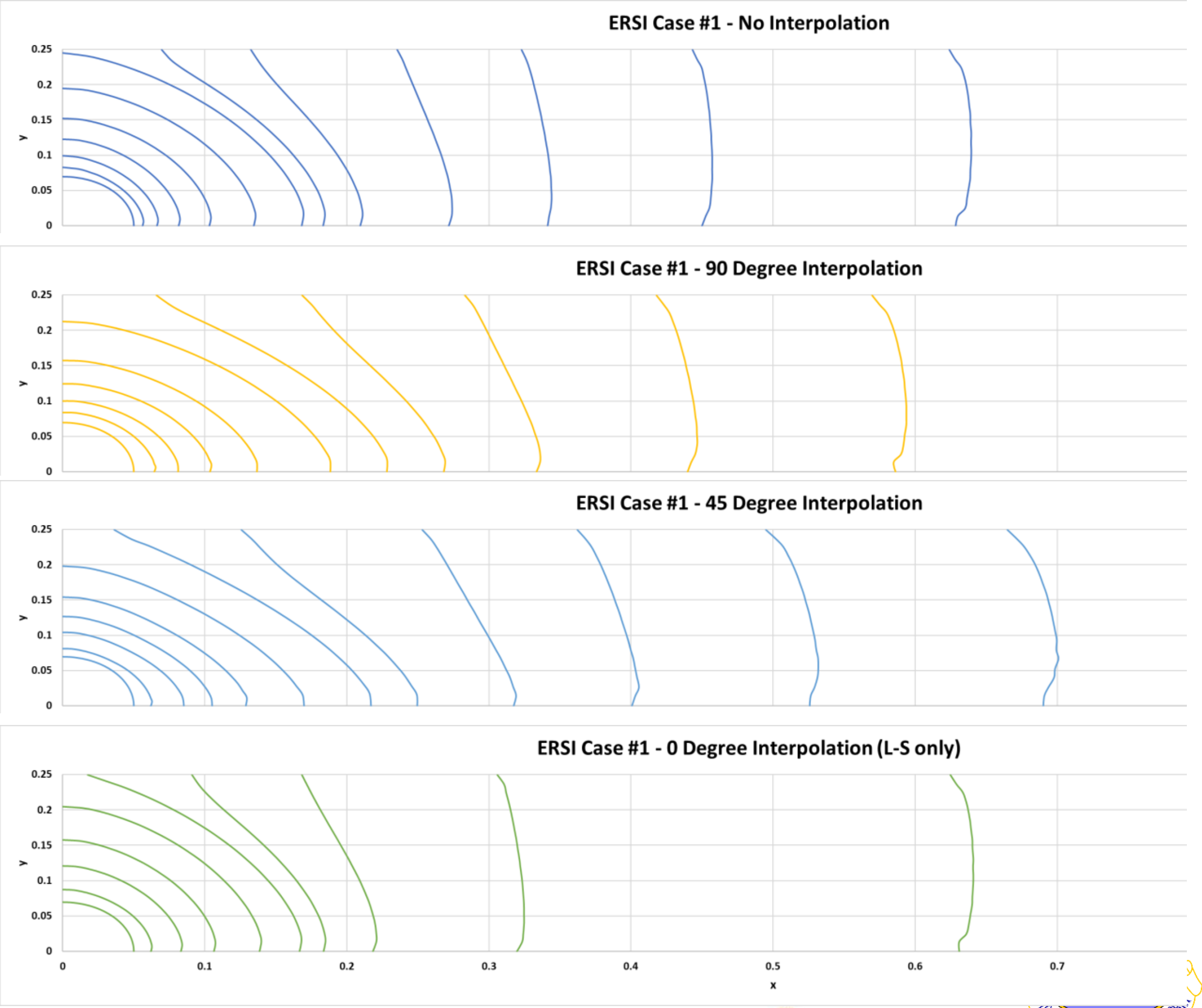
Multi-Directional Material Properties

- Results





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Closure Modeling

Seeking to understand and better model crack growth behavior at CX holes

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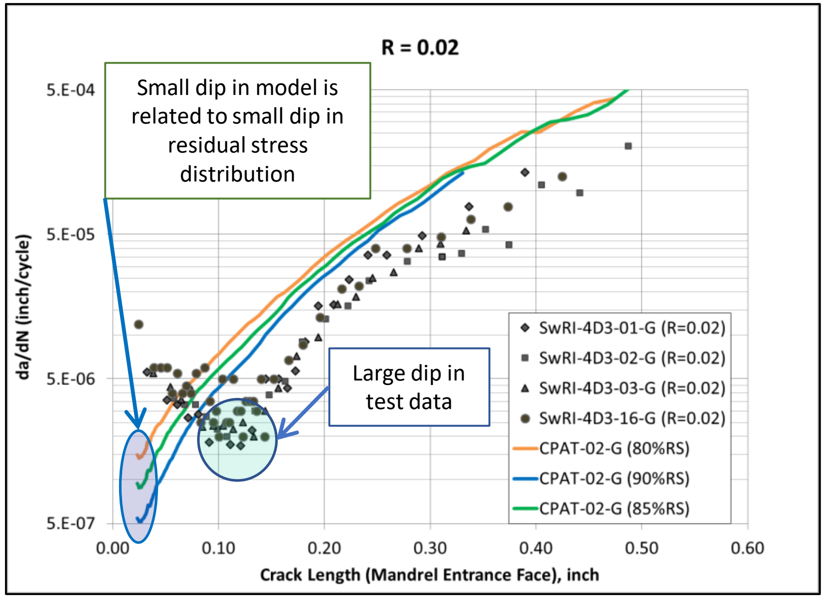
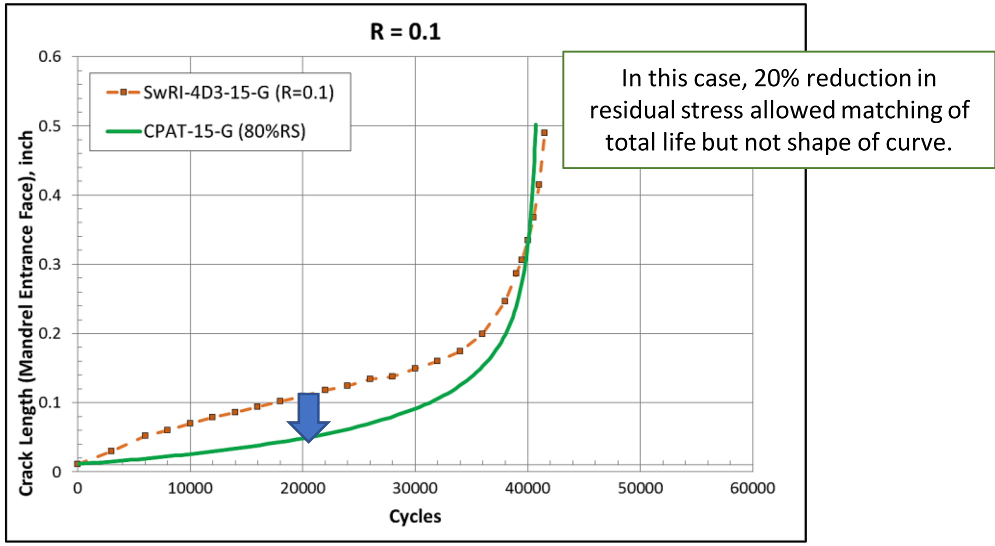
Refresher from 2018: Key Observations

- 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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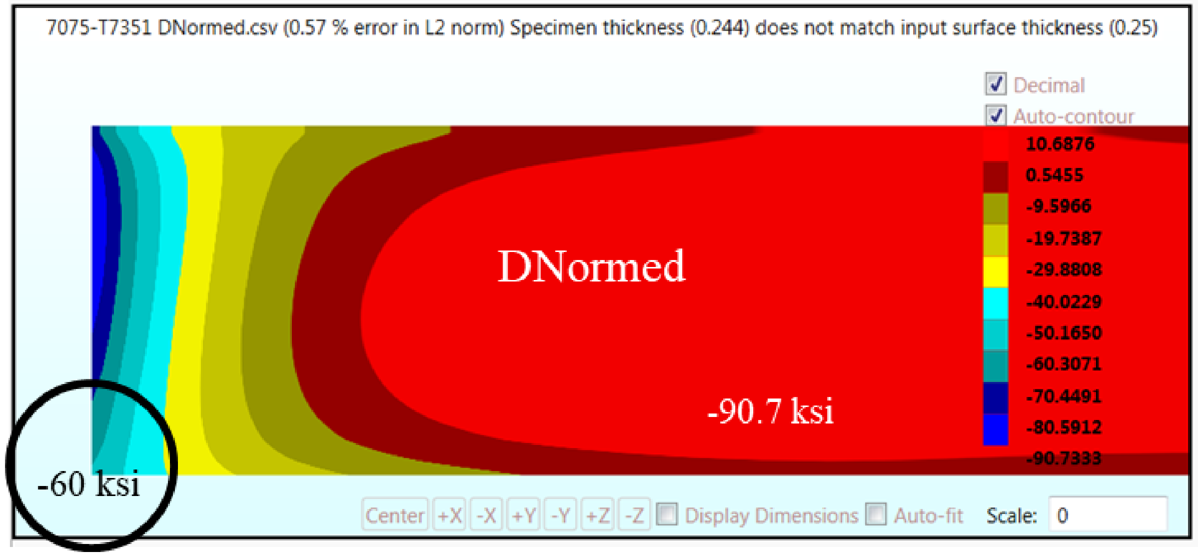
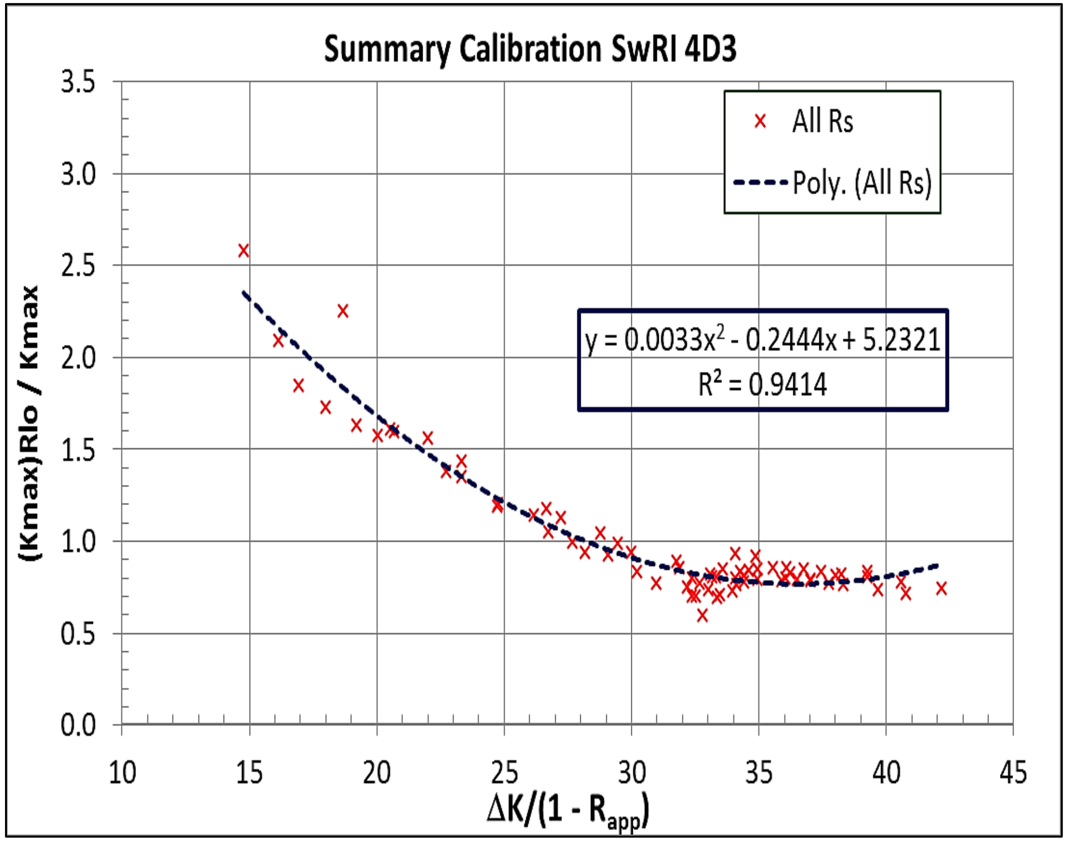
Data Analysis

- Calibration
  - Empirical study showed that Kmax as much as 2.5x higher than calculated was needed to correlate with early crack growth rates
  - Deeply negative RS





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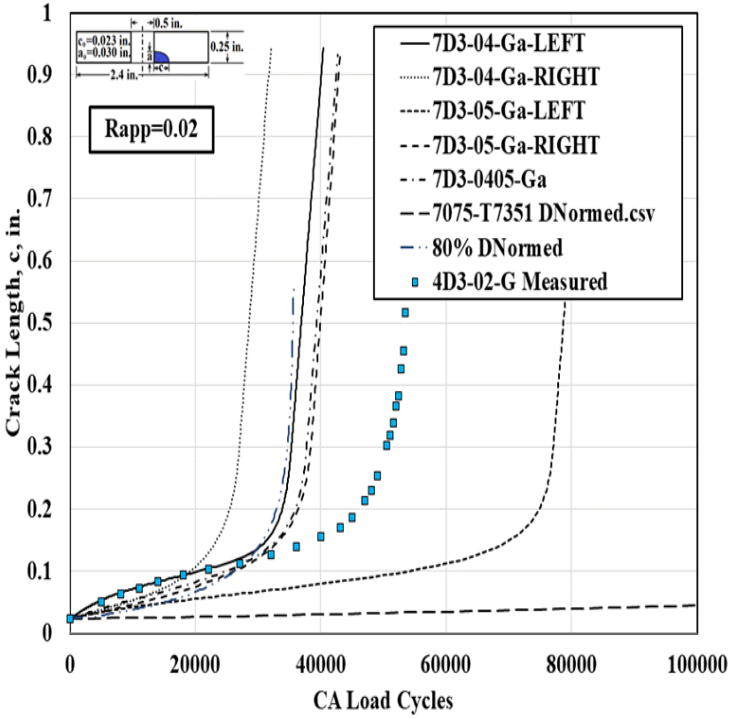
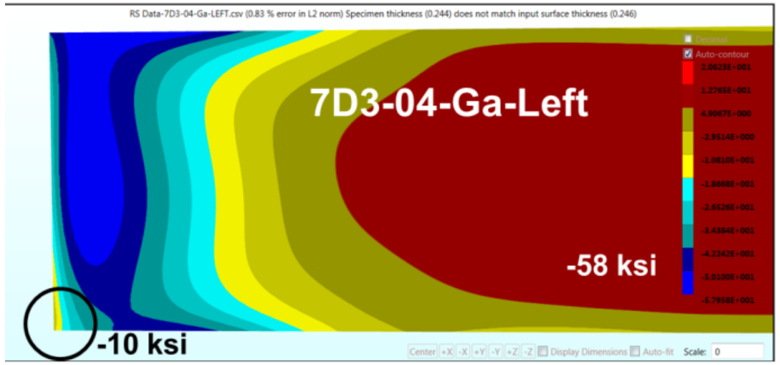
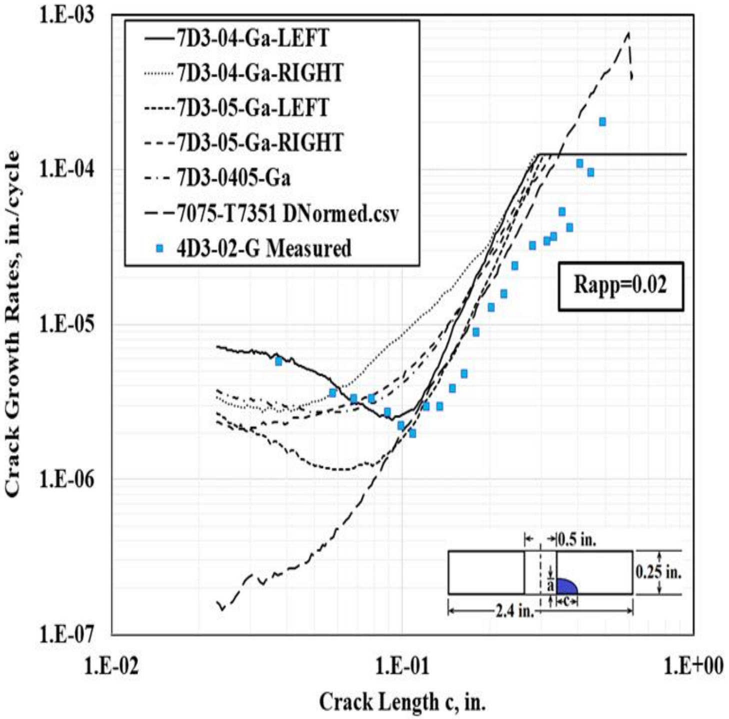
Redistributed Residual Stress Leads to Improved Modeling

- 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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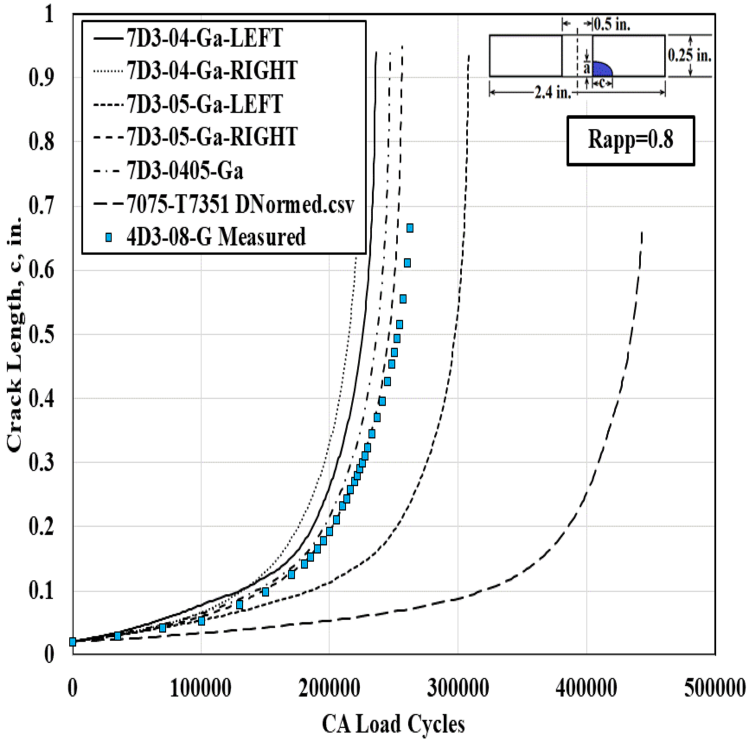
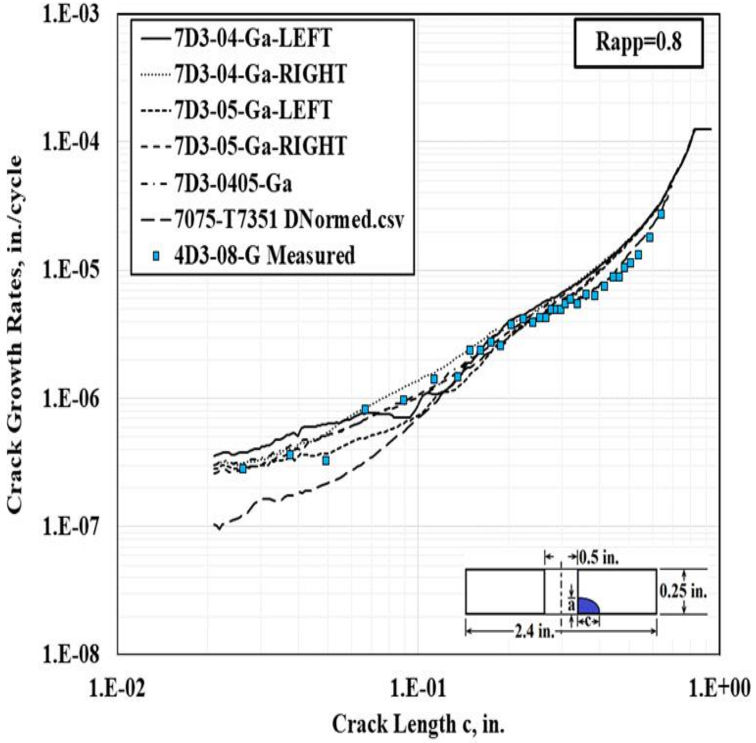
Redistributed Residual Stress Leads to Improved Modeling

- Same RS Correlates Well at $R_{app} = 0.8$ ($R_{tot} > 0$)
  - No dip in da/dN test data when $R_{tot} > 0$
  - New RS captures this behavior as well





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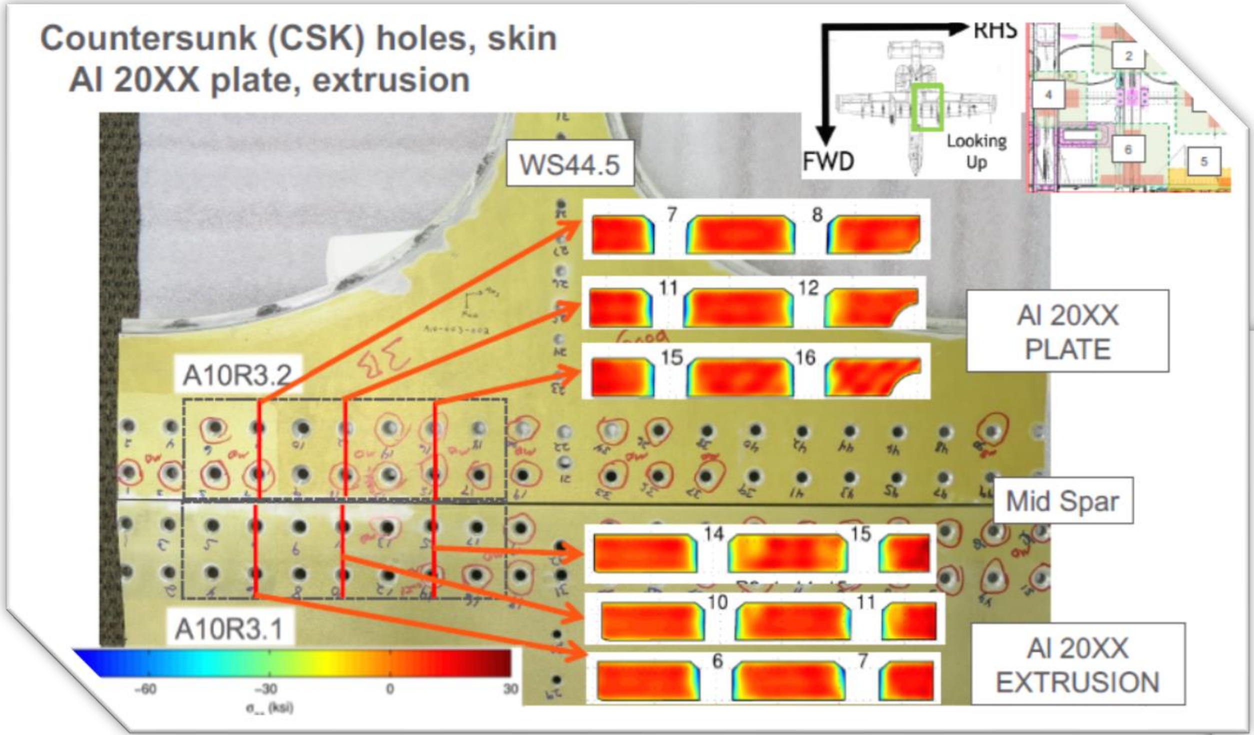
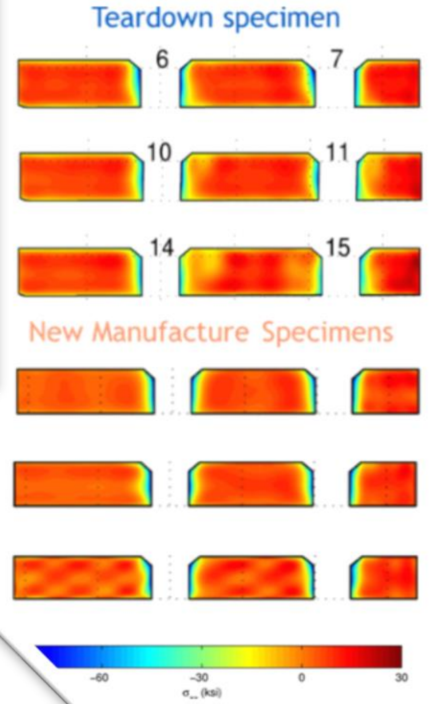
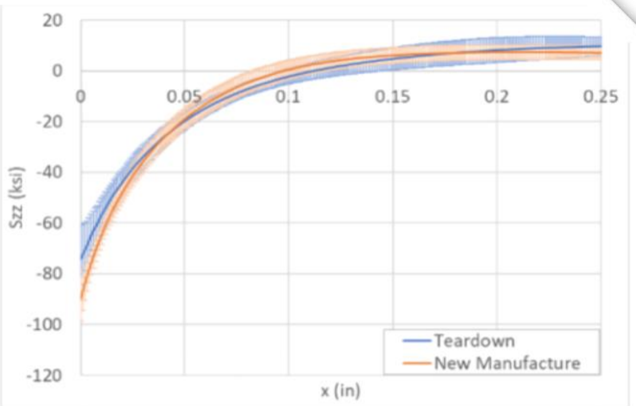
Residual Stress Shakedown

- Why is the behavior not evident in teardown assets?

HILL ENGINEERING
Predict. Test. Perform.







Sample ID	Midthickness 0.125*rad (ksi)	Midthickness 0.25*rad (ksi)	Midthickness 0.5*rad (ksi)	Midthickness 0.75*rad (ksi)	Depth at crossover (midthickness) (in)	Point Value of Entrance (ksi)	Avg RS in 0.05" Radius Entrance (ksi)	Point Value CSK Knee (ksi)	Avg RS in 0.05" Radius CSK knee (ksi)
Mean	-47.15	-31.04	-12.29	-2.60	0.13	-51.30	-34.67	-77.92	-44.59
Stdev	5.17	4.10	2.71	2.99	0.04	21.61	6.68	16.67	10.37
Mean	-52.82	-32.95	-10.82	-0.19	0.10	-49.72	-31.57	-98.82	-55.33
Stdev	3.68	3.91	3.91	3.65	0.02	21.46	3.05	14.72	2.64
Residuals (Td-NM)	5.68	1.91	-1.46	-2.42	0.03	-1.58	-3.09	20.90	10.74
P Value	0.00	0.13	0.15	0.05	0.02	0.43	0.08	0.00	0.00
Significant	Yes	No	No	Yes	Yes	No	No	Yes	Yes

Filled Hole Effects?

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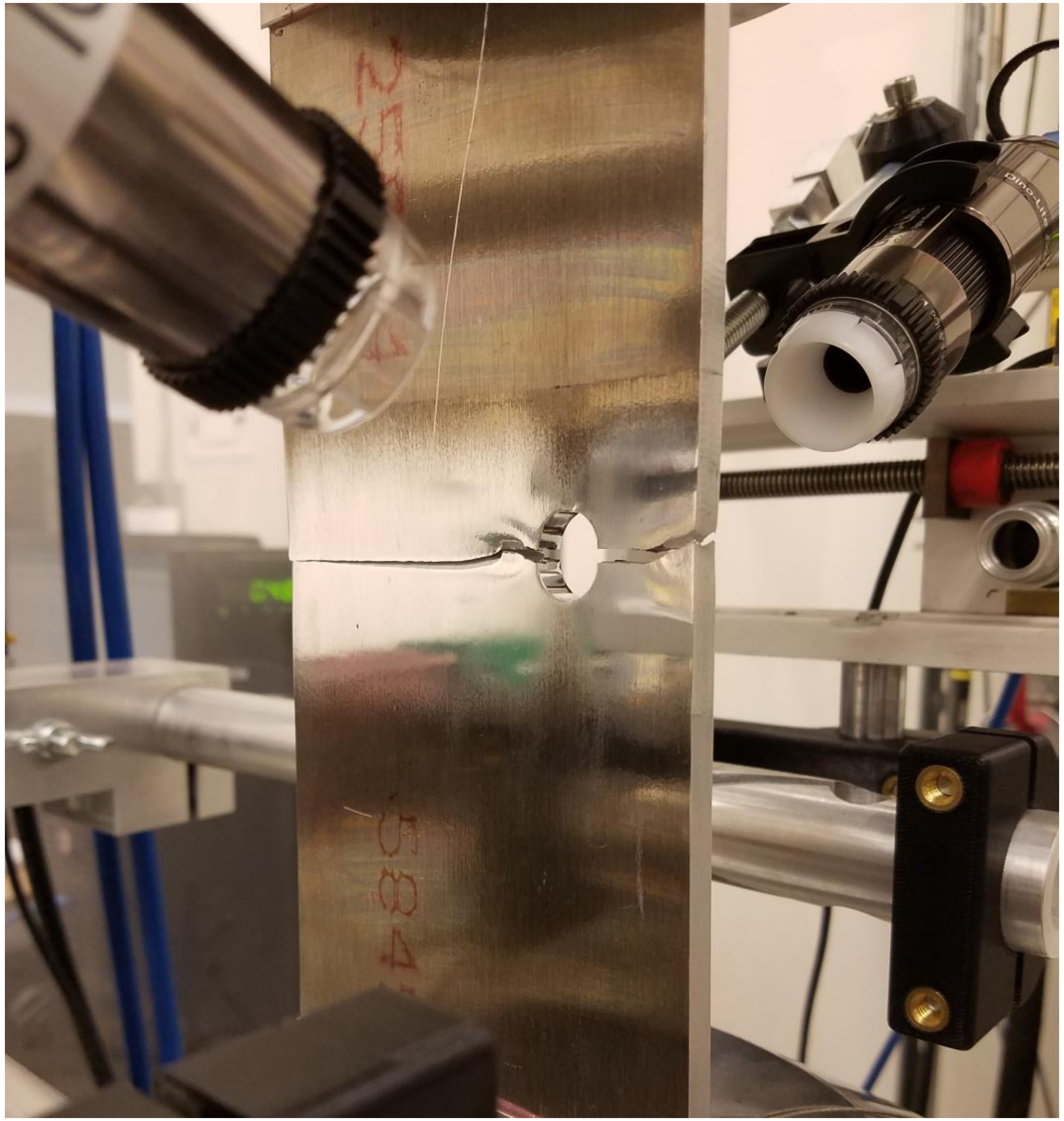
Residual Stress Shakedown

- Next Steps
  - Complete initial investigate for standard configurations
- Approach
  - Investigate differences between:
    - non-cycled coupons (utilize existing data)
    - open hole cycled coupons
    - filled hole cycled coupons
- Scope
  - Coupon configurations (12 total)
  - Material: 2024-T351 and 7075-T651
  - Diameter: 0.50-inch
  - Hole Offset: centered
  - Thickness: 0.25-inch
  - Applied expansion: mean

Swift, Taylor. (2014), "Shake It Off"

Crack Closure Imaging

- Objective
  - Capture images of cracks at CX holes
  - Determine stress level required to open crack
  - May be useful for validating closure models
- Approach
  - Digital microscope controlled by test software
  - Periodically stepped stress from 0 to 33ksi at 3.3ksi (10%) increments
  - Captured image at each stress level
  - Visually determine if crack is open



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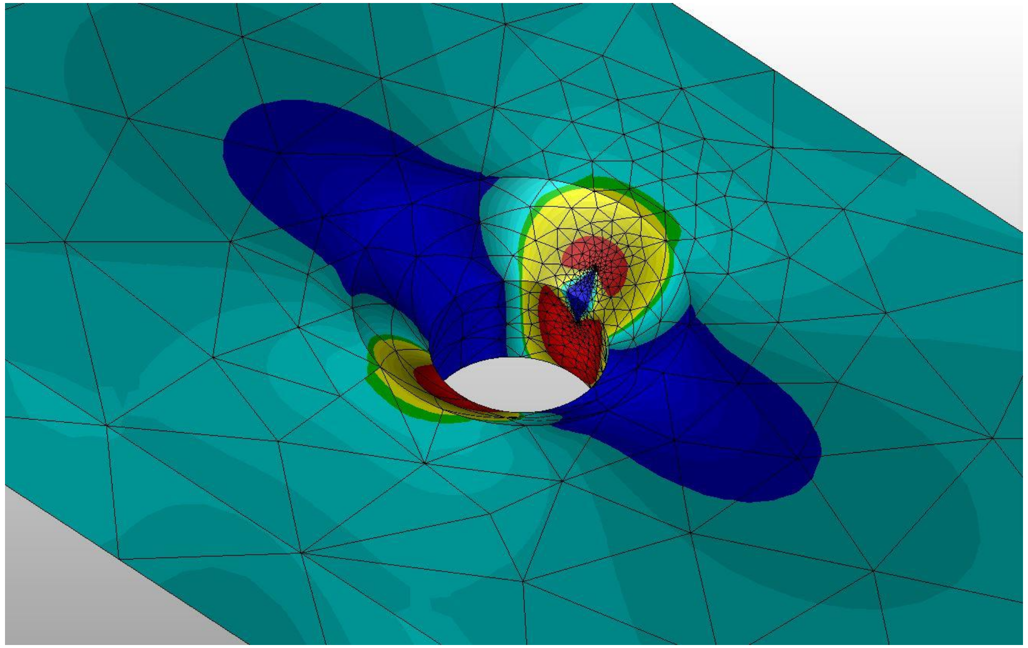
Notch Plasticity

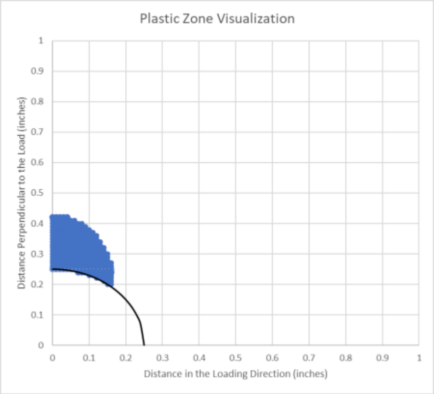
- Objective
  - Investigate the notch plasticity and size of plastic zone at a non-Cx and Cx fastener hole
  - Answer question:
    - Does notch plasticity impact Cx residual stress locally at the hole?
- Approach
  - Investigate handbook solutions
  - Compare/contrast to linear and non-linear FEA
  - Investigate open and filled hole configurations
  - Build macros and plots to compare results

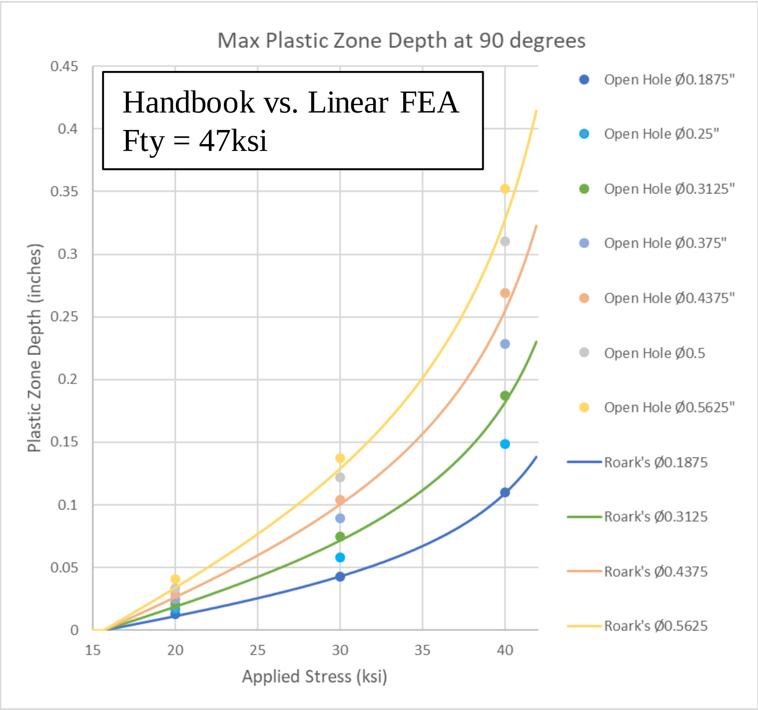


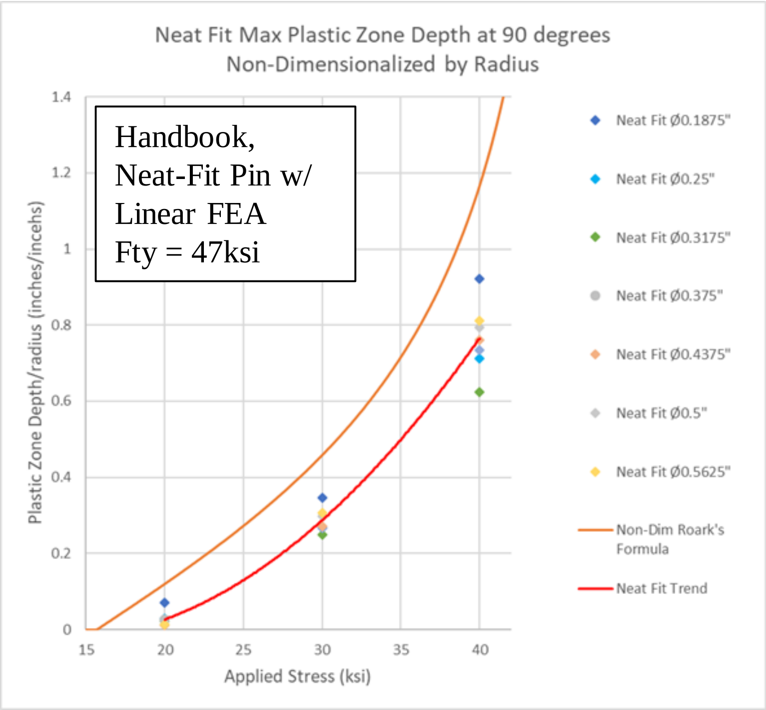
Notch Plasticity

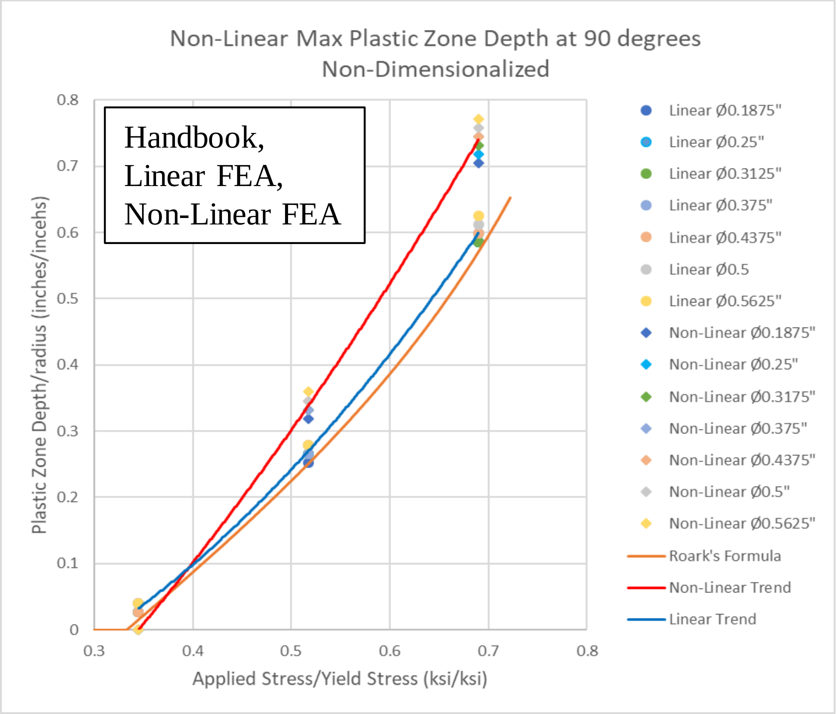
- Handbook Solutions
  - Roark's Formulas for Stress and Strain, 7th edition
  - Linear Elastic solution
- FEA
  - Linear and non-linear predictions

$$\sigma_\theta = \frac{\sigma}{2}\left[1 + \frac{a^2}{r^2} - \left(1 + 3\frac{a^4}{r^4}\right)\cos 2\theta\right]$$





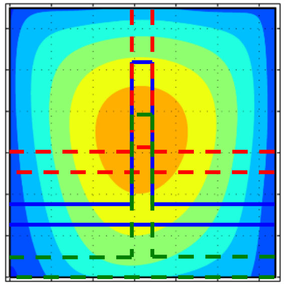




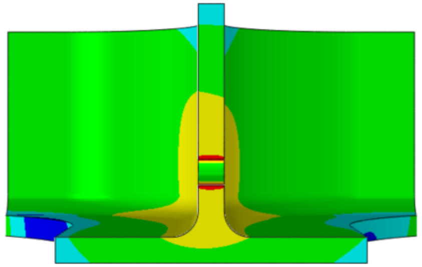
FCG in Coupons with Quench Residual Stress

- 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
- 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?

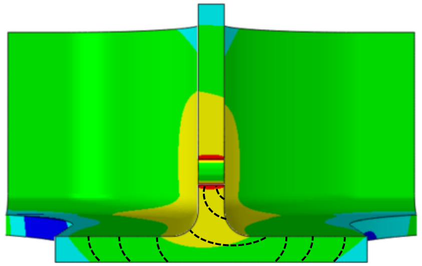
Renan L. Ribeiro, UC Davis



Measure RS in Raw Product Form



Predict RS in Part Cut from Raw Product Form



Predict Fatigue Performance Including RS

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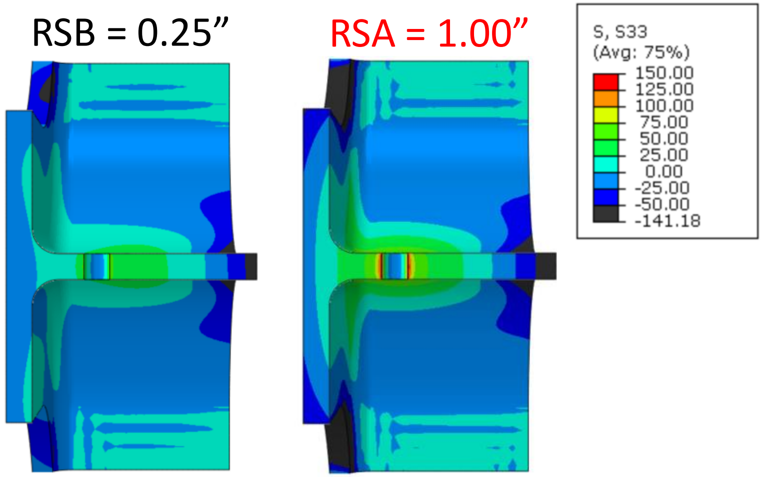
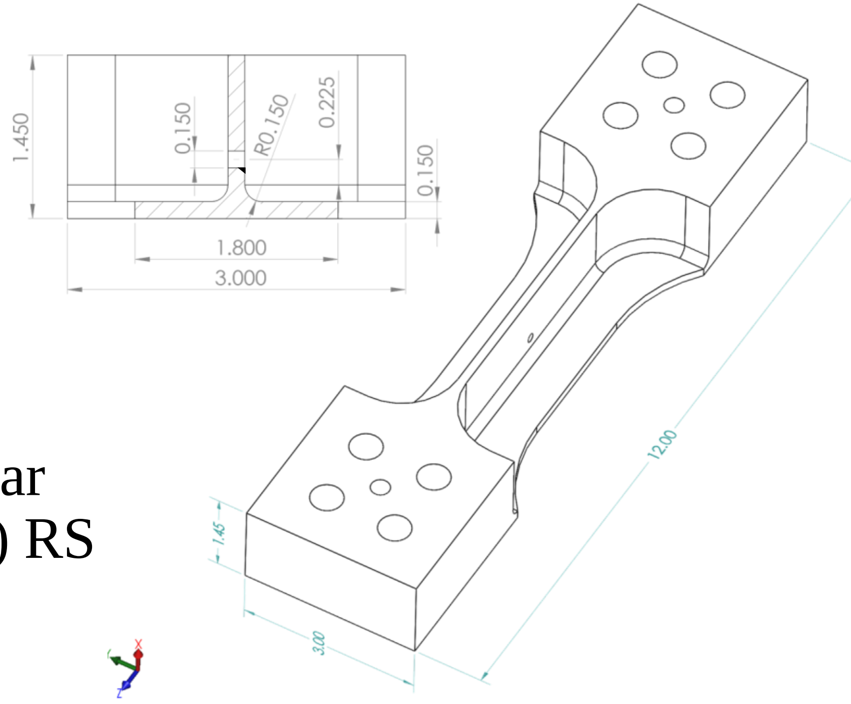
FCG in Coupons with Quench Residual Stress

- Coupon Design and Conditions
  - Geometry shown below (representative of airframe detail)
  - Produced coupons in 3 conditions:
    - RS0: low RS cut from AA7050 T7451 (stretched)
    - RSA: high RS, cut from AA7050 T74 (quenched)
    - RSB: moderate RS, cut from AA7050 T74 (quenched)
  - Corner crack starter milled at the edge of hole
    - Crack grows towards the base flange
- Residual Stress Prediction (eigenstrain)
  - Predict RS for coupons removed from different locations within bar
  - Chose two locations that provide moderate (RSB) and high (RSA) RS

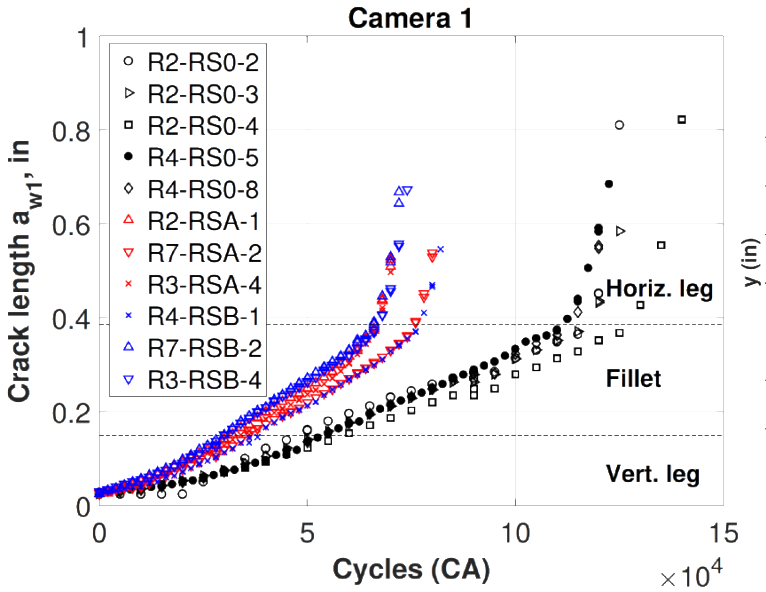


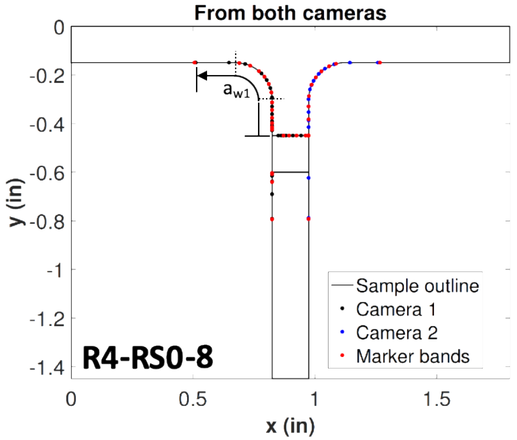


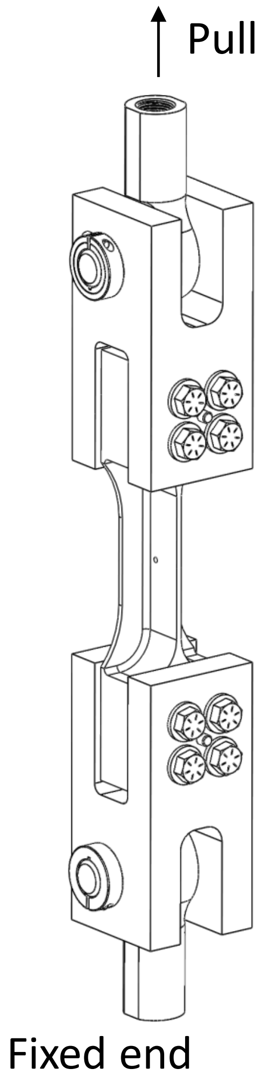
All dimensions in inches

FCG in Coupons with Quench Residual Stress

- Fatigue Crack Growth Testing
  - Test in pull-pull configuration, constant amplitude (CA) loading, R = 0.1
    - Fixture provides consistent load, known restraint
  - Monitor crack growth using three techniques
    - Direct Current Potential Drop (DCPD)
    - Digital photogrammetry (DP)
    - Quantitative fractography (QF), also called marker banding
      - Number of marker bands 13 to 41 per sample







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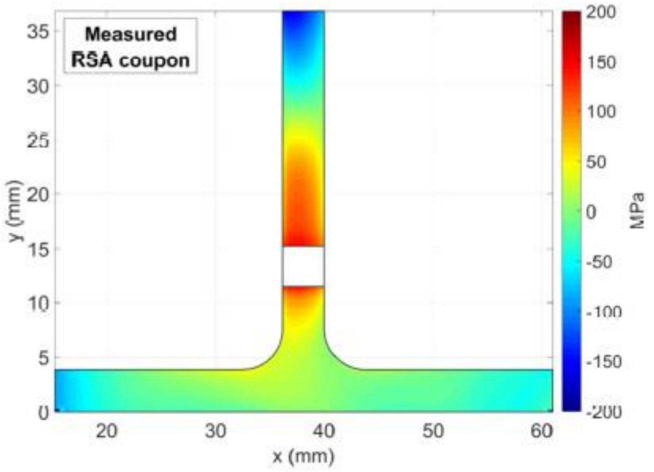
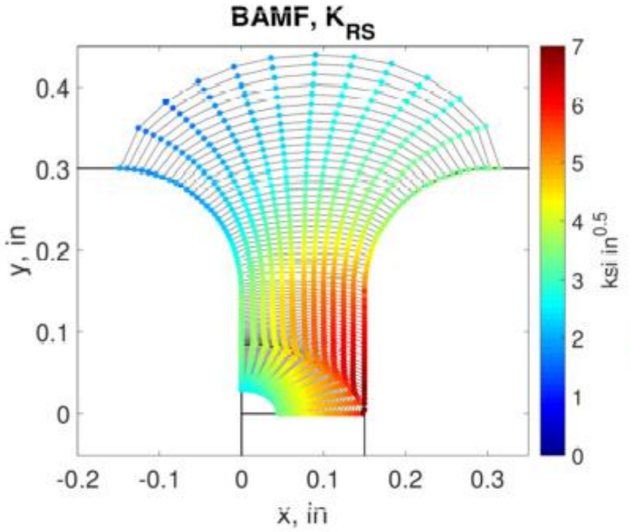
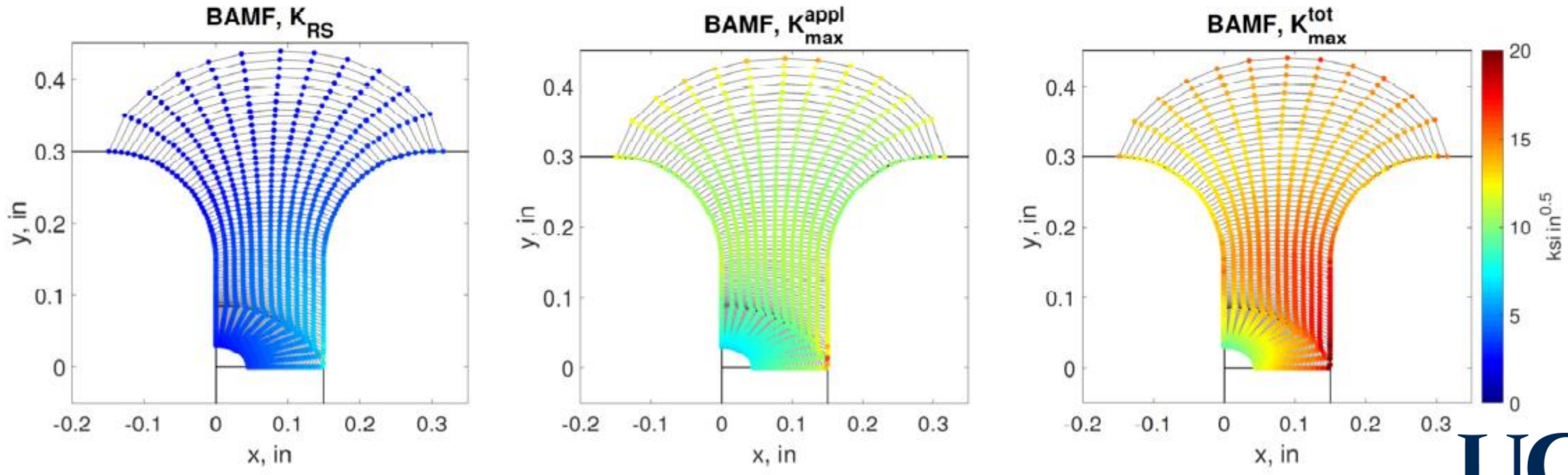
FCG in Coupons with Quench Residual Stress

- Fatigue Crack Growth Predictions



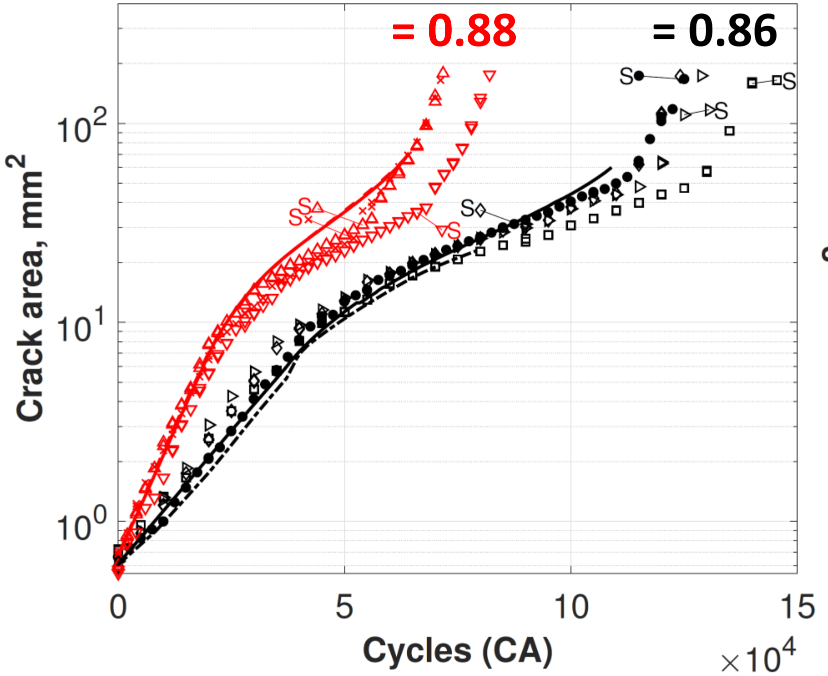


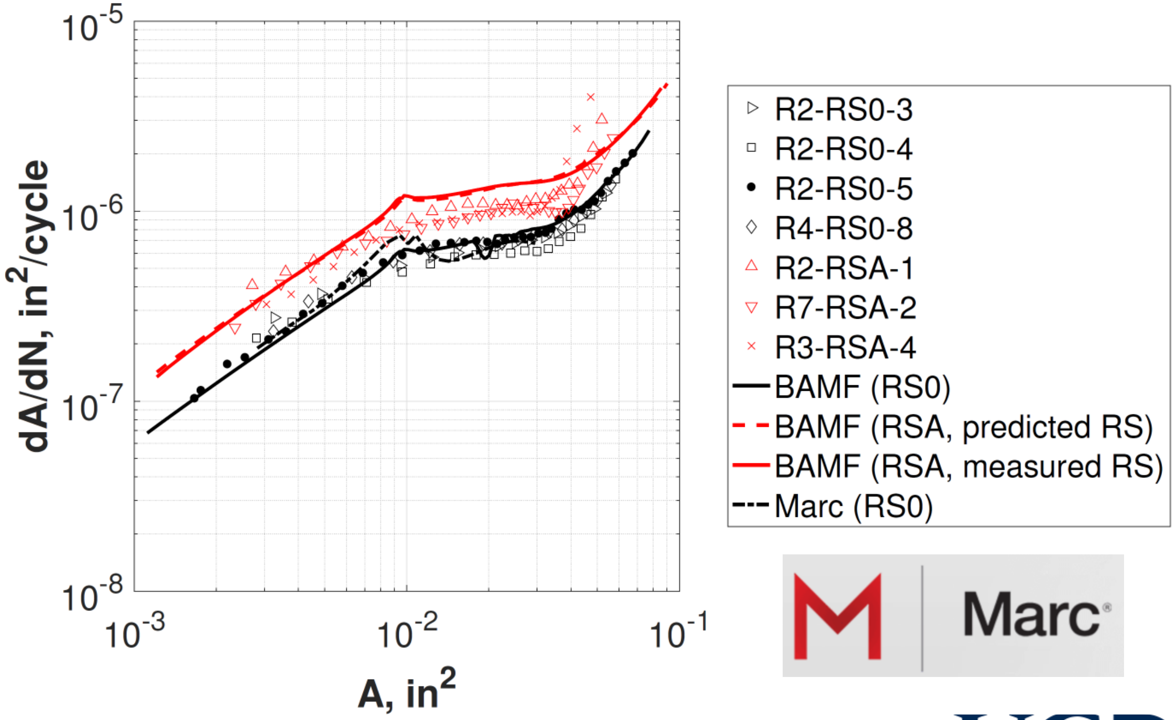


FCG in Coupons with Quench Residual Stress

- Fatigue Crack Growth Validation
  - Comparisons of MPFM model and test data below
  - Overall, crack growth is predicted accurately
    - Ignoring RS for the RSA condition is non-conservative at about 1.5X

RSA Pred/Test = 0.88 **RS0 Pred/Test = 0.86**





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Marc

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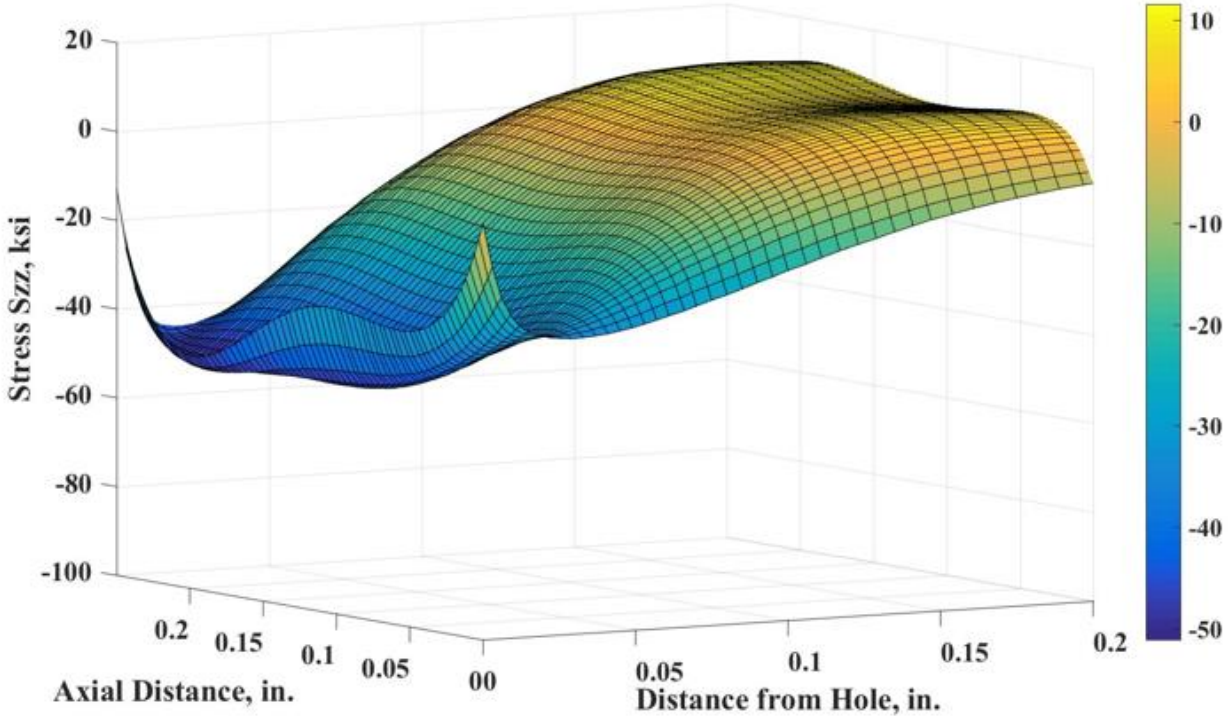
Fatigue Life Variability

- Background
  - Investigate sensitivity of fatigue life prediction with varying interference levels and replicates
- Specimen Geometry
  - 2024-T351,
  - 0.25 inch thick,
  - 0.5 inch hole
  - e/D = 4
- Three different interference levels
  - Low CX = 3.16% (5 specimens – 10 replicates)
  - Mid CX = 3.67% (5 specimens – 10 replicates)
  - High CX = 4.16% (3 specimens – 6 replicates)



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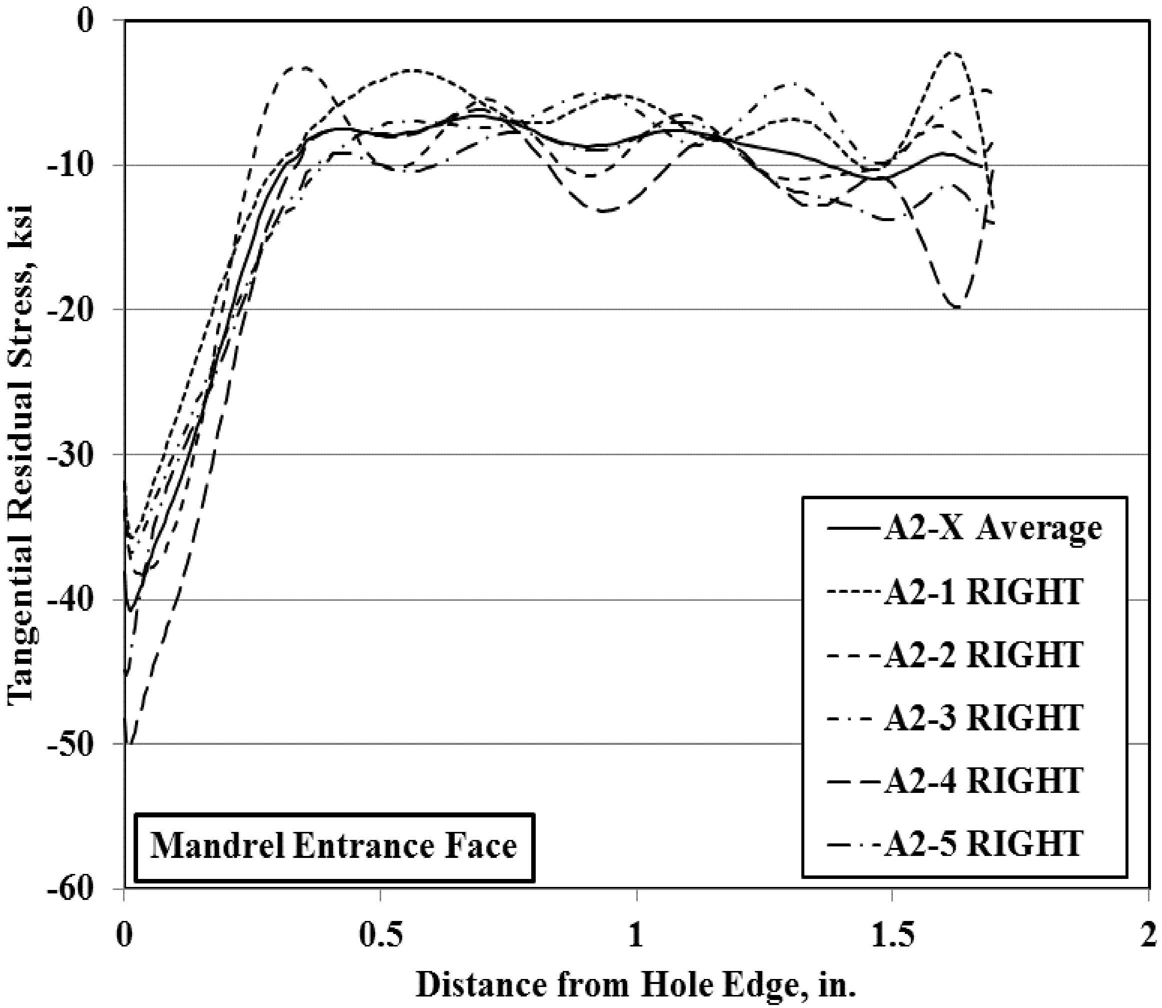
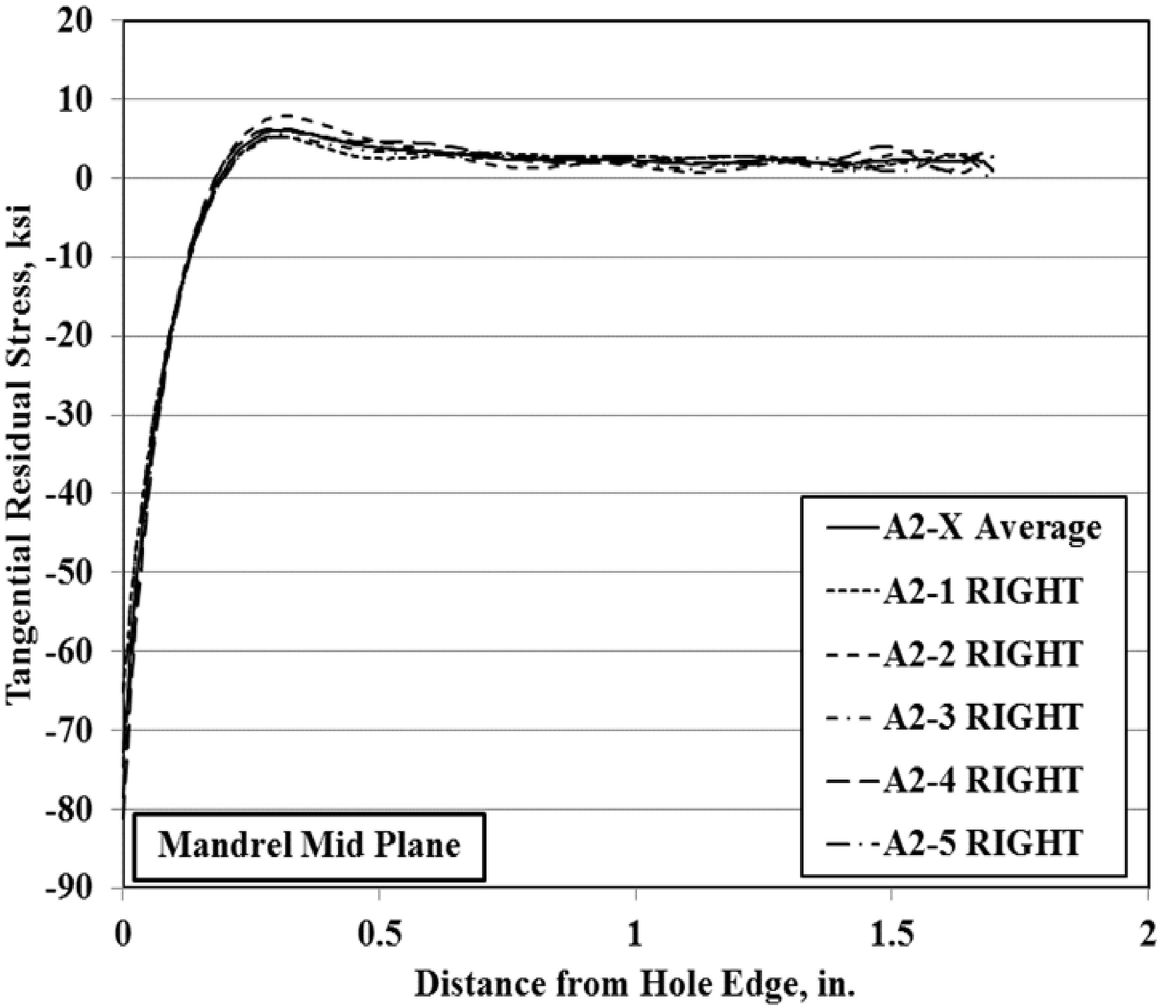
Fatigue Life Variability





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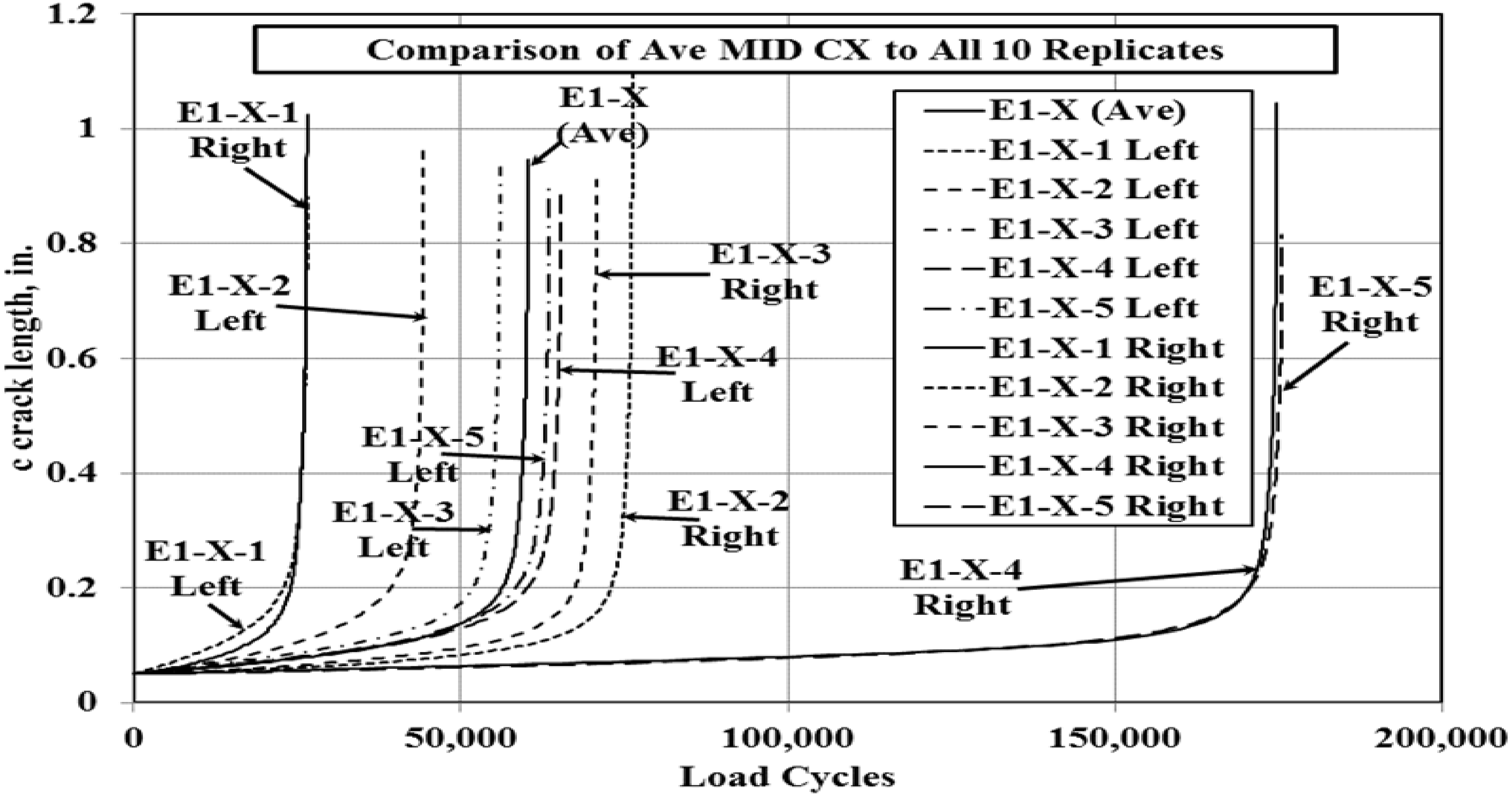
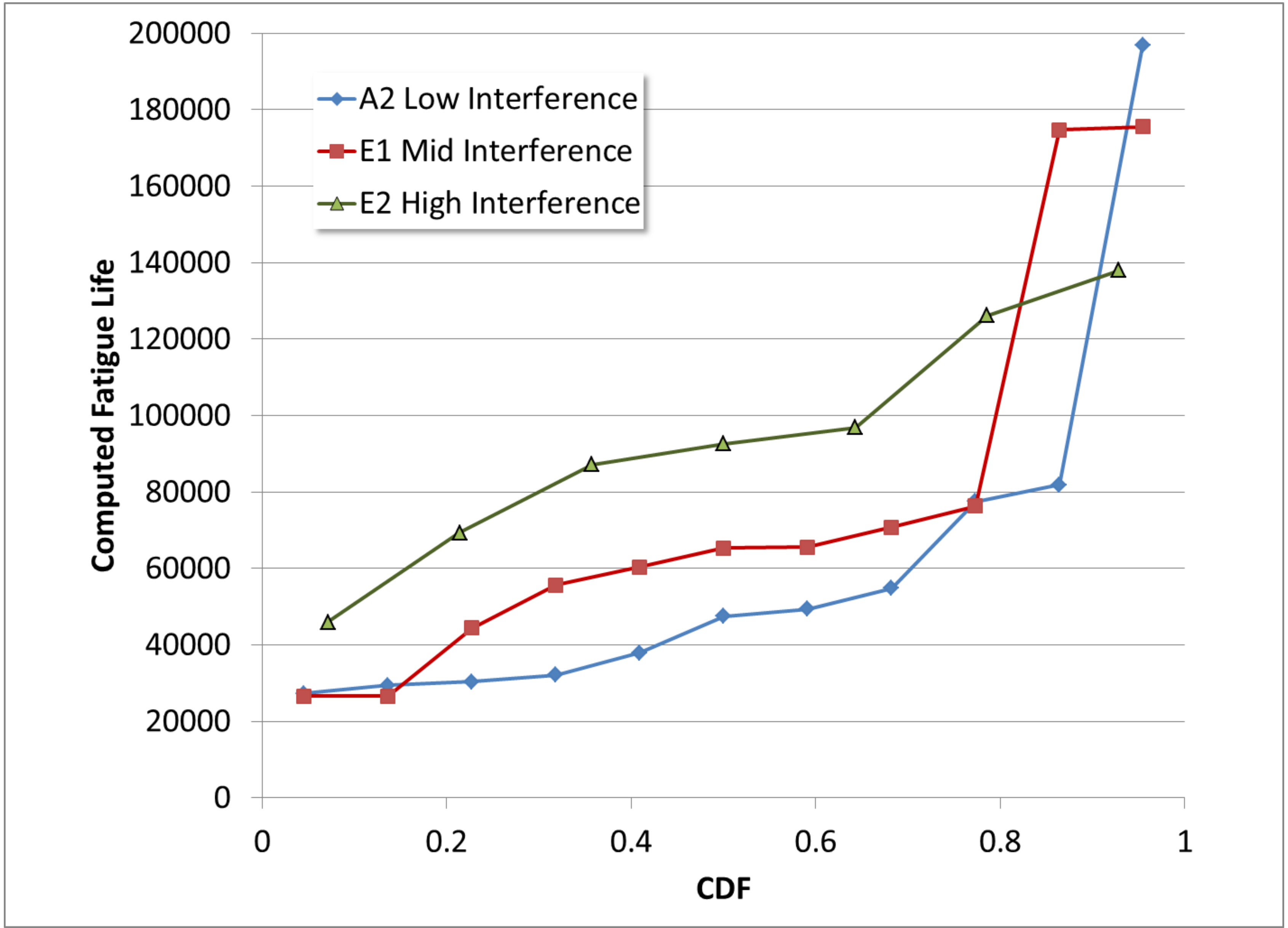
Fatigue Life Variability



Fatigue Life Variability

- Computed lives segregate as expected in the middle of the distributions.
- However, some curves cross at the extremes.
- Ratio of 7.5 Max/Min Life Computed in A2 data set



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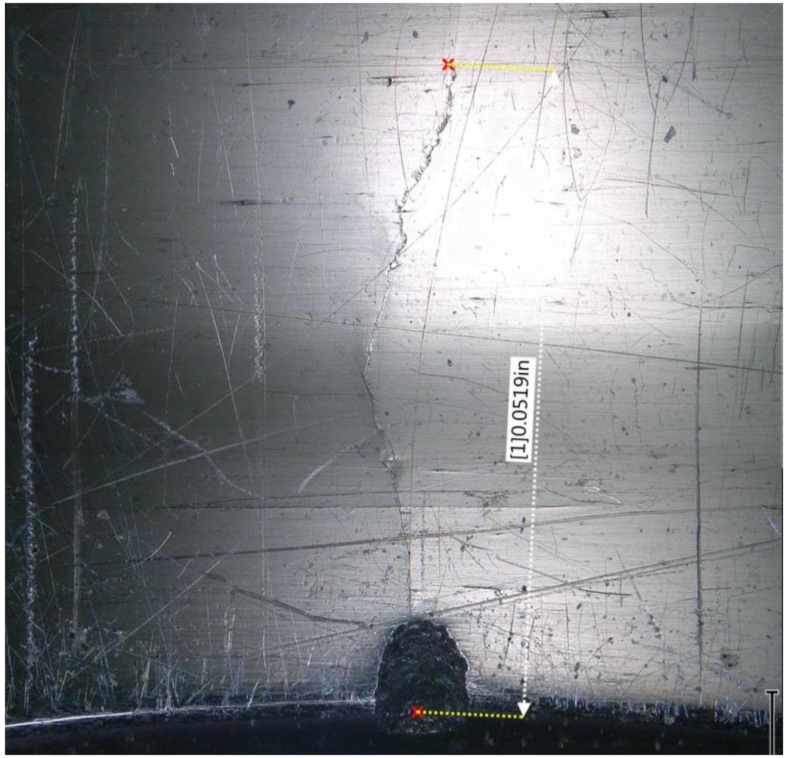
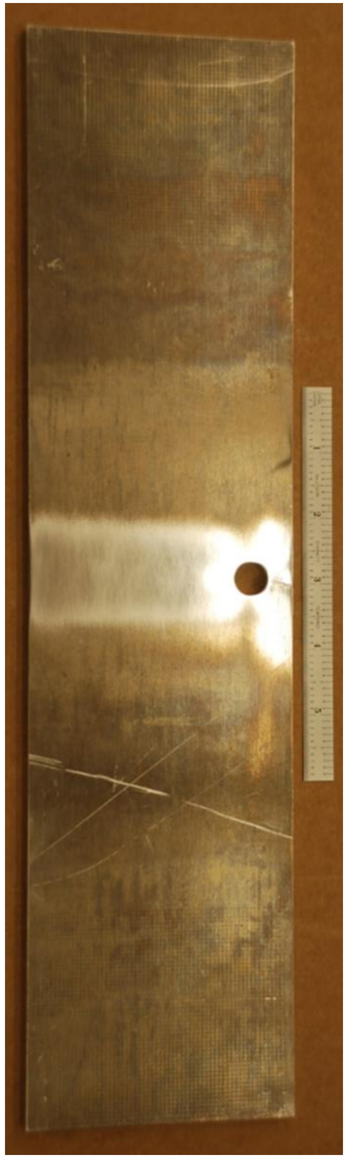
Validation Testing

Short Edge Margin Testing

- Objectives
  - Evaluating reduced IFS (0.005”) for short e/D (≤ 2.0)
  - 0.005” is unconservative for 1.2 e/D, 33 ksi max stress (Dallen Andrew)
  - When does 0.005” become unconservative?
  - Is explicitly modeling residual stress in BAMF conservative?
- Approach
  - e/D Tested:1.3, 1.4, 1.5, 2.0
  - 2024-T351 Aluminum
  - 0.05” precrack before CX
  - 33 ksi max stress spectrum
  - Compared tests to 0.005” IFS AFGROW
  - Compared tests to 0.05” BAMF
    - Residual Stress Toolbox (blind)





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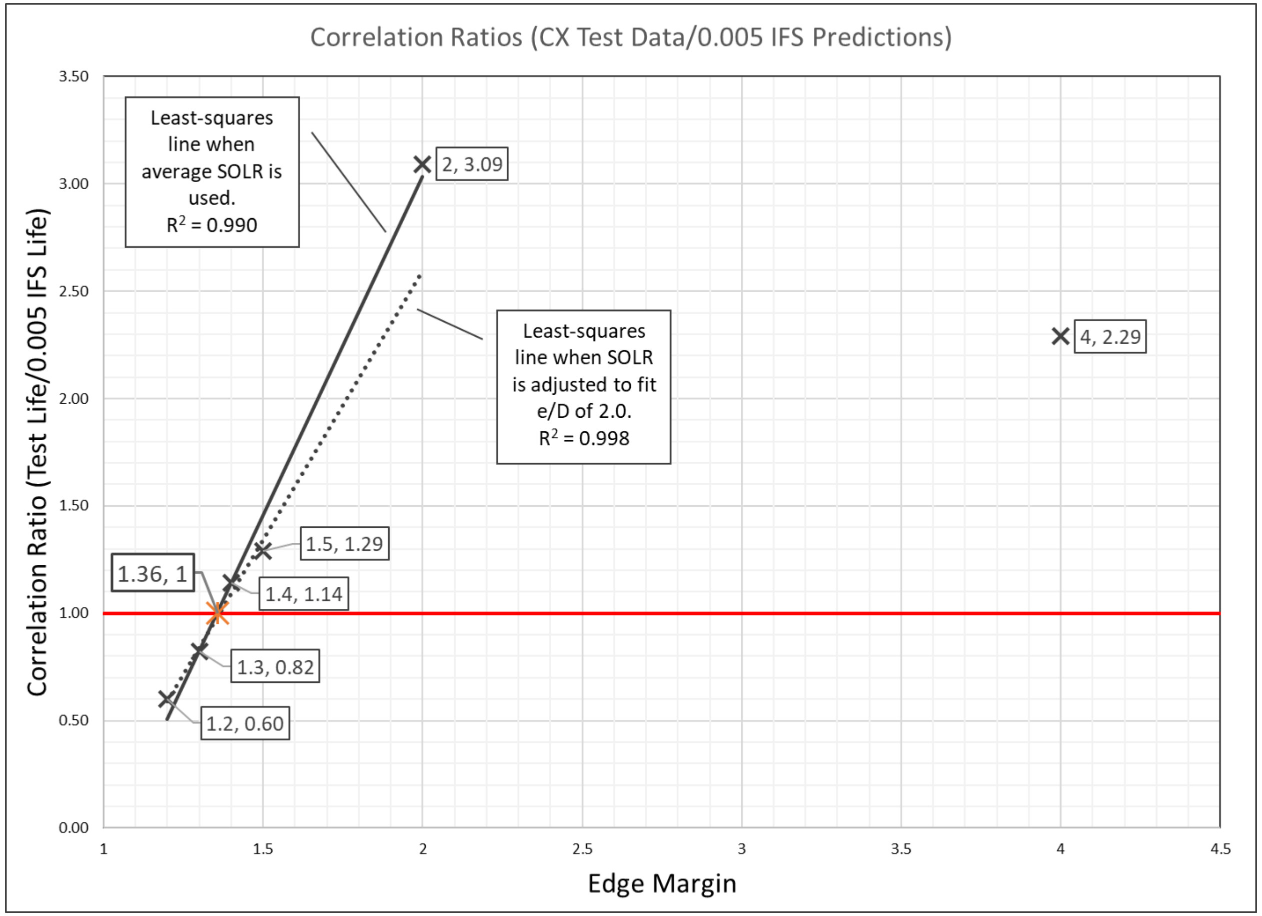
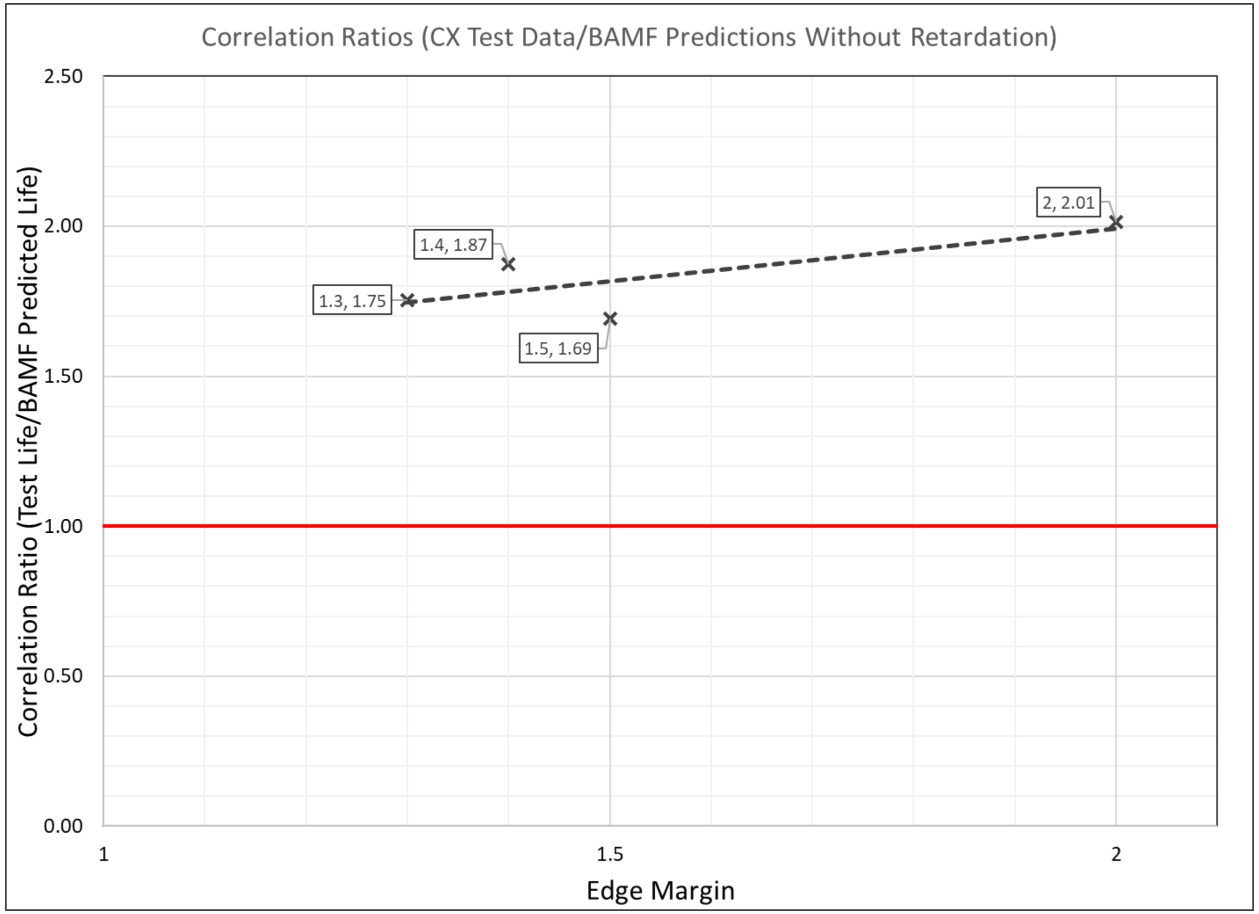
Short Edge Margin Testing

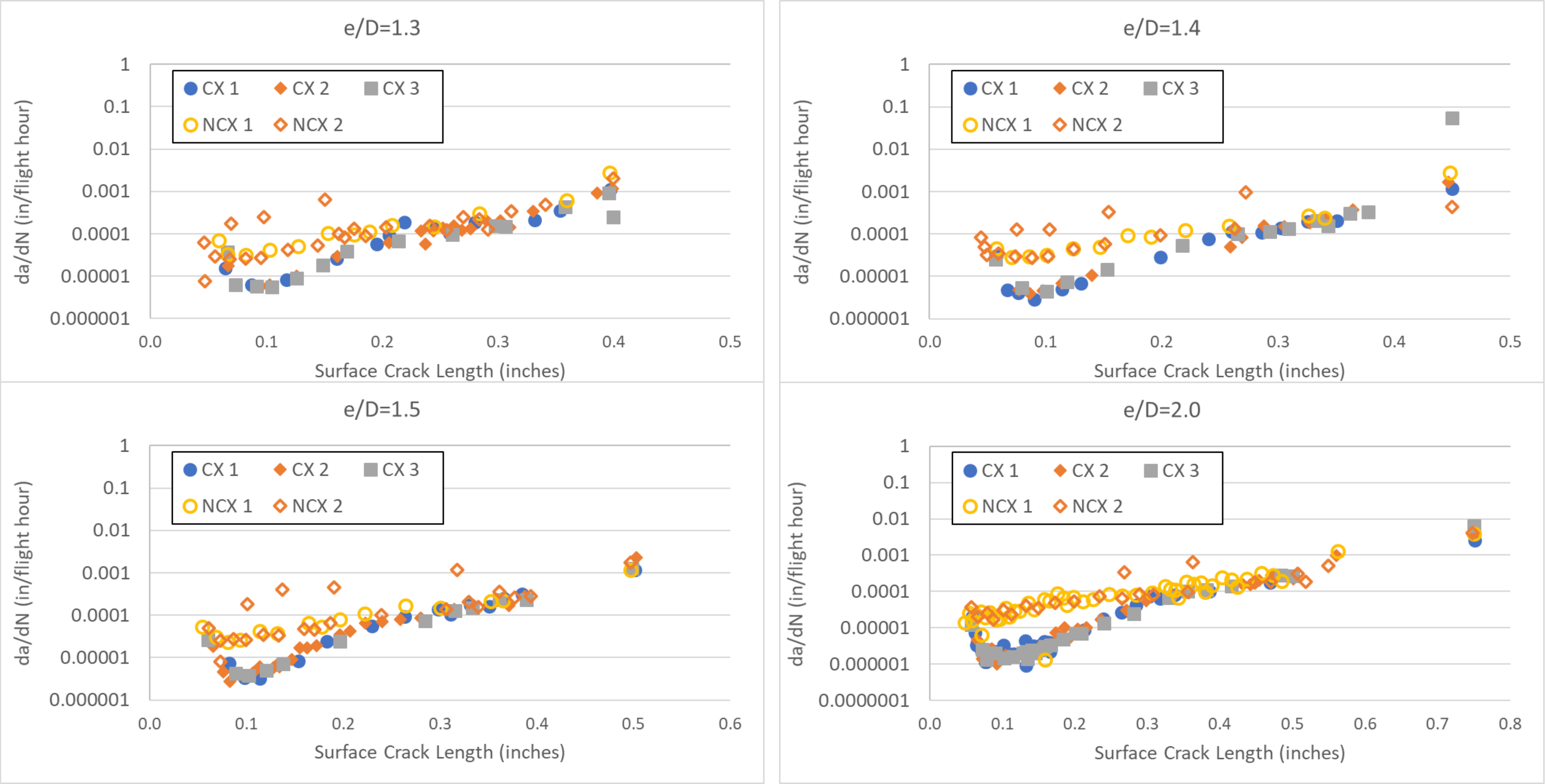
- Results
  - 0.005” IFS is not conservative……………………………………BAMF is





Short Edge Margin Testing

- Results

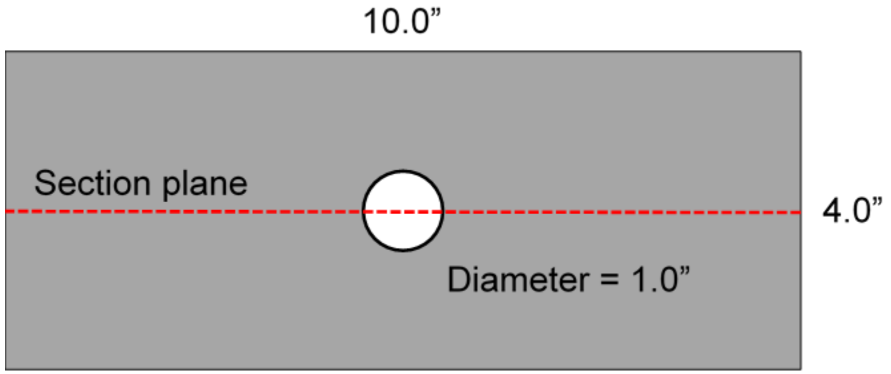


Short Edge Margin Testing

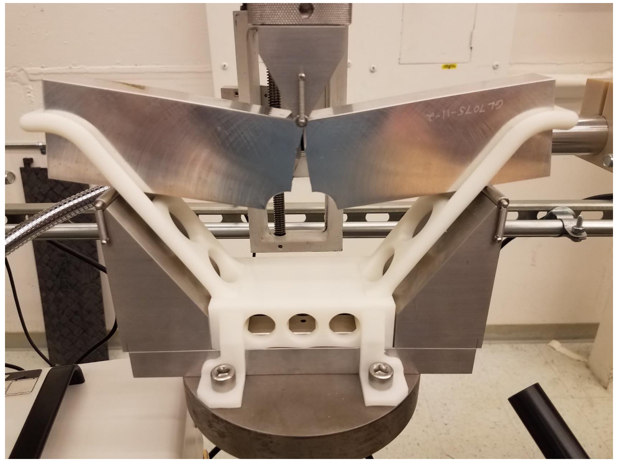
- Crack Videos

Geometrically "Large" Coupons

- Background
  - Part of the difficulty with the CX hole problem is the significance of the RS and applied stress gradients near the hole. Both gradients are very steep, which creates issues for measurements and life correlations. In an effort to minimize the impact of the gradients and increase the understanding of the RS near the hole, geometrically "large" coupons were developed to accomplish RS measurements and fatigue testing



- Approach
  - Year 1 – Manufacture coupons & contour measurements
  - Year 2 – Fatigue testing
  - Year 3 – Additional measurement refinement
- Coupon details:
  - Material: 2024-T351 Plate, 7075-T651 Plate
  - Thickness: 1.0 inch
  - Hole Diameter: 1.0 inch
  - Centered Hole, Baseline (no CX) and Mid CX



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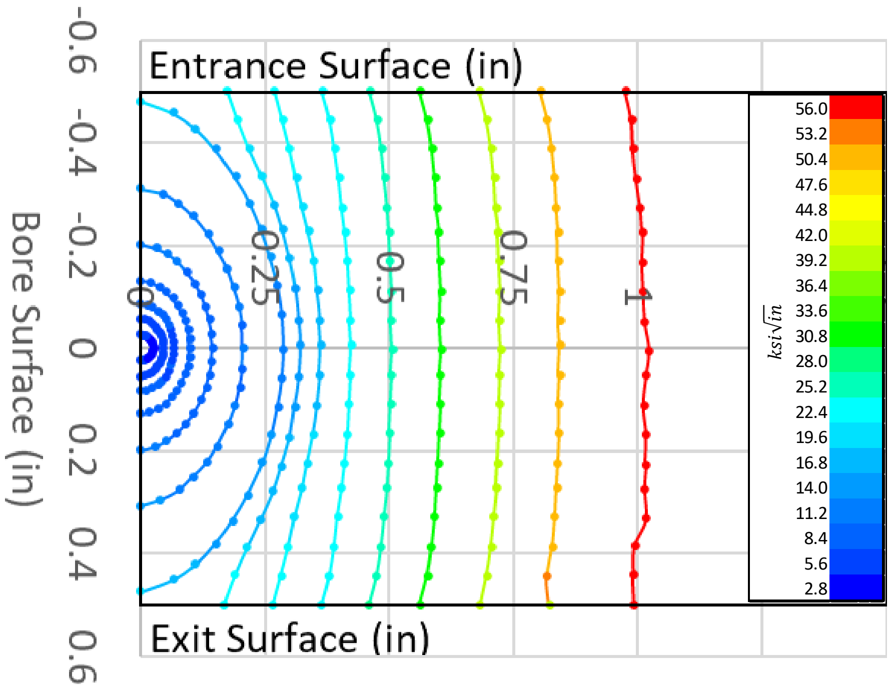
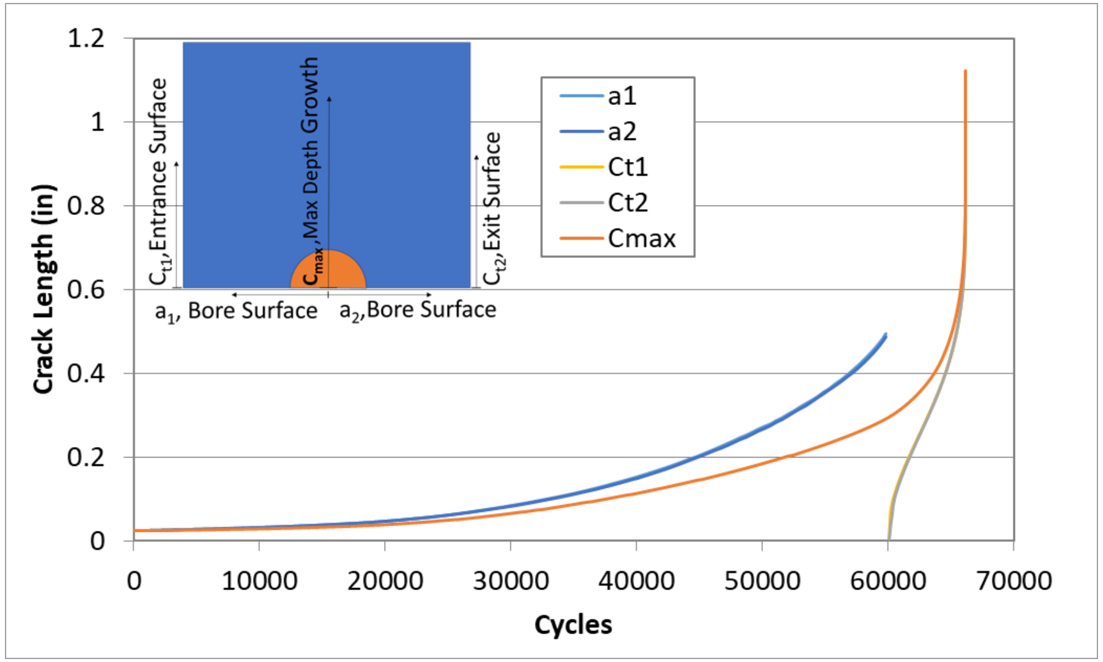
Geometrically “Large” Coupons

- 7075 Baseline NonCx Coupons
  - Applied Load - 3.5 kips
  - Material - 7075-T651
  - Starting flaw - 0.025” semi-circular





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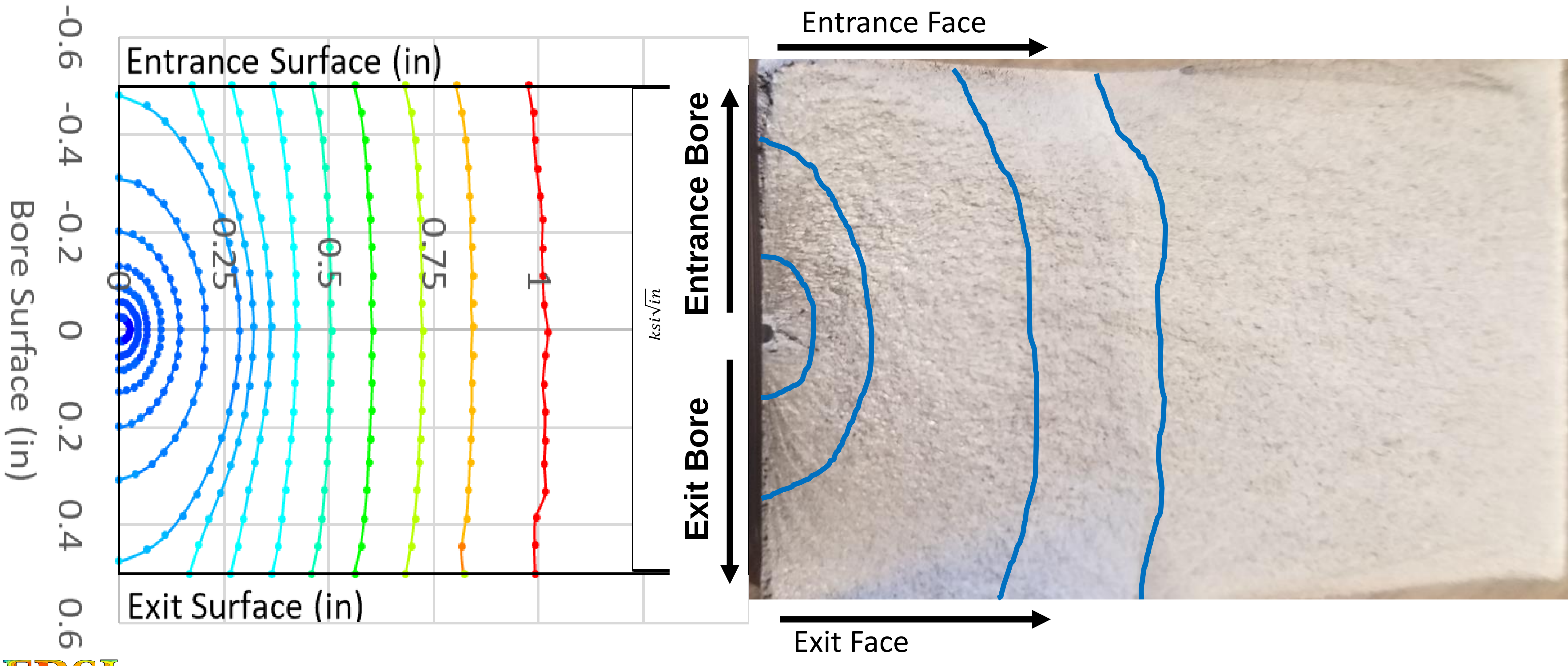
7075 NCX Prediction vs. Test



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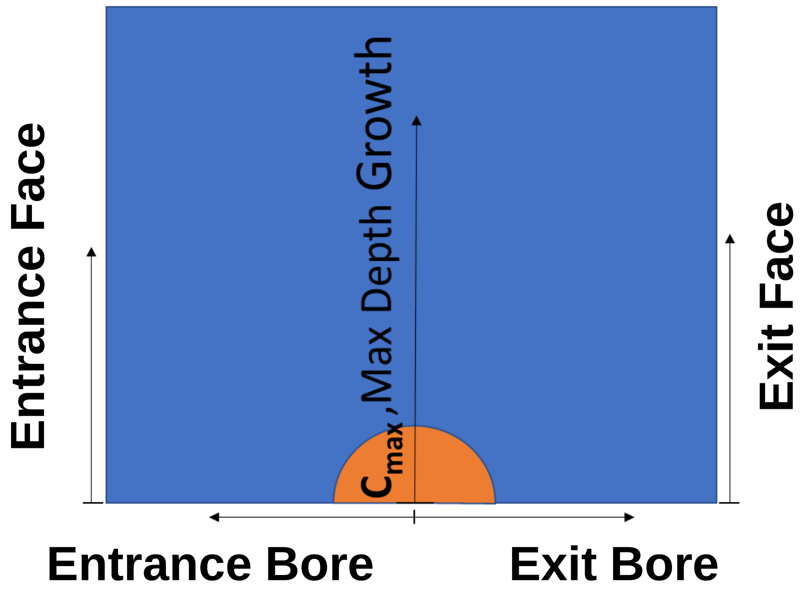
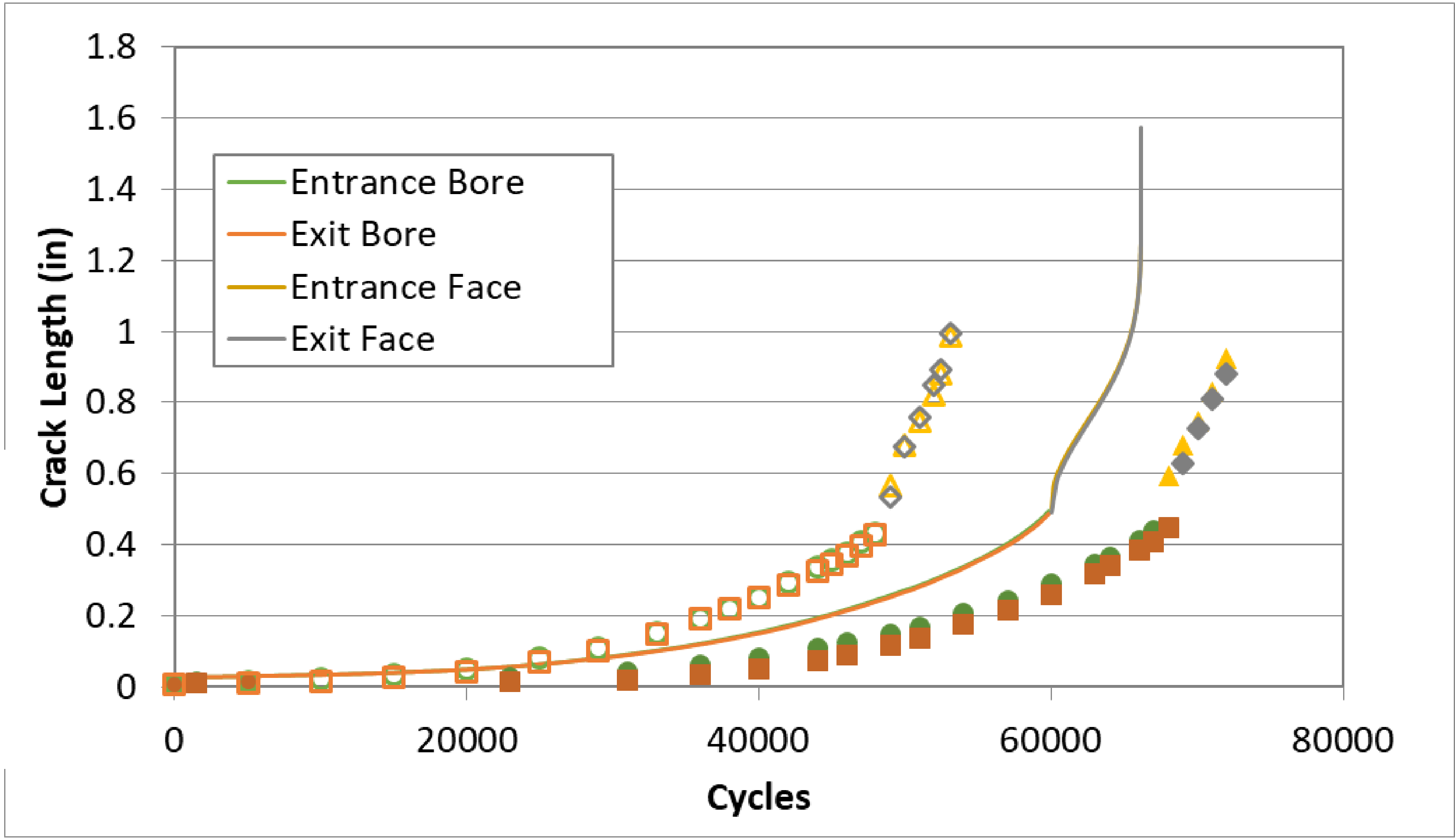
7075 NonCX Prediction vs. Test

- Prediction splits test
- Tests are halves of same coupon, same hole





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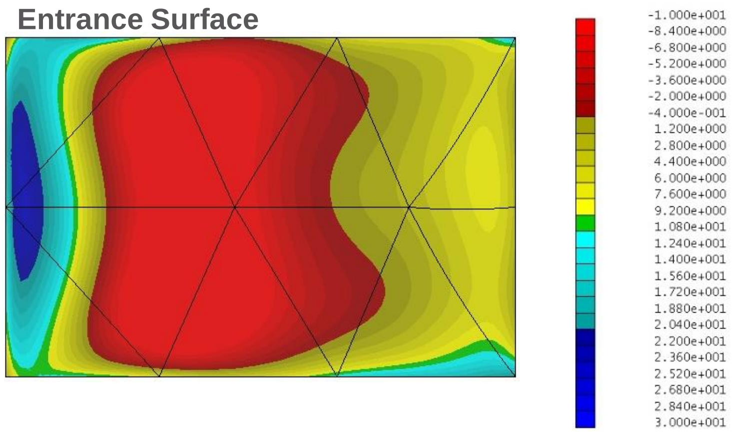
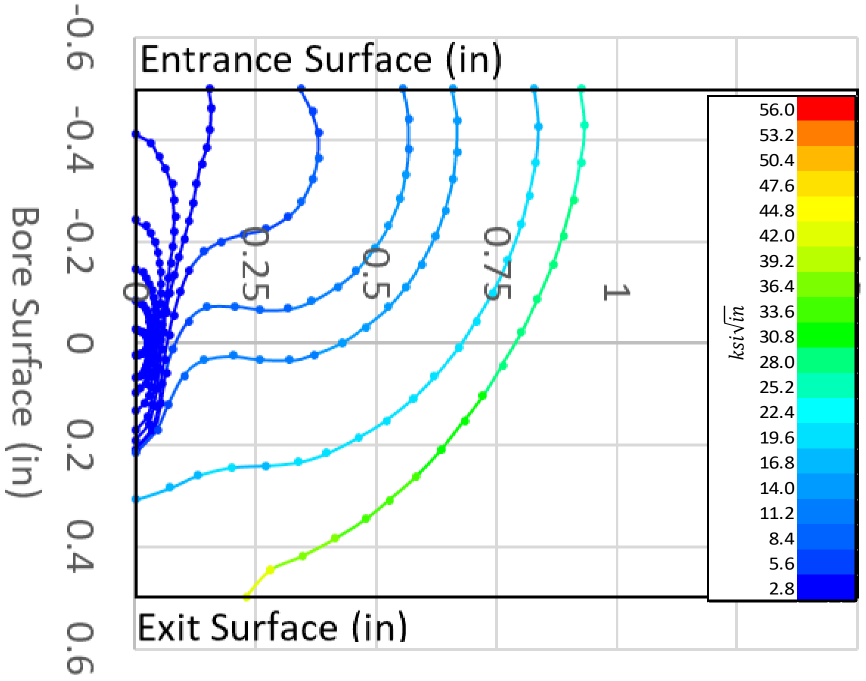
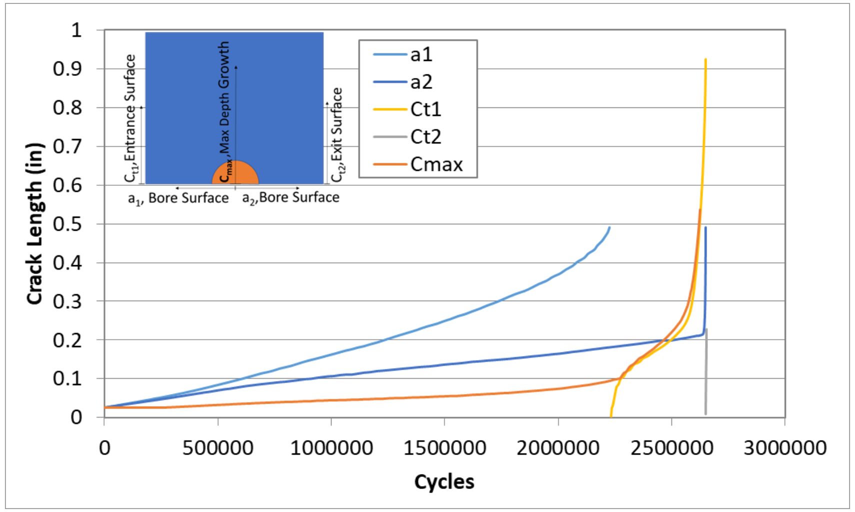
Geometrically "Large" Coupons

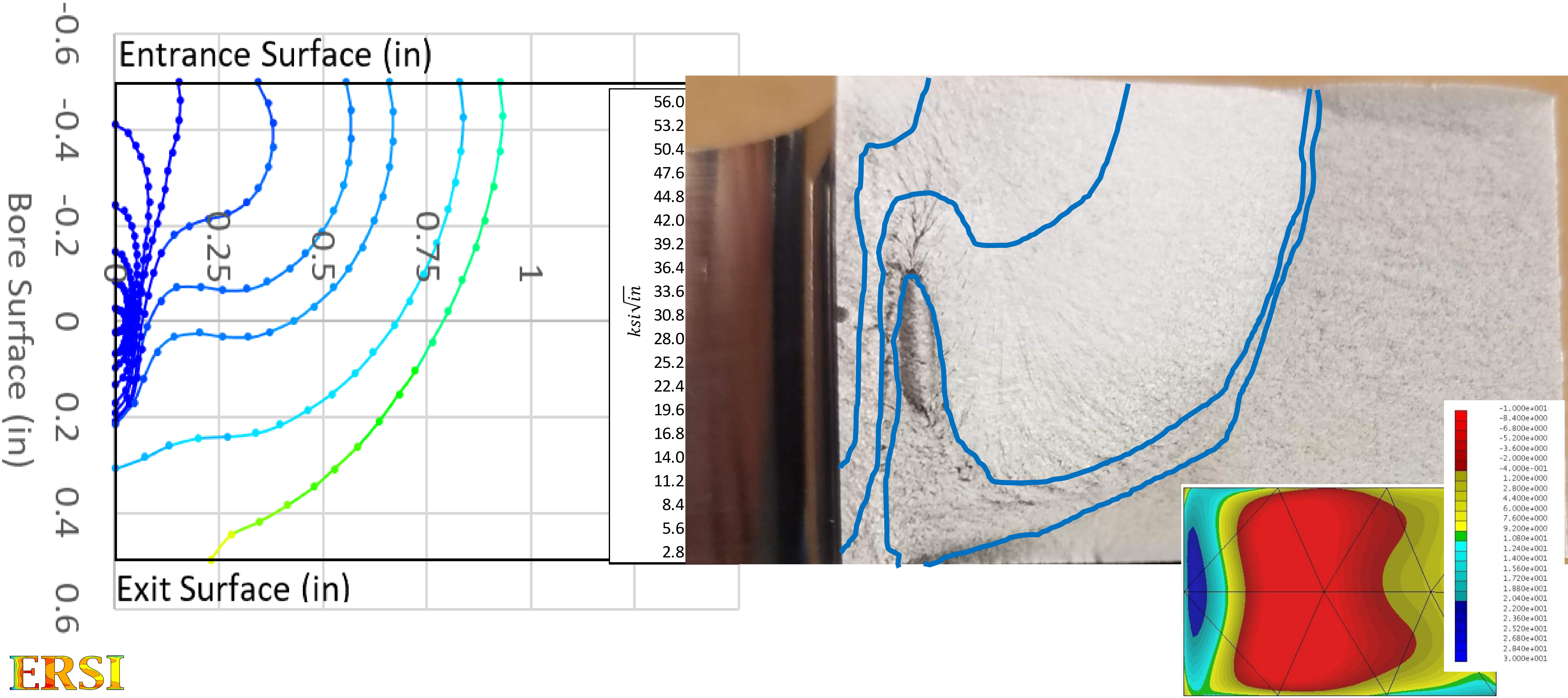
- Cx Coupons
  - Applied Load - 3.5 kips
  - Material - 7075-T651
  - Starting flaw - 0.025" semi-circular







7075 CX Prediction vs. Test



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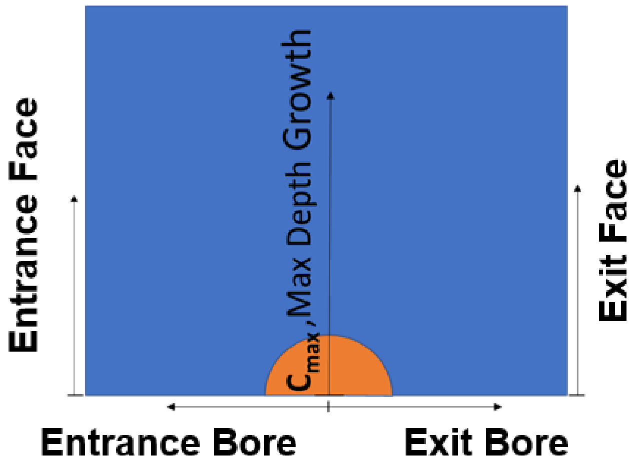
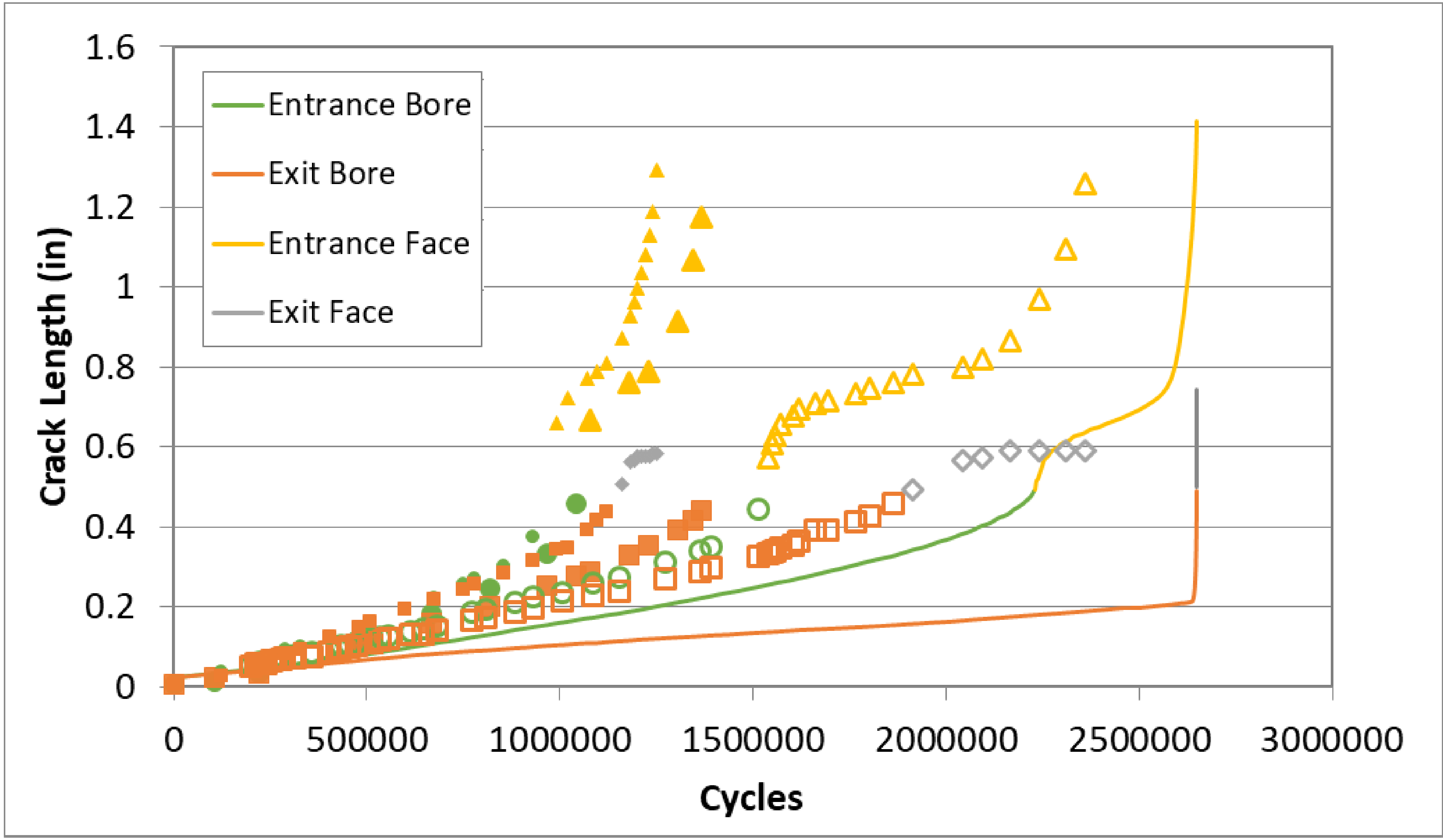
7075 CX Prediction vs. Test

- Blind predictions
- Unconservative, test scatter needs to be quantified





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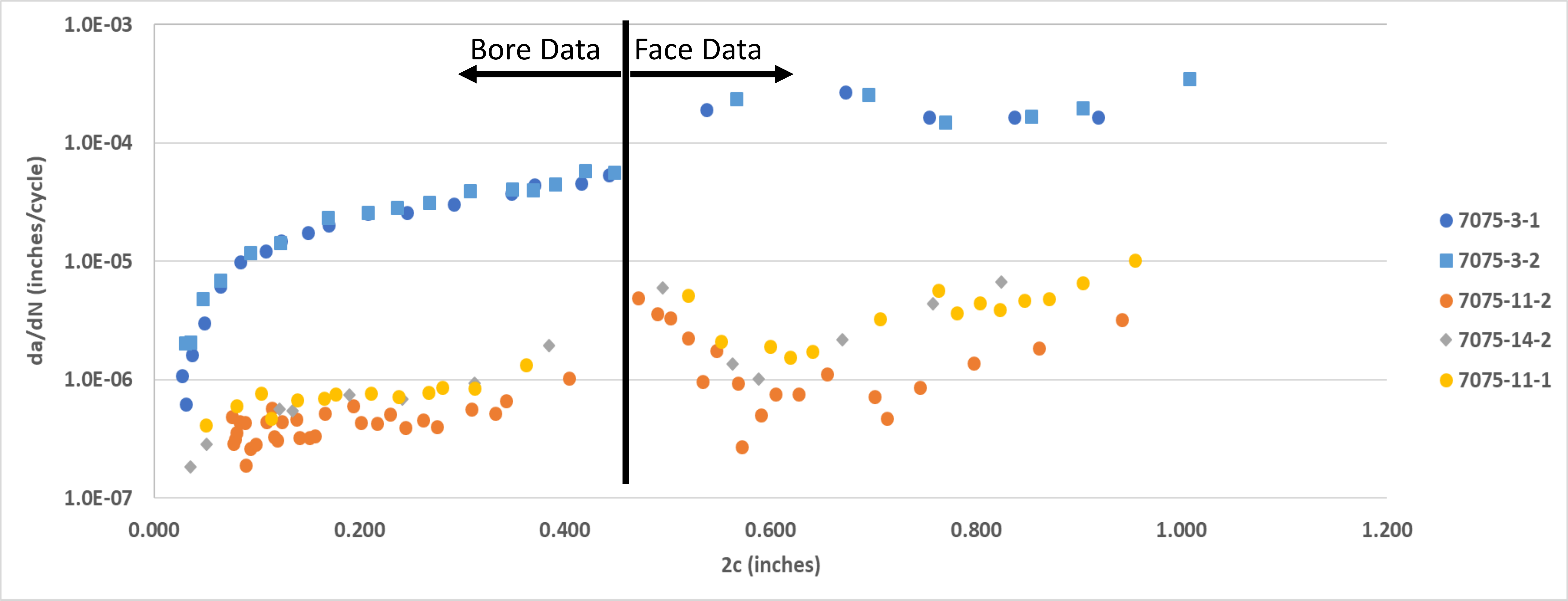
7075 Rate Data



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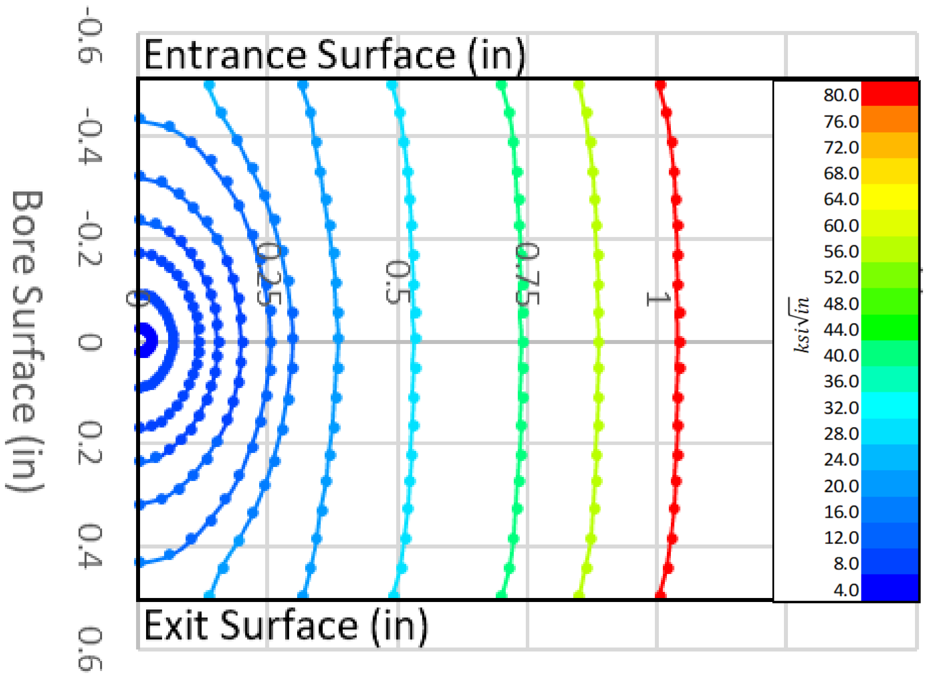
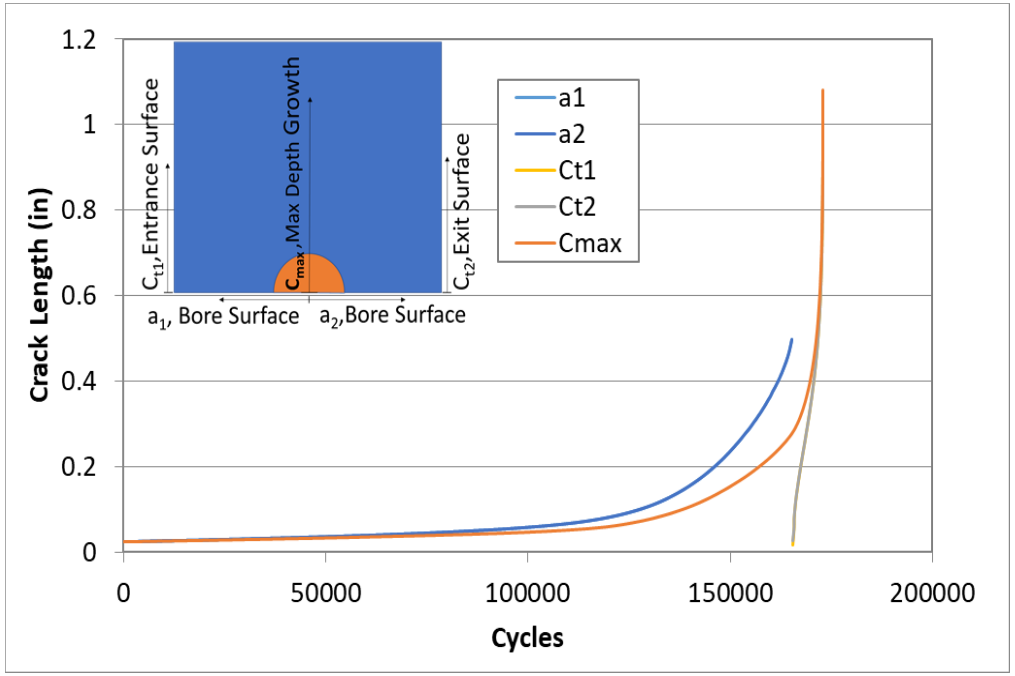
Geometrically "Large" Coupons

- Baseline NonCx Coupons
  - Applied Load - 3.5 kips
  - Material - 2024-T351
  - Starting flaw - 0.025" semi-circular





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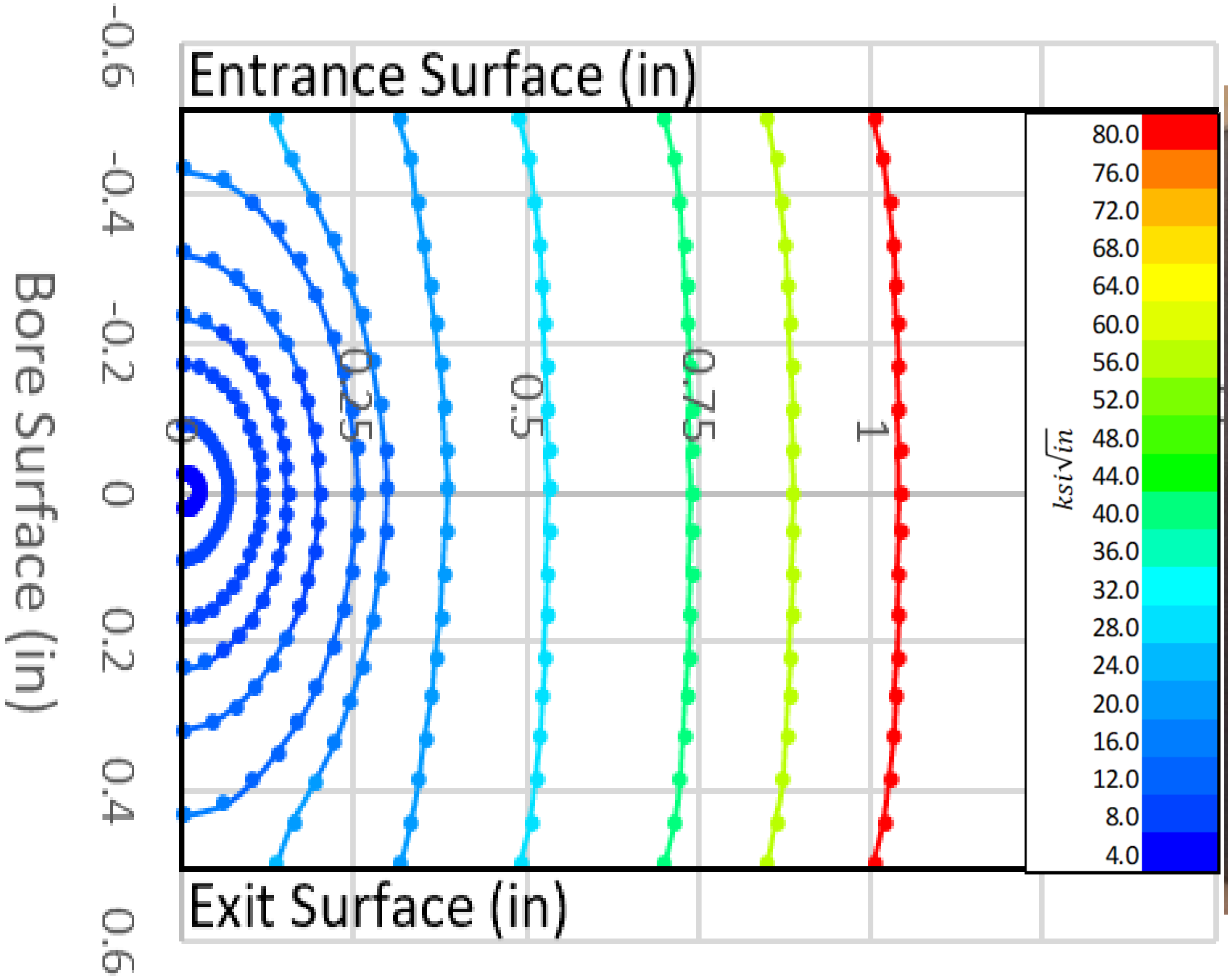
2024 NonCX Prediction vs. Test



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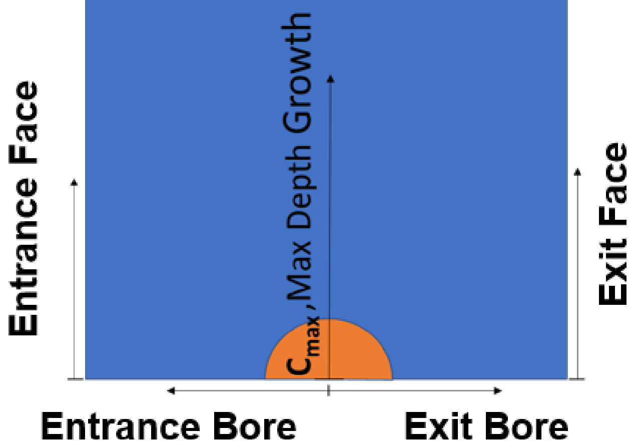
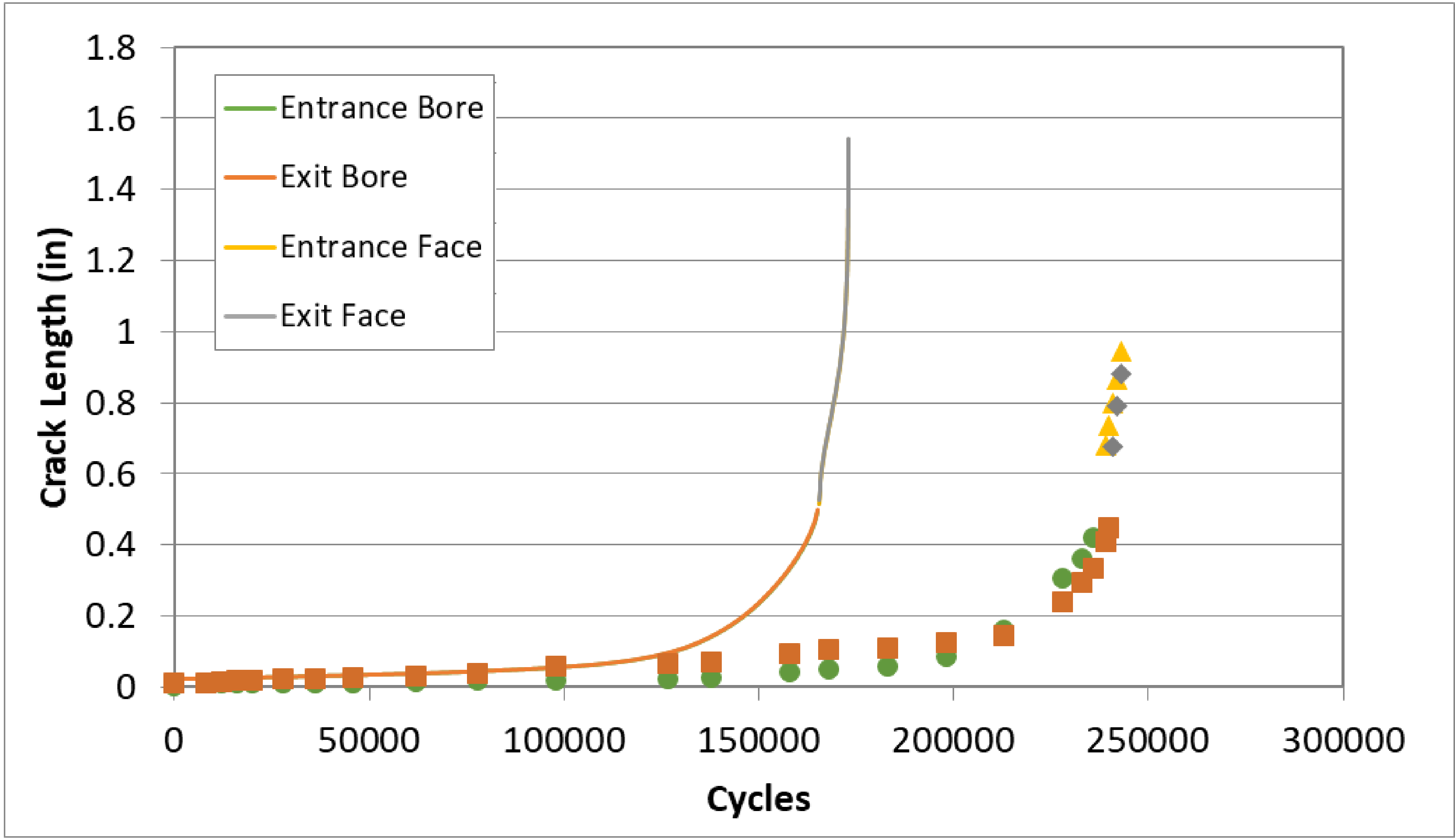
2024 NCX Prediction vs. Test

- Conservative prediction
- Essentially symmetric growth entrance and exit





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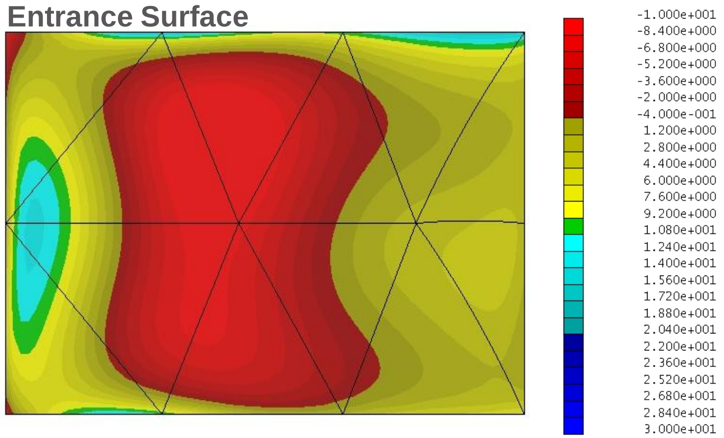
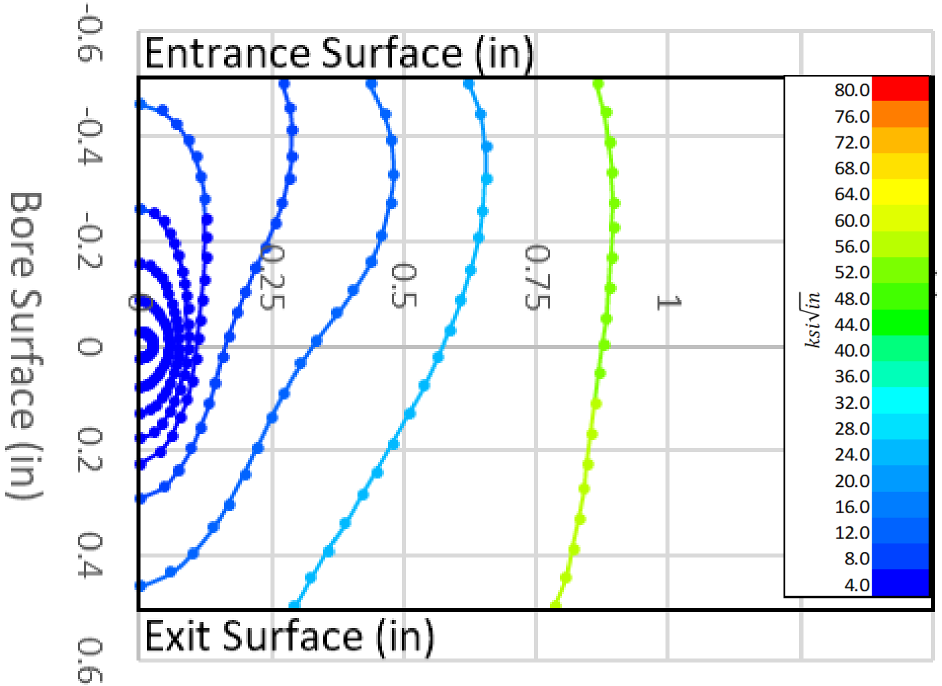
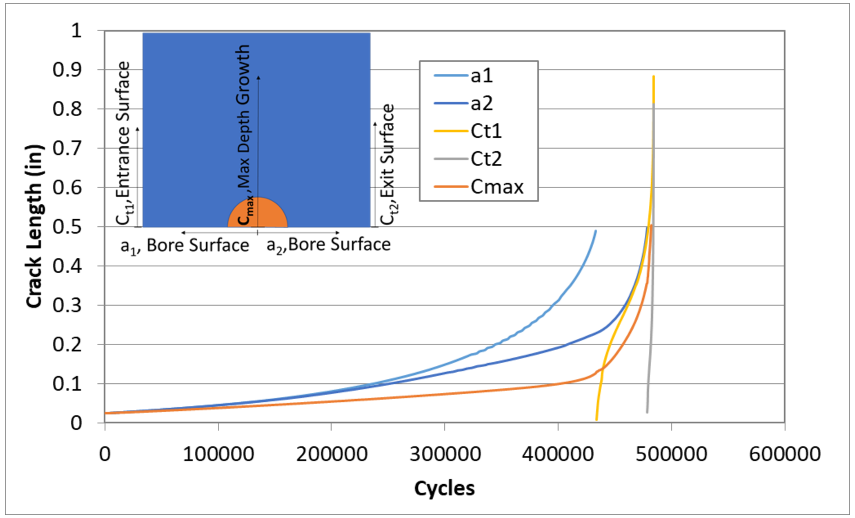
Geometrically “Large” Coupons

- Cx Coupons
  - Applied Load - 3.5 kips
  - Material - 2024-T351
  - Starting flaw - 0.025” semi-circular

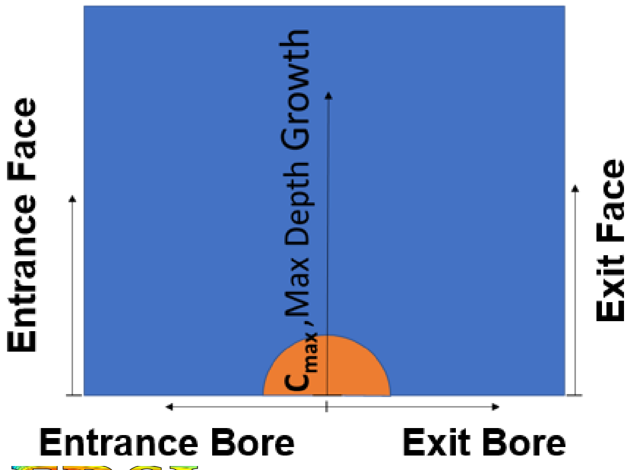


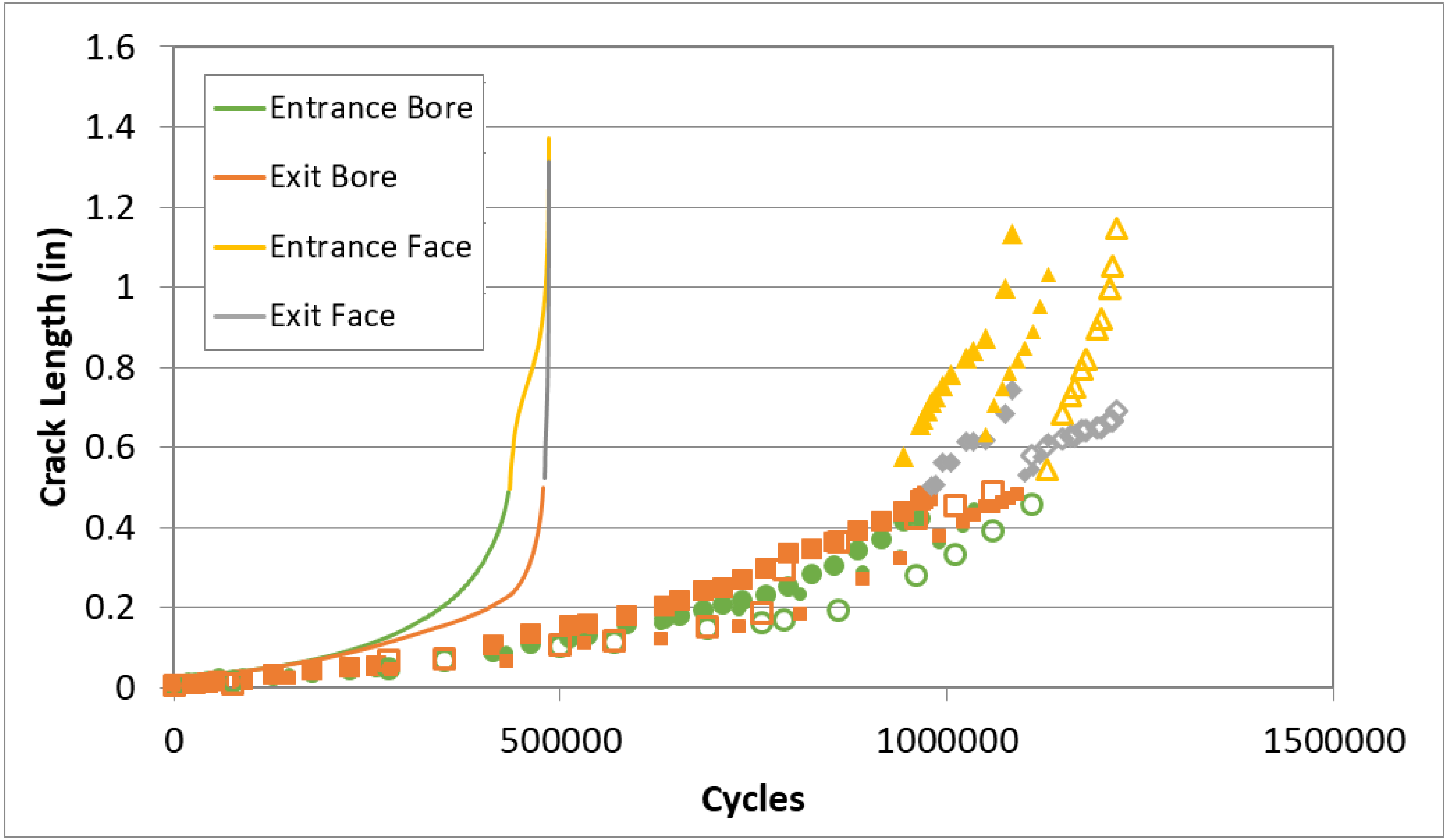




2024 CX Prediction vs. Test

- Prediction conservative
- Shape matches well on front face





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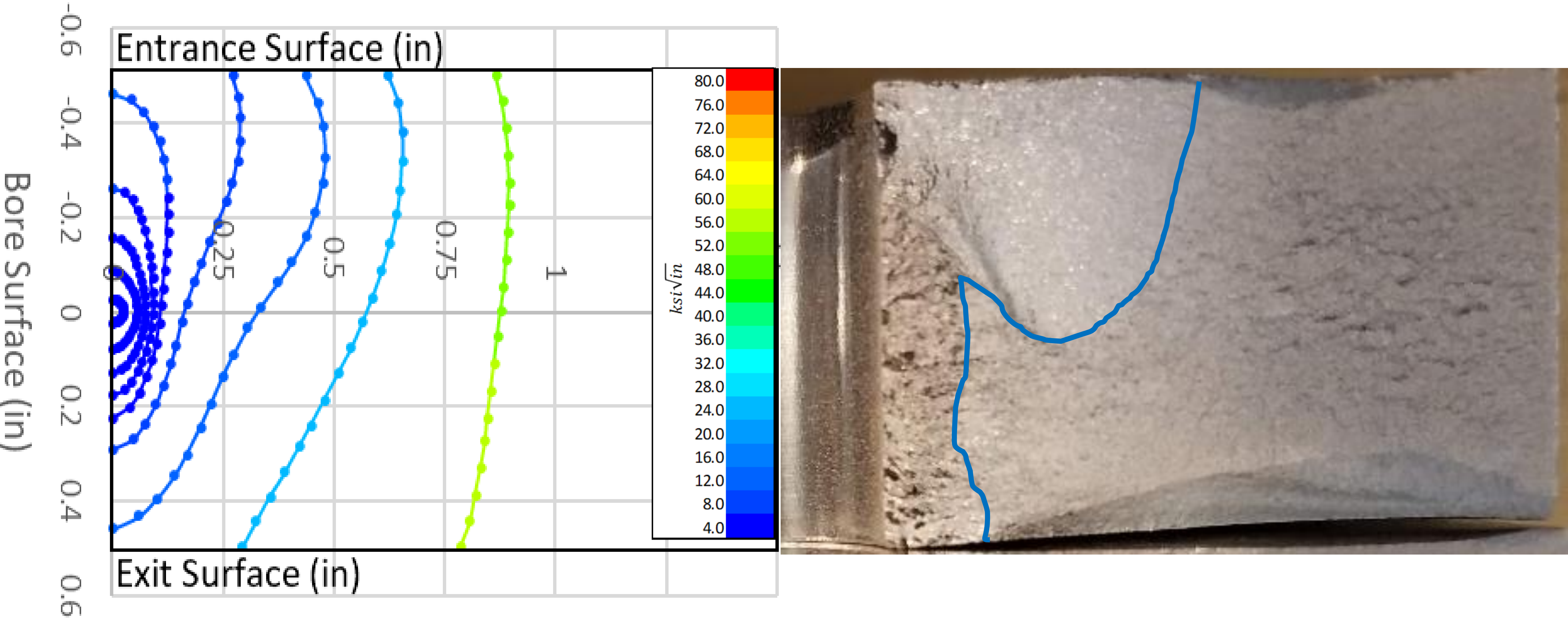
2024 CX Prediction vs. Test



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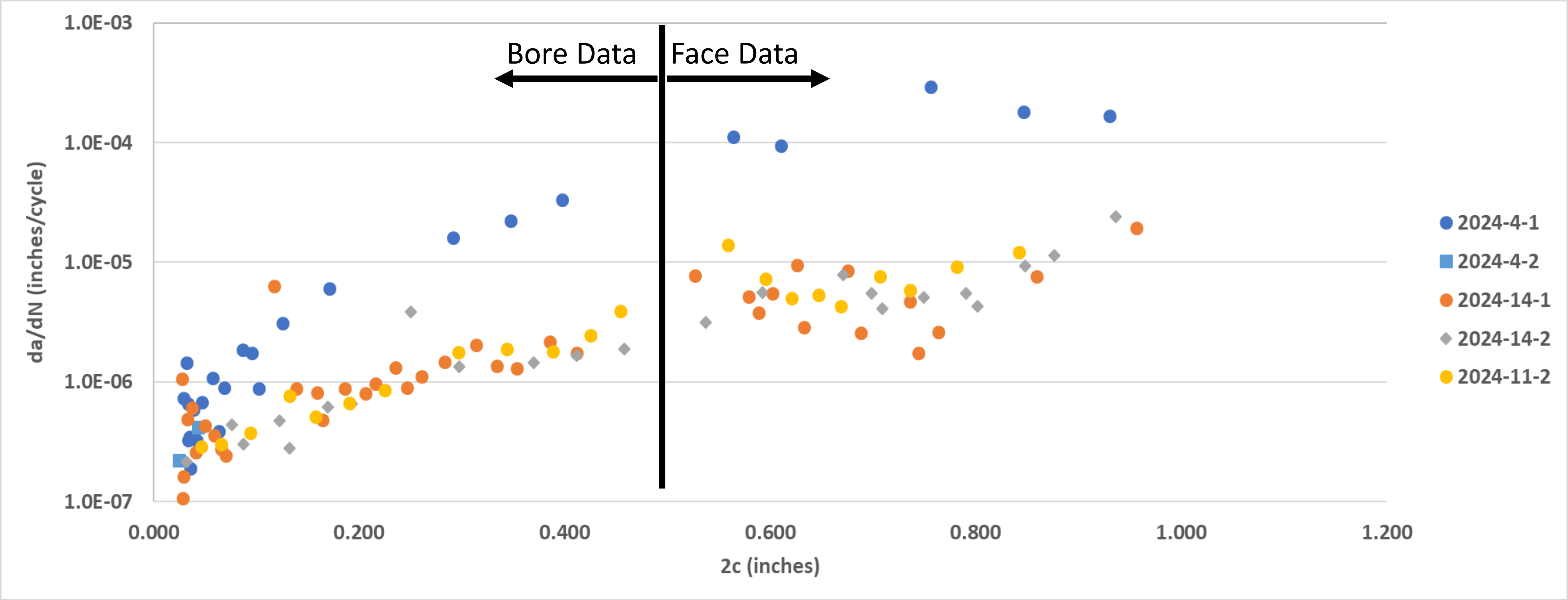
2024 Rate Data



Weapon System Applications

Modelling fatigue cracking in F/A-18 Wing Root Shear Tie

- Complex Geometry
- With and without Residual Stress
- Residual Stress due to shot peening
- Representative coupon testing under a known load spectrum gave the basis for comparison with analysis
- Analysis performed with BAMF which includes Stress Check and AFGROW
- Analysis results compared very well with the experimental data

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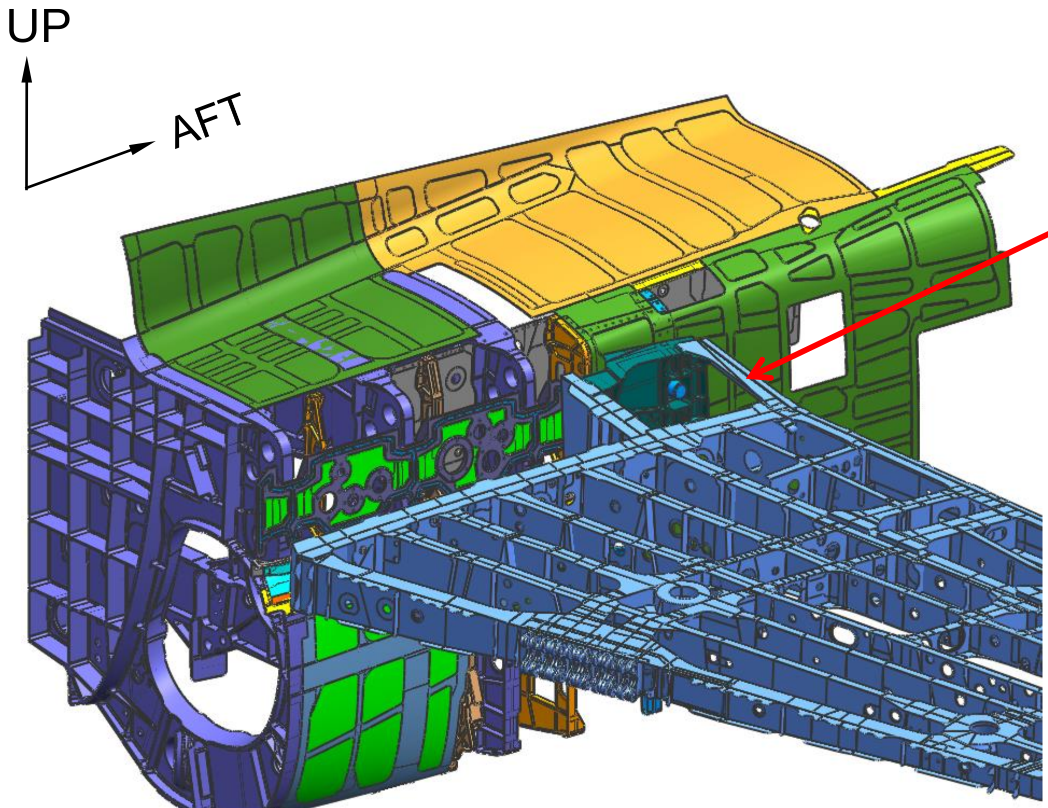
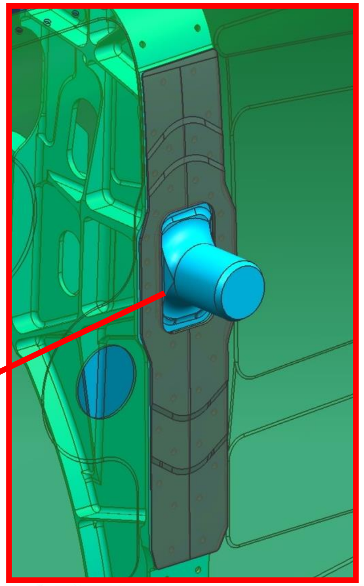
Problem Description - F-18 Wing Root Shear Tie

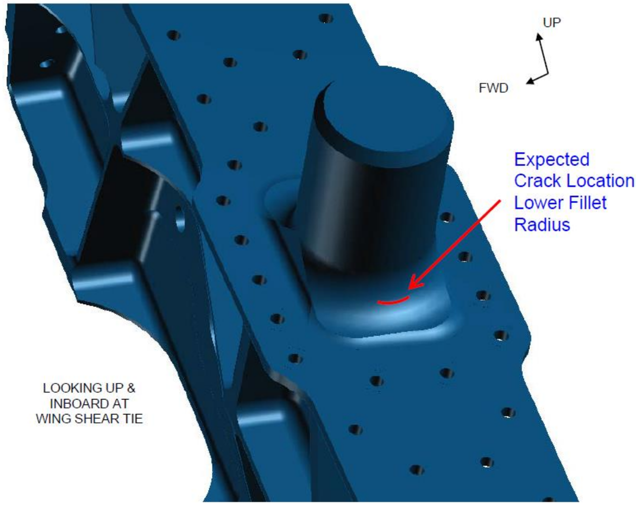
Flight Loads: Combination of Wing Root Shear and Trailing Edge Flap (TEF) Hinge Moment buffet introduced from the adjacent inboard TEF hinge and back-up structure.



FS508 Former Analysis Review (2010) *Northrup Grumman*



Materials and Surface Finish: Integral post machined from AA7050-T7451 plate. Pre-Ion Vapour Deposition (IVD) etched. Shot peened radius (steel shot) at production.



AFB-728 (2011) *Naval Air Systems Command (NAVAIR)*

Acknowledgement: Parts of this slide adapted from : Main, B. etal., "Component Testing of the F/A-18 A/B Y508 Wing Root Shear Tie", ASIP Conference November 27-30 2017, Jacksonville, FL, USA

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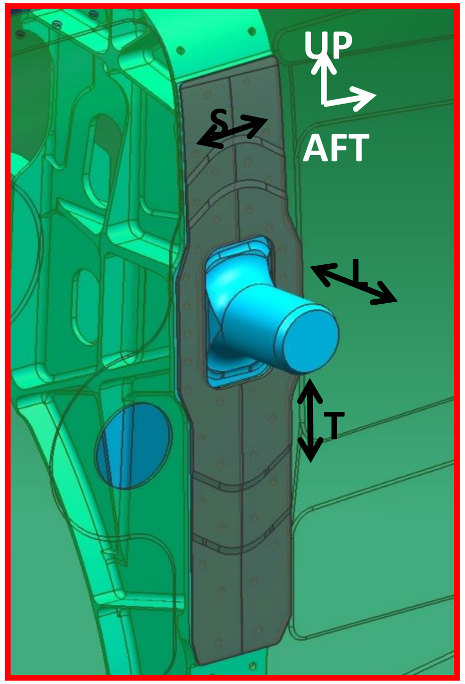
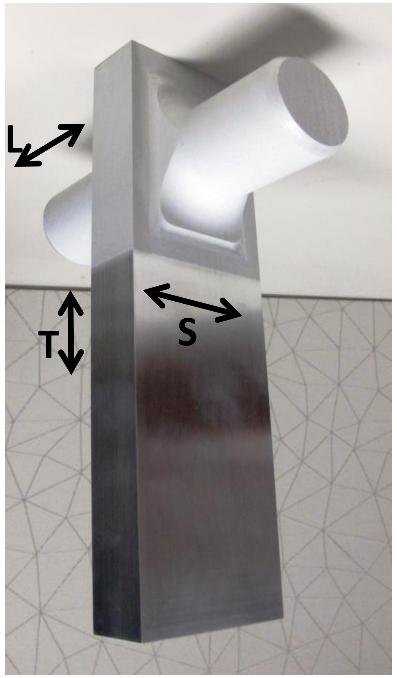
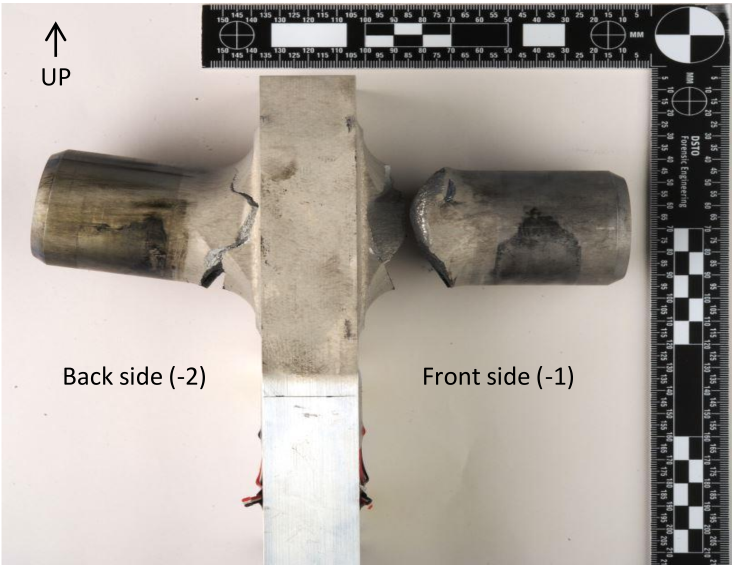
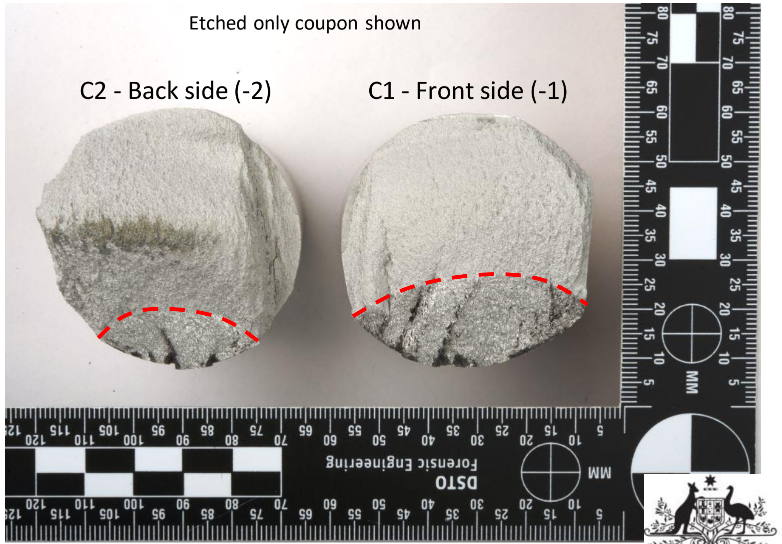
Representative Coupon Design and Production





Etched only coupon shown





20 coupons machined from AA7050-T7451 plate. As machined finish and where noted:

- nitric acid etched per PS 13143 (1980) *McDonnell Douglas*
- steel shot peening to 0.001A per PS 14023 Rev G (1980) *McDonnell Douglas*

Acknowledgement: Parts of this slide adapted from : Main, B. etal., “Component Testing of the F/A-18 A/B Y508 Wing Root Shear Tie”, ASIP Conference November 27-30 2017, Jacksonville, FL, USA

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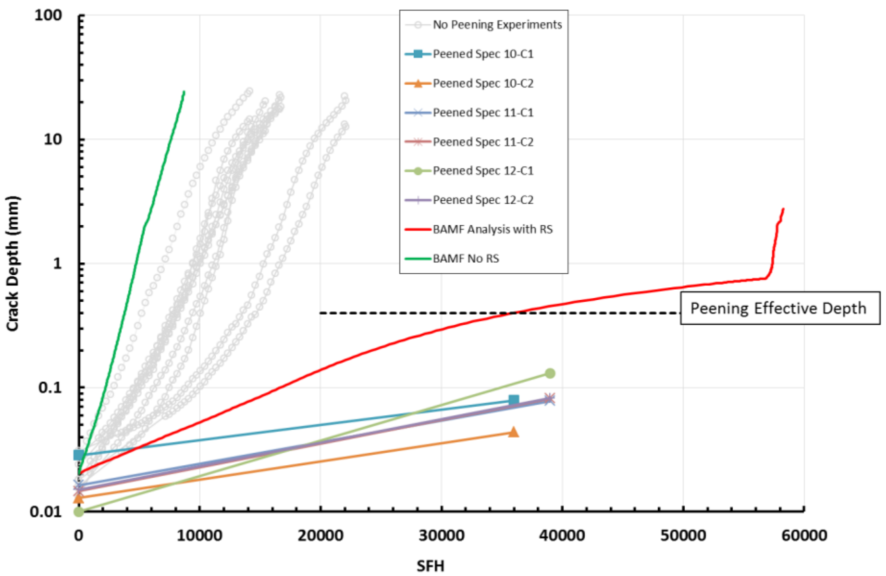
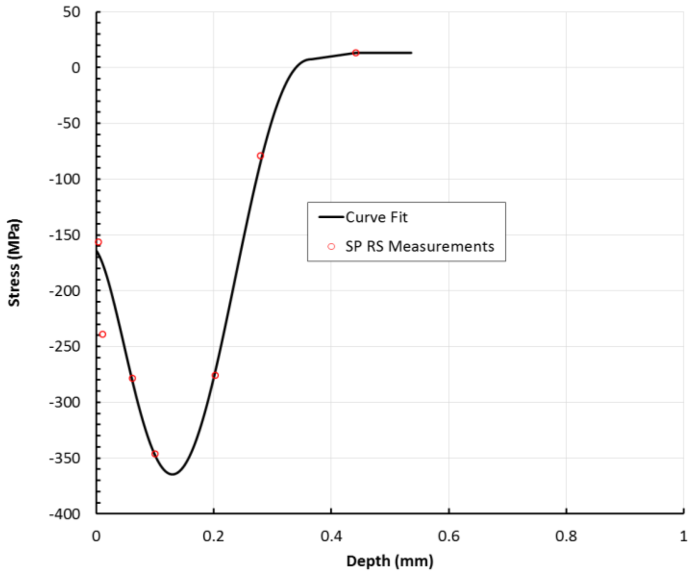
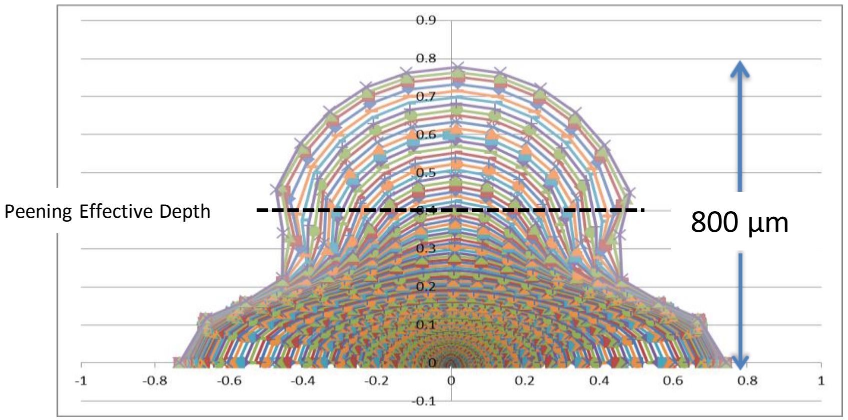
BAMF Results – With and without Shot Peening RS







Predicted crack shapes at 800 µm (0.8 mm) depth, beyond the effective peening range

Observations

- BAMF analysis and test results for no RS also shown for comparison
- BAMF analysis with RS compares very well against test observations
- Rapid growth predicted beyond the shot peening effective depth
- Predicted crack shape affected by the RS as expected

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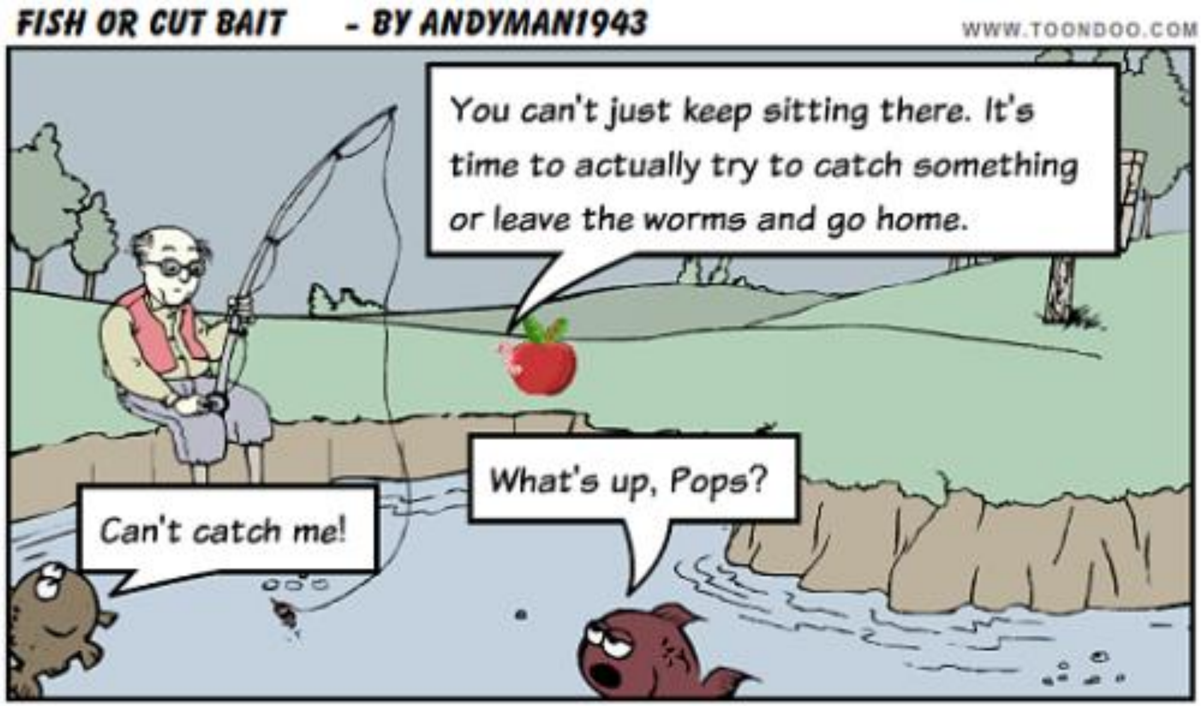
Control Point Analyses

- Objectives
  - Utilizing state-of-the-art methods and inputs, update DTAs for select Control Points (CPs), explicitly incorporating residual stress
  - Compare/contrast with reduced flaw size predictions (partial credit)
  - Identify gaps and refine best practices
  - Define initial ground rules
- Approach
  - Select candidate locations (3)
    - Typical & extreme locations
  - Review baseline input data/methods
  - Complete baseline analyses
  - Complete multi-point analyses w/ RS
  - Compare/contrast predictions
  - Provide conclusions and recommendations



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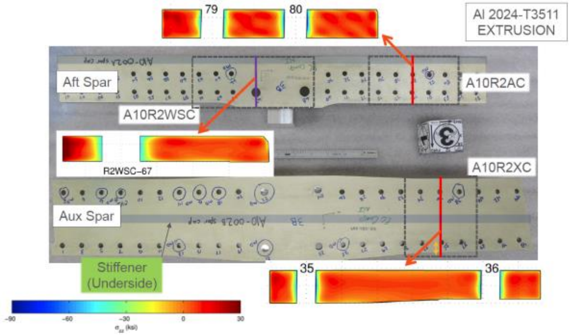
Control Point Analyses

- Inputs and Results
  - Oversized conditions
  - Variations in residual stress
  - Variation in stress spectrum



Location 1 residual stresses

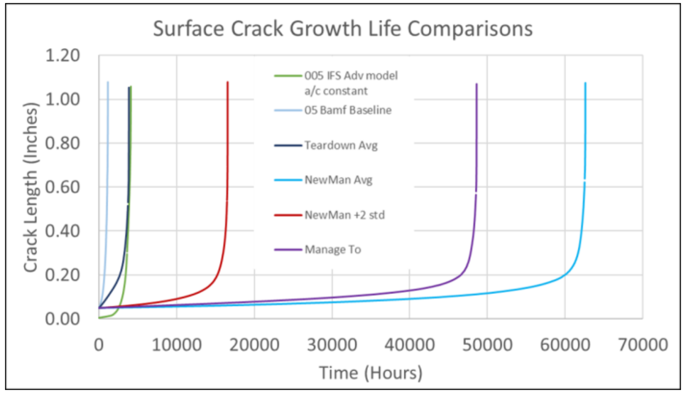
Analysis Details

Location	Description	Material	Thickness (in)	Hole Size (in)	Edge Margin (e/D)	Max Stress (ksi)
1	Lwr Fwd Skin, WS 23 (SLEP)	2024-T3511	0.300	0.625	2.256	31.2
2	Lwr Fwd Skin, WS 23 (Thick Skin)	2024-T3511	0.420	0.562	2.508	24.0
3	Lwr Wing Skin at Mid Spar, WS 23 (SLEP)	2024-T351	0.300	0.328	1.981	42.4

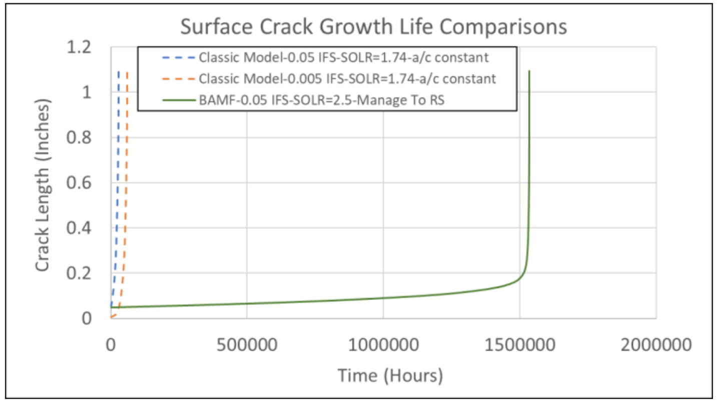
Residual Stresses

Location	New Manufacture Mean	Teardown mean	New Manufacture +2 Std	Teardown +2 Std	Manage To
1	x	x*	x		x
2		x			
3	x	x	x	x	

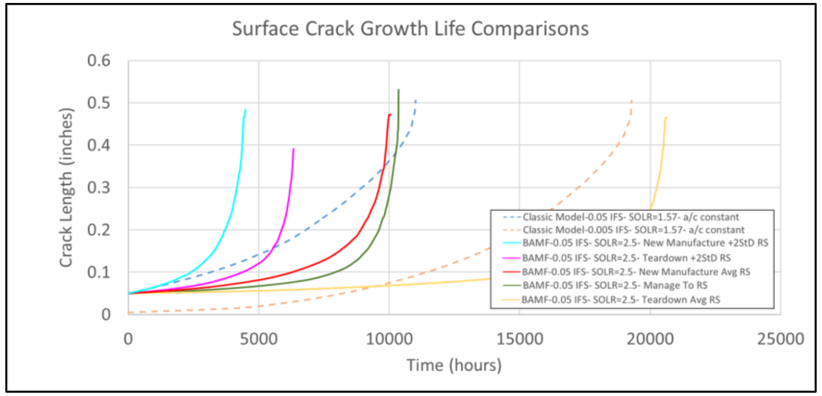
Location 1 Predictions



Location 2 Predictions



Location 3 Predictions



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Control Point Analyses

- Conclusions
  - Peak spectrum stress has a key influence on the LIF at Cx holes
  - The LIF from traditional DTA methods, that also have high applied stresses and are account for the benefit of Cx, could be unconservative if utilizing 0.005” RIFS
  - Cx benefit is significantly reduced for locations with peak spectrum stresses greater than 85% of the yield strength. Experimental results demonstrate minimal benefit.
  - Appropriate crack retardation values with explicit residual stress range from 2.5-4.0 based on initial evaluations
    - Retardation parameters established from non-Cx holes should not be used for Cx hole analyses
    - Retardation values derived from 0.05” tests may not be appropriate for modeling RS with the RIFS assumption (0.005-inch)
  - The residual stress utilized for analyses is critical for the predictions and must be considered closely, considering the impacts of in-service degradation and statistical variation
  - The “Manage-To” approach results in a reasonable conservative prediction of the residual stress (as intended)

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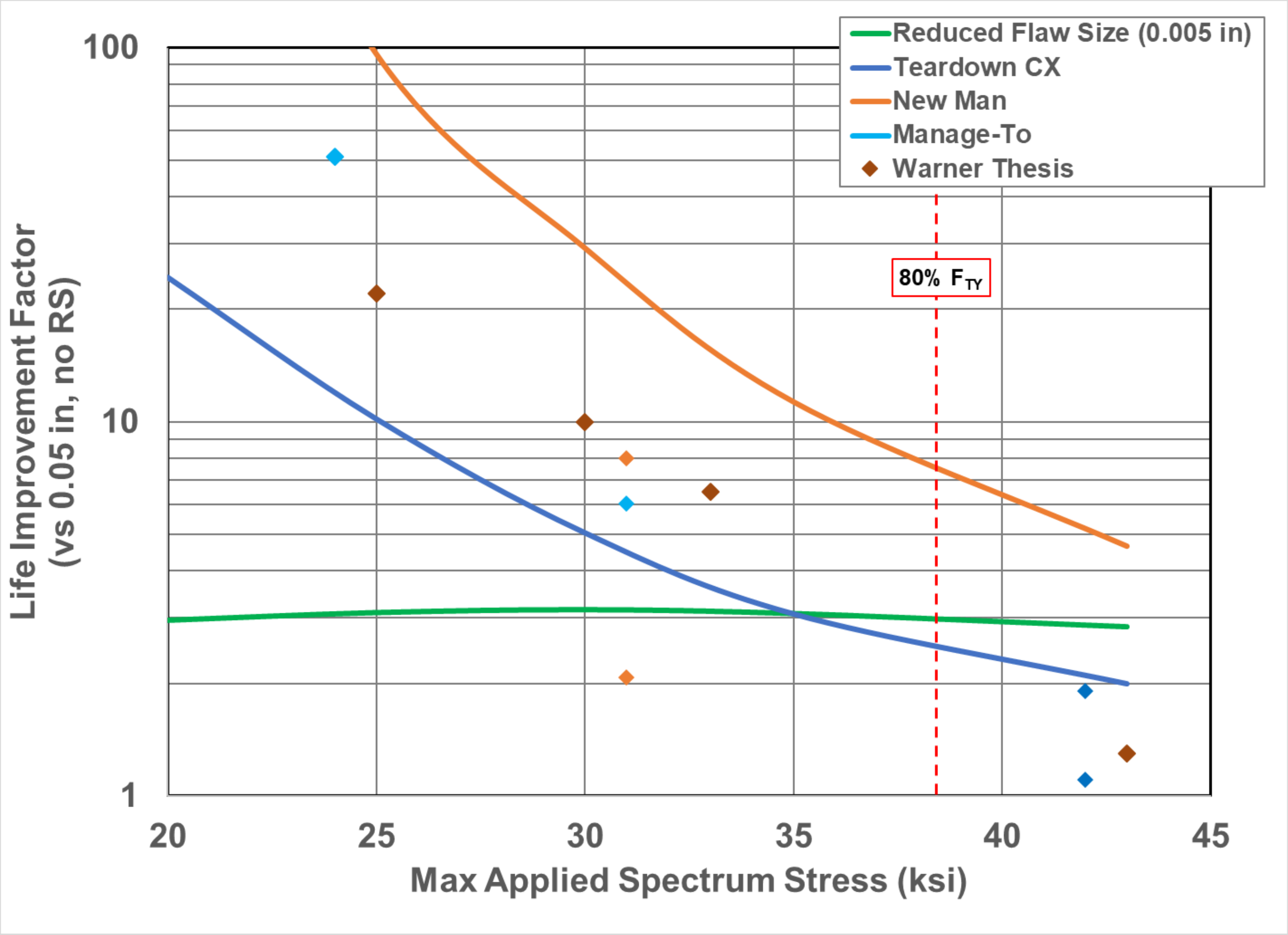
Control Point Analyses

- Results and Conclusions



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B-1 Taper-Lok Program Overview

- There are a number of current damage tolerance assessments requiring widespread initial inspections within the next 5 years
  - Removing Taper-Lok fasteners is difficult due to the interference fit of the fastener, and damage is often accrued
- The upcoming initial inspections are primarily based on testing data from the 1990’s and are considered to be conservative (partial-credit)
- The lack of a robust analytical approach requires costly testing and conservative methodologies to garner a benefit

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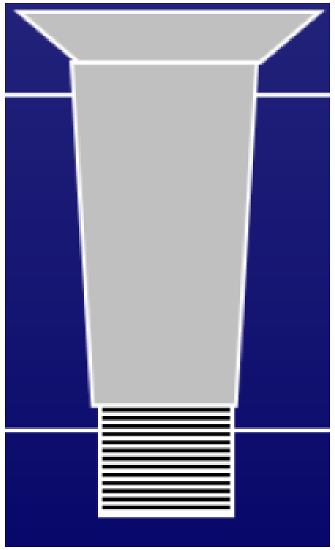
B-1 Taper-Lok Background

- 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
- Taper-Lok Locations
  - Hundreds of Taper-Loks common to wing rear spar and wing carry through

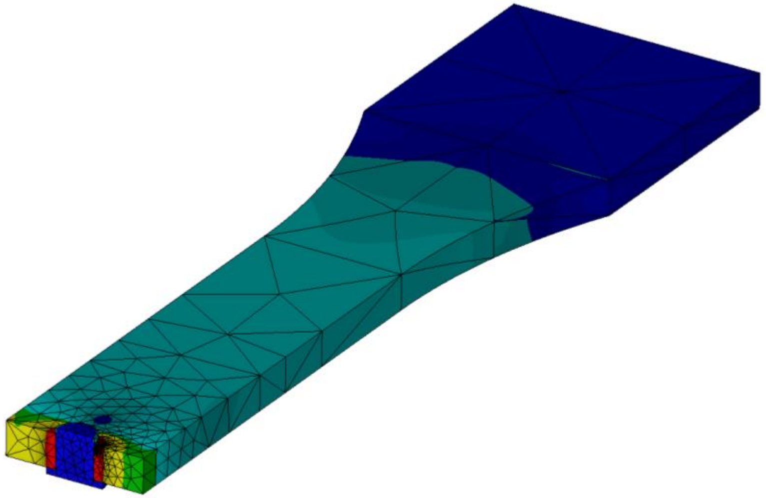


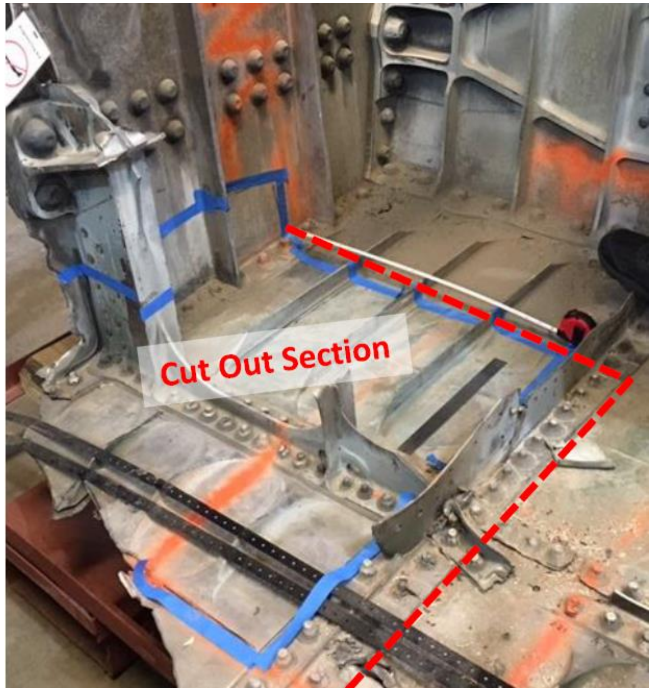
Taper-Lok Diagram

B-1B Wing Assembly at Avco (Chatanooga, TN)

B-1 Taper-Lok Program Objectives

- Develop a robust analytical approach to predict the damage tolerance life at Taper-Lok fastener holes
- Perform measurements to quantify interference, elastic/plastic deformation, and stresses 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





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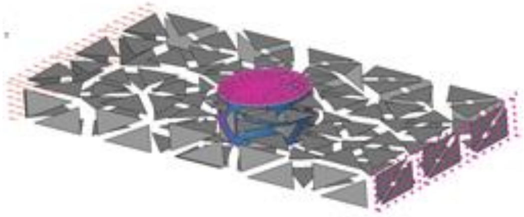
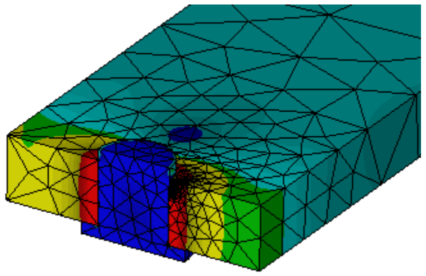
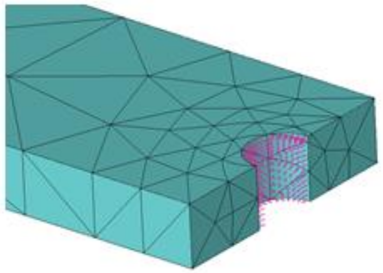
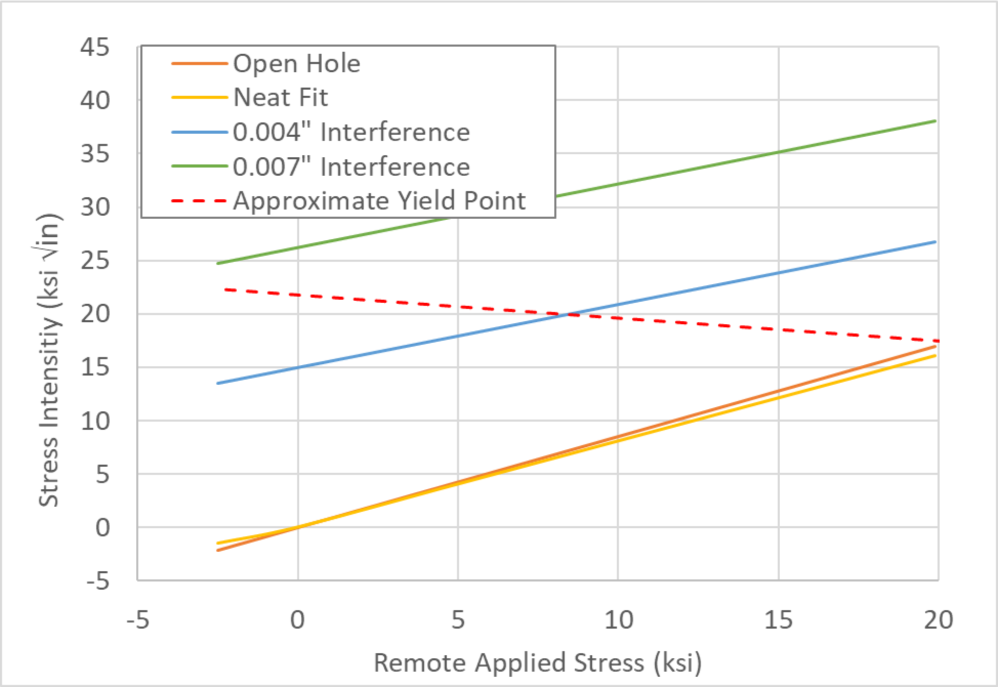
Analytical Approach

- Investigate Key Factors for Explicit Taper-Lok Modeling
  - Hole propping/interference, pre-stresses, and residual stress
- Modeling Approaches
  - Multi-point fracture mechanics
    - Explicit model geometry, loading, etc.
    - Enables natural crack shape evolution
  - Hole propping/interference
    - Multi-body contact
    - Springs
    - Pressure distributions
  - Pre-stresses
    - Reduced ΔK and R_{eff}
    - K vs. σ_{ref} characterization
  - Residual stress
    - Crack face pressures
    - Full-field residual stress
  - Characterize elastic and plastic response
  - Investigate variations in key factors and their influence on damage tolerant life
- Tool Updates
  - Incorporate ability to pass tabular lookup (K vs. σ_{ref}) instead of alpha to AFGROW from BAMF to address non-linearity of SIFs from interference





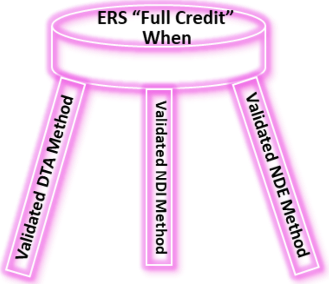


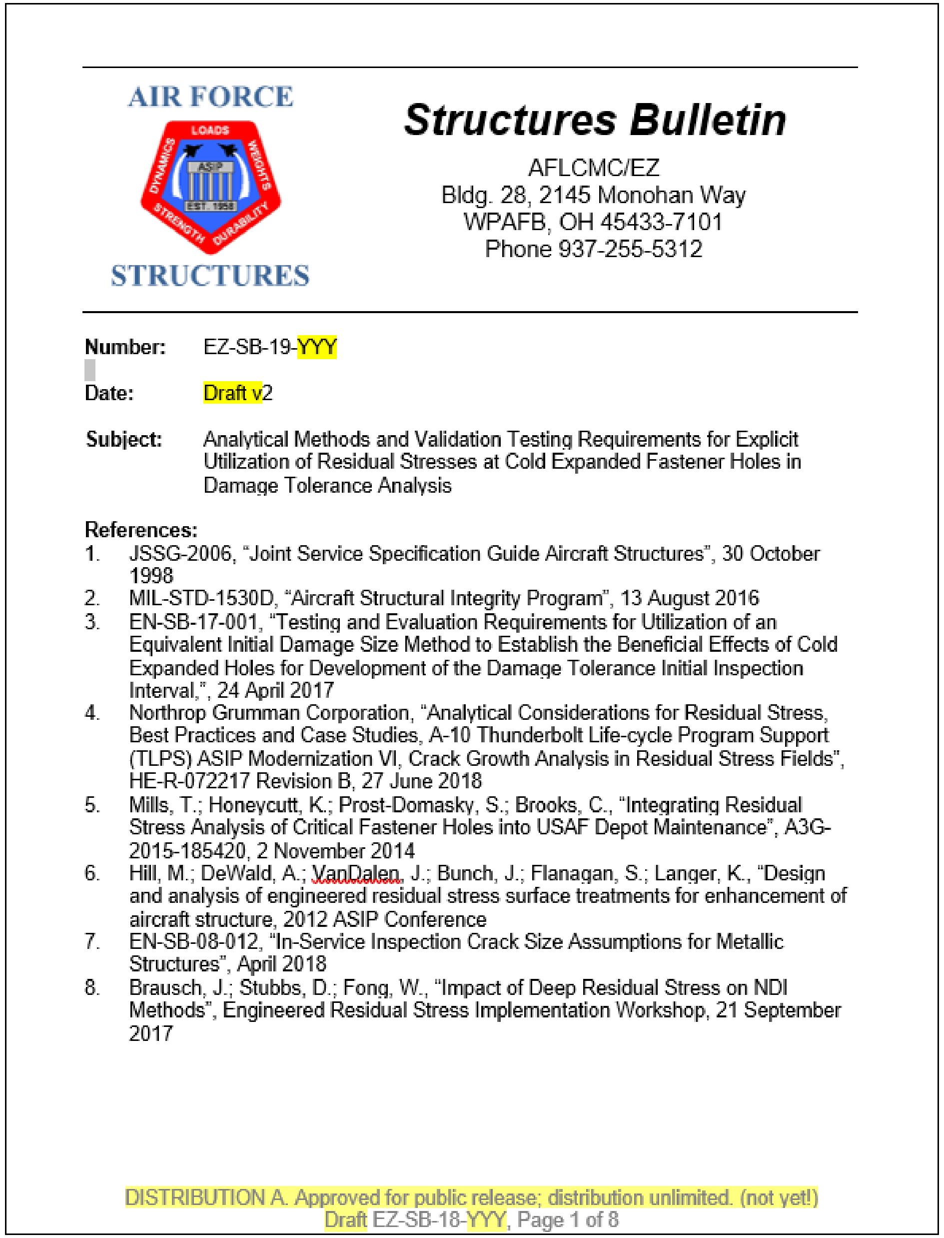


Misc. Other

USAF Structures Bulletin for ERS

- Objective
  - Provide guidance and requirements for "full credit"
- Approach
  - Considers the 5 factors for new materials, processes, joining methods and/or structural concepts in MIL-STD-1530D (para 5.1.7)
    - Stable: established process to impart ERS?
    - Producible: validated Quality Assurance (QA) or Non-Destructive Evaluation (NDE) method?
    - Characterized properties: known ERS field and known damage growth rates through ERS field?
    - Predictable performance: validated DT Analysis (DTA) method?
    - Supportable: validated QA/NDE and Non-Destructive Inspection (NDI) methods during sustainment phase?
- Initial Scope
  - Primarily focused on initial inspection benefit
  - NDE is required for recurring inspection interval benefit
- Status
  - Release for ASIP Manager review is imminent





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: Draft v2

Subject: Analytical Methods and Validation Testing Requirements for Explicit Utilization of Residual Stresses at Cold Expanded Fastener Holes in Damage Tolerance Analysis

References:

1. JSSG-2006, "Joint Service Specification Guide Aircraft Structures", 30 October 1998
2. MIL-STD-1530D, "Aircraft Structural Integrity Program", 13 August 2016
3. EN-SB-17-001, "Testing and Evaluation Requirements for Utilization of an Equivalent Initial Damage Size Method to Establish the Beneficial Effects of Cold Expanded Holes for Development of the Damage Tolerance Initial Inspection Interval,", 24 April 2017
4. Northrop Grumman Corporation, "Analytical Considerations for Residual Stress, Best Practices and Case Studies, A-10 Thunderbolt Life-cycle Program Support (TLPS) ASIP Modernization VI, Crack Growth Analysis in Residual Stress Fields", HE-R-072217 Revision B, 27 June 2018
5. Mills, T.; Honeycutt, K.; Prost-Domasky, S.; Brooks, C., "Integrating Residual Stress Analysis of Critical Fastener Holes into USAF Depot Maintenance", A3G-2015-185420, 2 November 2014
6. Hill, M.; DeWald, A.; VanDalen, J.; Bunch, J.; Flanagan, S.; Langer, K., "Design and analysis of engineered residual stress surface treatments for enhancement of aircraft structure, 2012 ASIP Conference
7. EN-SB-08-012, "In-Service Inspection Crack Size Assumptions for Metallic Structures", April 2018
8. Brausch, J.; Stubbs, D.; Fong, W., "Impact of Deep Residual Stress on NDI Methods", Engineered Residual Stress Implementation Workshop, 21 September 2017

DISTRIBUTION A. Approved for public release; distribution unlimited. (not yet!)
Draft EZ-SB-18-YYY, Page 1 of 8

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Literature Review

- Objective
  - Develop a consolidated summary of Cx references for the community
  - Increase visibility of existing Cx references
- Approach
  - Developed a template to identify key parameters
  - Divvy 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

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

Breakout Session Agenda

- Breakout Discussions, Session 1 (Thursday, 3-5pm)
  - Individual presentations
    - Closure (Mills)
    - Interference Fasteners (Mills)
    - FCG Testing of Complex Coupons with Quench Induced Residual Stress (Hill)
  - Re-Vectoring
    - Revisit our current focus areas and technology gaps
    - Discuss new focus areas for upcoming year
- Breakout Discussions, Session 2 (Friday, 8:30-10:30am)
  - Individual presentations
    - Short Edge Margin Evaluation (Ross)
  - Round Robin #2 Planning (Warner)
  - Open discussion and task assignments

Questions?