Fatigue Crack Growth & Testing Committee

2023 ERSI Workshop

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Overview

- **Committee summary**
  - Roster summary
  - Mission and key objectives
  - Implementation roadmap
  - Focus areas and active working groups
- **Accomplishments**
- **Working groups**
  - Spectrum loading
  - Interference fit fasteners
- **Breakout presentations**
- **Future plans & open discussion**

ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Roster Summary

- **Committee members**
  - 68 members
  - Diverse participation from government, OEMs, small businesses, and academia
- **Active participants**
  - ~20-25 participants in monthly meetings
- **Working groups**
  - Two primary working groups
    - Spectrum loading
      - Leads – Moises, Walker, Newman
      - Participants – 7 members
    - Interference fit fasteners
      - Leads – Pilarczyk, Loghin, Ribeiro
      - Participants – 19 members

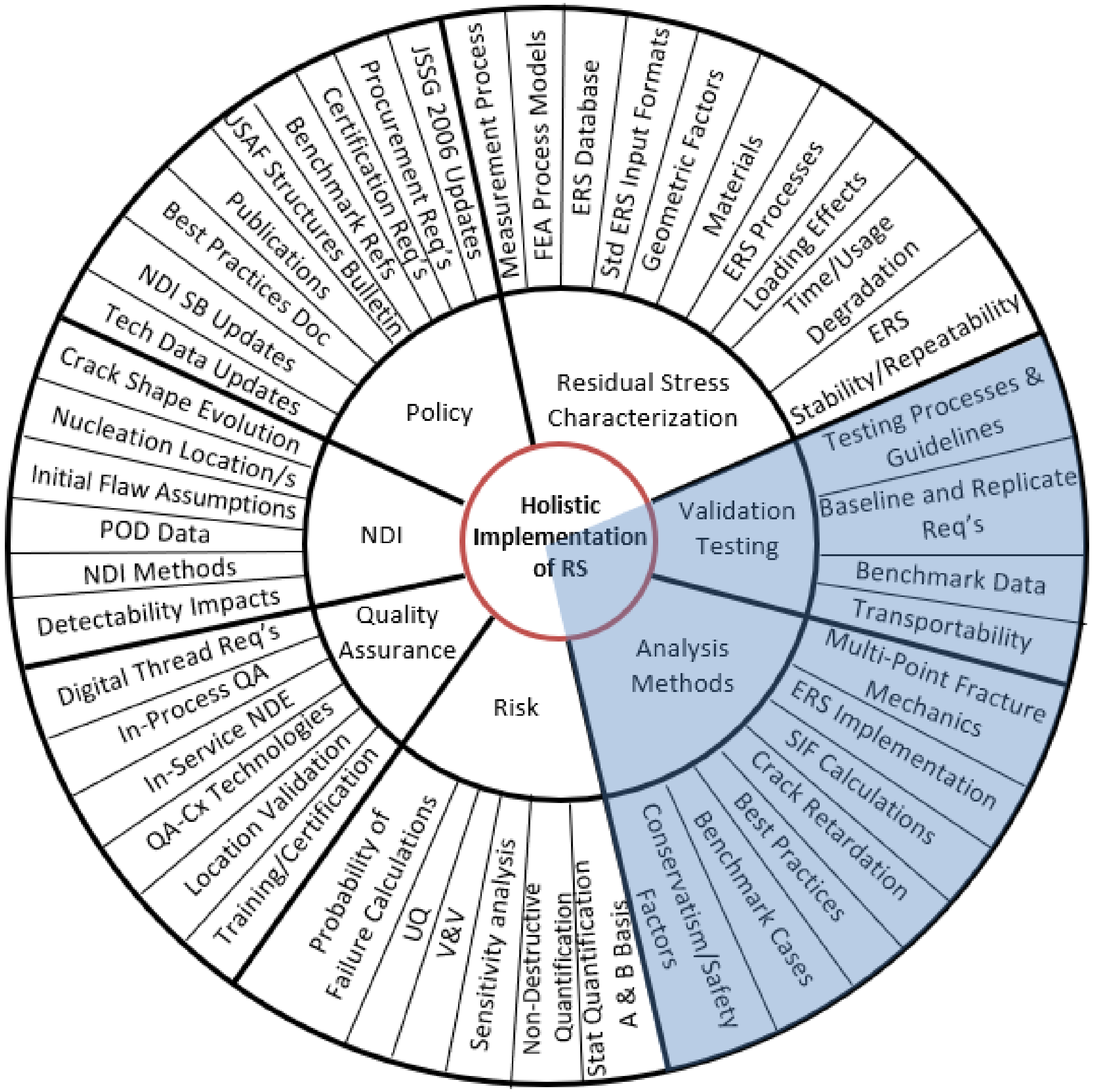
Vision

- **Mission statement**
  - Establish **analytical and testing guidelines** to support the implementation of engineered residual stresses
- **Key objectives**
  - Develop and document **best practices** for the integration of engineered residual stresses into fatigue crack growth prediction methodologies
  - Establish **testing requirements** considering the impacts of residual stress on fatigue crack growth
  - Develop **datasets and case studies** to support analysis methods validation
  - Identify, define, and enable the **resolution of gaps** in the analytical methods state-of-the-art
  - Support the development of an **implementation roadmap**

Implementation Roadmap

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

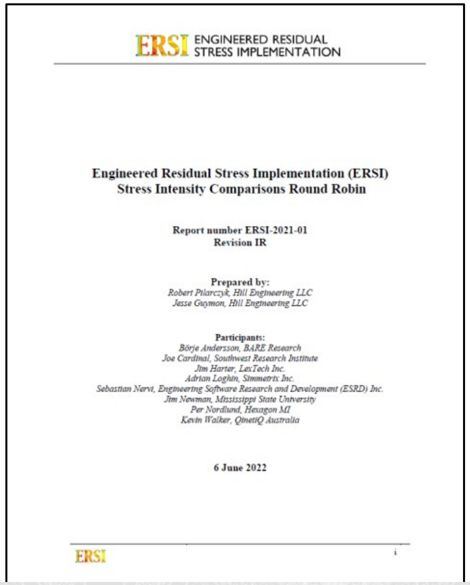
- **Approach**
  - Leverage ASIP Lincoln Wheel
  - Tailored for ERS
  - Identify key focus areas
  - Highlight focus areas based on criticality and maturity
- **Benefits**
  - Utilize to communicate development needs



ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Accomplishments

- **SIF round robin**
  - Final report
    - Complete
  - Publications
    - Planned to publish review article in Engineering Fracture Mechanics
      - Mixed responses from editor team and article was not accepted
    - Alternatively:
      - Data and final report will be loaded to ERSI website
      - Summary included in the Swedish National ICAF 2023 Review
  - Presentations
    - Presented at 2022 ASIP conference by Kevin Walker



ERSI ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Engineered Residual Stress Implementation (ERSI)
Stress Intensity Comparisons Round Robin

Report number ERSI-2021-01
Revision IR

Prepared by:
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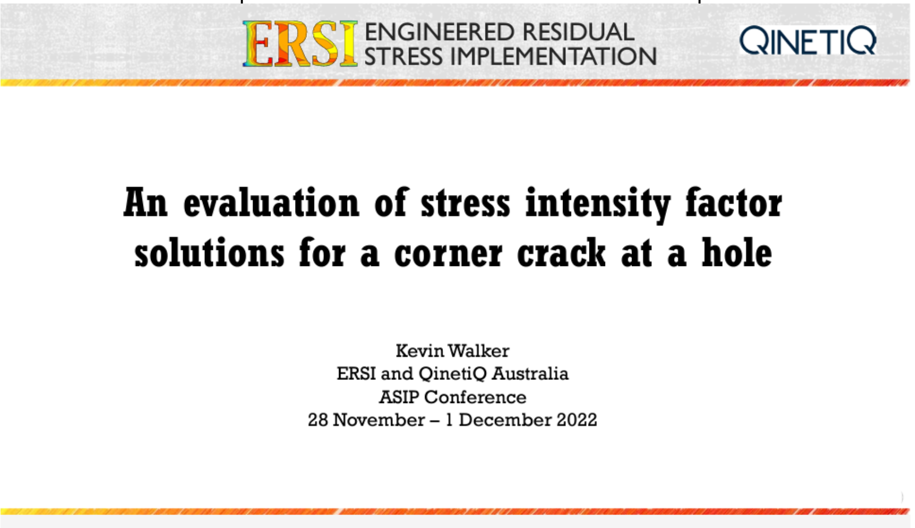
Jim Harter, LexTech Inc.
Adrian Loghin, Simmetrix Inc.
Sebastian Nervi, Engineering Software Research and Development (ESRD) Inc.
Jim Newman, Mississippi State University
Per Nordlund, Hexagon MI
Kevin Walker, QinetiQ Australia

6 June 2022

ERSI i



Accomplishments

- **DTA for variability in residual stresses at cold expanded holes round robin**
  - Objective
    - Identify the sensitivity of DTA, both two-point and multi-point, capabilities to variability in a CX fastener hole treated within specifications
  - Approach
    - Phased approach with increasing complexity (Complete)
      - Phase I: Baseline (non-CX) DTA verification for both CA and VA spectra (corresponding Nf test data released after receipt of prediction results)
      - Phase II: CX treated DTA predictions for both CA and VA spectra
    - Validation testing sponsored by AFRL/RX and RQ (Ongoing)
  - Current Status
    - Phase I & II: Complete!
      - Hot wash debrief given earlier this year
    - Test plan complete for purposes of this study
      - Additional data being produced for additional insight
  - Timeline
    - Phase I & II: Complete as of 28 November 2022
    - Test plan (Nf for limited population) complete as of 1 October 2022
      - Running additional replicates and fractography due ~1 June 2023 (PAQs and Junior Engineer recruited to assist)

Focus Areas

- **Spectrum loading and retardation (active)**
  - Investigate the appropriate methods to characterize crack retardation due to spectrum loading for conditions with residual stress
  - Gather and/or develop test data to support validation of methods
  - Document best practices and lessons learned
- **Interference fit fasteners (IFF) and residual stress (active)**
  - Investigate the relationship between interference fit fasteners and residual stresses from Cx and/or Taper-Lok
  - Identify appropriate methods to incorporate interference fit fastener benefit for conditions with residual stress
  - Document best practices and lessons learned
- **Durability testing and fatigue life benefits (not active)**
  - Review existing test data and develop summary to document Cx life impacts on early crack nucleation and growth
  - Identify any testing needs to further refine understanding

Spectrum Loading Working Group

- **Participation**
  - ~ 10 members
- **Objectives**
  - Collaborate to understand load interaction effects on crack growth using simple spectrum loading (spike overload) and spectrum loading. Validate and understand limitations of proposed modeling for plastic tip constrain loss.
- **Approach**
  - Perform blind predictions with various analysis tools and retardation approaches
  - Develop validation test data to compare/contrast with analysis predictions
- **Key collaboration areas**
  - Boeing CSM Spectrum Loading Round Robin (Moises)
  - Spike Overload Testing (Boeing & QinetiQ Australia/Mississippi State)

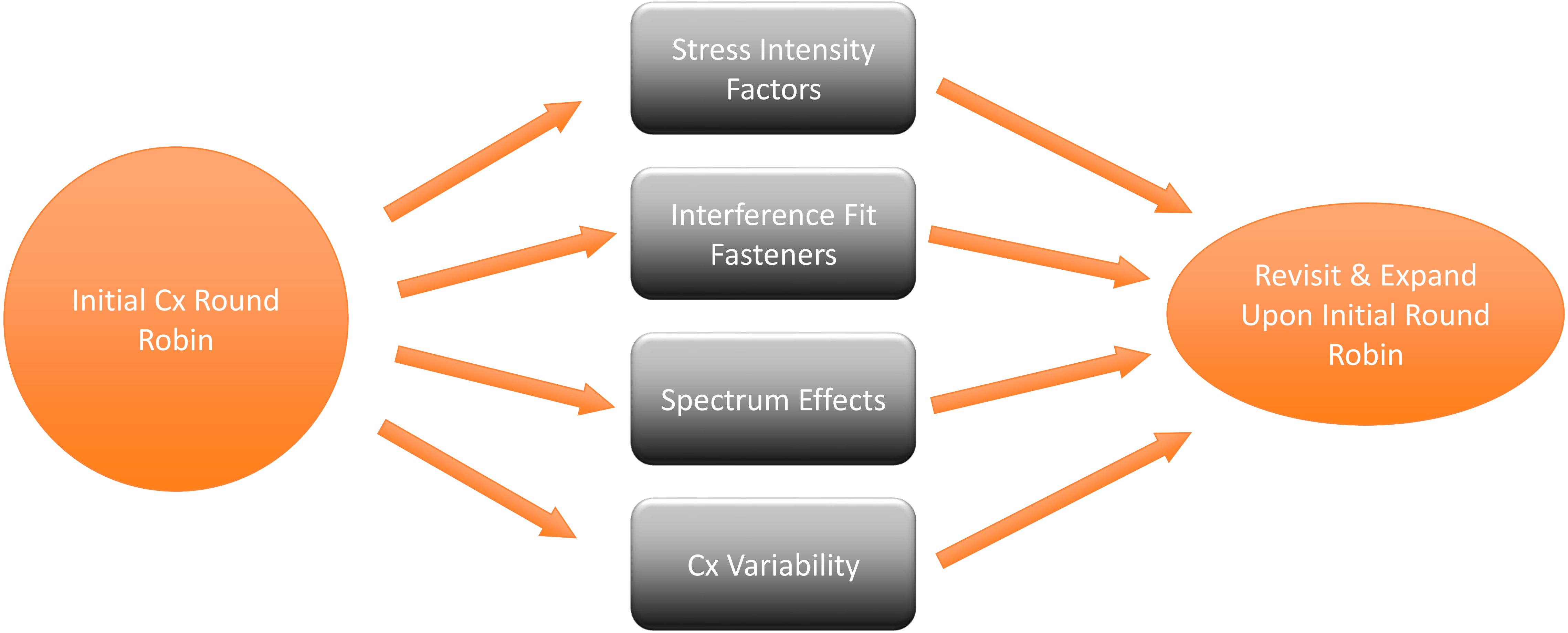
IFF Working Group

- **Participation**
  - 13 members
- **Objective**
  - Collaborate to establish validated analytical methods for Interference Fit Fasteners (IFF)
    - Review Physics of Interference Fit Fastener
    - Characterize Existing Methods & Data
    - Identify Key Factors and Gaps in Current Methods/Data
- **Approach**
  - Phased approach with increasing complexity
    - Phase I: Baseline stress analysis verification
    - Phase II: Stress intensity factor comparisons
    - Phase III: Crack growth analyses comparisons
  - Validation tests sponsored by A-10 team to accompany analyses
- **Key collaboration areas**
  - IFF Analysis Round Robin (Pilarczyk, Loghin, Ribeiro)
  - A-10 IFF Testing & Analysis Program (Warner, Smith)

Breakout Presentations

- Spectrum loading / spike overload (Ocasio-Latorre)
- Cx variability round robin (Spradlin)
- IFF round robin (Pilarczyk)
- IFF update (Loghin)

Committee Goals



Past	Present	Future

Future Plans

- **Key focus areas for 2023-2024**
  - Re-visit initial ERSI Cx round robin
  - Continuation of Interference Fit Fastener work
  - Extend Spectrum effects work into cases with cold work and interference fit fasteners

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Revisit 2018 CW Hole Round Robin

- **RR background**
  - Conducted in 2018 around 2024-T351 material
  - Corner crack at a 0.5 inch dia hole, 4 inch wide, 0.25 inch thick
  - Conditions of constant amplitude loading with and without Cx RS
- **Impacts**
  - Established baseline for ERSI prediction capability
  - Initiated several follow-on efforts (e.g., SIF Round Robin)
- **Moving forward**
  - Revisit original round robin incorporating what we've learned in ERSI
    - SIF solutions and other improvements
    - Measurement committee best practices and new data
  - Continue to investigate differences between test and analysis
  - Start investigation combined effects of Cx with spectrum and IFF
- **With the knowledge and data developed over the last 5 years, can we do better in terms of accuracy of prediction and understanding the variability due to issues like known accuracy of SIF solutions and quantification of RS distributions, etc.?**

Interference Fit Fasteners

- **Continue collaborative working group**
- **Phase I: Baseline stress analysis verification**
  - Complete remaining predictions
  - Verify against known published solutions and new test data (tollgate)
  - Define best practices and lesson's learned
  - Establish benchmark solutions for the community
- **Phase II: Stress intensity factor comparison**
  - Complete predictions and comparisons for corner and through cracks at IFF holes
  - Define best practices and lesson's learned
  - Establish benchmark SIF dataset for the community
- **Phase III: Crack growth analysis**
  - Complete FCG predictions for corner and through crack IFF conditions
  - Define best practices and lesson's learned
  - Compare/contrast relative to new test data
- **Cx & IFF**
  - Utilized lesson's learned to incorporate effects of both technologies
  - Define test program to support expanded round robin for Cx and IFF

Spectrum Loading

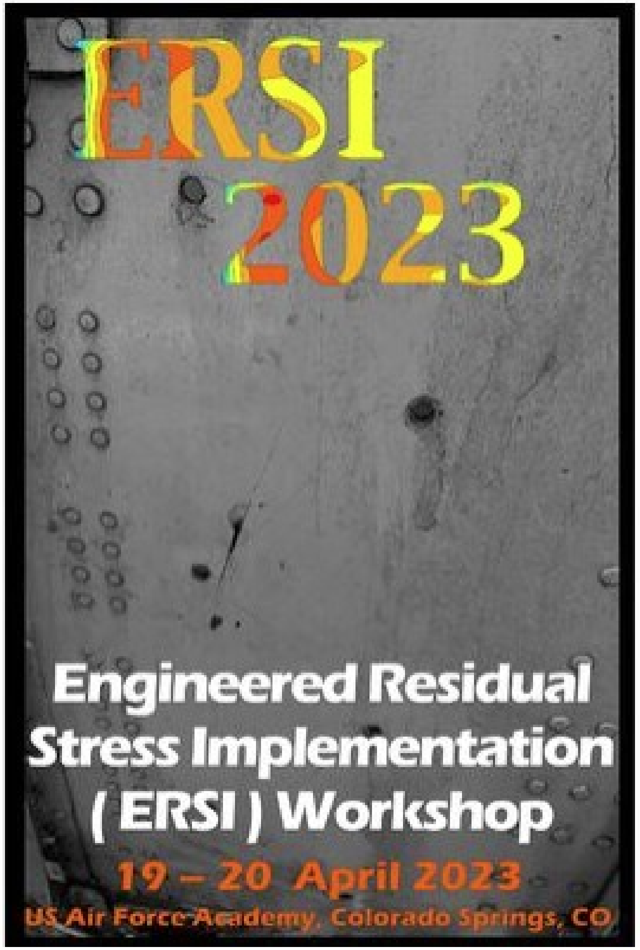
- **Spike overload testing**
  - Complete current testing at QinetiQ, Mississippi State, and Boeing
  - Characterize crack growth rate constraint-loss behavior and duration
  - Building block towards prediction of real life scenarios (e.g., local residual in structure loaded with variable amplitude spectrum
- **Cx and spectrum effects**
  - Build upon original RR and recent TJ RR incorporating spectrum testing and analysis predictions
    - Consider expanding to additional materials (7050-T7451, etc.)

Summary

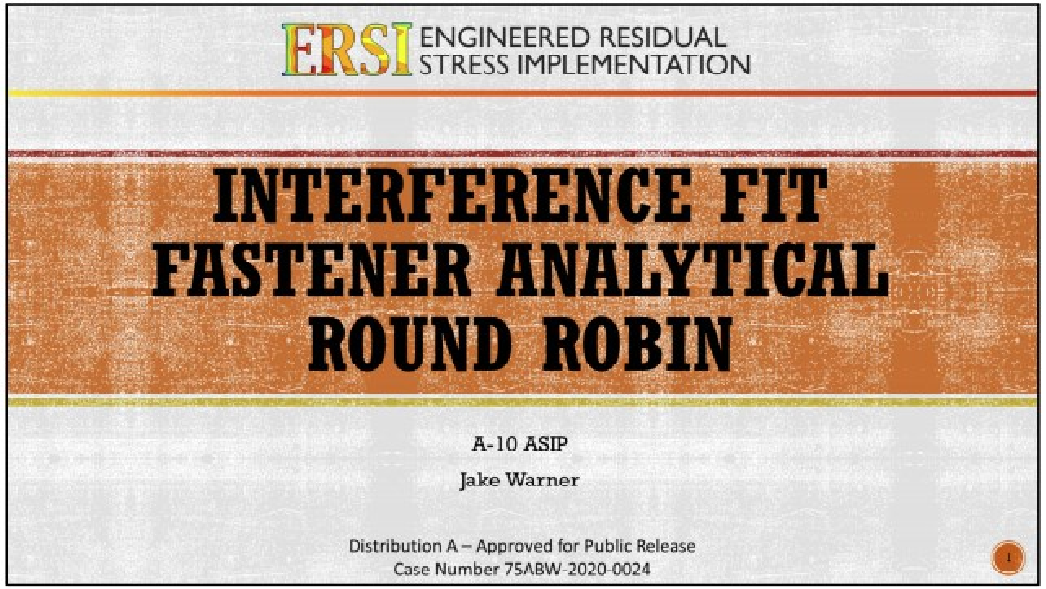
- **Diverse, active committee focused on key aspects for accurate analytical predictions with supporting validation data**
- **Topic areas have expanded beyond Cx since the original round robin**
  - Areas are critical for practical application
- **Refocusing on Cx cases is important moving forward**
  - Address differences between predictions and tests
  - Incorporate effects of IFF and spectrum
- **More active engagement in roadmap to address gaps**

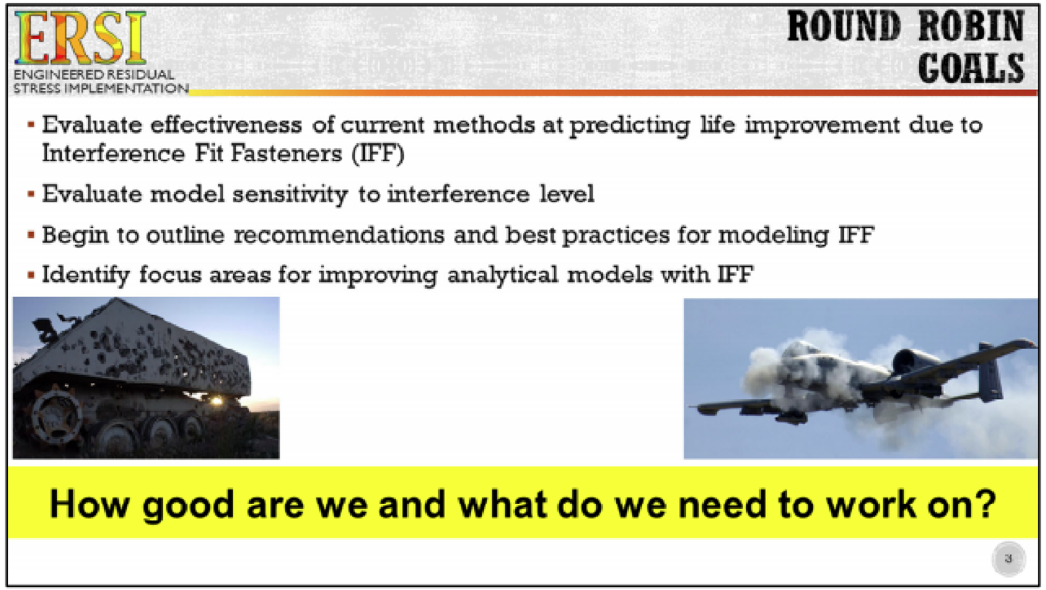
Verification&Validation and UQ
2020 Interference Fit Round Robin: revisited

Adrian Loghin
Simmetrix Inc.
Clifton Park, NY



IFF Round Robin Challenge: V&V Opportunity





Reference:
https://afgrow.net/workshop/documents/2020/Jacob-Warner-Interference-Fit%20Fastener-Analytical-Round-Robin_Workshop-2020.pdf

- Round Robin Challenge Report: “Interference Fit Fastener Analytical Round Robin”, Jake Warner, A-10 ASIP, 2020.
  - Potential to extend inspection intervals at interference fit fastener holes
  - Modeling procedures need to pass verification and validation requirements (V&V), best practices to follow.
- Any round robin challenge is a V&V opportunity
  - Verification&Validation (V&V) requirements need to be satisfied to the greatest extend possible to provide confidence in the methodology application at component level.

IFF Round Robin Challenge: Problem Statement

Interference Fit Fastener Prediction Challenge

Analysis Methods Subcommittee

Round-Robin Life Prediction Invitation for Interference Fit Holes

Purpose:

Early discussions within the Engineered Residual Stress Implementation (ERSI) Analysis Methods Committee identified a need to perform a series of round-robin exercises. The primary focus of these round-robin exercises is to identify the random and systematic uncertainties associated with Damage Tolerance Analyses (DTA) related to residual stresses. Many factors influencing the total uncertainty have been discussed and are currently under investigation by various members of the ERSI

This is the
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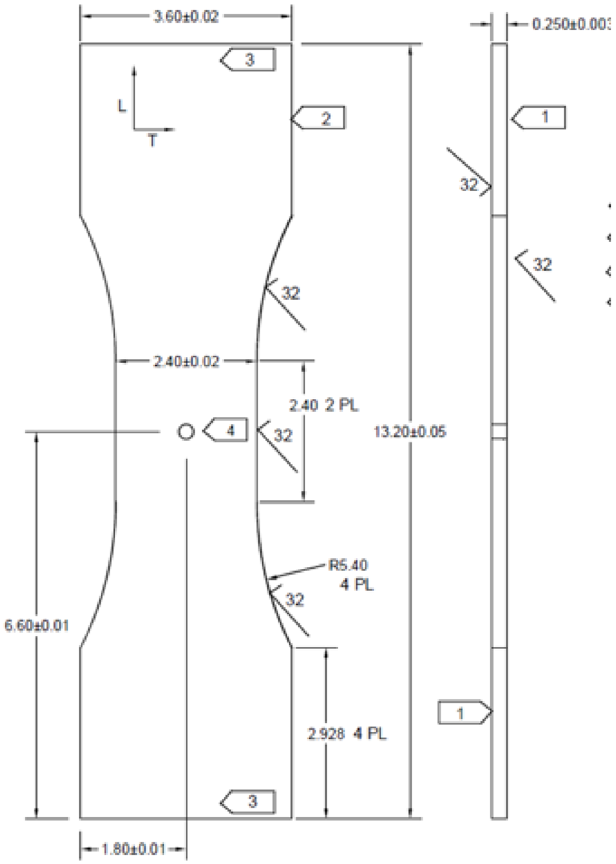
Conditions:

Specific conditions were selected to target existing datasets as well as the most basic conditions to predict. For all conditions, sufficient fatigue test and crack growth rate data exists to provide a sound foundation for comparison. As shown in Table 1, three conditions are identified with similar geometry, the baseline condition is an open hole test. The second and third conditions incorporate an IFF. The second condition, 0.4% interference, was the target interference for the test program that will be compared to. However, typical final hole tolerances permit a 0.6% interference condition, condition 3, so predictions at both interference levels are of interest.

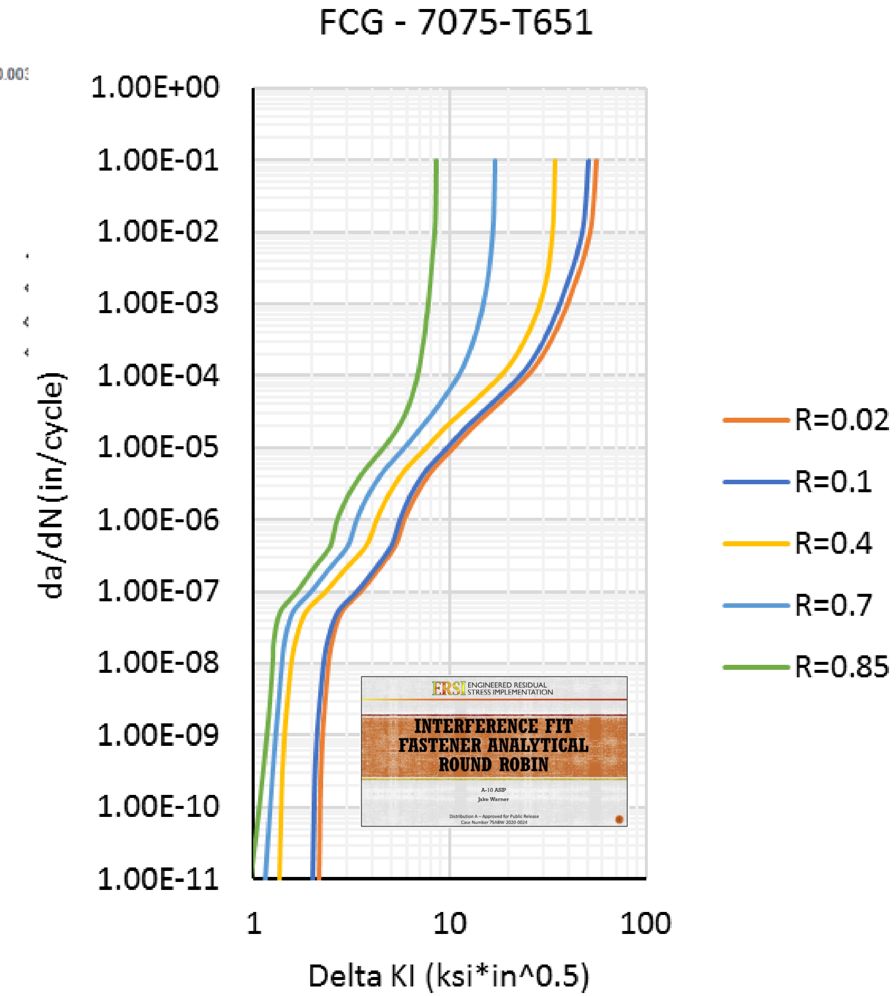
Table 1. Round-robin analysis conditions

Condition	Specimen Type	Hole Diameter (in)	Fastener Diameter (in)	Surface Precrack Length (in)	Bore Precrack Length (in)	Loading	Max Stress (ksi)
1	Open Hole	0.25	N/A	0.027	0.0278	CA (R=0.1)	27.9
2	0.4% IFF	0.2479	0.24885	0.0257	0.042		
3	0.6% IFF	0.2474	0.24885	0.0257	0.042		

Property	Value
Material	7075-T651 plate
Modulus (ksi)	10400
Poisson	0.33
Ultimate Strength (ksi)	83
Yield Strength (ksi)	73
Plane Stress Fracture Toughness (ksi-root(inch))	58
Plane Strain Fracture Toughness (ksi-root(inch))	27
RLo	-0.15
Rhi	0.85

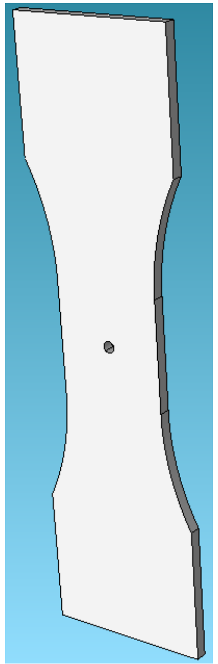


Length unit system: Imperial

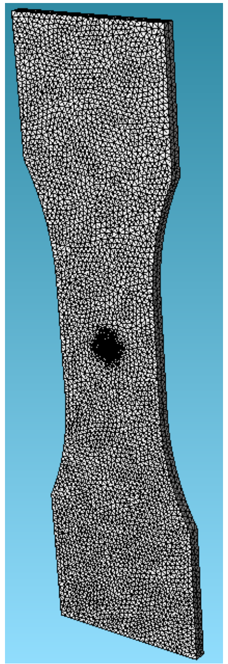


IFF Round Robin Challenge: 3D Modeling

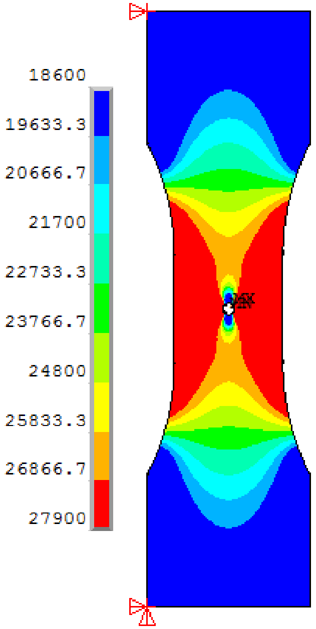
3D Geometry



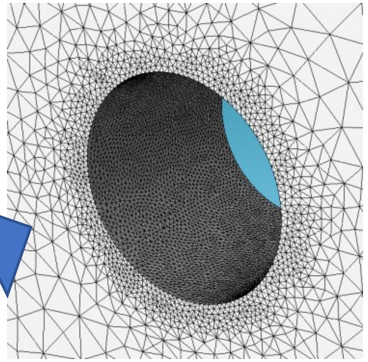
Mesh



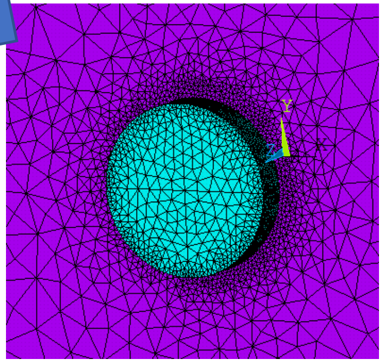
FE Model

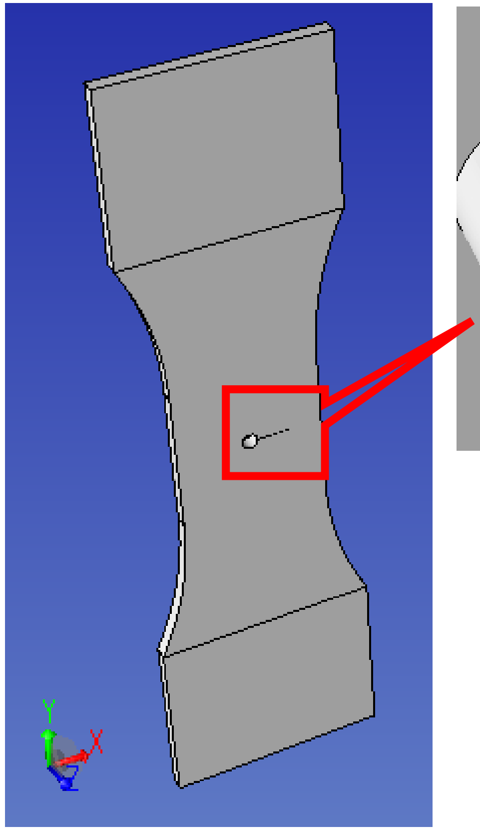


Open Hole Condition

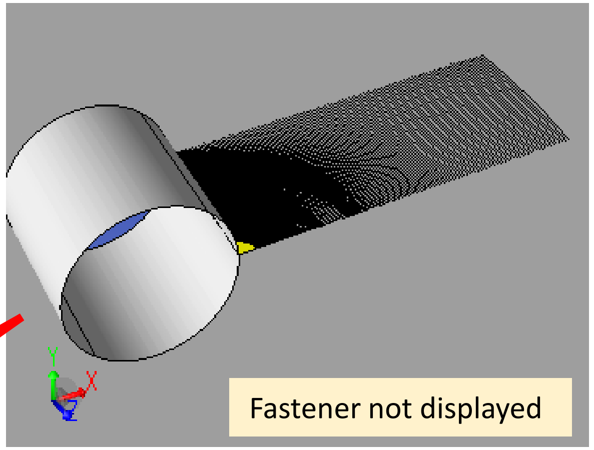


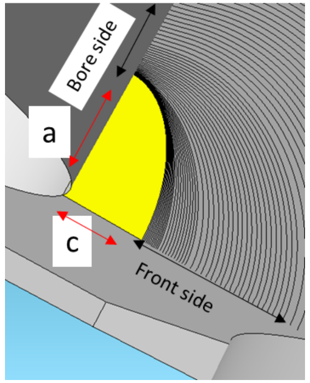
IFF Condition

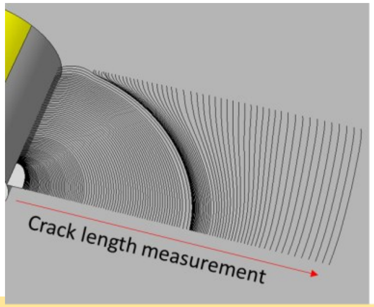




Typical solution: crack front increments





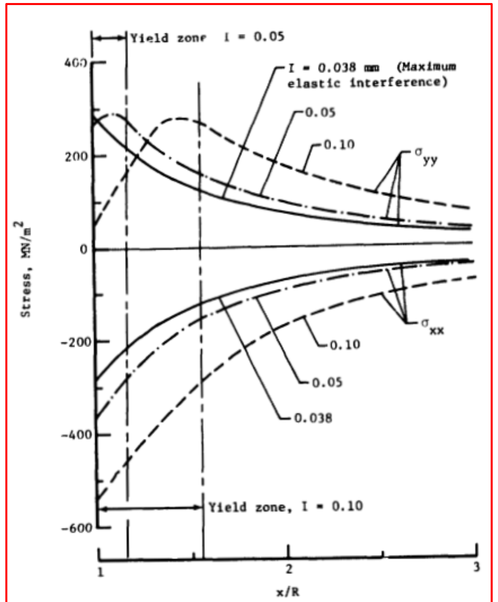


- Only 3D models are used in this assessment. The overall mesh pattern is maintained for all simulations
- Nominal bore and fastener diameters as provided in the challenge were used to create the 3D models for each condition.
- IFF stress levels are captured by solving the fastener-specimen bore contact for each increment.
- Far field loading conditions: max load = 18600 psi, min load = 1860 psi
- 3D solutions performed with SimModeler coupled with Ansys

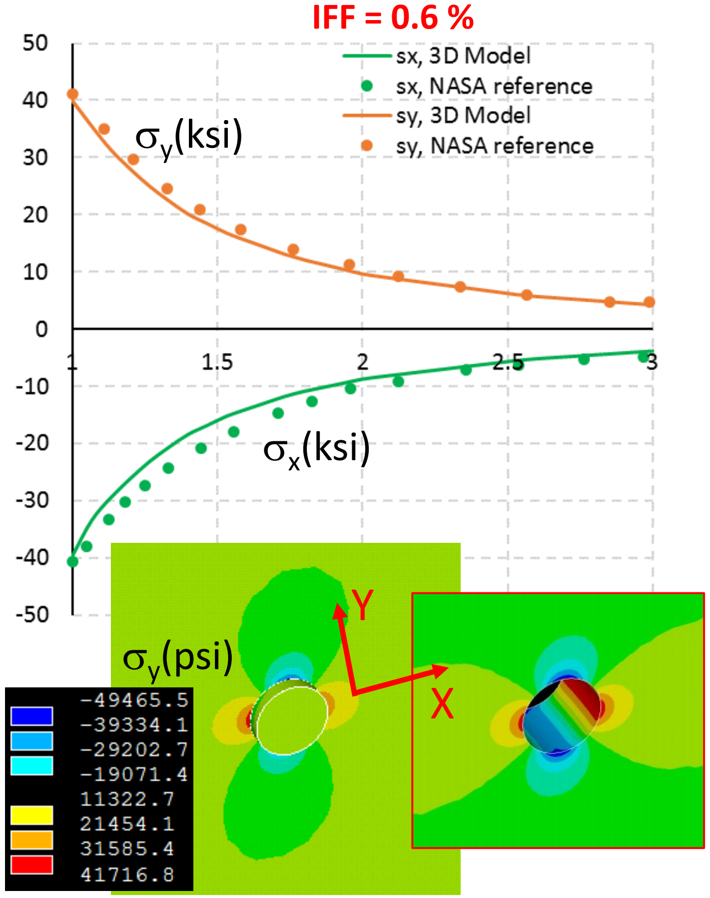
Same setup used for the finite element model without and with the crack

3D Model Verification

Stress gradient comparison for different IFF values



(a) Stress distributions along the X-axis.

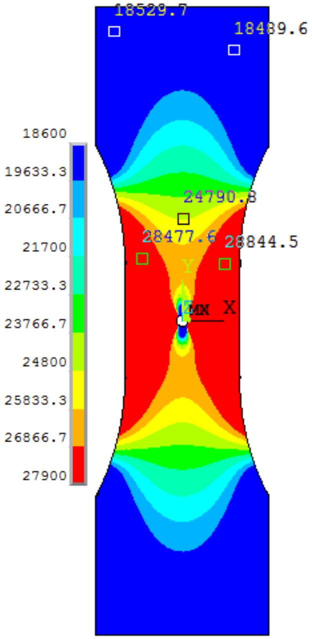


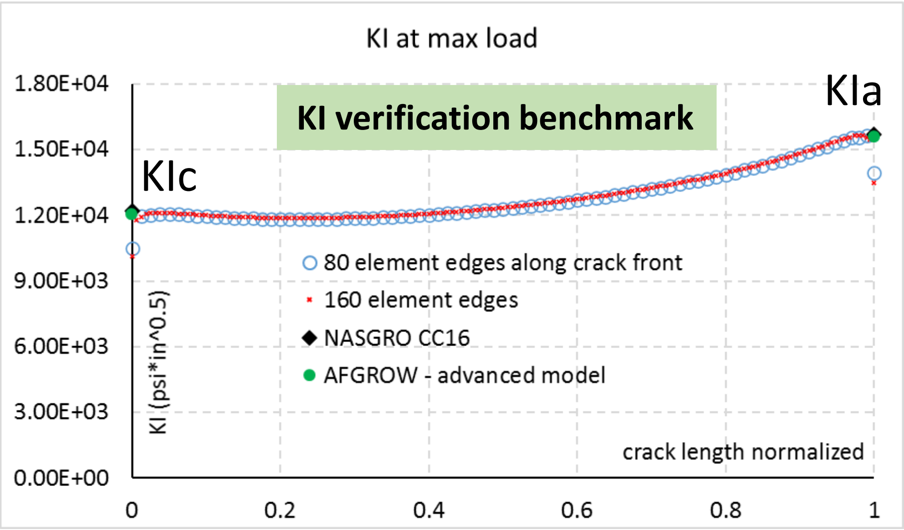
Reference: **John Crews, An elastoplastic analysis of a uniaxially loaded sheet with an interference-fit bolt, NASA, 1974.**

- Mid-thickness stress gradient extraction from the 3D model
- Elastic constitutive model for fastener and specimen

3D IFF stress gradients verification

K_I benchmark at max load (18.6 ksi grip section)





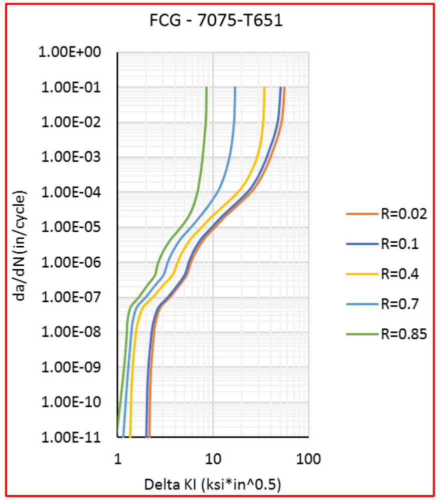
- Very good agreement between the 3D model prediction, AFGROW's advanced model and NASGRO's CC16
- Both NASGRO and AFGROW solutions are based on a geometry representative of the gauge section under uniform tension
- AFGROW (advanced model) solution was provided by Jim Harter
- NASGRO (CC16) solution provided by Shak Ismonov

Stress intensity factor (K_I) calculation is verified

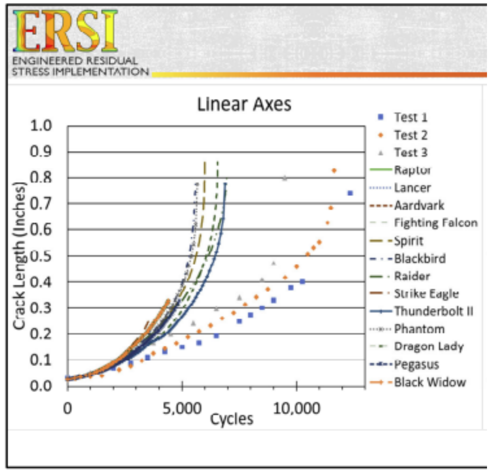
Open Hole solutions

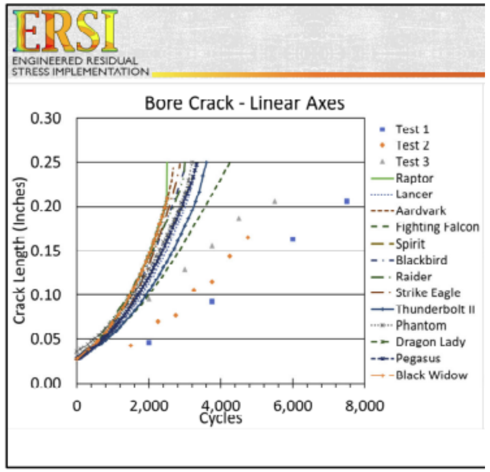
Engineered Residual Stress Implementation (ERSI) Workshop
19 – 20 April 2023
US Air Force Academy, Colorado Springs, CO

FCGR data 7075-T651 provided in the Round robin challenge

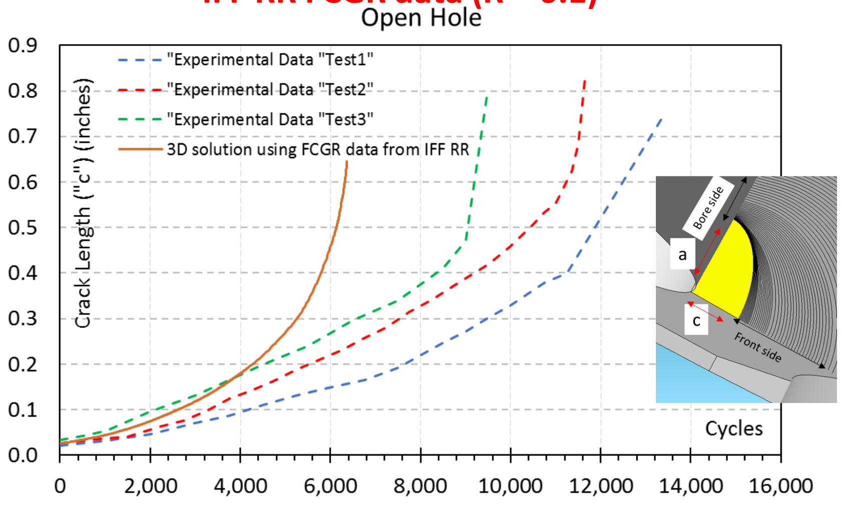


Interference Fit Fastener Analytical Round Robin, Jake Warner, 2020, AFGROW workshop.

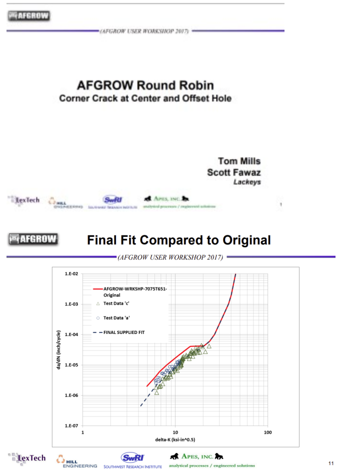


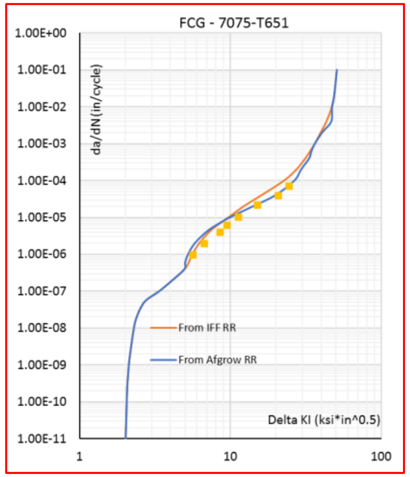


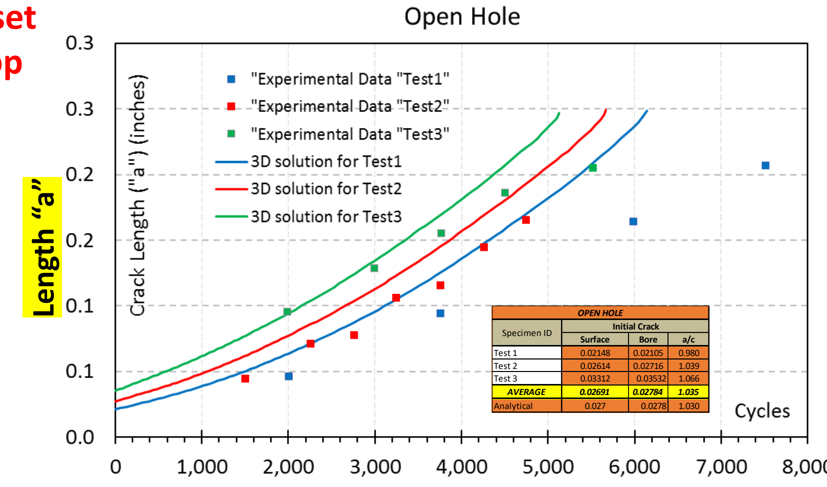
3D solution vs. experimental measurement using IFF RR FCGR data (R = 0.1)

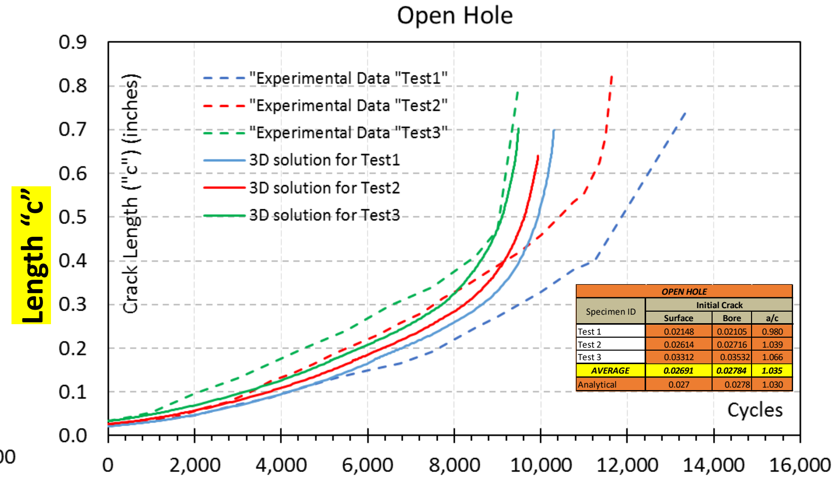


AFGROW Round Robin – Corner Crack at Center and Offset Hole, Tom Mills & Scott Fawaz, 2017 AFGROW Workshop





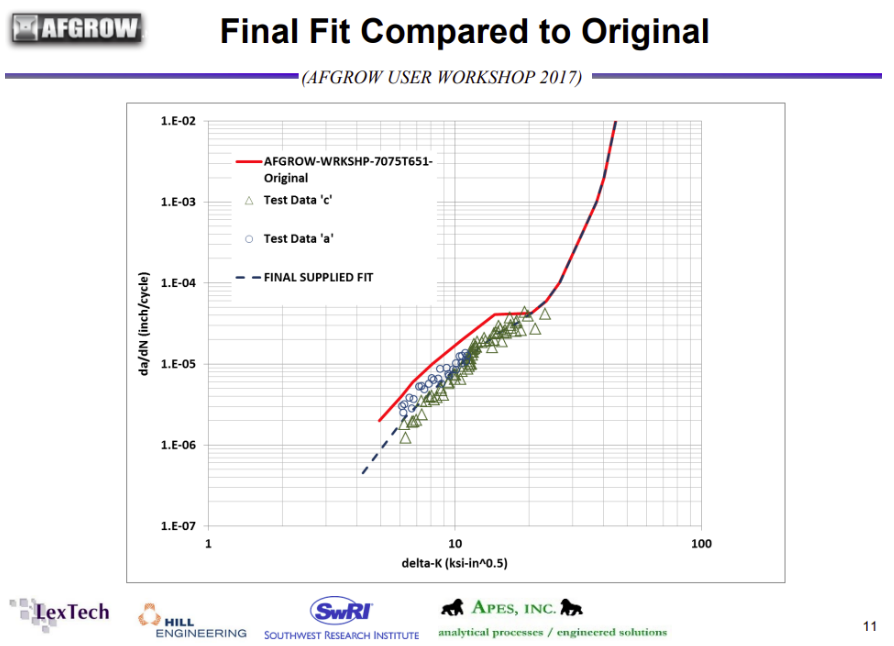


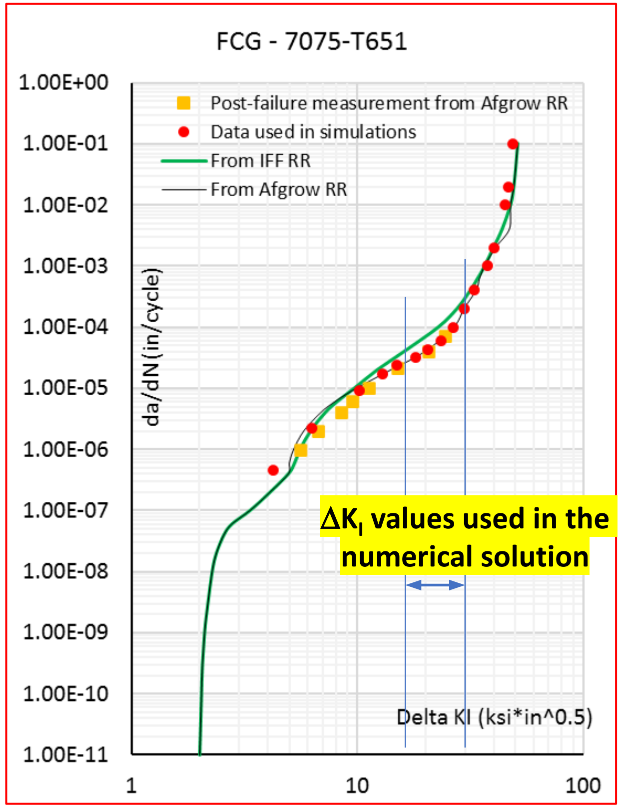


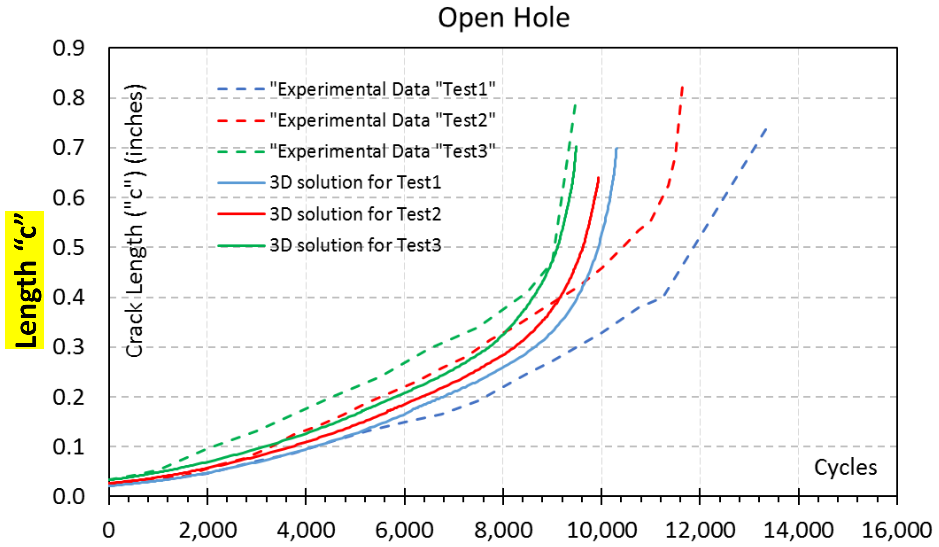
Numerical solutions are very sensitive to the FCGR data

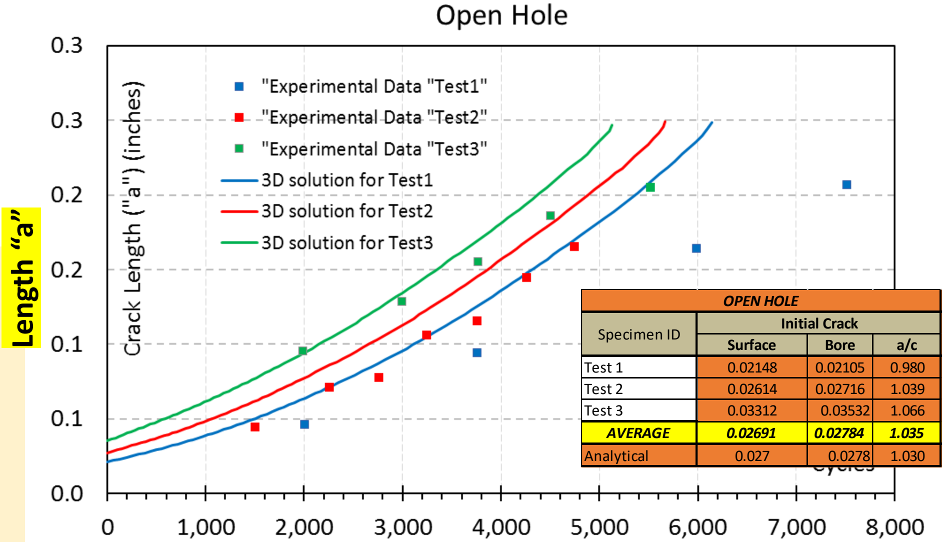
Open Hole solutions: FCGR sensitivity

AFGROW Round Robin – Corner Crack at Center and Offset Hole, Tom Mills & Scott Fawaz, 2017 AFGROW Workshop







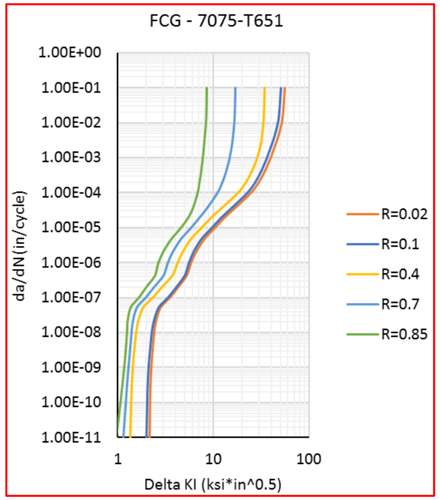


OPEN HOLE			
Specimen ID	Initial Crack		
	Surface	Bore	a/c
Test 1	0.02148	0.02105	0.980
Test 2	0.02614	0.02716	1.039
Test 3	0.03312	0.03532	1.066
AVERAGE	***0.02691***	***0.02784***	***1.035***
Analytical	0.027	0.0278	1.030

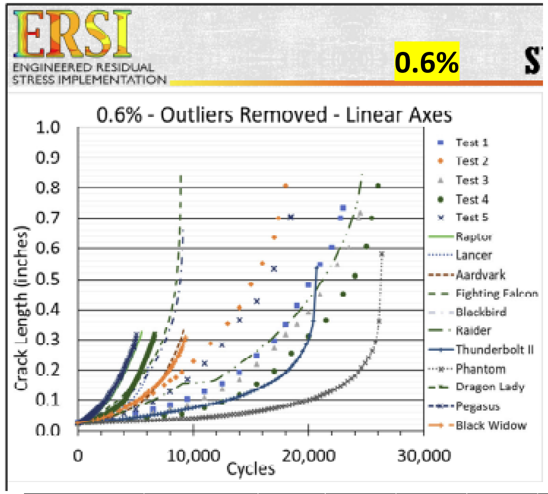
- **There are different sources of uncertainty that were not addressed in the round robin challenge. In general, additional instrumentation data is necessary to assess modeling solution sensitivity due to different sources of uncertainty.**
- **In this example, solution sensitivity due to FCGR scatter was evaluated in a simple manner by using the R = 0.1 for 7075-T651 from a different round robin**
- **Assessing FCGR experimental measurements at a given R ratio (average curve, ±2σ) needs to be well documented & accessible. This can be a topic that can be covered in ERSI's Analysis Methods & Testing, Risk Analysis and UQ.**

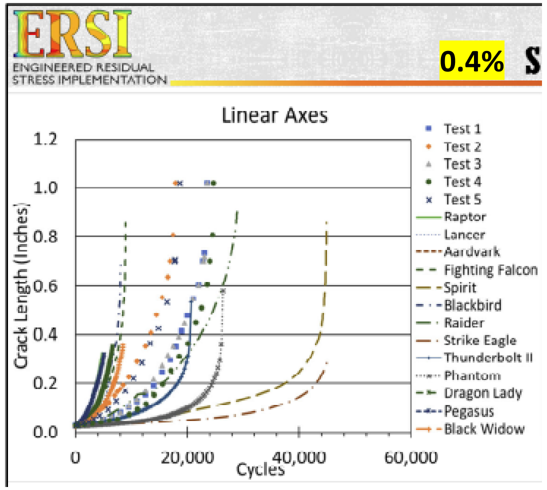
IFF 3D Crack Growth Solutions presented at AA&S 2021

FCGR data 7075-T651 provided in the Round robin challenge



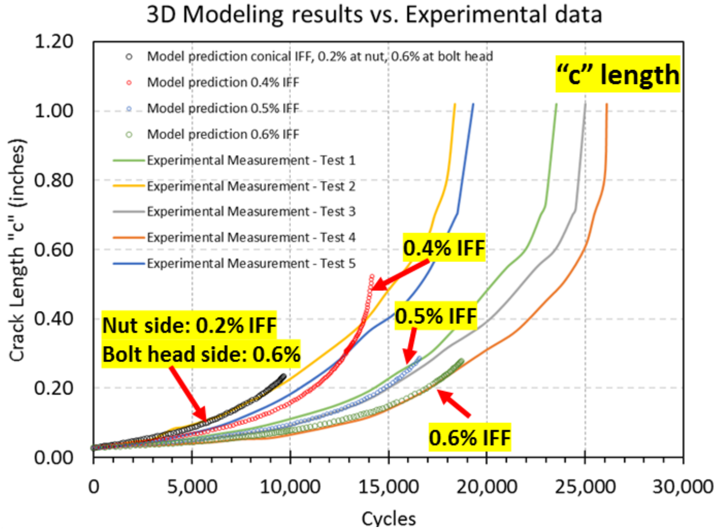
Interference Fit Fastener Analytical Round Robin, Jake Warner, 2020, AFGROW workshop.

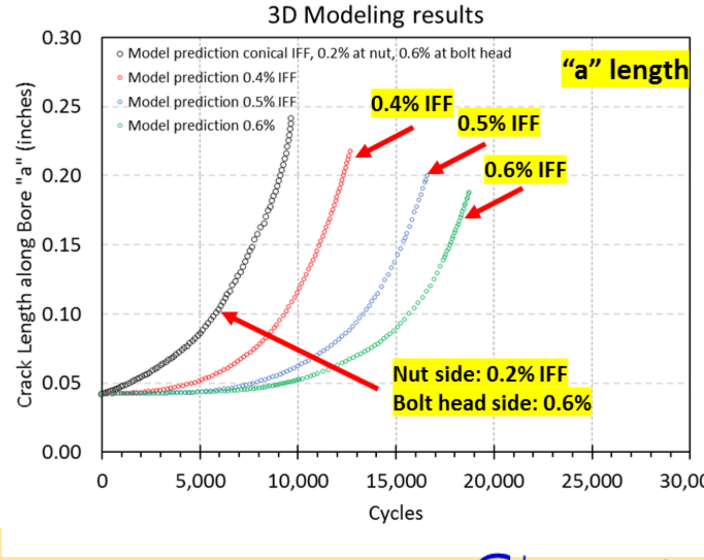




FILLED HOLE												
Specimen	Hole Diameter	Fastener Diameter			Interference			Fatigue Life	Initial Crack		
		MAX	AVE	MIN	MAX	AVE	MIN	Total	Surface	Bore	a/c
7D3-16-Da-2480	0.24786	0.24932	0.24884	0.24841	0.589%	0.397%	0.222%	23545	0.02978	0.04504	1.512
7D3-17-Da-2480	0.24784	0.24932	0.24884	0.24841	0.597%	0.405%	0.230%	18390	0.02522	0.04144	1.643
7D3-18-Da-2480	0.24789	0.24932	0.24884	0.24841	0.577%	0.385%	0.210%	24997	0.02252	0.04052	1.799
7D3-19-Da-2480	0.24788	0.24932	0.24884	0.24841	0.581%	0.389%	0.214%	26107	0.02480	0.03648	1.471
7D3-20-Da-2480	0.24788	0.24932	0.24884	0.24841	0.581%	0.389%	0.214%	19303	0.02616	0.04662	1.782
AVERAGE	*0.24787*				*0.585%*	*0.393%*	*0.218%*	*22468*	*0.02570*	*0.04202*	*1.635*

Corner Crack Round Robins: V&V and UQ, Adrian Loghin, 2021, AA&S.



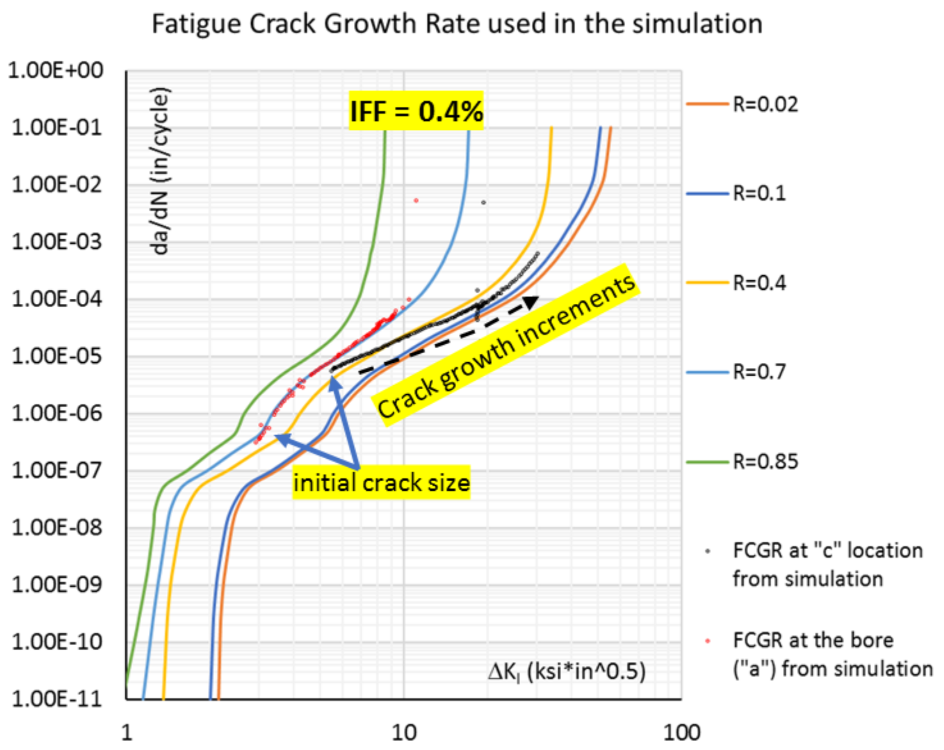


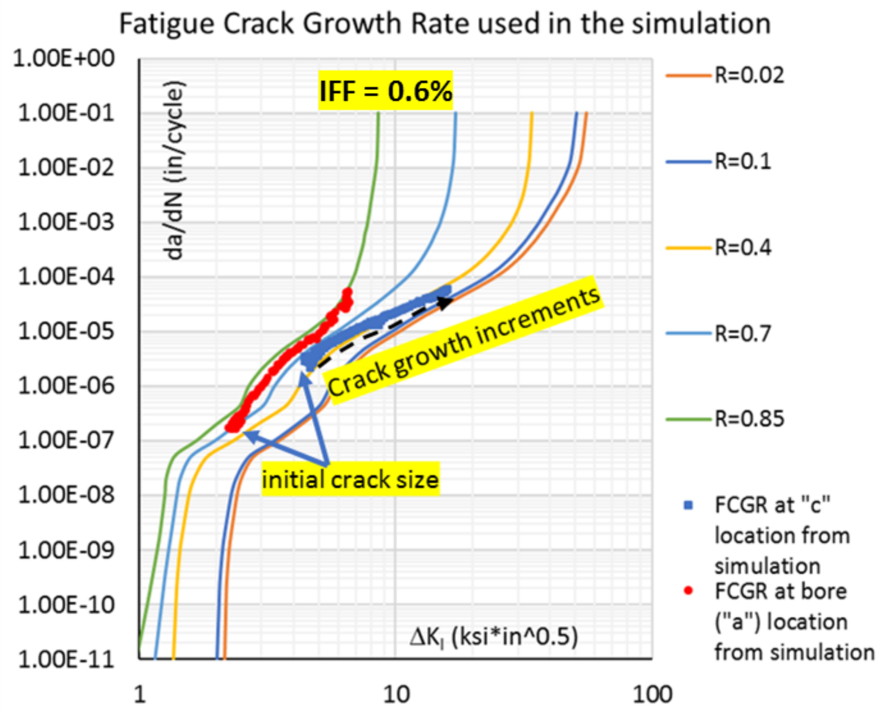
- **There is a discrepancy between the submitted solutions and the recorded measurement.**
- **Modeling details/tools that can lead to a scatter among the submitted solutions is currently addressed in the follow-up Round Robin challenge (stress gradient comparison among different numerical implementations).**

- **Using different IFF levels, the 3D FEA based approach seems to capture quite well the experimental measurement at least in the initial 50% of RUL.**
- **The numerical procedure relies on interpolation between the R curves since the R values along each crack front varies from the bore to the front side of the specimen. This can be a major contributor to the modeling uncertainty.**

IFF 3D Crack Growth Solutions presented at AA&S 2021

Corner Crack Round Robins: V&V and UQ, Adrian Loghin, 2021, AA&S.



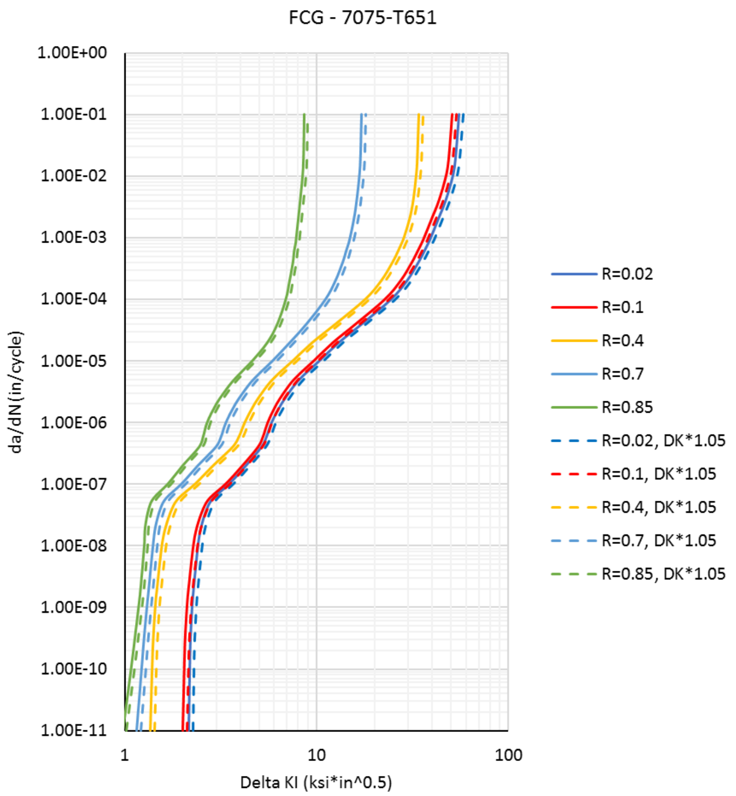


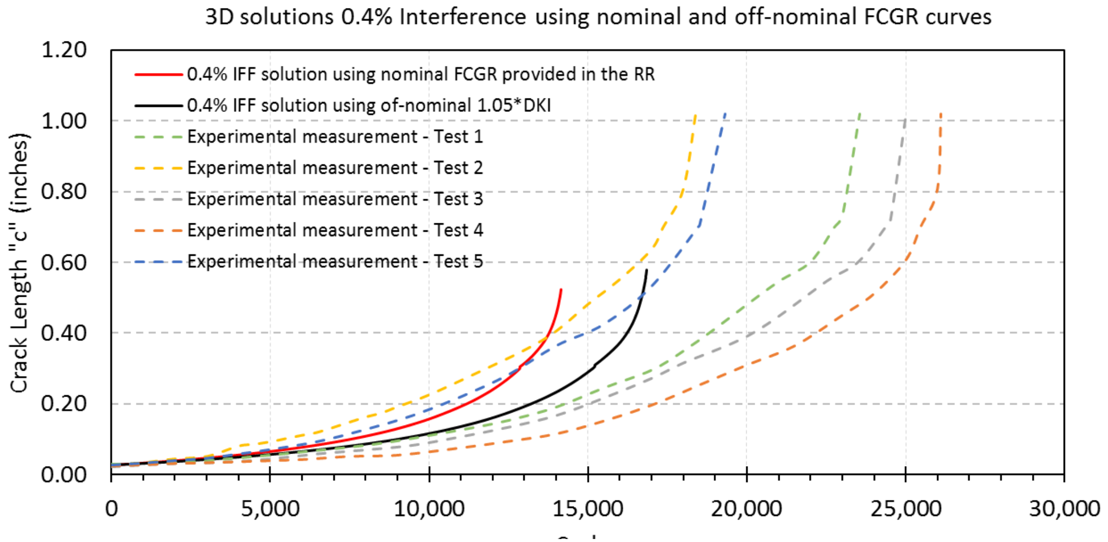
- **The 3D model does capture the evolution of the R values along each crack front increment**
- **The modeling uncertainty increases for da/dN values close to Region 3**
- **Adding FCGR curves for more R ratios should increase the accuracy of the numerical solutions especially for larger cracks where the numerical solutions seem to diverge from the test data**

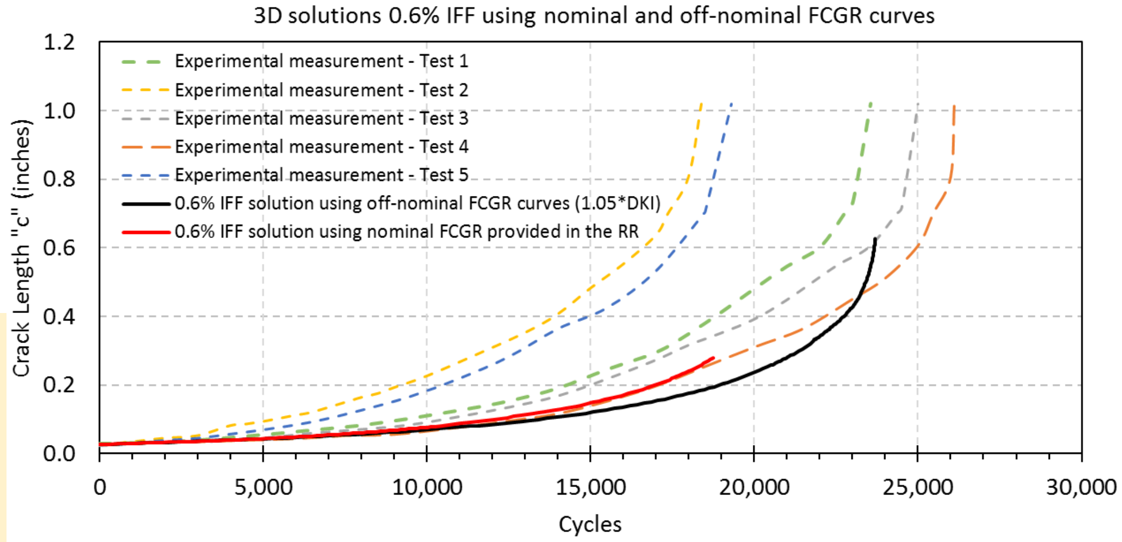
IFF 3D FEA based Crack Growth Solutions: FCGR sensitivity

Engineered Residual Stress Implementation (ERSI) Workshop
19 – 20 April 2023
US Air Force Academy, Colorado Springs, CO

Off-nominal FCGR were generated by shifting the nominal curves to ΔKI*1.05



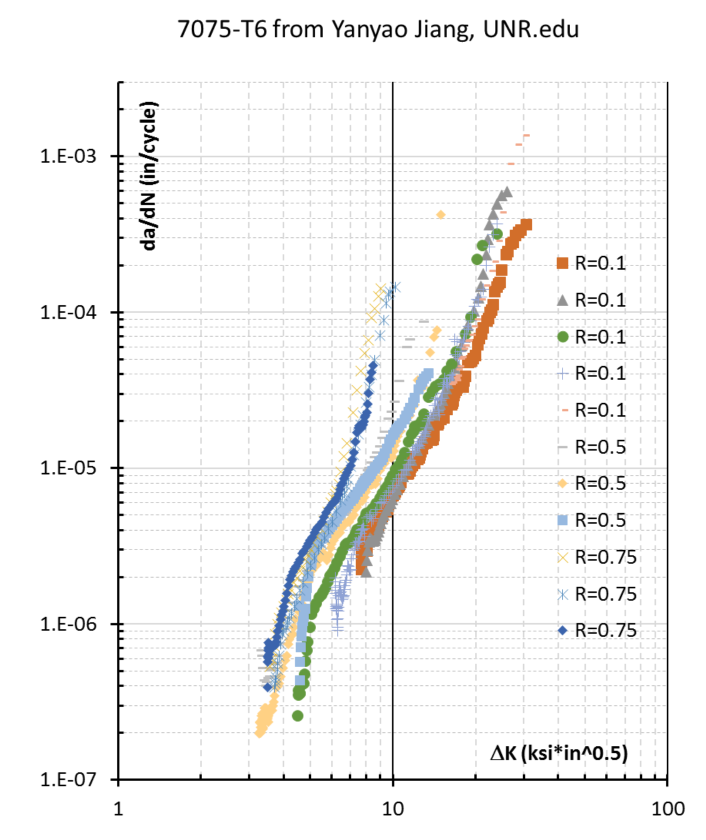




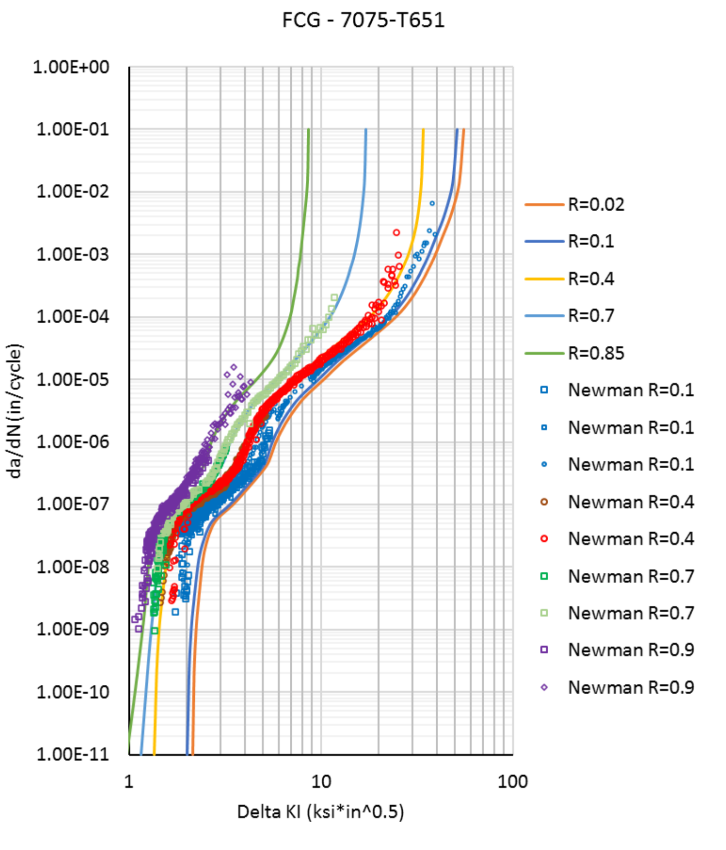
- **A simple study is performed to evaluate the sensitivity of the 3D solution to an eventual FCGR scatter.**
- **A slight modification of nominal FCGR curves (ΔKI*1.05 which is within the FCGR scatter bounds) can lead to ~20% RUL shift.**
- **Average and bounds of each FCGR curve (different R values) need to be identified from the experimental procedure and supplied to the RR participants.**

7075-T651 FCGR Data

A study of fatigue crack growth of 7075-T651 aluminum alloy, T. Zhao, J. Zhang, Y. Jiang



Fatigue and crack growth analyses on 7075-T651 aluminum alloy under constant and variable-amplitude loading, JC Newman, EL Anagnostou, D. Rusk



DOT/FAA/AR-05/15
Fatigue Crack Growth Database for Damage Tolerance Analysis

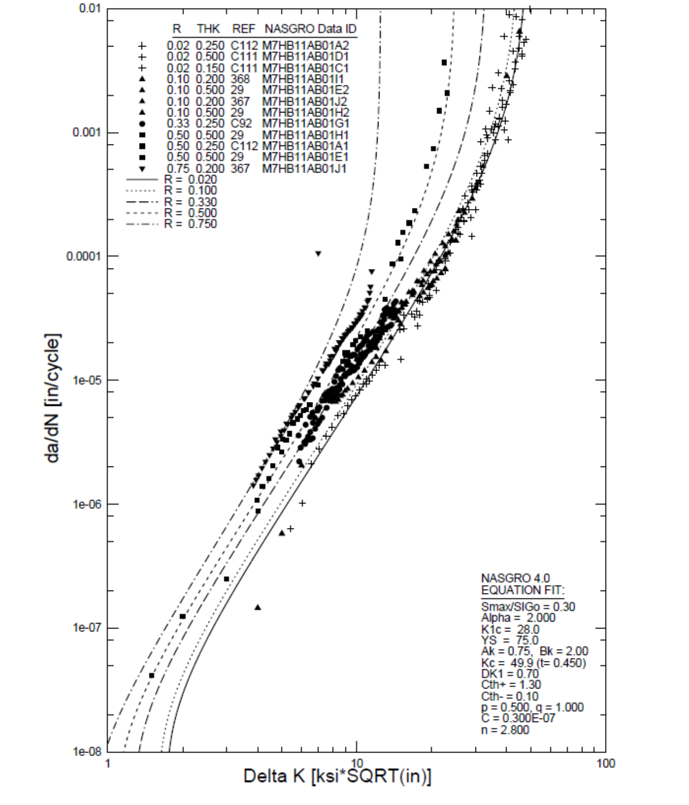


FIGURE B-25. NASGRO EQUATION FIT FOR 7075-T651 PLATE, L-T (M7HB11AB1)

- **There are multiple FCGR datasets in the literature. Details behind generation of each dataset (curve) might not be well documented. An assessment of all available experimental measurements for 7075-T651 might be useful in this RR IFF follow-up.**

Conclusions

Engineered Residual Stress Implementation (ERSI) Workshop
19 – 20 April 2023
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- More instrumentation is needed during mechanical testing to provide more data to the modelers (DIC, complete shape of the fastener and the bore to identify IFF conditions)
- Description of fastener insertion into the specimen can be useful in modeling development
- Any beach mark that can be induced on the fracture surface can be very beneficial to modelers in validation benchmarking. Heat tinting can be an option since the crack stays open all the time.
- A comprehensive assessment of FCGR average and $\pm 2\sigma$ bound can be also beneficial in validation benchmarking
- Sources of uncertainty (experimental, numerical) were not properly addressed in the IFF fatigue crack growth round robin challenge

ROUND ROBIN STATUS UPDATE: IMPACT ON DTA DUE TO VARIABILITY IN RESIDUAL STRESSES AT COLD EXPANDED (CX) HOLES

Life Analysis & Test Methods Committee

Organizer: T. Spradlin (AFRL/RQVS)

ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

BOTTOM LINE UP FRONT

- Seven participants total using a variety of capabilities
- Comparisons for non-CX variants 3/4 complete
  - Most entrants did well for the non-CX treated analyses
  - Additional discussion concerning a or c vs N comparisons
- Comparisons for CX variants 1/4 complete
  - Most if not all failed to replicate crack breakthrough in CX treated specimens
- Testing for Nf comparisons completed in October
- Additional testing/data reduction underway
  - Primarily quantitative fractography and additional replicates
    - All spectra/treatment conditions

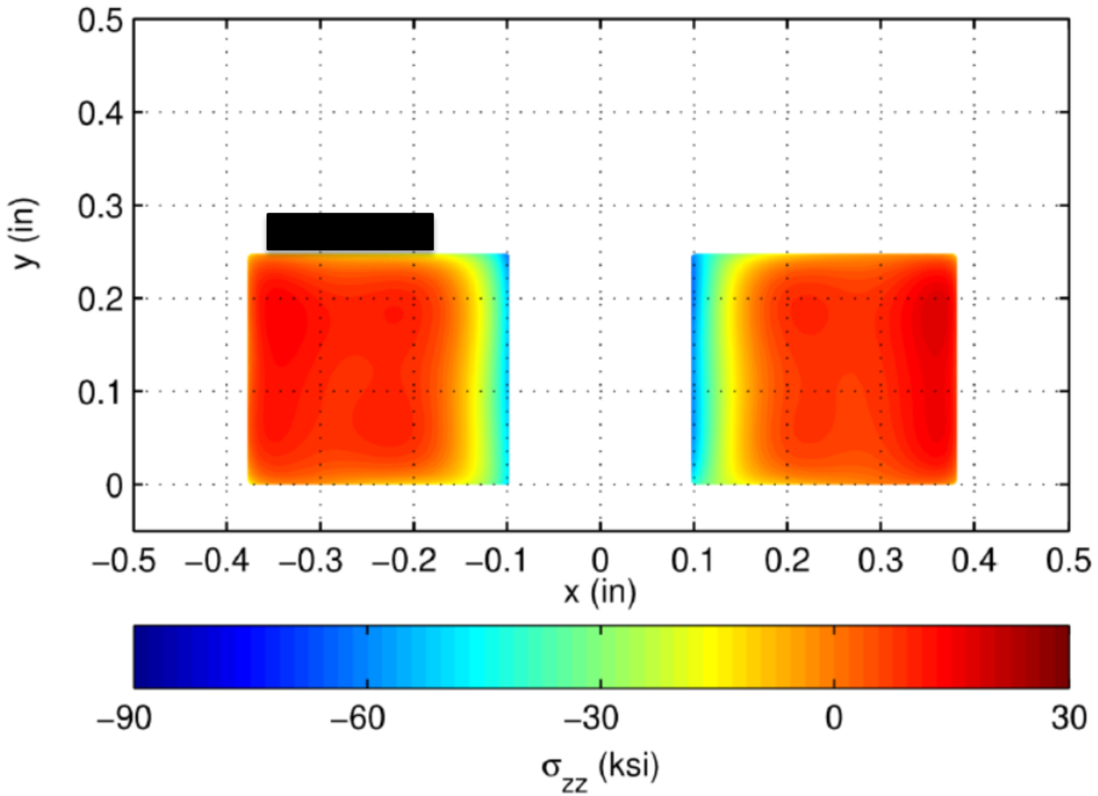
BACKGROUND

What Drove This RR: Tier Levels

- **Level 1**
  - Current Structures Bulletin approach (>=0.005" IFS) for initial inspection
  - No RS in analysis
  - No benefit for recurring inspections
  - Validation fatigue testing
- **Level 2**
  - Minimal RS benefit (limited by 0.005" IFS)
  - RS included in analysis
  - Current DTA requirements
  - Benefit for recurring inspections
  - Validation fatigue testing
- **Level 3+**
  - Intermediate to full RS benefit
  - Intermediate to advanced analysis
  - QA requirements
  - RS characterization & validation fatigue testing

LEVEL 3+

- Currently working through advanced analysis validation project (MAI NG-11)
  - Set to end CY22 – UPDATE: NCTE through this CY
- Need more data to quantify requirements
  - Strong foundation from work conducted both by ASTM and ERSI
  - Analysis and QA will be costly
  - Potential benefit may be worth it depending on location and maintenance burden
- Will update again once we have more details



ROUND ROBIN: RESULTS AND COMPARISONS

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

SOFTWARES REPRESENTED (Q1)

- FEA Software
  - BAMpF v7/StressCheck 10.5
  - StressCheck v11.0
  - StressCheck v11.1 (w/ and w/o BAMpF API)
- Crack Growth Software
  - NASGRO (v10.1 - Univariant weight function mode CC08)
  - AFGROW (V5.03.04.23)
  - AFGROW (5.3.5.24)
  - FASTRAN (Version 5.76)
  - CGRo v2.08.09
  - LifeWorks

ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

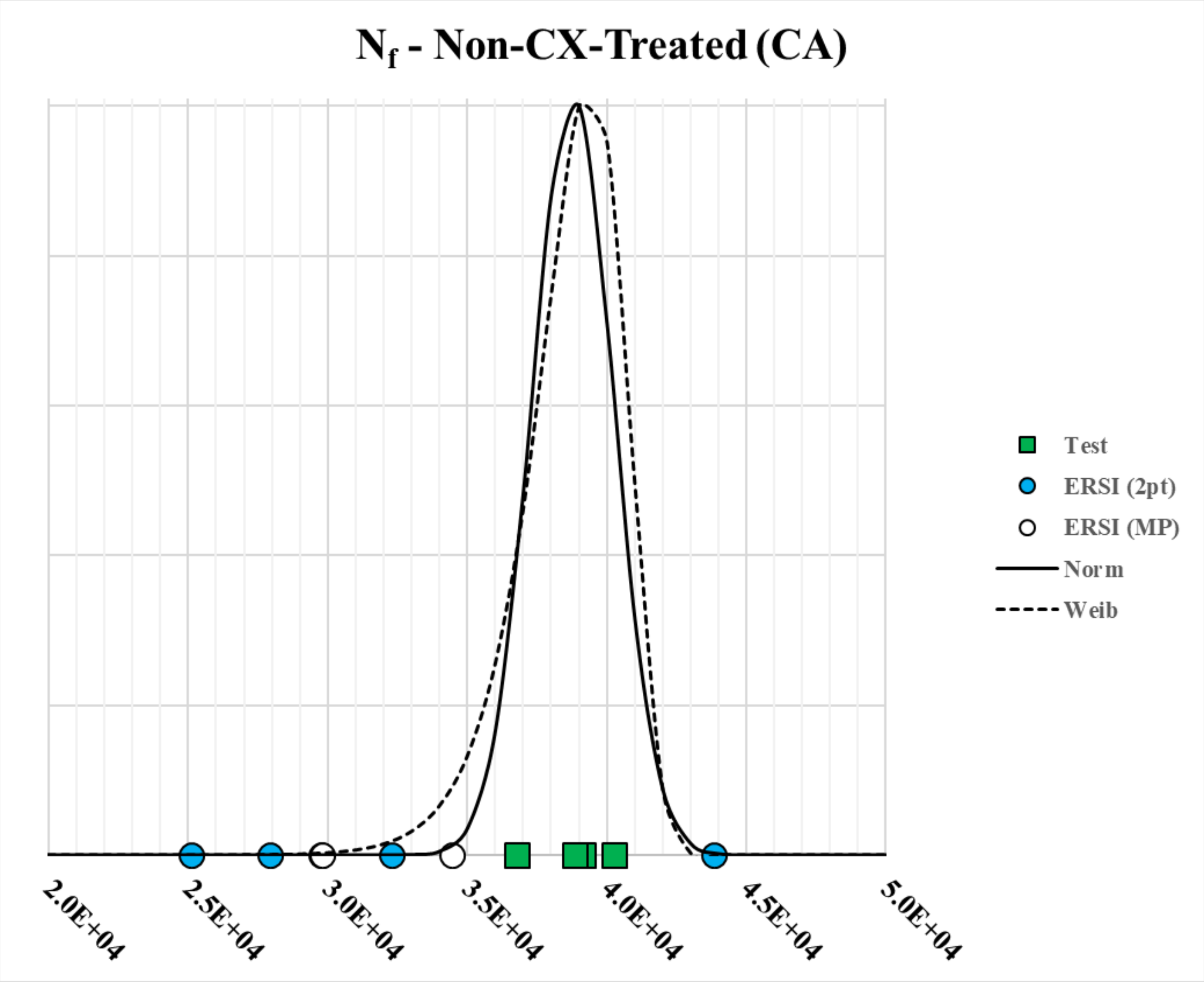
INCORPORATION OF RESIDUAL STRESS (Q3-5)

- RS Data Reduction (Q3)
  - Nominal treatment conditions (LHS and RHS) averaged and curve fit
  - Closest fit to proprietary database fit using 15th order polynomial and 25% mag. reductiton
  - 15th order polynomial fit for each treatment level (average of all replicates)
  - Spike overloaded modification
  - Through thickness average for univariate function fit (50% reduction at bore location)
  - Lowest measured value for the nominal treatment
- RS SIF Incorporation (Q4)
  - Superposition
  - NASGRO weight function model
- Rate Date Incroporation (Q5)
  - Alternate rate data from prior efforts (after rigorous comparison to provided)
  - CGRo tabular lookup w/ 1.5 ksi√in imposed threshold and curve shifting for neg. R
  - NASGRO tabular lookup with linear extrapolation (log-log space) for neg. R
  - AFGROW tabular lookup
  - LifeWorks material rate data module w/ no threshold exception

CYCLES TO FAILURE: NON-CX (CA)

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

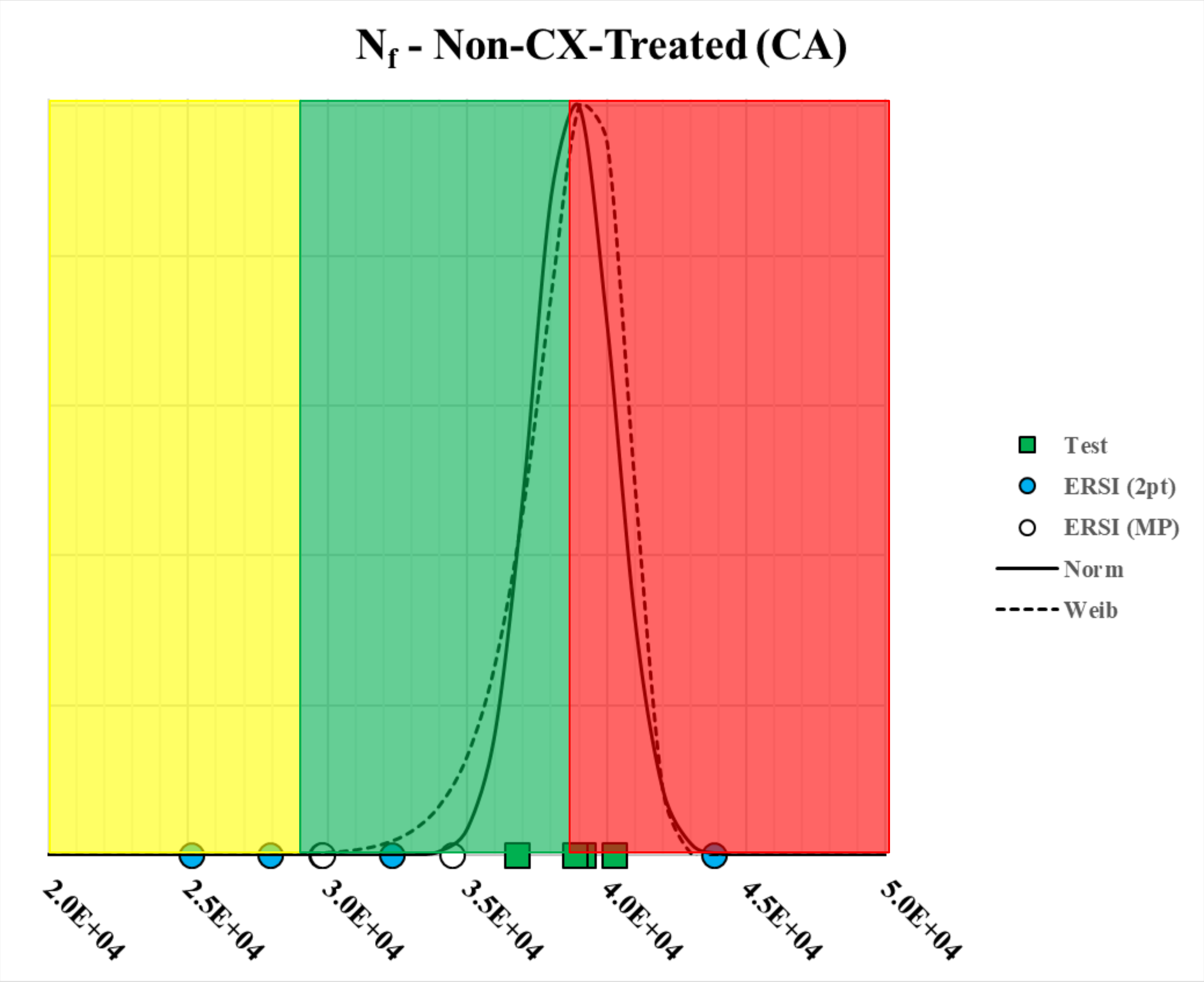
	N_f
Test (Mean)	38769
Entrant 1	27942
Entrant 2	25128
Entrant 3	43834
Entrant 4	32283
Entrant 5	29746
Entrant 6	34461
Entrant 7	29810



CYCLES TO FAILURE: NON-CX (CA)

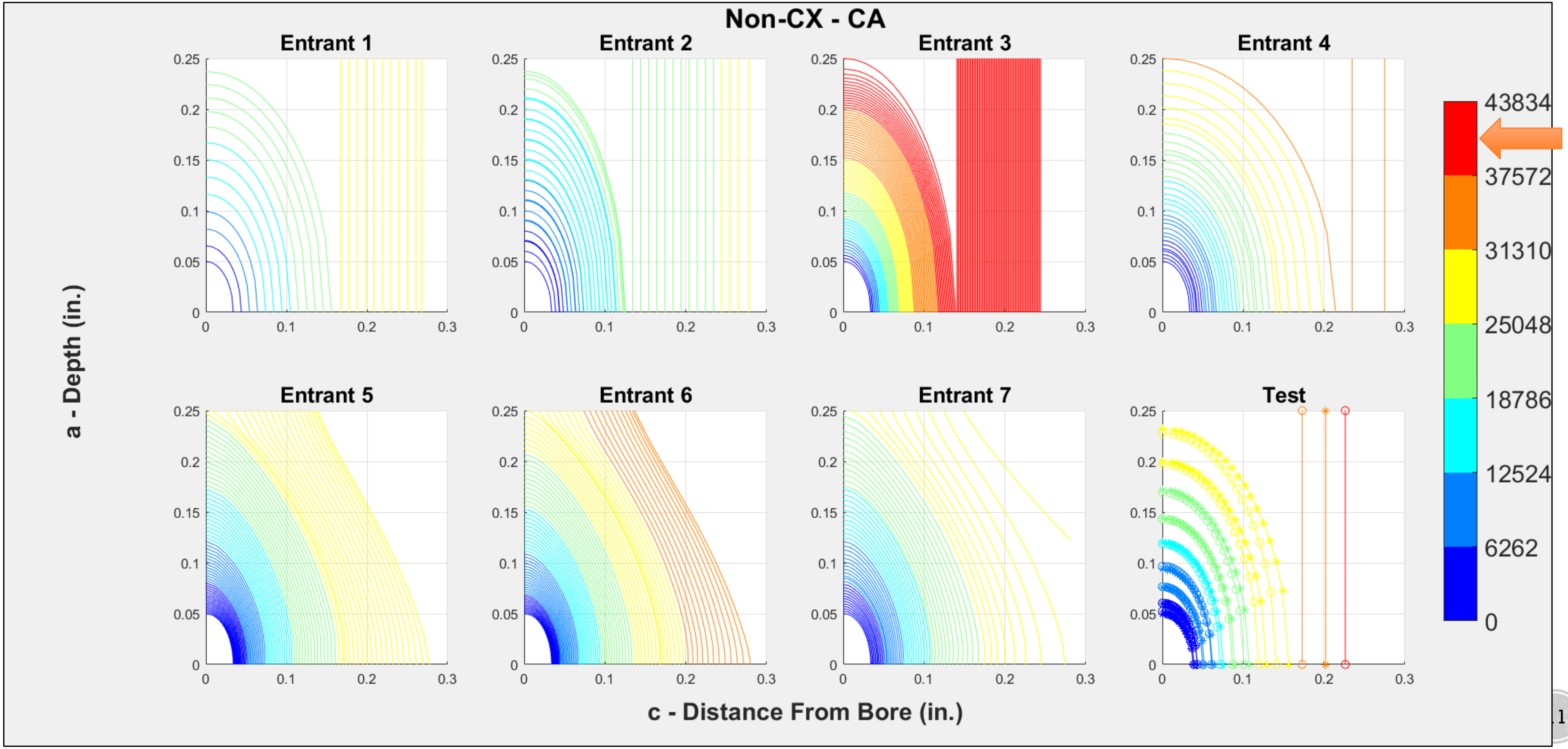
	N_f
Test (Mean)	38769
Entrant 1	27942
Entrant 2	25128
Entrant 3	43834
Entrant 4	32283
Entrant 5	29746
Entrant 6	34461
Entrant 7	29810

- **Green: 3/4Mean<Nf<Mean**
- **Yellow: 1/2Mean<Nf<3/4Mean**
- **Red: Mean<Nf**



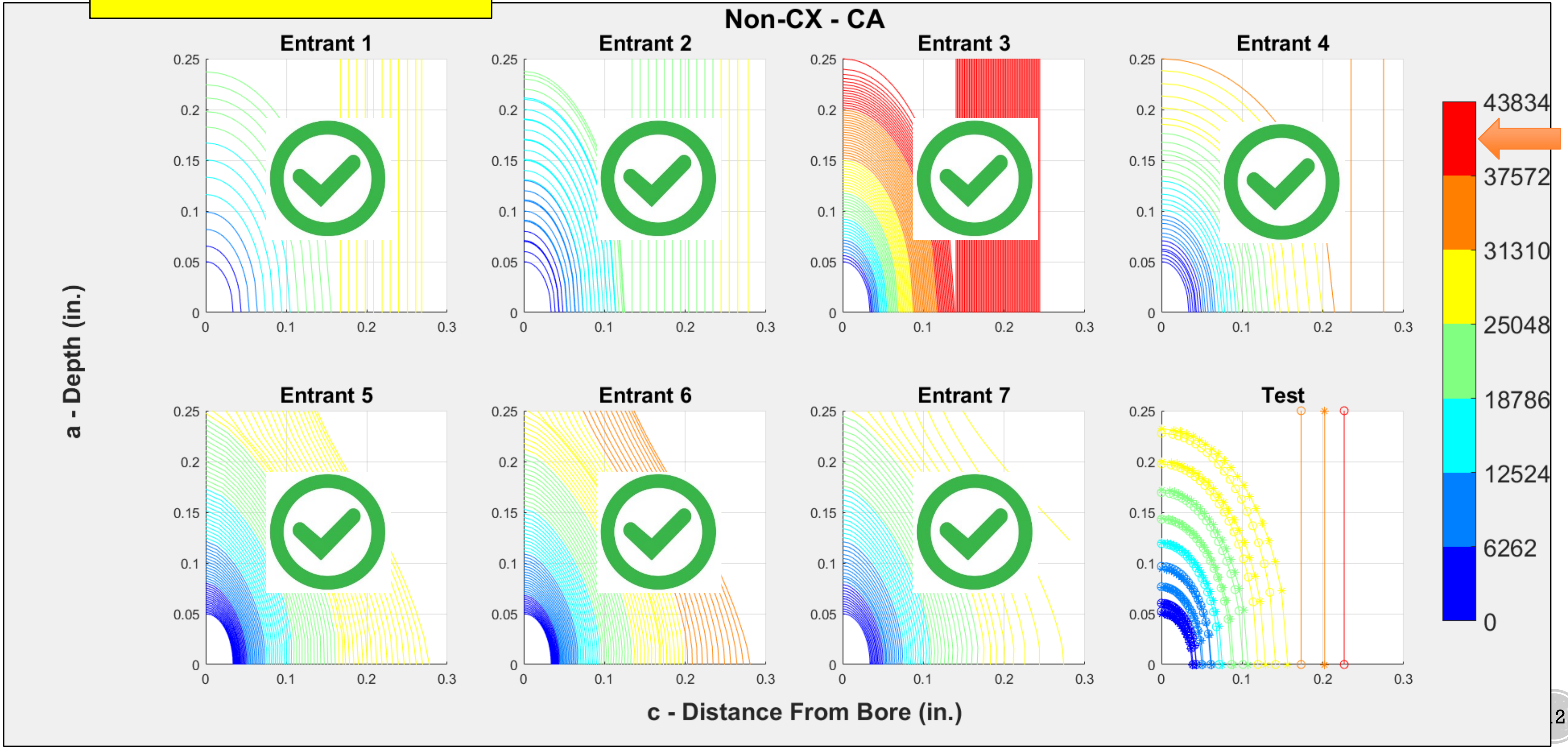
ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

CRACK MORPHOLOGY: NON-CX (CA)

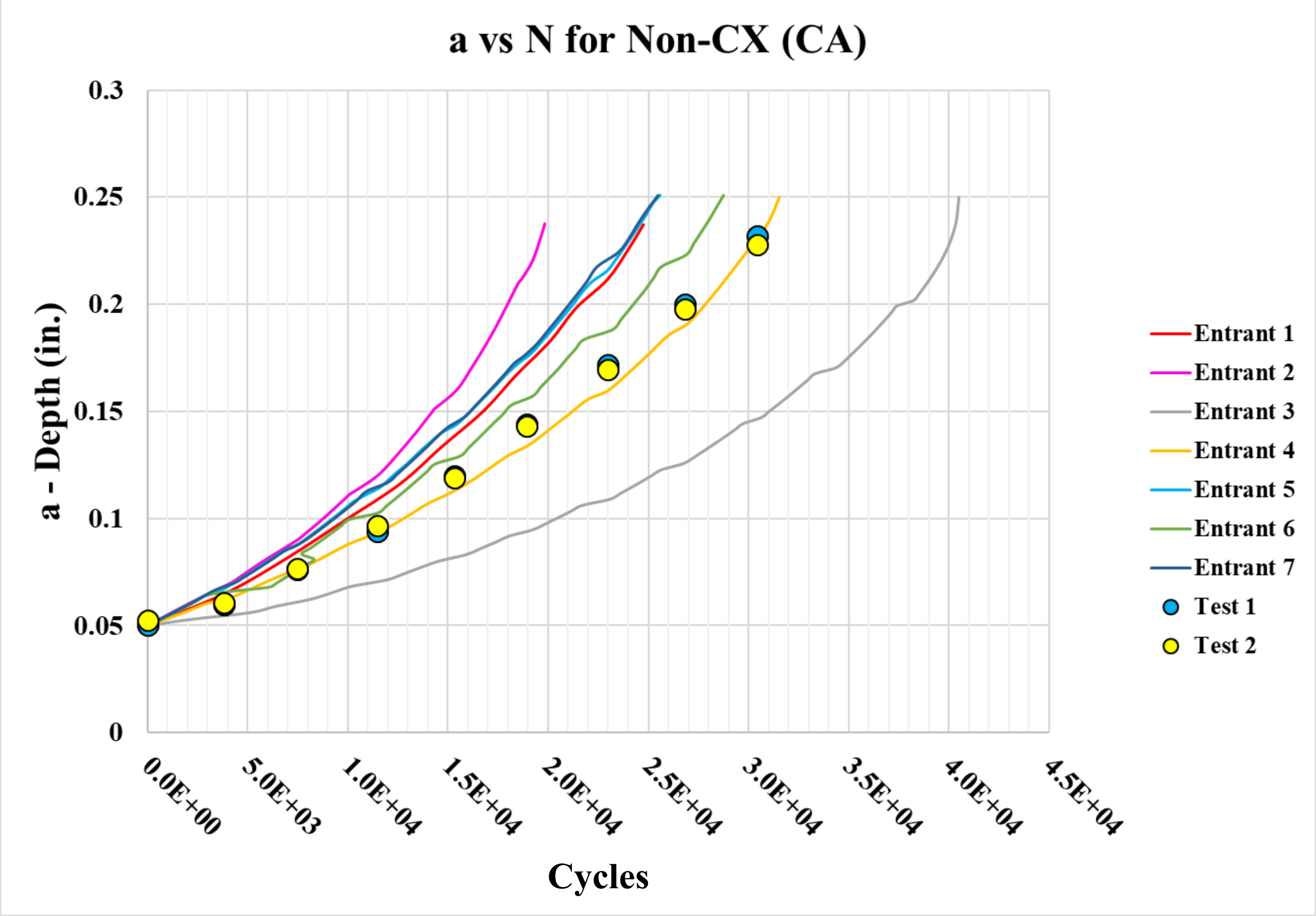


CRACK MORPHOLOGY: NON-CX (CA)

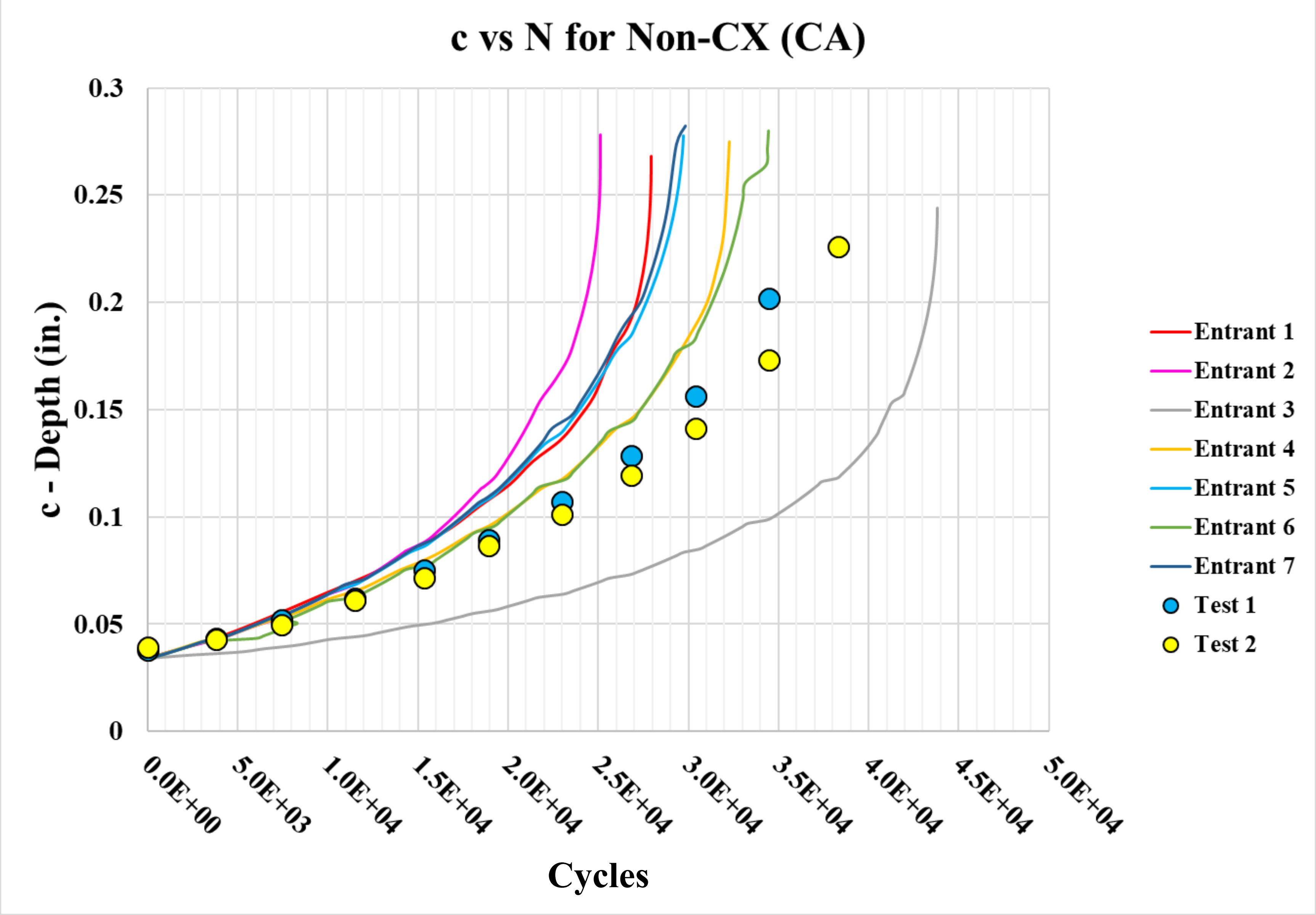
Did it break through?



CRACK PROGRESSION: NON-CX (CA)



CRACK PROGRESSION: NON-CX (CA)



ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

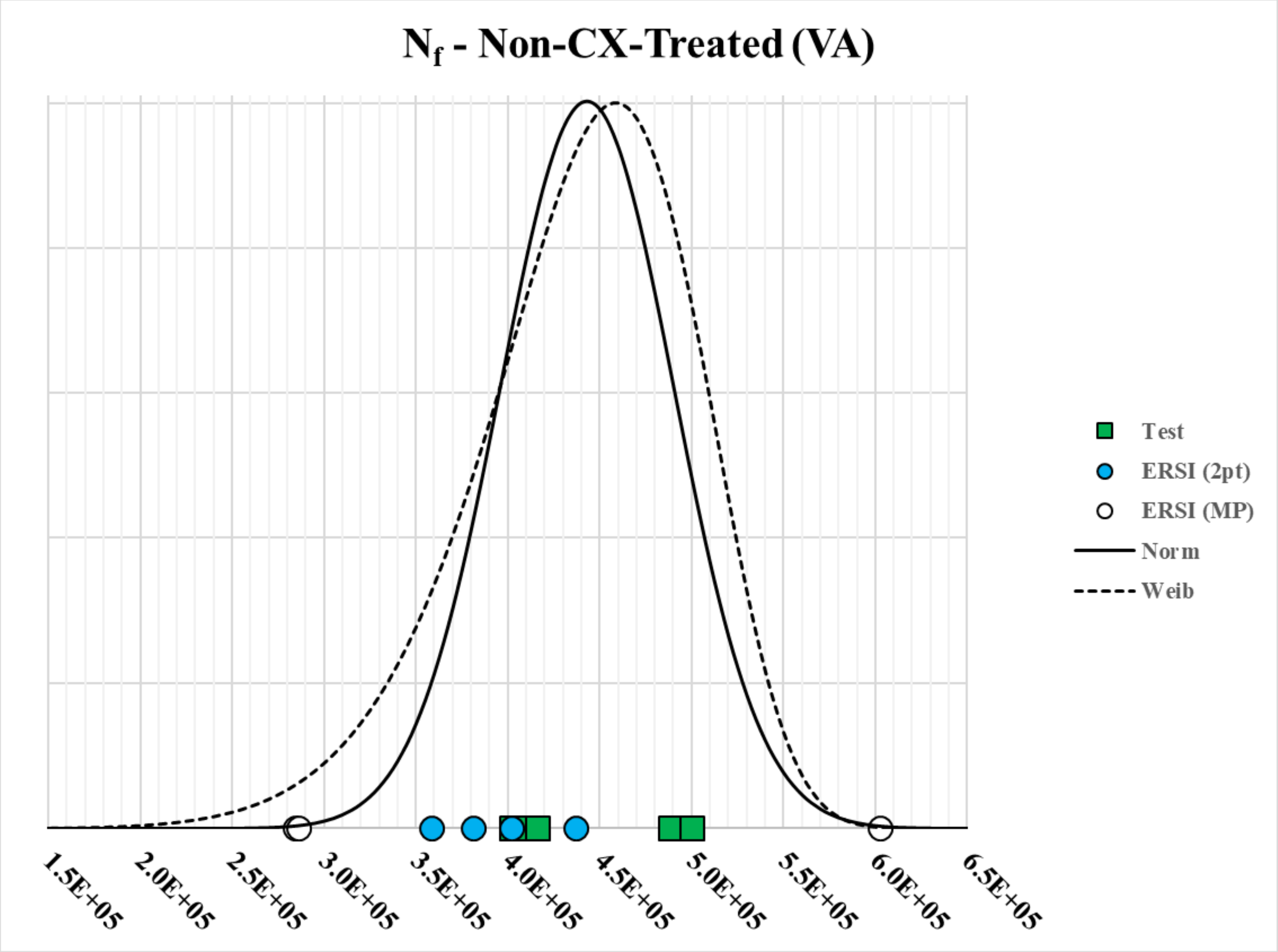
SCORE CARD: NON-CX (CA)

Entrant	Nf	Morphology	a vs N Shape	c vs N Shape
1				
2				
3				
4				
5				
6				
7				

ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

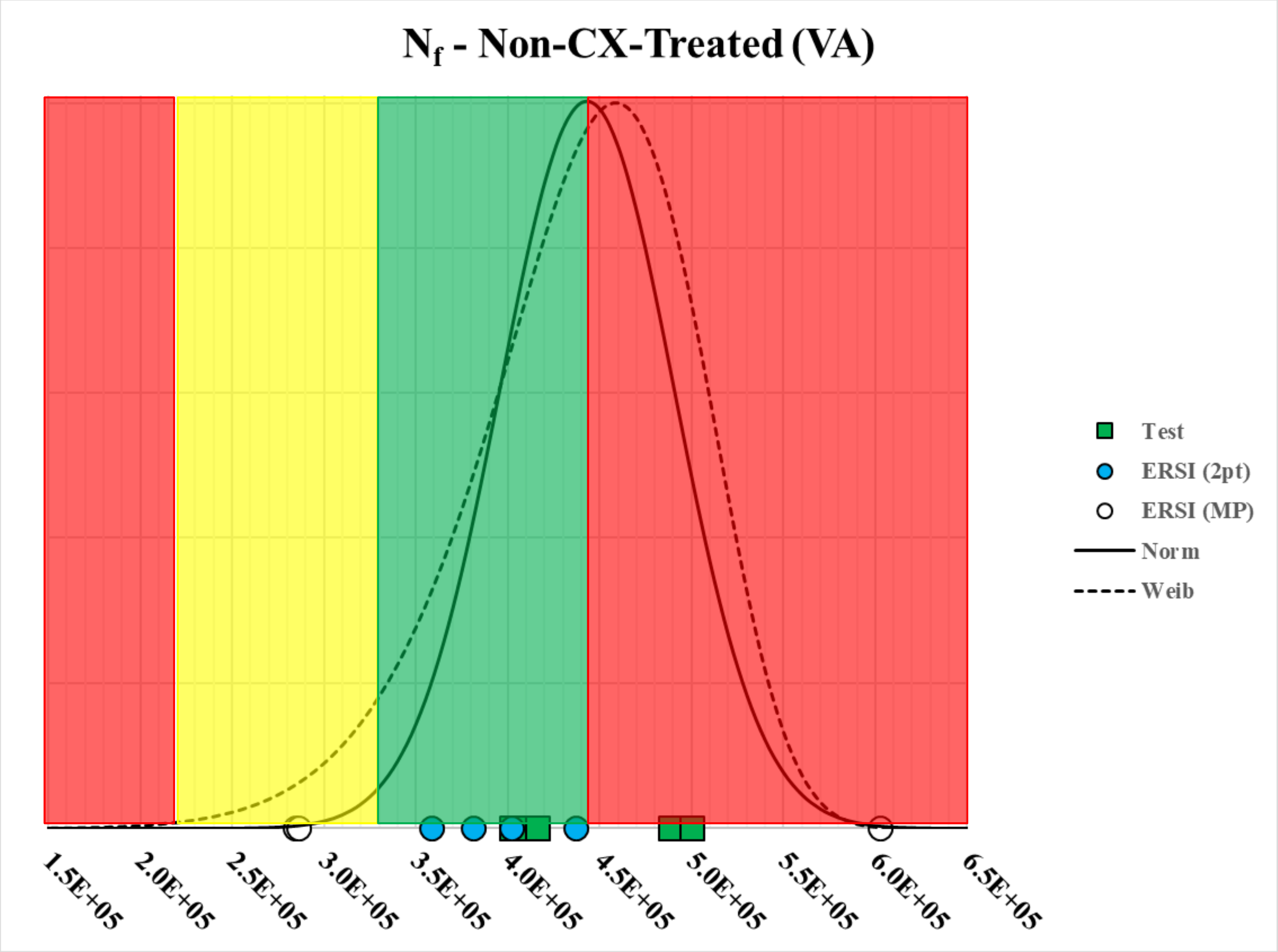
CYCLES TO FAILURE: NON-CX (VA)

	N_f
Test (Mean)	442986
Entrant 1	381371
Entrant 2	358473
Entrant 3	402261
Entrant 4	437033
Entrant 5	284404
Entrant 6	602252
Entrant 7	286272



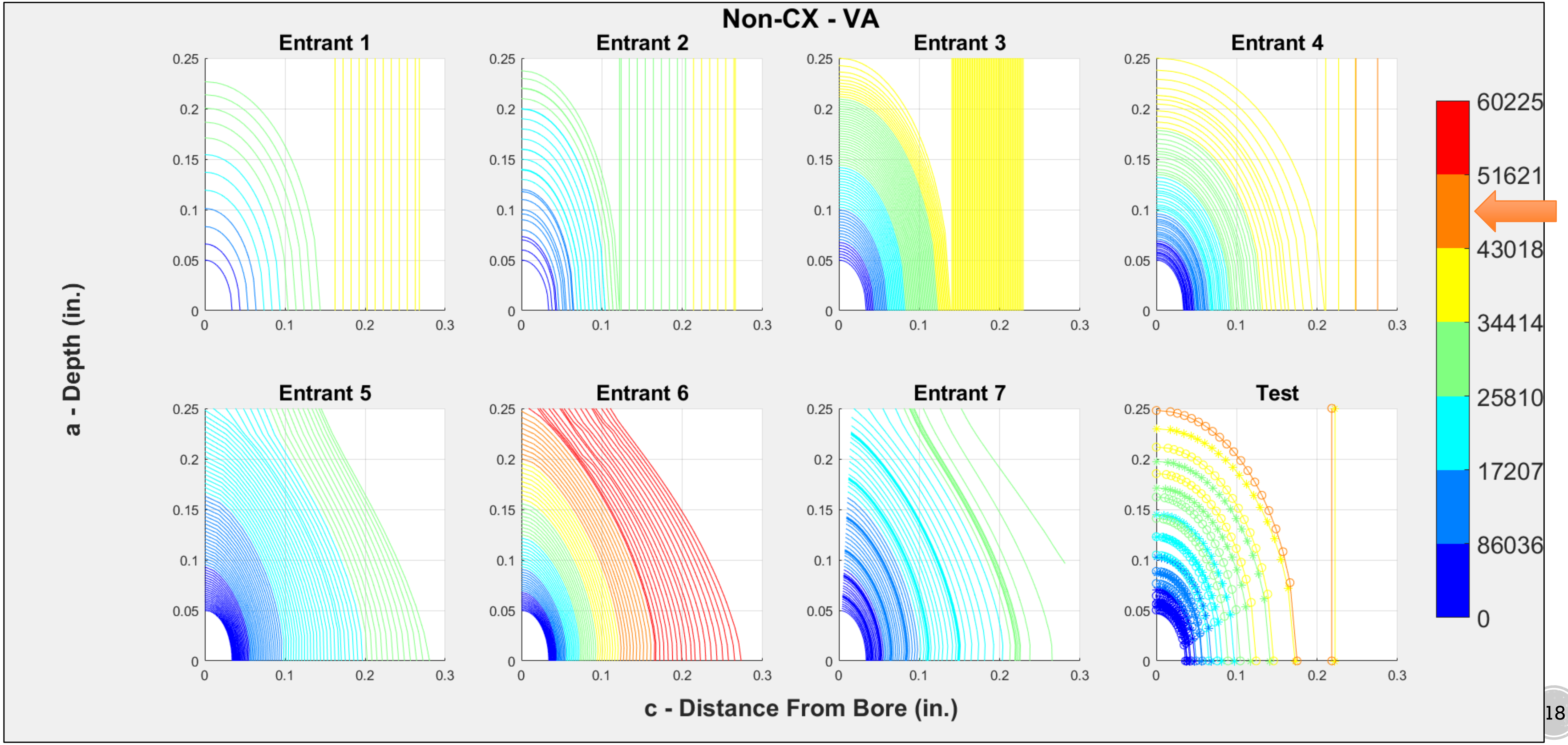
CYCLES TO FAILURE: NON-CX (VA)

	N_f
Test (Mean)	442986
Entrant 1	381371
Entrant 2	358473
Entrant 3	402261
Entrant 4	437033
Entrant 5	284404
Entrant 6	602252
Entrant 7	286272



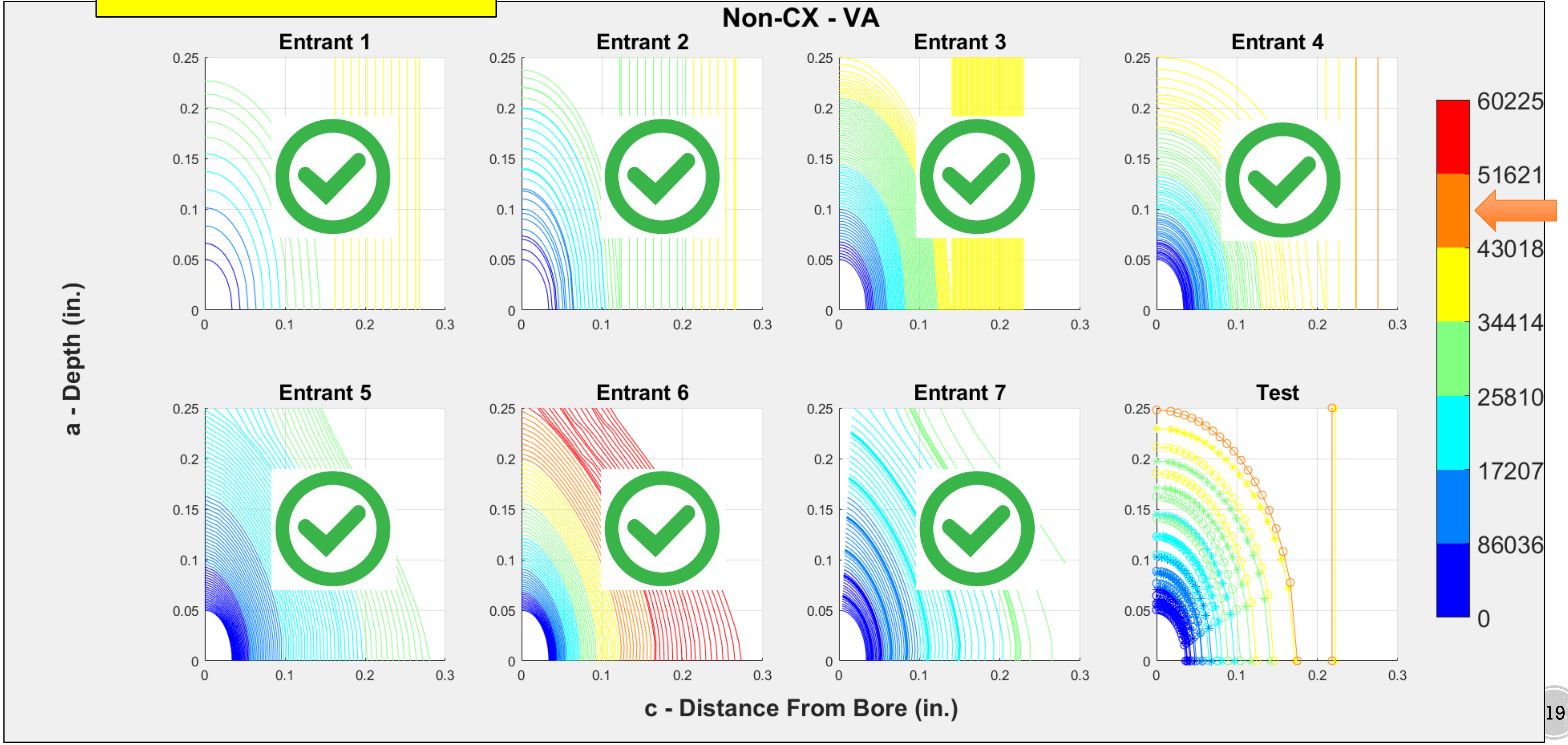
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

CRACK MORPHOLOGY: NON-CX (VA)



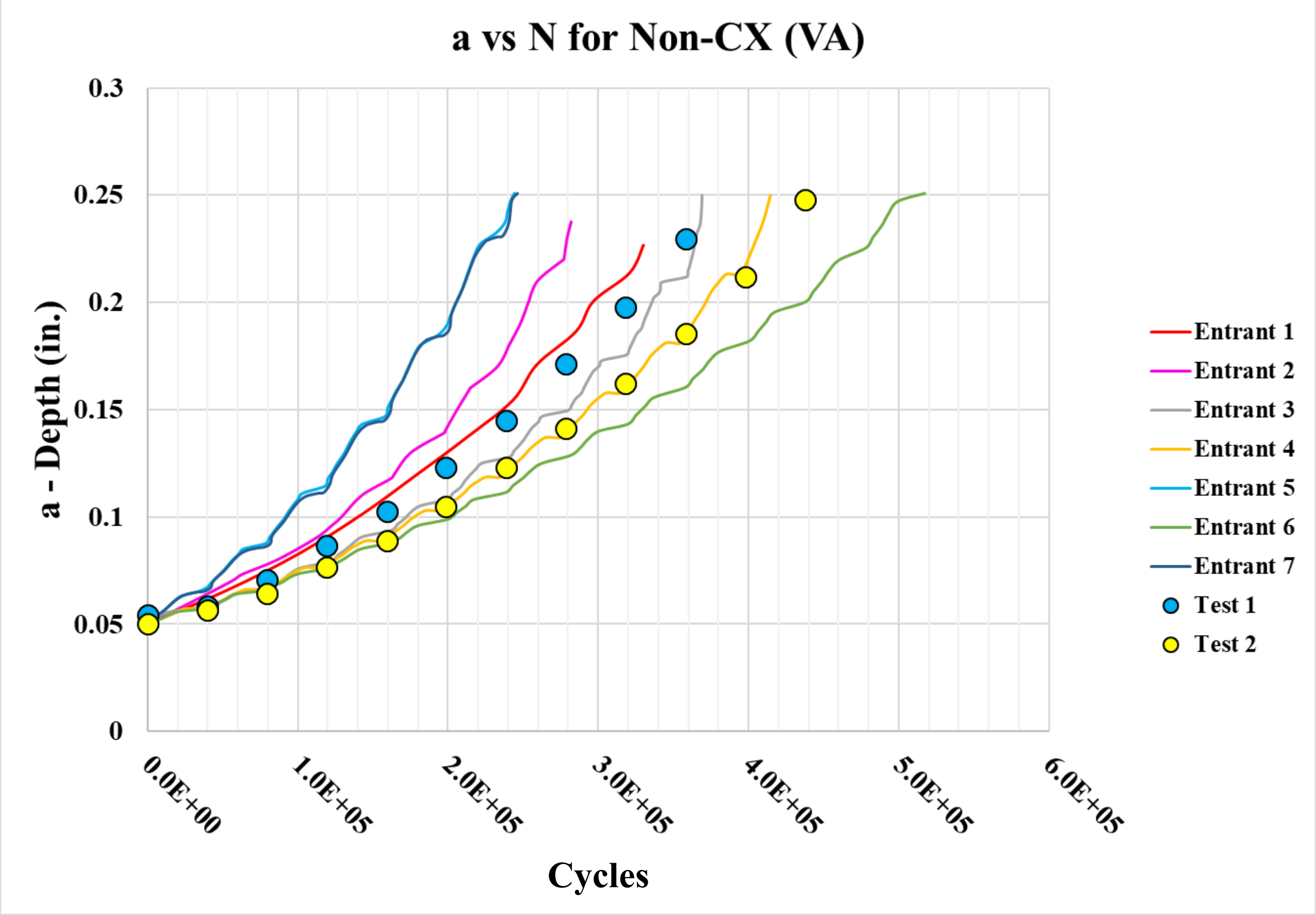
CRACK MORPHOLOGY: NON-CX (VA)

Did it break through?



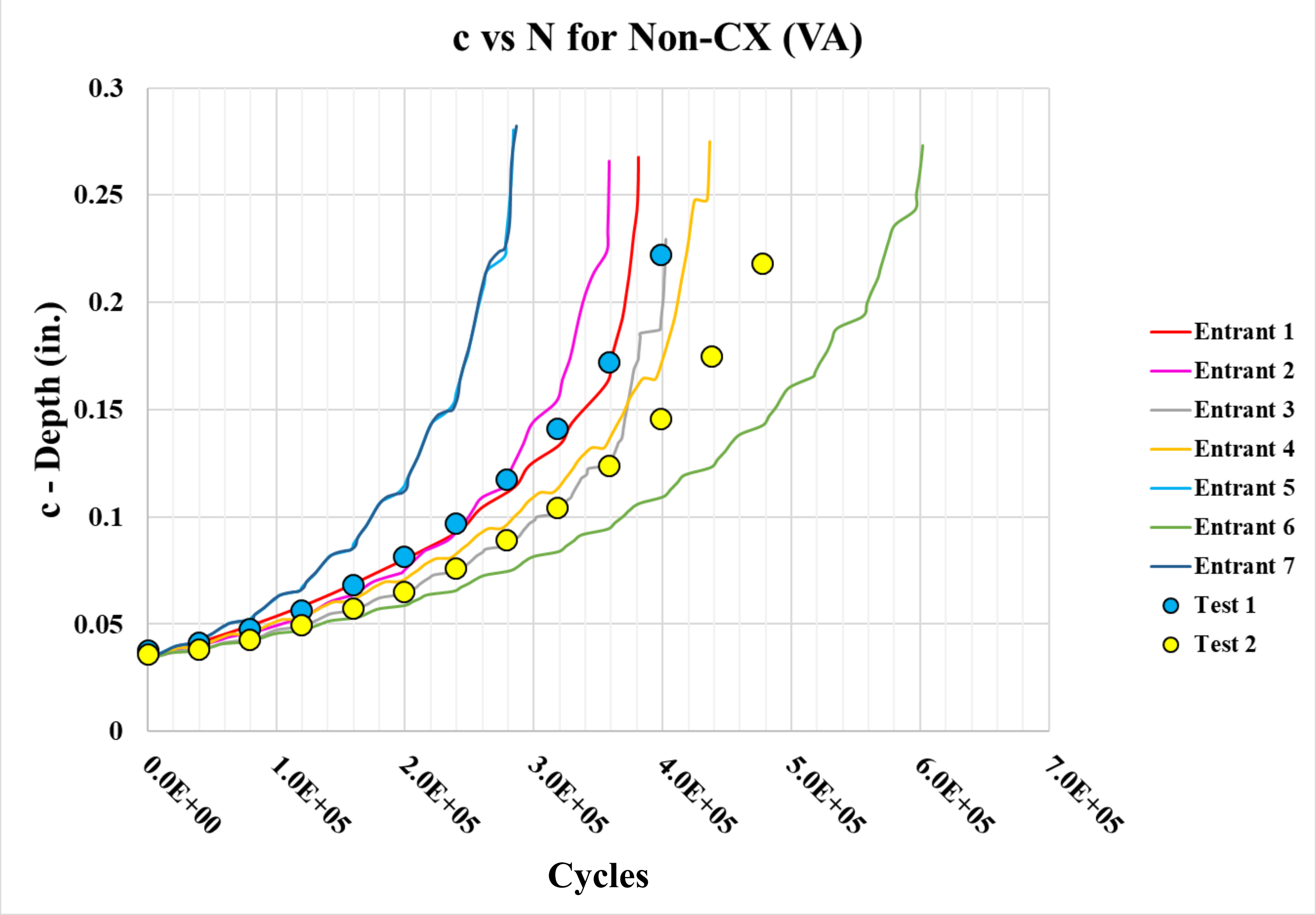
ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

CRACK PROGRESSION: NON-CX (VA)



ERSI
ENGINEERED RESIDUAL
STRESS IMPLEMENTATION

CRACK PROGRESSION: NON-CX (VA)



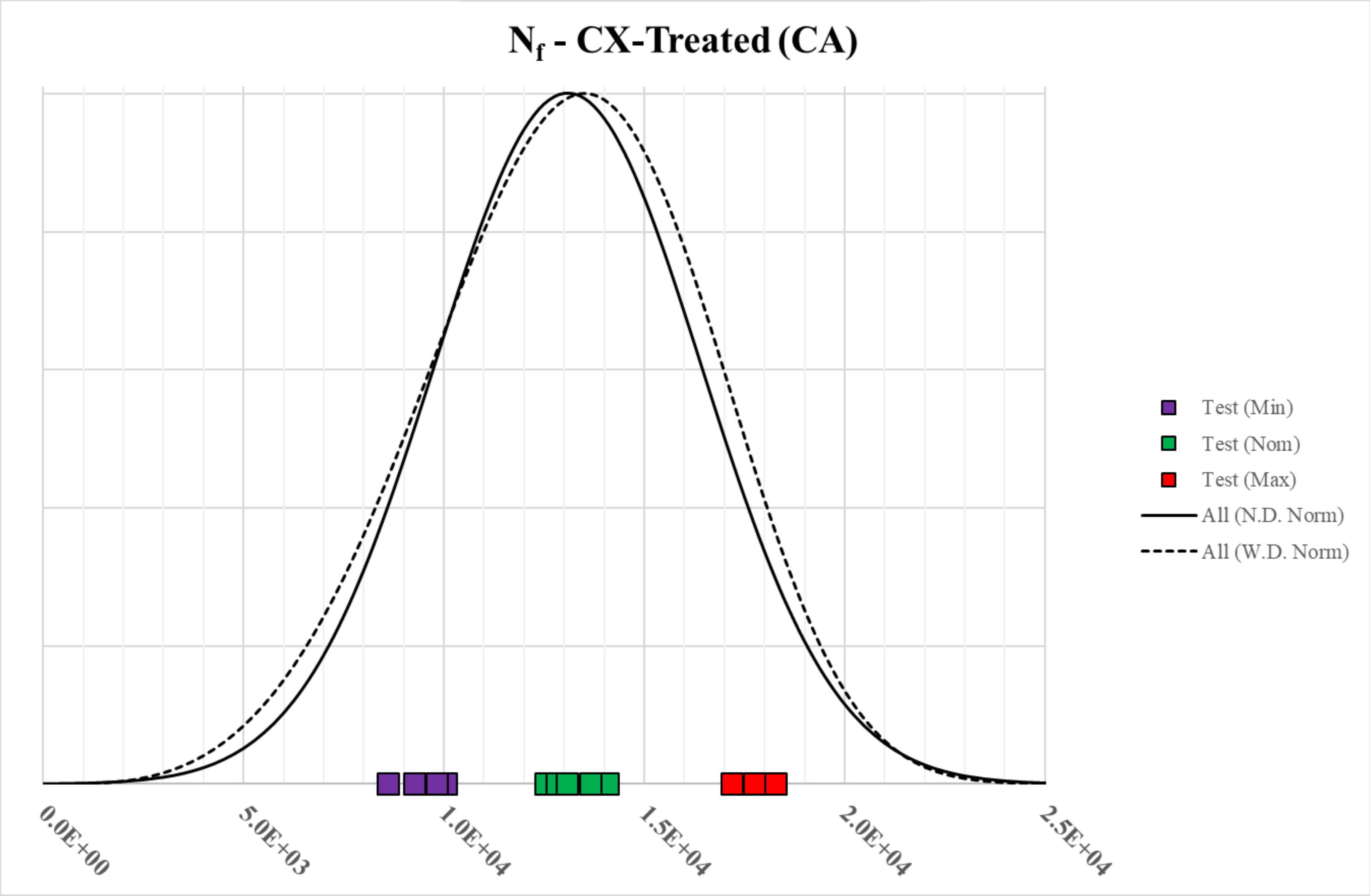
SCORE CARD: NON-CX (VA)

Entrant	Nf	Morphology	a vs N Shape	c vs N Shape
1				
2				
3				
4				
5				
6				
7				

ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

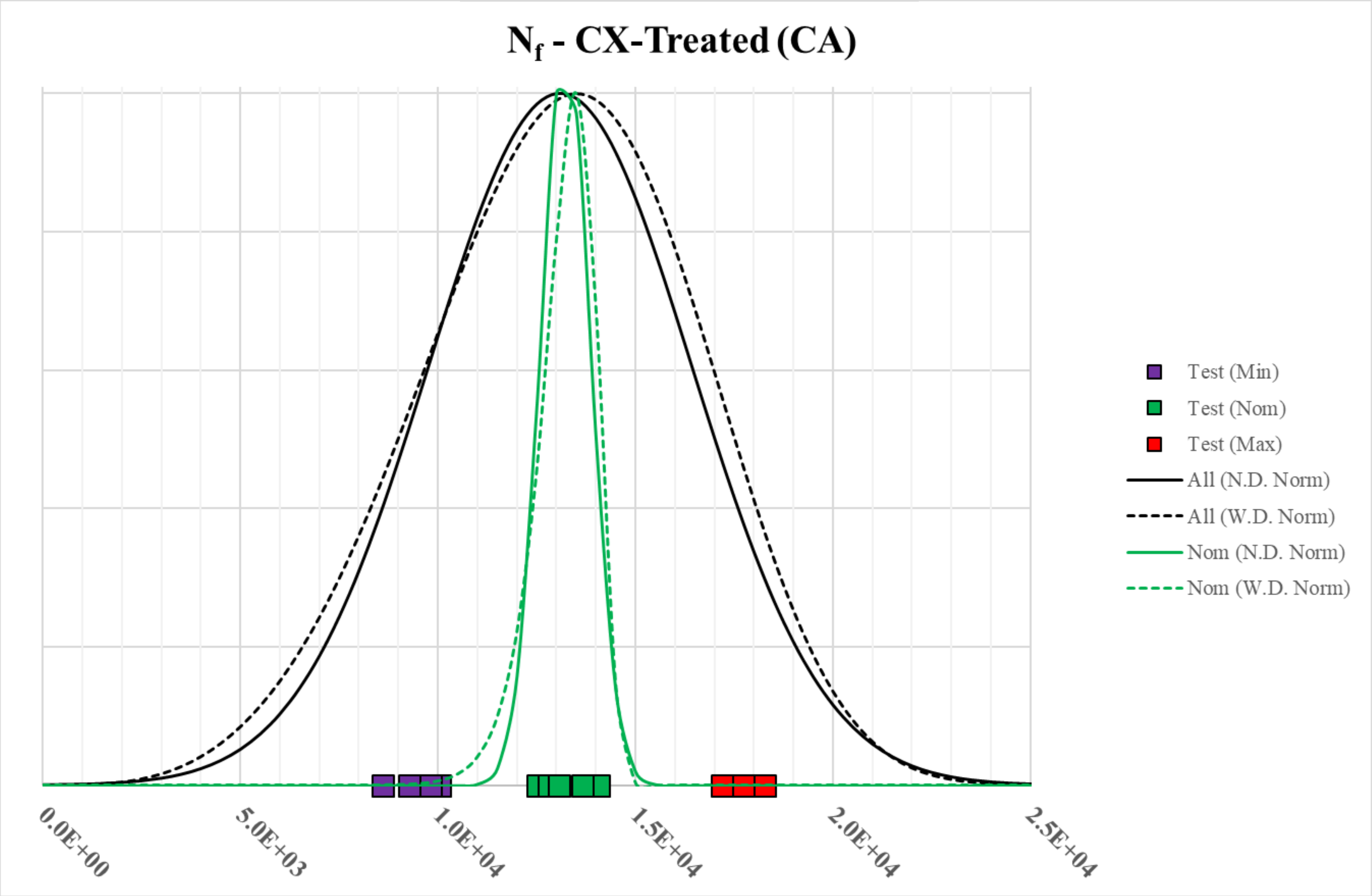
CYCLES TO FAILURE: CX (CA)

- Test data considered as a single population has significant scatter…
- Representative? No, not really.
- What if we consider each treatment as a separate population?



CYCLES TO FAILURE: CX (CA)

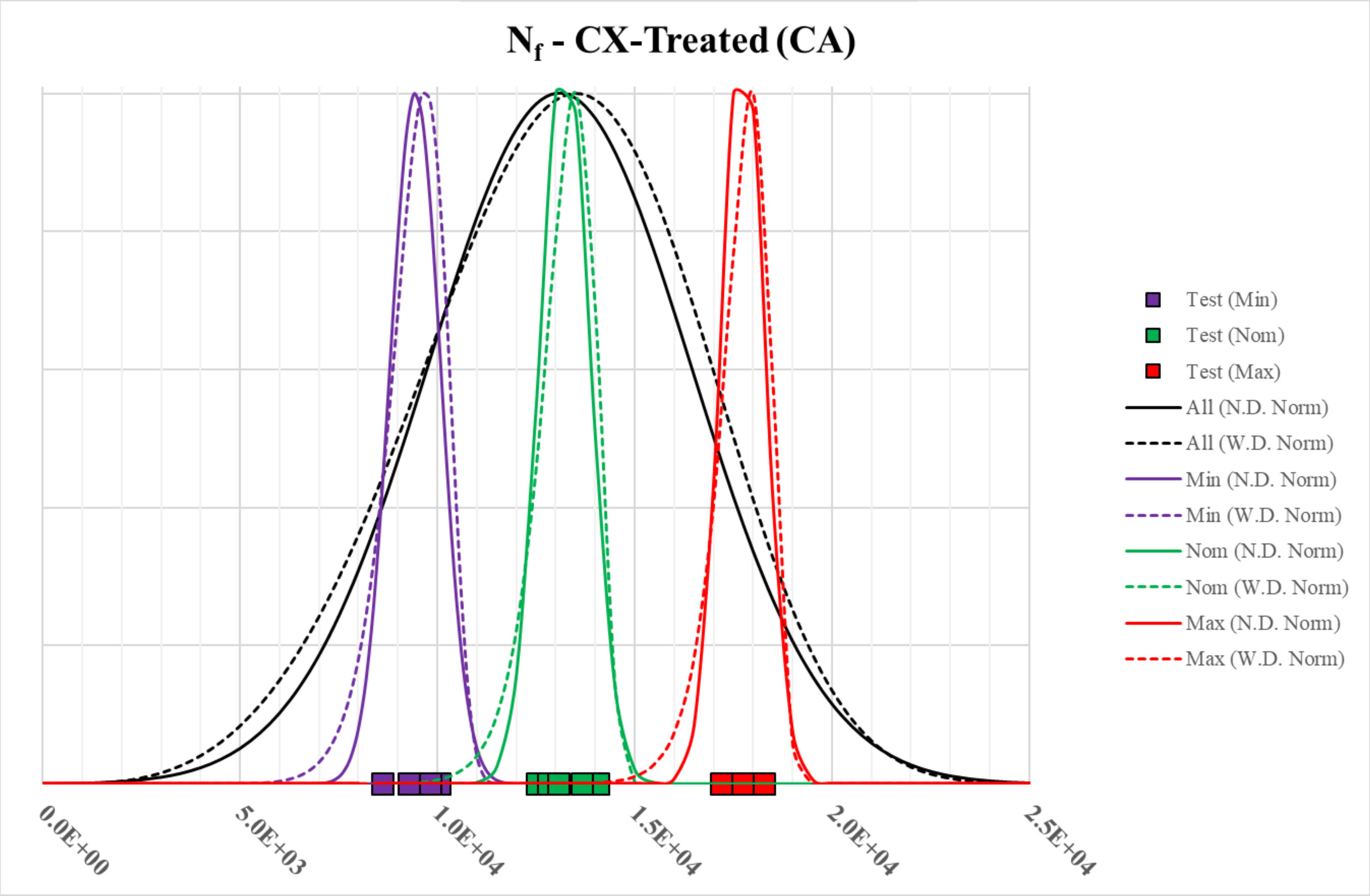
- First, let's isolate the nominal treatment



ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

CYCLES TO FAILURE: CX (CA)

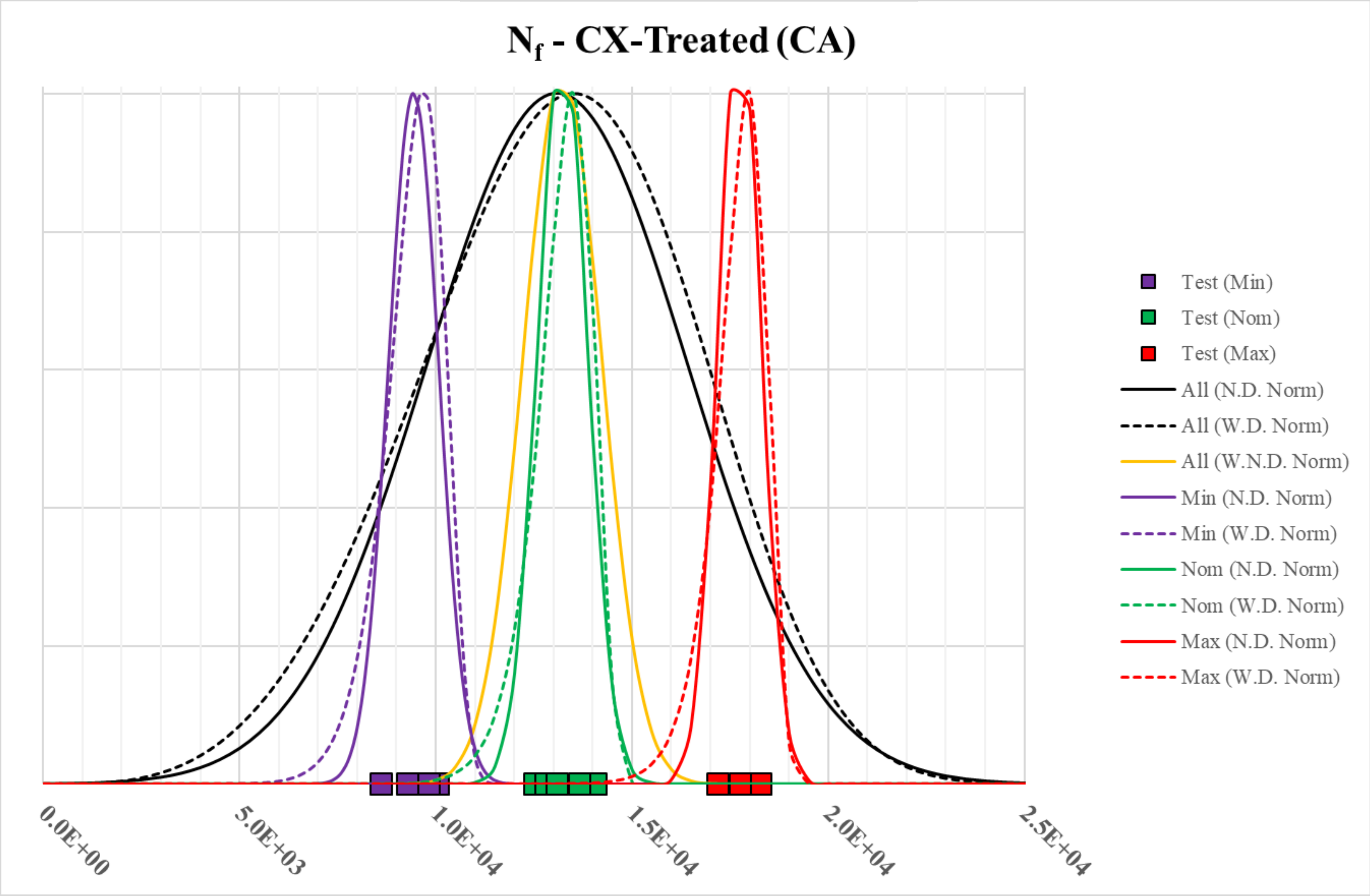
- Now the extrema
- Very clearly dealing with three disctinct populations
- Confirmed with single factor ANOVA
  - Alpha = 0.05
  - P-value ~1e-6



ENGINEERED RESIDUAL STRESS IMPLEMENTATION

CYCLES TO FAILURE: CX (CA)

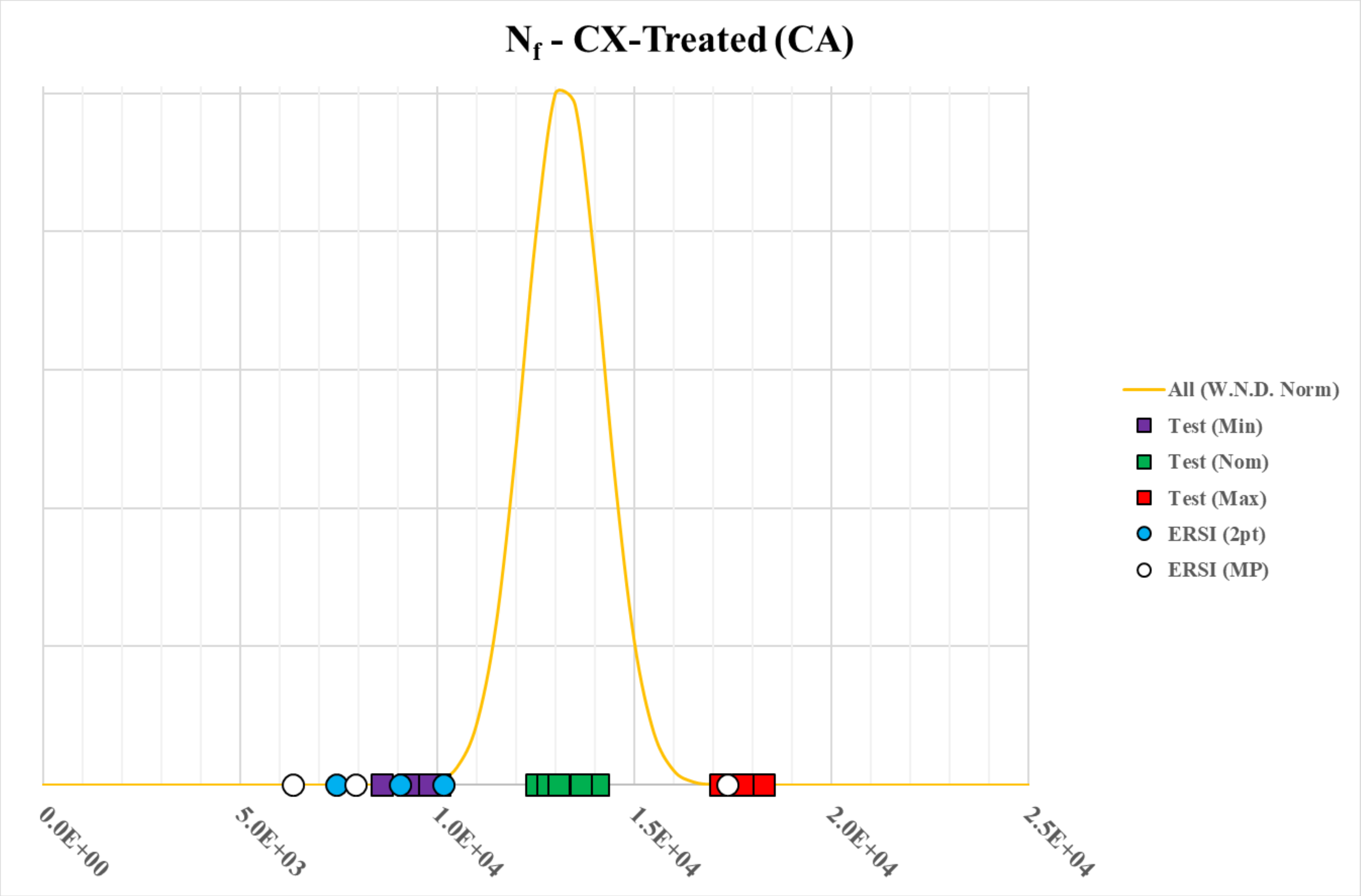
- Extrema represent the random occurrence (~3σ)
- Use weighted normal dist. to better represent actual scenario
  - Nom Weight = 0.95
  - Min = 0.025
  - Max = 0.025



ENGINEERED RESIDUAL STRESS IMPLEMENTATION

CYCLES TO FAILURE: CX (CA)

	N_f
Test (Mean)	13218
Entrant 1	10173
Entrant 2	9061
Entrant 3	7451
Entrant 4	17375
Entrant 5	6348
Entrant 6	7926
Entrant 7	N/A



CYCLES TO FAILURE: CX (CA)

	N_f
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Entrant 3	7451
Entrant 4	17375
Entrant 5	6348
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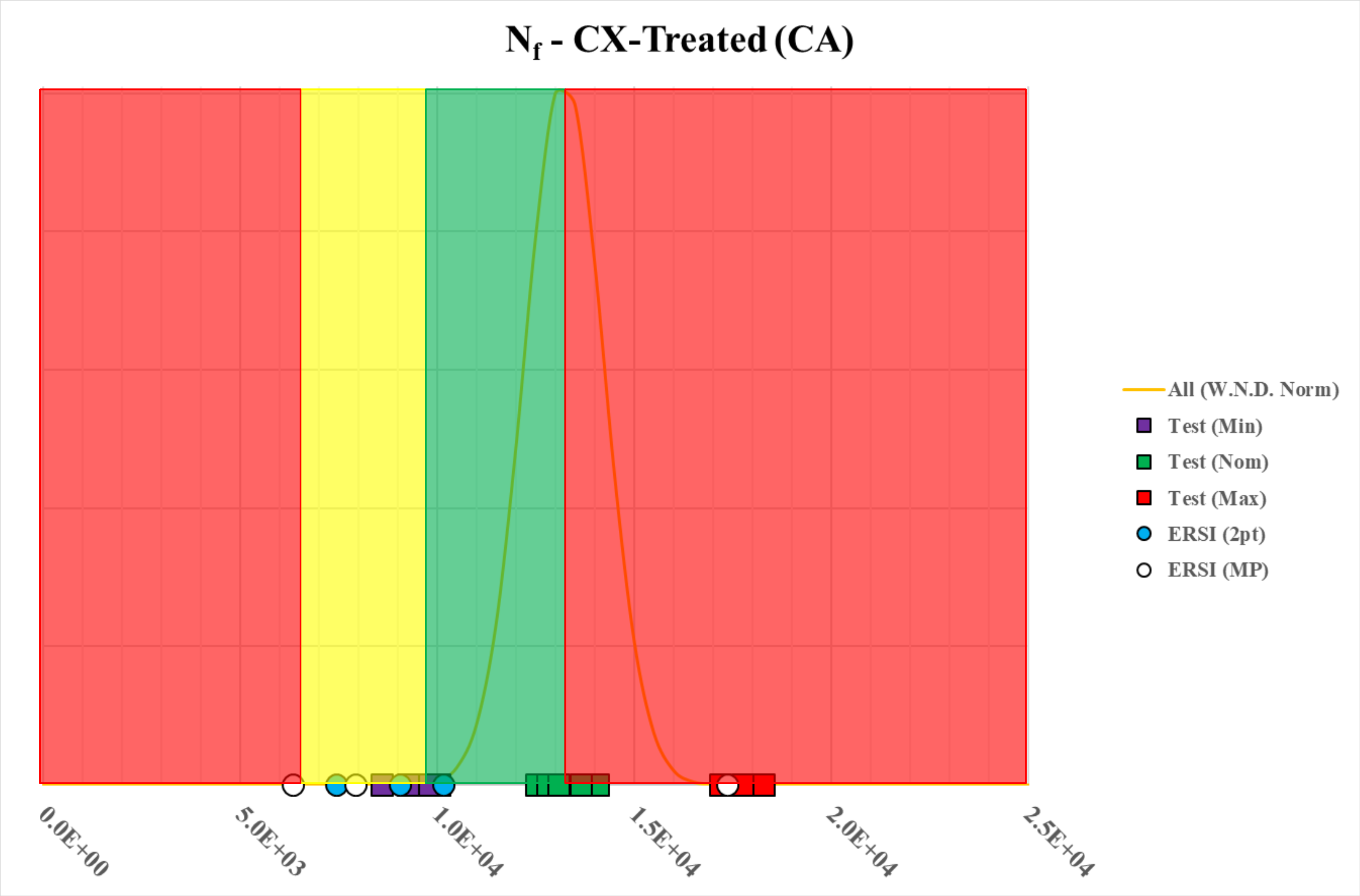
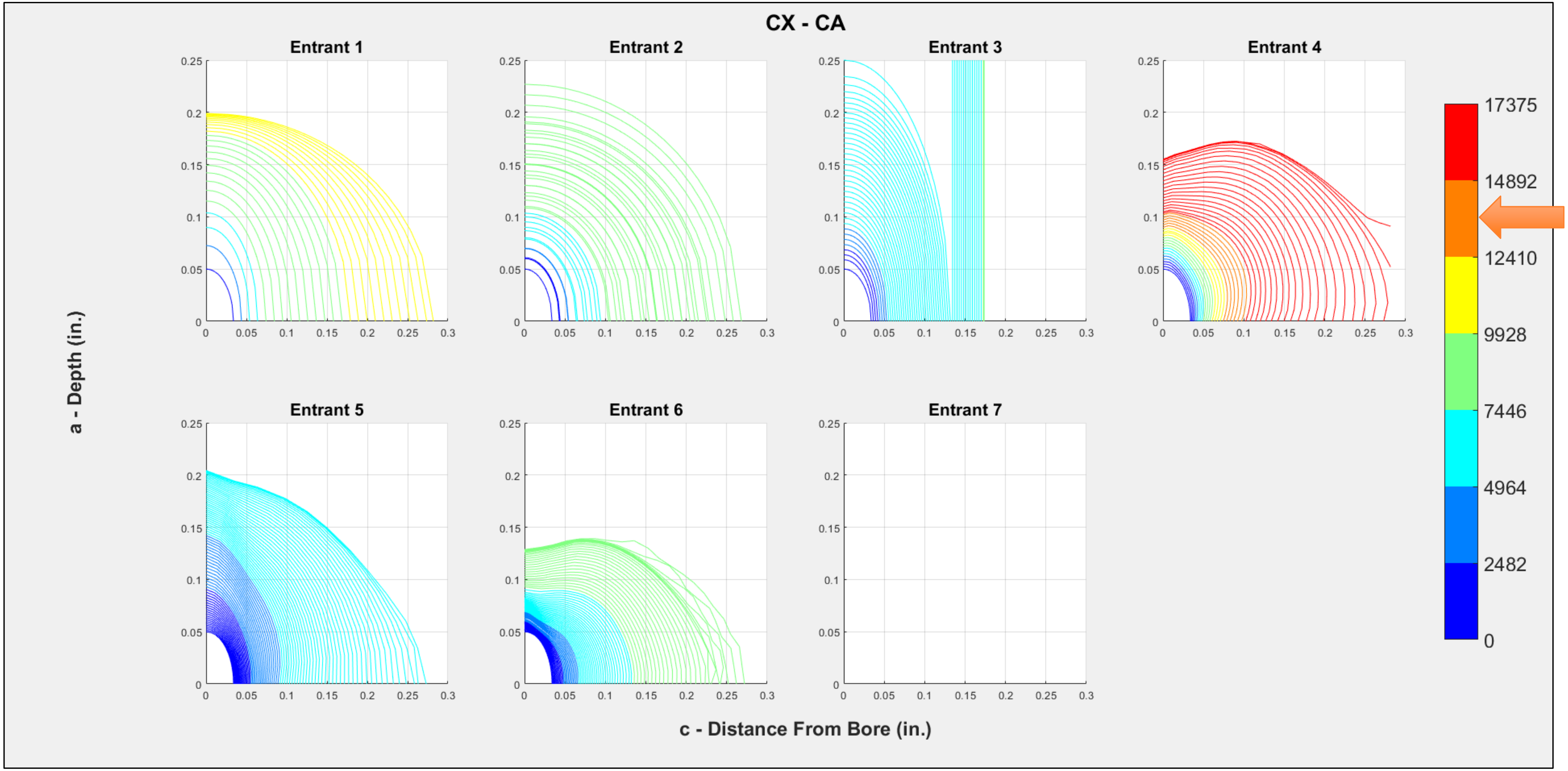
Entrant 7	N/A

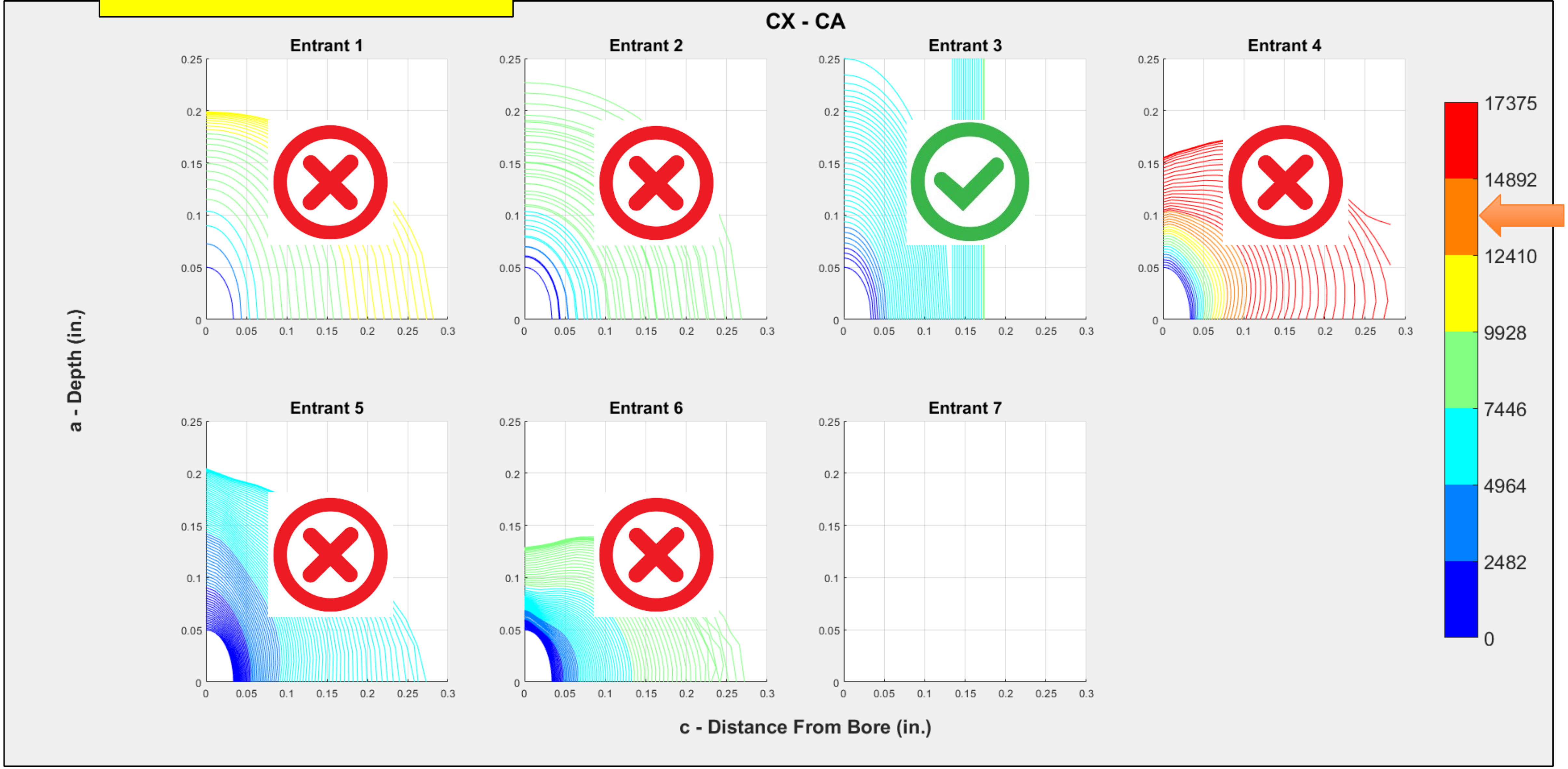


CRACK MORPHOLOGY: CX (CA)

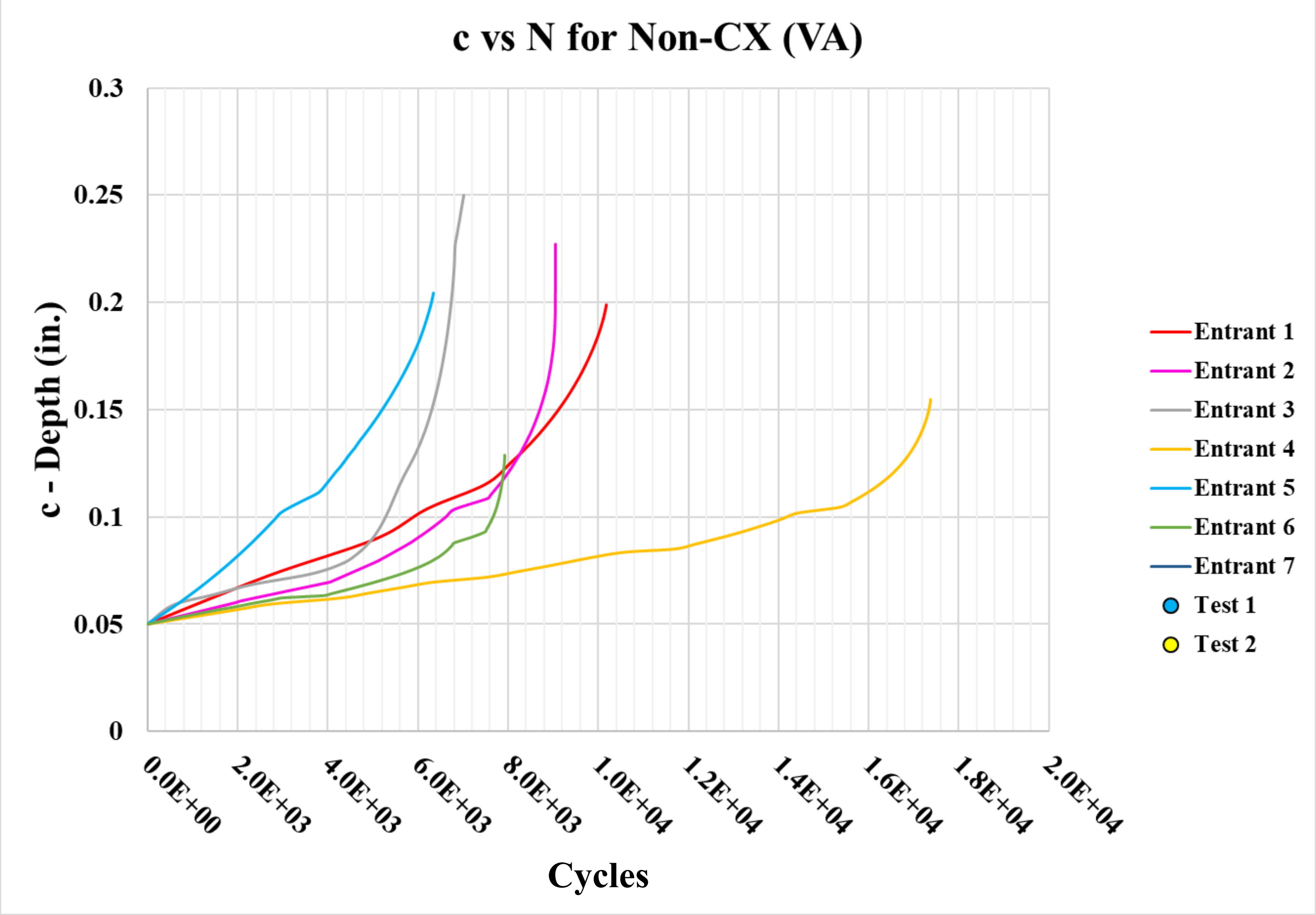


Did it break through?

CRACK MORPHOLOGY: CX (CA)

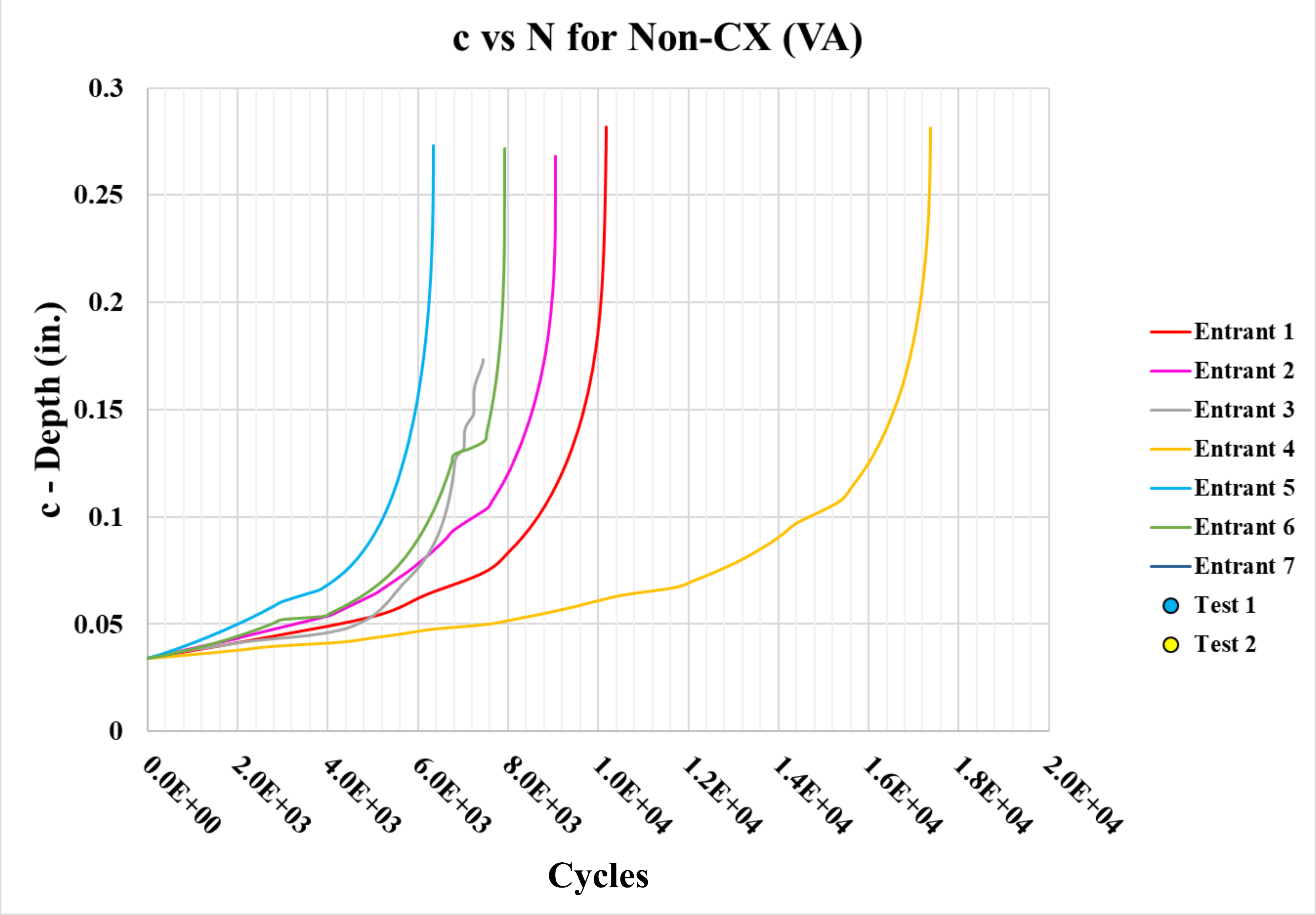


CRACK PROGRESSION: CX (CA)



ENGINEERED RESIDUAL STRESS IMPLEMENTATION

CRACK PROGRESSION: CX (CA)

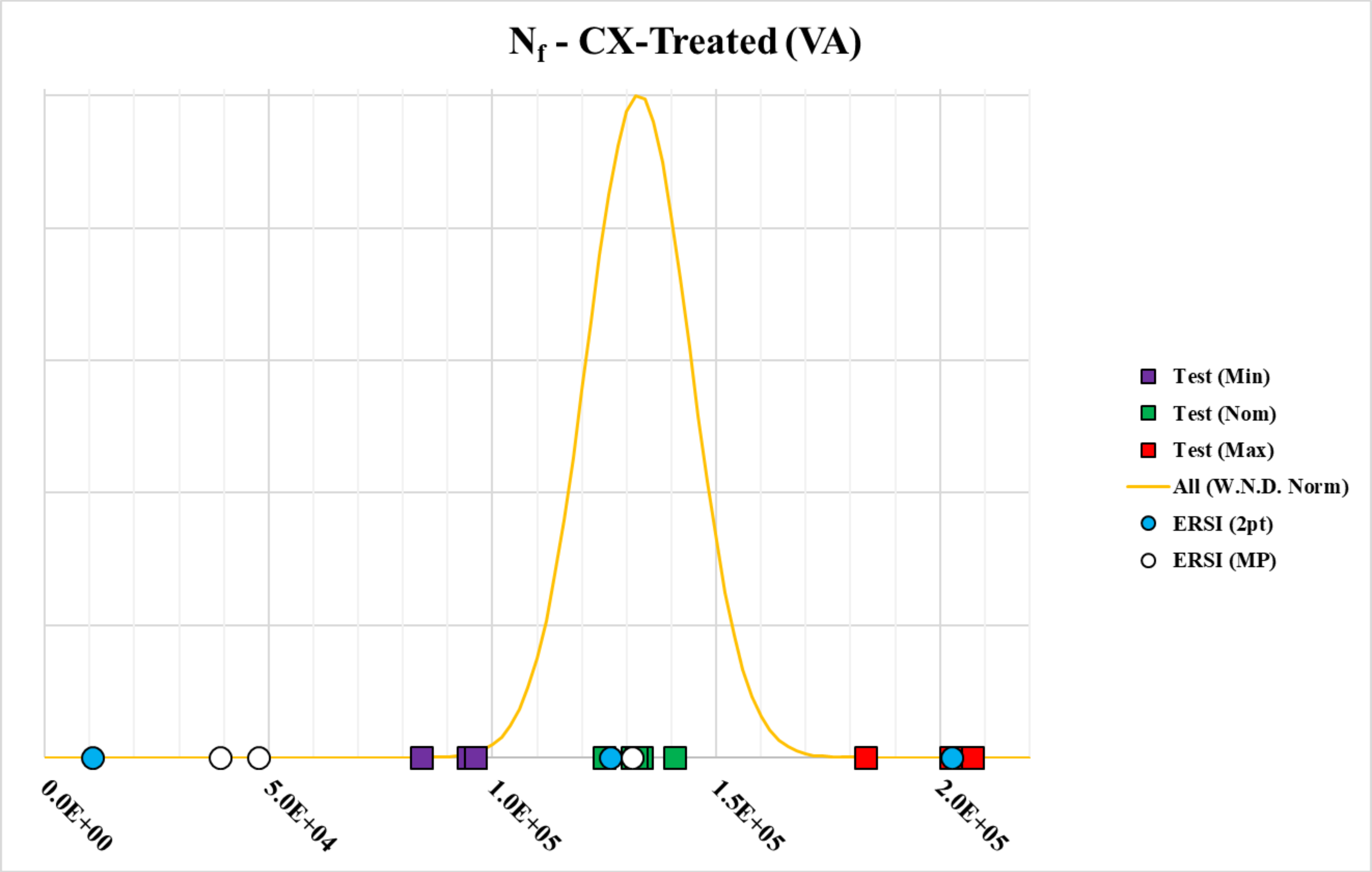


SCORE CARD: CX (CA)

Entrant	Nf	Morphology	a vs N Shape	c vs N Shape
1			TBD	TBD
2			TBD	TBD
3			TBD	TBD
4			TBD	TBD
5			TBD	TBD
6			TBD	TBD
7	N/A	N/A	N/A	N/A

CYCLES TO FAILURE: CX (VA)

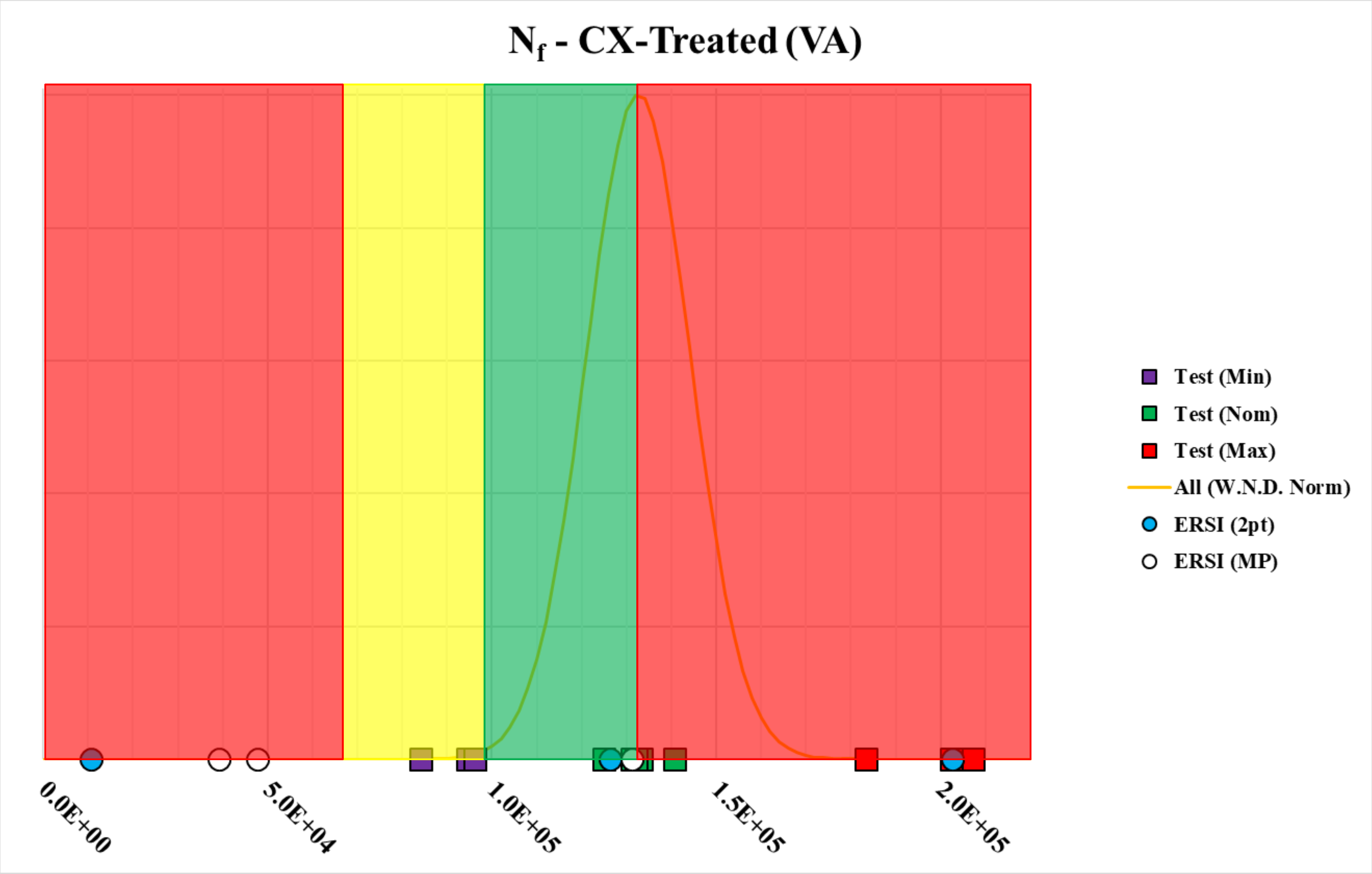
	N_f
Test (Mean)	132626
Entrant 1	202570
Entrant 2	126434
Entrant 3	10693
Entrant 4	131191
Entrant 5	39232
Entrant 6	47824
Entrant 7	N/A



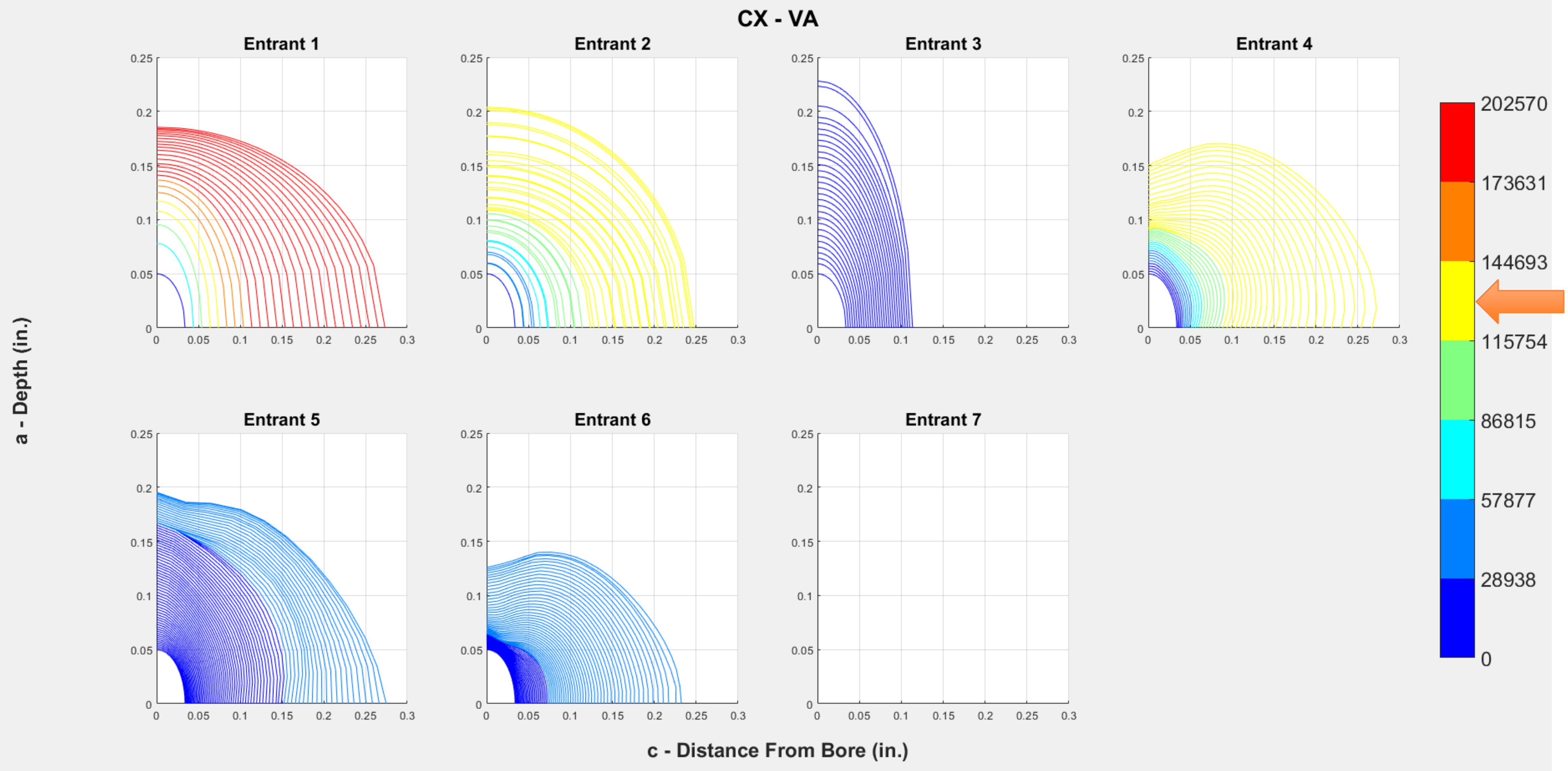
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

CYCLES TO FAILURE: CX (VA)

	N_f
Test (Mean)	132626
Entrant 1	202570
Entrant 2	126434
Entrant 3	10693
Entrant 4	131191
Entrant 5	39232
Entrant 6	47824
Entrant 7	N/A

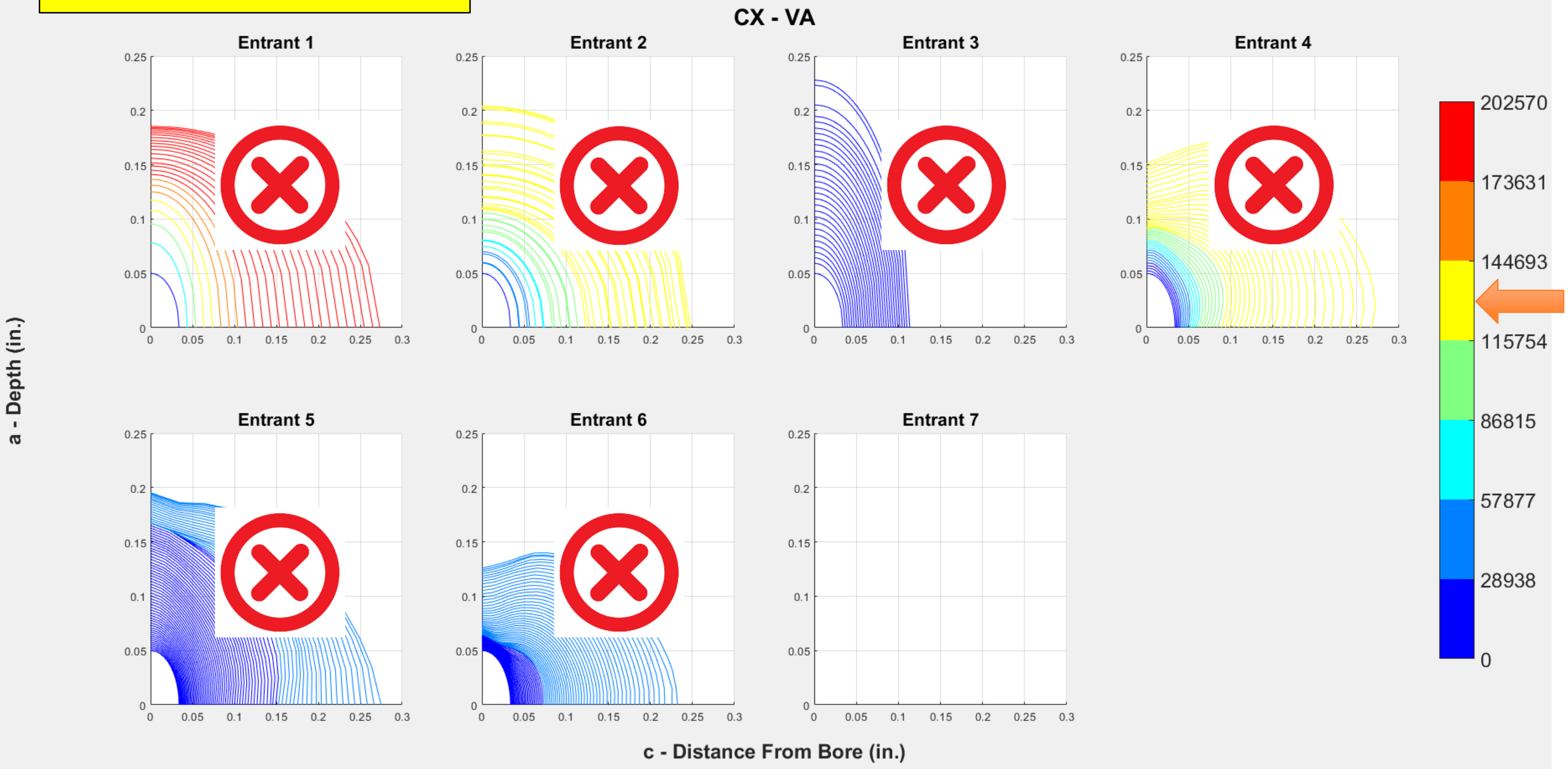


CRACK MORPHOLOGY: CX (VA)

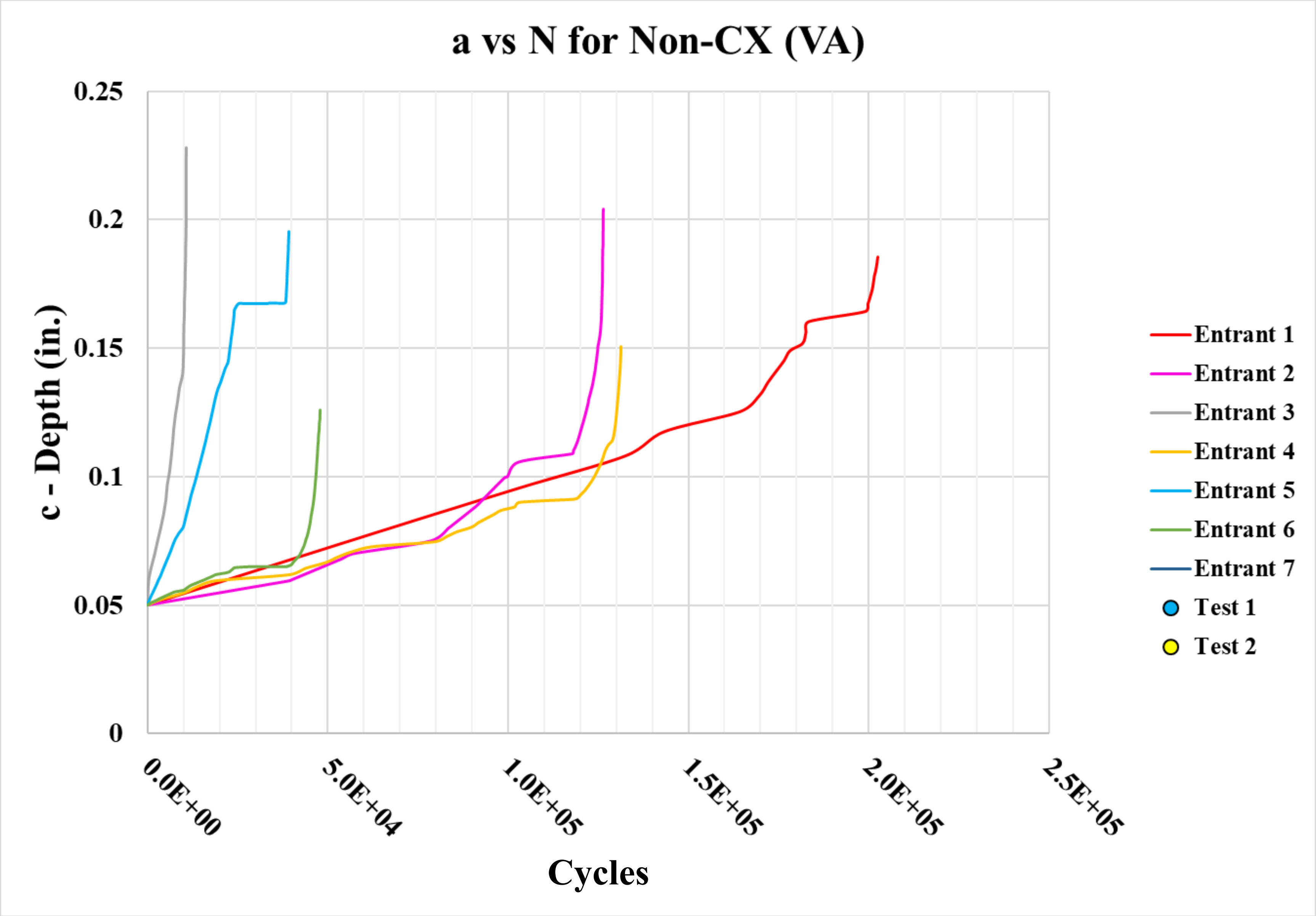


CRACK MORPHOLOGY: CX (VA)

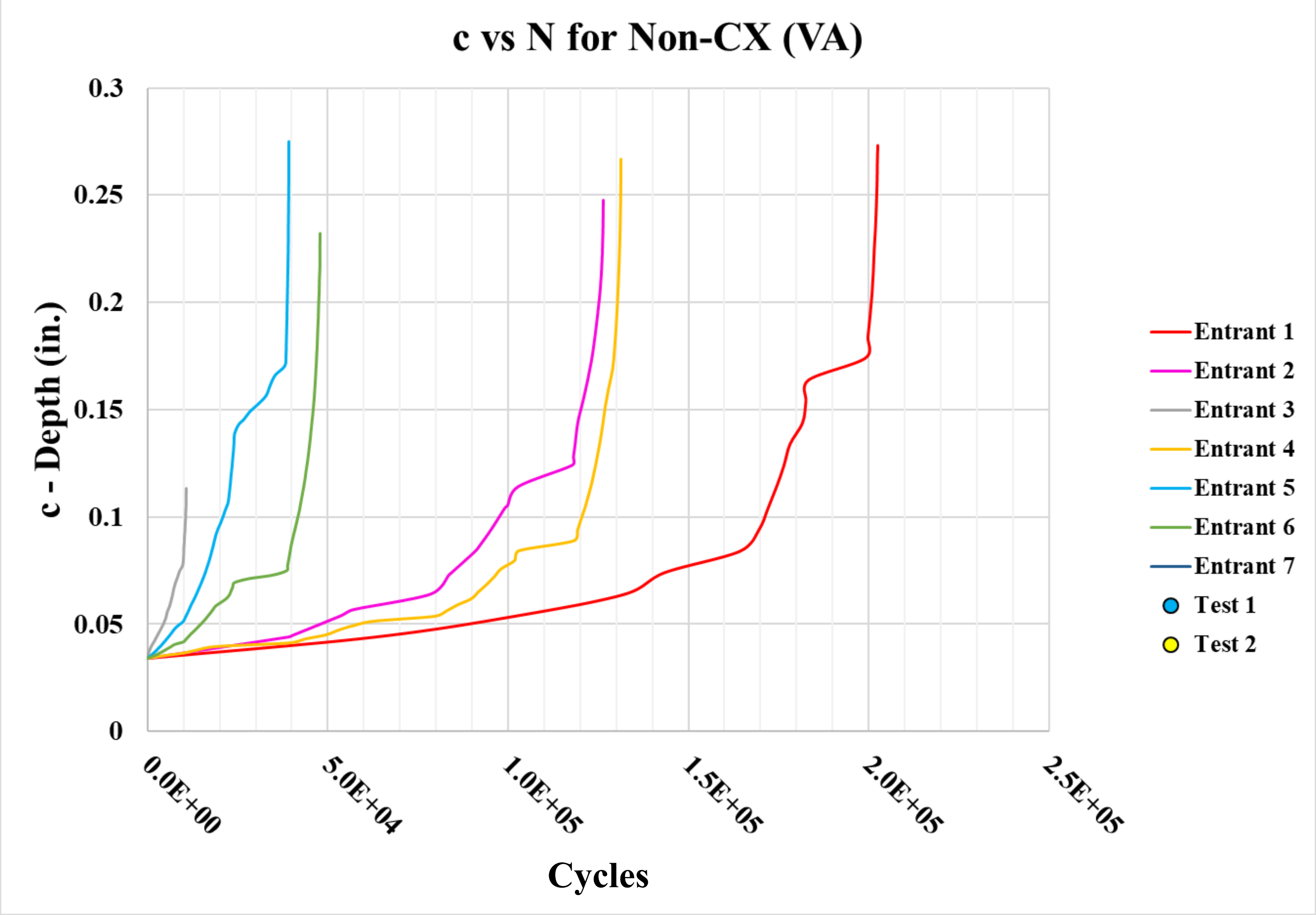
Did it break through?



CRACK PROGRESSION: CX (VA)



CRACK PROGRESSION: CX (VA)



ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

SCORE CARD: CX (VA)

Entrant	Nf	Morphology	a vs N Shape	c vs N Shape
1			TBD	TBD
2			TBD	TBD
3			TBD	TBD
4			TBD	TBD
5			TBD	TBD
6			TBD	TBD
7	N/A	N/A	N/A	N/A

CONCLUSIONS AND NEXT STEPS

Conclusions & Next Steps

- Conclusions
  - Sufficient data to make initial remarks on non-CX treated
    - Most analysts were able to hit Nf and crack shape relatively easily and within USAF requirements
    - Additional discussion about how to quantitatively compare * vs N shape needed
  - Insufficient data to draw conclusions for CX treated
    - Due to significant scatter in analysis results and no quantitative fractography, will need additional time to close this action item
    - Single case capturing break through behavior seen in analysis results despite Nf accuracy
      - Are we getting the right answer for the wrong reason?
- Next Steps
  - Derive process for quantitatively comparing * vs N shape between analysis and test
    - Open to input if this already exists
      - Develop statistics for each N value and plot * vs N with distribution from analysis scatter overlayed
  - Upcoming testing will test an open hole CX treated element specimen with bi-axial bending plus bypass loading, do we have sufficient answers from this effort to proceed with a follow on RR?
  - Do we have enough data to press forward with an SB rev?

Backup

Spectrum Loading Efforts:
Spike Overload and Spectrum Testing

Kevin Walker

Moises Y. Ocasio

Agenda

- Introduction
- Boeing CSM Verification Testing Round Robin (Boeing)
- Spike Overload Testing (QinetiQ Australia/Mississippi State University)
- Spike Overload Testing (Boeing)

- Stress Intensity Calculations and Geometrical Factors
- Load interaction models:
  - da/dN type models (e.g. Modified/Generalized Wheeler)
  - Effective R type models (e.g. Willenborg-Chang)
  - K-opening type models (e.g. Strip Yield)
  - J-based models (e.g. J algorithm)
- Plastic Constraint Effects in Crack Growth Behavior
- Large Crack Growth
- Small Crack Growth

Fatigue Life Enhancement

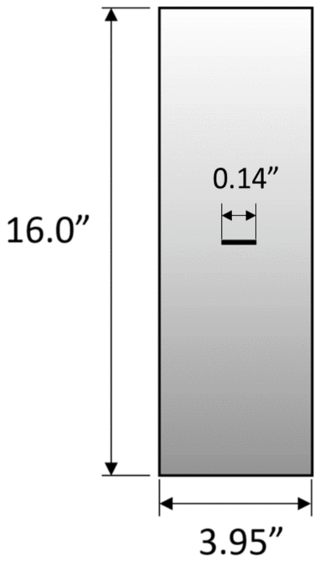
- Direct (e.g. Cold Work, IFF)
- Indirect (e.g. Local Plasticity)

Current Spectrum Efforts

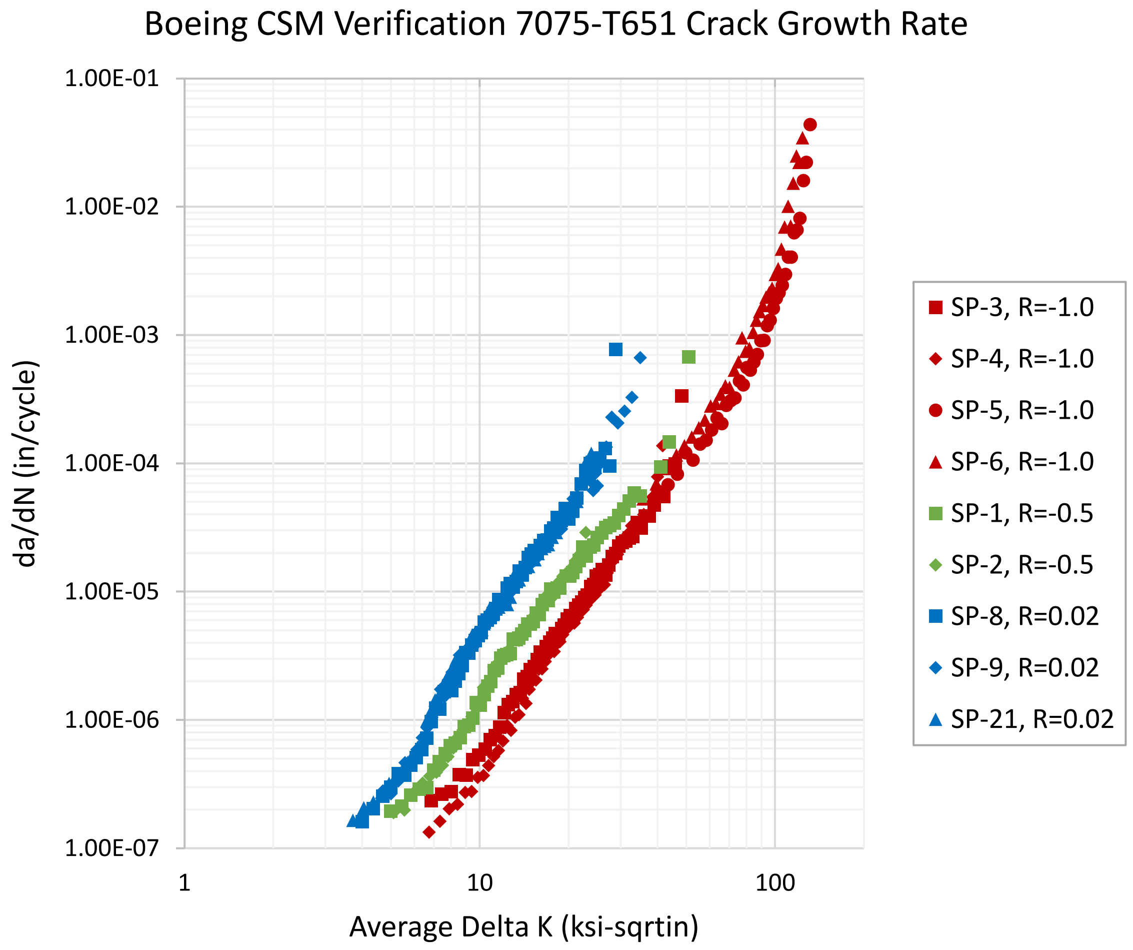
ERSI requires this complimentary approach to understand gaps in our methods, learn from each other and where possible deliver industry-wide guidelines (e.g. Structures Bulletin)

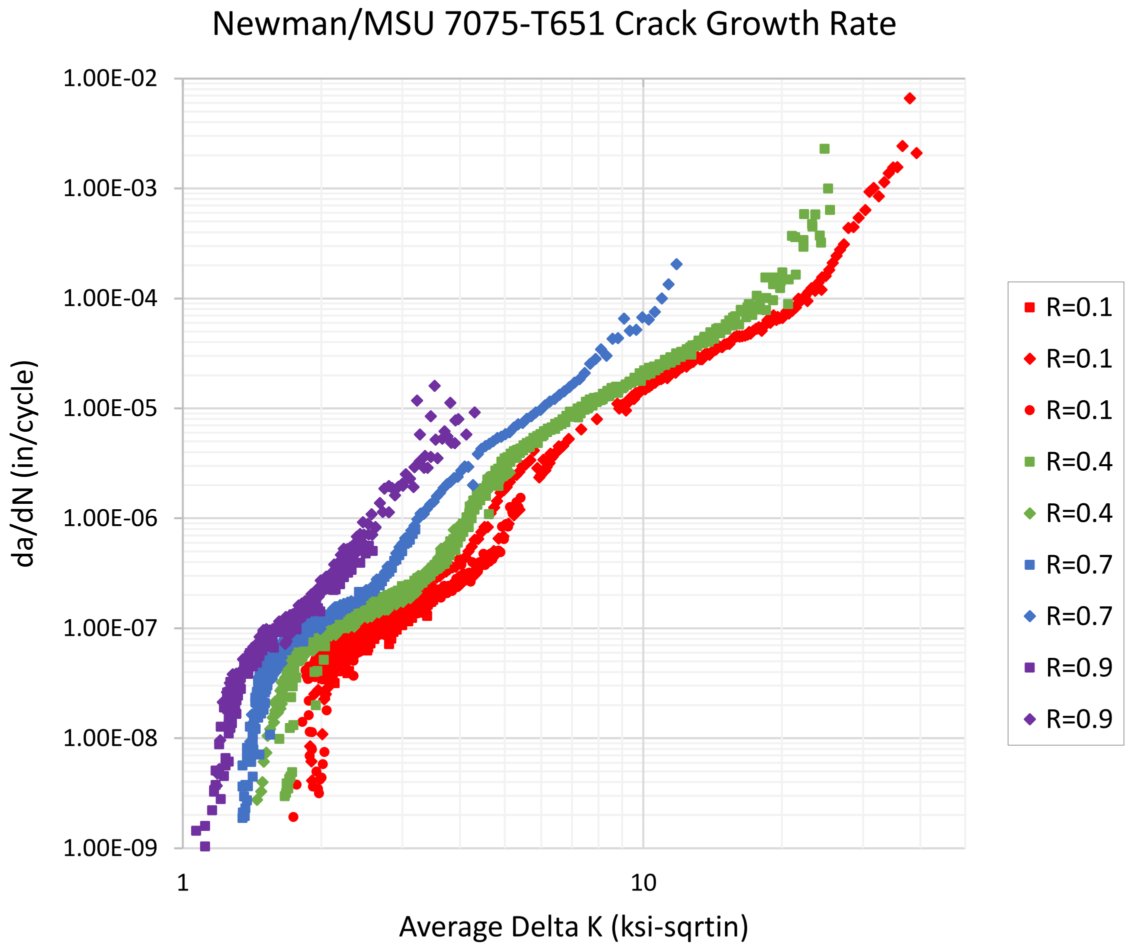
Summary

- Aluminum 7075-T651,
- Growth rate data provided from two sources : Boeing testing, MSU testing (Dr. Jim Newman)
- 2 tasks used for round robin exercise
  - Task A: Constant Amplitude with Spike Overloads
  - Task B: Fighter Lower Wing Spectrum



Round Robin Growth Rate Data Provided

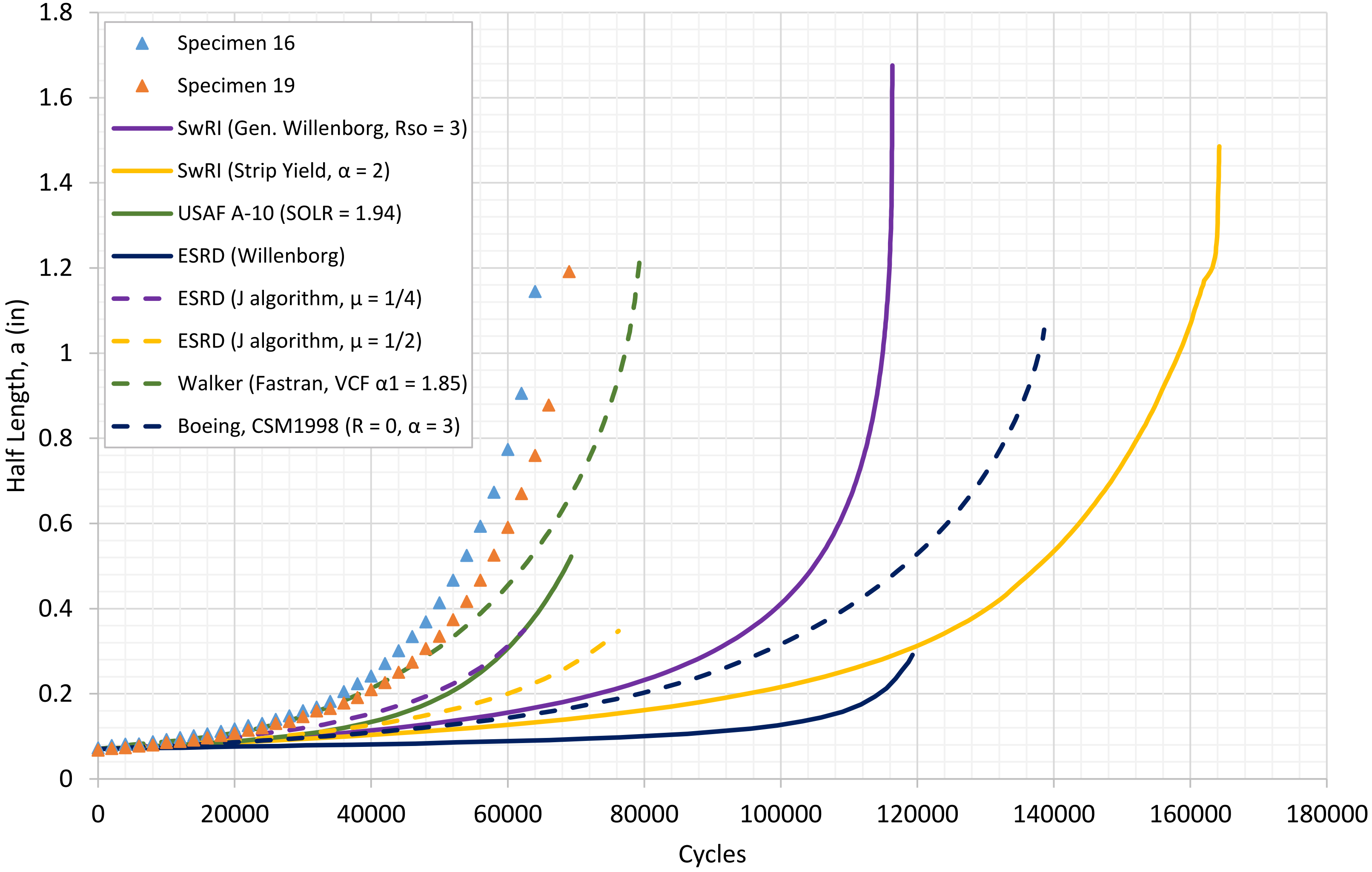




Boeing CSM Verification Testing Round Robin

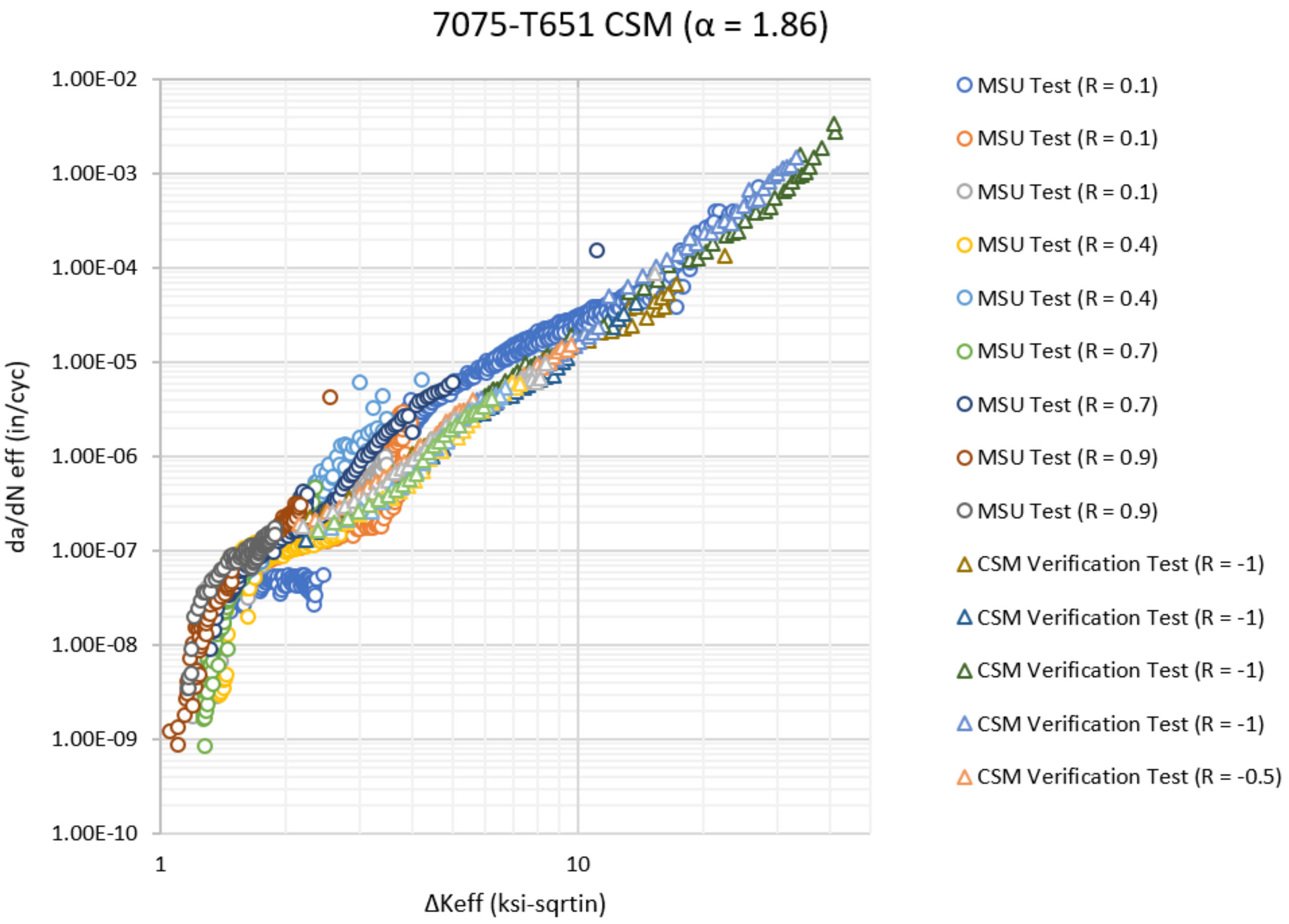
Task A: Constant Amplitude with Spike Overloads Prediction

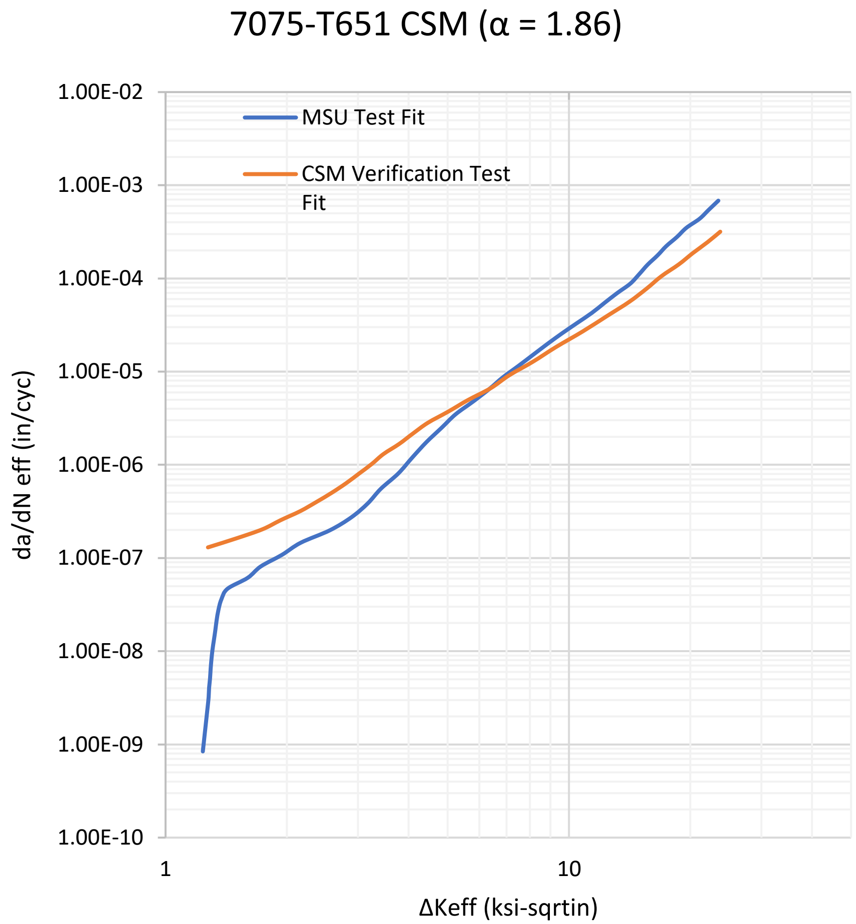
Configuration	Specimen Thickness (in)	Specimen Width (in)	Stress Level (ksi)	Stress Ratio	Test Type
A	0.245	3.950	15.0	0.0	Overload



Submission	Errors (v. Specimen 16)	
	CG Life %error	acrit %error
SwRI (Gen. Willenborg, Rso = 3)	82%	46%
SwRI (Strip Yield, α = 2)	157%	30%
USAF A-10 (SOLR = 1.94)	8%	-54%
ESRD (Willenborg)	86%	-75%
ESRD (J algorithm, μ = 1/4)	-2%	-69%
ESRD (J algorithm, μ = 1/2)	19%	-70%
Walker (Fastran, VCF α1 = 1.85)	24%	8%
Boeing, CSM1998 (R = 0, α = 3)	117%	-8%

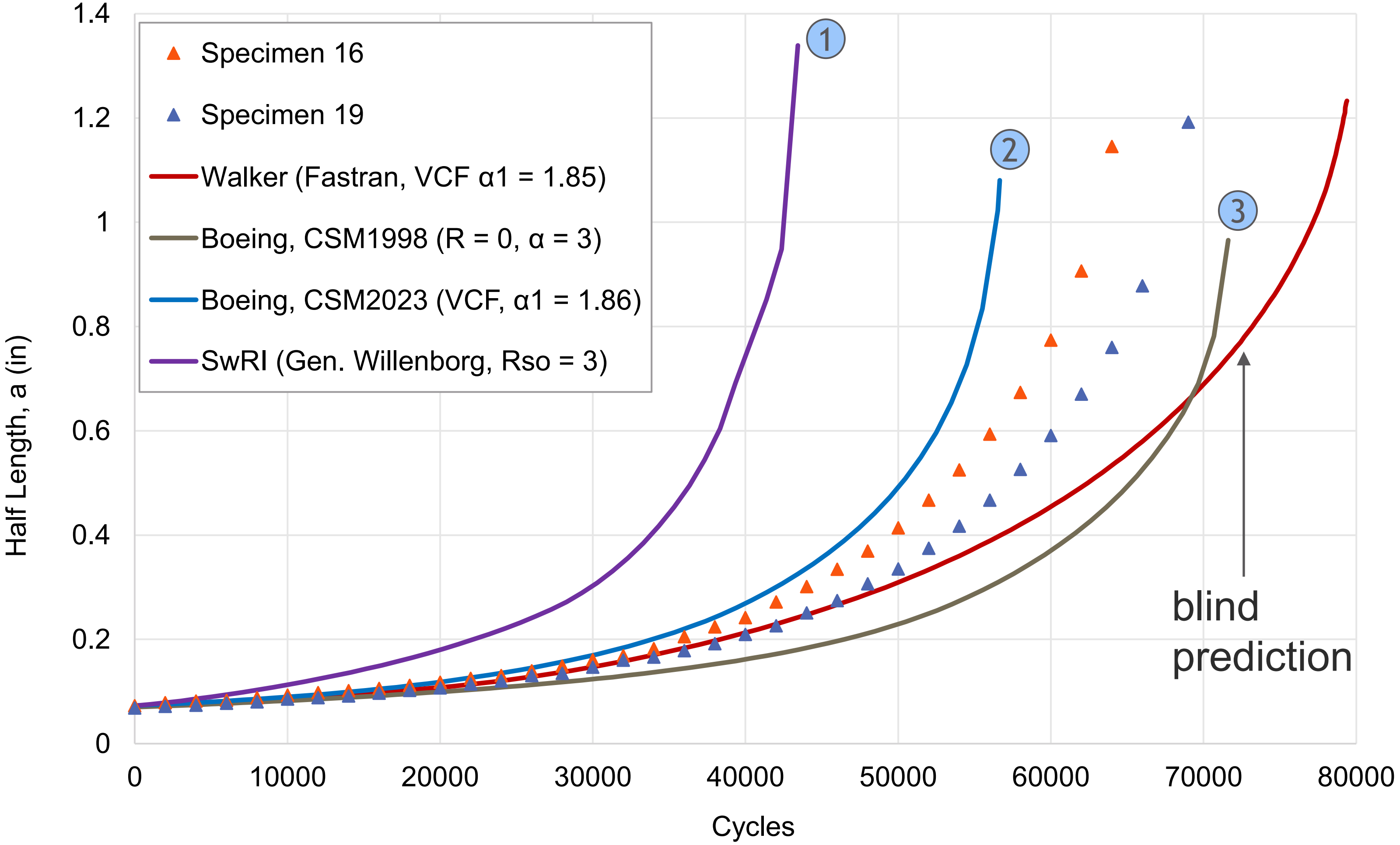
Crack Growth Rate Model





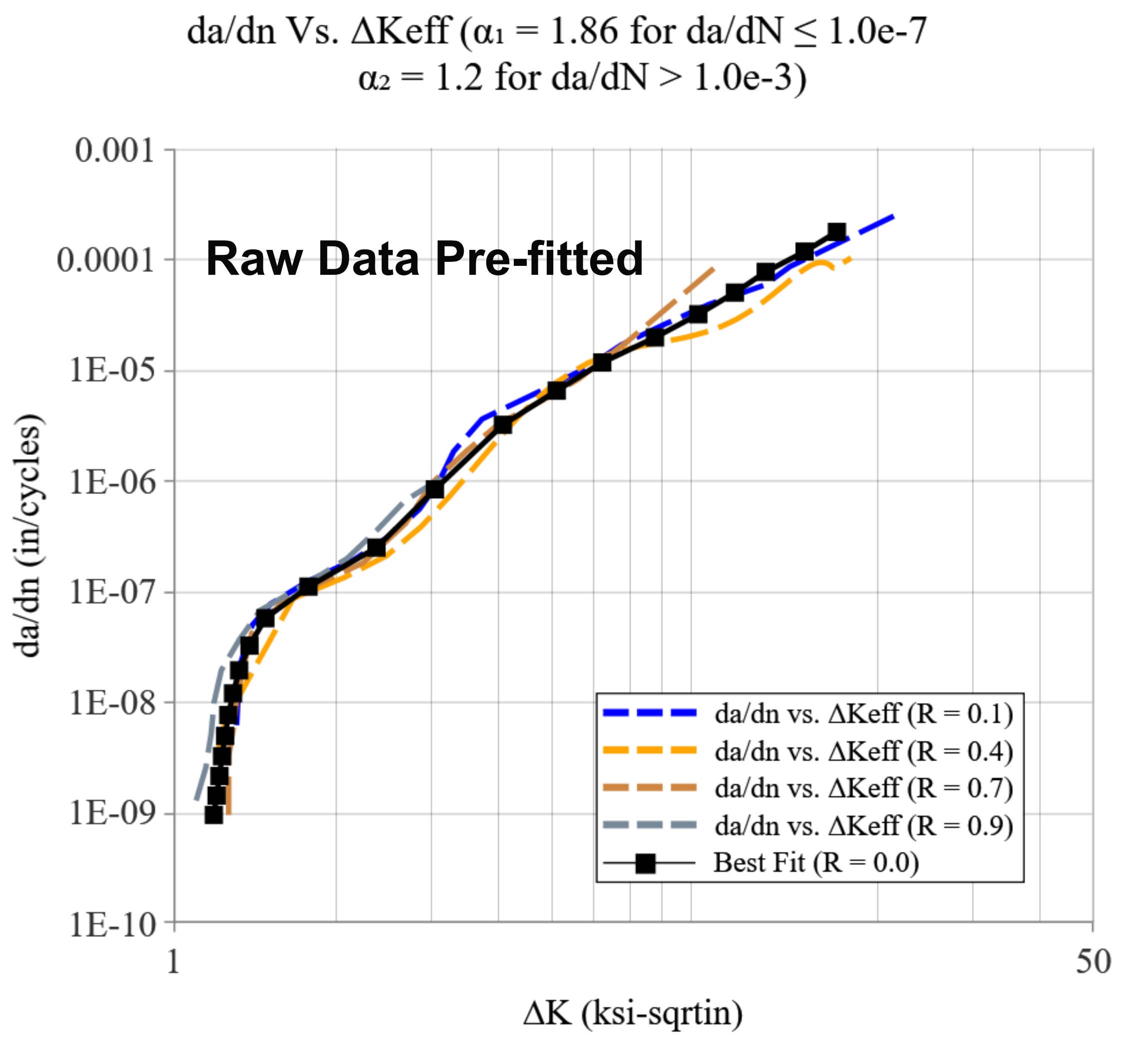
- CSM data: MT specimens, pre-cracked using load-shedding method. No Region I.
- MSU data: CT specimens, pre-cracked following CPCA method.

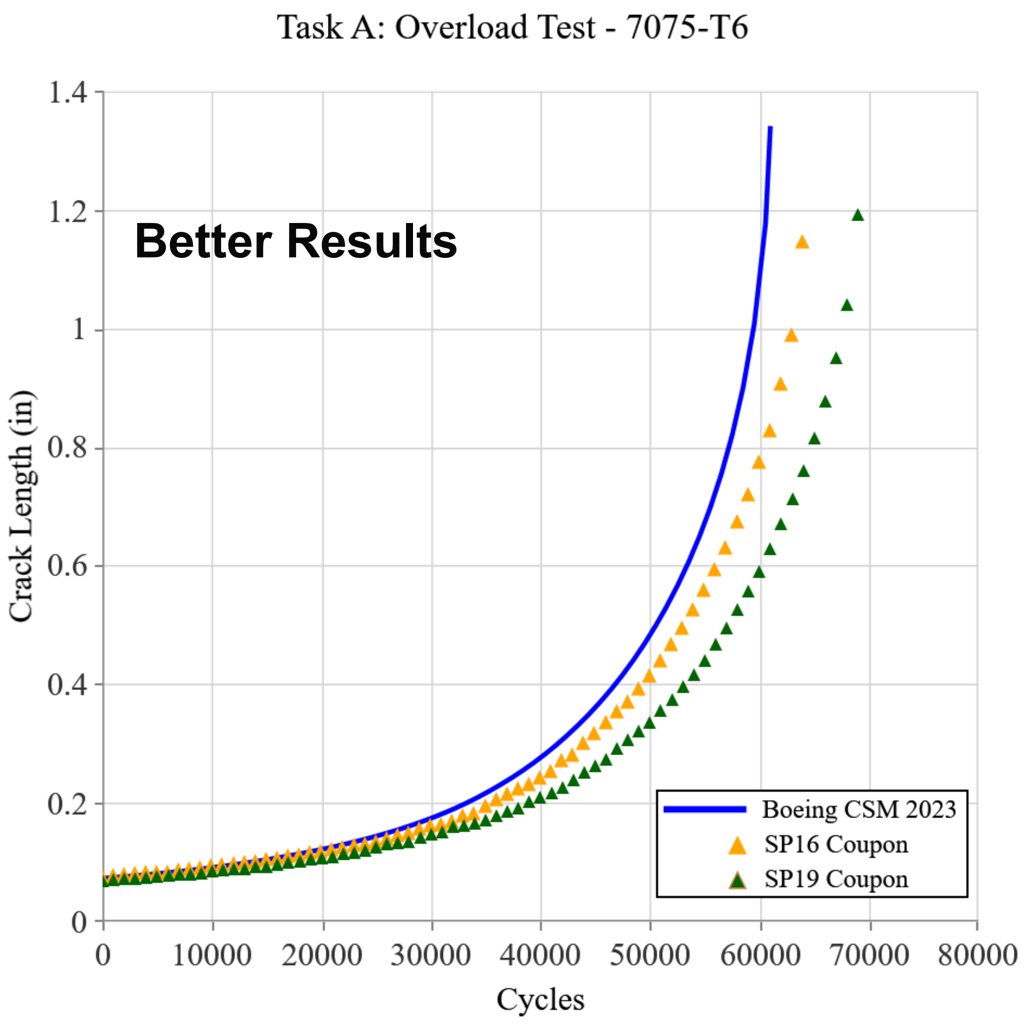
Task A: Constant Amplitude with Spike Overloads Lessons Learned



1. Tabular fit does better than the Nasgro equation fit for “wavy” data present in many Aluminum growth rate data.
2. Strip-yield type model with variable constraint factor (and constraint loss) accurately captures OL benefits.
3. Originally over-predicted due to exclusion of high R da/dN curves from fit.

Crack Growth Rate Constraint Factor and Overload Test Prediction

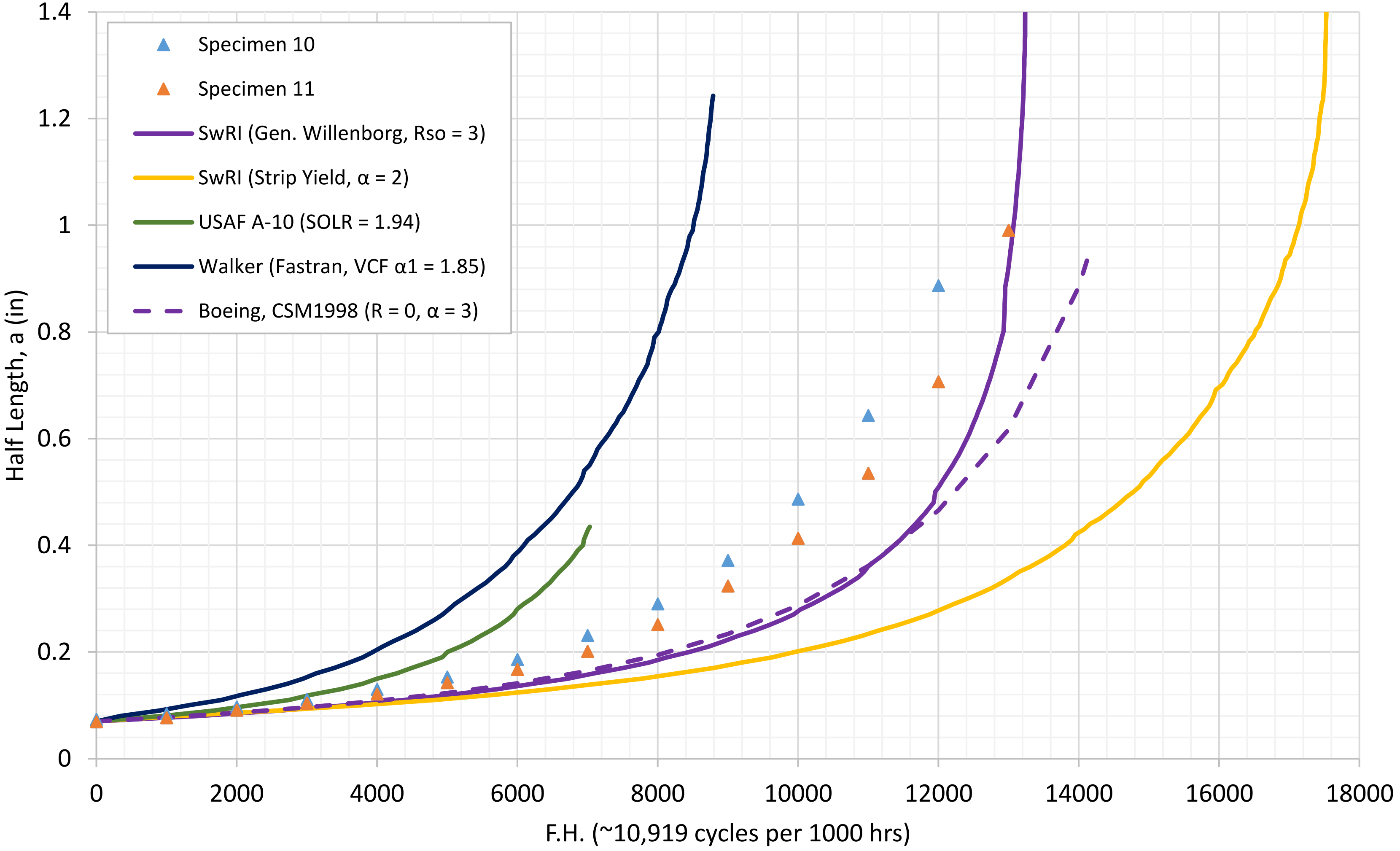


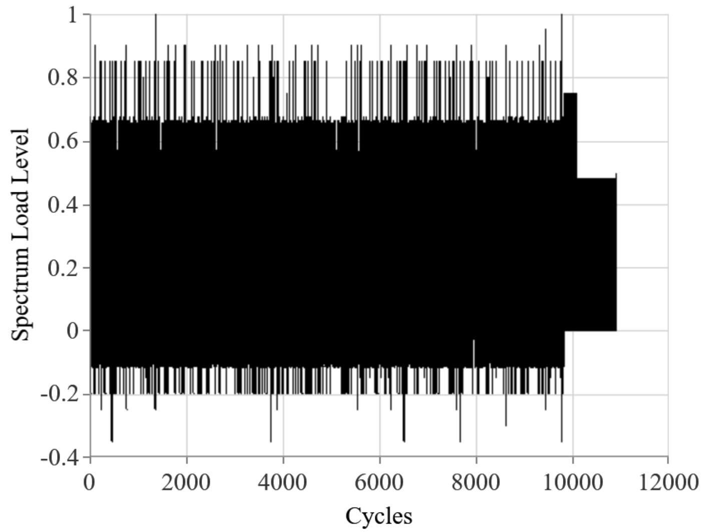


Task B: Fighter Lower Wing Spectrum Prediction

Configuration	Specimen Thickness (in)	Specimen Width (in)	Stress Level (ksi)	Test Type
B	0.246	3.960	25.0	Lower Wing

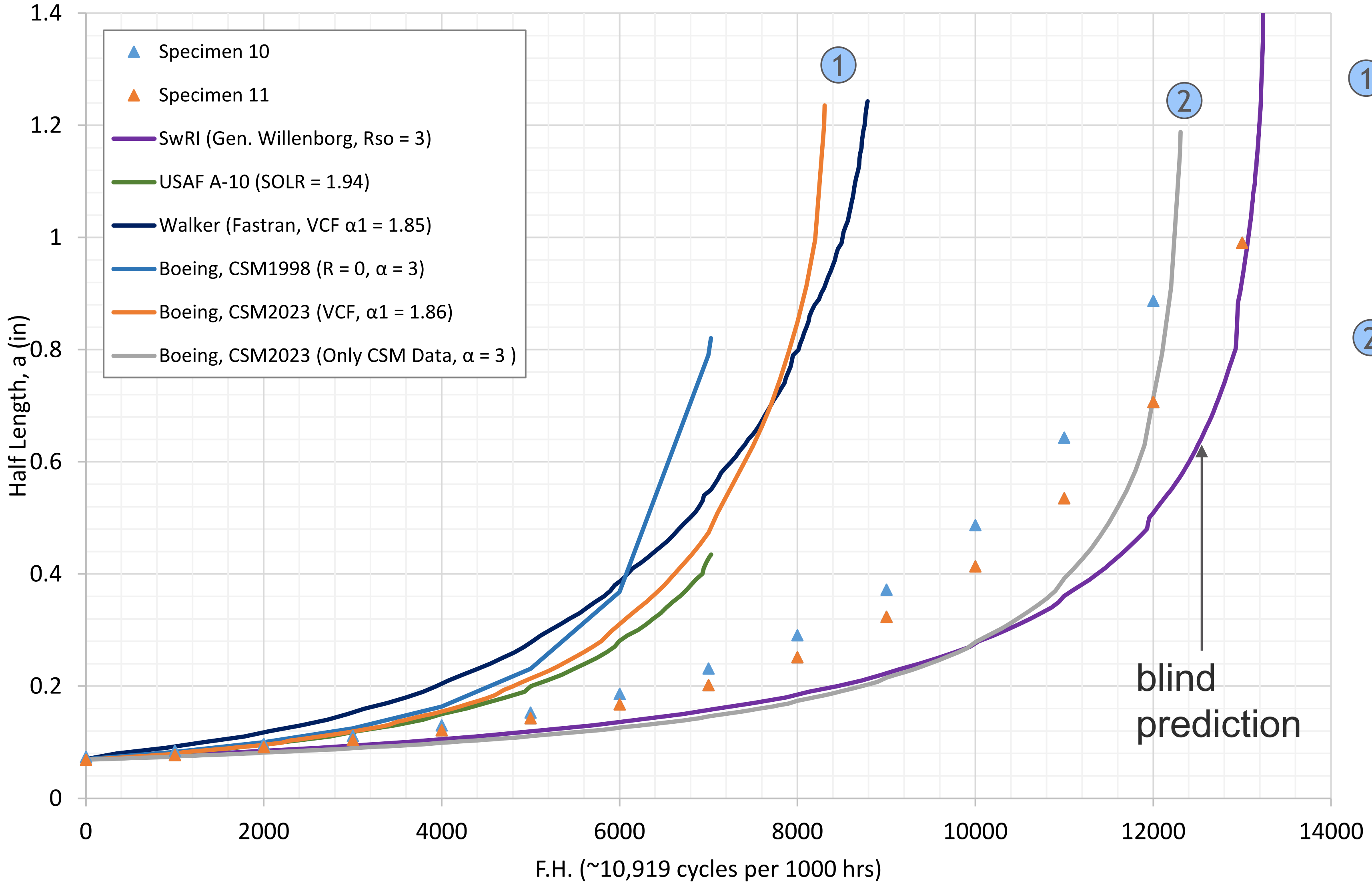
Submission	Errors (v. Specimen 10)	
	CG Life %error	acrit %error
SwRI (Gen. Willenborg, Rso = 3)	10%	74%
SwRI (Strip Yield, α = 2)	46%	68%
USAF A-10 (SOLR = 1.94)	-41%	-51%
Walker (Fastran, VCF α1 = 1.85)	-27%	40%
Boeing, CSM1998 (R = 0, α = 3)	18%	6%





ERSI Working Group on Engineered Residual Stress Implementation

Task B: Fighter Lower Wing Spectrum Lessons Learned



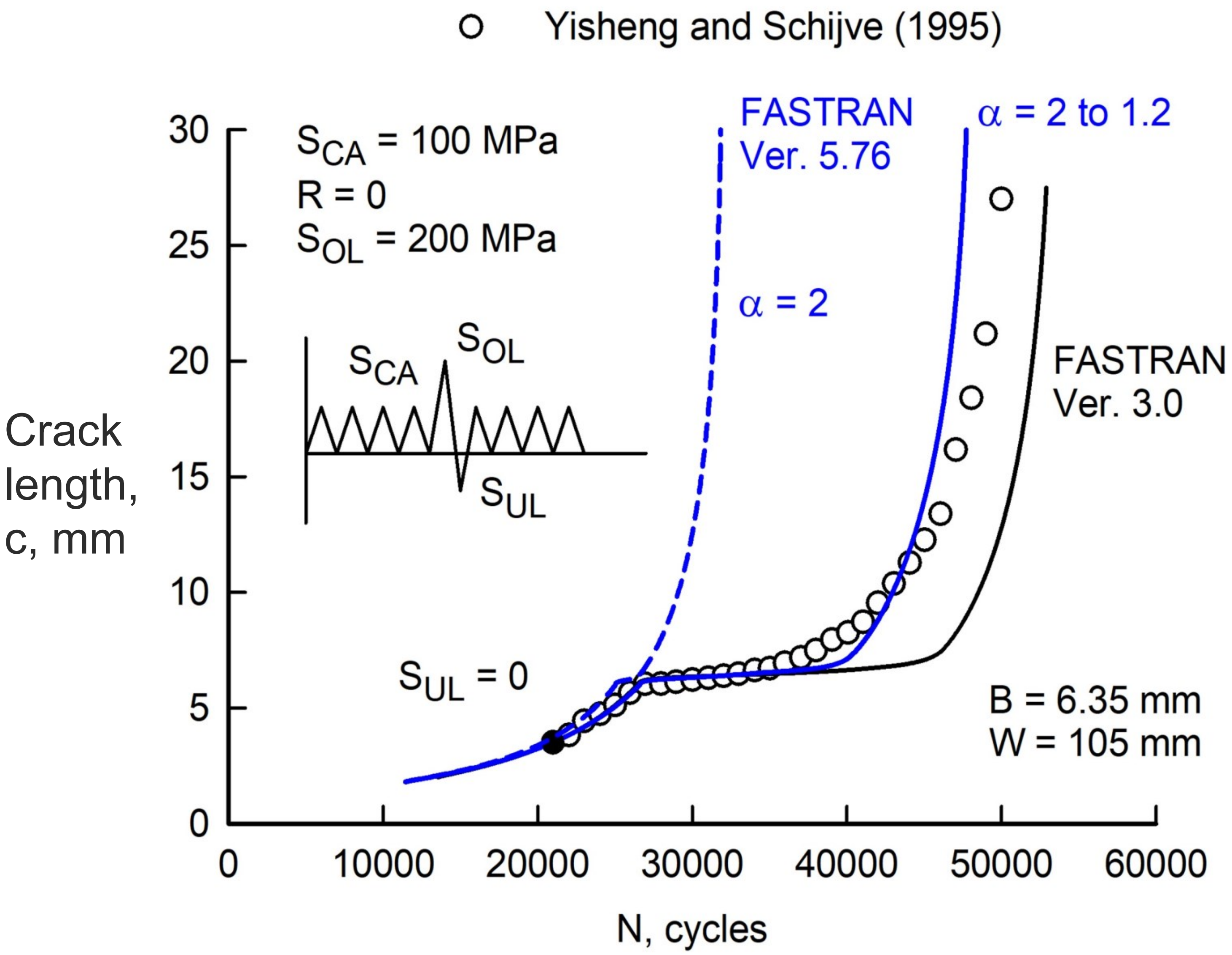
1. Strip-yield models (and Generalized Willenborg with SOLR correlation) produce conservative predictions due to higher Region II slope in MSU 7075-T651 data.
2. Using only CSM R=0 data improves final life prediction.

It is challenging (although not impossible) to combine rate data obtained from different configurations (MT and CT) and methods (e.g. LR VS. CPCA).

QinetiQ Sponsored Test and Analysis (Kevin Walker and Jim Newman)

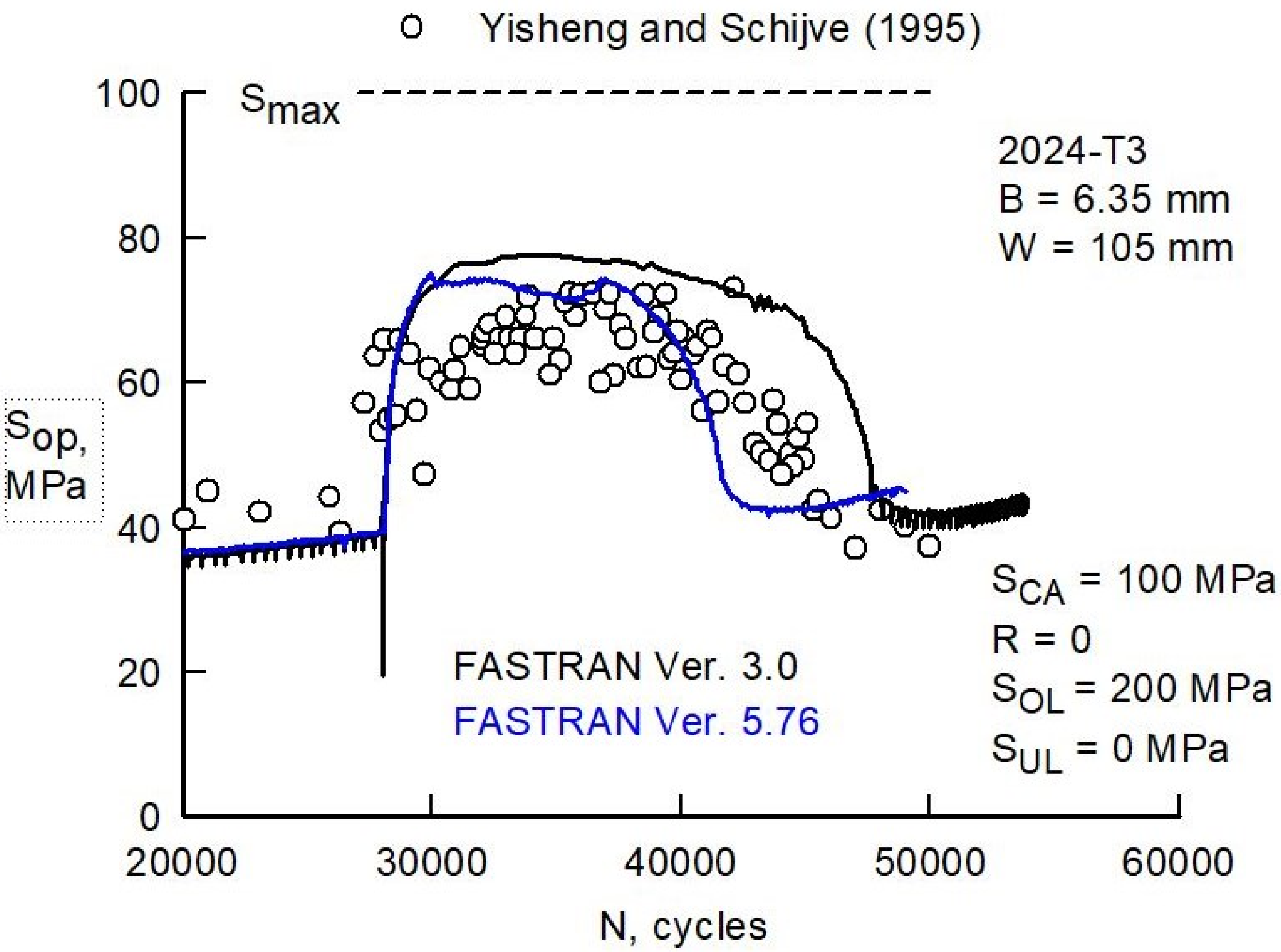
- 22 M(T) specimens from 7075-T6 and 2024-T3 tested so far under CA and spike overload conditions
- Results shown at ASIP 2022 with further presentation at ICAF Conference Delft Netherlands late June 2023
- Small adjustment needed for constraint loss parameters for 7075-T6, but updates to FASTRAN also in progress
- Correlation for 2024-T3 very good
- Further tests now completed/nearly completed under more combinations of overload/underload and mini-TWIST spectrum loading
- Also investigated analysis against literature data from Yisheng and Schijve
- Testing of nine specimens from 7075-T7351 to be conducted in Australia commencing May 2023

Spike Overload Testing (QinetiQ Australia/Mississippi State University)

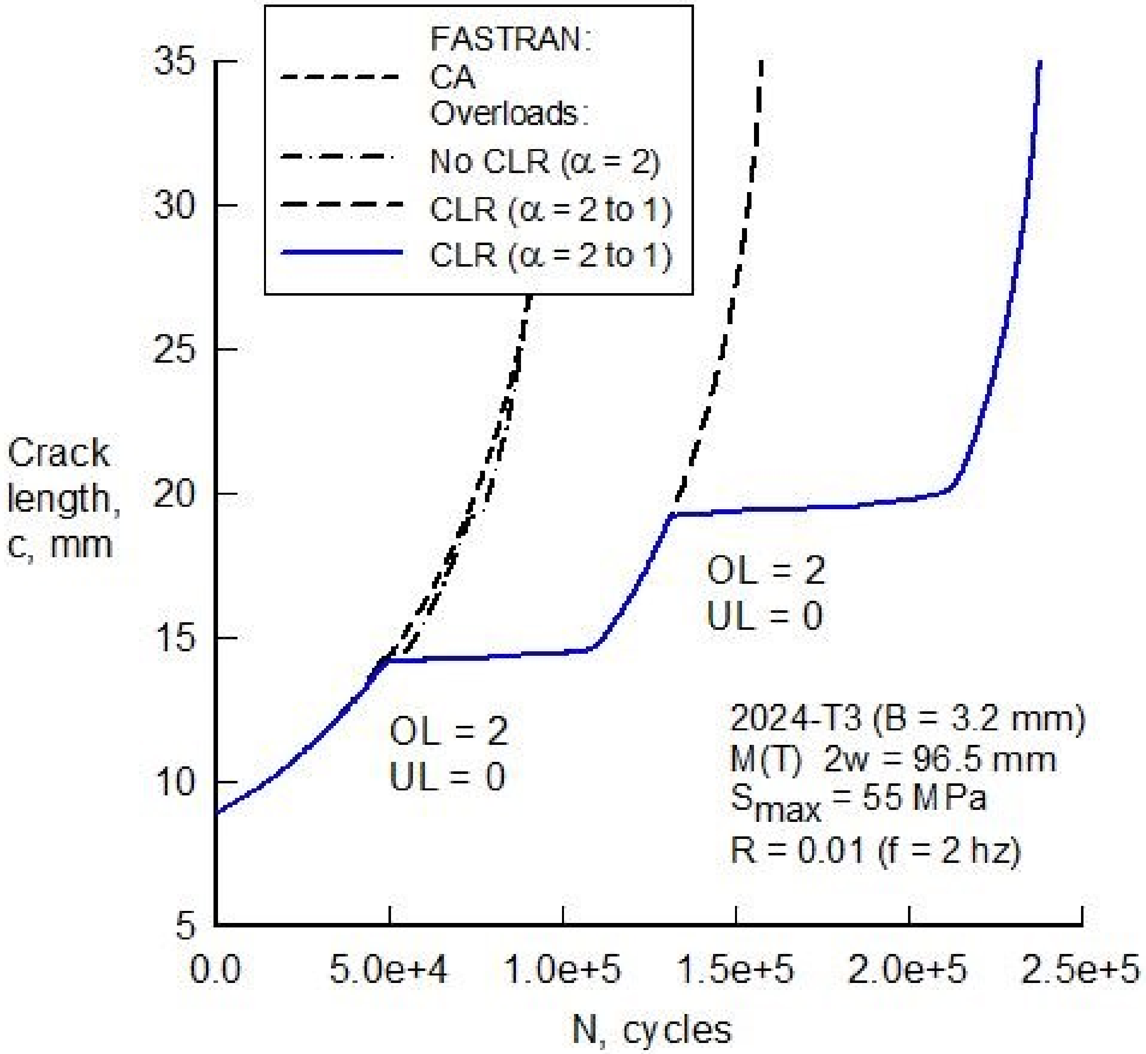


Test and Analyses of a Single-Spike Overload on 2024-T351 Plate

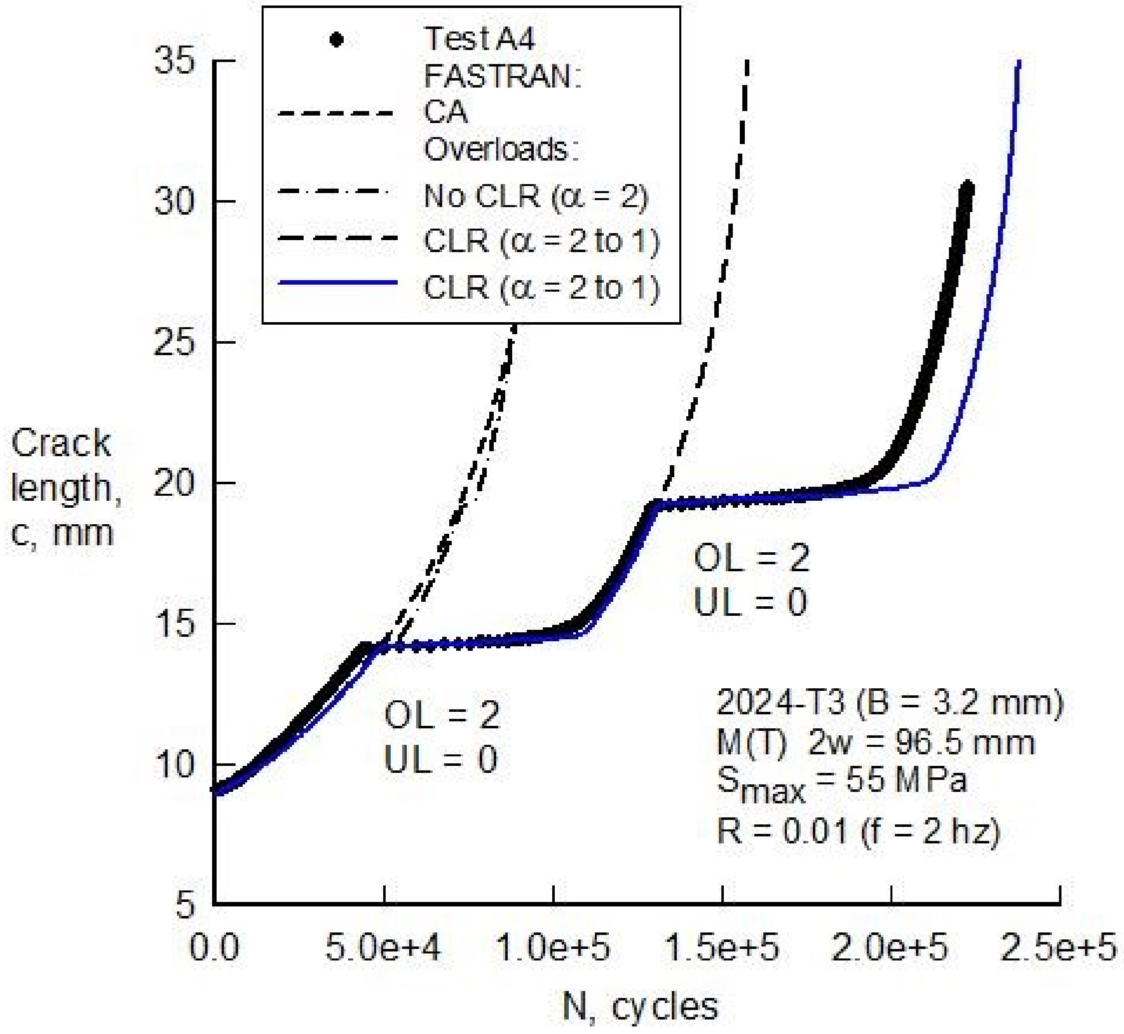
Measured and Calculated Crack-Opening Stress after a Single-Spike Overload on 2024-T351 Plate

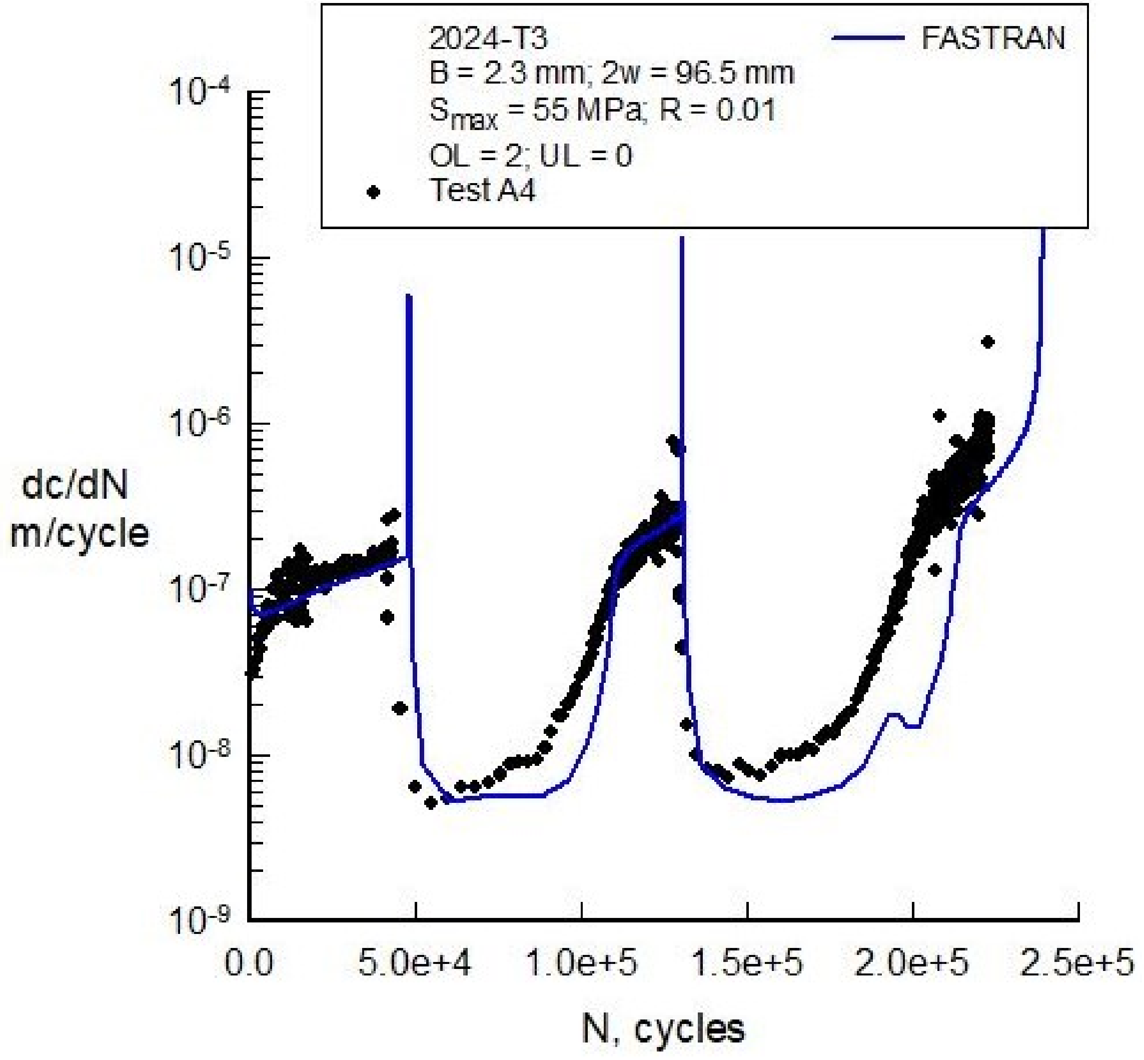


Predicted Crack-Length against Cycles under Repeated Single-Spike Overloads in 2024-T3 Sheet

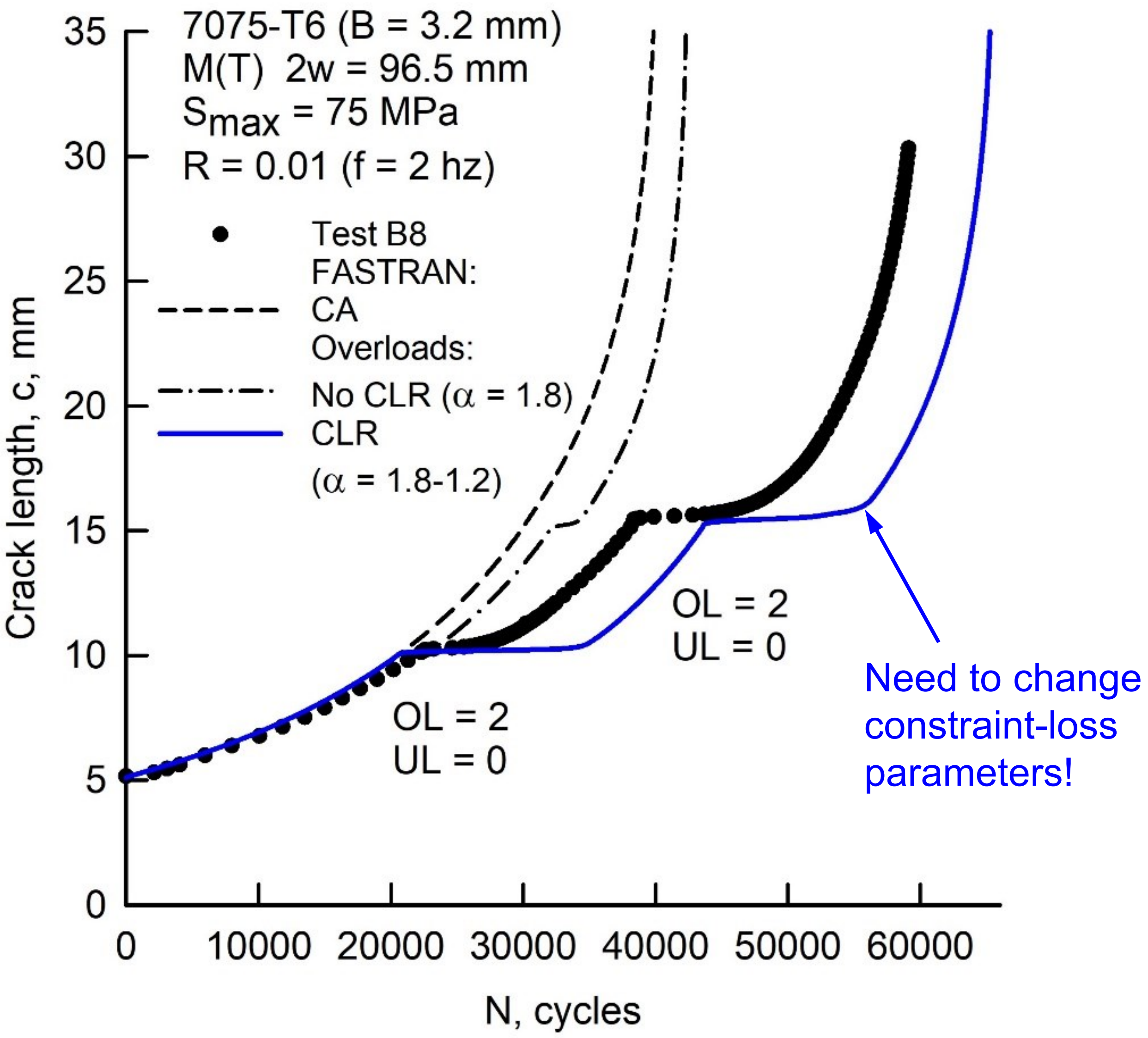


Measured and Predicted Crack-Length against Cycles under Repeated Single-Spike Overloads in 2024-T3 Sheet





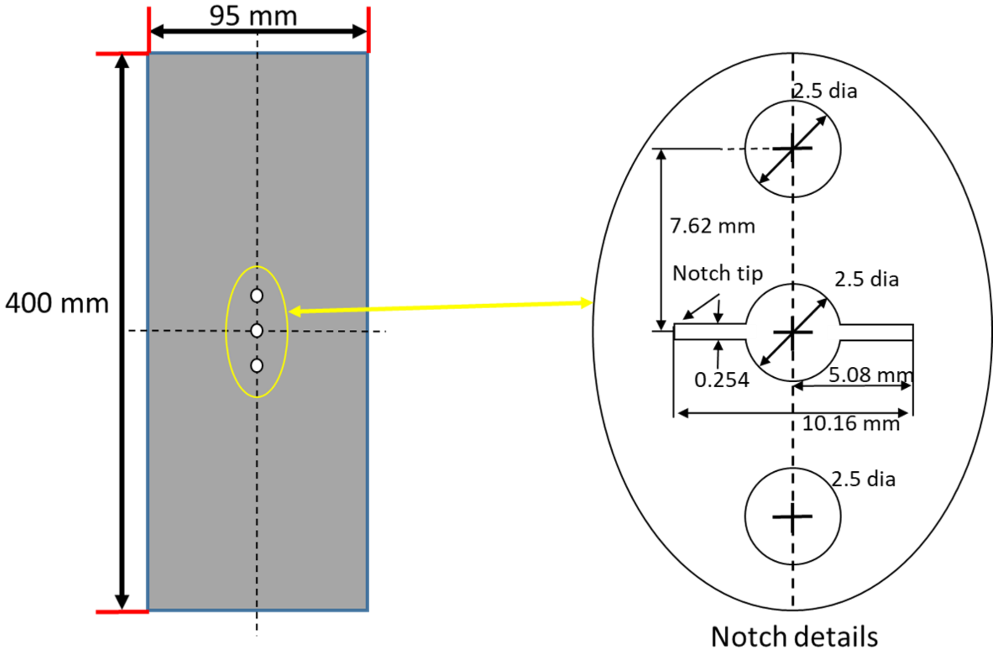
Measured and Predicted Crack-Growth-Rate against Cycles under Repeated Single-Spike Overloads in 2024-T3 Sheet



Measured and Predicted Crack-Length against Cycles under Repeated Single-Spike Overloads in 7075-T6 Sheet

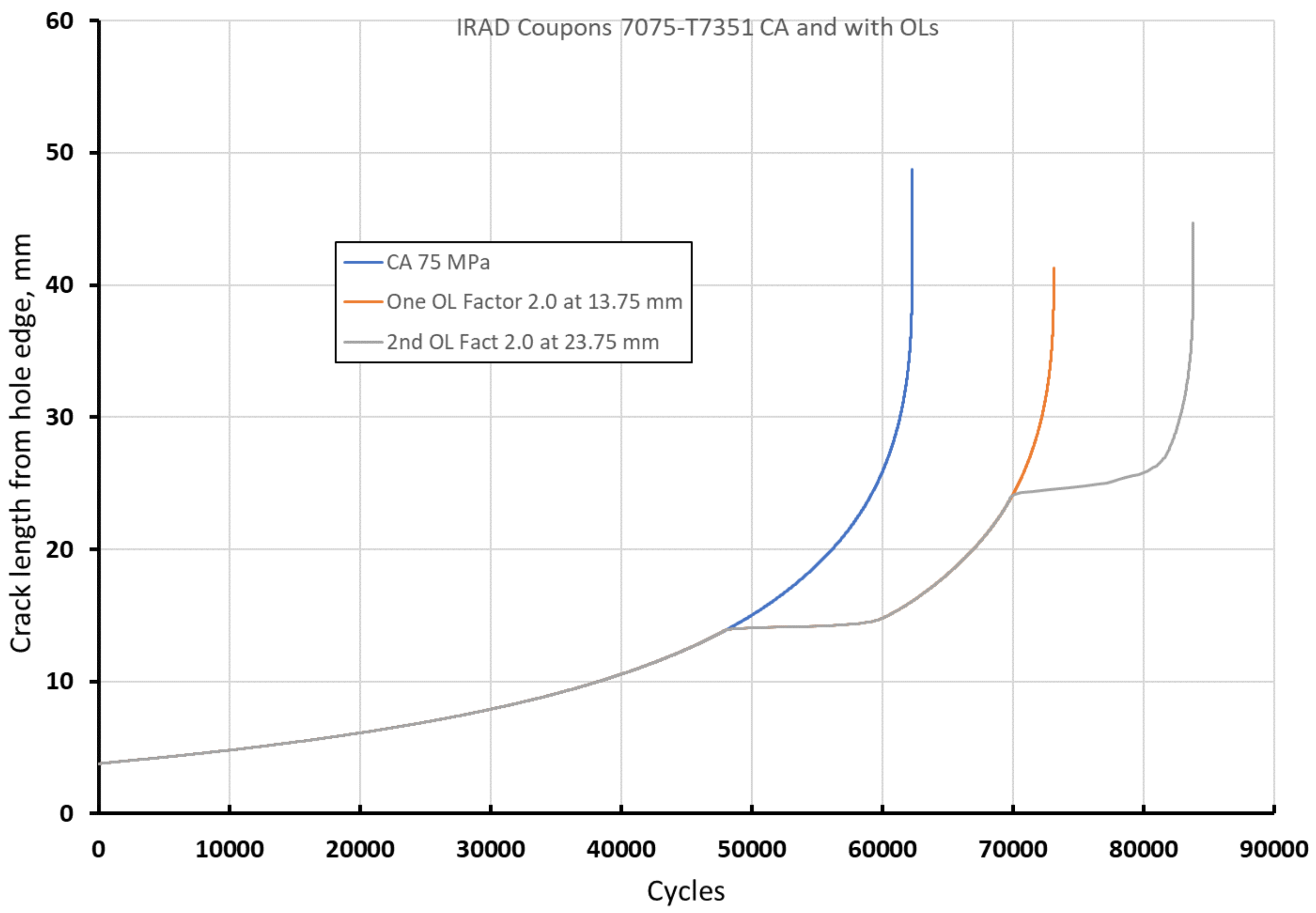
IRAD Coupons 7075-T7351

- Nine specimens
- Constant Amplitude loading, R=0.0 and 0.5, with and without spike overloads
- Spectrum loading under mini-TWIST Level III
- Testing to commence early May 2023

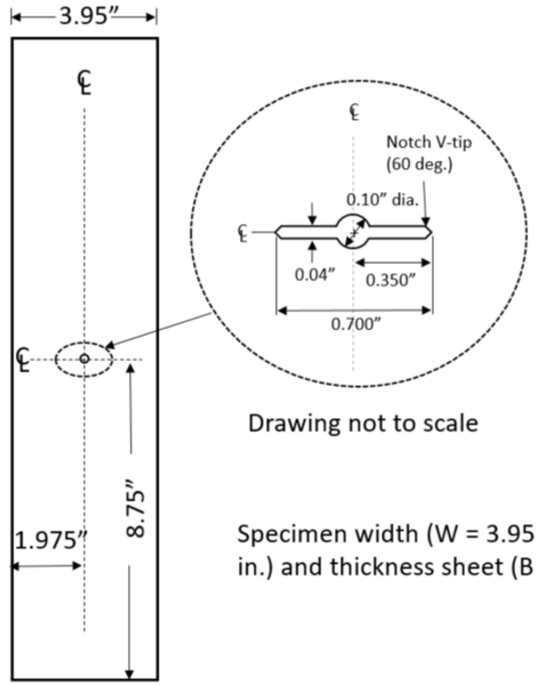


Notch details

Example of predictions before tests



- 7075-T6 Sheet Spike Overload Testing
- Crack Growth Rate Characterization (R = 0.1 and R = 0.7, 8 specimens)
- Spike Overload Test of 3 configurations (9 specimens)
  - W = 3.95 in, B = 0.09 in (complimentary to Kevin Walker's effort)
  - W = 10 in, B = 0.09 in
  - W = 3.95 in, B = 0.19 in



Specimen width (W = 3.95 in.), length (L = 17.50 in.) and thickness sheet (B = 0.19 in)

- Objectives:
  - Measure growth and COD (Op0 vs. crack length)
  - Characterize growth rate constraint-loss behavior and duration
  - Building block towards prediction of real life scenarios (e.g. local residuals in structure loaded with variable amplitude spectrum)

Characterization testing underway, spike overload test to start in May 2023

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BOEING

Working Group on
Engineered Residual
Stress Implementation

Interference Fit Fastener

Working Group

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IFF Working Group

Composition

- 13 participants

Objective

- Collaborate to establish validated analytical methods for Interference Fit Fasteners (IFF)
  - Review Physics of Interference Fit Fastener
  - Characterize Existing Methods & Data
  - Identify Key Factors and Gaps in Current Methods/Data

Approach

- Phased approach with increasing complexity
  - Phase I: Baseline stress analysis verification
  - Phase II: Stress intensity factor comparisons
  - Phase III: Crack growth analyses comparisons
- Validation tests sponsored by A-10 team to accompany analyses

Key collaboration areas

- IFF Analysis Round Robin (Pilarczyk, Loghin, Ribeiro)
- A-10 IFF Testing & Analysis Program (Warner, Smith)

IFF Implementation Plan

Phase I: Baseline Stress Analysis Verification

- Start with a 3D FE model that represents the IFF test specimen from RR. Identify the reference stress analysis that anyone would agree with.
  - Use different tools, Ansys, Nastran, StressCheck etc
- Use a IFF reduced order model (plate like) and compare the stress analysis against the specimen level results
- Verification against known published solutions and new test data (tollgate)

Phase II: Stress Intensity Factor Comparisons

- Add a corner crack to the IFF 3D model and perform the same comparison: specimen vs. reduced order model, different tools
- Add an edge crack to the IFF 3D model and perform the same comparison: specimen vs. reduced order model, different tools
- Complete a verification tollgate

Phase III: Crack Growth Analyses

- Perform crack growth for a IFF corner crack using different tools and compare results
- Perform crack growth for a IFF edge crack using different tools and compare results
- Complete a verification tollgate
- At this point continue with validation (comparison with RR test data)

IFF Phase I: Baseline Stress Analysis

Objectives

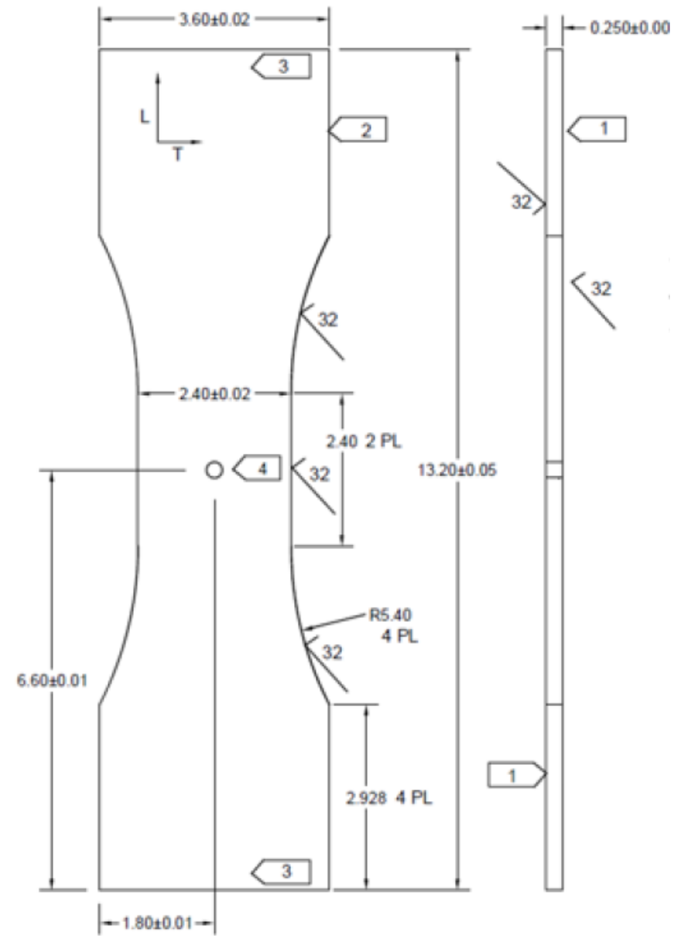
- The accuracy of SIFs and crack growth predictions for IFF conditions is highly dependent on the accuracy of the stress analysis
- The primary objective of Phase I is to establish a set of reference stress analyses agreed upon by the working group
- These analyses will establish the baseline stress state and can be utilized for follow-on phases
- Additionally, the analyses can by utilized to characterize:
  - The onset of plastic deformation and the bounds of elastic vs. elastic/plastic regimes
  - The relationship between far field loading and local strain cycles
  - The variability as a function of key factors (e.g. interference level, modeling assumptions, remote loading)
- Verification against known published solutions and new test data (tollgate)

IFF Phase I: Baseline Stress Analysis

Analysis Inputs

- Geometry
  - Dogbone with centered hole
  - Width W = 2.40”
  - Length L = 3W = 13.20”
  - Thickness t = 0.25”
  - Diameter D = 0.25”
- Material properties
  - Plate
    - Aluminum 2024-T351 plate
    - E = 10,800 ksi
    - ν = 0.33
  - Pin/Plug
    - Steel 4340 rod
    - E = 29,000 ksi
    - ν = 0.29

No Cracks for Phase I



IFF Phase I: Baseline Stress Analysis

Analysis Inputs, cont.

Table 1. Round-robin analysis conditions, group 1

Group	Condition	Sequence Step	Interference Condition	Applied Stress (ksi)
1	1	1 – Apply Remote Stress 2 – Unload	Open Hole	-10, 10, 20, 30

Table 2. Round-robin analysis conditions, group 2

Group	Condition	Sequence Step	Interference Condition	Applied Stress (ksi)
2	1	1 – Installed Fastener 2 – Remove Fastener	0.3% IFF	0
	2		0.6% IFF	
	3		1.2% IFF	

INW

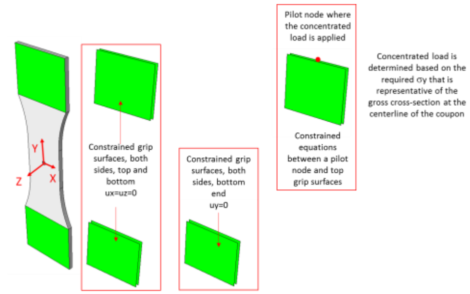
Table 3. Round-robin analysis conditions, group 3

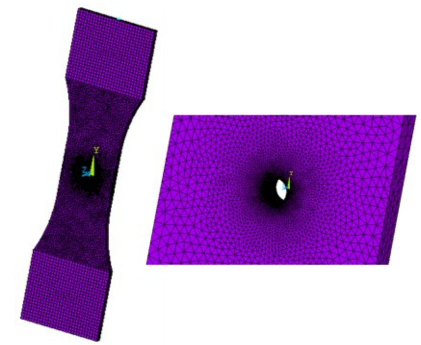
Group	Condition	Sequence Step	Interference Condition	Applied (ksi)
3	1	1 – Installed Fastener 2 – Apply Remote Stress 3- Unload 4 – Remove Fastener	Neat Fit	-10, 10, 20, 30
	2		0.3% IFF	
	3		0.6% IFF	
	4		1.2% IFF	

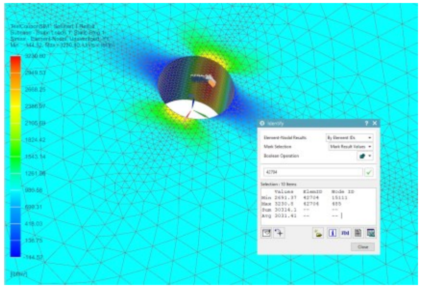
Group 1 – Open Hole Results

Summary of Submissions

Sub ID	Analysis Software	General Setup	Boundary Conditions: Constraints	Boundary Conditions: Loads
1	Ansys 2021 R2 w/ SimModeler Mesher	Full geometry model	Constrained grip surfaces both sides, top and bottom, ux=uz=0 Constrained grip surfaces, both sides, bottom end, uy=0	Pilot node with applied concentrated load
2	SimCenter 3D 2019.2 version 1892 using NASTRAN solver	1/4 symmetry model	Symmetry on x and y midplanes. Fixed in y-direction on one end of model.	Remote load applied in y-direction on one end of model
3	StressCheck v11.1	1/8 symmetry model	Symmetry on x, y, and z midplanes	Surface traction at far end of model
4	Abaqus 2020	1/4 symmetry model	The top grip surfaces are constrained, one along x (left-right, along T) and z (through thickness) directions, and the other along x (left-right, along T) direction only. The two symmetry surfaces are constrained with symmetry boundary conditions (x-symmetry at the long ligament surface (vertical direction of the part, along L), and y-symmetry at the short ligament surface (along T).	
5	StressCheck V11.0	1/8 symmetry model	Symmetry constraints on L-T, T-L, and T-S planes.	Normal tractions on far field surface
6	Marc 2022.2	1/8 symmetry model	Symmetry on x, y, and z midplanes; fixed in x-direction on top of coupon	Force applied with rigid elements (RBE2) with DOF=y to top of coupon
7	StressCheck V11.1	1/8 symmetry model	Symmetry on x, y, and z midplanes. Floating constraint in x,y and z directions was applied on the tab section which is fixed in the grip. Floating constraint in Stresscheck means all faces/edges are constrained to move by the same amount.	The load was applied on the tab. Therefore, the applied stress for group 1 was multiplied by the ratio of the width of tab/the width of gauge section.
8	NX NASTRAN V2022.1	1/4 symmetry model	Symmetry on the x and y midplane.	Force applied to a rigid element. Rigid node constrained from deflections and rotations except for the load direction.

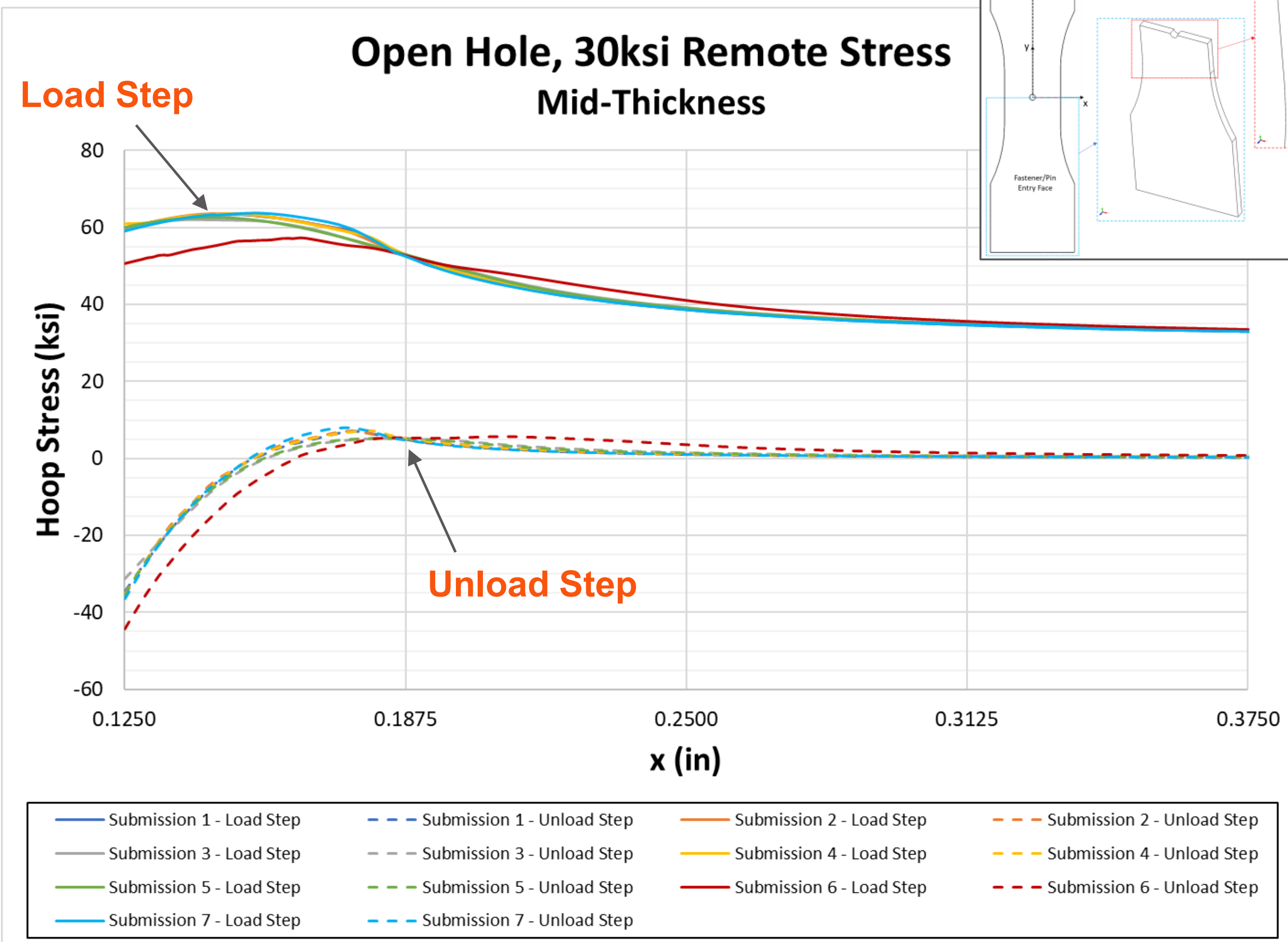


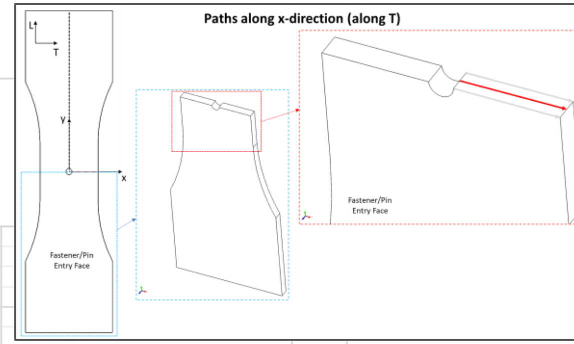




Group 1 – Open Hole Results

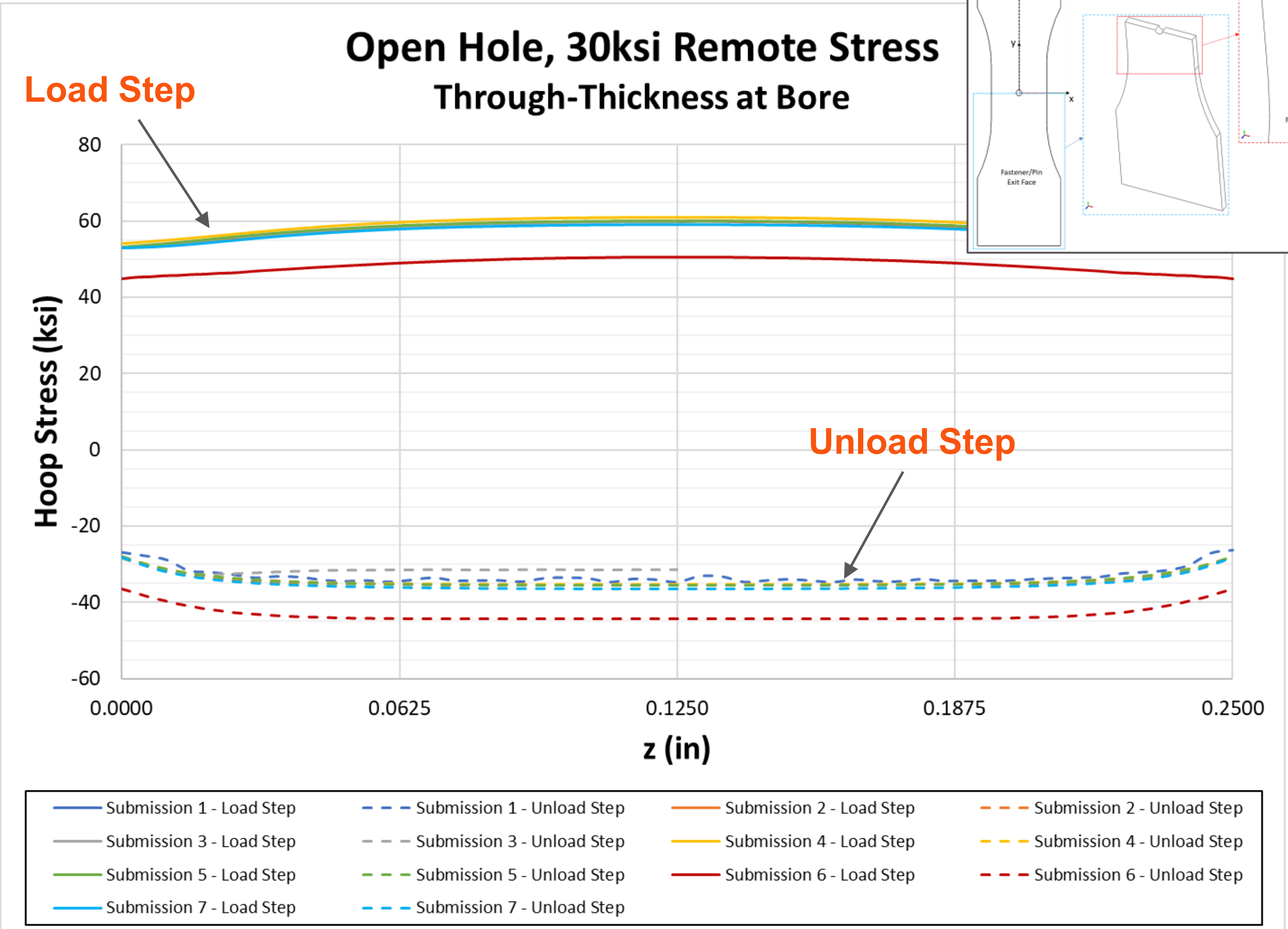
Summary of Results

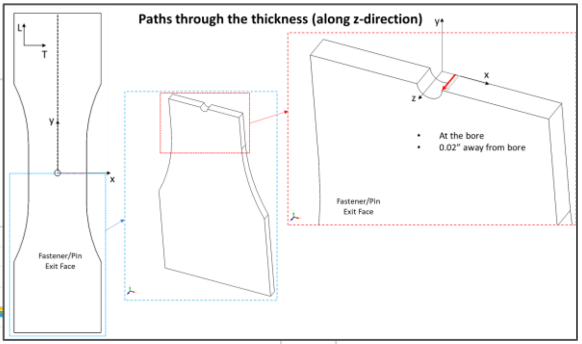




Group 1 – Open Hole Results

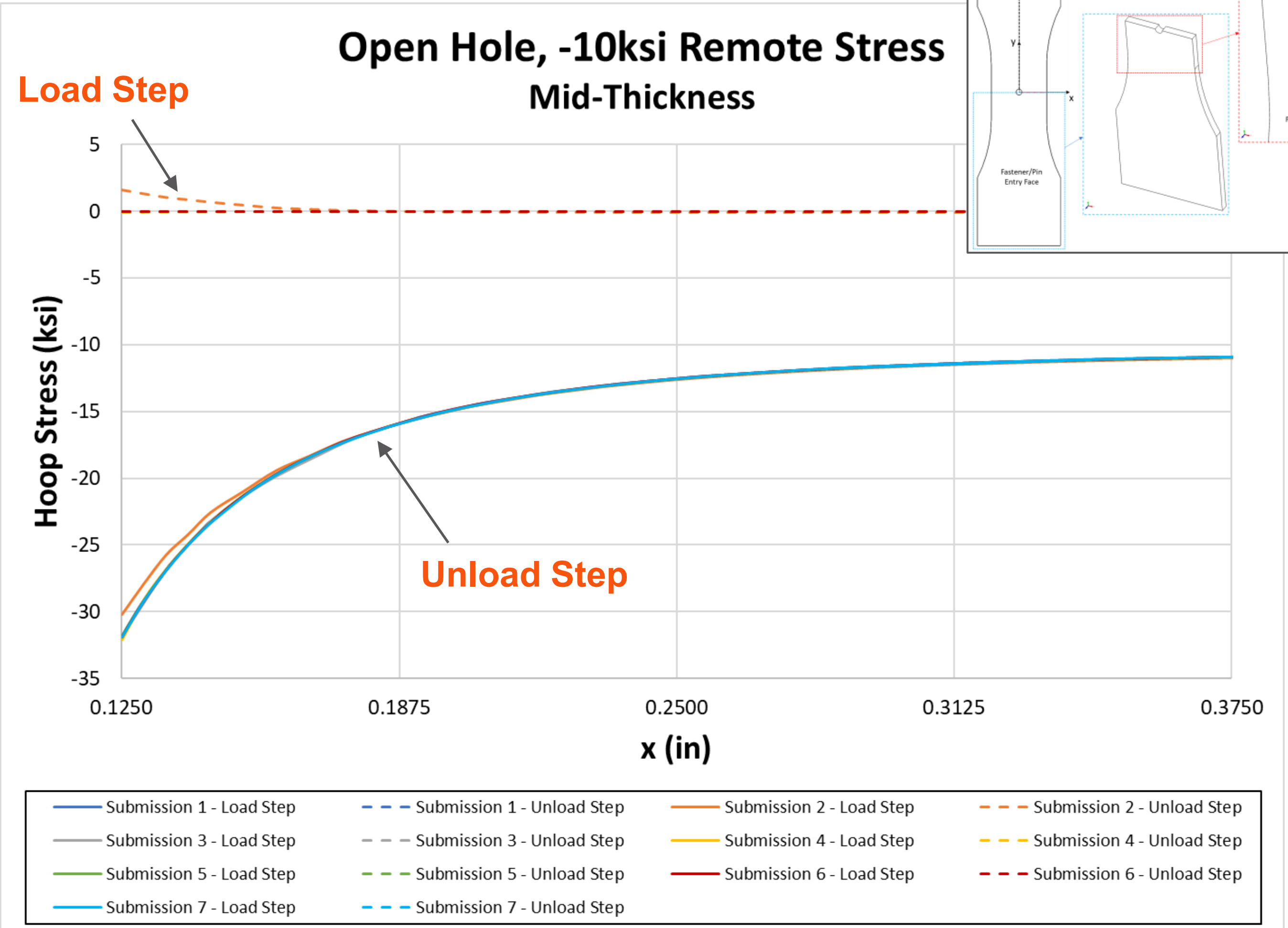
Summary of Results

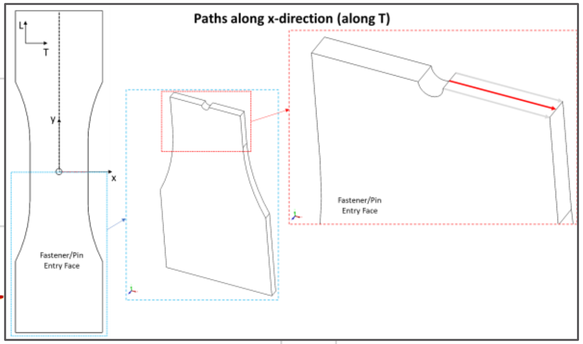




Group 1 – Open Hole Results

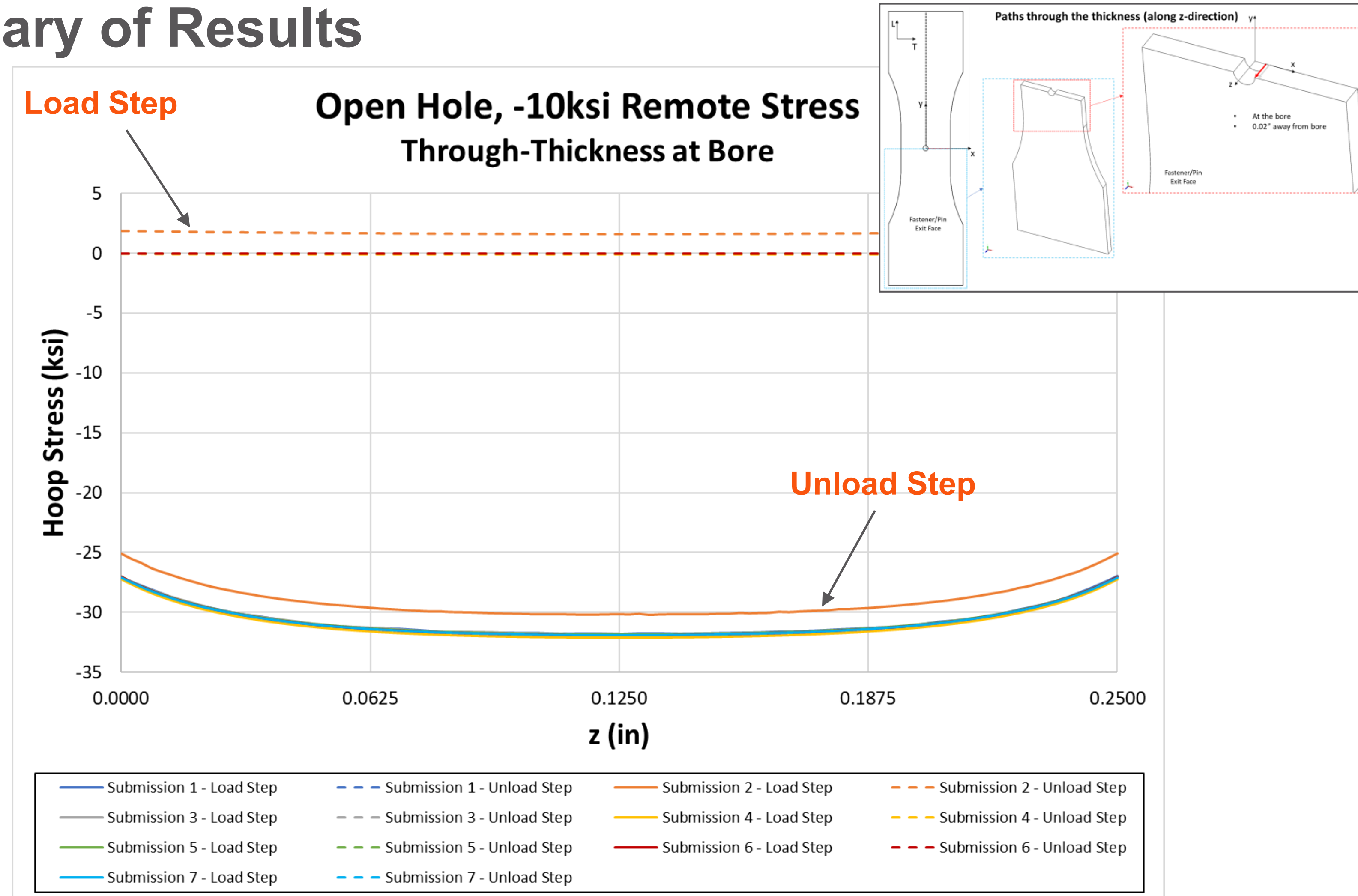
Summary of Results





Group 1 – Open Hole Results

Summary of Results



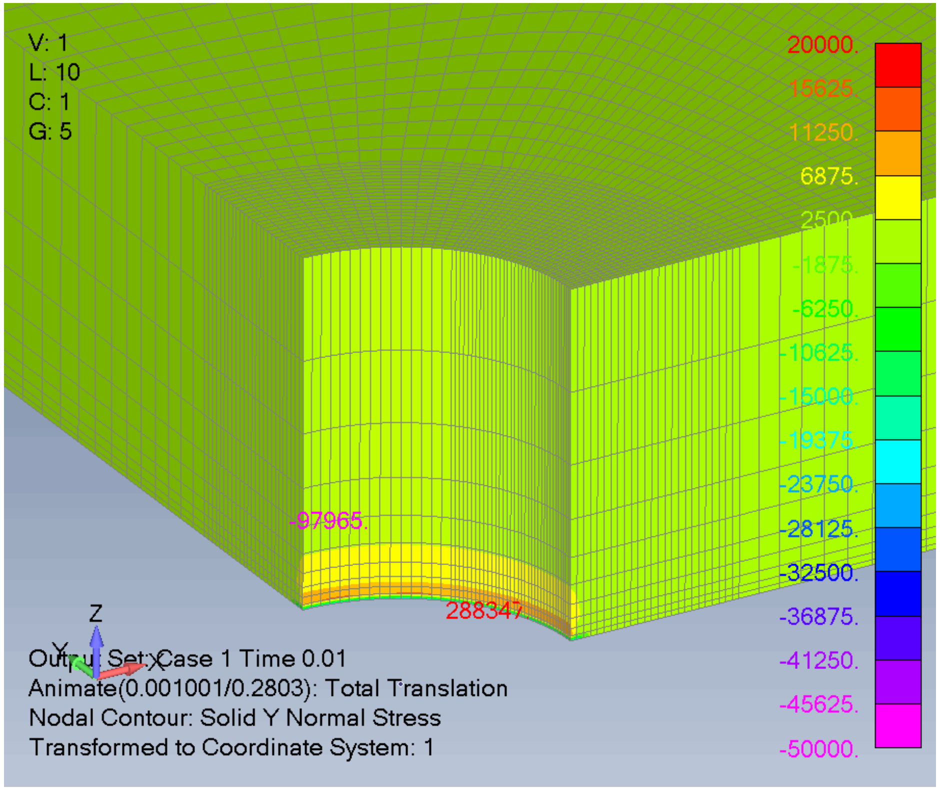
Group 2 – Fastener Install and Removal Results

Summary of Submissions

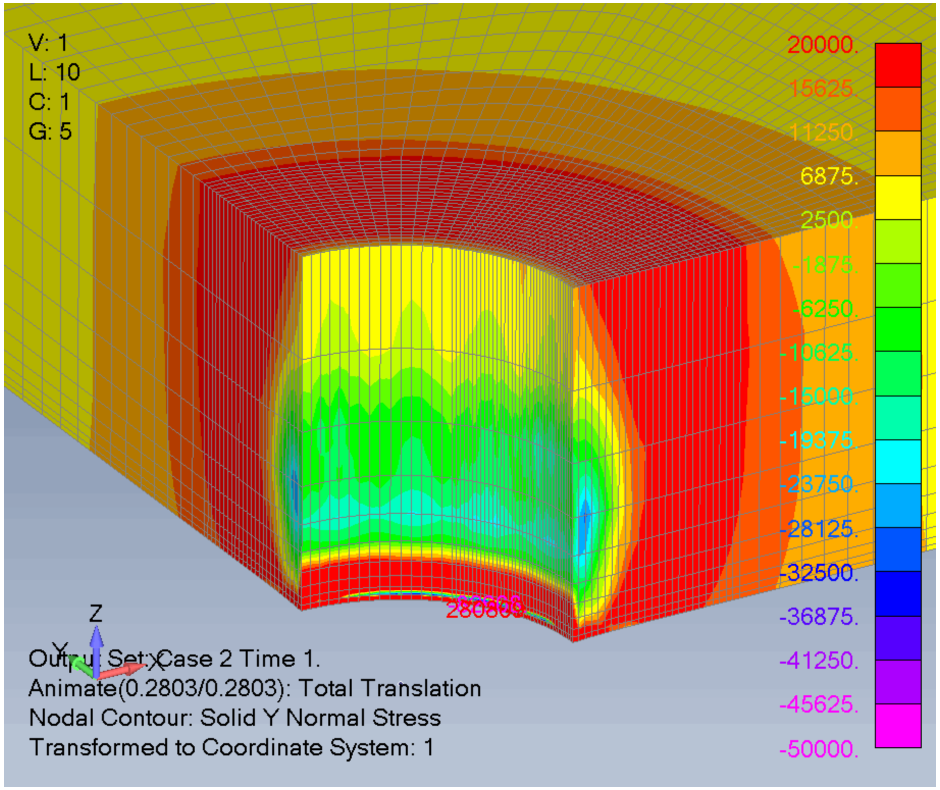
Sub ID	Analysis Software	General Setup	Boundary Conditions: Constraints	Boundary Conditions: IFF Modeling	Material Model
1	Ansys 2021 R2 w/ SimModeler Mesher	Full geometry model	Constrained grip surfaces both sides, top and bottom, ux=uz=0 Constrained grip surfaces, both sides, bottom end, uy=0	A cylindrical solid that represents the fastener was set into the specimen's hole. The IFF stress-strain solution is based on contact between the specimen and the fastener.	A multilinear isotropic hardening was used as a constitutive model for the specimen. The input data for the model is based on "Material Uniaxial Monotonic Stress/Strain Properties" provided in this document.
2	SimCenter 3D 2019.2 version 1892 using NASTRAN solver	1/4 symmetry model	Symmetry on x and y midplanes. Fixed in y-direction on one end of model.	Multi-body contact. Fastener installation process not modeled (fastener assumed in "installed position").	For the plate material, an elastoplastic material was defined in Simcenter using the data in the round-robin announcement. The fastener was assumed to be elastic.
3	StressCheck v11.1	1/8 symmetry model	Symmetry on x, y, and z midplanes	Normal springs with an appropriate stiffness were placed inside the hole. An imposed spring displacement was coupled with the normal springs to simulate the various levels of interference.	SC was used with full kinematic hardening (Incremental Theory of Plasticity). Provided cyclic stress-strain data was fit (by eye) with Ramberg-Osgood equation.
4					
5	StressCheck V11.0	1/8 symmetry model	Symmetry constraints on L-T, T-L, and T-S planes.	Fastener insertion and removal simulated with normal springs (stiffness 30,000,000 psi) on hole bore, with uniform radial displacement. Nonlinear kinematics—springs are compression only; when the springs are in tension, the normal traction goes to zero. No contact, no friction.	Incremental plasticity. Nonlinear elastic-plastic material behavior fit with Ramberg-Osgood constitutive relation using Appendix C table, Material Uniaxial Monotonic Stress/Strain. Young's modulus: 10,800,000 psi. Poisson ratio: 0.33. Syield=51,396 psi. n=19.5. Cyclic stress-strain test results indicated Kinematic hardening was most appropriate; plasticity with kinematic hardening was modeled.
6					
7					
8	NX NASTRAN V2022.1	1/4 symmetry model	Symmetry on the x and y midplane.	Idealized pin made of steel was used. Insertion of the pin was modeled. Distributed constraint slightly remote from hole to resist the pin being inserted. Multi-body contact was used. The fastener was assumed to be linear steel. The friction coefficient used was 0.459. The pin was inserted into the hole from the bottom. Once the pin was fully engaged, the contacts were removed to determine the removed fastener results.	Supplied stress strain curve with isotropic and kinematic hardening.

Group 2 – Fastener Install and Removal Results

Summary of Submissions



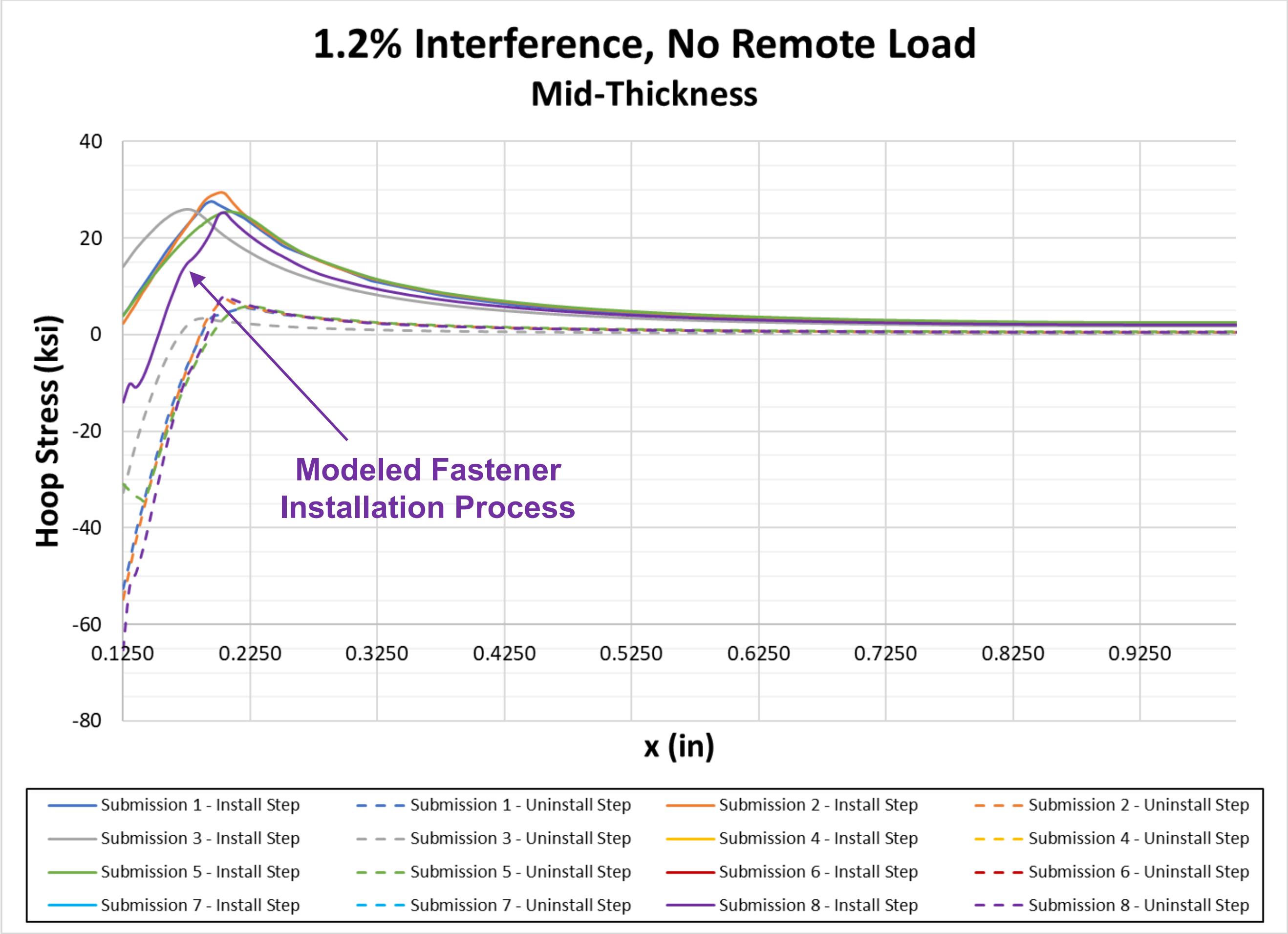
Pin Inserted



Pin Removed

Group 2 – Fastener Install and Removal Results

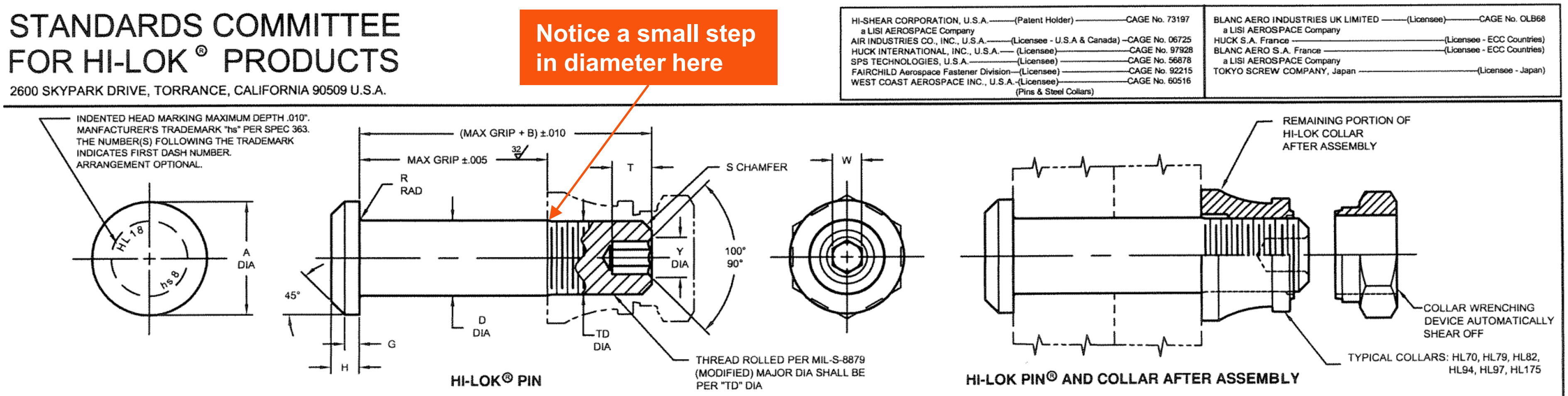
Summary of Results



Fastener Geometry and Installation

Fasteners have a transition region

- From threaded portion to straight shank
  - Chamfer/fillet
- Depending on modeling approach, this geometric feature could be important
- Specifications don't always detail this geometry in specifications
  - ¼" Hi-Loks initial "rough" measurements indicate transition length of 0.025"
    - + In the process of measuring actual fasteners

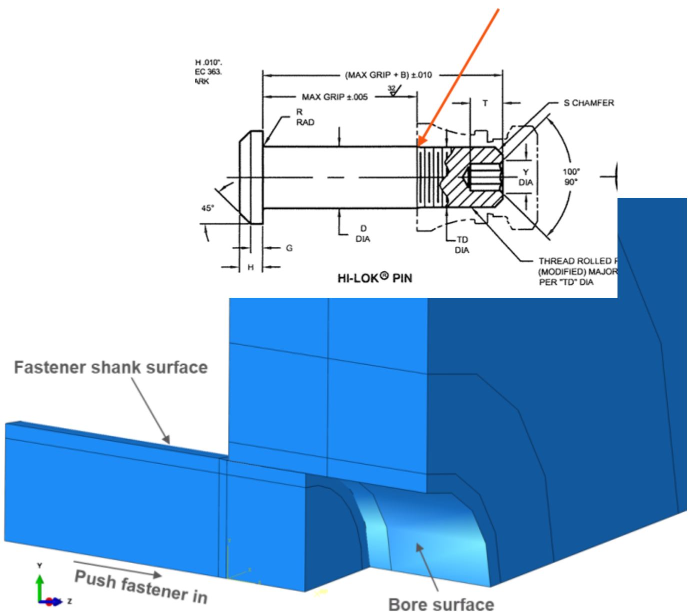


http://www.jet-tek.com/hi-lok-pins/hl18.pdf

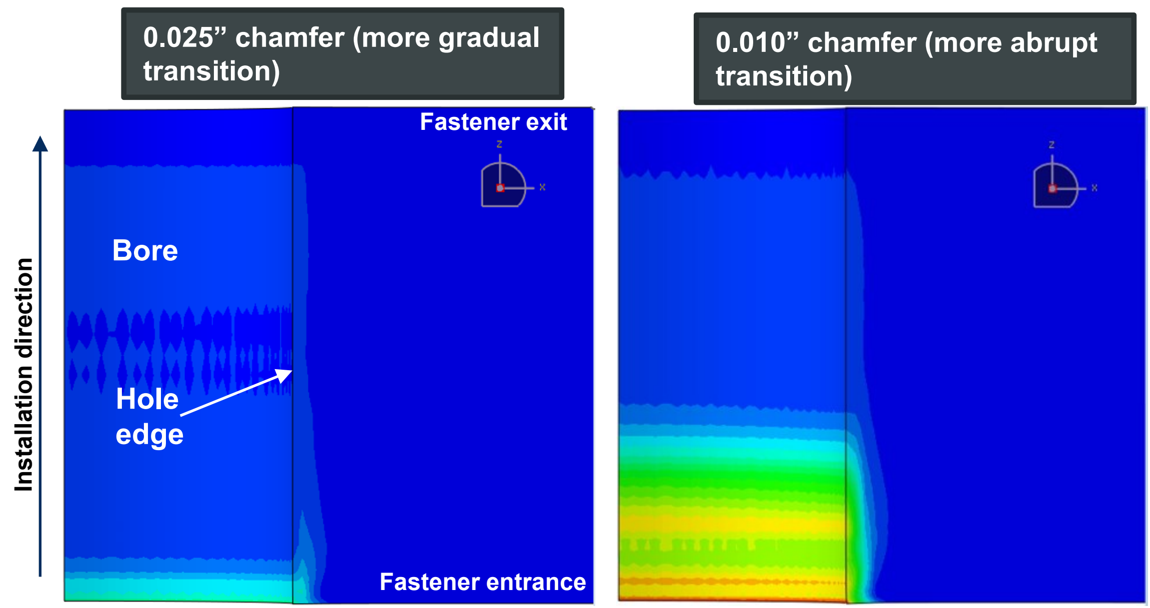
Fastener Geometry and Installation

FE modeling shows a significant influence of the chamfer geometry

- 3D model, nonlinear elastic-plastic
- Fastener is incrementally pushed into the hole
  - Solution for equilibrium for each incremental step
- More aggressive chamfer leads to higher levels of plasticity near the fastener entry side
- Longer, more gentle chamfer leads to lower levels of plasticity and more uniform results through the thickness
- Equivalent plastic strain comparison below



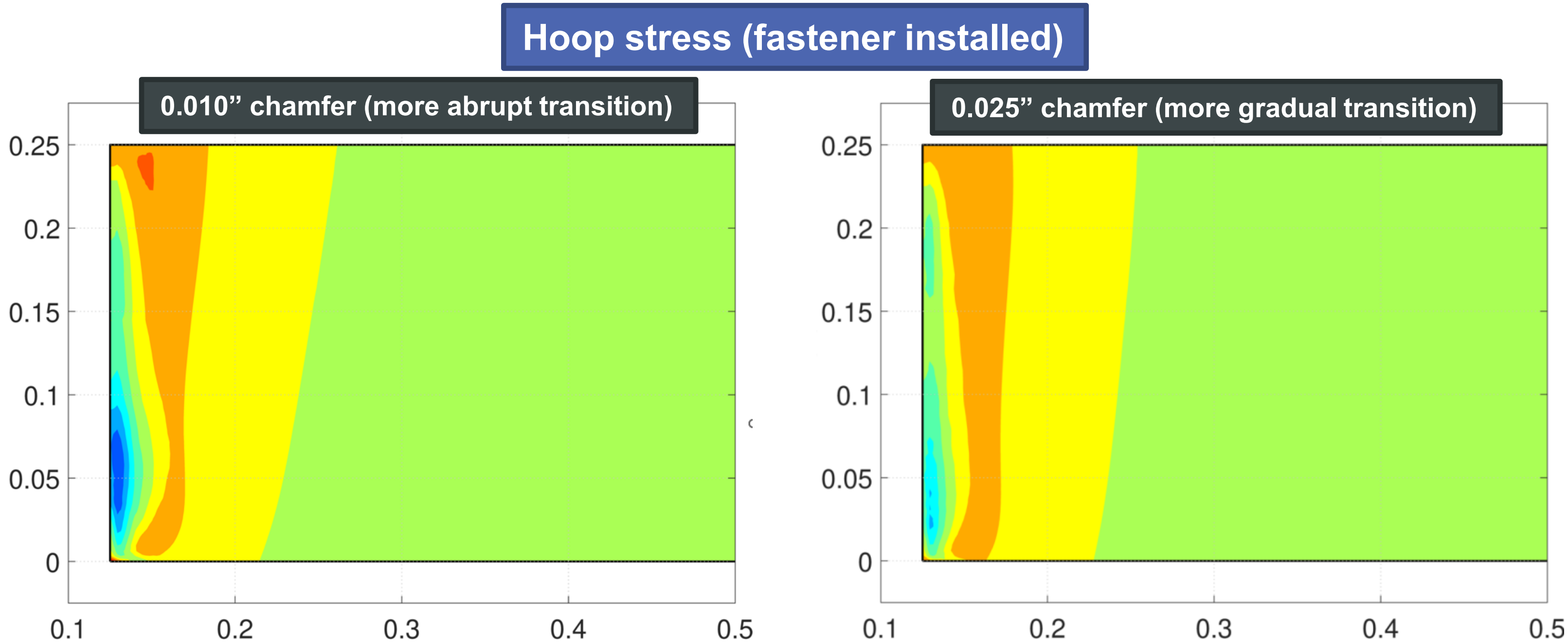
Equivalent plastic strain (PEEQ)



Fastener Geometry and Installation

FE modeling shows a significant influence of the chamfer geometry

- Influence of chamfer geometry on hoop stress field below
- More abrupt transition leads to more variation through the thickness near the bore
- More gradual transition leads to a stress field more uniform through the thickness
  - Similar to what would be obtained with a simplified model expanding the entire bore surface at once



Fastener Geometry and Installation

3D scanned Hi-Lok fasteners

- 4 0.25” fasteners (HL18PB8-6)
- 4 0.50” fasteners (H118PB16-6)
- Png images with cross section measurements
- .stl files

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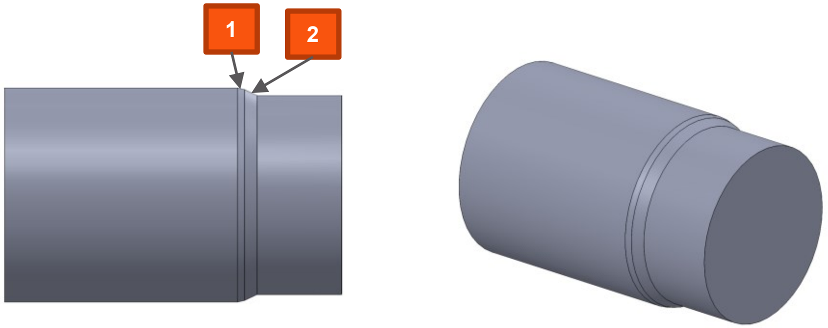
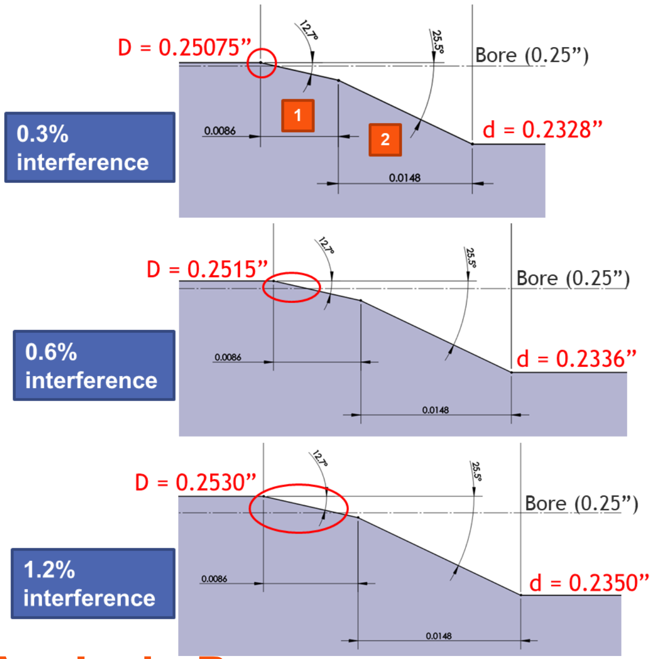
Fastener Geometry and Installation

Pin geometry for each interference level

- Length and angle of region 1 and 2 are fixed
- Major diameter D defines the interference level
- For 0.3, 0.6, and 1.2% interference, only region 1 contacts bore surface
  - Bore surface illustrated for a 0.25" hole
  - Contact area with red ellipse





Funded by A-10 IFF Test and Analysis Program

A-10 IFF Testing & Analysis Program

Overview

- Open literature documents fatigue life benefits due to neat fit and IFF, however, there are no well-established and validated methods to account for the benefits
- A-10 Damage Tolerance Analyses (DTAs) currently do not include any such benefit

Objective

- Develop an empirically validated analytical methodology to quantify the damage tolerance impacts of applicable A-10 fastener installations with neat or interference fits

Current Status

- Test plan in progress
  - Currently working on coupon manufacturing

Timeline

- Coupon manufacturing expected to finish by April 2023
- Phase 1 testing to be performed by June 2023

A-10 IFF Testing & Analysis Program

Phased approach with increasing complexity

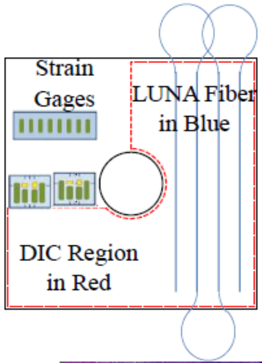
- Phase 1: assessment of as-installed state
  - Simulate and empirically quantify the strain and stress state near a hole in the presence of an interference fit fastener
    - 3 levels of interference
    - 3D nonlinear FE process modeling; DIC and strain gages for surface strain measurements
- Phase 2: fastener installed + remote loading
  - Repeat Phase 1 but with the addition of remote loading and unloading (multiple load levels and interference levels)
- Phase 3: analytical methodology to account for interference fit fasteners during crack growth
  - Perform multi-point fatigue crack growth analyses including interference fit fastener conditions
  - Blind predictions prior to fatigue testing to be performed in Phase 4
- Phase 4: fatigue crack growth testing with interference fit fasteners
  - Perform fatigue crack growth testing of neat fit and interference fit conditions
  - Use fatigue test data for validation and refinement of analytical methodology

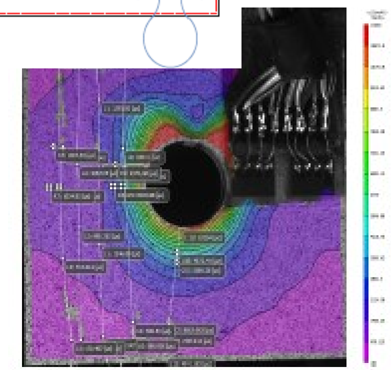
Parameter	Levels
Coupon material	2024-T351 plate
Pin material	52100 steel pin
Coupon thickness	0.25 inch
Nominal hole size	0.25 inch
Interference conditions	Open hole
	Neat fit
	0.3% interference
	0.6% interference
	1.2% interference
Strain monitoring	DIC (all specimens)
	Strain gage (initial specimen)
Static stress levels (Phase 2)	-30 ksi
	-10 ksi
	0
	10 ksi
	20 ksi
	30 ksi
Fatigue crack growth testing (Phase 4)	Constant amplitude loading Smax = xxx ksi, R = xxx
	Spectrum?

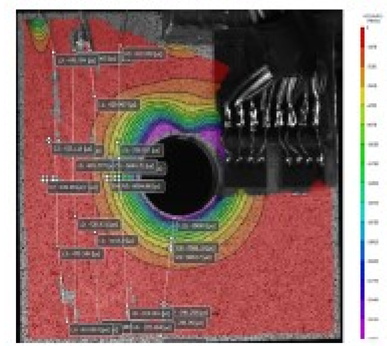
A-10 IFF Testing & Analysis Program

Verification Tests

- Design conditions
  - Fasteners – gauge pins with ground transition geometry
- Data capture
  - 3D geometric measurements of fastener and hole
    - + Calculate applied interference along bore
  - Surface strains (primarily DIC)
    - + Leverage lessons learned from ERSI Cx 2x2 Residual Stress Validation Effort
    - + Conditions
      - After fastener install
      - At each applied load
      - After each unload
      - After fastener removal
  - Transition point for fastener gapping
  - 3D geometric measurements after loading and fastener removal
    - + Calculate retained interference along bore and characterize any plasticity







Summary

Complimentary efforts

- IFF round robin
- A-10 IFF testing and analysis program

Phased building block approach

Results

- Analytical methods and validation data from round robin and A-10 program will provide a robust dataset for IFF
  - Benchmark for others
  - Starting point for IFF + Cx analyses