Fatigue Crack Growth & Testing Committee

2025 ERSI Workshop

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ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Outline for this 2.5 hour session

- Introduction, summary and overview (Kevin – 20 mins)
- Updates, achievements and plans from Focus Areas
  - Spectrum Loading (Moises/Kevin - 20 mins)
  - IFF and 2025 A-10 Cx Dataset (Bob – 40 mins)
  - Durability and Fatigue Life Testing (Adrian – 20 mins)
- Cx tolerance testing (Evan Ross - 20 mins)
- Building Block Approach (Moises – 20 mins)
- Discussion (All – 10 mins)

Outline of this presentation

- Roster summary
- Vision: Mission and key objectives
- Implementation roadmap
- Focus areas and working groups

Roster Summary

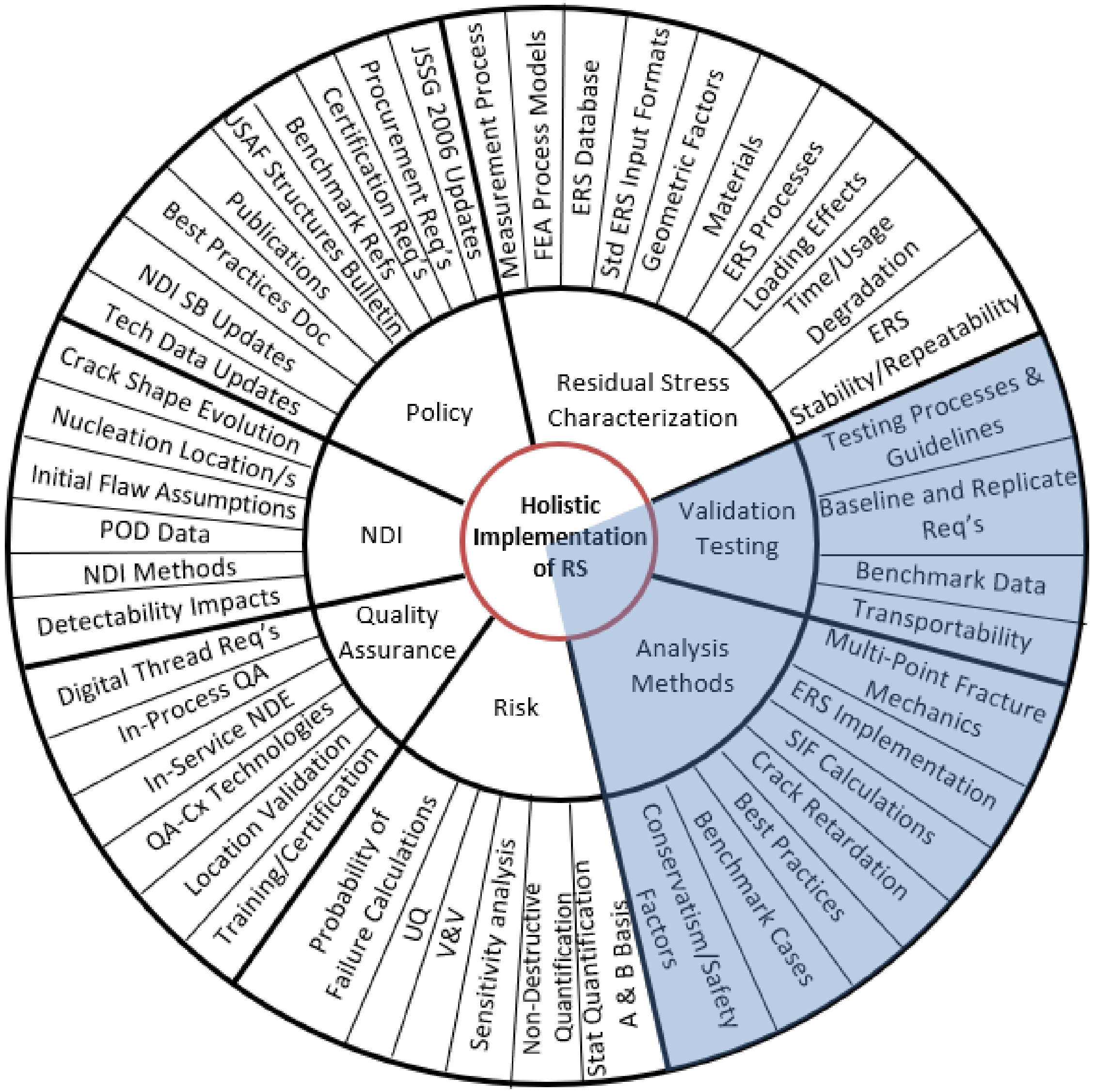
- **Committee members**
  - 75 members (up from 68 last year)
  - Diverse participation from government, OEMs, small businesses, and academia
- **Active participants**
  - ~15 participants in monthly meetings
- **Working groups**
  - Three working groups
    - Spectrum loading
      - Leads – Moises, Walker
      - Participants ~ 7 members
    - Interference fit fasteners
      - Leads – Pilarczyk, Loghin, Ribeiro
      - Participants ~ 19 members
    - Durability and fatigue life benefits
      - Lead – Adrian Loghin
      - Just getting started

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

- **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



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 (now 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 constraint 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)
  - Re-visit of Cx RR#1 (Kevin)

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Accomplishments – Spectrum Loading

- **Spectrum loading constraint-loss**
  - Publications as follows:

  - Walker, K.F., et al., Simulation of fatigue crack growth in aluminium alloy 7075-T7351 under spike overload and aircraft spectrum loading. International Journal of Fatigue, 2025. 190: p. 108660.
  - Newman, J.C. and K.F. Walker, Fatigue Crack Growth on Several Materials under Single-Spike Overloads and Aircraft Spectra during Constraint-Loss Behavior. Materials Performance and Characterization, 2024. 13(2).
  - Newman , J.C., Jr., and Walker, K.F., Fatigue Crack Growth in 7075-T6 Aluminium Alloy Under Single-Spike Overloads and Aircraft Spectra, in Variable-Amplitude Loading (VAL5). 2024: Dresden, Germany.
  - Newman , J.C., Jr., and Walker, K.F., Fatigue crack growth on several materials under single spike overloads and aircraft spectra, in International Committee on Aeronautical Fatigue. 2023: Delft, The Netherlands.

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)

Accomplishments IFF

- ERSI IFF Analysis Round Robin
  - Predictions received for baseline stress analysis
  - Eight different participants utilizing five different software packages
- A-10 IFF Testing
  - Testing completed to characterize as-installed + remote load stress states
  - Comparisons with blind predictions in work
- Publications
  - Ribeiro, R.L., et al., Interference Fit Fasteners: A Finite Element Process Modeling Round Robin. Materials Performance and Characterization, 2025. (in coordination for publication)
  - Pilarczyk, R.T., et al., Testing & Analysis of Interference Fit Fasteners: An A-10 ASIP & ERSI Joint Effort. 2024 USAF ASIP Conference Proceedings.

Durability and Fatigue Life Test Working Group

- **Participation: 1 (Adrian)**
- **Objective:**
  - Extend our understanding and modeling capabilities beyond long crack behavior
- **Approach**
  - It is not clear what would be the best initial approach. It was suggested in a previous Tcon to investigate the 0.005 inch initial crack size usage in different damage tolerance practices. If this is a desired goal of this working group, we could define some approaches that could be accomplished.
  - Any feasible approach would include a collaboration between various expertise domains: modeling, testing, material characterization, NDE.
- **Key collaboration areas (very general)**
  - Short crack behavior, measurement, modeling
  - Microstructural small crack measurement and modeling
  - Microstructure characterization, reconstruction, crystal plasticity, ...

Future Plans

- **Key focus areas for 2025-2026**
  - **To be discussed at this Workshop**

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

Spectrum Loading Effects: Progress and Path Forward

Moises Y. Ocasio, committee co-lead
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Agenda

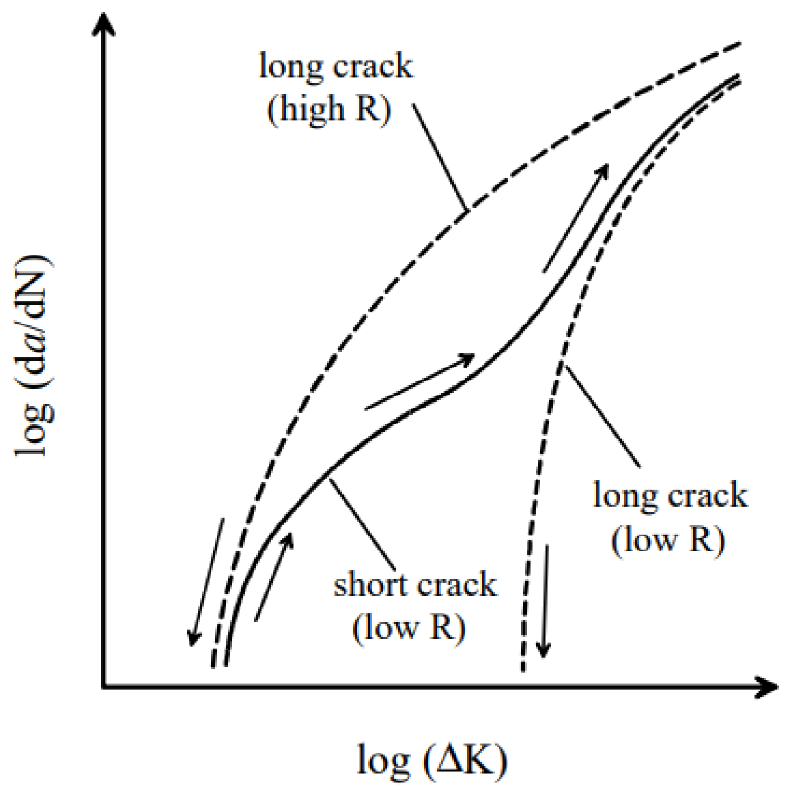
- Goals and Key Lessons Learned
- Spike Overload Testing
- 7075-T7351 Round Robin Effort
- Spectrum Loading Effects on Cracks Growing from Fastener Holes
- Path Forward

Goals and Key Lessons Learned

- Goals
  - Investigate and validate 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
- Lessons Learned
  - "Understanding and improving our ability to model spike overload cases is considered fundamental to the prediction for spectrum loading" – *2021 Overload Challenge conclusion*
  - Residual crack wake plasticity from pre-cracking leads to artificially high da/dN threshold values. This has been extensively studied by J.C. Newman and others, and the community is becoming increasingly aware of this as methodologies for spectrum loading effects in residual stress conditions are refined.
  - Constraint loss is crucial for predicting retardation, especially in spike overload testing. Newman's model suggests that the transition to complete slant crack growth (plane stress) occurs when ΔK_{eff} reaches a specific percentage of the sheet thickness, providing a reliable estimate of constraint loss behavior.

Lessons Learned

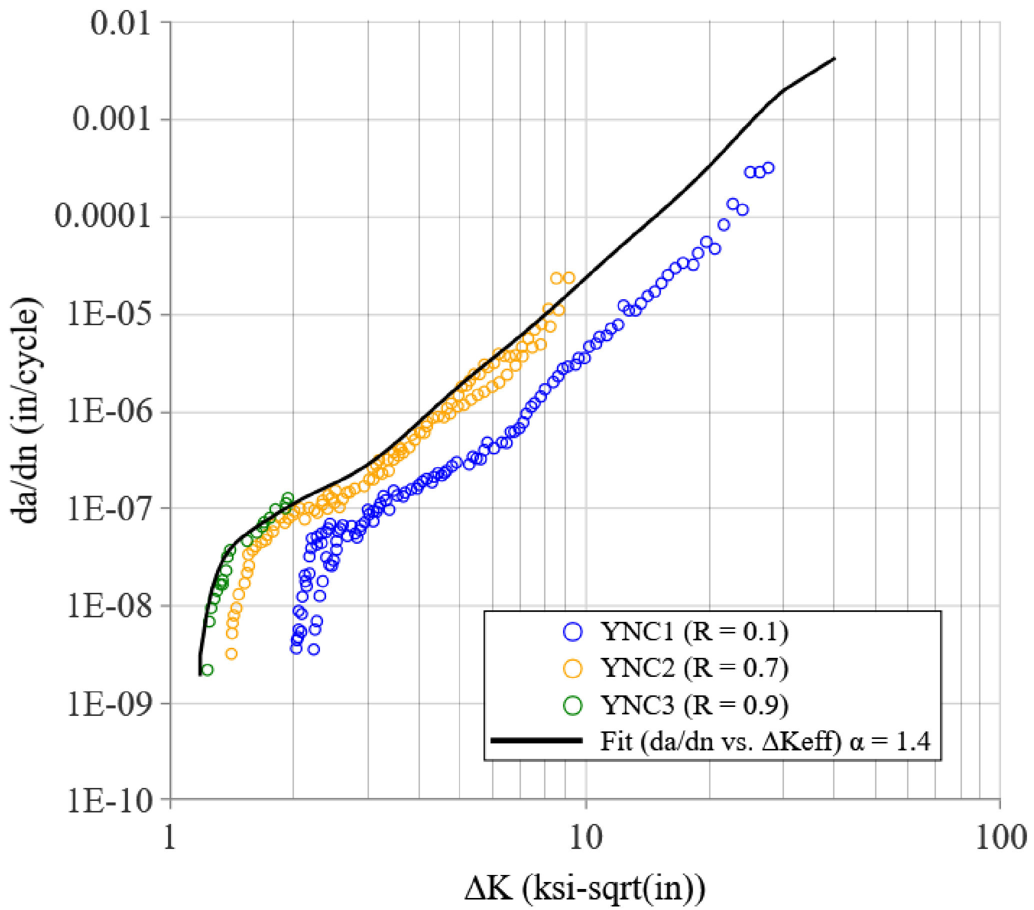
Lesson #1: Region I "Adjustments"



- This effect often refer as "short crack anomaly", but it should be called "long crack anomaly". In other words, the problem is that long cracks – due to residual crack wake plasticity (from pre-cracking) –produce artificially high FCGR threshold values.
- In contrast, short cracks align with high stress ratio long cracks near the threshold because they are essentially 'closure-free.'
- Two solutions are proposed:
  1. CPCA-like pre-cracking.
  2. Adjusting the analysis curve to either short crack data or high stress ratio data near the threshold (this will be illustrated on the next slide)."

K. Tokaji, T. Ogawa, and Y. Kameyama, "The Effects of Stress Ratio on the Growth Behavior of Small Fatigue Cracks in an Aluminum Alloy 7075-T6 (With Special Interest in Stage I Crack Growth)," Fatigue and Fracture of Engineering Materials and Structures, v. 13 (1990), pp. 411-421.

da/dN Fit: 7050-T7451 L-T example

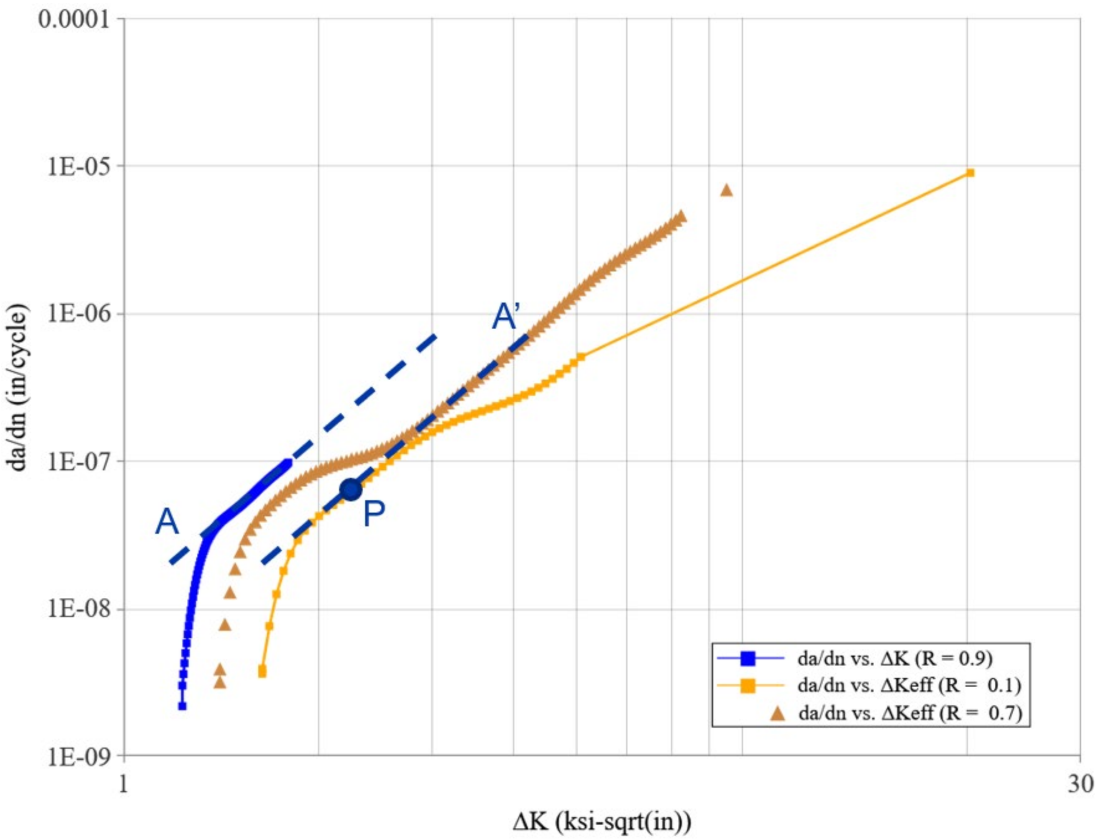


- Maximum Likelihood Estimate (MLE) approach used to fit through 7050-T7451 L-T data from (1).
- Curve fit to R = 0.9 was assumed to be 'closure free'
- α = 1.4 provides the best fit constraint

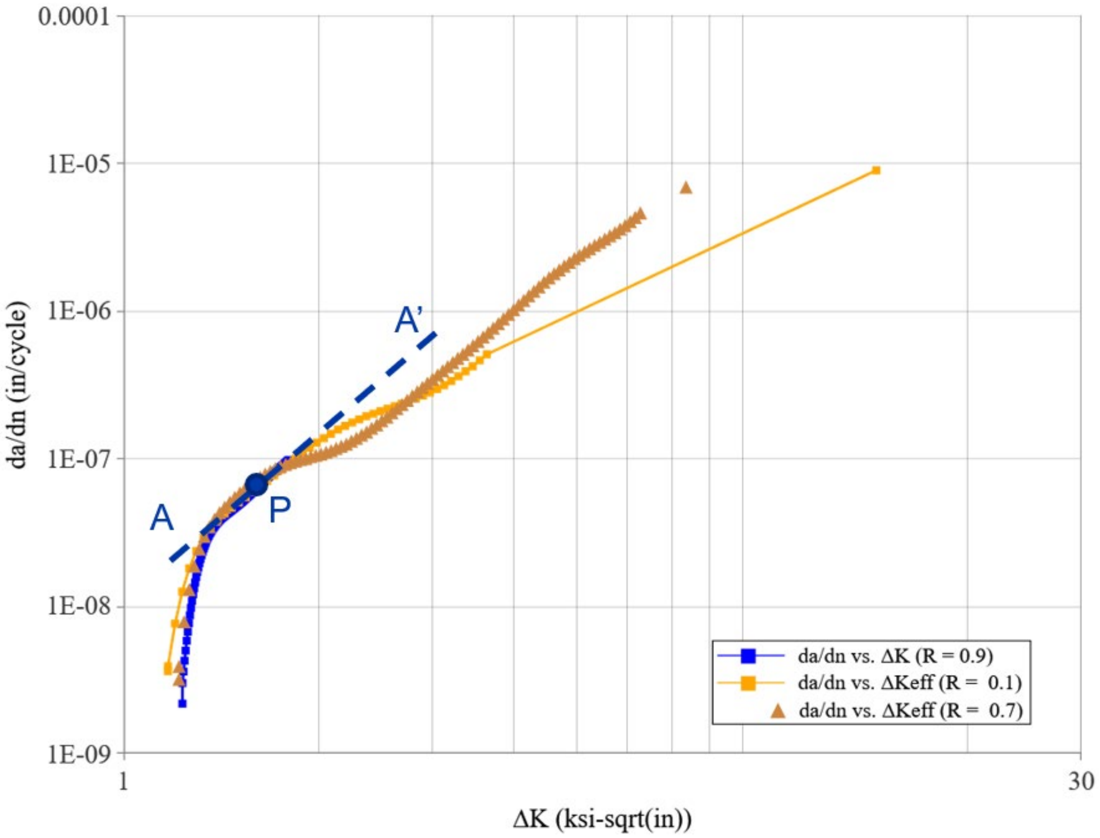
(1) Newman, J. C., Jr., Yamada, Y., and Newman, J. A. (April 1, 2010). "Crack-Closure Behavior of 7050 Aluminum Alloy near Threshold Conditions for Wide Range in Load Ratios and Constant K_{max} Tests."

da/dN Fit: 7050-T7451 L-T example, cont.

α = 3, Plane Strain

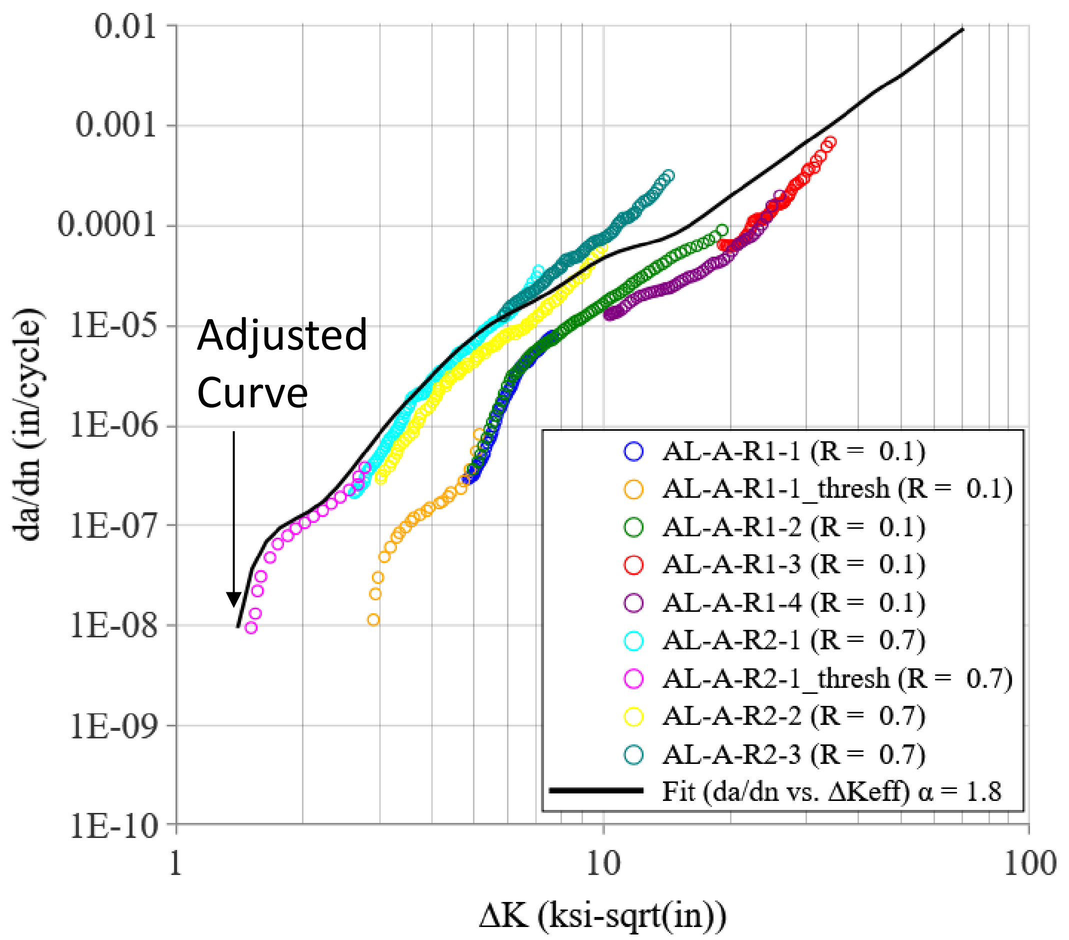


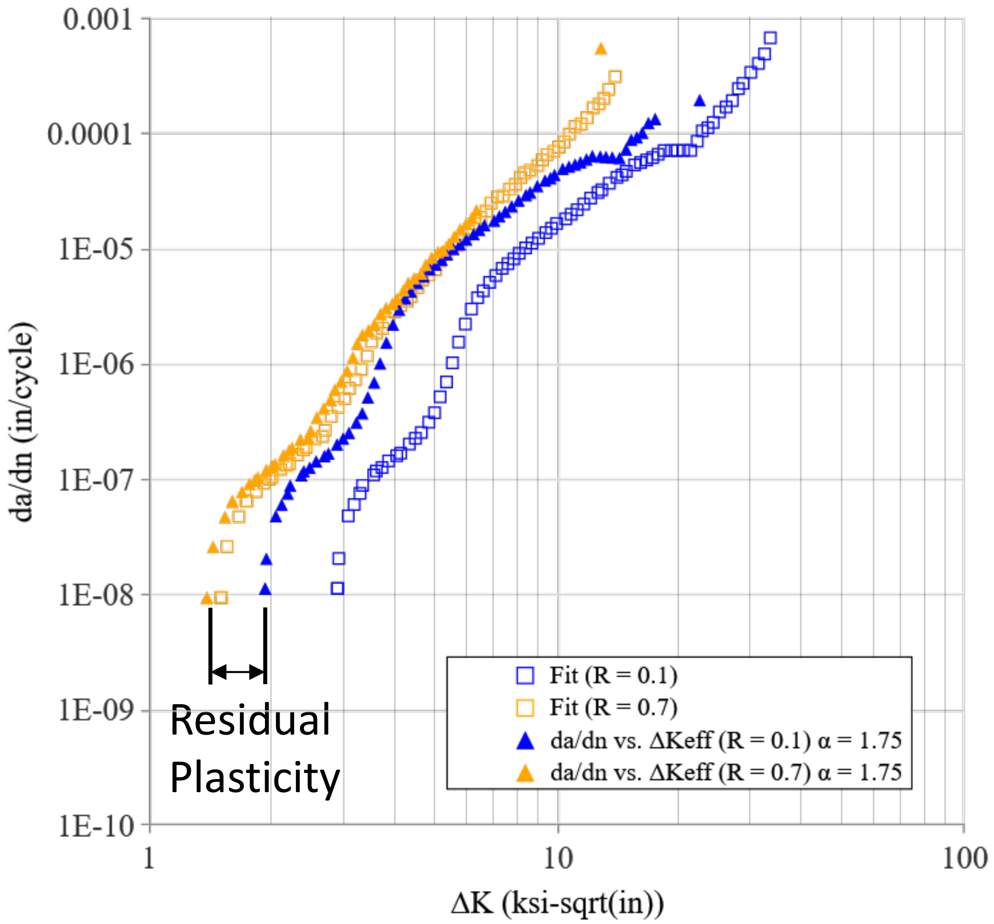
α = 1.3



This is a good example where effective curves collapse is enough to get a good fit without further modification of region I, but … baseline data was CPCA!

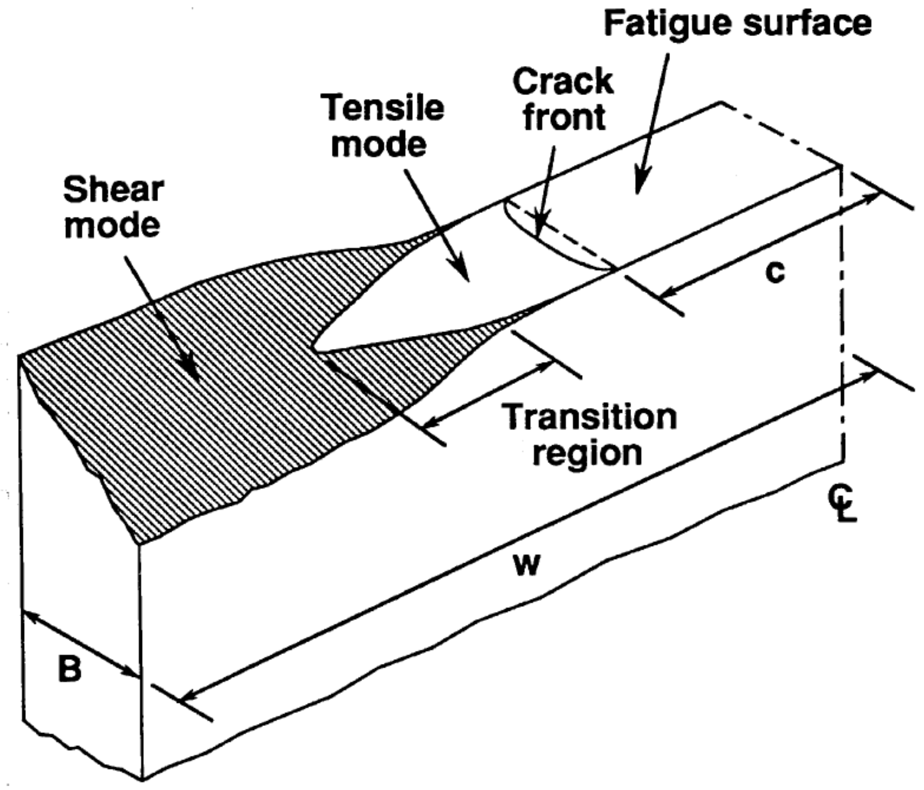
da/dN Fit: 7075-T6 L-T Boeing IRAD





da/dN-ΔKeff curve needs Region I adjustment. Pre-cracking method was ASTM LR.

Lesson #2: Constraint Loss



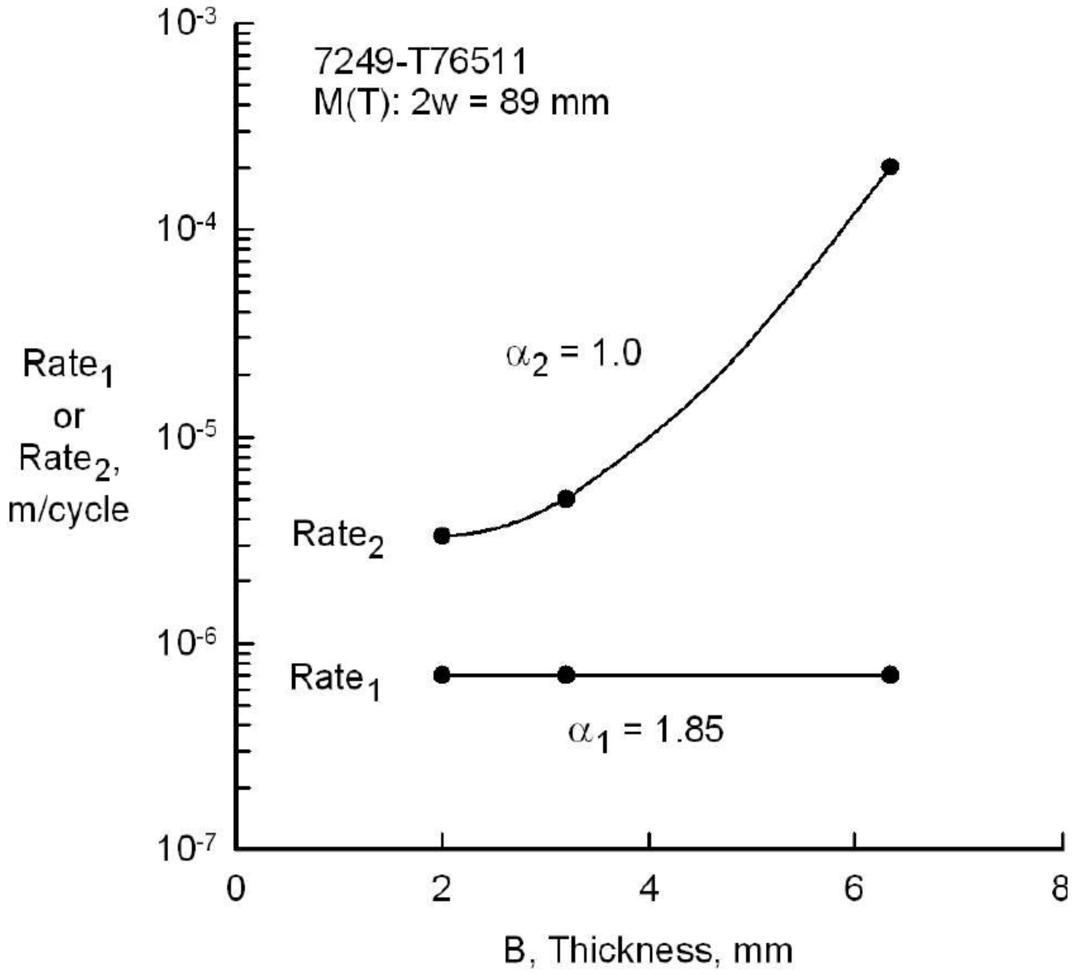
Newman JC Jr, Bigelow CA, Shivakumar KN. *Three-dimensional elastic-plastic finite-element analysis of constraint variations in cracked bodies*. Eng. Frac. Mech 1993

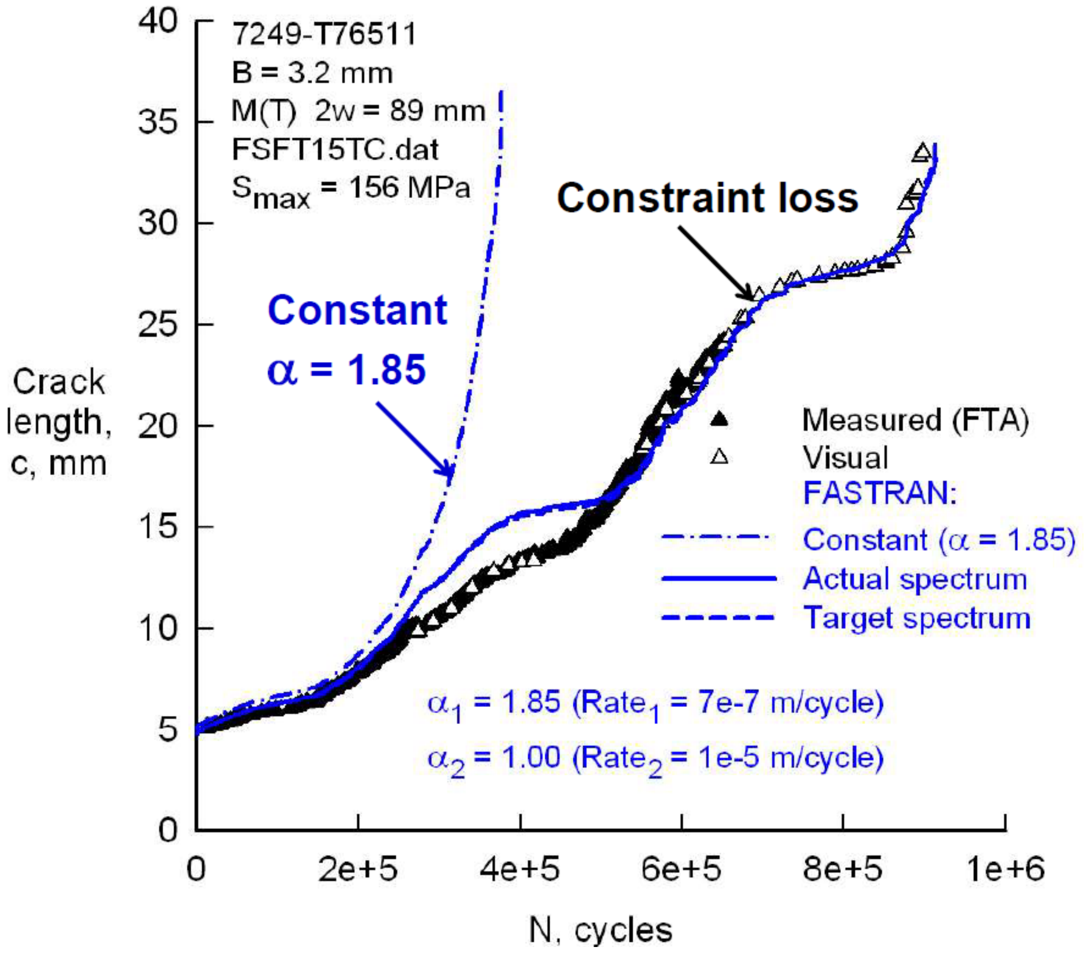
- The global constraint decreases as ΔK increases.
- The development of shear lips is evidence of the transition from a flat to a slant type of crack growth, which is closely associated with the loss of constraint.
- Schijve (1979) proposed ΔK_{eff} should control this transition.
- Newman (1992) proposed that transition happens when the plastic zone reaches a certain percentage of material thickness.

$$\mu = \frac{\left(\Delta K_{eff}\right)_T}{\sigma_0 \sqrt{B}}$$

$$\mu = 0.5 \pm 0.1 \; (Empirical)$$

Example: 7249-T76511 Spectrum Loading

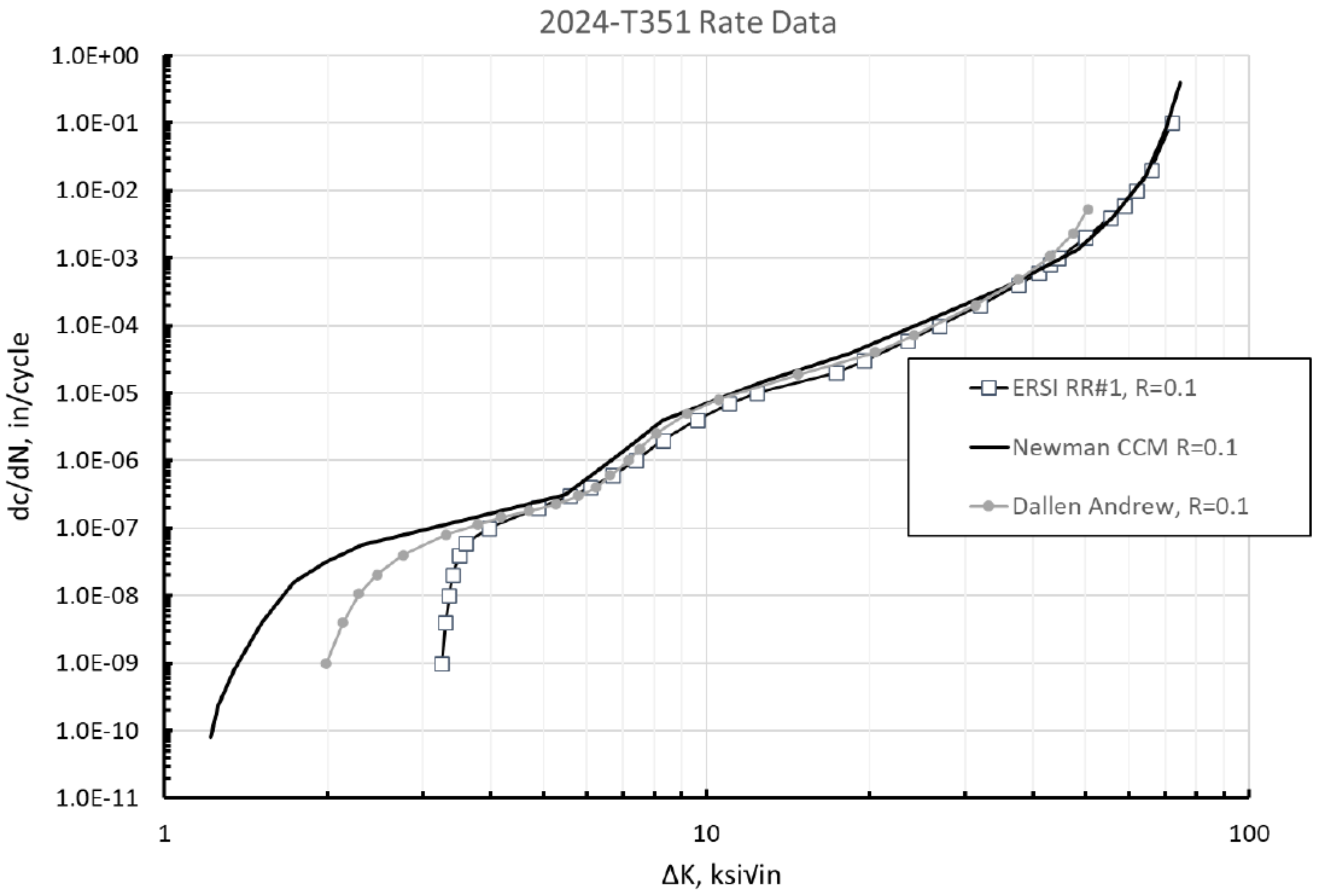


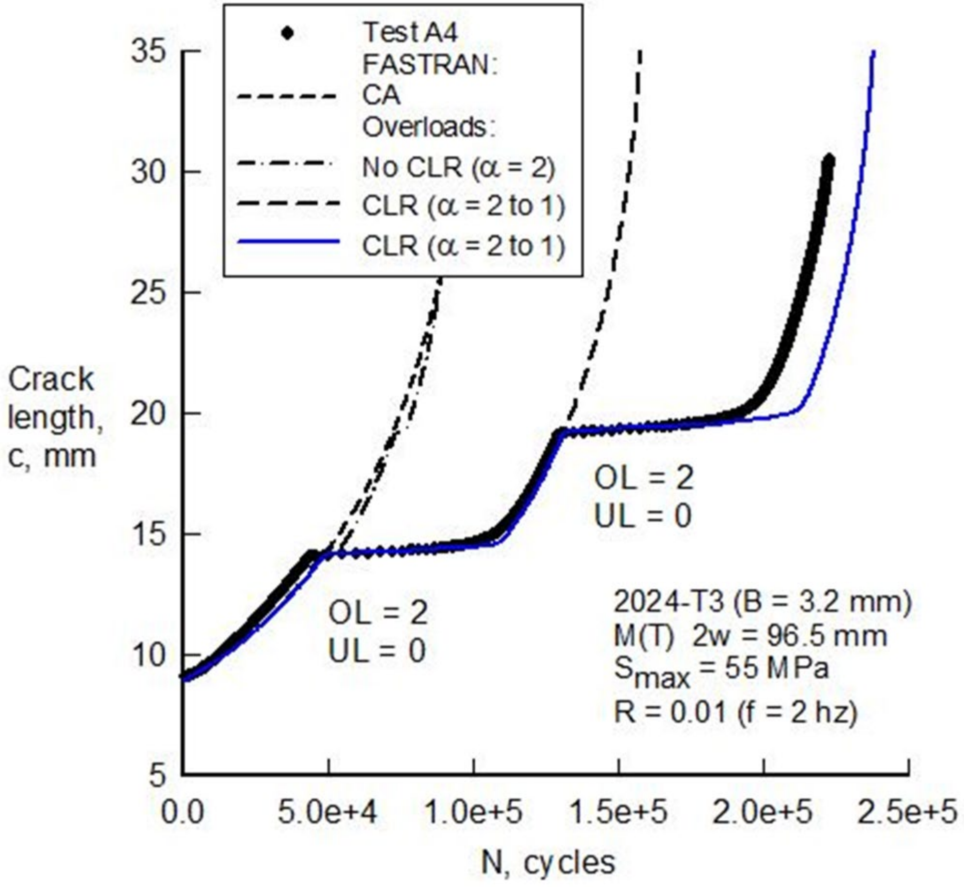


Newman, J.C. and K.F. Walker, *Fatigue Crack Growth Tests and Analyses on 7075 T6 and 7249 T76511 Aluminum Alloy Specimens of Various Thickness under Simulated Aircraft Wing Loading*, in USAF ASIP Conference. 2017: Jacksonville Florida USA.

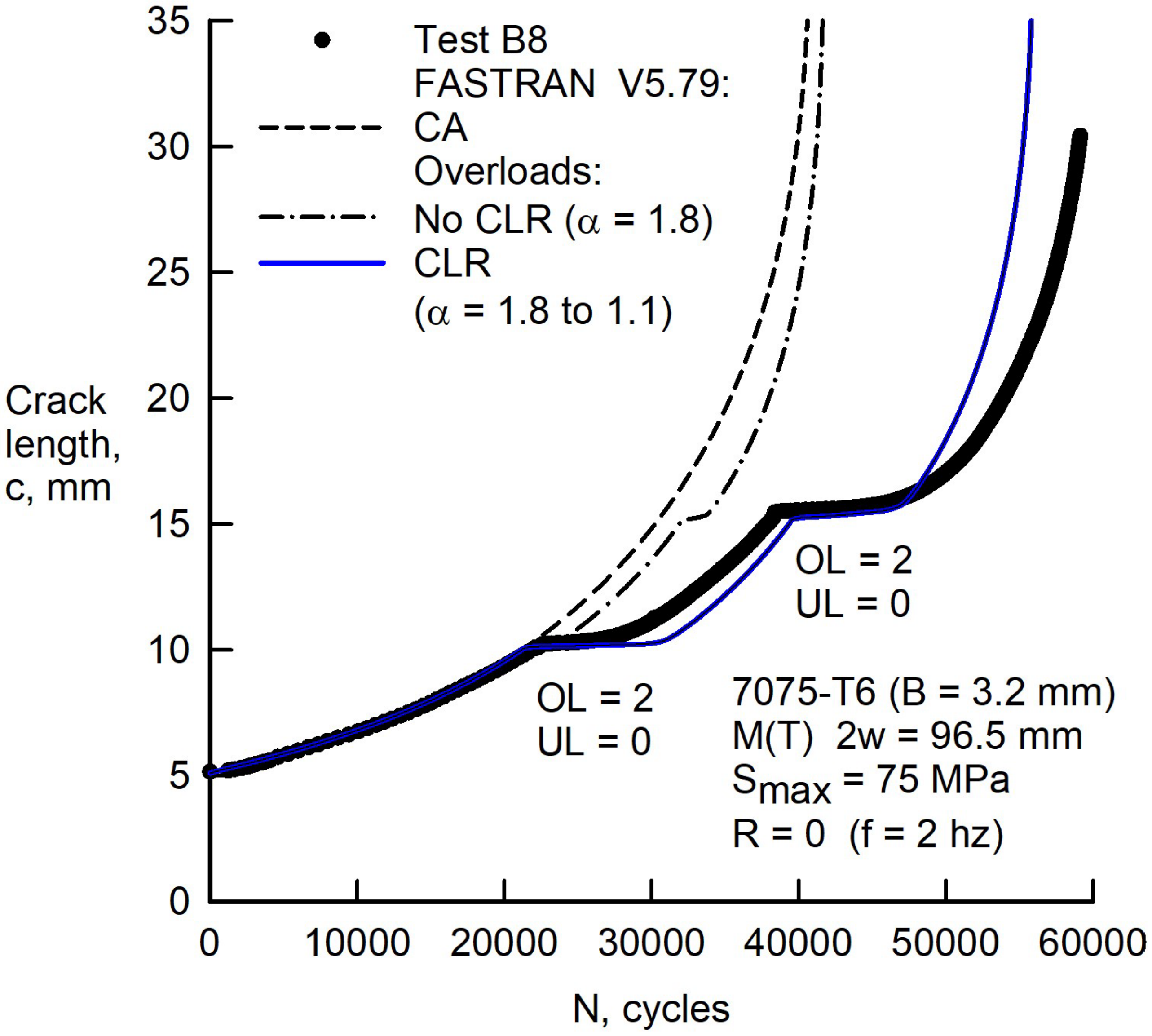
Testing Overview

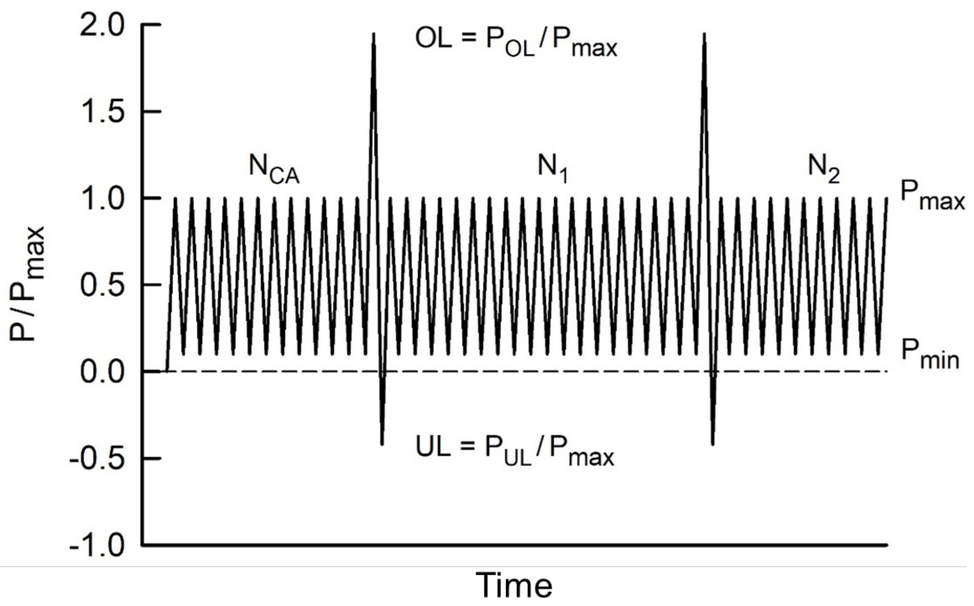
2024-T3 Spike Overload (QinetiQ Australia/MSU)





7075-T6 Spike OL (QinetiQ Australia/MSU), cont.





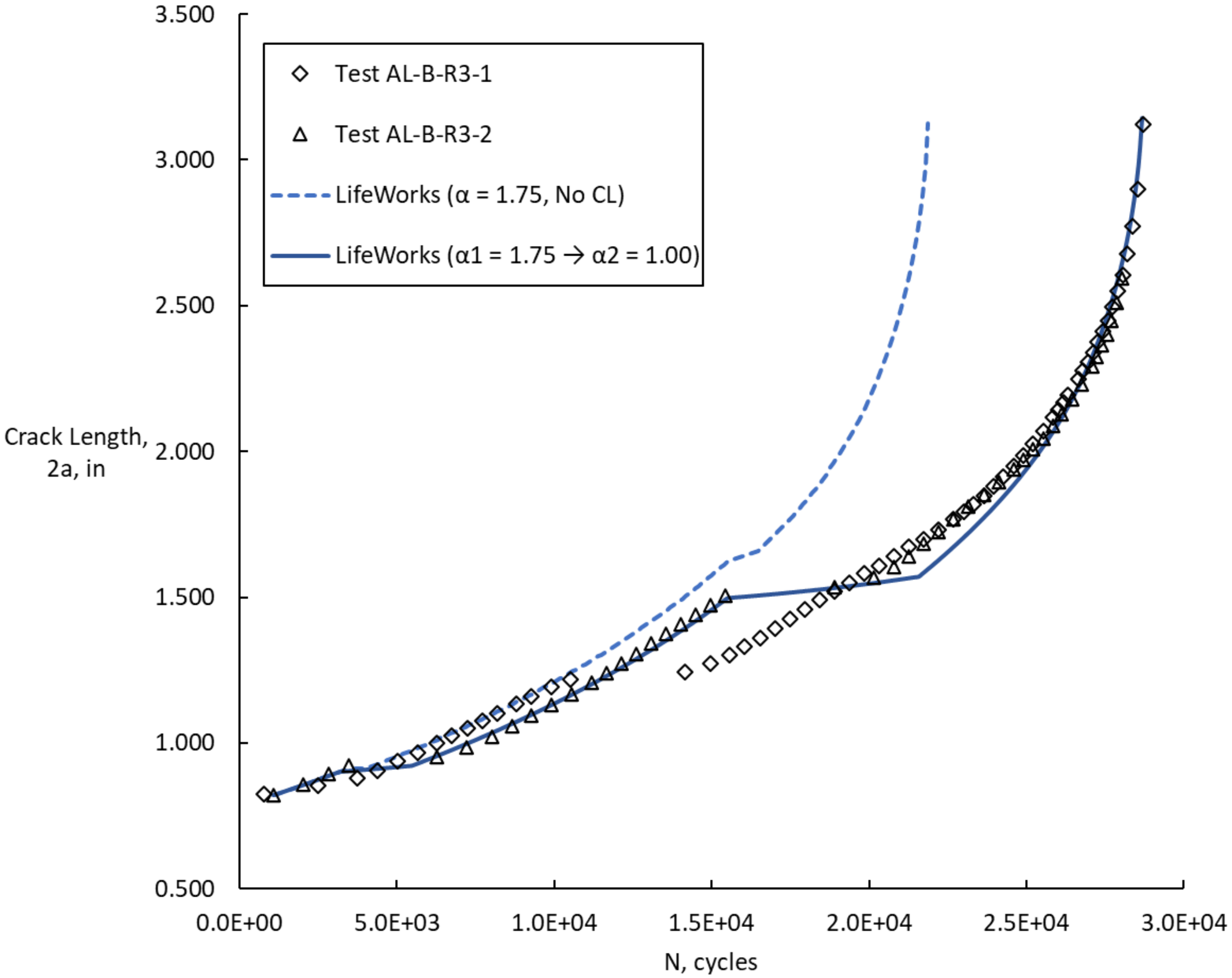
Other QinetiQ Australia IRAD Efforts

- Spike Overload/Underload
  - 2024-T3, 7075-T6, 7075-T7351
  - Stress Ratios: 0, 0.5, 0.7
  - Multiple Stress Levels
- TWIST Spectrum Loading
  - 2024-T3, 7075-T6, 7075-T7351
  - TWIST Levels I and III

- Contact

  - Kevin Walker, PhD
  - Email: KFWalker@QinetiQ.com.au

7075-T6 Spike Overload (Boeing, Task B)



Specimen	M(T)
W	3.95"
B	0.09"
L	17.5"
Notch total length	0.7”
Grain Direction	L-T
Loading Type	Constant Amplitude with OL = 1.8·Pmax
Pmax	3.91 kips
Stress Ratio	0.01

Overloads were applied at two different crack lengths:

$$2a_{OL-1} = 0.84 \text{ inches}$$

$$2a_{OL-2} = 1.2 \text{ inches}$$

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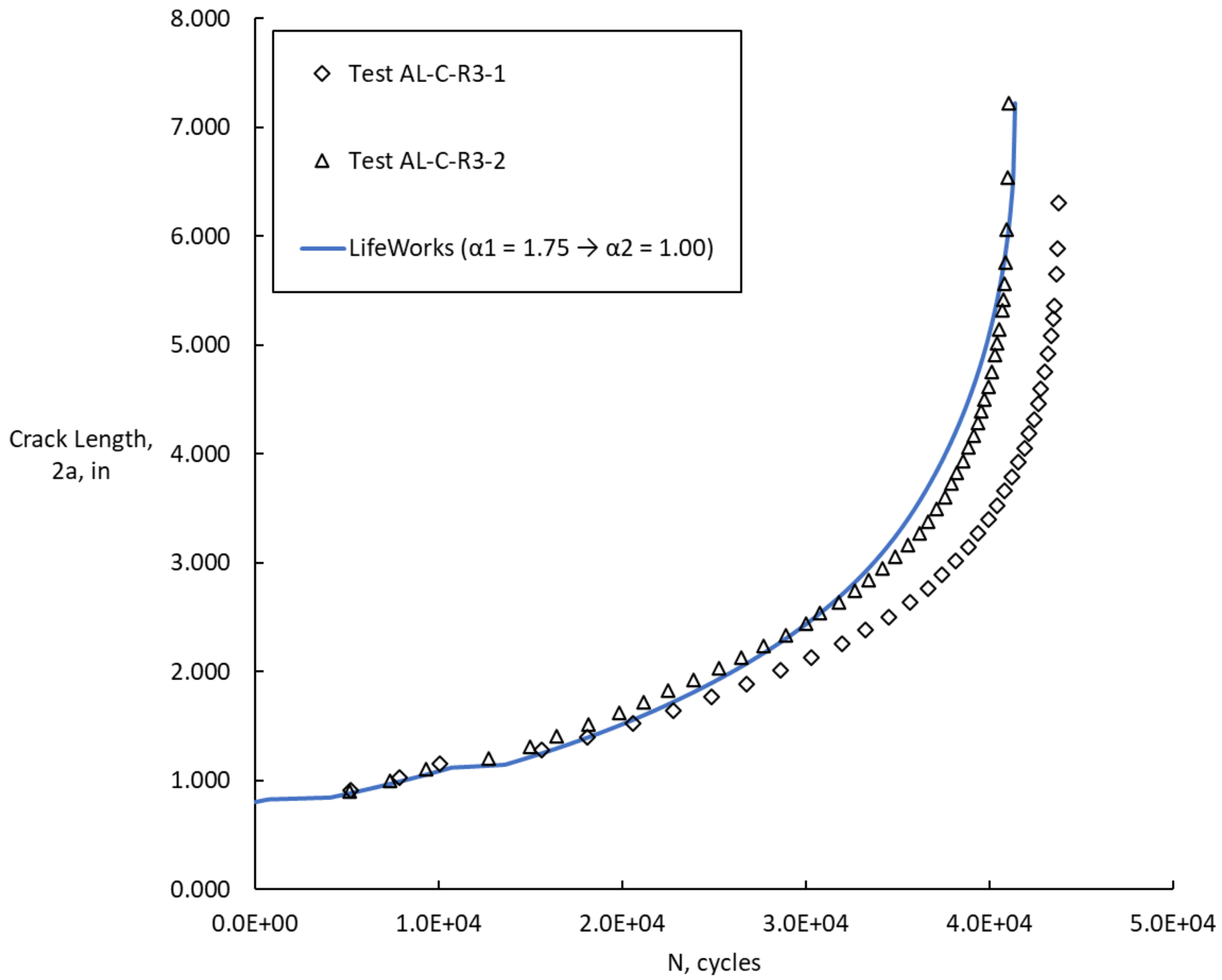
7075-T6 Spike Overload (Boeing, Task C)



Specimen	M(T)
W	10"
B	0.09"
L	26"
Notch total length	0.7”
Grain Direction	L-T
Loading Type	Constant Amplitude with OL = 1.8·Pmax
Pmax	9.9 kips
Stress Ratio	0.01

Overloads were applied at two different crack lengths:

$$2a_{OL-1} = 0.84 \text{ inches}$$

$$2a_{OL-2} = 1.2 \text{ inches}$$

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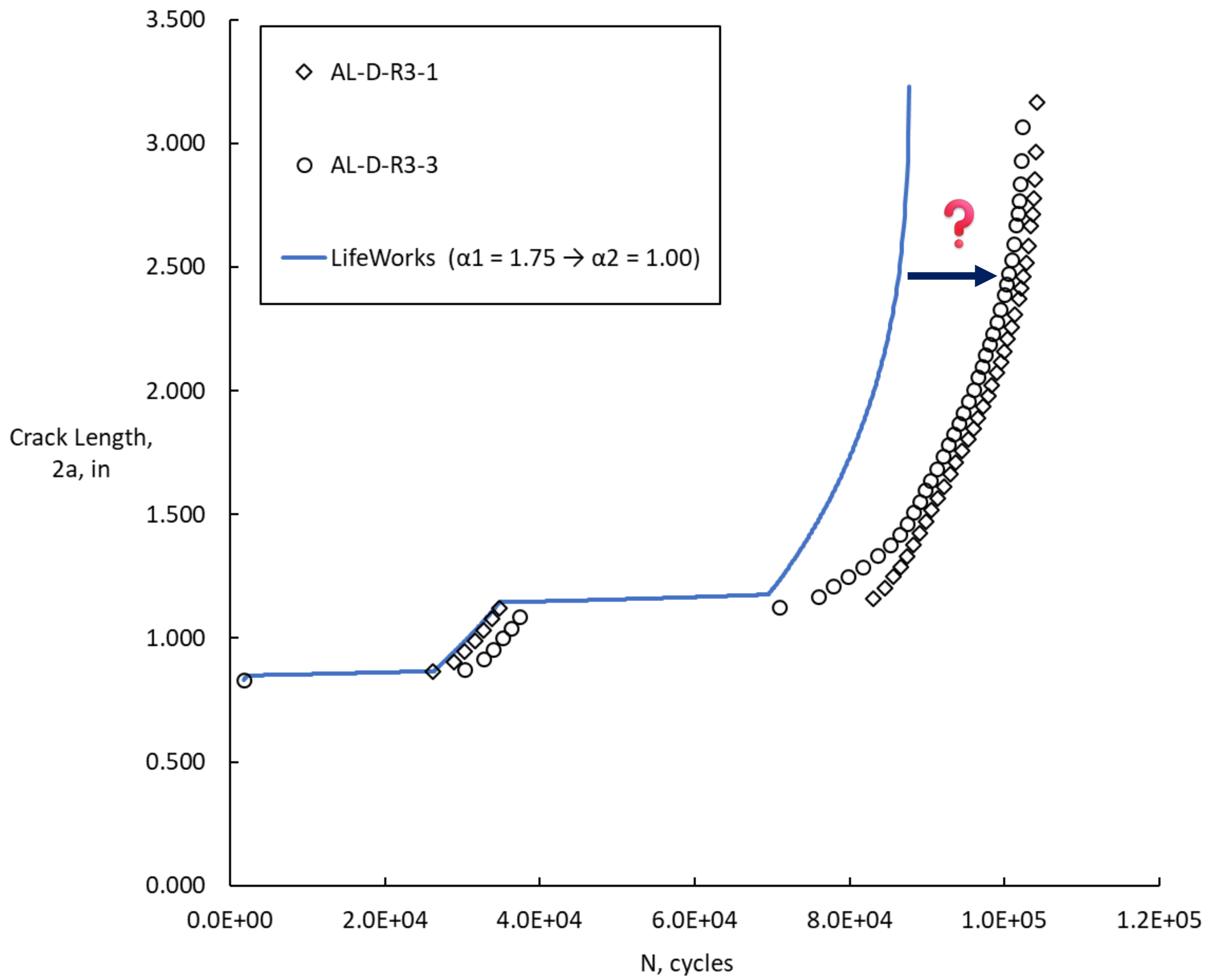
7075-T6 Spike Overload (Boeing, Task D)



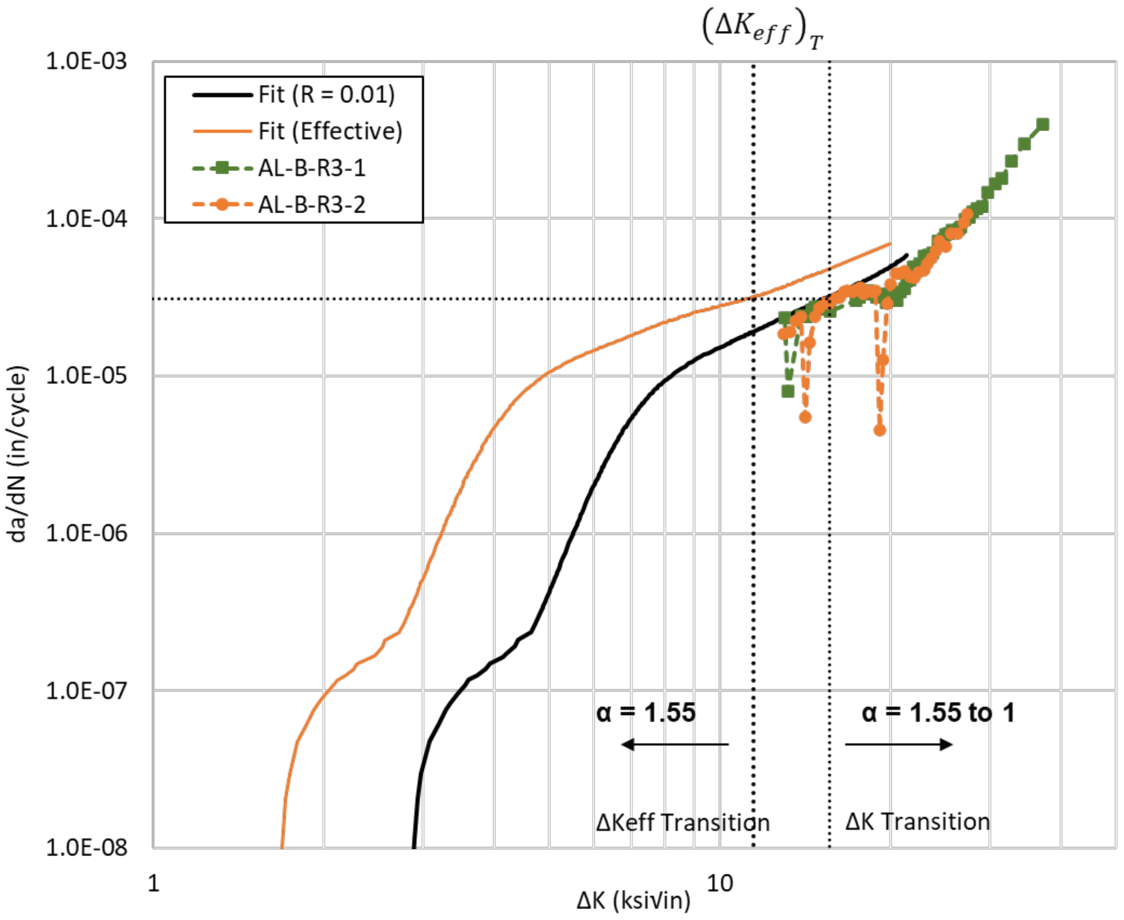
Specimen	M(T)
W	3.95"
B	0.19"
L	17.5"
Notch total length	0.7"
Grain Direction	L-T
Loading Type	Constant Amplitude with OL = 1.8·Pmax
Pmax	6.75 kips
Stress Ratio	0.01

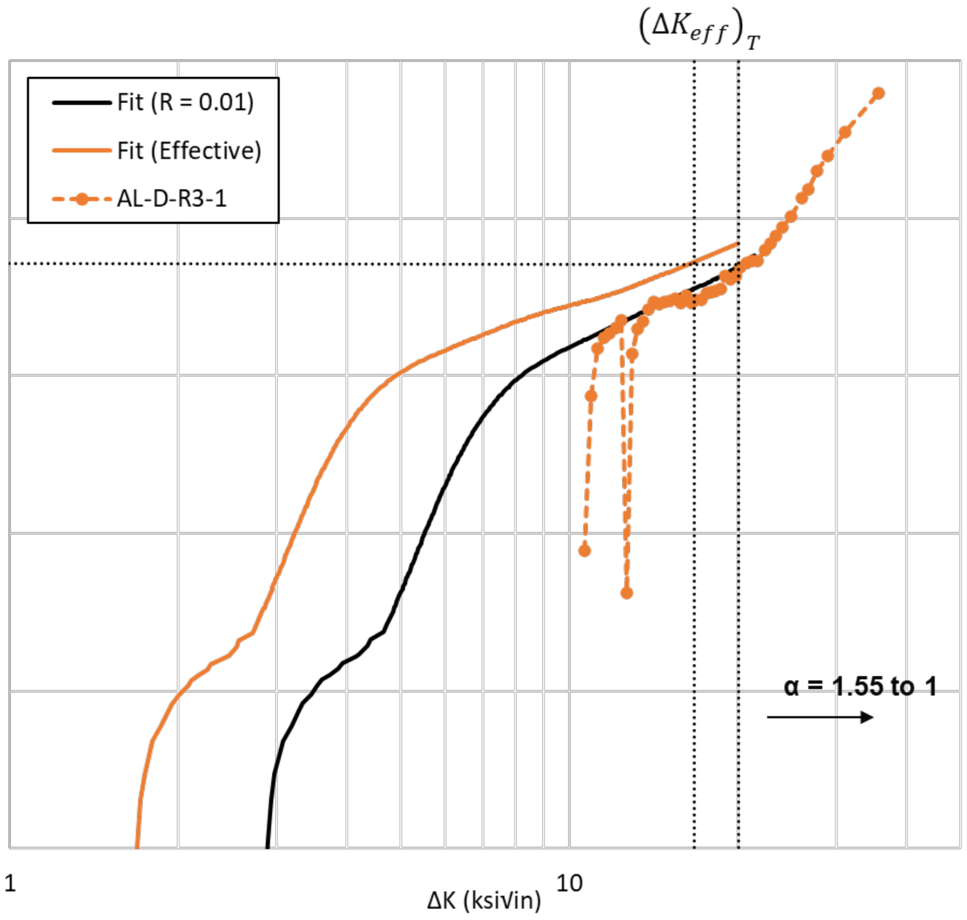
Overloads were applied at two different crack lengths:

$$2a_{OL-1} = 0.84 \text{ inches}$$

$$2a_{OL-2} = 1.2 \text{ inches}$$

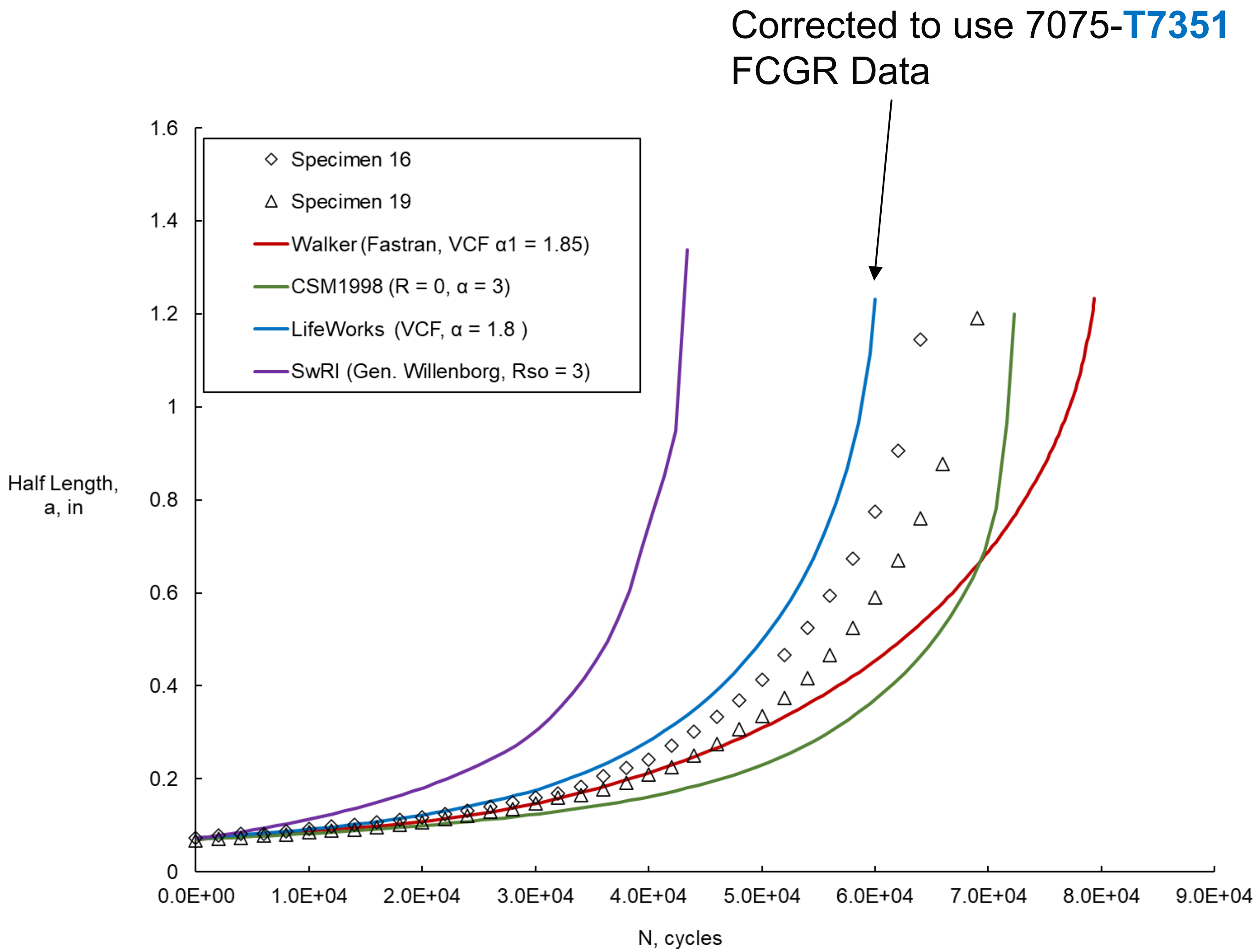
Task B vs. Task D



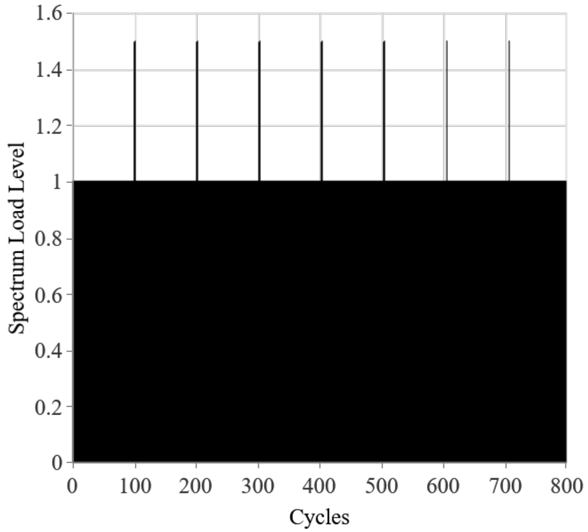


Is $(\Delta K_{eff})_T$ too high? Is plastic zone too small? Is constraint modeling appropriate for this “thicker” geometry?

7075-T651 Boeing RR Effort (Task A)



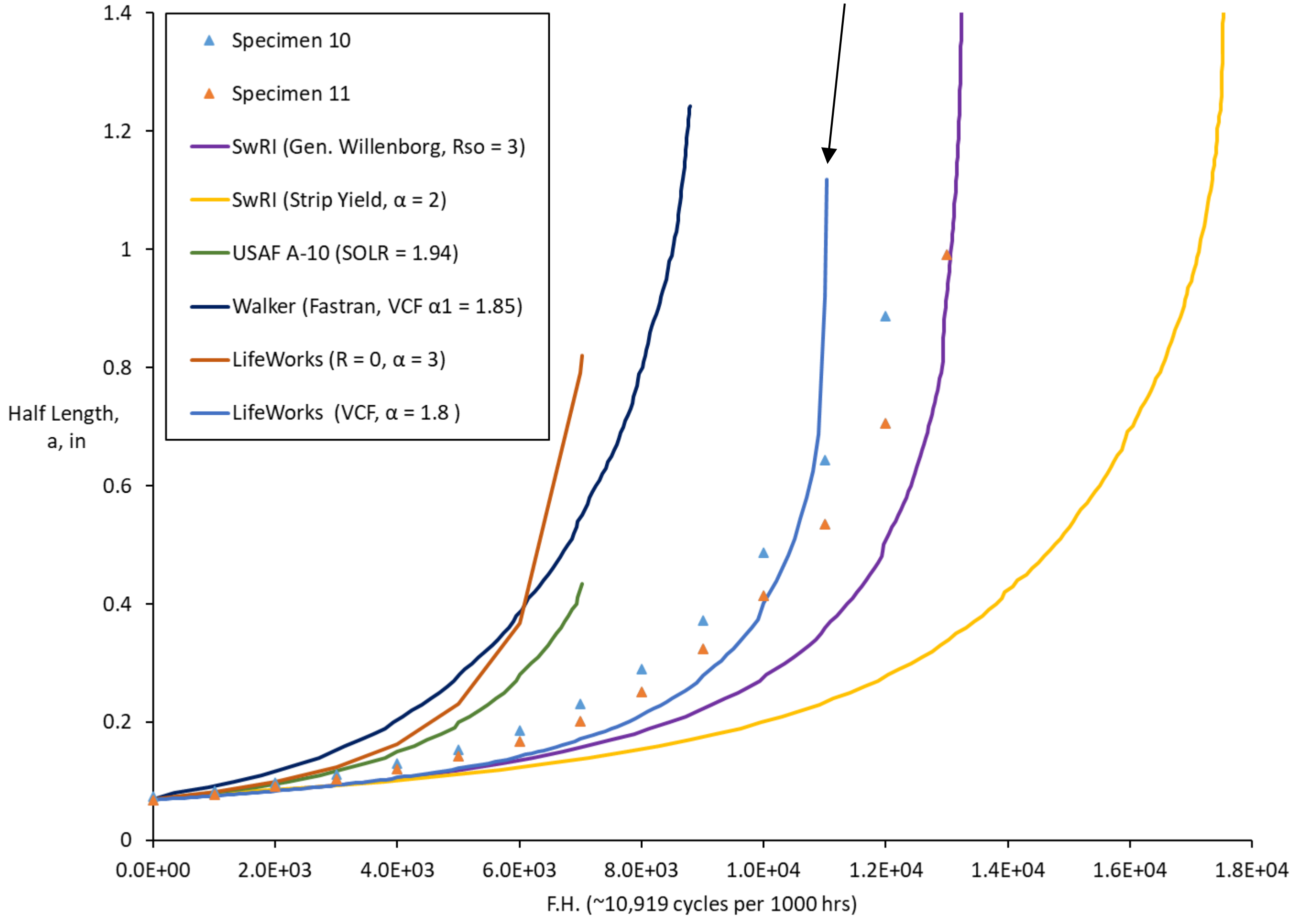
Specimen	M(T)
W	3.95"
B	0.246"
L	16"
Notch total length	0.14”
Grain Direction	L-T
Loading Type	Constant Amplitude with OL = 1.5·Pmax
Pmax	14.7 kips
Stress Ratio	0.01



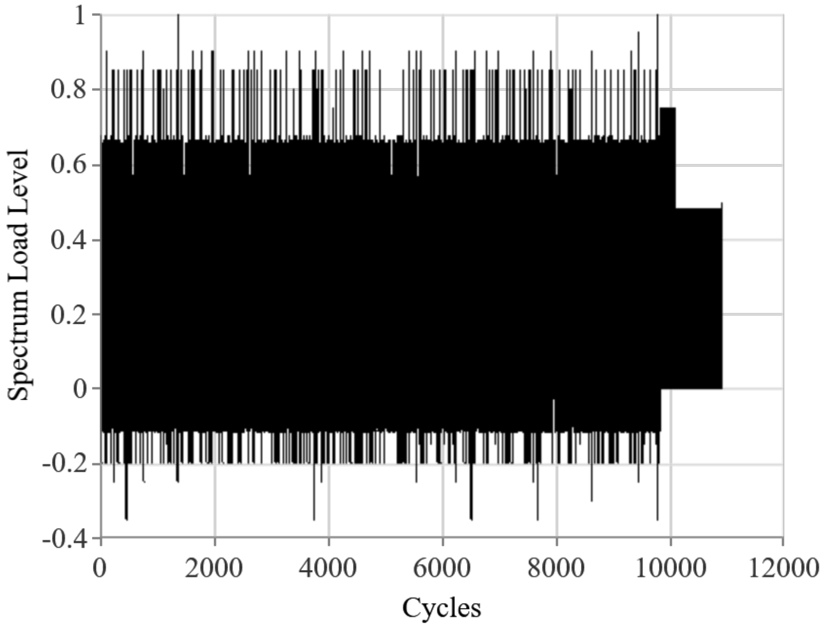
Predictions were misleading because test report incorrectly stated that the material used was 7075-**T7651**

7075-T7351 Boeing RR Effort (Task B)

Corrected to use 7075-**T7351** FCGR Data

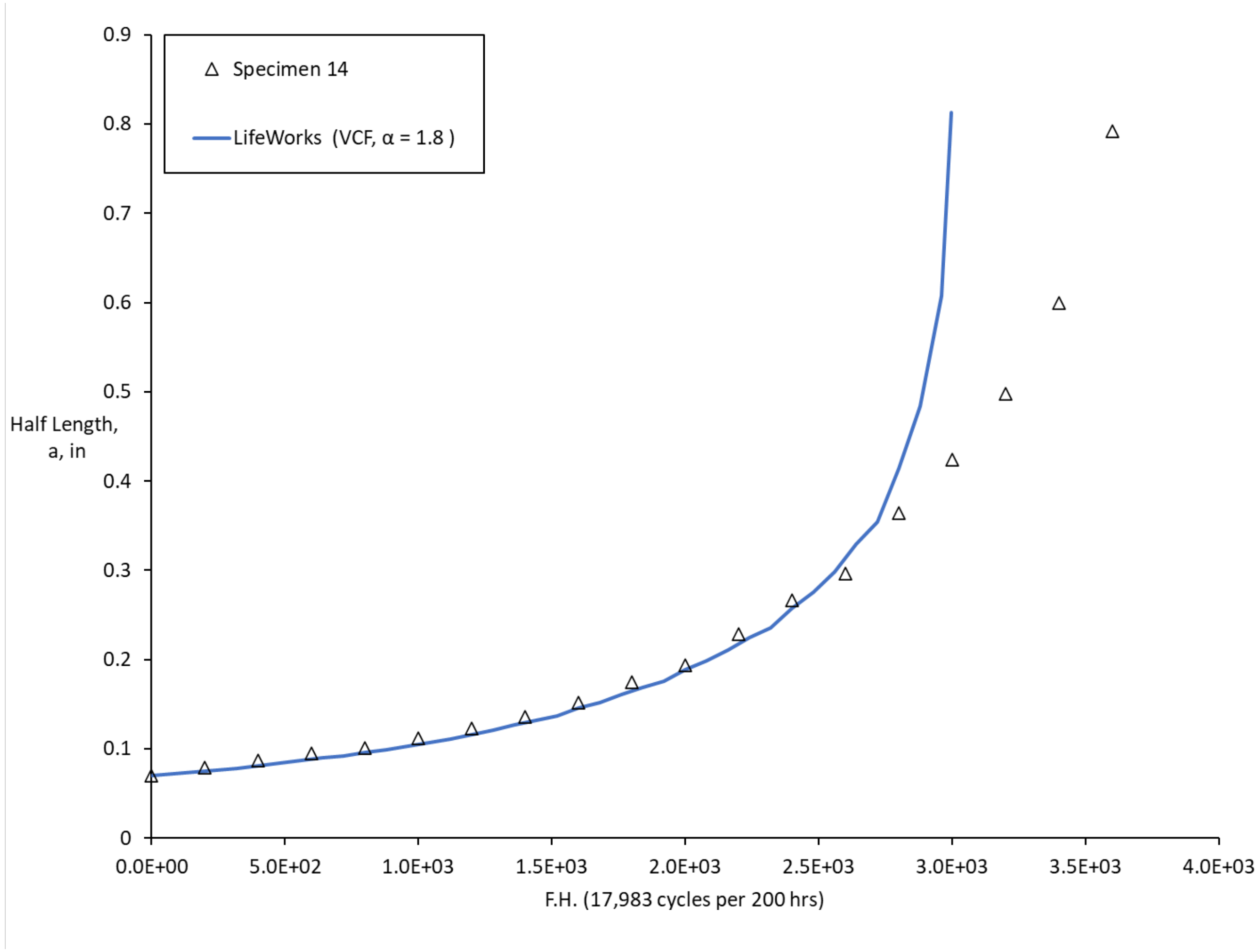


Specimen	Thickness (in)	Width (in)	Stress Level (ksi)	Test Type
M(T)	0.246	3.960	25.0	Lower Wing

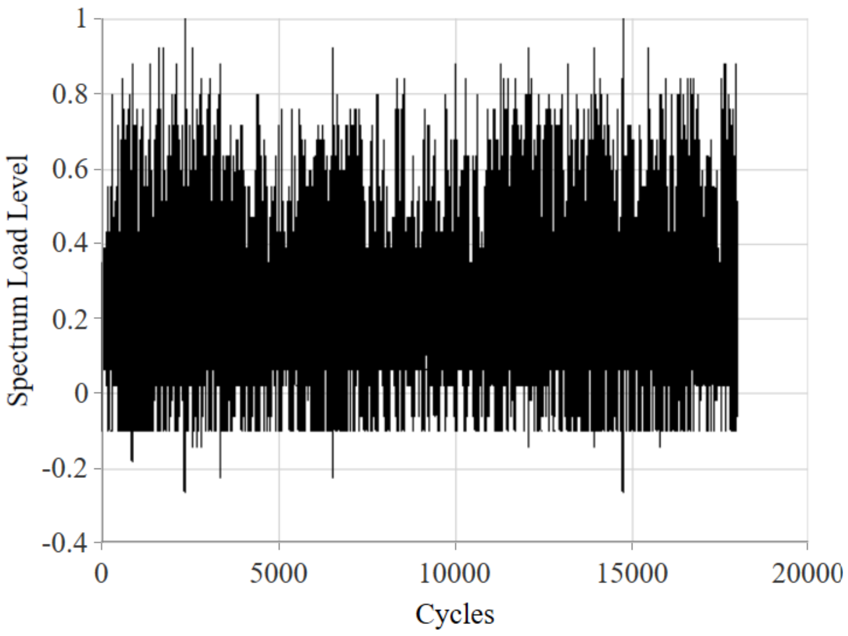


Predictions were misleading because test report incorrectly stated that the material used was 7075-**T7651**

7075-T7351 Boeing RR Effort (Task C)



Specimen	Thickness (in)	Width (in)	Stress Level (ksi)	Test Type
M(T)	0.246	3.953	35.0	FALSTAFF



Spectrum Loading Effects on Cracks Growing from Fastener Holes

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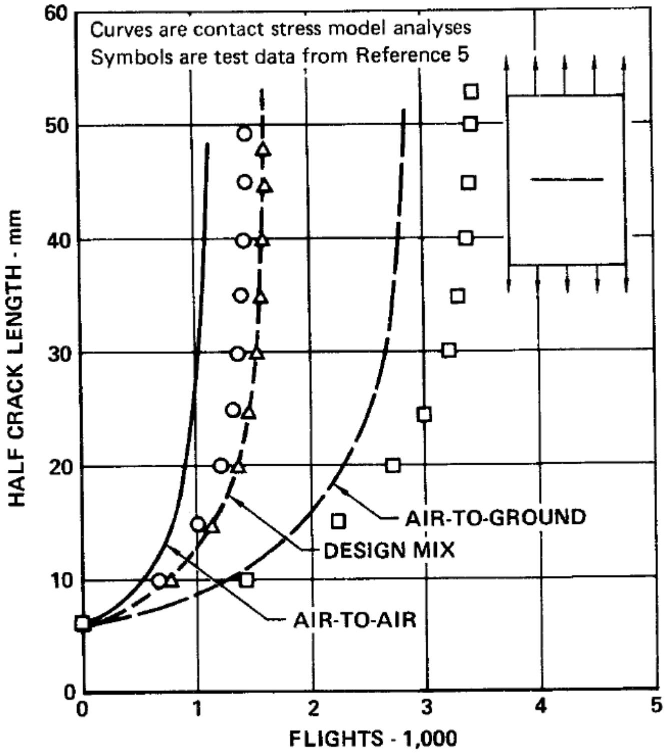
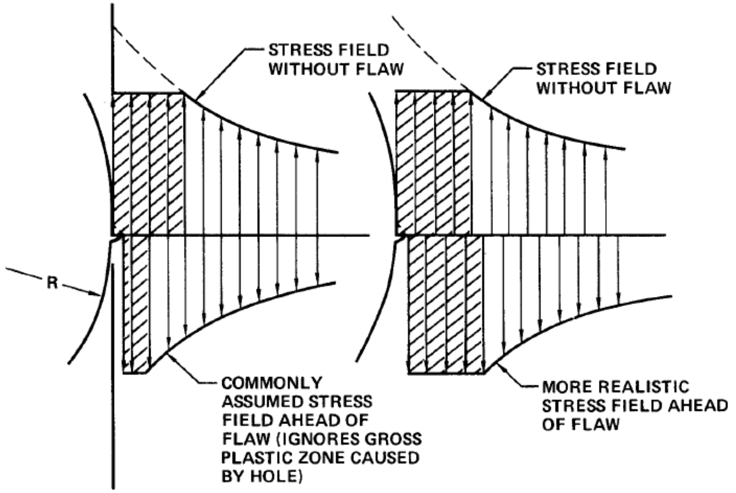
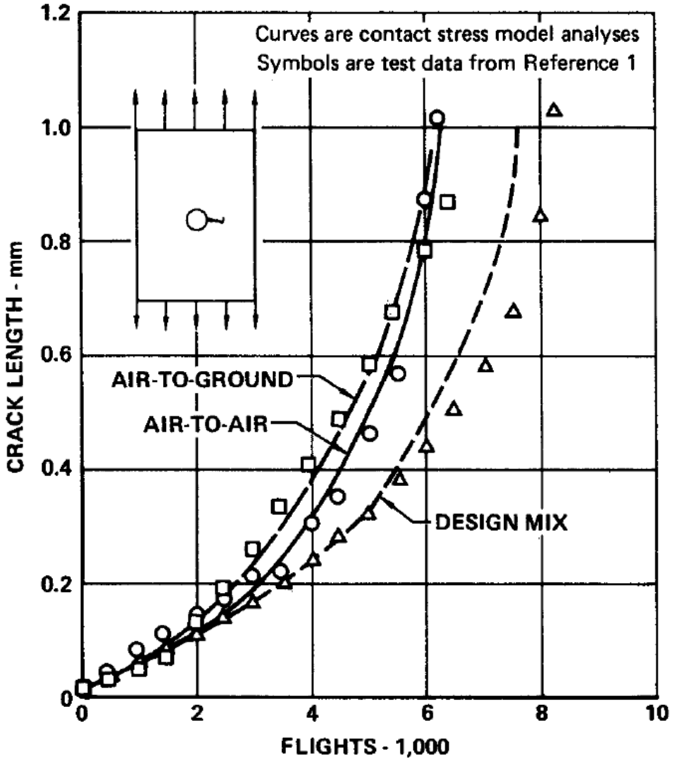
Historical Efforts





The challenge is to understand the interaction of crack tip plasticity and hole notch plasticity.



Saff, C.R., *Crack Growth Retardation and Acceleration Models*, in ASTM Forum on Damage Tolerance Analysis. 1981: Los Angeles California USA.

Scales of Plasticity

Small Scale

Tensile overloads and compressive underloads can affect (e.g. retard, accelerate, arrest) crack growth rate

Load interaction models try to account for crack growth rate changes due to load sequencing effects.

Large Scale

Extreme loads observed on aircraft components often lead to local yielding at stress concentrations

Cyclic shakedown models try to account for the impact subsequent loads have on stress field

Fatigue Life Prediction

- SIF Calculations and Geometrical Factors
- **Load interaction models**
- **Plastic Constraint Effects in FCG**
- Large Crack Growth
- Small Crack Growth

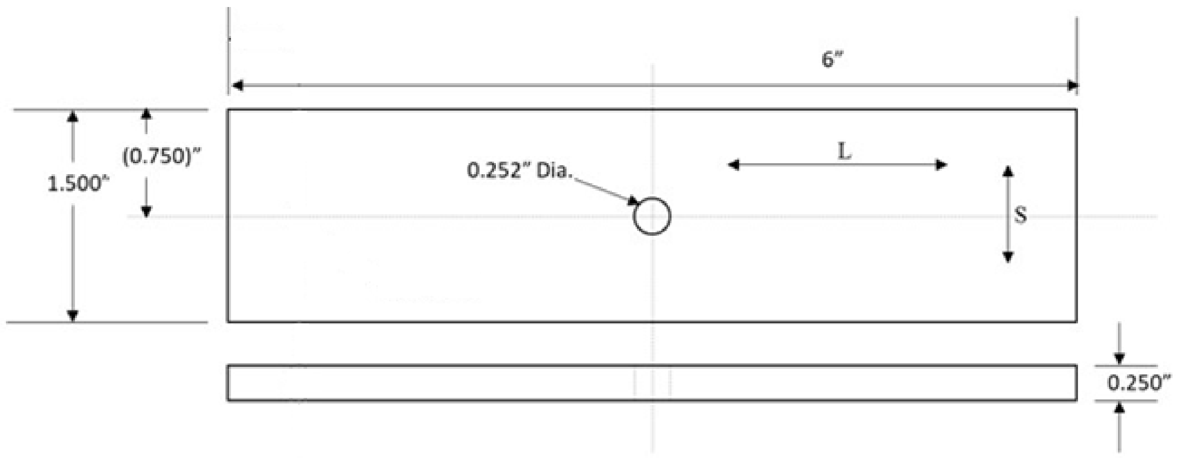
↔

Fatigue Life Enhancement

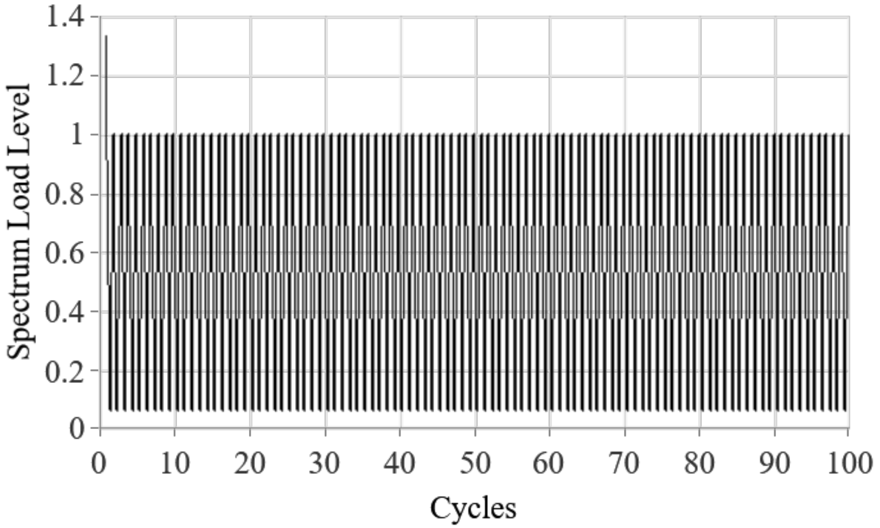
- Direct (e.g.; Cold Work, IFF)
- **Indirect (e.g. Local Plasticity)**

Ti-6Al-4V Boeing IRAD Shakedown Test

- Alloy: Ti-6Al-4V RA Forging
- Grain Direction: L-S
- Yield Strength: 131 ksi
- Max Stress: 28 ksi (L1), 42.1 ksi (L2), 56.1 (L3)
- Constant amplitude loading (R = 0.06) with 1.33 overload at the beginning of the test



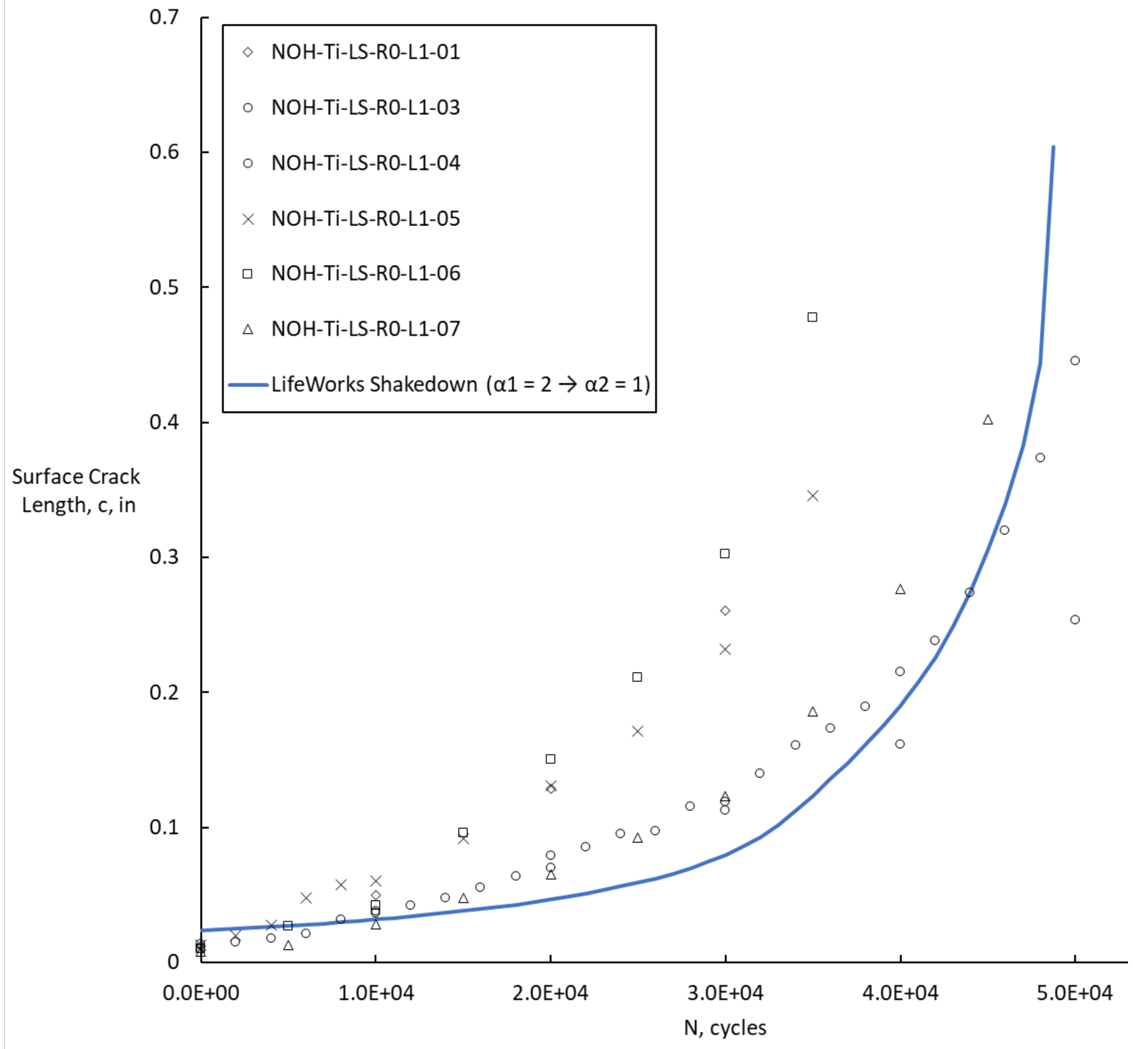
Open Hole Specimen



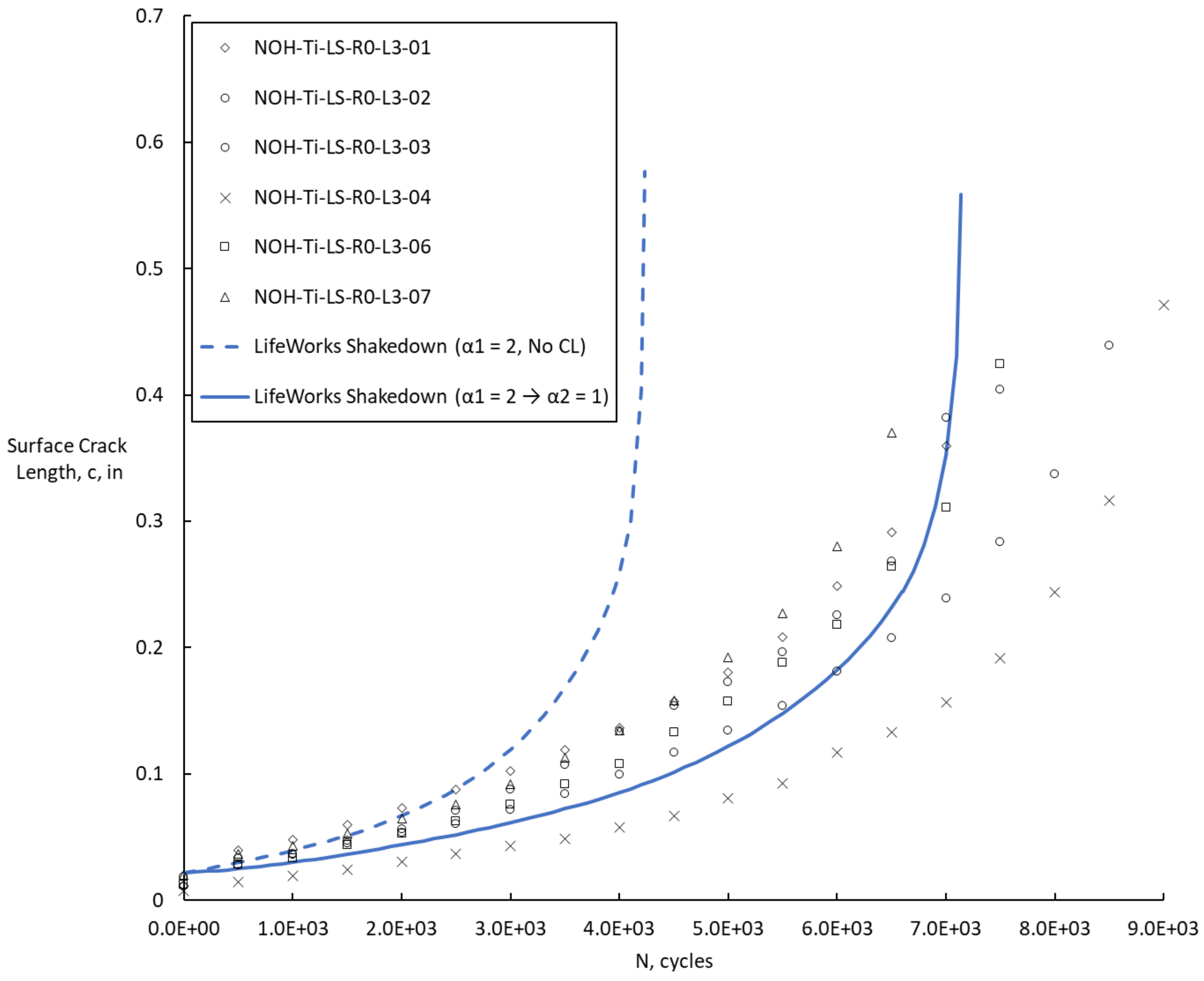
Test Spectrum

Ti-6Al-4V Hole Shakedown Correlation

Max Stress = 28 ksi



Max Stress = 56.1 ksi



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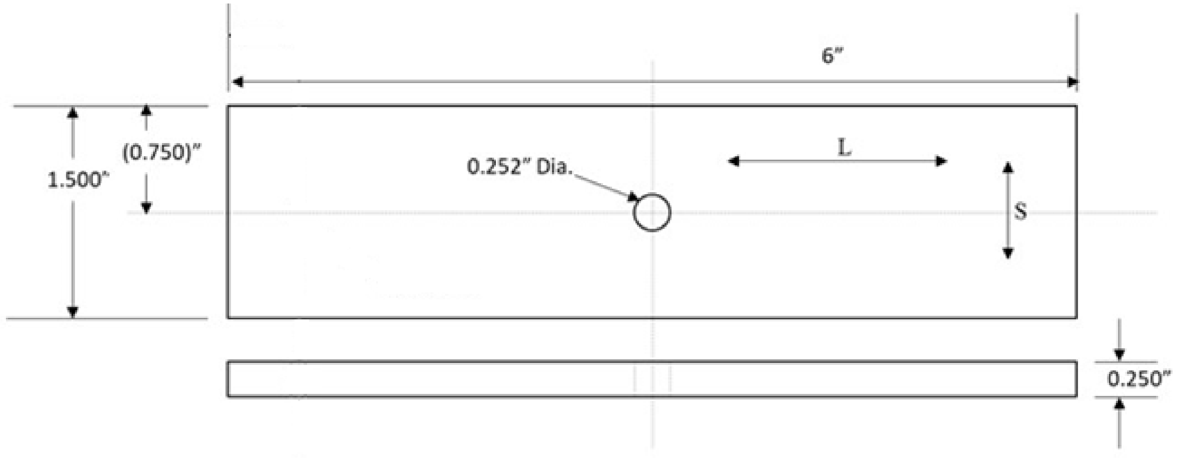
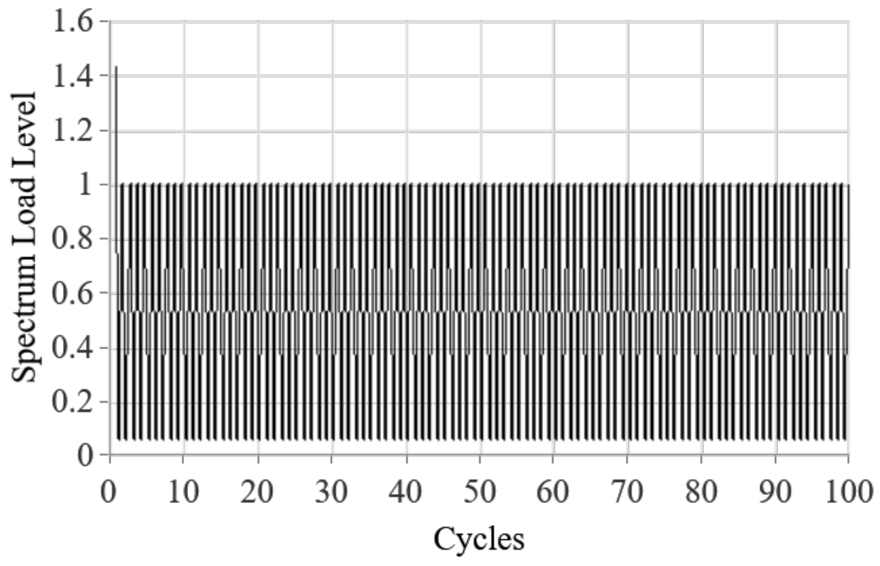
PH13-8Mo Boeing IRAD Shakedown Test

- Alloy / Condition: PH13-8Mo H1000 Bar
- Grain Direction: L-S
- Yield Strength: 229 ksi
- Max Stress: 46.7 ksi (L1), 70.1 ksi (L2), 83.6 (L3)
- Constant amplitude loading (R = 0.06) with 1.43 overload at the beginning of the test



Open Hole Specimen



Test Spectrum

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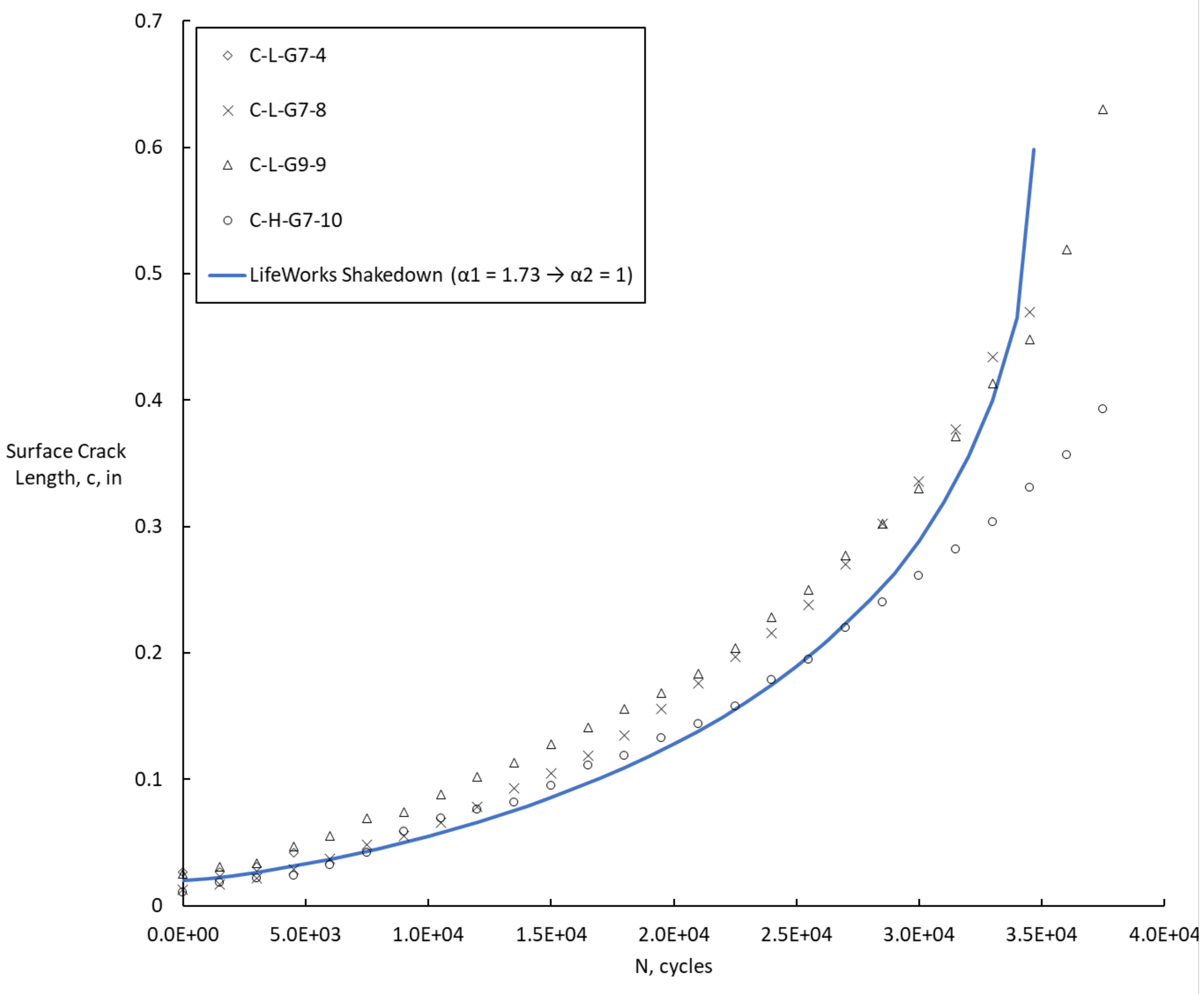
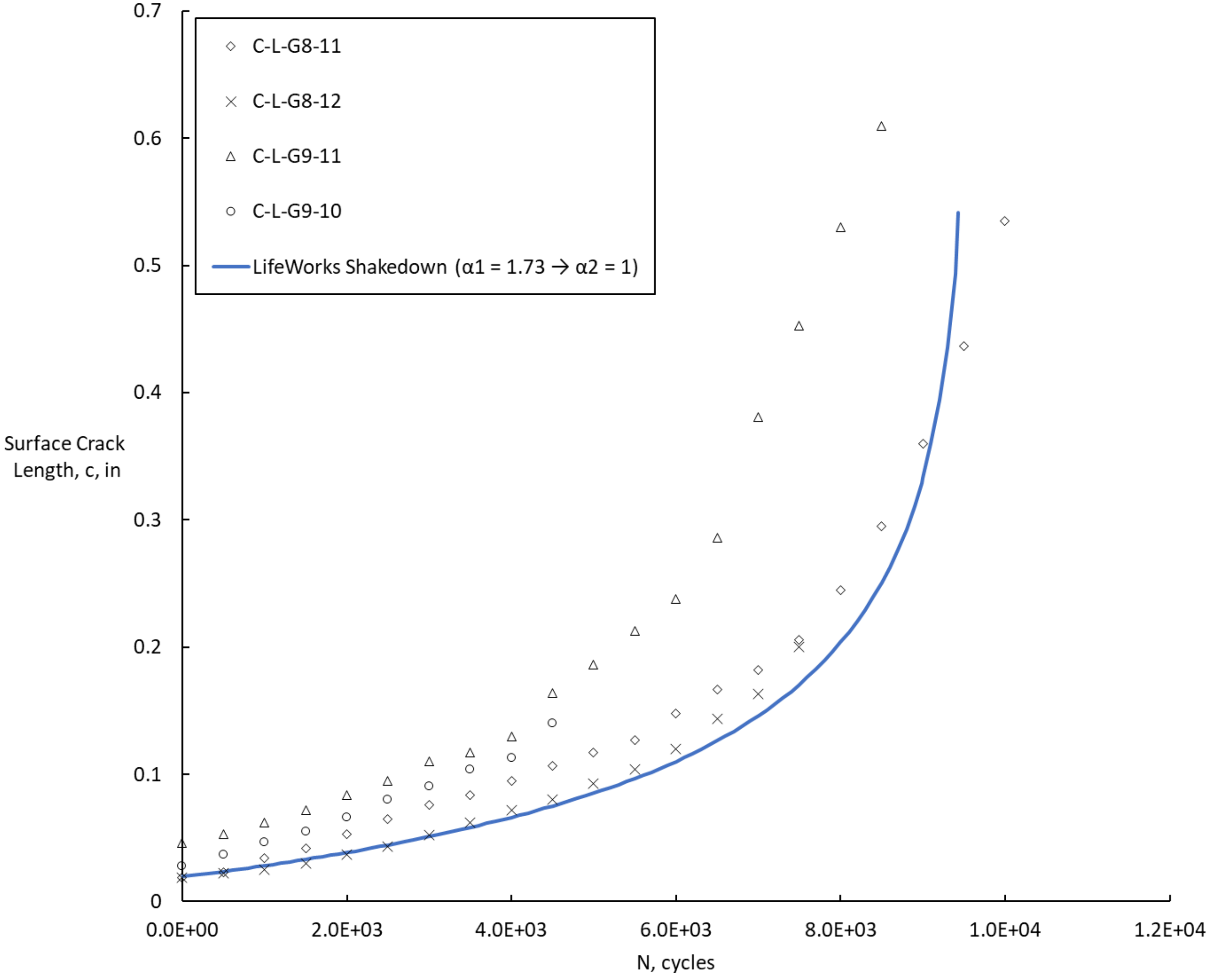
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

PH13-8Mo Hole Shakedown Correlation

Max Stress = 46.7 ksi



Max Stress = 83.6 ksi



Path Forward

ERSI
ENGINEERED RESIDUAL
STRESS IMPLEMENTATION

Path Forward

- Develop guidelines for considering spectrum loading effects based on lessons learned to date.
- Follow Building Block Approach to link spectrum loading efforts with common ERSI goals.

Geometry	Crack	Spectrum	Residuals	Stress Intensity	Growth Rate	Load Interaction	Plasticity
Middle Tension (MT)	Thru	CA	N/A	Data Available and Correlation Effort Started	Data Available and Correlation Effort Started		
		CA + OL	N/A	Data Available and Correlation Effort Started	Data Available and Correlation Effort Started	Data Available and Correlation Effort Started	
		VA	N/A	Data Available and Correlation Effort Started	Data Available and Correlation Effort Started	Data Available and Correlation Effort Started	
Hole in Plate	Corner	CA	N/A	Data Available and Correlation Effort Started	Data Available and Correlation Effort Started		
		CA + OL	Shakedown	Data Available and Correlation Effort Started	Data Available and Correlation Effort Started	Data Available and Correlation Effort Started	Data Available and Correlation Effort Started
		VA	Shakedown	Testing and/or Historical Test Data Evaluation Started	Testing and/or Historical Test Data Evaluation Started	Testing and/or Historical Test Data Evaluation Started	Testing and/or Historical Test Data Evaluation Started
		CA	Cx + Shakedown	Data Available from other ERSI Related Efforts	Data Available from other ERSI Related Efforts		Data Available from other ERSI Related Efforts
		CA + OL	Cx + Shakedown	Data Not Available or Identified	Data Not Available or Identified	Data Not Available or Identified	Data Not Available or Identified
		VA	Cx + Shakedown	Data Available from other ERSI Related Efforts	Data Available from other ERSI Related Efforts	Data Available from other ERSI Related Efforts	Data Available from other ERSI Related Efforts
		CA	IFF	Data Available from other ERSI Related Efforts	Data Available from other ERSI Related Efforts	Data Available from other ERSI Related Efforts	Data Available from other ERSI Related Efforts
		CA + OL	IFF	Data Not Available or Identified	Data Not Available or Identified	Data Not Available or Identified	Data Not Available or Identified
		VA	IFF	Data Available from other ERSI Related Efforts	Data Available from other ERSI Related Efforts	Data Available from other ERSI Related Efforts	Data Available from other ERSI Related Efforts

Data Available and Correlation Effort Started

Testing and/or Historical Test Data Evaluation Started

Data Available from other ERSI Related Efforts

Data Not Available or Identified

Testing & Analysis of Interference Fit Fasteners
An A-10 ASIP & ERSI Joint Effort

2025 ERSI Workshop

ERSI

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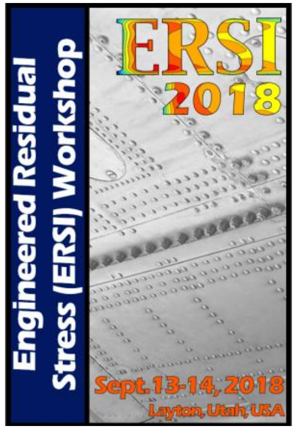
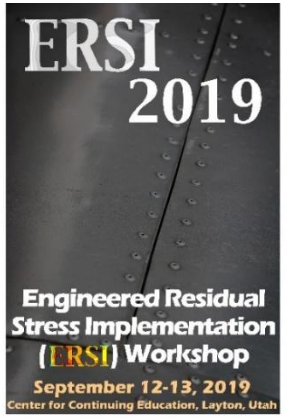
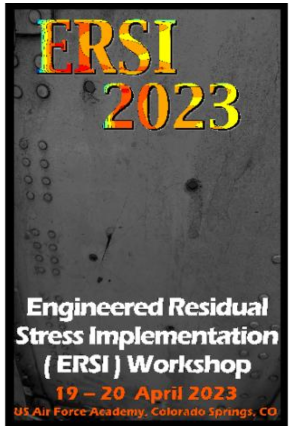
  - A-10 ASIP Team: Jacob Warner, Brian Boeke
  - SwRI: Lucky Smith, Marcus Stanfield, Trenten Wahlen, Michael Worley, Jim Feiger, Paul Clark
  - Hill Engineering: Dallen Andrew

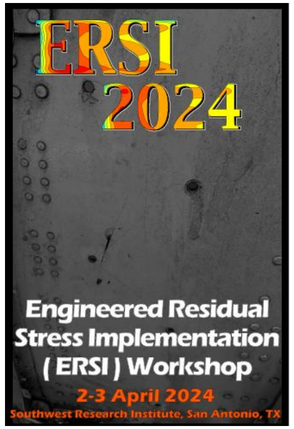
Thanks to the ERSI Working Group for all your hard work!!!

- **Round robin participants**
  - Renan Ribeiro – Hill Engineering, LLC
  - Yan Bombardier – NRC-Canada
  - Adrian Loghin – Simmetrix Inc
  - Connor Hood – A-10 Program Office
  - Jason Hawks – Boeing
  - Scott Prost-Domasky – APES
  - Zohren Asaee – NRC – Canada
  - David Wieland – SwRI



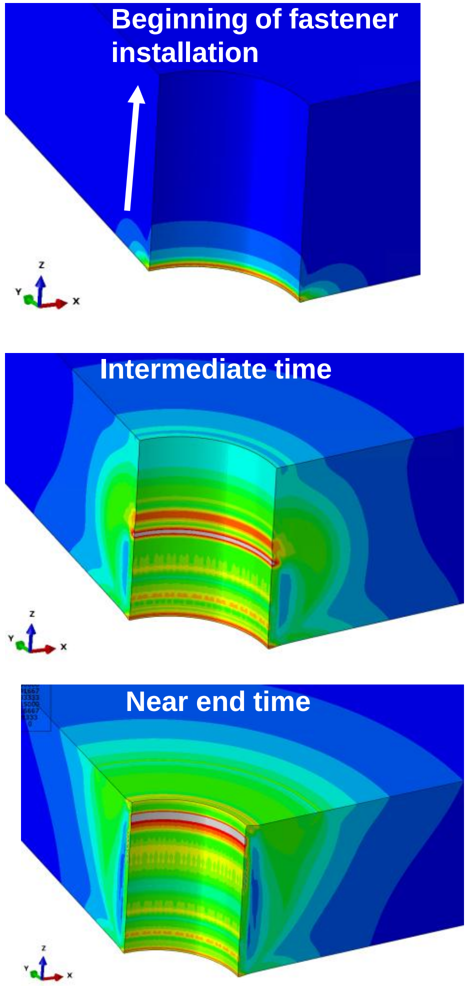






Agenda

- A-10 interference fit fastener testing
- ERSI round robin predictions
  - Objectives and approach
  - Results and comparisons
- A-10 test results
  - Findings and comparisons
- Next steps
- Conclusions



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
- **Phased Approach**
  - Phase 1: assessment of as-installed state
  - Phase 2: fastener installed + remote loading
  - Phase 3: analytical methodology to account for IFF during crack growth
  - Phase 4: fatigue crack growth testing with IFF

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A-10 IFF Testing & Analysis Program

Coupon Details:

- Coupon Material: 2024-T351 plate
- Pin Material: 52100 steel pin
- Thickness: 0.25 inch
- Hole Diameter: 0.25 inch

Strain Monitoring:

- Digital Image Correlation (all specimens)
- Strain Gage (initial specimen)

Interference Conditions:

- Open Hole
- Neat Fit
- 0.3% Interference
- 0.6% Interference
- 1.2% Interference

Fastener Details:

- Precisely Controlled Gauge Pins
- Ground Transition Geometry to Represent Hi-Lok
- Cetyl Alcohol Lubricant

Stress Levels:

- Static (Phase 2):
  - -30, -10, 0, 10, 20, and 30 ksi
- Fatigue (Phase 4):
  - CA: Smax = TBD, R = TBD
  - VA: TBD

Data Capture:

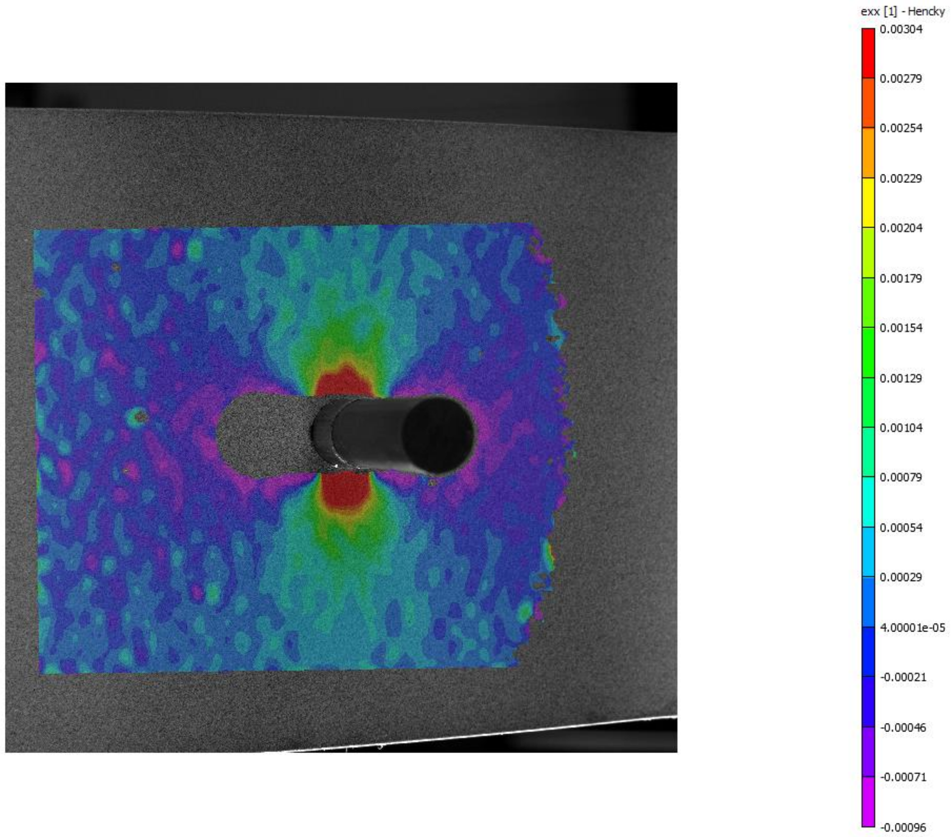
- Geometric measurements of fastener and hole before/after installation/loading
  - Capture applied/retained interference
- Surface strains at fastener install, load, unload, and removal steps
- Transition point for fastener gapping

Very close attention to small details

ERSI

A-10 IFF Testing & Analysis Program

- Example DIC setup & results



ERSI IFF Round Robin – Implementation Plan

- **Objective**
  - Collaborate to establish validated analytical methods for IFF applications
  - Utilizing a phased approach, evaluate the influence of IFF on the stress state, stress intensity factors, and crack growth life of critical fastener holes
  - Evaluate differences between working group members' process simulation techniques against carefully planned and executed physical test
  - Improve understanding and validate influence of key factors on IFF performance
- **Phased approach to match A-10 efforts**
  - Phase I: Baseline Stress Analysis Verification
  - Phase II: Stress Intensity Factor Comparisons
  - Phase III: Crack Growth Analyses

ERSI IFF Round Robin Conditions

- Data from A-10 summarized and shared with participant
- Three groups of analyses defined with increasing complexity
  - Group 1: open hole, remote load
  - Group 2: fastener installation, no remote load
  - Group 3: fastener installation + remote load

Table 1. Round-robin analysis conditions, group 1

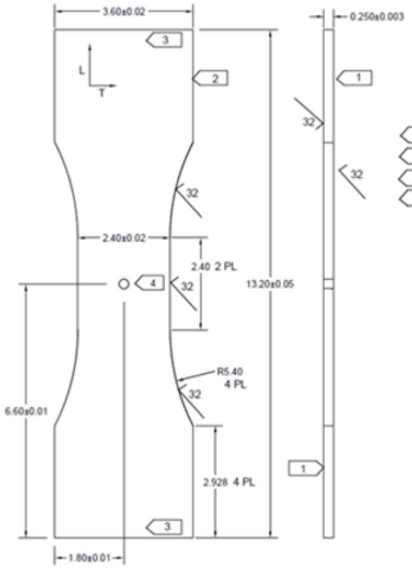
Group	Condition	Sequence Step	Interference Condition	Applied Stress (ksi)
1	1	1 – Apply Remote Stress 2 – Unload	Open Hole	-10, 10, 20, 30

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	

Table 3. Round-robin analysis conditions, group 3

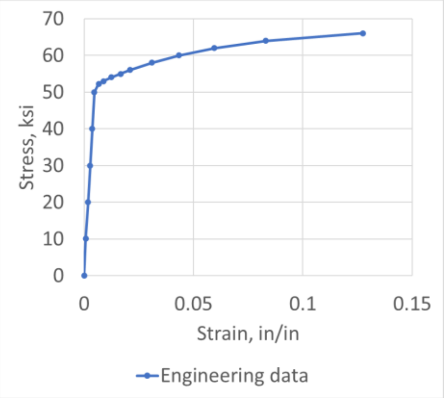
Group	Condition	Sequence Step	Interference Condition	Applied (ksi)
3	1	1 – Installed Fastener 2 – Apply Remote Stress 3- Unload 4 – Remove Fastener	Neat Fit	-10, 10, 20, 30
	2		0.3% IFF	
	3		0.6% IFF	
	4		1.2% IFF	



Dimensions in inches unless otherwise noted.
Stock thickness is approximately 0.250 inch. Use as-is.

1. Hand sand with emery cloth in longitudinal direction (each face) to remove mill scale
2. Last 0.020" removal on edges must be done in 0.005" passes.
3. Specimen ID will be engraving in format 7D3-xx-Da-2480, with xx ranging sequentially from 13 to 28
4. Hole preparation (drill & reamer entry face are on Specimen ID side)

Condition	Hole Diameter (in)	Pin Diameter (in)
Open Hole	0.2500	N/A
Neat Fit	0.2500	0.2500
0.3% Interference	0.2500	0.2508
0.6% Interference	0.2500	0.2515
1.2% Interference	0.2500	0.2530

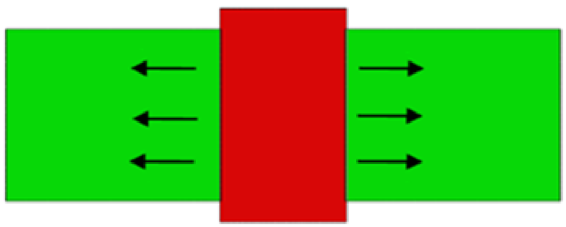
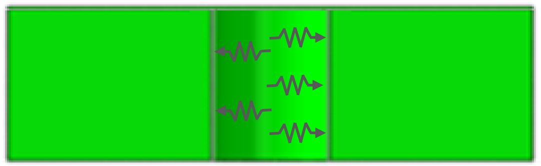
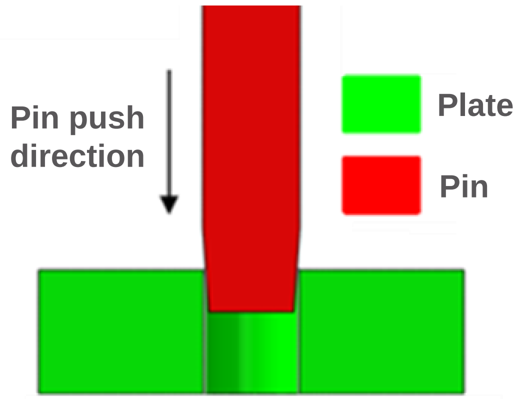


General Material Properties

Property	Coupon	Pin/Plug
Material	2024-T351 plate	4340 Steel
Modulus (ksi)	10,800	29,000
Poisson	0.33	0.29
Ultimate Strength (ksi)	66.7	Model as Elastic
Yield Strength (ksi)	52.2	
Stress-Strain Curve	See note	N/A
Source	A-10 ASIP	N/A

Round Robin Participants

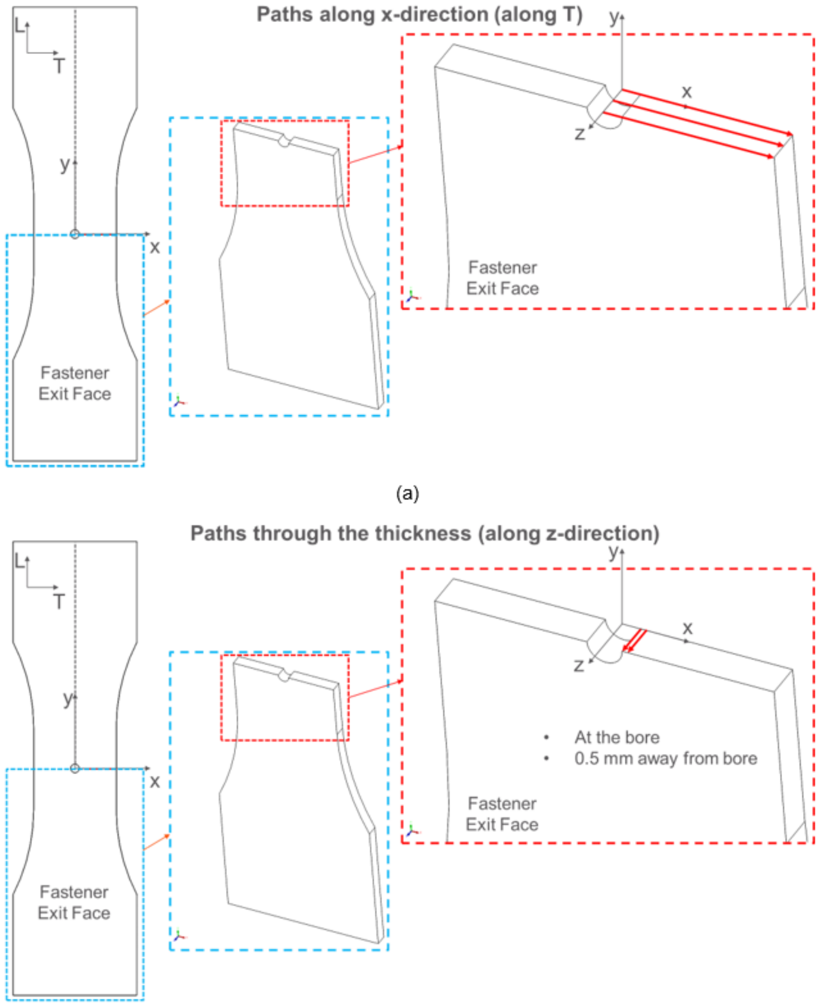
- **Details about participants**
  - From 8 different organizations
  - Five different software packages
    - Abaqus, Ansys, StressCheck, SimCenter 3D, Nx Nastran
  - Several different modeling techniques for fastener installation

Method 1	Method 2	Method 3
Uniform Expansion, then Resolve Interference	Springs to Simulate Interference	Incrementally Push Fastener into Hole, Solve for Equilibrium
3 Submissions	1 Submission	3 Submissions
Radial expansion of pin 	**Springs to simulate interference** 	

IFF Round Robin - Predictions

- Summary of analysis approaches & data collected

Submission ID	Software	Material behavior (hardening)	IFF modeling	Contact definition
1	Ansys	Isotropic	Uniform expansion	Surface-surface contact Friction (0.3 coeff.)
2	SimCenter 3D	Isotropic	Uniform expansion	Surface-surface frictionless contact
3	StressCheck	Kinematic	None	-
4	Abaqus	Isotropic	Incremental movement of fastener	Surface-surface frictionless contact
5	StressCheck	Kinematic	Normal springs and imposed displacement	No contact (no fastener included)
6	MSC Marc	Combined	Uniform expansion (thermal)	Surface-surface frictionless contact
7	StressCheck	Isotropic	None	-
8	NX Nastran	Isotropic and kinematic	Incremental movement of fastener	Surface-surface Friction (0.459 coeff.)
9	Abaqus	Isotropic	Incremental movement of fastener	Surface-surface frictionless contact



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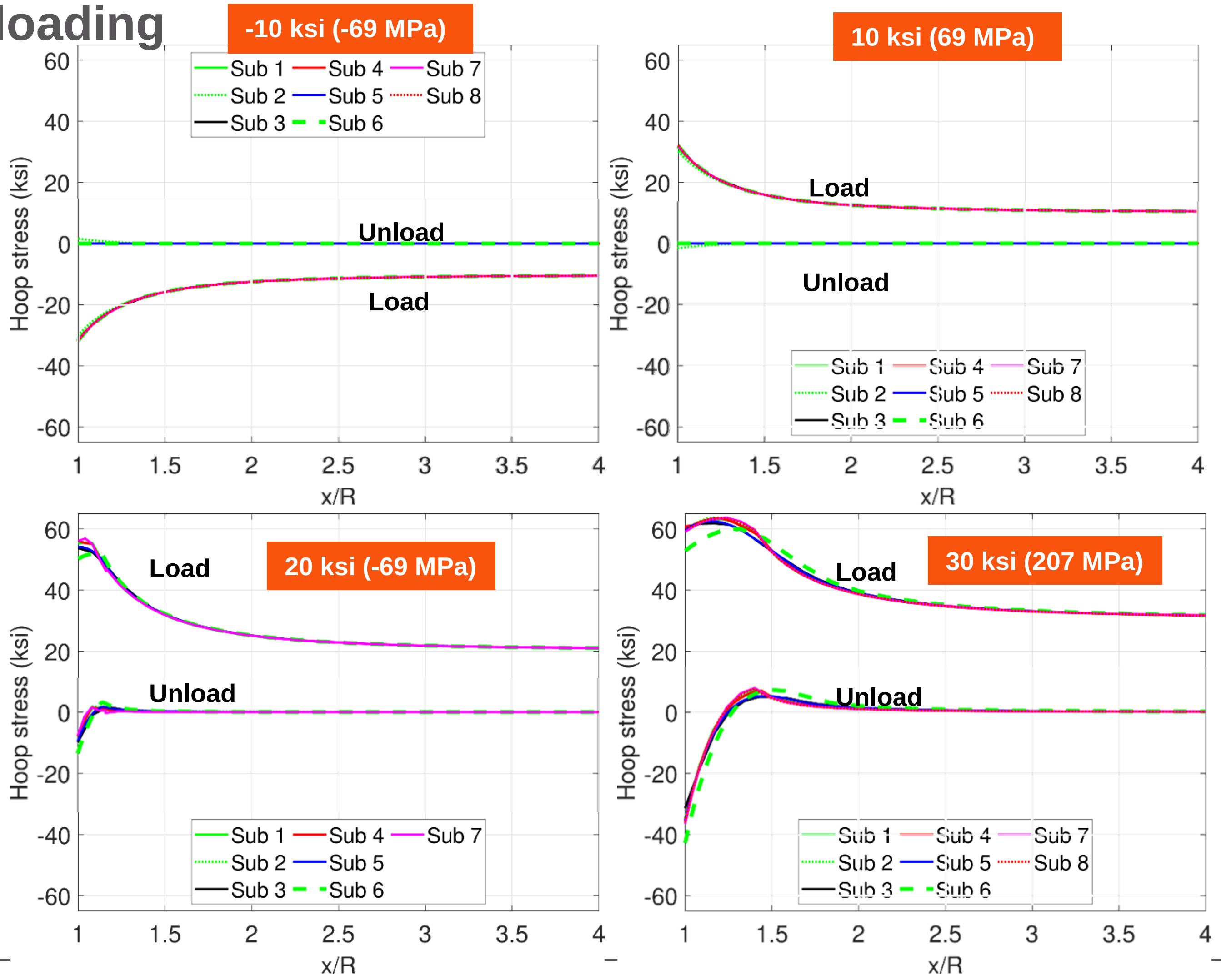
IFF Round Robin - Predictions

- Group 1 – open hole, no fastener, remote loading



Key Takeaways:

- **Consistent predictions across submissions**
  - Plastic onset occurs as expected
    - ~ 33% of Fty
  - Yield zone size
  - ~ 0.25R (20 ksi), 1.00R (30 ksi)

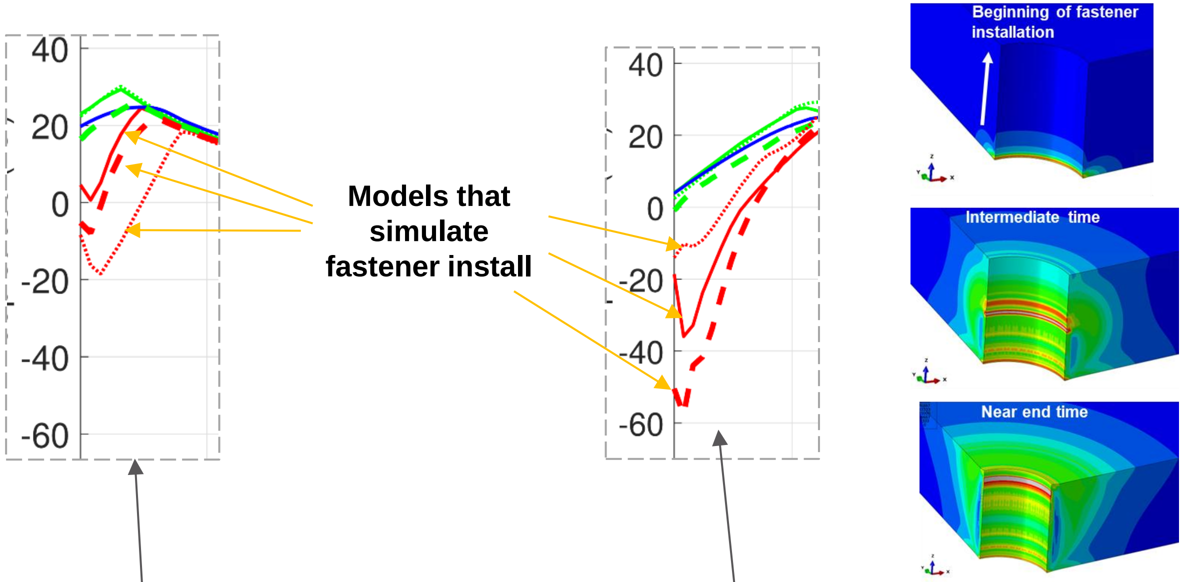
Note: this work has been submitted to the Materials Performance and Characterization journal and approved for publication.

IFF Round Robin - Predictions

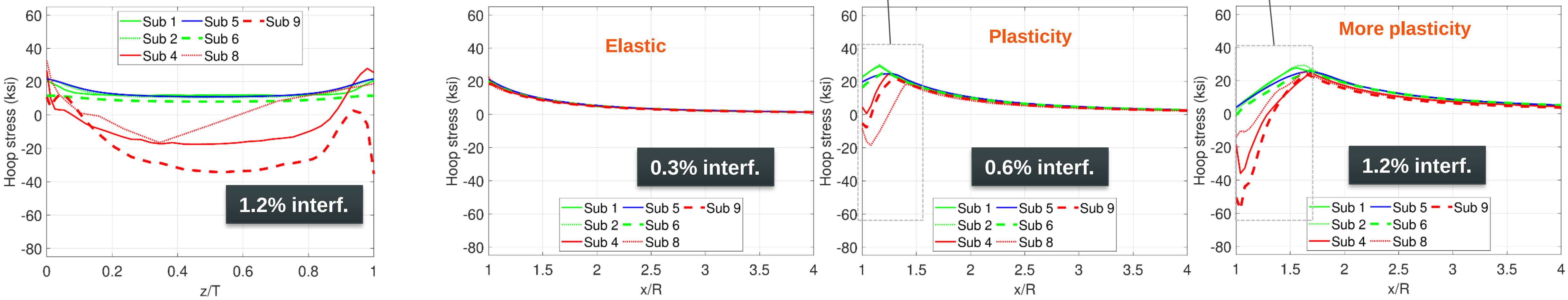
- Group 2 – fastener install (no remote loading)

Key Takeaways:

- **Distinct differences based on modeling approaches**
  - Radial expansion and springs give similar results
  - Simulated fastener install results in distinct differences
- **Through thickness behavior differences even more distinct**



Through Thickness at 0.02" from Bore Surface



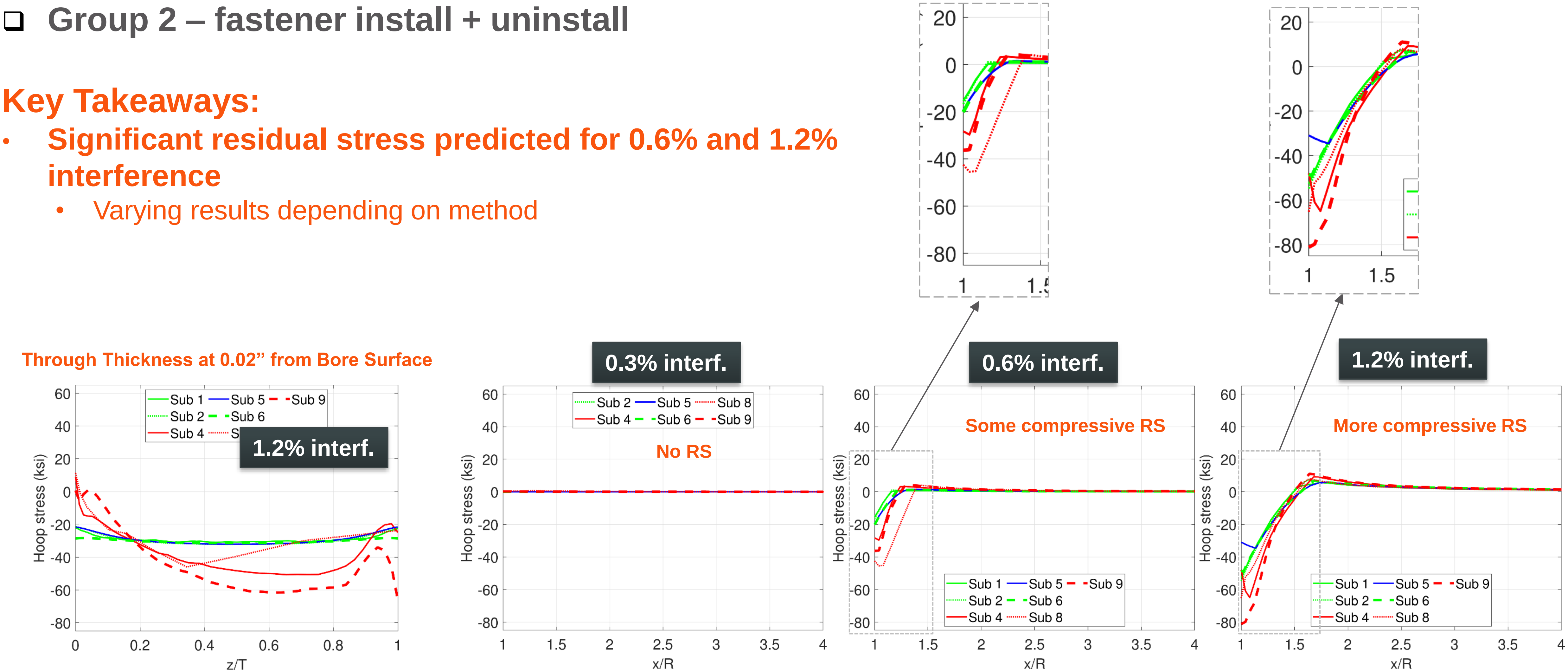
Note: this work has been submitted to the Materials Performance and Characterization journal and approved for publication.

IFF Round Robin - Predictions

- Group 2 – fastener install + uninstall

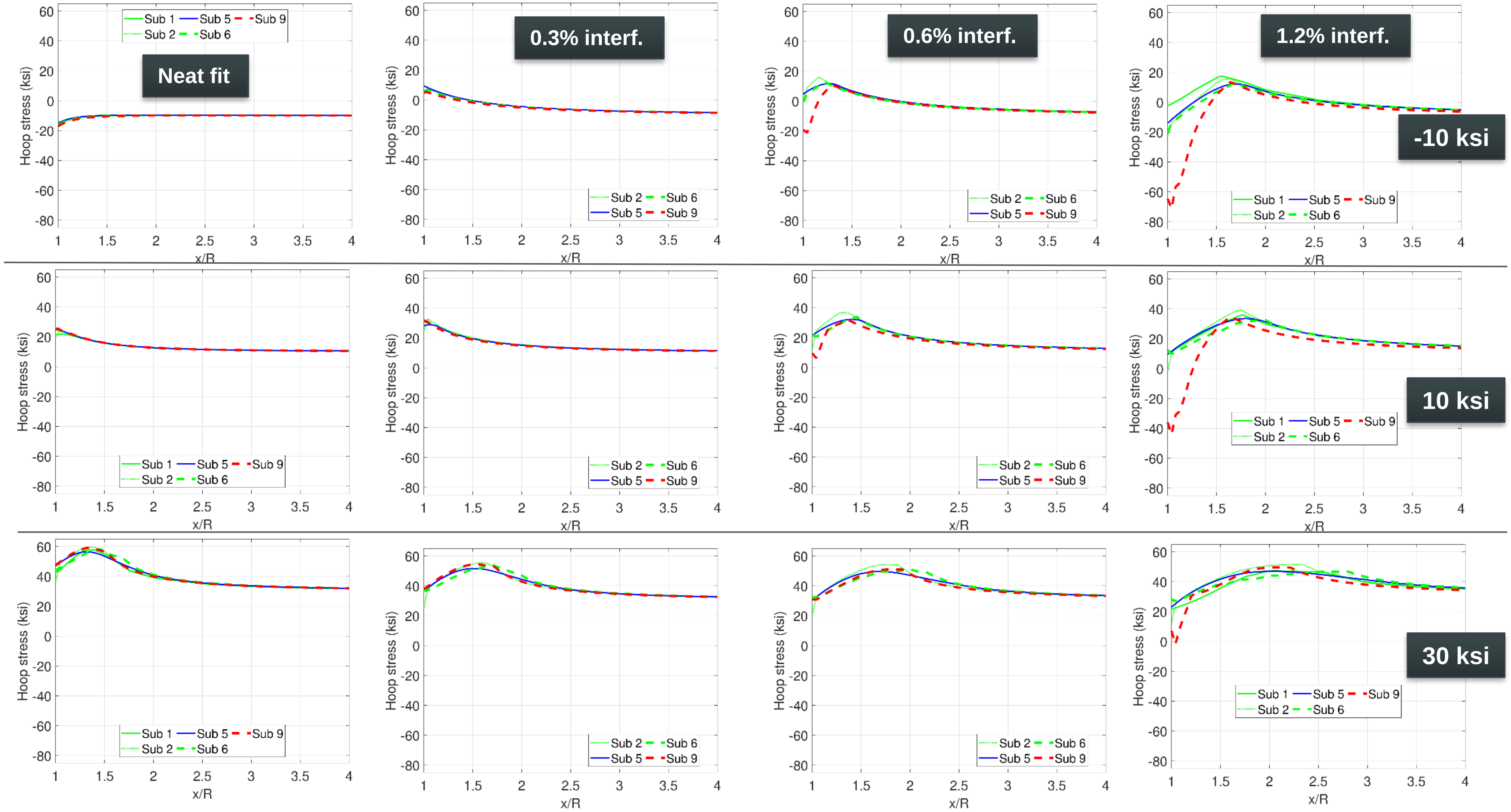
Key Takeaways:

- **Significant residual stress predicted for 0.6% and 1.2% interference**
  - Varying results depending on method



IFF Round Robin - Predictions

- Group 3 – install + load



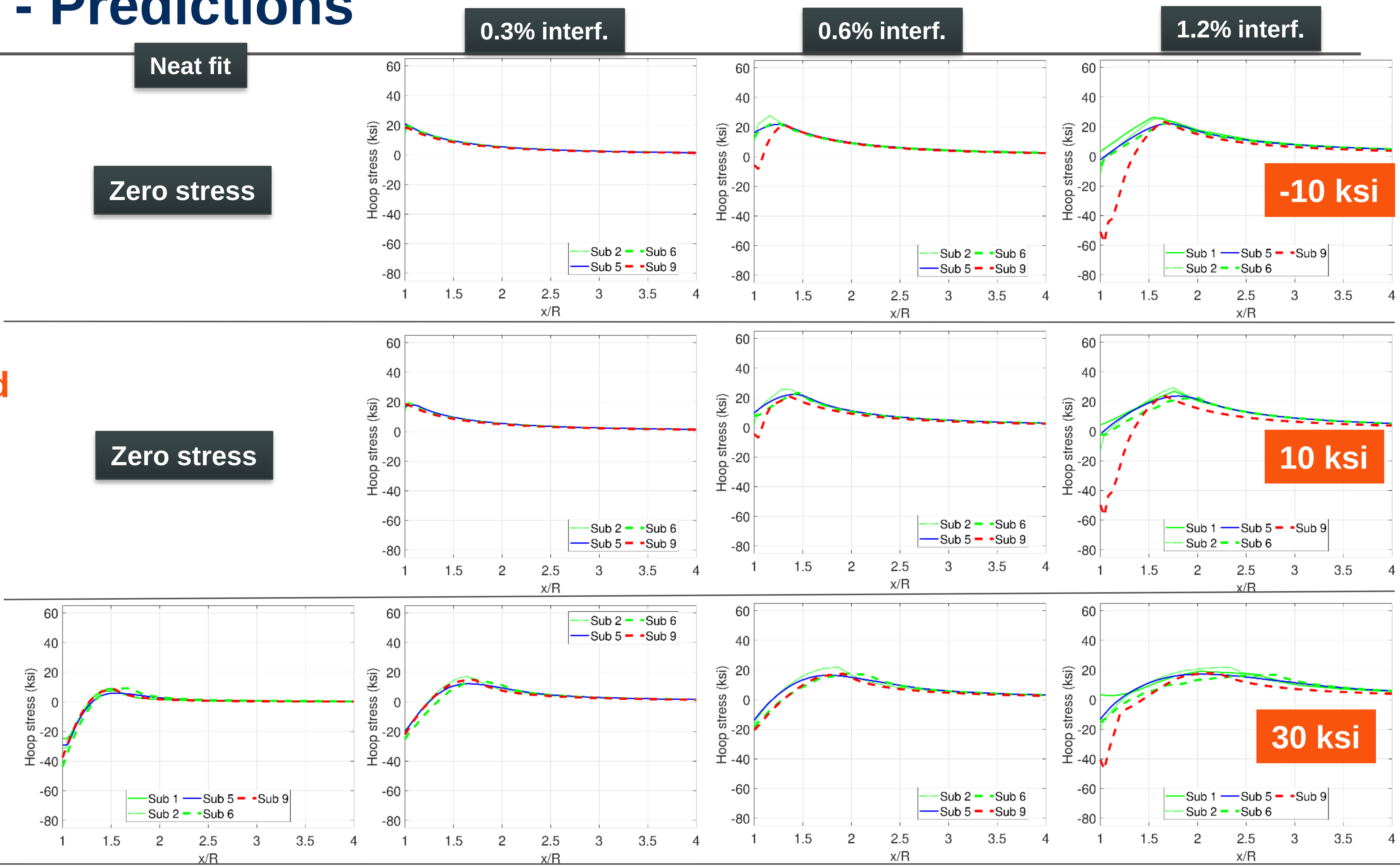
Key Takeaways:

- Higher applied loads tend to collapse predictions
- Consistent differences for model with simulated fastener install

Note: this work has been submitted to the Materials Performance and Characterization journal and approved for publication.

IFF Round Robin - Predictions

- Group 3 – install, load, and unload



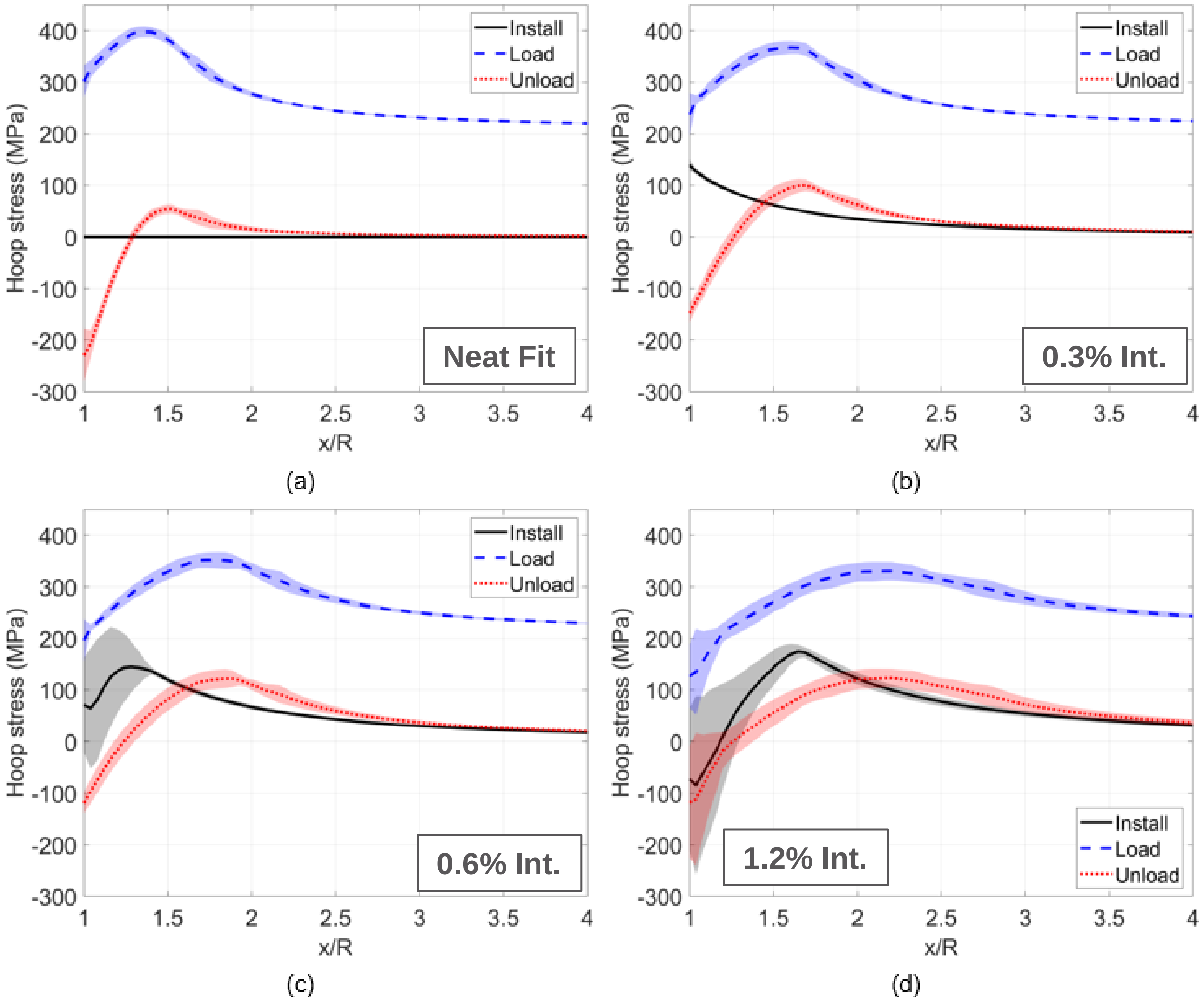
Key Takeaways:

- **Compressive stress near bore, even though fastener is still installed**
  - Stress state is a combination of:
    - Applied stress from interference
    - Residual stress

Note: this work has been submitted to the Materials Performance and Characterization journal and approved for publication.

IFF Round Robin - Predictions

- **Summary of predictions**
  - 30 ksi remote load
  - Combining all predictions with +/- one standard deviation error bars
  - Consistent results for neat fit and 0.3% interference
  - Large variability for 0.6% interference mitigated once load and unload steps are completed
  - Large variability is reduced for 1.2% interference, however, still persists in the load and unload steps



ERSI

Note: this work has been submitted to the Materials Performance and Characterization journal and approved for publication.

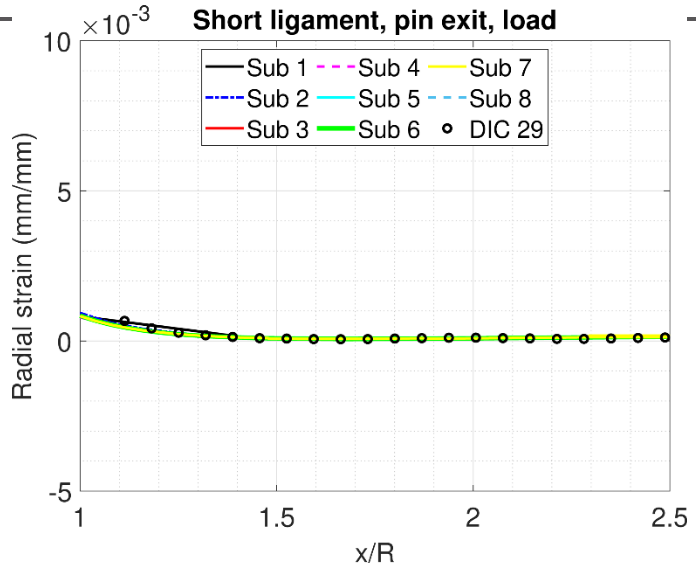
Open Hole: Test Results

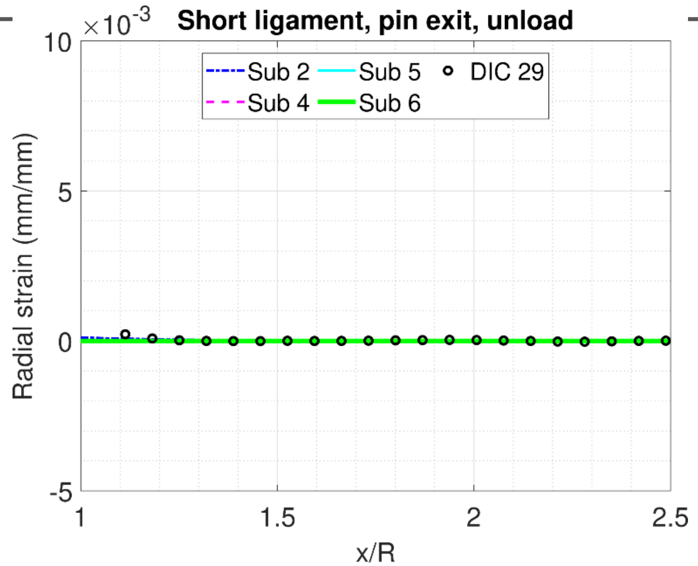
FE round robin (pointwise)

DIC strains (averaged)

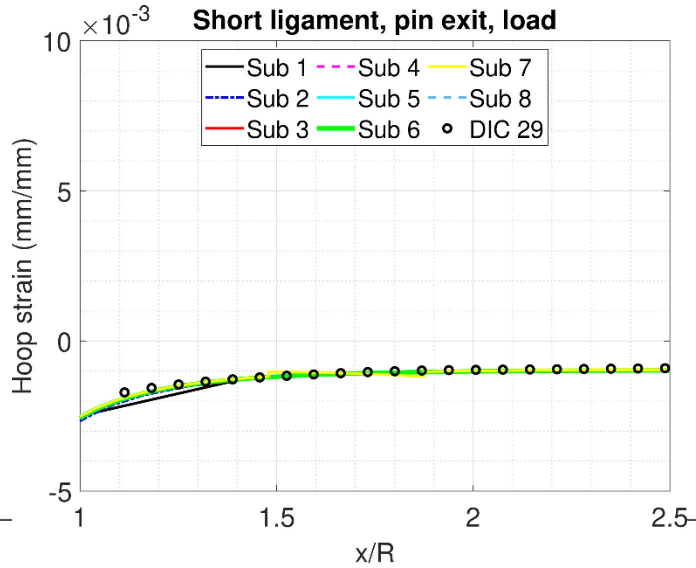
Models vs DIC – Open hole, -10 ksi remote stress

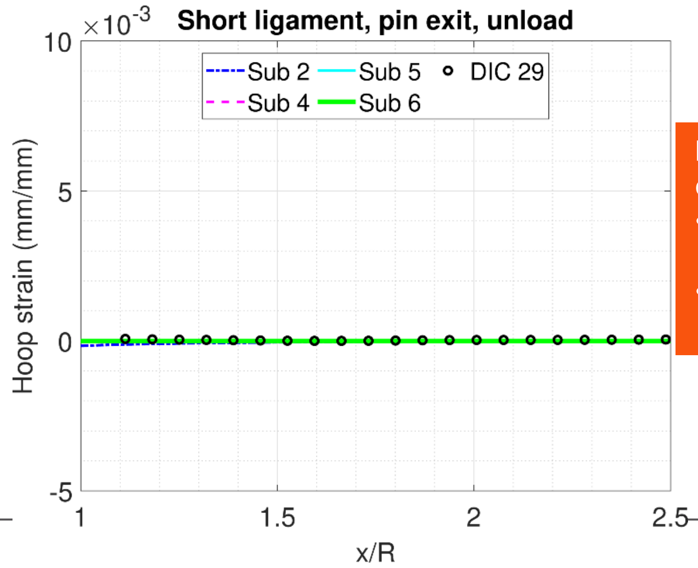
Radial strain





Hoop strain





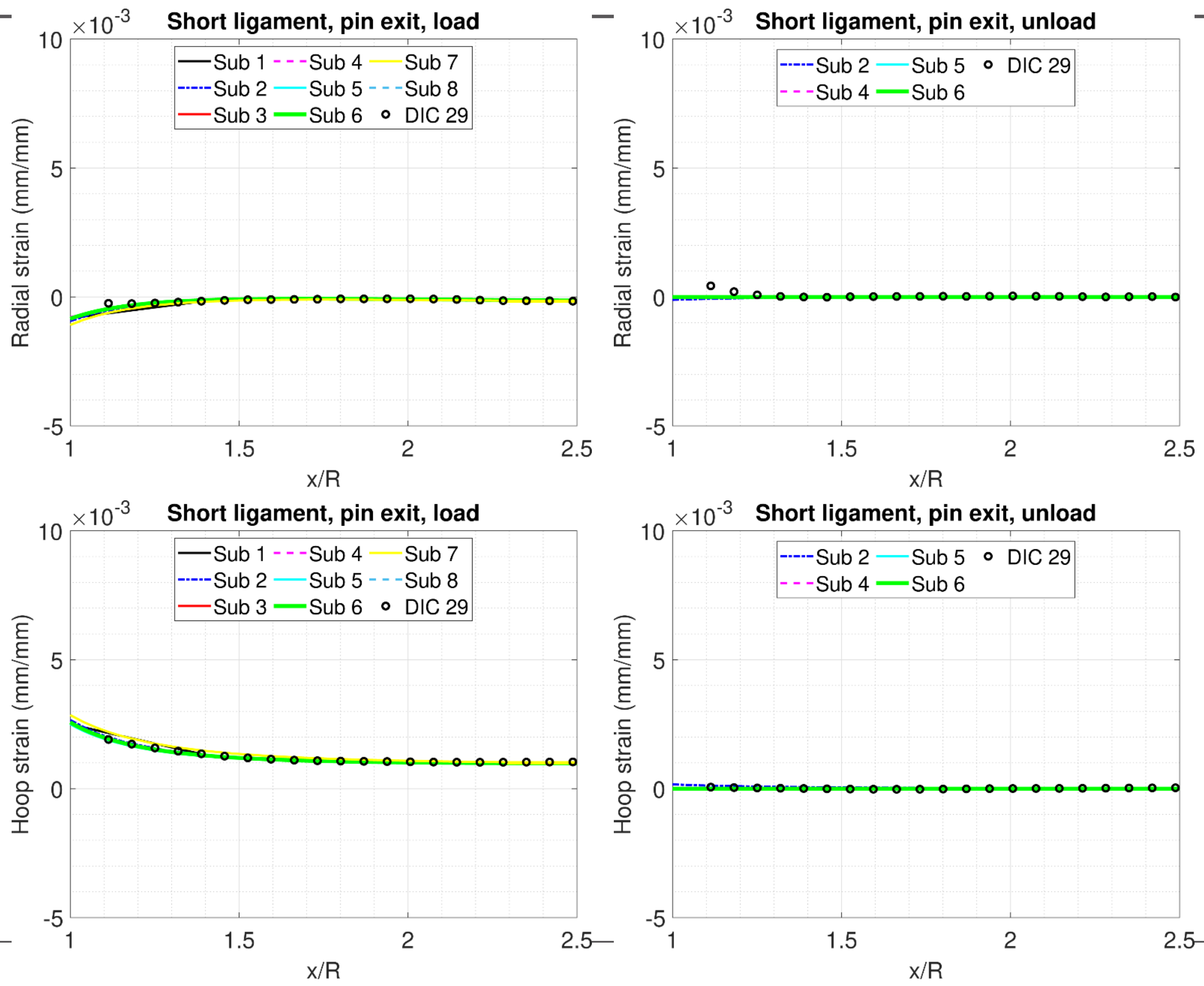
Notes (applies to all results from here on):

- **Results beyond x/R = 2.5 not shown to focus plot near hole only**
- **DIC points were subsampled to plot for easier visualization**

Models vs DIC – Open hole, 10 ksi remote stress

Radial strain

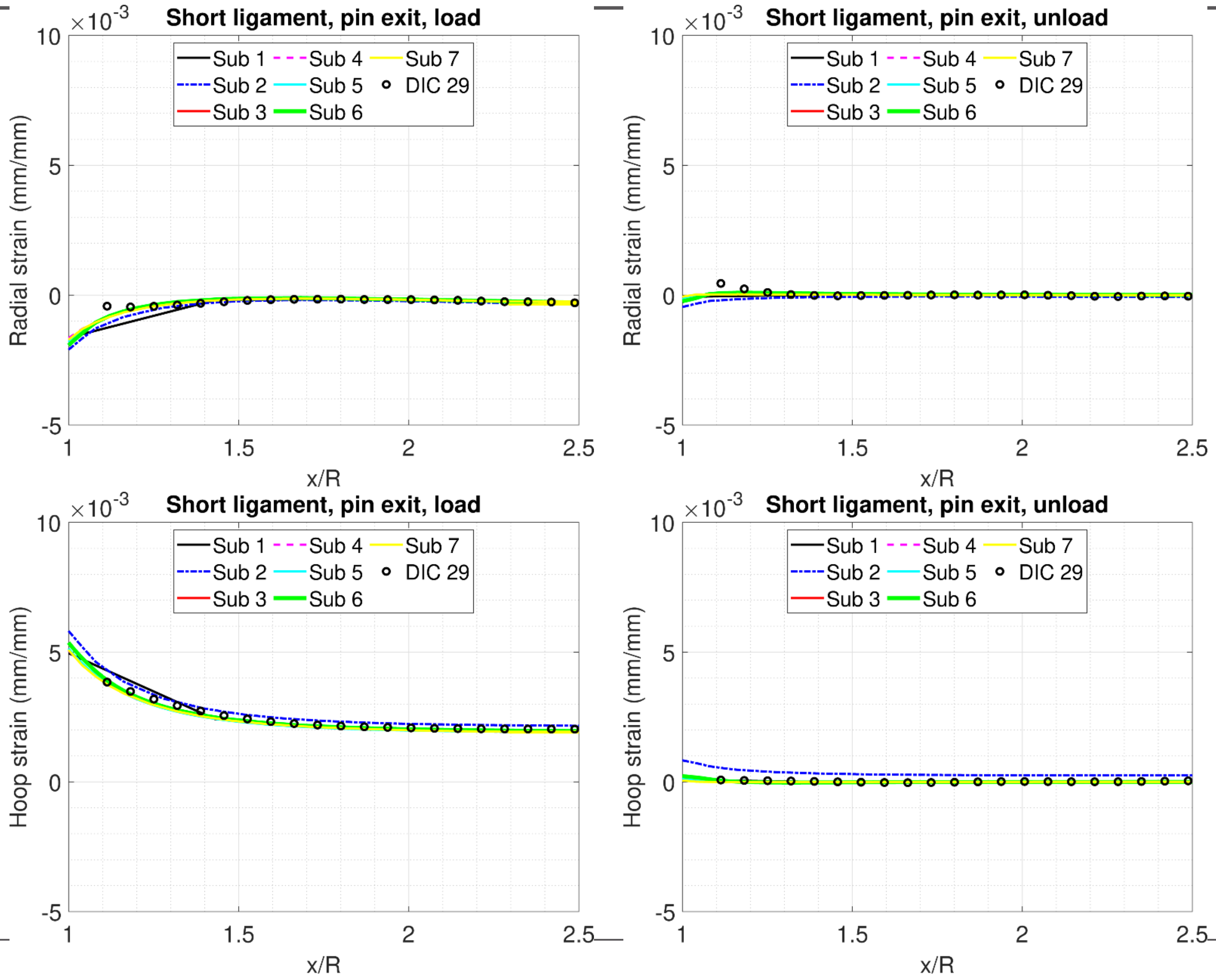
Hoop strain



Models vs DIC – Open hole, 20 ksi remote stress

Radial strain

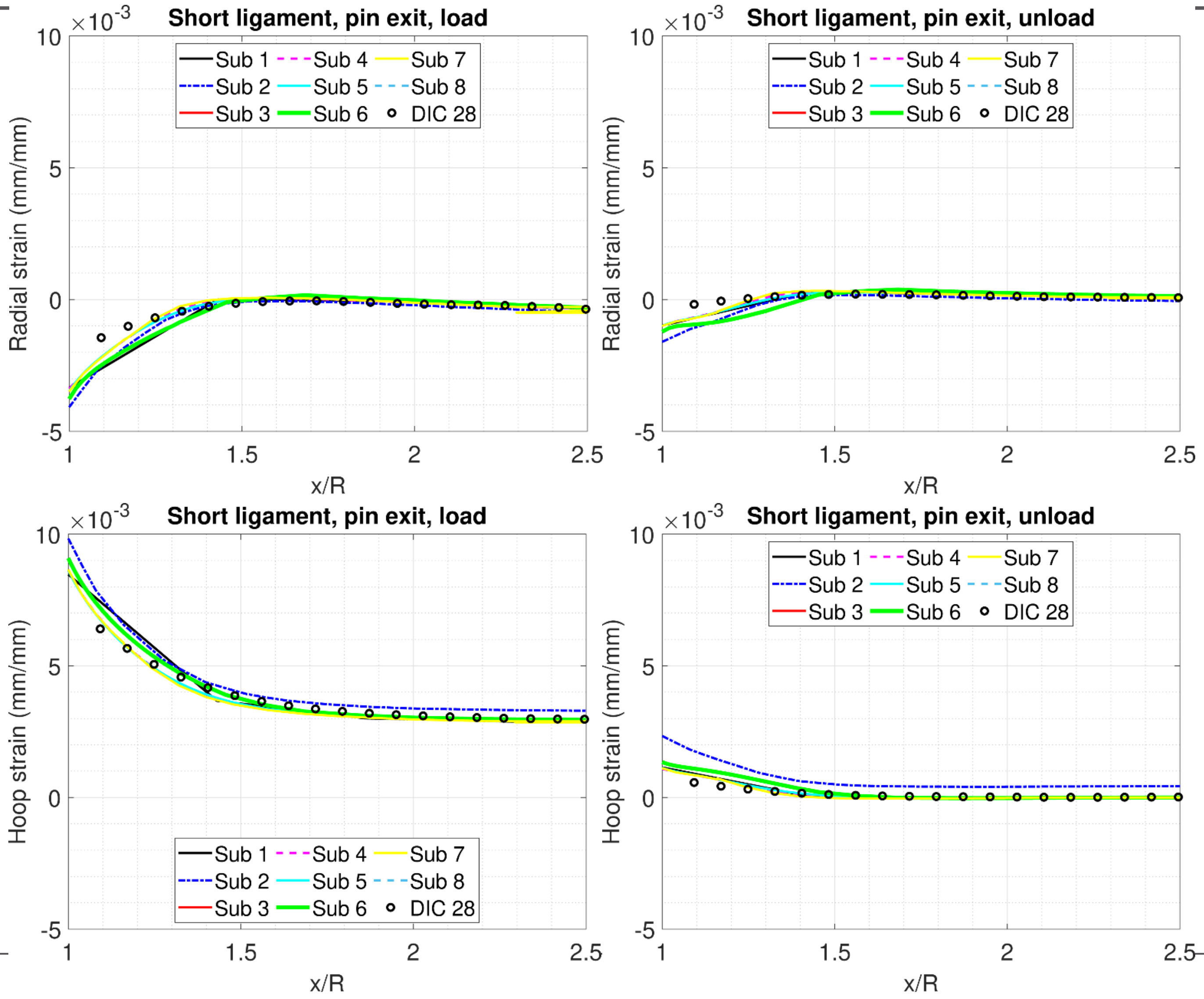
Hoop strain



Models vs DIC – Open hole, 30 ksi remote stress

Radial strain

Hoop strain



Key Takeaways:

- **Overall, models are slightly over-predicting strain relative to test results**

Neat Fit + Remote Load: Test Results

FE round robin (pointwise)

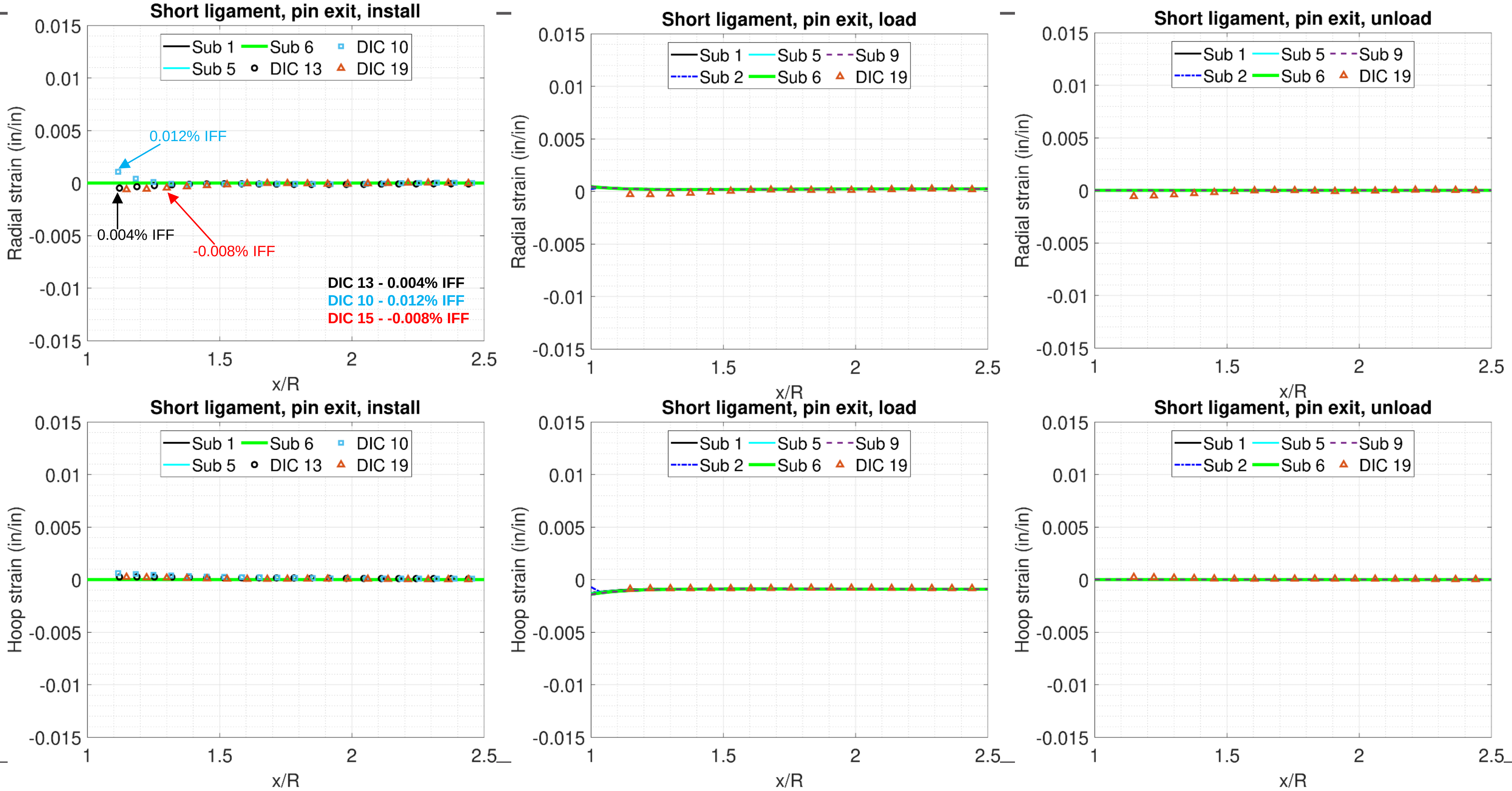
DIC strains (averaged)

Models vs DIC – neat fit, -10 ksi remote stress

DIC coupons
% IFF is based on pin and hole diameter measurements

Radial strain

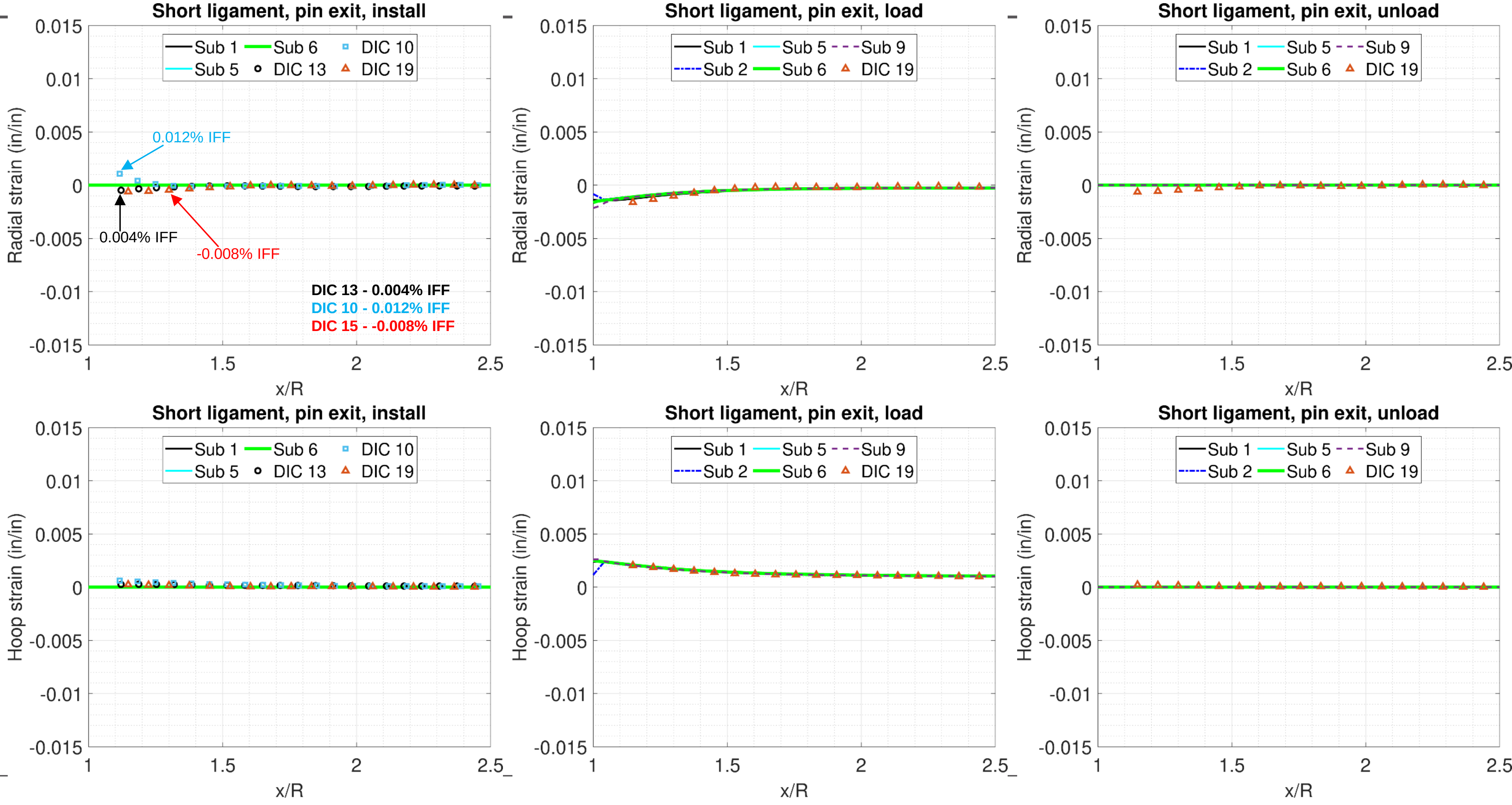
Hoop strain



Models vs DIC – neat fit, 10 ksi remote stress

Radial strain

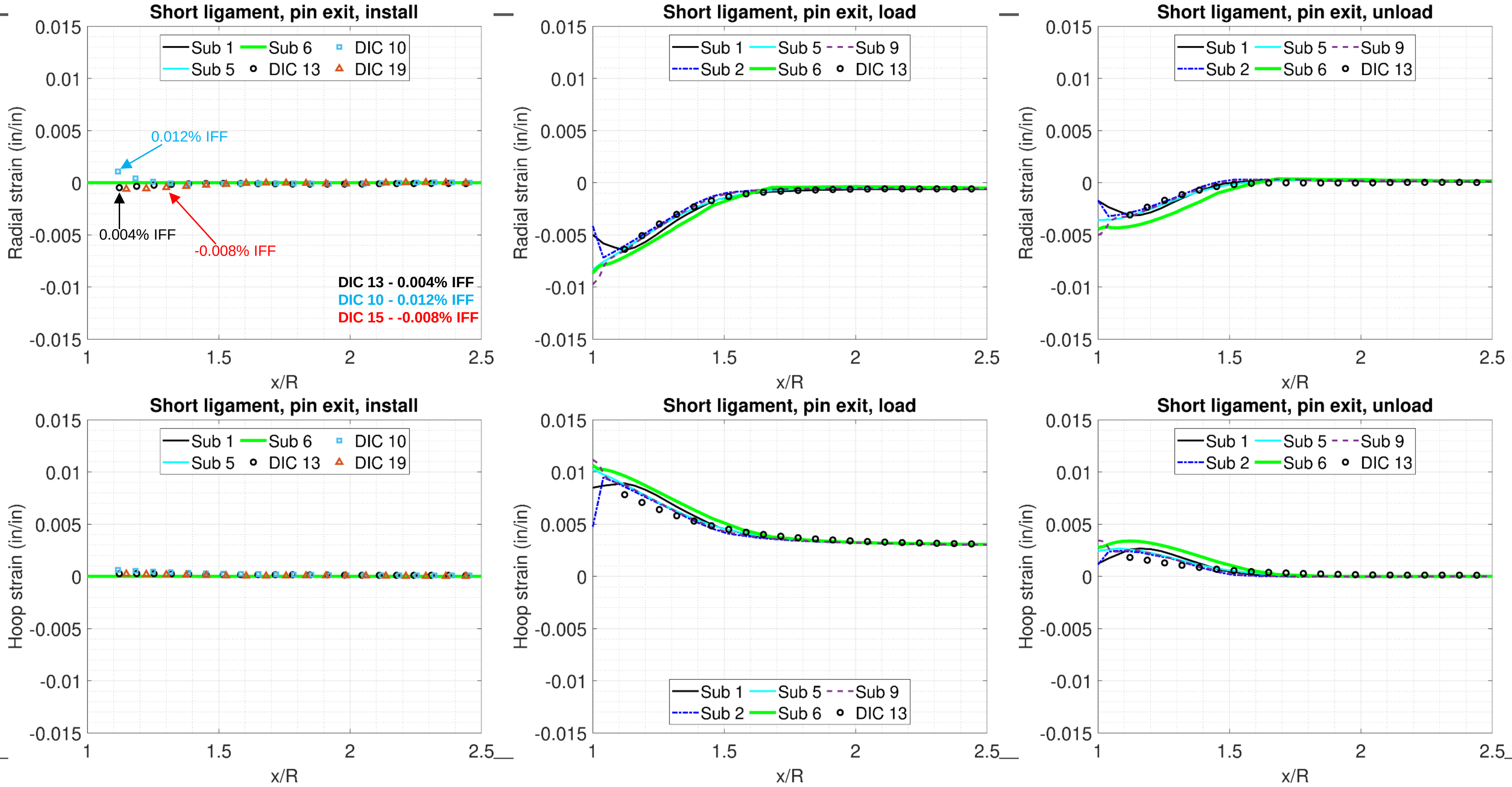
Hoop strain



Models vs DIC – neat fit, 30 ksi remote stress

Radial strain

Hoop strain



0.3% IFF + Remote Load: Test Results

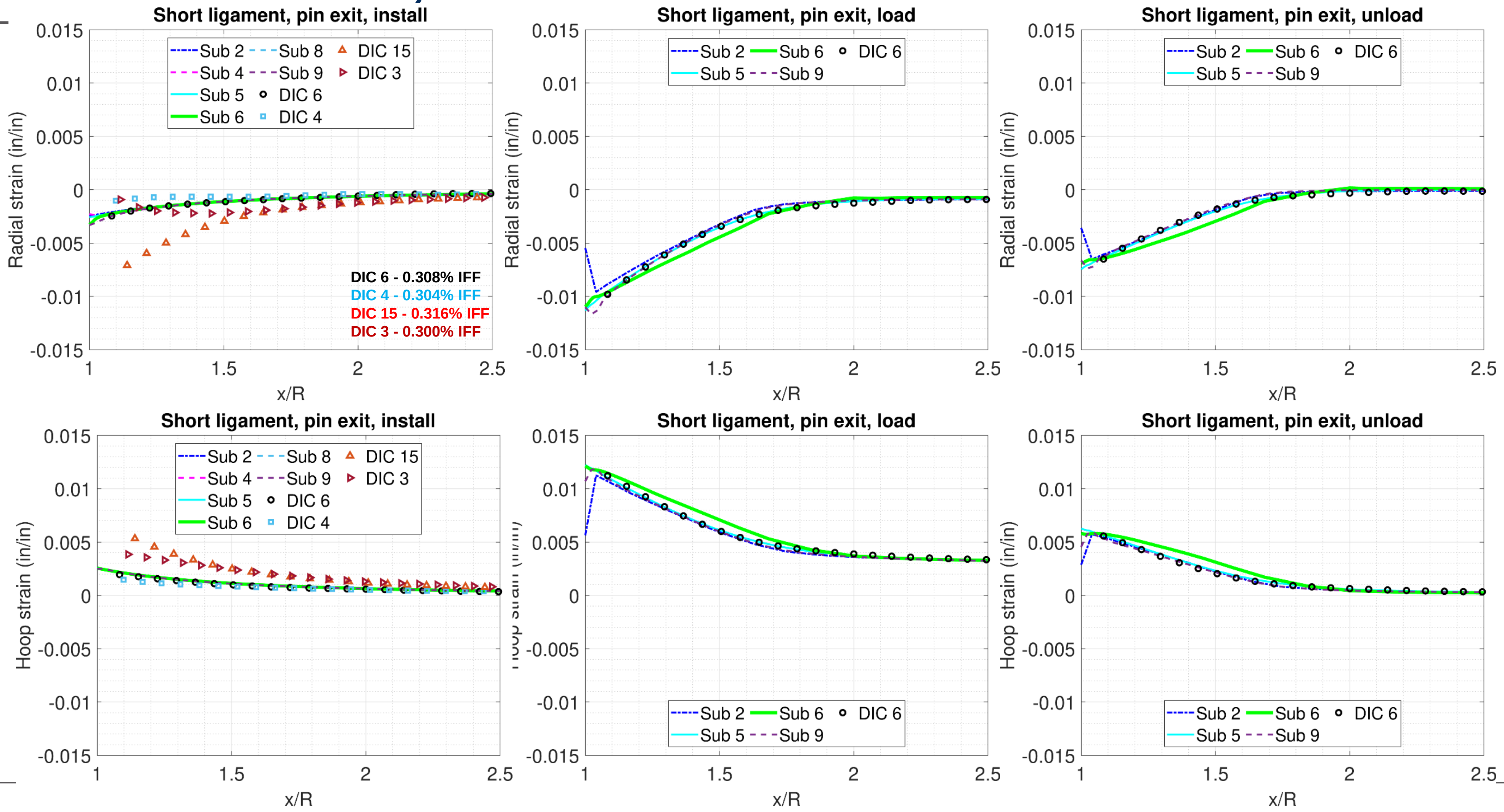
FE round robin (pointwise)

DIC strains (averaged)

Models vs DIC – 0.3% IFF, 30 ksi remote stress

Radial strain

Hoop strain



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0.6% IFF + Remote Load: Test Results

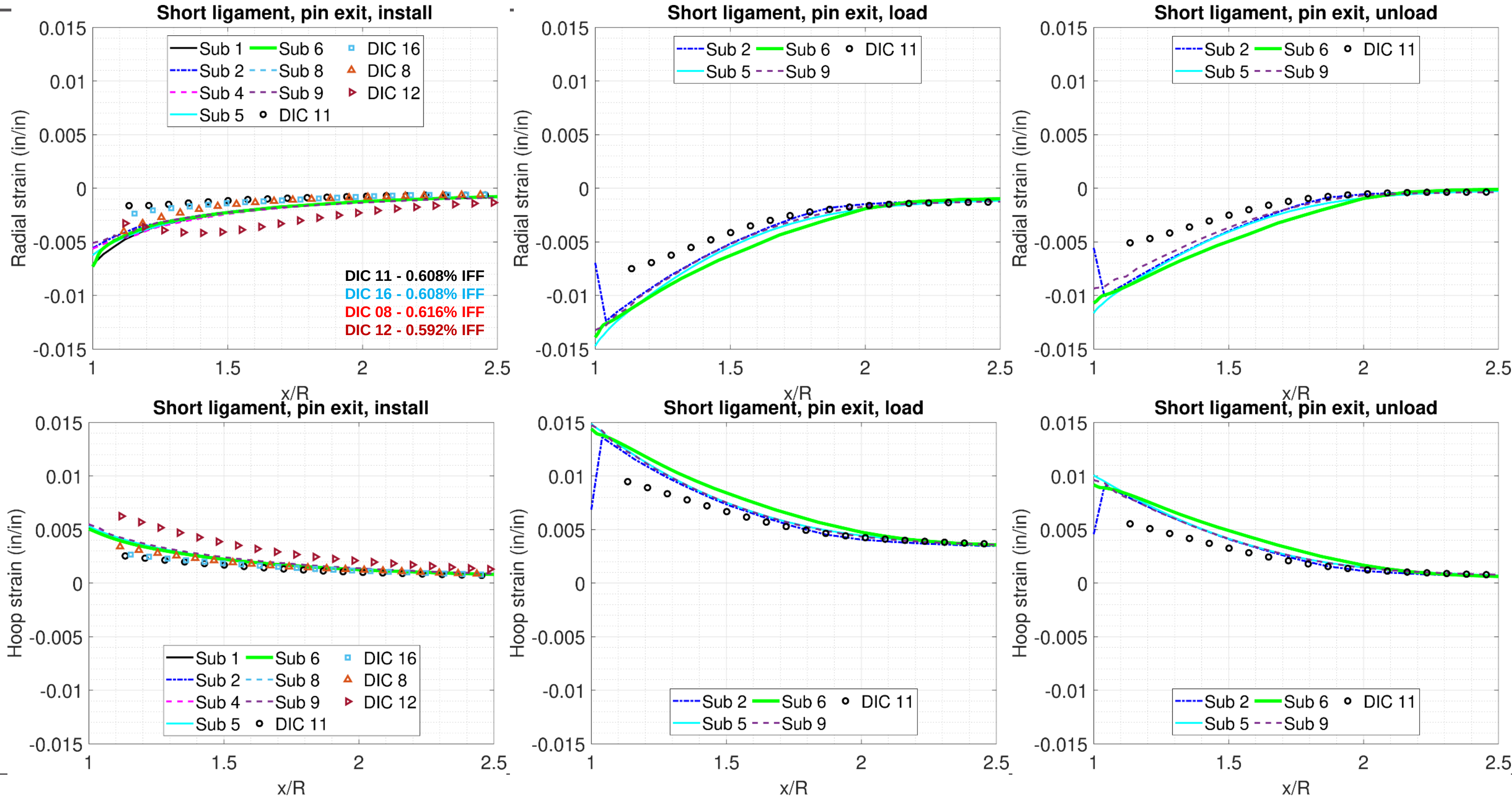
FE round robin (pointwise)

DIC strains (averaged)

Models vs DIC – 0.6% IFF, 30 ksi remote stress

Radial strain

Hoop strain



1.2% IFF + Remote Load: Test Results

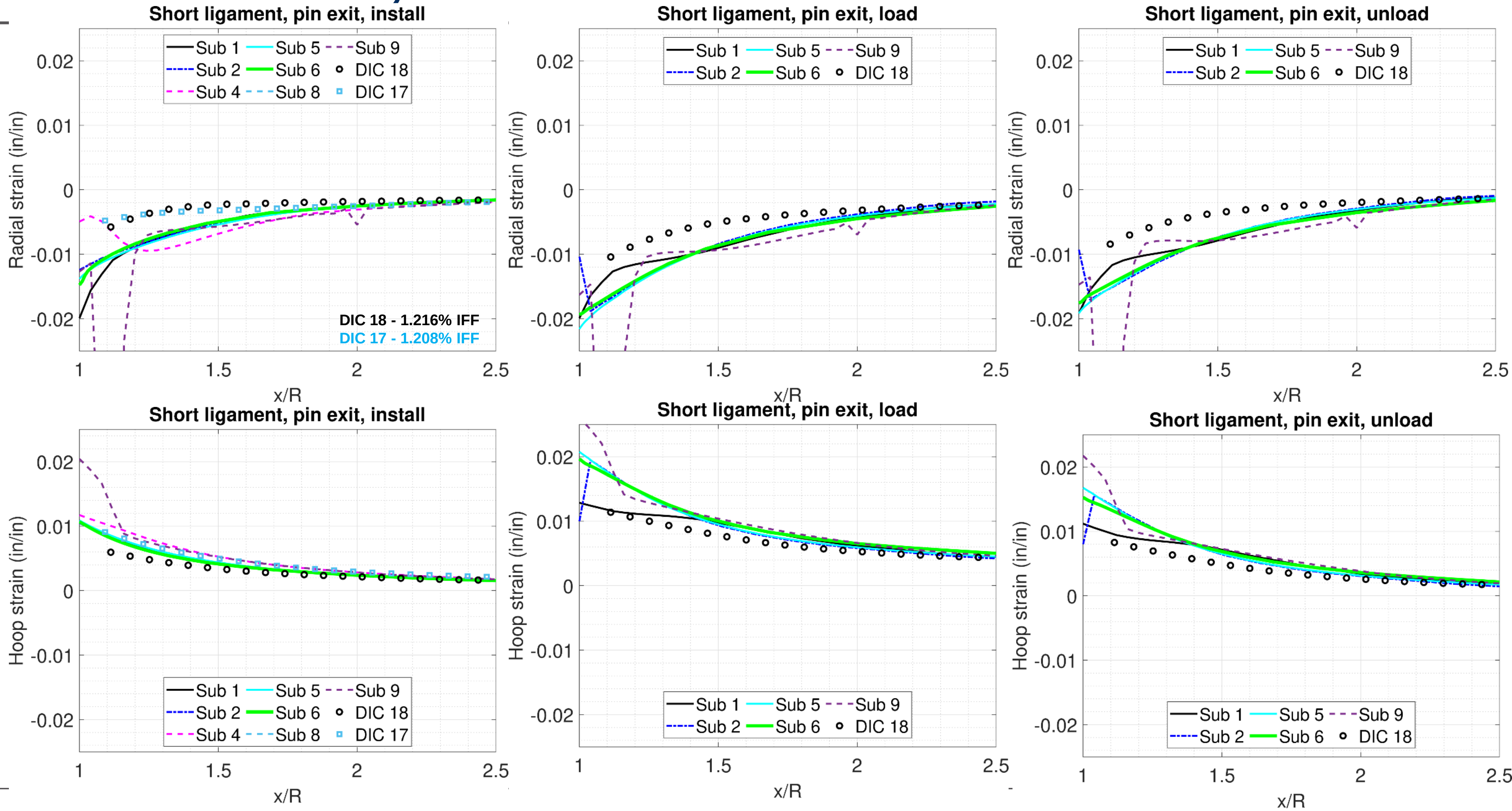
FE round robin (pointwise)

DIC strains (averaged)

Models vs DIC – 1.2% IFF, 30 ksi remote stress

Radial strain

Hoop strain



Next Steps

- **Continue comparisons between predictions vs test results**
- **Resolve any discrepancies, where possible**
- **Refine analysis approaches, as required**
- **Utilize modeling approaches to:**
  - Complete SIF comparisons
  - Complete FCG predictions
- **Complete A-10 Phase 4 testing (FCG with IFF)**
- **Compare/contrast FCG predictions vs test results**

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Conclusions/Summary

- **Robust IFF dataset being generated by A-10 team**
  - Initial Phase 1 and 2 testing complete
    - Data processing in work
  - FCR testing about to begin
- **Complimentary ERSI round robin effort intended to evaluate performance of differing analysis methods**
  - Initial blind predictions complete
  - Highlights differences in modeling approaches
- **Once complete, a detailed comparison between predictions and test data will be shared with the community**
  - Identify lessons learned and best practices

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ERSI

Thanks for your attention

Any questions?

References

1. Sun, Y., Hu, W., Shen, F., Meng, Q., Xu, Y. “Numerical simulations of the fatigue damage evolution at a fastener hole treated by cold expansion or with interference fit pin." International Journal of Mechanical Sciences 107 (2016): 188-200.
2. Chakherlou, T. N., M. Mirzajanzadeh, B. Abazadeh, and Kh Saeedi. "An investigation about interference fit effect on improving fatigue life of a holed single plate in joints." European Journal of Mechanics-A/Solids 29, no. 4 (2010): 675-682.
3. Ribeiro, R. Bombardier, Y., Loghin, A., Hood, C., Hawks, J., Prost-Domasky, S., Asaee, Z., Wieland, D., Pilarczyk, R., Warner, J. “Interference fit fasteners: a finite element process modeling round robin.”, Materials Performance and Characterization, Submitted October 2024.

Backup Slides

A-10 IFF Testing & Analysis Program

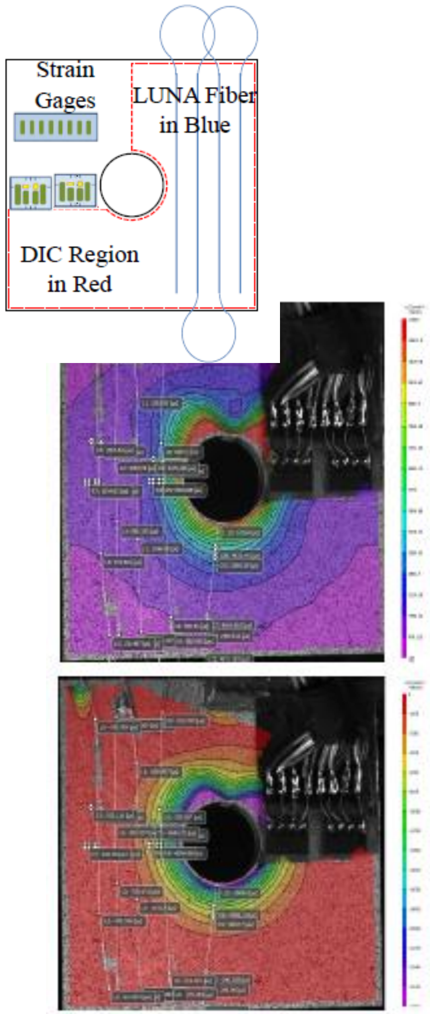
- **Phased approach with increasing complexity**
  - Phase 1: assessment of as-installed state
    - Simulate and empirically quantify the strain and stress state near a hole in the presence of an interference fit fastener
      - 3 levels of interference
      - 3D nonlinear FE process modeling; DIC 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

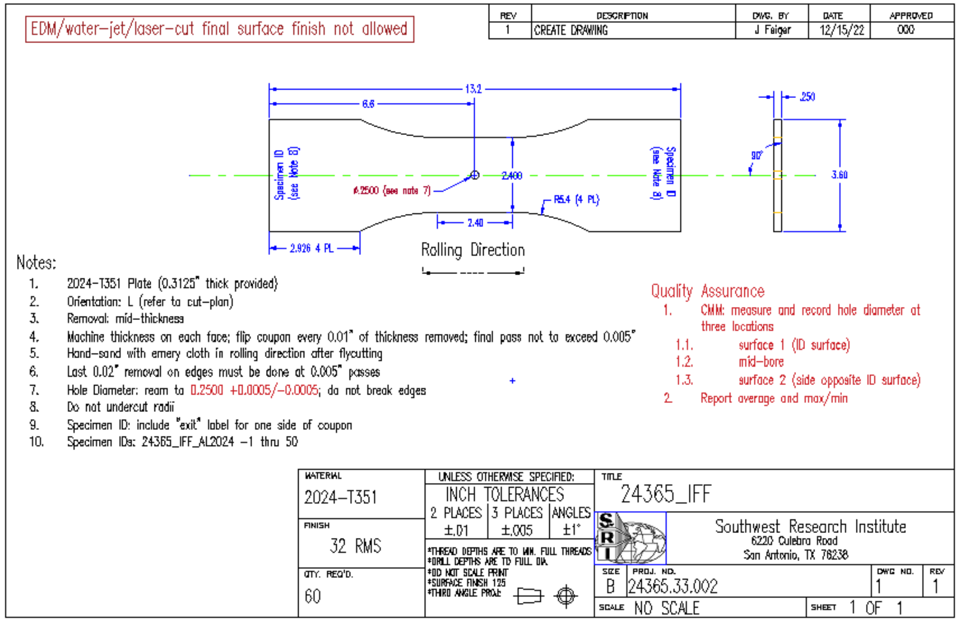
❑ Verification Tests

- ➢ 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



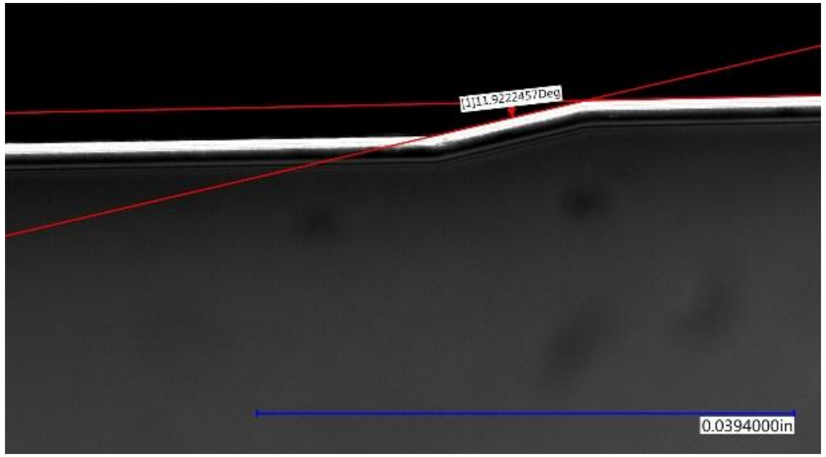
A-10 IFF Testing & Analysis Program

- **Coupon design**
  - “Dog-bone” with geometric center located 0.25” diameter hole
  - Same geometry used in prior ERS studies
  - Extracted in the L direction at mid-thickness
- **Material**
  - 2024-T351 plate (0.3125” thick)
  - Material Testing
    - Tensile (5 coupons)
      - ASTM E8
    - FCGR (multiple R values)
      - ASTM E647
      - M(T) geometry



A-10 IFF Testing & Analysis Program

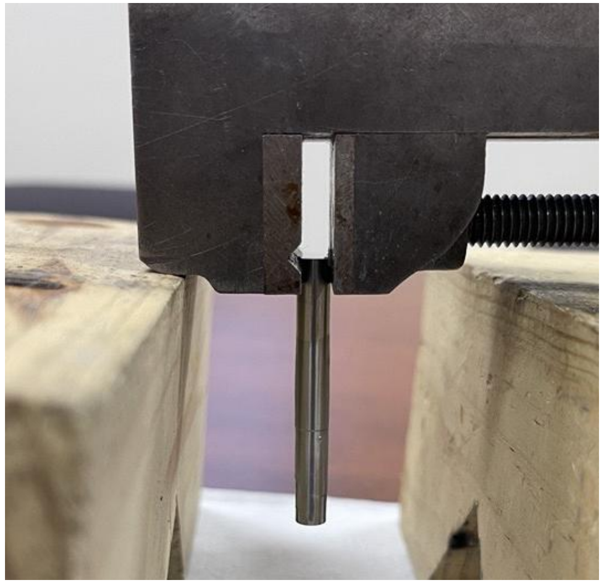
- **Coupon manufacturing**
  - 50 coupons have been fabricated
  - Holes measured via CMM
  - Gage pins were custom ordered to match the interference fit required per specimen
    - 0.3%, 0.6%, and 1.2% interference
  - Gage pins were machined to match the chamfer of a Hi-Lok
    - One pin from each interference level was measured using an optical comparator to ensure the appropriate chamfer angle was achieved during machining. A sample measurement is provided below.



A-10 IFF Testing & Analysis Program

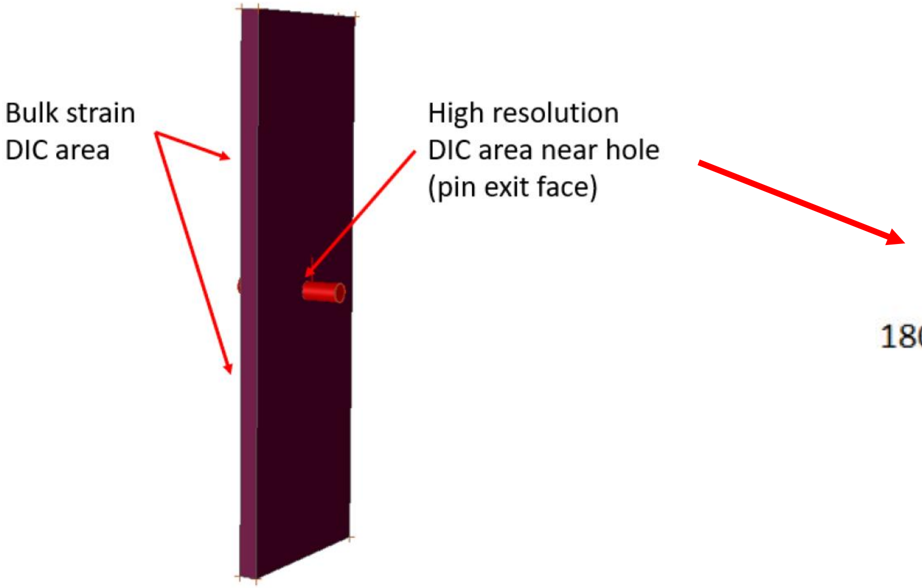
❑ Fastener Preparation

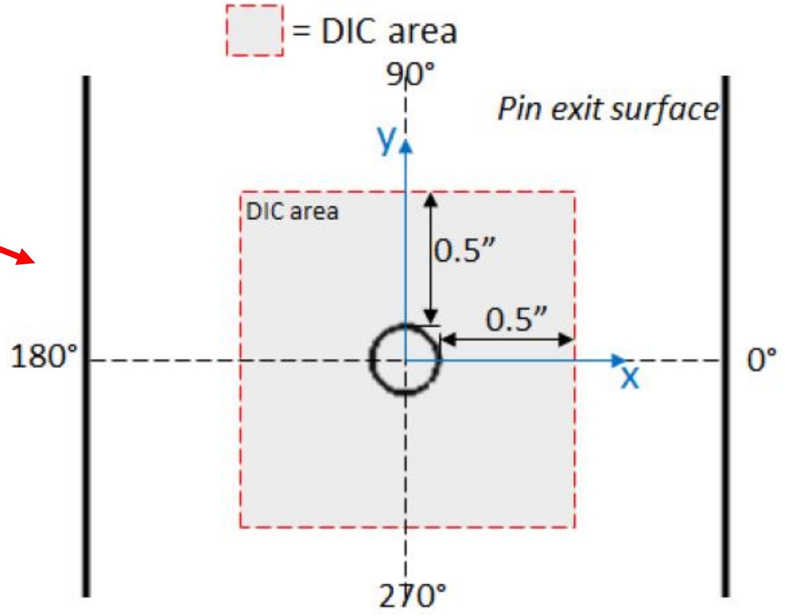
- To mimic the Hi-Lok installation, cetyl alcohol lubricant, Perma-Slik 1460W, will be used to coat the pins prior to installation.
  - Per the lubricant’s instructions, the pins will be degreased with trichlorethylene. Then, the pins will be dipped in the lubricant and dried in a slow moving, heated air oven.
  - A coated pin is shown on the left and the degreasing process on the right.



A-10 IFF Testing & Analysis Program

- **DIC setup**
  - Collect digital image correlation (DIC) data globally on the pin entrance side and locally on the pin exit side
    - Global Side: 6” x 2.5” FOV
    - Local Side: 1” X 1” FOV

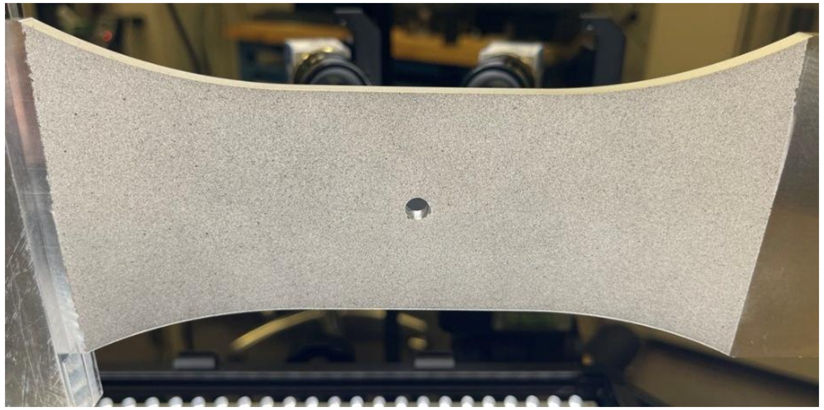




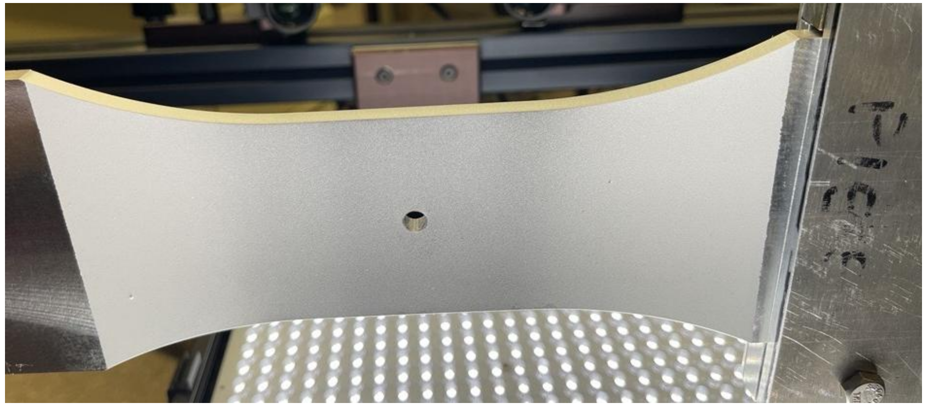
A-10 IFF Testing & Analysis Program

- Coupon prep for DIC

Global Side: speckled with black spray paint/stamp



Local Side: airbrushed with a fine, black ink mist



A-10 IFF Testing & Analysis Program

- **DIC Setup**
  - Correlated Solutions software and hardware
  - 3D setup
  - Global side: 5 MP cameras with 25mm lens
  - Local side: 8 MP cameras with 17 mm lens

A-10 IFF Testing & Analysis Program

- **Pin installation setup**
  - Servo-mechanic test frame at constant rate of displacement
  - Gage section supported
  - Relief hole at 3x diameter the fastener hole
  - Record load and displacement during installation
  - Preserve speckle pattern with Teflon and silicone layer

A-10 IFF Testing & Analysis Program

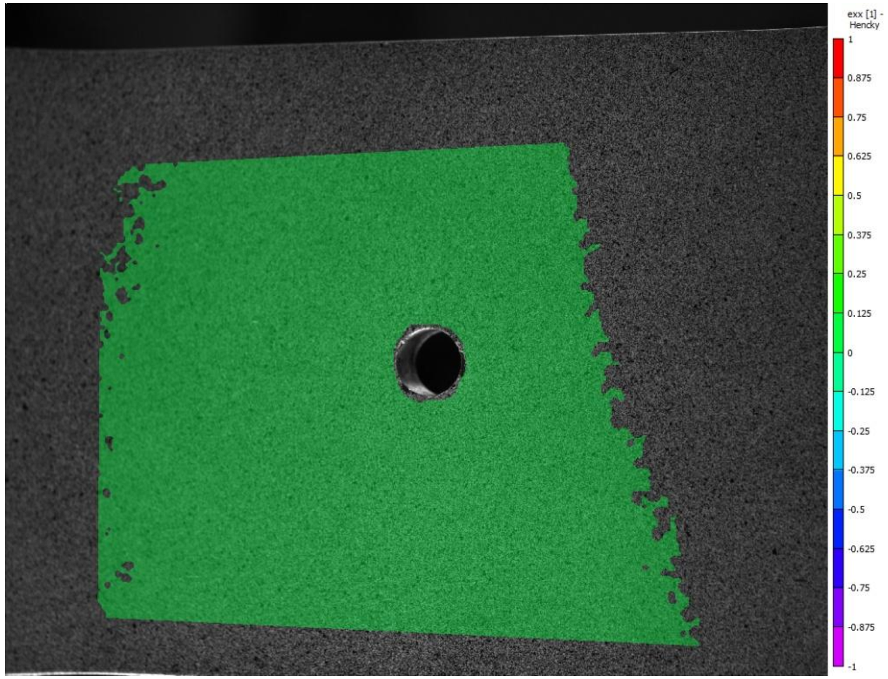
- DIC prior to pin installation

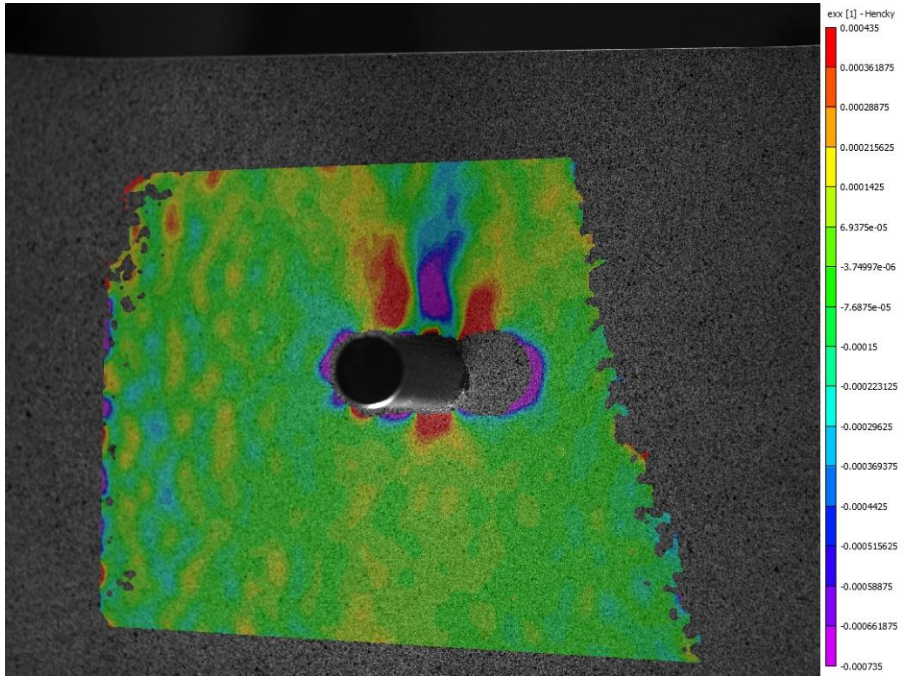
A-10 IFF Testing & Analysis Program

- DIC after to pin installation

A-10 IFF Testing & Analysis Program

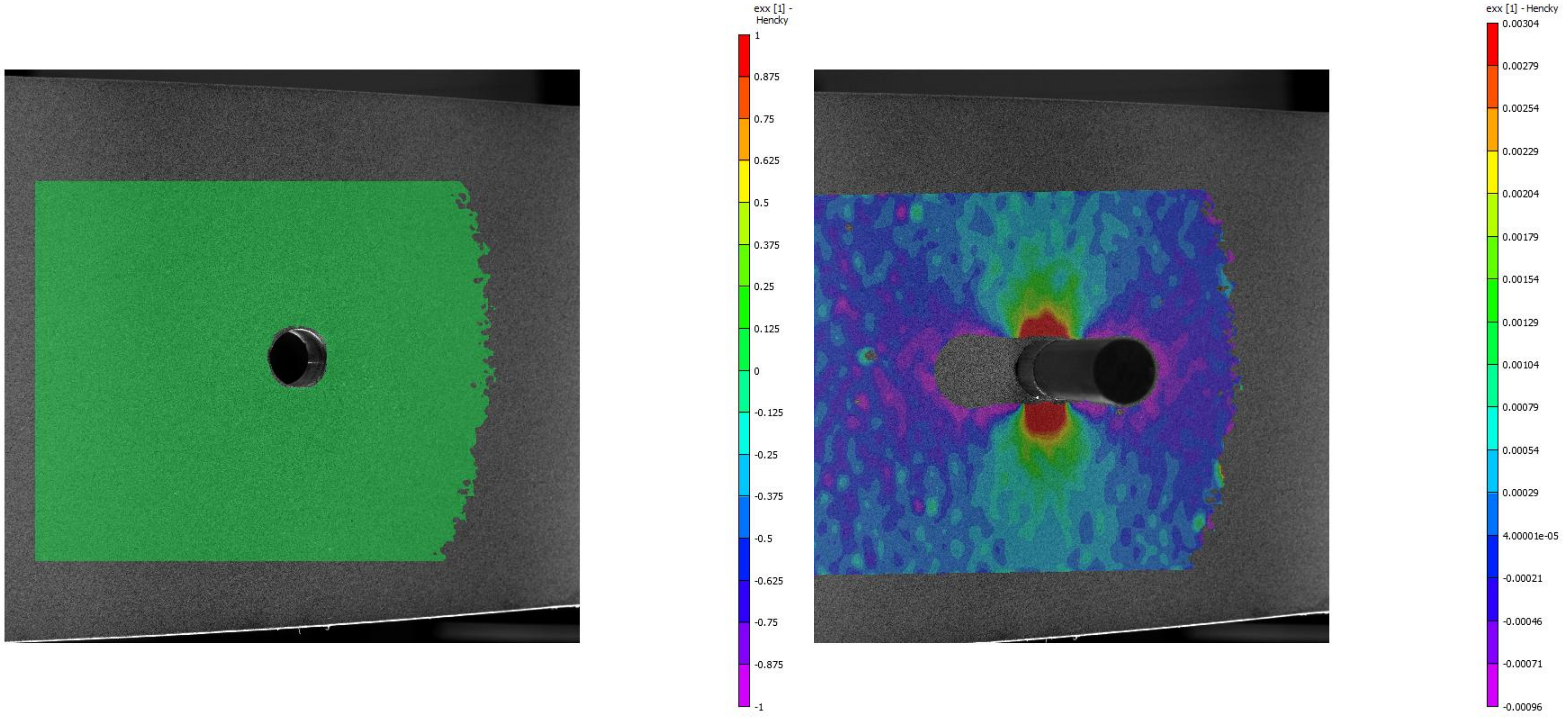
- Global results





A-10 IFF Testing & Analysis Program

- Local results



A-10 Cx Dataset: ERSI Blind Predictions

Robert Pilarczyk
Group Lead – Structural Integrity
Hill Engineering, LLC
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Phone: 801-391-2682

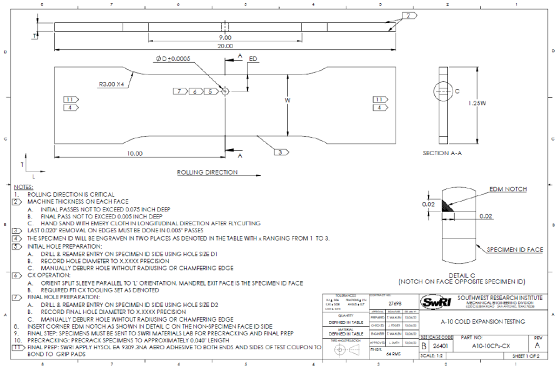
New A-10 Cx Testing

- Purpose
  - The A-10 program is transitioning toward using residual stresses from cold expansion directly in damage tolerance analyses. A test program was developed to target and isolate the load history and residual stress effects for Cx holes. Fatigue tests include baseline non-Cx and Cx holes, constant amplitude and spectrum loading, and are complimented with residual stress measurements for each condition
- Test Data
  - Testing and fractography completed by SwRI and APES

New A-10 Cx Testing, Constant Amplitude Tests

- **Input Data**
  - Geometry
    - Various (see table)
  - Material
    - Various (see table)
  - Starting flaw
    - Notched, pre-cracked, and final reamed
  - Cx conditions
    - Baseline non-Cx and Cx holes
  - Loading
    - Constant amplitude w/ markerbands
    - Max stresses = 23 and 25 ksi
    - Stress ratio = 0.1, 0.15

Material
7075-T76511 extrusion
2024-T351 plate
2024-T3511 extrusion
7075-T651 plate

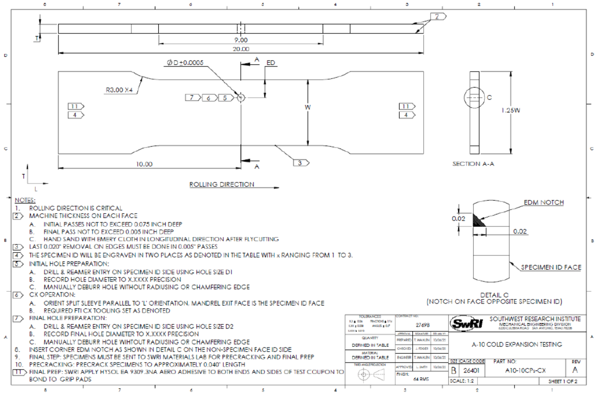


Location	Thickness, in.	Hole Diameter, in.	Hole Offset, in.	Test Type	Replicates
	0.125	0.249	0.500	Baseline	3
				Cx	3
	0.410	0.501	1.690	Baseline	3
				Cx	3
	0.394	0.501	1.040	Baseline	3
				Cx	3
FALSTAFF	0.250	0.250	2.000	Baseline	3
				Cx	3

New A-10 Cx Testing, Variable Amplitude Tests

- Input Data
  - Geometry
    - Various (see table)
  - Material
    - Various (see table)
  - Starting flaw
    - Notched, pre-cracked, and final reamed
  - Cx conditions
    - Baseline non-Cx and Cx holes
  - Loading
    - Variable amplitude

Material	Location	Thickness, in.	Hole Diameter, in.	Hole Offset, in.	Test Type	Test Replicates	RS Replicates
7075-T76511 extrusion		0.125	0.249	0.500	Baseline	3	2
					Cx	3	
7075-T76 sheet		0.190	0.438	1.000	Baseline	3	2
					Cx	3	
AMS 6526		0.190	0.438	0.830	Baseline	3	2
					Cx	3	
2024-T351 plate		0.200	0.197	0.500	Baseline	3	2
					Cx	3	
2024-T351 plate		0.208	0.202	0.470	Baseline	3	NA
					Cx	3	
2024-T3511 extrusion		0.260	0.187	0.680	Baseline	3	2
					Cx	3	
2024-T351 plate		0.410	0.501	1.690	Baseline	3	NA
					Cx	3	
2024-T3511 extrusion		0.394	0.501	1.040	Baseline	3	NA
					Cx	3	
7075-T351 plate		0.245	0.438	1.050	Baseline	3	2
					Cx	3	
AMS 6526		0.250	0.438	0.760	Baseline	3	2
					Cx	3	
7075-T651 plate	FALSTAFF	0.250	0.250	2.0	Baseline	3	NA
					Cx	3	
7075-T651 plate	TWIST/ miniTWIST	0.250	0.250	2.0	Baseline	3	NA
					Cx	3	



ERSI - A-10 Round Robin

- Goals
  - As a collective working group, complete blind predictions based on our best practices
  - Compare/contrast predictions vs test results
  - Utilize findings to refine analysis approach and best practices
- Approach
  - Down select dataset to define analysis conditions
  - Establish initial data and analysis approach/approaches
  - As a team, complete blind predictions

ERSI - A-10 Round Robin

- Down-Selection of Conditions

ERSI Analysis Priority	Location	Spectrum	Max Stress ksi	Stress Ratio R	Material	Thickness in.	Hole Diameter in.	Hole Offset in.	Test Type	Test Replicates
1	A-10 CP 7T	Constant Amplitude	23.00	0.10	2024-T351 plate	0.410	0.501	1.690	Baseline	3
3									Cx	3
2		Constant Amplitude	25.00	0.15	7075-T651 plate	0.250	0.250	2.000	Baseline	3
4									Cx	3
		A-10 Spectrum		N/A	7075-T76511 extrusion	0.125	0.249	0.500	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	7075-T76 sheet	0.190	0.438	1.000	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	AMS 6526	0.190	0.438	0.830	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	2024-T351 plate	0.200	0.197	0.500	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	2024-T351 plate	0.208	0.202	0.470	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	2024-T3511 extrusion	0.260	0.187	0.680	Baseline	3
									Cx	3
5		A-10 Spectrum		N/A	2024-T351 plate	0.410	0.501	1.690	Baseline	3
8									Cx	3
		A-10 Spectrum		N/A	2024-T3511 extrusion	0.394	0.501	1.040	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	7075-T351 plate	0.245	0.438	1.050	Baseline	3
									Cx	3
		A-10 Spectrum		N/A	AMS 6526	0.250	0.438	0.760	Baseline	3
									Cx	3
6		FALSTAFF		N/A	7075-T651 plate	0.250	0.250	2.000	Baseline	3
9									Cx	3
7		TWIST/miniTWIST		N/A	7075-T651 plate	0.250	0.250	2.000	Baseline	3
10									Cx	3

ERSI - A-10 Round Robin

- Conditions
  - Materials
    - 2024-T351 and 7075-T651
  - Spectrum
    - Constant and variable amplitude
    - A-10 wing spectrum, FALSTAFF, and miniTWIST
  - Residual stress
    - Baseline and Cx conditions
    - Gathering applicable RS data
  - Test replicates
    - Typically (3) each condition
  - Additional information
    - Post-test fractography for each coupon

ERSI - A-10 Round Robin

- Approach
  - Phase I: Baseline non-cx conditions, CA loading (in work)
    - Complete predictions & compare/contrast relative to test data
    - Update any analysis inputs, as required
  - Phase II: Cx conditions, CA loading
    - Complete predictions & compare/contrast relative to test data
    - Evaluate life and crack shape evolution
    - Revisit residual stresses and implementation approach, as necessary
  - Phase III: Baseline non-cx conditions, VA loading
    - Complete predictions & compare/contrast relative to test data
    - Review crack retardation and define approach for Cx conditions
  - Phase IIII: Cx conditions, VA loading
    - Complete predictions & compare/contrast relative to test data
  - Document comparisons and associated lessons learned / best practices for all phases

ERSI - A-10 Round Robin

Phase I

- Baseline non-cx conditions, CA loading
  - Follow similar analysis approach & inputs as Cx conditions
  - Complete predictions & compare/contrast relative to test data
  - Update any analysis inputs, as required

ERSI Analysis Priority	Location	Spectrum	Max Stress ksi	Stress Ratio R	Material	Thickness in.	Hole Diameter in.	Hole Offset in.	Test Type	Test Replicates
1	A-10 CP 7T	Constant Amplitude	23.00	0.10	2024-T351 plate	0.410	0.501	1.690	Baseline	3
3									Cx	3
2		Constant Amplitude	25.00	0.15	7075-T651 plate	0.250	0.250	2.000	Baseline	3
4									Cx	3

ERSI - A-10 Round Robin

- **Phase I Summary**
  - Analysis inputs provided to participants
  - Submissions received from 5 participants
  - Results summarized and up for review in meeting tomorrow
- **Phase II Planning**
  - Need to finalize approach for residual stress input
  - Asking for inputs from RS characterization committee

Backup Slides

ERSI - A-10 Round Robin

7075-T651 Rate Data

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

da/dN	Stress Ratios (R)					
	K_{max}	ΔK				
	-0.15	0.02	0.1	0.4	0.7	0.85
1.00E-11	1.957	2.15	2.01	1.36	1.15	0.972
1.00E-10	1.995	2.175	2.045	1.39	1.22	1.071
3.00E-10	2.015	2.193	2.065	1.408	1.255	1.119
1.00E-09	2.062	2.237	2.111	1.442	1.3	1.172
2.00E-09	2.103	2.278	2.152	1.473	1.33	1.201
1.00E-08	2.233	2.4	2.28	1.562	1.4	1.255
2.00E-08	2.336	2.492	2.38	1.634	1.44	1.269
4.00E-08	2.529	2.675	2.57	1.765	1.53	1.326
6.00E-08	2.744	2.897	2.787	1.919	1.645	1.41
1.00E-07	3.302	3.485	3.354	2.322	1.965	1.663
2.00E-07	4.052	4.275	4.115	2.89	2.4	1.993
4.00E-07	4.878	5.15	4.955	3.65	2.975	2.425
6.00E-07	5.191	5.49	5.275	3.95	3.175	2.552
1.00E-06	5.477	5.825	5.575	4.225	3.36	2.672
2.00E-06	6.064	6.55	6.2	4.75	3.765	2.984
4.00E-06	7.026	7.65	7.2	5.55	4.4	3.488
6.00E-06	7.895	8.63	8.1	6.26	4.95	3.914
1.00E-05	9.419	10.339	9.675	7.51	5.875	4.596
2.00E-05	11.885	13.11	12.225	9.53	7.25	5.515
4.00E-05	15.605	17.3	16.075	12.6	8.85	6.216
1.00E-04	22.061	24.55	22.75	17.925	11.1	6.874
2.00E-04	26.617	29.7	27.47	21.725	12.5	7.192
4.00E-04	30.493	34.1	31.49	24.885	13.65	7.487
6.00E-04	32.597	36.5	33.675	26.55	14.2	7.595
8.00E-04	34.115	38.225	35.25	27.69	14.625	7.724
1.00E-03	35.231	39.5	36.41	28.5	14.9	7.79
2.00E-03	38.526	43.25	39.83	30.5	15.6	7.979
4.00E-03	42.037	47.25	43.475	31.87	16.13	8.164
1.00E-02	45.77	51.5	47.35	33	16.65	8.401
2.00E-02	47.313	53.25	48.95	33.5	16.875	8.5
1.00E-01	49.287	55.5	51	34.1	17.1	8.575

ERSI - A-10 Round Robin

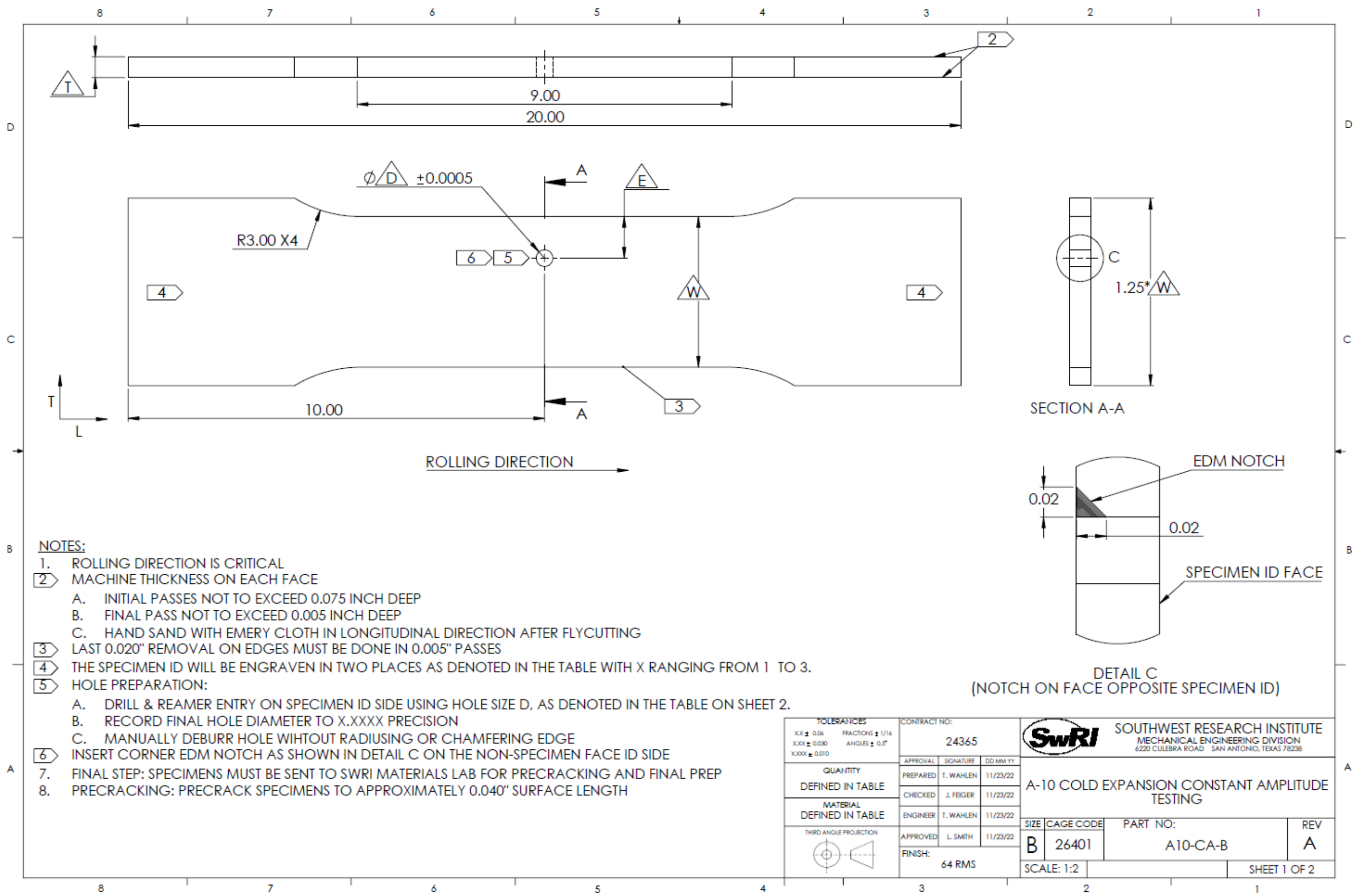
2024-T351 Rate Data

Property	Value
Material	2024-T351 Plate
Modulus (ksi)	10700
Poisson	0.33
Ultimate Strength (ksi)	66
Yield Strength (ksi)	50
Plane Stress Fracture Toughness (ksi-root(inch))	80
Plane Strain Fracture Toughness (ksi-root(inch))	32
Rlo	-0.5
Rhi	0.85

da/dN	Stress Ratios (R)					
	K_{max}		ΔK			
	-0.5	-0.25	0	0.1	0.5	0.8
7.87E-11	1.275	1.300	1.326	1.218	0.959	0.864
2.36E-10	1.318	1.344	1.370	1.259	0.991	0.893
7.87E-10	1.410	1.438	1.466	1.346	1.060	0.955
3.94E-09	1.586	1.617	1.649	1.514	1.192	1.074
1.57E-08	1.815	1.850	1.887	1.733	1.364	1.229
3.15E-08	2.083	2.122	2.165	1.988	1.565	1.409
5.51E-08	2.419	2.466	2.514	2.310	1.817	1.634
1.34E-07	3.757	3.829	3.905	3.586	2.820	2.516
3.15E-07	5.757	5.868	5.983	5.496	4.500	4.100
1.28E-06	7.247	7.383	8.200	8.000	5.800	4.838
3.94E-06	8.713	8.880	10.200	9.200	7.000	6.400
1.46E-05	13.307	13.560	16.000	14.800	10.200	8.225
3.94E-05	19.300	19.704	22.000	21.000	14.000	9.200
1.34E-04	27.553	28.224	32.000	29.000	19.000	10.500
3.94E-04	37.533	38.536	41.000	36.220	23.500	12.000
1.34E-03	49.900	51.360	52.880	48.340	28.000	13.200
3.94E-03	58.507	59.976	61.480	56.060	33.000	14.500
1.65E-02	68.933	70.088	71.210	64.610	37.000	15.600
7.87E-02	76.133	76.696	78.000	70.010	40.000	16.000
3.94E-01	80.800	81.120	82.510	74.800	41.000	16.100

ERSI - A-10 Round Robin

Coupon Drawings



Working Group on
Engineered Residual
Stress Implementation

ERSI - A-10 Round Robin

Coupon Drawings

DESIGN INPUTS FOR BASELINE COUPONS							
LOCATION	MATERIAL	WIDTH (W)	THICKNESS (T)	EDGE DISTANCE (E)	HOLE DIAMETER (D)	SPECIMEN ID	QUANTITY
CP 47	7075-T76/ 7075-T76511	3.84	0.125	0.500	0.249	CP47-B-X	3
CP 7T	2024-T351	4.00	0.410	1.690	0.5005	CP7T-B-X	3
CP 5T	2024-T3511	4.00	0.394	1.040	0.5005	CP5T-B-X	3
FALSTAFF	7075-T651	4.00	0.250	2.000	0.250	FALSTAFF-B-X	3

SwRI SOUTHWEST RESEARCH INSTITUTE
MECHANICAL ENGINEERING DIVISION
6220 CULEBRA ROAD SAN ANTONIO, TEXAS 78238

A-10 COLD EXPANSION CONSTANT AMPLITUDE TESTING

SIZE	CAGE CODE	PART NO:	REV
B	26401	A10-CA-B	A
		TABLE OF DIMENSIONS	SHEET 2 OF 2

ERSI - A-10 Round Robin

- Priority #1 (Baseline non-Cx, CA loading)
  - Coupons CP7T-B-01 through -03
  - Geometry
    - Thickness: 0.410”
    - Width (test section): 4.00”
    - Width (grips): 5.00”
    - Hole Diameter: 0.501”
    - Hole Offset: 1.690”
    - EDM notch and crack on short ligament side
  - Material: 2024-T351plate
    - Source: Kevin Walker’s recently updated tabular lookup

ERSI - A-10 Round Robin

- Priority #1 (Baseline Non-Cx, CA loading)
  - Loading: CA, R=0.1, max stress: 23 ksi
    - Stress represents gross cross-section (no hole) of the gauge section

Block file name:	*CP7T-Baseline-27APR*			
Max Normalized	**Min Normalized**	**Cycles**	**Component**	**Component Cycles**
1.00	0.10	1325	CA Block	1325
1.00	0.70	170	Marker	375
1.00	0.10	35		
1.00	0.70	170		
		1700	**TOTAL CYCLES**	**1700**

- Starting crack sizes:

Coupon CP7T-B-02

EDM	
Surface	**Bore**
0.00000	0.03209
0.02415	0.00000

Crack Front Points

Markerband	
Surface	**Bore**
0.02932	0.00000
0.03217	0.00641
0.03332	0.01698
0.02210	0.03368
0.00528	0.04093
0.00000	0.03965

Coupon CP7T-B-03

EDM	
Surface	**Bore**
0.00000	0.02363
0.02735	0.00000

Crack Front Points

Markerband	
Surface	**Bore**
0.04407	0.00000
0.04502	0.00343
0.04601	0.00575
0.04461	0.02467
0.04079	0.03723
0.02101	0.05583
0.01464	0.05998
0.00149	0.06248

ERSI - A-10 Round Robin

- Priority #2 (Baseline Non-Cx, CA loading)
  - Coupons FALSTAFF-B-01 through -03
    - Note: coupon IDs are for consistency with later FALSTAFF spectrum tests, however, these tests are subject to constant amplitude loading
  - Geometry
    - Thickness: 0.250”
    - Width (test section): 4.00”
    - Width (grips): 5.00”
    - Hole Diameter: 0.250”
    - Hole Offset: 2.000”
  - Material: 7075-T651plate
    - Source: Jake Warner’s IFF Round Robin

ERSI - A-10 Round Robin

- Priority #2 (Baseline Non-Cx, CA loading)
  - Loading: CA, R=0.15, max stress: 25 ksi
    - Stress represents gross cross-section (no hole) of the gauge section

Block file name:	*FALSTAFF-MarchOne (BASELINE)*			
Max Normalized	**Min Normalized**	**Cycles by Line**	**Component**	**Component Cycles**
1.00	0.15	1025	Primary Block	1025
1.00	0.70	125	Marker Band	275
1.00	0.15	25		
1.00	0.70	125		
		1300	**TOTAL CYCLES**	**1300**

- Starting crack sizes:

X = surface
Y = bore

FALSTAFF-B-02

Band	EDM Notch
X	Y
0.00000	0.02499
0.01096	0.01315
0.02342	0.00000

Crack Front Points

X	Y
0.03231	0.00000
0.03411	0.00928
0.03342	0.01631
0.02594	0.03083
0.01257	0.04043
0.00620	0.04016
0.00000	0.03781

FALSTAFF-B-03

Band	EDM Notch
X	Y
0.00000	0.02260
0.00983	0.01159
0.02206	0.00000

Crack Front Points

X	Y
0.03329	0.00000
0.03449	0.00718
0.03405	0.01014
0.03501	0.01666
0.03054	0.02520
0.02502	0.03257
0.01639	0.04052
0.00534	0.04499
0.00000	0.04417

ERSI
Fatigue Crack Growth & Testing Committee
Durability Activity

Prepared by Adrian Loghin, Simmetrix Inc.

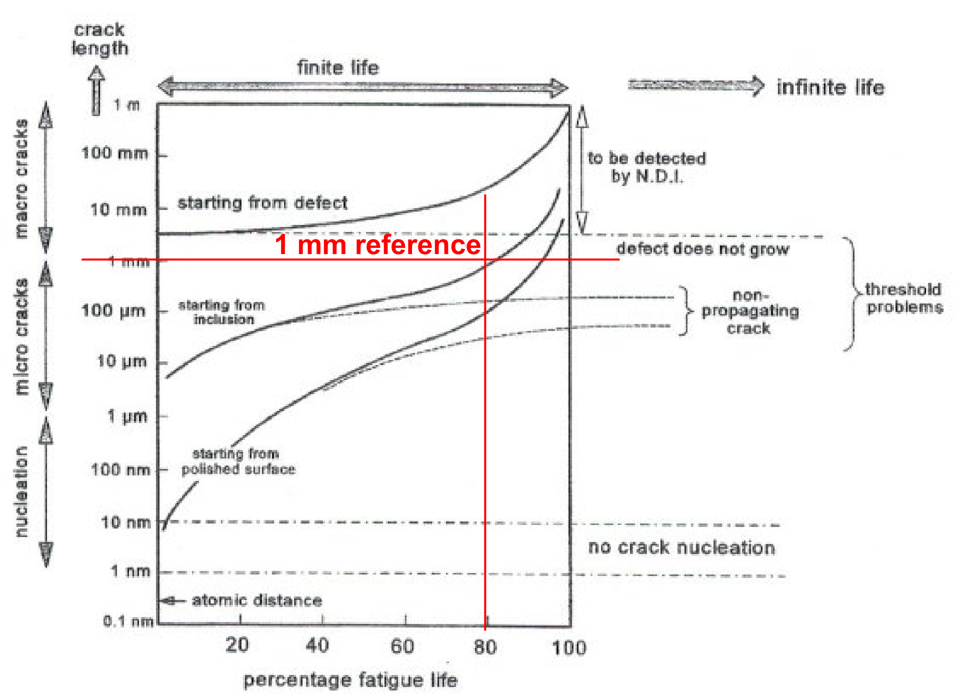
Importance

- Depending on material choice, component application, current fracture-critical methodology for metallic structural components (long crack behavior) might address ~20% of the total life.

- Durability methodology targets damage progression throughout the entire life of the material, from incubation and at different scales relative to the grain size (the common reference)

  - Much more difficult to address and implement due to technology readiness (measurement, modeling), cost, uncertainties that must be accounted for.

  - If such methodology would pass validation requirements, it could have a tremendous value in material assessment and component lifing. Even extending current damage tolerance (validation included) and NDE methodology to crack sizes lower than current detection limit will have a positive impact in industry.



Jaap Schijve, Fatigue of Structures and Materials, Springer, 2009.

TABLE 1
Classes of small fatigue cracks

Type of small crack	*Dimension*	*Responsible mechanism*	*Potential solution*
Mechanically small	$a \lesssim r_y$ [a]	Excessive (active) plasticity	Use of ΔJ, ΔS or crack-tip-opening displacement
Microstructurally small	$a \lesssim d_g$ [b]	Crack tip shielding, enhanced $\Delta\epsilon_p$	Probabilistic approach
	$2c \lesssim (5\text{-}10)\, d_g$	Crack shape	
Physically small	$a \lesssim 1$ mm	Crack tip shielding (crack closure)	Use of ΔK_{eff}
Chemically small	Up to about 10 mm [c]	Local crack tip environment	

[a] r_y is the plastic zone size or plastic field of notch.
[b] d_g is the critical microstructural dimension, *e.g.* grain size, a is the crack depth and $2c$ the surface length.
[c] Critical size is a function of frequency and reaction kinetics.

Ritchie R.O., Lankford J., Overview of the small crack problem, 1986.

Working Group on Engineered Residual Stress Implementation

From Grains to Properties: Challenges (some …)

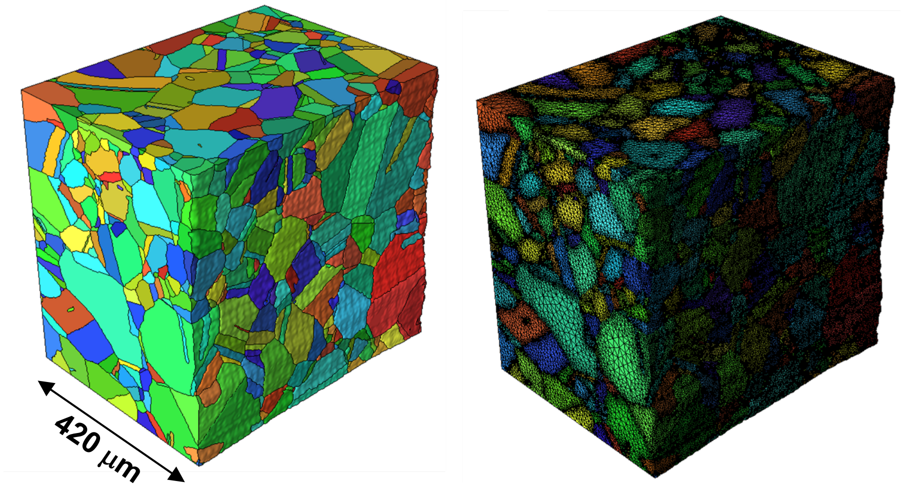
- Technology gaps to perform efficient and accurate 3D grain measurements prior to and during deformation process, capture crack nucleation and growth at various stages (microstructurally small, mechanically short)
- Statistical metrics to identify grain characteristics: size, shape, number of neighbors, orientation
- Validated crystal plasticity models for various material systems
- Similitude principle not applicable, local anisotropy
- Increased model complexity to capture relevant physics
- **Verification&Validation (V&V) and Uncertainty Quantification (UQ) across scale levels**

"Detailed observations over many years has shown that, under cyclic loading, all materials can go through four phases to failure: crack nucleation, stable growth of short cracks, stable growth of long cracks, final unstable failure.", Jeal R.H., Rolls-Royce, 1989.

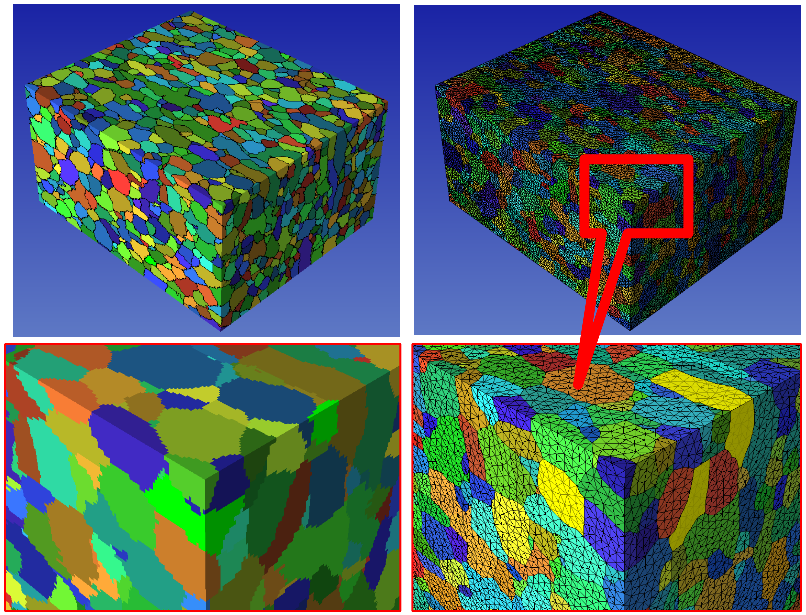
Higher level of uncertainty for microstructural small and short crack lengths in comparison to long crack behavior

Examples of RVE digital reconstructions suitable for FEA

In718 RVE courtesy of UCSB



Ti64 RVE courtesy of UCSB



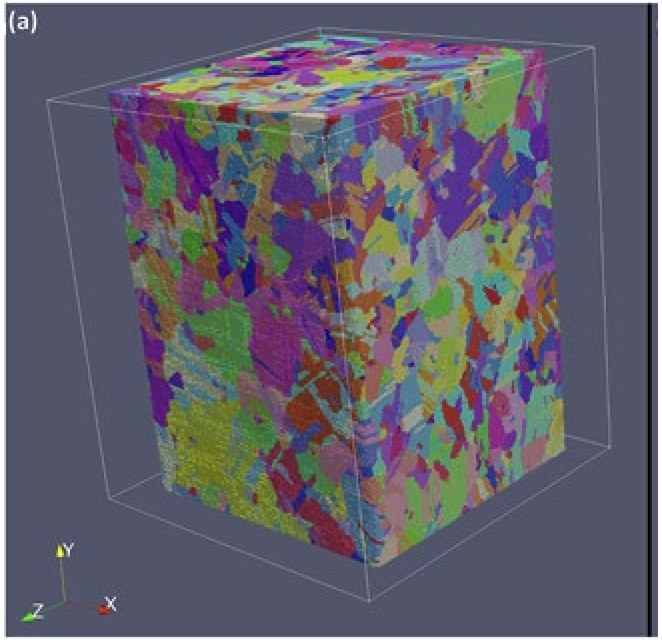
Reference: J. C. Stinville et. al., Multi-modal Dataset of a Polycrystalline Metallic Material: 3D Microstructure and Deformation Fields, https://www.nature.com/articles/s41597-022-01525-w, 2022.

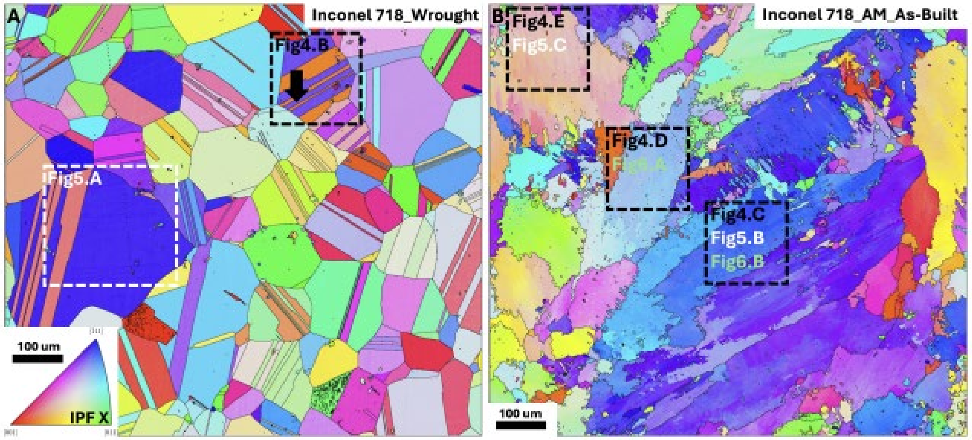
Reference: Klass O., Beall M., Loghin A., Enabling 3D FEA solvers perform mesoscale simulations, NAFEMS20 UK Conference, 2020.

Very limited data on crack nucleation, growth at microstructural scale

Other microstructure measurements

IN625, RVE, from an AFRL challenge





Reference: Chapman M. et al, **AFRL** Additive Manufacturing Modeling Series: Challenge 4, 3D Reconstruction of an IN625 High-Energy Diffraction Microscopy Sample Using Multi-modal Serial Sectioning, 2021.

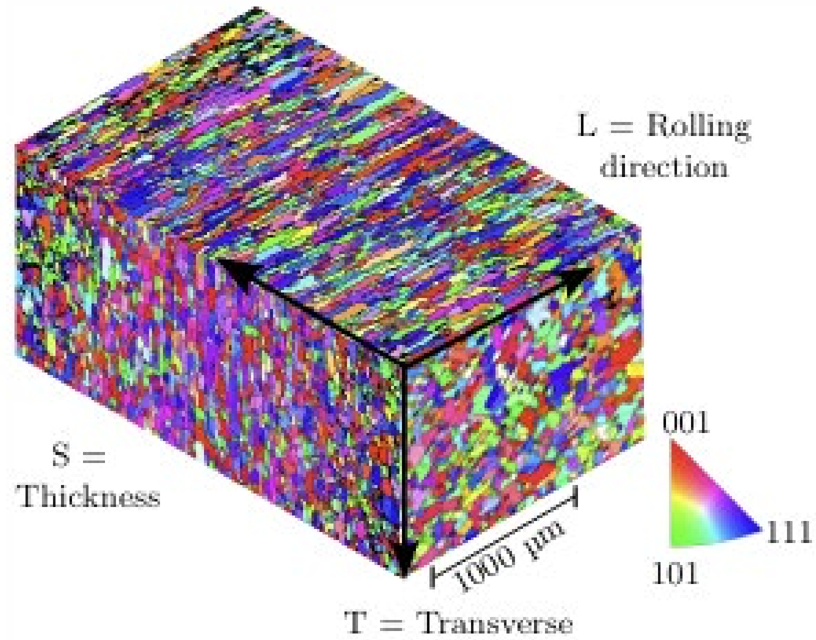
Reference: Calvat M. et al, Learning Metal Microstructural Heterogeity through Spatial mapping of Diffraction Latent Space Features, 2025.

Increased microstructural complexity in AM alloys

Other microstructure measurements

- It is important to note that an initial crack size of 0.005 inches (0.127 mm) that could be considered in crack propagation life assessment is equivalent to about half length of the grain along the rolling direction

AA2024-T351, EBSD performed along the three planes, ST, LT, SL (not a volumetric RVE)

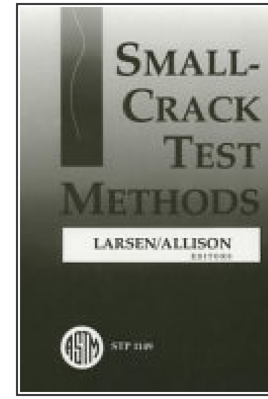


Reference: Kalina M., Schone V. et al, Fatigue crack growth in anisotropic aluminum sheets – phase-field modelling and experimental validation, 2023.

Since we are trying to identify some feasible objective under this task, should we consider investigating usage of initial crack sizes under 0.04″ in fatigue crack growth assessment?

AFRL related work / mostly high temp. applications

- Larsen J., et. al., Reducing uncertainty in fatigue life limits of turbine engine alloys, 2013.
- Small-crack test methods, ASTM STP 1149, 1992
- Caton M., et. al., Developing the capability to monitor small fatigue crack growth under elevated temperature, ultra-high conditions, 2011
- Rosenberg A., et. al., The variability of fatigue in notched bars of IN100, 2012.
- Larsen J., et. al., Prognosis of Turbine Engine Materials, ASIP 2007.
- Manning S.D., et. al., Durability methods development, AFFDL-TR-79-3118, 1979.



Is there anything that we can use from prior work in this ERSI activity?

More Literature (just some...)

Selection of some review publications

- Jaap Schive, Fatigue of Structures and materials, Springer, 2009.
- Anton Hohenwarter, Thomas Leitner and Reinhard Pippan, Fatigue Crack Propagation Across the Multiple Length Scales of Technically Relevant Metallic Materials, Annual Review of Materials Research, 2024.
- P. Chowdhury, H. Sehitoglu, Mechanisms of fatigue crack growth – a critical digest of theoretical developments, 2016.
- Stinville J.C., et. al., Competing Modes for Crack Initiation from Non-metallic Inclusions and Intrinsic Microstructural Features During Fatigue in a Polycrystalline Nickel Based Superalloy, Metallurgical and materials Transactions A, 2018.
- Sangid M., The physics of fatigue crack propagation, International Journal of Fatigue, 2025.
- Davidson D., et. al., Small Fatigue Cracks, SwRI, 2007.
- Suresh S. and Ritchie R.O., Propagation of short fatigue cracks, International Metals Reviews, 1984.
- Ritchie R.O., Lankford J., Overview of the small crack problem, 1986.

TMS White Papers related to durability, V&V, opportunities in material behavior modeling

- The Minerals, Metals & Materials Society (TMS), Accelerating the Broad Implementation of V&V in Computational Models of the Mechanics of Materials and Structures, 2020, www.tms.org/VVaccelerator
- The Minerals, Metals & Materials Society (TMS), Modeling Across Scales: A Roadmapping Study for Connecting Materials Models and Simulations Across Length and Time Scales, 2015, www.tms.org/multiscalestudy
- The Minerals, Metals & Materials Society (TMS), Advanced Computation and Data in Materials and Manufacturing: Core Knowledge Gaps and Opportunities, 2018, www.tms.org/coreknowledge

Short term goals

- It could be beneficial if we understand what was achieved at AFRL in the last decade regarding short crack behavior on high temperature material applications. It would be nice if we could have somebody from AFRL provide a review of the public work related to short crack behavior.
- Should we consider usage of initial crack sizes < 0.04 inch in fatigue crack growth assessments as a potential task under this activity?
  - This was proposed by an attendee (cannot remember who) in a regular ERSI Tcon.
  - The goal makes sense because it could impact current practices

The purpose of keeping this activity alive

- There will be difficulties holding this activity alive within this committee since there are no durability activities or technology developments reported by the group members, round-robin challenges where members can participate.

- There are efforts outside this group (I would say mostly academic research) that focus on durability modeling. Acknowledging the advancement, failures or challenges coming from these activities can be beneficial for this group.

- There are and there will be technological advancements related to imaging, DIC, test procedures, microscopy, modeling procedures that aim at quantification of mechanical behavior of materials used in aerospace industry. It could be very beneficial for this group to discuss these advancements because we can learn and improve our own technology.

Ogden Air Logistics Complex

U.S. AIR FORCE

Cold Expanded Hole Tolerance Effects: Testing

Evan Ross[1], Jacob Warner[1],
Trevor Shoemaker[1]

2025 ERSI Workshop
Layton, UT
April 30 – May 1, 2025

[1] United States Air Force

Motivation

- **Questions ERSI has heard often:**
  - **How do we know that each hole was CX'd within tolerance?**
  - **Can the fatigue life be accurately (or conservatively) predicted?**
- **What does "in-tolerance" CX look like for A-10 drain holes?**
  - **What I_a levels could arise?**
  - **What RS fields are induced?**
  - **How does I_a impact fatigue performance?**
  - **Can we accurately predict the fatigue performance?**

SHD (in)	t (in)	D (in)	Ia (%)	Notes
0.3560	0.0104	0.3542	5.34	Max tol - 0.003" SHD
0.3580	0.0104	0.3542	4.75	Max tol - 0.001" SHD
0.3590	0.0104	0.3542	4.46	Max in-tol
0.3605	0.0100	0.3540	3.74	Nominal
0.3620	0.0098	0.3530	2.93	Min in-tol
0.3630	0.0098	0.3530	2.64	Min tol + 0.001" SHD
0.3650	0.0098	0.3530	2.08	Min tol + 0.003" SHD

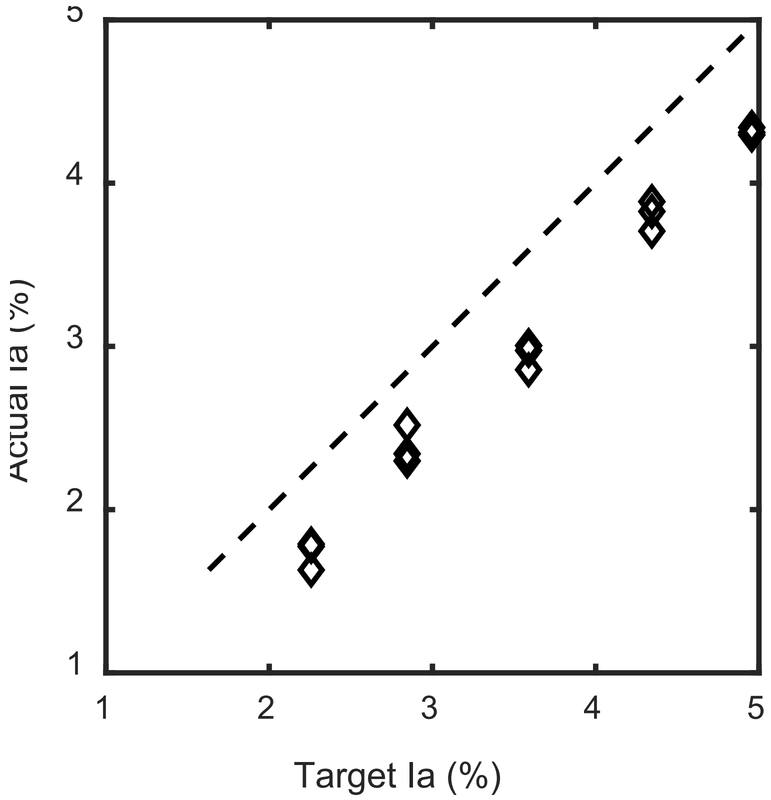
$$I_a = \frac{(D + 2t - SHD)\times 100\%}{SHD}$$

Where:

D = Major Mandrel Diameter
t = Sleeve Thickness
SHD = Starting Hole Diameter

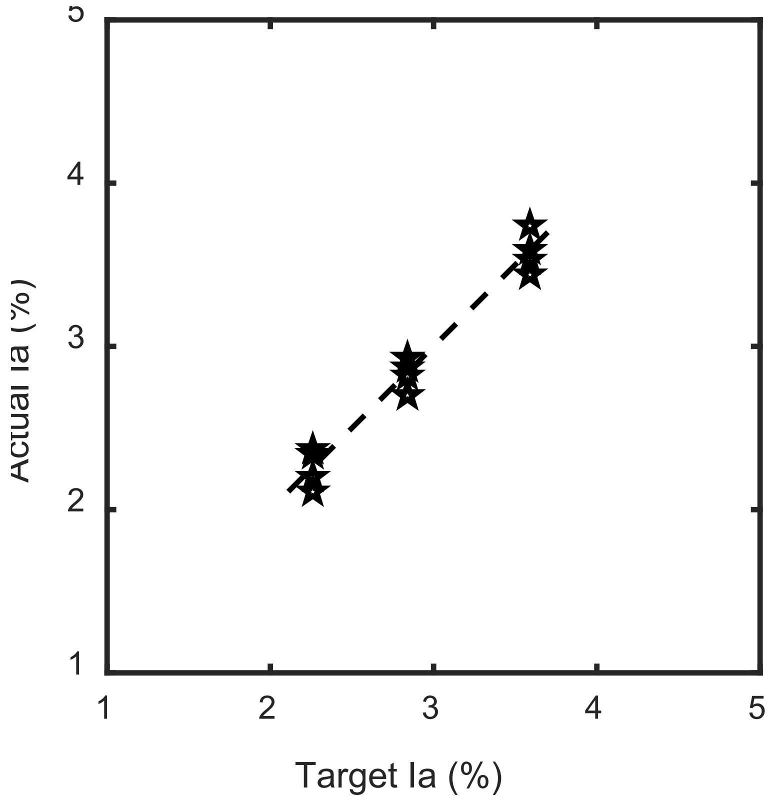
RS Field Characterization

Loc1



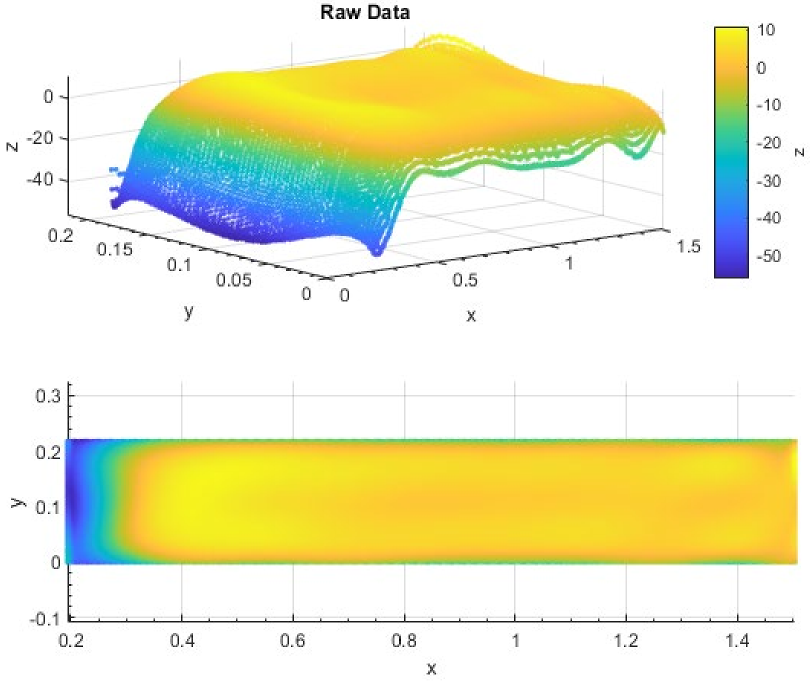
- 2 sets of 15 contour specimens
- I_a varied <0.3% among replicates

103N

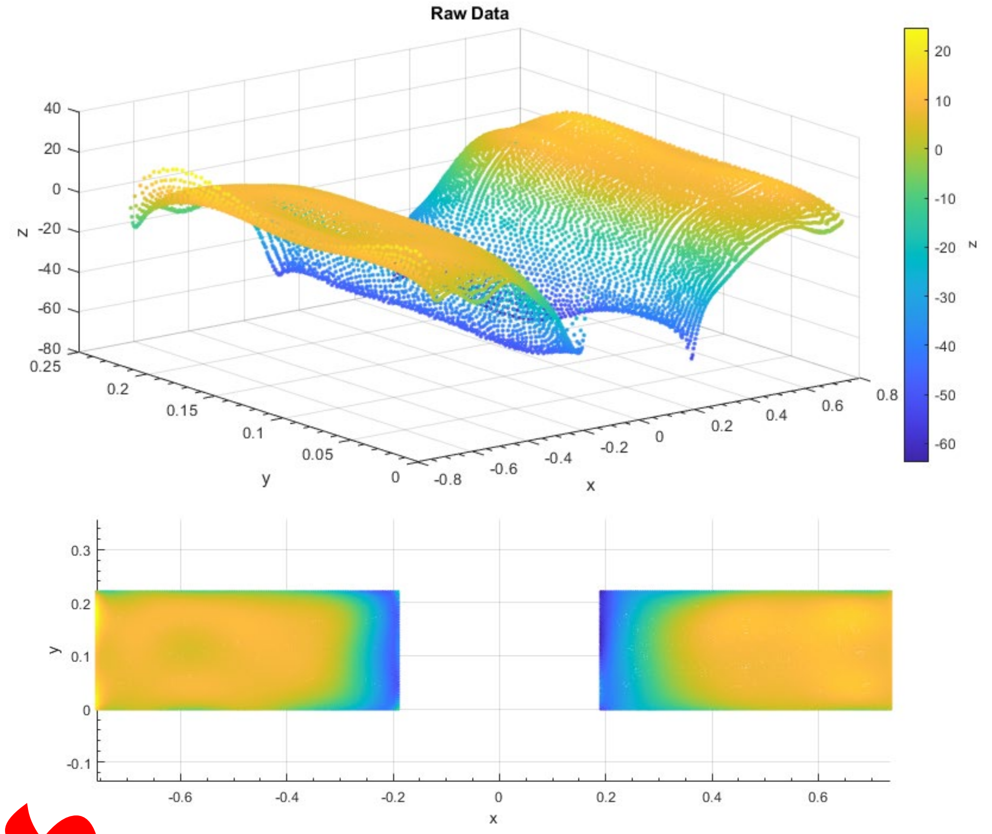


RS Field Characterization

Loc1



103N

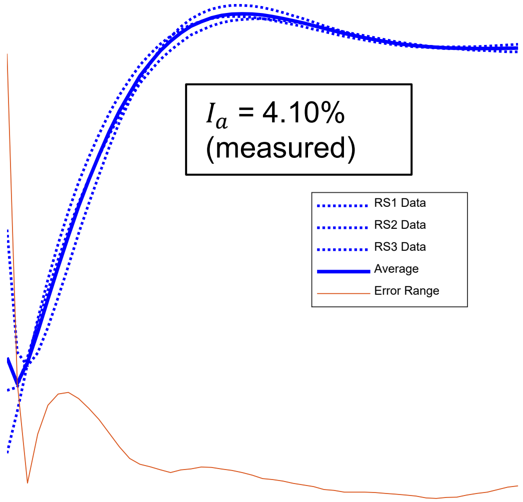


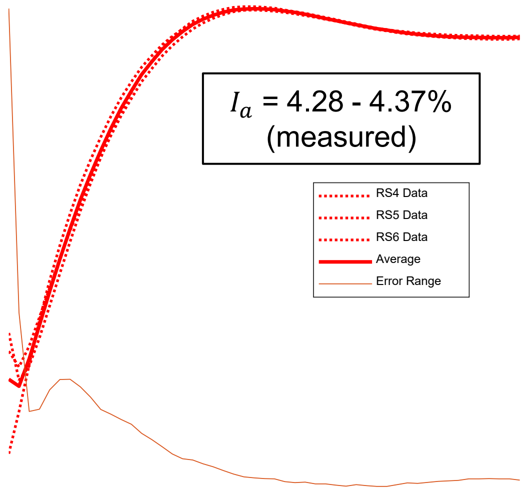
- 2 sets of 15 contour specimens
- I_a varied <0.3% among replicates
- Loc1: Single-sided
- 103N: Double-sided; RT, LT, Avg fields

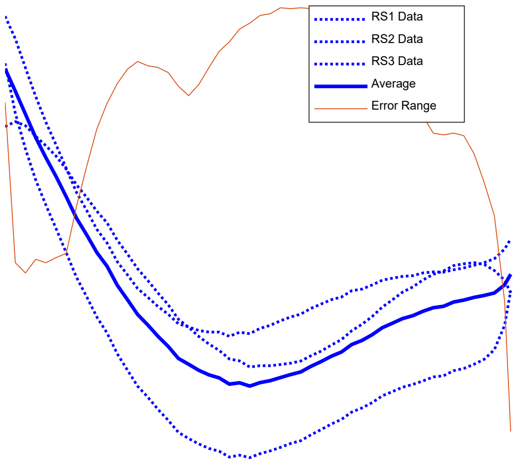
✓ Lengthwise split (stress-relief cut) before contour measurement ✗

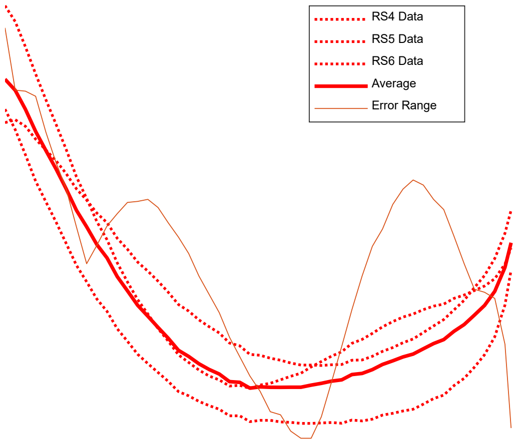
RS Field Characterization (Loc1)

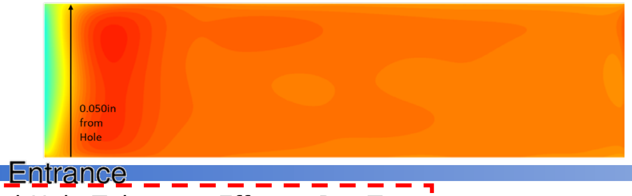
- **Data from 6 specimens shown (groups of 3 replicates)**
- **At mid-thickness, fields varied by 18-35 ksi at the hole bore**
- **At 0.05" from hole bore, fields varied >5 ksi**
- **Is this specimen-to-specimen variation?**







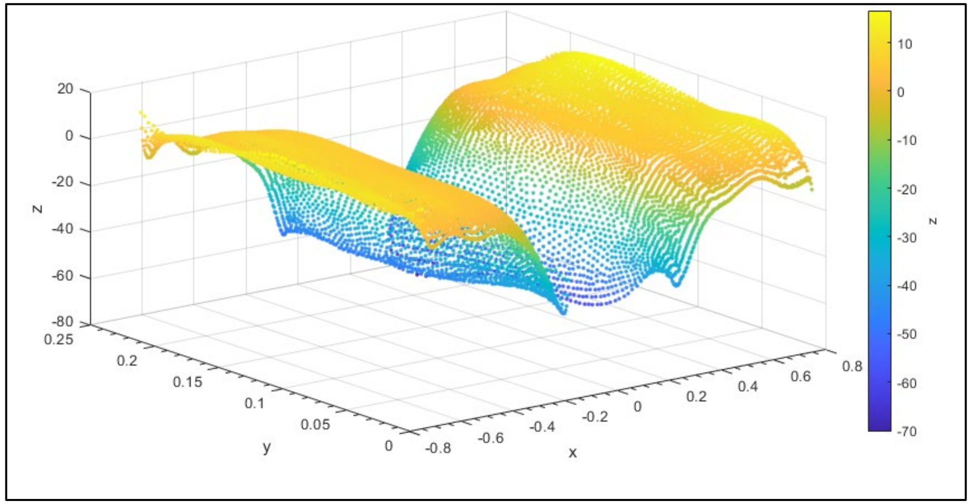


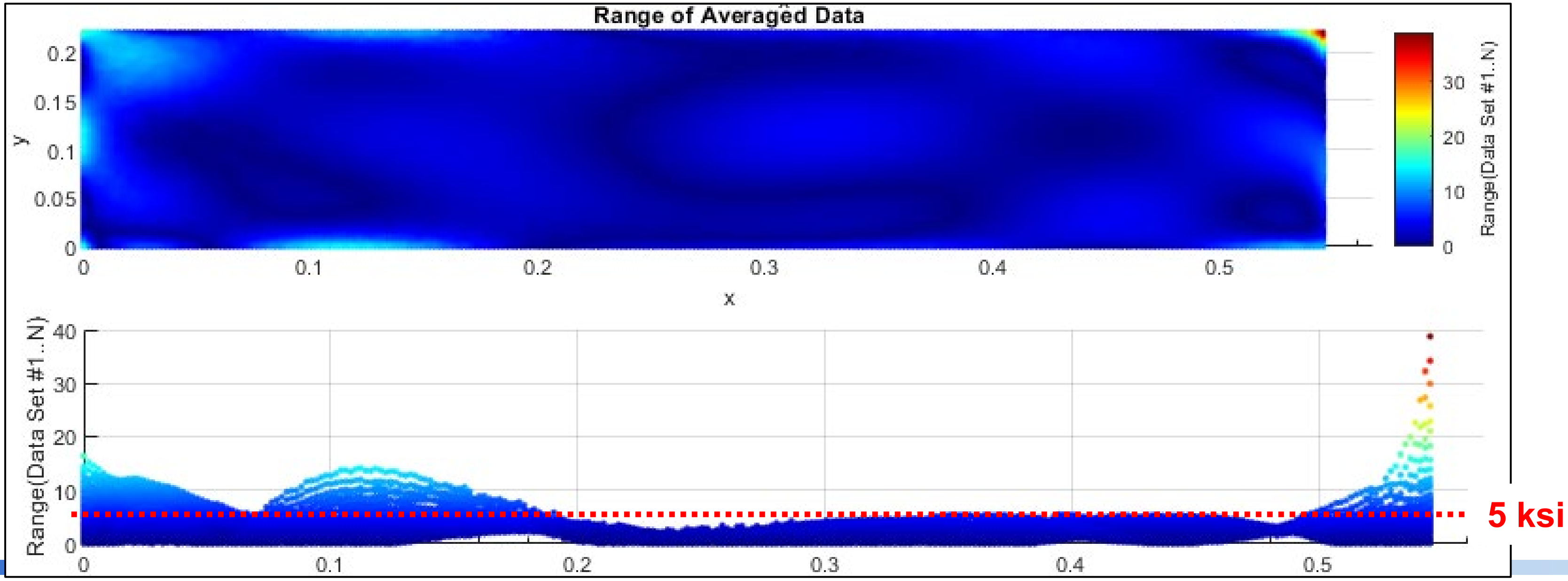


Shoemaker, T. K. Cold-Expanded Hole Tolerance Effects: Pre-Test Predictions (AFGROW Workshop 2023)

RS Field Characterization (103N)

- Double-sided fields should be true replicates
- Fields were compared point-by-point
- >5 ksi difference, typical across 15 specimens
- Remember: No stress-relief cut was performed on the 103N samples prior to contour measurement.
- How does this translate to fatigue life?

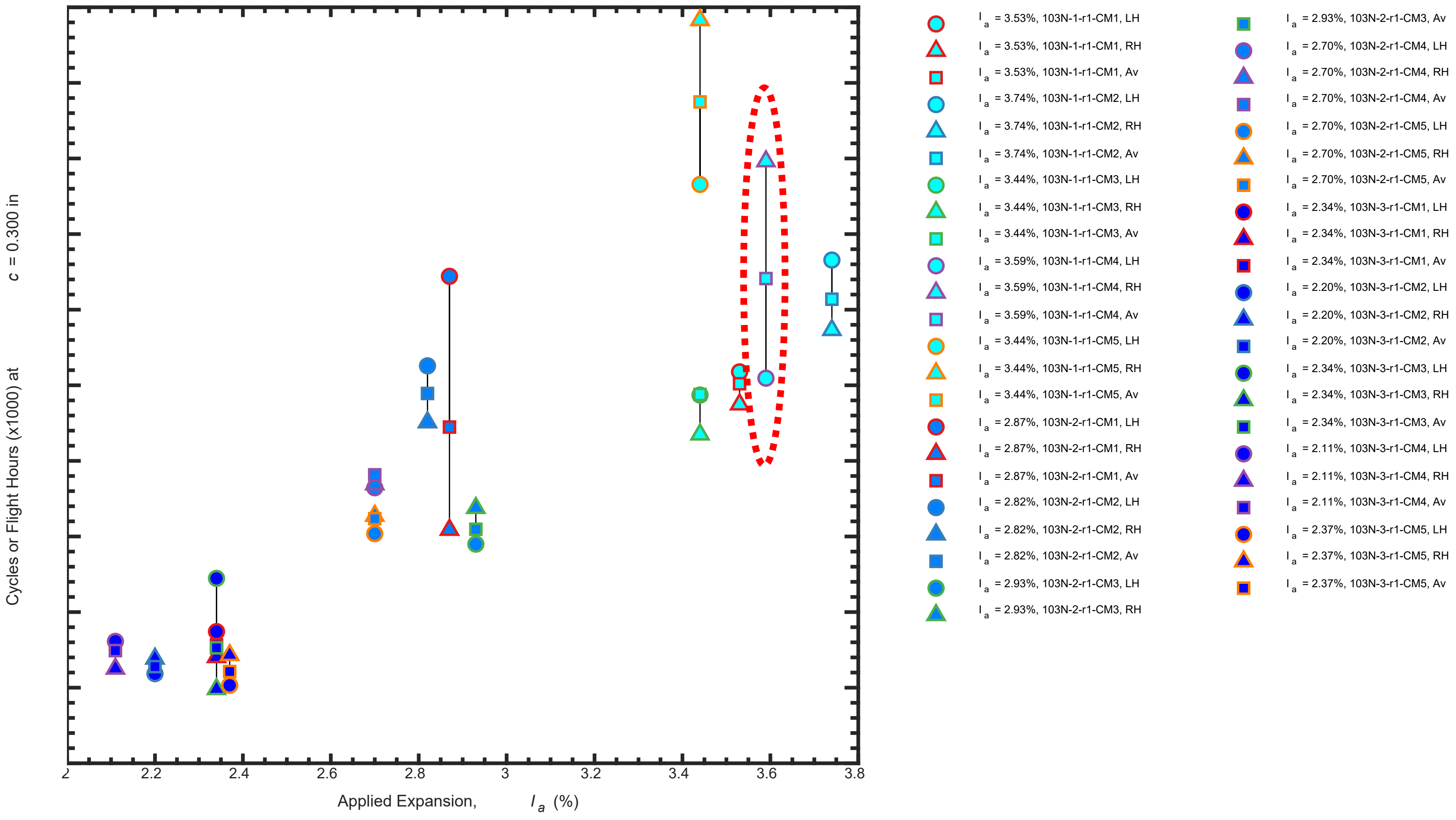




Shoemaker, T. K. Cold-Expanded Hole Tolerance Effects: Pre-Test Predictions (AFGROW Workshop 2023)

RS Field Characterization (103N)

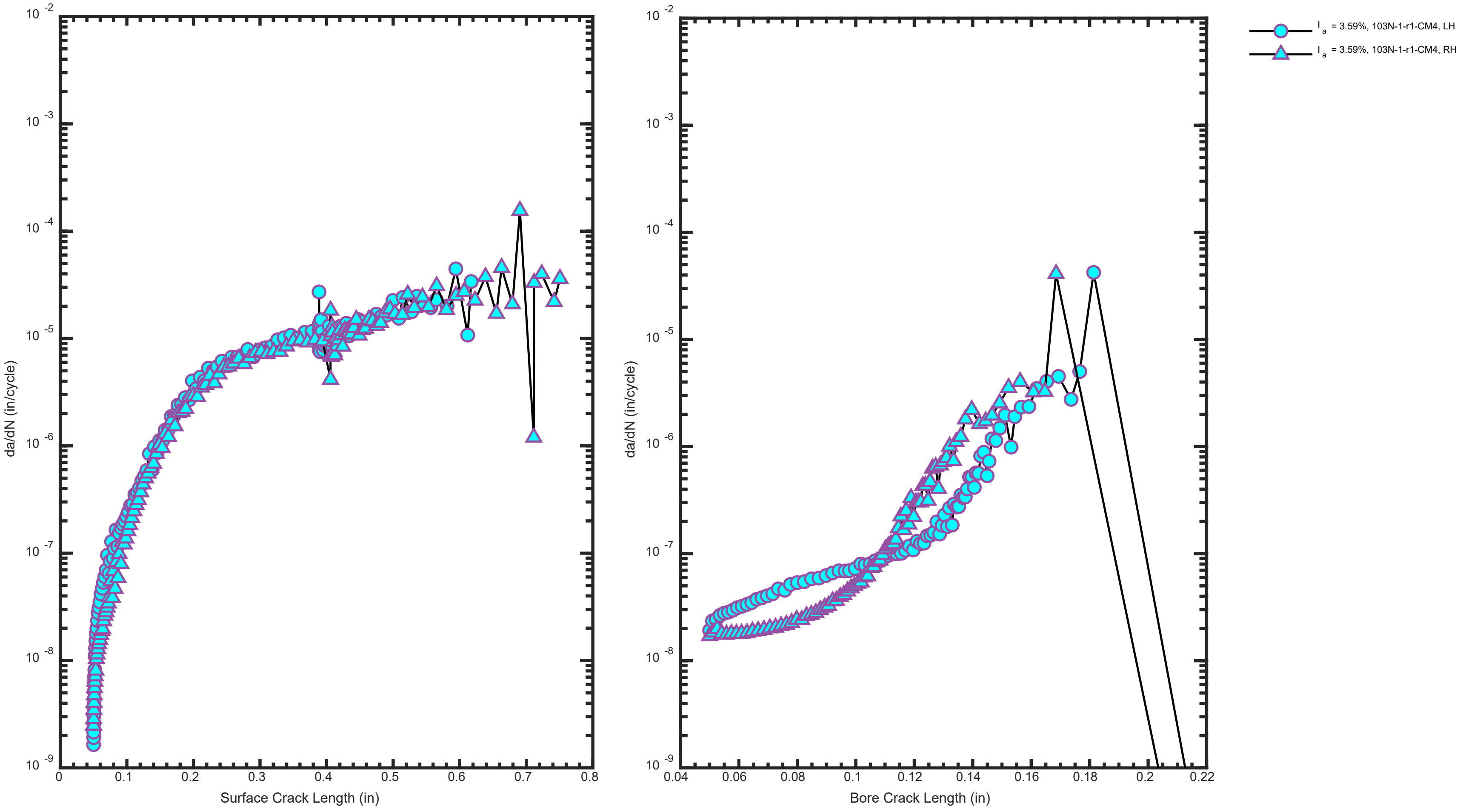
- BAMpF predictions varied widely between RH-LH sides of this hole
- Other predictions with seemingly comparable RS fields were more repeatable
- What part of growth is impacted most?



Shoemaker, T. K. Cold-Expanded Hole Tolerance Effects: Pre-Test Predictions (AFGROW Workshop 2023)

RS Field Characterization (103N)

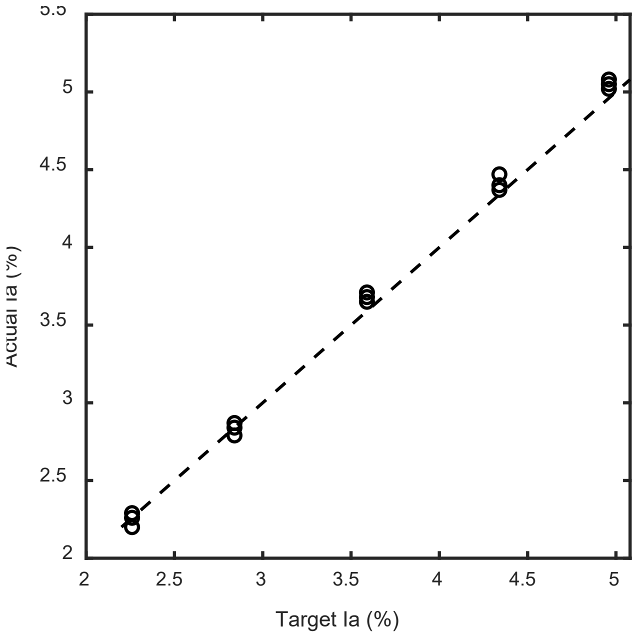
- **Surface crack growth rates were comparable**
- **Differences showed primarily in the bore crack growth rate**
- **Intuitive based on RS uncertainty at the hole bore**
- **Does testing show similar variation?**

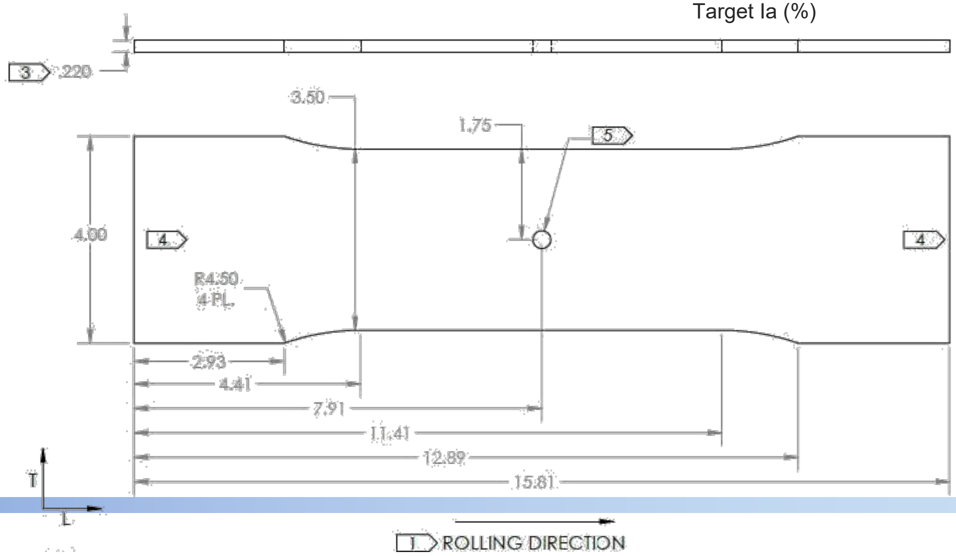


Test Conditions

- 15 total fatigue specimens
  - 5 I_a levels, 3 replicates each
  - All within 0.1% of target I_a
- 2024-T351 plate
  - 0.22" thick, 3.5" wide, ~16" long
- EDM corner notch (entrance face)
- Precracked to ~ 0.020"
- Flight spectrum applied at 31.7 ksi to failure
- Surface and bore crack length measurements
- Marker bands for fractographic analysis

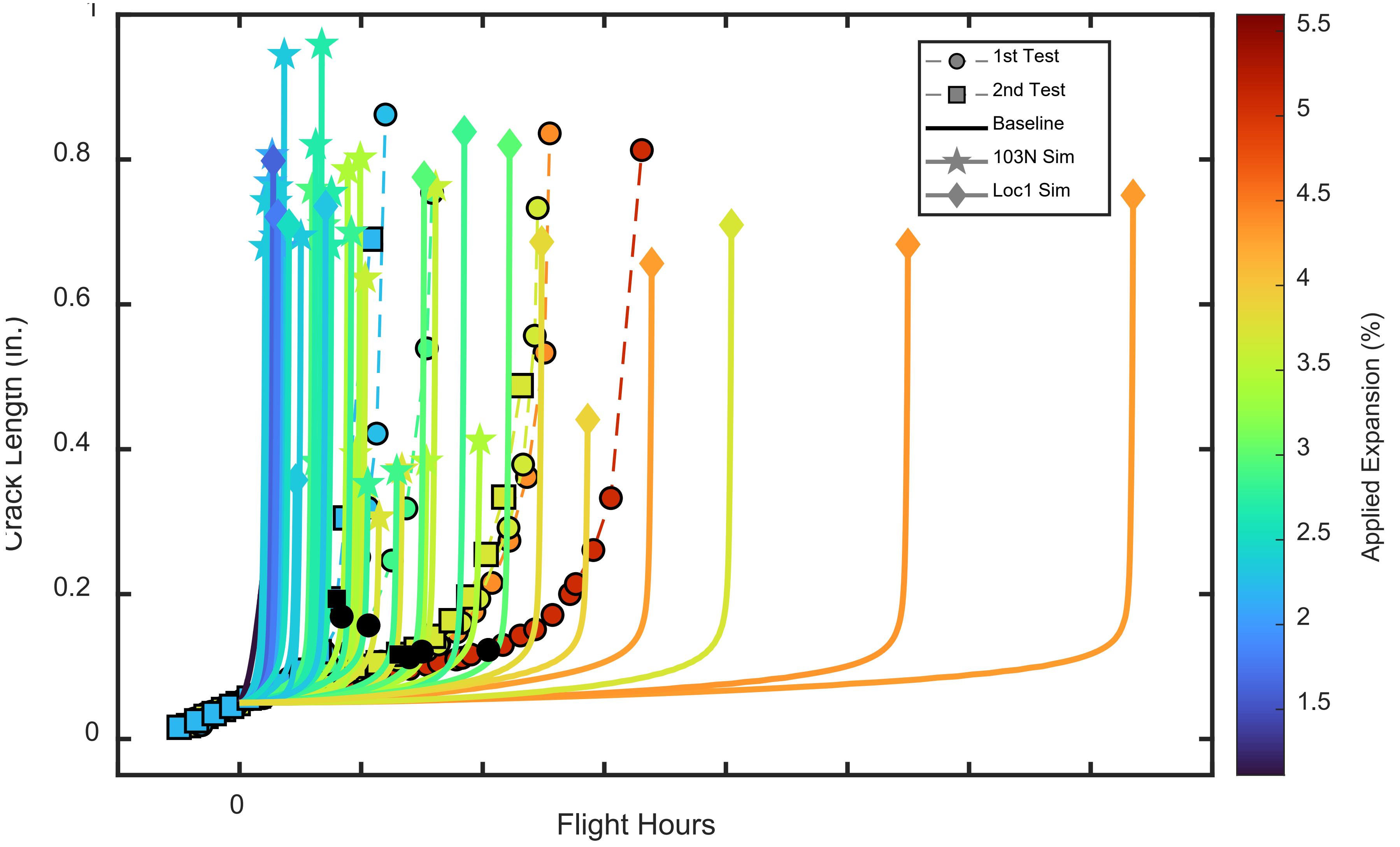
Qty.	Ia (%)
3	4.96
3	4.34
3	3.59
3	2.84
3	2.26





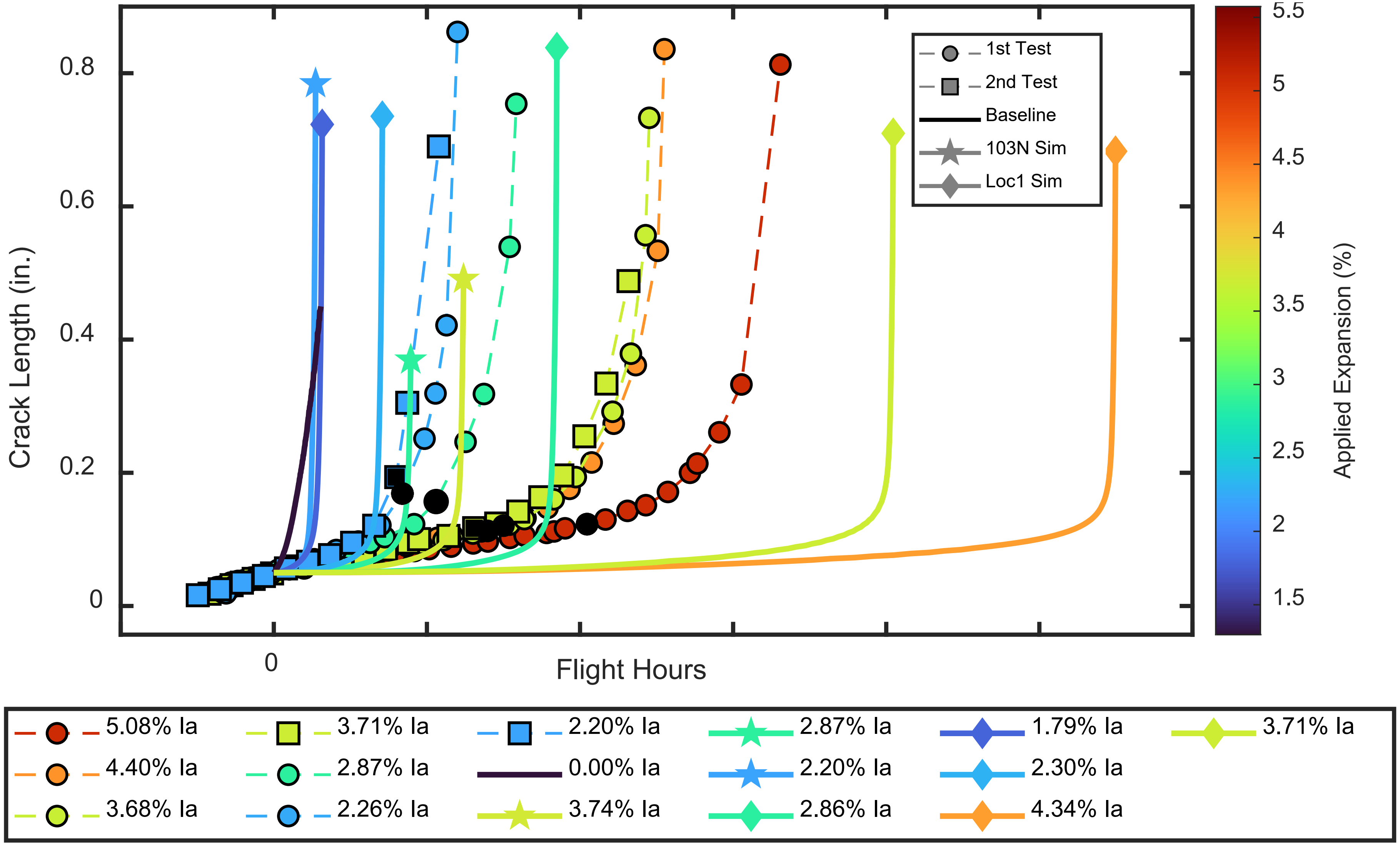
Test Results

- **Test data with all 45 simulations (15 from Loc1 and 15 RH/LH pairs from 103N)**
- **Notice color scale: Longest test has higher I_a than any simulation**



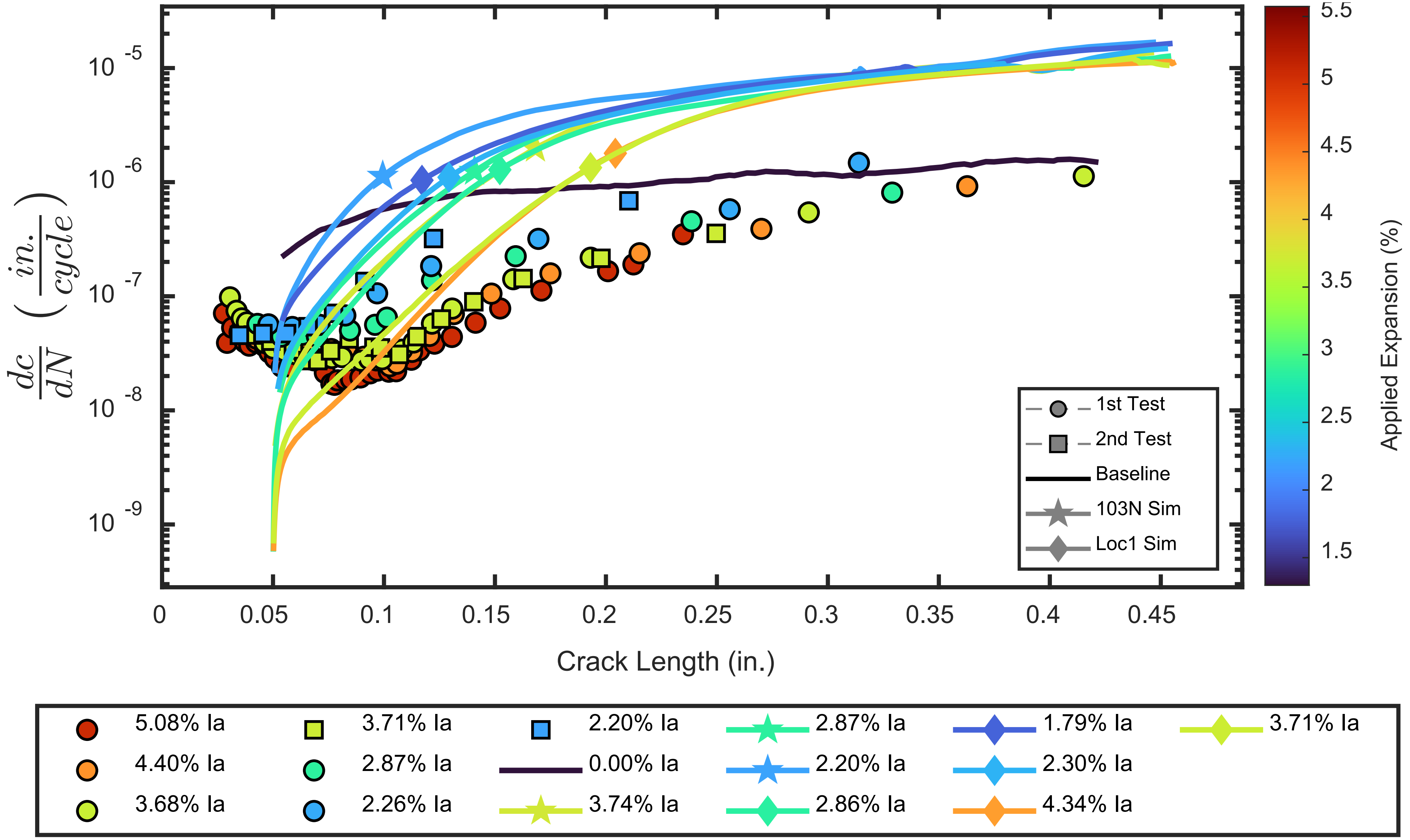
Test Results

- 9 simulations: 1 per target I_a level, plus a no-RS baseline
- Test data pinned at 0.05”
- Life correlates with I_a
- Lives are all similar orders of magnitude, but test vs simulation curve shapes differ



Test Results

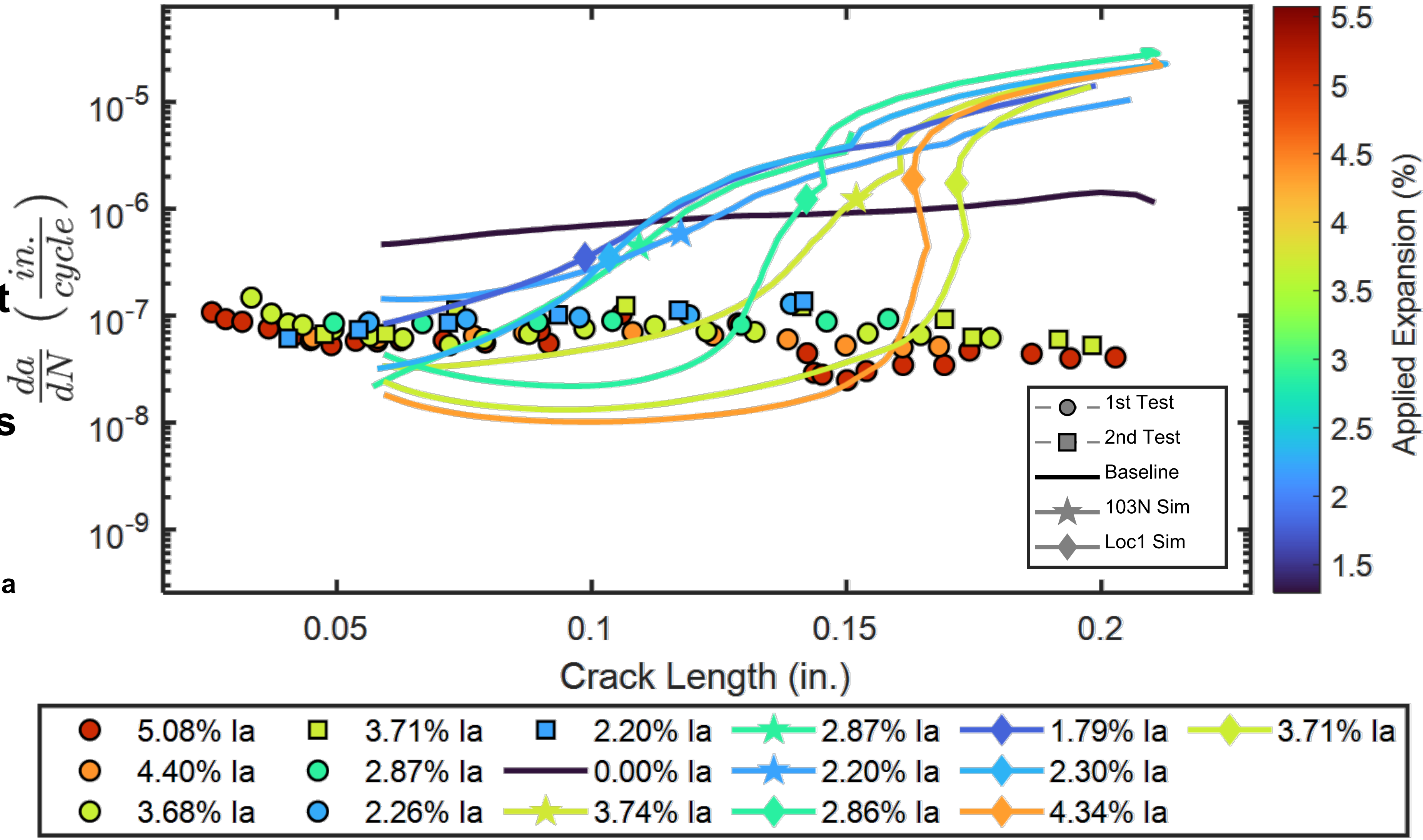
- **Surface crack growth rates correlate with I_a**
- **Shape mismatch, especially near-bore**
- **Tests seem to approach baseline simulation at longer c**
- **Contour fields maintain ~3ksi but specimens may be reaching ~0 RS**
- **We have not done baseline (I_a = 0) tests**



Test Results

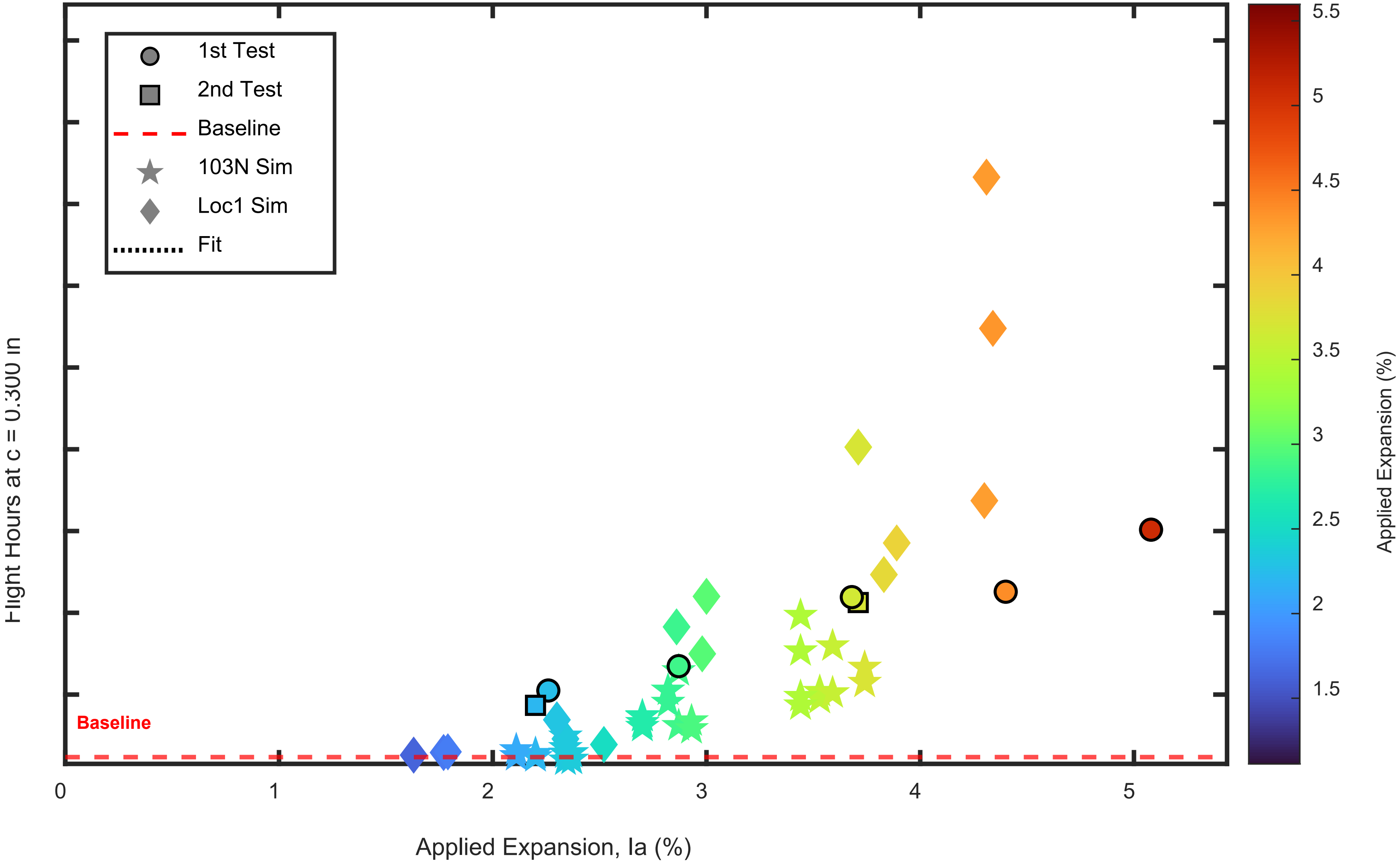
OGDEN AIR LOGISTICS COMPLEX

- Bore crack growth rates are less distinguishable by I_a
- Monotonically decreasing with slight inflection <0.05”
- Test results show less variation across all I_a than predictions showed for matched I_a
- Would this trend hold at different test stresses?



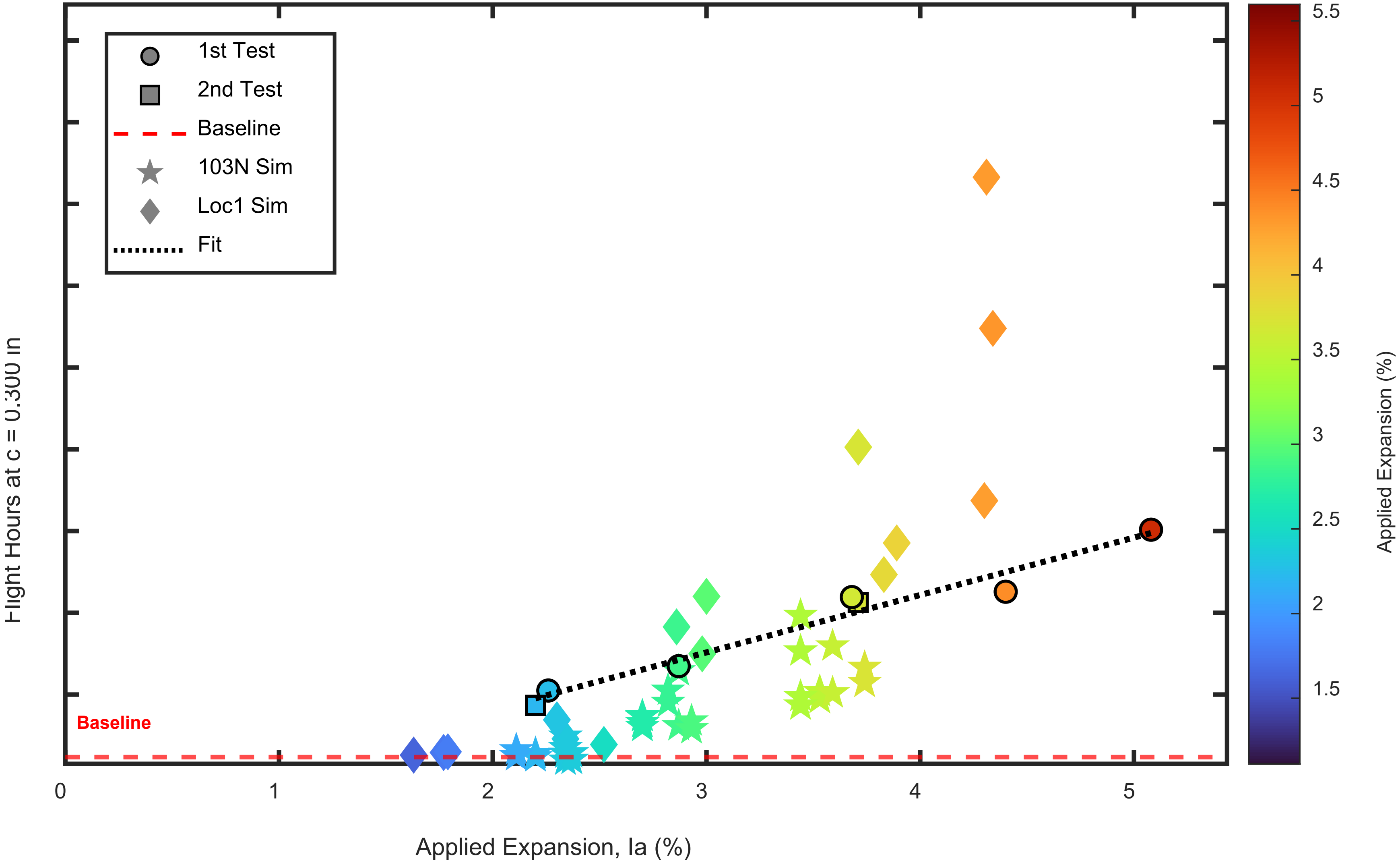
Test Results

- **Excellent test repeatability compared to simulation**



Test Results

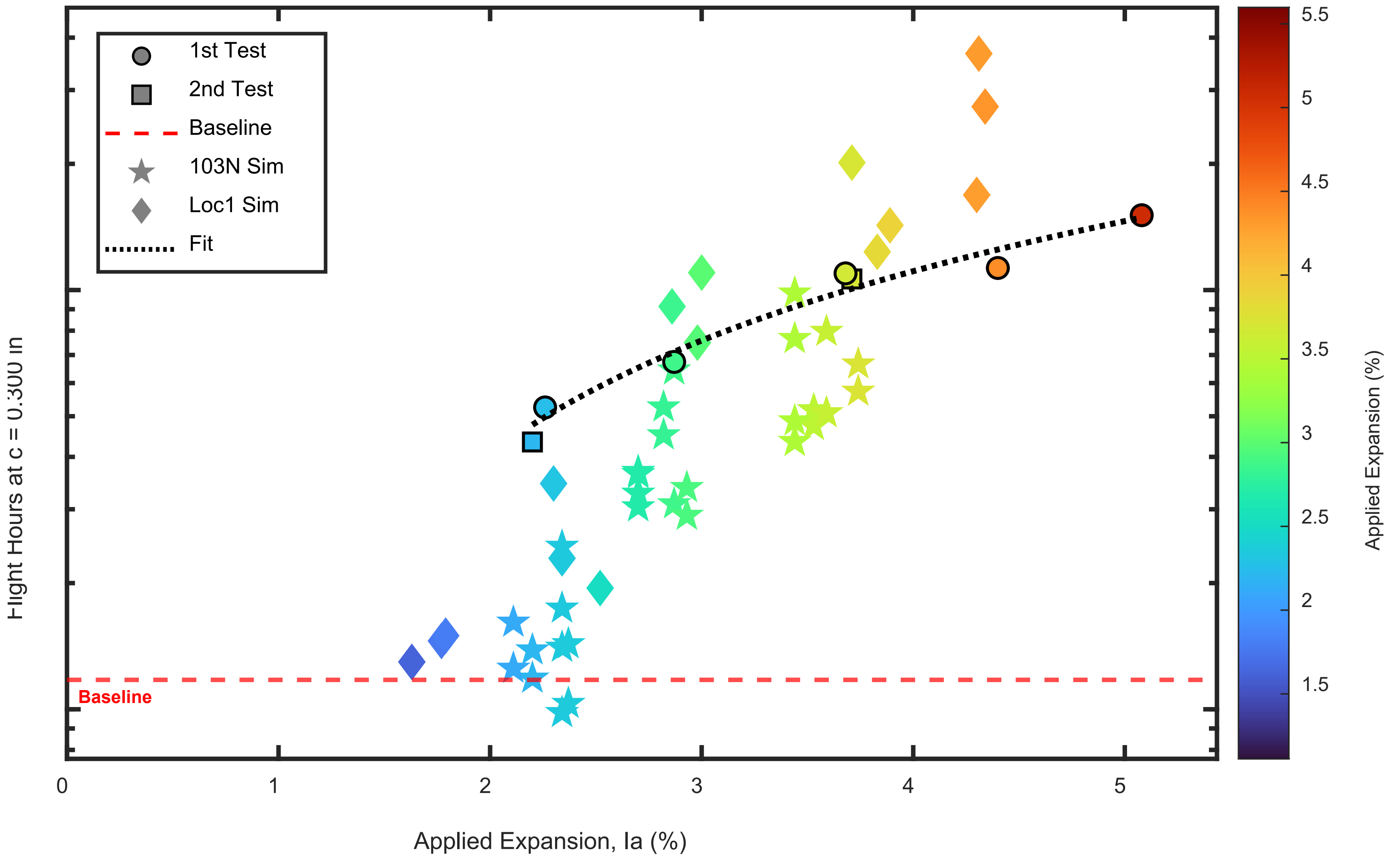
- **Excellent test repeatability compared to simulation**
- **Test life seems to have a linear relationship with I_a**
- **Simulations aren't as clear**



Test Results

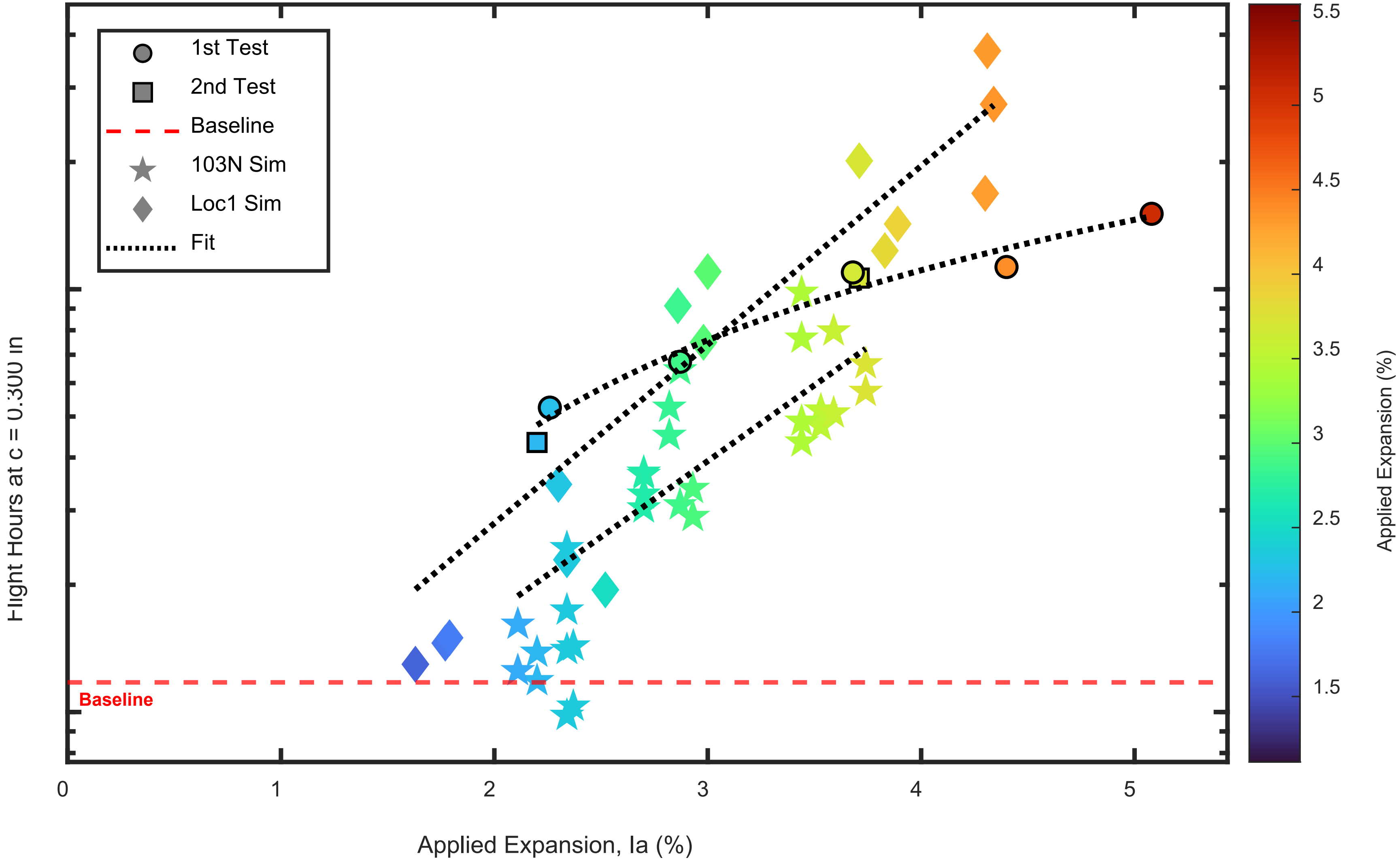
OGDEN AIR LOGISTICS COMPLEX

- **Logarithmic Y-axis shows simulations more clearly**
- **Possible overall log-linear trend**
- **Loc1 simulations have consistently longer life than 103N**



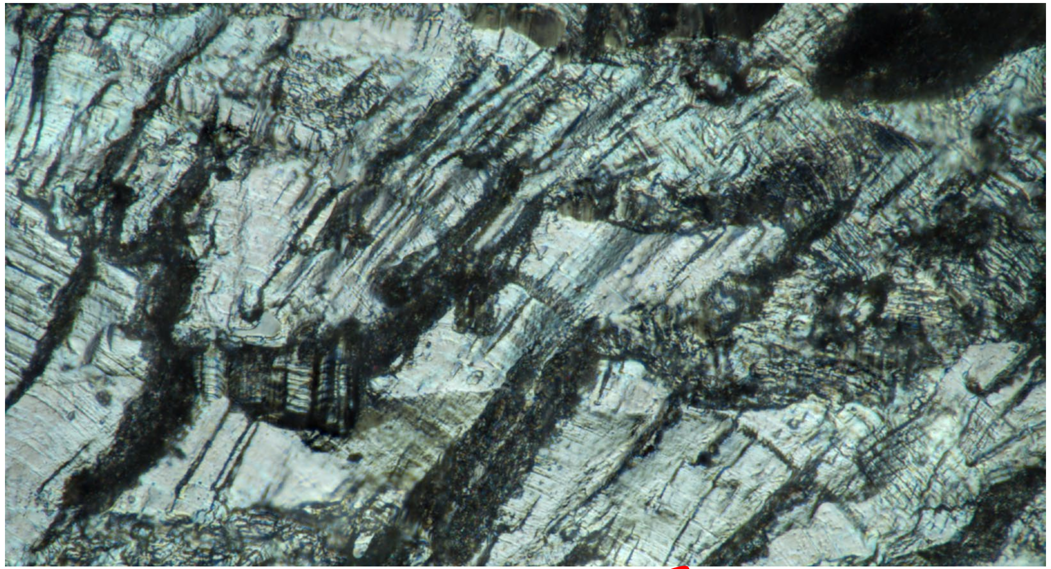
Test Results

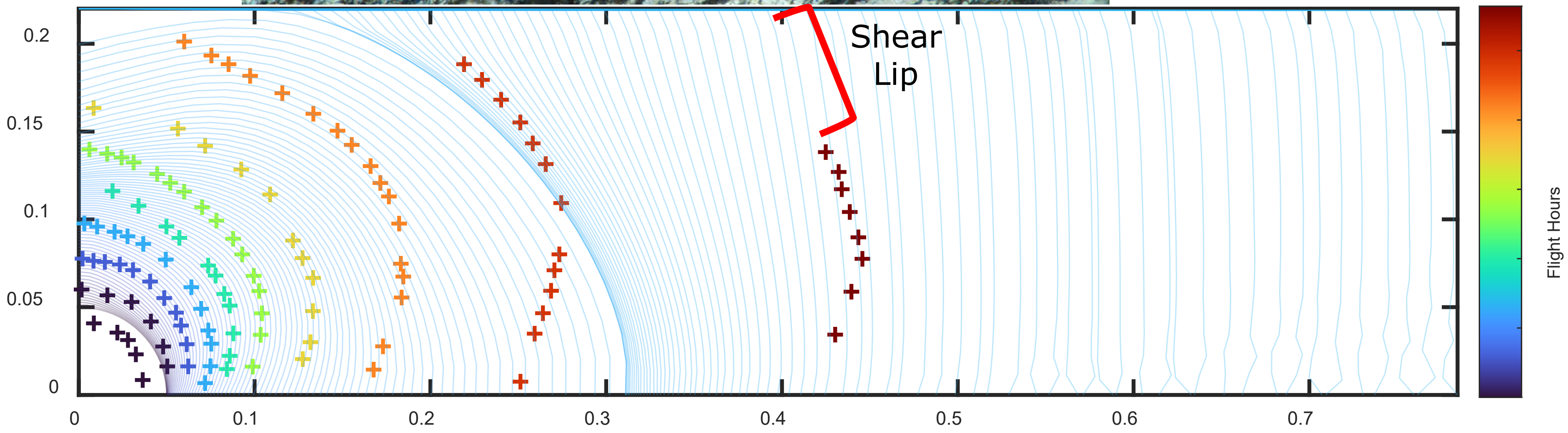
- **Logarithmic Y-axis shows simulations more clearly**
- **Possible overall log-linear trend**
- **Loc1 simulations have consistently longer life than 103N**
- **Treated separately, simulations aren't as (log) linear**
- **Are we seeing the impact of the contour stress-relief cut?**



Marker Bands

- Optical microscope was used to map bands
- Surface marked well, and most were identifiable
- Later bands are shortened due to shear lip formation
- Aiming to use these maps to back-calculate RS fields with StressCheck





Conclusions

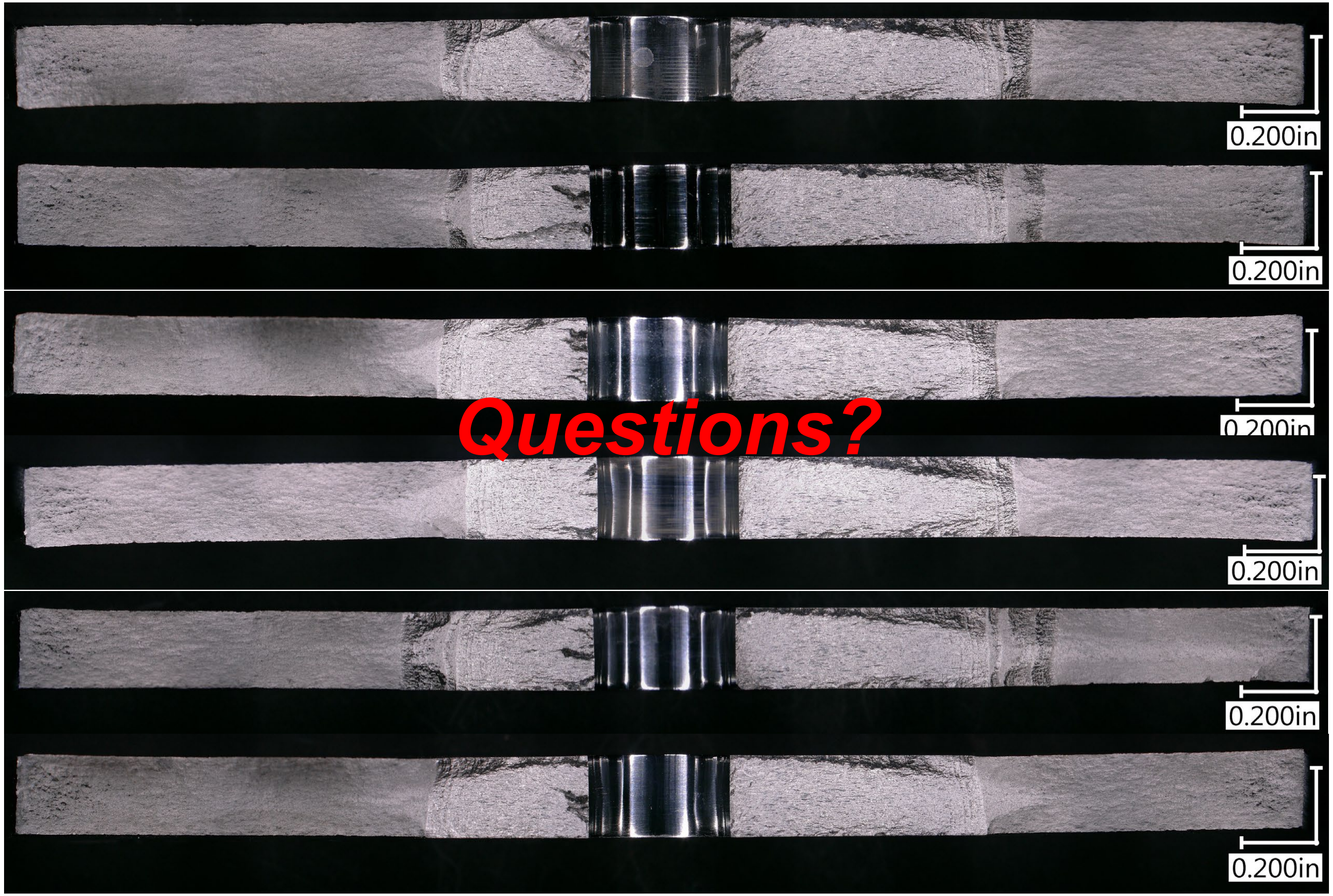
- I_a variation, even within tolerance, greatly impacts fatigue life
- With well-controlled I_a, CX fatigue tests can be very repeatable
- Tight control of I_a should be the standard
- Less scatter in test than simulation highlights measurement uncertainty

Acknowledgements

- Jake Warner
- Hill AFB Materials Lab
  - Trevor Shoemaker
  - Mikki Keller
  - Carl Grimaud
  - Chad Stamey

Discussion

- We are building a high-quality dataset
- Have we achieved our goal to understand the impact of I_a on fatigue life?
- Are there other ways to use replicates with tightly-controlled I_a?
- Considering options:
  - Continue with tests to build confidence
  - Vary loading to examine other facets of the problem
    - Lower stress to see if bore crack growth rates separate
    - Raise stress to see the limit of CX benefit
    - Change spectrum (or constant amplitude) to see different load interactions
- What would make this dataset most useful?



Questions?

Analysis and Test
RR#1 Cx Holes Revisit

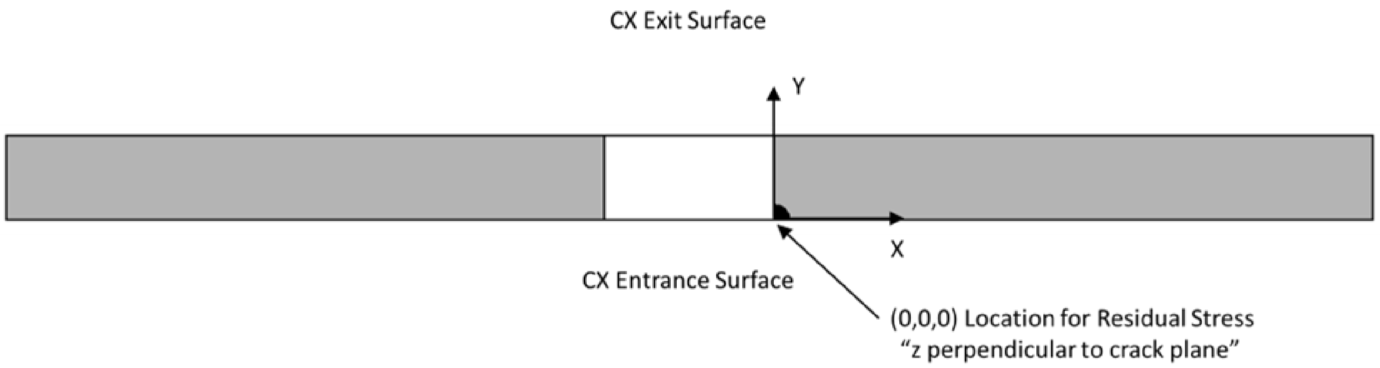
Kevin Walker

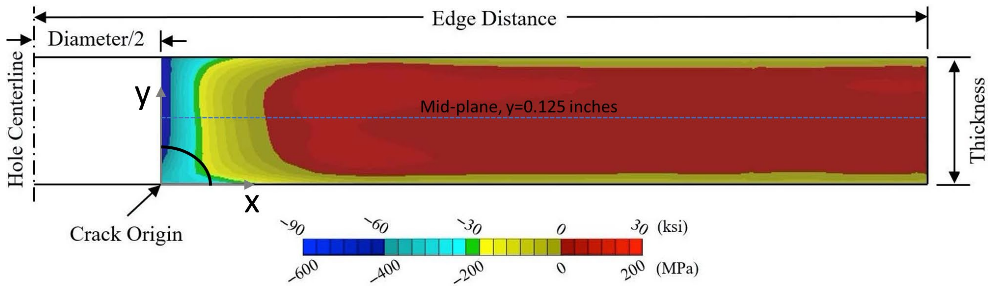
Initial version: 1 August 2024
Rev1 : OCT/NOV 2024
Rev2 : MAR 2025

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Re-cap on RR#1

Benchmark Condition #	Material	Specimen Type	Thickness (in)	Width (in)	Hole Diameter (in)	Hole Edge Margin	Loading	Max Stress (ksi)
1	2024-T351	Non-CX Baseline	0.25	4.00	0.50	4.0	CA (R=0.1)	10
2		CX						25
3		Non-CX Baseline				1.2		10
4		CX						25





ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Issues considered in review

- Used AFGROW 2 point analysis
- SIF Solution – Advanced Model
- Updated/improved Finite Width Correction (Harter)
- Rate Data (threshold and low-rate regime)
- Surface crack closure correction (βR)
- Offset distance for Residual Stress Profile
- Discovered an issue with the RS database where it adds a final line in the data which needs to be removed!! With this corrected, the results look much better!!

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Issue with RS database

- RS file with 100 lines ends like this:

1.69697	-0.86	0
1.714646	-0.86	0
1.732323	-0.86	0
1.75	-41.2	0

- But the last line is incorrect!! Should be deleted

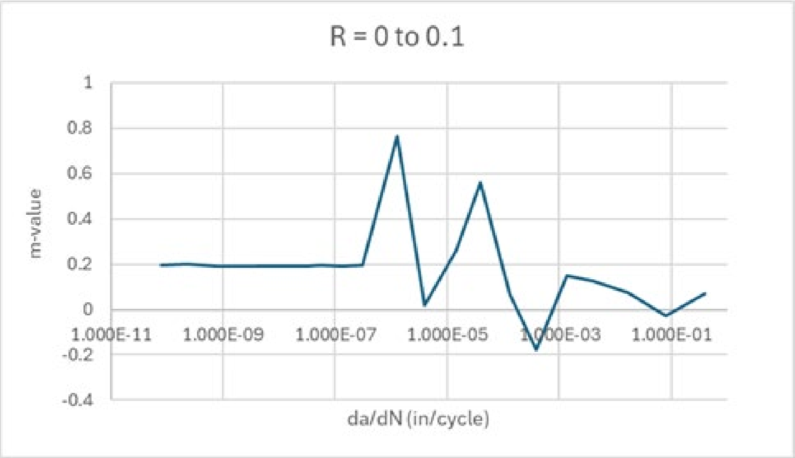
Rate Data

- Rate data has been through several revisions
- Newman analysis and modelling has shown that the threshold is lower than earlier fits
- Jim Harter showed that the "m-curve" fits for the updated rate data were not "smooth" as preferred for the Harter-T method, so some very minor changes were made to correct that, but it had very little impact on the analysis results

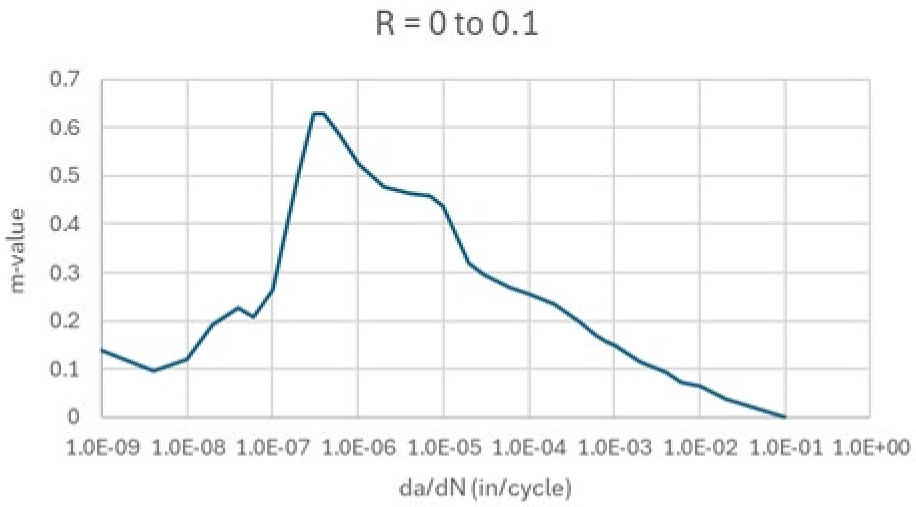
ERSI ENGINEERED RESIDUAL STRESS IMPLEMENTATION

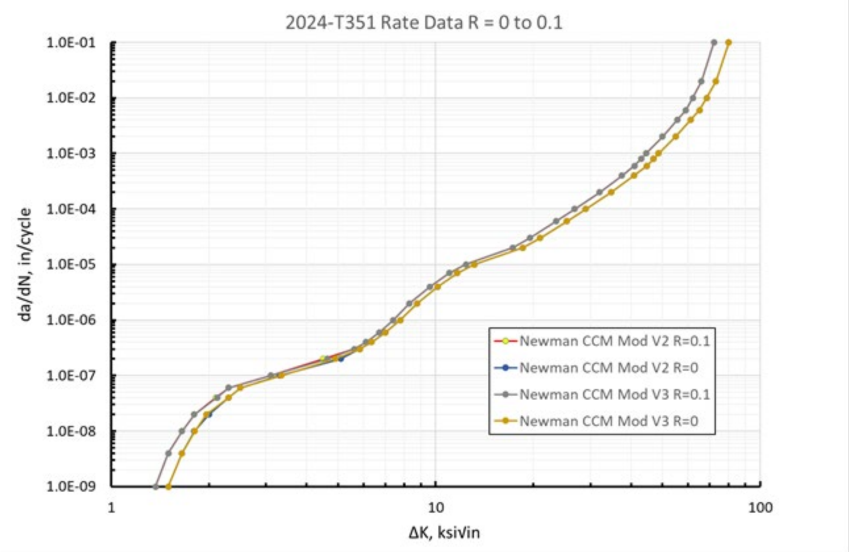
m-curve correction

V2



V3





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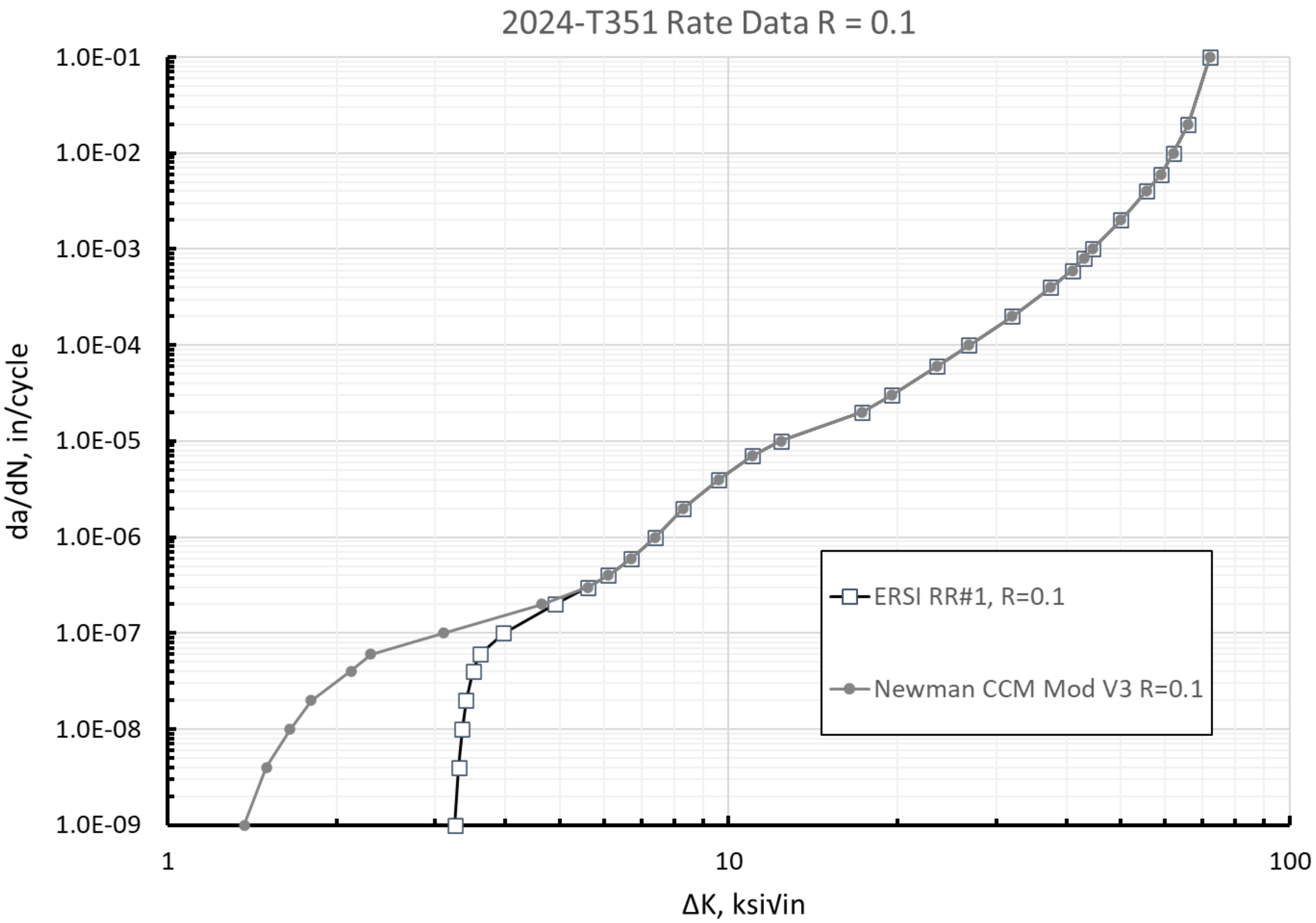
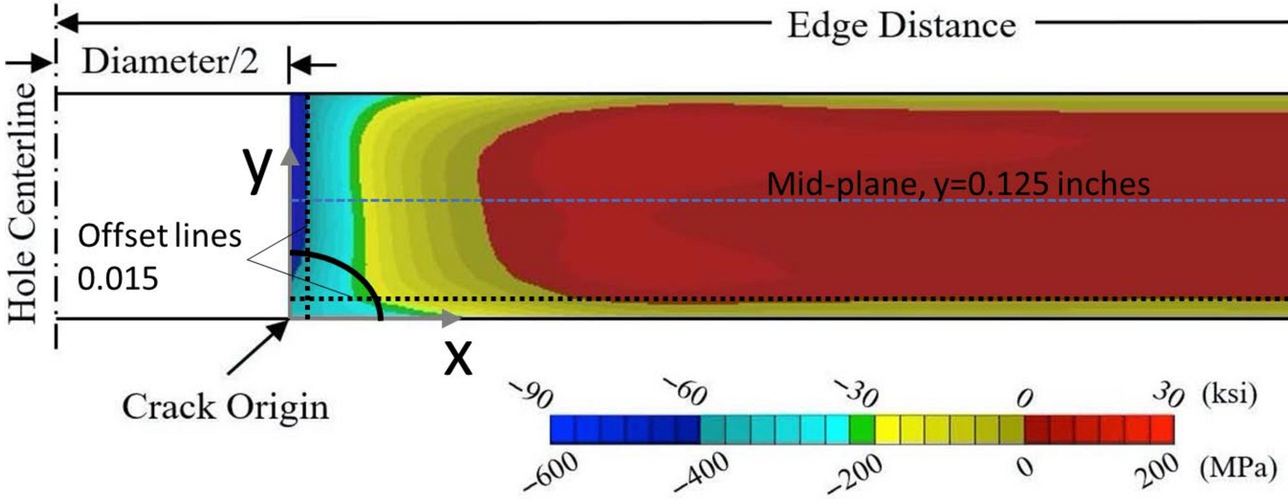
ENGINEERED RESIDUAL
STRESS IMPLEMENTATION

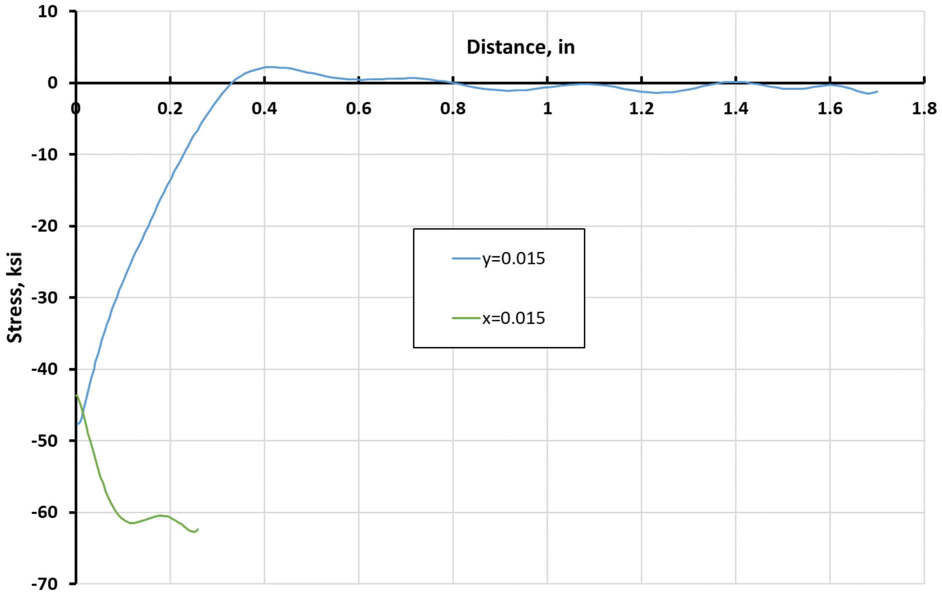
Rate Data



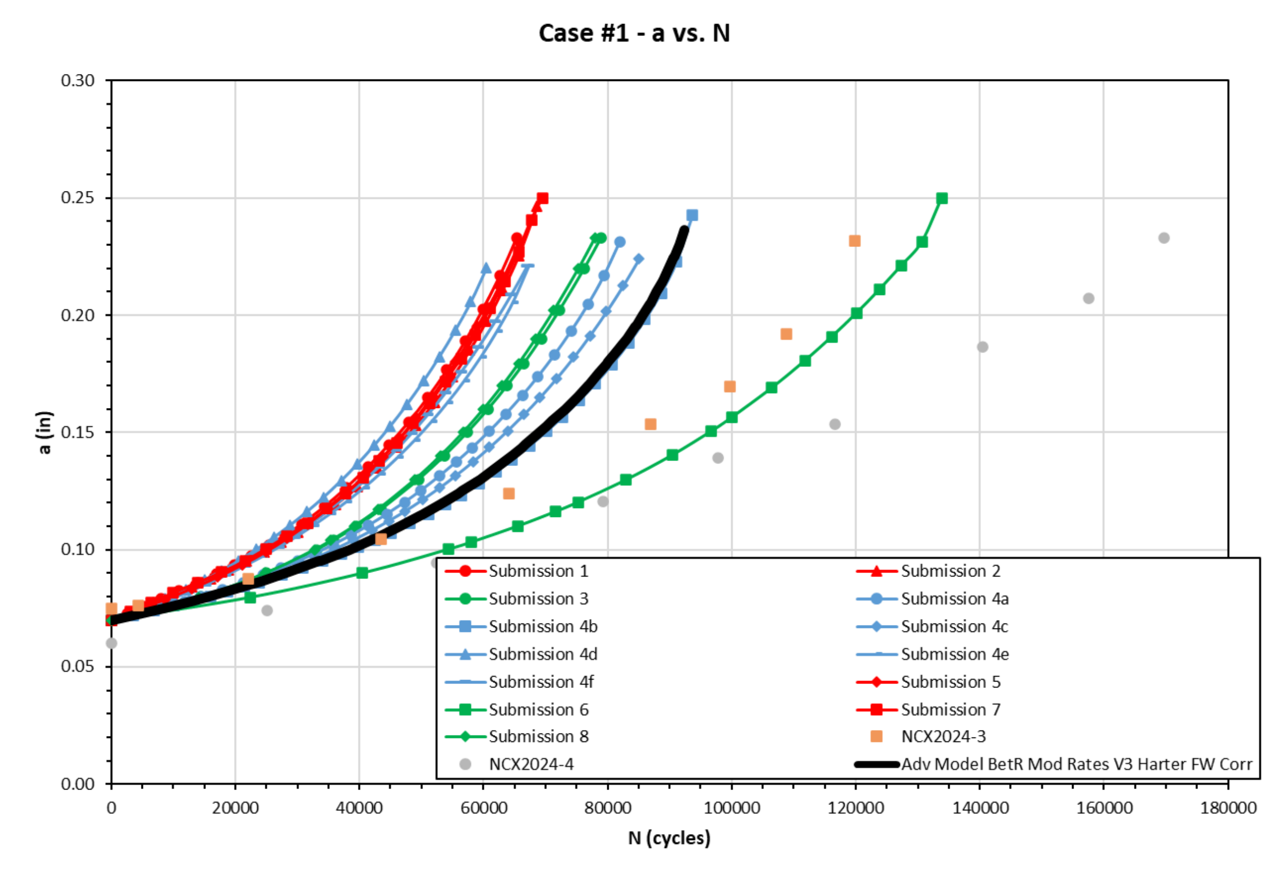
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

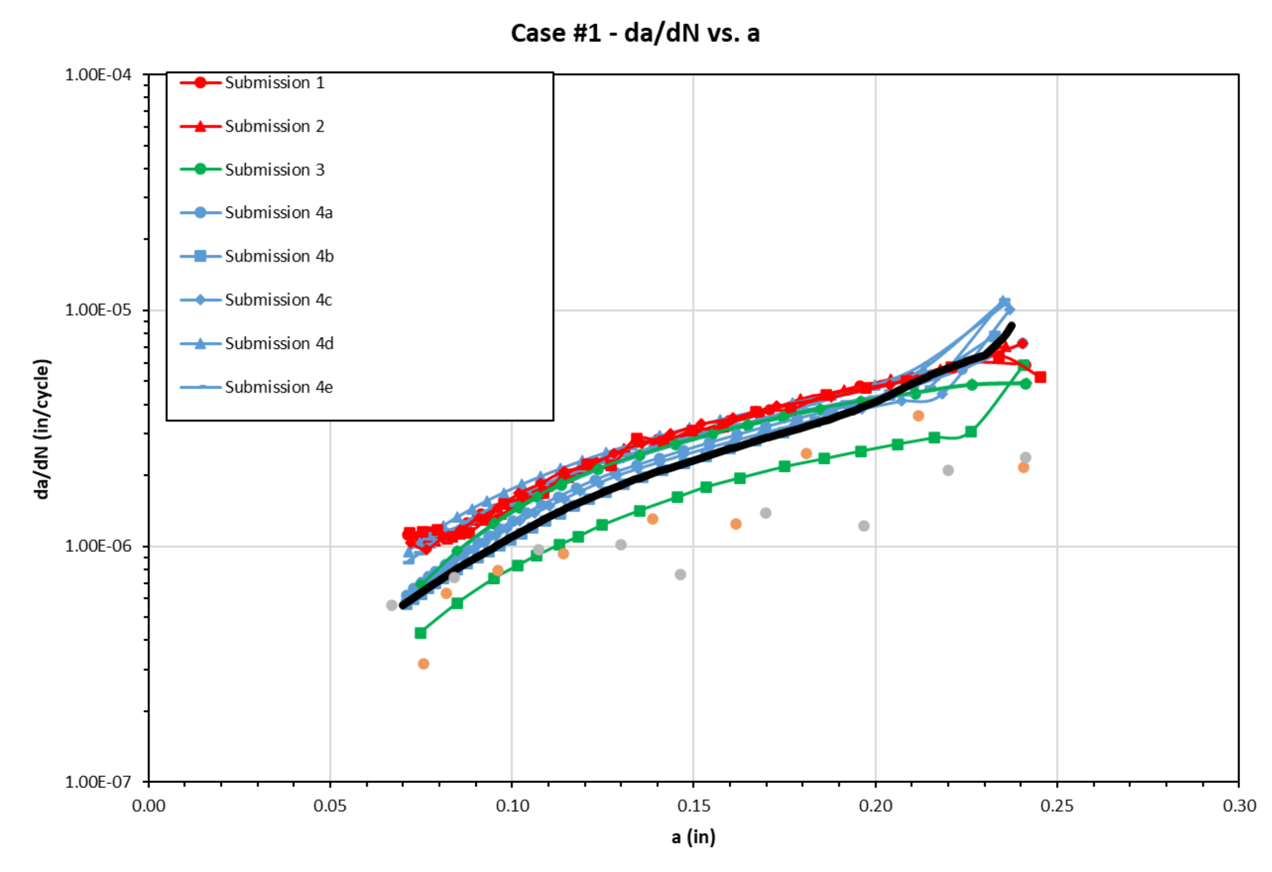
Offset distance – found 0.015 worked best





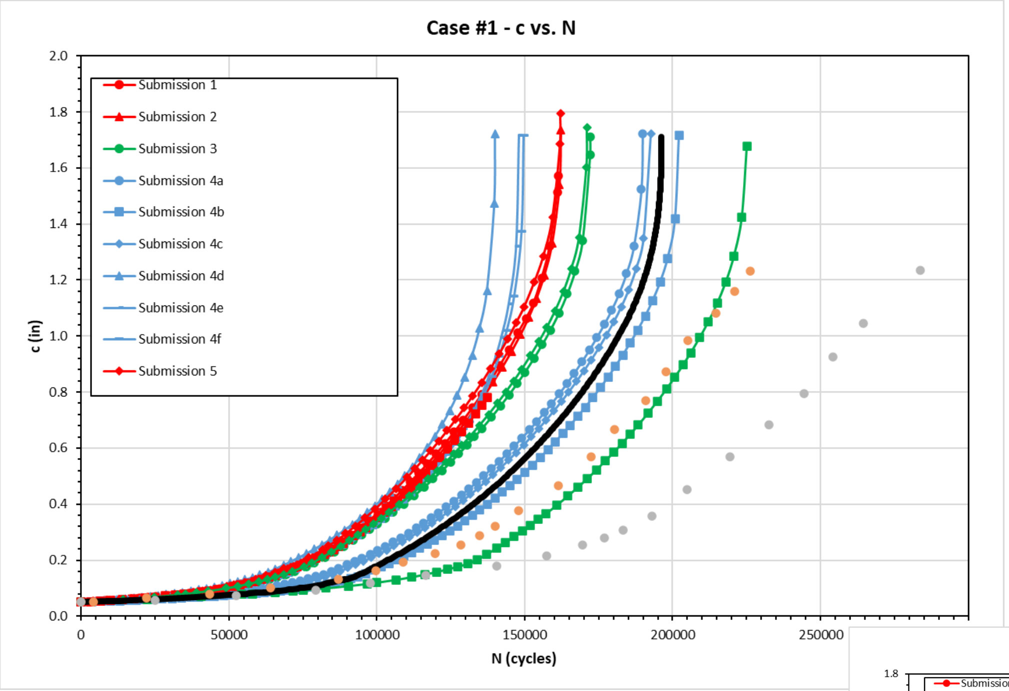
Results – Case 1 no Cx CA R=0.1 10 ksi

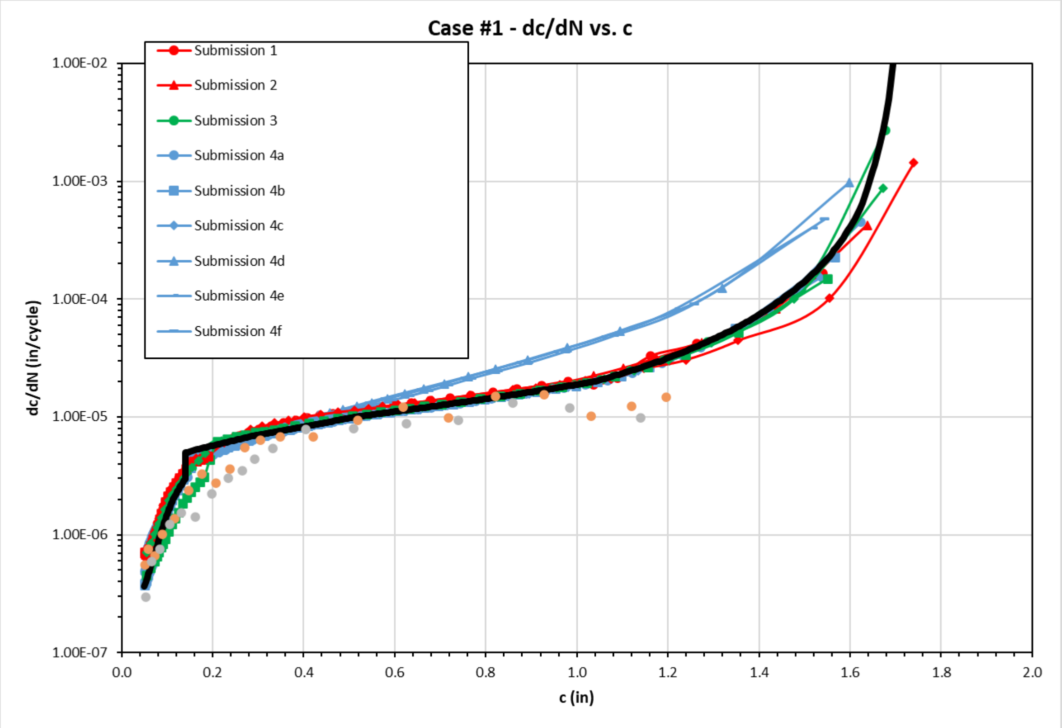


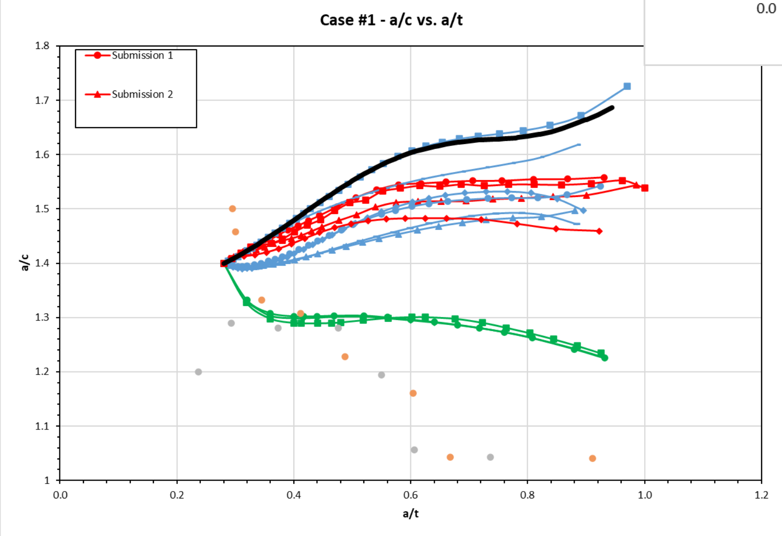


ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Results – Case 1 no Cx CA R=0.1 10 ksi

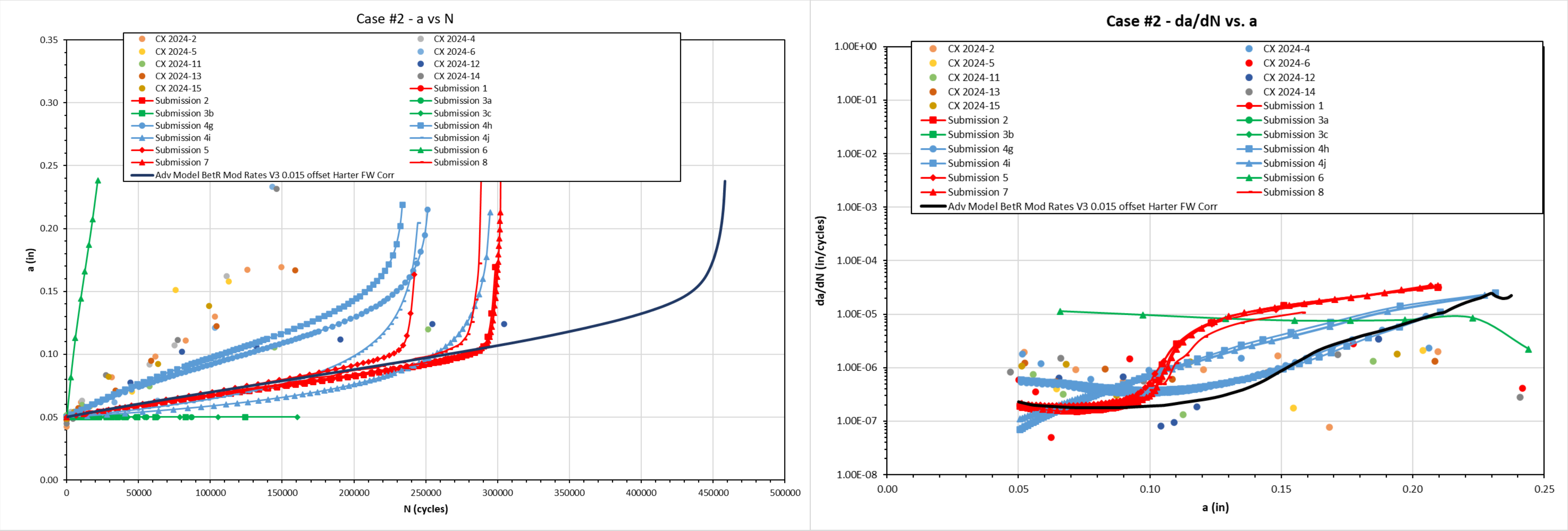






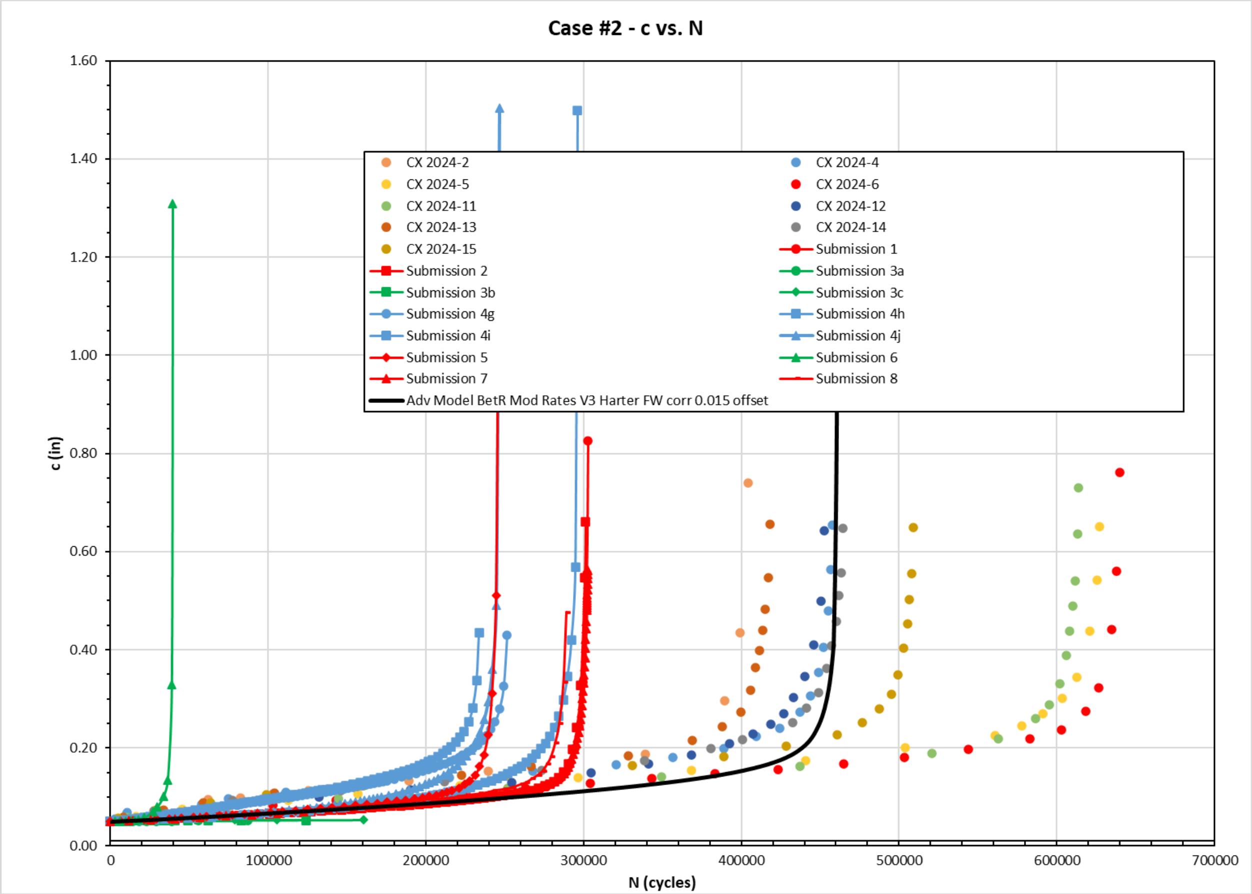
ERSI ENGINEERED RESIDUAL STRESS IMPLEMENTATION

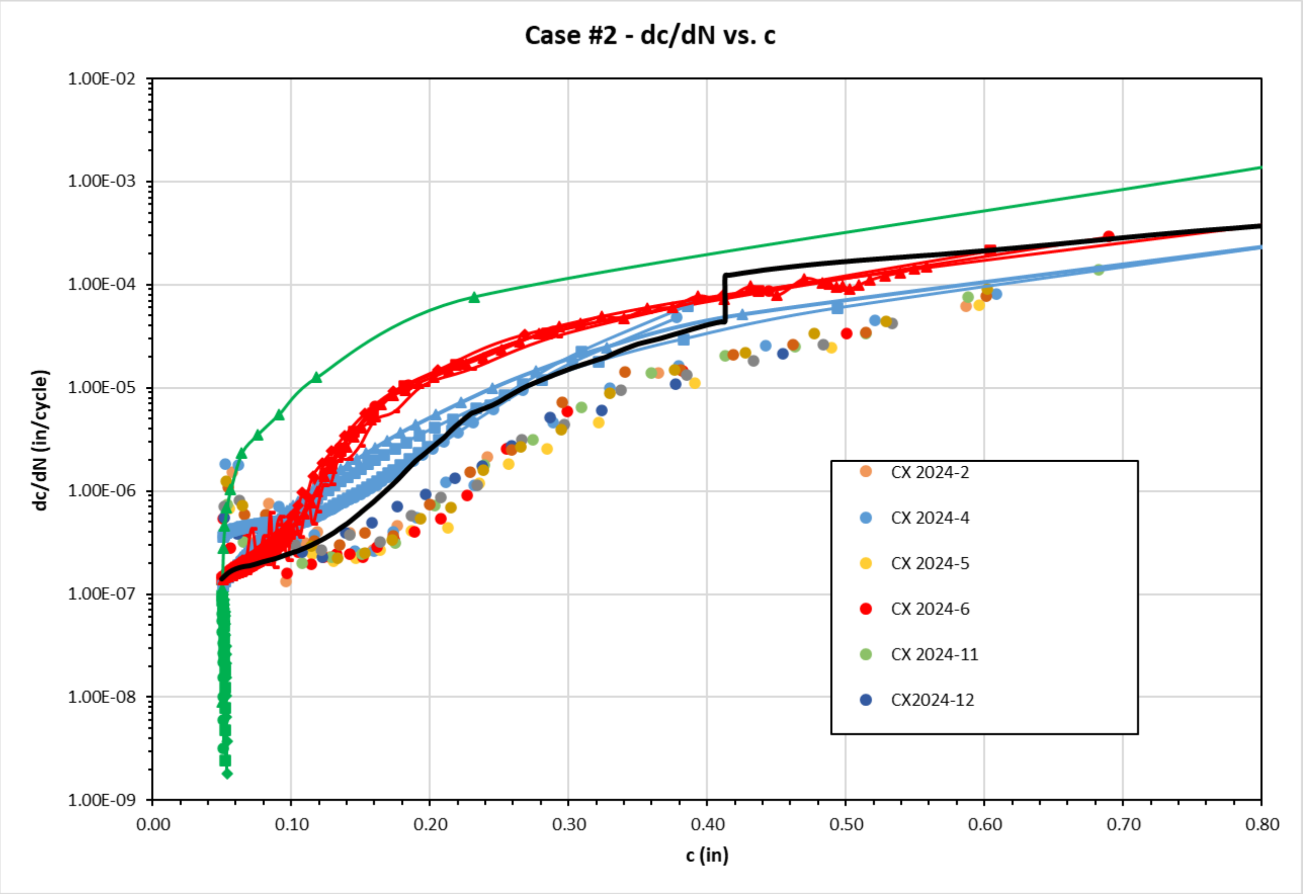
Results – Case 2 Cx CA R=0.1 25 ksi



ERSI ENGINEERED RESIDUAL STRESS IMPLEMENTATION

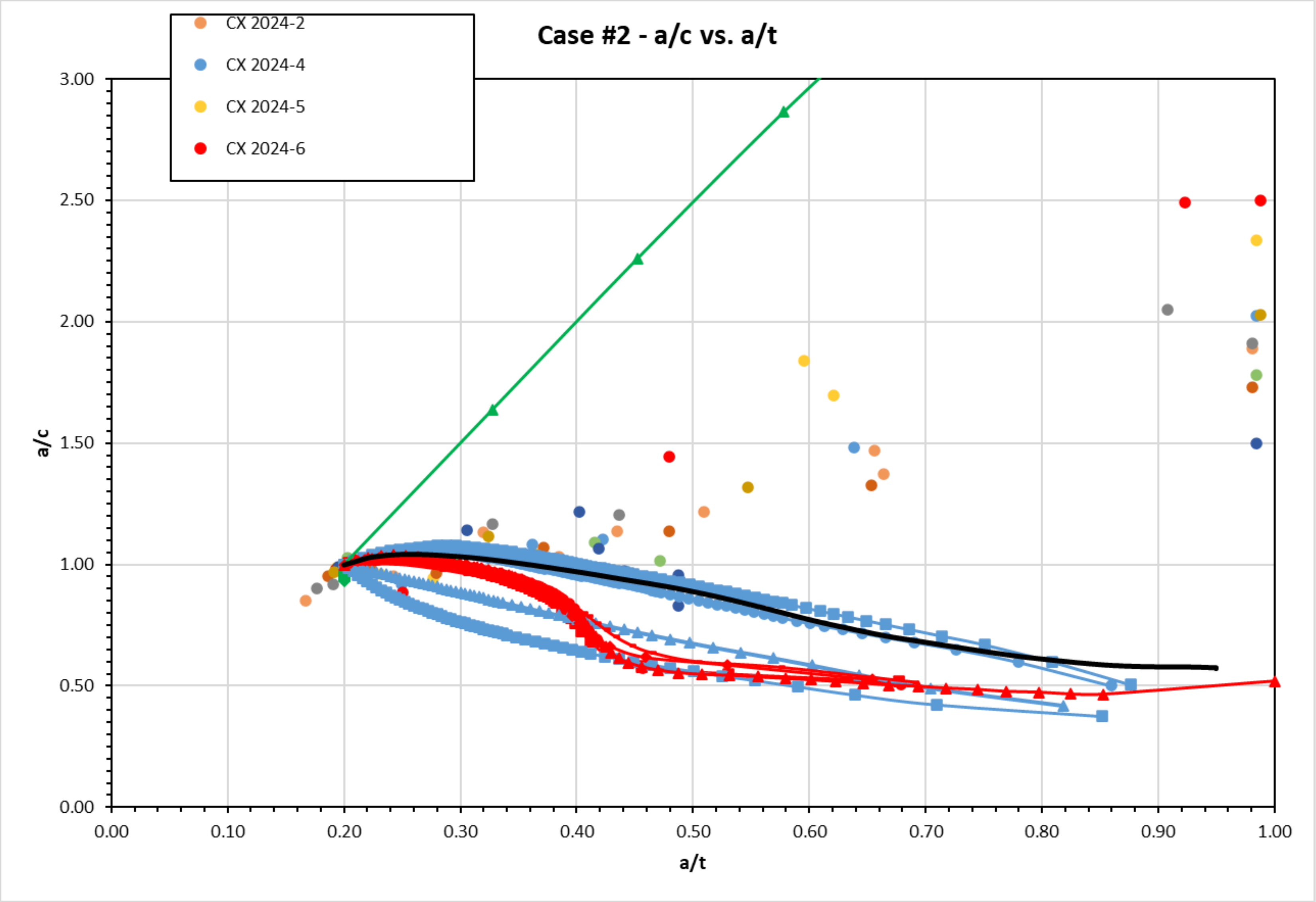
Results – Case 2 Cx CA R=0.1 25 ksi





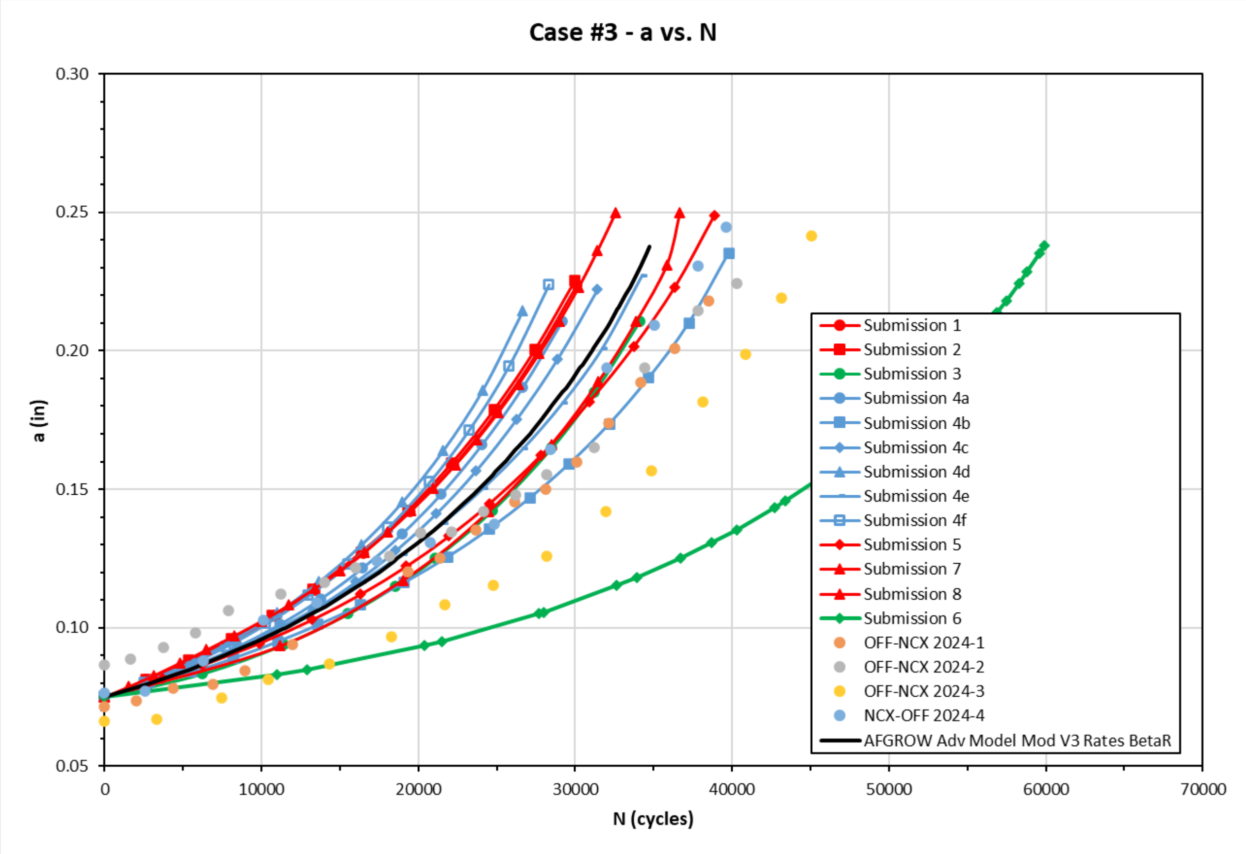
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

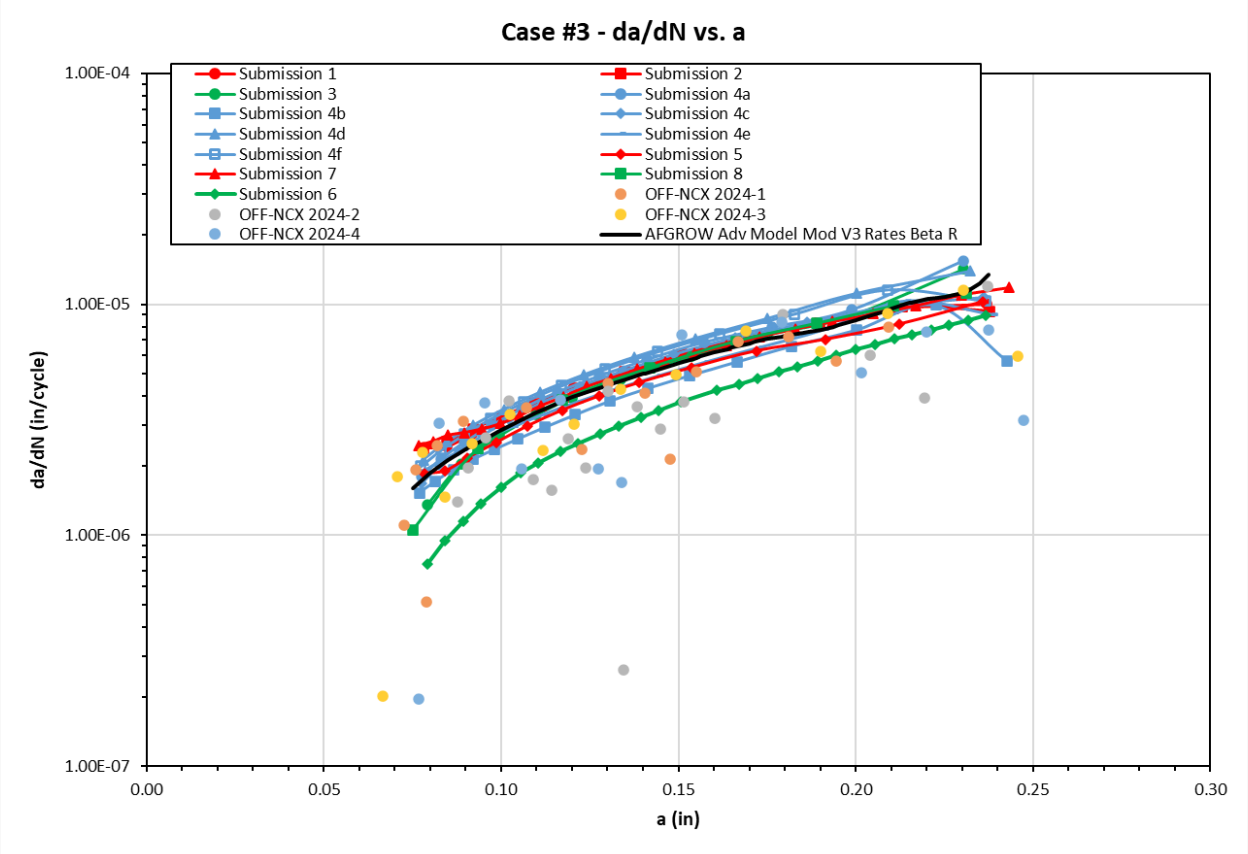
Results – Case 2 Cx CA R=0.1 25 ksi



ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

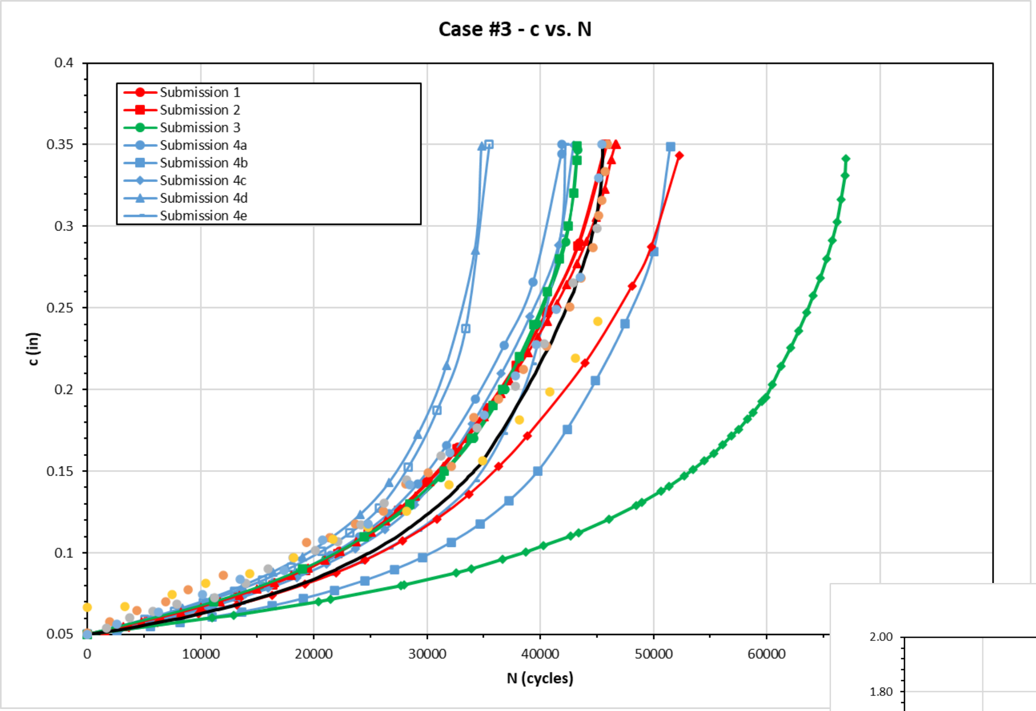
Results – Case 3 no Cx CA R=0.1 10 ksi

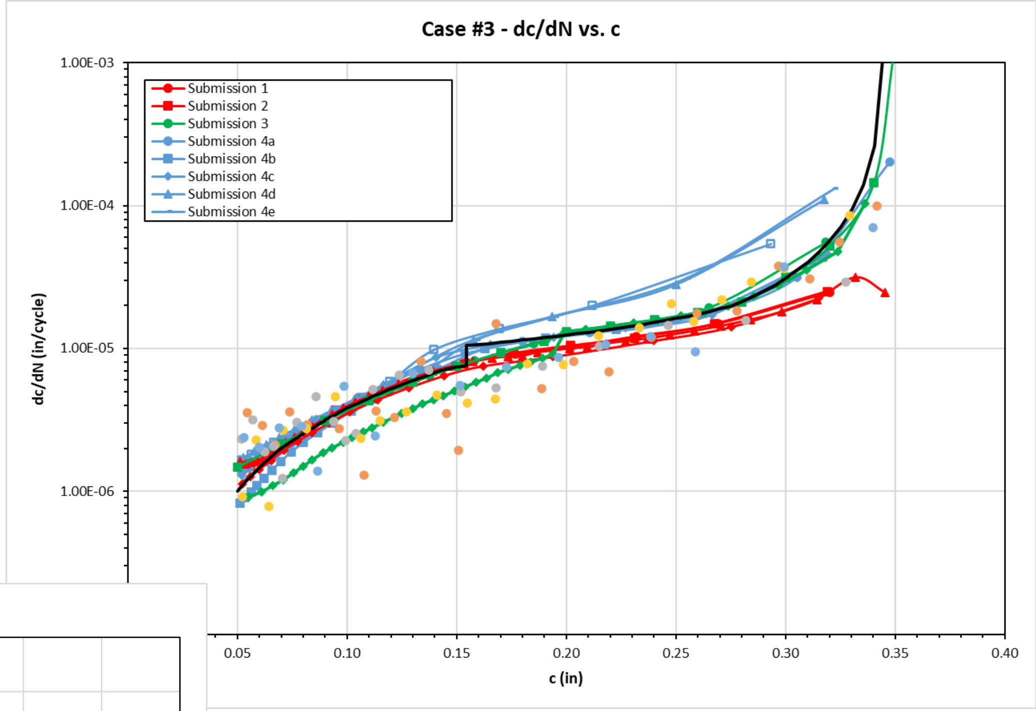


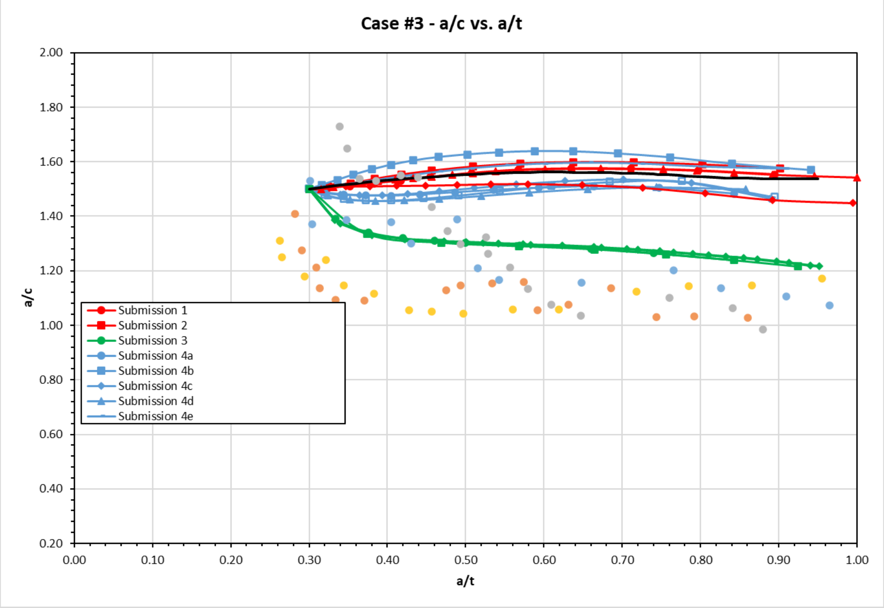


ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Results – Case 3 no Cx CA R=0.1 10 ksi

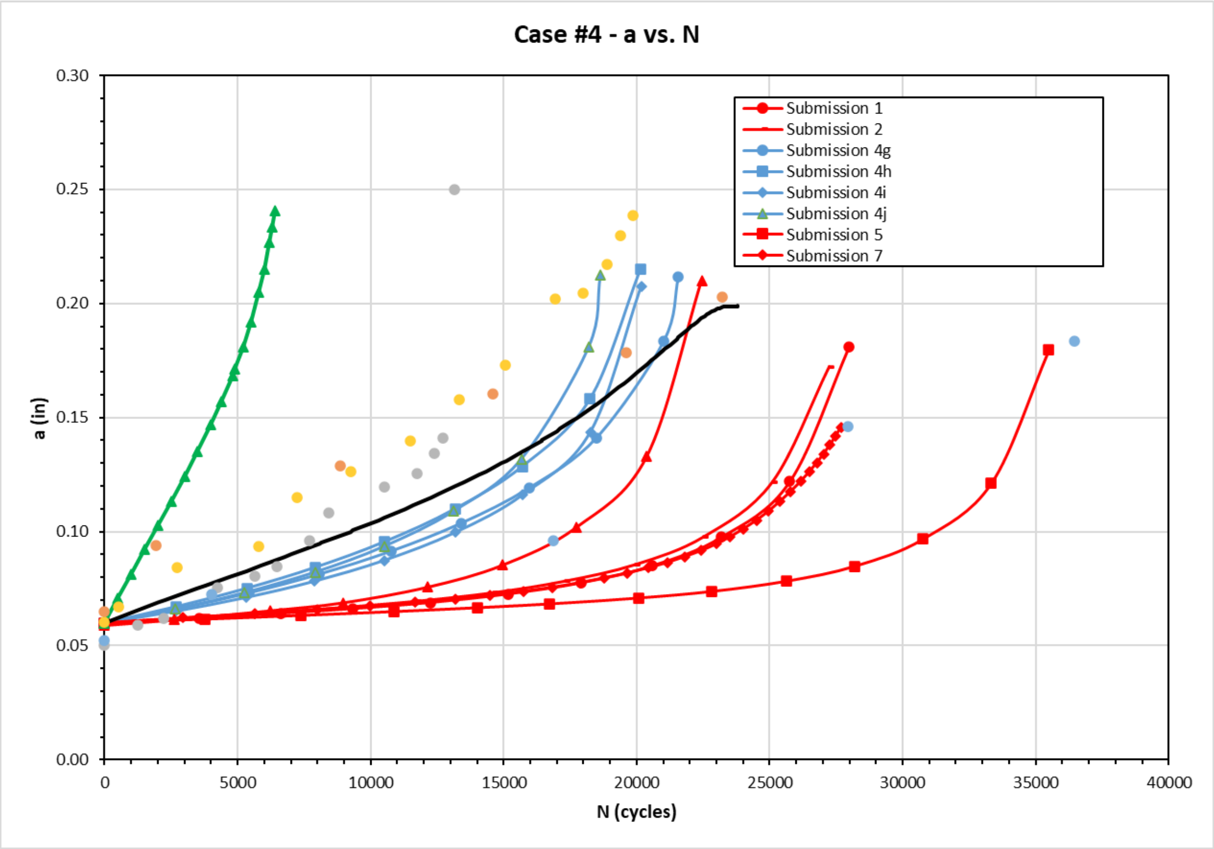


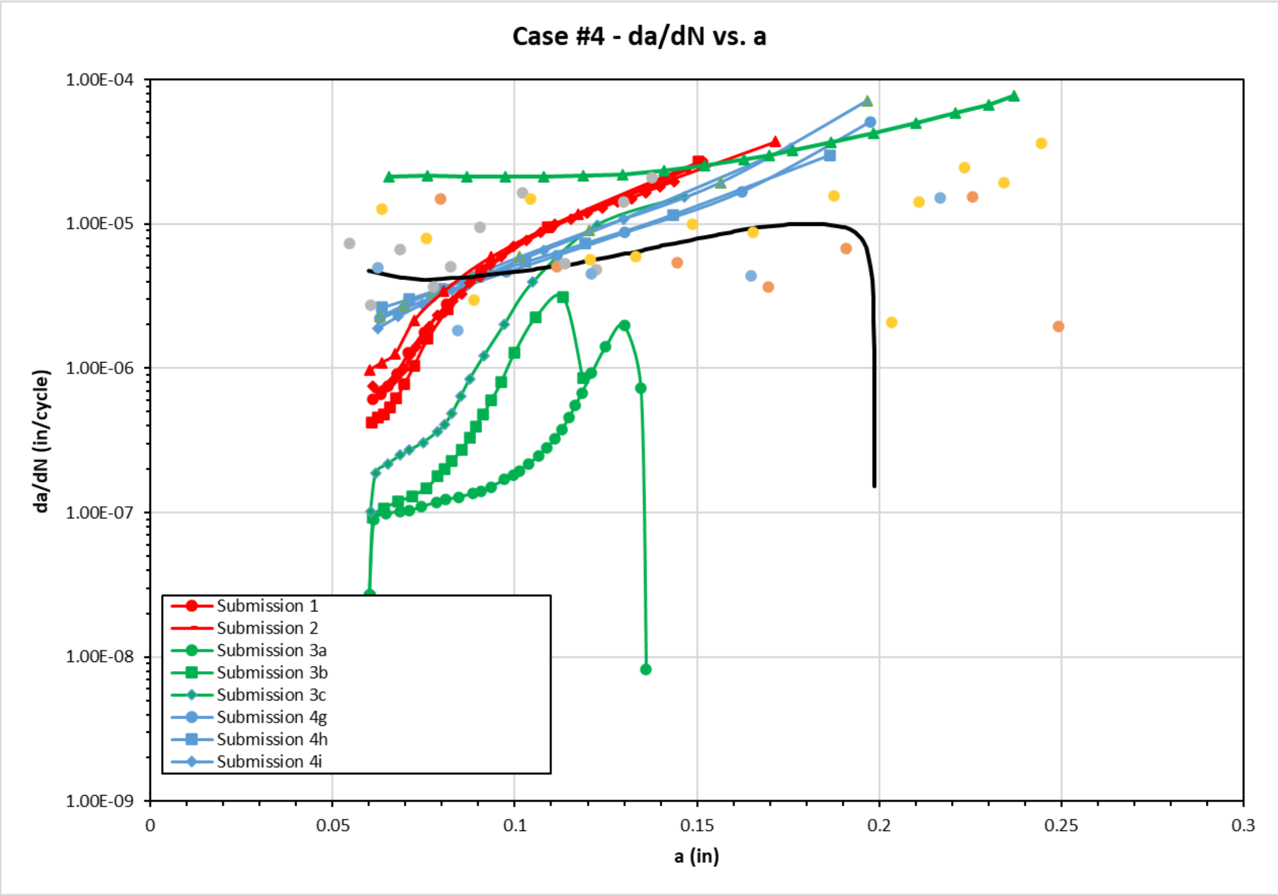




ENGINEERED RESIDUAL STRESS IMPLEMENTATION

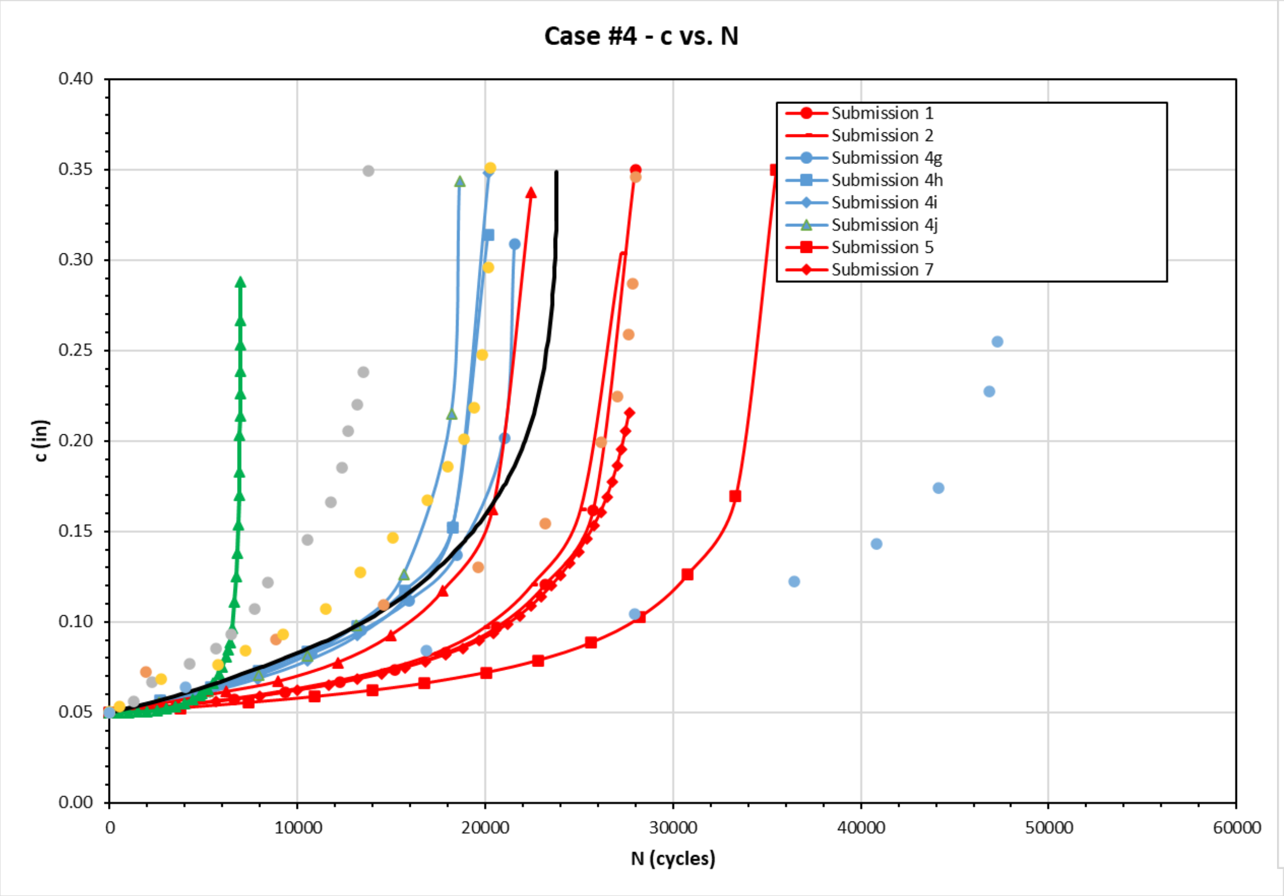
Results – Case 4 Cx CA R=0.1 25 ksi

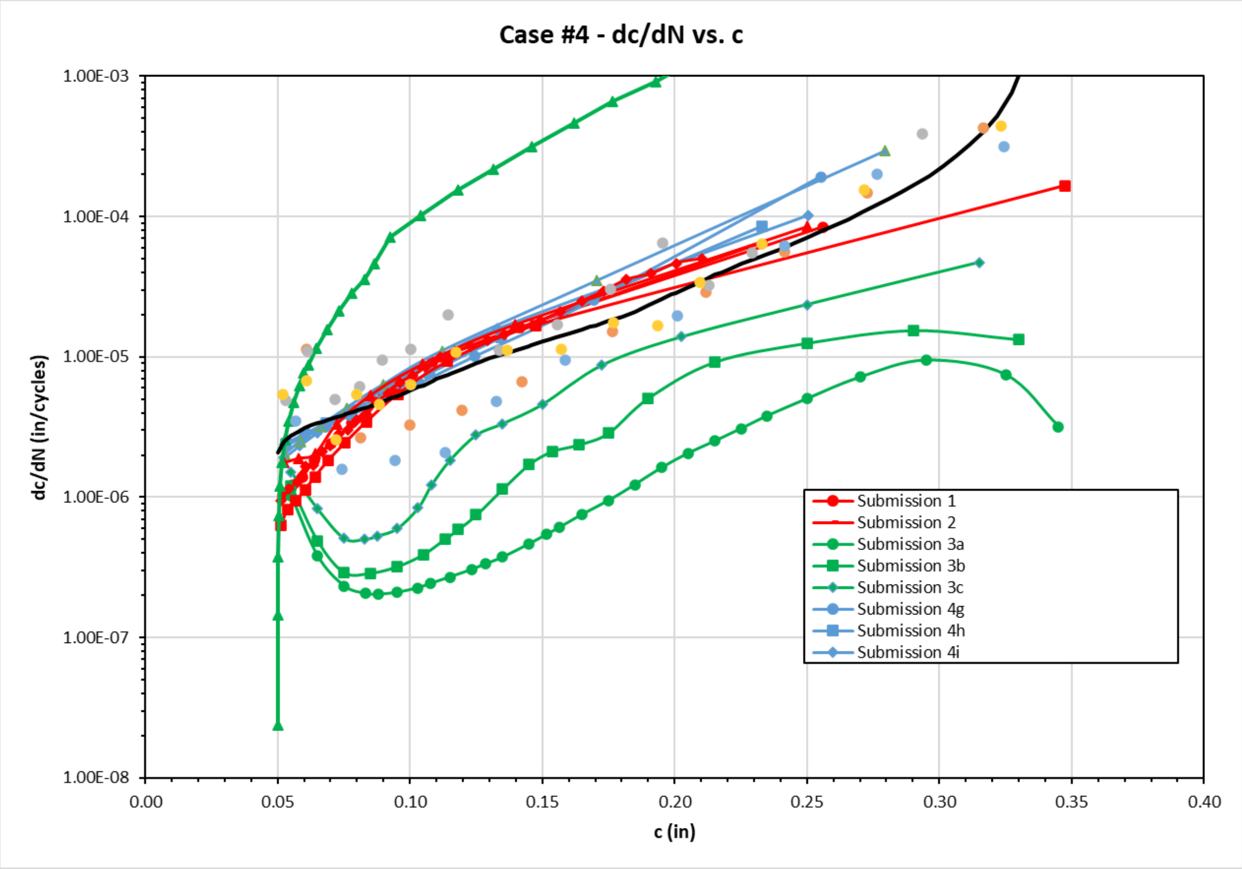




ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Results – Case 4 Cx CA R=0.1 25 ksi





Results – Case 4 Cx CA R=0.1 25 ksi