ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Fatigue Crack Growth & Testing Committee

2024 ERSI Workshop

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Overview

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

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Roster Summary

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

Vision

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

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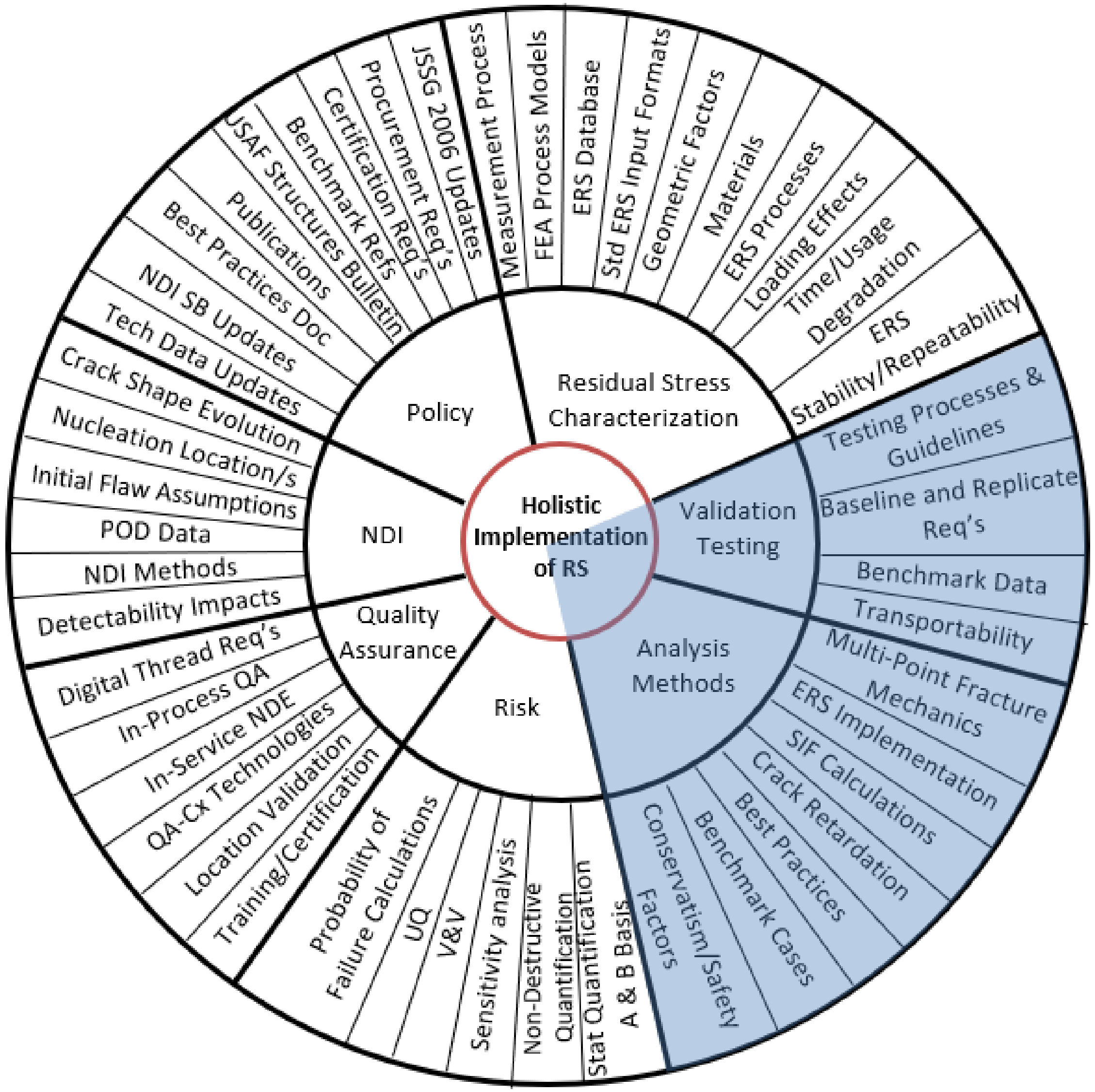
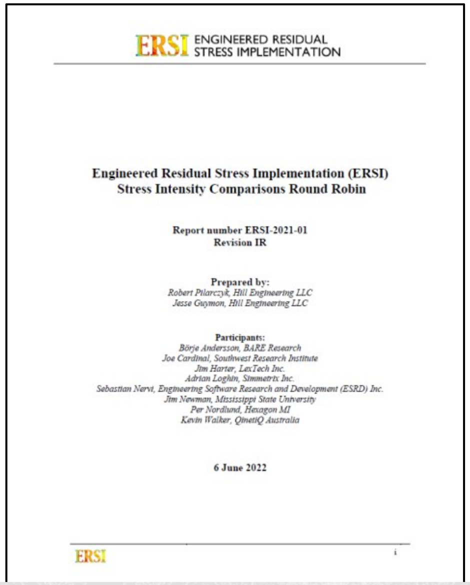
Implementation Roadmap

- **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



Accomplishments

- **SIF round robin**
  - Final report
    - Complete
  - Publications
    - Data and final report loaded to ERSI website
    - Summary included by Börje Andersson in the Swedish National ICAF 2023 Review
  - Presentations
    - Presented at 2022 ASIP conference by Kevin Walker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Engineered Residual Stress Implementation (ERSI)
Stress Intensity Comparisons Round Robin

Report number ERSI-2021-01
Revision IR

Prepared by:
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6 June 2022

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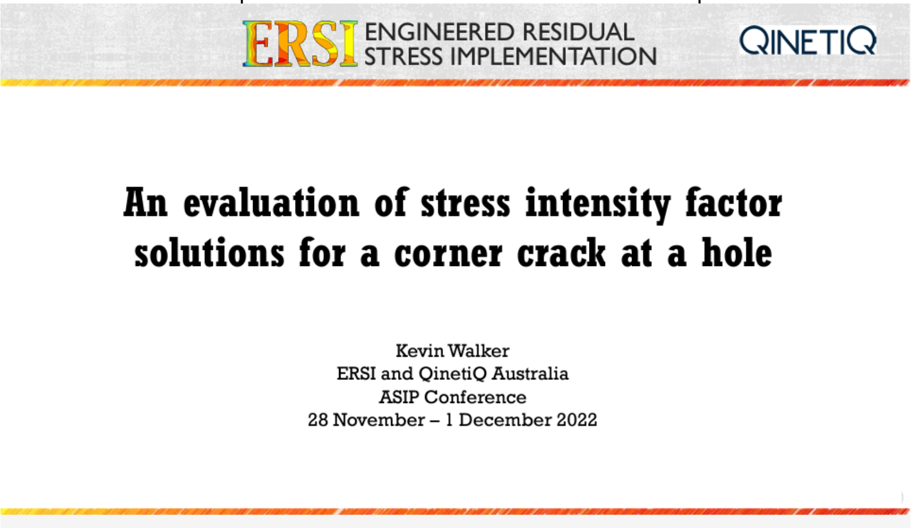


Accomplishments

- **DTA for variability in residual stresses at cold expanded holes round robin**
  - Objective
    - Identify the sensitivity of DTA, both two-point and multi-point, capabilities to variability in a CX fastener hole treated within specifications
  - Approach
    - Phased approach with increasing complexity (Complete)
      - Phase I: Baseline (non-CX) DTA verification for both CA and VA spectra (corresponding Nf test data released after receipt of prediction results)
      - Phase II: CX treated DTA predictions for both CA and VA spectra
    - Validation testing sponsored by AFRL/RX and RQ (Ongoing)
  - Current Status
    - Phase I & II: Complete!
    - Presentations by TJ Spradlin and Pete Phillips at 2023 ASIP Conference
    - Further work to complete fractography on all specimens ongoing
    - Bob Pilarczyk seeking insights from RR participants around lessons learned

Focus Areas

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

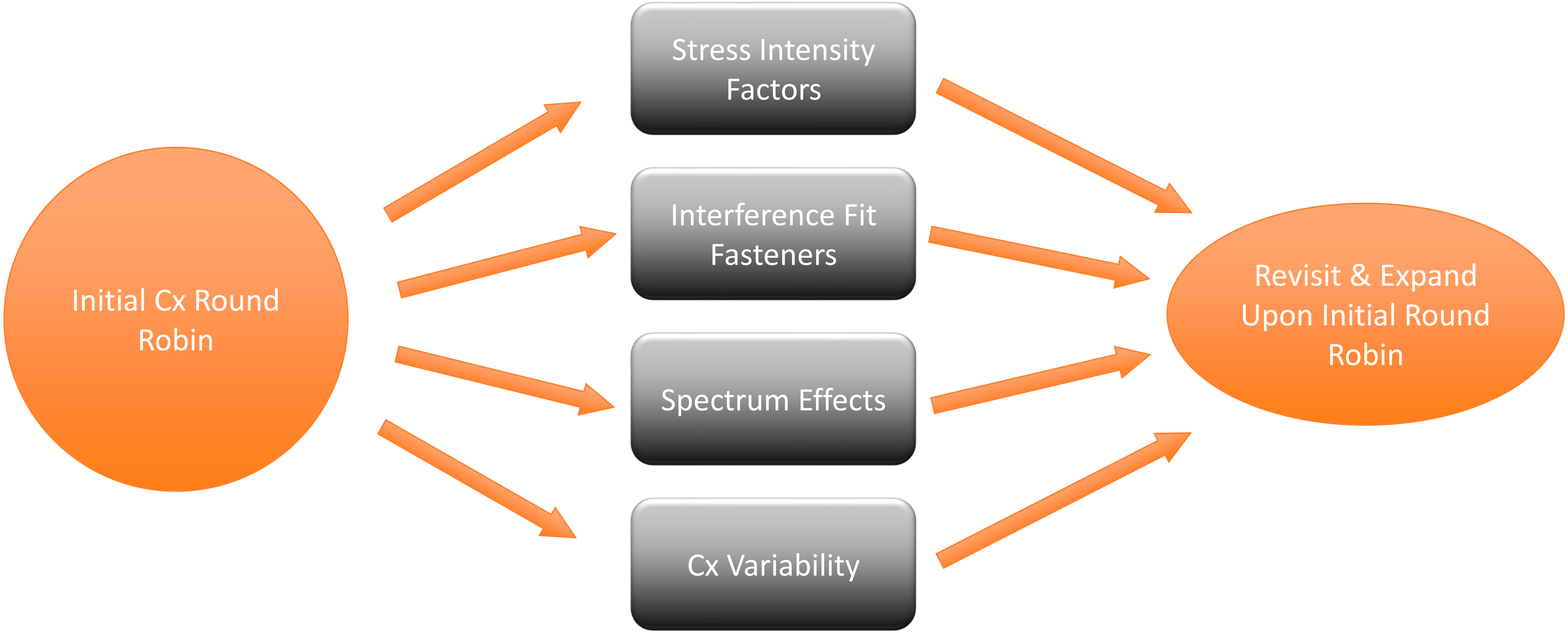
Spectrum Loading Working Group

- **Participation**
  - ~ 10 members
- **Objectives**
  - Collaborate to understand load interaction effects on crack growth using simple spectrum loading (spike overload) and spectrum loading. Validate and understand limitations of proposed modeling for plastic tip 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)

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)

Revisiting Previous Round Robins



Past	Present	Current Focus

Revisiting Previous Round Robins

- **The team noted the need to go back to previous round robins**
  - Understand key factors influencing predictions
  - Utilize updated methods to complete post-dictions
  - Collectively develop best practices and lessons learned
- **Leveraging the work above, complete a new round of predictions as a team for the upcoming dataset from A-10**
  - Dataset provides an opportunity for building block approach with non-cx and cx holes, constant amplitude and spectrum loading, markerbands/fractography, etc.
  - Need to decide how we approach it as a committee vs. individual round robin effort
  - Leverage efforts from Spectrum Loading Working Group
  - Future tests could also incorporate IFF

Revisiting Previous Round Robins

- **Proposed Approach**
  - 1 – Review Lesson's Learned
    - Review each relevant Round Robin and document key lessons learned
    - Capture actionable items based on lessons learned
  - 2 – Capture Key Analysis Factors
    - Categorize key analysis factors and document findings from each Round Robin
    - Example categories:
      - FCGR material data (in work)
      - Root SIF solutions (in work)
      - Multi- vs two-point crack front
      - Residual stress source, processing, etc. (in work)
  - 3 – Resolve Questions
    - Collectively work action items based on reviews above to resolve and refine best practices
  - 4 – Recomplete Analyses
    - Methodically complete post-dictions of previous Round Robins
  - 5 – Document Best Practices
    - Based on efforts above, document recommended approach and best practices
  - 6 – Blind Predictions – New A-10 Data
    - Complete blind predictions for select new A-10 test conditions

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Revisiting Previous Round Robins

No.	Title	Lead	Material etc
1.	IFF Round Robin (2022, in-work)	Bob Pilarczyk	2023-T351, monotonic data provided, no rate data yet
2.	MAI Round Robin (2022, completed)	T.J. Spradlin	7050-T7451, material data provided in AFGROW format
3.	Stress Intensity Factor Round Robin (2021, completed)	Bob Pilarczyk	No material data needed
4.	Cx Round Robin (2017, completed)	Bob Pilarczyk	2024-T351, material data provided in AFGROW format
5.	AFGROW Workshop Round Robin (2017, completed)	Jim Harter	7075-T651, rate data provided for R=0.1
6.	AFGROW Workshop RR (2021) – Completed	Kevin Walker	7075-T6, material data not provided
7.	Boeing Spectrum Challenge (2022) – Completed	Moises Ocasio	7075-T651, some rate data provided
8.	DST Assist Wide Plate spectrum challenge (2019) – Completed	Kevin Walker	7075-T7351, rate data not provided
9.	Validation of Fatigue Crack Growth Modeling Solutions using Measurements Collected on API X65 Piping Specimens, Adrian Loghin and Jim Harter	Adrian Loghin	
10.	Walker/Newman IRAD (2022) In work	Kevin Walker	2024-T3, 7075-T6, 7075-T7351. Data not provided
11.	IFF RR (2019)	Jake Warner	7075-T651, rate data provided in AFGROW format

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Revisiting Previous Round Robins

- **Subgroups Created**
  - FCGR material data review
    - See subsequent slides
  - Root SIF solutions review
    - See breakout presentation
  - Residual stress sources and processing review
    - See subsequent slides

Rate data sub-group status update

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Rate data sub-group status

- Earlier efforts reviewing ERSI RR#1 (Crack growth under CA loading at Cx and Non Cx holes 2024-T351 material for central and offset holes) raised questions about the variation in SIF solutions for corner crack at a hole.
- The SIF solution matter was comprehensively investigated and was reported at the 2022 ASIP Conference. We now have a much better understanding of where the traditional SIF solutions have some limitations (mainly for the short edge distance offset hole case).
- Attention then turned to potential differences in rate data from various sources and the implications for analysis efforts
- A sub-group was formed to consider this aspect

Analysis and Test – Rate data sub-group

- **The rate data sub-group includes:**
  - Kevin Walker, QinetiQ Australia
  - Ana Barrientos, Northrop Grumman
  - Moises Ocasio, Boeing
  - Scott Prost-Domasky, APES
  - Bob Pilarczyk, Hill Engineering
  - Jim Harter, LexTech/AFGROW

Materials considered so far

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- Materials involved in previous efforts include:
  - 2024-T3, 7075-T6, 7075-T7351 and 7050-T7451
- 7075-T6 and 2024-T3 were used in several efforts so they were considered first
- Some results as follows

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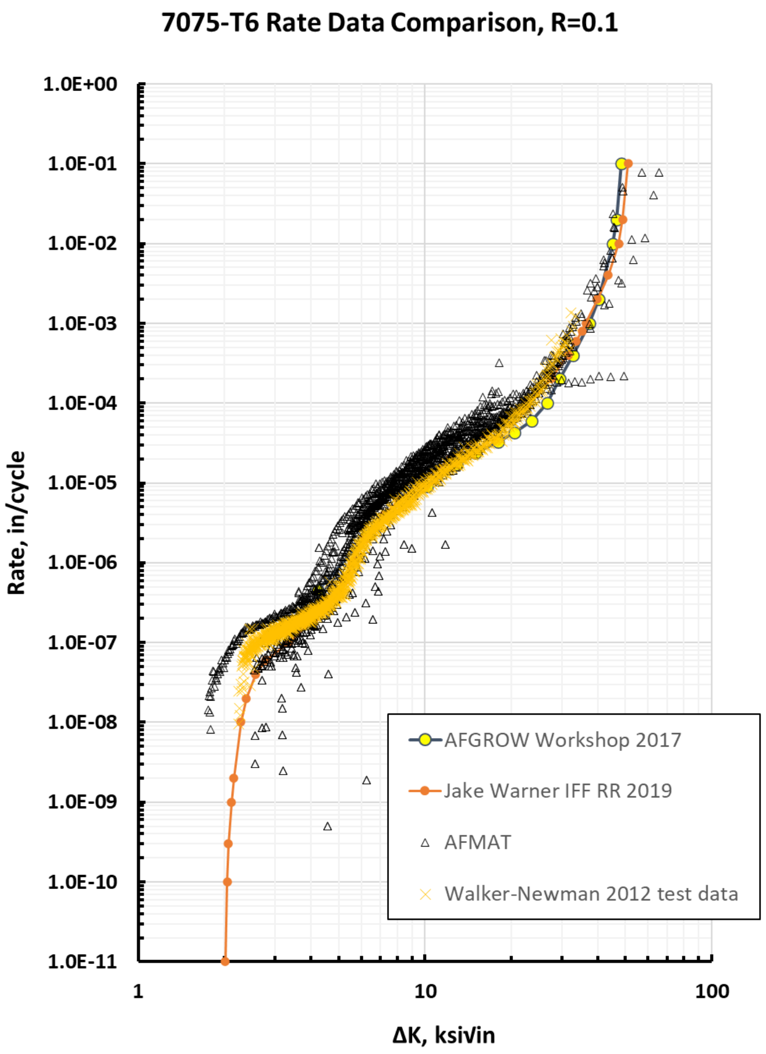
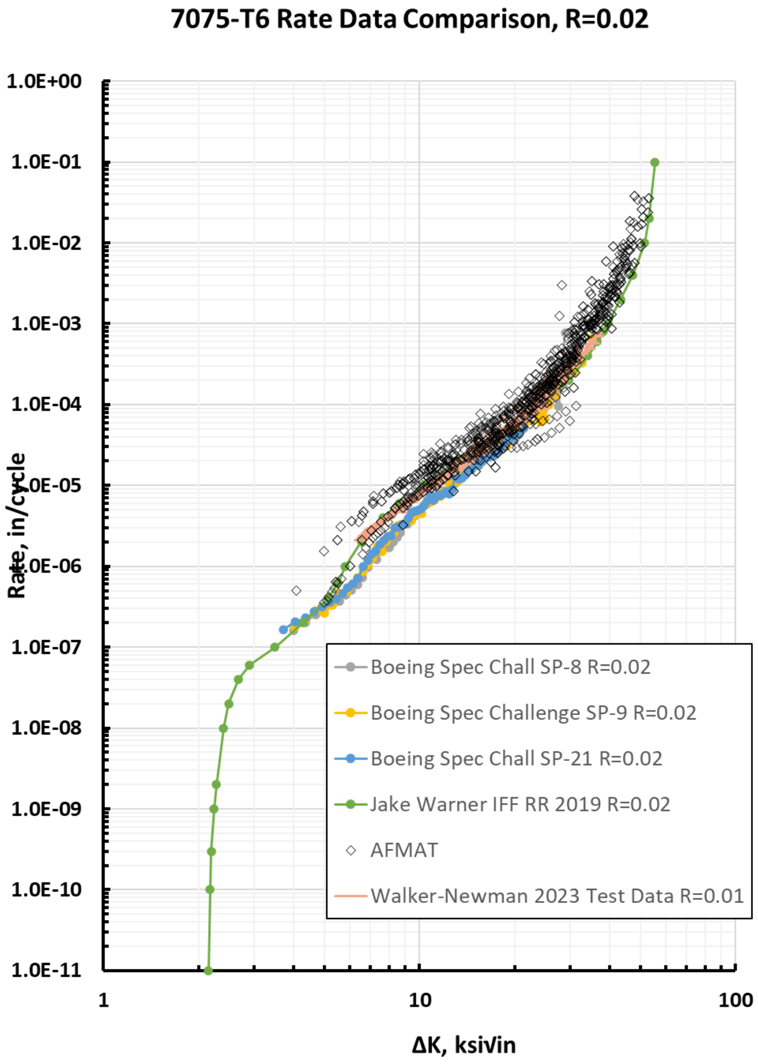
7075-T6 Rate Data

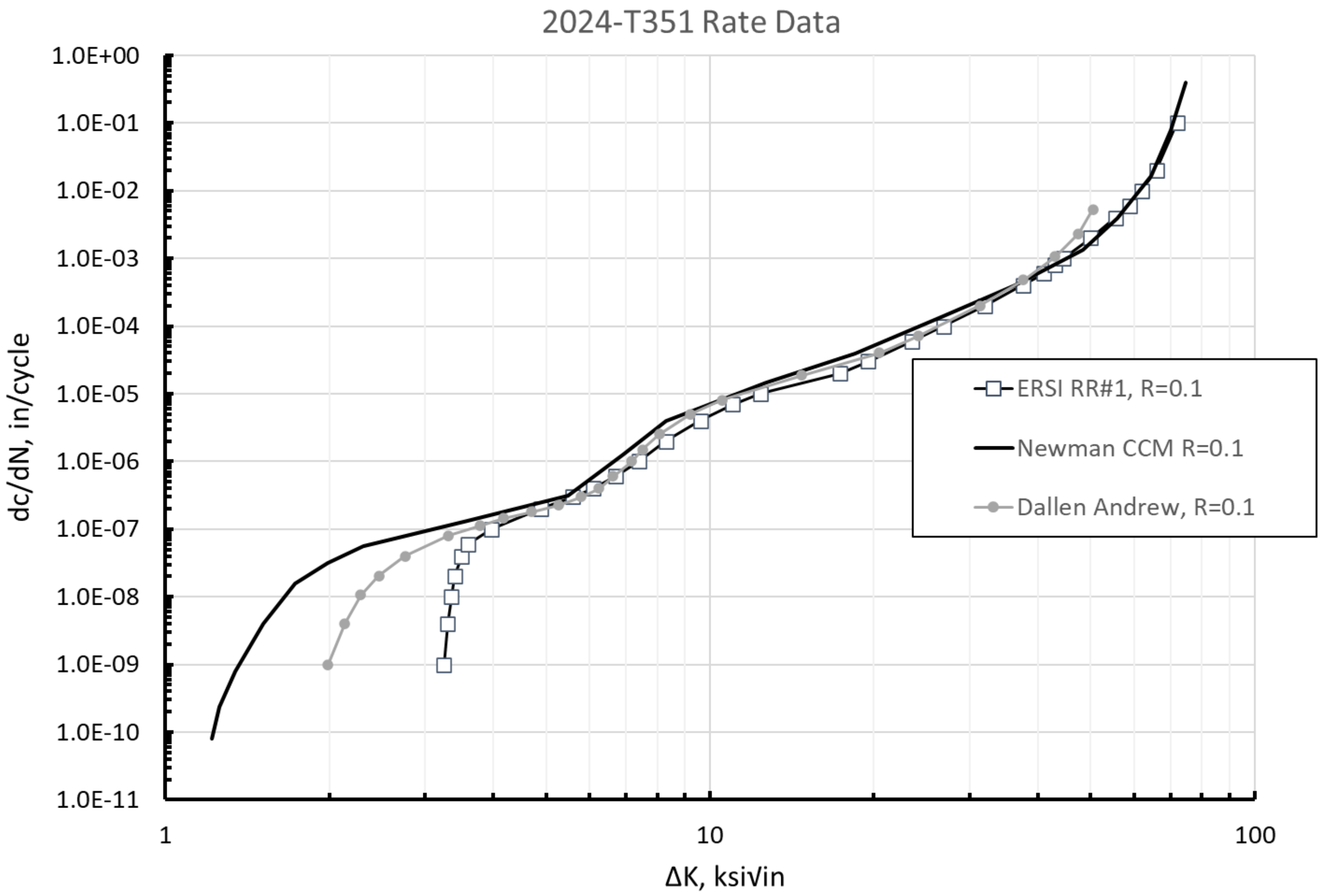
- Data supplied with the RR efforts were compared with other sources of data
- Comparisons are shown at common values of R
- Included data from the AFMAT Database in AFGROW
- Some variability in some AFMAT data, but overall the data were in reasonable agreement





2024-T3 Rate Data

- Data supplied with the RR efforts were compared with other sources of data
- Comparisons are shown at common values of R
- Preliminary comparison only between supplied data from ERSI RR#1 supplied data, Dallen Andrew data, and Newman data suggests significant differences in the threshold and near-threshold region
- Investigation is ongoing, including considering possible implications for RR#1



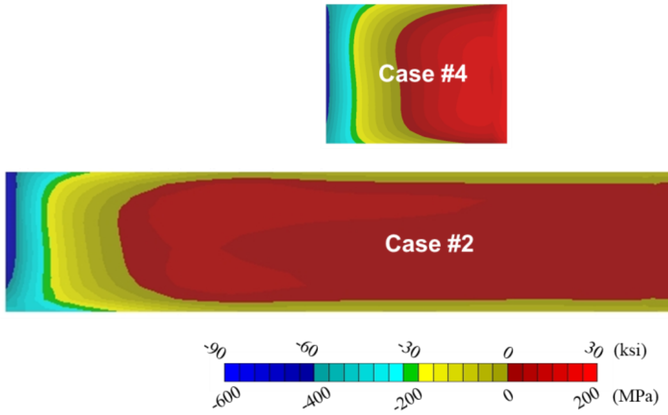
Residual stress inputs sub-group status update

Revisiting Residual Stress Inputs

- **Approach**
  - Review previous round robins with Cx residual stress
  - Capture approaches for residual stress inputs
  - Review their influence on overall predictions
  - Coordinate with participants to understand details and resolve questions
  - Recomplete analyses, where appropriate
  - Document best practices
- **Relevant round robins**
  - (2017-2020) – ERSI Round-Robin Life Prediction Invitation for Centered and Offset Cold Expanded (Cx) Holes
  - (2022-2023) – ERSI/MAI Round-Robin Life Prediction Invitation for Variability in Residual Stresses at Cold Expanded (Cx) Holes

Revisiting Residual Stress Inputs

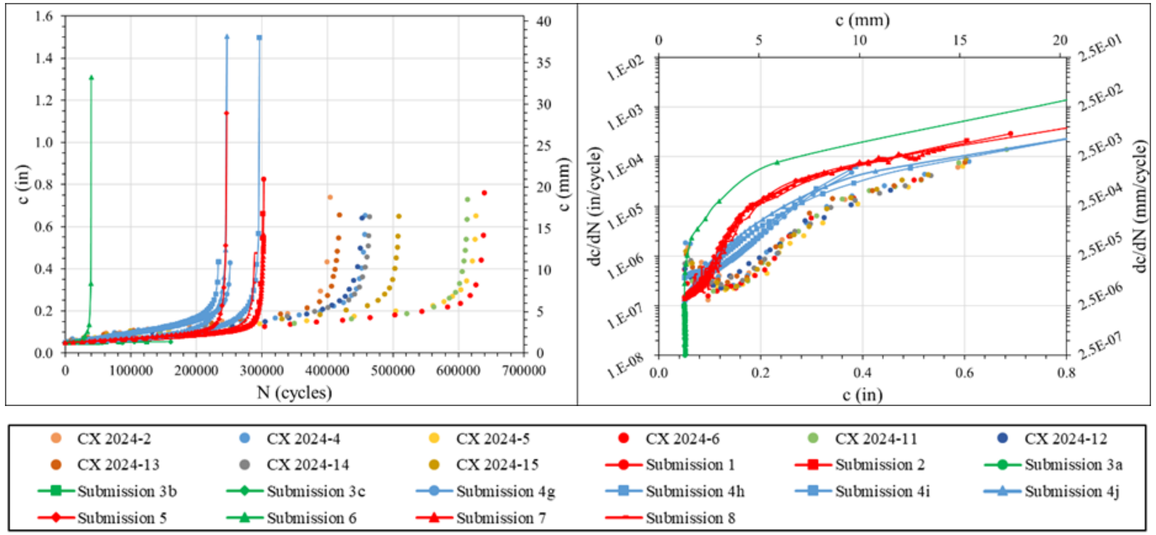
- **(2017-2020) – ERSI Round-Robin Life Prediction Invitation for Centered and Offset Cx Holes**
  - Source of residual stresses
    - Average of (5) and (2) replicate contour measurements for conditions 2 (centered hole) and 4 (offset hole)
  - Implementation
    - Many approaches including:
      - FEA w/ crack face pressure
      - 1-D and 2-D Gaussian Integration
      - Univariant and Bivariant weight functions

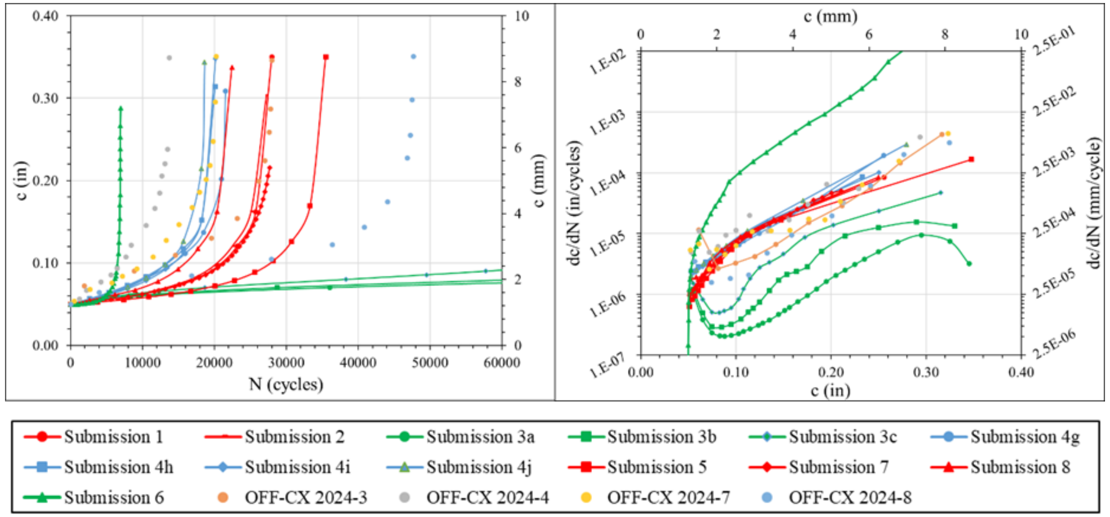


RS Incorporation Approach
Crack Face Pressure (B-Spline)
Crack Face Pressure (Legendre Polynomial)
2-D Gaussian Integration (Free Surface)
2-D Gaussian Integration (5 degrees)
2-D Gaussian Integration (10 degrees)
Bivariant WF
Bivariant WF
Univariant WF
Univariant WF
Polynomial Fit Crack Face Pressure
1-D Gaussian Integration (20% from free surface)
Crack Face Pressure (Legendre Polynomial)
Crack Face Pressure (Legendre Polynomial)

Revisiting Residual Stress Inputs

- **(2017-2020) – ERSI Round-Robin Life Prediction Invitation for Centered and Offset Cx Holes**
  - Results
    - Centered hole conditions
      - Conservative predictions for non-Cx and Cx conditions
      - Mismatch in crack growth curve shapes
      - (Action Item) – rerun predictions w/ updated FCGR material characterization
    - Offset hole conditions
      - Predictions within range of experimental results





Revisiting Residual Stress Inputs

- (2017-2020) – ERSI Round-Robin Life Prediction Invitation for Centered and Offset Cx Holes
  - Follow-up studies
    - Again, conservative predictions for center hole condition (Case #2)
    - SpARS statistical approach reasonable captures test behavior

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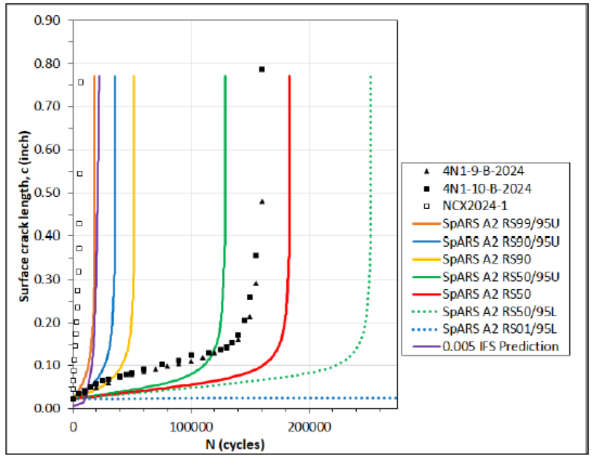
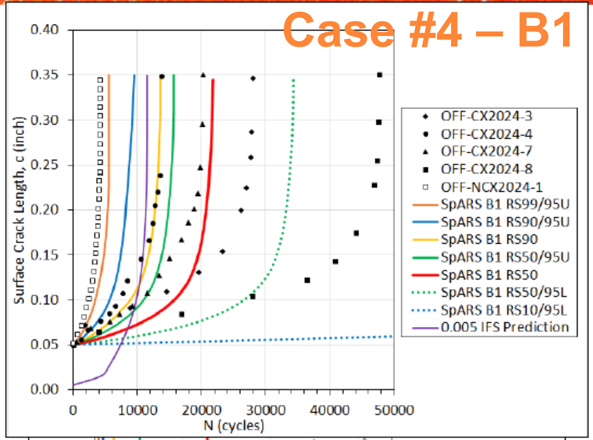
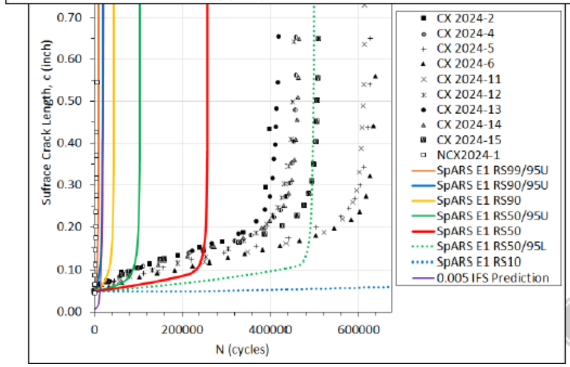
Spatial Analysis of Residual Stress (SpARS) Crack Growth Analysis

- FCG test data (2024-T351)
  - Geometry: W = 4", t = 0.25", D = 0.5"
- Case 'A2'
  - Min (~3.2% Cx)
  - ERS reps = 5,
  - Fatigue reps = 2
- Case 'E1'
  - Mean (~3.7% Cx)
  - ERS reps = 5,
  - Fatigue reps = 9
- Case 'B1'
  - Min (~3.2% Cx)
  - ERS reps = 4,
  - Fatigue reps = 4



Case #4 – B1





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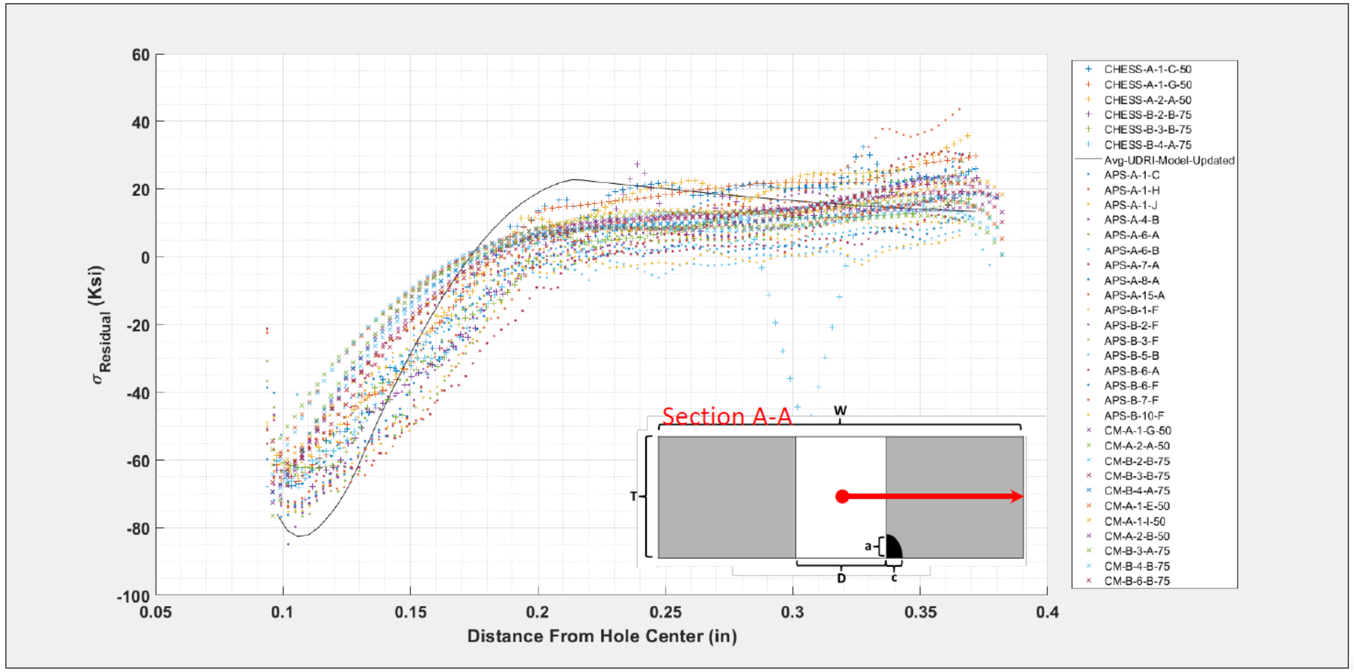
Case #2 – E1

Revisiting Residual Stress Inputs

- **(2022-2023) – ERSI/MAI Round-Robin Life Prediction Invitation for Variability in Residual Stresses at Cold Expanded (Cx) Holes**
  - CX treatment variations meant to represent the nominal and extrema for a given tooling set within specification per FTI-8101
  - Source of residual stresses
    - Energy Dispersive X-Ray Diffraction
    - Contour Method (CM)



Revisiting Residual Stress Inputs

- **(2022-2023) – ERSI/MAI Round-Robin Life Prediction Invitation for Variability in Residual Stresses at Cold Expanded (Cx) Holes**
  - Approach
    - Analyst allowed to implement RS as they saw fit
    - Question 3 from submission survey: How were Residual Stresses incorporated into your analysis?
  - Status
    - Currently collaborating with participants to understand details of approach for residual stress implementation
    - Gathering inputs and summarizing key findings
    - Assumptions/approach can play a significant role and obfuscate the key takeaways from the round robin

Breakout Presentations

- **Walker/Newman IRAD Testing and Analytical Modelling - Moises**
- **Spectrum loading effects – Building Block Approach – Moises**
- **SIF Evaluations of Recent MAI Round Robin - Adrian**
- **IFF Round Robin – Renan**
- **IFF Testing - Lucky**

Future Plans

- **Key focus areas for 2024-2025**
  - Re-visit initial ERSI Cx round robin
  - Continuation of Interference Fit Fastener work
  - Extend Spectrum effects work into cases with cold work and interference fit fasteners

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

Analysis and Test
QinetiQ sponsored spectrum and spike overload test and analysis

Kevin Walker (presented by Moises Ocassio)
April 2024

QinetiQ sponsored IRAD testing and analytical model development for three materials

QinetiQ sponsored IRAD testing and analysis on three materials as follows:

- 7075-T6
- 2024-T3
- 7075-T7351

- Objective was to investigate constraint and constraint-loss effects and develop a robust and reliable modelling approach for spike overloads and spectrum loading
- This is applicable to ERSI objectives because although a lot of work has been done so far under constant amplitude loading to investigate residual stress effects, ultimately it is necessary to also account for load interaction and spectrum effects

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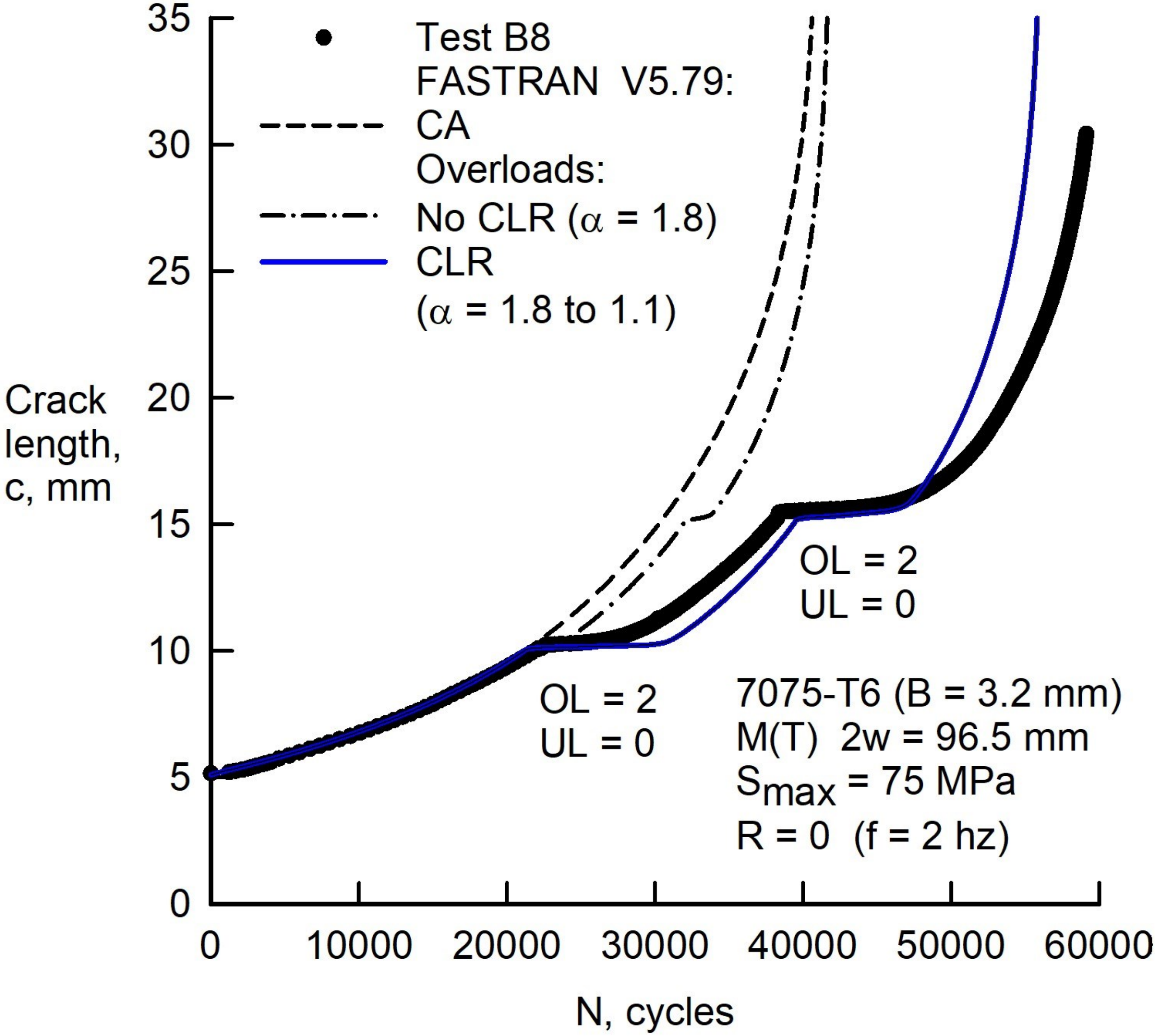
Test summary

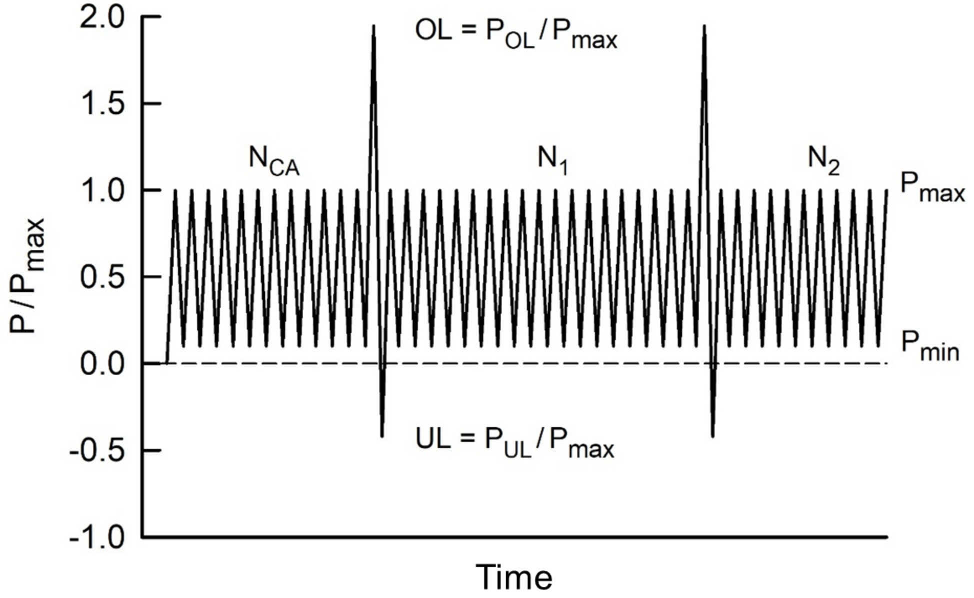
- Middle tension test coupons, approximately 95 mm wide
- 2024-T3, 3.2 mm thick, 24 coupons
- 7075-T6, 3.2 mm thick, 24 coupons
- 7075-T7351, 6.8 mm thick, 9 coupons
- Tests included:
  - Constant amplitude loading at low and high R (0.0 and 0.5) in constraint-loss regime
  - Constant amplitude with spike overloads/underloads
  - Spectrum loading including Mini-TWIST sequence

- 2024-T3 and 7075-T6 tests and analyses conducted at Mississippi State University by Professor Jim Newman
- 7075-T7351 tests and analyses conducted at RMIT University in Melbourne Australia by Kevin Walker

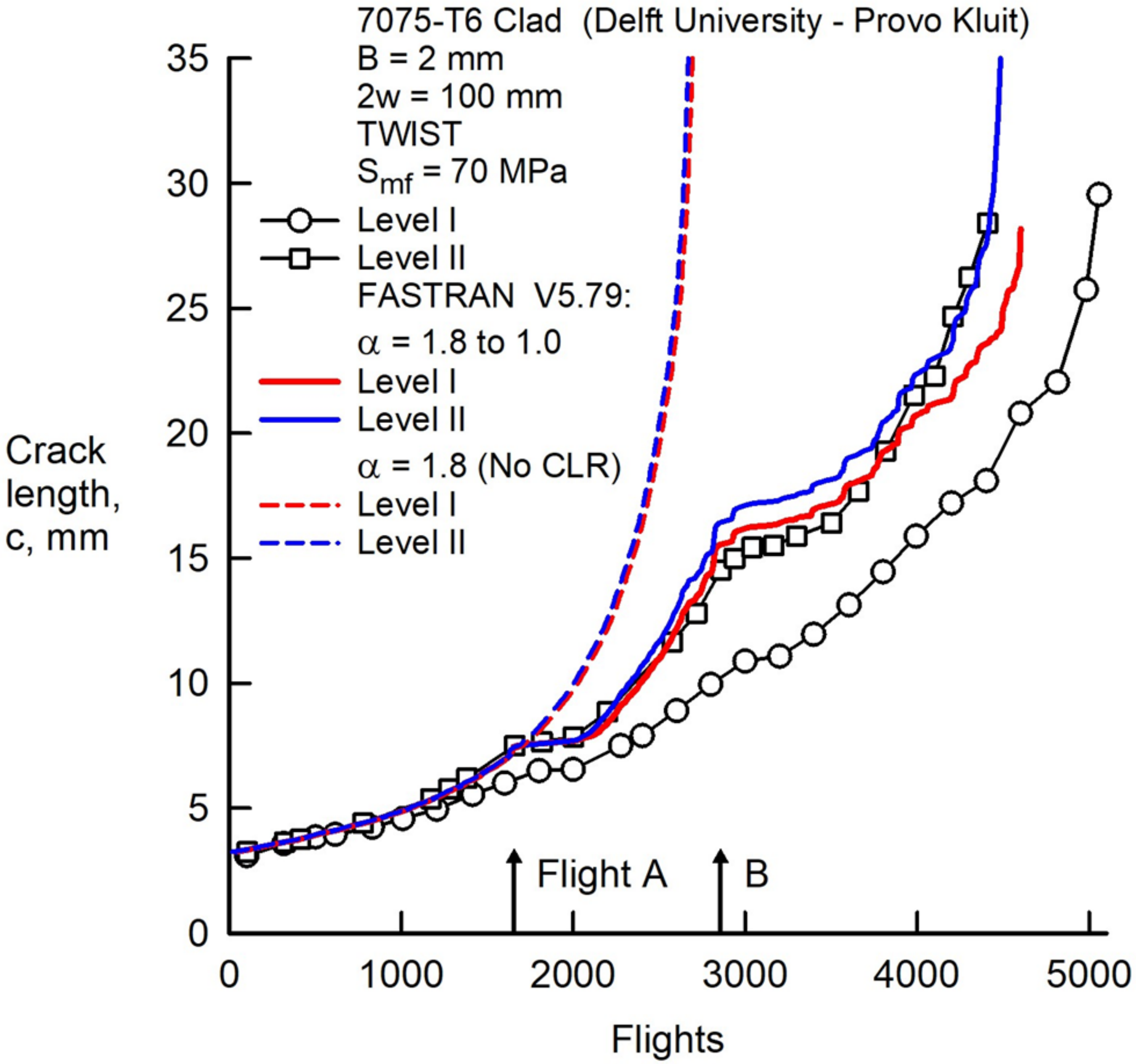
7075-T6

Measured and Predicted Crack-Length-against-Cycles under Single-Spike Overloads at R = 0





Measured and Predicted Crack-Length-against-Cycles under TWIST (Level I and II) Aircraft Spectrum



2024-T3

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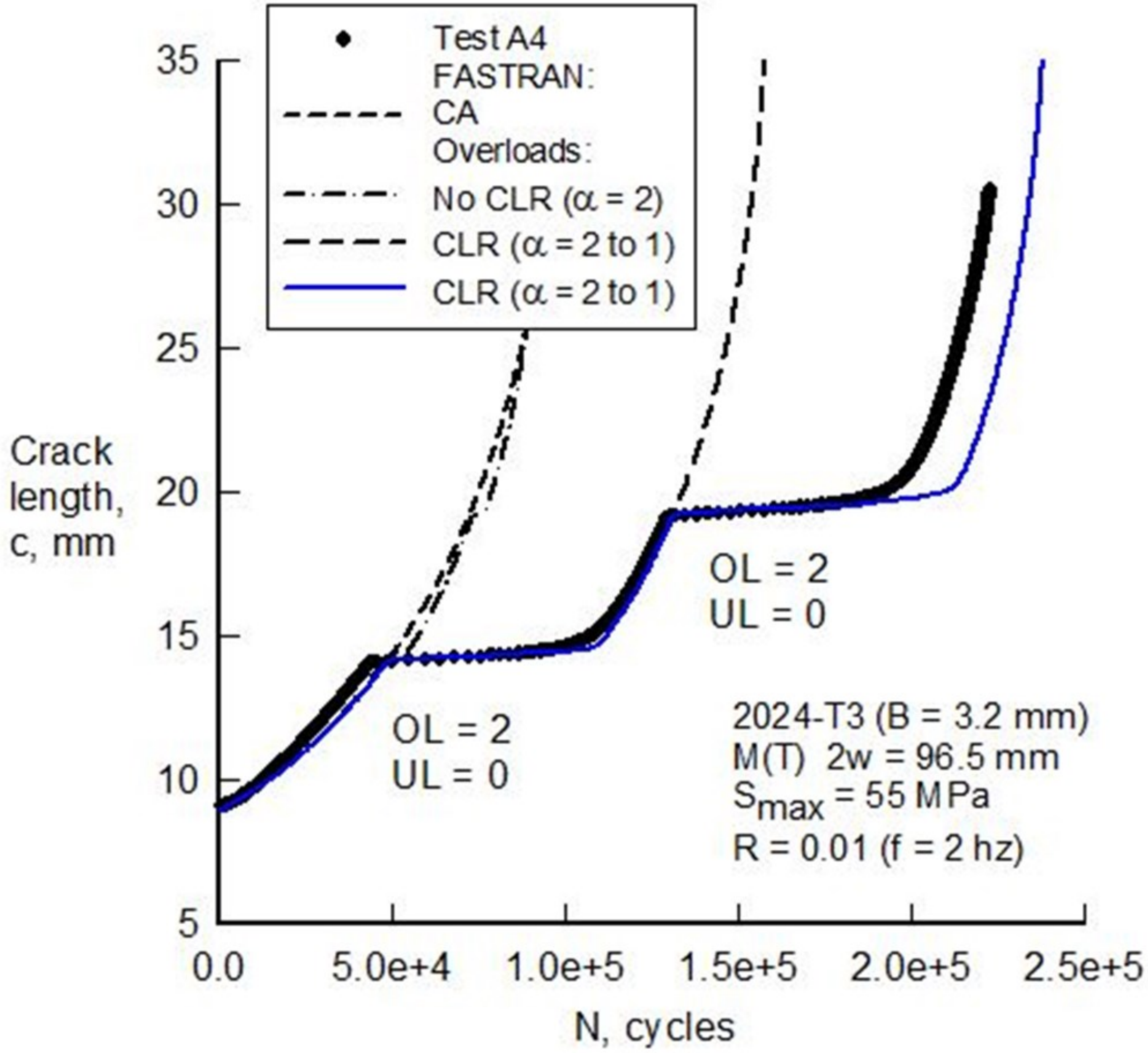
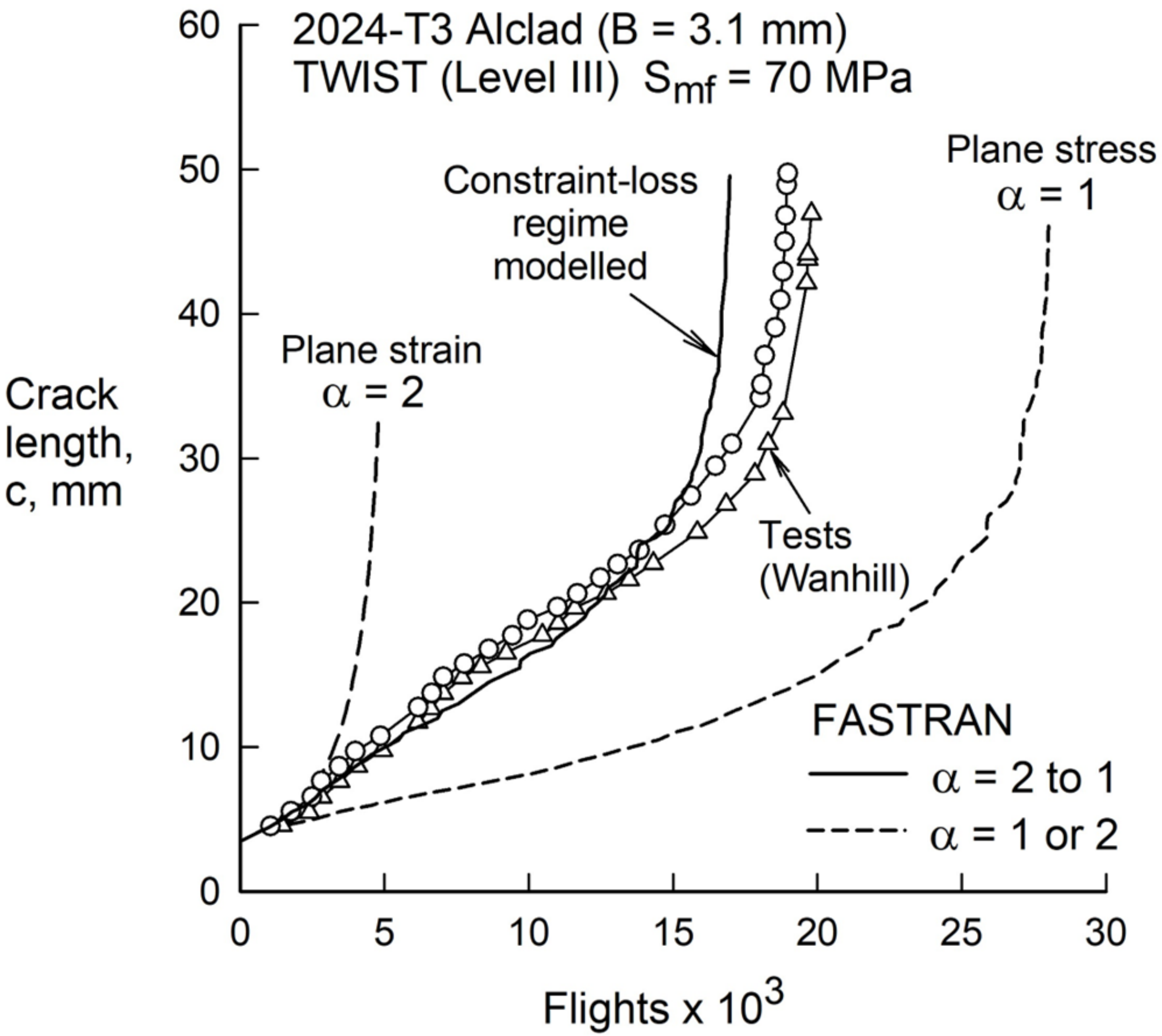
Measured and Predicted Crack-Length against Cycles under Repeated Single-Spike Overloads in 2024-T3 Sheet

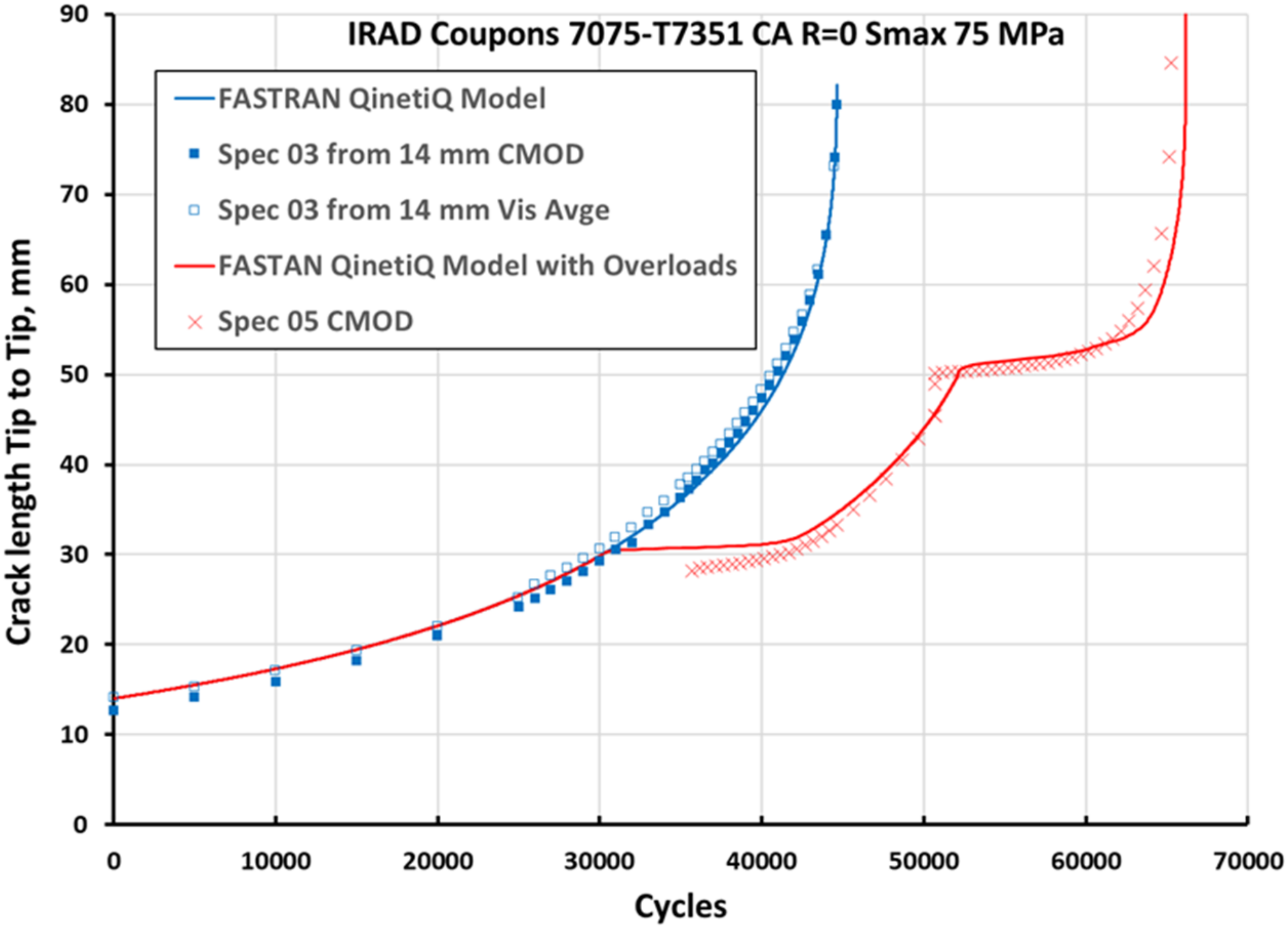


Crack Growth under TWIST (Level III) Spectrum Loading

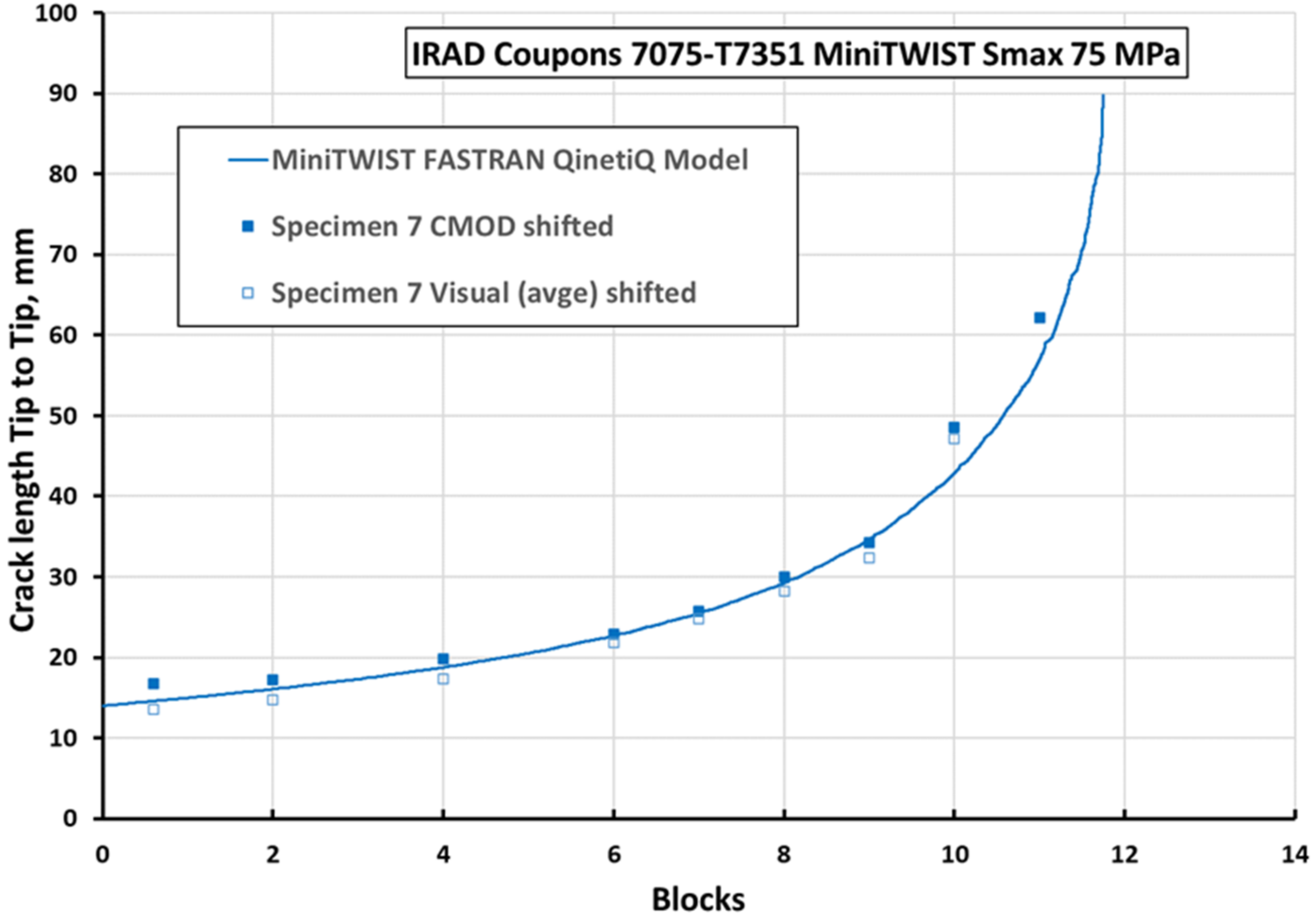


7075-T7351

Test and analysis results CA loading with and without Factor 2 spike overloads



Mini-TWIST spectrum loading results



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IRAD related publications

[1] J.C. Newman, K.F. Walker, Fatigue Crack Growth on Several Materials under Single-Spike Overloads and Aircraft Spectra during Constraint-Loss Behavior, Materials Performance and Characterization, 13 (2024).

[2] J.C. Newman , Jr. and Walker, K.F., Fatigue-Crack-Growth under Single-Spike Overloads/Underloads and Aircraft Spectra during Constraint-Loss Behavior, in: Aircraft Structural Integrity Program Conference, Phoenix AZ USA, 2022.

[3] J.C. Newman , Jr., and Walker, K.F., Fatigue crack growth on several materials under single spike overloads and aircraft spectra, in: International Committee on Aeronautical Fatigue, Delft, The Netherlands, 2023.

[4] K.F. Walker, Grice, A., Newman, J.C. Jr., Zouev, R., Russell, D., and Barter, S.A., Simulation of fatigue crack growth in aluminium alloy 7075-T7351 under spike overload and aircraft spectrum loading International Journal of Fatigue, (2024). (to be submitted soon)

Focus areas for 2024 and beyond

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Focus areas for 2024 and beyond

- Spectrum loading with residual stress included (eg TJ Spradlin RR with 7050-T7451 material)
- Continue investigations into effects of differences in crack growth rate data, including investigations into RR #1 with 2024-T3, also relevant for current IFF RR
- Further development of "Building Block Approach"
- Applications to IFF cases

ERSI Spectrum Loading Effects: Boeing IRAD Spike Overload Test

Moises Y. Ocasio

Agenda

- Building Block Approach
- 7075-T6 Spike Overload Test
  - Task A: Crack Growth Rate Characterization
  - Task B: Spike Overload Test (W = 3.95”, B = 0.09”)
  - Task C: Spike Overload Test (W = 10.0”, B = 0.09”)
  - Task D: Spike Overload Test (W = 3.95”, B = 0.19”)
- Hole Shakedown Test
- Future Work

Introduction

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

Fatigue Life Enhancement

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

Current Spectrum Efforts

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

Building Block Approach

Geometry	Crack	Spectrum	Residuals	Stress Intensity	Growth Rate	Load Interaction	Plasticity
Middle Tension (MT)	Thru	CA	N/A	X	X		
		CA + OL	N/A	X	X	X	
		VA	N/A	X	X	X	
Hole in Plate	Corner	CA	N/A	X	X		
		CA + OL	Shakedown	X	X	X	X
		VA	Shakedown	X	X	X	X
		CA	Cx + Shakedown	X	X		X
		CA + OL	Cx + Shakedown	X	X	X	X
		VA	Cx + Shakedown	X	X	X	X
		CA	IFF	X	X	X	X
		CA + OL	IFF	X	X	X	X
		VA	IFF	X	X	X	X

Increasing complexity

Data Available and Correlation Effort Started (blue)

Testing and/or Historical Test Data Evaluation Started (purple)

*Goal: Build from spectrum loading effect efforts and connect to Cx and IFF efforts

7075-T6 Sheet L-T Spike Overload Testing (Boeing)

- All 4 Tasks Completed.
- Objectives: Characterize growth rate constraint-loss behavior and duration. Develop set of best practices.
- Data will be soon provided to upload to https://residualstress.org/
- Test results correlated using Boeing ***LifeWorks*** contact stress model with Newman's constraint loss modeling methodology.
- It is desirable to replicate these correlations with commercial tool suites (e.g. AFGROW + Fastran). This would be a good opportunity for collaboration.

(A) Growth Rate Characterization

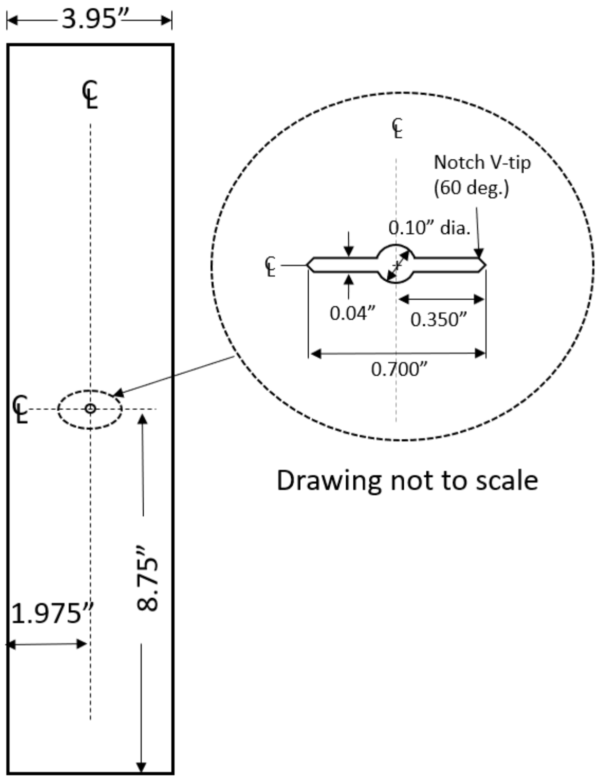
(B) Constrain Loss

(C) Constraint Loss Width Effects

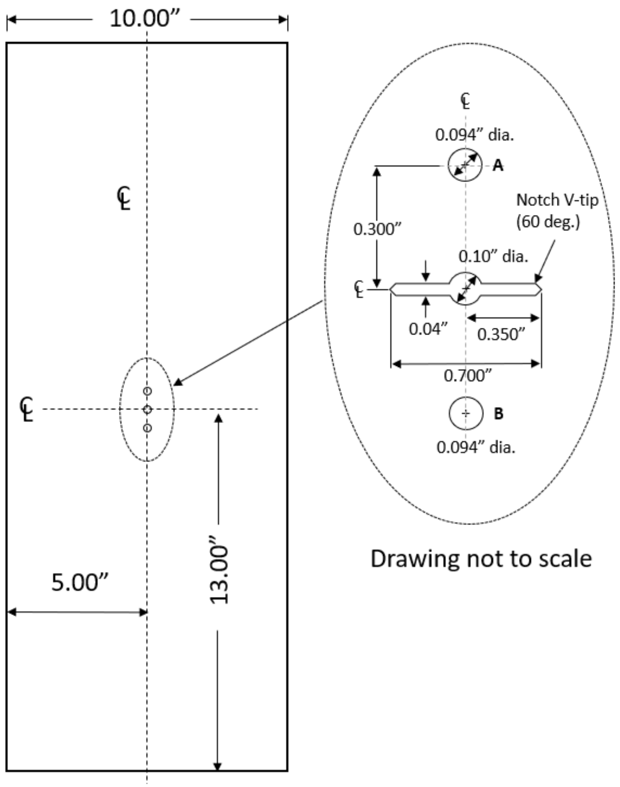
(D) Constraint Loss Thickness Effects

Configuration	Task No.	No. of specimens	Starter notch type	Width, in.	Height, in.	Thickness, in.	Additional Instrumentation
A	1	8	EDM[1]	3.95	17.5	0.19	CMOD gauges[3]
B	2	3	EDM[2]	3.95	17.5	0.09	CMOD gauges[3]
C	3	3	EDM[2]	10	26	0.09	CMOD gauges[3]
D	4	3	EDM[2]	3.95	17.5	0.19	CMOD gauges[3]

Test Configurations

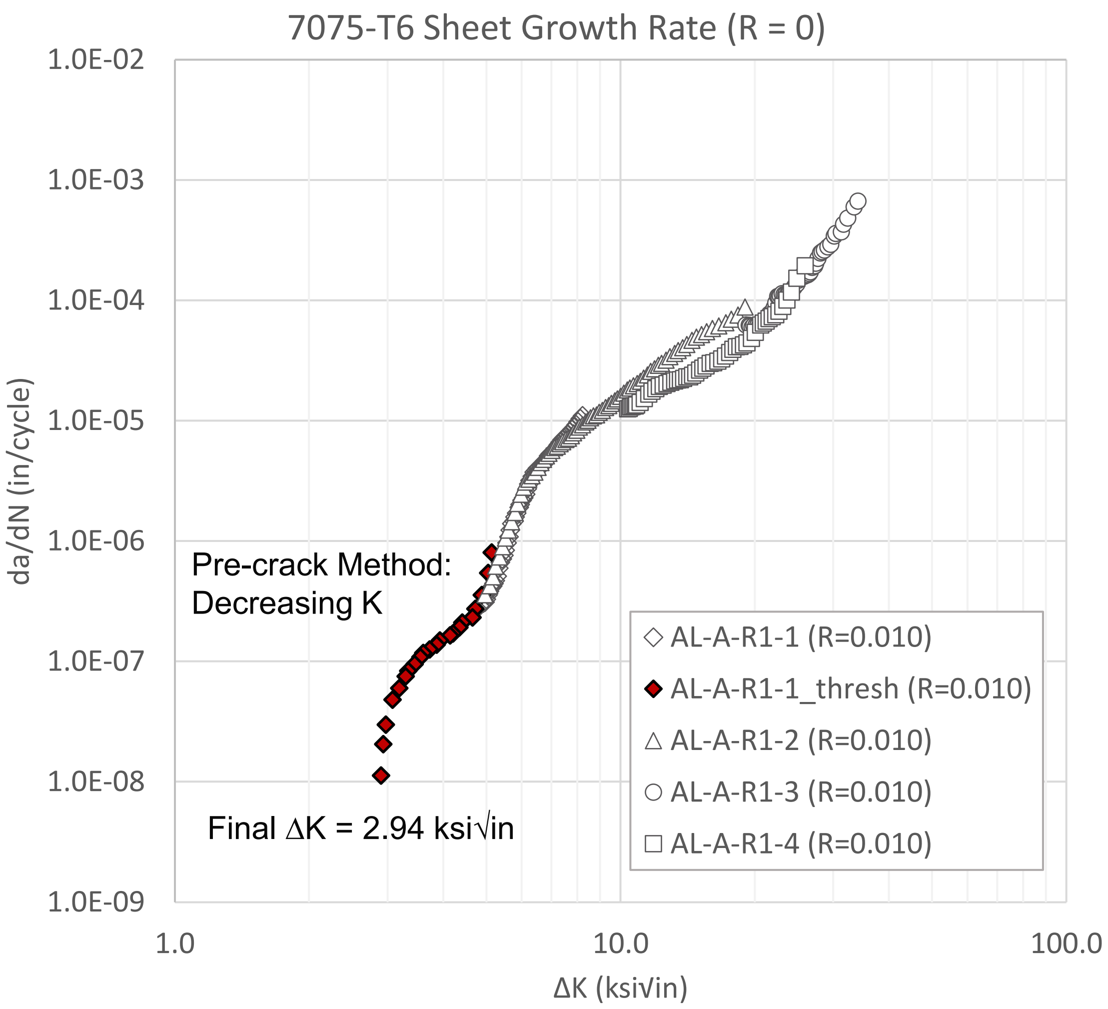


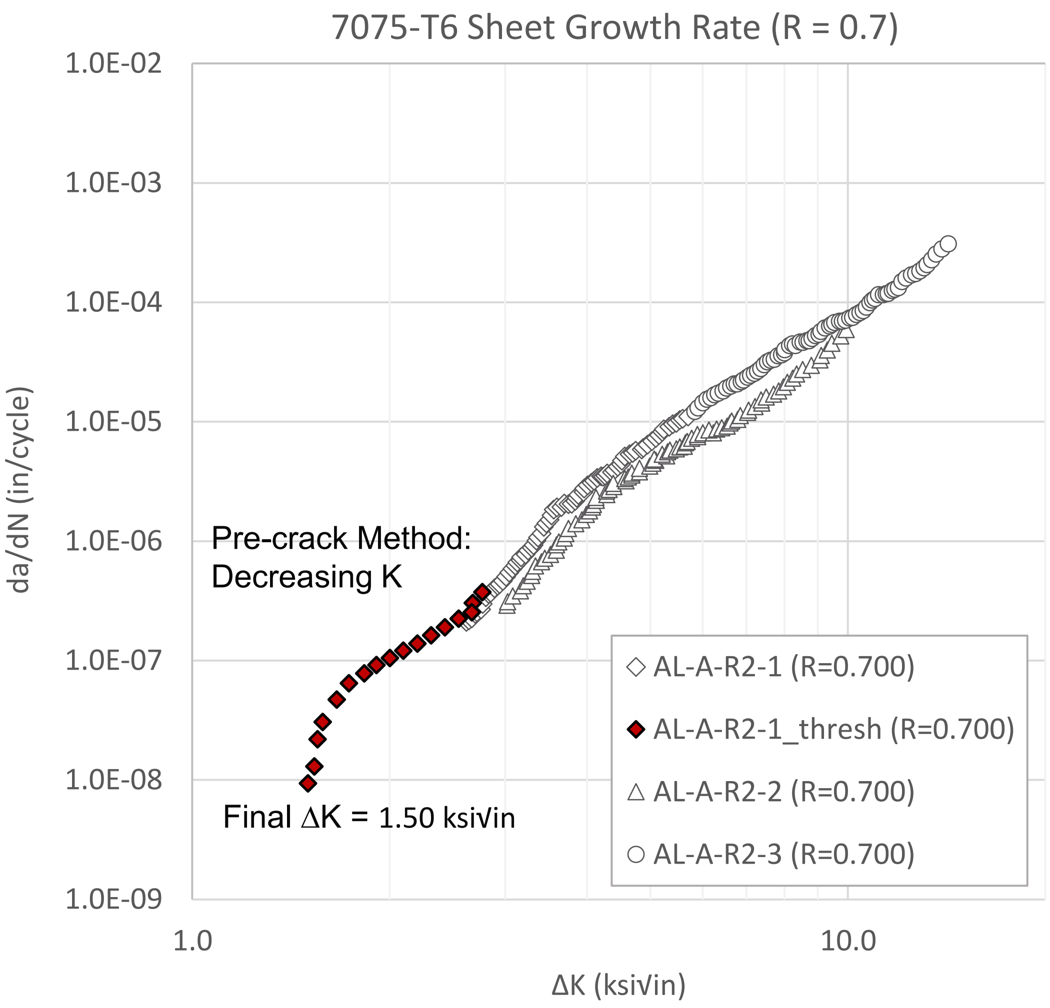
Tasks A and D (thickness = 0.19 in)
Task B (thickness = 0.09 in)



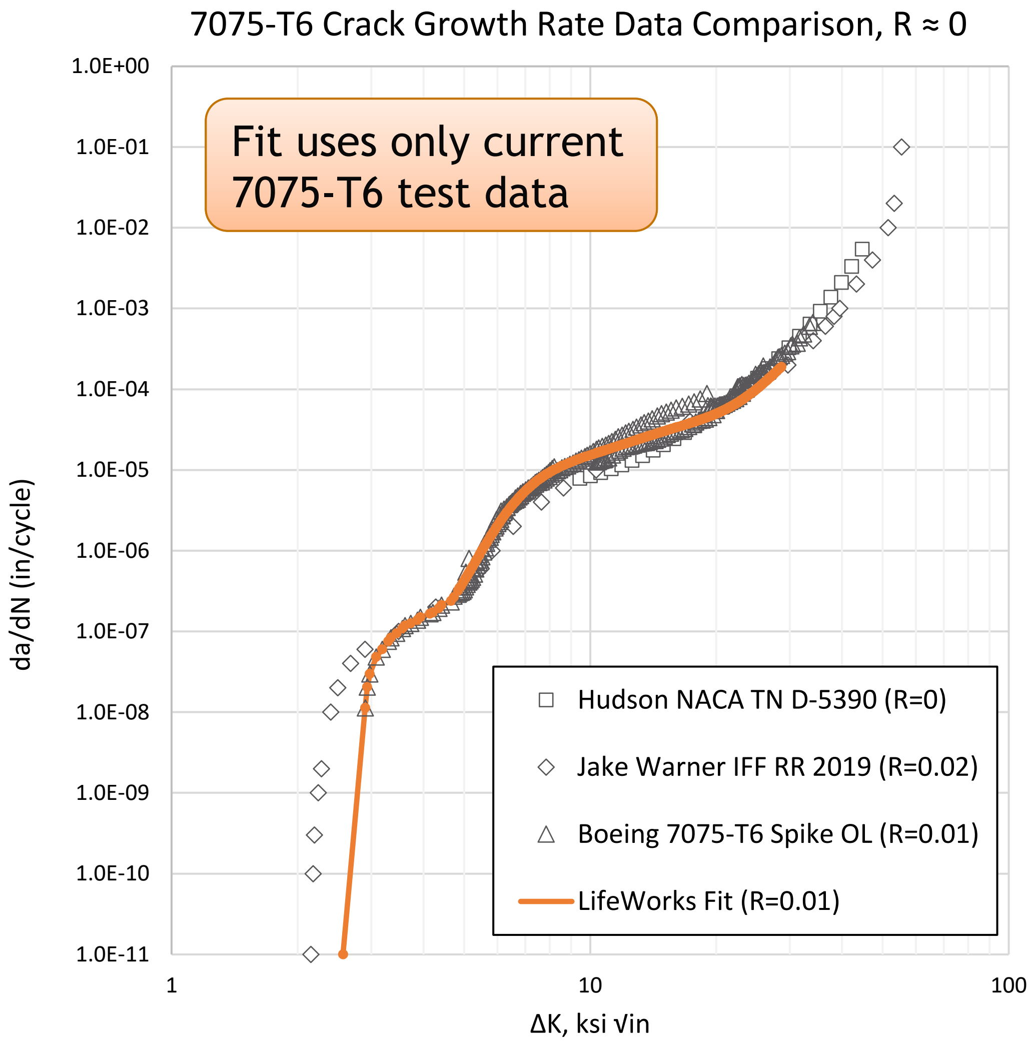
Tasks C (thickness = 0.09 in)

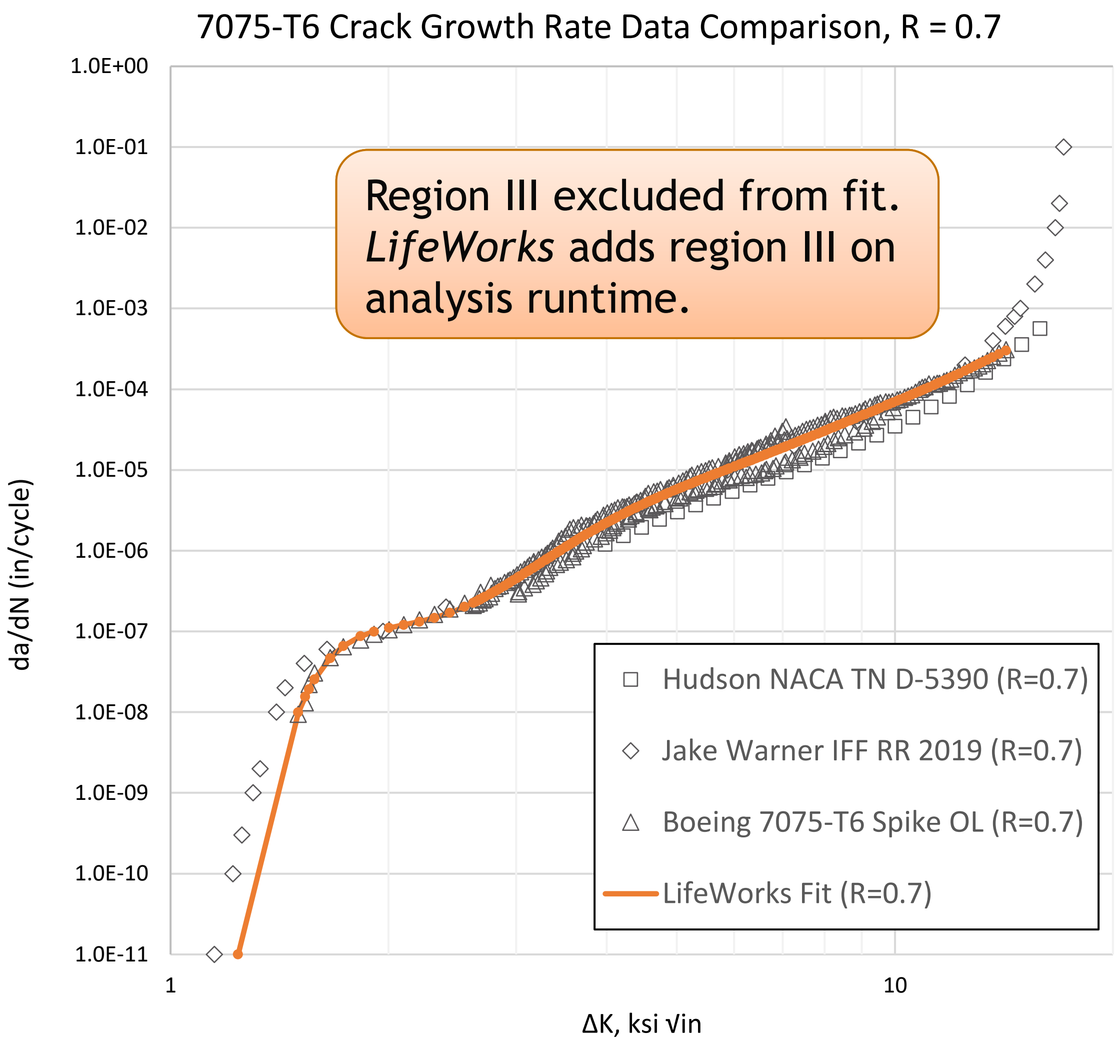
Task A: Crack Growth Rate Characterization



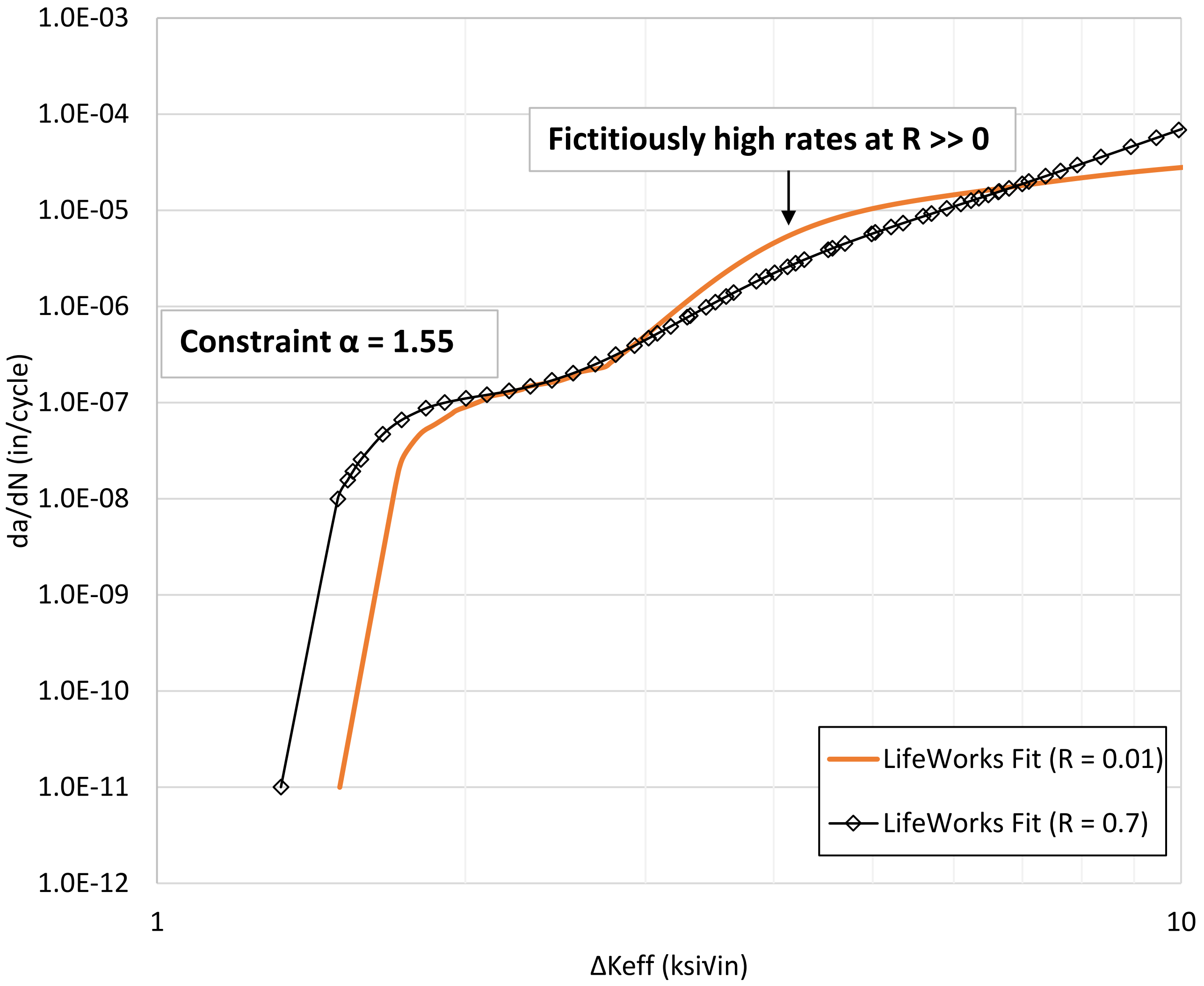


Growth Rate Comparison



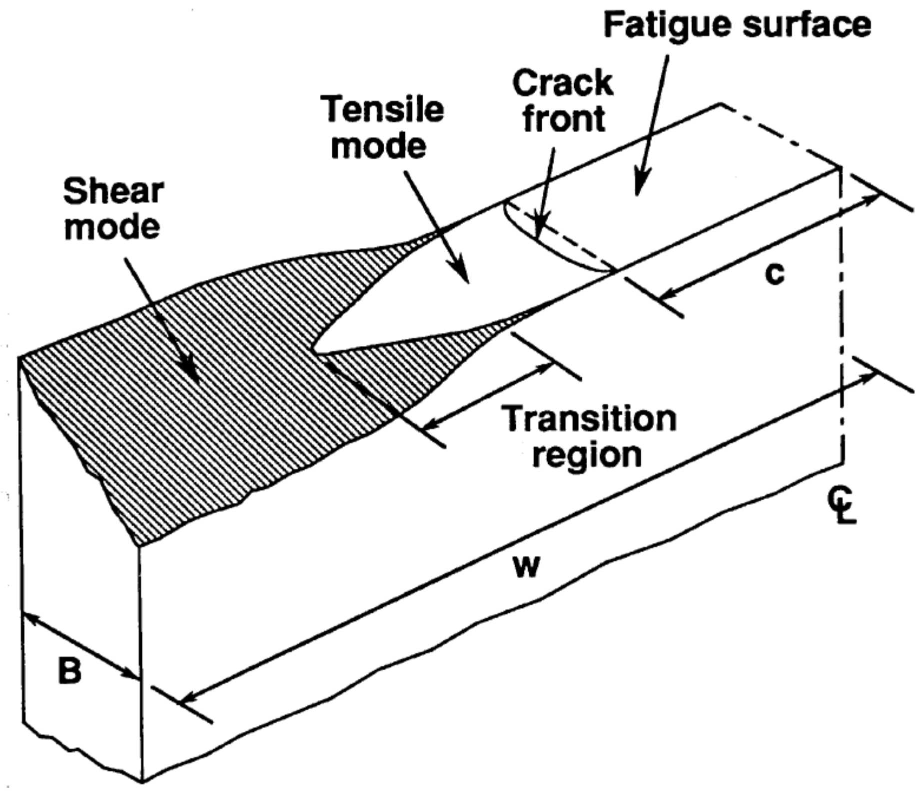


Constraint Parameter



- Constraint $\alpha \rightarrow$ elevation of normal stress near the crack tip
- α = 1.55 provided best region I collapse.
- Expected value for alpha (from literature) was ≈ 1.8
- *LifeWorks* CSM defines α in terms of effective yield stress. Other methods define constraint in terms of flow stress.

Constraint Loss



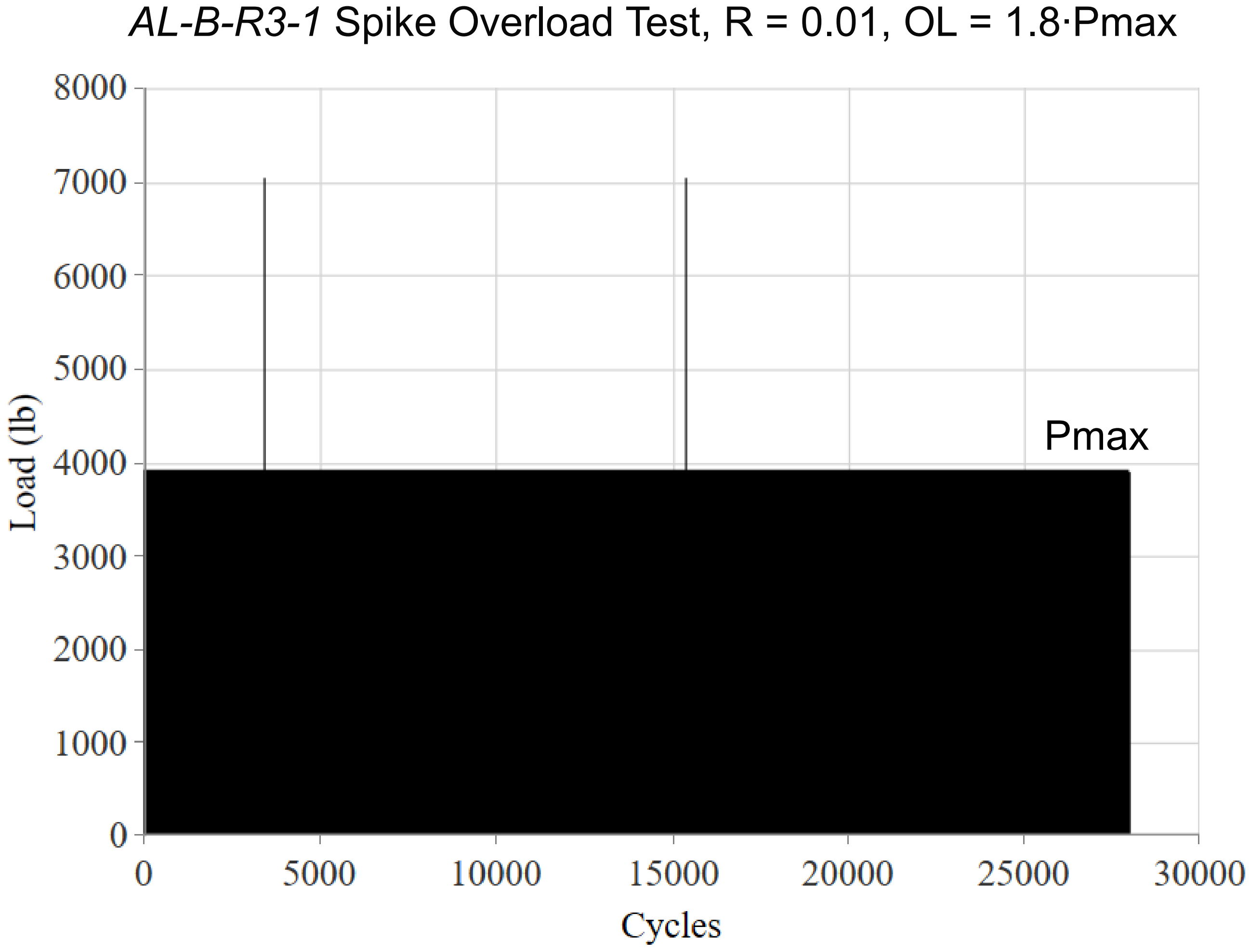
Newman JC Jr, Bigelow CA, Shivakumar KN. *Three-dimensional elastic-plastic finite-element analysis of constraint variations in cracked bodies*. Eng. Frac. Mech 1993

- 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 proposed ΔK_{eff} should control this transition.
- Newman proposed that transition happens when the plastic zone reaches a certain percentage of material thickness.

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

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

Spike Overload Test Spectrum

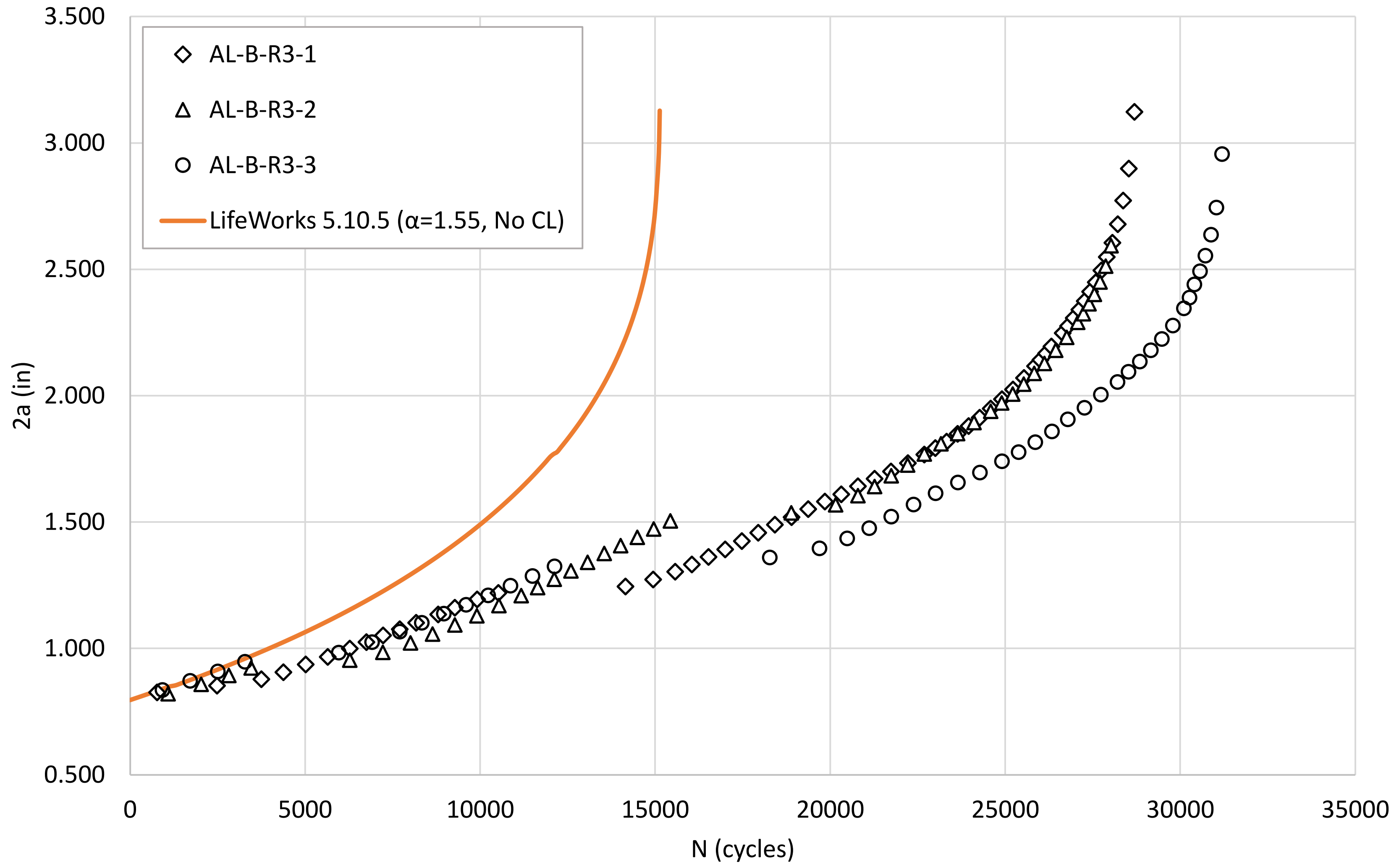


Overloads were applied at two different crack lengths:

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

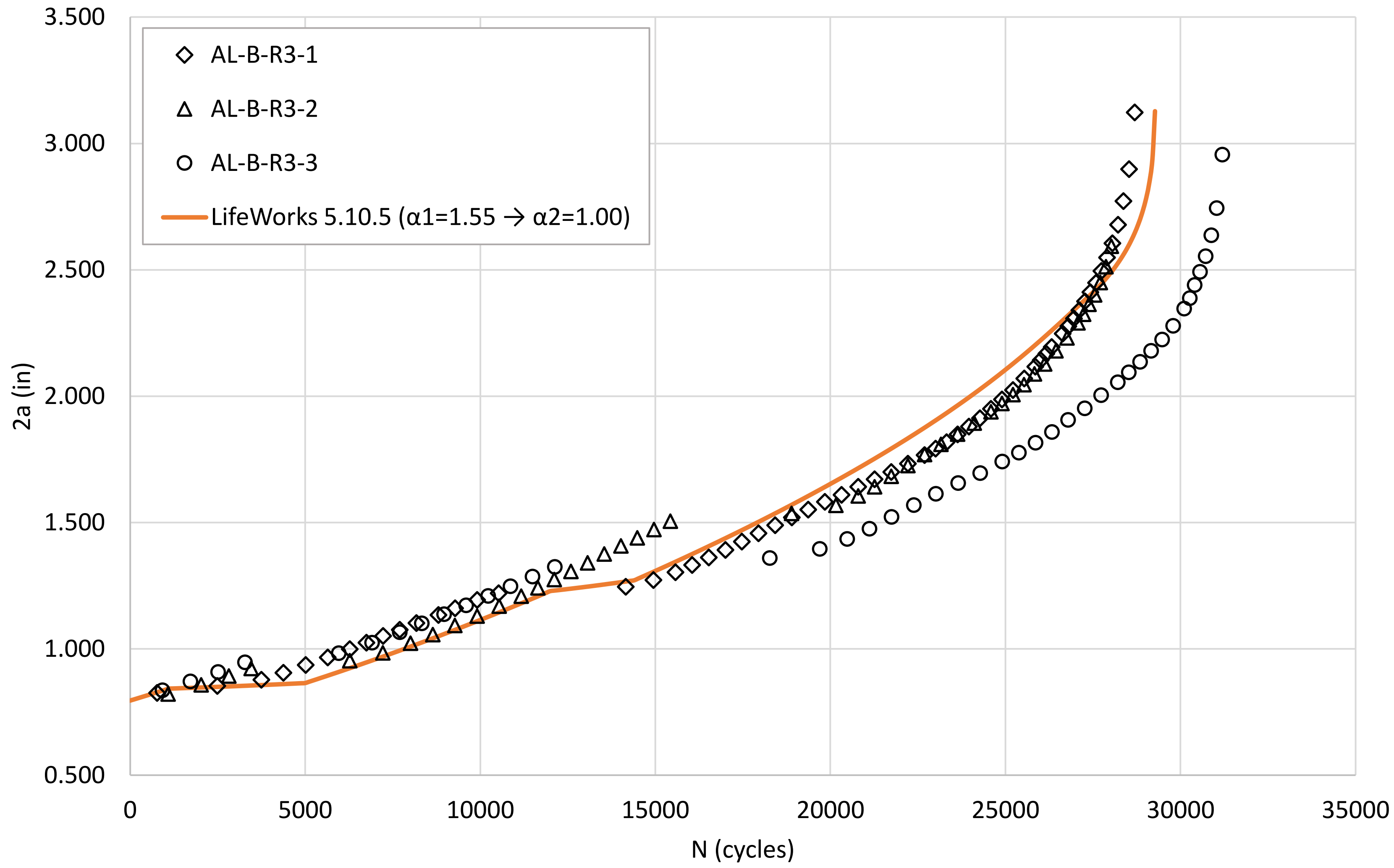
$$2a_{OL-2} = 1.2 \text{ inches}$$

Task B: Results (No Constraint Loss)



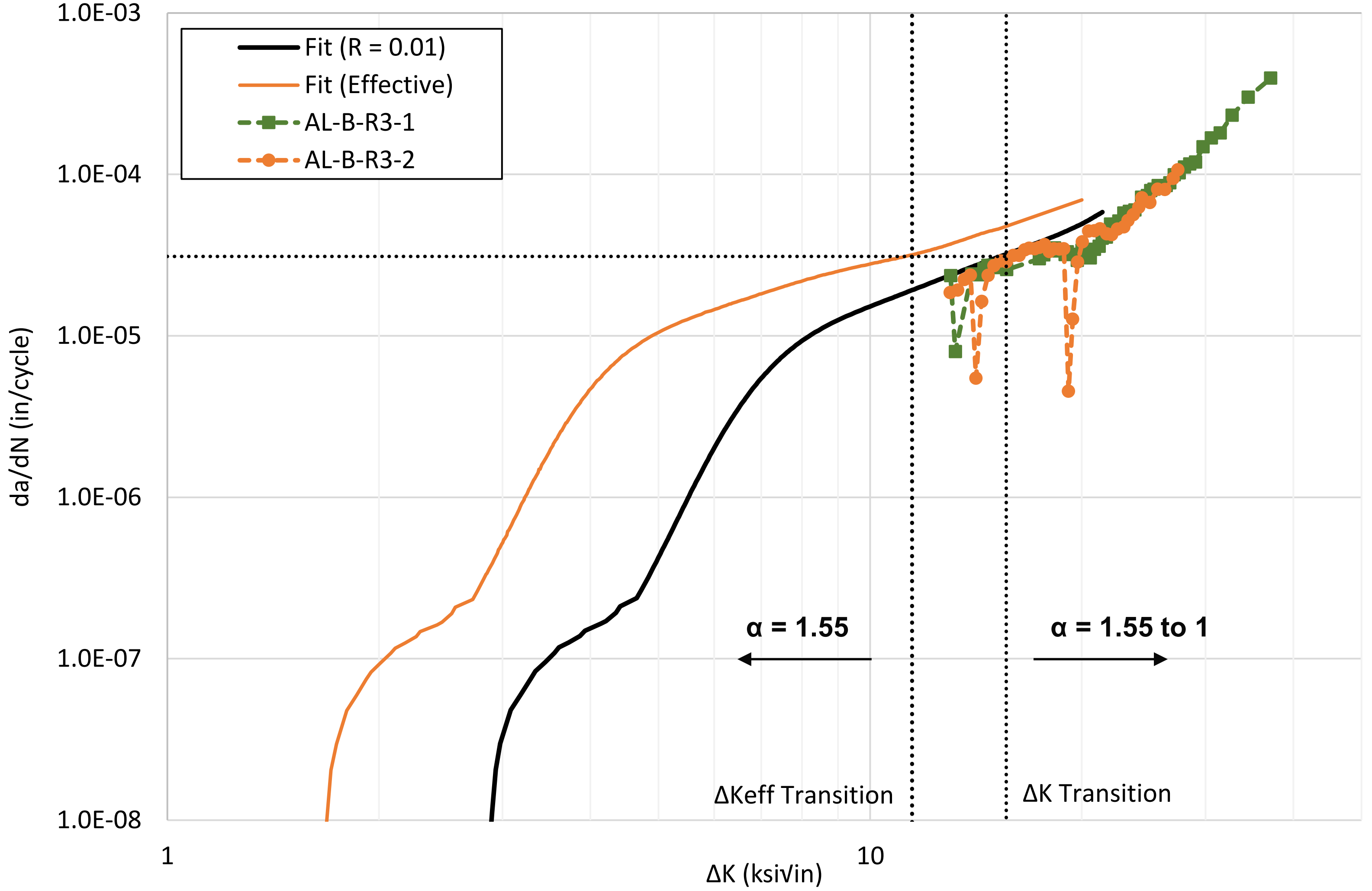
W	3.95"
B	0.09"
L	17.5"
Notch total length	0.7”
Grain Direction	L-T
Loading Type	Constant Amplitude with OL = 1.8·Pmax
Pmax	3.91 kips
Stress Ratio	0.01

Task B: Results (With Constraint Loss)

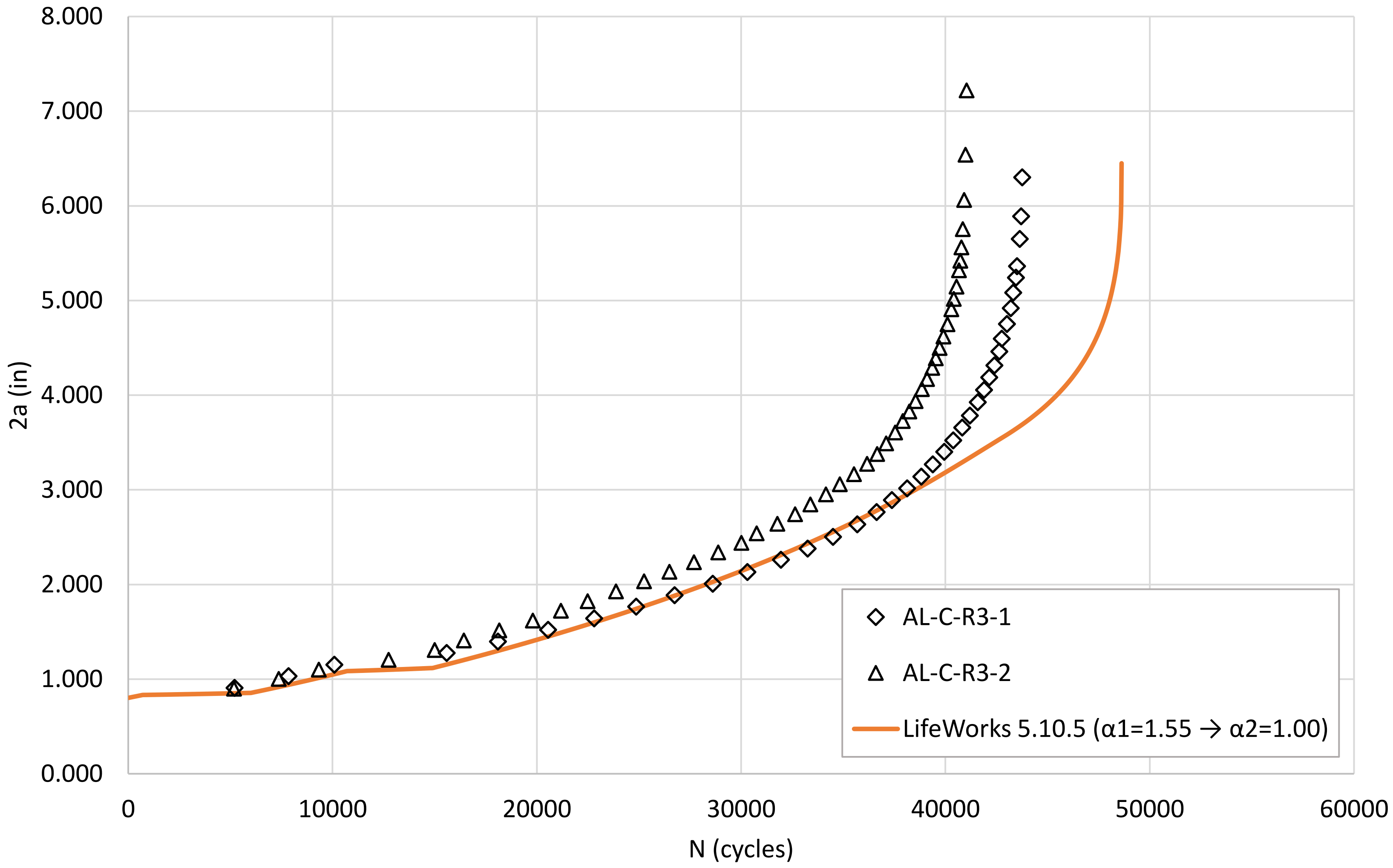


W	3.95"
B	0.09"
L	17.5"
Notch total length	0.7”
Grain Direction	L-T
Loading Type	Constant Amplitude with OL = 1.8·Pmax
Pmax	3.91 kips
Stress Ratio	0.01

Task B: Growth Rate

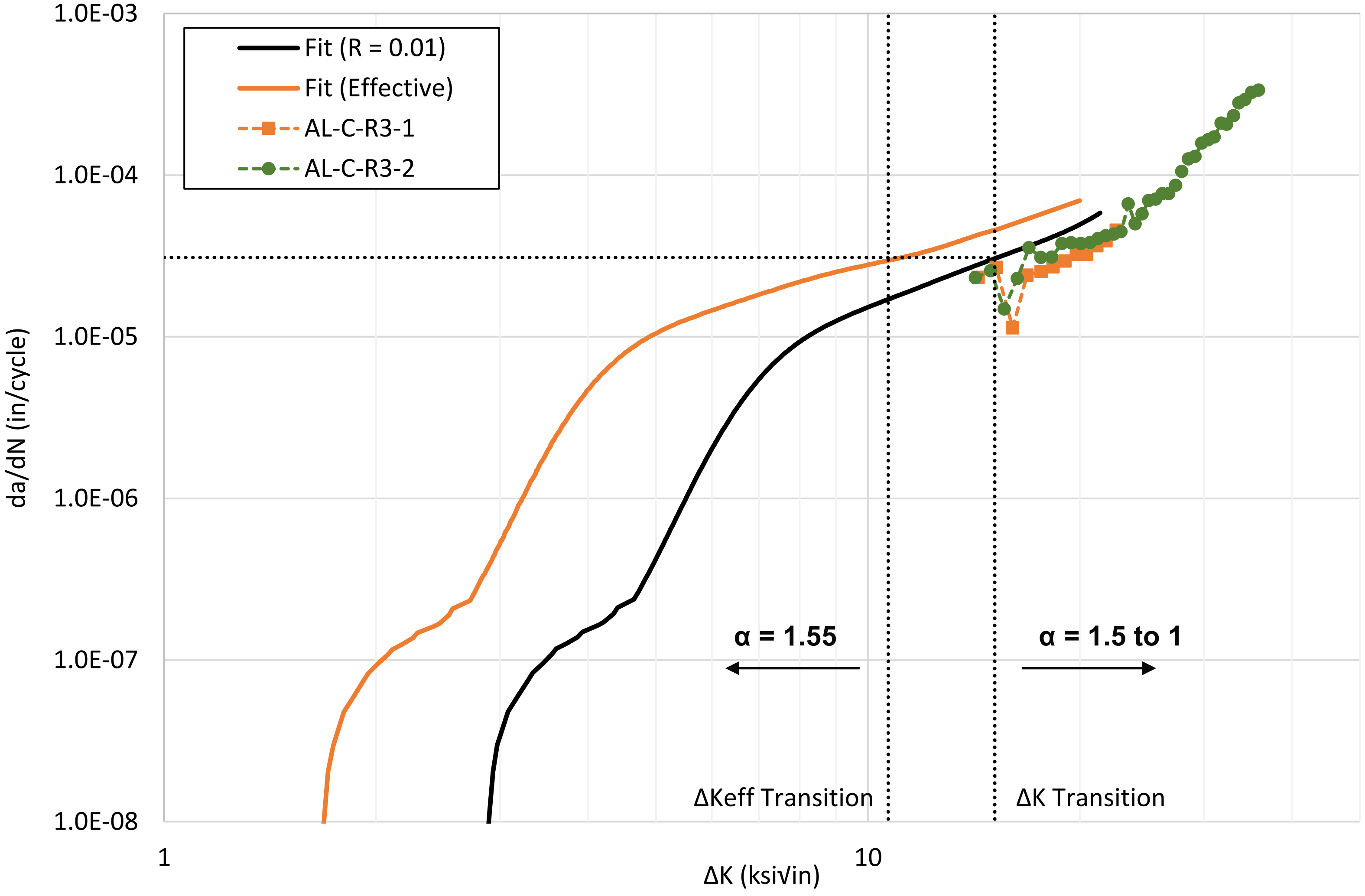


Task C: Results

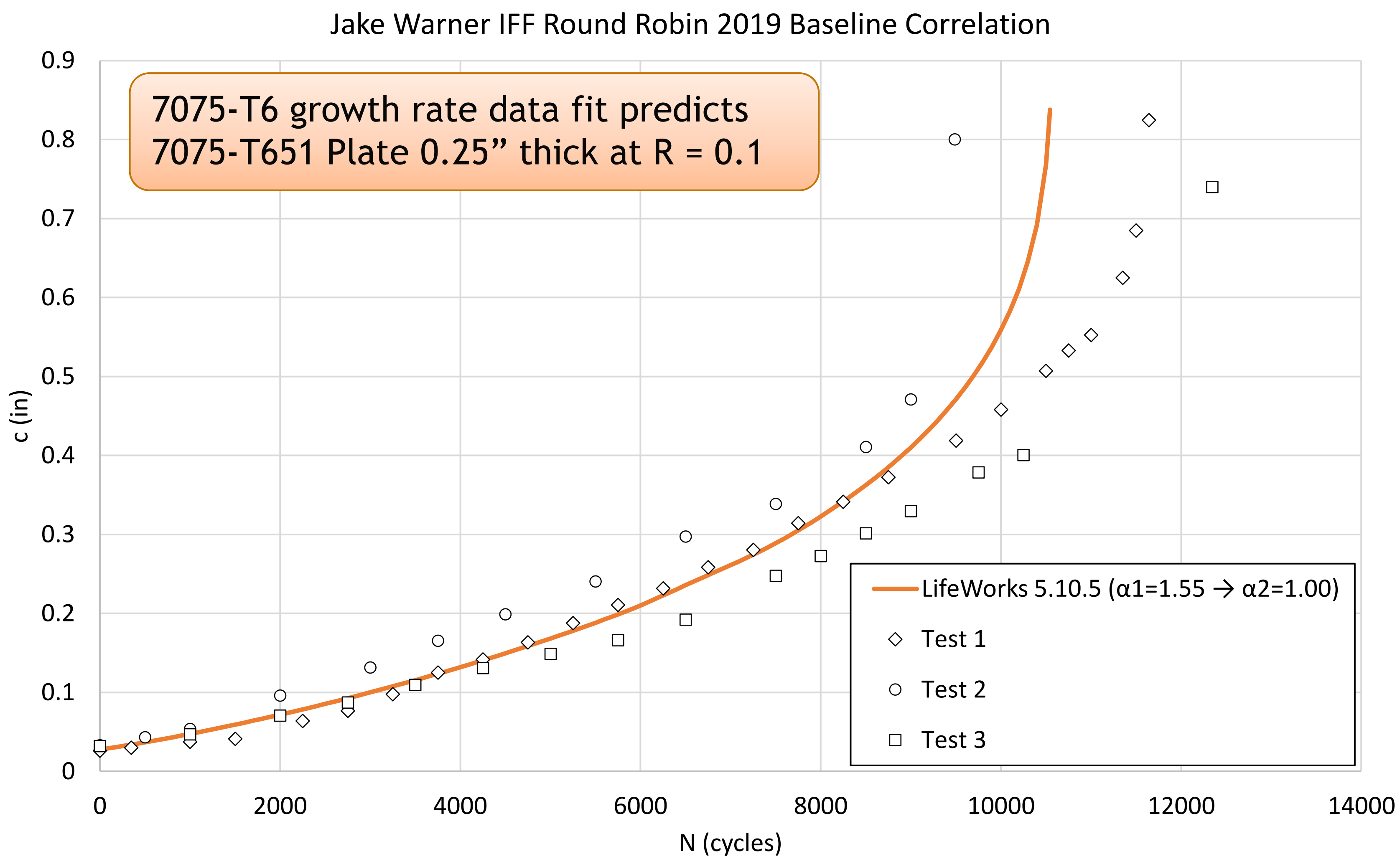


W	10"
B	0.09"
L	26"
Notch total length	0.7”
Grain Direction	L-T
Loading Type	Constant Amplitude with OL = 1.8·Pmax
Pmax	9.9 kips
Stress Ratio	0.01

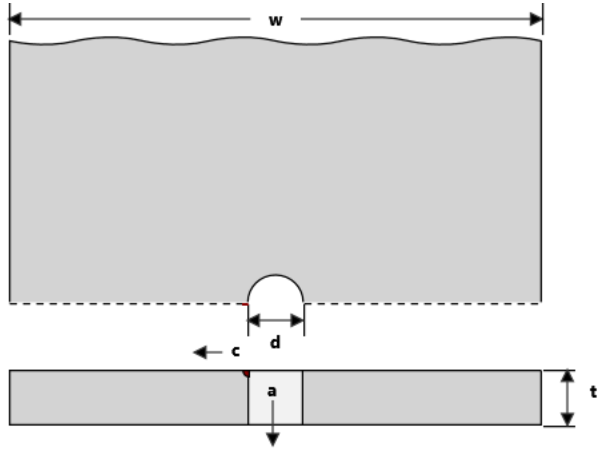
Task C: Growth Rate



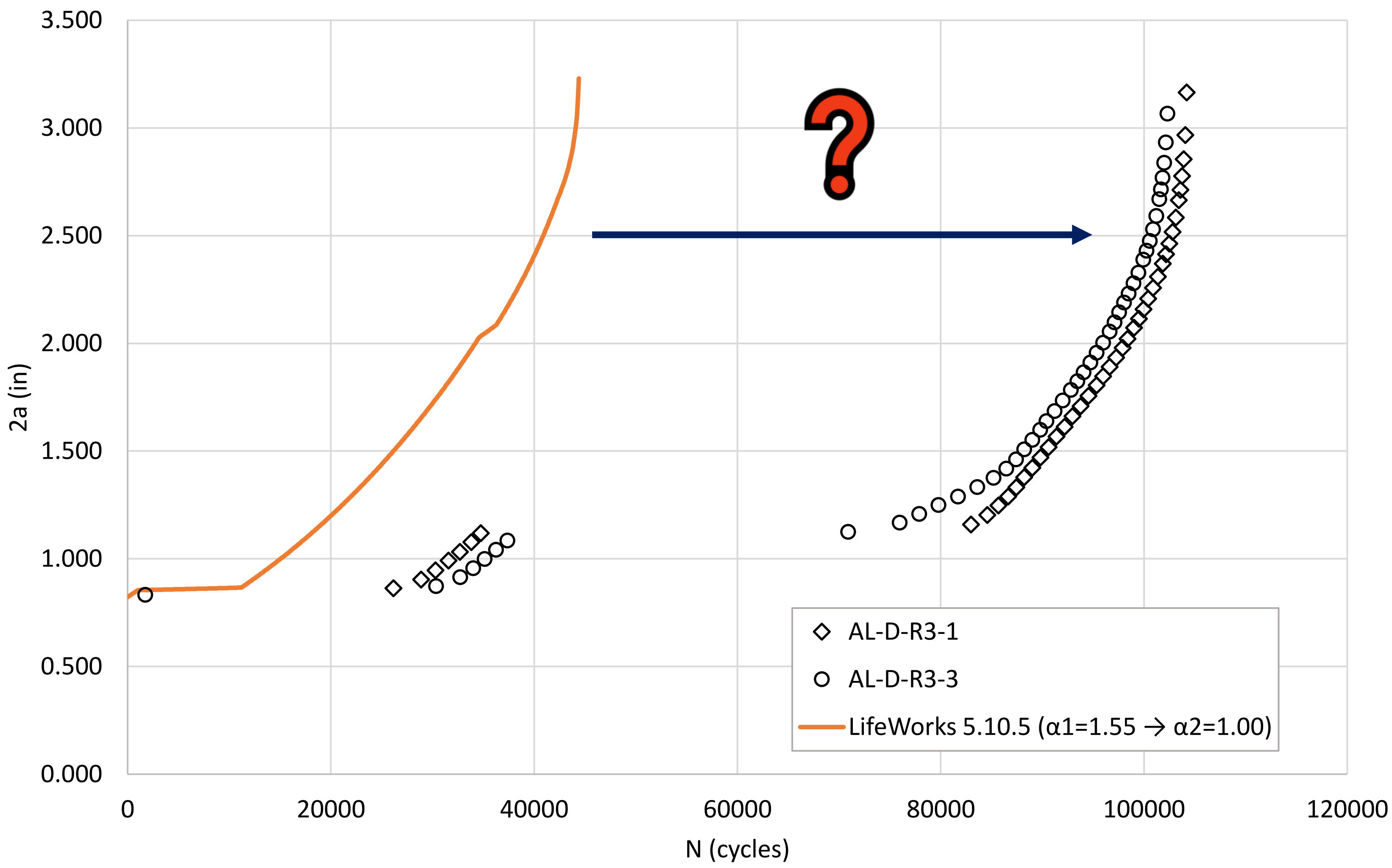
Thicker specimen crack growth prediction



Material	7075-T651 Plate
w	2.4"
d	0.25”
t	0.25"
Initial Flaw (c x a)	0.027” x 0.0278”
Grain Direction	L-T
Loading Type	Constant Amplitude
Smax	27.9 ksi
Stress Ratio	0.1

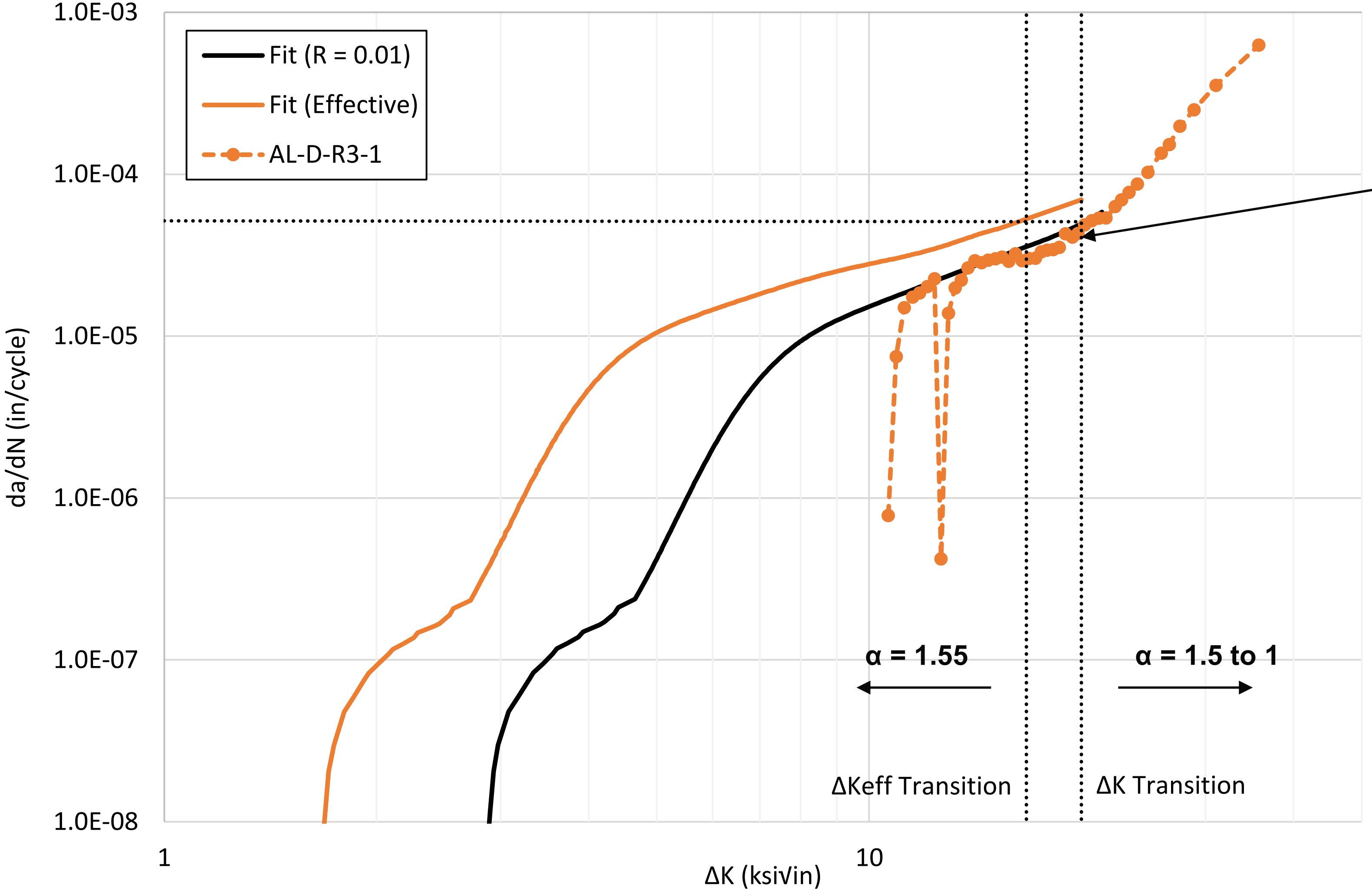


Task D.1: Results



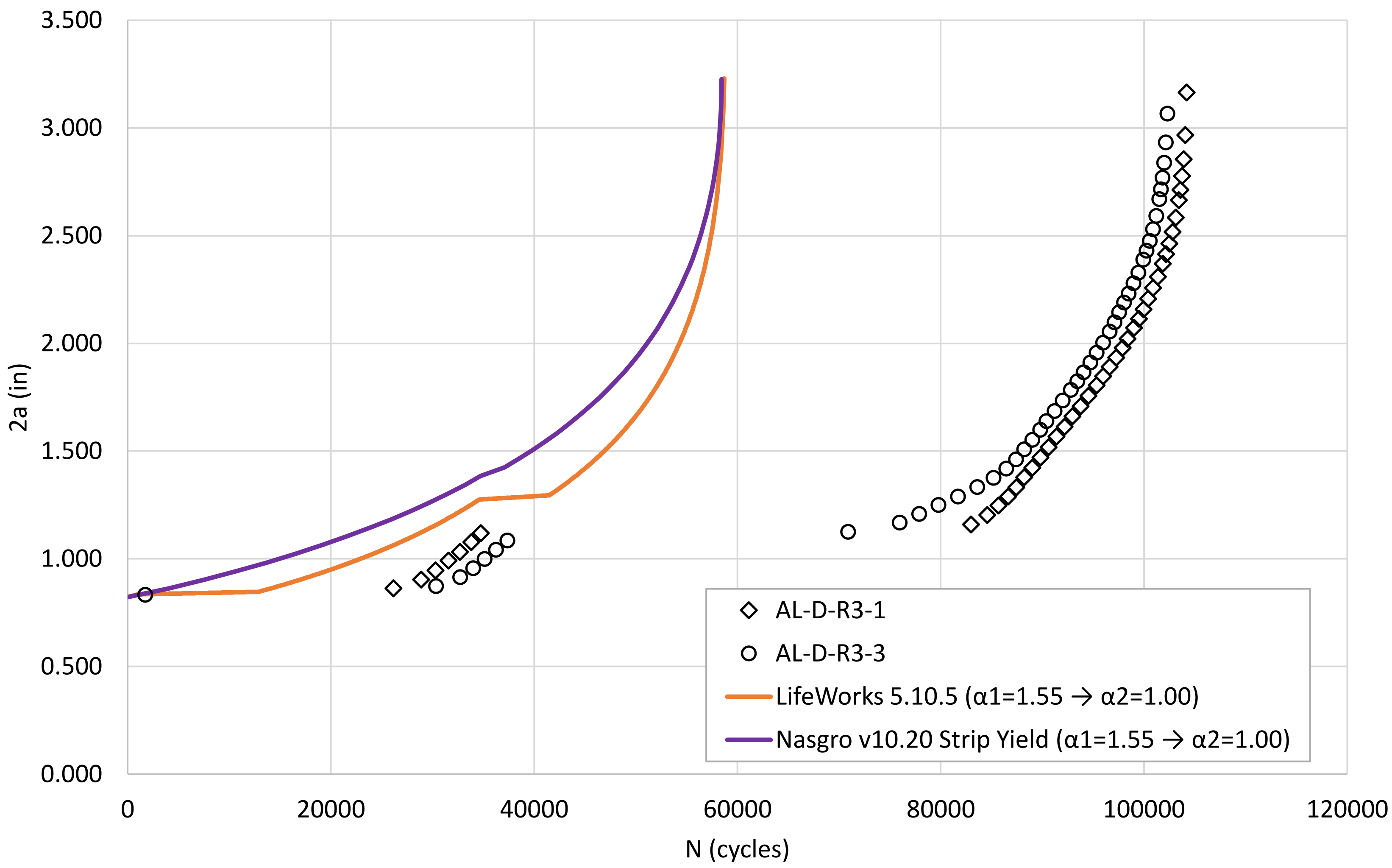
W	3.95"
B	0.19"
L	17.5"
Notch total length	0.7”
Grain Direction	L-T
Loading Type	Constant Amplitude with OL = 1.8·Pmax
Pmax	6.75 kips
Stress Ratio	0.01

Task D.1: Growth Rate



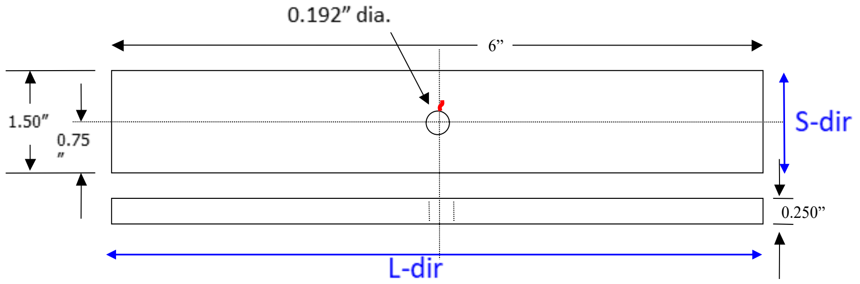
Is the transition ΔK too high?
Is plastic zone too small?
Is constraint modeling appropriate for this geometry?

Task D.1: Results (using Nasgro 7075-T6 data)



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

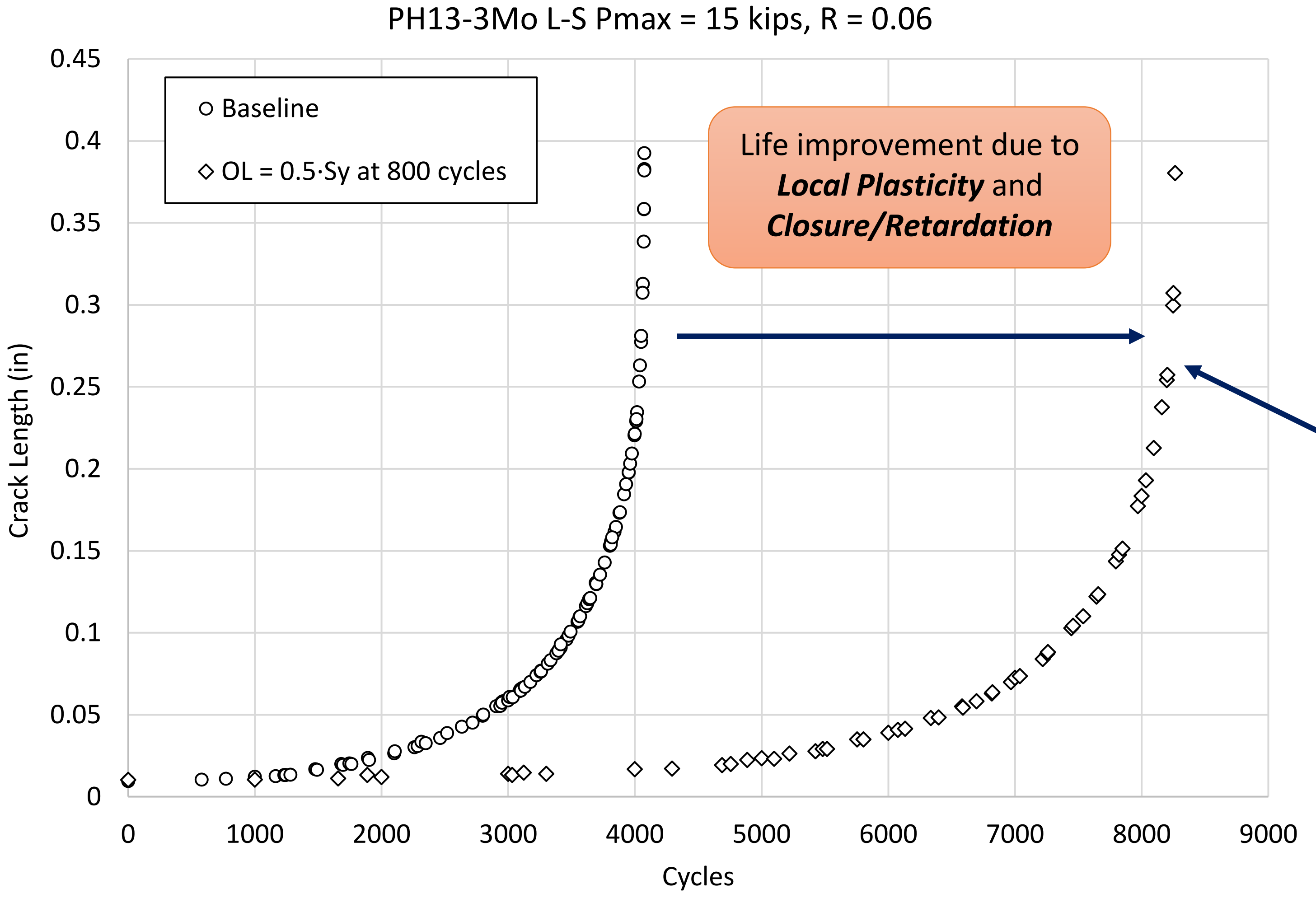
Boeing IRAD Hole Shakedown Test

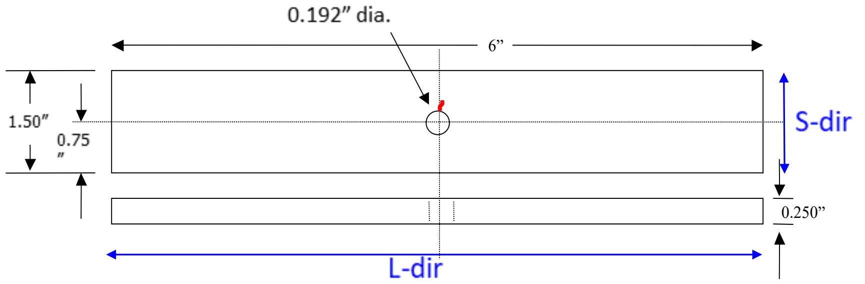


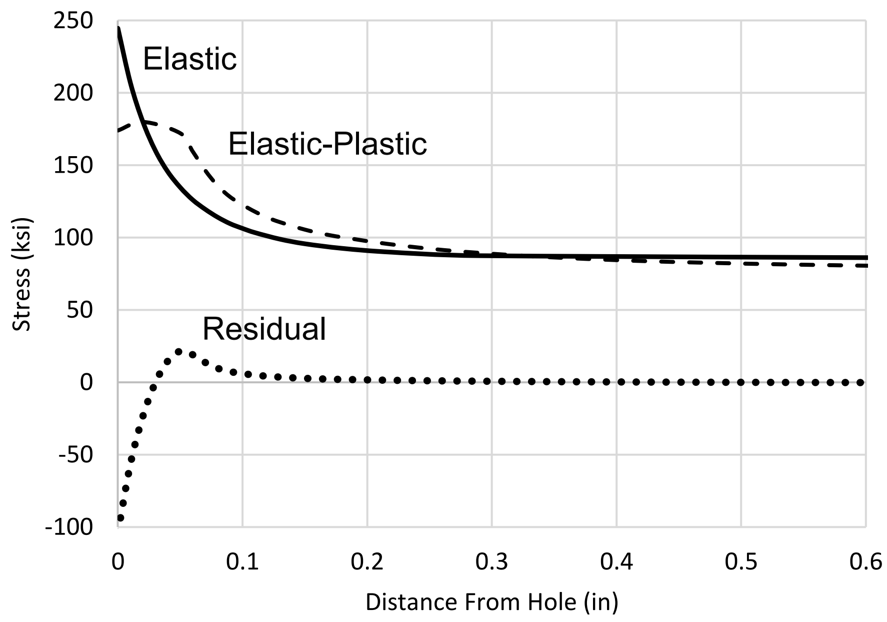
- Materials: Ti-6Al-4V RA and PH13-8Mo (might add 2024-T6 if available)
- Grain Direction: L-S (plan to expand to L-T in the near future)
- Status: Test Completed
- Objectives: Consider local plasticity effects (i.e. Hole Shakedown)
- Procedure: Specimens were pre-cracked and subjected to constant amplitude spectrum. To account for hole yielding, specimens were subjected to an overload at three different levels 0.32·Fty, 0.48·Fty and 0.64·Fty.

SPECIMEN TYPE	SPECIMEN CONFIGURATION (in)				MAT	DIR	LOADING TYPE	R	LOAD LEVEL ID	# OF SPECIMENS
	LENGTH	WIDTH	THICK	DIA						
Open Hole Crack Growth	6	1.5	0.25	0.252	Ti-6Al-4V RA	L-S	Constant Amplitude	0.06	1-OL	8
Open Hole Crack Growth	6	1.5	0.25	0.252	Ti-6Al-4V RA	L-S	Constant Amplitude	0.06	2-OL	8
Open Hole Crack Growth	6	1.5	0.25	0.252	Ti-6Al-4V RA	L-S	Constant Amplitude	0.06	3-OL	8
Open Hole Crack Growth	6	1.5	0.25	0.252	PH13-3Mo	L-S	Constant Amplitude	0.06	1-OL	8
Open Hole Crack Growth	6	1.5	0.25	0.252	PH13-3Mo	L-S	Constant Amplitude	0.06	2-OL	8
Open Hole Crack Growth	6	1.5	0.25	0.252	PH13-3Mo	L-S	Constant Amplitude	0.06	3-OL	8
									Total	48

Boeing IRAD Hole Shakedown Test







Future Work

- **Thickness Effect on Plastic Tip Constraint**
  - 7075-T6 (compare to thick specimen behavior in literature, replicate test)
  - 7075-T351 0.245” Overload Testing and Spectrum Testing (FALSTAFF)
  - Ti-6Al-4V MA Overload/Underload Testing and Spectrum Testing (FALSTAFF)
  - Revisit previous round robin datasets with thick specimens
- **Boeing Hole Shakedown Test**
  - Collaboration: Prediction challenge?
  - Building block next steps (CA open hole → Spike OL No Yielding → Spike OL Shakedown)

Contact Information

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Working Group on
Engineered Residual
Stress Implementation

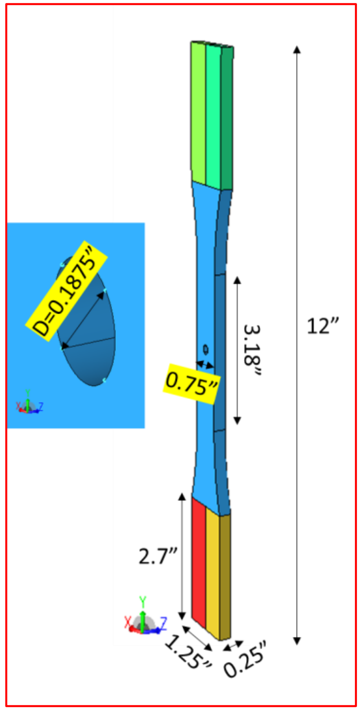
Analysis Methods and Testing
April 02, 2024

Comparison of 3D FEA based solutions against Non-CX (CA) marker bands (2 sets) from the recent Round Robin challenge

Adrian Loghin, Simmetrix Inc.

Round-Robin Problem Definition*

This work is related to: Round-Robin Life Prediction Invitation for Variability in Residual Stresses at Cold Expanded (Cx) Holes



Phase	Loading	Ref. Stress (Ksi)	Specimen Type	Material	Thickness (in.)	Width (in.)	Final Hole Diameter (in.)
I	CA (R=0.1)	15.0	Non-CX	7050-T7451	0.25	0.75	0.1875

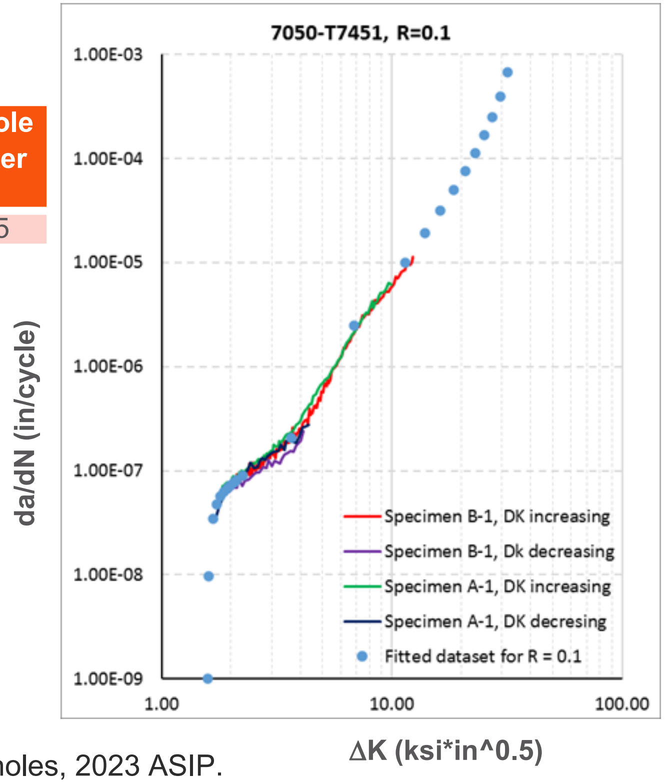
- All constant amplitude loading used a load ratio of R= 0.1

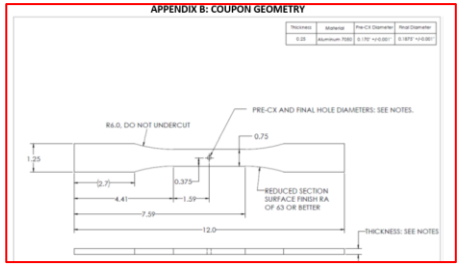
- Marker bands were applied after fixed blocks of spectrum loading
  - Constant amplitude (CA) – 3,000 cycles followed by a marker band
    - Marker bands were applied in a 4/3/5 pattern (e.g. – CA block, 4 band CA marker sequence, CA block, 3 band CA marker sequence, CA block, 5 band CA marker sequence, and so on)

Initial crack size to be considered:

a	0.050"
c	0.034"

Units: inch, psi, ksi

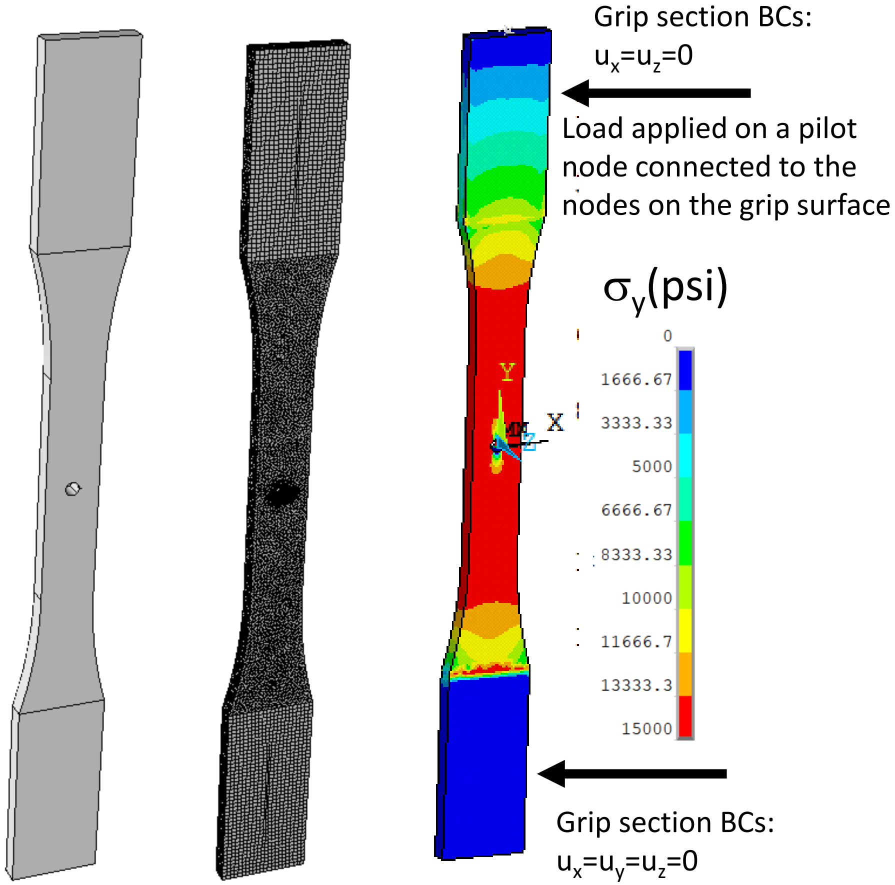


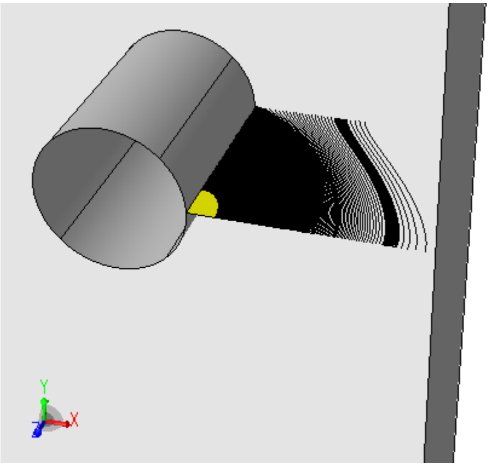


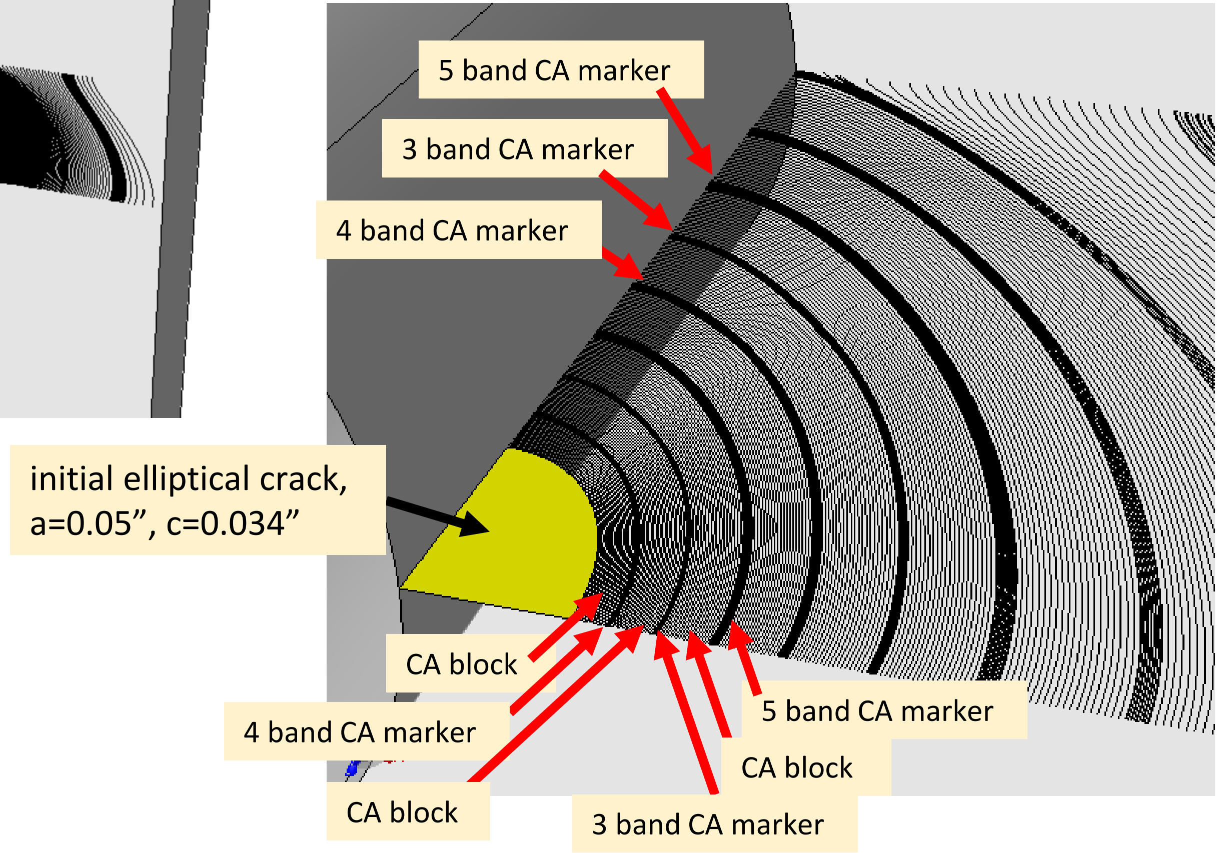
*References used throughout this presentation:
TJ Spradlin, E. Burba, Uncertainty in DTA due to variability in residual stress at cold work expanded holes, 2023 ASIP.
PL Phillips, TJ Spradlin, E. Burba, Fatigue Testing of 7050-T7451 cold expanded specimens and subcomponent specimen development, 2023 ASIP.
PL Phillips, W. Braisted, E. Burba, TJ Spradlin, Fatigue Testing and in-situ crack monitoring of 7050-T7451 specimens with engineered residual stresses from split-sleeve cold expansion, 2022 ASIP.
TJ Spradlin, Round-Robin Life Prediction Invitation for Variability in Residual Stresses at Cold Expanded (Cx) Holes

3D FEA based solution: setup and post-processing

- 3D FEA based solutions (multi-DoF) were completed with SimModeler capabilities, LEFM.
- The setup used only data from the round robin announcement: specimen geometry, CA loading mission, tabular FCGR, initial crack size.



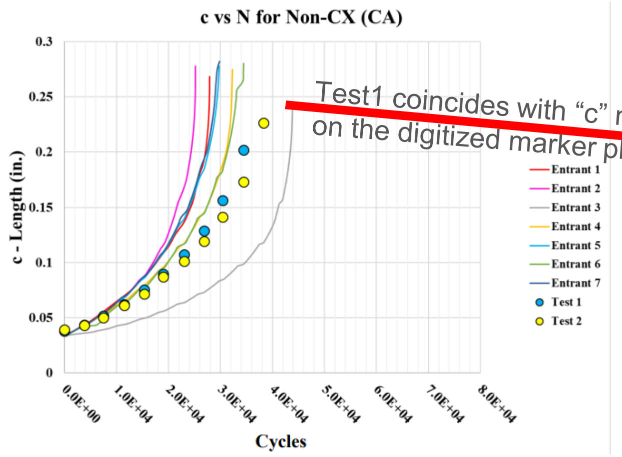




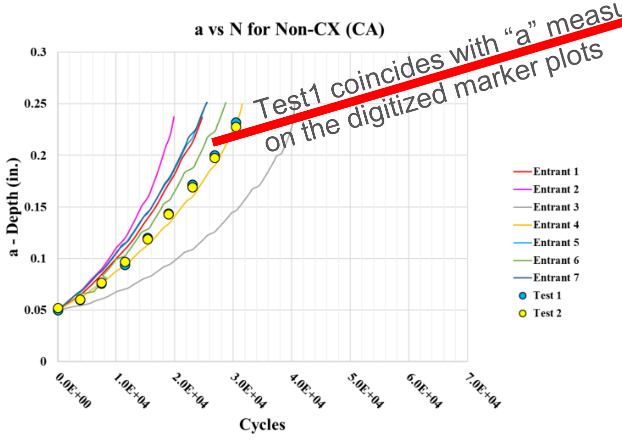
The 3D FEA solution uses the same loading mission as the experimental procedure

Fatigue crack growth measurement references (2 sets)

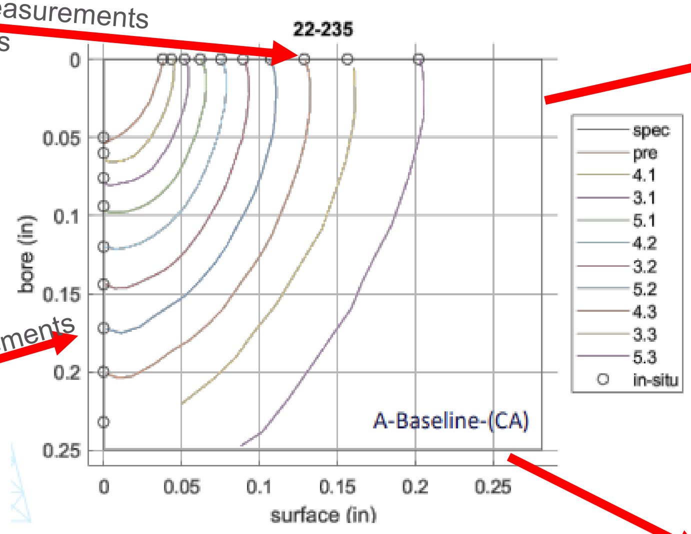
- Since the raw test data was not yet released, the plots available in the references were digitized to relate marker bands to loading mission for the two non-Cx measurements

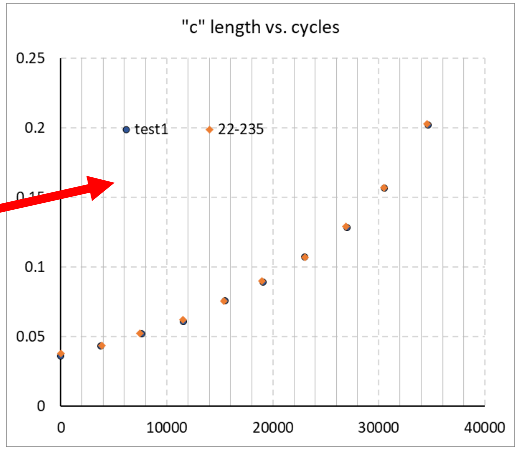


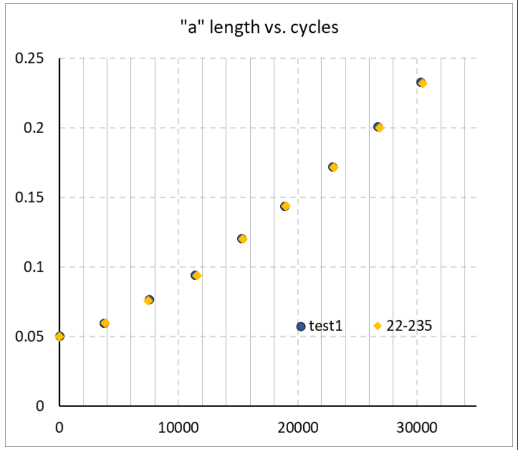
Test1 coincides with “c” measurements on the digitized marker plots



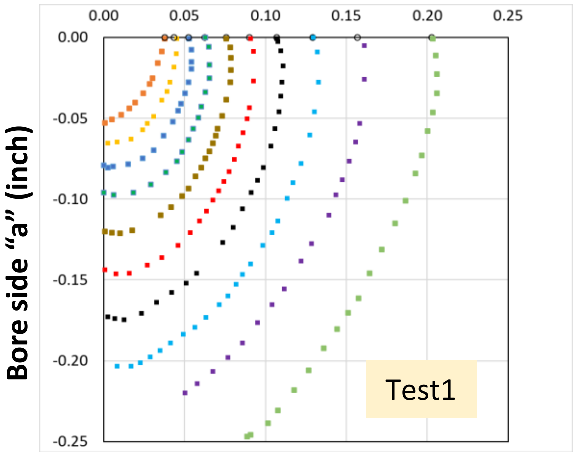
Test1 coincides with “a” measurements on the digitized marker plots

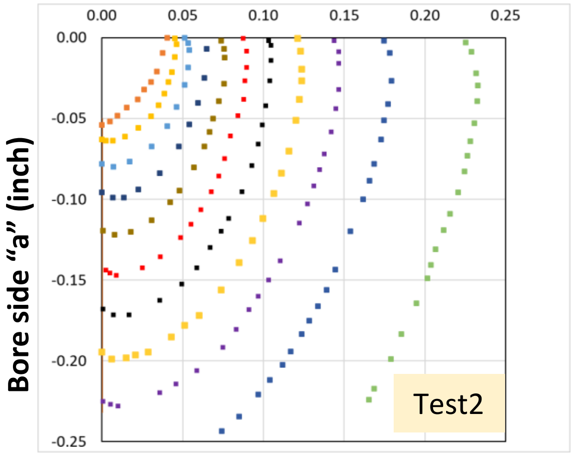






Specimen front side “c” (inch)



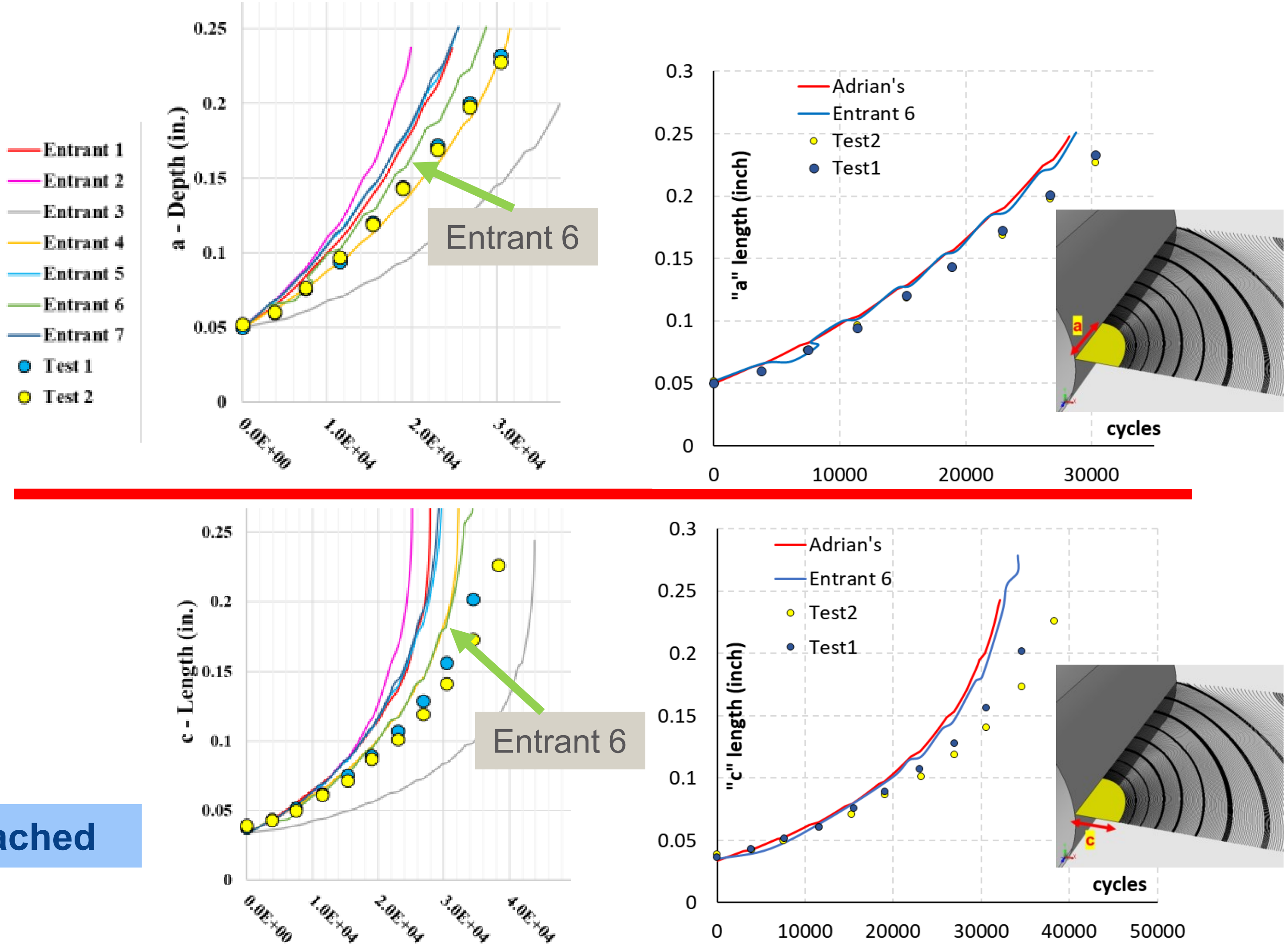


The marker bands are used as a validation reference for the 3D FEA solutions

3D FEA solution vs. other round-robin entries

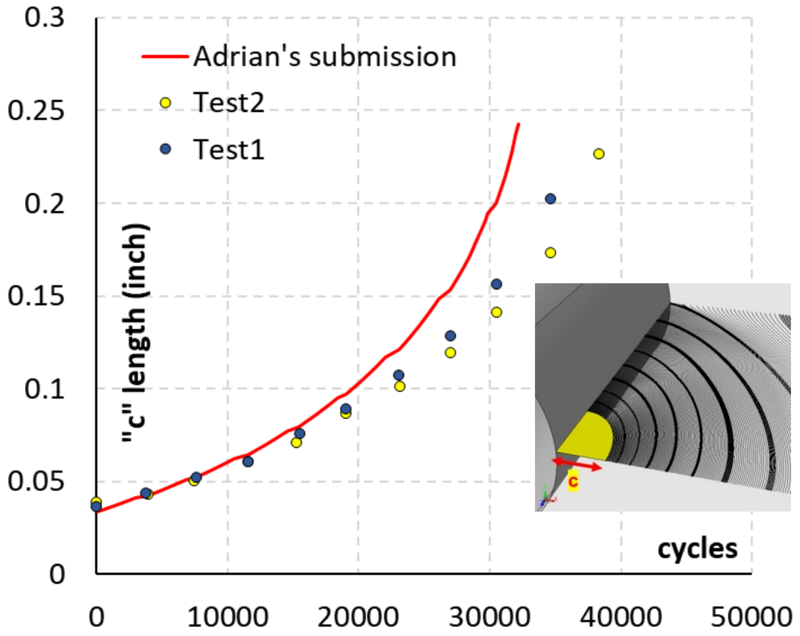
- The solution presented herein was completed and submitted before the RR challenge deadline
- The outcome of the round-robin challenge (see public references) indicate 2-DoF as well as multi-DoF solutions submitted by the participants
- The 3D-FEA based solution (no crack front increment shape constraint) is compared against the published solutions submitted by the participants
- My solution is similar to the solution submitted by Entrant 6 (a multi-DoF solution)

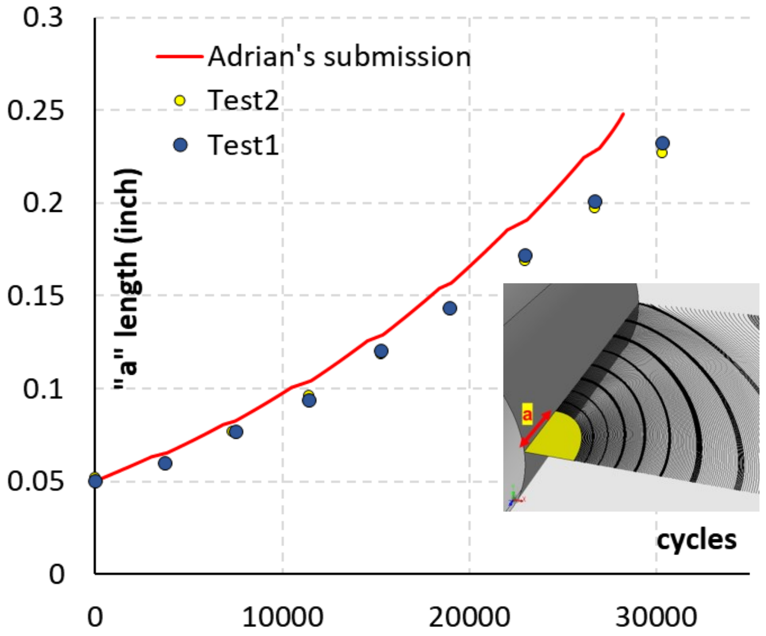
Verification against a different submission is reached

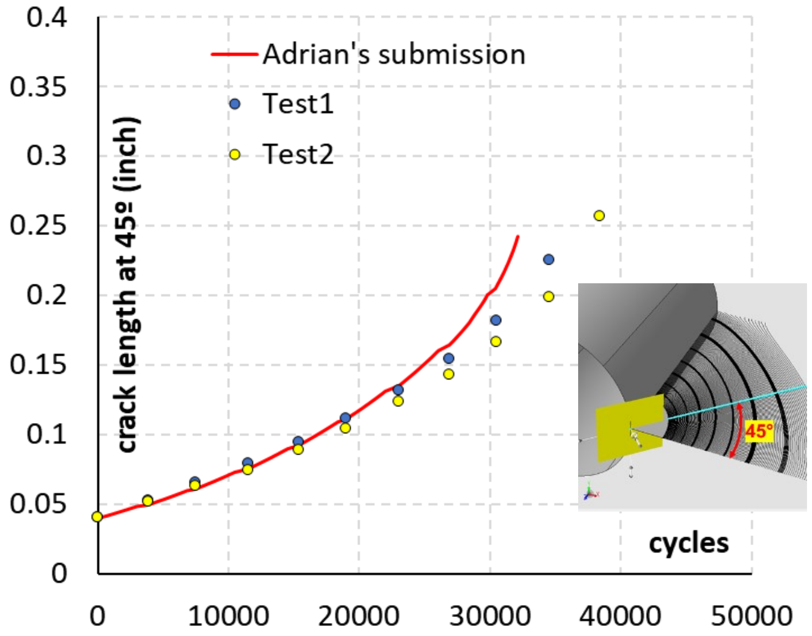


3D FEA solution vs. crack size measurement along three directions

- For validation purposes, different directions could be used to assess crack depth during the test procedure (accumulated cycles)
- The 45º crack length solution seems to capture better the two post-failure fractography measurements (no surface effects)





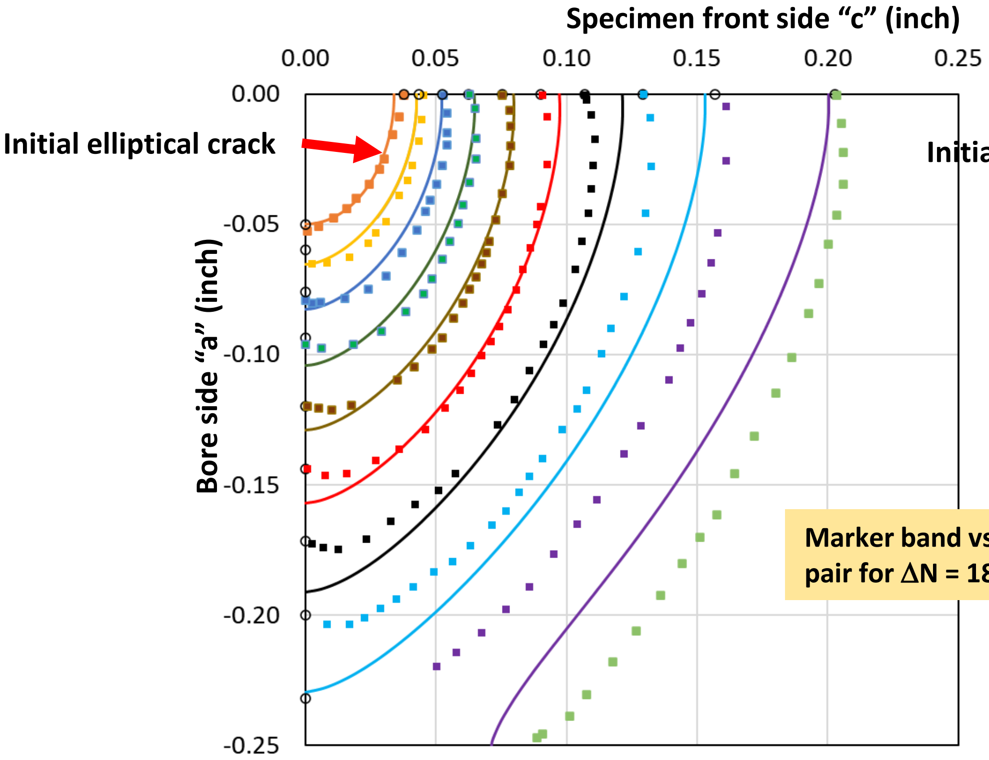


Given the different sources of uncertainty (modeling and experimental), 3D FEA based solutions capture well the experimental measurements

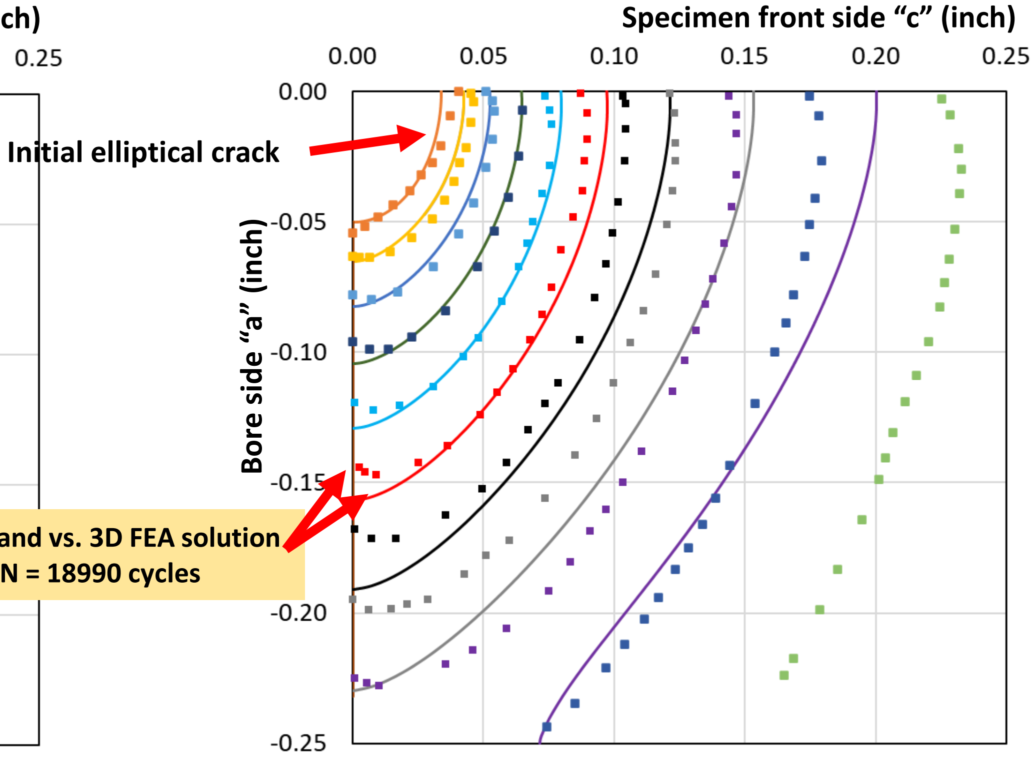
3D FEA solution vs. beach mark data

- Crack front solutions at same cycle intervals as the marker band loading blocks might provide a better visual comparison
  - 3D solution does not account for any surface effects, crack front shape is not constrained to be elliptical

Numerical solution vs. reference marker bands from Test1



Numerical solution vs. reference marker bands from Test2



- Dotted crack front representations: marker bands
- Continuous crack front representations: 3D FEA solutions
- Same color representations = same accumulated number of cycles

Marker band data seems to be a better option to assess accuracy of the solution

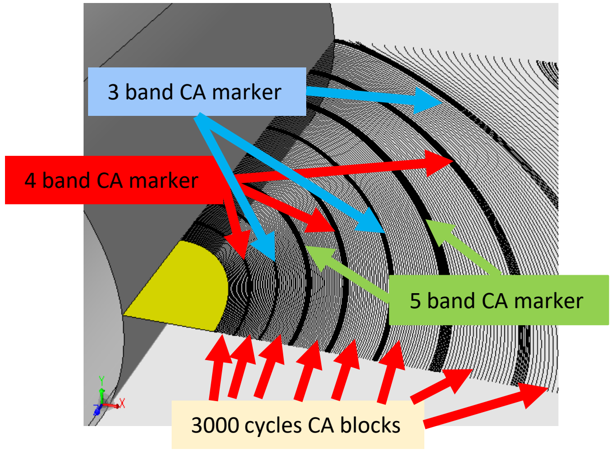
Additional work post round-robin challenge deadline

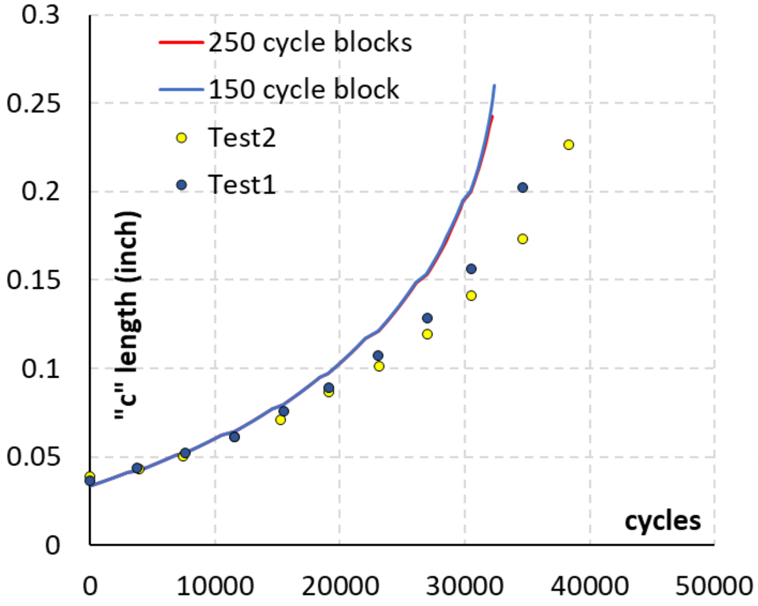
Sources of uncertainty addressed further in this study:

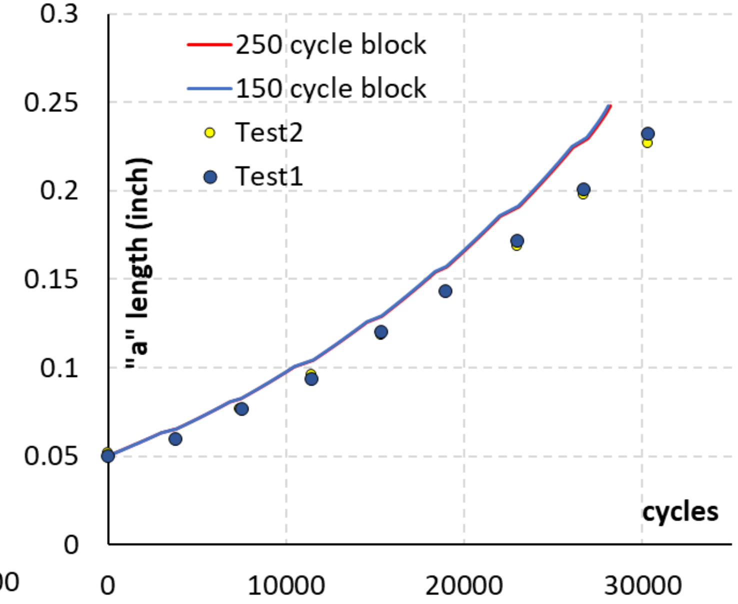
- Loading block definition in the model
- Mesh refinement along crack front
- Fatigue crack growth scatter
- Crack front shape: assumed to stay elliptical vs. no shape constraint

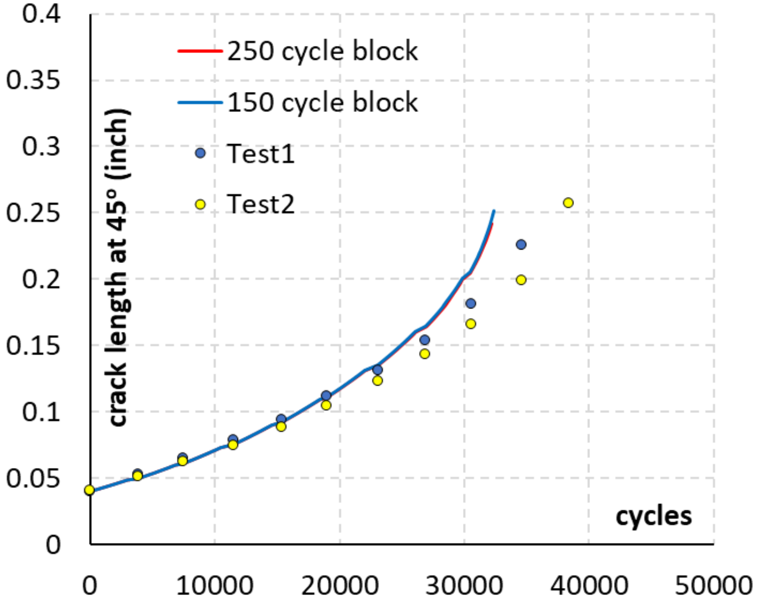
Solution uncertainty due to loading block sequence definition: multi-DoF model

- Two solutions using different ΔN incremental definitions are compared:
  - Loading block definition: 150 loading sub-blocks for the 3000-cycle block
  - Loading block definition: 250 loading sub-blocks for the 3000-cycle block





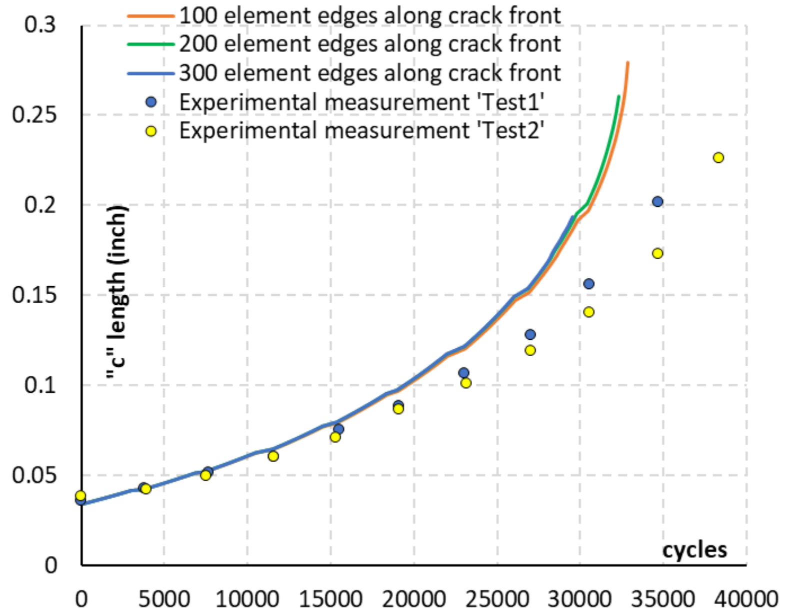


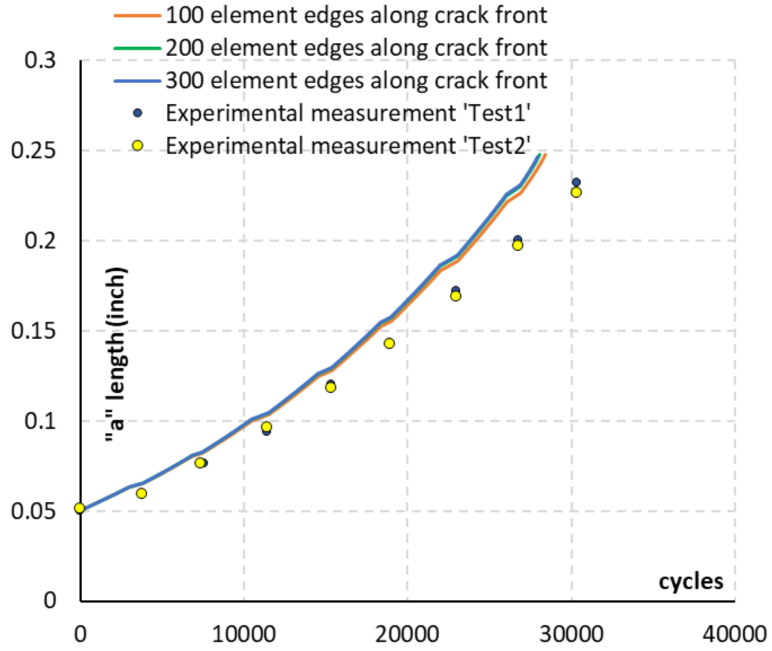


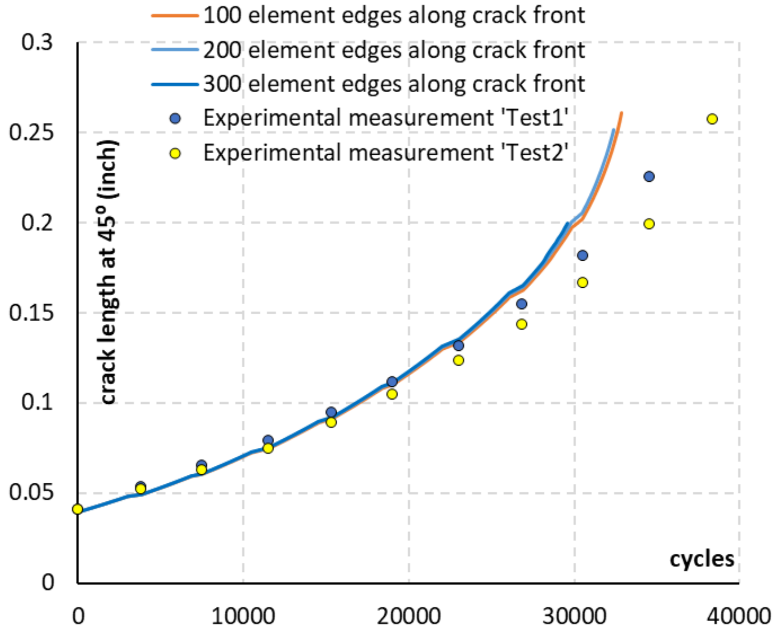
Solution is not sensitive to the loading block definition

Solution uncertainty due to mesh refinement along crack front edge

- Is solution sensitive to the mesh refinement along each crack front increment?
  - Mission definition using loading sub-blocks of 150 cycles, FCGR data as provided in the round-robin announcement
  - Three mesh refinements are used in the assessment: 100, 200, 300 element edges consistently along each crack front edge generated in the crack growth solution





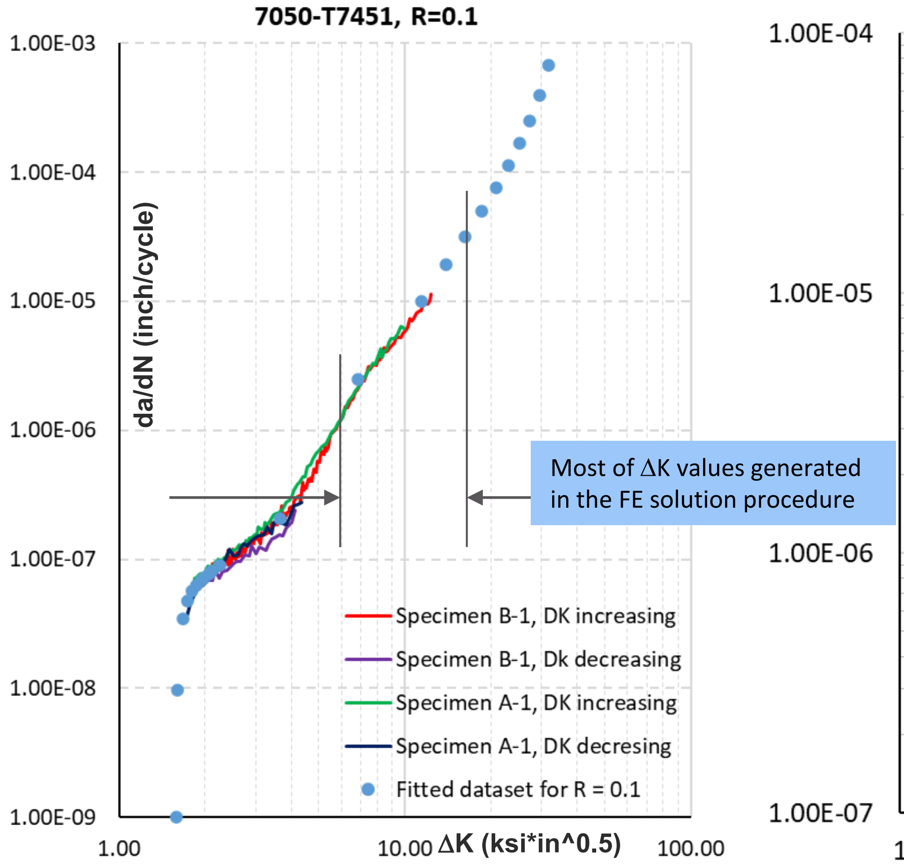


Solutions provided in this study are not sensitive to the mesh refinement (along crack front or overall)
The level of mesh refinement is quite high

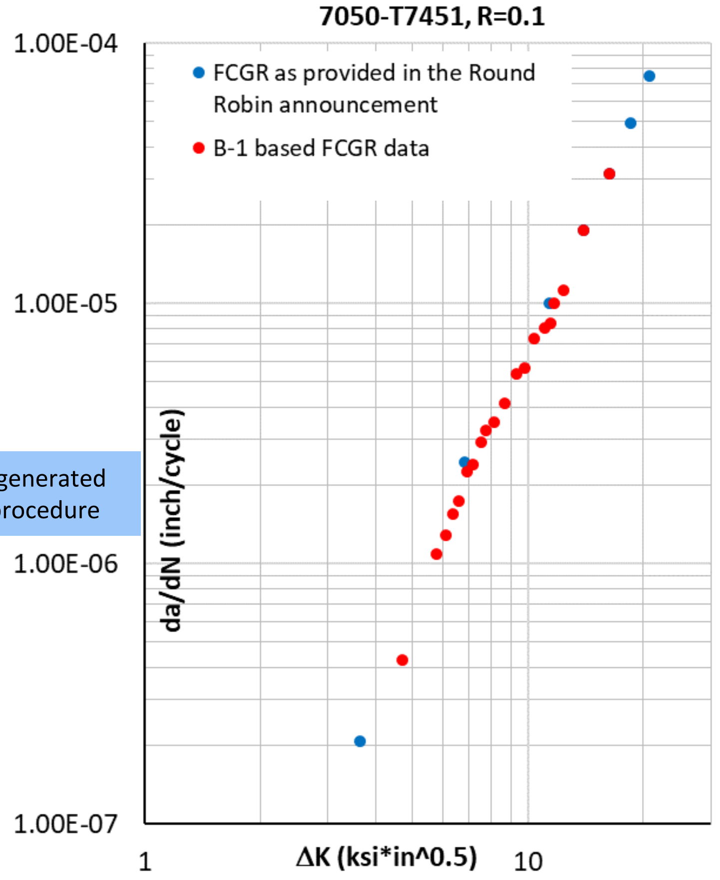
FCGR assessment and solution uncertainty

- The FCGR data as provided in the RR problem statement contains only few datapoints in the corner crack growth regime (ΔK_I = (6, 18) ksi*in^0.5)
- B-1 (CT specimen) data was used to add more points to the tabular FCGR used in the numerical solution and to evaluate solution sensitivity (corner crack case)
- FCGR assessment and numerical solution sensitivity can be a subject for a round-robin challenge

FCGR as provided in the RR announcement



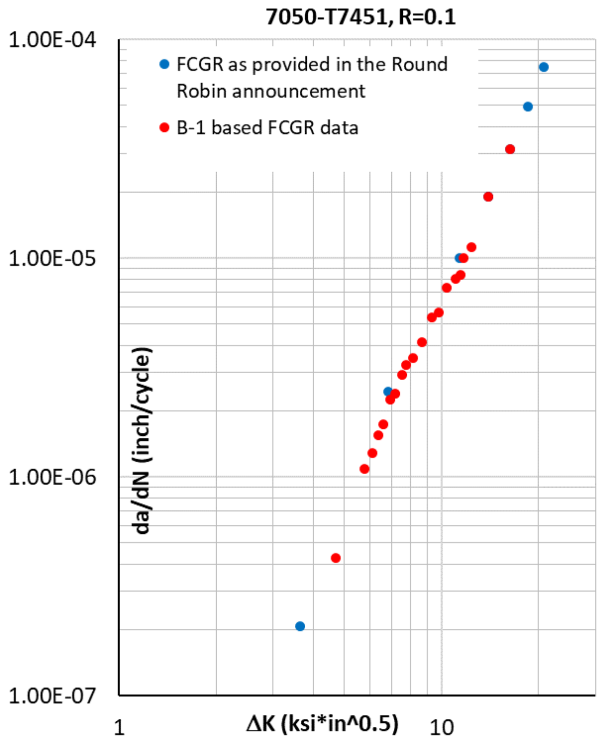
B-1 FCGR used in the 3D solutions

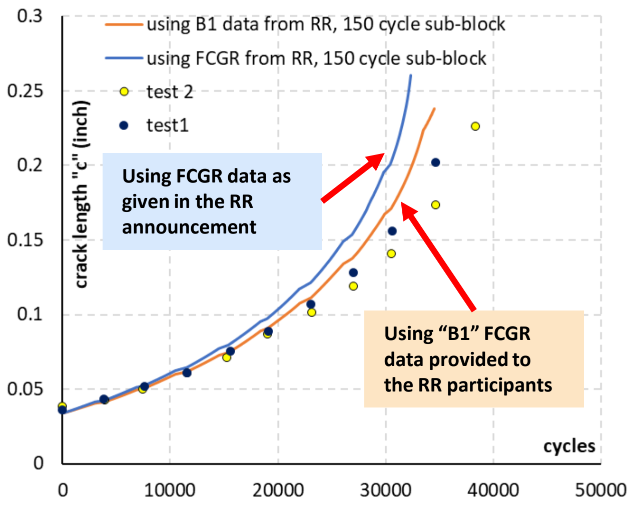


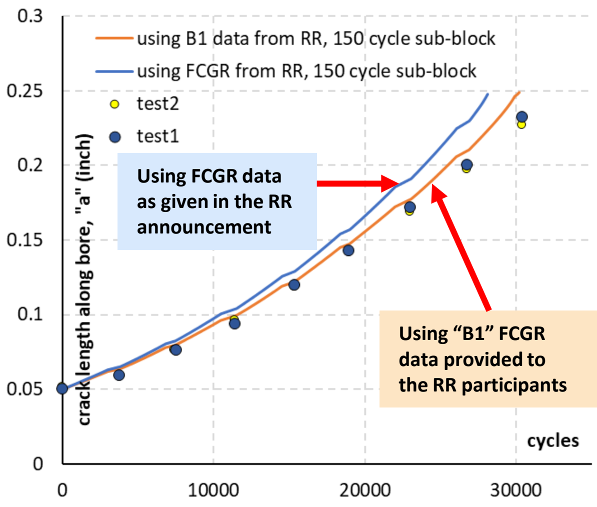
B-1 based FCGR was considered in the numerical procedure to evaluate solution sensitivity

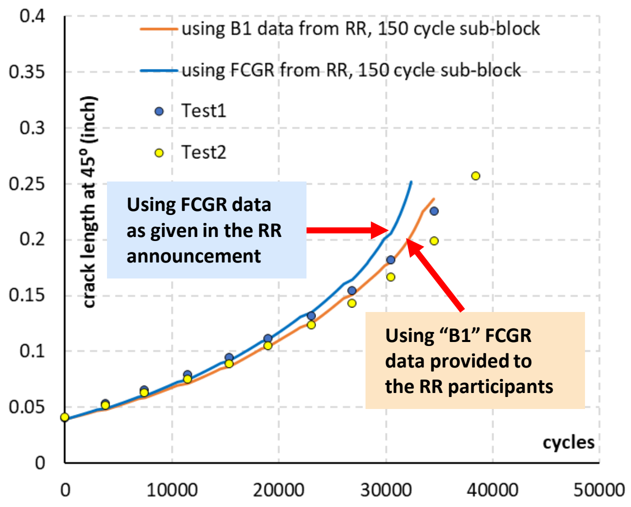
FCGR assessment and solution uncertainty

- Solutions from two fatigue crack growth rate datasets are compared at the free boundary (“a” and “c” dimensions and at 45º): the FCGR as provided in the round-robin announcement and, the fatigue crack growth measurement collected on “B-1” CT specimen (was provided with the RR announcement).







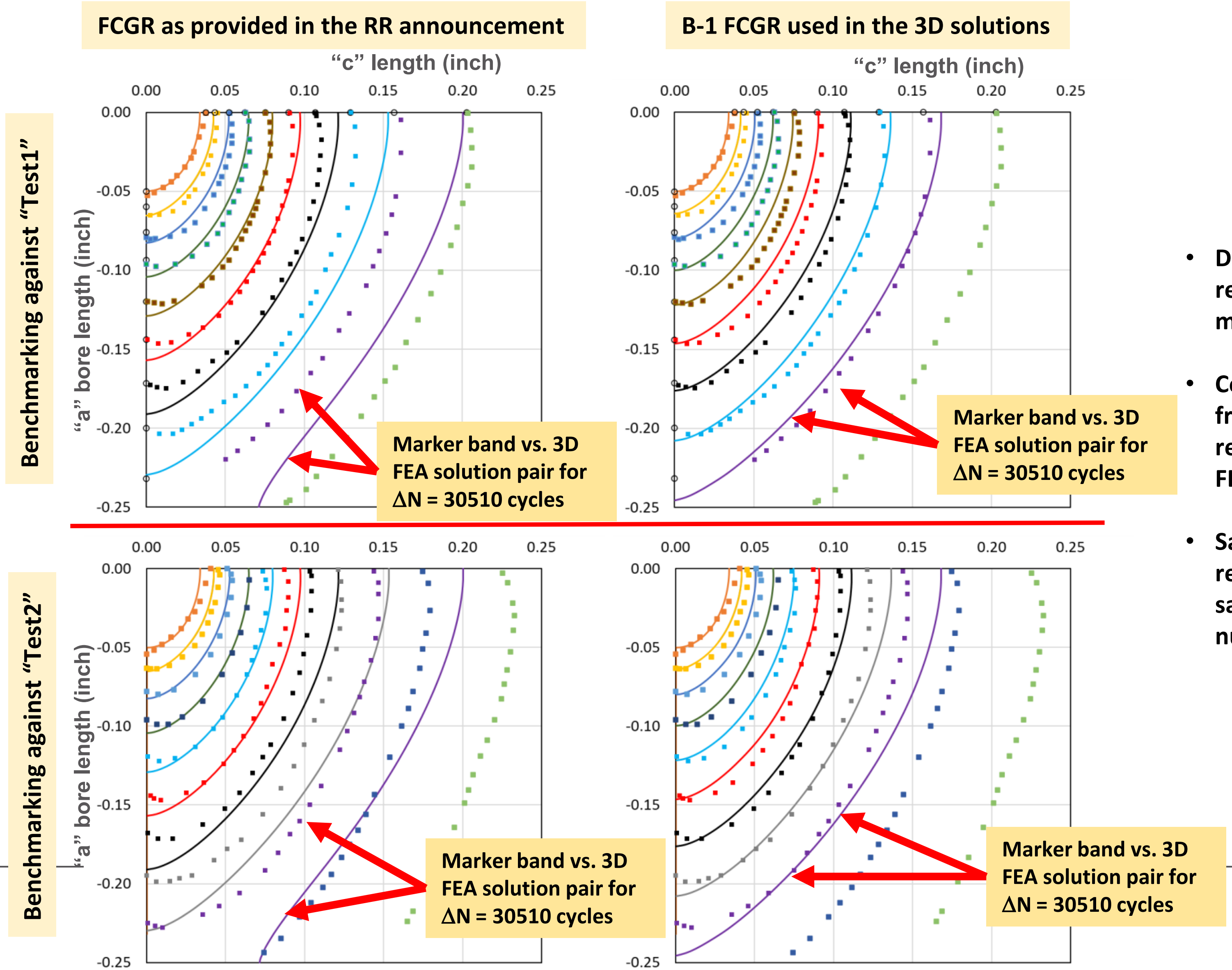


Usage of B-1 FCGR data seems to improve solution accuracy
As expected, numerical solution is sensitive to the FCGR

FCGR assessment and solution uncertainty

- The same solution comparison can be carried out for the two sets of marker bands
- Overall, usage of FCGR recorded for the B-1 compact tension specimen in the numerical solution for the corner crack growth at the rim of a hole in a rectangular cross-section bar, seems to capture better the reported marker bands

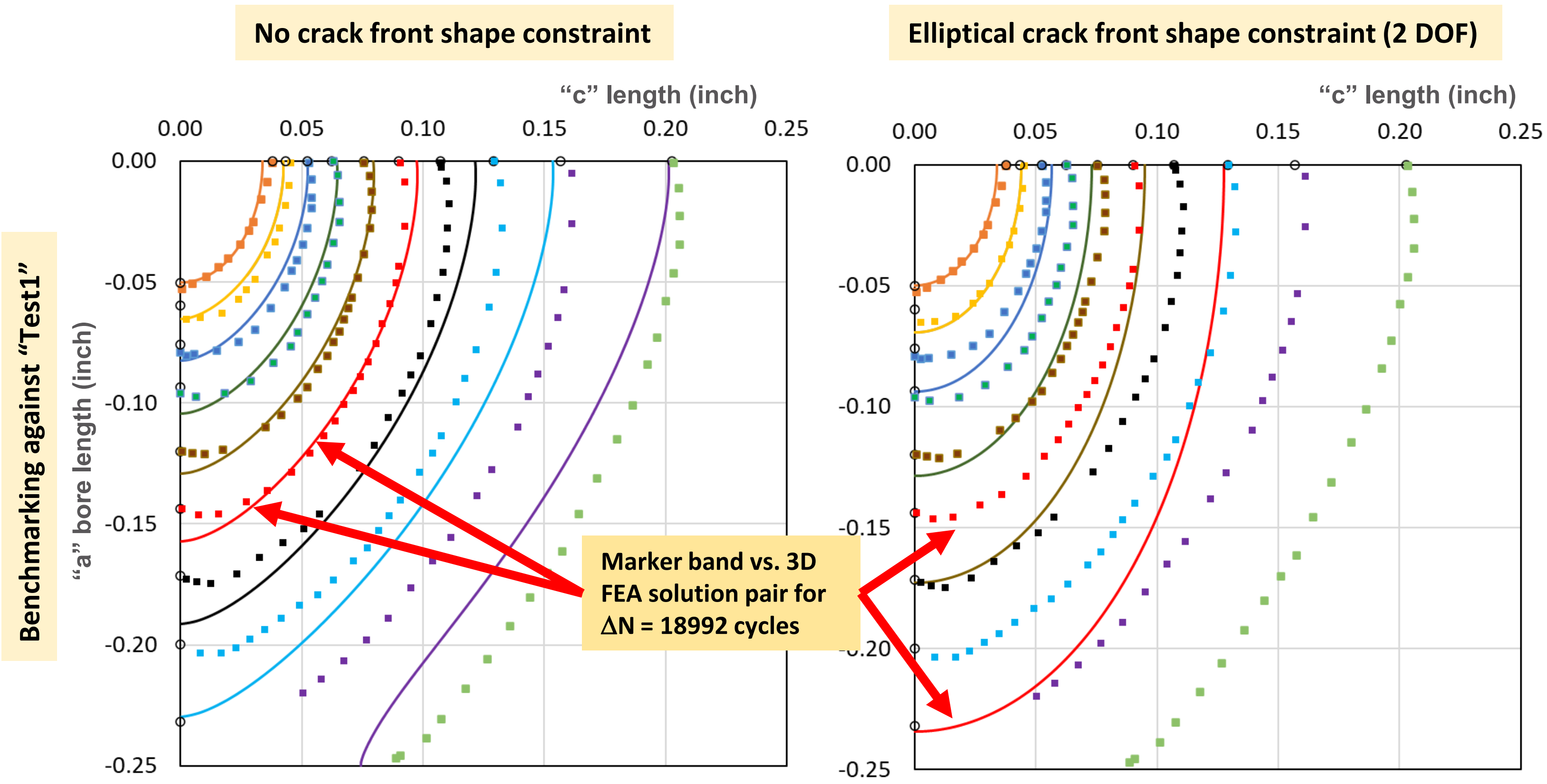
Usage of B-1 FCGR data in the numerical procedure improves solution accuracy



- Dotted crack front representations: marker bands
- Continuous crack front representations: 3D FEA solutions
- Same color representations = same accumulated number of cycles

3D FEA: 2-DoF vs. multi-DoF solution

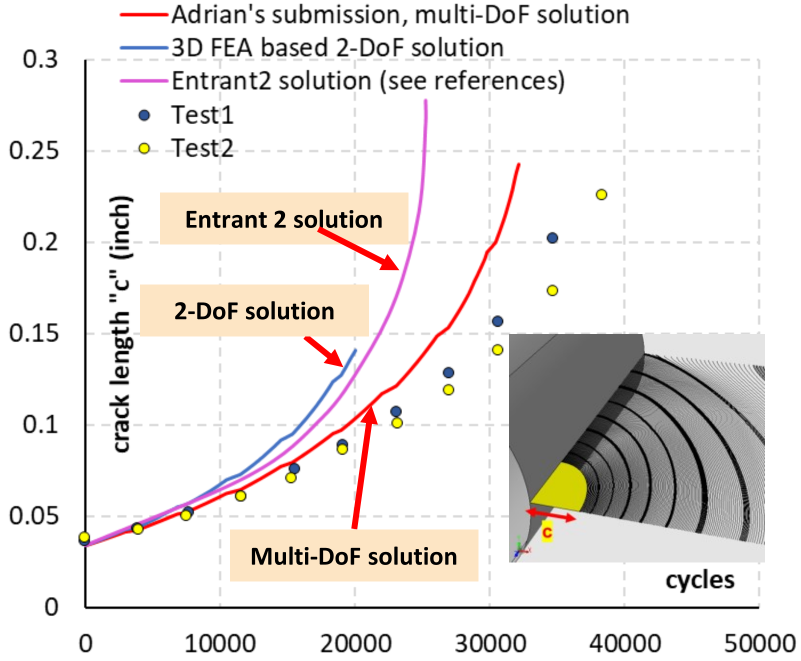
- The 3D FEA procedure can also be used as a 2-DoF crack growth solution
- Using 150-cycle sub-block partitions of the 3000 CA loading blocks, a comparison can be made between the two solutions: elliptical and, no shape constraint for the crack front increments
- No surface effects are included in both solutions
- The 2-DoF solution has a larger error in comparison to the multi-DoF solution.
- Both solution types use the FCGR data as provided in the RR problem
- Both solutions are conservative for this benchmark

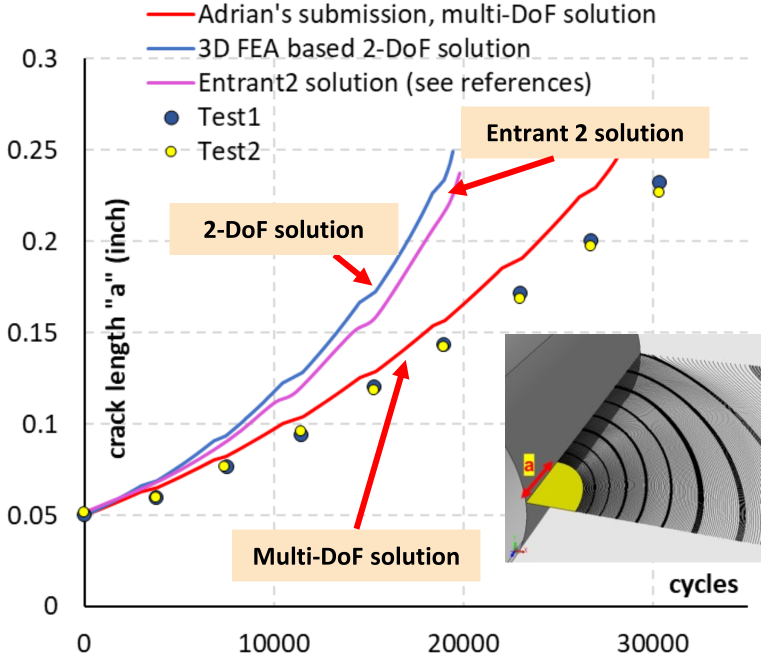


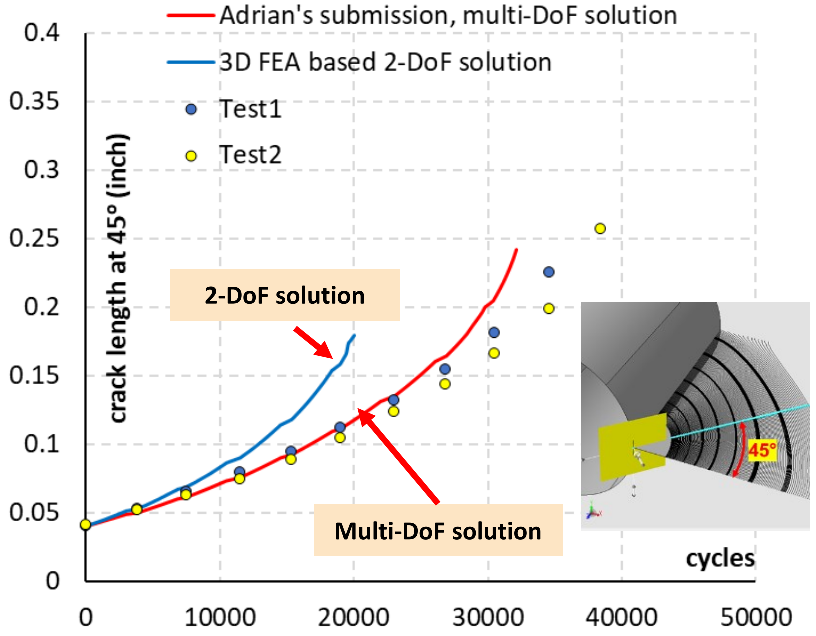
The multi-degree of freedom solution is more accurate than the 2-DoF (surface effects not included)

3D FEA: 2-DoF vs. multi-DoF solution

- Crack length along the bore (“a”), specimen frontal side (”c”) and at 45° provide a similar quantitative difference between the multi-DoF and the 2-DoF solutions
  - Sensitivity of the 2-DoF solution to loading mission definition (150, 250, 500 loading sub-blocks) was also checked. It was found that solution is not sensitive to the loading sub-block size.
  - The 2-DoF solution is about 4% from the solution submitted under “Entrant2” (most conservative solution submitted to the RR challenge)



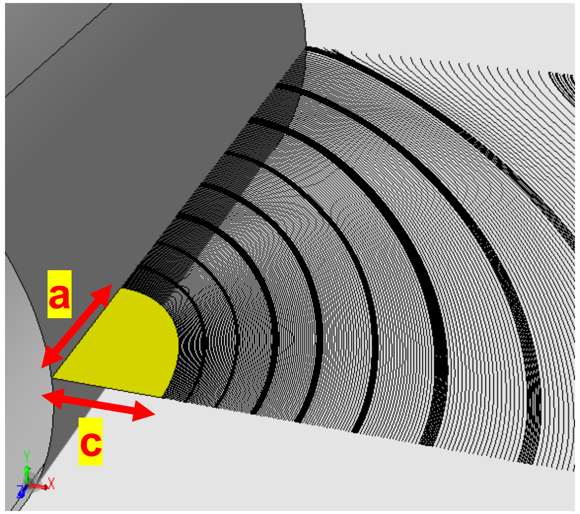


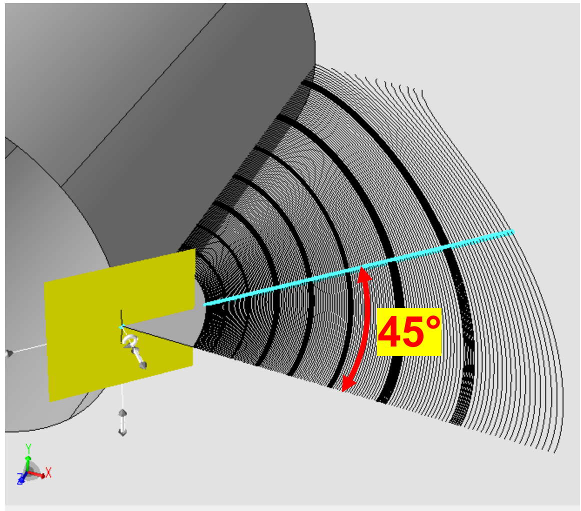


The multi-degree of freedom solution is more accurate than the 2-DoF (surface effects not included)

Conclusions

- The 3D FEA procedure (multi-DoF) provides a solution:
  - 23% off along "c", 15% off along "a", 10% off at 45° direction from the actual measurement for FCGR provided in the RR statement
  - 14% off along "c", 7% off along "a", 3% off at 45° direction from the actual measurement for FCGR using the B-1 measurement
  - All solutions are conservative
- Solutions from 3D FEA procedure are verified against two other RR submissions:
  - Multi-degree of freedom (solution marked "Entrant 6")
  - 2-DoF (solution marked "Entrant 2").
- Uncertainties were addressed deterministically since the 3D FEA is robust to carry out automatically the fatigue crack growth solution for the entire loading mission
  - FCGR is an important source of uncertainty that needs to be considered in the numerical solution. Maybe this subject should be considered as a new round robin challenge.
  - Mesh refinement and loading mission definition did not contribute to a significant solution variation.
  - Crack front shape constraint (2-DoF vs. multi-DoF) is an important source of solution variability (the published RR solutions indicate the same conclusion).





Questions?

Working Group on
Engineered Residual
Stress Implementation

Interference Fit Fastener Round Robin

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Overview

Round robin description, conditions, objectives

Summary of results

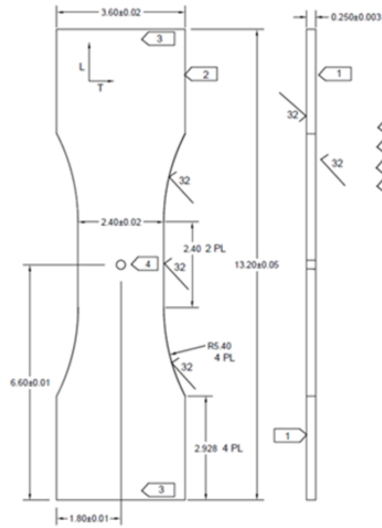
- Group 1
- Group 2
- Group 3

Next steps

Round robin description

Objectives

- Establish a set of reference stress analyses that can be utilized for follow-up phases
- Characterize:
  - The onset of plastic deformation and the bounds of elastic vs. plastic regimes
  - The stress state dependency as a function of key factors (e.g. interference level, modeling assumptions, remote loading)



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

2024-T351 dogbone sample with interference fit steel pin

5 conditions

- Open hole
- Neat fit (no interference, no clearance)
- 0.3% interference
- 0.6% interference
- 1.2% interference

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 description

3 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	

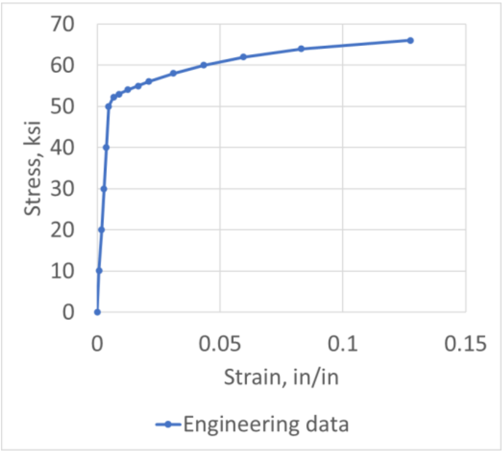
Table 3. Round-robin analysis conditions, group 3

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	

Stress-strain data provided for characterization of elastic-plastic behavior

Material Uniaxial Monotonic Stress/Strain Properties

Courtesy A-10 ASIP, USAF

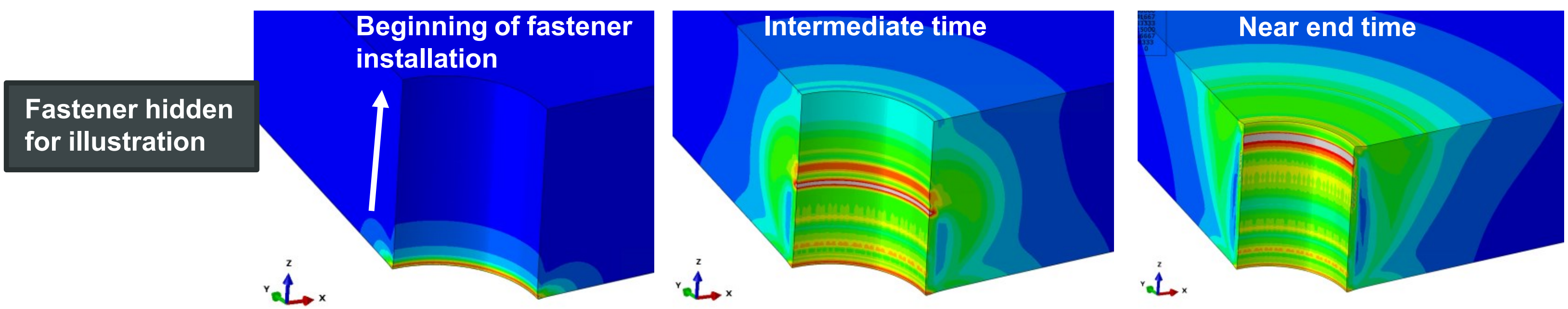


2024-T351, two tests Averages	
Engineering strain in/in	Engineering stress ksi
0	0.000
0.00079	10.032
0.00182	19.979
0.00279	29.948
0.00375	39.985
0.00468	49.998
0.00673	52.252
0.00887	53.000
0.01255	54.007
0.01665	54.995
0.02095	56.003
0.03100	57.995
0.04340	59.993
0.05955	62.006
0.08315	64.002
0.12760	66.001

Round robin description

Details about participants

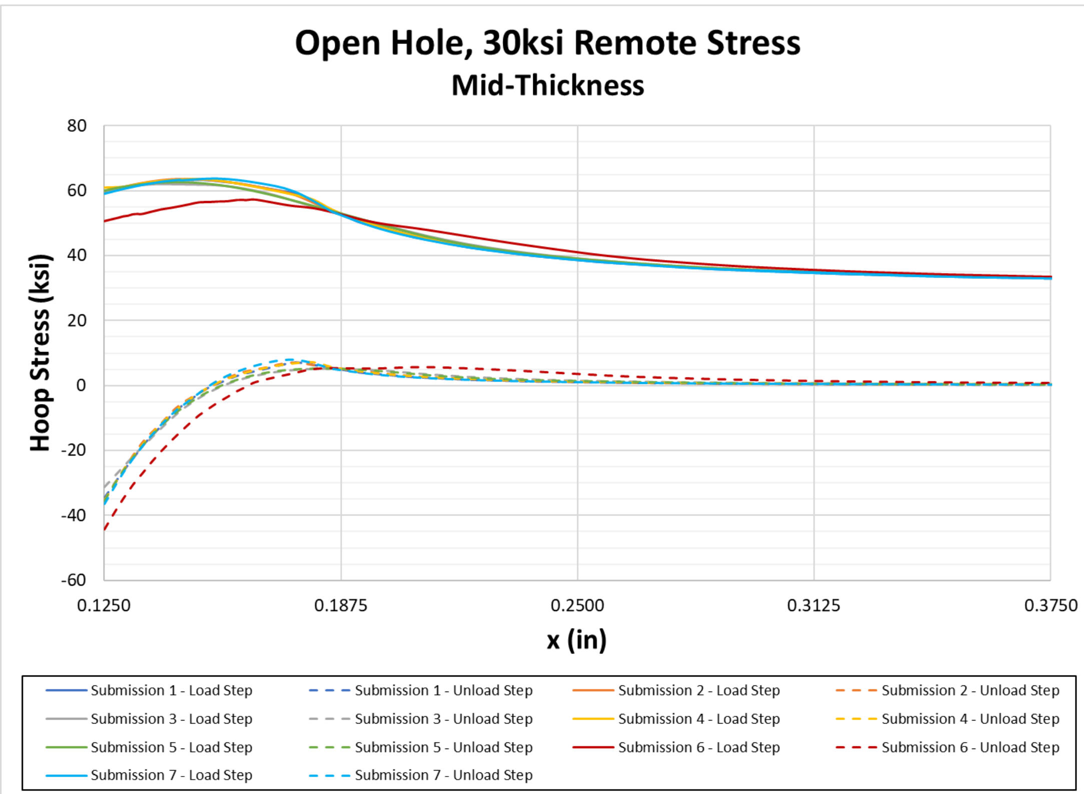
- From 8 different organizations
- Five different software packages used
  - Abaqus, Ansys, StressCheck, SimCenter 3D, Nx Nastran
- Several different modeling techniques for fastener installation
  - Fastener in hole at beginning, then resolve interference
  - Springs to simulate interference
  - Incrementally push fastener in, solve for equilibrium

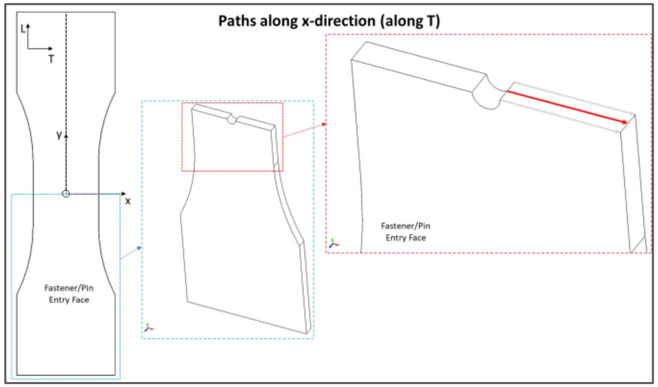


Group 1 – open hole, no fastener

30 ksi applied stress, mid-thickness

- Plastic deformation near the hole
- After unloading, compressive residual stress near hole
- Consistent results between participants

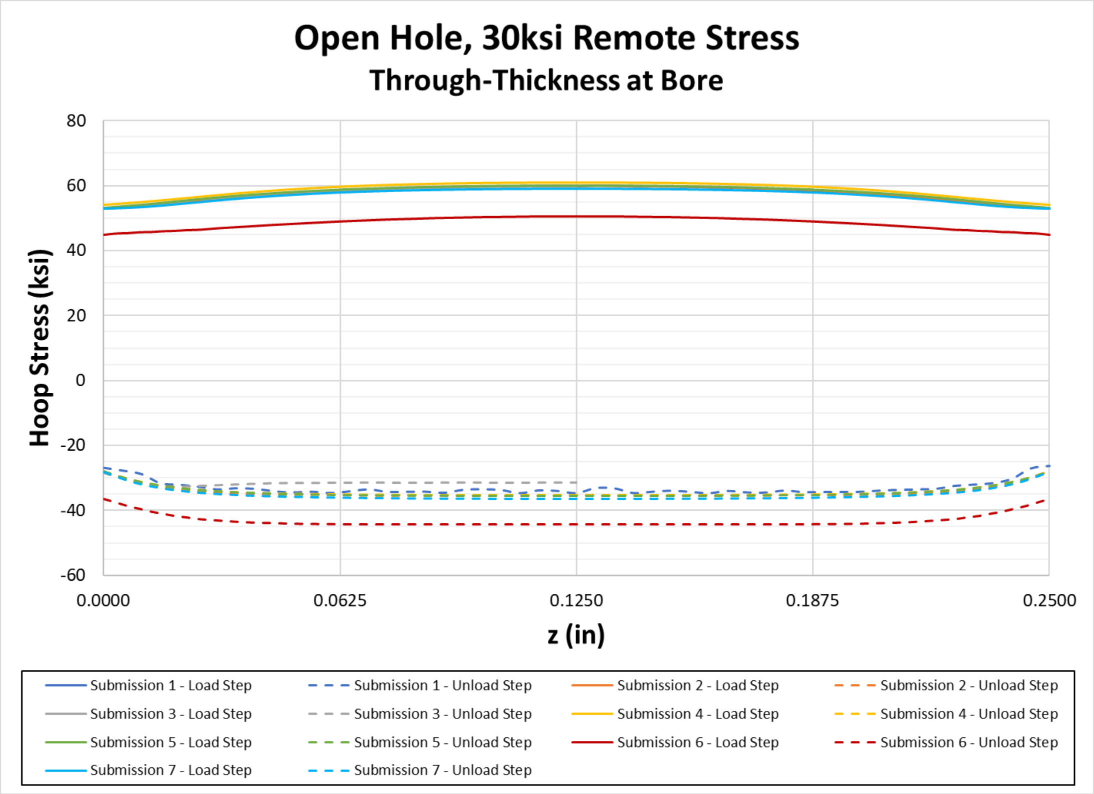




Group 1 – open hole, no fastener

30 ksi applied stress, through thickness at bore review

- After unloading, compressive residual stress through the thickness



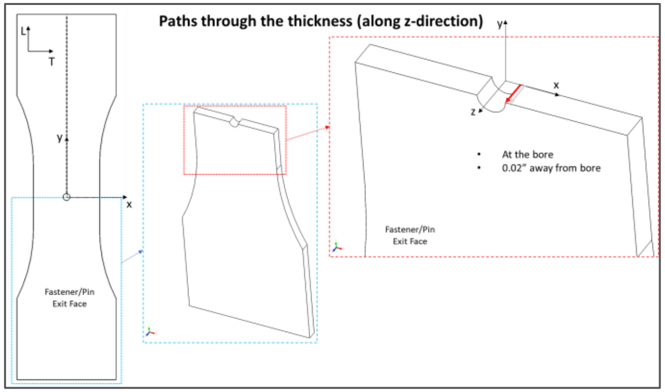
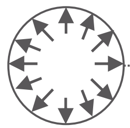


Table 2. Round-robin analysis conditions, group 2

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	

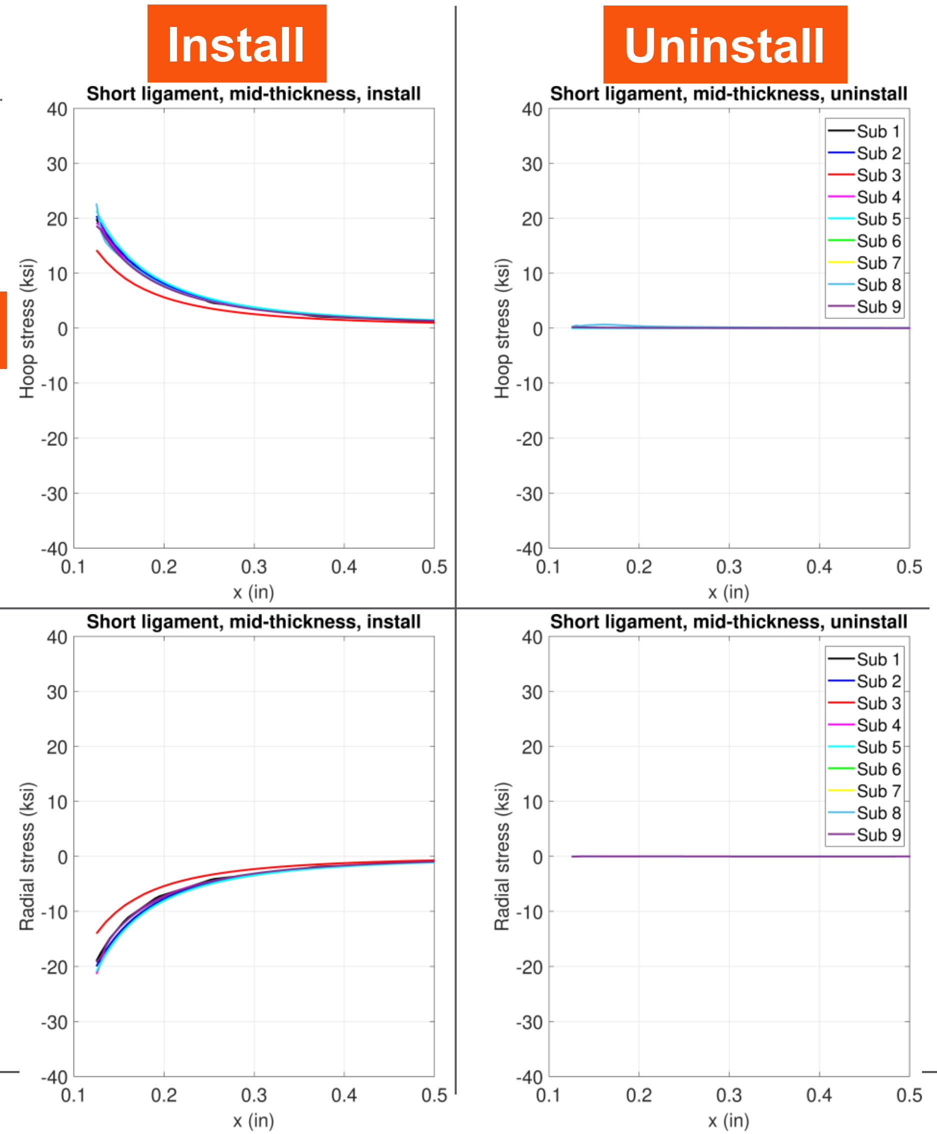
Group 2 – fastener install + uninstall

0.3% interference condition



- Typical hoop and radial stress near the hole
- Hoop stress
  - Tensile, maximum at bore, decays with distance from bore
- Radial stress
  - Compressive, same trend as hoop

After unloading, no residual stress at mid-thickness



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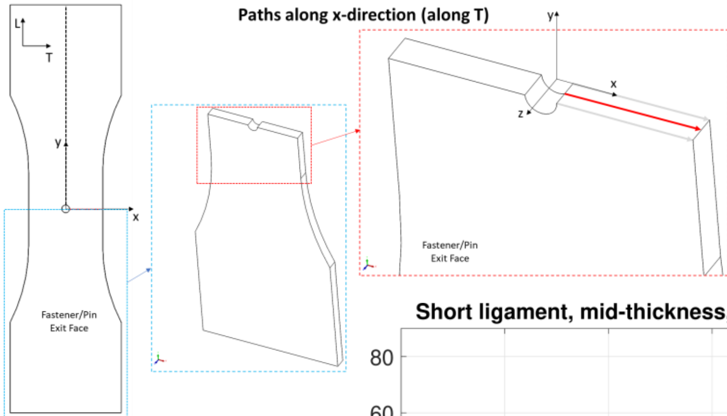
Group 2 – fastener install + uninstall

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	

Stress from installation for all conditions below

- At mid-thickness



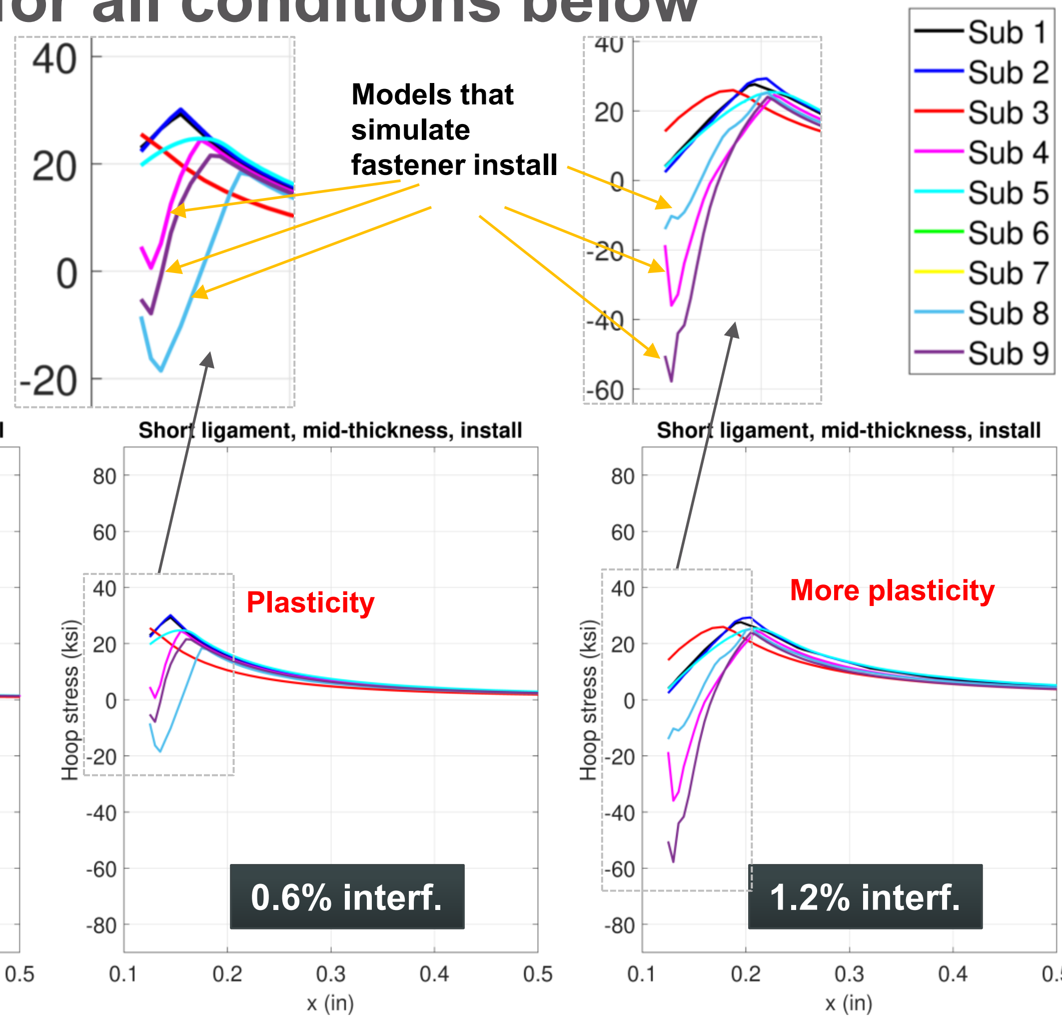


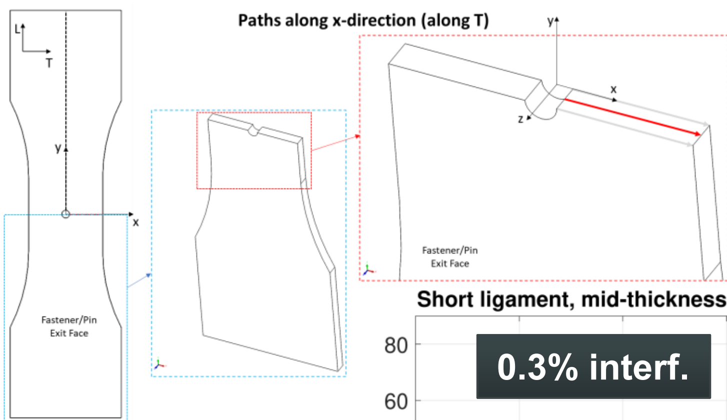
Table 2. Round-robin analysis conditions, group 2

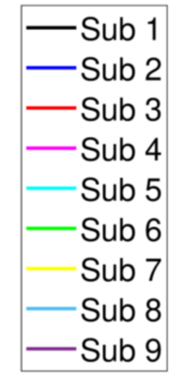
Group	Condition	Sequence Step	Interference Condition	Applied Stress (ksi)
2	1	1 – Installed Fastener 2 – Remove Fastener	0.3% IFF	0
	2		0.6% IFF	
	3		1.2% IFF	

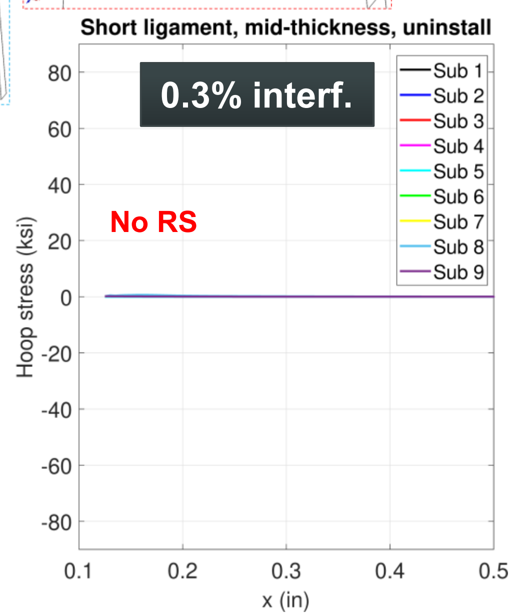
Group 2 – fastener install + uninstall

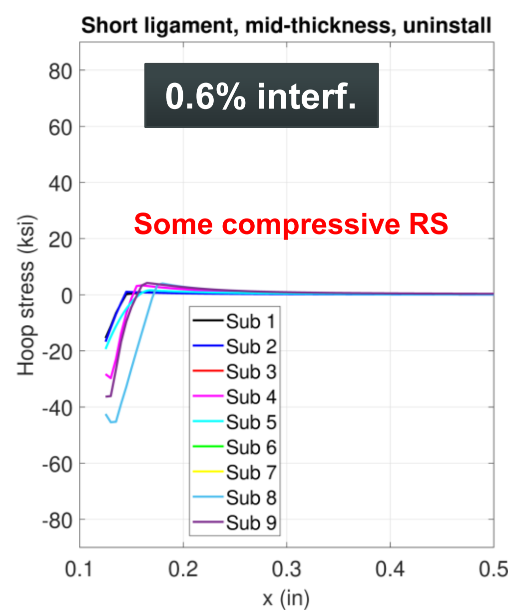
Stress after fastener removal for all conditions below

- At mid-thickness









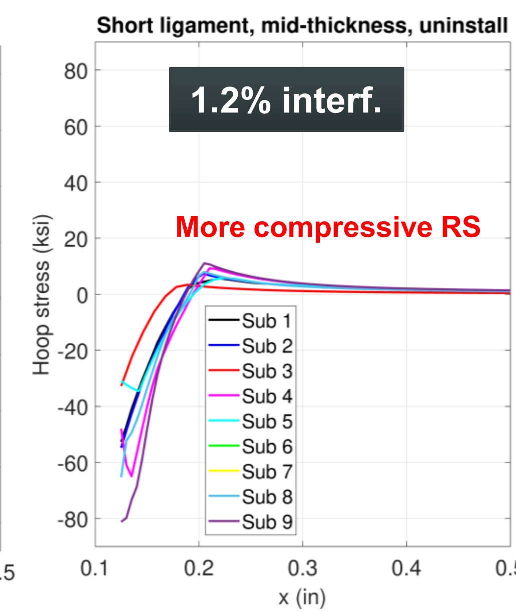


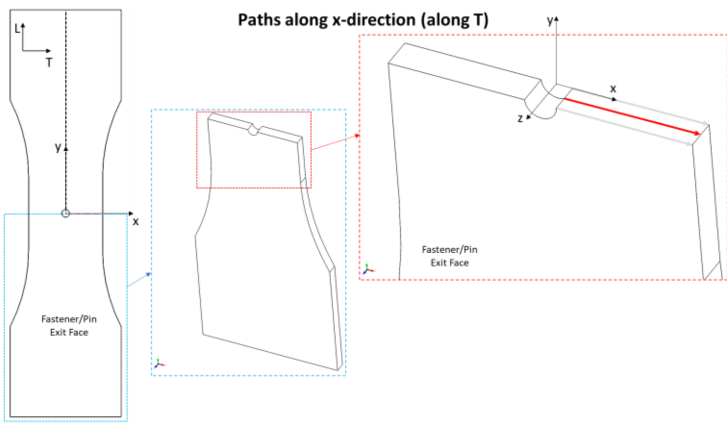
Table 3. Round-robin analysis conditions, group 3

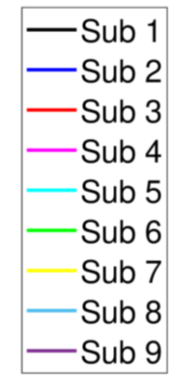
Group	Condition	Sequence Step	Interference Condition	Applied (ksi)
3	1	1 – Installed Fastener	Neat Fit	-10, 10, 20, 30
	2	2 – Apply Remote Stress	0.3% IFF	
	3	3- Unload	0.6% IFF	
	4	4 – Remove Fastener	1.2% IFF	

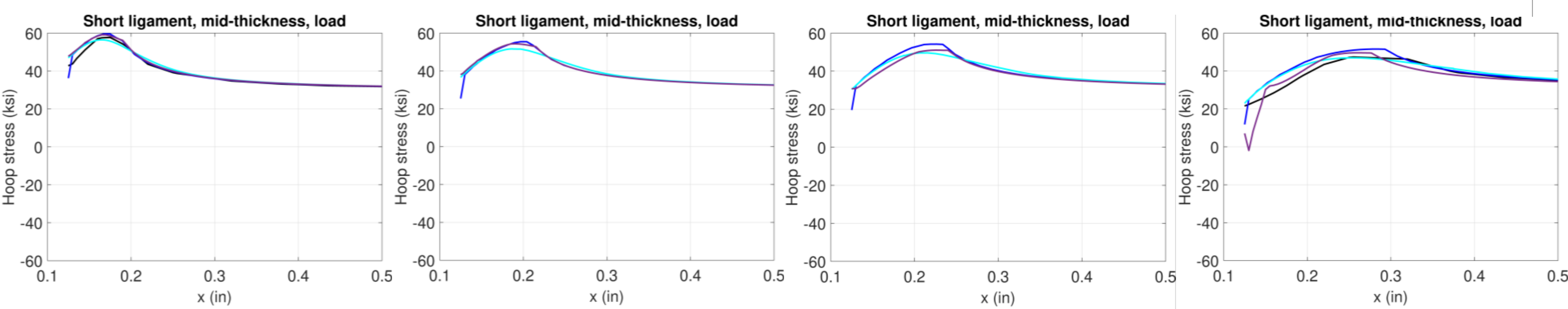
Group 3 – install, load, unload, remove

Stress from installation + remote load (30 ksi) for all conditions below

- At mid-thickness







Neat fit **0.3% interf.** **0.6% interf.** **1.2% interf.**

Group 3 – install, load, unload, remove

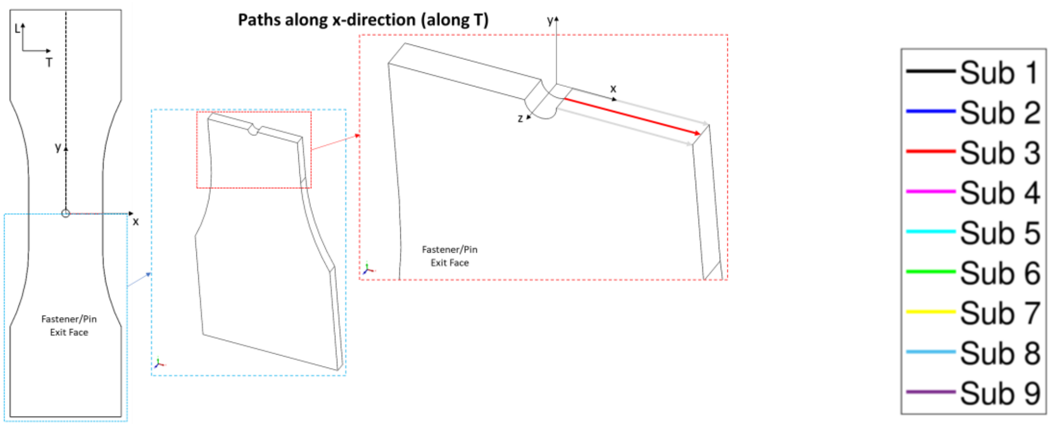
Table 3. Round-robin analysis conditions, group 3

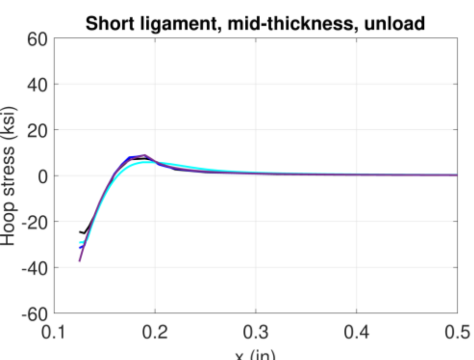
Group	Condition	Sequence Step	Interference Condition	Applied (ksi)
3	1	1 – Installed Fastener	Neat Fit	-10, 10, 20, 30
	2	2 – Apply Remote Stress	0.3% IFF	
	3	3- Unload	0.6% IFF	
	4	4 – Remove Fastener	1.2% IFF	

Stress after install, loading and unloading for all conditions below

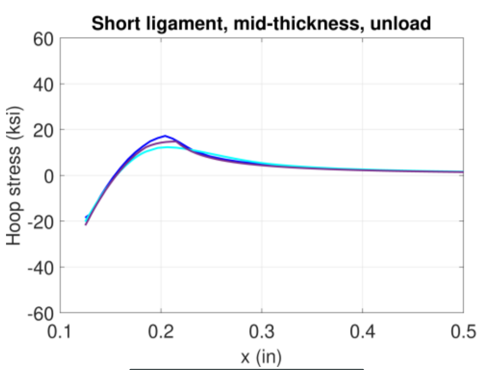
- At mid-thickness
- **Load to 30 ksi, then unload (fastener is still installed)**

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

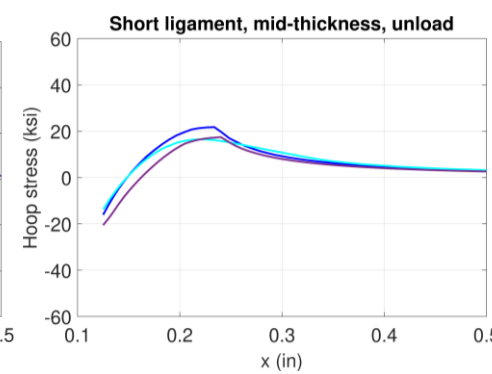




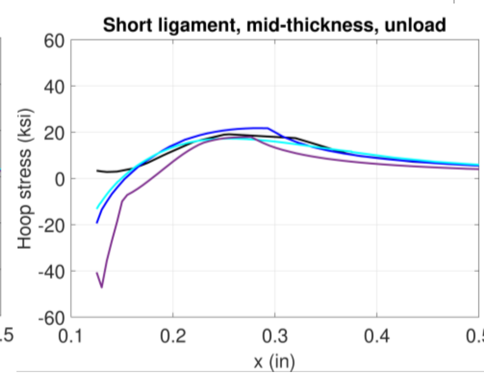
Neat fit



0.3% interf.



0.6% interf.



1.2% interf.

Next steps

Testing is in progress at SwRI

- Phase 1 – assessment of as-installed state
  - characterize stress/strain state due to fastener installation only
- Phase 2 – repeat Phase 1 with the addition of remote loading and unloading (same loading and interference levels as this round robin)
- Phase 4 – fatigue crack growth testing with interference fit fasteners

Testing results will be used for comparison to analytical models once available

- Revisit each above phase
- Compare/contrast predictions vs. test
- Document lessons learned and best practices

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A-10 Interference Fit Fastener Testing & Analysis Program

A-10 IFF Testing & Analysis Program

Acknowledgements

- Special thanks to A-10 team for sponsoring this testing

Overview

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

Objective

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

Current Status

- Initial testing underway

Timeline

- Coupon manufacturing complete
- Phase 1: Complete by end of April
- Phase 2: Complete by end of May

A-10 IFF Testing & Analysis Program

Phased approach with increasing complexity

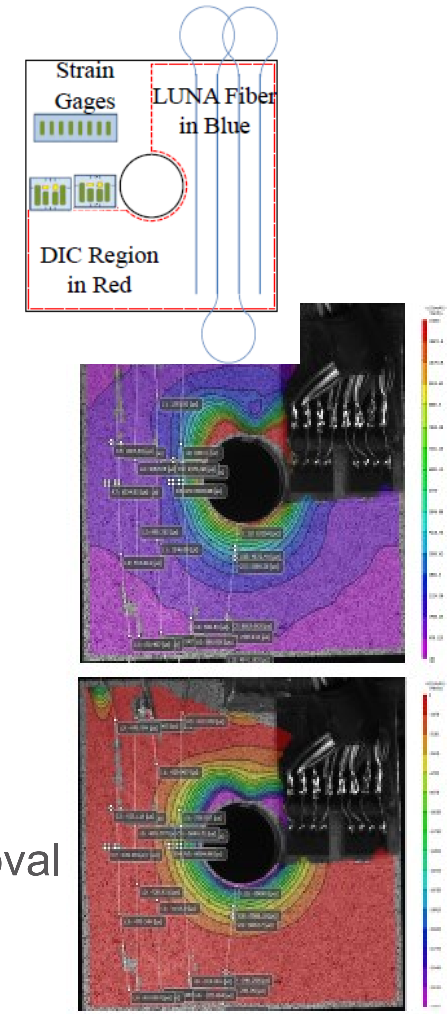
- Phase 1: assessment of as-installed state
  - Simulate and empirically quantify the strain and stress state near a hole in the presence of an interference fit fastener
    - 3 levels of interference
    - 3D nonlinear FE process modeling; DIC and strain gages for surface strain measurements
- Phase 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

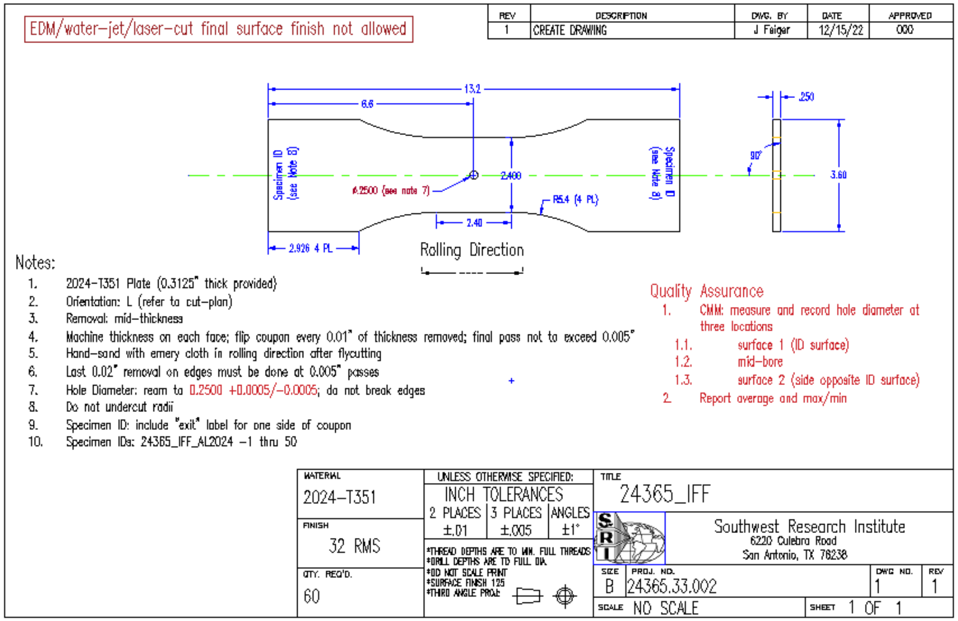
- Design conditions
  - Fasteners – gauge pins with ground transition geometry
- Data capture
  - 3D geometric measurements of fastener and hole
    - \+ Calculate applied interference along bore
  - Surface strains (primarily DIC)
    - \+ Leverage lessons learned from ERSI Cx 2x2 Residual Stress Validation 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

Current Progress

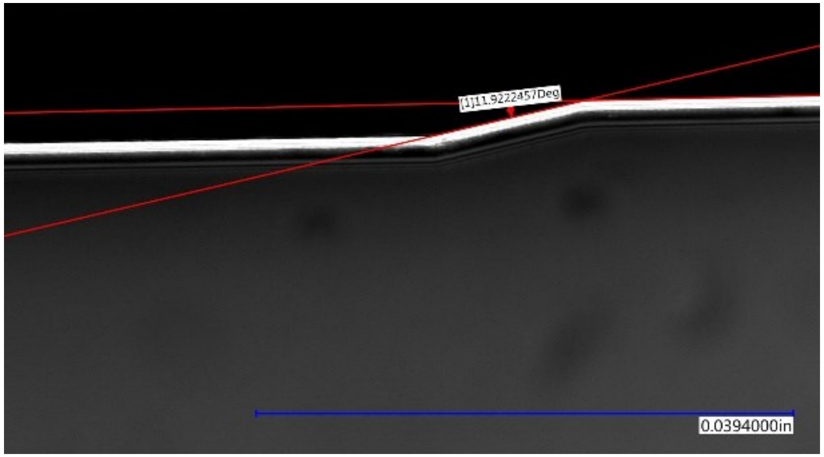
- Coupon design
  - "Dog-bone" with geometric center located 0.25" diameter hole
  - Same geometry used in prior ERS studies
  - Extracted in the L direction at mid-thickness
- Material
  - 2024-T351 plate (0.3125" thick)
  - Material Testing
    - + Tensile (5 coupons)
      - ASTM E8
    - + FCGR (multiple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



A-10 IFF Testing & Analysis Program

Current Progress

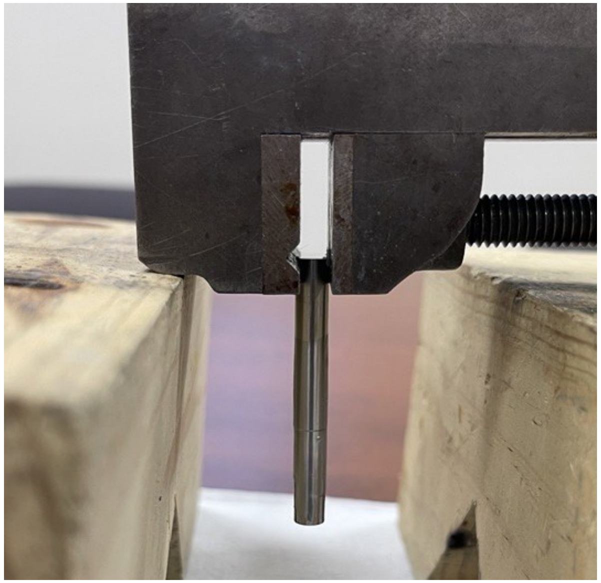
- Coupon manufacturing
  - 50 coupons have been fabricated
  - Holes measured via CMM
  - Gage pins were custom ordered to match the interference fit required per specimen
    - 0.3%, 0.6%, and 1.2% interference
  - Gage pins were machined to match the chamfer of a Hi-Lok
    - One pin from each interference 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

Current Progress

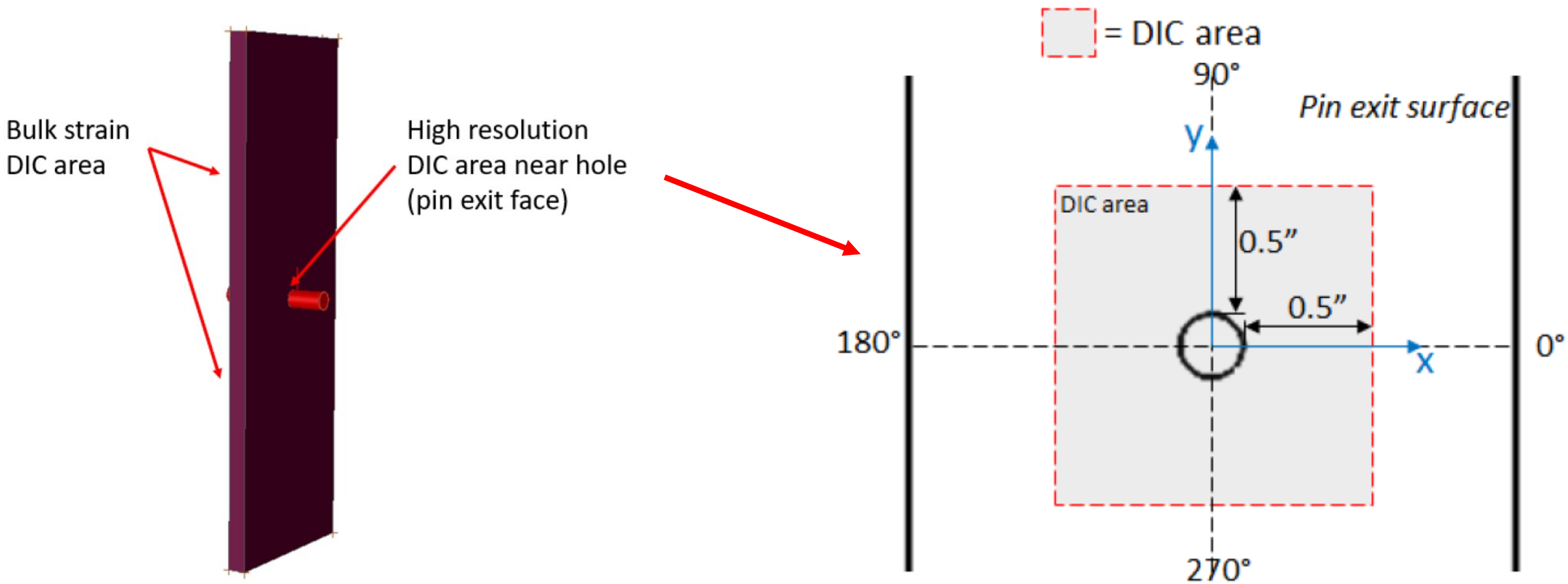
- Fastener Preparation
  - To mimic the Hi-Lok installation, cetyl alcohol lubricant, Perma-Slik 1460W, will be used to coat the pins prior to installation.
    + Per the lubricant's instructions, the pins will be degreased with trichlorethylene. Then, the pins will be dipped in the lubricant and dried 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

Current Progress

- 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

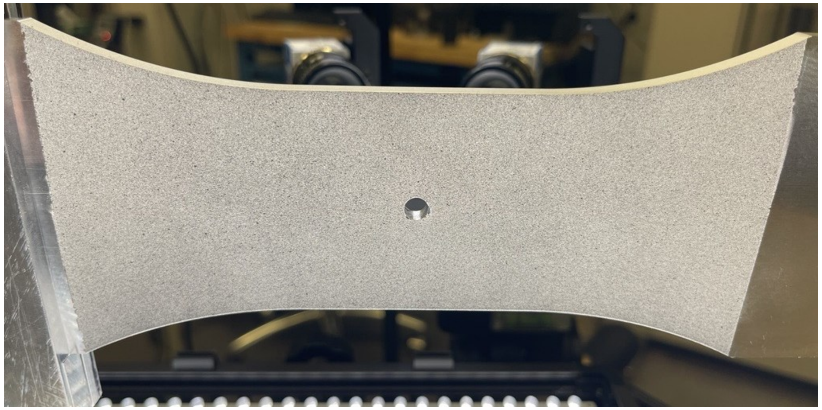


A-10 IFF Testing & Analysis Program

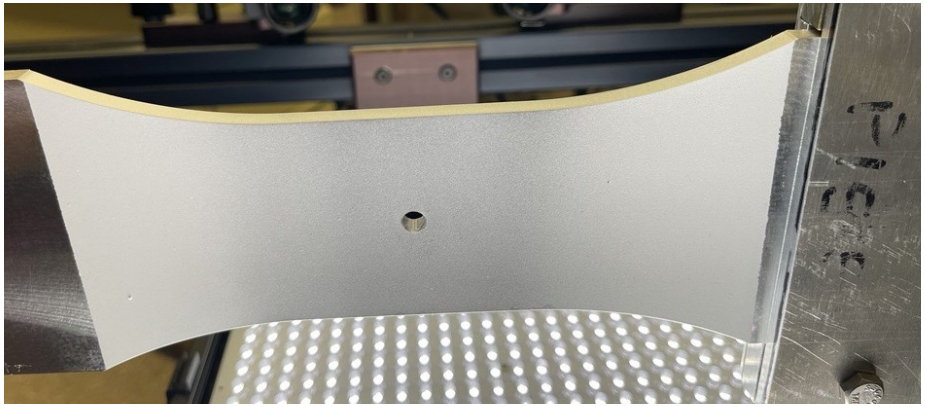
Current Progress

- 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

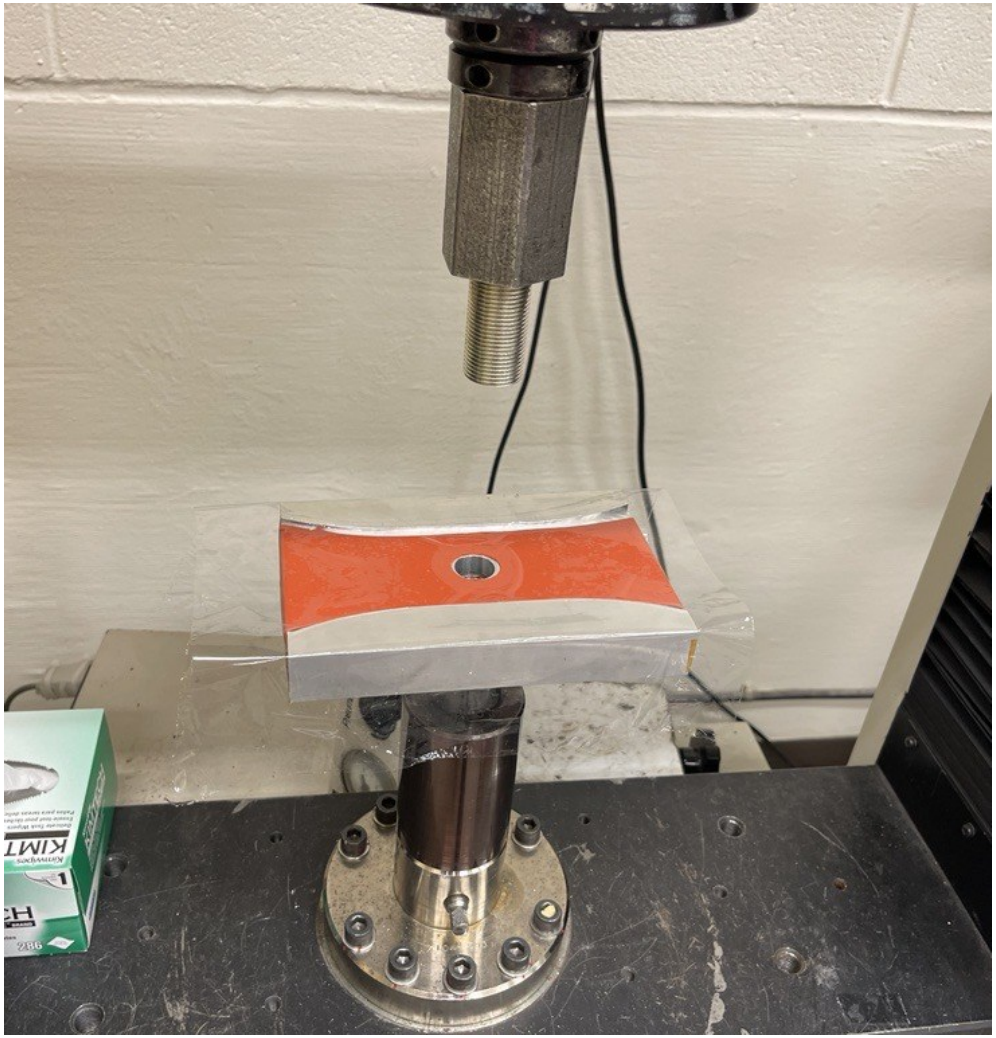
Current Progress

- 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

Current Progress

- Pin installation setup
  - Servomechanic 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

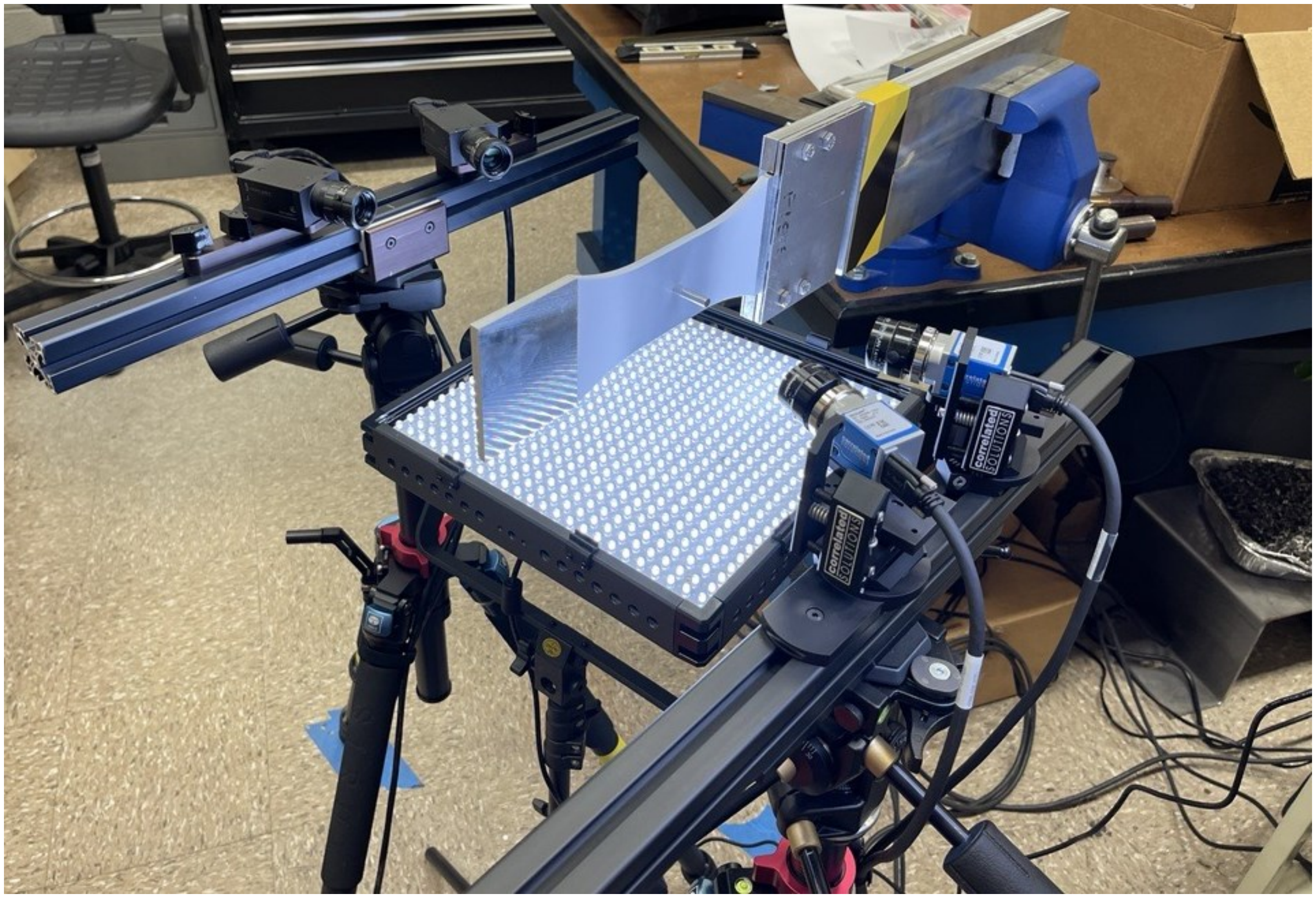
Current Progress

- DIC prior to pin installation

A-10 IFF Testing & Analysis Program

Current Progress

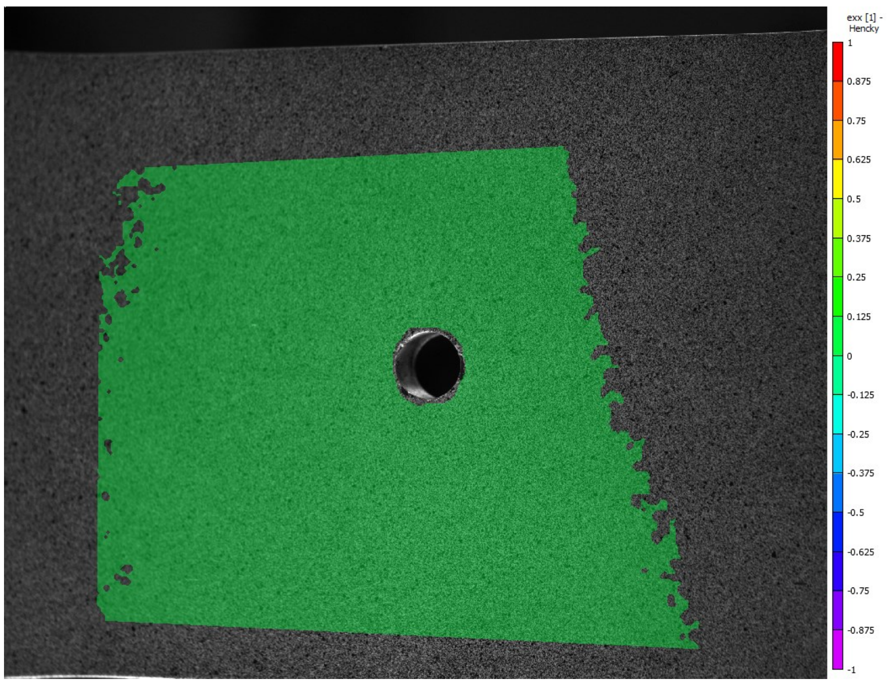
- DIC after to pin installation

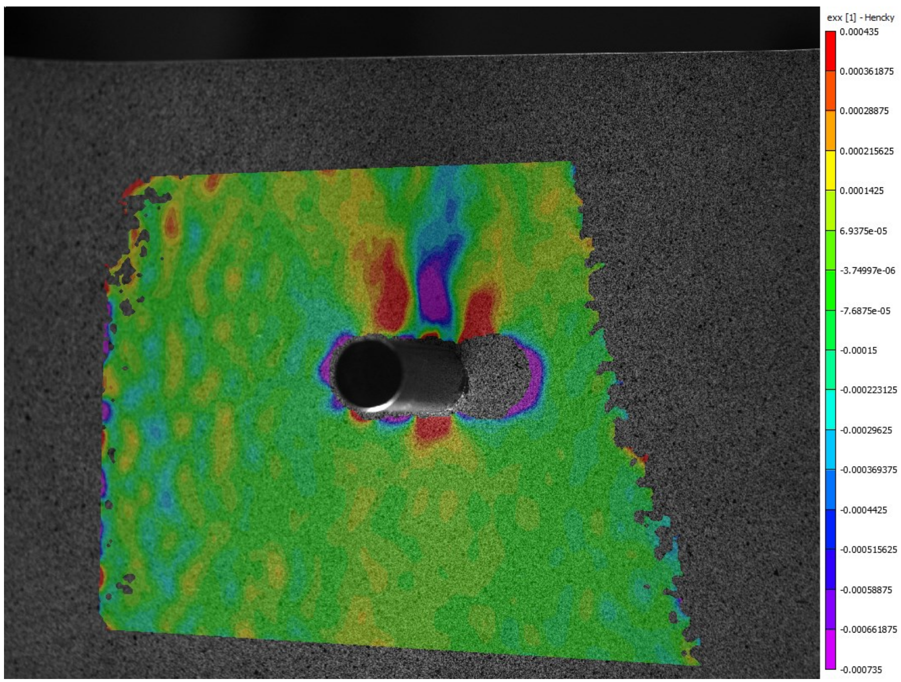


A-10 IFF Testing & Analysis Program

Current Progress

- Global results

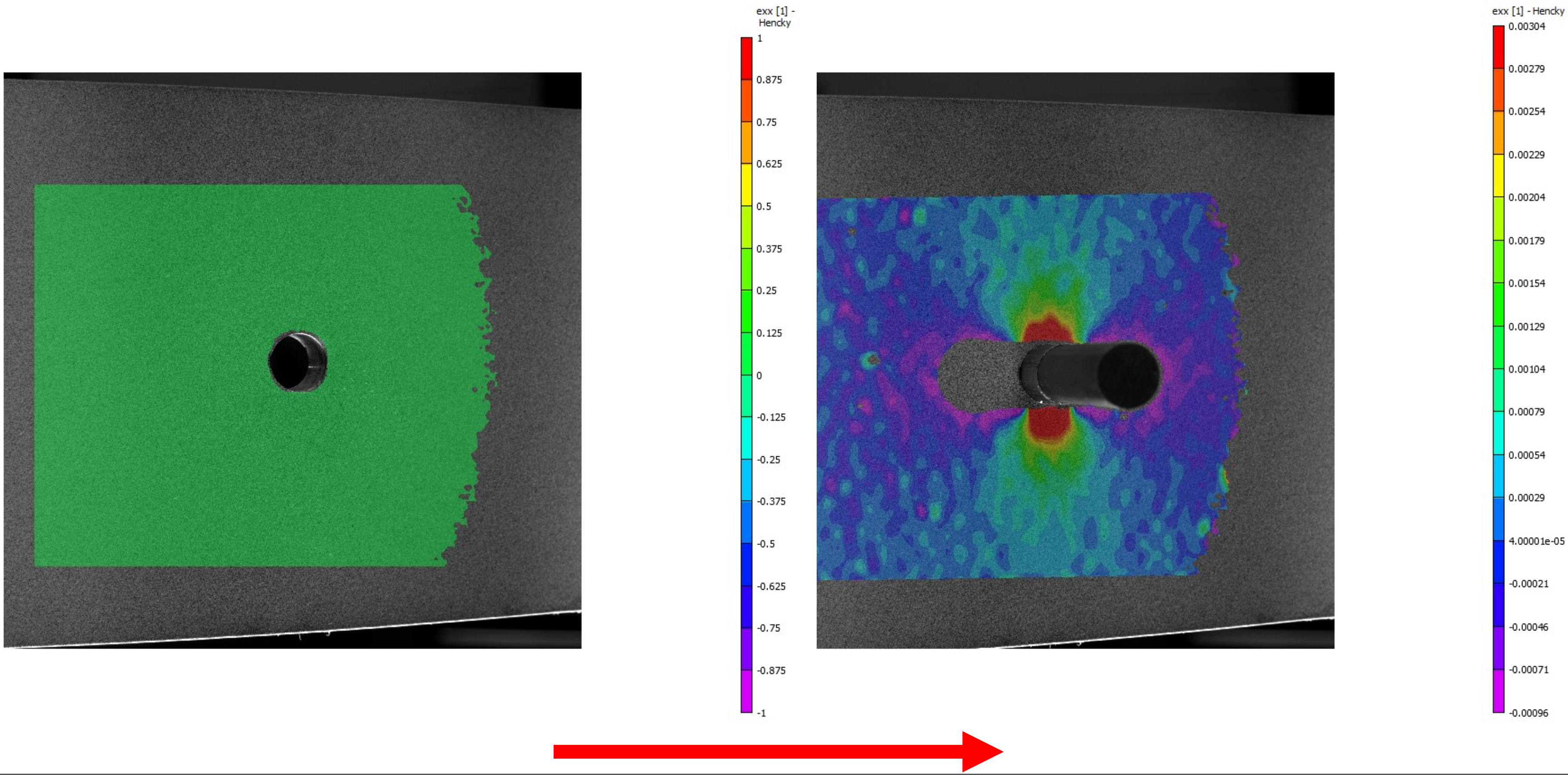




A-10 IFF Testing & Analysis Program

Current Progress

- Local results



A-10 IFF Testing & Analysis Program

Current Progress

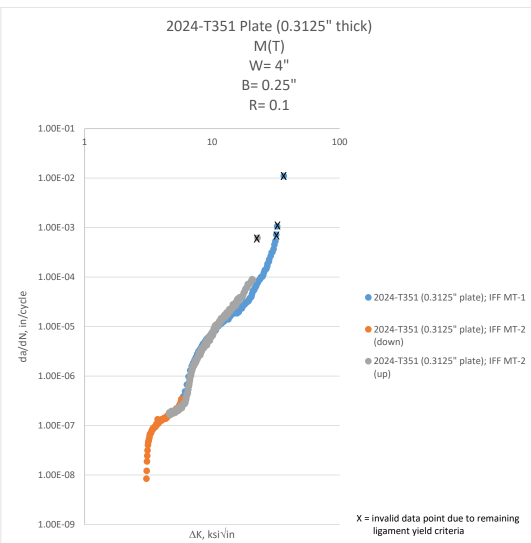
- Initial testing
  - Initial testing at 0.3%, 0.6%, and 1.2% interference was conducted
    - During this testing, the SwRI team noticed that the white underlayment was flaking and causing smearing of the speckle pattern
    - A higher quality application and paint are now being used for the white underlayment (professional spray gun vs spray can)
- Test plan updates
  - A final version of the test plan was released. By committee, it was determined that the pins will remain installed in the specimens

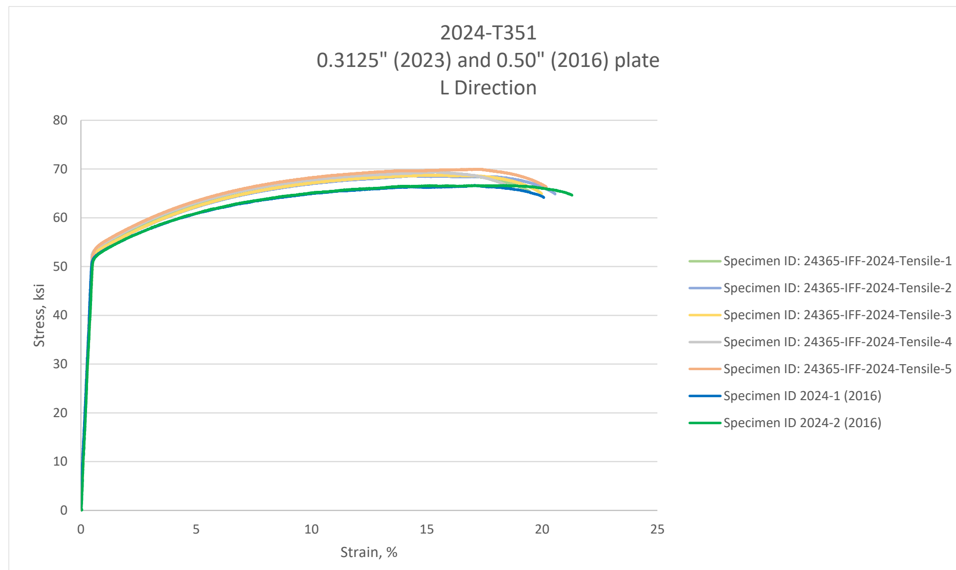
A-10 IFF Testing & Analysis Program

Current Progress

- Material Testing
  - Tensile properties as well as full stress-strain data gathered
  - Fatigue crack growth data for R= 0.1

Material	Specimen ID	Individual			Average		
		UTS, ksi	YS, ksi	Final Elong, %	UTS, ksi	YS, ksi	Final Elong, %
2024-T351 (0.3125" plate) 2023	24365-IFF-2024-Tensile-1	68.8	53.4	20.0	69.1	53.5	20.4
	24365-IFF-2024-Tensile-2	68.6	53.3	21.2			
	24365-IFF-2024-Tensile-3	68.8	53.1	20.8			
	24365-IFF-2024-Tensile-4	69.4	53.8	19.9			
	24365-IFF-2024-Tensile-5	70.0	54.0	20.4			
2024-T351 (0.5" plate) 2016	2024-1	66.7	52.3	22.0	66.7	52.2	22.0
	2024-2	66.7	52.1	22.0			





A-10 IFF Testing & Analysis Program

Current Roadblocks

- The current lens setup has limited focus; therefore, the smallest field of view obtainable for the local side is roughly 2” X 2”. This is causing resolution loss compared to the 1” X 1” FOV requested.
- After the installation of the pin, obtaining DIC measurements around the entire hole is not feasible. The pin blocks/shadows approximately 50+% of the hole.
  - Cutting the pin ends flush could potentially jeopardizes the speckle pattern
- Speckle pattern on global side was too fine. An increased speckle size stamp will be used on successive iterations.

A-10 IFF Testing & Analysis Program

Path Forward

- Are we happy with the results we have obtained?
- If not, we could obtain a pair of Schneider 50mm lenses with extension tubes that will allow us to obtain 1:1 magnification. With this setup, 1” X 1” FOV and smaller is possible.
  - The decreased FOV will require different calibration targets
- Re-evaluate the requested field of view. Instead, we aim to acquire measurements for half of the hole. The cameras could be more appropriately positioned to clearly capture 50% of the hole with less loss. Then, symmetry of the results would be assumed.