Tuesday, 2 April 2024	
Southwest Research Institute, San Antonio, TX	
8:15 AM to 8:30 AM	*Executive Committee Arrive, Check-in*
8:30 AM to 10:00 AM	*Executive Committee Discussion*
9:45 AM to 10:15 AM	**Arrive, Check-in**
10:15 AM to 10:30 PM	**SwRI Welcome & Overview**
10:30 AM to 12:00 PM	**SwRI Tour (Bldgs. 128, 249, and 231)**
12:00 PM to 1:30 PM	**Lunch break**
1:30 PM to 2:00 PM	**ERSI Welcome, Announcements, Around the room**
1:30 PM to 4:00 PM	**Committee Updates, Session 1**
2:00 PM to 4:00 PM	Analysis & Testing

Wednesday, 3 April 2024	
Southwest Research Institute, San Antonio, TX	
7:45 AM to 8:00 AM	**Arrive**
8:00 AM to 10:30 AM	**Committee Updates, Session 2**
8:00 AM to 10:00 AM	Residual Stress Characterization
10:00 AM to 10:15 AM	Break
10:15 AM to 11:00 AM	NDE/NDI/QA/Data Management
11:00 AM to 11:45 AM	**Discussion: ERSI Path Forward**
11:45 AM to 1:15 PM	**Lunch break**
1:15 PM to 2:00 PM	**Open Discussion**
2:00 PM to 3:30 PM	**Committee Break-out Meetings** Analysis Methods & Testing Residual Stress Characterization NDE/NDI/QA/Data Management
3:30 PM to 4:00 PM	**Regroup & Dismiss**

ERSI ENGINEERED RESIDUAL STRESS IMPLEMENTATION

2024 ERSI Workshop: Welcome!

2 April 2024

Dallen L. Andrew

Agenda

1:30 PM to 2:00 PM
ERSI Welcome, Announcements, Around the room

- Purpose
- Around the room
- Committee
- Roadmap
- USAF Academy Testing
- EZ-SB-17-001 Rev A
- ERSI Interactions
- Feedback

The real important things

- Nametags
- Coffee/Candy/Cookies/Drinks
- SwRI Guest wifi available
- Breakfast tacos tomorrow
- Attendee appreciation gifts

Contributors

- Southwest Research Institute
- ESRD
- Fatigue Technology Inc.
- Hill Engineering
- LexTech
- Proto
- PartWorks

ERSI purpose

- Where & why did we start ERSI?
- Where does ERSI add value? (next slides)
  - Round robin activities
  - Opportunity for collaboration
  - Dissemination of Cx-related information/data to raise awareness & interest
- Where do we want to go now?
- What is the primary goal/target?

Vision

- Develop a framework for fleet wide implementation of a more holistic, physics based approach for taking analytical advantage of the deep residual stress field induced through the cold expansion process, into the calculations of initial and recurring inspection intervals for fatigue and fracture critical aerospace components

Mission Statement

- Develop a holistic paradigm for the implementation of engineered residual stresses into lifing of fatigue and fracture critical components

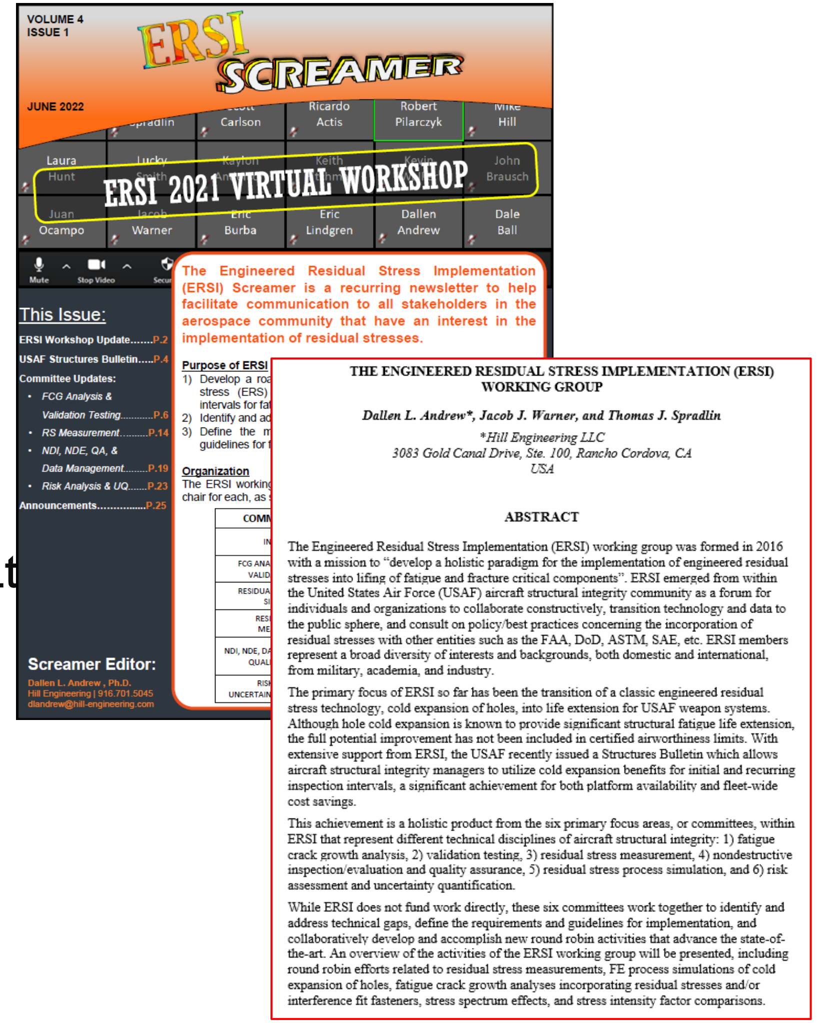
ERSI Key Objectives

- Define a common vision for the accounting of engineered residual stress at Cx fastener holes
- Provide forum to collaborate on new developments, best practices, lessons learned
- Develop an implementation roadmap
- Identify, define, and enable the resolution of gaps in the state of the art

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

ERSI purpose: Where does ERSI add value?

- **Analysis and testing**
  - 2016: FCG analysis of Cx holes
  - 2020: Interference fit fasteners
  - 2021: SIF Comparison
  - 2021: Overload challenge
  - 2022: Interference fit fasteners round 2
- **Residual stress characterization**
  - 2017: 2x2 material modeling data
  - 2017: 2x2 Cx Coupons
  - 2017: Contour method inter-laboratory reproducibility uncertaint
  - 2019: 2x2 process simulation analysis
  - 2021: Texture and anisotropy sub-team
  - 2021: Bulk RS measurements in Cx geometrically large holes
  - 2022: Contour method reproducibility experiment A (CMRE-A)
- **NDI / NDE / Data management / Quality assurance**
  - xx: Cx hole blind study [POC: Dallen Andrew, Hill Engineering]



THE ENGINEERED RESIDUAL STRESS IMPLEMENTATION (ERSI) WORKING GROUP

Dallen L. Andrew, Jacob J. Warner, and Thomas J. Spradlin*

**Hill Engineering LLC*
3083 Gold Canal Drive, Ste. 100, Rancho Cordova, CA
USA

ABSTRACT

The Engineered Residual Stress Implementation (ERSI) working group was formed in 2016 with a mission to "develop a holistic paradigm for the implementation of engineered residual stresses into lifing of fatigue and fracture critical components". ERSI emerged from within the United States Air Force (USAF) aircraft structural integrity community as a forum for individuals and organizations to collaborate constructively, transition technology and data to the public sphere, and consult on policy/best practices concerning the incorporation of residual stresses with other entities such as the FAA, DoD, ASTM, SAE, etc. ERSI members represent a broad diversity of interests and backgrounds, both domestic and international, from military, academia, and industry.

The primary focus of ERSI so far has been the transition of a classic engineered residual stress technology, cold expansion of holes, into life extension for USAF weapon systems. Although hole cold expansion is known to provide significant structural fatigue life extension, the full potential improvement has not been included in certified airworthiness limits. With extensive support from ERSI, the USAF recently issued a Structures Bulletin which allows aircraft structural integrity managers to utilize cold expansion benefits for initial and recurring inspection intervals, a significant achievement for both platform availability and fleet-wide cost savings.

This achievement is a holistic product from the six primary focus areas, or committees, within ERSI that represent different technical disciplines of aircraft structural integrity: 1) fatigue crack growth analysis, 2) validation testing, 3) residual stress measurement, 4) nondestructive inspection/evaluation and quality assurance, 5) residual stress process simulation, and 6) risk assessment and uncertainty quantification.

While ERSI does not fund work directly, these six committees work together to identify and address technical gaps, define the requirements and guidelines for implementation, and collaboratively develop and accomplish new round robin activities that advance the state-of-the-art. An overview of the activities of the ERSI working group will be presented, including round robin efforts related to residual stress measurements, FE process simulations of cold expansion of holes, fatigue crack growth analyses incorporating residual stresses and/or interference fit fasteners, stress spectrum effects, and stress intensity factor comparisons.

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Who am I?

- **Original Bio**
  - Dallen started his career off working with the A-10 team under Dr. Mark Thomsen & Dr. Paul Clark, where he learned how to be both personable and silver tongued. His love of ridiculous belt buckles grew strong and pulled him to Texas where he worked for Southwest Research Institute for 5 years where he spent his free time finding ways to break the USAF cybersecurity policies, among other things. To be closer to family his wife and 4 children moved back to Utah accepting a job with Hill Engineering where he has spent the last 5 years using his impeccable helping skills to help.
- **Work**
  - USAF A-10 ASIP, Hill AFB, Utah (2009-2014)
  - SwRI, San Antonio, Texas (2014-2019)
  - Hill Engineering, Utah (2019-current)
- **School**
  - BS, Utah State University (2009)
  - MS, University of Utah (2011)
  - PhD, University of Texas at San Antonio (2020)

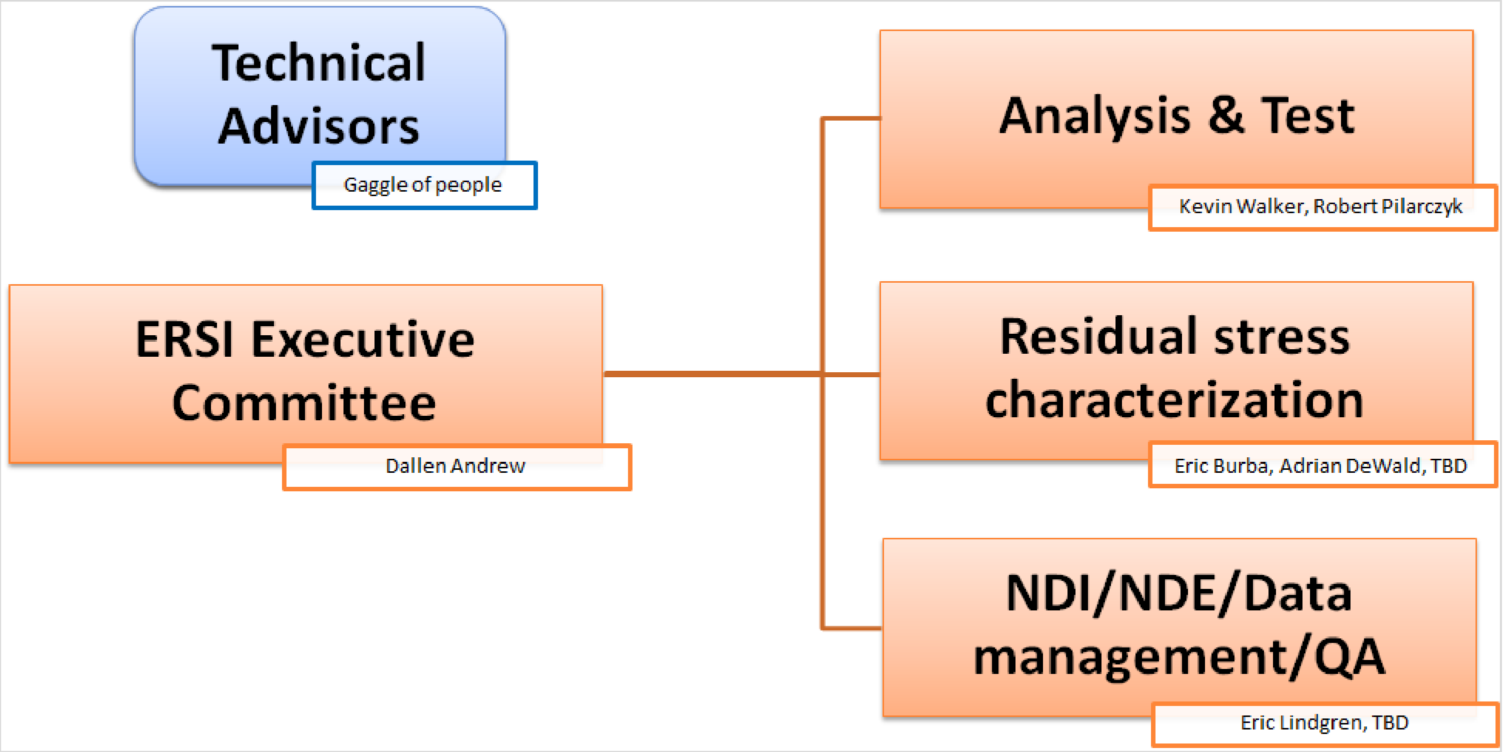
Who are you?

- (30-60 seconds)
- Name
- Company
- What do you do
- Why are you here

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

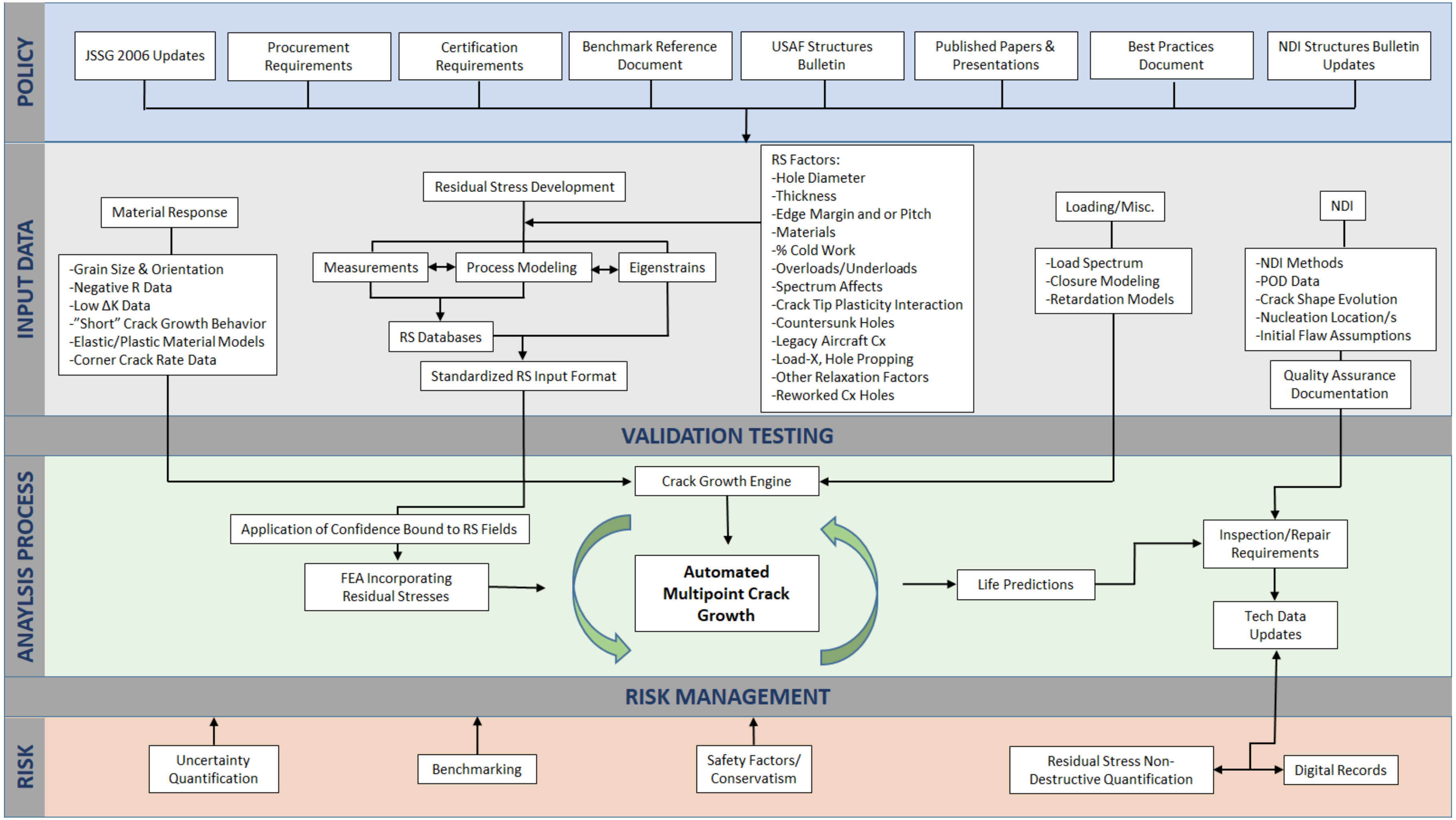
Committees

- How is the new committee structure working for you?
- Thoughts on committee leads and needs



Roadmap Concept

- Flowchart version



ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Roadmap Concept

- Task version

	Focus Area
1	Multipoint Crack Growth
2	Analysis Best Practices & Case Study Document
3	RS Input Format
4	Benchmarking RS Inputs
5	Hole Diameter Influence on RS
6	Thickness Influence on RS
7	Edge Margin Influence on RS
8	Fastener Pitch Influence on RS
9	Material Difference Influence on RS
10	Overloads/Underloads Influence on RS
11	Spectrum Loading Influence on RS
12	Crack Tip Plasticity Interaction w/ RS
13	Countersunk Hole RS
14	Legacy vs New CX RS - Relaxation/Redistribution
15	Load Transfer Influence on RS
16	Reworked CX Holes
17	Retardation Modeling
18	Crack Closure

Multi-Point Fracture Mechanics

Overview

Focus Item #	1	Multi-Point Fracture Mechanics (MPFM) has evolved in recent years with USAF organic and COTS options available. In recent applications, the capability has demonstrated improved analysis correlation to test as well as the ability to replicate unique crack shape evolution. For analyses incorporating residual stress, multipoint crack growth is essential to accurately predict the behavior and is central to the analytical toolbox for CX holes.
Focal	Robert Pilarczyk	
Maturity Level	TRL 3	

Constraints/Roadblocks	Threshold Criteria	Objective Criteria
	Complete benchmark problems and demonstrate MPFM relative to handbook solutions and test data. Ensure MPFM tools can facilitate implementation of RS. KPPs - correlated crack shape evolution, incorporate RS	Mature MPFC capability will multiple+ demonstration cases. Consistent results across available MPFM tools.

Questions to Resolve

Area	Focal/Contract	ECD	Current Status
1) Should we develop a best practices document for MPFM analysis?	Robert Pilarczyk, Josh Hodges	9/1/2017	Not Started
2) How do we facilitate greater utilization of MPFM to take on challenging geometric, loading, RS fatigue problems?			

Action Items

Item	Focal/Contract	ECD	Current Status
1) Val/Ver MPFM capability with multiple tools. Are results consistent with handbook solutions, test data, etc.	Possible new AFRL effort	12/1/2017	Not Funded
2) Multiple weapon system specific demonstrations comparing to fleet and/or test data. (Not necessarily RS focused)	Possible new AFRL effort	12/1/2018	Not Funded
3) Identify 3-5 benchmark RS problems to exercise current capability. Utilized different analysis tools. Round-Robin - AP/ES, NRC, A-10/T-38, H	TBD		
4) Need to review crack front and K smoothing to determine recommended best practices			

Timeline

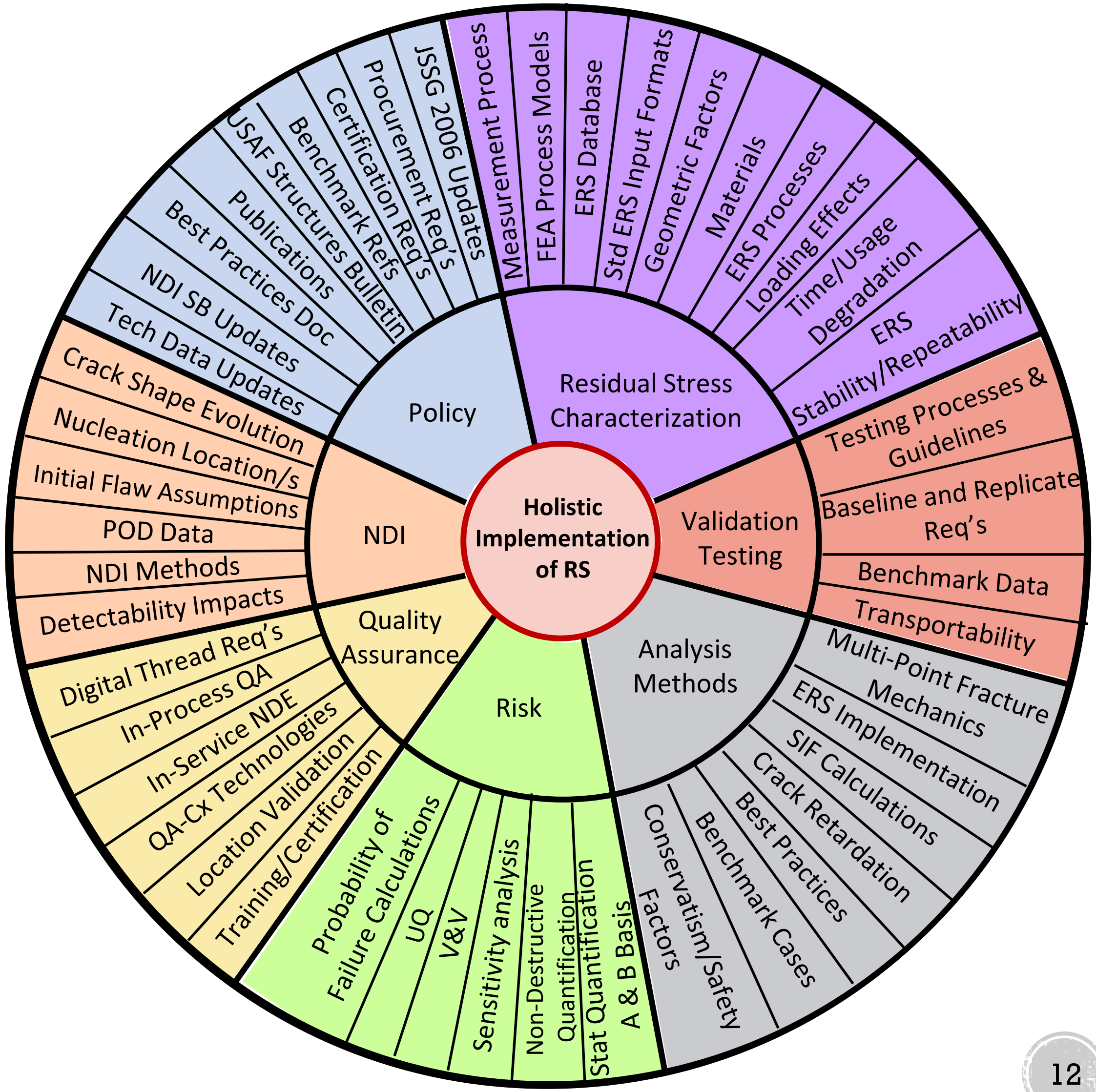
2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025

4 7

ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

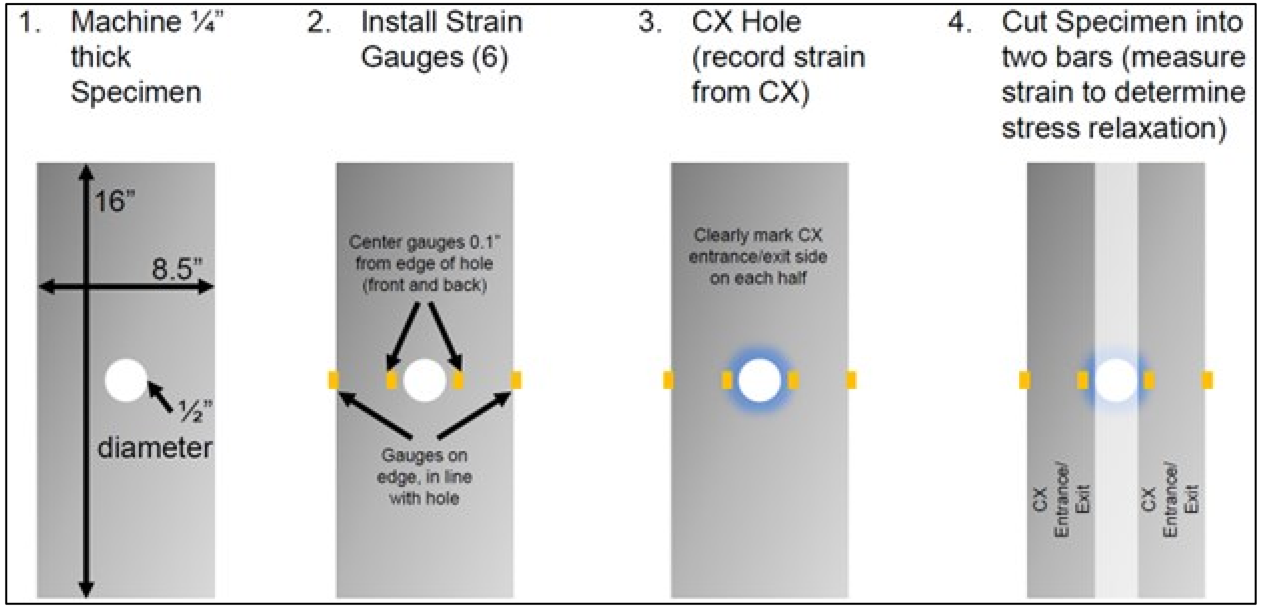
Roadmap Concept

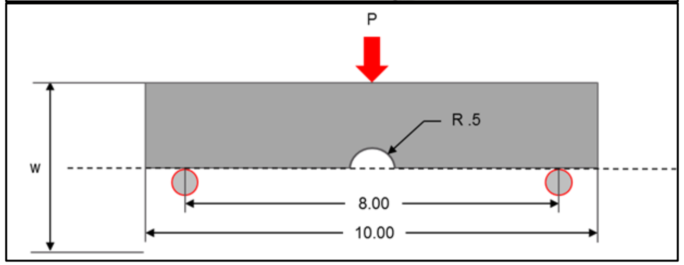
- 'Lincoln Wheel' version
  - Adding references for different focus areas
  - Highlighting where we are doing well, not so well
  - Realizing duplicate or dependent efforts
  - Gap for the focus area 'Policy'



USAF Academy Testing

- Reminder
- Previous examples
  - Kt-free Cx samples
  - GL coupons





- We do have a cadet looking for a good CAStLE project for next Fall. If anything comes to mind during the meeting, I'll be happy to discuss.

EZ-SB-17-001 Rev A

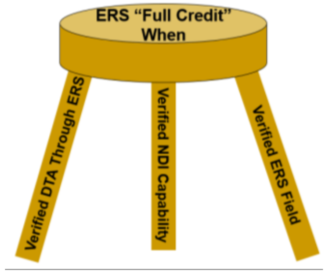
- Applications to IFF, ForceTec, ForceMate, Taper-Lok, other
- Rev B status
  - Targeting Level 2 benefit
  - Challenges
    - Defining/prescribing the MPFM analysis process & associated details
    - Defining/prescribing requirements for RS field
    - Verifying Cx was done & was in-spec

Benefit Levels:

Variations in the amount of benefit needed for the range of aircraft structure applications, their associated complexity, and the cost to substantiate each, has prompted the need to establish different benefit levels as follows:

Level I: Initial inspection interval benefit, using the method described in References 1 and 2 and further defined below, with no recurring inspection interval benefit.

Level II. Level I initial inspection interval benefit and limited recurring inspection interval benefit through explicit incorporation of the non-verified residual stress field in the crack growth analysis.



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FCG BENEFIT FOR CX HOLES: LEVEL 2 REQUIREMENTS (TESTING)

- Coupon testing under representative spectrum loading
  - Minimum 5 replicates of baseline and CX condition
  - More replicates required if scatter amongst replicates is greater than factor of 2
- Validation testing required for similar geometry, "similar" meaning:
  - Representative loading spectrum, max spectrum stress less than or equal to stress tested
  - e/D < 2.0 must match edge margin within 0.25, no requirement for e/D > 2
  - Diameter within ¼" for holes < ¾", > ¾" must match design geometry
  - Thickness must be within neighboring thickness range for MMPDS allowables [7]
  - Same alloy series and representative applied expansion

Table 3.2.4.0(b_1). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Sheet and Plate.

Specification	AMS 4037[a]					AMS 4269[a]		
Form	Sheet					Sheet		Plate
Temper	T3					T361		
Thickness, in.	0.008-0.009	0.010-0.128		0.129 - 0.249		0.020-0.062	0.063-0.249	0.250-0.500
Basis	S	A	B	A	B	S	S	S
Mechanical Properties:								
F_{tu}, ksi:								

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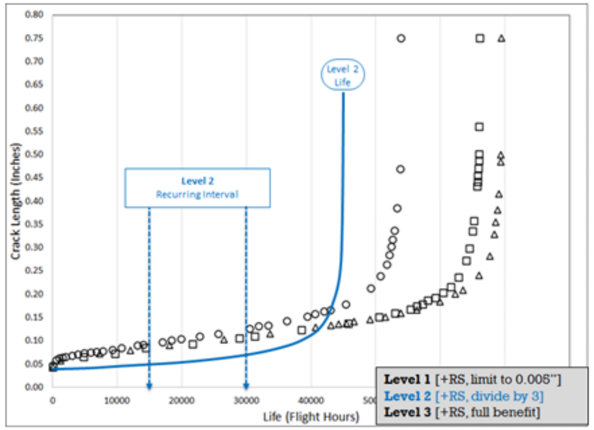
FCG BENEFIT FOR CX HOLES: LEVEL 2 REQUIREMENTS (ANALYSIS)

- Validated RS field
  - "Validated" means obtained from a direct determination method or from a model/tool that has been validated to a direct determination method
  - Same design space as testing requirements
- Analysis correlated to test
  - "Correlated" includes evaluating goodness of fit for curve shape to test data, not just total life
  - Load interaction (retardation) effects are not permitted for use in a Level 2 analysis
  - Prediction must under predict the test average
  - Inspections required at predicted life **divided by 3**
- Auditable verification of proper Cx required



ERSI Interactions

- ASIP Manager Update (semi-annual, ASIP and AA&S)
- Annual briefing to Chuck
  - Part of an ASIP review?
- Location for next year
  - Do we know if we want to plan on one?
- Review and approve all outward facing communications and publications (Like journal papers, reports)
- Coordinate ERSI-related efforts to present at ASIP, AA&S each year (could even take a session)
- Feedback on Screamer
- Feedback on website
  - ERSI committee page
- Do we need a 'chair' for communications


VOLUME 5
ISSUE 1

ERSI SCREAMER

MARCH 2024

This Issue:

The Engineered Residual Stress Implementation (ERSI) Screamer is a recurring newsletter to help facilitate communication to all stakeholders in the aerospace community that have an interest in the implementation of residual stresses.

Purpose of ERSI
1) Develop a roadmap for the implementation of engineered residual stress (ERS) for calculation of initial and recurring inspection intervals for fatigue and fracture critical aerospace components.
2) Identify and address gaps in state-of-the-art.
3) Define the most effective way to document requirements and guidelines for fleet-wide implementation.

Organization
The ERSI working group is broken up into 3 major committees with a chair for each, as shown below.

COMMITTEE NAME	CHAIR(S)
EXECUTIVE COMMITEE Dr. Dallen Andrew (Hill Engineering)	
ANALYSIS & TEST	Robert Pilarczyk (Hill Engineering) Dr. Kevin Walker (QinetiQ)
RESIDUAL STRESS CHARACTERIZATION	Dr. Eric Burba (USAF AFRL) Dr. Adrian DeWald (Hill Engineering)
NDI, NDE, DATA MANAGEMENT, & QUALITY ASSURANCE	Dr. Eric Lindgren (USAF AFRL)

Screamer Editor:
Dallen L. Andrew, Ph.D.
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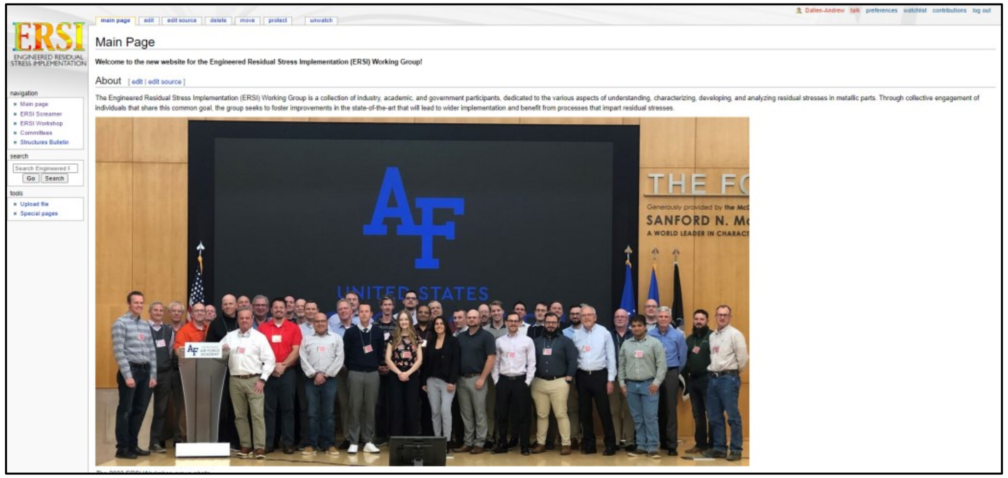
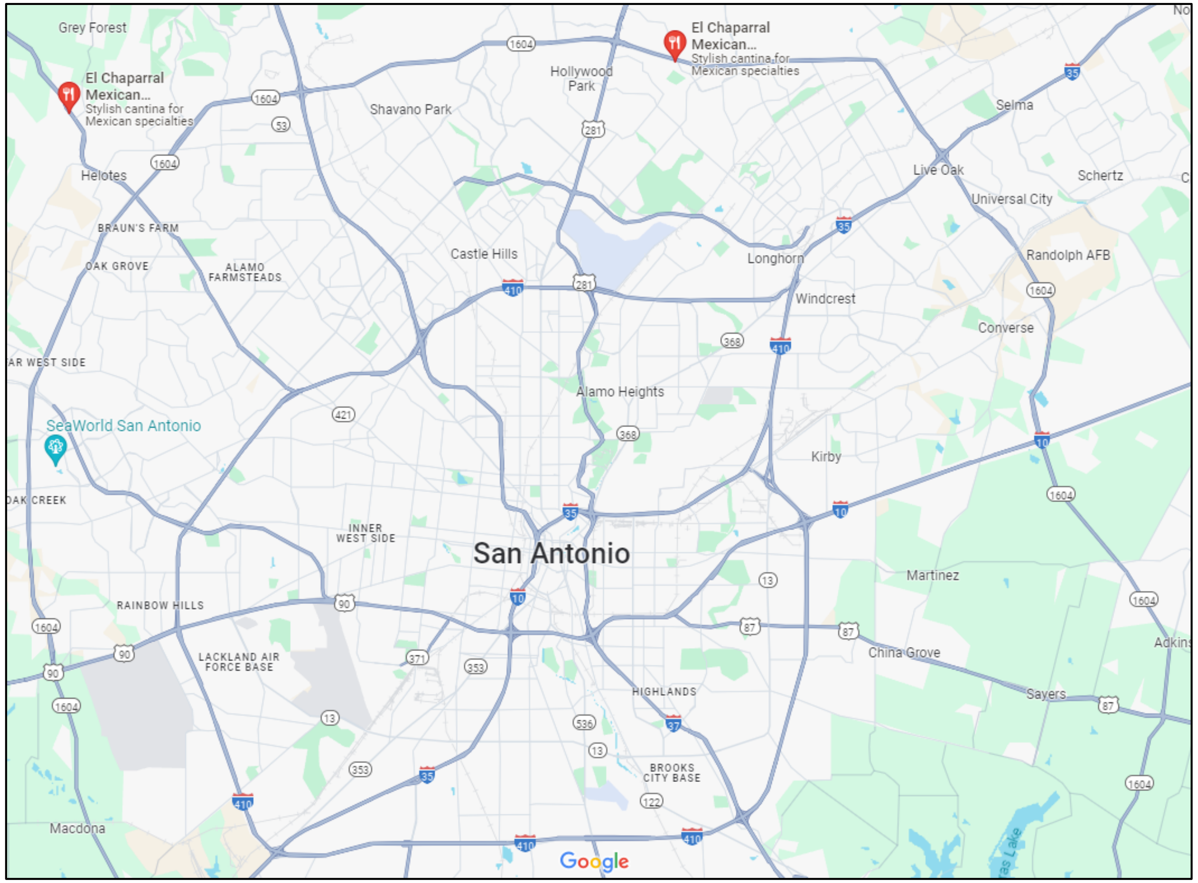


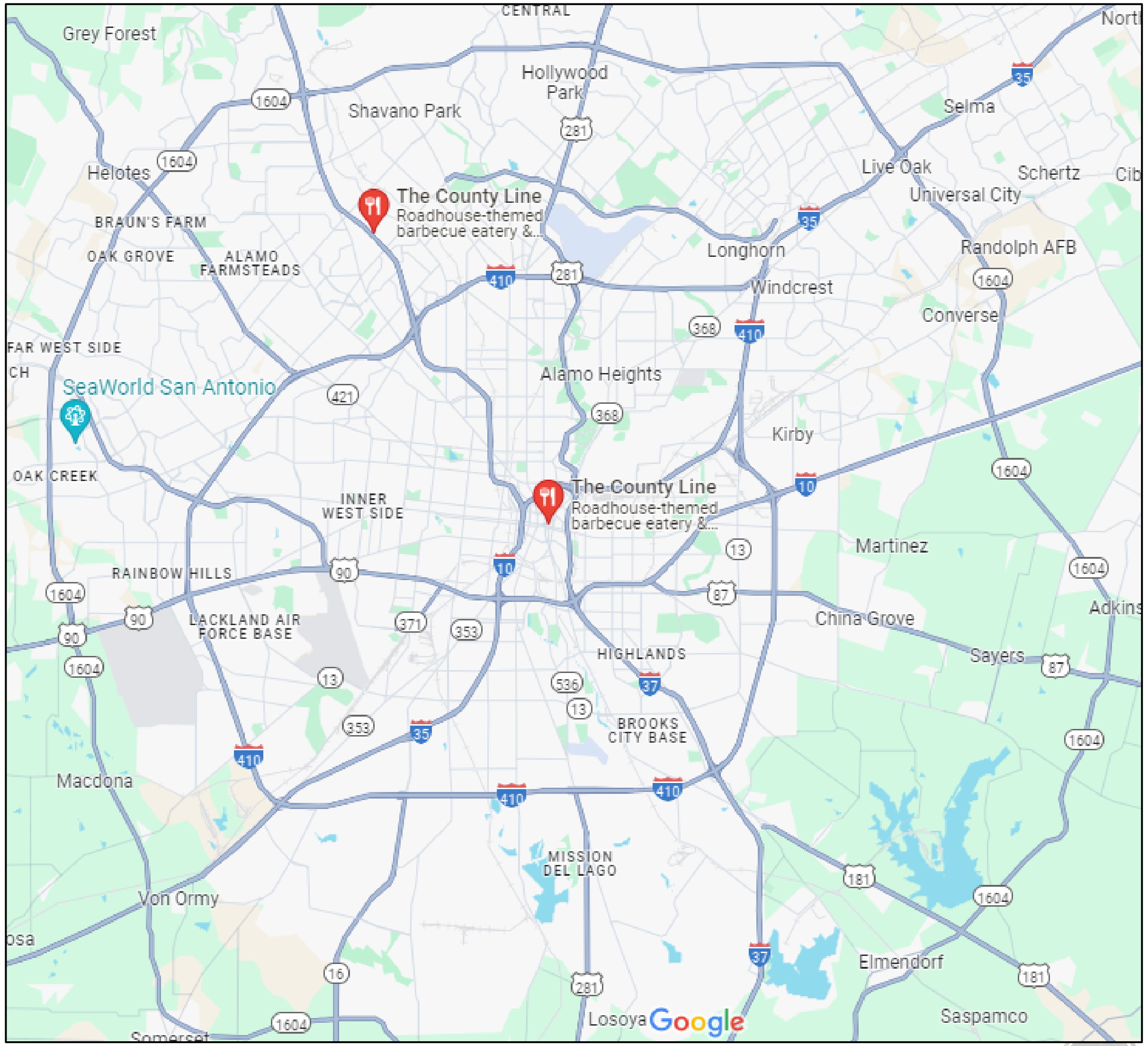
Feedback

- **Questions to help facilitate some discussions at the workshop**
  - Why are you attending the ERSI workshop and/or what do you hope to get from it?
  - How does ERSI add value to your area(s) of interest (or if it doesn't)?
  - What areas/topics do you want to see ERSI focus on in the near future?
  - What do you see the value of ERSI being going forward?

Dinner options

- El Chaparral
- The County Line
- Many, many, MANY more





Fatigue Crack Growth & Testing Committee

2024 ERSI Workshop

Kevin Walker, committee lead
kwalker999@hotmail.com

Robert Pilarczyk, committee co-lead
rtpilarczyk@hill-engineering.com

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**

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Roster Summary

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

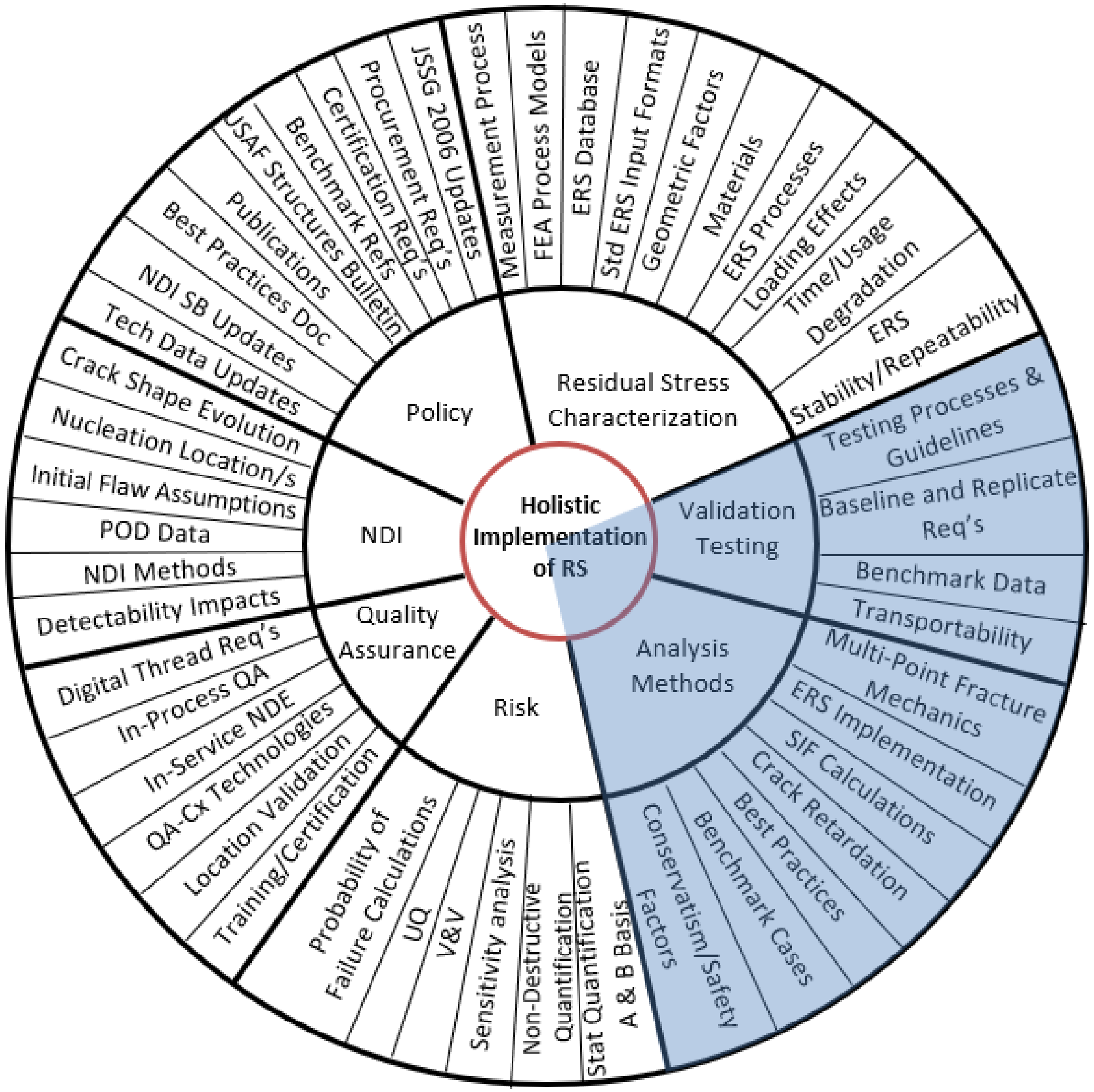
Vision

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

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Implementation Roadmap

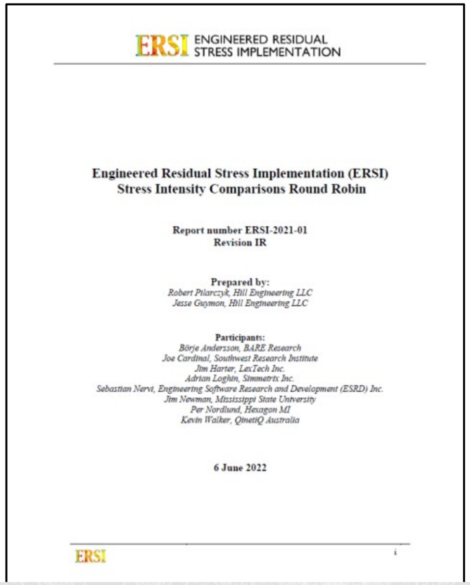
- **Approach**
  - Leverage ASIP Lincoln Wheel
  - Tailored for ERS
  - Identify key focus areas
  - Highlight focus areas based on criticality and maturity
- **Benefits**
  - Utilize to communicate development needs



ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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


ERSI ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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

Report number ERSI-2021-01
Revision IR

Prepared by:
Robert Pilarczyk, Hill Engineering LLC
Jesse Guymon, Hill Engineering LLC

Participants:
Börje Andersson, BARE Research
Joe Cardinal, Southwest Research Institute
Jim Harter, LexTech Inc.
Adrian Loghin, Simmetrix Inc.
Sebastian Nervi, Engineering Software Research and Development (ESRD) Inc.
Jim Newman, Mississippi State University
Per Nordlund, Hexagon MI
Kevin Walker, QinetiQ Australia

6 June 2022

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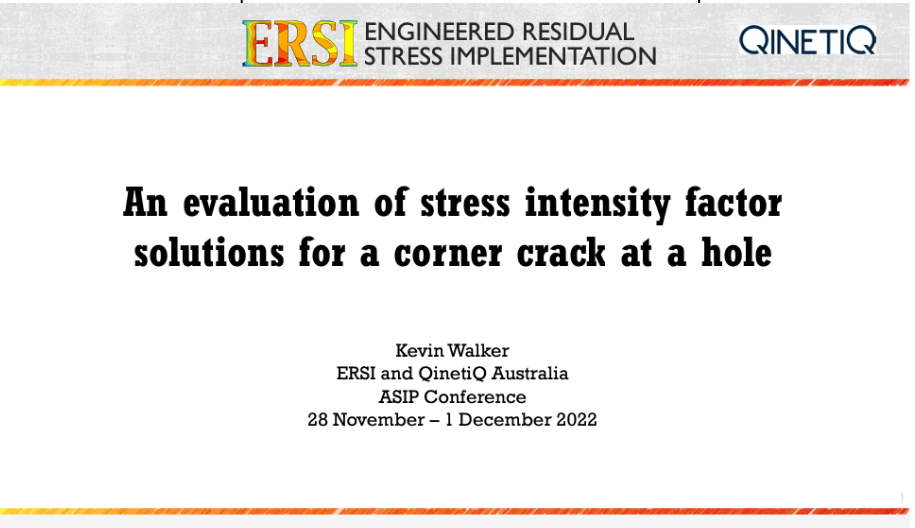

Accomplishments

- **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

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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)

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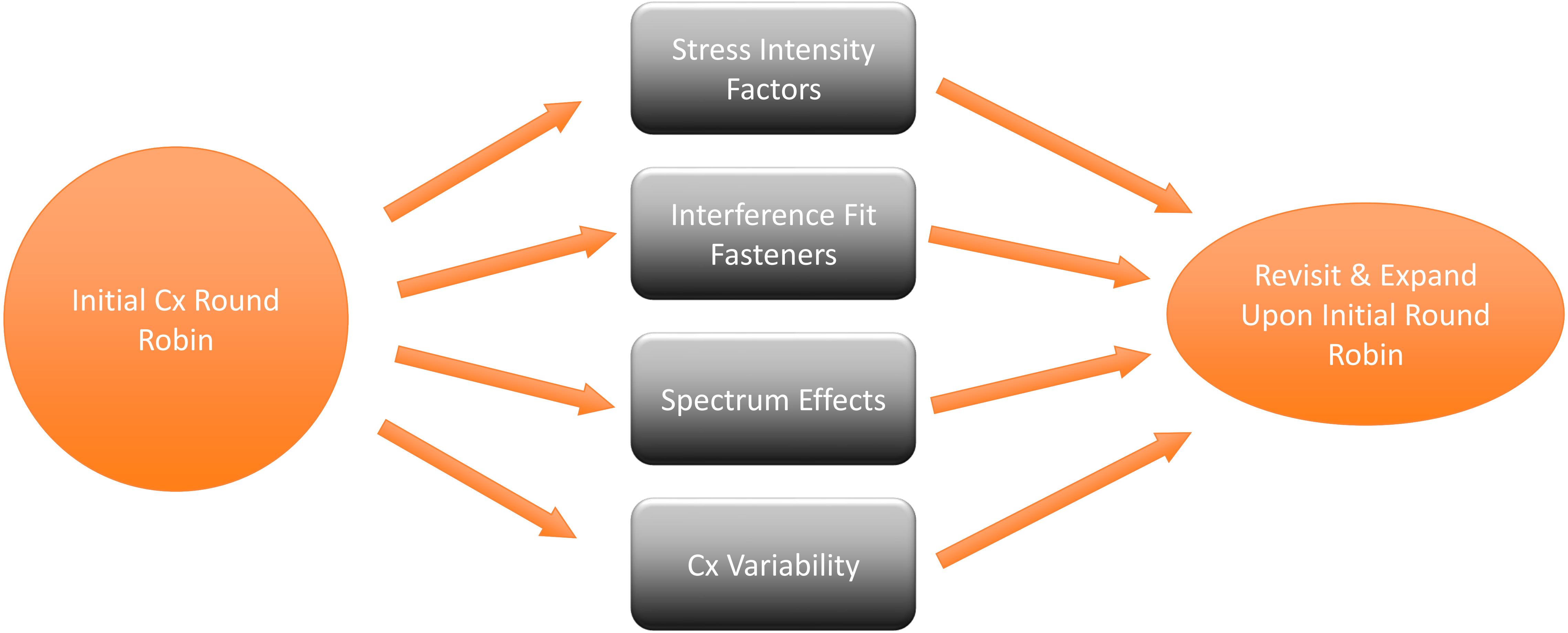
Revisiting Previous Round Robins



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

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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

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**

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Analysis and Test – Rate data sub-group

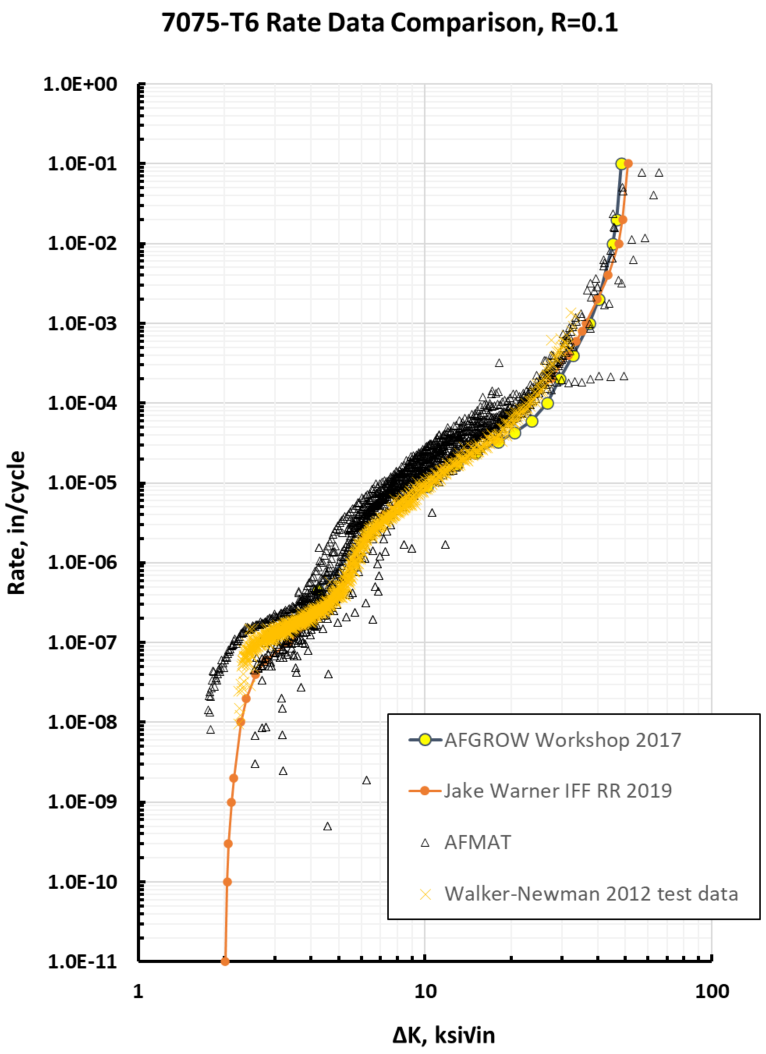
- **The rate data sub-group includes:**
  - Kevin Walker, QinetiQ Australia
  - Ana Barrientos, Northrop Grumman
  - Moises Ocasio, Boeing
  - Scott Prost-Domasky, APES
  - Bob Pilarczyk, Hill Engineering
  - Jim Harter, LexTech/AFGROW

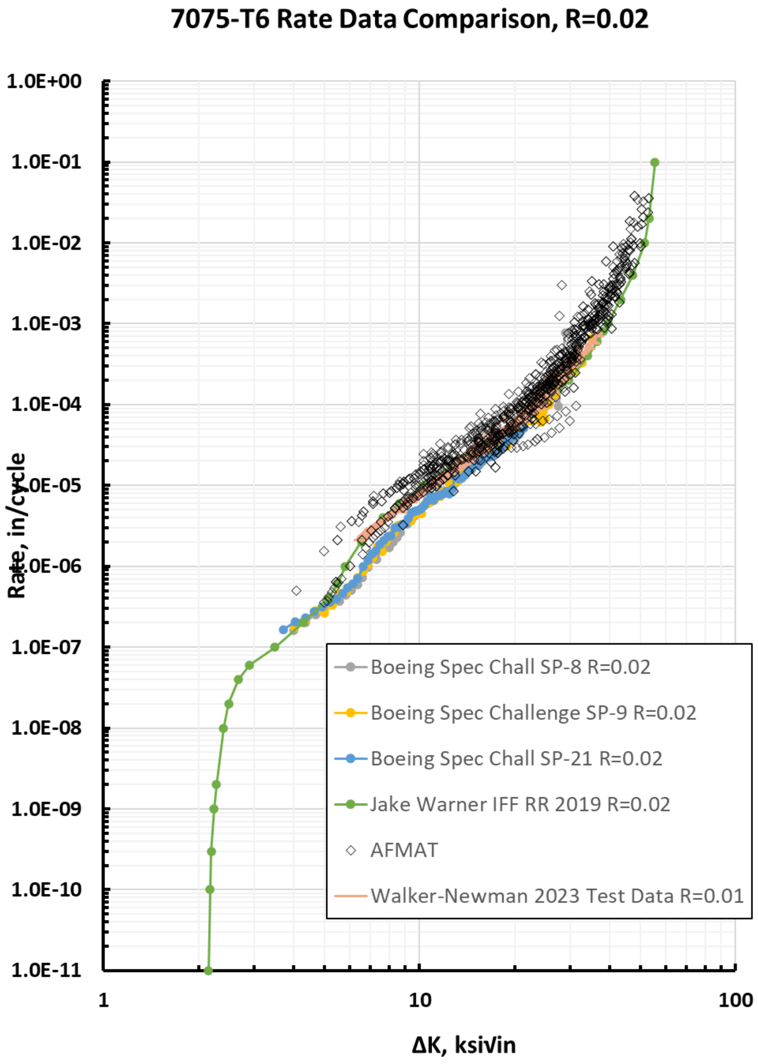
Materials considered so far

- **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**

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





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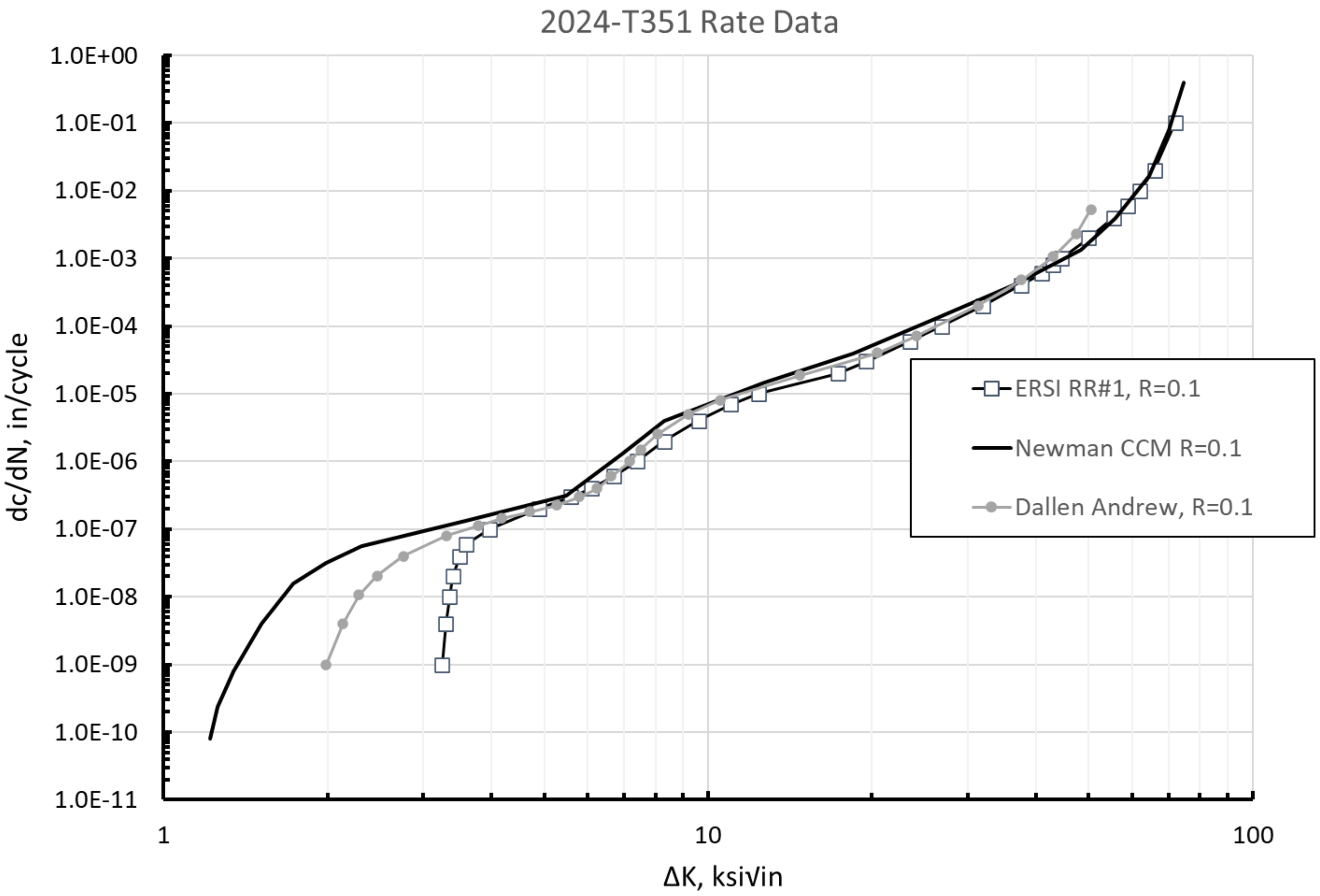
2024-T3 Rate Data

- **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**



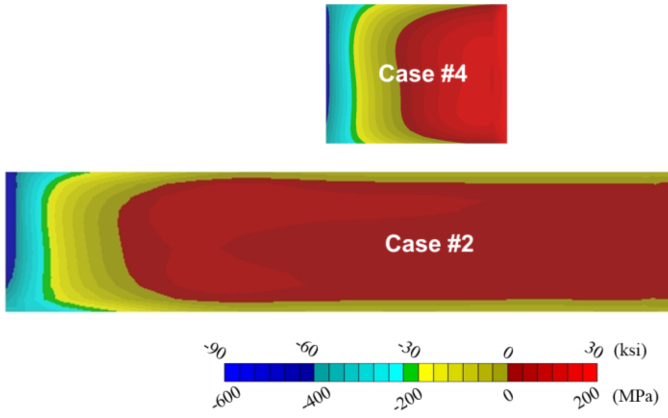
Residual stress inputs sub-group status update

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

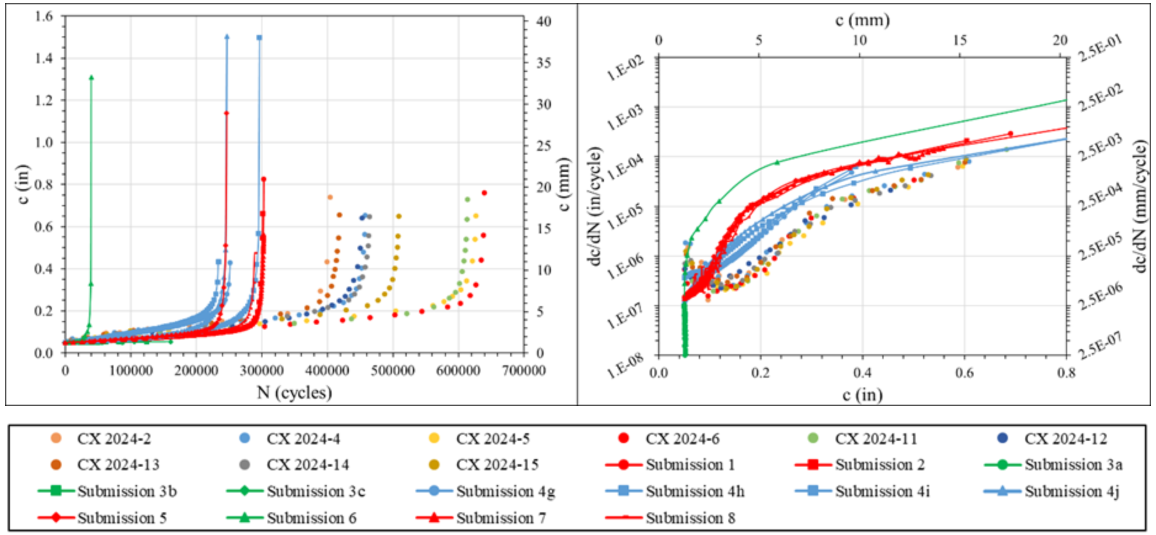


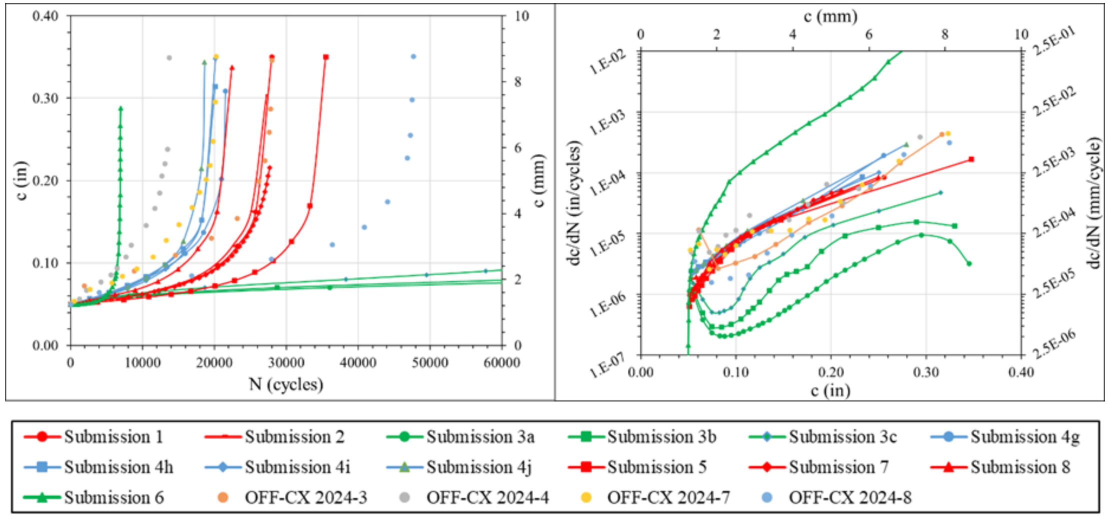
RS Incorporation Approach
Crack Face Pressure (B-Spline)
Crack Face Pressure (Legendre Polynomial)
2-D Gaussian Integration (Free Surface)
2-D Gaussian Integration (5 degrees)
2-D Gaussian Integration (10 degrees)
Bivariant WF
Bivariant WF
Univariant WF
Univariant WF
Polynomial Fit Crack Face Pressure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

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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

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- (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

Spatial Analysis of Residual Stress (SpARS) Crack Growth Analysis

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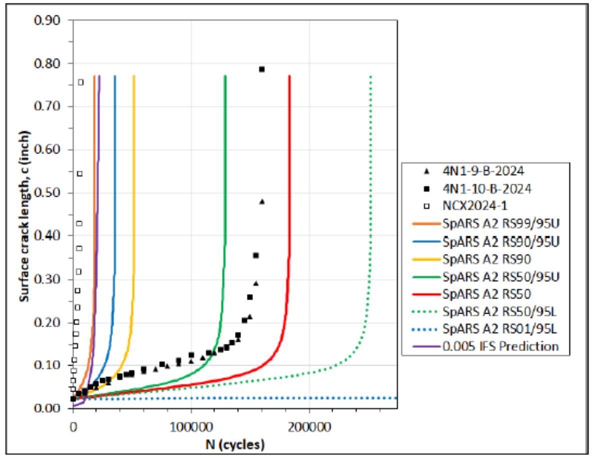
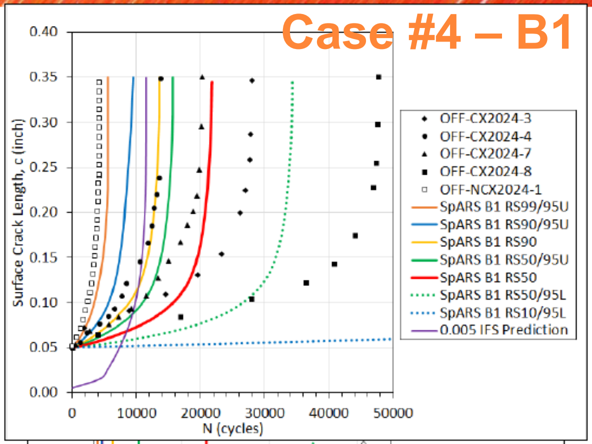
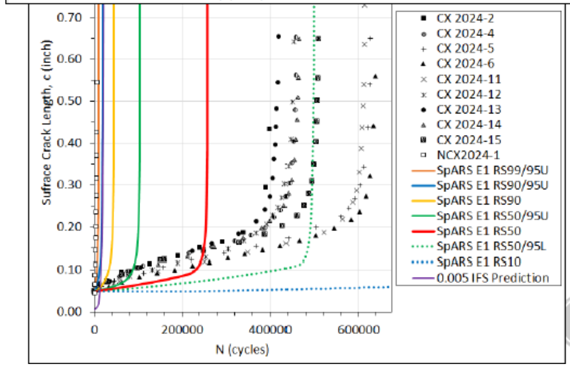
- FCG test data (2024-T351)
  - Geometry: W = 4", t = 0.25", D = 0.5"
- Case 'A2'
  - Min (~3.2% Cx)
  - ERS reps = 5,
  - Fatigue reps = 2
- Case 'E1'
  - Mean (~3.7% Cx)
  - ERS reps = 5,
  - Fatigue reps = 9
- Case 'B1'
  - Min (~3.2% Cx)
  - ERS reps = 4,
  - Fatigue reps = 4



Case #4 – B1



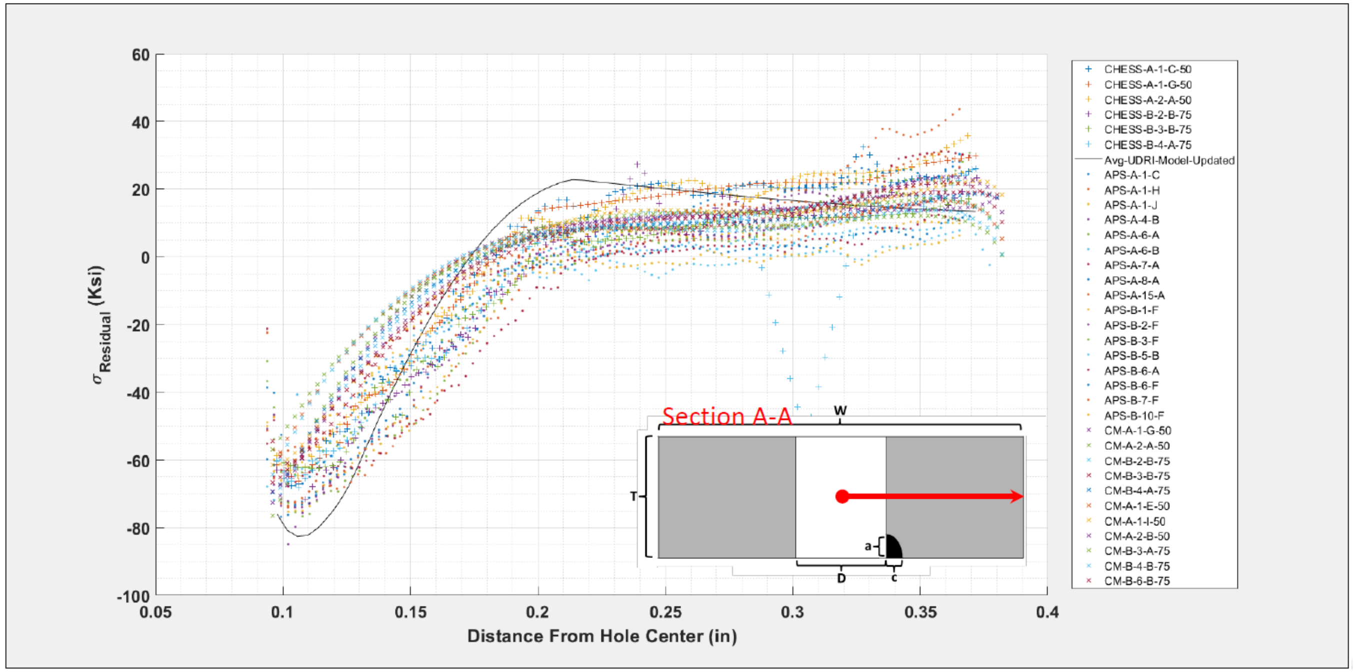


Case #2 – E1

15

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)



ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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

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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

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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

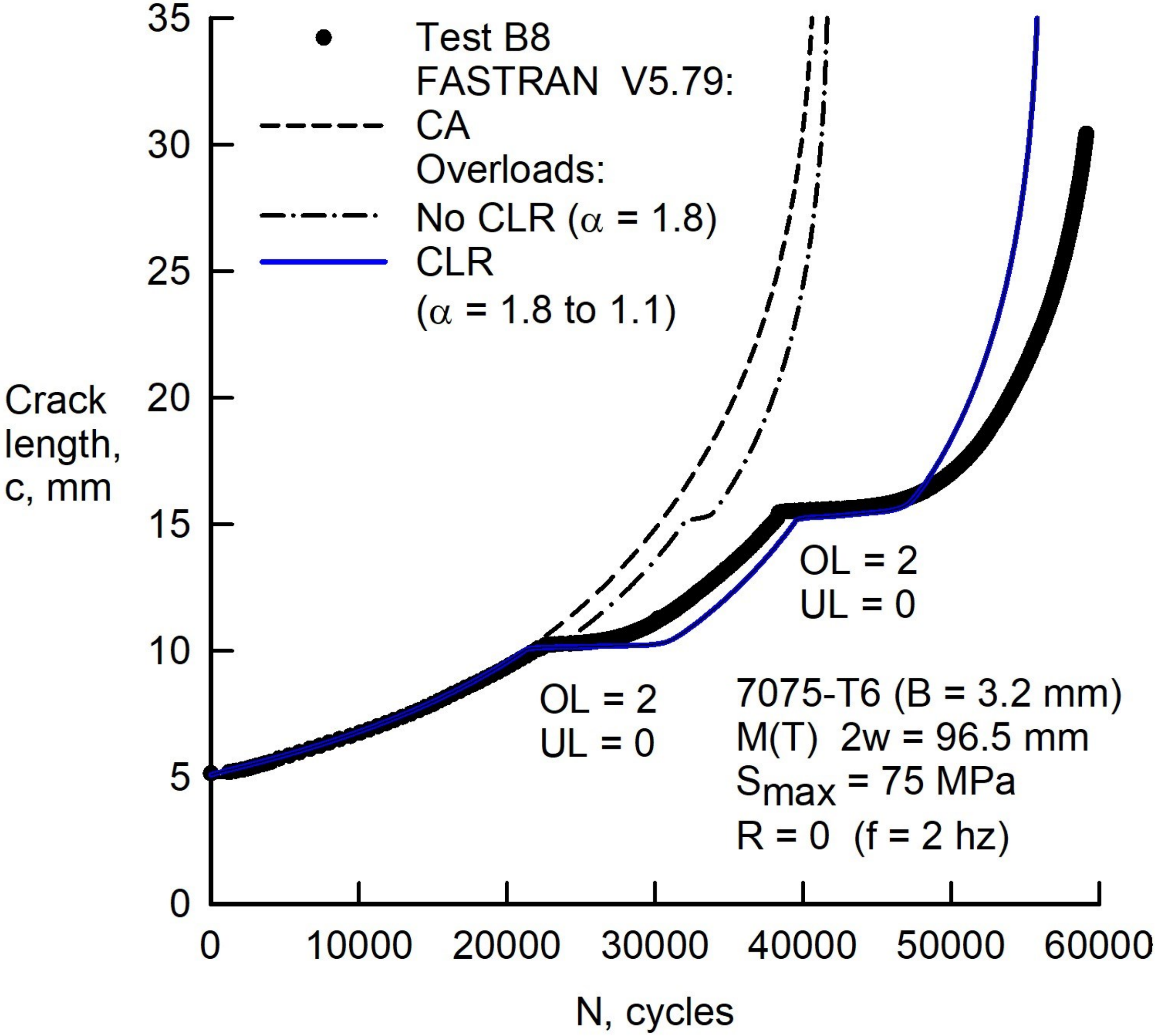
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

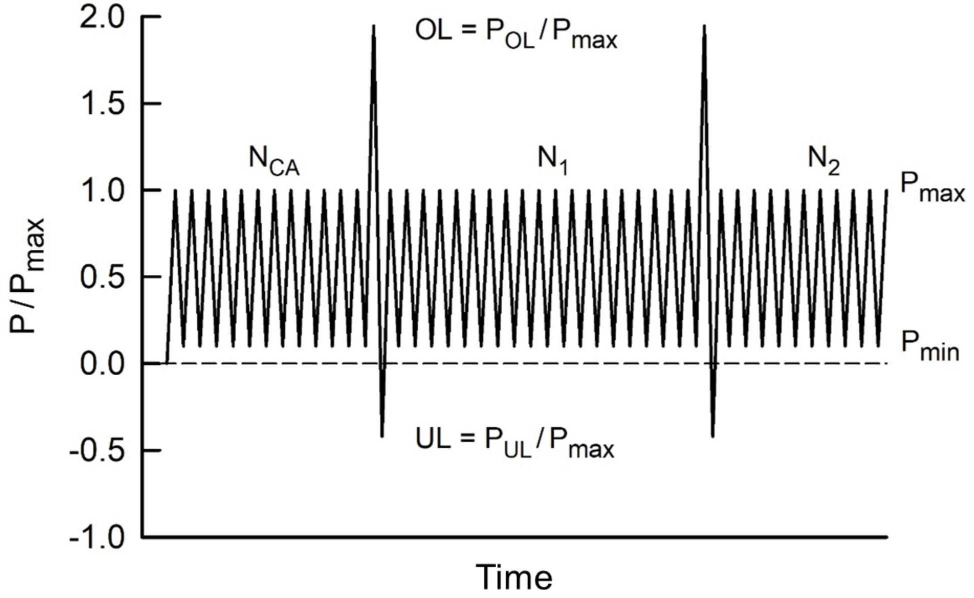
Test summary

- 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

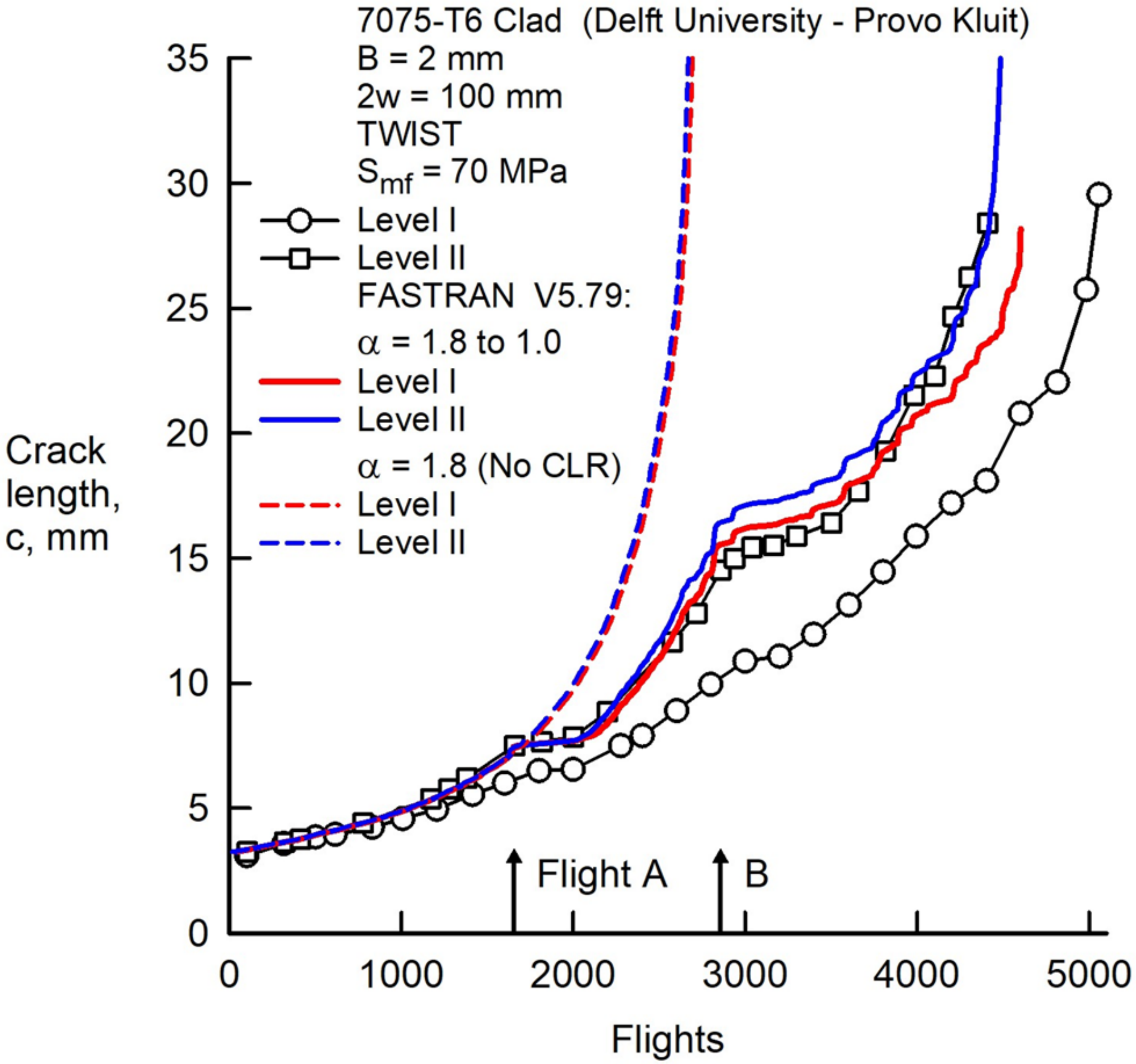
7075-T6

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



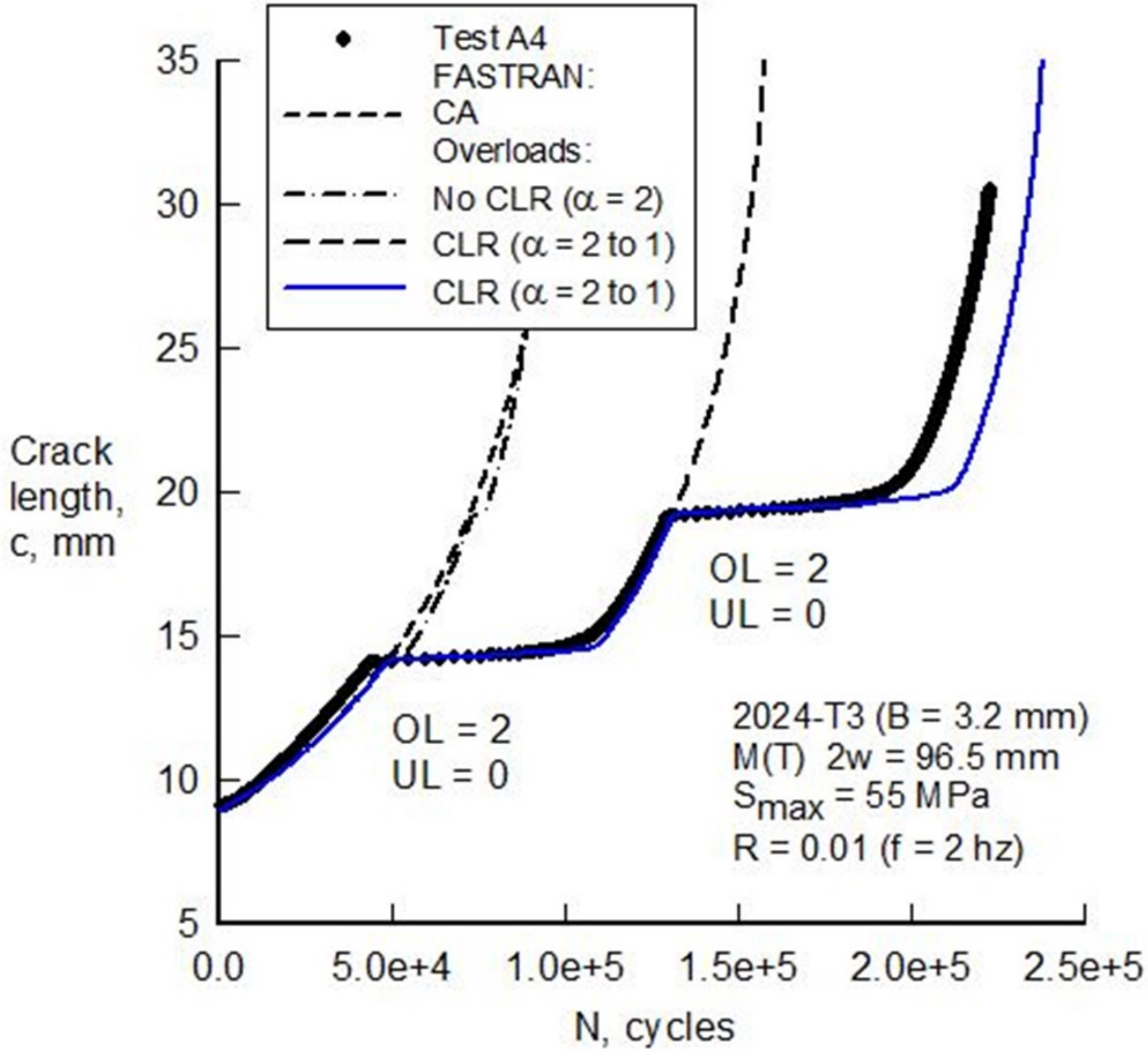


Measured and Predicted Crack-Length-against-Cycles under TWIST (Level I and II) Aircraft Spectrum

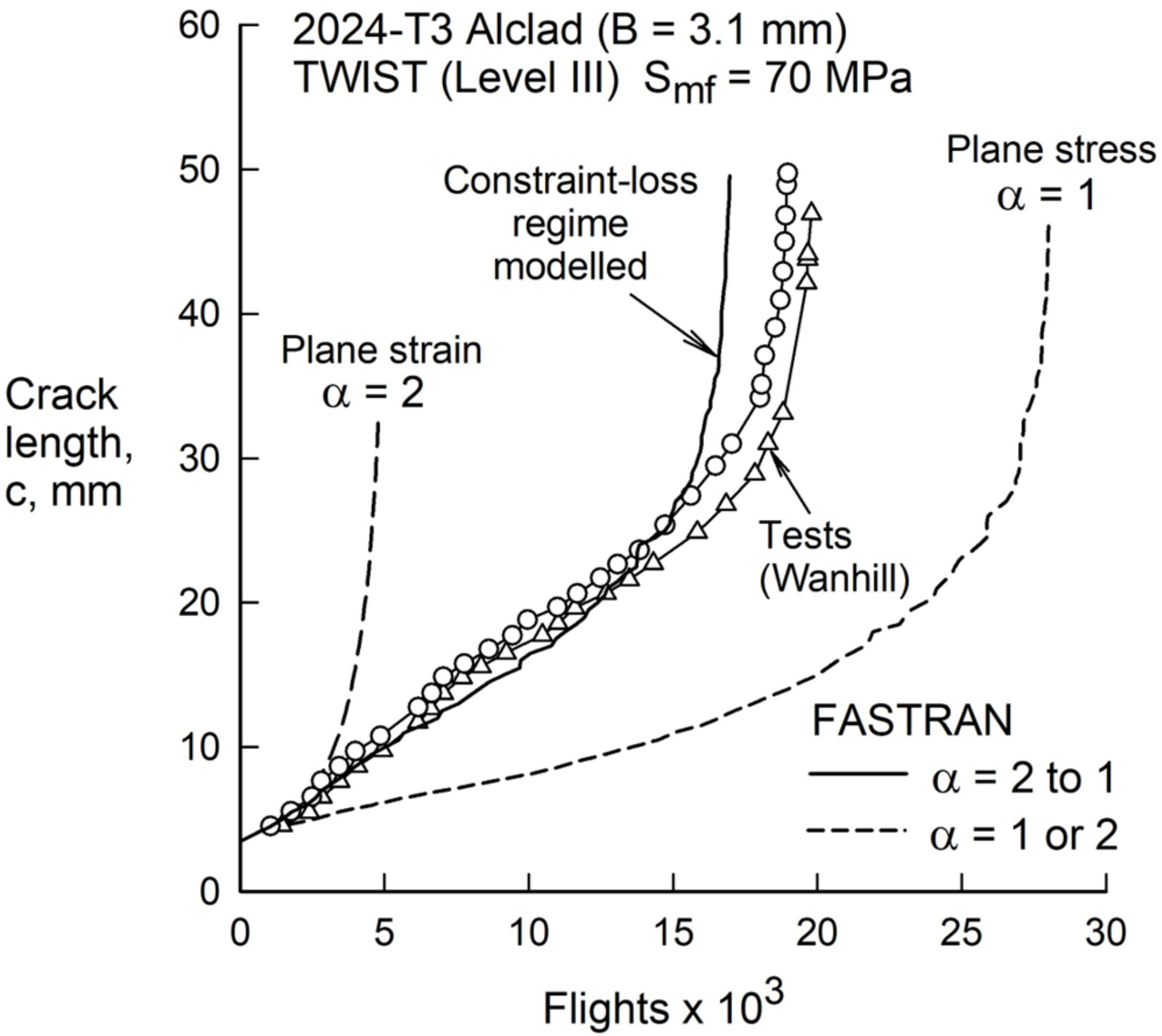


2024-T3

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



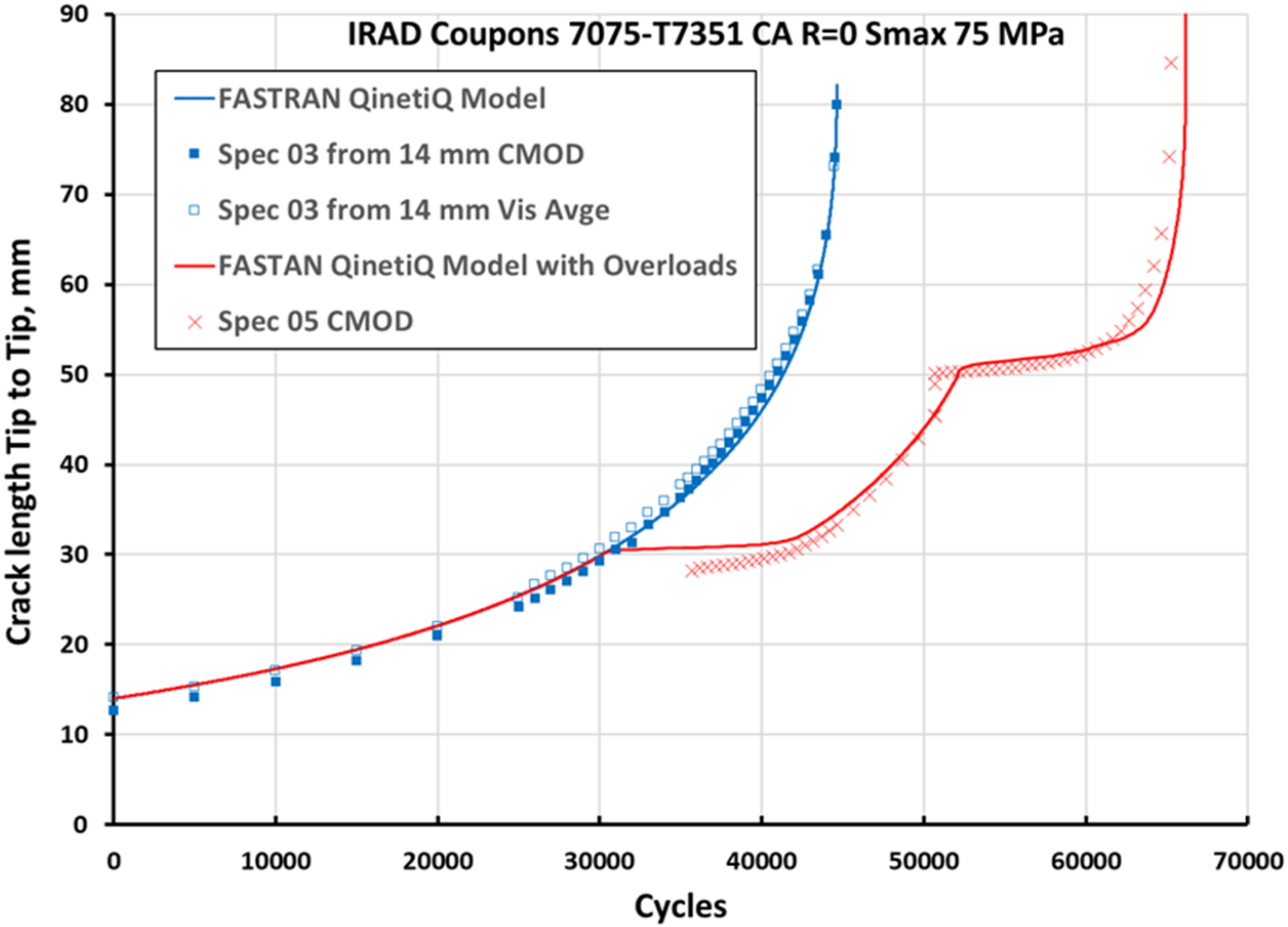
Crack Growth under TWIST (Level III) Spectrum Loading



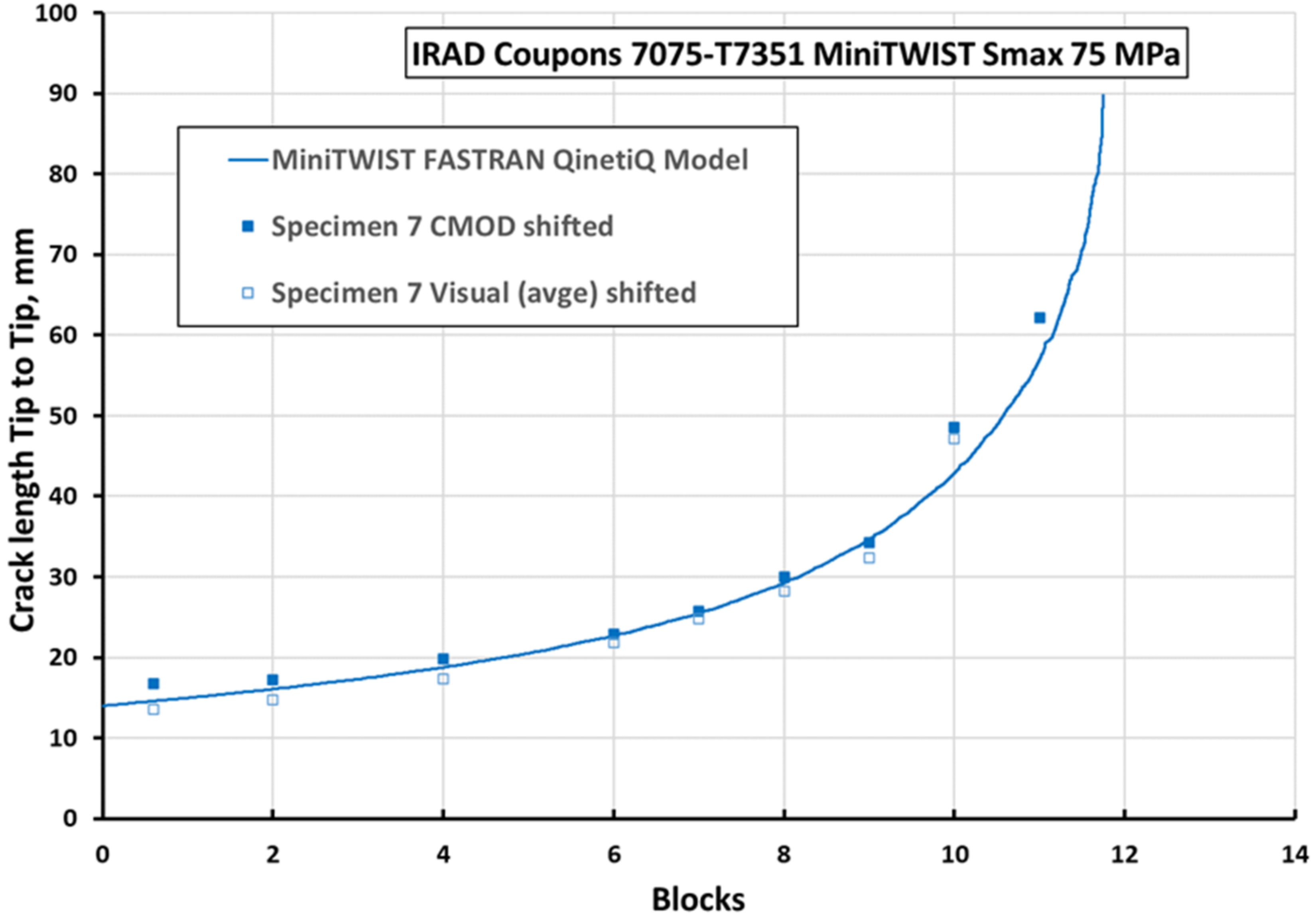
7075-T7351

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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



Mini-TWIST spectrum loading results



ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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

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

Testing and/or Historical Test Data Evaluation Started

*Goal: Build <u>from</u> spectrum loading effect efforts and connect <u>to</u> Cx and IFF efforts

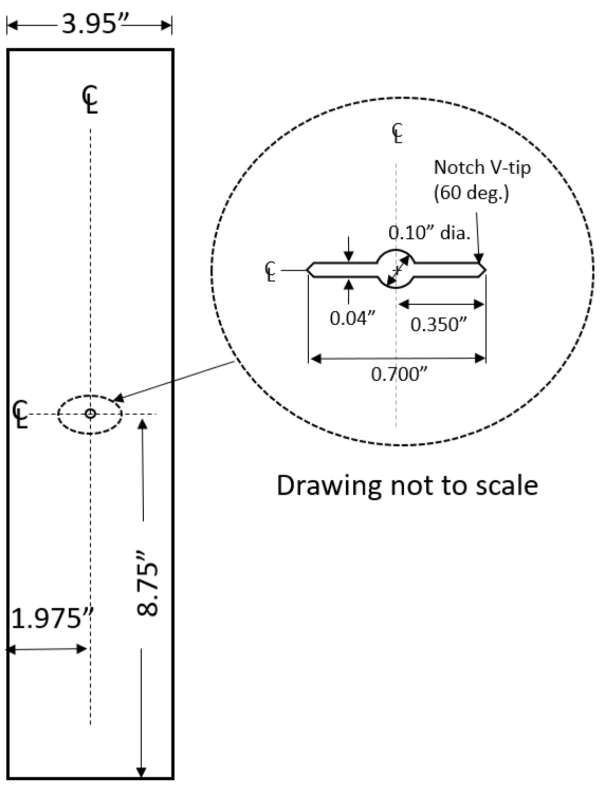
7075-T6 Sheet L-T Spike Overload Testing (Boeing)

- 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.

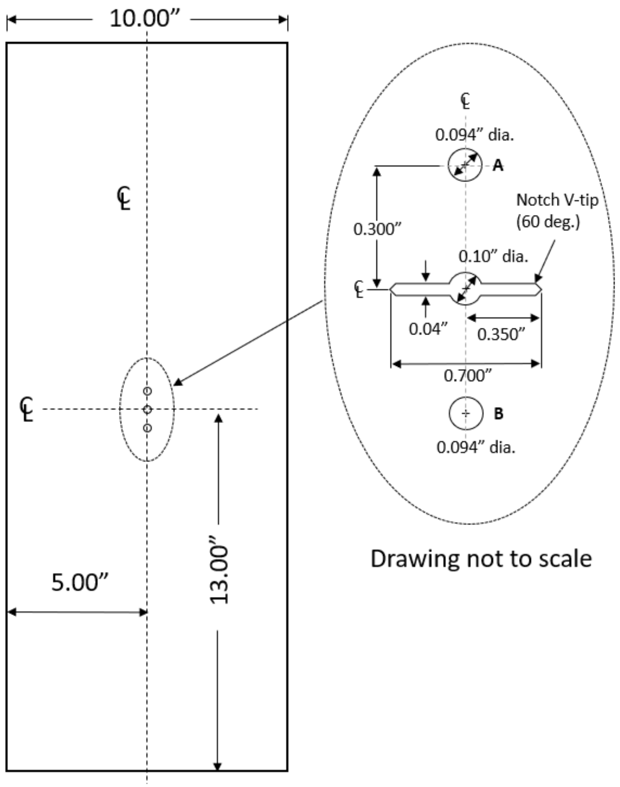
- (A) Growth Rate Characterization
- (B) Constrain Loss
- (C) Constraint Loss Width Effects
- (D) Constraint Loss Thickness Effects

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

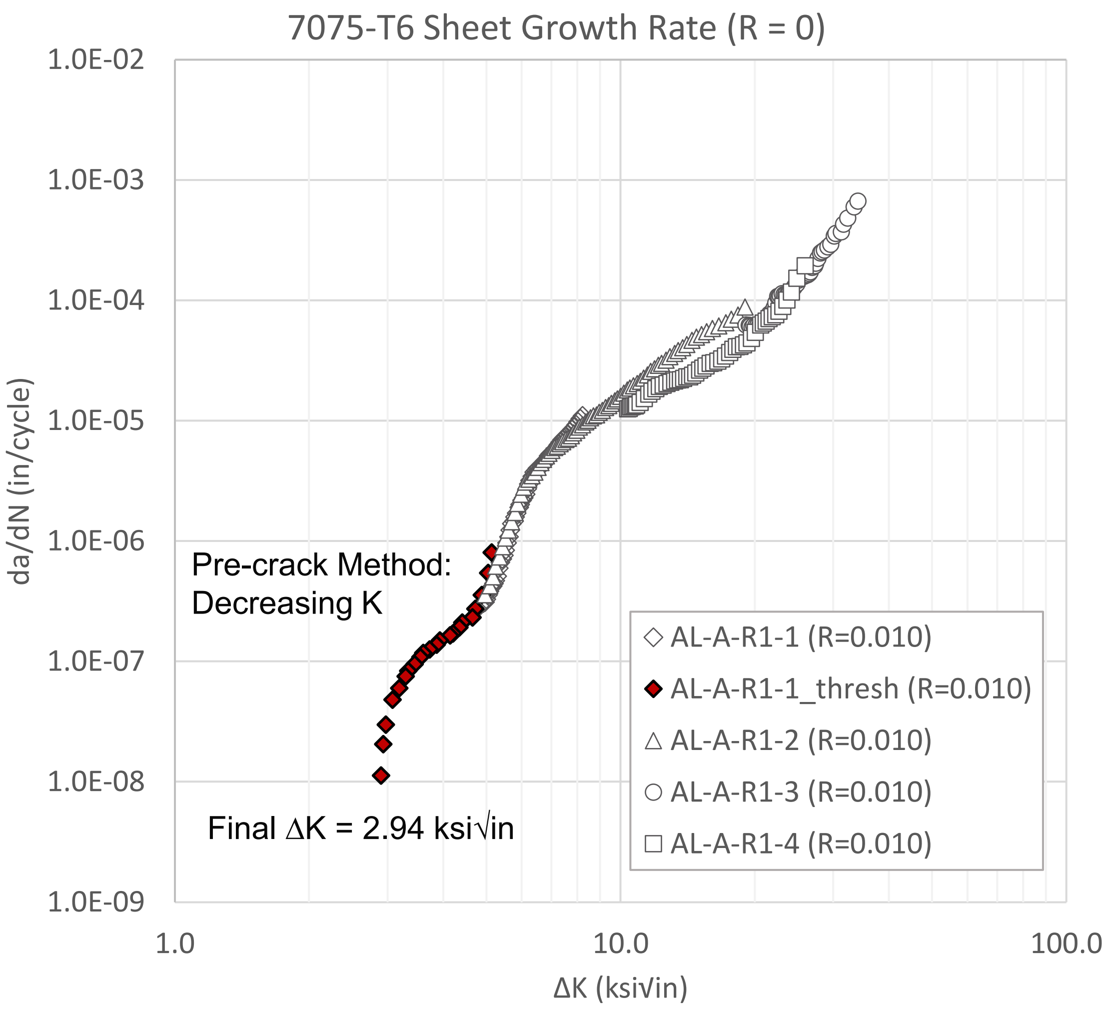


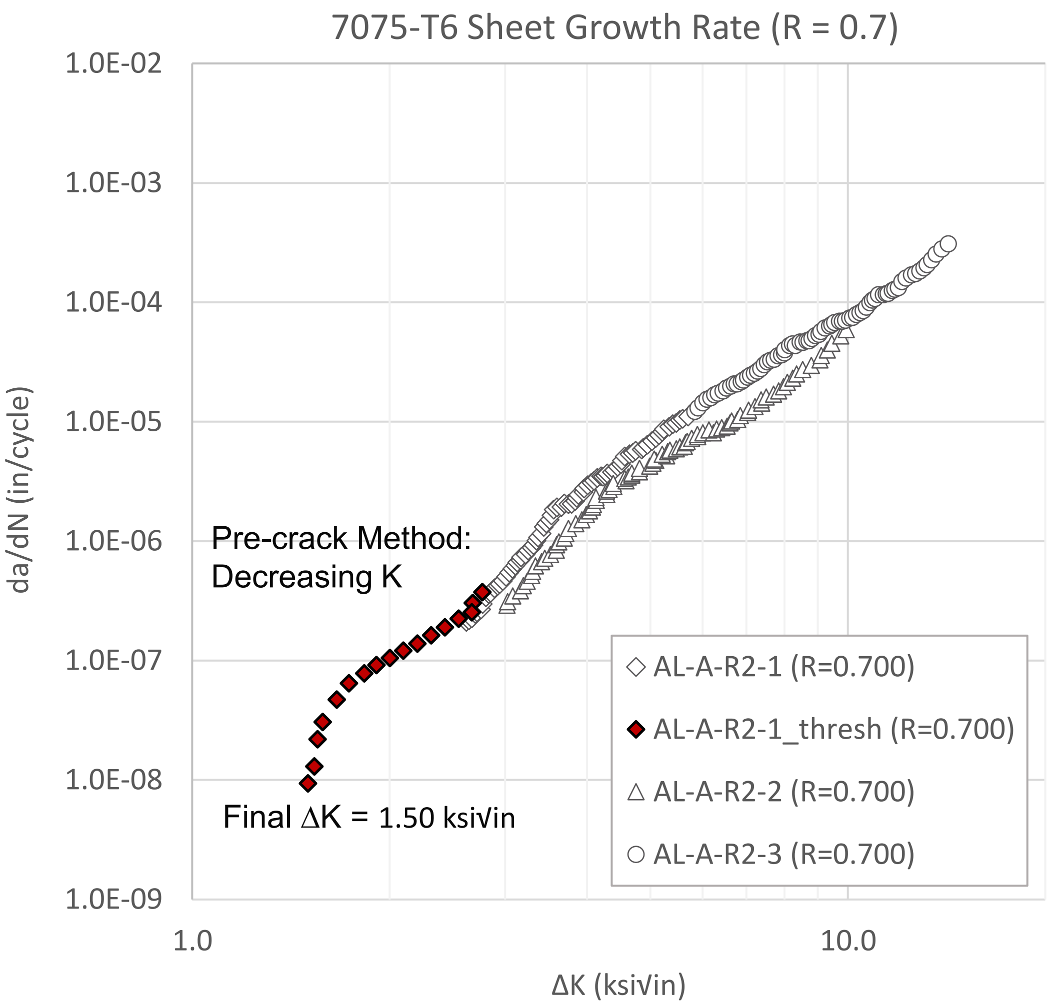
Tasks A and D (thickness = 0.19 in)
Task B (thickness = 0.09 in)



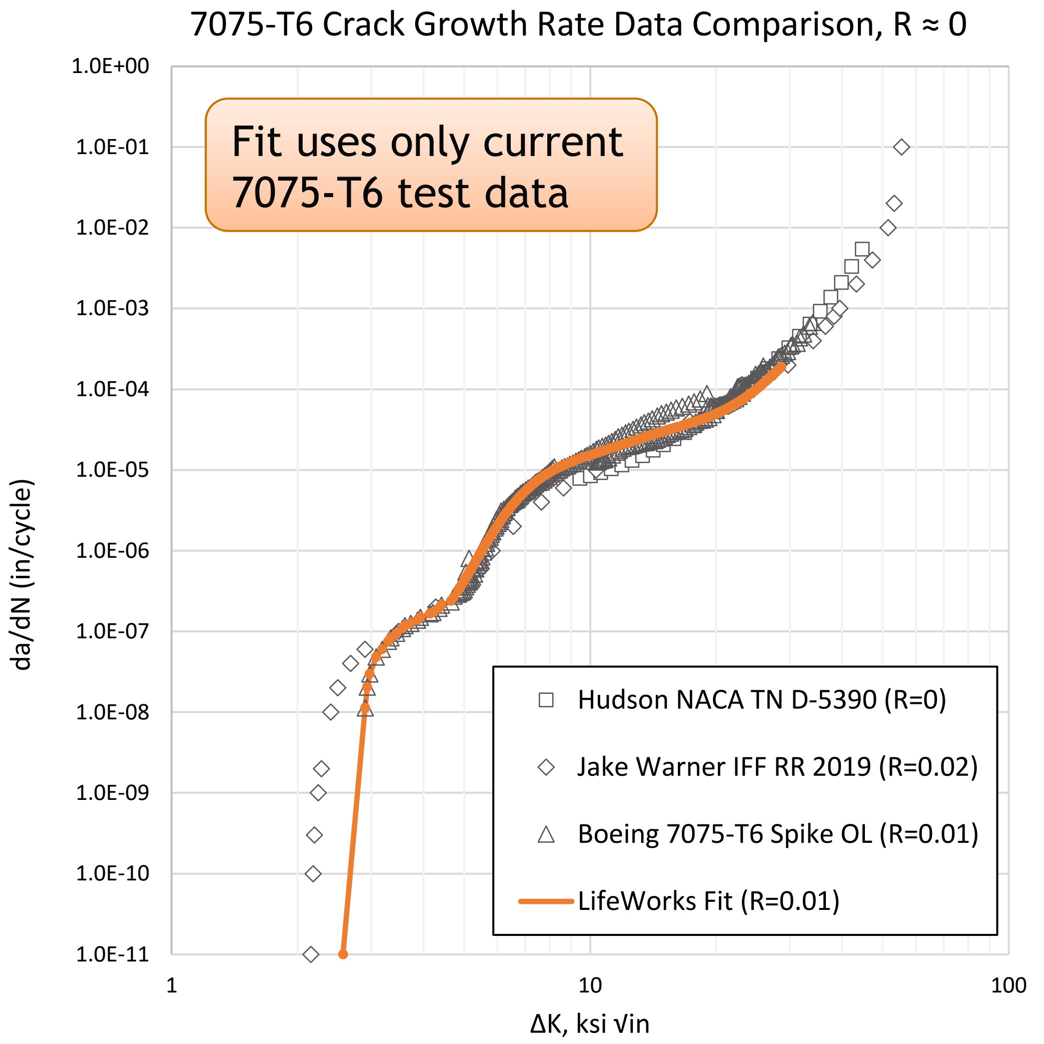
Tasks C (thickness = 0.09 in)

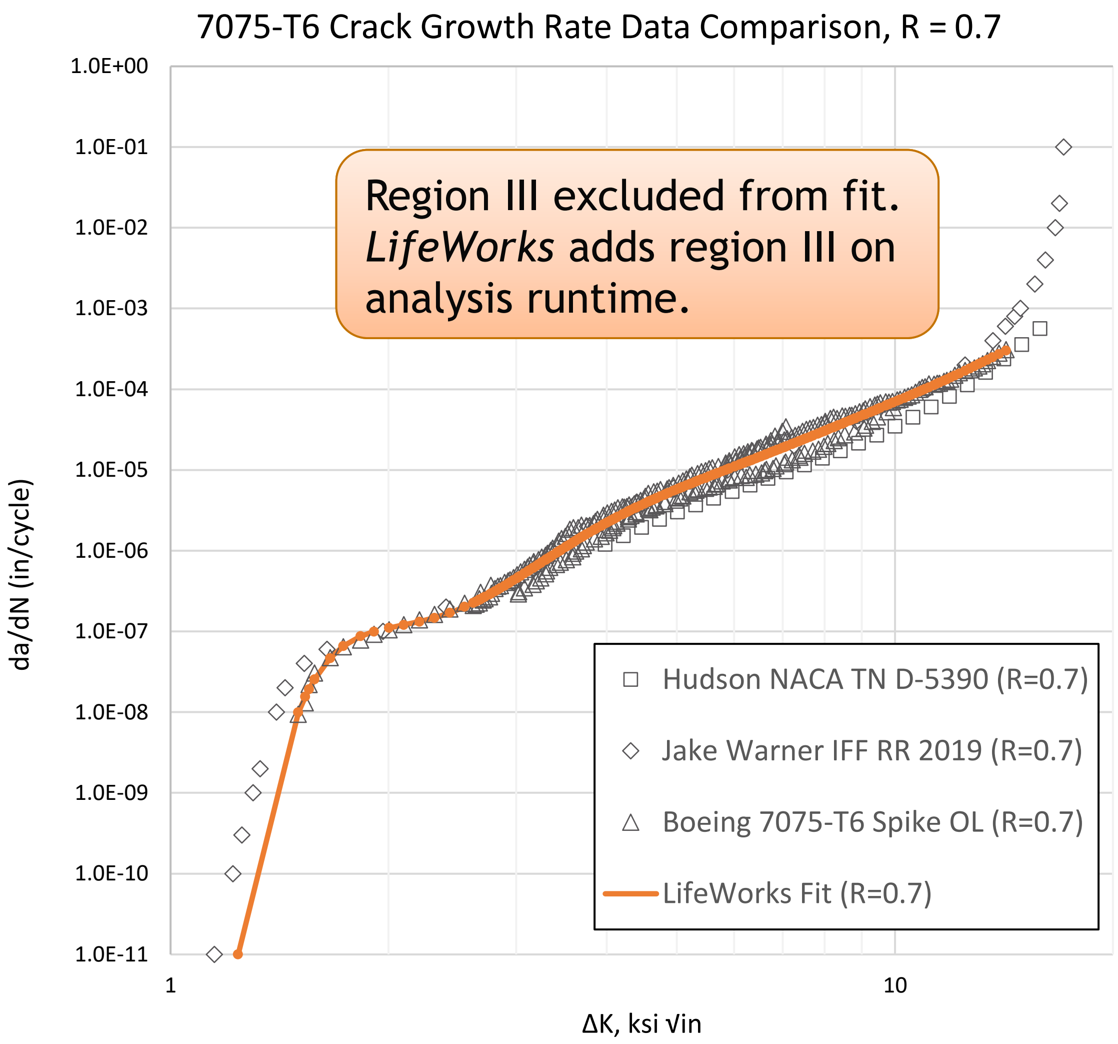
Task A: Crack Growth Rate Characterization



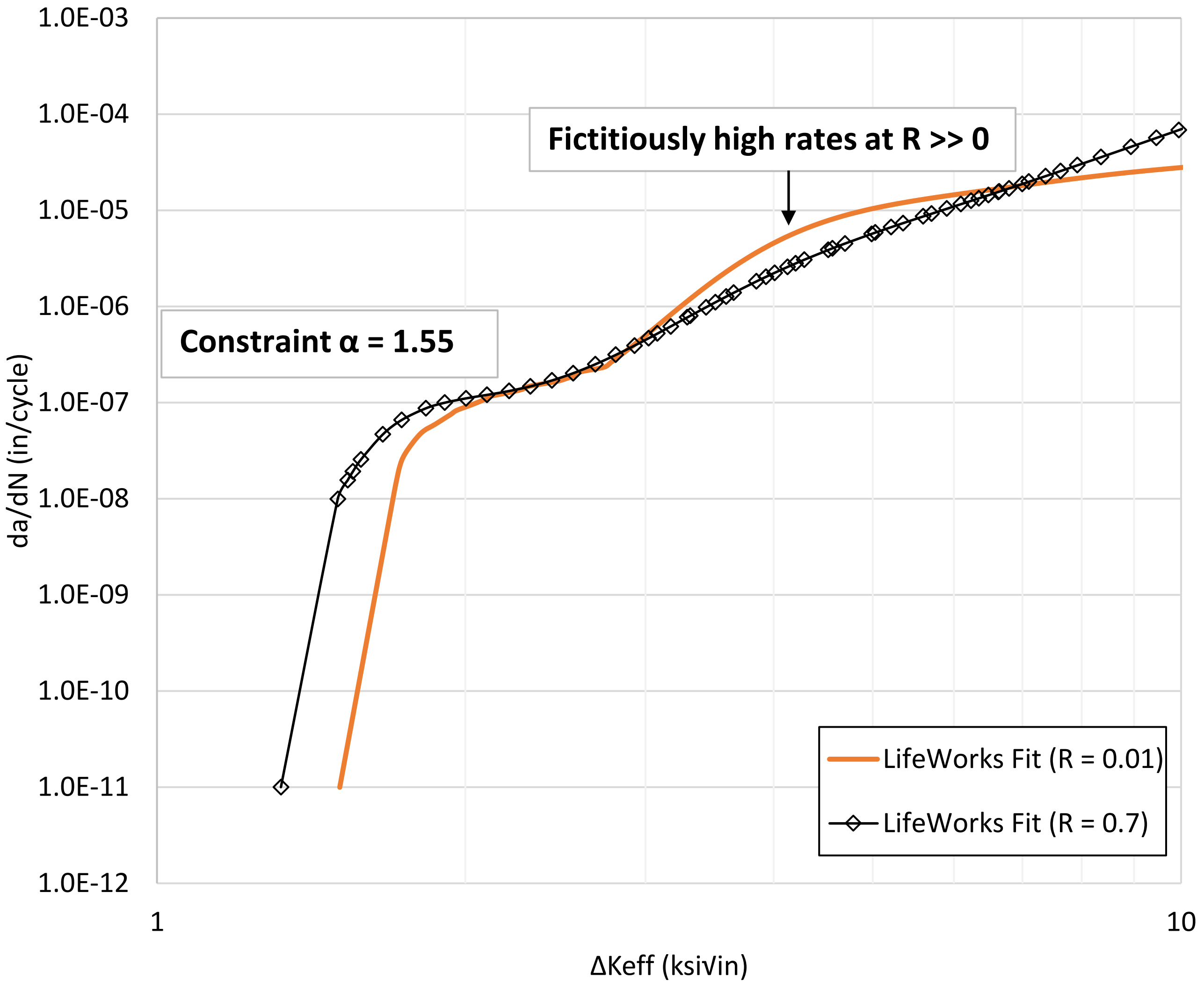


Growth Rate Comparison



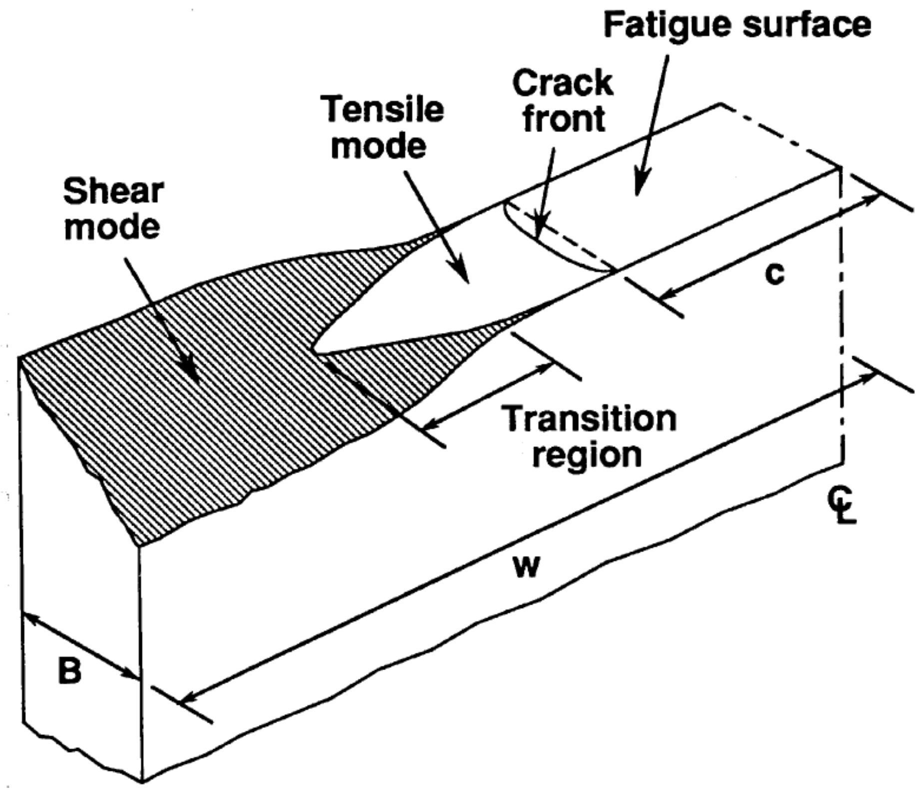


Constraint Parameter



- 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



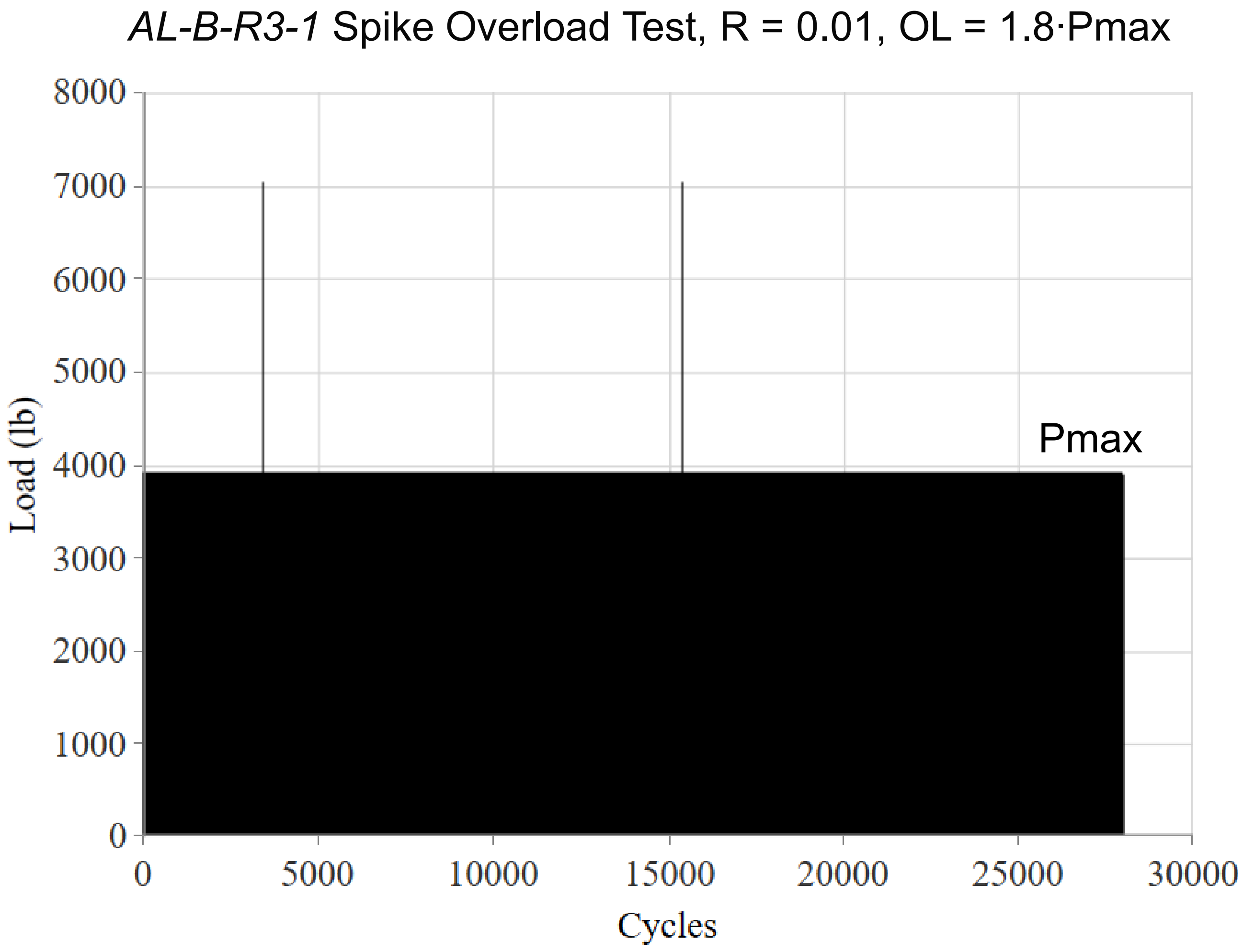
Newman JC Jr, Bigelow CA, Shivakumar KN. *Three-dimensional elastic-plastic finite-element analysis of constraint variations in cracked bodies*. Eng. Frac. Mech 1993

- 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

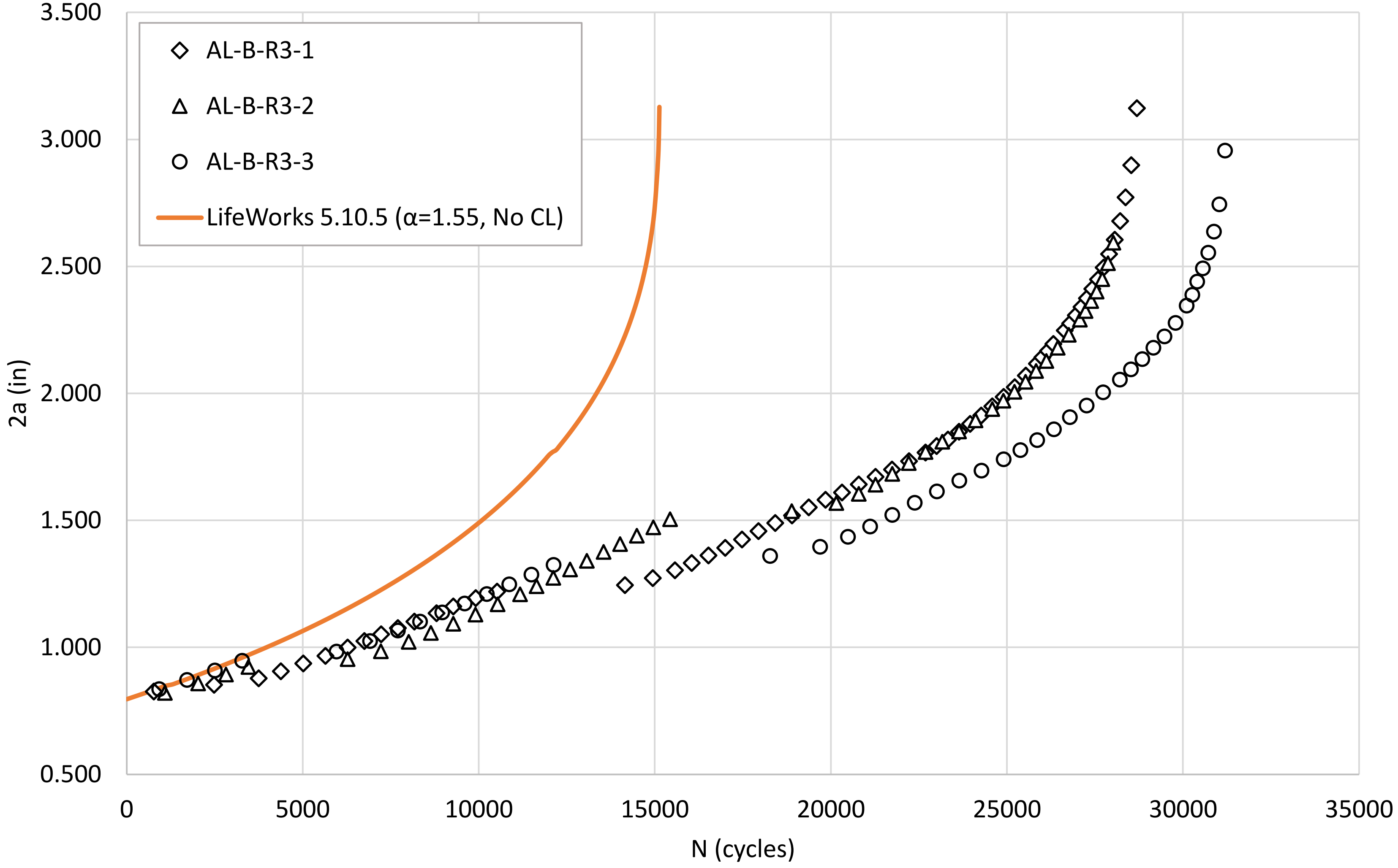


Overloads were applied at two different crack lengths:

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

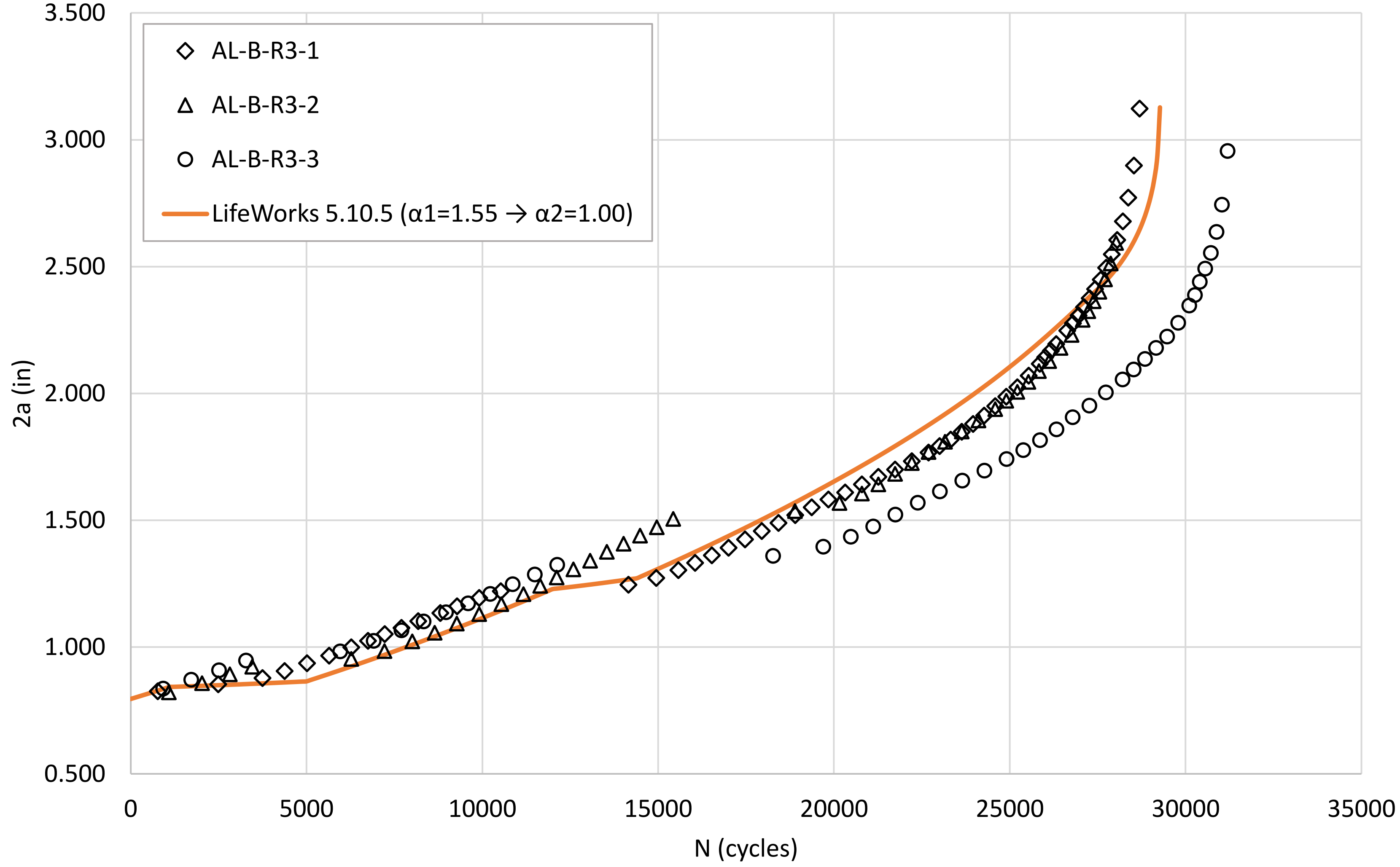
$$2a_{OL-2} = 1.2 \text{ inches}$$

Task B: Results (No Constraint Loss)



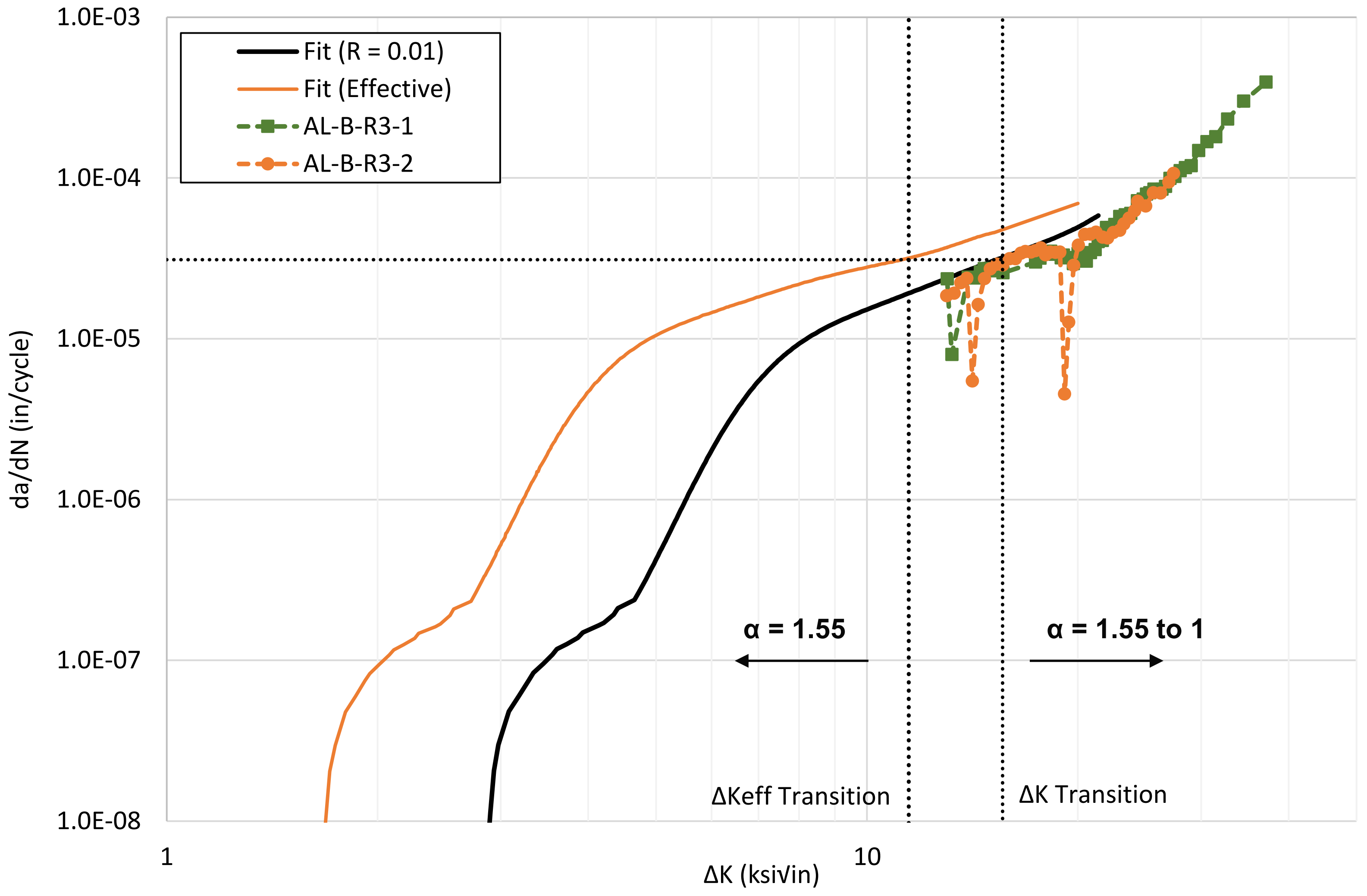
W	3.95"
B	0.09"
L	17.5"
Notch total length	0.7”
Grain Direction	L-T
Loading Type	Constant Amplitude with OL = 1.8·Pmax
Pmax	3.91 kips
Stress Ratio	0.01

Task B: Results (With Constraint Loss)

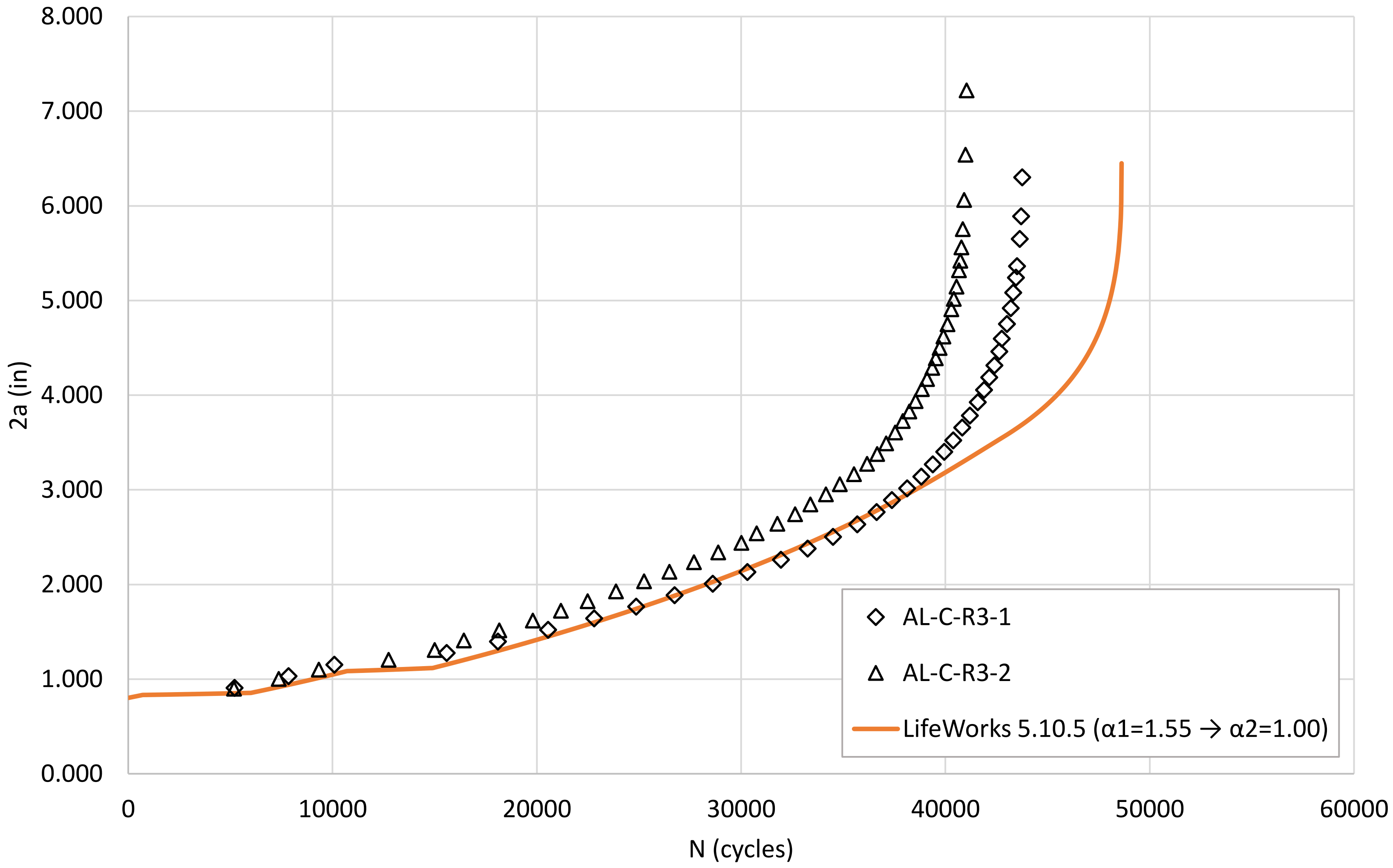


W	3.95"
B	0.09"
L	17.5"
Notch total length	0.7”
Grain Direction	L-T
Loading Type	Constant Amplitude with OL = 1.8·Pmax
Pmax	3.91 kips
Stress Ratio	0.01

Task B: Growth Rate

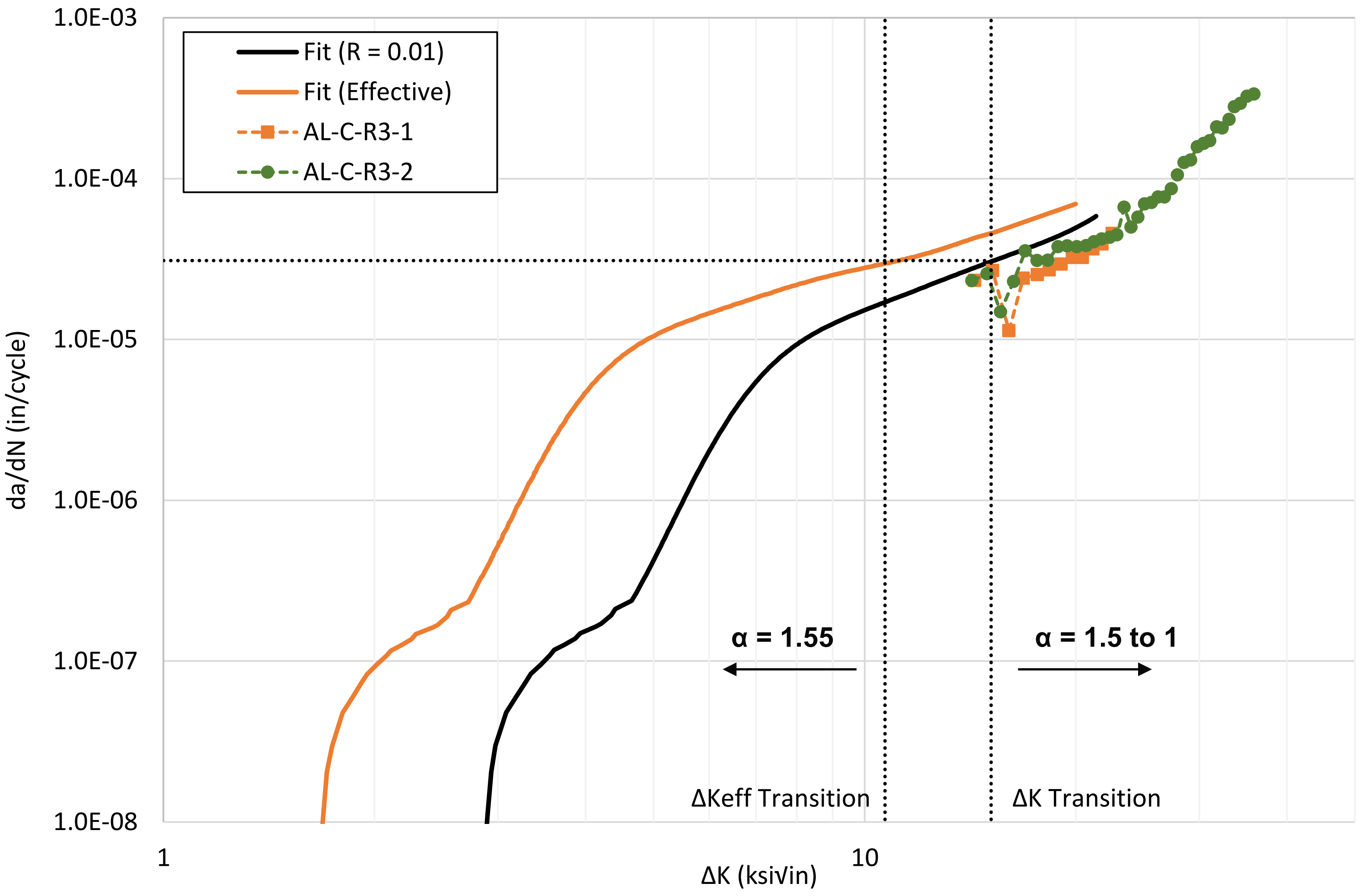


Task C: Results

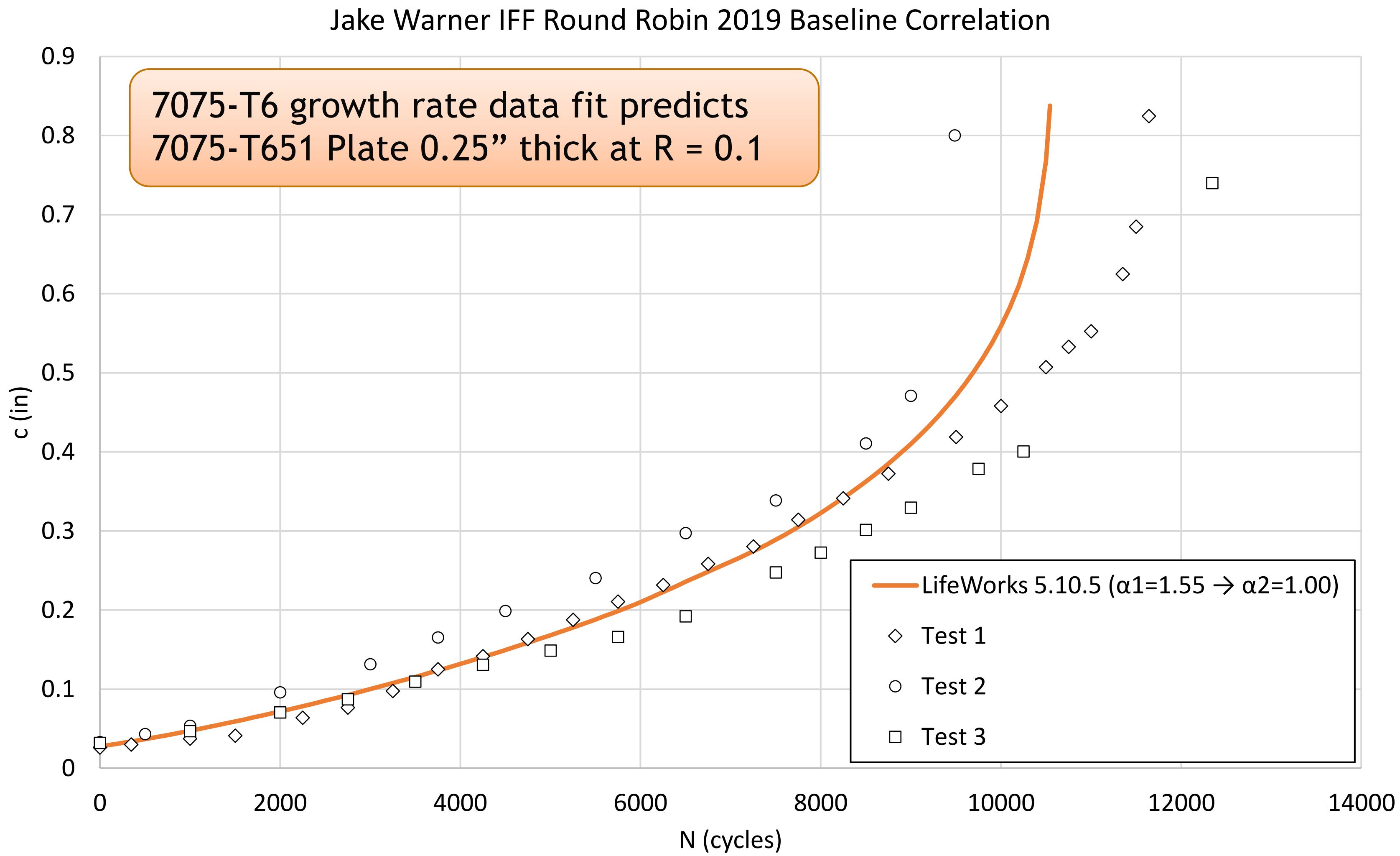


W	10"
B	0.09"
L	26"
Notch total length	0.7”
Grain Direction	L-T
Loading Type	Constant Amplitude with OL = 1.8·Pmax
Pmax	9.9 kips
Stress Ratio	0.01

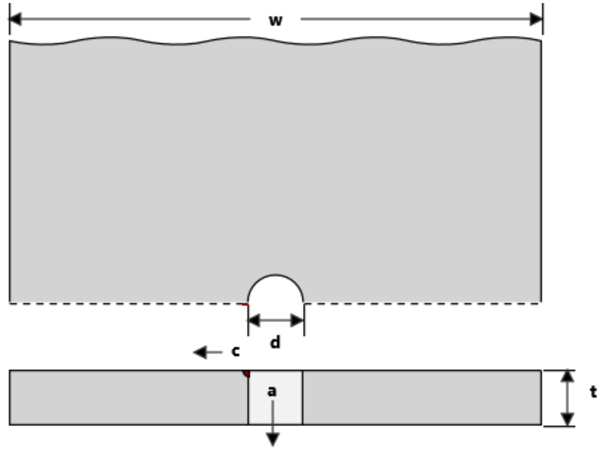
Task C: Growth Rate



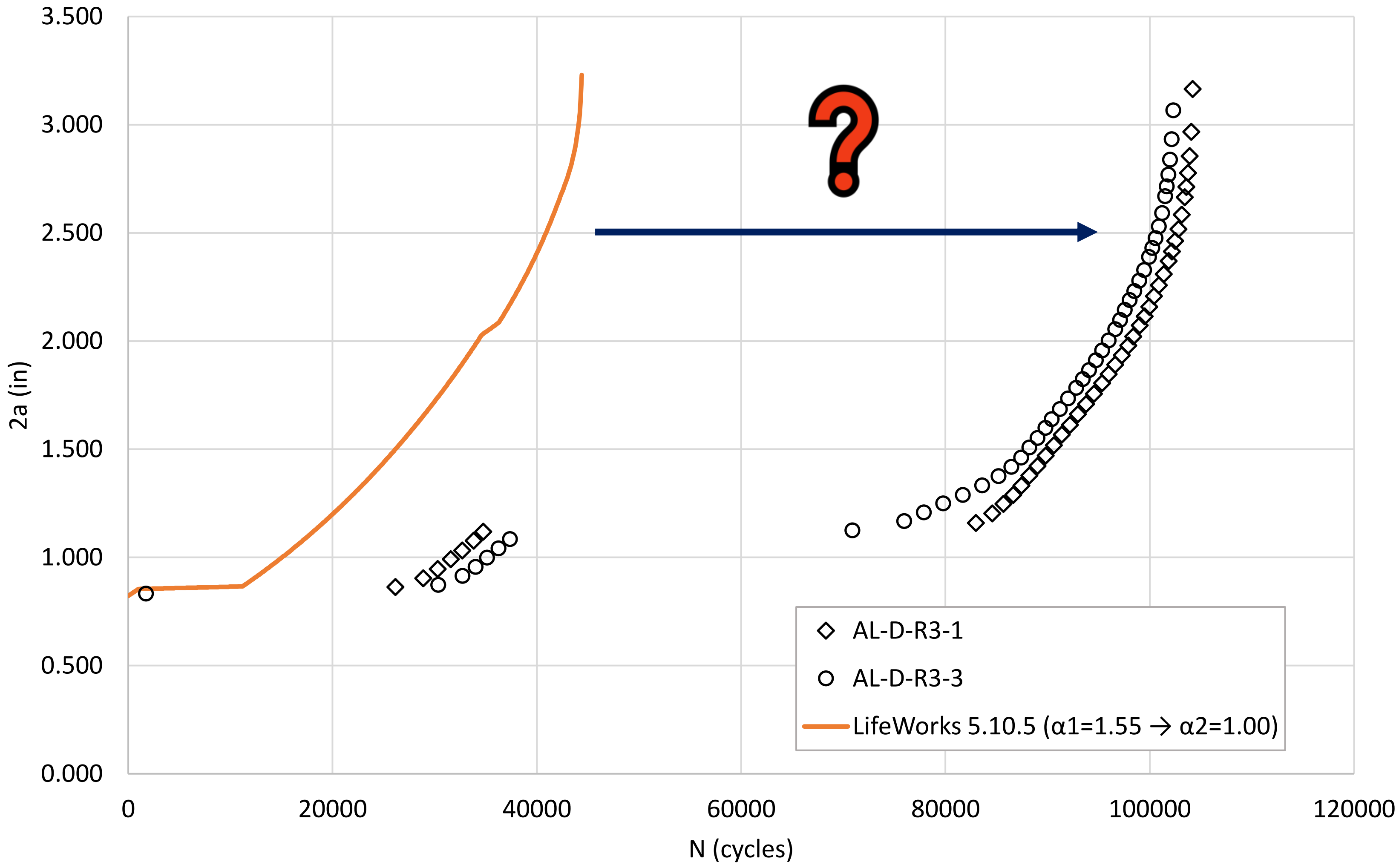
Thicker specimen crack growth prediction



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

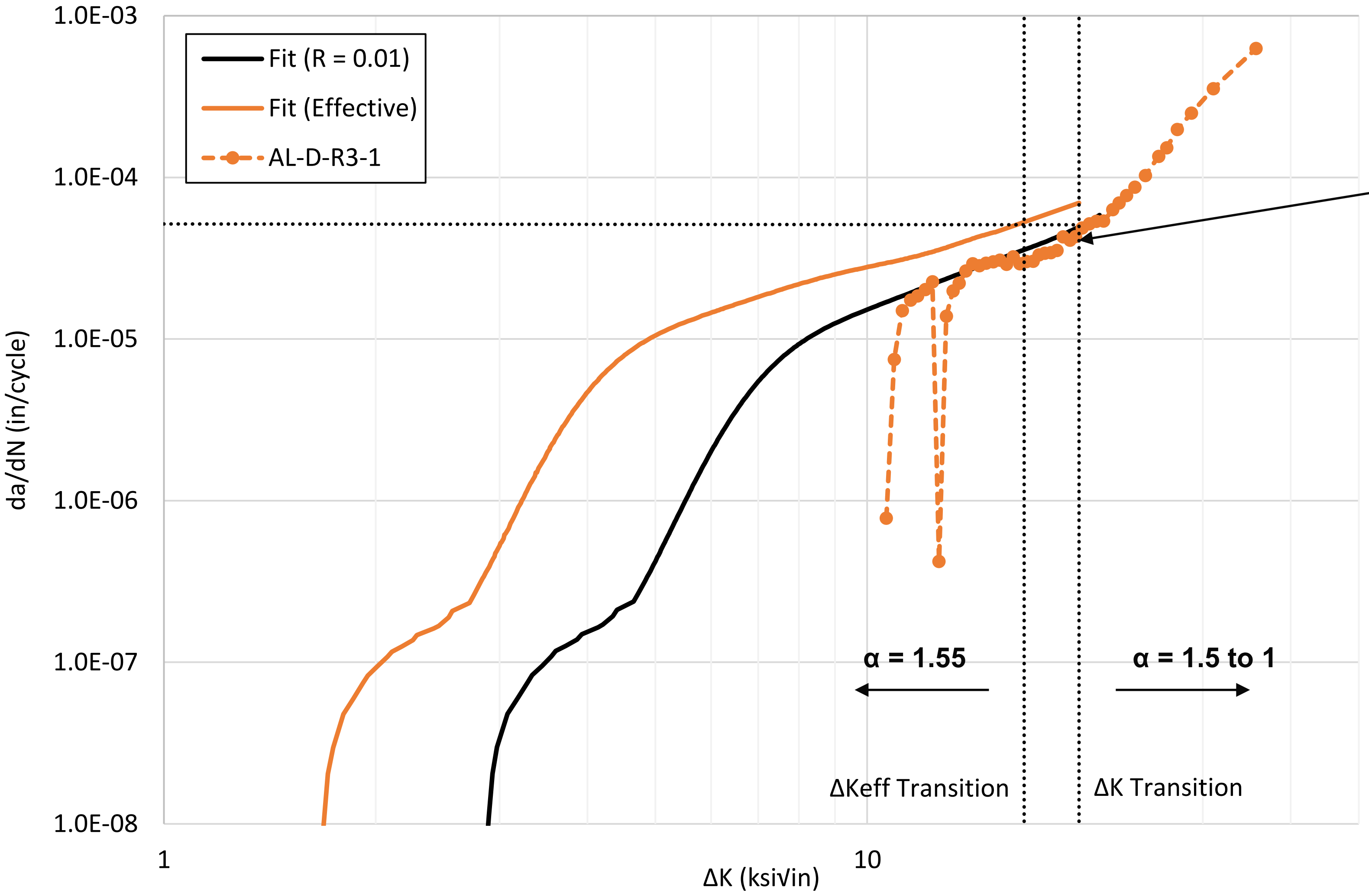


Task D.1: Results



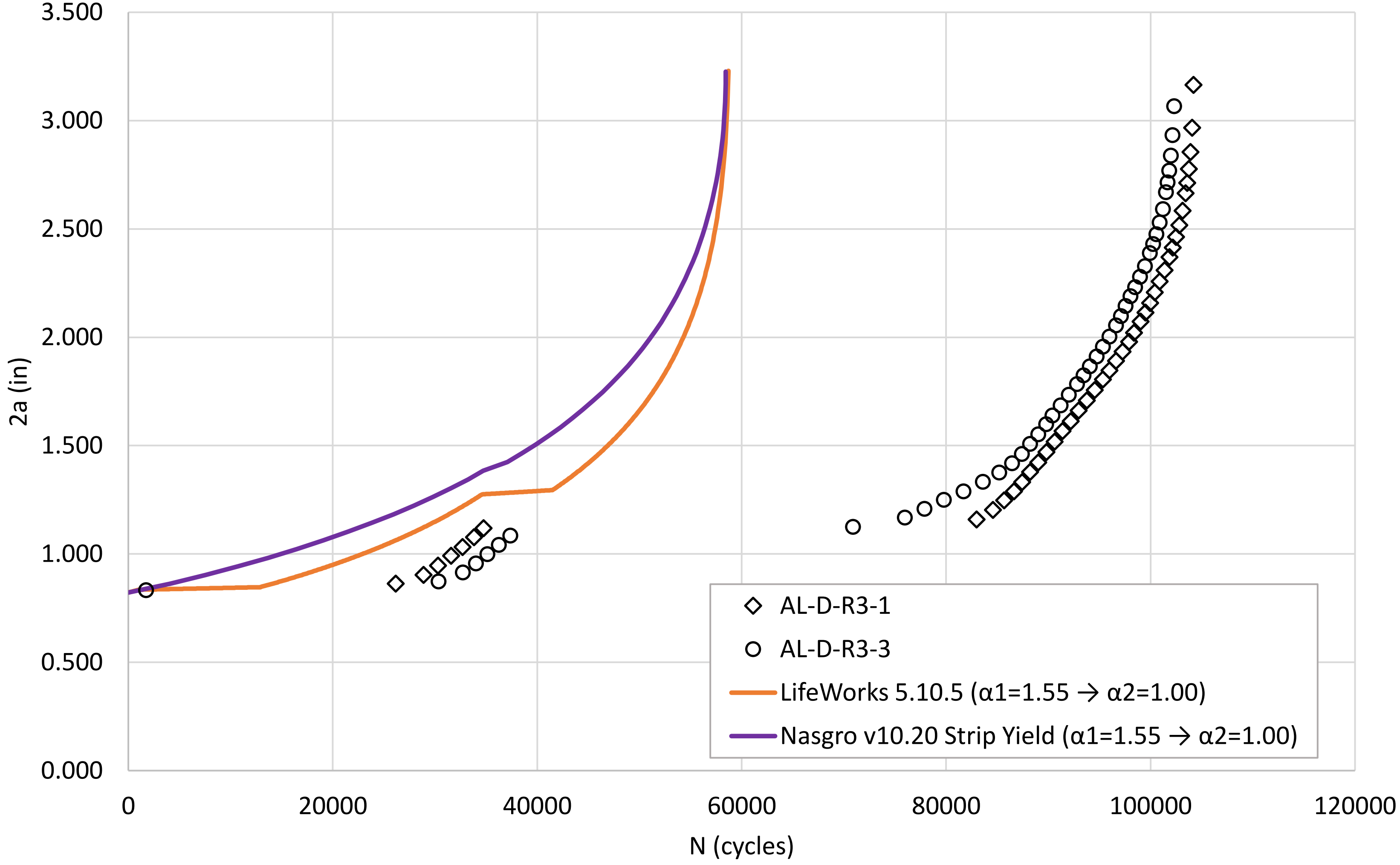
W	3.95"
B	0.19"
L	17.5"
Notch total length	0.7"
Grain Direction	L-T
Loading Type	Constant Amplitude with OL = 1.8·Pmax
Pmax	6.75 kips
Stress Ratio	0.01

Task D.1: Growth Rate



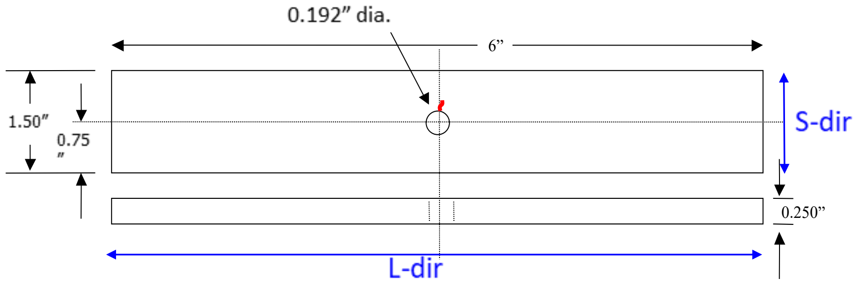
Is the transition ΔK too high?
Is plastic zone too small?
Is constraint modeling appropriate for this geometry?

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

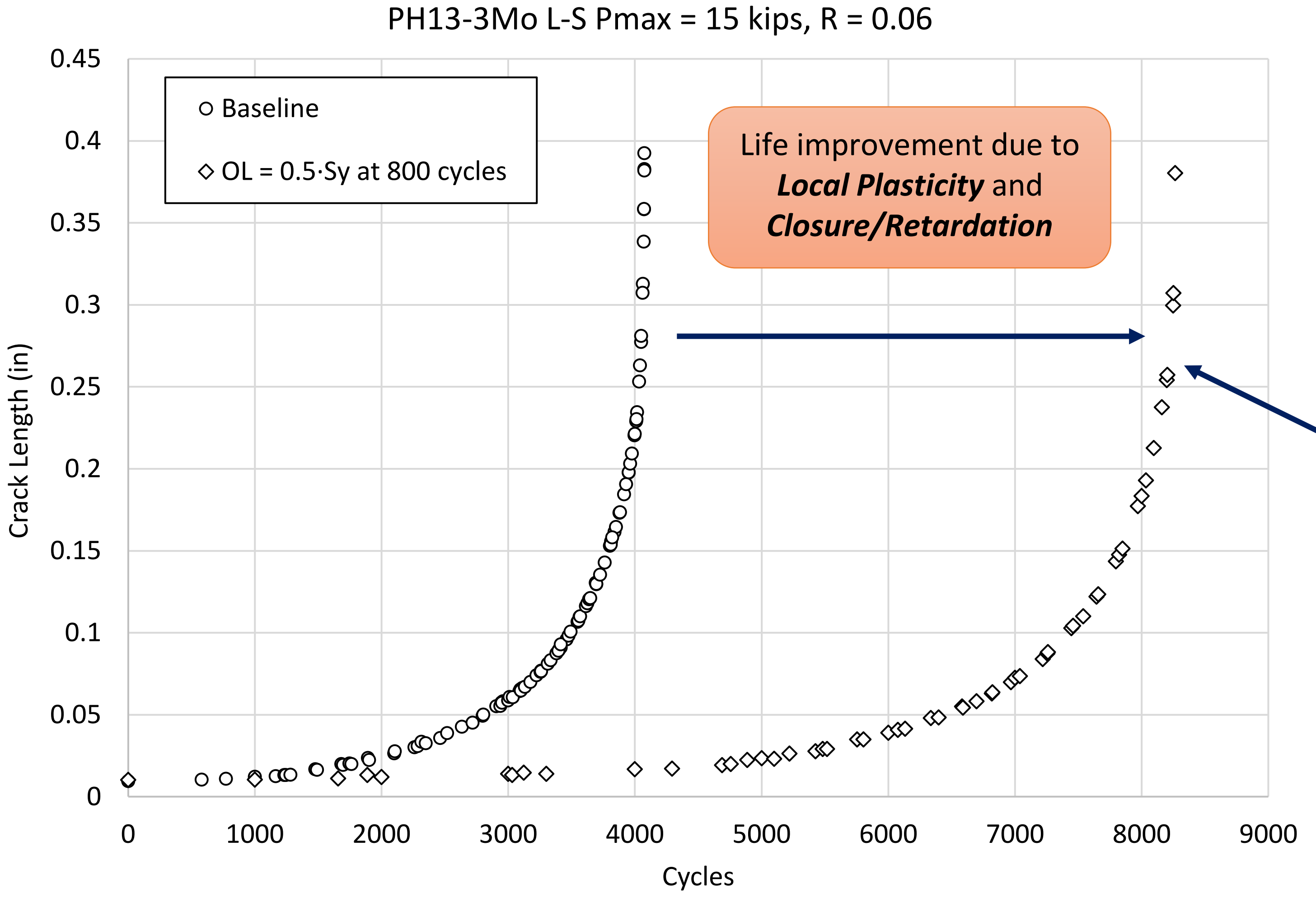
Boeing IRAD Hole Shakedown Test

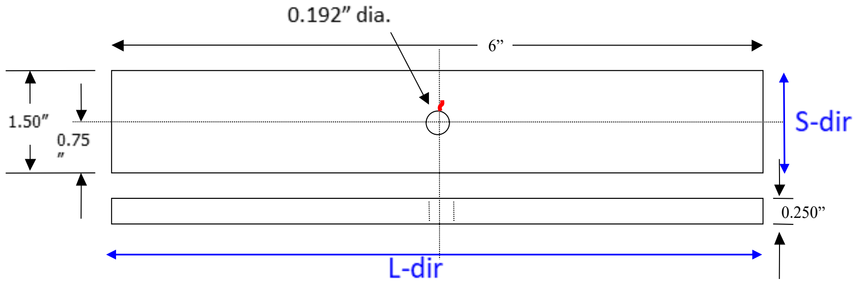


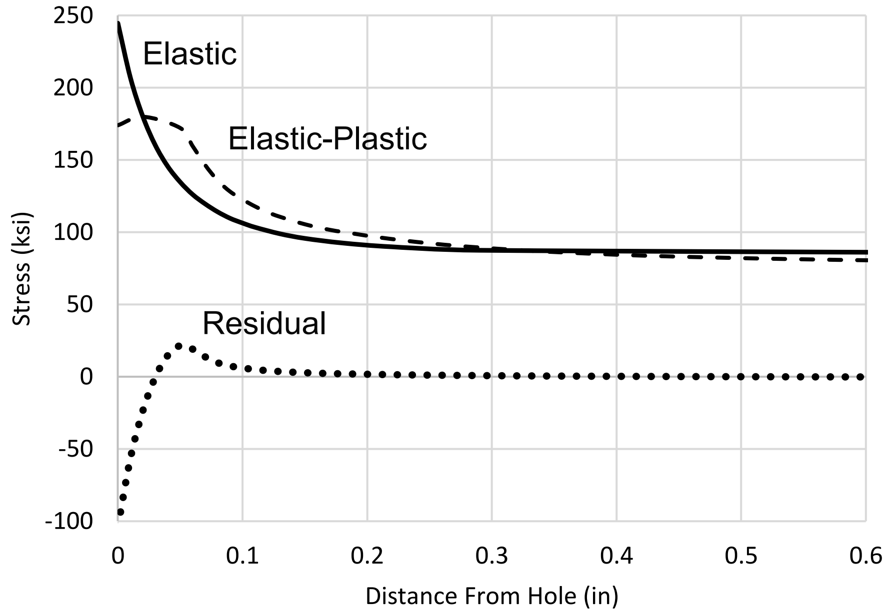
- Materials: Ti-6Al-4V RA and PH13-8Mo (might add 2024-T6 if available)
- Grain Direction: L-S (plan to expand to L-T in the near future)
- Status: Test Completed
- Objectives: Consider local plasticity effects (i.e. Hole Shakedown)
- Procedure: Specimens were pre-cracked and subjected to constant amplitude 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)

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Working Group on
Engineered Residual
Stress Implementation

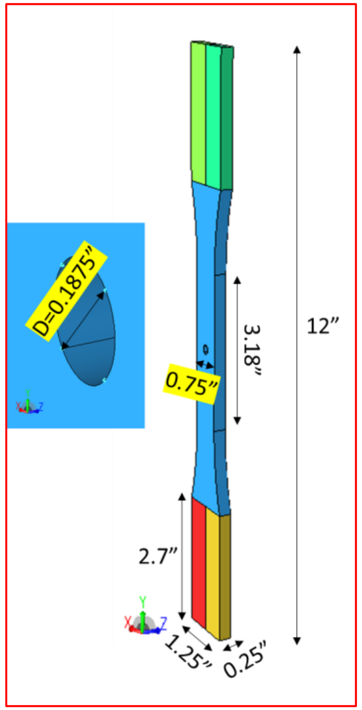
Analysis Methods and Testing
April 02, 2024

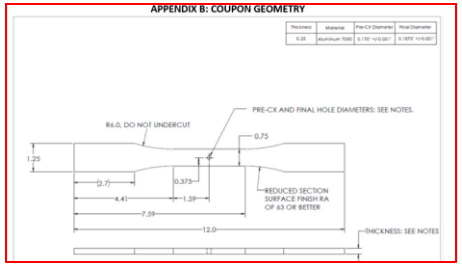
Comparison of 3D FEA based solutions against Non-CX (CA) marker bands (2 sets) from the recent Round Robin challenge

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

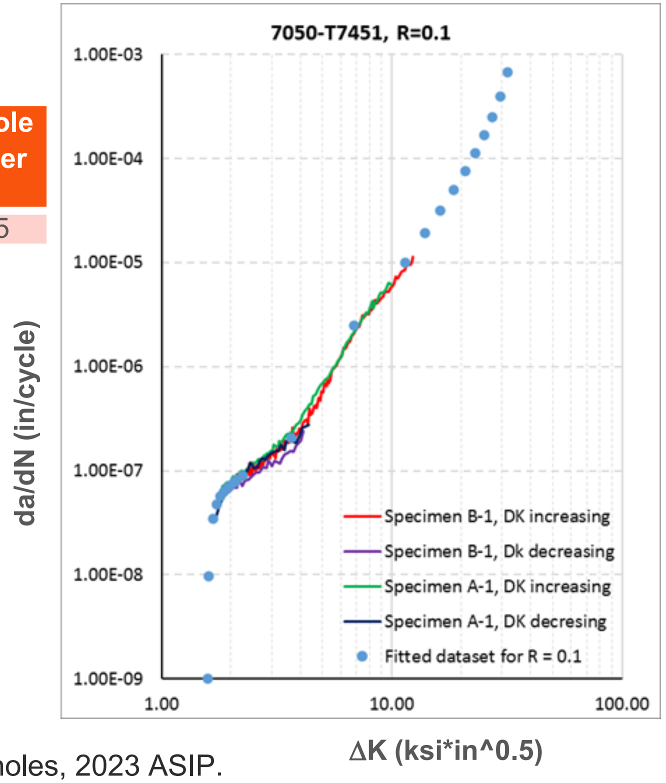
- All constant amplitude loading used a load ratio of R= 0.1

- 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"

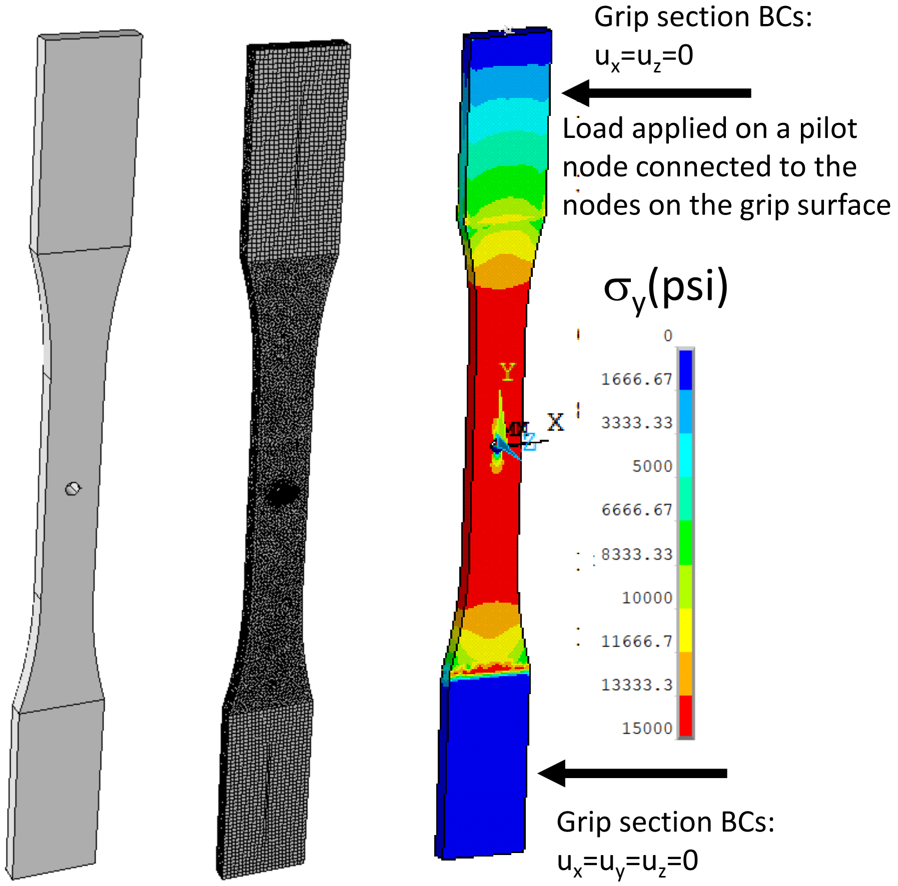
Units: inch, psi, ksi

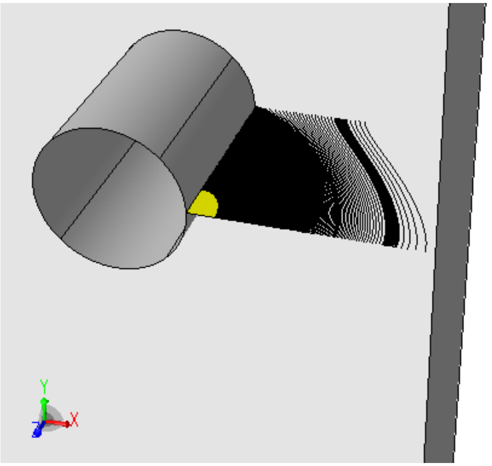


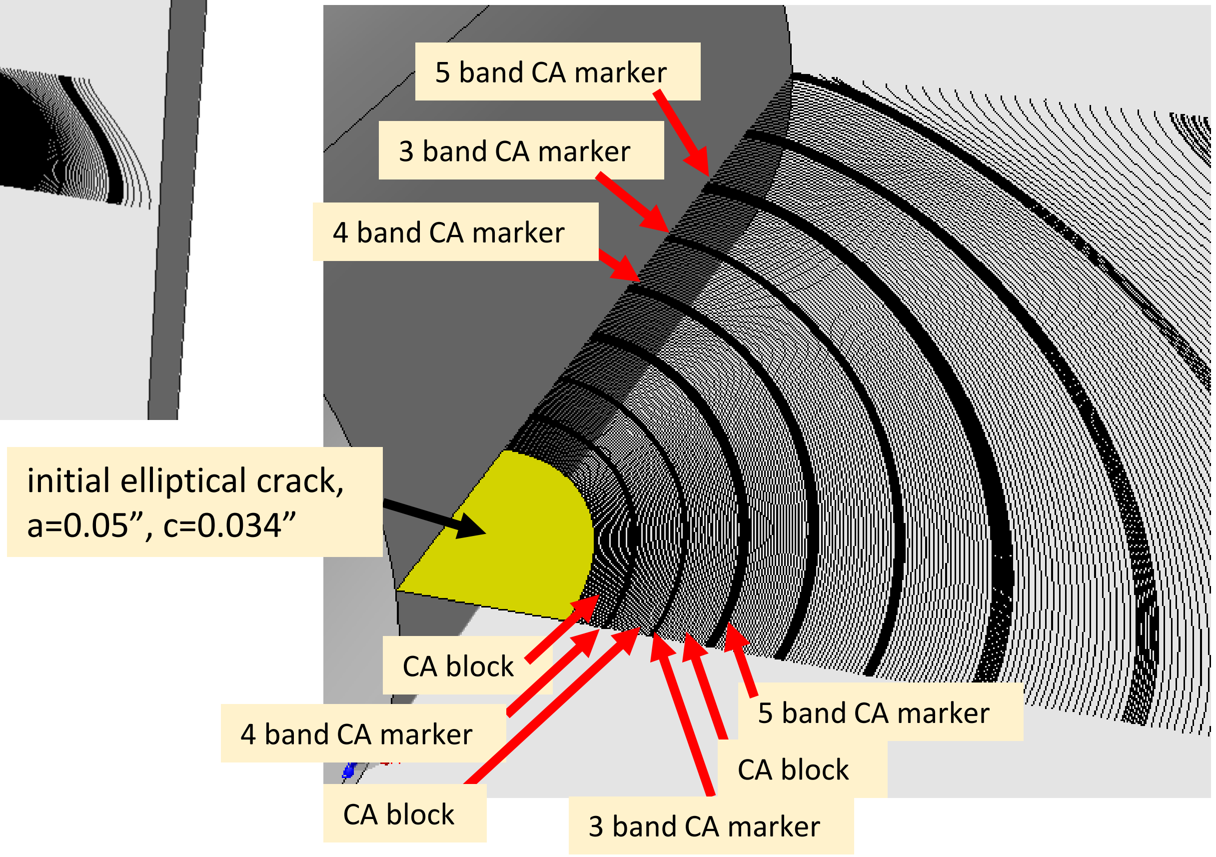
*References used throughout this presentation:
TJ Spradlin, E. Burba, Uncertainty in DTA due to variability in residual stress at cold work expanded holes, 2023 ASIP.
PL Phillips, TJ Spradlin, E. Burba, Fatigue Testing of 7050-T7451 cold expanded specimens and subcomponent specimen development, 2023 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.





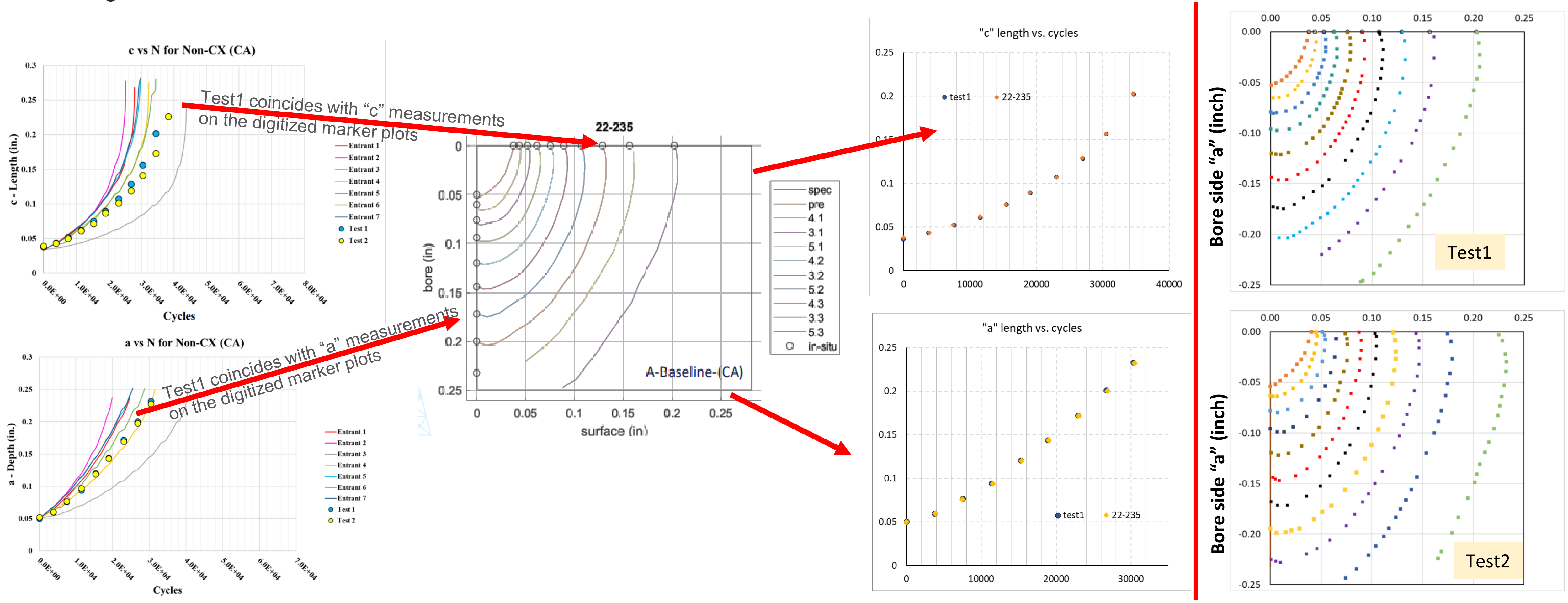


The 3D FEA solution uses the same loading mission as the experimental procedure

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

Specimen front side “c” (inch)



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

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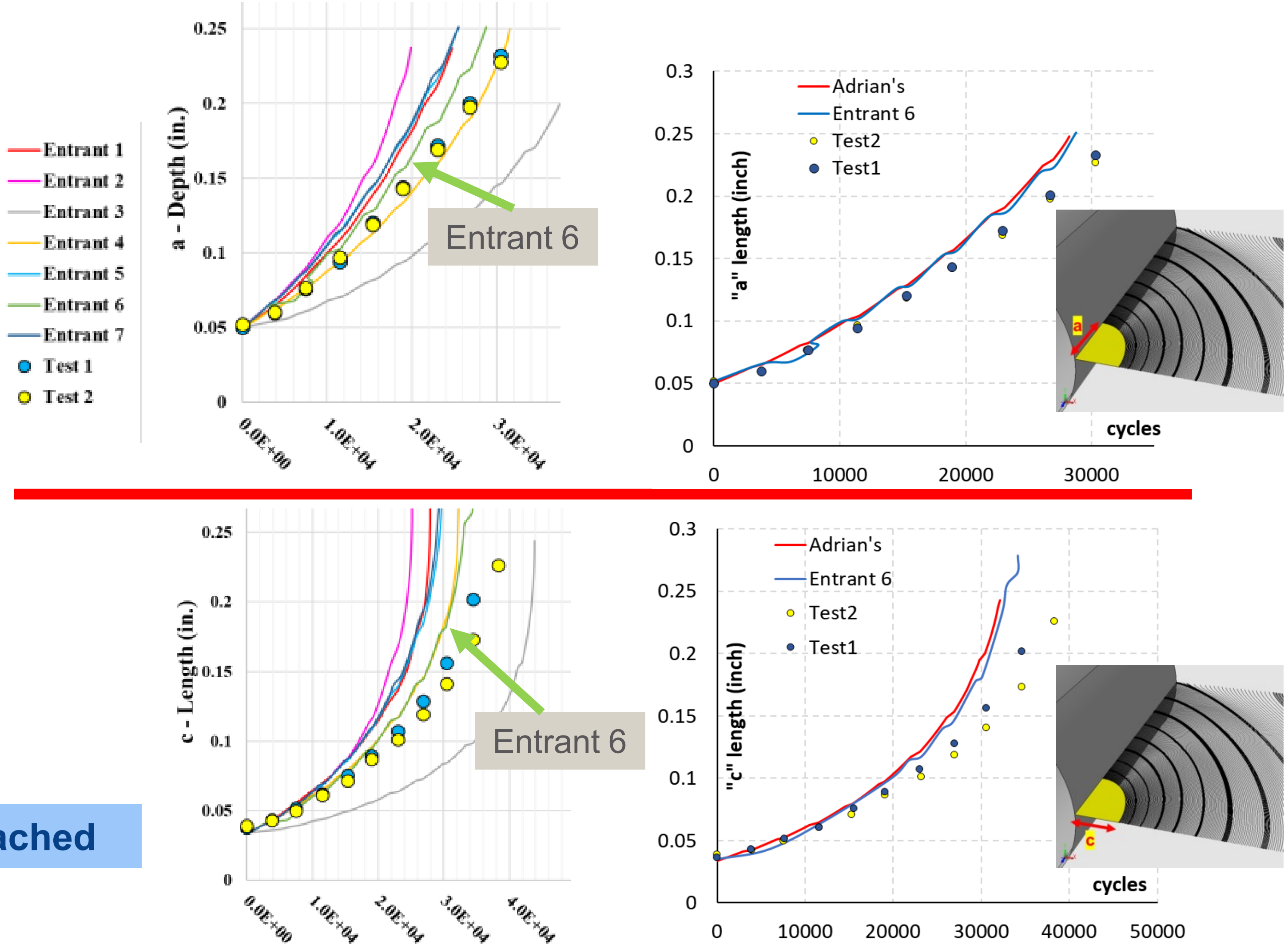
3D FEA solution vs. other round-robin entries

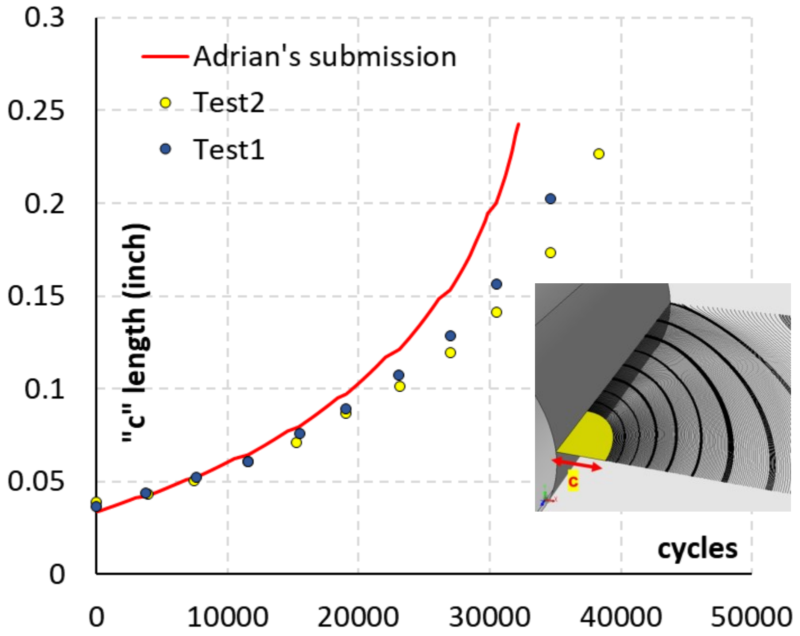
- The solution presented herein was completed and submitted before the RR challenge deadline
- The outcome of the round-robin challenge (see public references) indicate 2-DoF as well as multi-DoF solutions submitted by the participants
- The 3D-FEA based solution (no crack front increment shape constraint)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

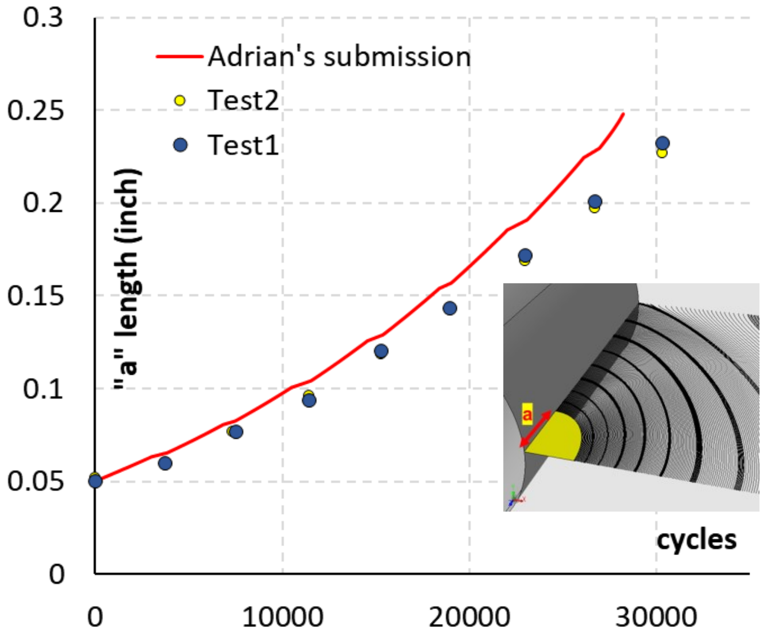
Verification against a different submission is reached

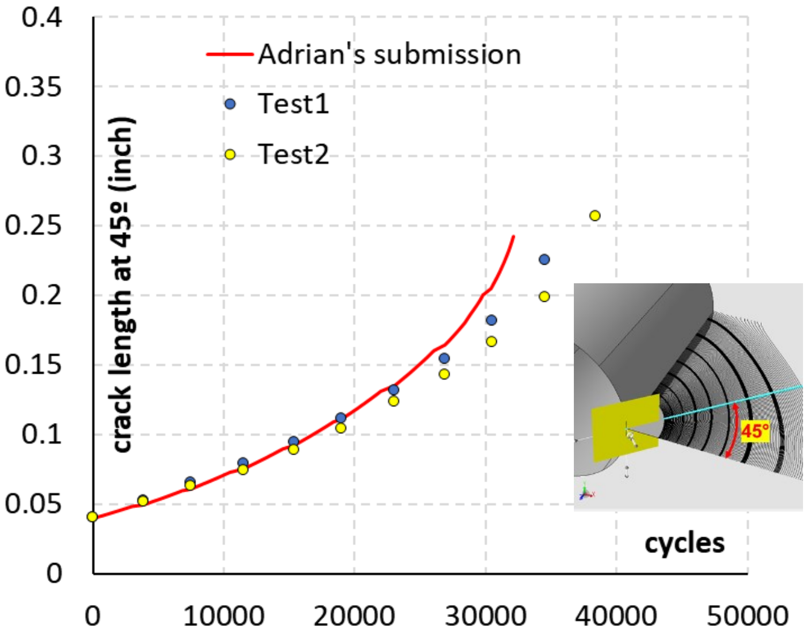


3D FEA solution vs. crack size measurement along three directions

- 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)





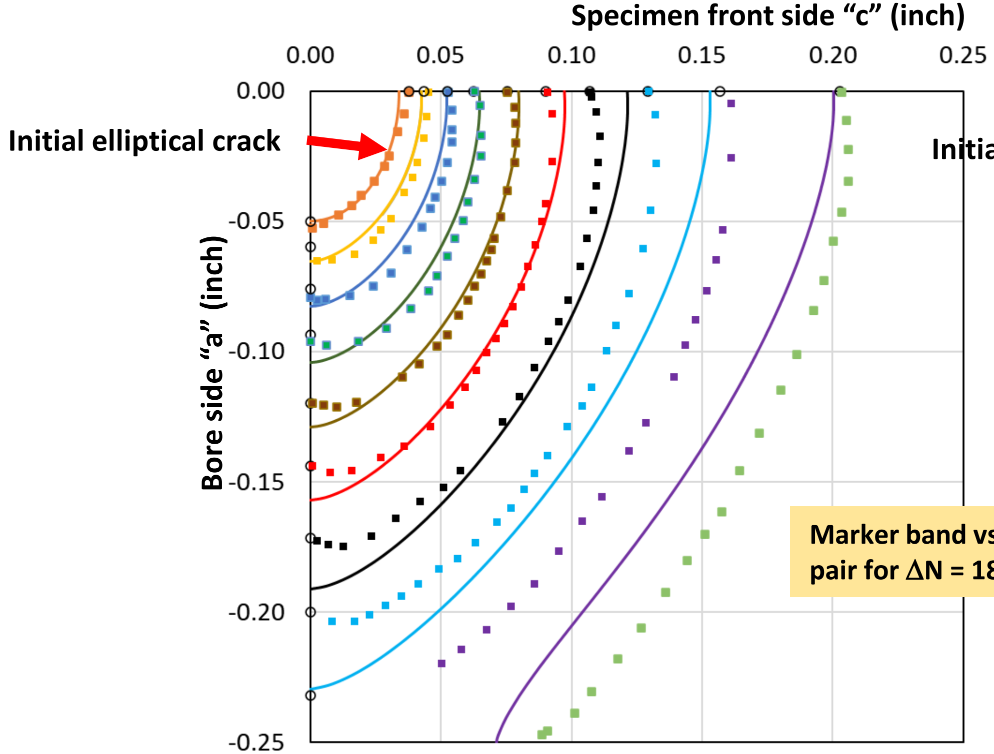


Given the different sources of uncertainty (modeling and experimental), 3D FEA based solutions capture well the experimental measurements

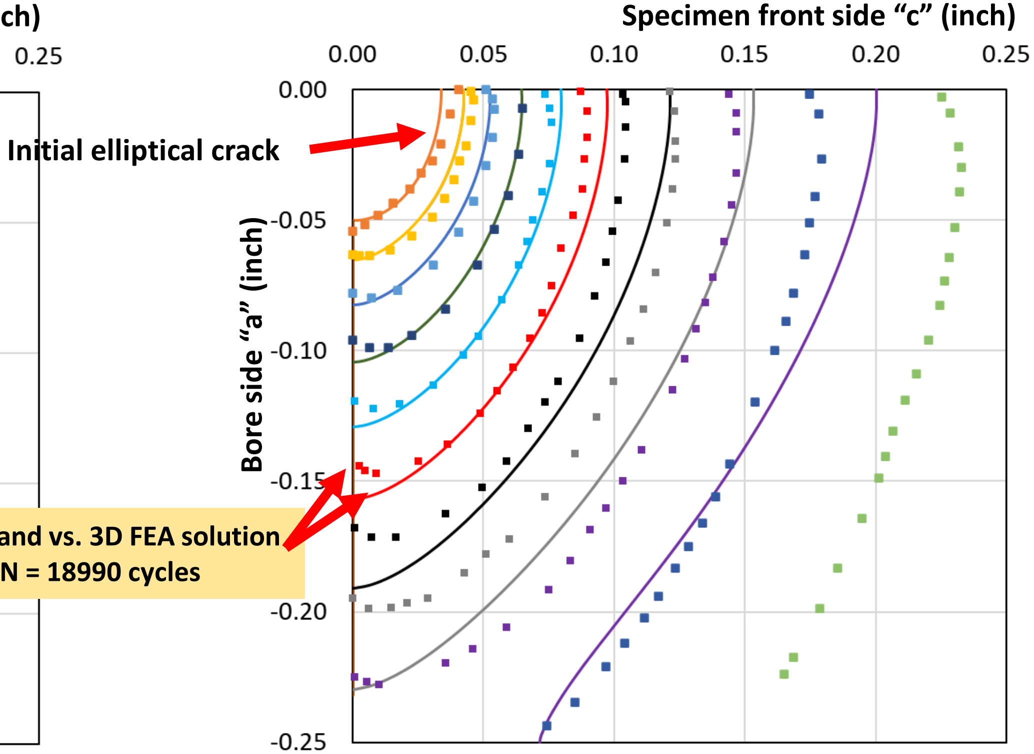
3D FEA solution vs. beach mark data

- 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

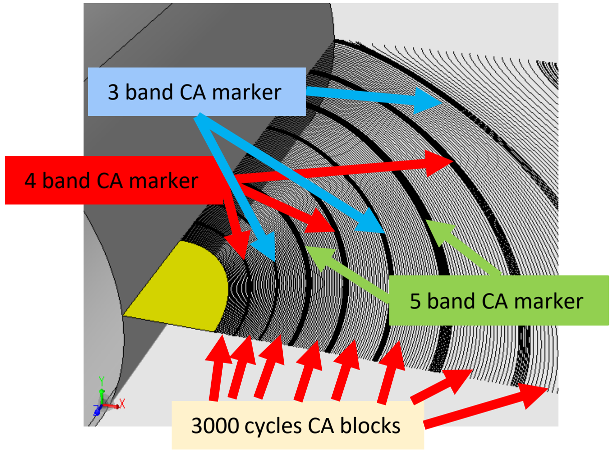
Additional work post round-robin challenge deadline

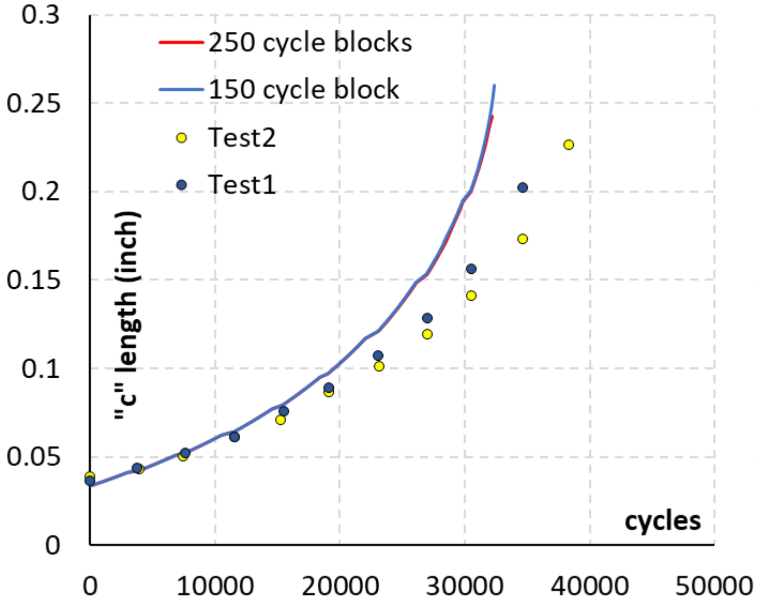
Sources of uncertainty addressed further in this study:

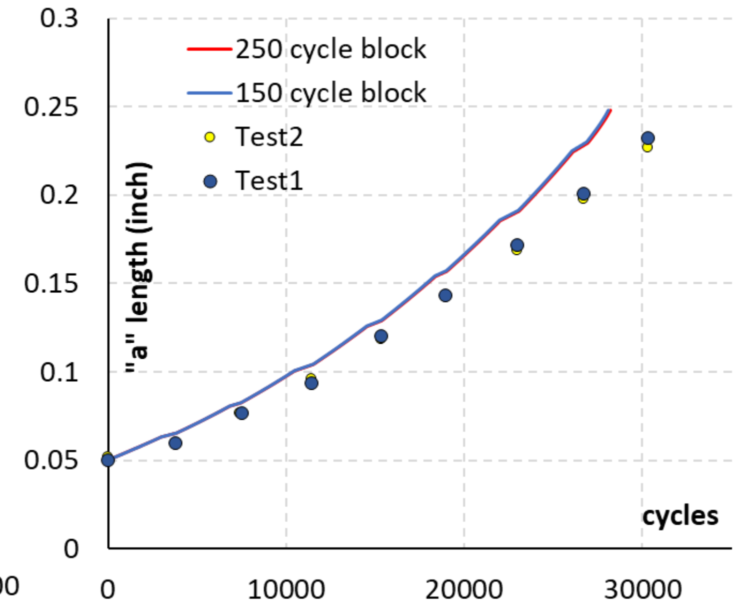
- Loading block definition in the model
- Mesh refinement along crack front
- Fatigue crack growth scatter
- Crack front shape: assumed to stay elliptical vs. no shape constraint

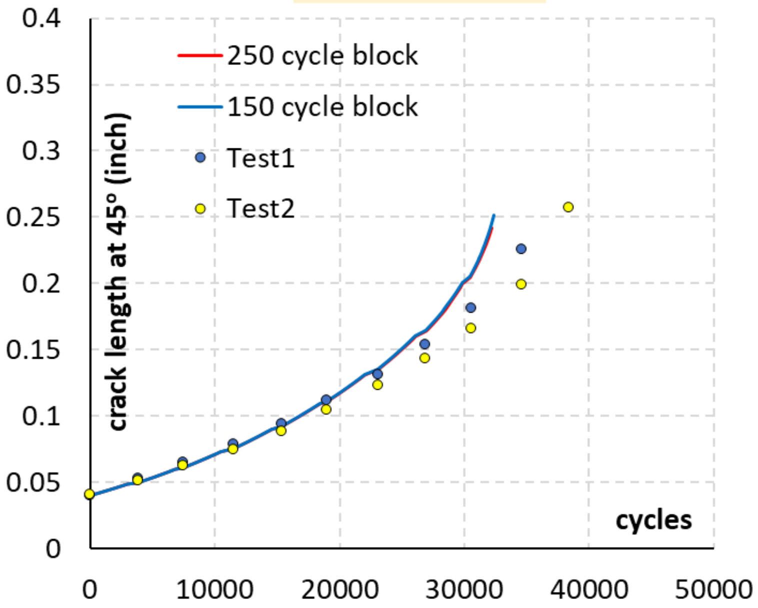
Solution uncertainty due to loading block sequence definition: multi-DoF model

- 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





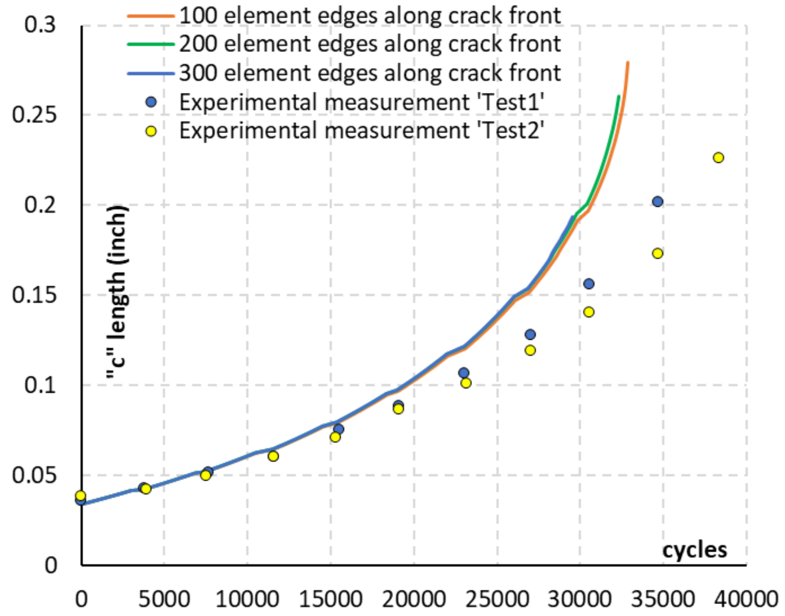


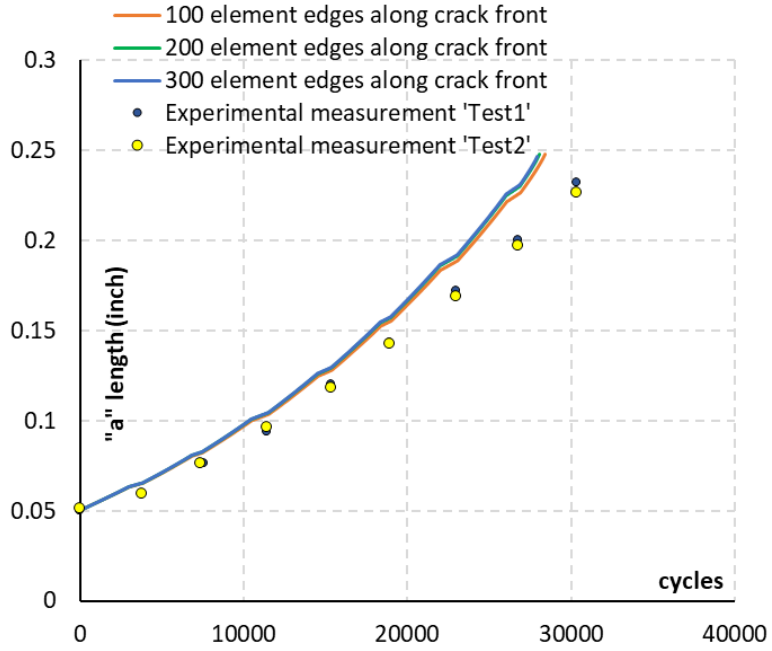


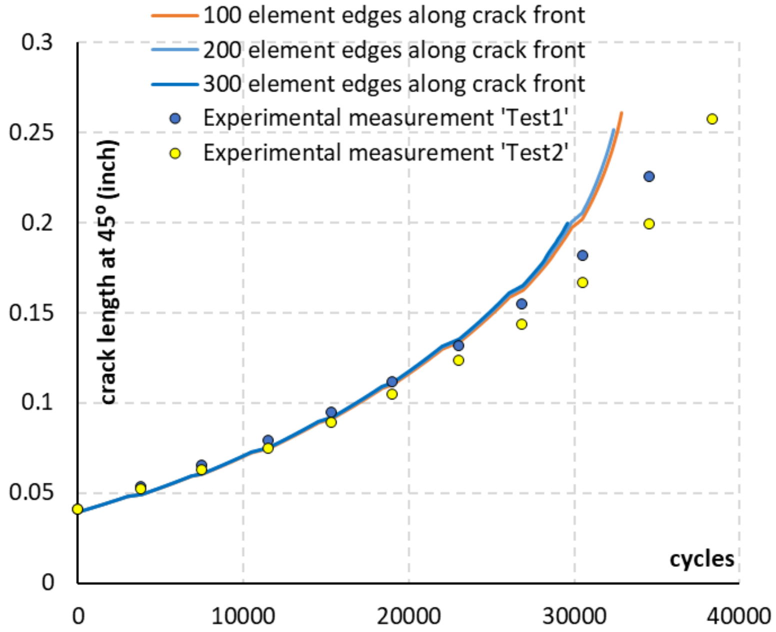
Solution is not sensitive to the loading block definition

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





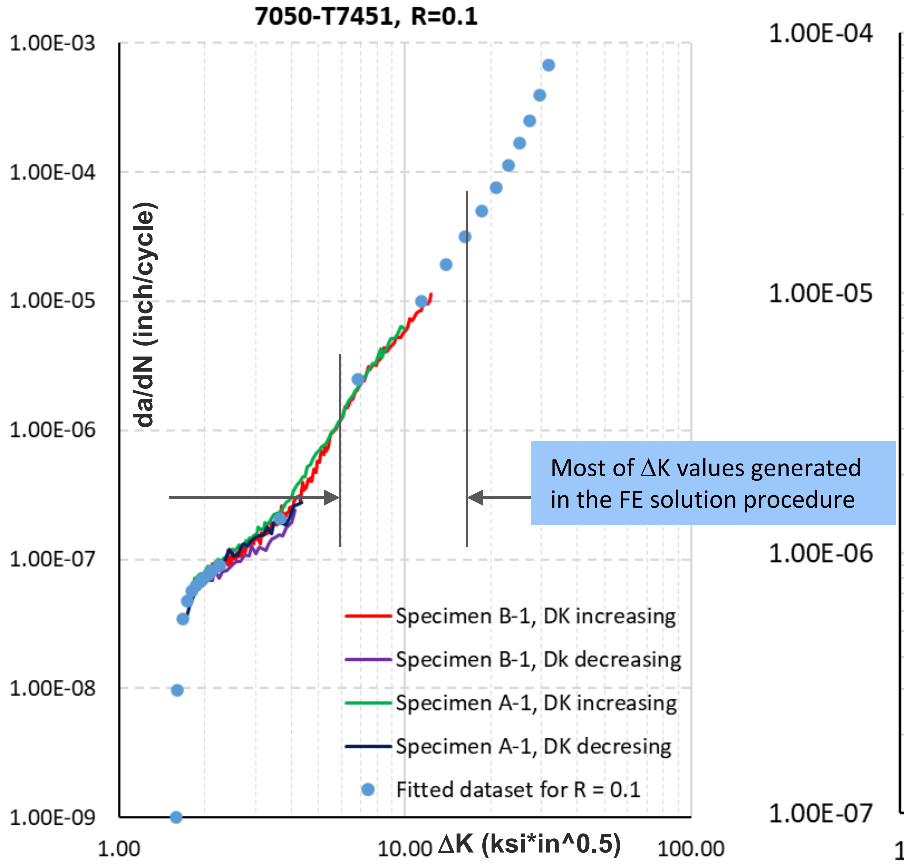


Solutions provided in this study are not sensitive to the mesh refinement (along crack front or overall)
The level of mesh refinement is quite high

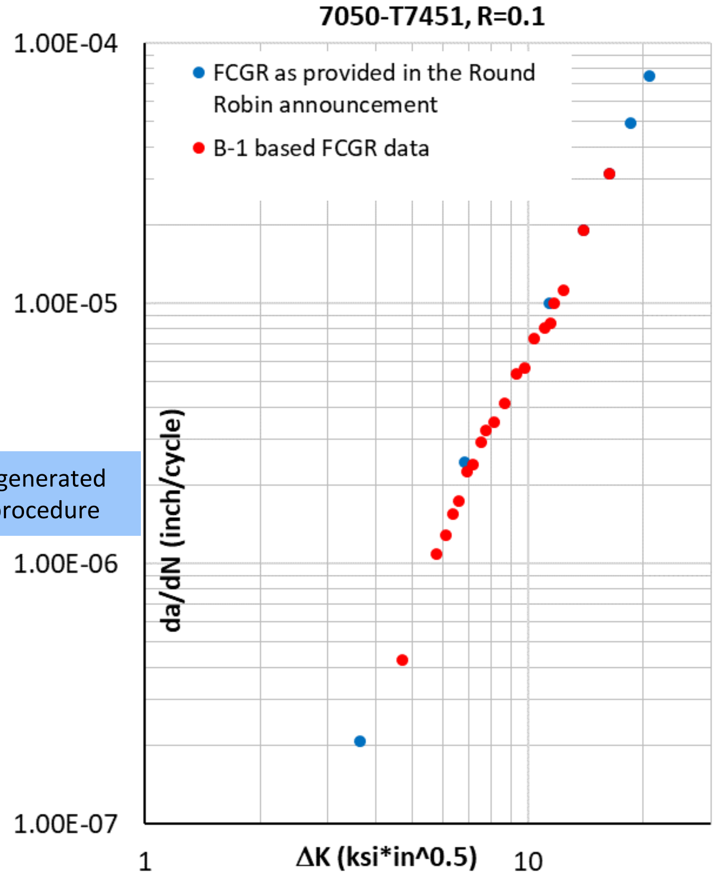
FCGR assessment and solution uncertainty

- 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



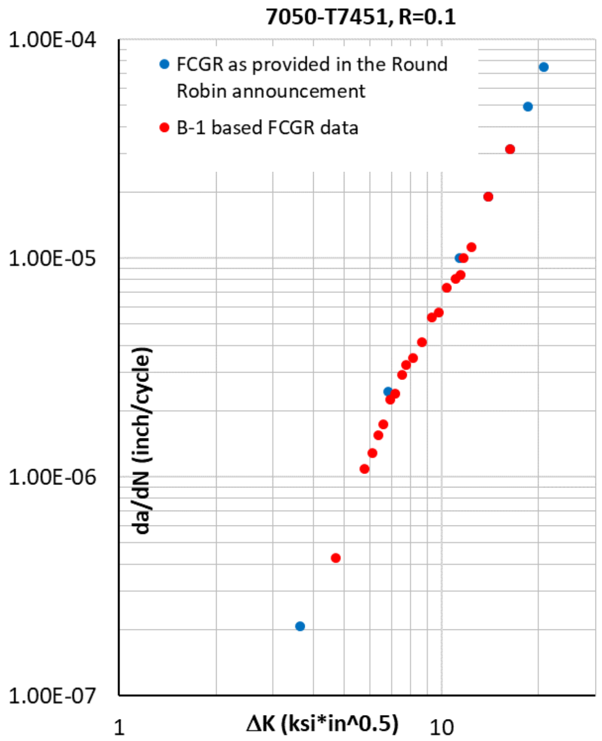
B-1 FCGR used in the 3D solutions

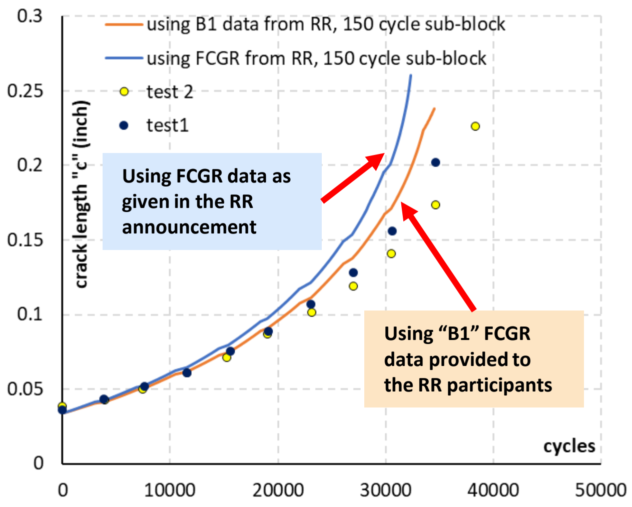


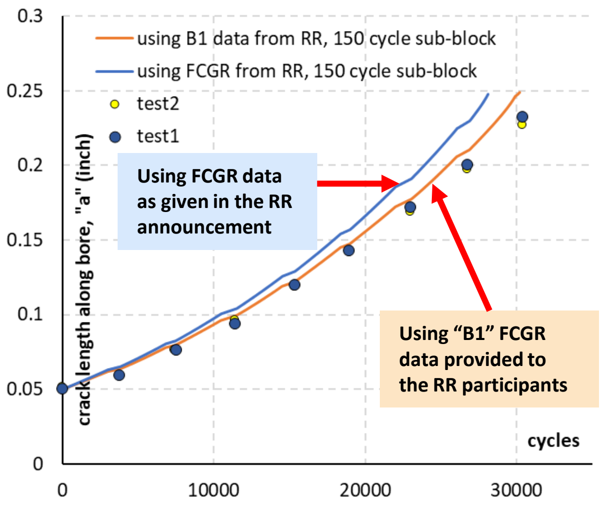
B-1 based FCGR was considered in the numerical procedure to evaluate solution sensitivity

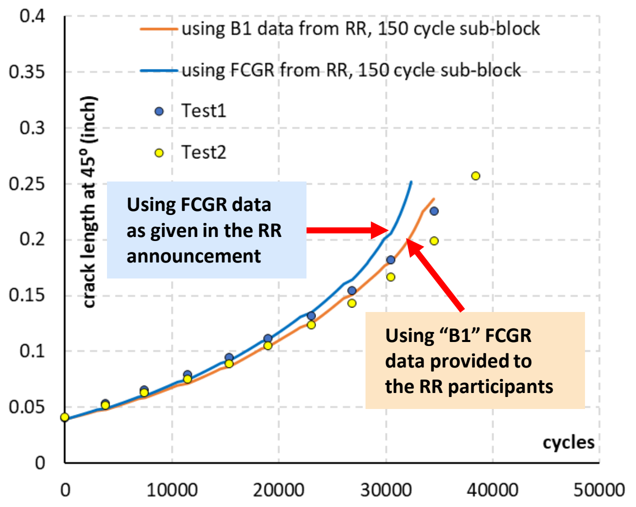
FCGR assessment and solution uncertainty

- 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).









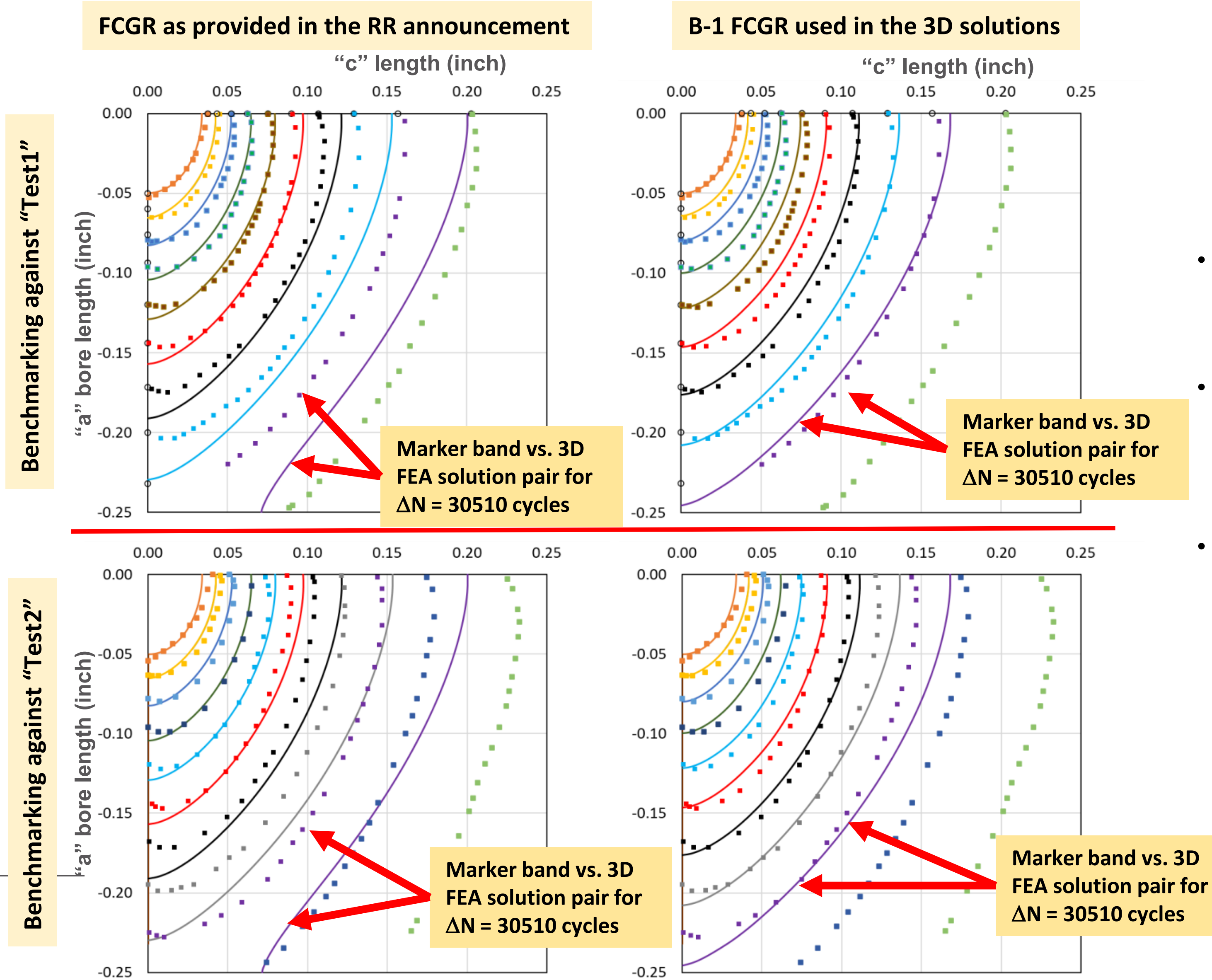
Usage of B-1 FCGR data seems to improve solution accuracy
As expected, numerical solution is sensitive to the FCGR

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

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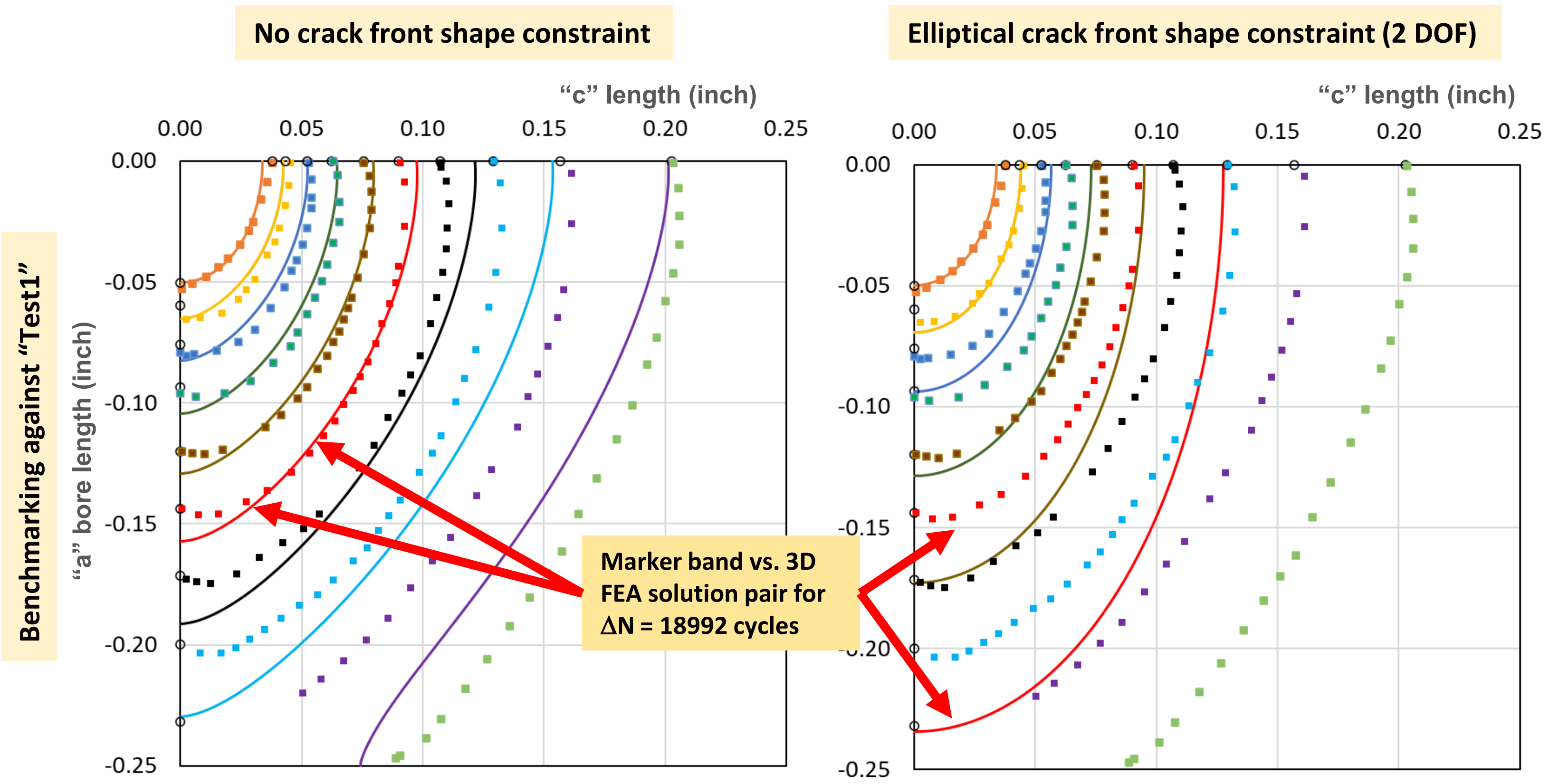
3D FEA: 2-DoF vs. multi-DoF solution

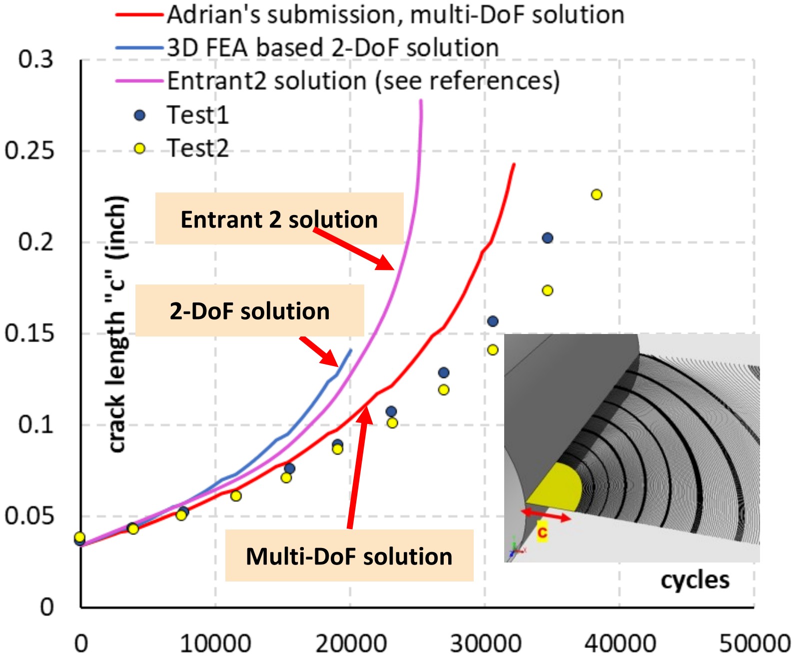
- The 3D FEA procedure can also be used as a 2-DoF crack growth solution
- Using 150-cycle sub-block partitions of the 3000 CA loading blocks, a comparison can be made between the two solutions: elliptical and, no shape constraint for the crack front increments
- No surface effects are included in both 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

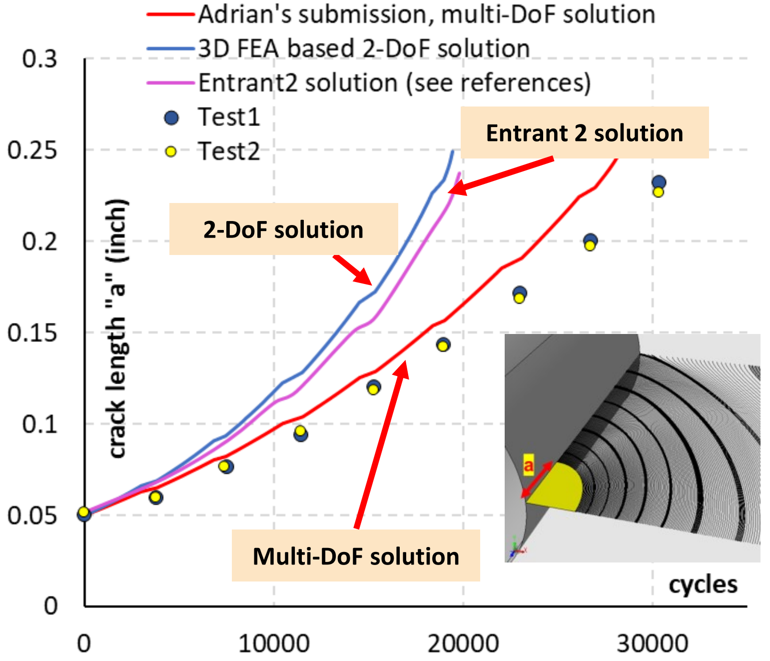


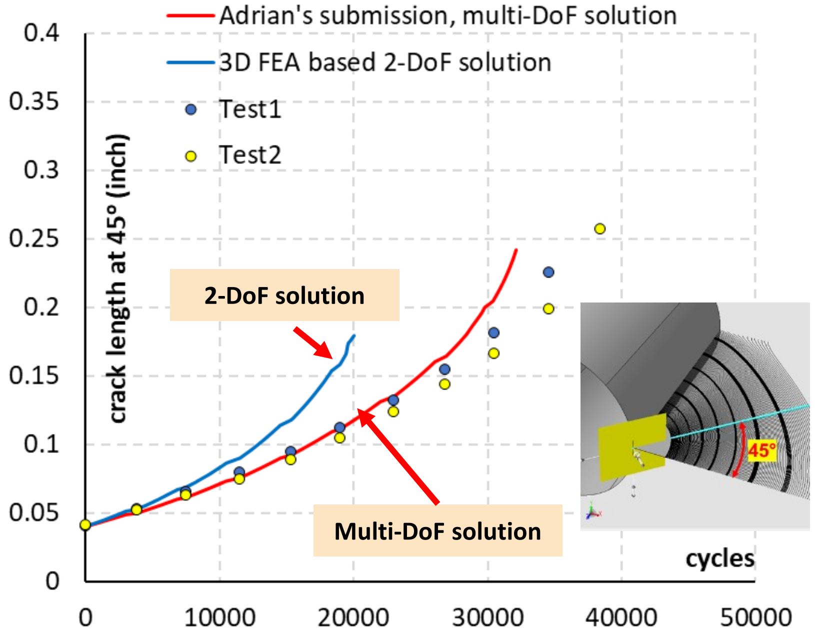
The multi-degree of freedom solution is more accurate than the 2-DoF (surface effects not included)

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)



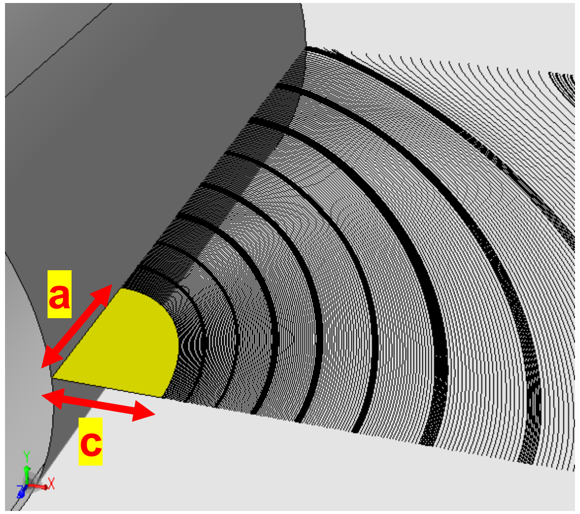


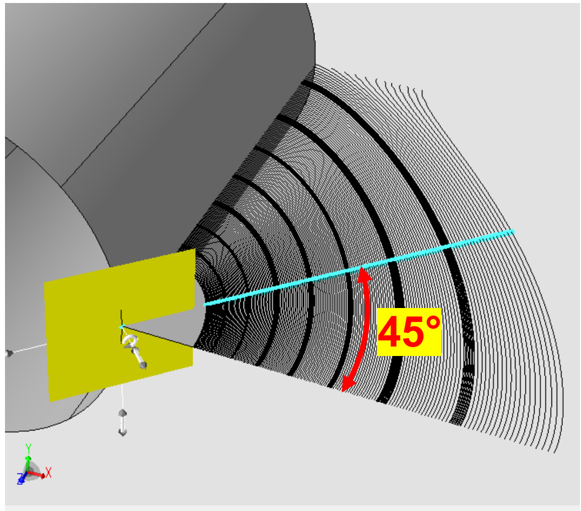


The multi-degree of freedom solution is more accurate than the 2-DoF (surface effects not included)

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?

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Engineered Residual
Stress Implementation

Interference Fit Fastener Round Robin

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Renan Ribeiro

rlribeiro@hill-engineering.com

Overview

Round robin description, conditions, objectives

Summary of results

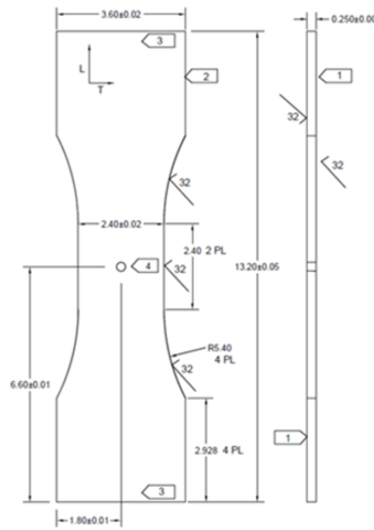
- Group 1
- Group 2
- Group 3

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	

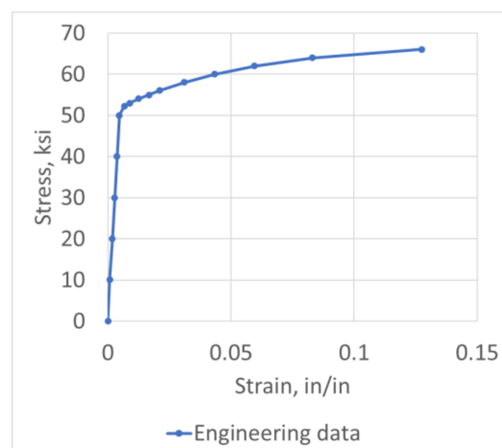
Table 3. Round-robin analysis conditions, group 3

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

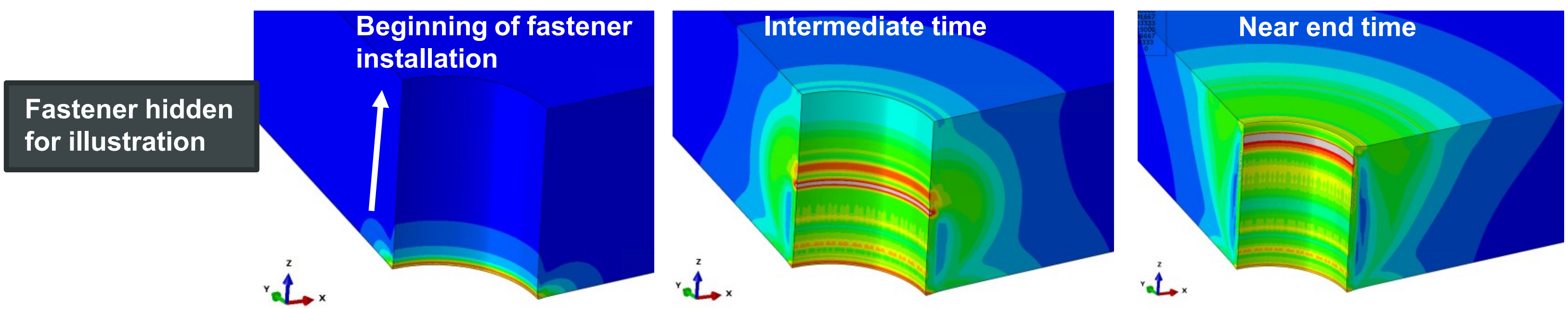
Abaqus/CAE 2020

Ansys

SIMCENTER Simcenter 3D software

StressCheck

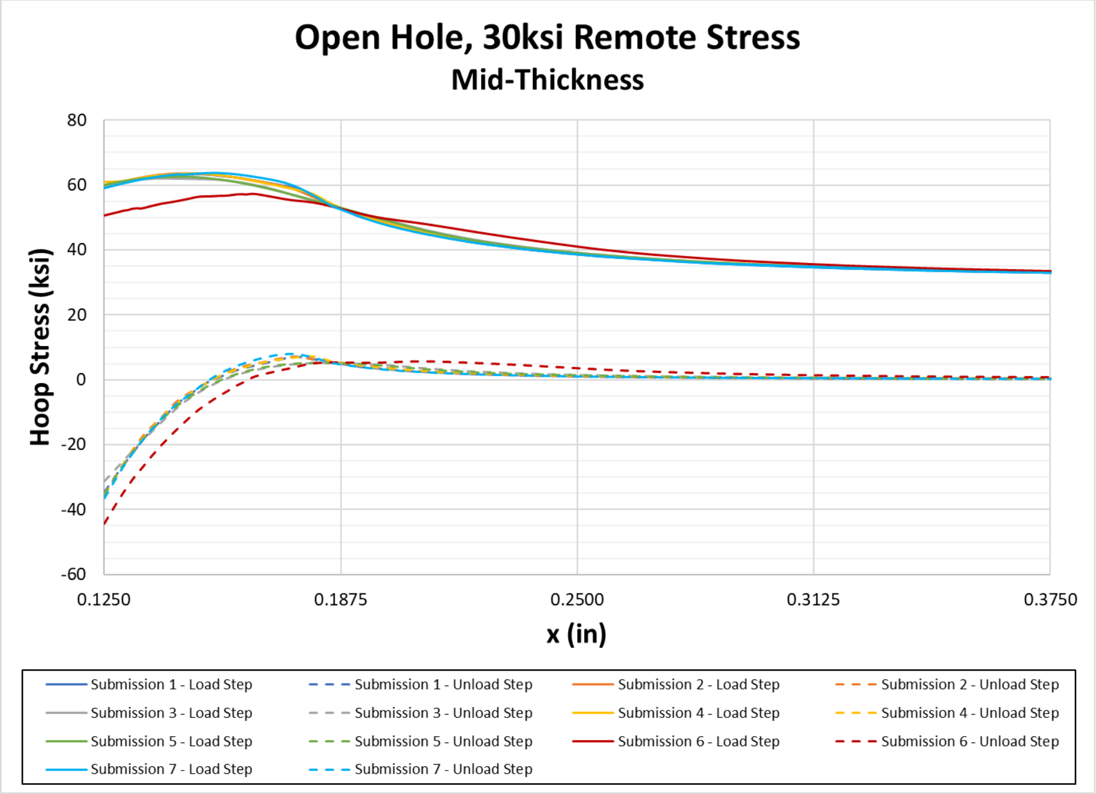
Na MSC Nastran

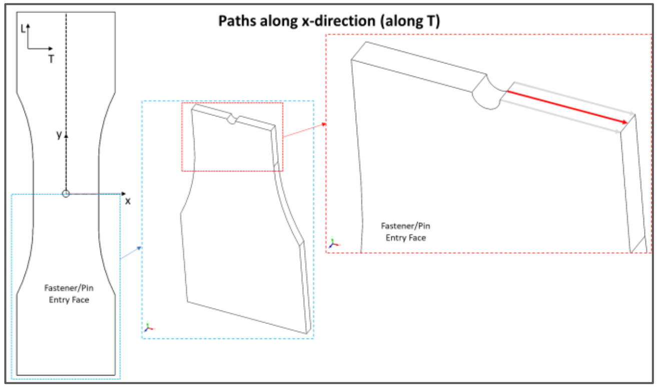


Group 1 – open hole, no fastener

30 ksi applied stress, mid-thickness

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

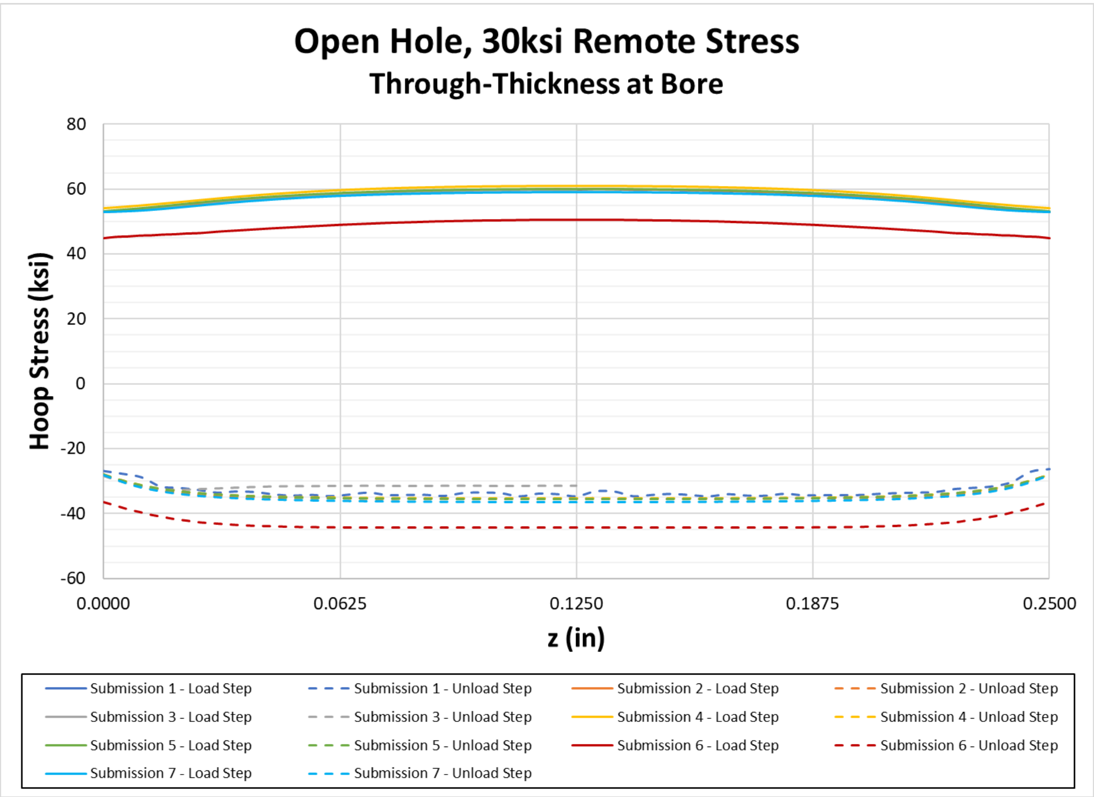


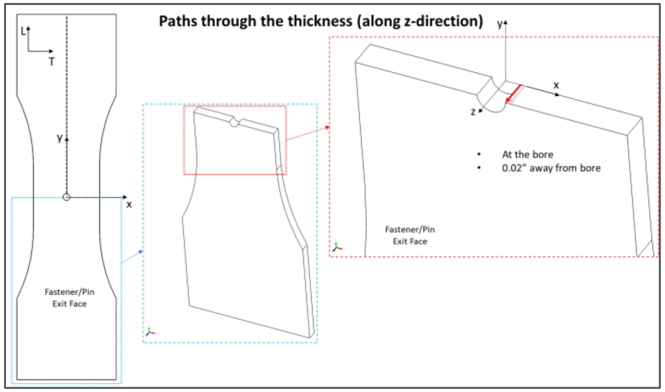


Group 1 – open hole, no fastener

30 ksi applied stress, through thickness at bore review

- After unloading, compressive residual stress through the thickness



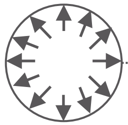


Group 2 – fastener install + uninstall

Table 2. Round-robin analysis conditions, group 2

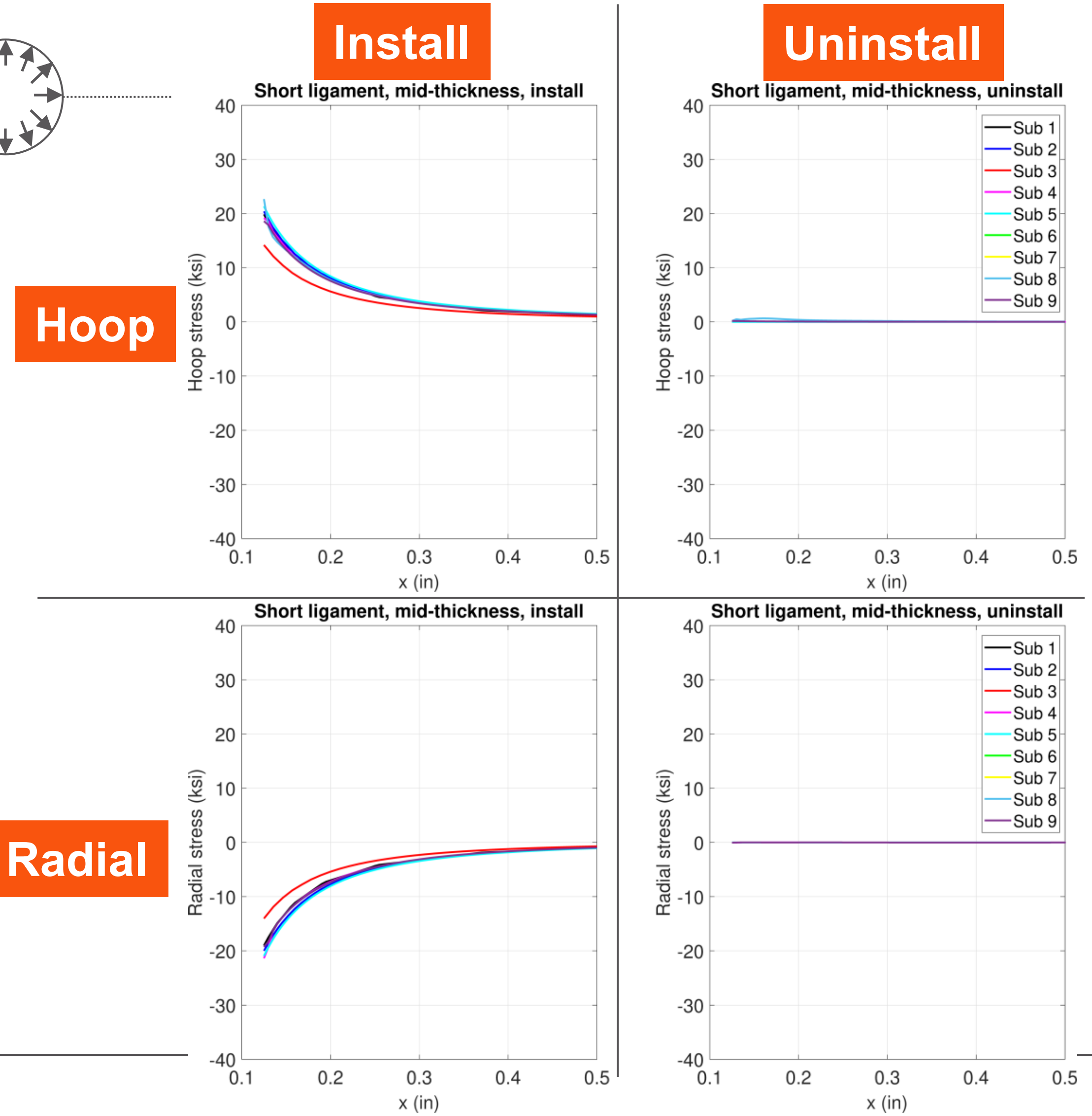
Group	Condition	Sequence Step	Interference Condition	Applied Stress (ksi)
2	1	1 – Installed Fastener 2 – Remove Fastener	0.3% IFF	0
	2		0.6% IFF	
	3		1.2% IFF	

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



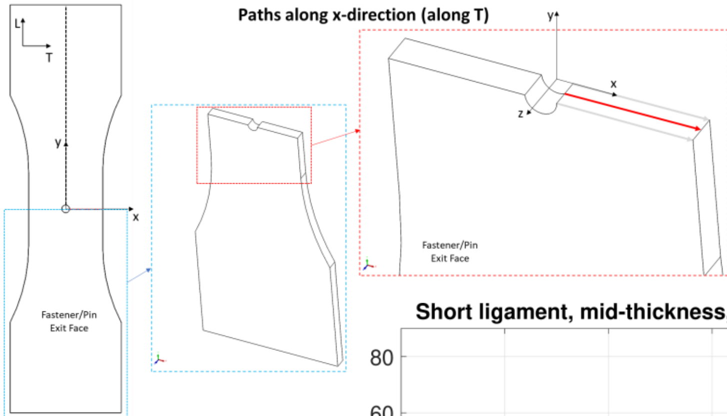
Group 2 – fastener install + uninstall

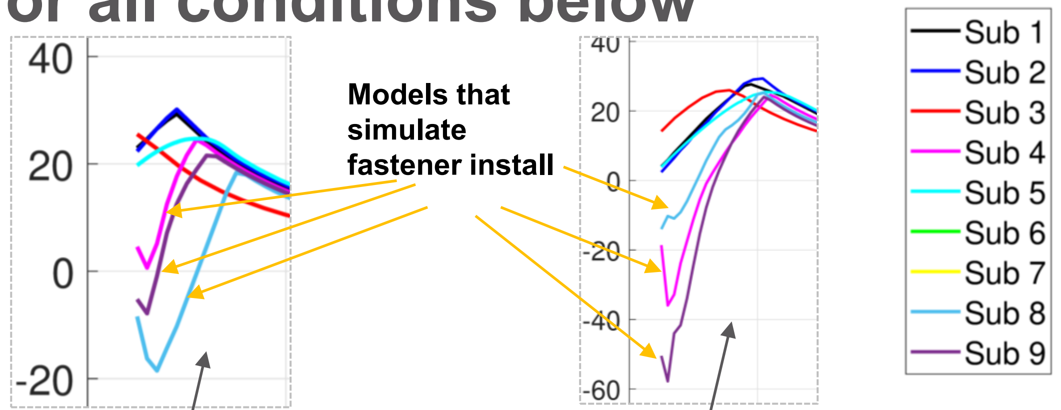
Table 2. Round-robin analysis conditions, group 2

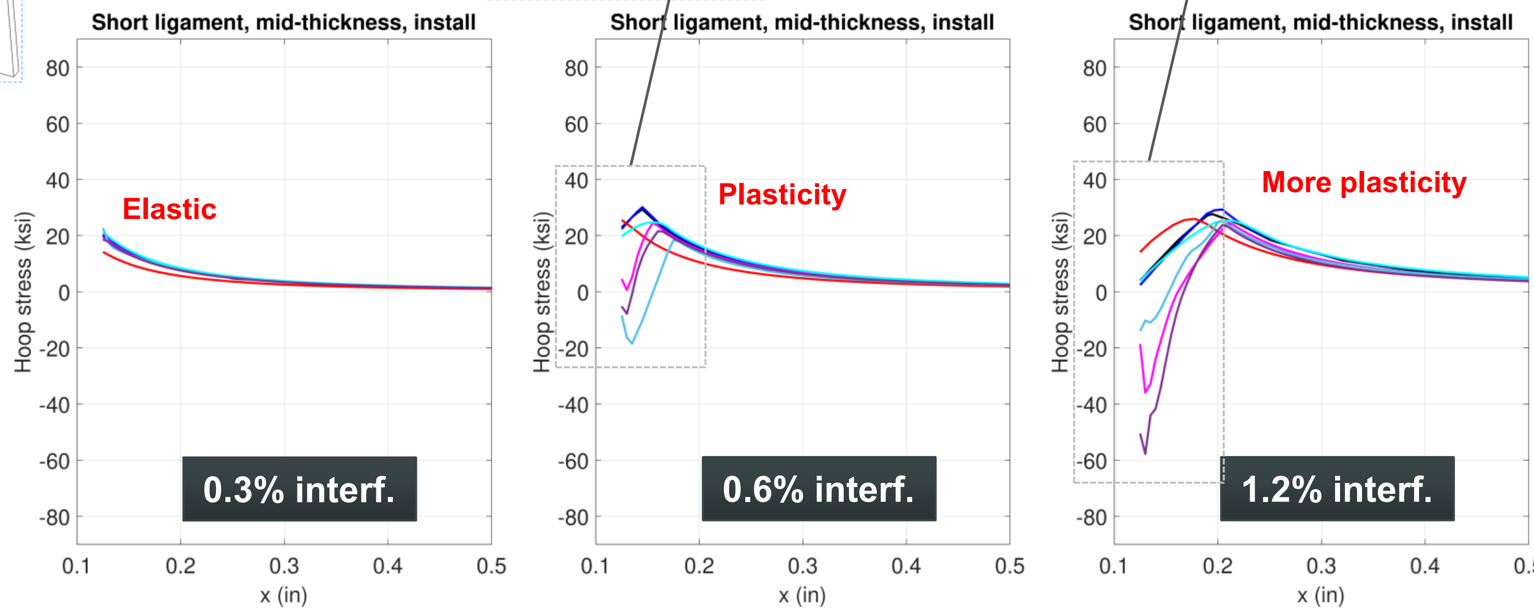
Group	Condition	Sequence Step	Interference Condition	Applied Stress (ksi)
2	1	1 – Installed Fastener 2 – Remove Fastener	0.3% IFF	0
	2		0.6% IFF	
	3		1.2% IFF	

Stress from installation for all conditions below

- At mid-thickness







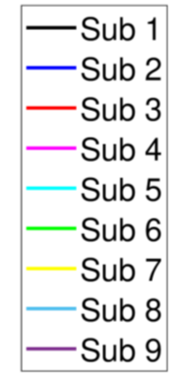
Group 2 – fastener install + uninstall

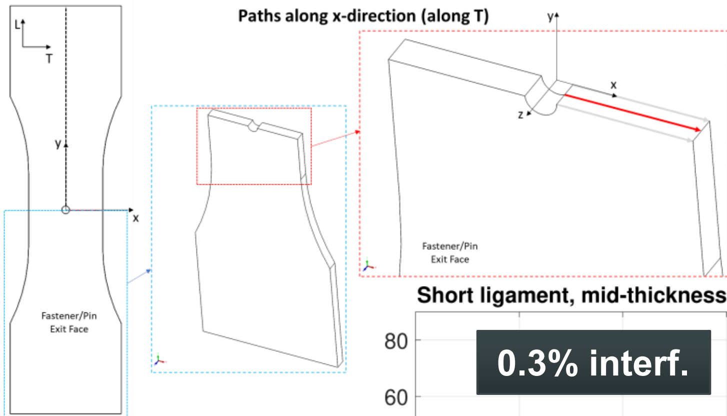
Table 2. Round-robin analysis conditions, group 2

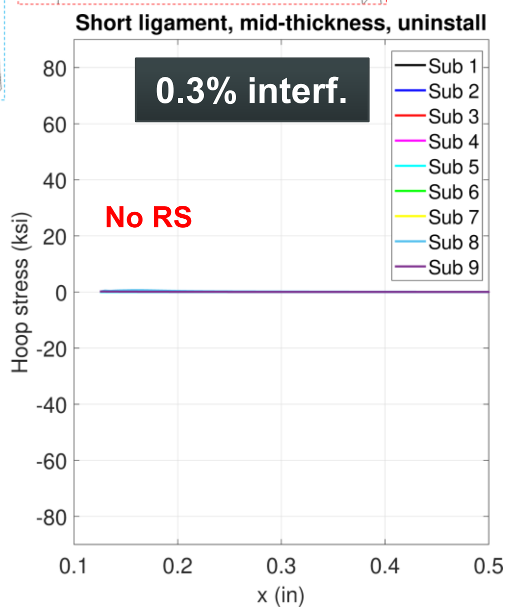
Group	Condition	Sequence Step	Interference Condition	Applied Stress (ksi)
2	1	1 – Installed Fastener 2 – Remove Fastener	0.3% IFF	0
	2		0.6% IFF	
	3		1.2% IFF	

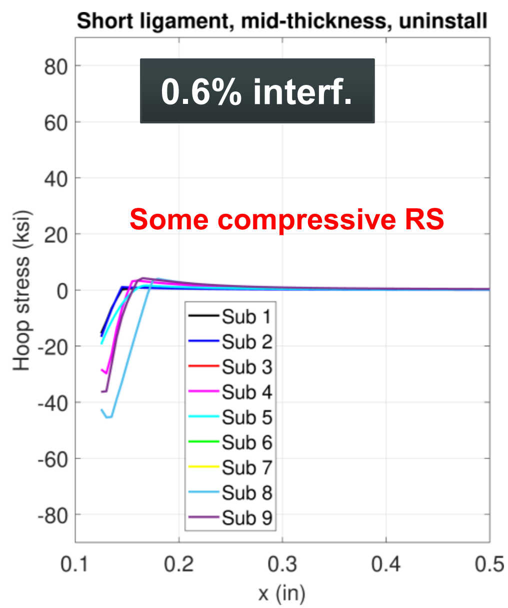
Stress after fastener removal for all conditions below

- At mid-thickness









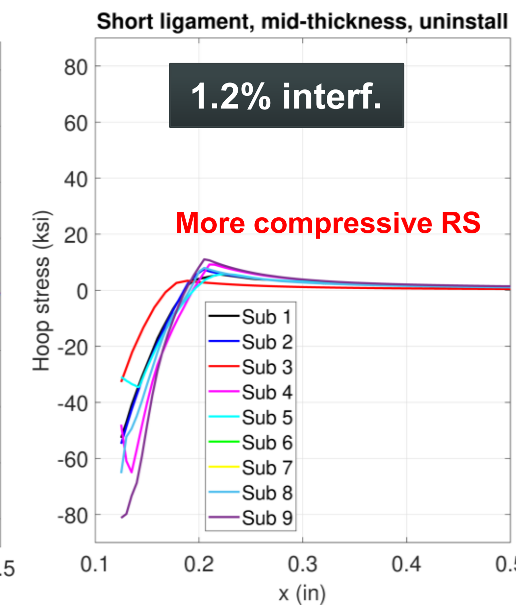


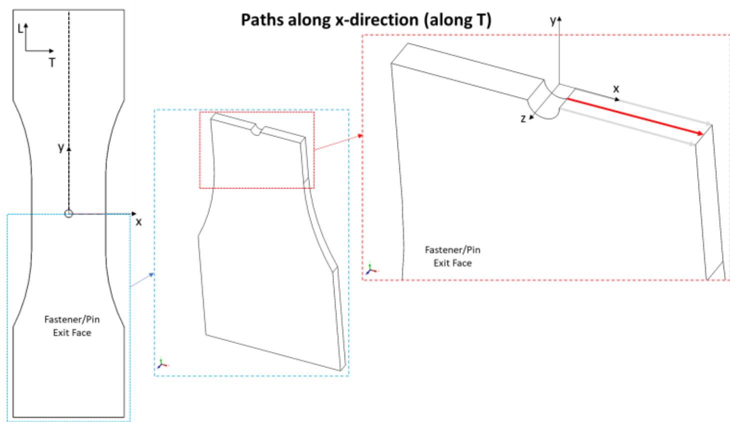
Table 3. Round-robin analysis conditions, group 3

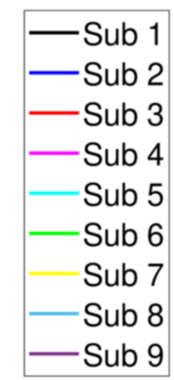
Group	Condition	Sequence Step	Interference Condition	Applied (ksi)
3	1	1 – Installed Fastener	Neat Fit	-10, 10, 20, 30
	2	2 – Apply Remote Stress	0.3% IFF	
	3	3- Unload	0.6% IFF	
	4	4 – Remove Fastener	1.2% IFF	

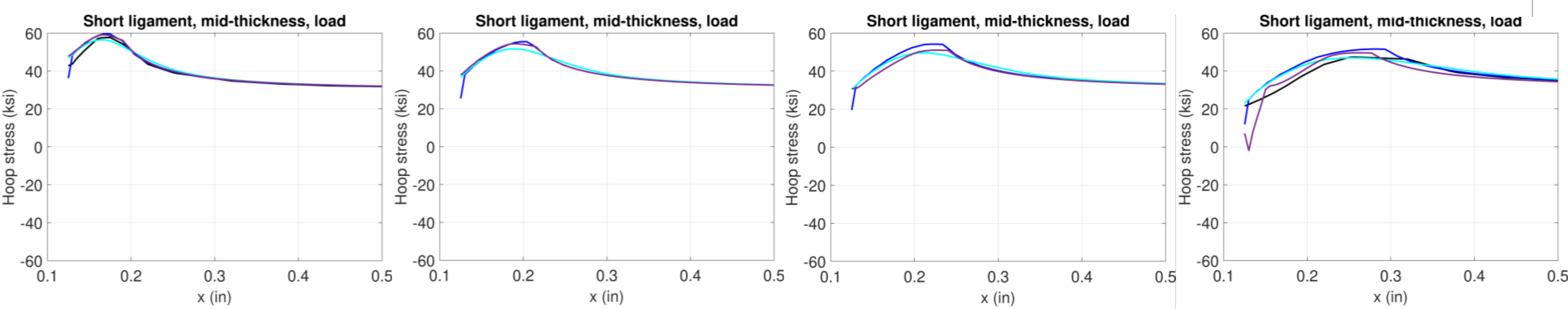
Group 3 – install, load, unload, remove

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.**

Table 3. Round-robin analysis conditions, group 3

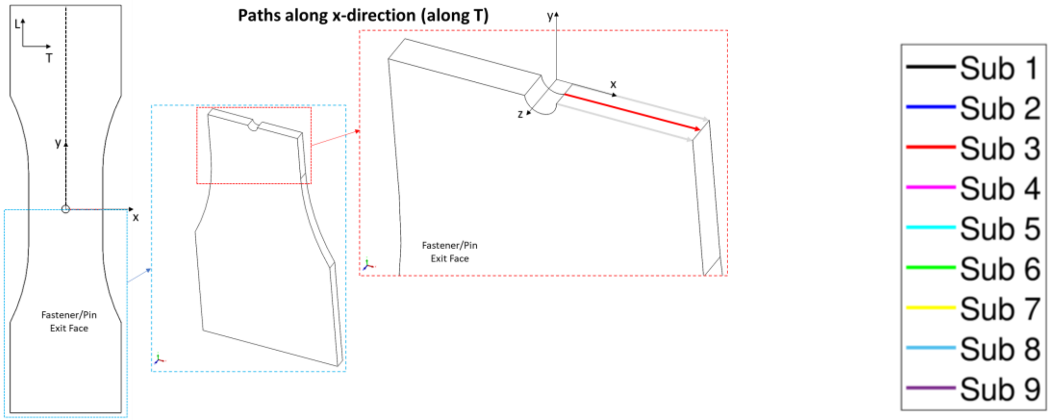
Group	Condition	Sequence Step	Interference Condition	Applied (ksi)
3	1	1 – Installed Fastener	Neat Fit	-10, 10, 20, 30
	2	2 – Apply Remote Stress	0.3% IFF	
	3	3- Unload	0.6% IFF	
	4	4 – Remove Fastener	1.2% IFF	

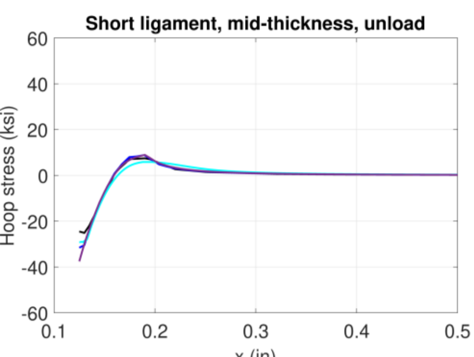
Group 3 – install, load, unload, remove

Stress after install, loading and unloading for all conditions below

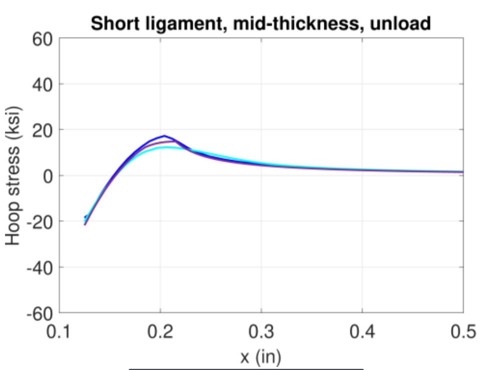
- At mid-thickness
- **Load to 30 ksi, then unload (fastener is still installed)**

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

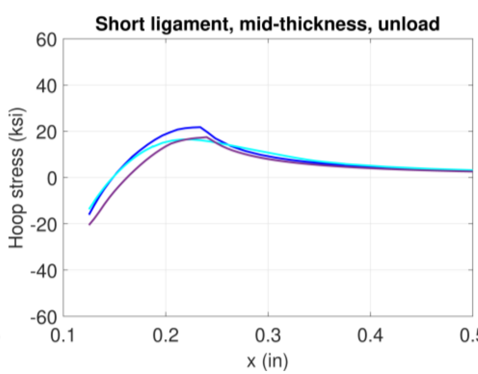




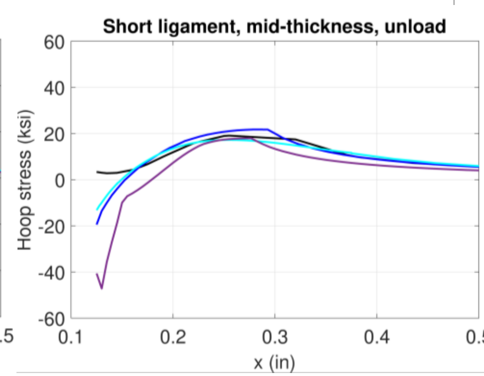
Neat fit



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

ERSI Working Group on Engineered Residual Stress Implementation

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

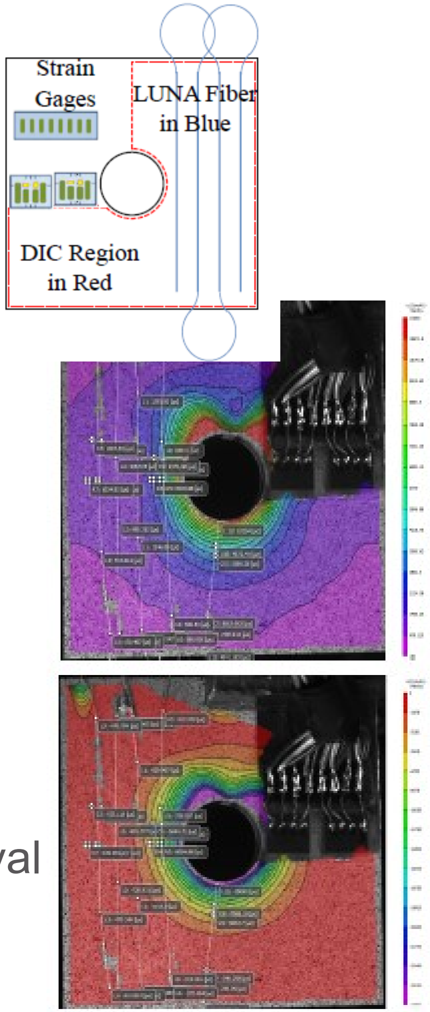
- Phase 1: assessment of as-installed state
  - Simulate and empirically quantify the strain and stress state near a hole in the presence of an interference fit fastener
    - 3 levels of interference
    - 3D nonlinear FE process modeling; DIC and strain gages for surface strain measurements
- Phase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

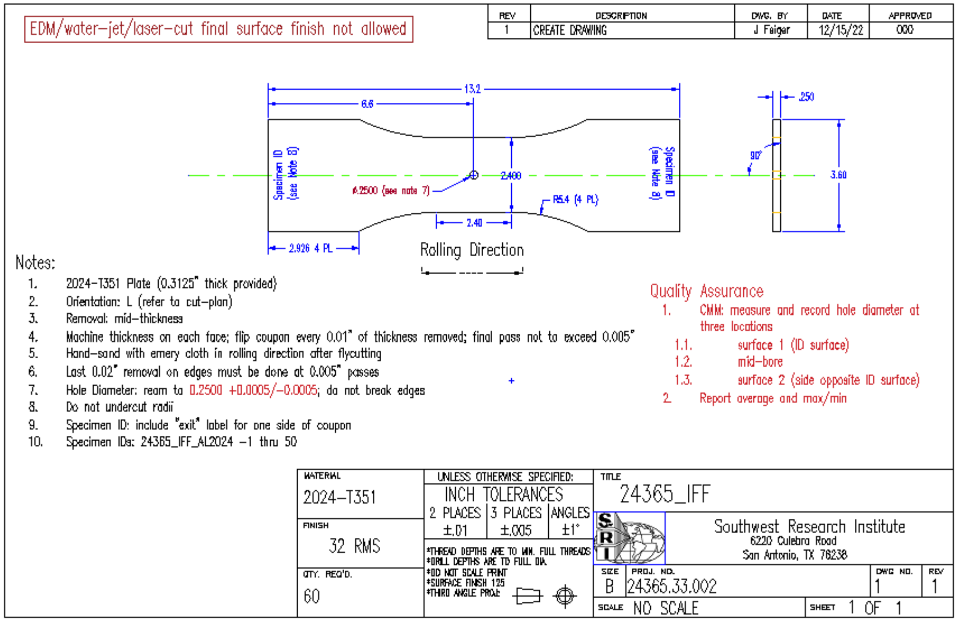
- Design conditions
  - Fasteners – gauge pins with ground transition geometry
- Data capture
  - 3D geometric measurements of fastener and hole
    - + Calculate applied interference along bore
  - Surface strains (primarily DIC)
    - + Leverage lessons learned from ERSI Cx 2x2 Residual Stress Validation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

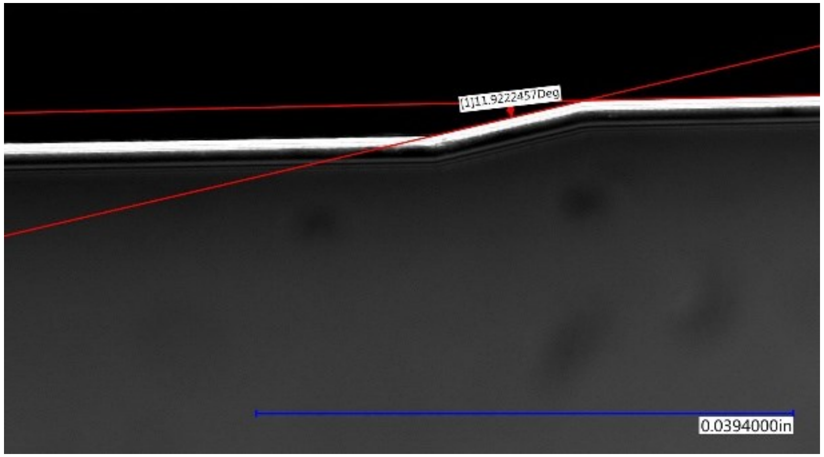
- Coupon design
  - "Dog-bone" with geometric center located 0.25" diameter hole
  - Same geometry used in prior ERS studies
  - Extracted in the L direction at mid-thickness
- Material
  - 2024-T351 plate (0.3125" thick)
  - Material Testing
    - + Tensile (5 coupons)
      - ASTM E8
    - + FCGR (multiple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



A-10 IFF Testing & Analysis Program

Current Progress

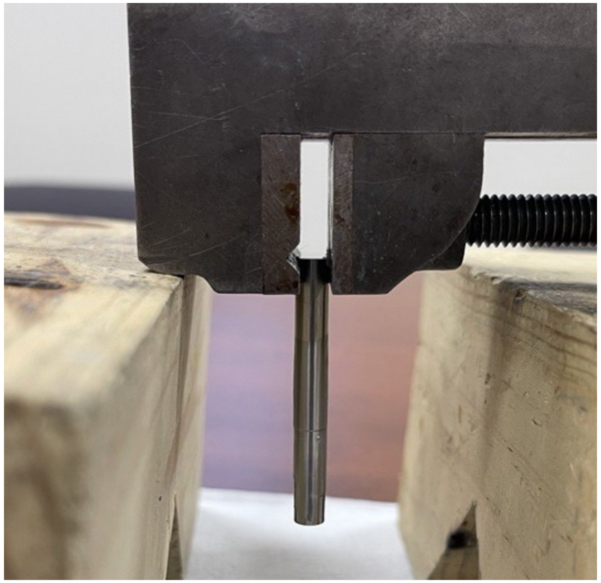
- Coupon manufacturing
  - 50 coupons have been fabricated
  - Holes measured via CMM
  - Gage pins were custom ordered to match the interference fit required per specimen
    - 0.3%, 0.6%, and 1.2% interference
  - Gage pins were machined to match the chamfer of a Hi-Lok
    - One pin from each interference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

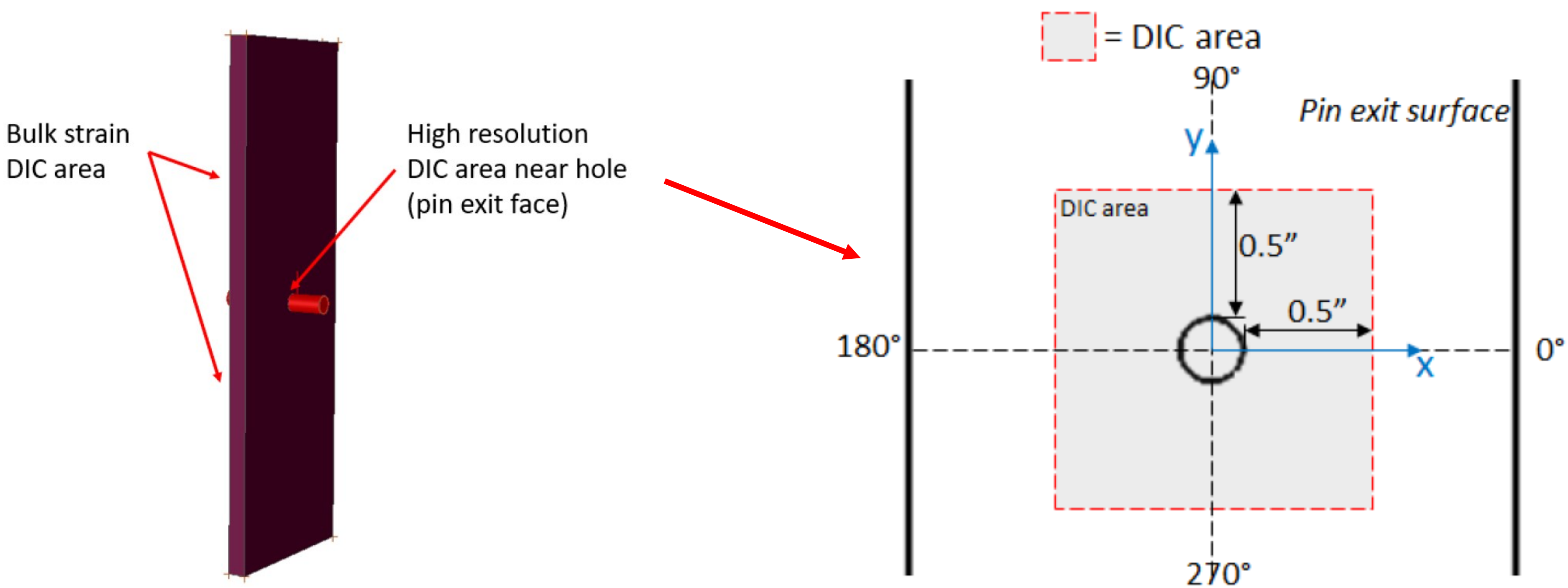
- Fastener Preparation
  - To mimic the Hi-Lok installation, cetyl alcohol lubricant, Perma-Slik 1460W, will be used to coat the pins prior to installation.
    - Per the lubricant's instructions, the pins will be degreased with trichlorethylene. Then, the pins will be dipped in the lubricant and dried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

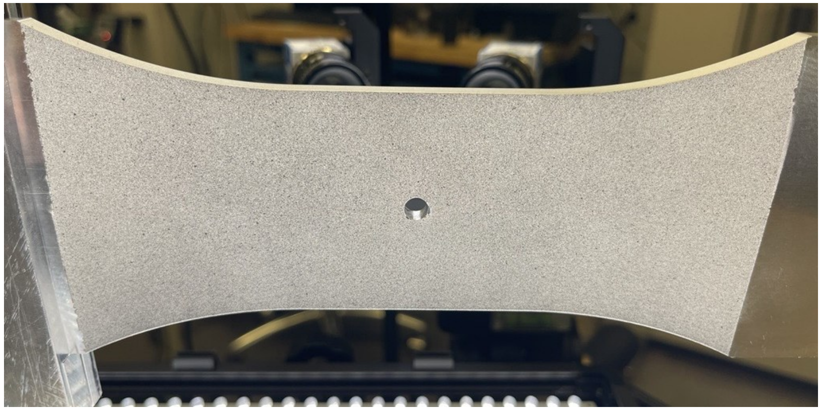


A-10 IFF Testing & Analysis Program

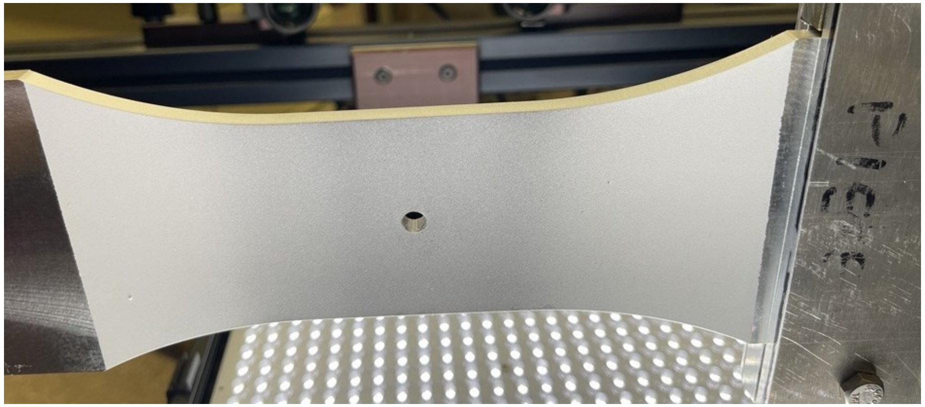
Current Progress

- 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

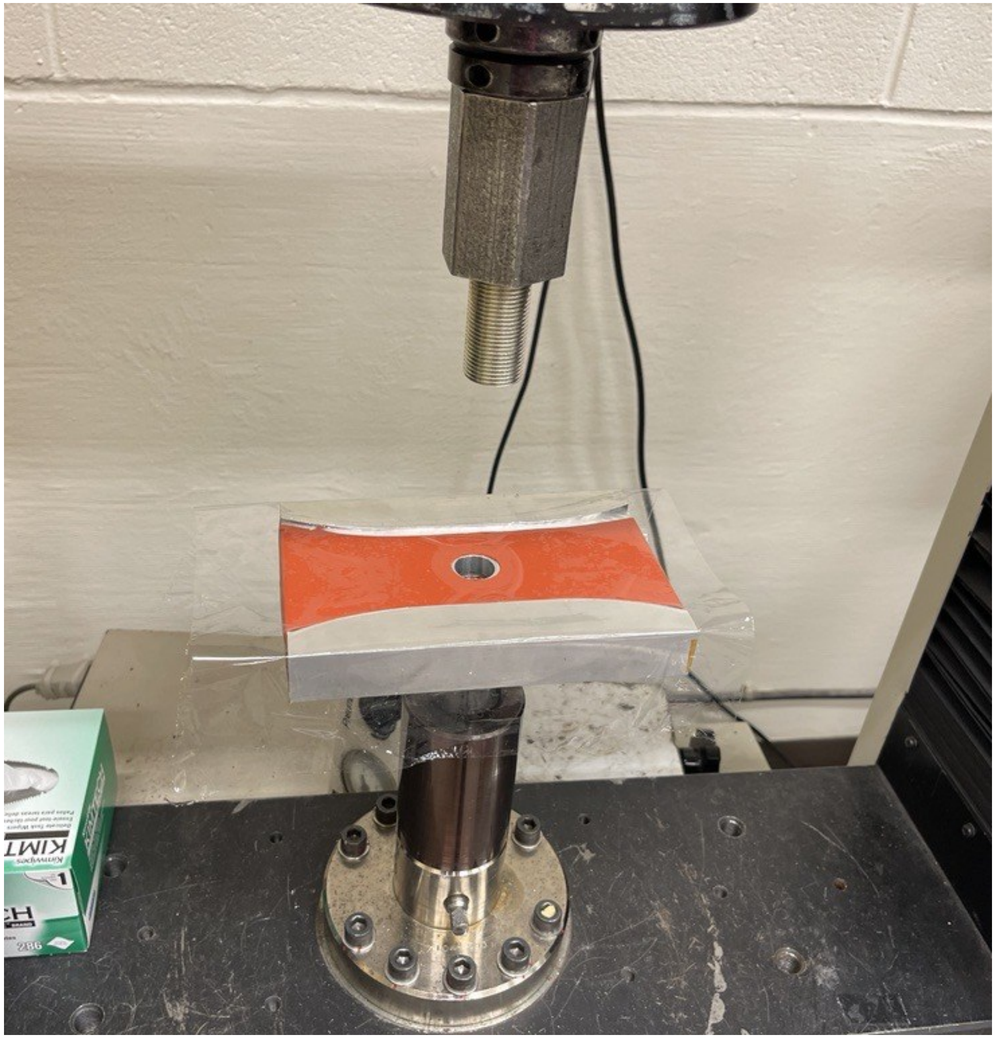
Current Progress

- 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

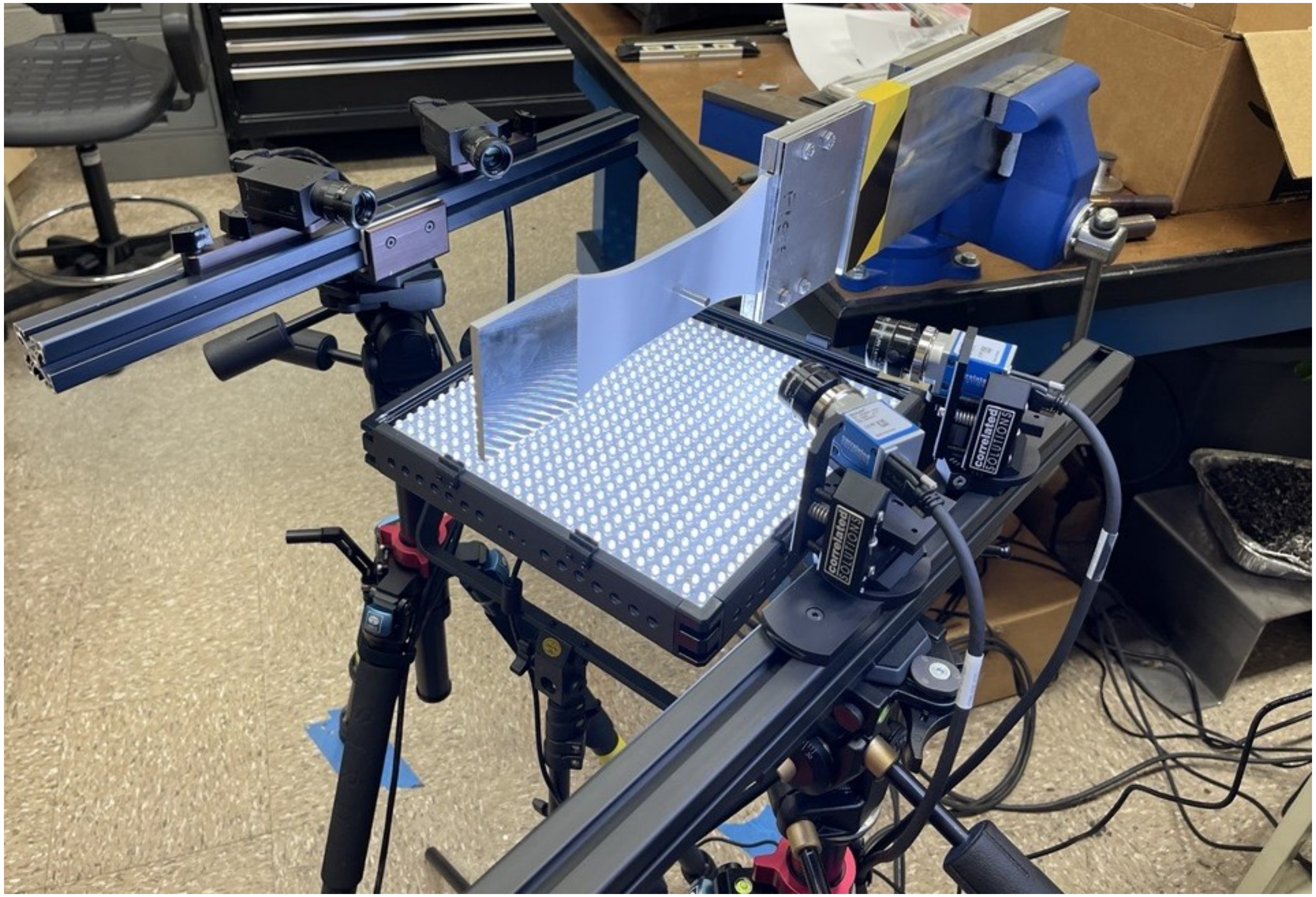
Current Progress

- DIC prior to pin installation

A-10 IFF Testing & Analysis Program

Current Progress

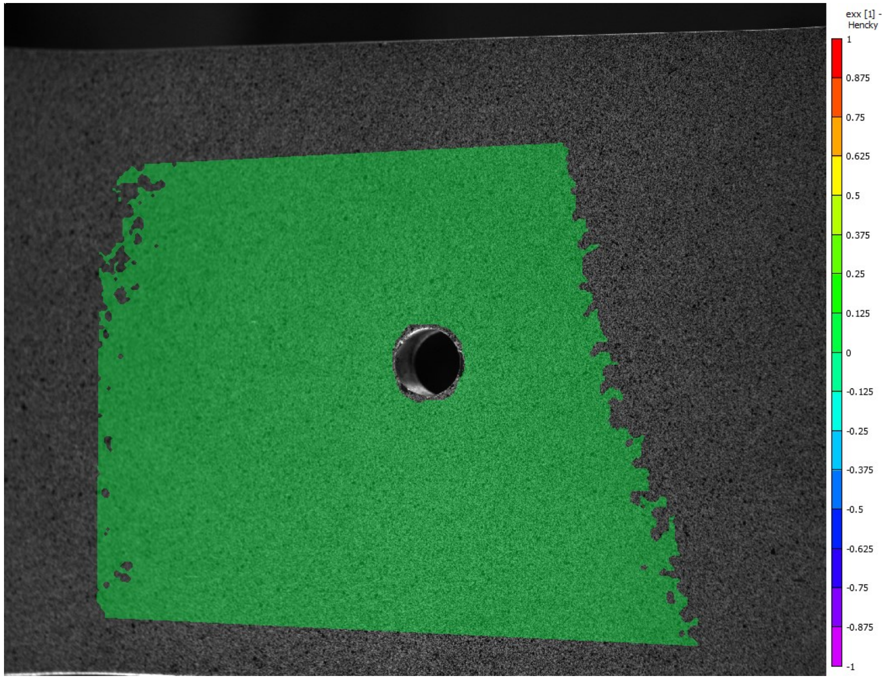
- DIC after to pin installation

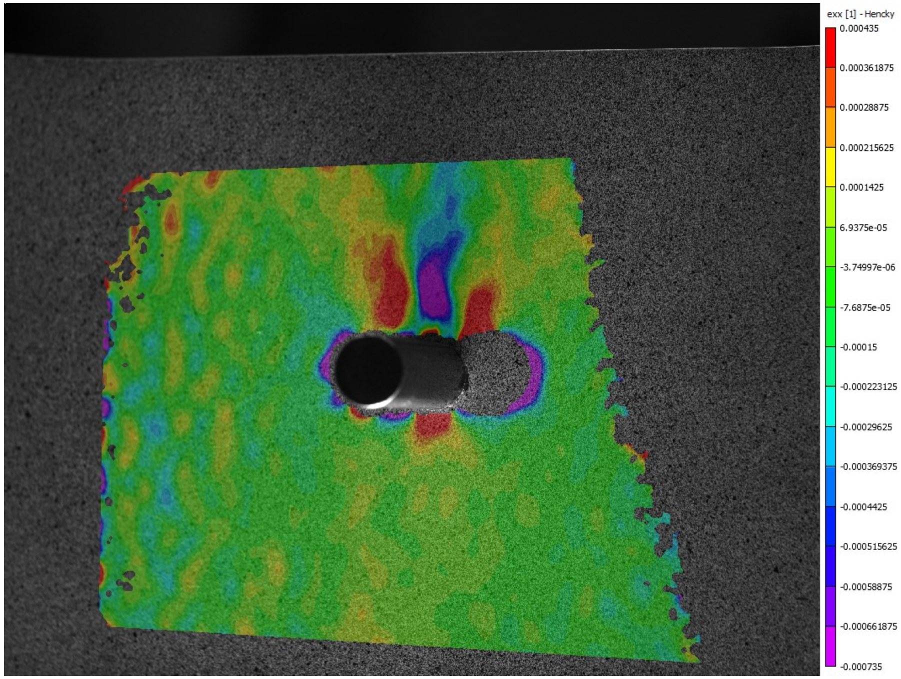


A-10 IFF Testing & Analysis Program

Current Progress

- Global results

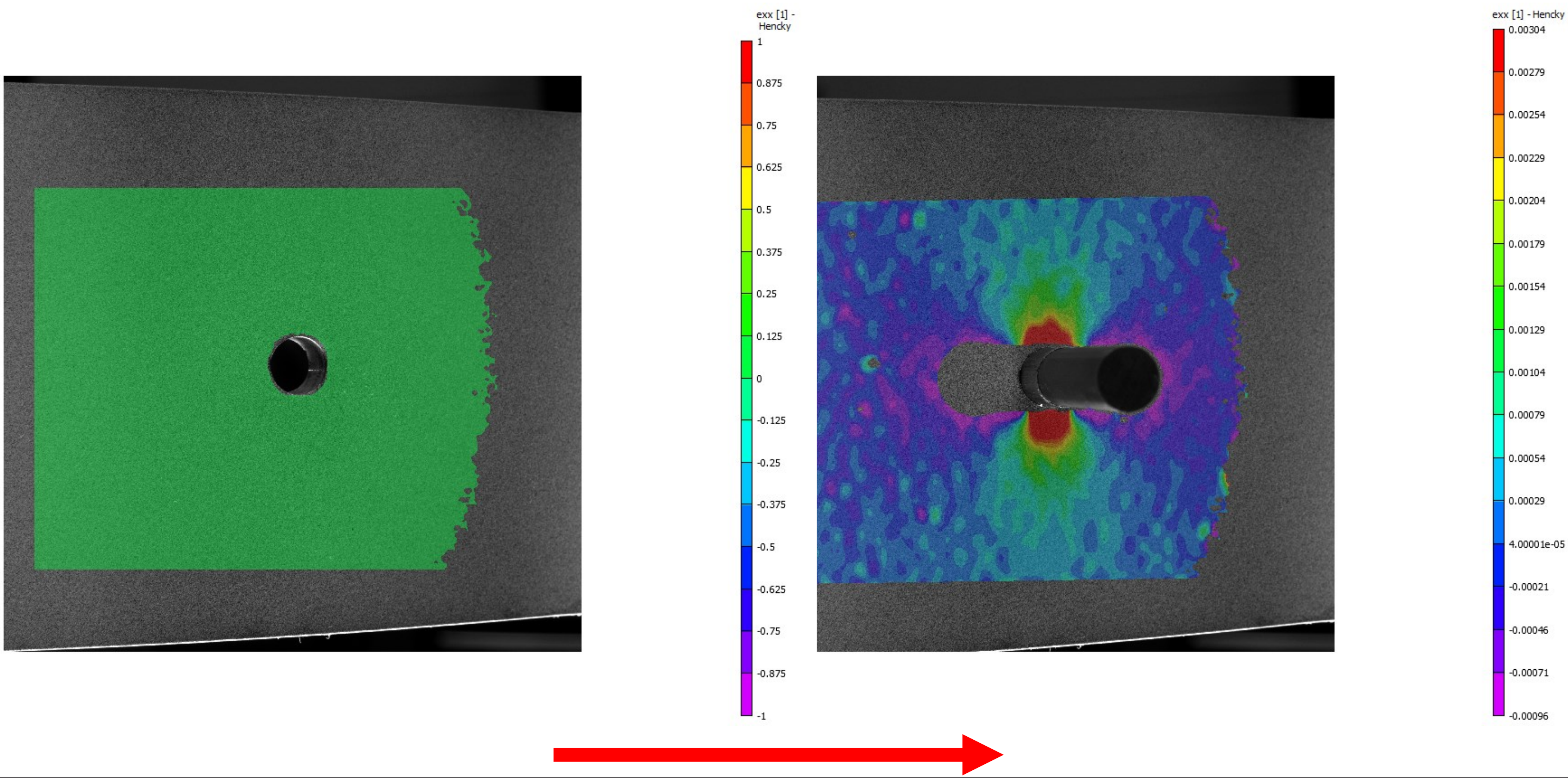




A-10 IFF Testing & Analysis Program

Current Progress

- Local results



A-10 IFF Testing & Analysis Program

Current Progress

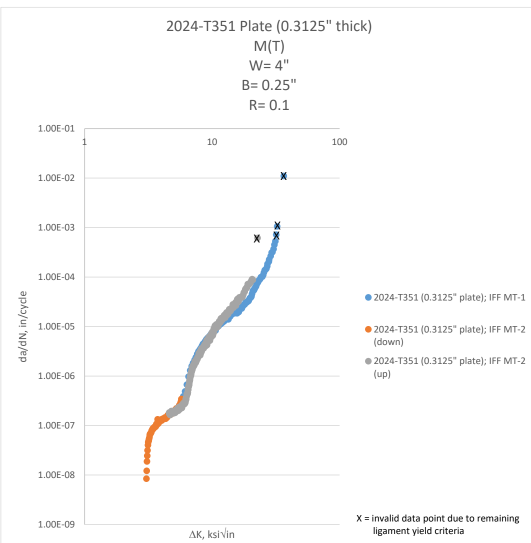
- Initial testing
  - Initial testing at 0.3%, 0.6%, and 1.2% interference was conducted
    - During this testing, the SwRI team noticed that the white underlayment was flaking and causing smearing of the speckle pattern
    - A higher quality application and paint are now being used for the white underlayment (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

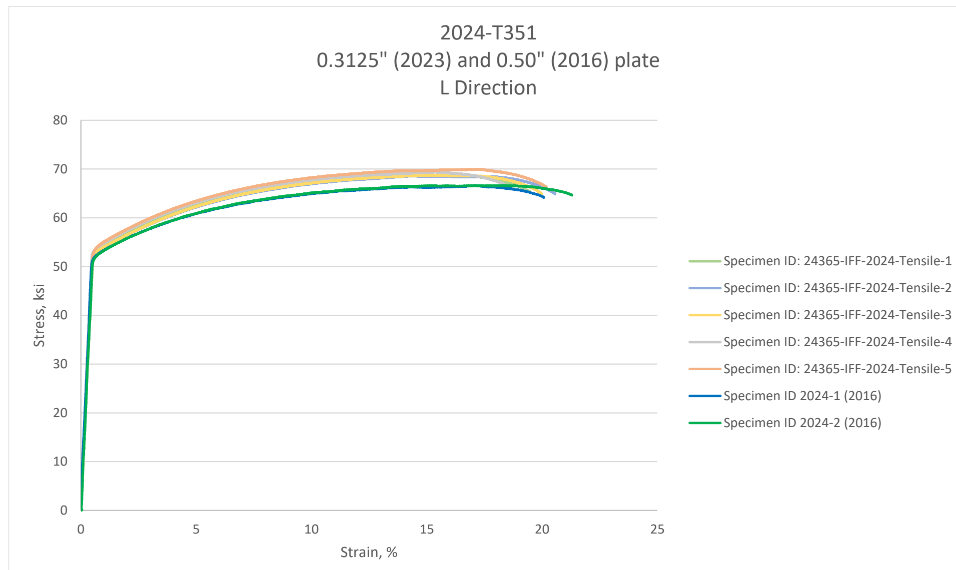
A-10 IFF Testing & Analysis Program

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.

Working Group on
Engineered Residual
Stress Implementation

Residual Stress Measurement Committee Annual Summary

3 April 2024

(These charts are a team product)

Eric Burba, committee lead

micheal.burba.1@us.af.mil

Adrian DeWald, committee co-lead

atdewald@hill-engineering.com

Overview

Committee Logistics

- Mission Statement
- Monthly Meeting Framework
- Roster and Attendance

Update on Current and Future Projects

- Inclusion of Texture and Anisotropy into Residual Stress Measurements (Josh Ward, UDRI & James Pineault, Proto)
- Harmonization of Differing RS Measurement Datasets (James Pineault, Proto)
- Cutting Induced Plascity Modeling for Short Edge Margin Holes and the Effects of Cutting Sequence (Scott Carlson, Lockheed Martin)
- Different Cx Processes (Split Sleeve vs Split Mandrel) Residual Stress and Test Data (Scott Carlson, Lockheed Martin)
- 2x2 Working Group Update (Scott Carlson, Lockheed Martin)

Summary and Future Opportunities

Mission Statement

Provide unwavering support to ERSI stakeholders, encompassing end users and aircraft programs, as they navigate the intricate landscape of designing and executing tailored residual stress implementation initiatives.

A well-established group of professionals specializing in residual stress measurement and process modeling, we offer a comprehensive suite of services that includes:

- Repeatability of Residual Stress Measurement Data (In-lab Variability)
- Reproducibility of Residual Stress Measurement Data (Lab-to-lab Variability)
- Inter-Method Residual Stress Comparisons (e.g., ND to X-ray to Contour)
- Measurement Model Comparisons (e.g., for CX Holes)
- Uncertainty Quantification (UQ) and Statistical Methods Relative to Residual Stress Data

https://residualstress.org/index.php?title=Residual_Stress_Characterization

Committee Roster

First Name	Last Name	Organization
Dallen	Andrew	Hill Engineering, LLC
Jeferson	Araújo de Oliveira	StressMap - Director
David	Backman	National Research Council Canada / Government of Canada
Ana	Barrientos Sepulveda	Northrup Grumman Aerospace Systems
John	Bourchard	Professor of Materials Engineering Open University - Director of StressMap
Michael	Brauss	Proto Manufacturing Inc.
Dave	Breuer	Curtiss-Wright, Surface Technologies Division
Stan	Bovid	Hepburn and Sons
Eric	Burba	U.S. Air Force (AFRL - RXC - Materials & Manufacturing Directorate)
Scott	Carlson	Lockheed Martin Aero (F-35 Service Life Analysis Group)
James	Castle	The Boeing Company (Associate Technical Fellow BR&T Metals and Ceramics)
Allen	Christopher	BAH
David	Denman	Fulcrum Engineering, LLC. (President & Chief Engineer)
Adrian	DeWald	Hill Engineering, LLC
Daniele	Fanteria	Dipartimento di Ingegneria Civile e Industriale
Eric	Greuner	LMCO
Mike	Hill	Hill Engineering, LLC
Ketih	Hitchman	FTI
Laura	Hunt	Southwest Research Institute (SwRI)
Andrew	Jones	U.S. Air Force (B-52 ASIP Structures Engineer)
Min	Liao	NRC
Eric	Lindgren	U.S. Air Force (AFRL - Materials and Manufacturing Directorate)
Marcias	Martinez	Clarkson University (Department of Mechanical & Aeronautical Engineering)
B	McGinty	MERC Mercer
Teresa	Moran	Southwest Research Institue (SwRI)
Mark	Obstalecki	U.S. Air Force (AFRL - RXCM)
Juan	Ocampo	St. Mary's University
T	Philbrick	MERC Mercer
Pete	Phillips	University of Dayton Research Institute (UDRI)
Robert	Pilarczyk	Hill Engineering, LLC
James	Pineault	Proto Manufacturing Inc.
Scott	Prost-Domasky	APE Solutions
Mike	Reedy	U.S. Navy (NAVAIR - Compression Systems Engineer)
Steven	Reif	AFLCMC/EZFS
Guillaume	Renaud	NRC
Zachary	Sanchez Archuleta	Los Alamos National Labs (LANL)
Matthew	Shultz	PCC Airframes
Lucky	Smith	SwRI
TJ	Spradlin	U.S. Air Force (AFRL - Aerospace Systems Directorate)
Marcus	Stanfield	Southwest Research Institute (SwRI)
Mike	Steinzig	Los Alamos National Labs - Weapons Engineering Q17
M	Tkokaly	Partworks
Kevin	Walker	QinetiQ
Josh	Ward	University of Dayton Research Institute (UDRI)
Michael	Worley	SwRI

Please contact Burba or DeWald if you would like to be added or removed from this rosters

Monthly Meeting Framework

Monthly Committee Meetings

- Held on the first Wednesday of the month at 1400 Eastern
- Hosting meetings using ESRI's Zoom account
- Please contact Burba or DeWald if you would like to attend

Meeting Agenda

Characterization Committee Projects & Updates

- UQ/Risk Update (Ocampo)
- Texture and Anisotropy Sub-Team (Obstalecki/Ward)
- Large Cx Hole Bulk Stress (Hill)
- Multi-Point Fracture Mechanics, AFRL (Burba)
- 2x2 Working Group (Carlson)

New Business

Around the Room

Texture and Anisotropy Sub-Team

Team:

Joshua Ward (AFRL)
Mark Obstalecki (AFRL)
Eric Burba (AFRL)
Mike Hill (Hill Engineering)

Mike Steinzig (LANL)
Zachary Sanchez (LANL)
James Pineault (Proto)

Outline

- Introduction
  - Mission Statement & Background
  - Residual Stress Hole Drilling
- Main Points
  - Measuring Anisotropic Elastic Constants
    - How can we Measure Anisotropy?
    - Resonant Ultrasound Spectroscopy (RUS)
    - RUS System
  - Round-Robin study of Stainless Steel Ring-Plug Specimen
    - Comparison of Hole Drilling and X-Ray Diffraction
- Summary
  - Future Work
  - Accomplishments

Mission Statement & Background

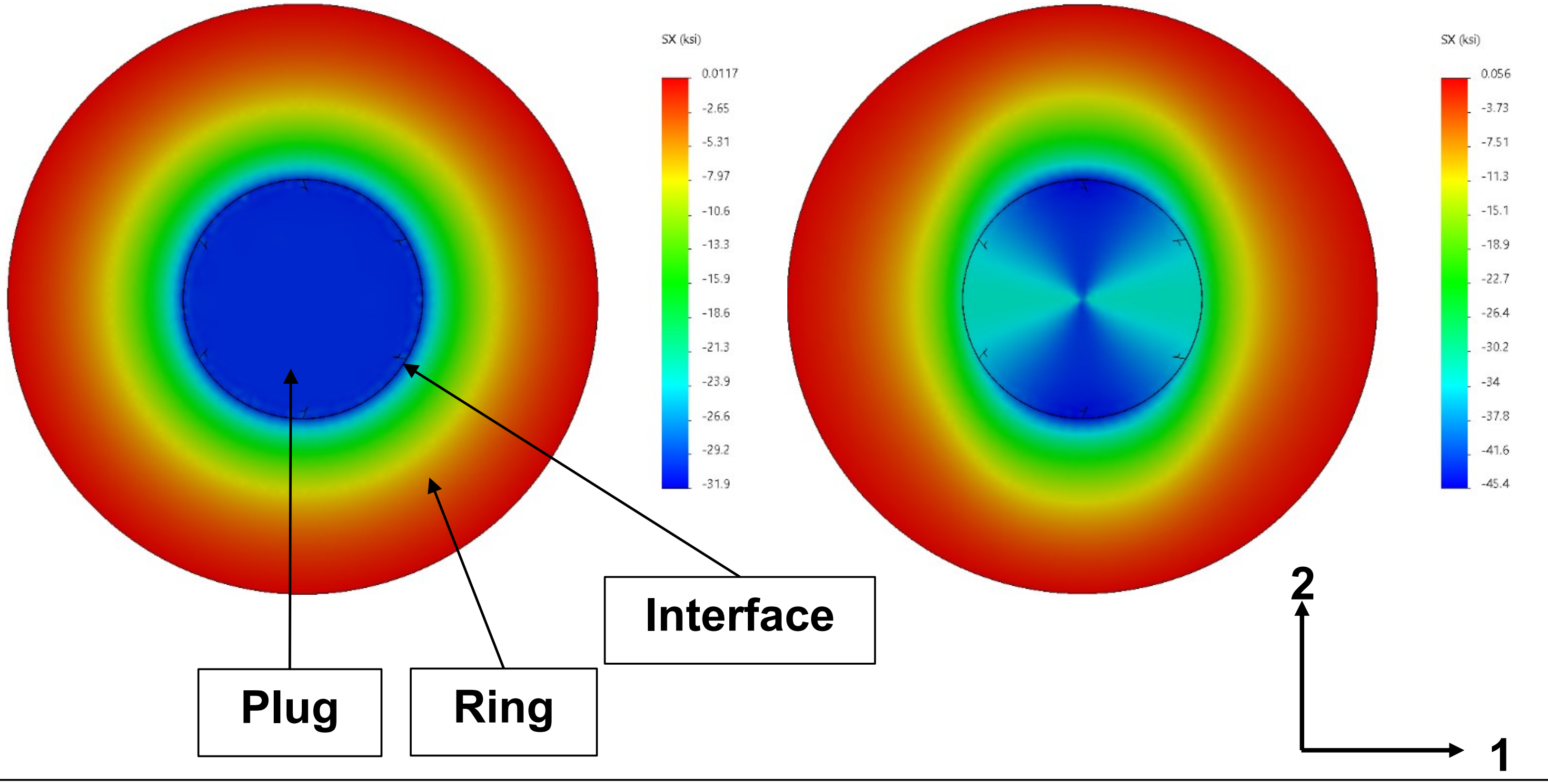
Quantify and incorporate the effects of crystallographic texture and elastic anisotropy into residual stress measurement workflows

$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{23} \\ 2\varepsilon_{13} \\ 2\varepsilon_{12} \end{bmatrix} = \frac{1}{E} \begin{pmatrix} 1 & -v & -v & 0 & 0 & 0 \\ -v & 1 & -v & 0 & 0 & 0 \\ -v & -v & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2+2v & 0 & 0 \\ 0 & 0 & 0 & 0 & 2+2v & 0 \\ 0 & 0 & 0 & 0 & 0 & 2+2v \end{pmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{bmatrix}$$

$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{23} \\ 2\varepsilon_{13} \\ 2\varepsilon_{12} \end{bmatrix} = \begin{pmatrix} \frac{1}{E_1} & -\frac{v_{21}}{E_2} & -\frac{v_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{v_{12}}{E_1} & \frac{1}{E_2} & -\frac{v_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{v_{13}}{E_1} & -\frac{v_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{pmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{bmatrix}$$

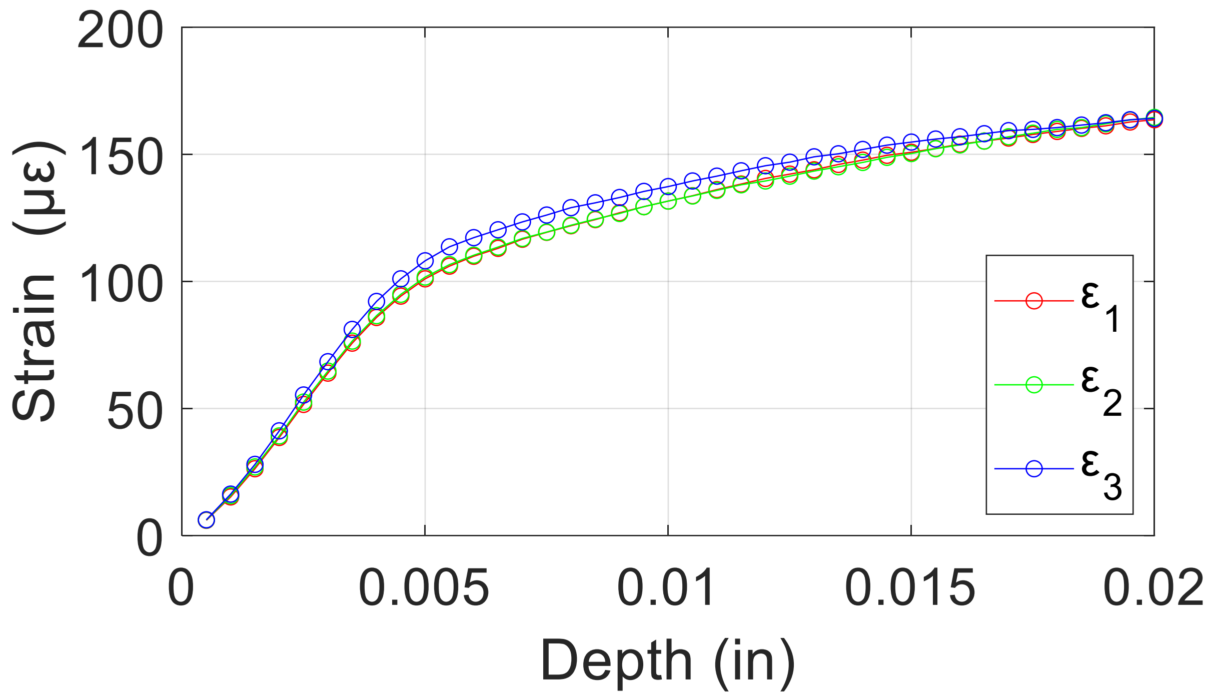
Isotropic Ring & Plug
E = 28,000 ksi

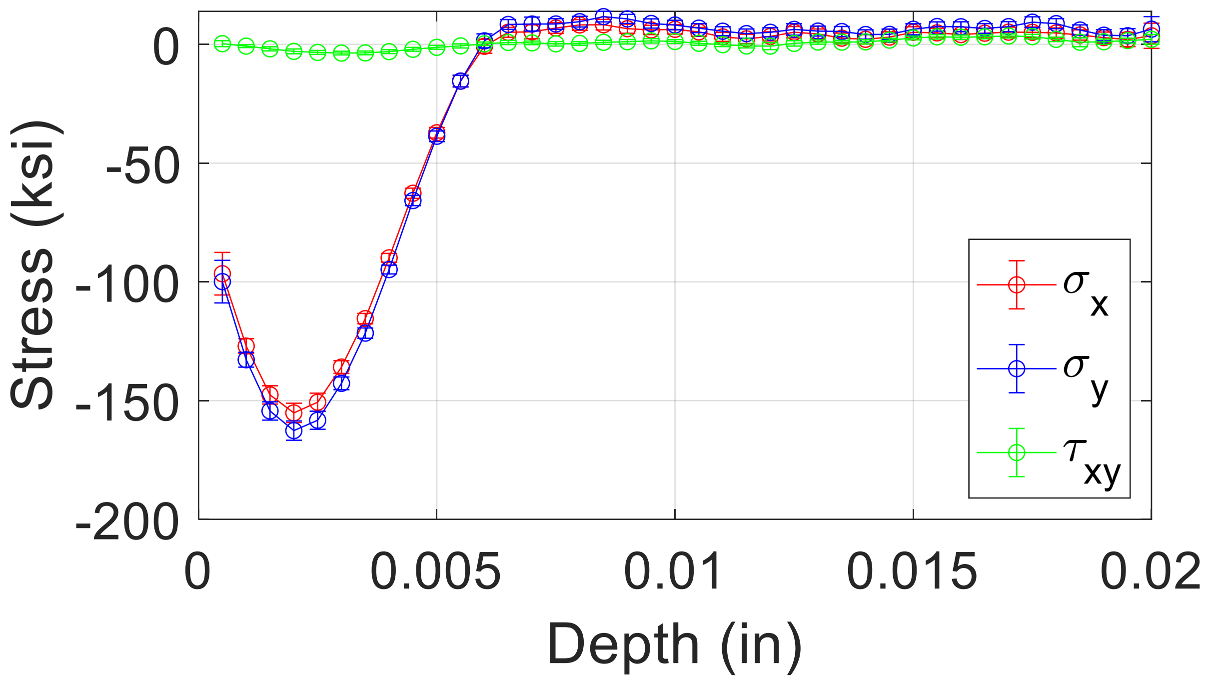
Anisotropic Ring & Plug
E_1 = 28,000 ksi E_2 = 36,400 ksi



Residual Stress via Hole-Drilling

- Incremental Hole Drilling (ASTM E837) utilizing the DART system (Hill Eng.)



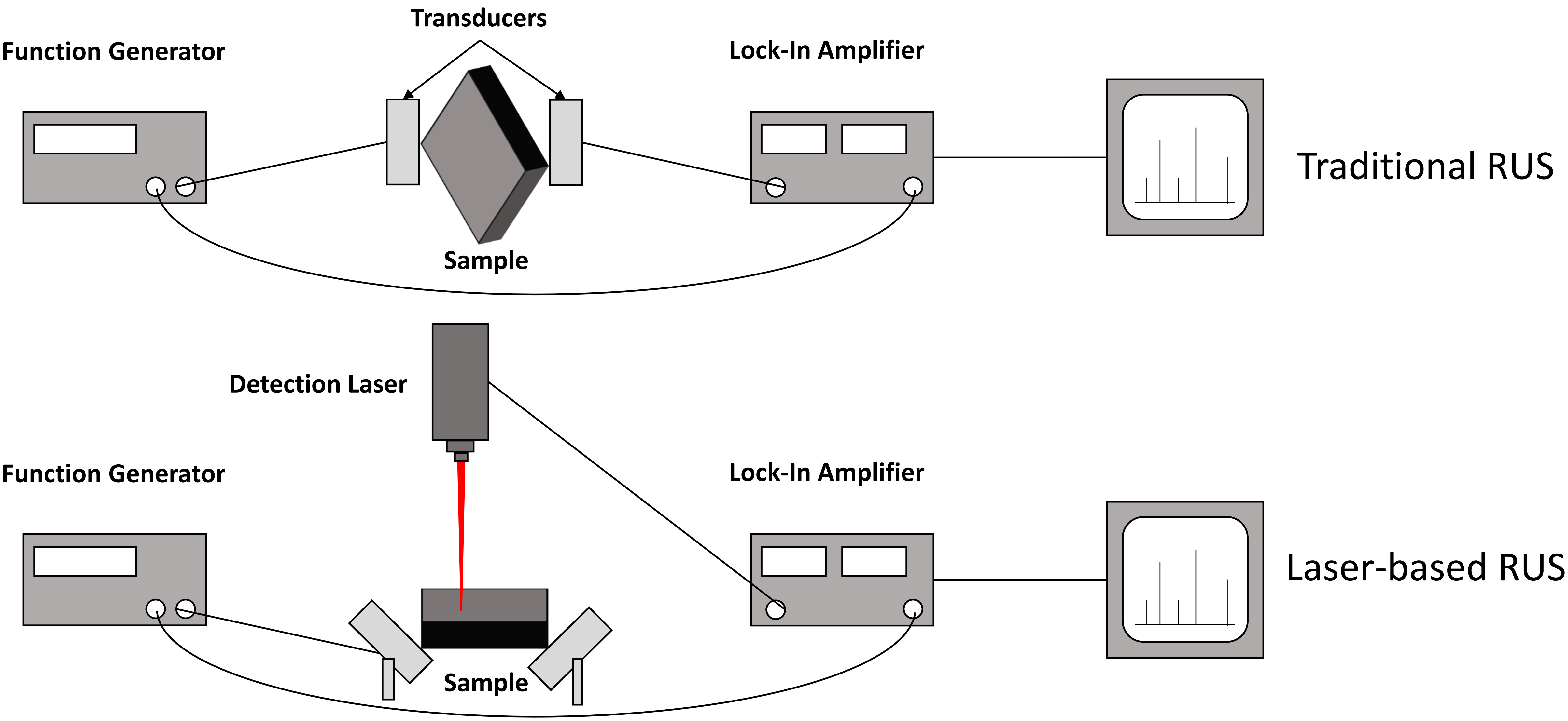


Measurement of Anisotropic Elastic Constants

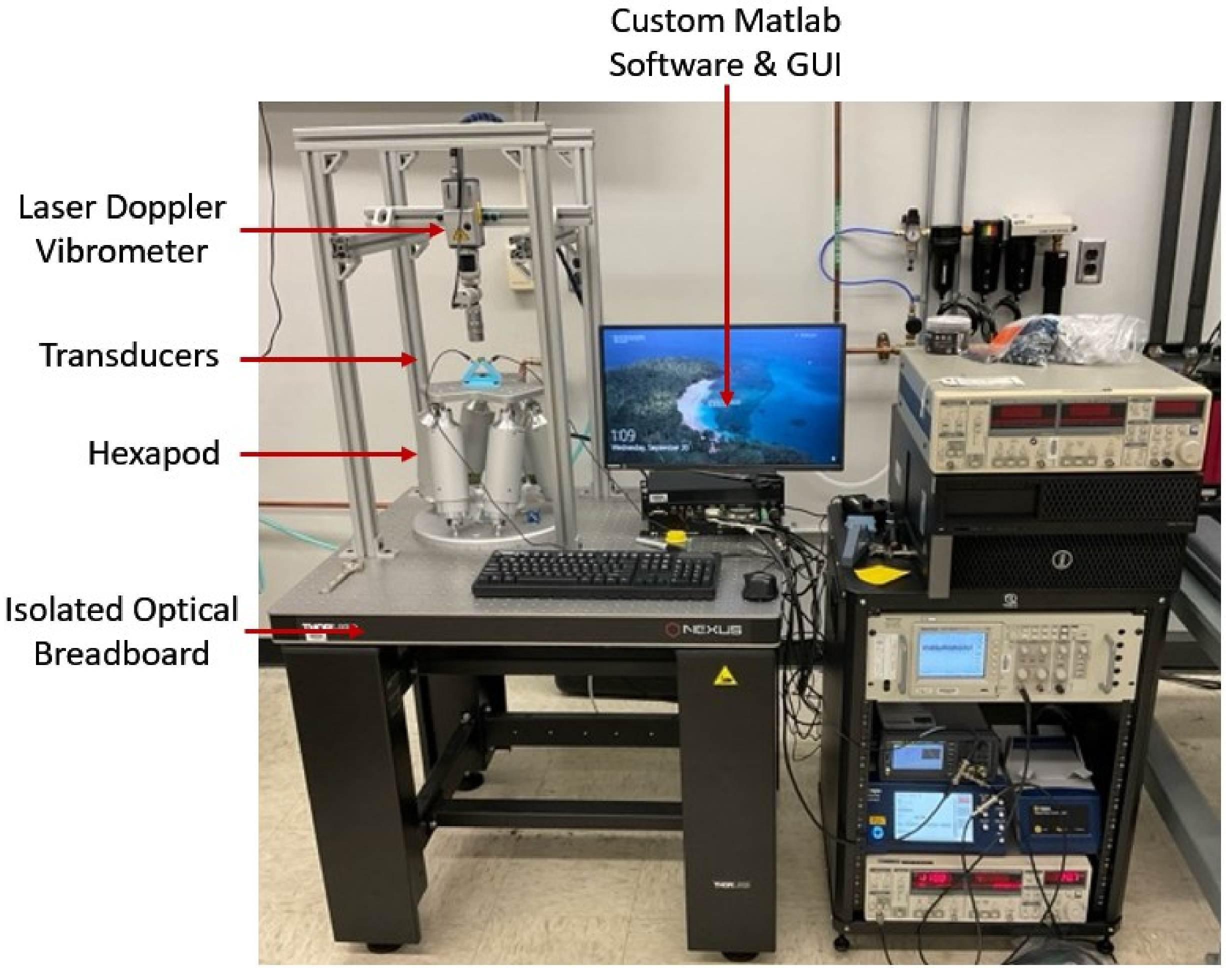
Measuring Anisotropic Elastic Constants

	Mechanical Testing	Time of Flight Ultrasound	Resonant Ultrasound Spectroscopy
Sample Cost	\$1,000s	\$100s	\$100s
Required material	Tens of specimens (flat/round dogbone)	One small cuboid ~ 1000 mm^3	One small cuboid ~ 500 mm^3
Test Cost	\$1,000s	\$100s	\$100s
Technical Difficulty	Requires trained technician	Requires trained technician	Requires subject matter expert to analyze results
Method Maturity			

Resonant Ultrasound Spectroscopy (RUS)

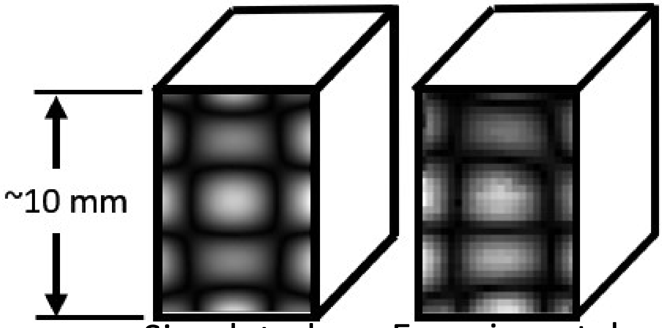


RUS System



System Capabilities

- **Rapidly measure anisotropic elastic stiffness tensor nondestructively using a small volume of material**
  - ~ 2 hr, significant savings on tension tests
  - Simple specimen preparation
- **Measures resonant frequencies <u>and</u> modal shapes**
- **Built in predictive models (FE & Rayleigh Ritz) and gradient descent optimizer for material constant determination**
- **Future: High temperature capabilities**
  - Modulus, Texture evolution as function of time & temperature



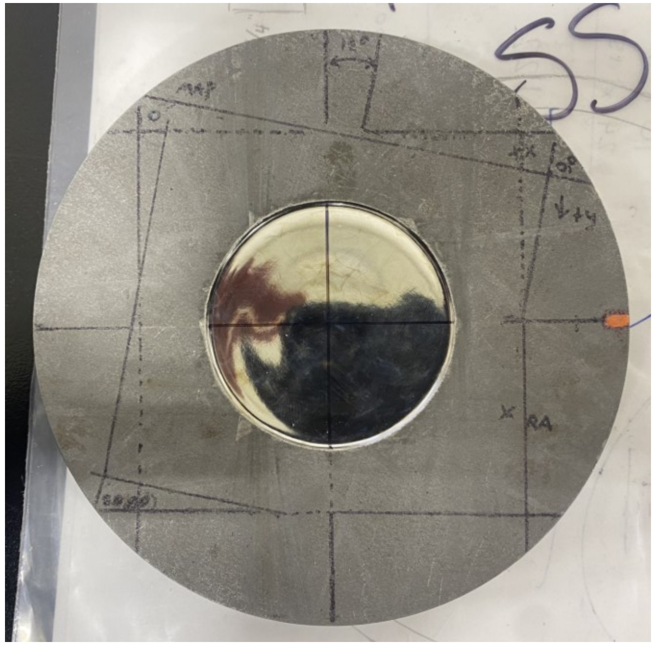
$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{23} \\ 2\varepsilon_{13} \\ 2\varepsilon_{12} \end{bmatrix} = \begin{pmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{31}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}} \end{pmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{bmatrix}$$

Round-Robin on 304SS Ring-Plug Specimen

- LANL fabricated and assembled Ring-Plug (304SS plug/Carbon Steel ring) for ERSI Texture Subcommittee circa 2021.
- Nominal Dimensions of Carbon Steel Ring: 4.9375” OD, 2” ID, 0.5” thick - 304SS Plug: 2” OD, 0.5” thick
- Purpose: further develop RS measurement protocols and work-flow for anisotropic materials.
- Premise: start with a presumably isotropic specimen, collect data, incorporate lessons learned on anisotropic materials in future.
- RS depth profiles collected up to 0.040” deep using RSHD on Side 1 (see holes) and XRD on Side 2 (see e-polished region).

Post HD – Side 1

Edge View

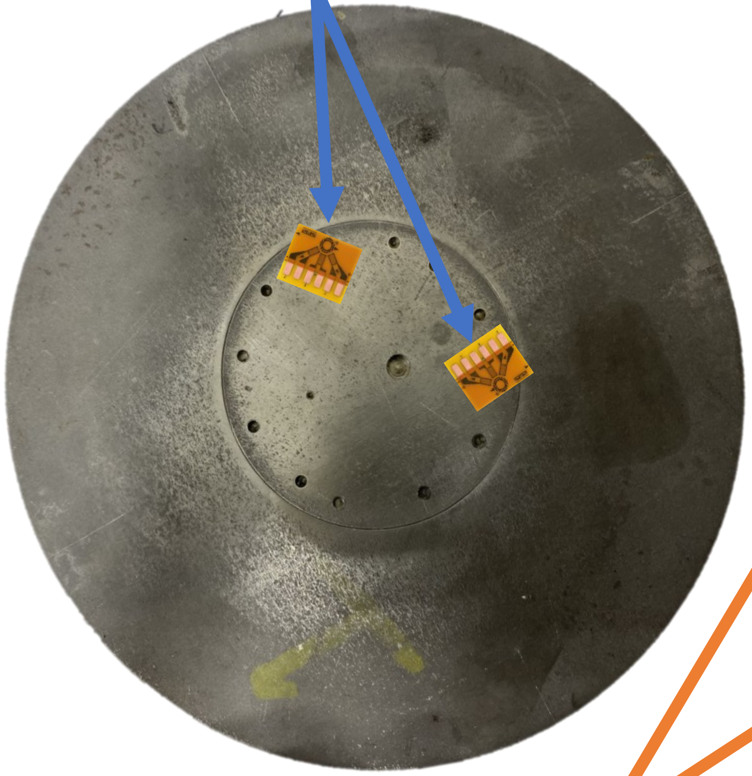


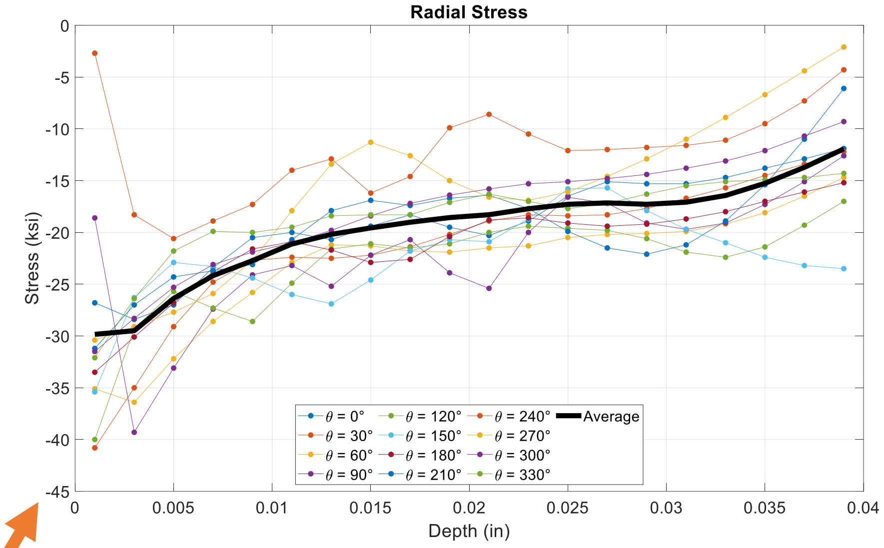
Post XRD – Side 2

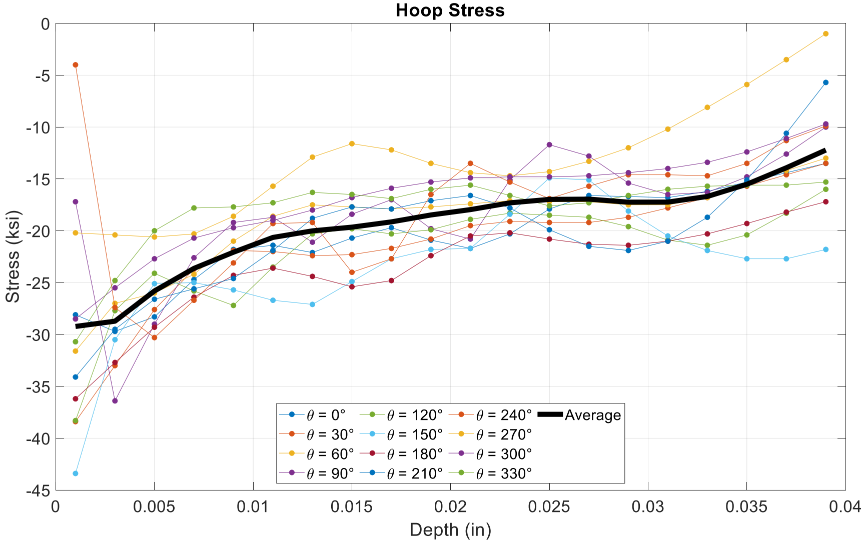
RSHD on Side 1 of 304SS Ring-Plug Specimen

- RSHD work performed at AFRL.
- 12 standard size (0.08"Ø hole) HD measurements performed 30° apart around the plug at the 22 mm radial position
- Oriented with σ_{xx} in radial direction and σ_{yy} in hoop direction
- Depth profiles indicate a surface RS gradient is present likely due to upstream cold work applied to 304SS cold rolled sheet/plate.
- Comparable average between radial (σ_{xx}) and hoop (σ_{yy}) stress as expected on ring-plug configuration.

Typical Rosette Placement





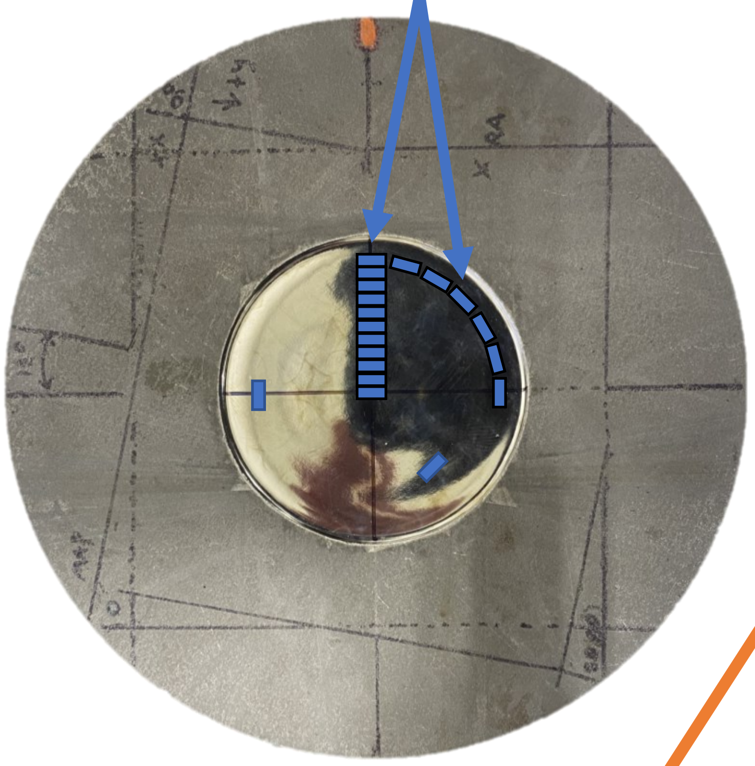


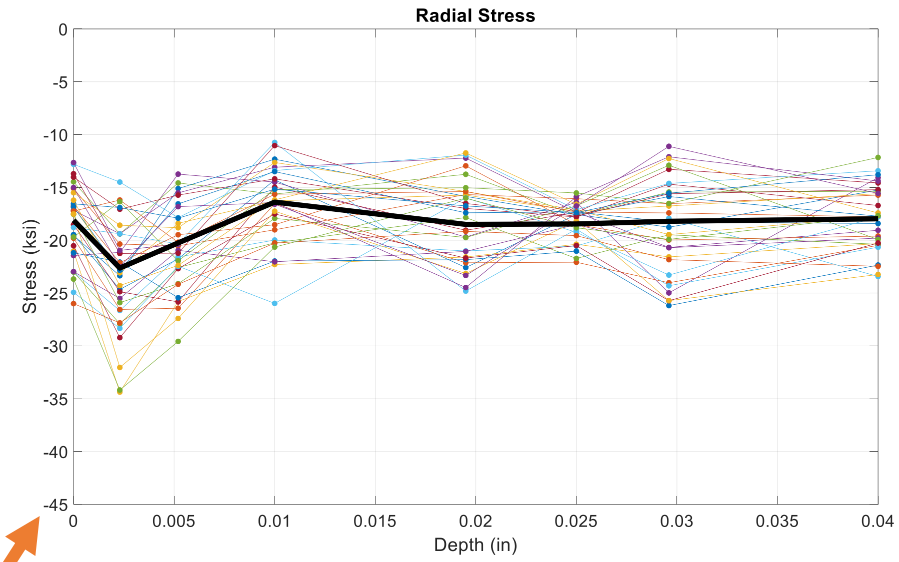
Hoop and Radial Stress vs. Depth profiles at 22 mm radial position

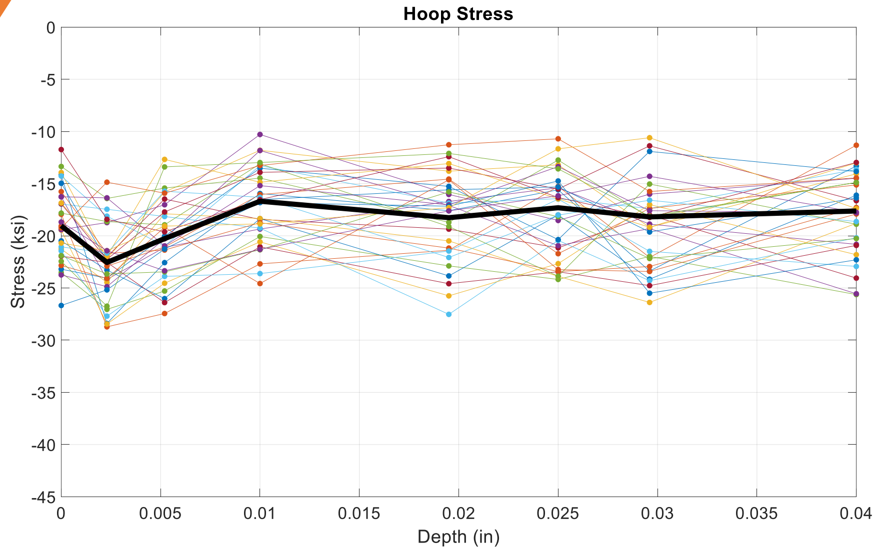
XRD on Side 2 of 304SS Ring-Plug Specimen

- XRD work performed at Proto.
- 264 locations used for XRD at **15° intervals** and **2 mm radial increments** (some examples of irradiated area highlighted in blue boxes).
- Depth profiles indicate a surface RS gradient is present likely due to upstream cold work applied to 304SS cold rolled sheet/plate.
- Comparable average between radial (σ_{xx}) and hoop (σ_{yy}) stress as expected on ring-plug configuration.

Typical Irradiated Area

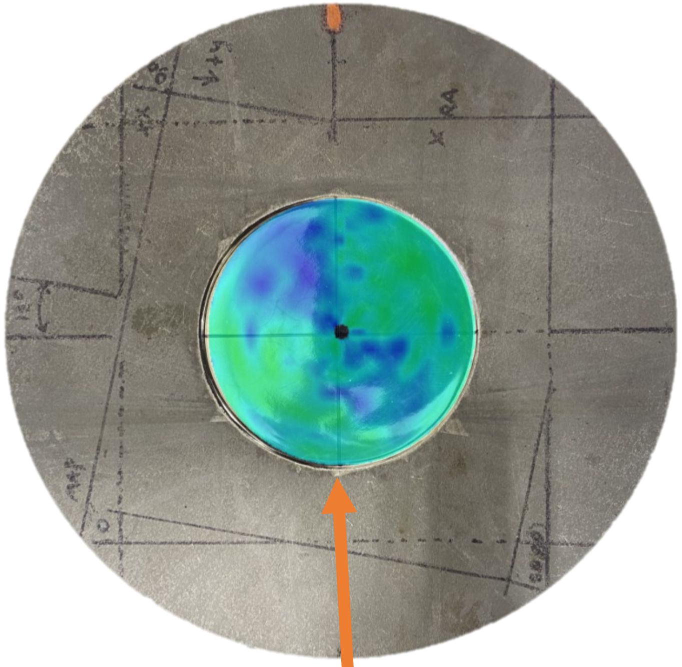




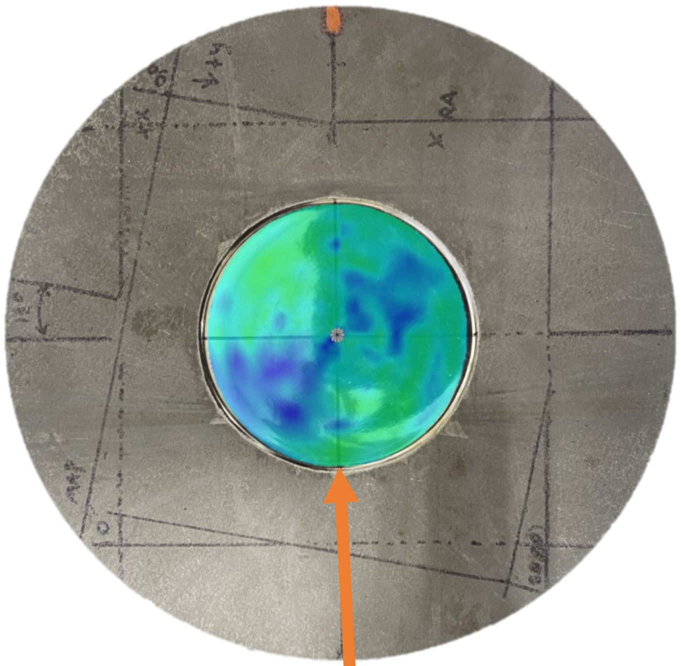


Typical Radial and Hoop Stress vs. Depth profiles – Example from R=8 mm

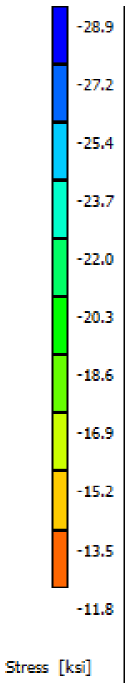
XRD Maps on Side 2 of 304SS Ring-Plug



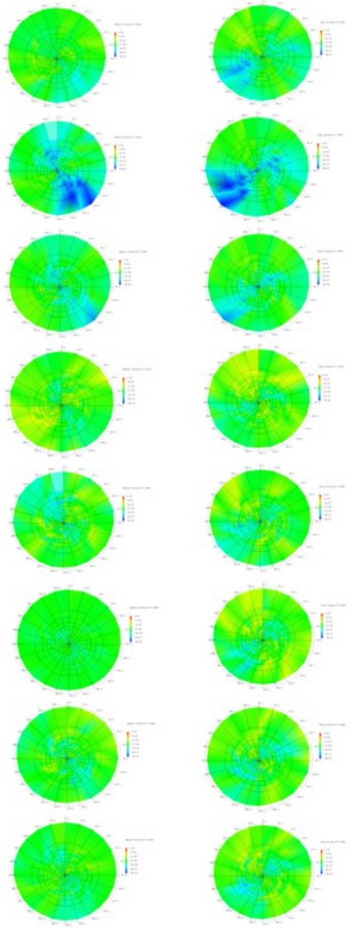
Radial Stress Map at 0.0195” deep



Hoop Stress Map at 0.0195” deep



Radial **Hoop**

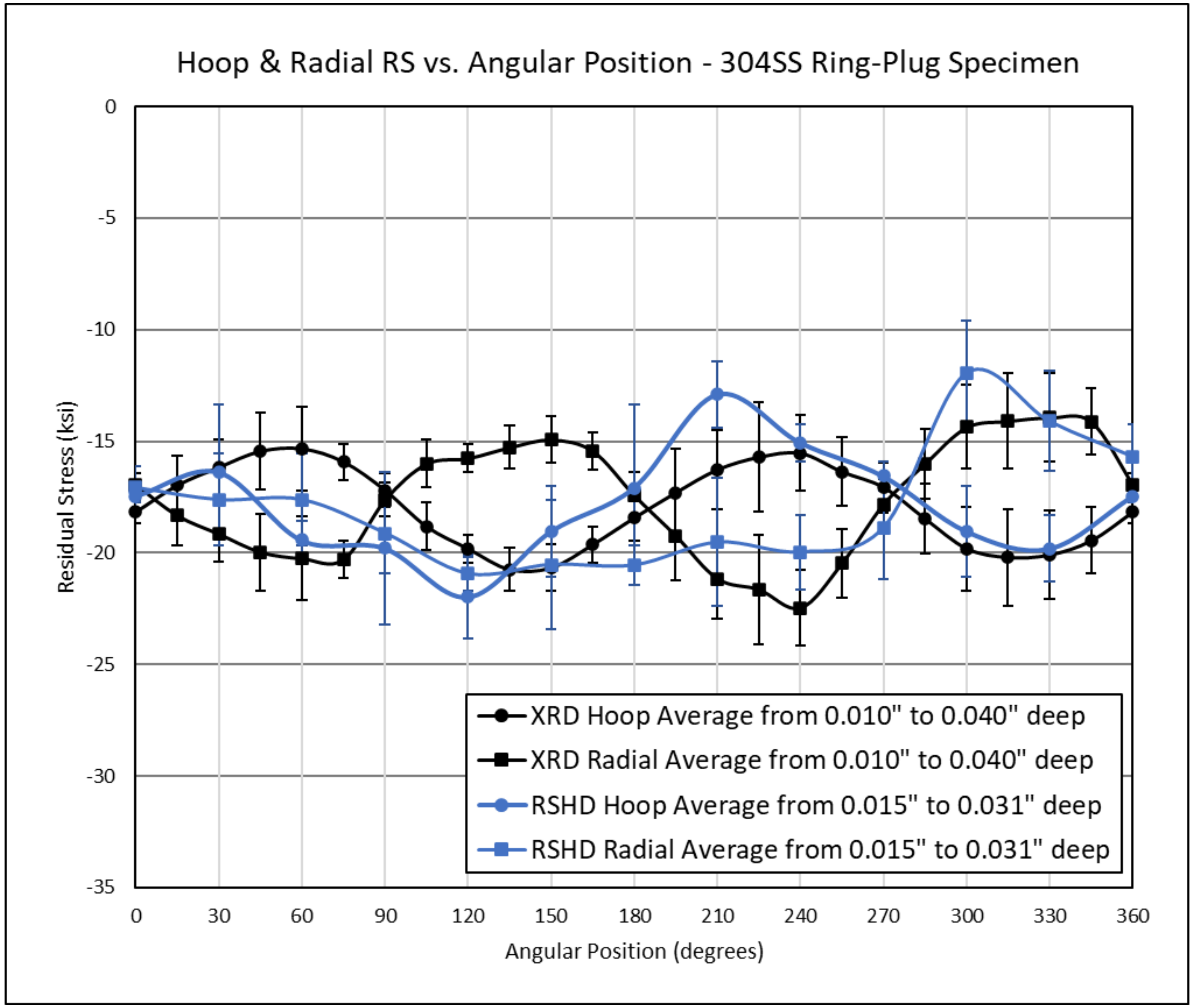


Note: color scale on above RS maps different than one shown above left

- Full field XRD RS maps indicate angular dependence on the magnitude of RS.
- Radial and Hoop RS maps “mirror images” indicating possible dependence on a) upstream fabrication residual stress, and/or b) anisotropic response to loading.
- Effect persists from near surface to maximum sampled depth of 0.040”.
- XRD data collection strategy developed to facilitate analysis of anisotropic materials in upcoming experiments.

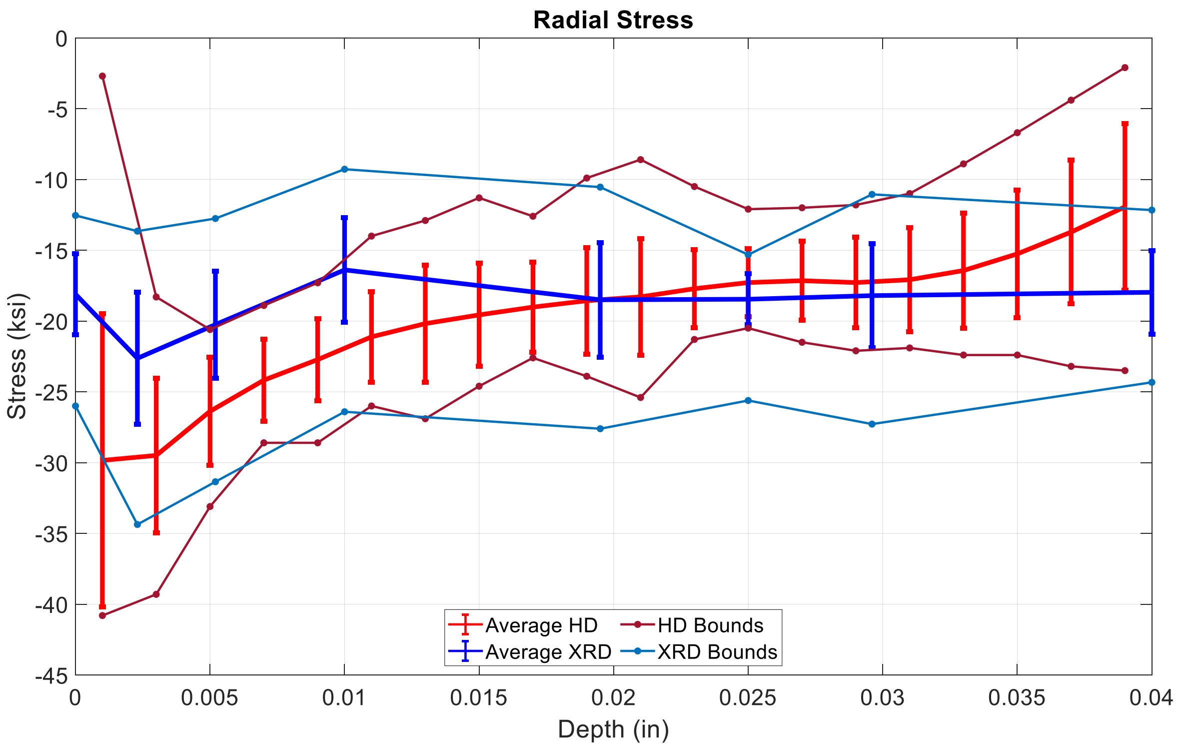
RSHD\XRD on 304SS Ring-Plug Specimen

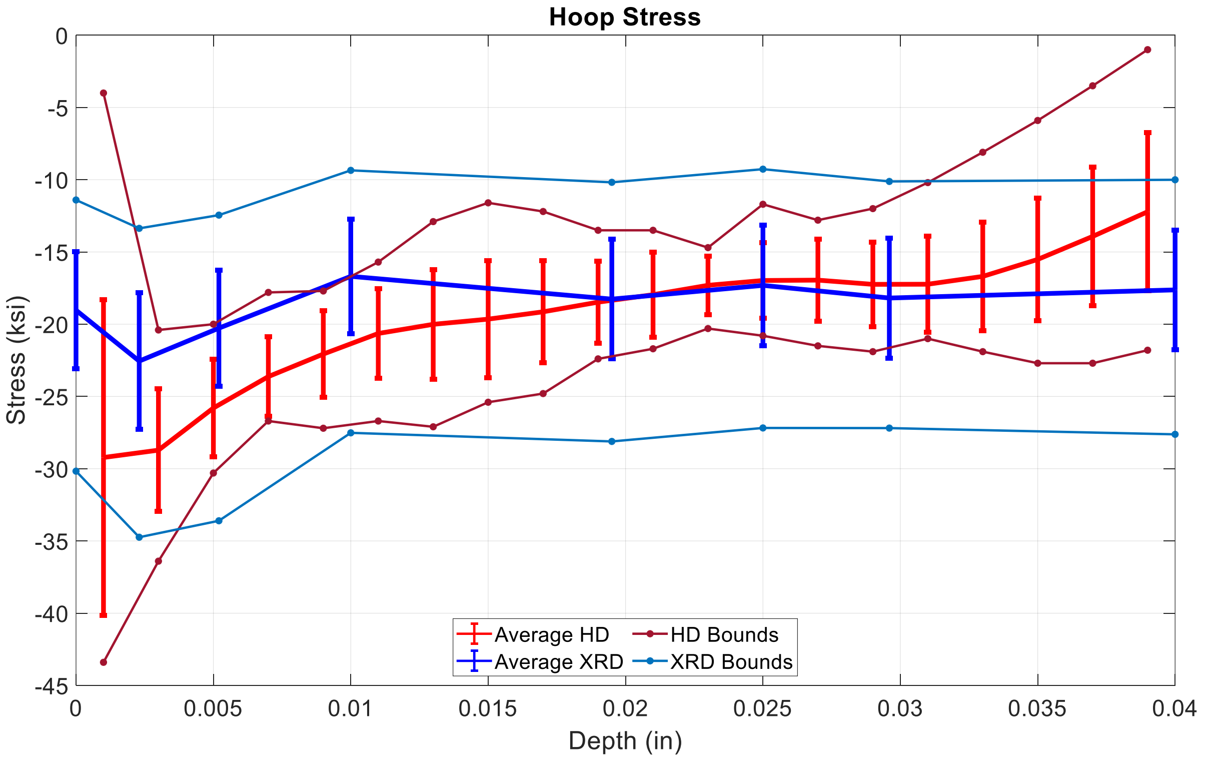
- Average residual stress below cold worked layer plotted versus angular position for both RSHD and XRD.
- Clear oscillatory trend observed in both RSHD and XRD data (as seen in XRD full field polar maps i.e. 90º out of phase).
- Effect of upstream fabrication residual stresses and/or anisotropy to be investigated:
  - a) micro/macro etching to determine rolling direction of 304SS plate.
  - b) perform EBSD/RUS to determine anisotropic characteristics
- Strain gauge and remove plug from ring to confirm interference RS applied as compared to designed interference at time of assembly.



RSHD\XRD on 304SS Ring-Plug Specimen

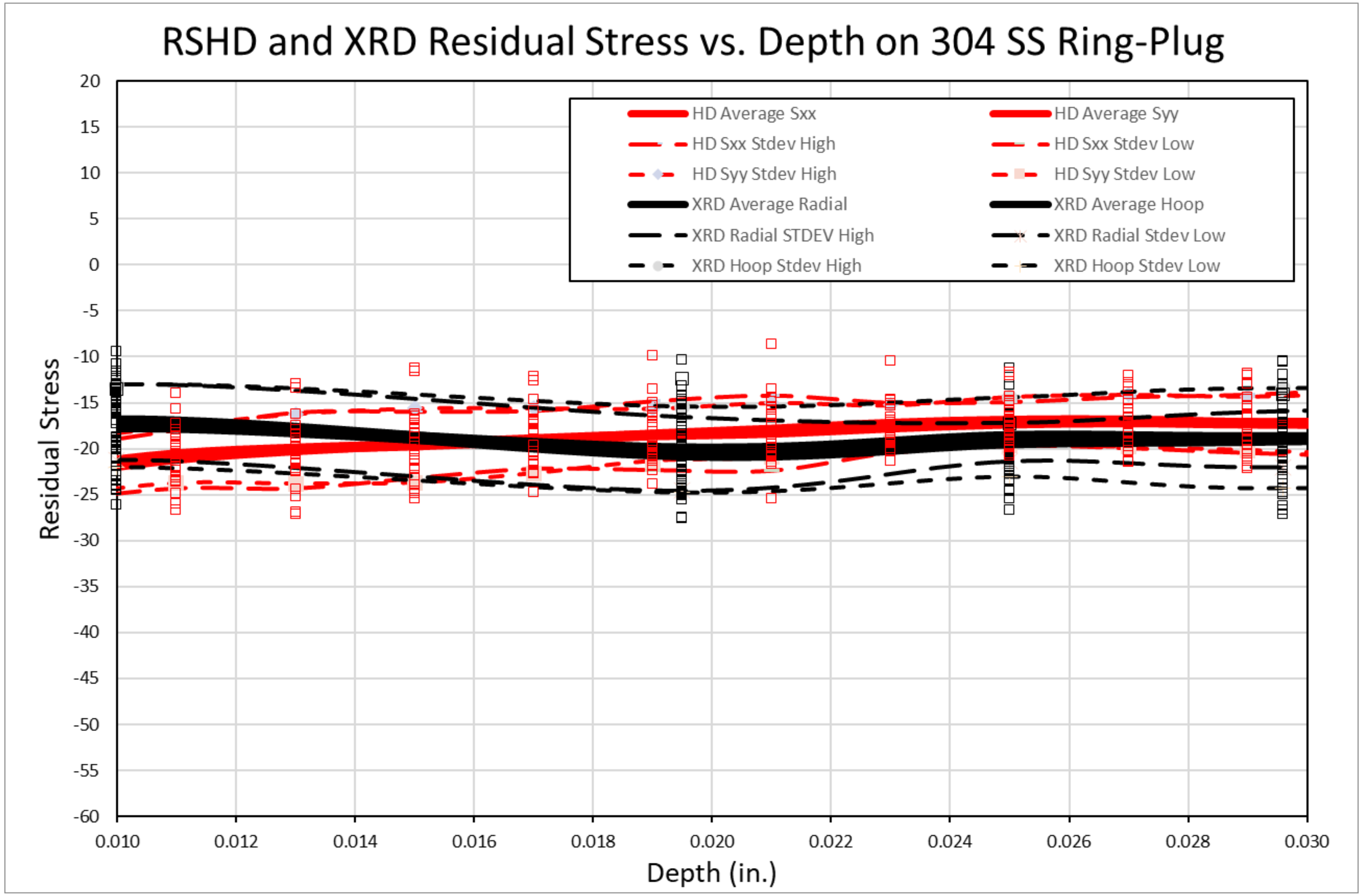
- Average residual stress versus depth from surface for RSHD and XRD
- Error bars calculated from standard deviation of all locations at a specific depth
- Bounds representative of minimum and maximum values at each depth (any location) for each method





RSHD\XRD on 304SS Ring-Plug Specimen

- Considered data <u>below</u> cold worked near surface region in the high confidence depth range for RSHD.
- XRD and RSHD results nominally equivalent despite measurements performed on opposite sides of 304SS Ring-Plug.
- Random errors one may typically expect from either RSHD or XRD shown via max/min bounds and standard deviations (nominally equivalent ~ ± 5ksi).
- Real baseline RS variances can be a factor as per observed oscillatory data.
- Underscores the need for statistically significant data sets (i.e. multiples) when grain size is relatively coarse using either RSHD or XRD.

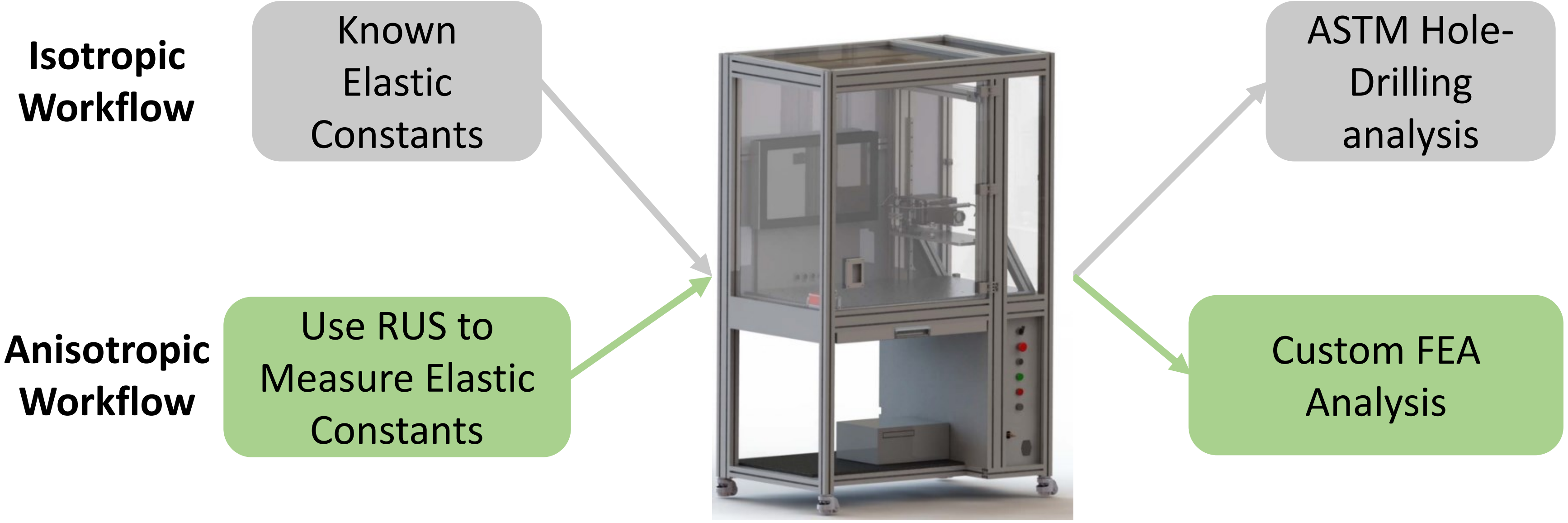


Summary of Round Robin

- Comparable data between RSHD and XRD, with the understanding of limitations of either method
- Finalized workflow for ring-plug specimens, including data collection using RSHD and XRD
- With the heavy lifting of workflow complete, ring-plug specimens fabricated from anisotropic materials is the next step

Future Work

- Validation of RUS inversion algorithm by comparing to traditional mechanical testing
- Looking at additively manufacturing samples with high degrees of anisotropy for residual stress measurement
- Writing up the round-robin measurements of aluminum ring-plug discussed last year
- Derive/Design a workflow to incorporate elastic anisotropy into RSHD



Accomplishments

- Conducted two round-robin studies of ring-plug samples
- Conducted residual stress hole-drilling (RSHD) measurements on textured ring-plug sample
- Developed an FEA tool to simulate RSHD

University of Dayton Research Institute

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Los Alamos
NATIONAL LABORATORY

Harmonizing Contour and XRD Residual Stress Measurement Data Sets

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The Proposed Approach
(recap on work done so far)

A Novel Approach to Integrating Residual Stress Determination Methods

2023 Aircraft Airworthiness & Sustainment Conference

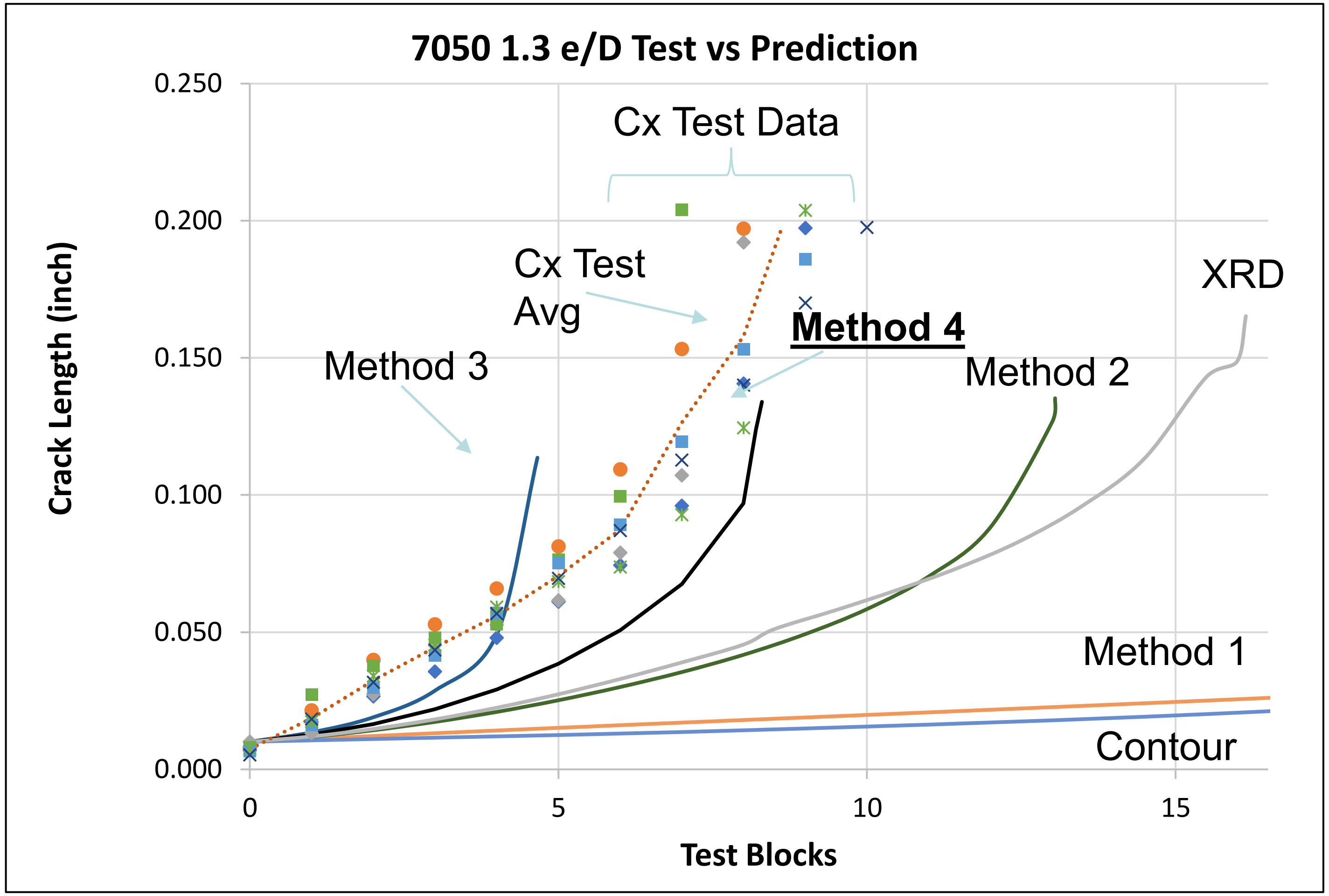
30 August 2023

James Prather: Presenter
Dr. Scott Carlson: Co-Author
F-35 Service Life Analysis Group

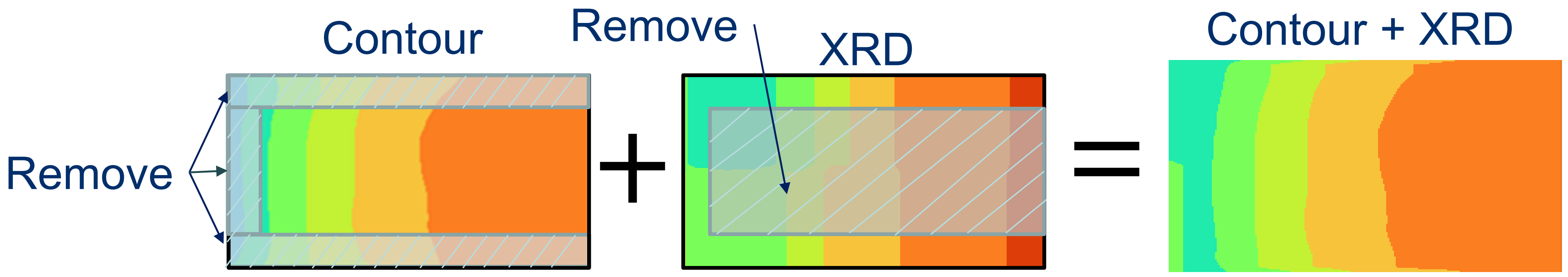
LOCKHEED MARTIN

FCG Life Predictions: XRD and Contour (All 4 Methods)

- **Same LEFM-based FCG analysis applied using each method's resultant residual stress profile as input**
  - Both XRD alone and Contour alone are unconservative
  - Both Methods 1 and 2 are unconservative
  - Method 3 is slightly conservative
  - Method 4 closely predicts the average test life and would provide reasonable initial and recurring inspection intervals



Integrating Datasets
(But I still like Method 2 in principle)

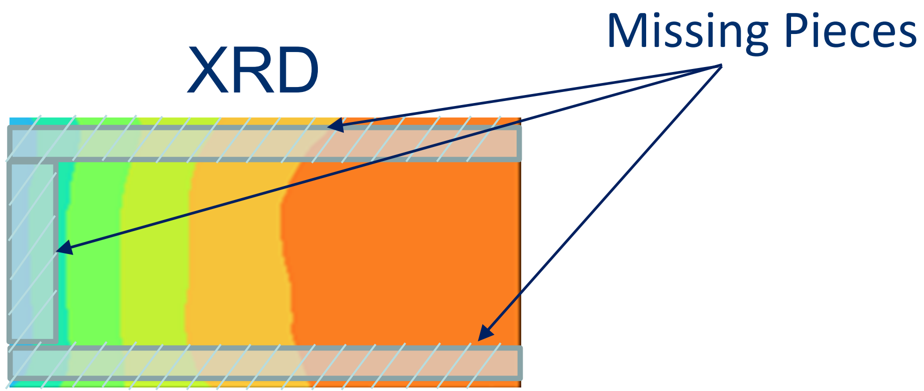


"Stitching" the datasets together where research literature claims they are most accurate

Leverages benefits of each method while removing areas of limitations

Why was Method 2 Unconservative?

I would posit some of the key pieces of the puzzle were missing?



We need these missing pieces of data.

The Proposed Approach
For Proof of Concept: Leverage Data Sets Already Available on GL Coupons

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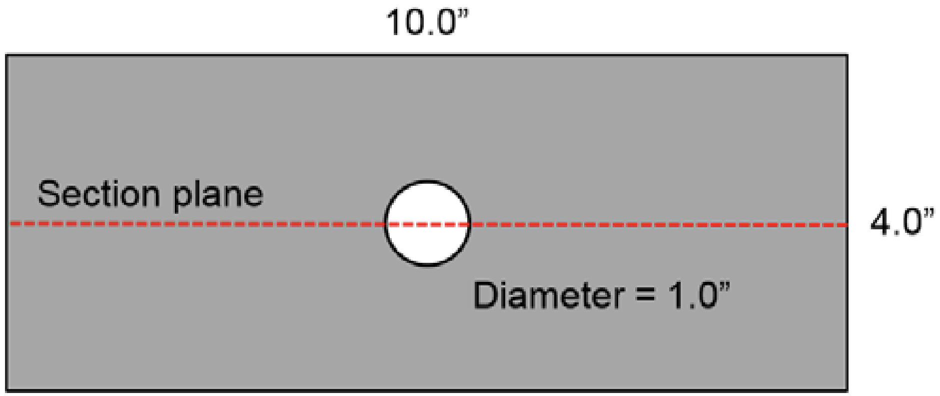
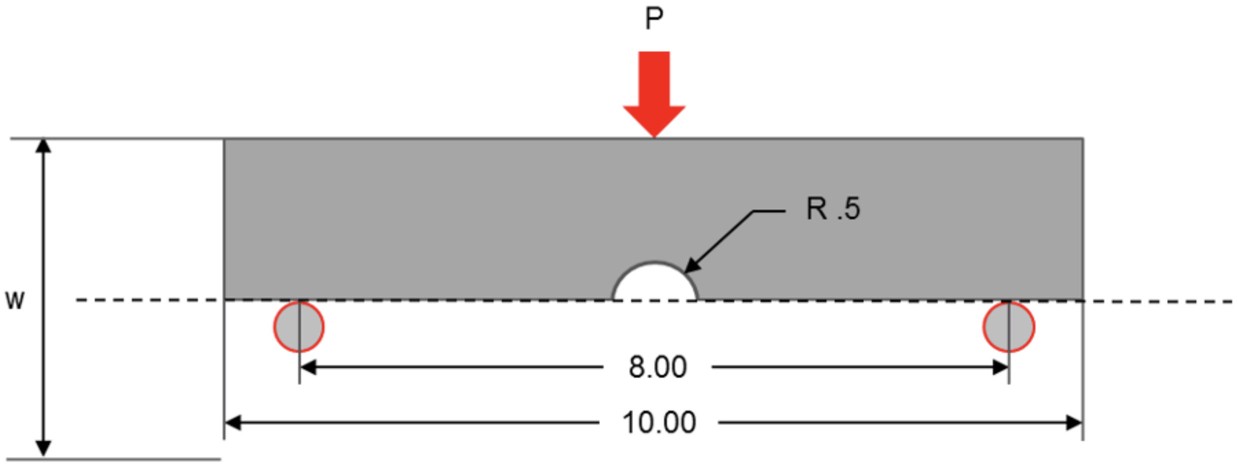
Case Study #1 - Geometrically Large Coupons

- Larger coupons scale-up the stress field to facilitate residual stress measurements using any method
- Full and split configurations
- Split configuration allows XRD access to bore ID but requires a correction for relaxation due to splitting
- XRD arc-averaging reduced to ± 45° on the face – must be accounted for if coupon is split.





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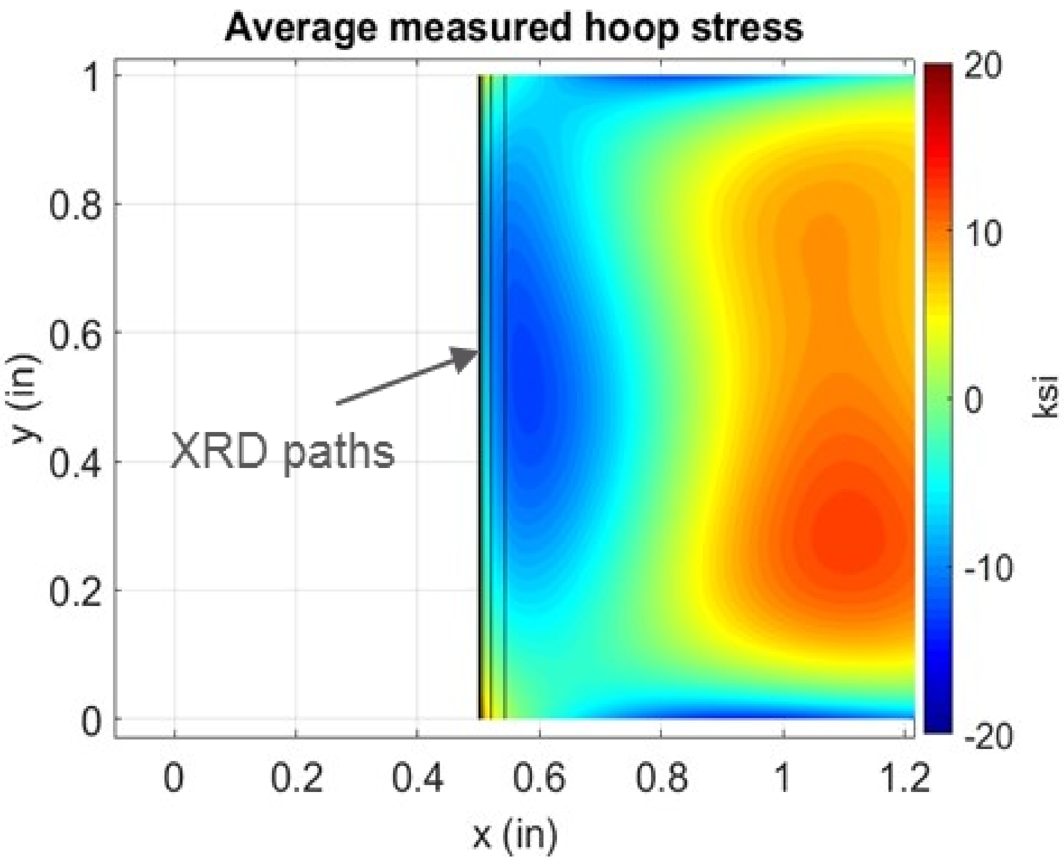
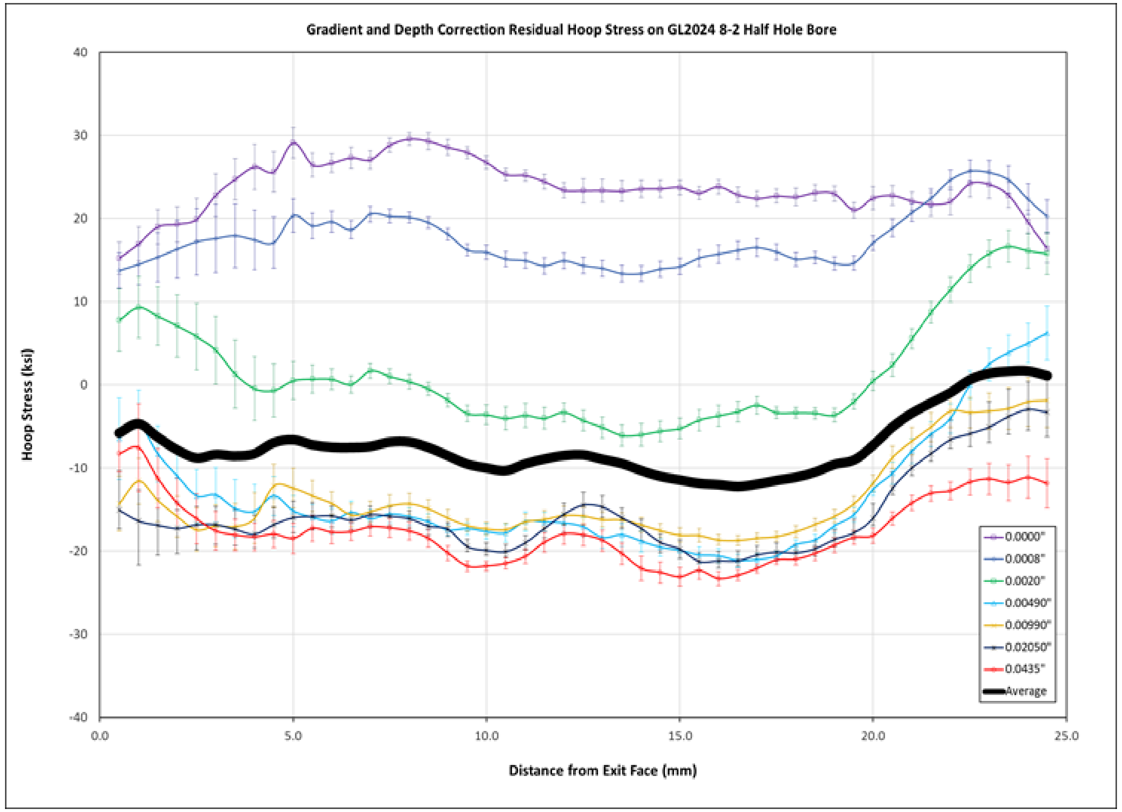
RS in <u>Bore</u> of Cx Hole in Geometrically Large Coupon

- Once a correction is available for splitting coupons for access to the bore, residual stresses can be measured via XRD – this correction can be obtained by either Contour data, strain gage data, or both.
- XRD + electropolishing can be used to get data on the bore to be stitched together with the Contour data.





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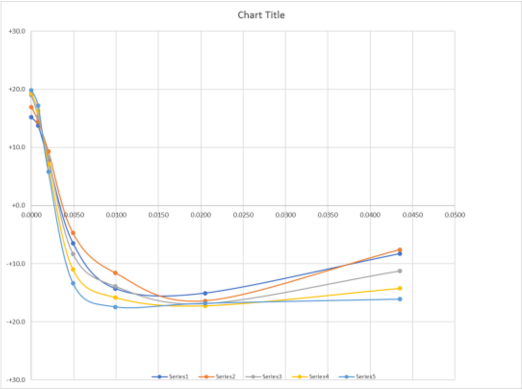
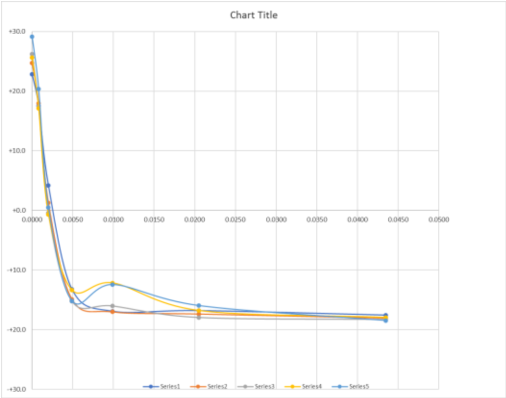
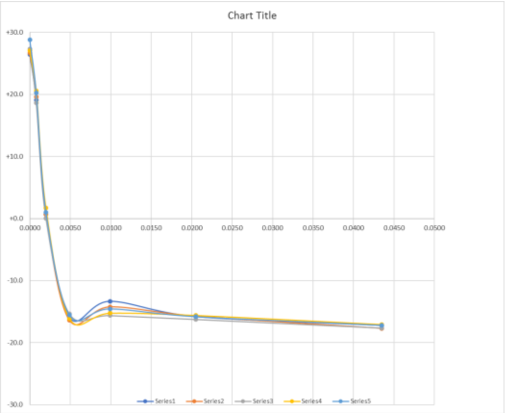
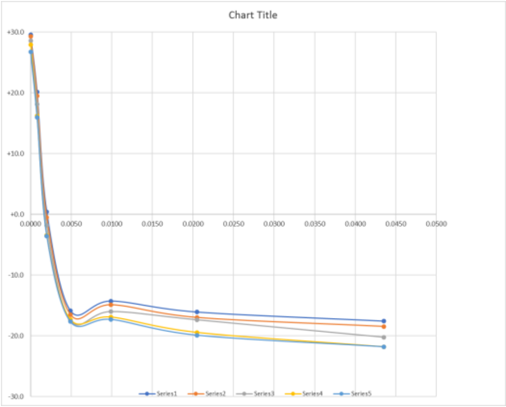
X-RAY DIFFRACTION

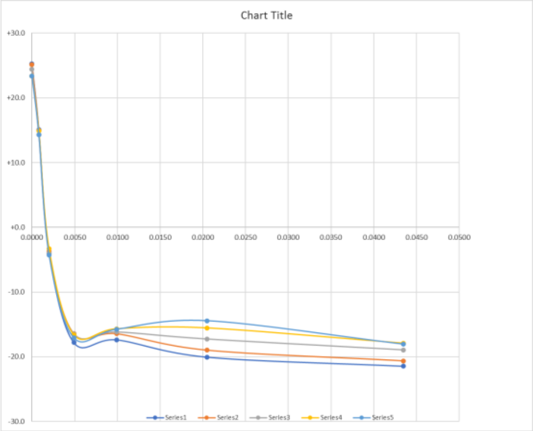
RS in Bore of Cx Hole in Geometrically Large Coupon – Depth profiles at individual points across the bore

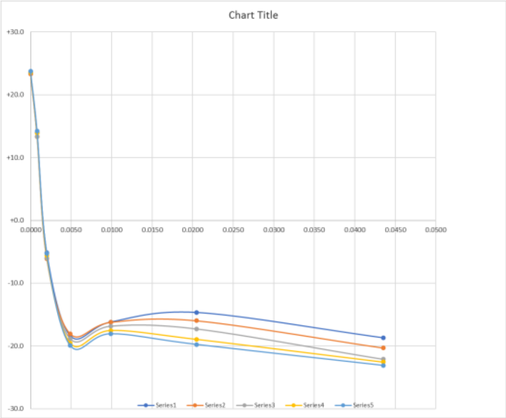


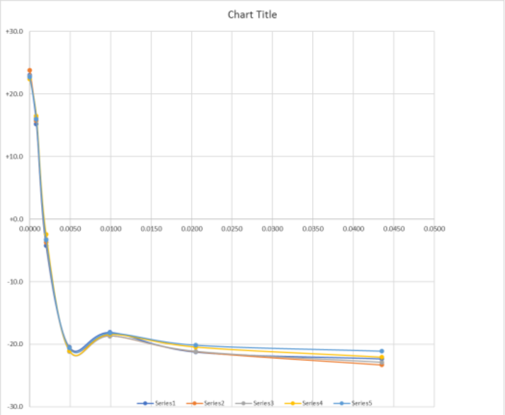


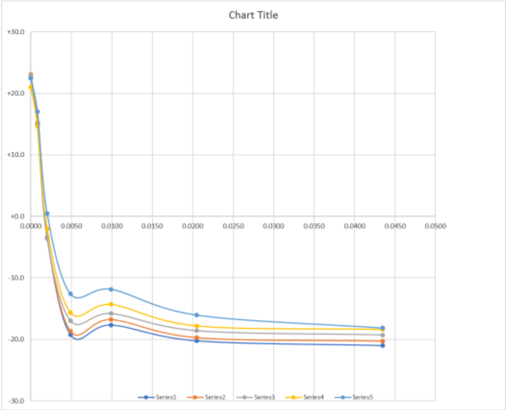












Note: Near surface cold working RS persist to about 0.010” deep

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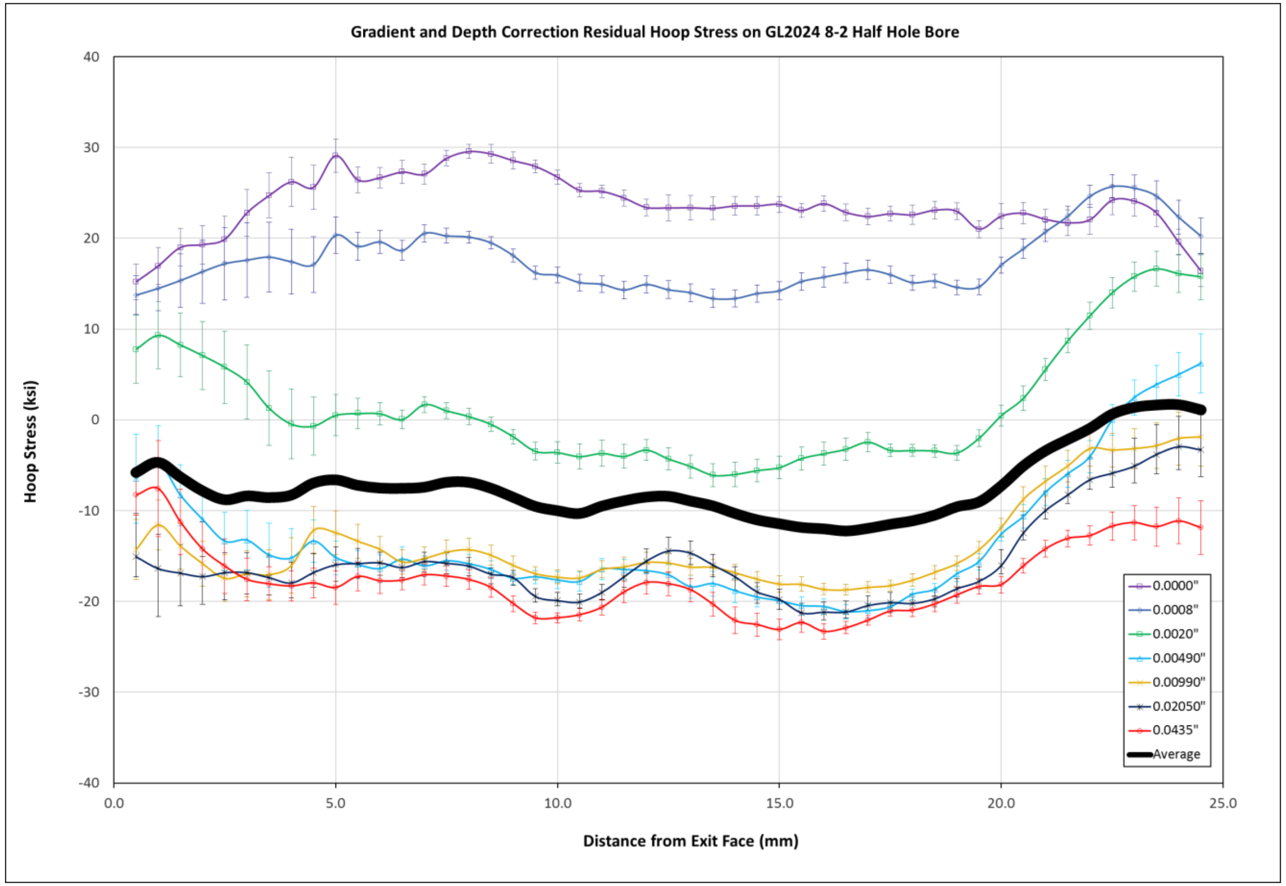
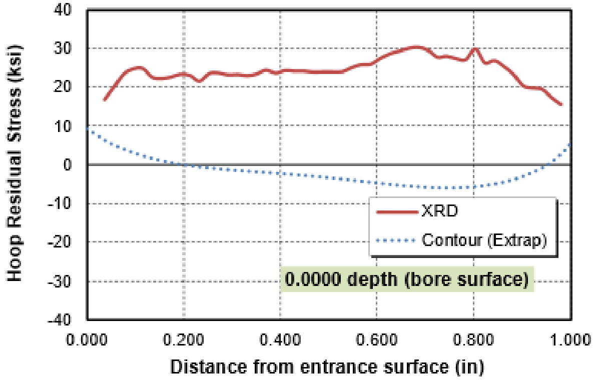
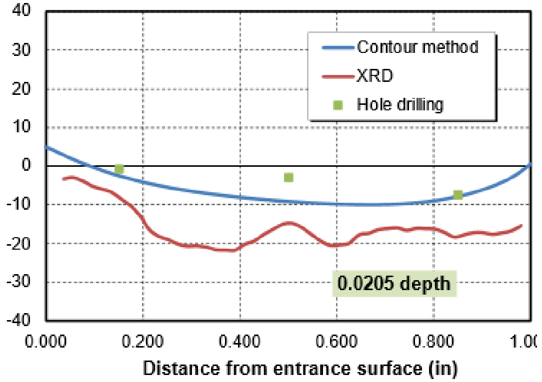
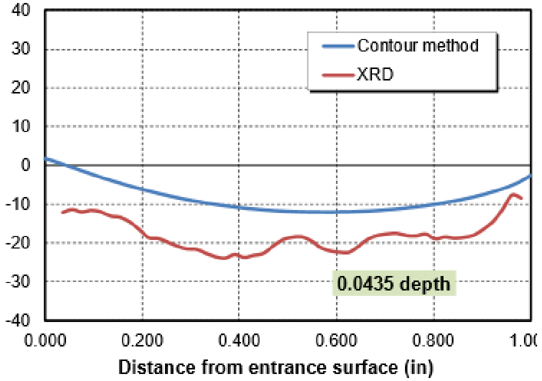
PROTO
X-RAY DIFFRACTION

RS in Bore of Cx Hole in Geometrically Large Coupon
XRD, Contour & Hole Drilling









PROTO X-RAY DIFFRACTION

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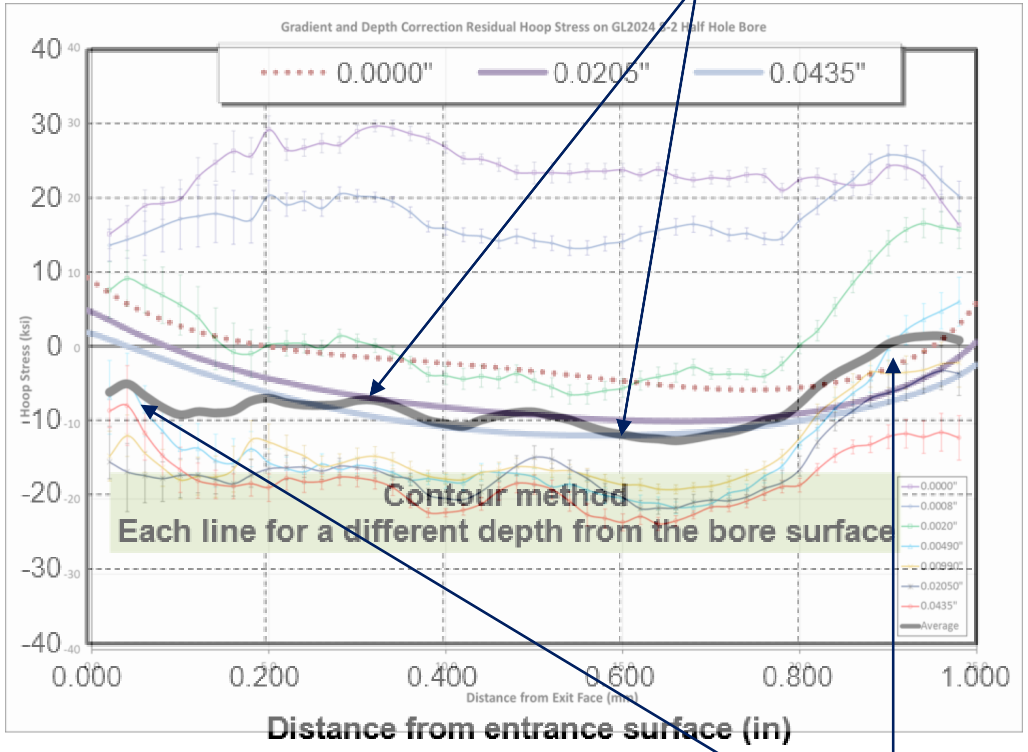
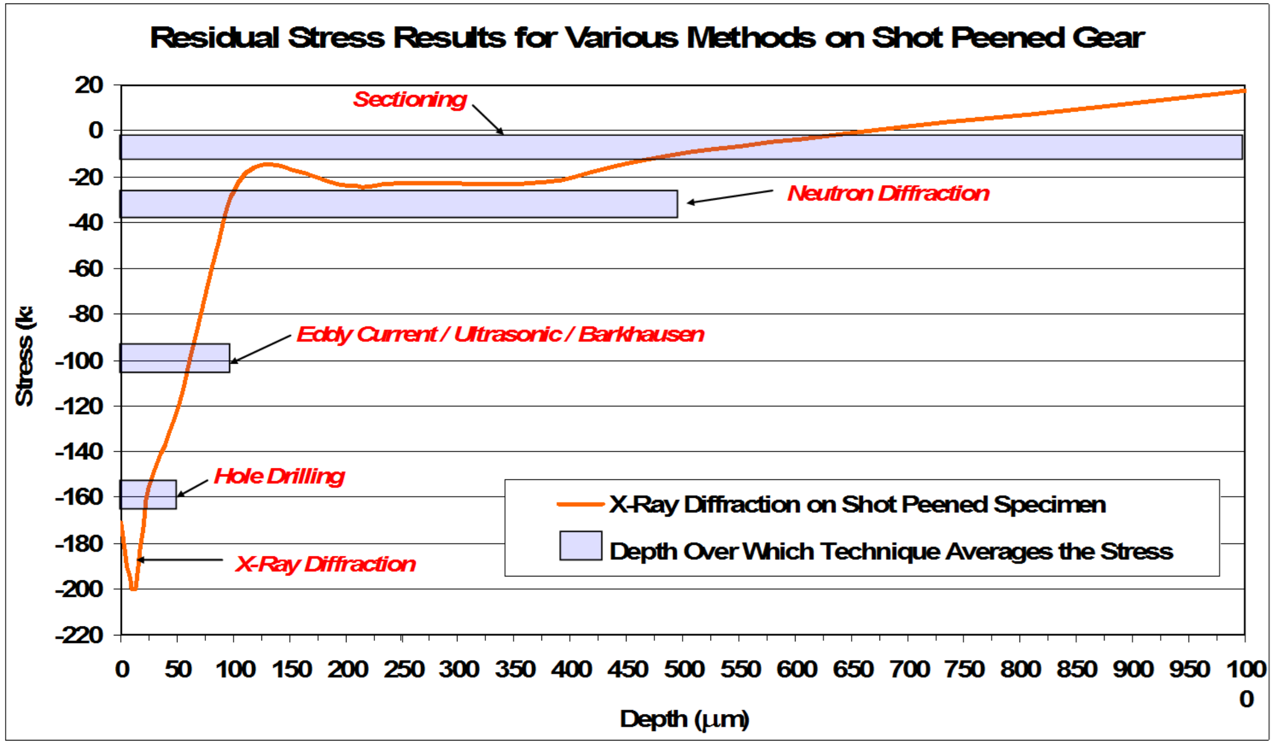
RS in Bore of Cx Hole in Geometrically Large Coupon
Inter-method considerations – yes, the world is round!

"pretty good" agreement in the center





"Ok" agreement near ENT and EXT faces

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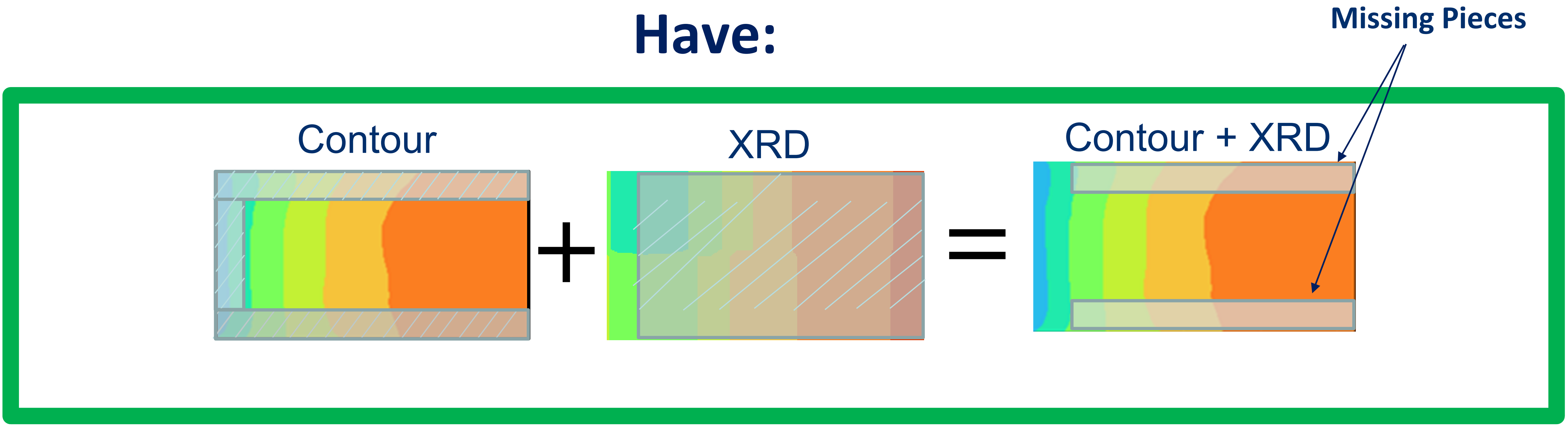
PROTO
X-RAY DIFFRACTION

Method 2 - With XRD Bore ID Data, We Now Have:



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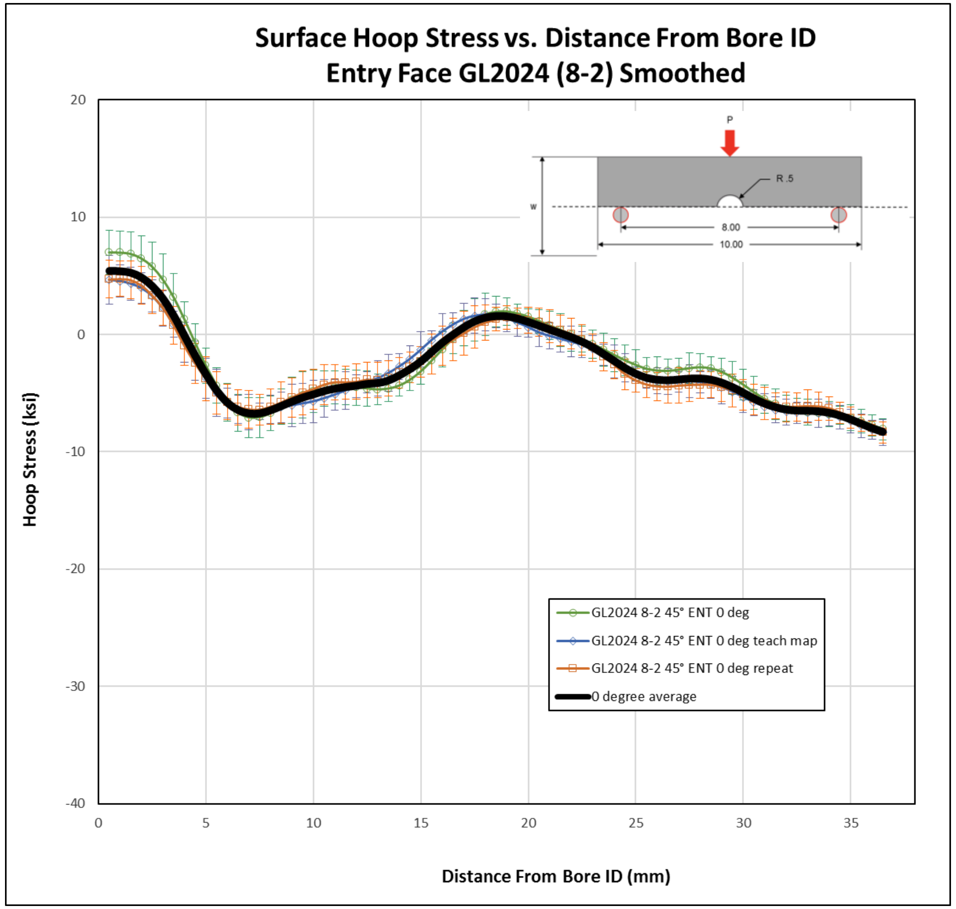
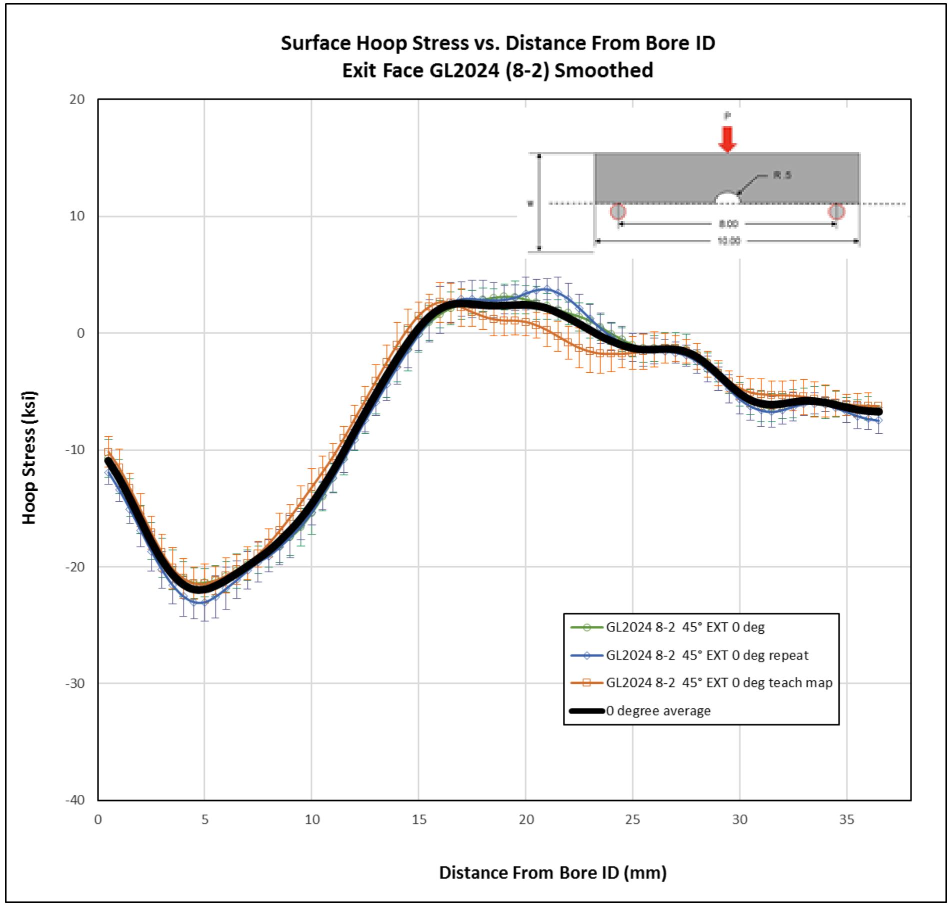
RS on Faces of Geometrically Large Coupon - Split





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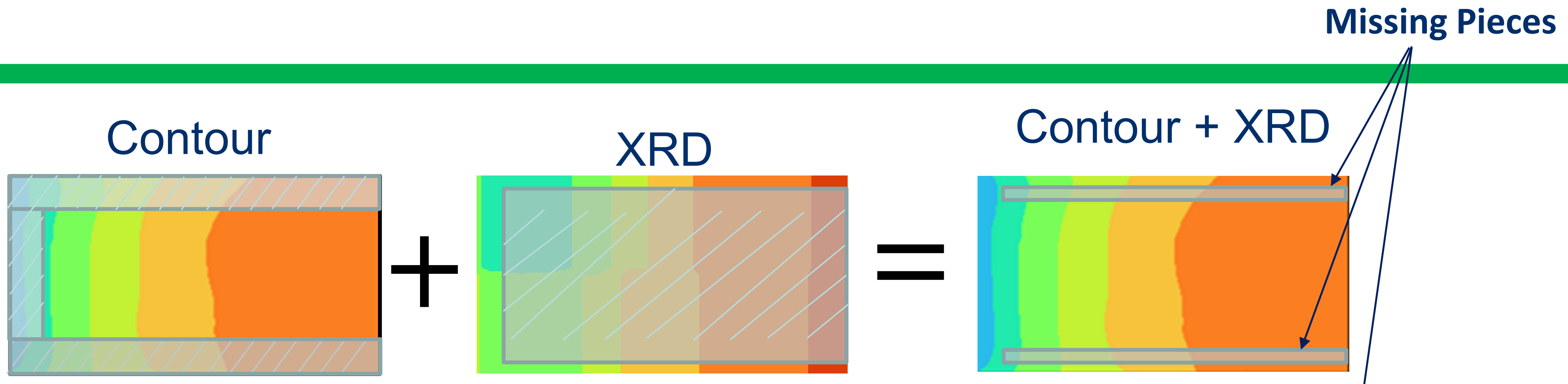
X-RAY DIFFRACTION

Method 2 -With XRD Bore ID & Face Data, We Will Have:



… and the coupon from which to obtain the last pieces of the puzzle.

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Predict. Test. Perform.

PROTO X-RAY DIFFRACTION

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The Proposed Approach (moving forward):

1) Proto to collect final data sets required to create a full field harmonized XRD + Contour RS data set.
2) Provide XRD & Contour data with GL coupon geometry & latest corner crack loading to FCG model predictions folks (blind study).
3) After blind predictions are made, compare FCG predictions to known corner crack loading FCG rates for the GL coupon configuration and loading.
4) Afford FCG model prediction folks the opportunity to revise chosen data harmonizing methods if required and re-analyze.

- Hill Engineering will provide the relevant Contour RS data, the loading and coupon information, and measured corner crack loading FCG rates after blind predictions are made.
- Proto will provide the XRD RS data.

Challenges:

1) Codify/formalize a method by which the splitting of coupons to access the bore can be corrected – leverage available Contour data and/or introduce strain gage or deformation data to account for relaxation where necessary.
2) Account for arc averaging in XRD data as may be required due to grain size where necessary and improve deconvolution methods to get optimal spatial resolution (i.e. Moate and Sprauel methods)
3) Codify/formalize methods of harmonizing XRD & Contour RS data sets for FCG predictions.
4) Note: crack growth work done to date has limitations, because the analyses are two-point analyses(?) that can be biased regardless of the data being used for residual stress.
5) The "Proposed Approach" appears to have potential but needs to be further investigated (i.e. the blind study that comes at the end).

FYI: 2x2 Group is working on a similar approach – more on that to come

Effects of Cutting Sequence & Restraint on Contour Method Residual Stress Determination in Cx Coupons

2024 ERSI Workshop – San Antonio, TX

Presented by: Scott Carlson
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  - www.stress-space.com
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stress-space Ltd

esa business incubation centre UK

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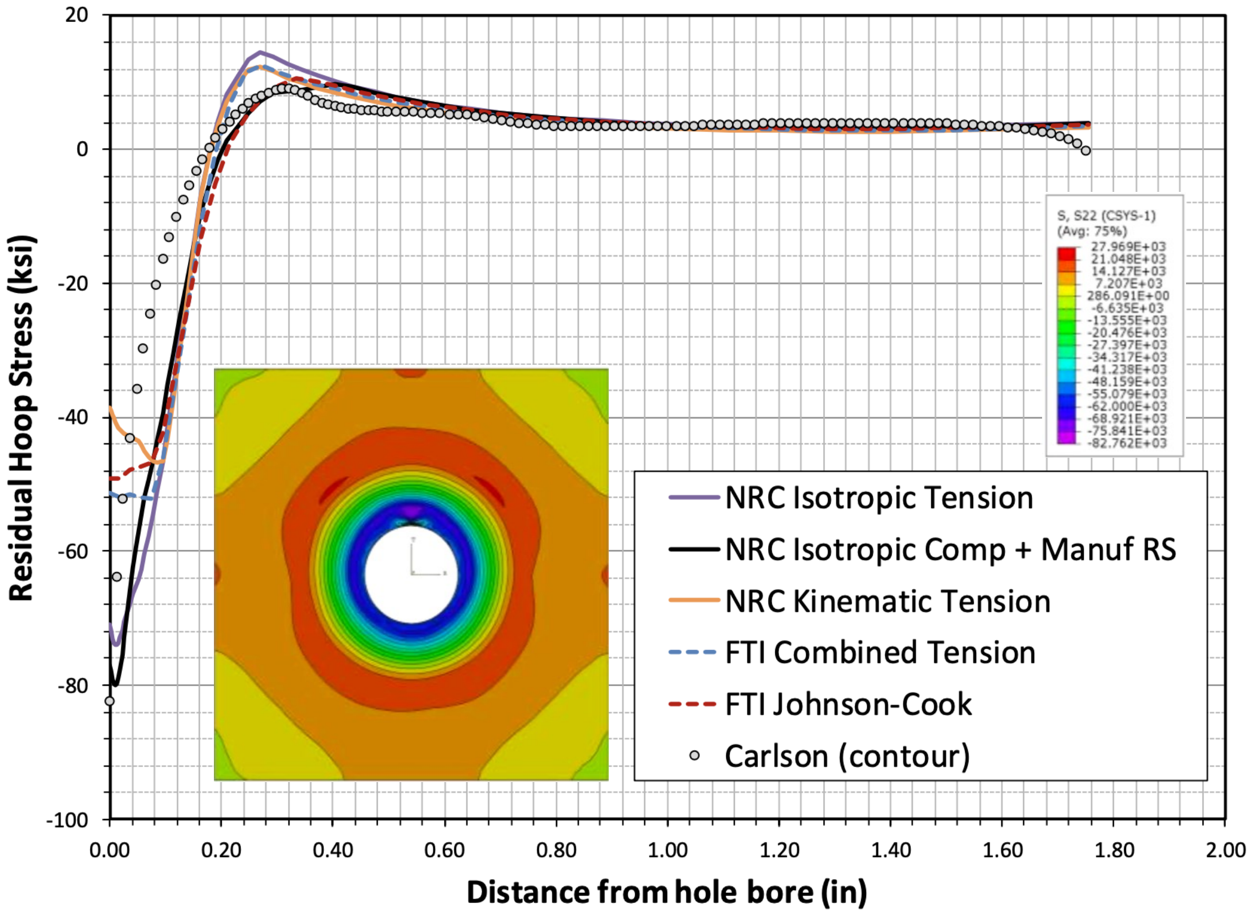
Cx Stress Characterization Requirements

- It is required to determine, with high certainty, the distribution of hoop residual stress approaching the bore of a cold expanded hole in order to take full benefit of the ”engineered residual stress” condition.



- A 2016 NRC-FTI-SwRI benchmark exercise comparing Cx residual stress predictions with average contour method data showed significant discrepancies in Cx stress profiles up to 5 mm (0.2”) from the bore.
- Characterizing the residual stress field of interest by modelling and measurement remains challenging today!

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Factors Affecting Cx Residual Stresses

- Test coupon geometry (representing the structure of interest).
  - Dimensions
  - Hole diameter
  - Edge margin
- Manufacturing history
  - Consequences of rolling (surface residual stresses and material texture)
- Material
  - Elastic properties
  - First cycle non-linear stress-strain behaviour under multi-axial loading
- Loading
  - Level of cold expansion introduced
  - Cx process design

The Contour Method (CM)

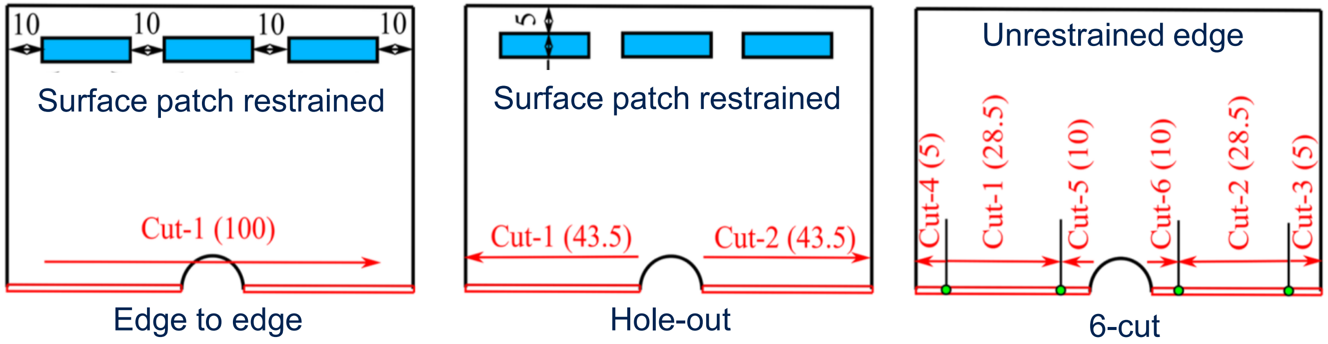
- The CM offers the prospect of determining cross-sectional maps of hoop residual introduced by the Cx process in laboratory fatigue test coupons
- But the accuracy of CM residual stress profiles can be compromised by:
  1. Cutting induced plasticity (CIP) error
  2. Cutting induced elastic error (referred to as bulge error)
  3. Cutting wire anomalies when exiting a sample
  4. Wire feed entry/exit cutting artefacts
  5. Wire EDM cutting anomalies (breaks, barrelling, steps, instabilities etc)
  6. Metrology and data processing methods
- Factors 4 to 6 can be mitigated by good measurement practice
- Factors 1 to 3 can be managed, and potentially mitigated, by controlling the **contour cutting sequence** and **boundary conditions**

CM Accuracy Assessment - Detailed

- Simulate the residual stress field introduced by the Cx process for the specific coupon design, manufacturing history, cold expansion and materials of interest.
  - Create 3D FE model of coupon and perform an elastic-plastic stress analysis for a uniform through-thickness radial expansion applied to the bore of the hole. This introduces a representative residual stress profile at mid-thickness and a surface average profile.
- Perform a series of elastic-plastic FE analyses simulating progressive CM cutting of the modelled Cx coupon in order to predict plastic strains (PEEQ) introduced along the cut path and the surface displacement.
  - Compare PEEQ profiles from different CM cutting sequence/boundary conditions.
  - Apply the predicted surface deformation profile to an elastic FE model of one half of the coupon to simulate the CM determined stress profile. Compare this profile with the initial simulation of the Cx stress field to quantify any error.

Assessment Results for ERSI (5x4)" Coupons

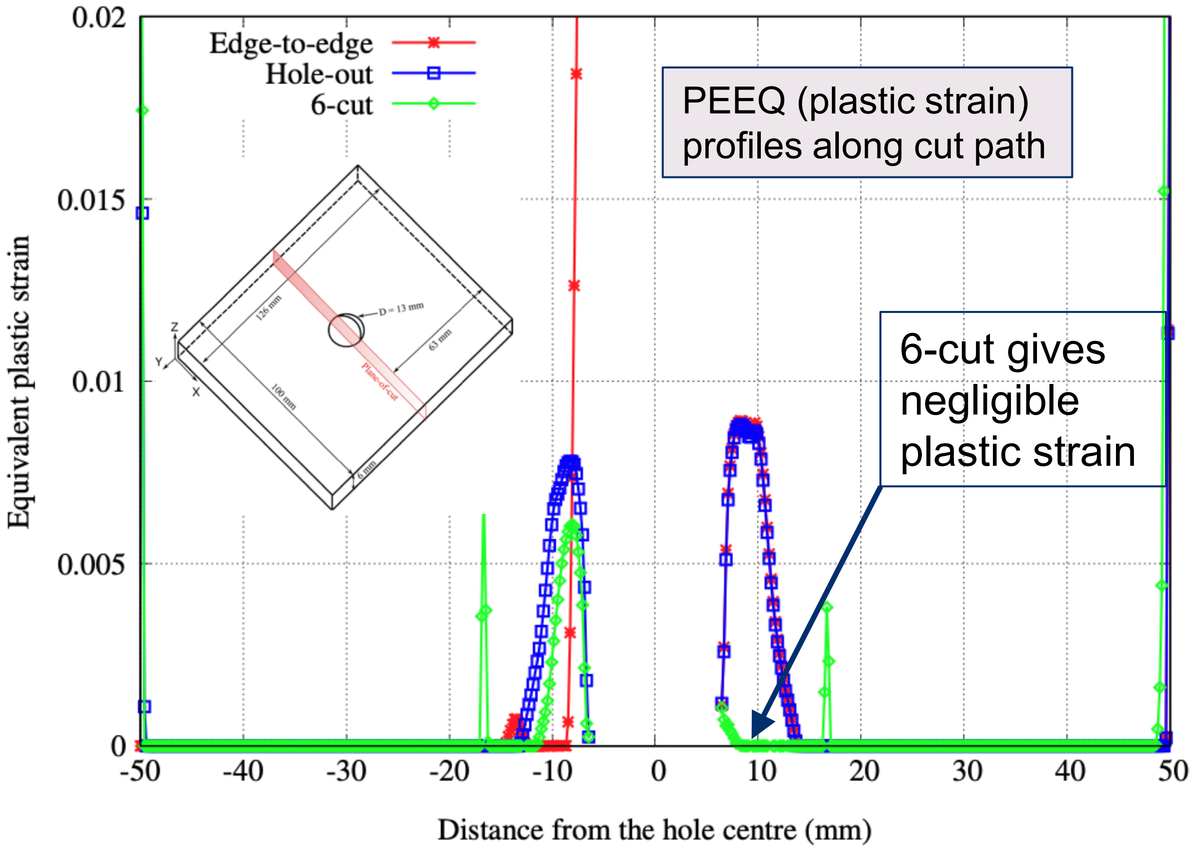
https://doi.org/10.1007/s11340-021-00756-z



6-cut and hole-out best on LHS

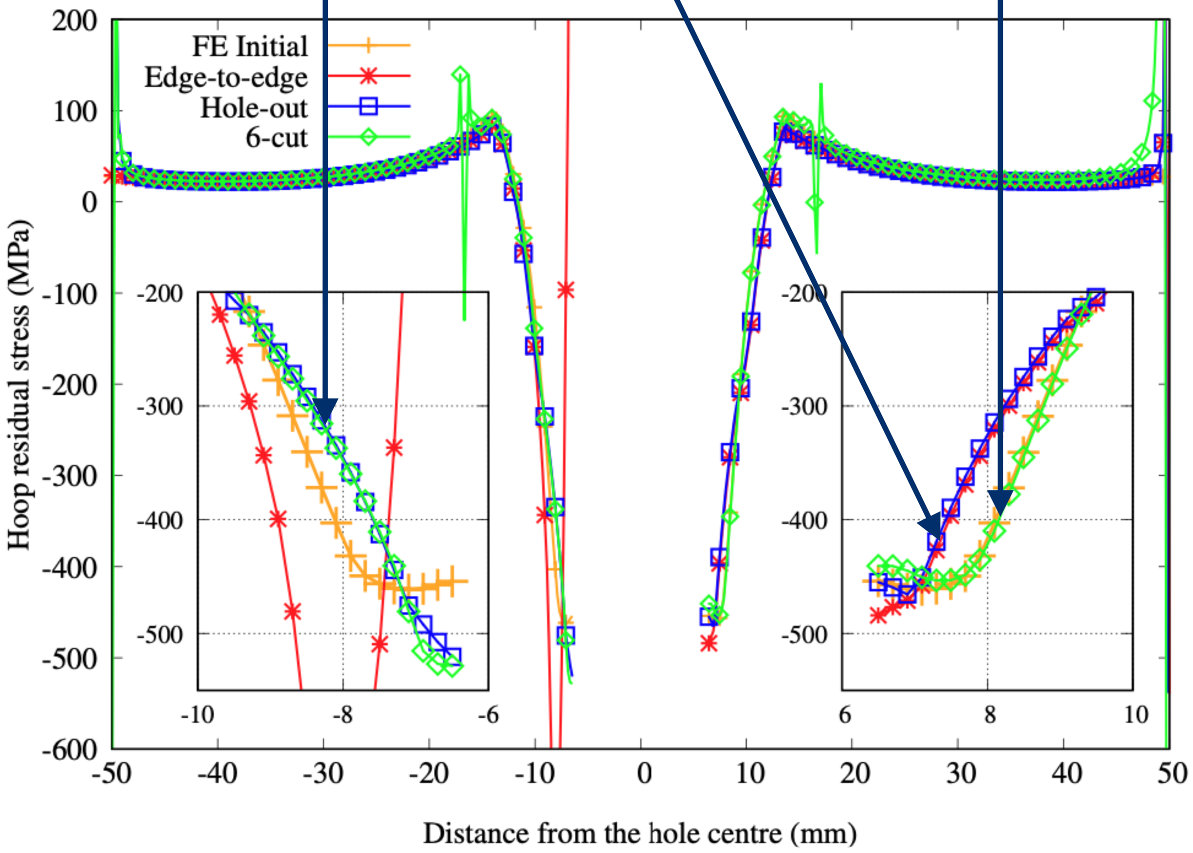
Hole-out 2nd best on RHS

6-cut gives accurate RHS stress profile



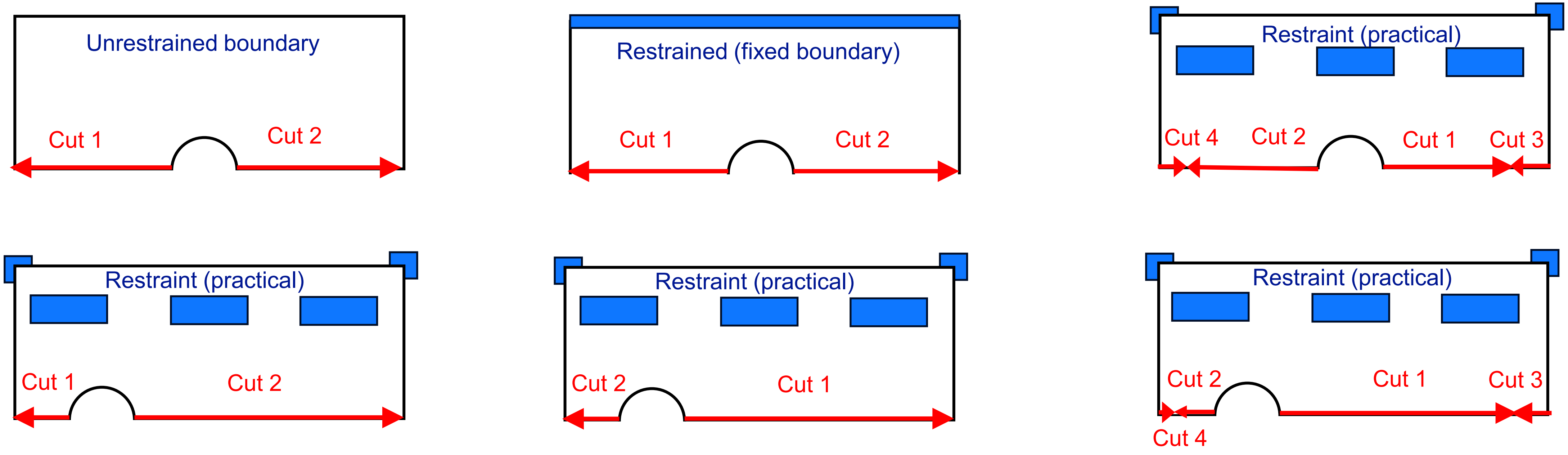
PEEQ (plastic strain) profiles along cut path

6-cut gives negligible plastic strain



CM Cut Sequencing and Restraint

- Cutting induced plasticity (CIP) arises when stresses ahead of the CM wire EDM cut (a blunt crack) exceed the material yield strength.
- The cut SIF can be used to help select the cutting sequence and coupon boundary conditions that will minimize CIP in the region of interest that can introduce stress errors.



Illustrating some CM cut sequence and coupon restraint options for symmetric and short edge margin coupons

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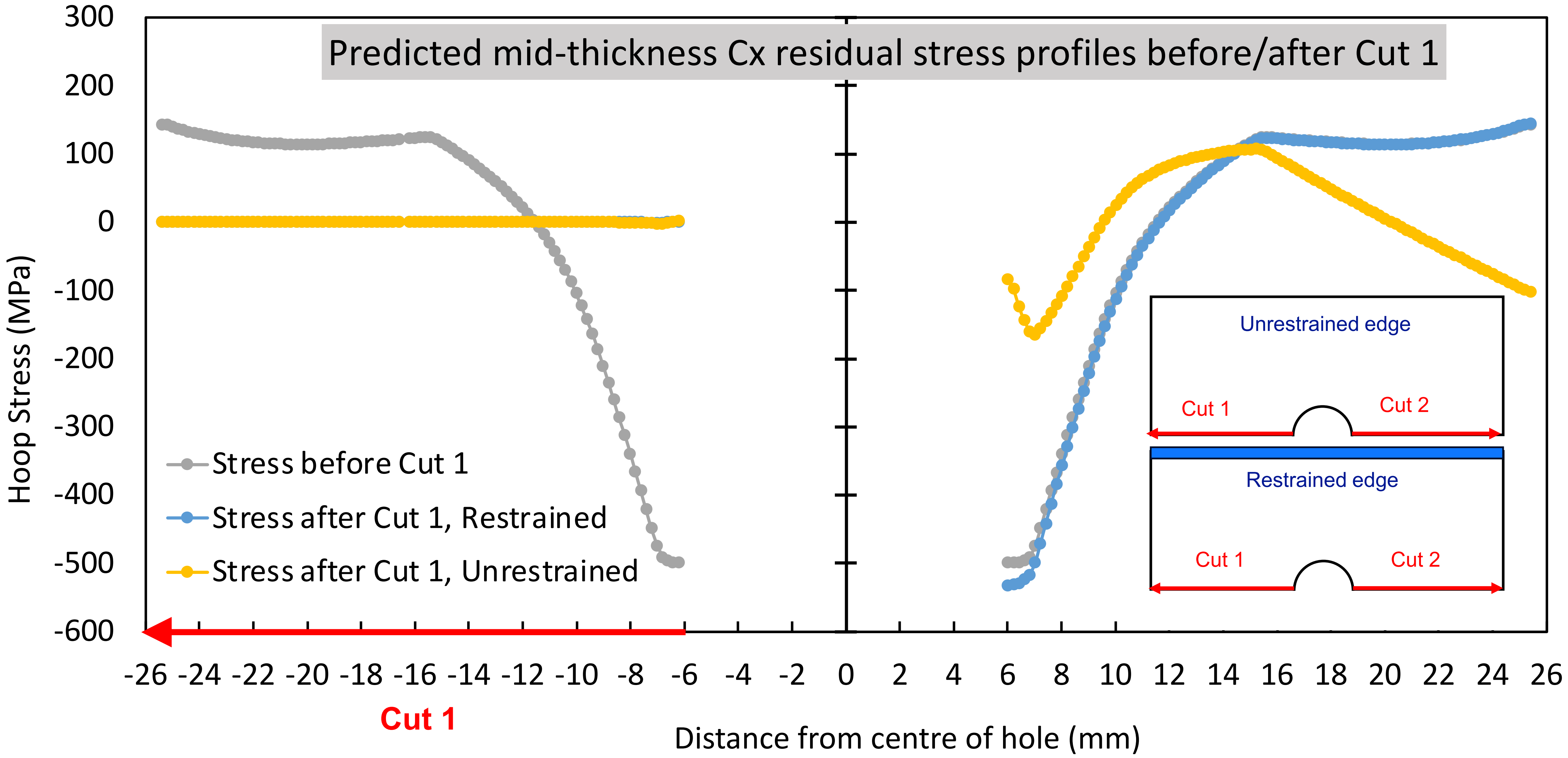
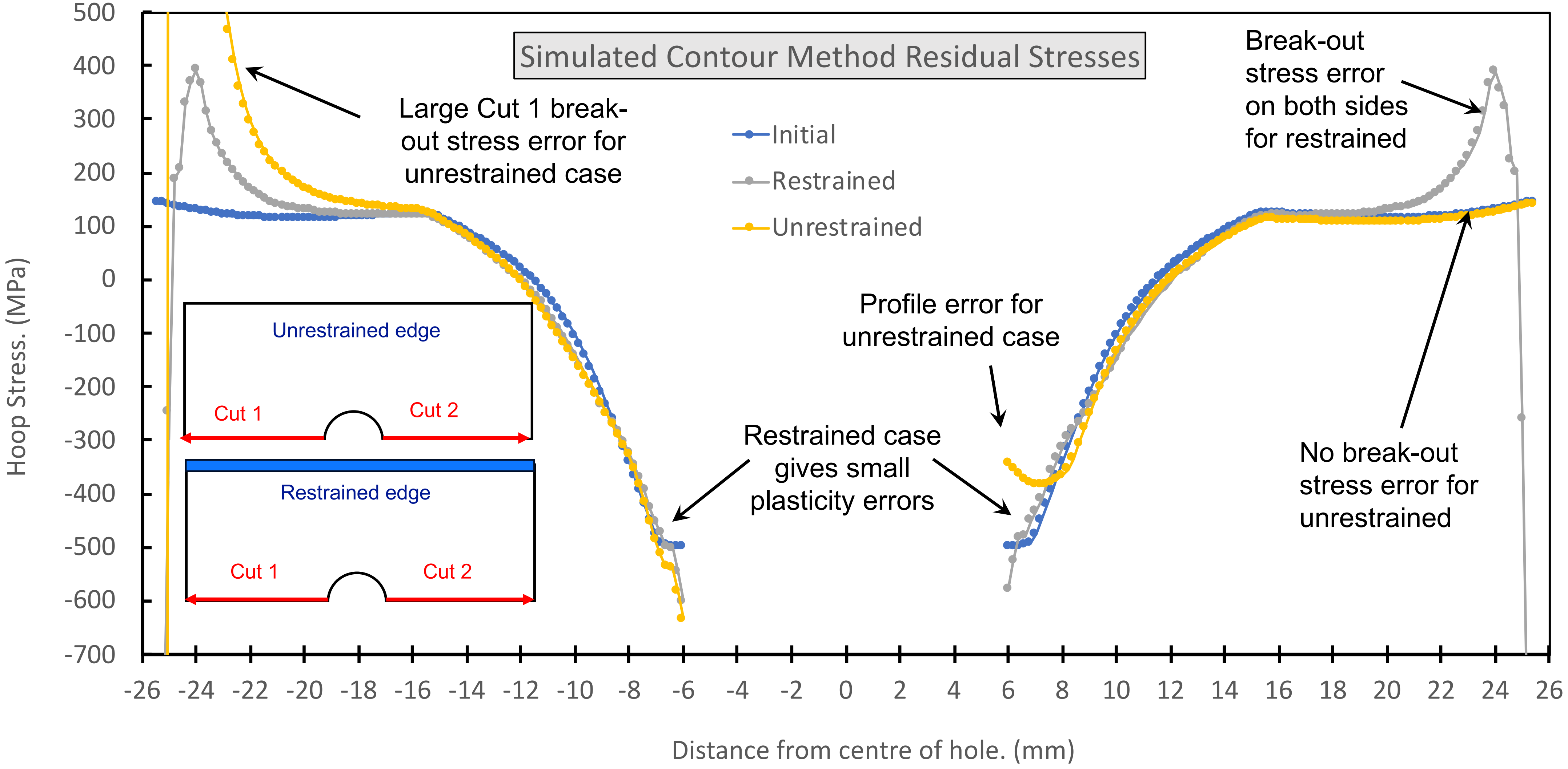
Predicted Stresses in ERSI Coupon 2024 H1

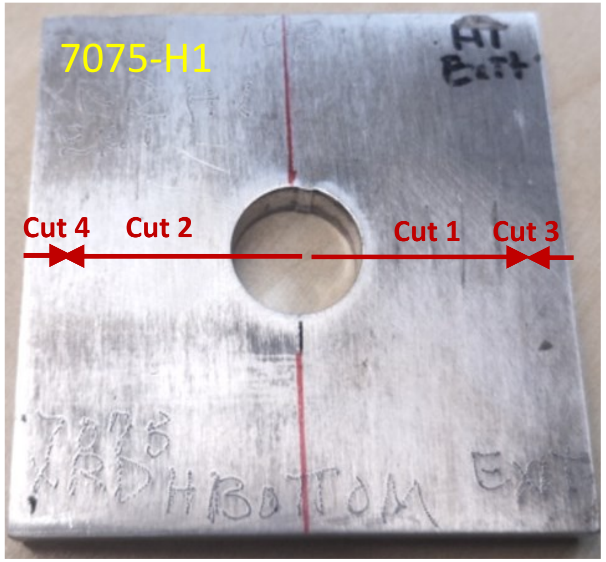


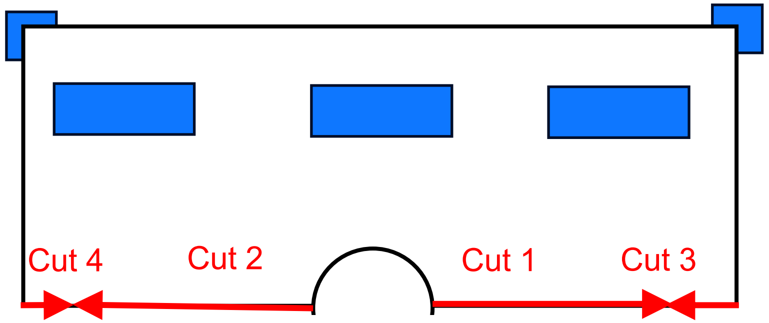
Detailed Prediction of CM Stress Profile

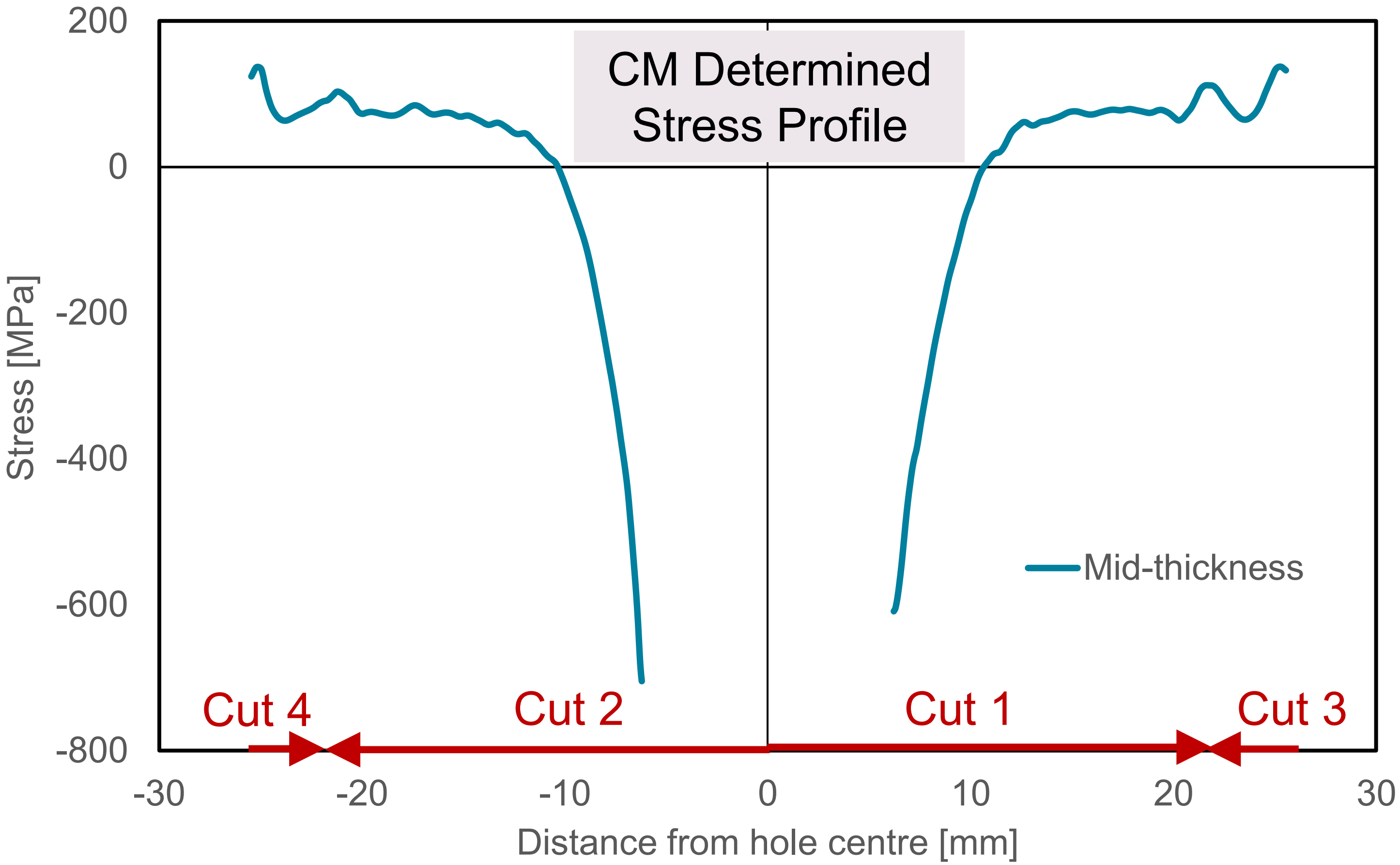


Application of Findings to ERSI 7075-H1

- Fully restrained case is predicted to give most accurate stresses approaching the hole bore.
- Accuracy of stresses near "break-out" can be improved by using a 4-pass cut sequence.







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Other Considerations

- The practicality of cutting sequences must be assessed (e.g. the 6-cut sequence is impractical for 2 x 2 inch coupons).
- Avoid cutting sequences where the wire exits the coupon at or near the region of interest (i.e. at the hole). This is because very high stresses and plasticity develop ahead of the cut prior to break-through generating CM displacement and stress errors.
- The practicality of applying restraint conditions during wire EDM cutting of coupons must be considered.
- The smallest dia wire should be used for EDM cutting as this reduces elastic bulge errors (which can be significant in the region of interest).
- Its possible to correct CM determined stress profiles for elastic bulge errors.

Insights into the Testing of Sleeveless Cold Expansion Processes *(Why we must be specific and "words mean stuff")*

2024 ERSI Workshop – San Antonio, TX

Presented by: Scott Carlson
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Acknowledgements

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- James Pineault (Proto) – xrdlab@protoxrd.com

Agenda for Presentation

- Motivation for Sleeveless Cx Implementation
- Mechanics of Sleeved vs. Sleeveless Cx Processes
- FEA Simulations of Residual Stress Profiles
  - XRD results of Ent. and Ext. surfaces
- Effects of Applied Expansion on Crack Growth Life
  - Crack growth life differences in original matrix
    - Nominal vs. Tailored applied expansion levels
- Effects of Expansion Methods on Cracking Morphology
  - "Entrance" and "pinning" effects on crack formation and propagation

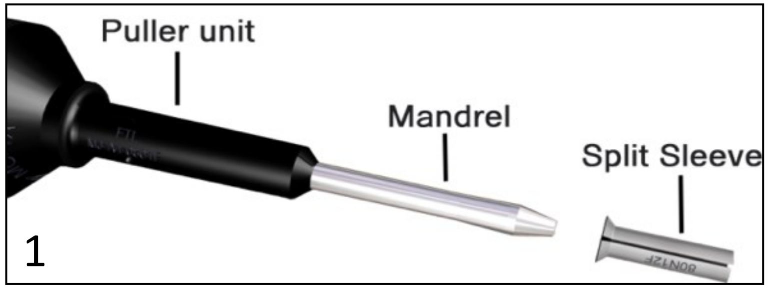
Motivation for Sleeveless Cx Process

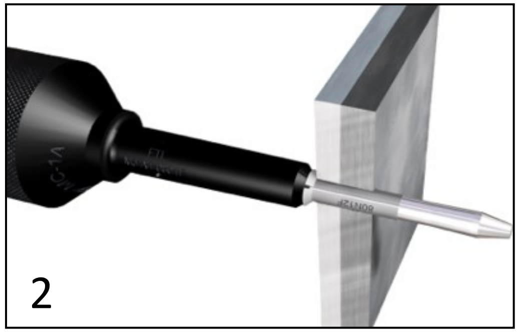
- Cx is Often Used During Production to Meet Life Requirements
- Potential for Automation of Cold Expansion Process
  - Very challenging to have a robot insert the split sleeve
    - Sleeveless would allow a “one-step” Cx process
    - Would eliminate the sleeve clocking requirement
  - Application of the Cx process requires significant touch hrs.
    - Multiple steps during the drilling and reaming process
    - Requires additional de-stack and deburr steps
    - Clocking orientation for the sleeve can require Eng. Approval
- Unlocks the Potential to Drill, Cx and Ream with 1 Tool
  - Dramatic decrease in process time for manufacturing

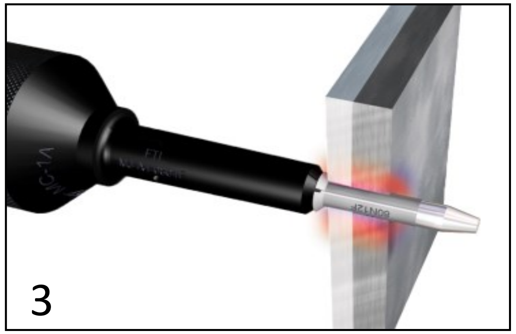
Split Sleeve Cx (SsCx) Process

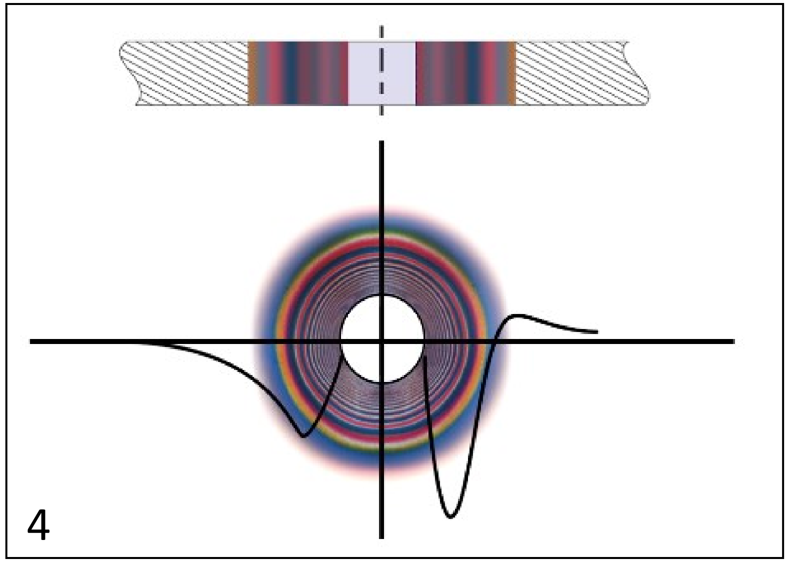
Split Sleeve Cold Expansion

- Legacy Cold Expansion process first conceptualized in 1969
- Proprietary lubricated split sleeve is key component in the process
  1. The split sleeve is slipped onto the mandrel, which is attached to the hydraulic puller unit.
  2. The mandrel and sleeve are inserted into the hole with the nosecap held firmly against the workpiece.
  3. When the puller is activated, the mandrel is drawn through the sleeve, radially expanding the hole.
  4. Residual Compressive stresses induced from the split sleeve cold expansion process improve in-service fatigue life.







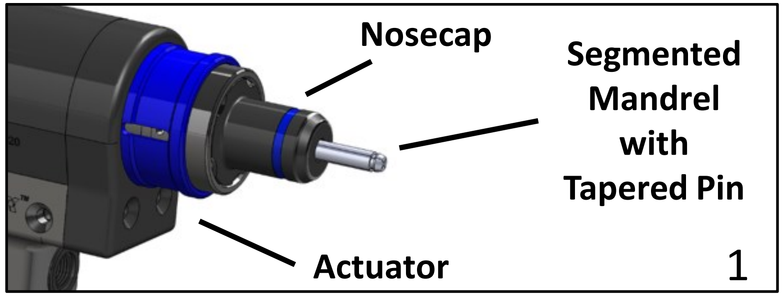


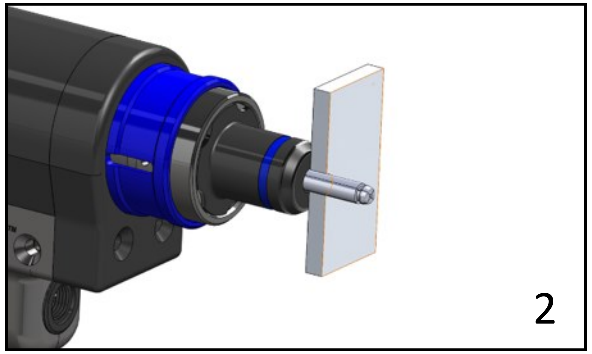
SmartCx (SmCx) Process

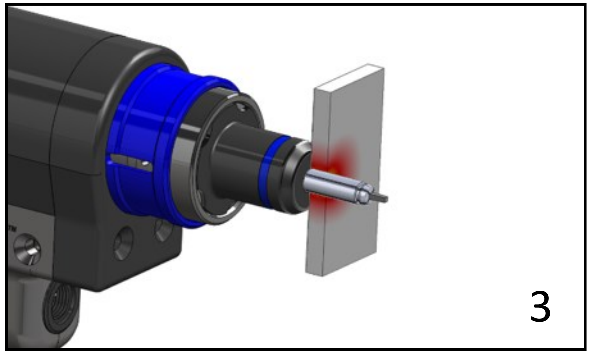
SmartCx Cold Expansion

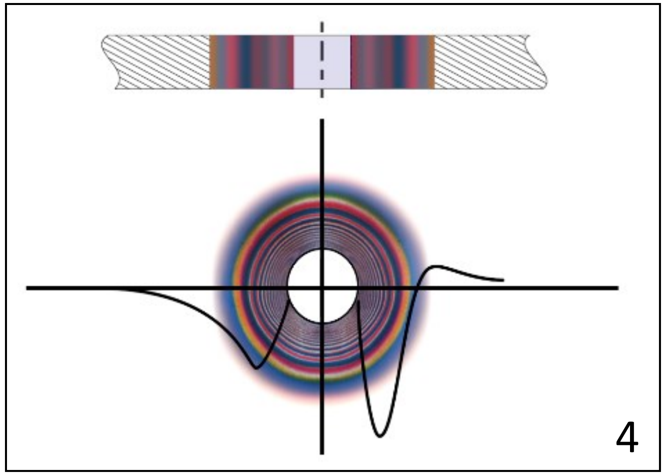
- New Cx process to provide a variable expansion, “sleeveless” solution for Cold Expansion
- Proprietary segmented expansion mandrel is the key component in the process:

1. The segmented mandrel and tapered pin are attached to the actuator and “tuned” to the required expansion.
2. The segmented mandrel is inserted into the hole with the nosecap held firmly against the workpiece.
3. When the actuator is activated, the piston pushes the tapered pin into the segmented mandrel, causing the mandrel segments to spread outward, radially expanding the hole.
4. Residual Compressive stresses induced from the SmartCx cold expansion process improve in-service fatigue life.





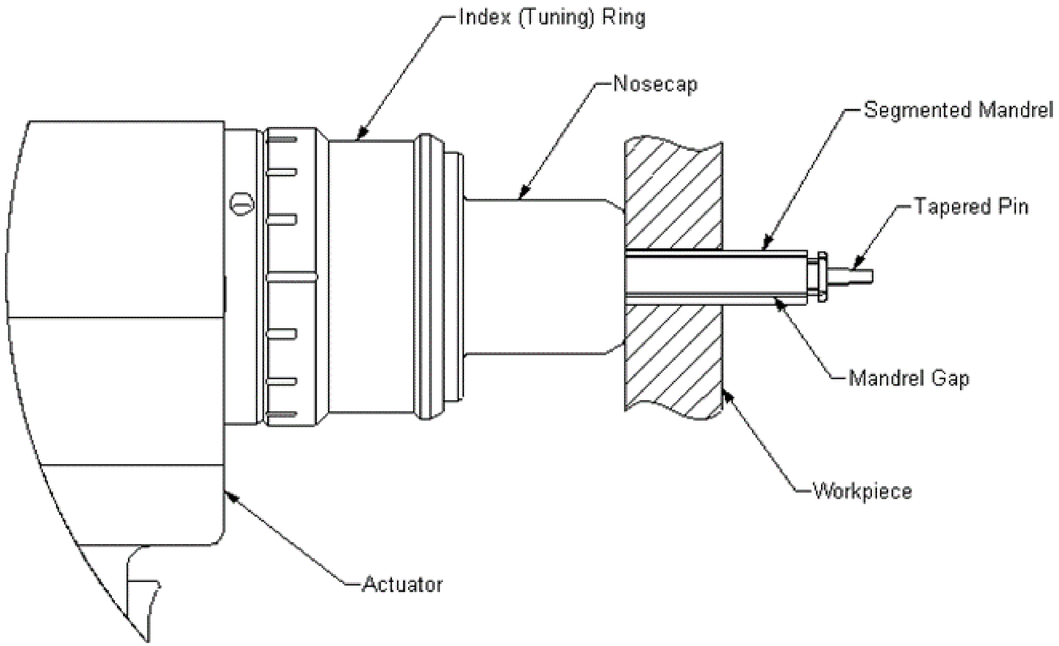


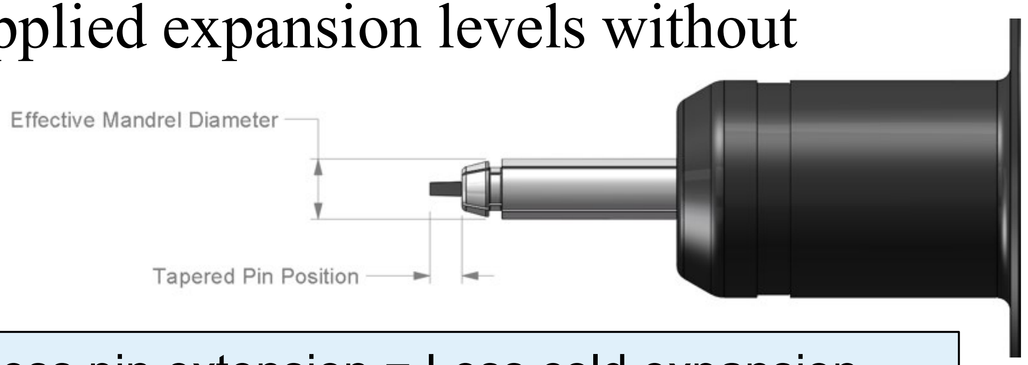


SmartCx Adjustable Expansion

Applied Expansion is variable by adjusting a “tuning” ring on the tool. Adjustments change the position of the segmented mandrel relative to the tapered pin, thus changing the Effective Mandrel Diameter.

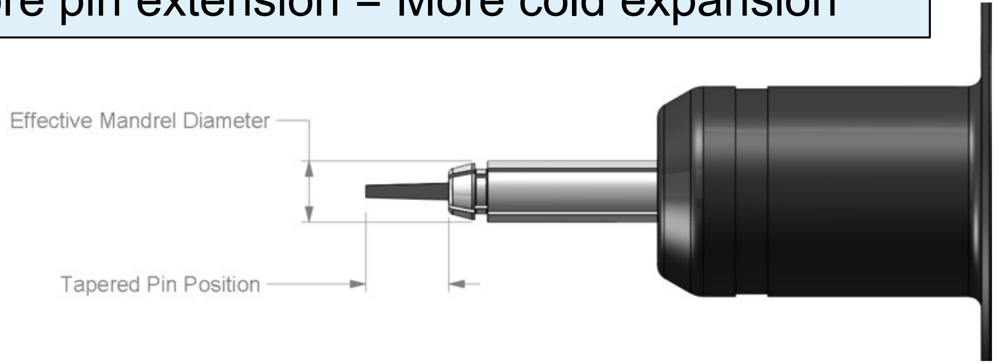
- “Tuning” the mandrel diameter supports various applied expansion levels without changing mandrels





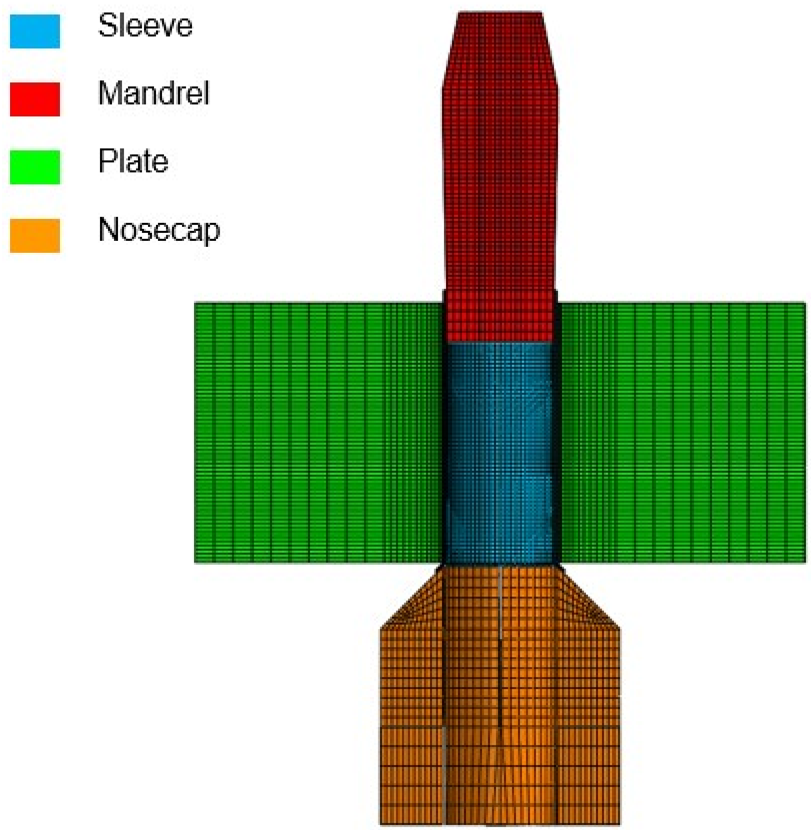
Less pin extension = Less cold expansion

More pin extension = More cold expansion



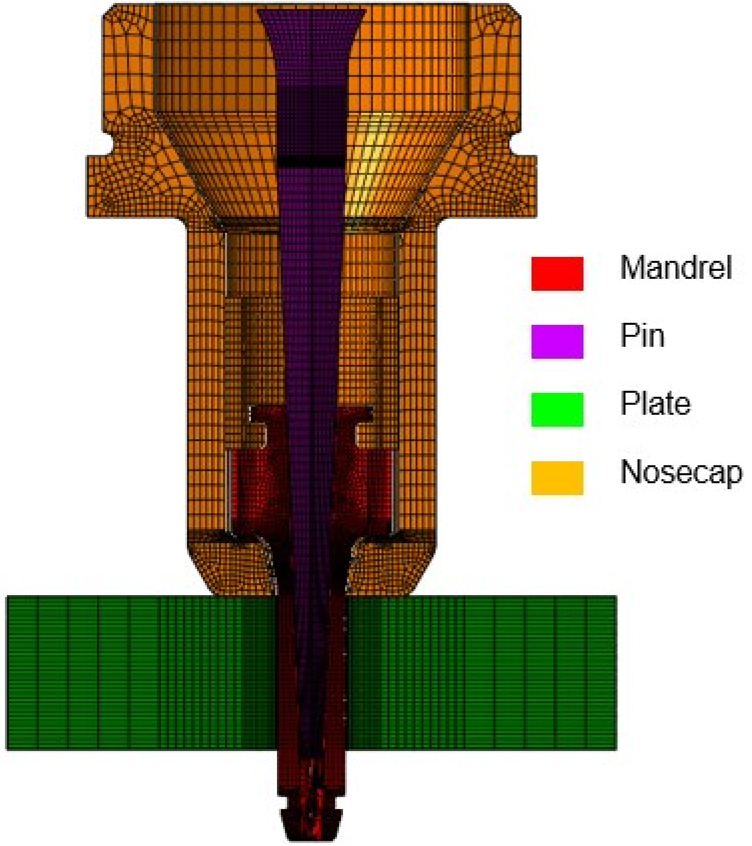
Process Modeling Comparison

SsCx



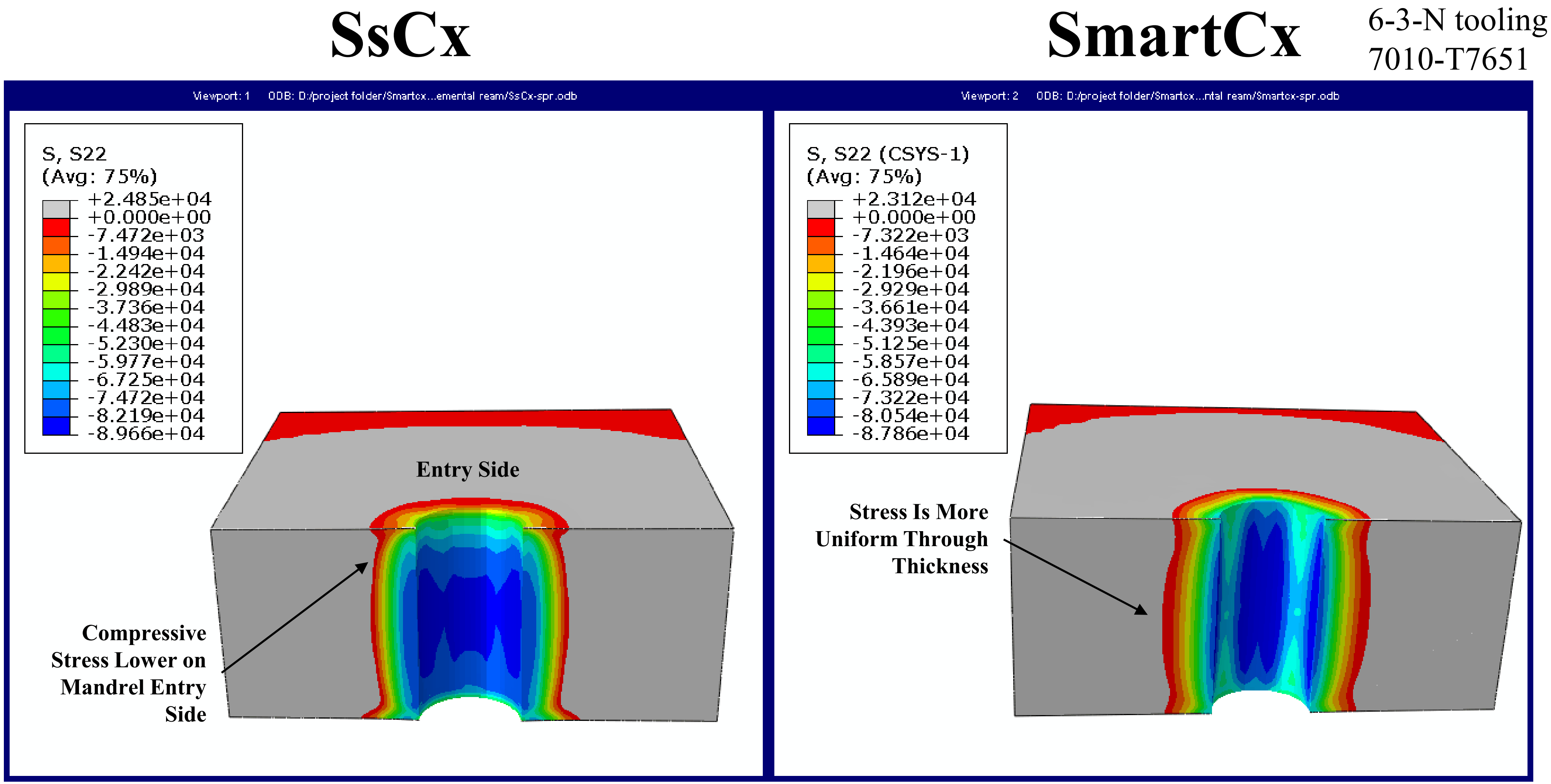
Parameters
6-3-N tooling (or equivalent)
7010-T7651

SmartCx



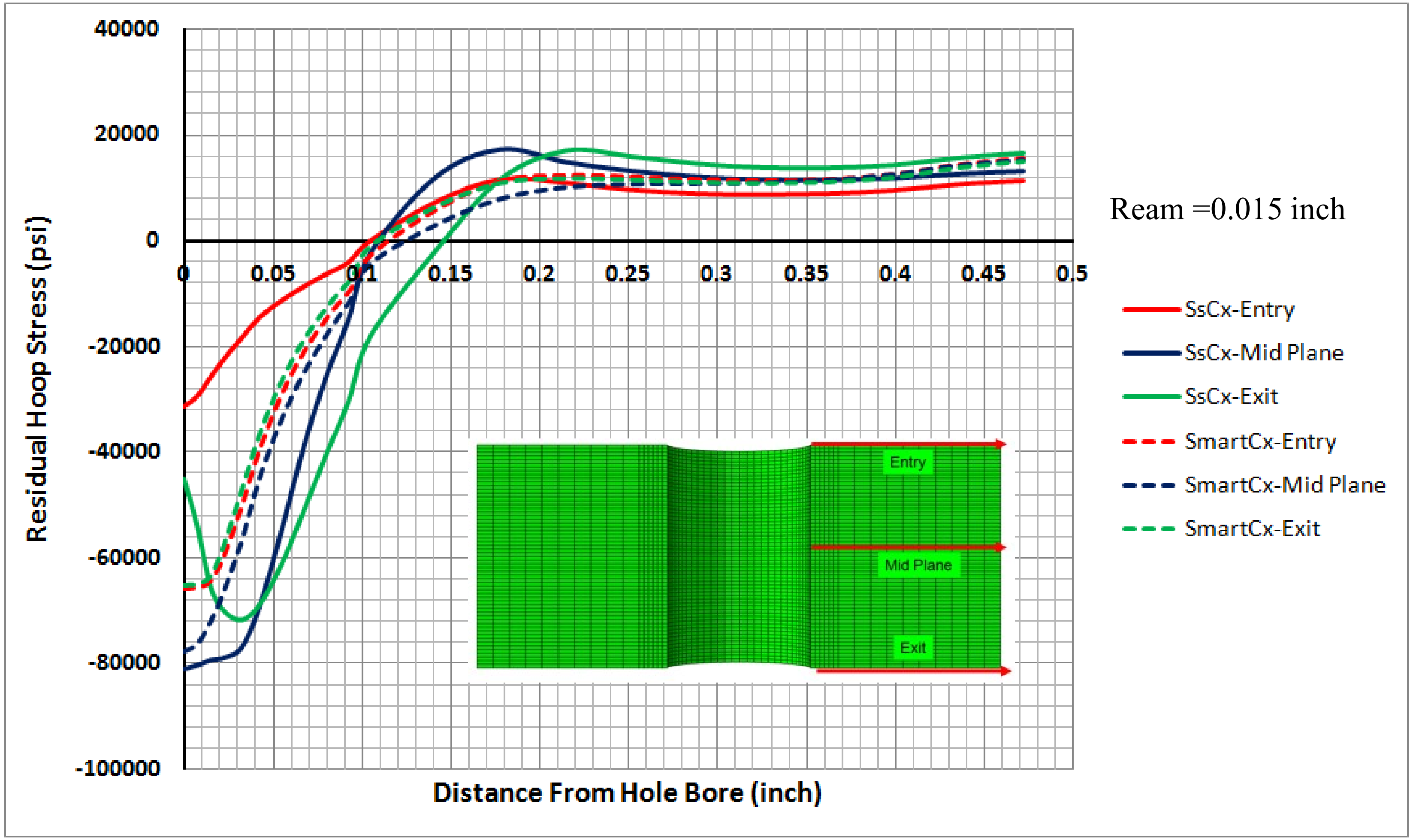
Process Modeling Comparison - Example

Parameters
6-3-N tooling (or equivalent)
7010-T7651



Post-Ream Compressive Hoop Stress (psi) – Contour Plot

Process Modeling Comparison - Example



Parameters
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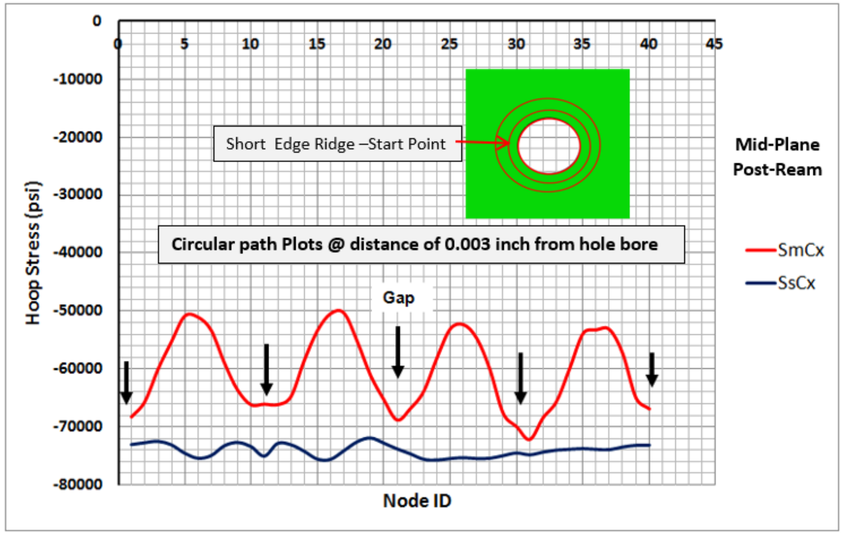
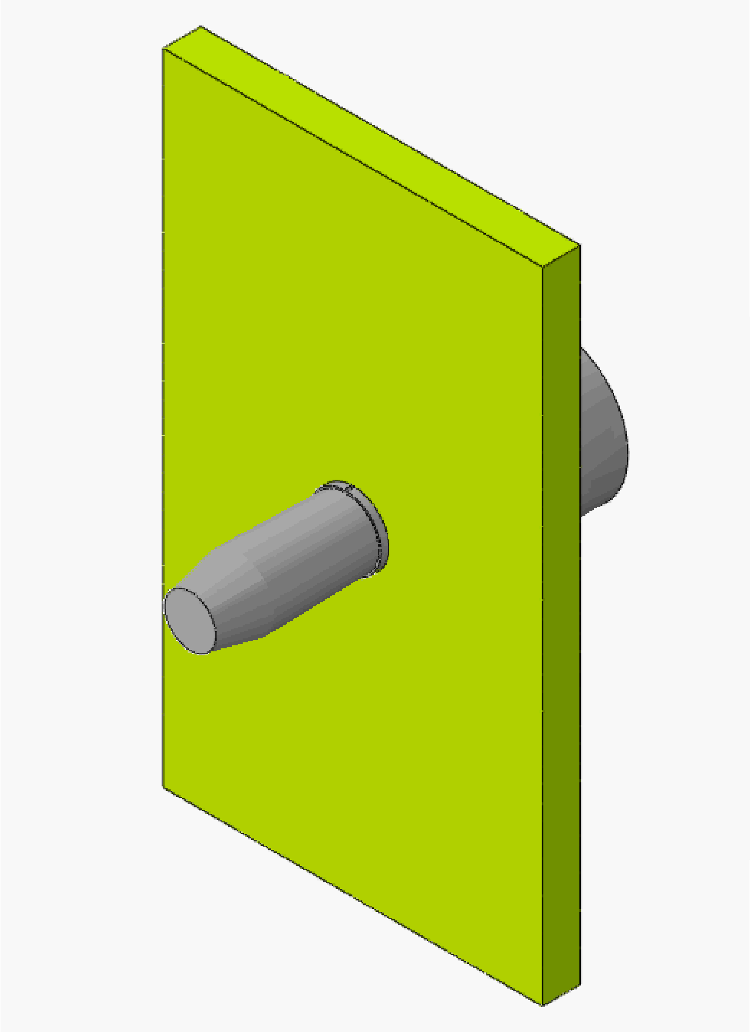
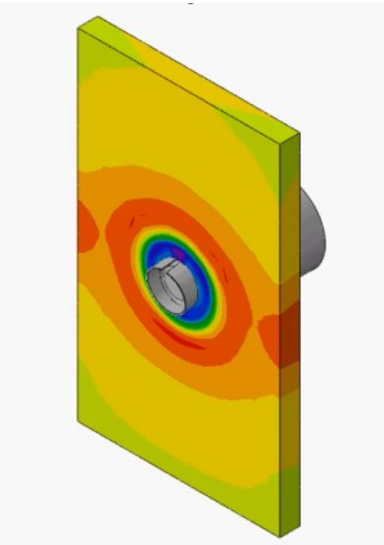
7010-T7651



Process Modeling Animations

SsCx





Parameters
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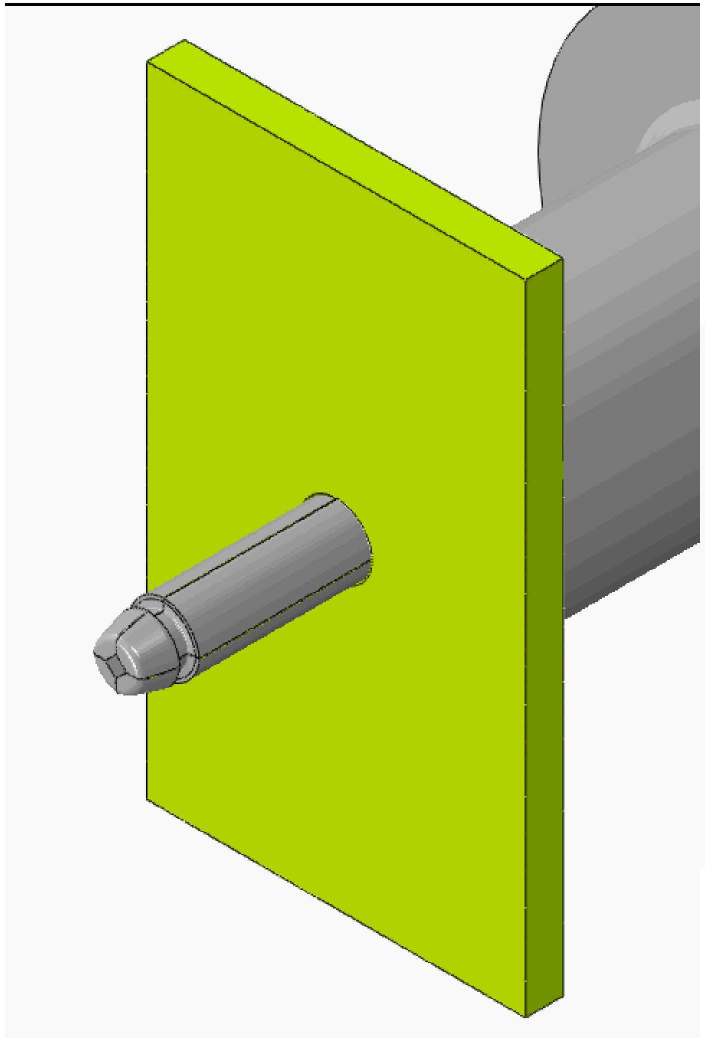
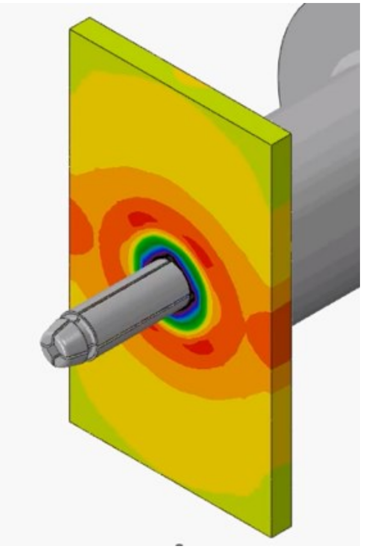
7010-T7651

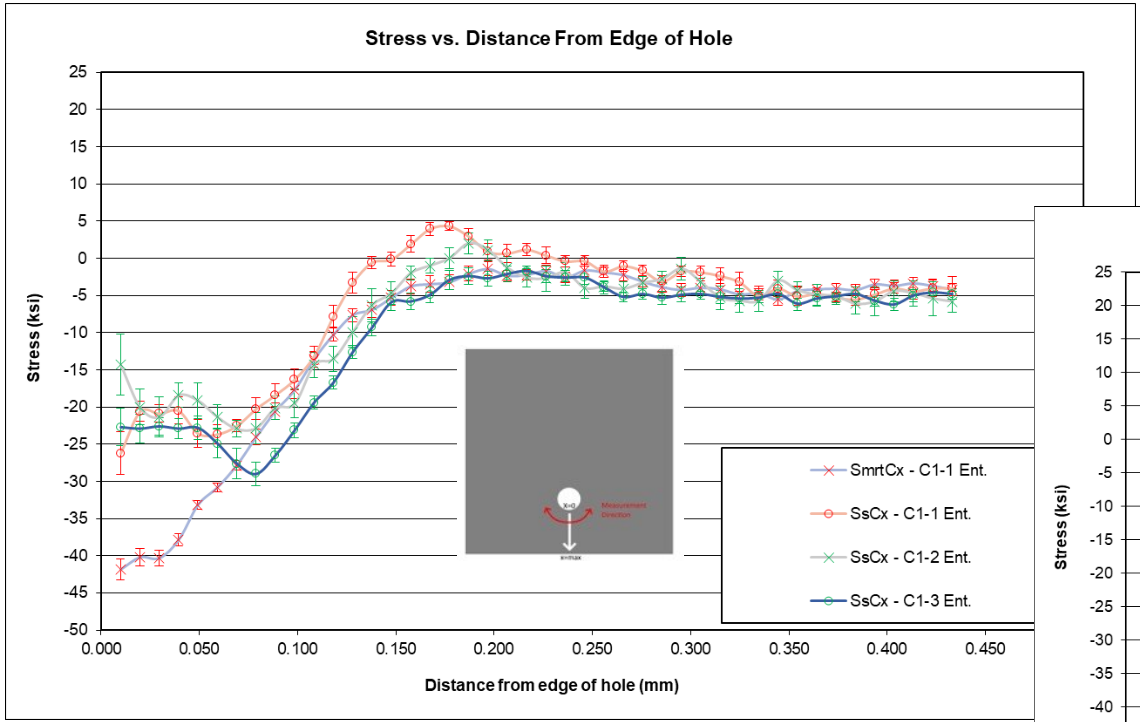
SmartCx

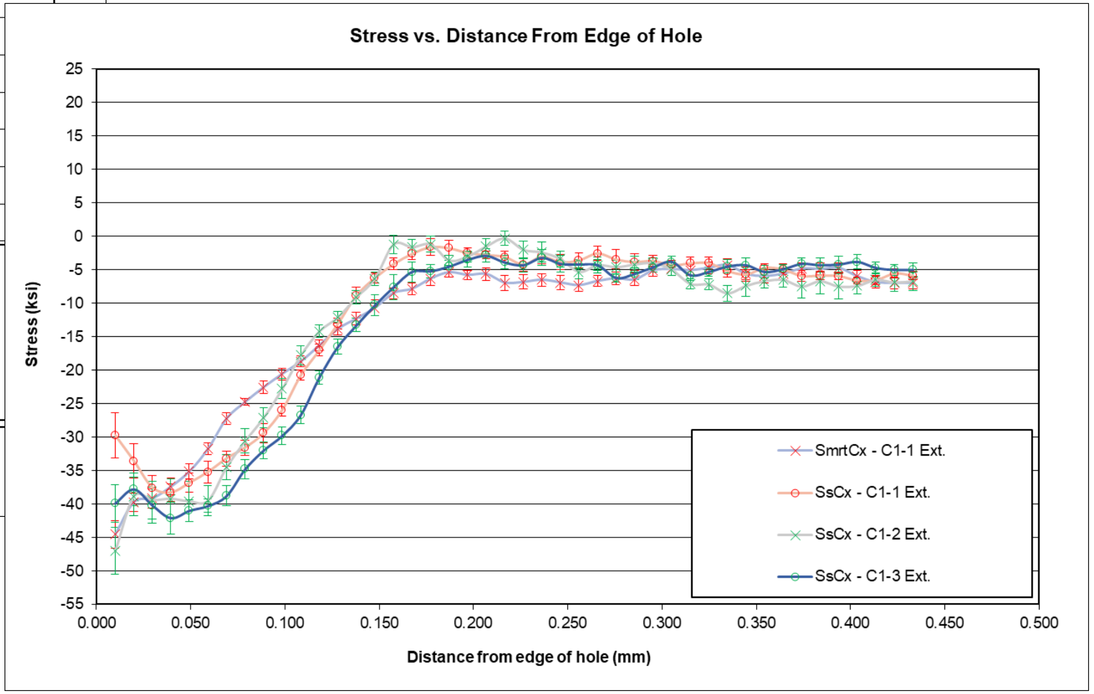




XRD Surface Residual Stress Differences

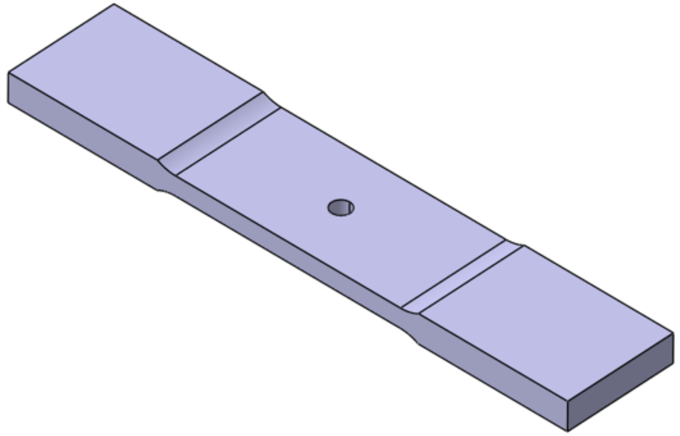
- Xray Diffraction Surface Stresses were Determined for a Range of Conditions that were Processed via SmartCx™ and SsCx™

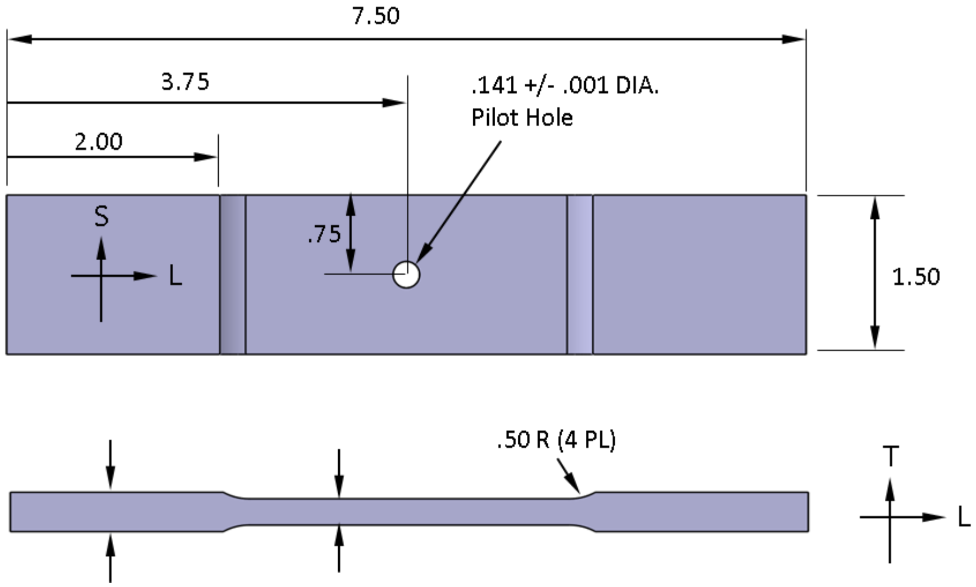




Purpose of Initial Sleeveless Evaluation

- Fatigue Testing Performed using Constant Amplitude, R=0.1, Smax = 23ksi
  - Purpose was to assess feasibility of a Sleeveless Cx process for future implementation
  - Coupons EDM Notched using plunge corner notch, avg. length = 0.025inch
  - Pre-Cracked to surface length = 0.035inch
  - Then final reamed to standard starting hole diameter
  - Imposed Marker Banding post repeatable "Block"
    - Used DST-G's Constant Amplitude Marker Band (CAMB) sequence
    - No post-test fractographic evaluation has been performed on these coupon sets yet





Effect of “Tuning” Applied Expansion

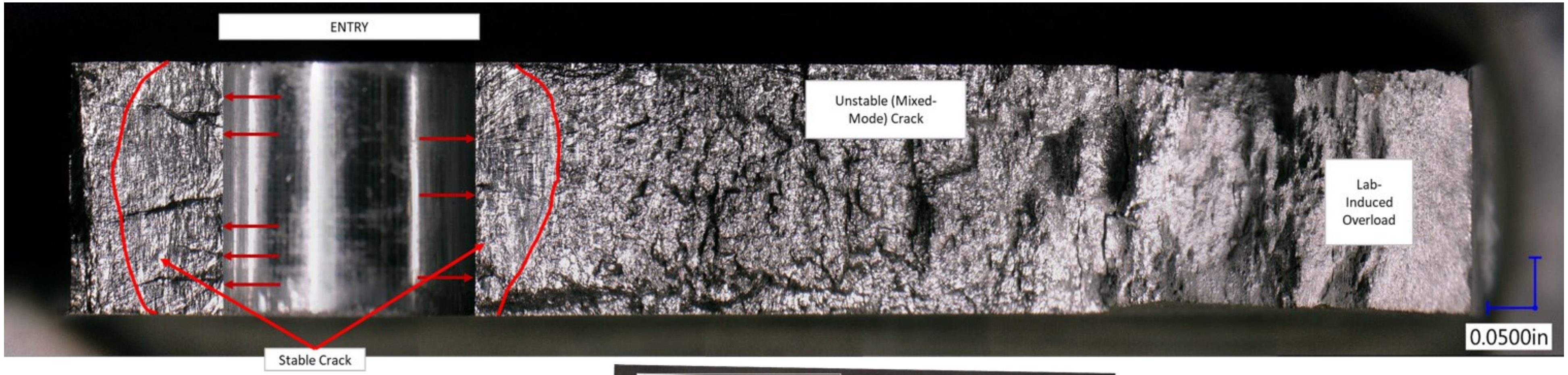
- Initial Testing Performed Using 6-3-N “Low” Retained Expansion Levels per the SsCx™ Tooling
  - Hypothesis was that if the level of retained Cx hole retention could be managed across methods that results would be similar
    - With sleeveless Cx processes it’s not possible to determine applied expansion due to the retraction of the tool during the Cx process
  - Method or “tuning” was based off of some level of trial and error after first measuring pre and post Cx hole diameters
    - How you measure makes a difference and so you want to have confidence in the method and stick with it
- Initial Results at “Standard” Retained Expansion Levels did Not Meet or Exceed the SsCx™ Life
- Pursued Tuning of Hole Diameter and Tooling Settings to Match Retained Expansion

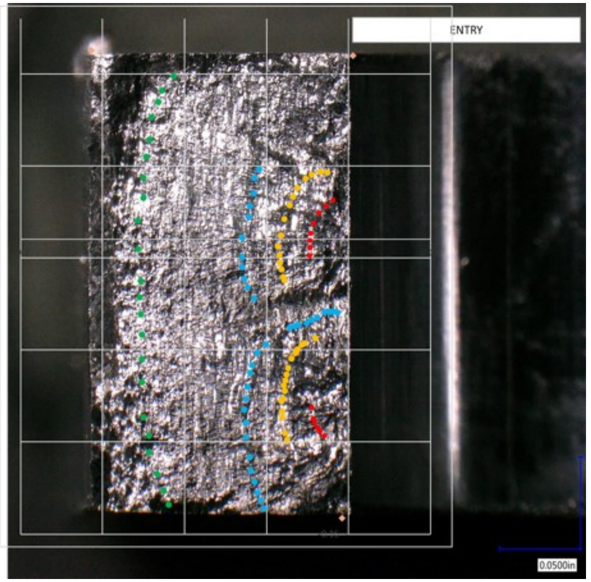
Fatigue Crack Test Results

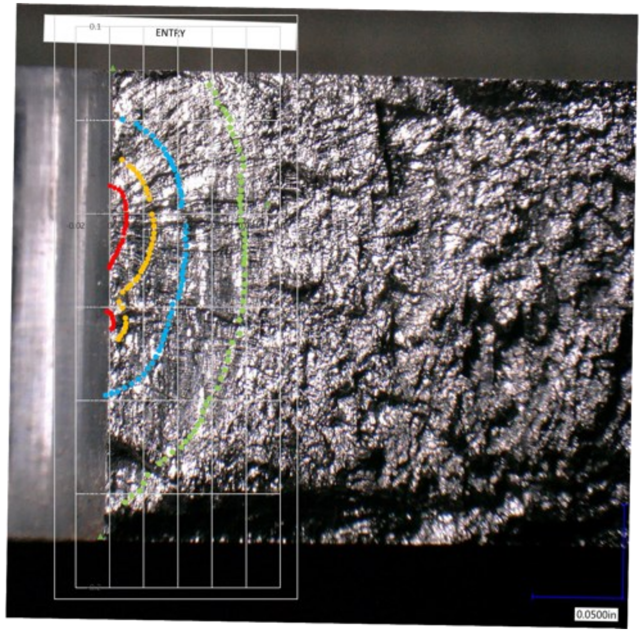
Cx Process	Average Life for Pre-Cracking	Std on Pre-Crack Life	Weibull Characteristic Life for Pre-Cracking	N90/90 Life for Pre-Cracking	Average Life Post Final Ream	Std on Life Post Final Ream	Weibull Characteristic Life Post Final Ream	N90/90 Life Post Final Ream
Baseline	9,701	1,029	10,094	3,900	17,508	1,700	18,253	6,155
SsCx	203,937	84,368	235,407	6,200	46,212	4,398	47,899	27,200
V1 SM1-STD	91,133	27,900	100,104	22,400	35,959	6,878	37,882	13,700
V2 SM1-STD	121,998	26,682	132,146	41,300	38,426	12,172	42,476	8,300
V2 SM1-TND	480,634	108,599	523,332	77,500	39,426	9,326	42,587	13,400
V1 SM1-TND	216,900	45,666	233,333	77,000	61,808	6,991	64,513	36,900
V2 SM1-MAX	519,848	66,414	546,027	228,500	53,331	7,806	59,400	20,100

QF Results of SmrtCx™ vs. SsCx™

- Maybe Use Data from the "C" Matrix

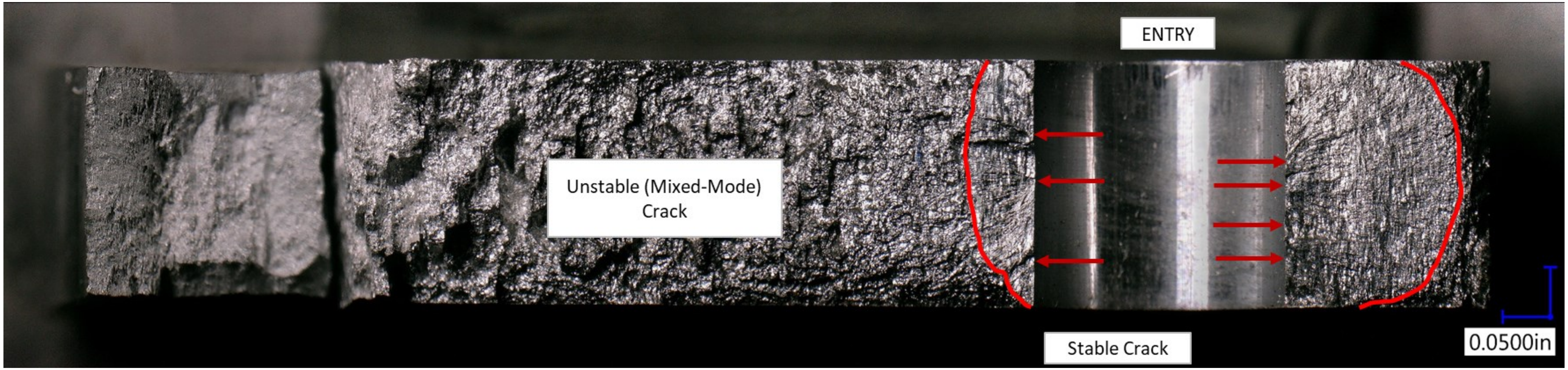


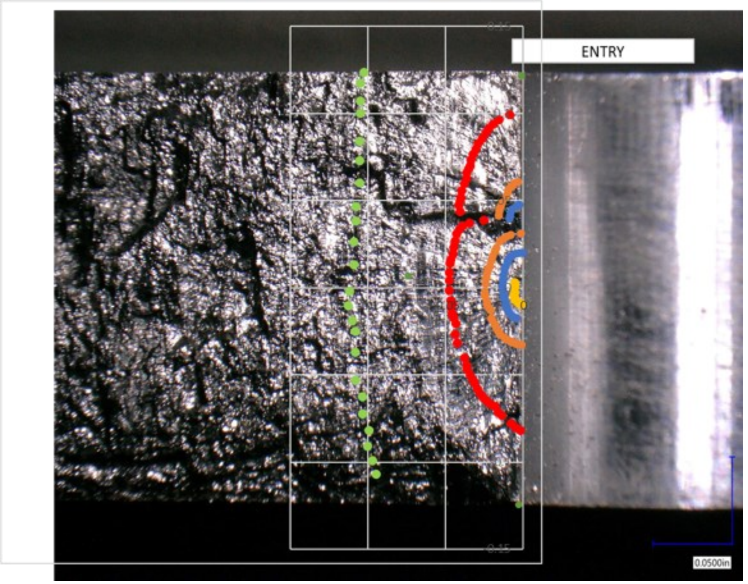


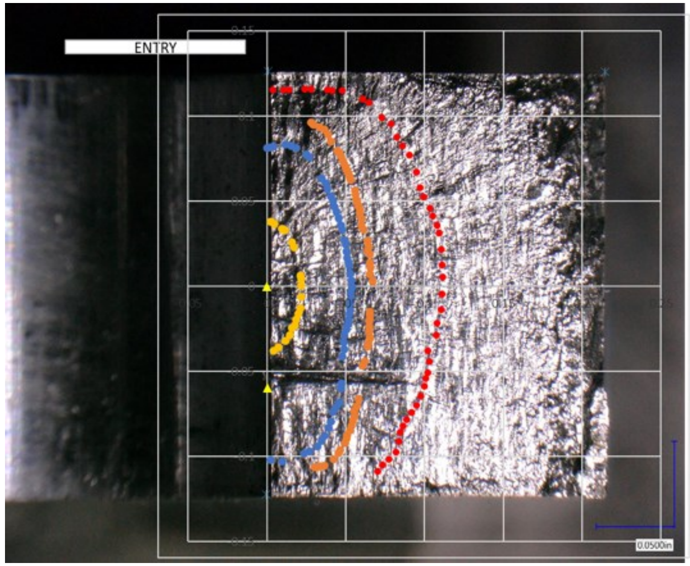


LOCKHEED MARTIN

QF Results of SmrtCx™ vs. SsCx™







Lessons Learned

- Split Mandrel Cold Expansion Methods Currently Have Limited Applicability
  - Due to materials and pulling forces
- Due to Tolerance Stack-ups in Sleeveless-Style Assemblies "Tuning" Retained Expansion Useful
  - Not possible to use applied expansion
  - This may be challenging if drawing/spec require updates/revisions for starting hole size
- In Sleeveless Cx Methods Cracks can Form All Along the Bore
  - Limited "pinning" due to higher compression near Exit surface
  - Can form a thru-crack faster than SsCx™ process
    - This has implications in NDI and other Holistic aspects

Additional Comments or Questions

Continuation of active work

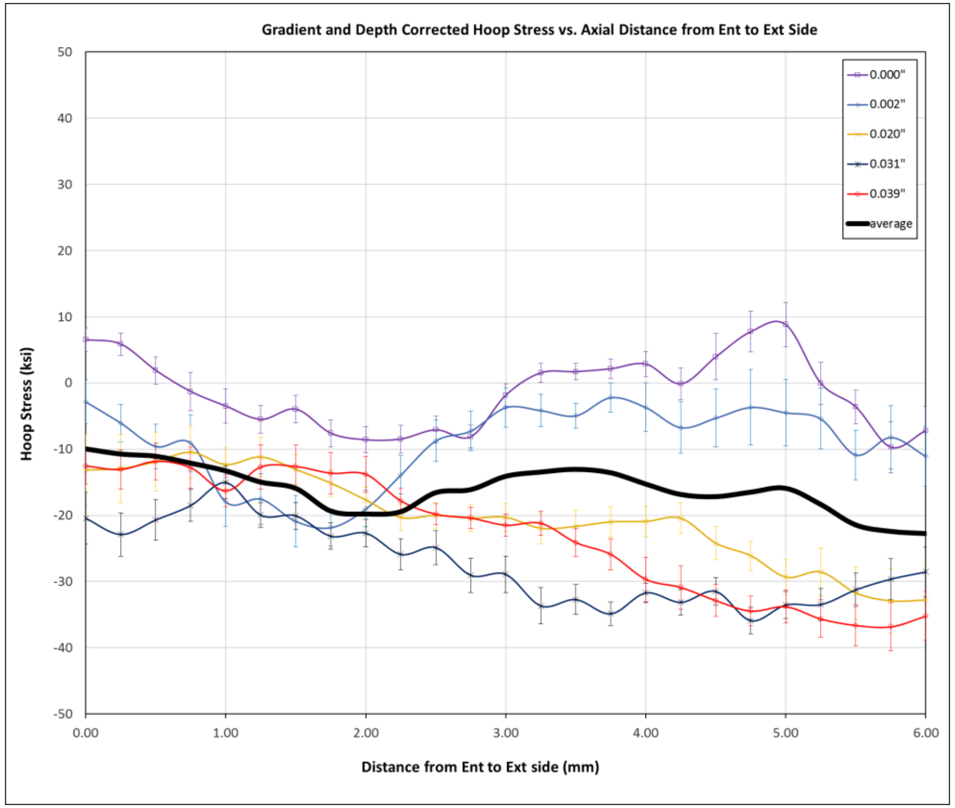
Bring us your problems!

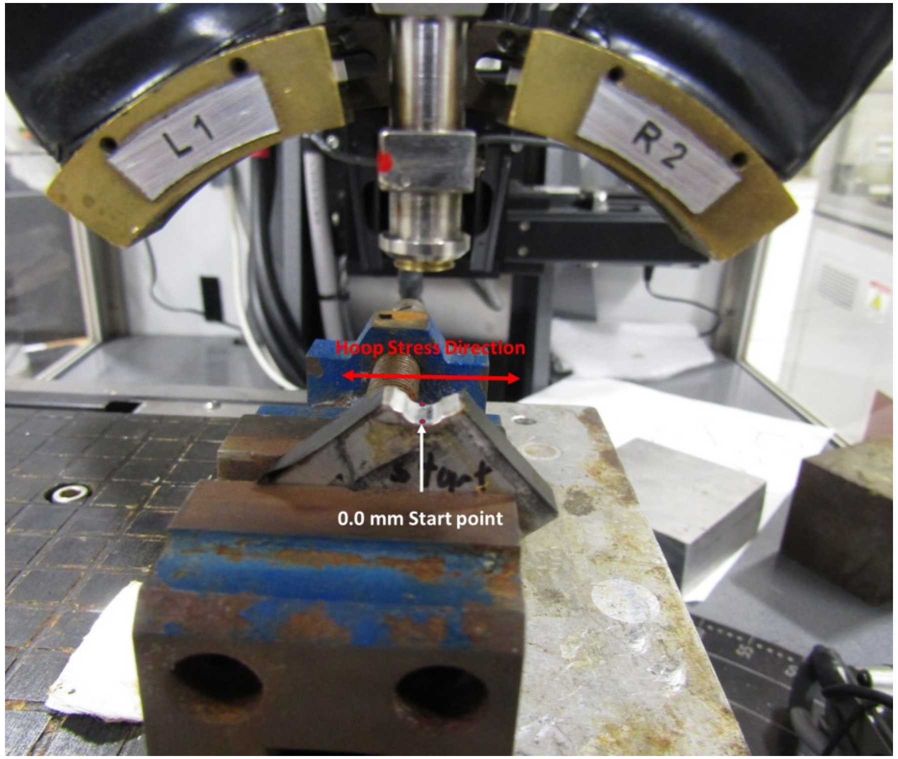
Extra Slides

Harmonizing Contour and XRD Residual Stress Measurement Data Sets

RS in bore of 2024-T351 Low Expansion Cx 2”x 2” Coupon

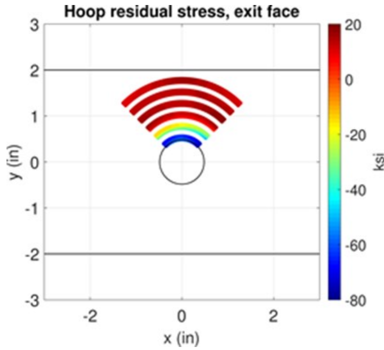
- Similarly, data was collected on the bore of a 2x2 Cx Hole coupon.
- Depth profiles via electropolishing were collected to bridge the gap between XRD and Contour data – correction required for splitting to access to the bore.
- Steep near surface stress gradients can be captured rather than averaging near surface.

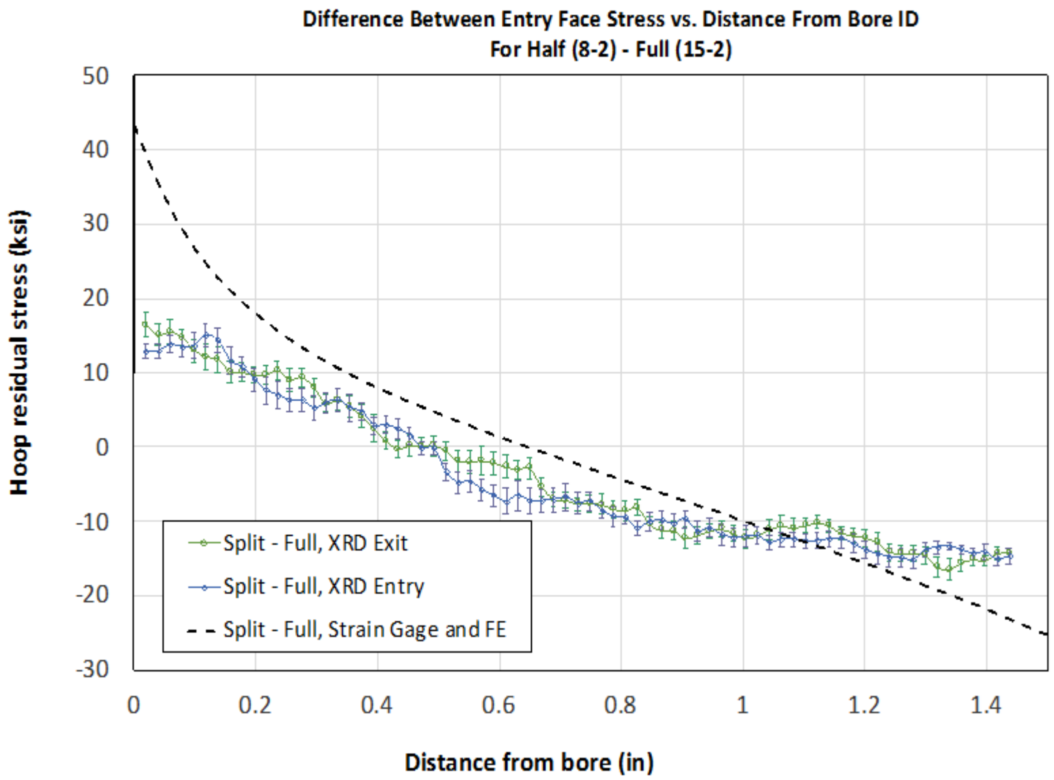


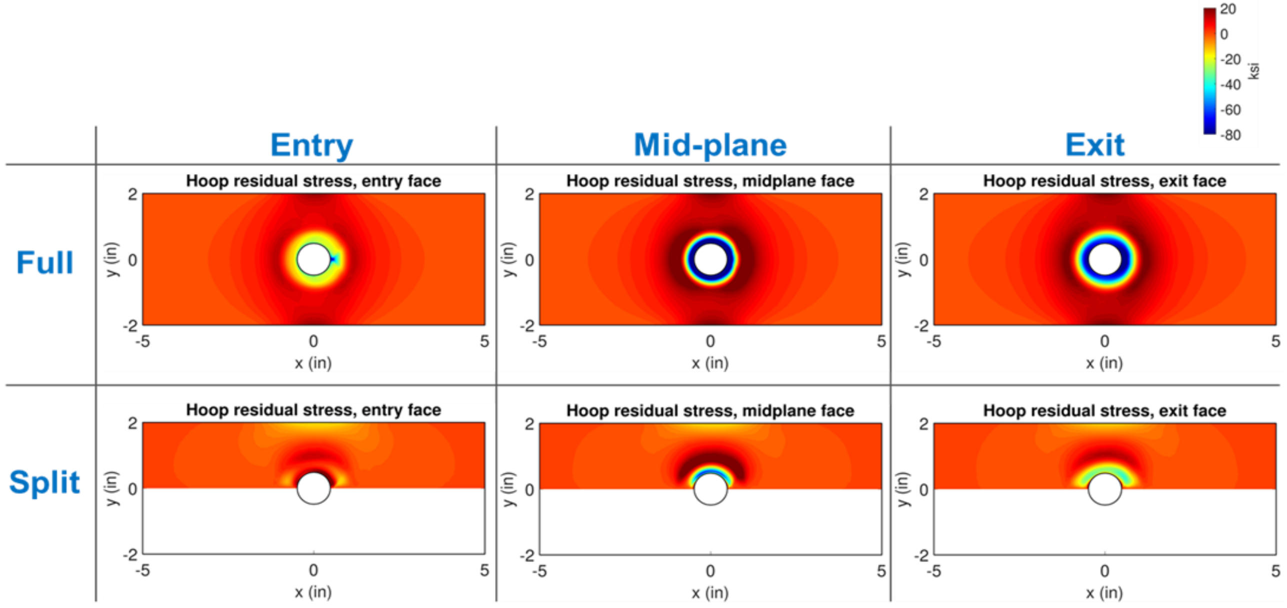


Effect of Split on Geometrically Large Coupon

- The difference between RS in full and split configurations was looked at to determine effect – the effect was significant – green and blue XRD data.
- This relaxation was then compared to that estimated by strain gage & FEM.
- The results were different, especially near the bore – thought to be due to XRD arc averaging – modeling was used to determine the effect of arc-averaging.

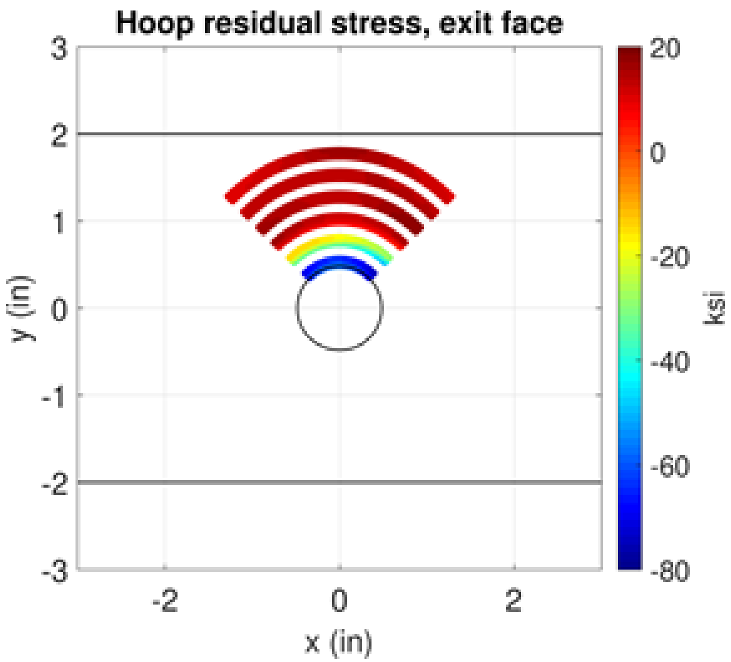


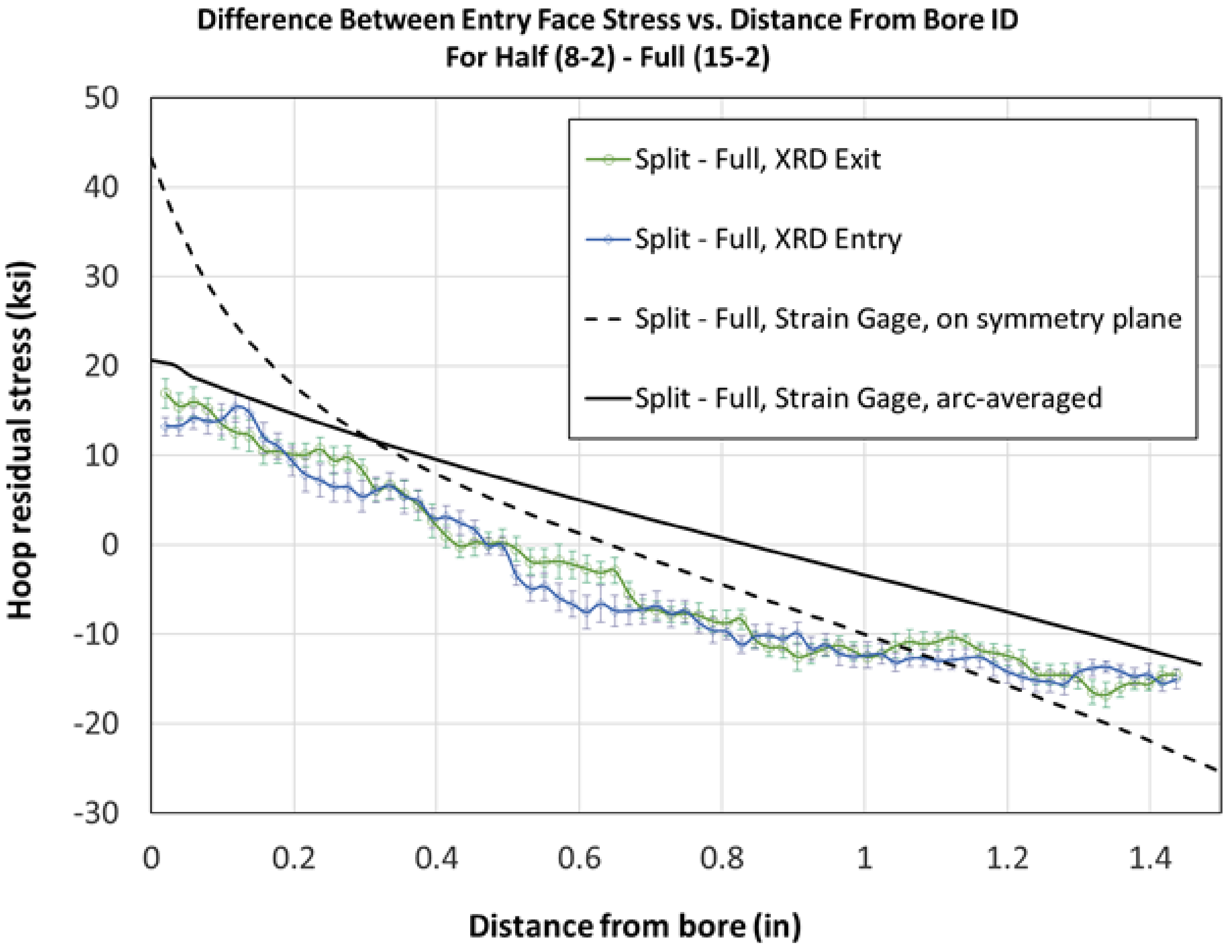




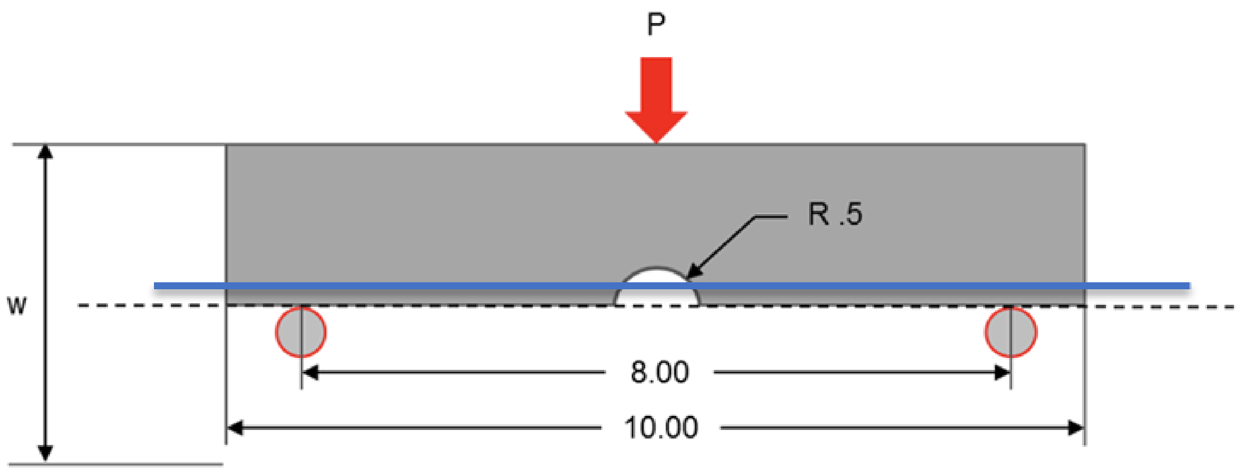
Effect of Split on Face of Geometrically Large Coupon

- When corrected for XRD arc averaging, the relaxation as measured by XRD vs. estimated by strain gage & FEM are more closely aligned



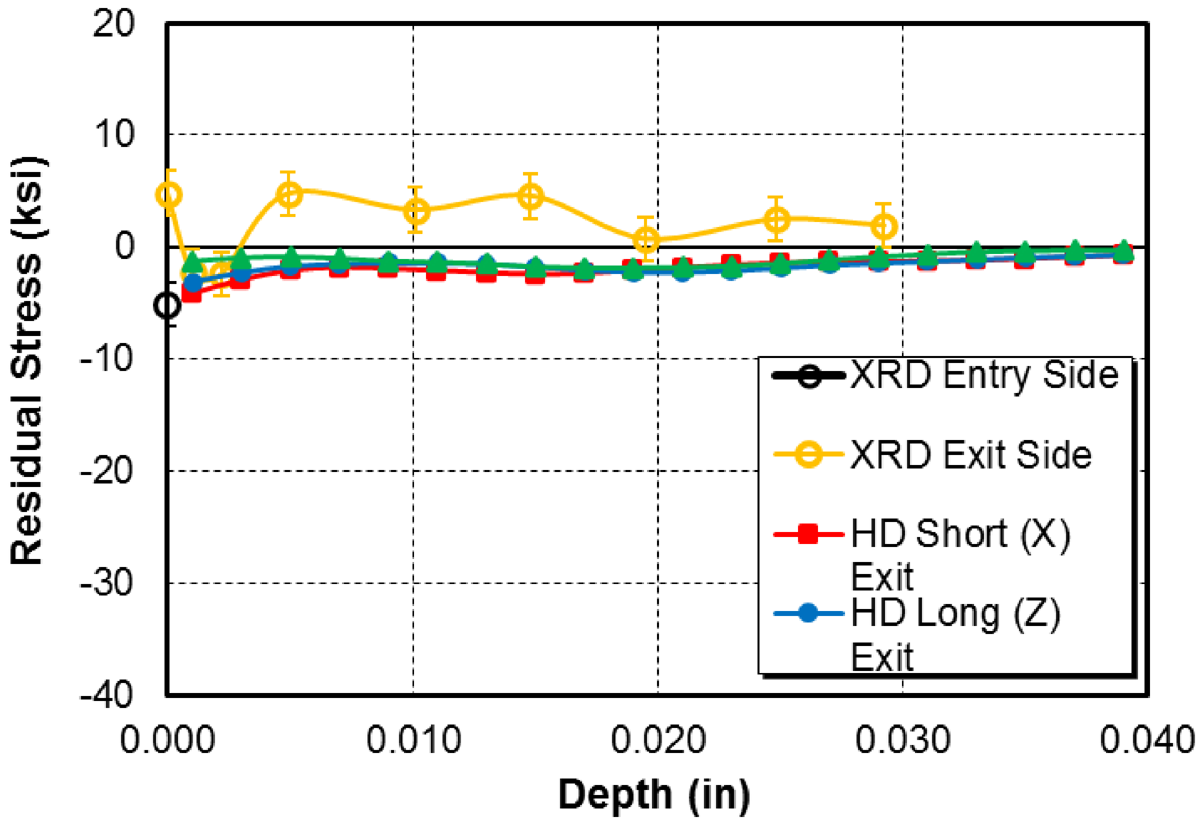


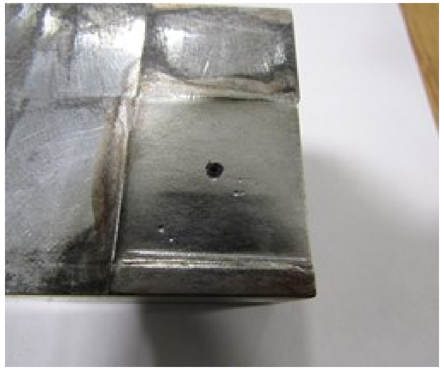
Case Study: Can we measure RS in the bore of Geometrically Large Cx Hole Coupons?



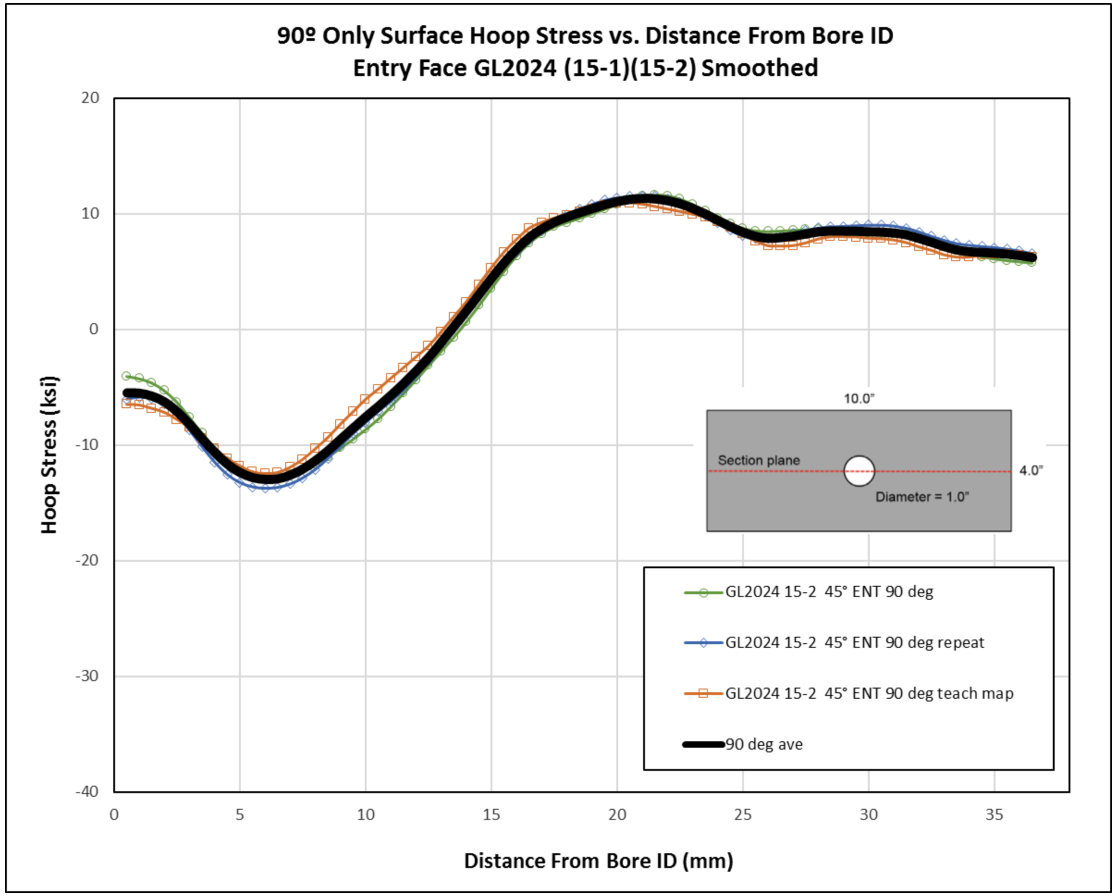
Far Field RS on Face of Geometrically Large Cx Coupon

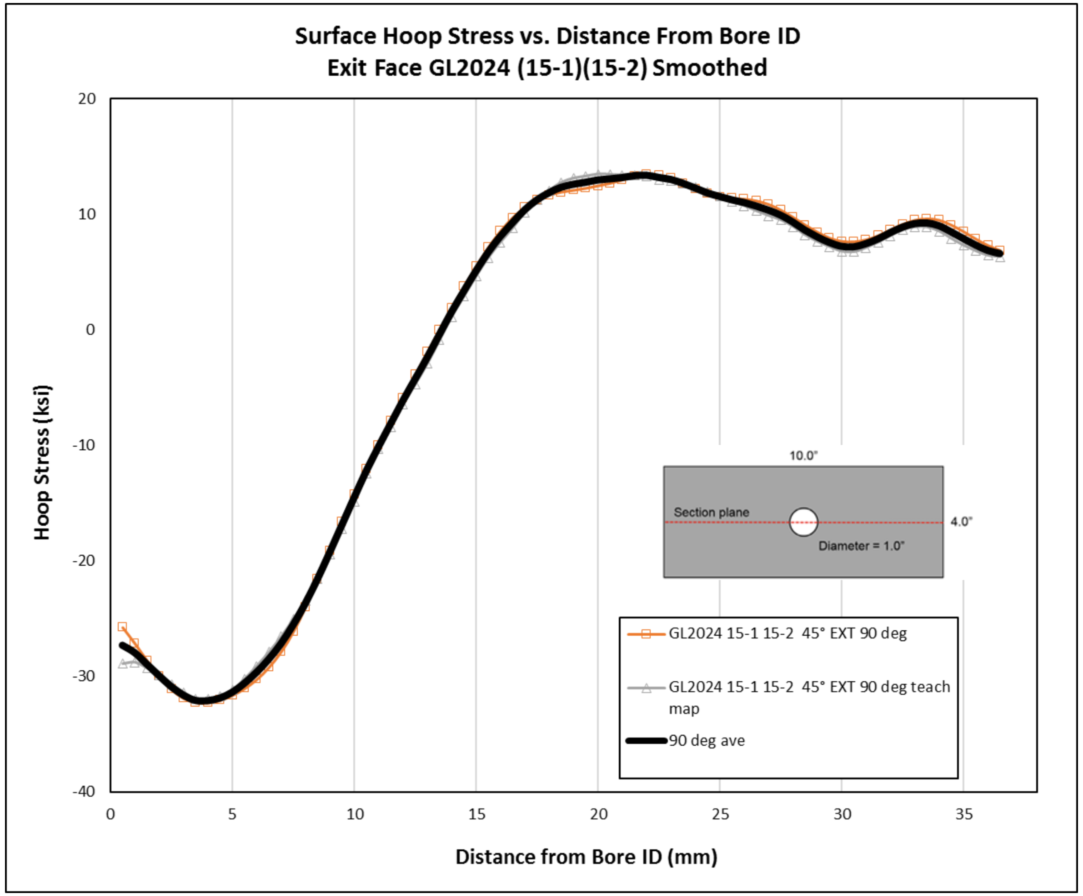
- Far field near surface RS measurements collected via XRD and HD indicate the magnitude of upstream processing RS to be low





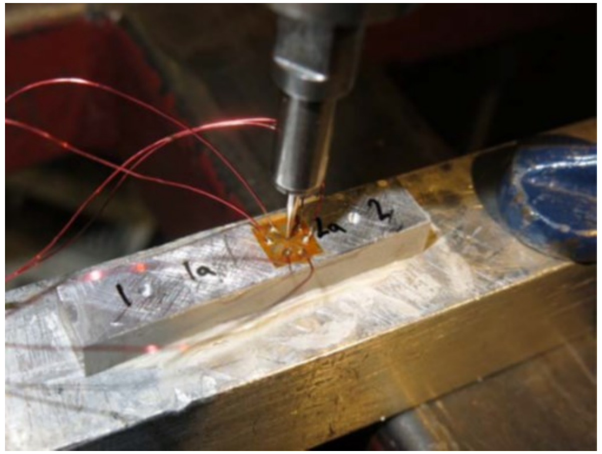
RS on Face of Geometrically Large Coupon

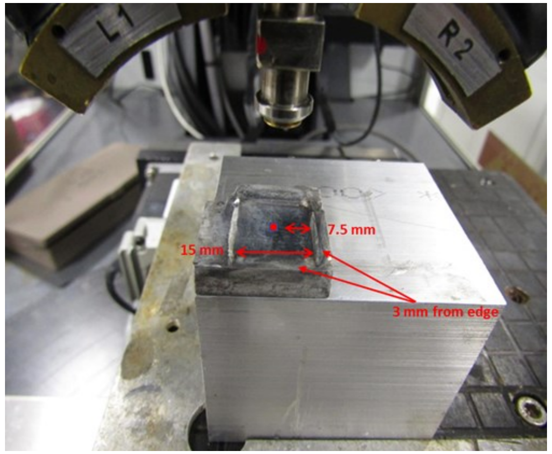


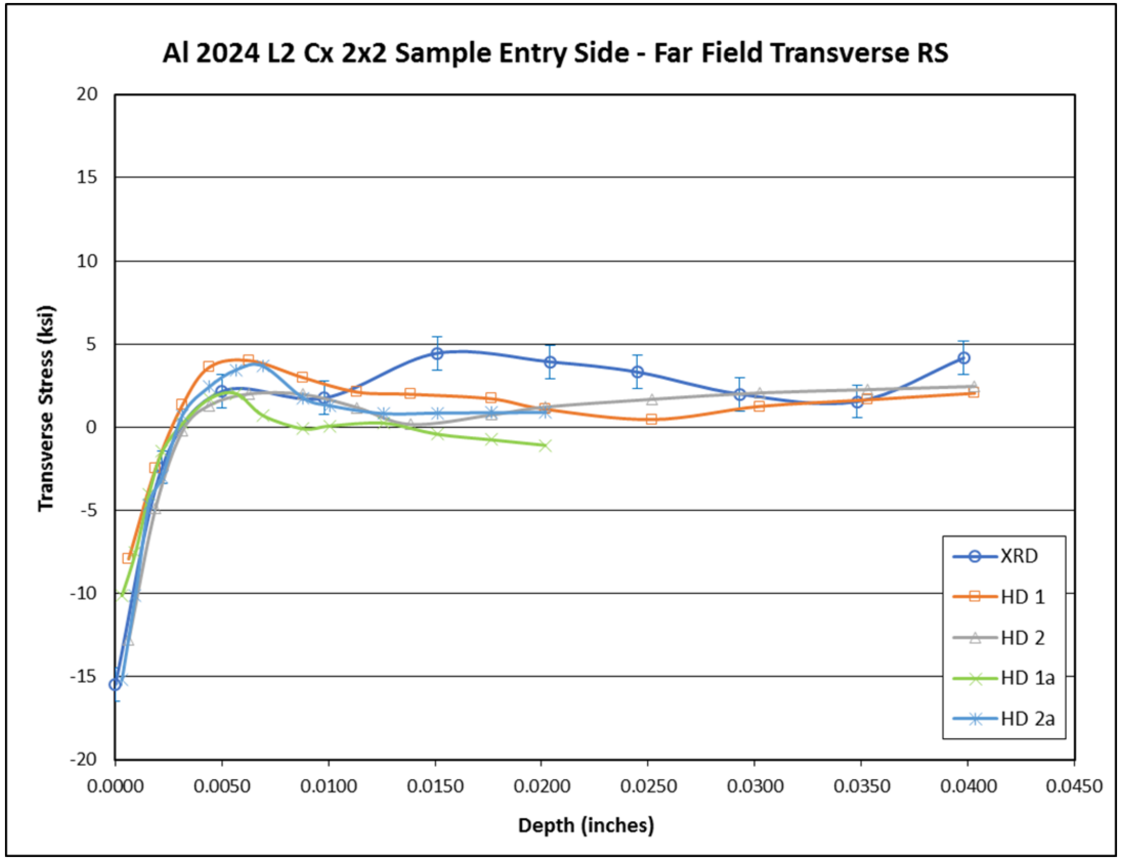


Far Field RS on Face of 2 x 2 Cx Hole Coupon

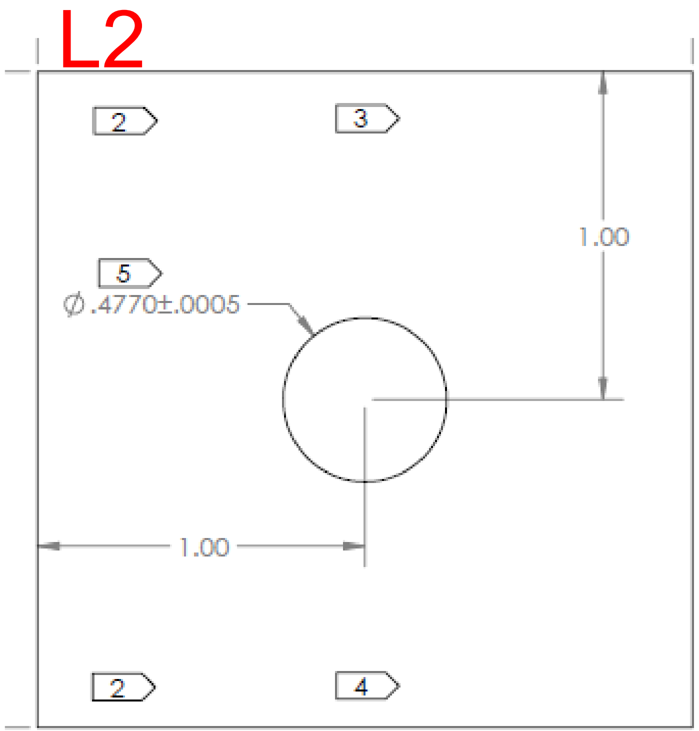
- Al 2024 L2 Cx Sample Far Field Transverse RS on Entry Side measured using XRD and HD
- RS measurements collected via XRD and HD to determine upstream processing RS.







Case Study #2: Can we measure RS in the bore of a 2024-T351 Low Expansion Cx 2" x 2" Coupon?



Takeaways

- XRD can be used to determine if Cx was applied to the right level on either coupons, or in the field on aircraft.
- XRD is able to pick up steep near surface stress gradients, especially in tricky areas like the bore of a Cx hole.
- Near surface bore ID measurements might explain why Cx vs. non-Cx holes crack propagate at nearly the same rate for the first few thou.
- A path forward to harmonize/splice XRD, Contour, HD, ND, etc. data sets such that the strengths of each can be exploited i.e. these are complimentary techniques.
- It is important to do your homework with regards to far field RS, grain size effects, gradient effects, elastic properties of the material, etc. i.e. use best practices!!!

Regulatory Considerations for RS, and ERSI' Scope and Charter

with excerpts from 2017 RS Summit Presentation

Presented at:

ERSI Workshop

April 3, 2024

San Antonio, TX

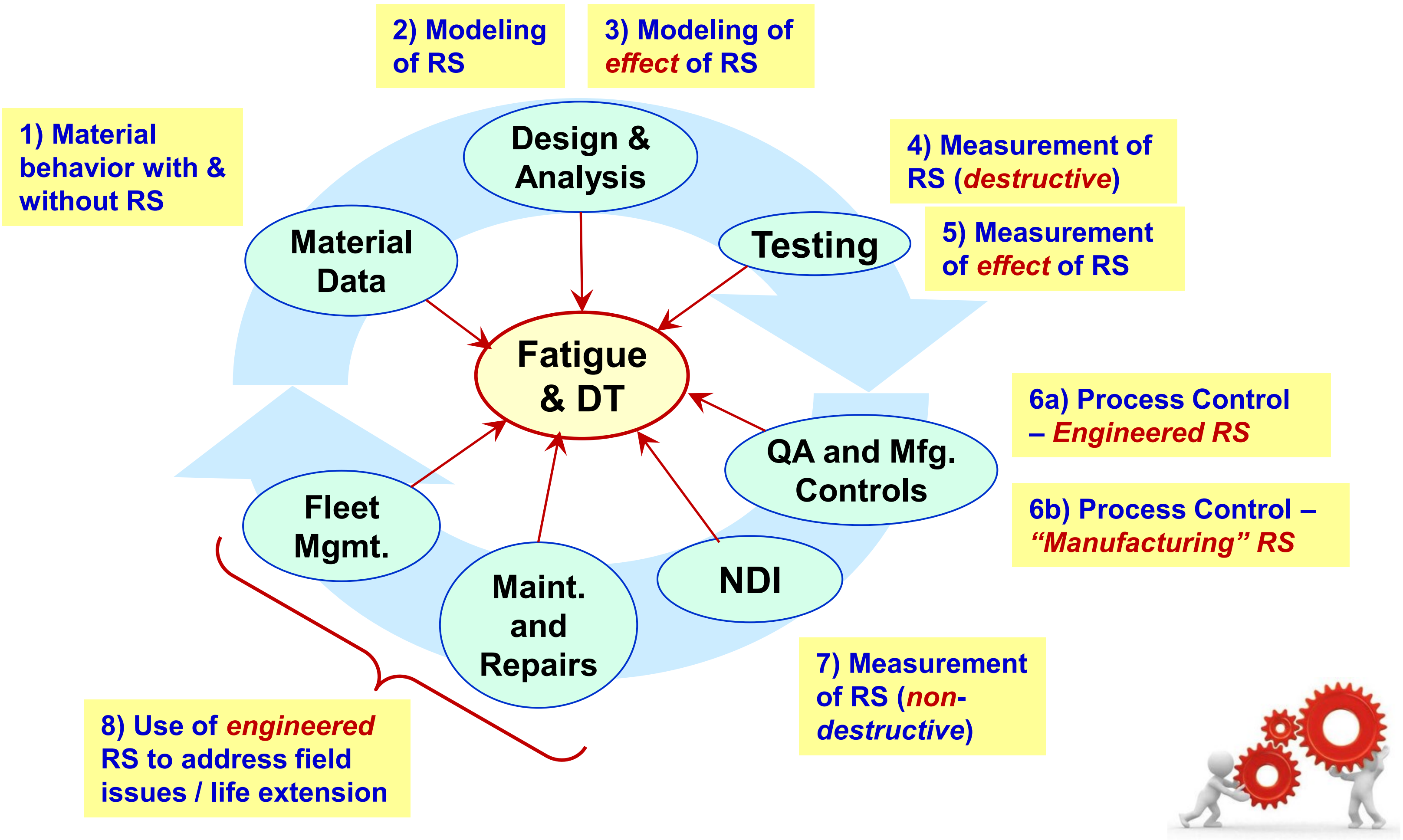
Presented by:

Michael Gorelik, PhD
FAA Chief Scientist and Technical Advisor
for Fatigue and Damage Tolerance

Disclaimer

The views presented in this talk are those of the author and should not be construed as official FAA position, rules interpretation or policy

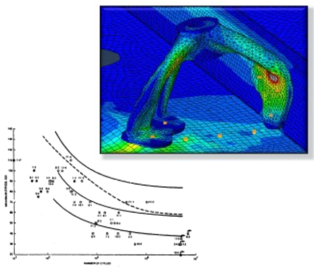
System-Level View of F&DT Discipline
… *and related RS considerations*



All elements of the system are essential to ensure safety …

Life Predictions vs. Life Management

(a highly simplified view)



From Models to Airplanes

Crack Initiation Predictions

Crack Propagation Predictions

Safe Life

Design Considerations

Damage Tolerance

- Manufacturing
- Airworthiness
- Design
- Testing
- Maintenance
- Repairs
- *Etc…*

Use of Fatigue and Fracture Models in Various Elements of LMS

(LMS - *Life Management System*)

Examples:

- **Damage tolerance (Part 25) – establishment of effective inspection / repair / modification plans**
- **Fatigue (Part 25) – reducing risk of design iterations and FSFT**
- **Fatigue (Part 33) – establishment of safe retirement limits**
- **Damage tolerance (Part 33) – supplemental design metric**
- **Flaw tolerance (Part 29) – a method to account for presence of flaws and damage**
- **Continued Operational Safety (COS) - total life assessment (*used as an input into risk assessment*)**
- **MRB (manufacturing review board) – disposition of manufacturing deviations**

Key Drivers

Refinement of Existing Lifing Methods

- **More accurate assessment**
- **Reduced level of conservatism**
- **Uncertainty reduction**

***Examples*:**

- Account of residual stresses
- More accurate fatigue and fracture prediction tools & methods (e.g. multiaxial fatigue, TMF, dwell fatigue, crack retardation, etc.)

"Lessons Learned" from Field Experience

- **New types of material or manufacturing defects *for existing materials***

***Examples*:**

- Undetectable near-surface machining damage
- New (or previously misunderstood) material anomalies
- Advanced failure mechanisms (e.g. cold dwell fatigue in Ti)
- SCC / EAC of high-strength *Al* alloys

Lifing Methods for New Materials or Manufacturing Processes

- **New types of material or manufacturing defects (failure modes) *for new materials***

***Examples*:**

- Additive Manufacturing
- Flow forming process
- LFW
- …

Excerpts from FAA Regulations *(relative to RS)*

Part 33 [*engine*]

- **Rules – *No references found***
- **AC 33.70-1 "Guidance Material for Aircraft Engine Life-Limited Parts Requirements"**
  - 8.b (7) (e) 2 [Damage Tolerance Assessment / surface damage monitoring] - Use beneficial *residual stresses* due to finishing processes, such as shot peening, if appropriate and if data supports the ability of the process to slow or suppress the growth of the damage.

Part 25 [*transport airplane*]

- **Rules / ACs - *No references found***
- **PS-ANM-25-22 "*Repair Deferral Limitations for Known Cracks*"**
  - 5.4.4 Preload and *residual stresses* in the structure should be well understood and accounted for in the analysis.

Part 29 [*transport rotorcraft*] – *No references found*

Part 23 [*general aviation*]

- **AC 23-13A "Fatigue, Fail-Safe, and Damage Tolerance Evaluation of Metallic Structure for Normal, Utility, Acrobatic, and Commuter Category Airplanes"**
  - This S-N data (*Appendix* 2) is applicable to conventional built-up aluminum structure with no fittings (other than continuous splice fittings), no parts with high *residual stresses*, …

Limited Guidance Relative to Residual Stress Considerations in Design and Fleet Management

Example of Legacy Practices

<u>Reference</u>: T. Swift, "*Fail-Safe Design Requirements and Features, Regulatory Requirements*", AIAA / ICAS International Air and Space Symposium and Exposition, Dayton, OH 2003 [https://arc.aiaa.org/doi/abs/10.2514/6.2003-2783].

"… If the fastener hole is cold expanded, the beneficial effects of *compressive residual stresses will retard the growth* of the standard 0.05" crack.

However, *accounting for the non-linear stress distributions in calculating stress intensity factors has been difficult*.

To avoid this complication an *equivalent initial crack size* of 0.005" has been used to conservatively account for the residual stress field.

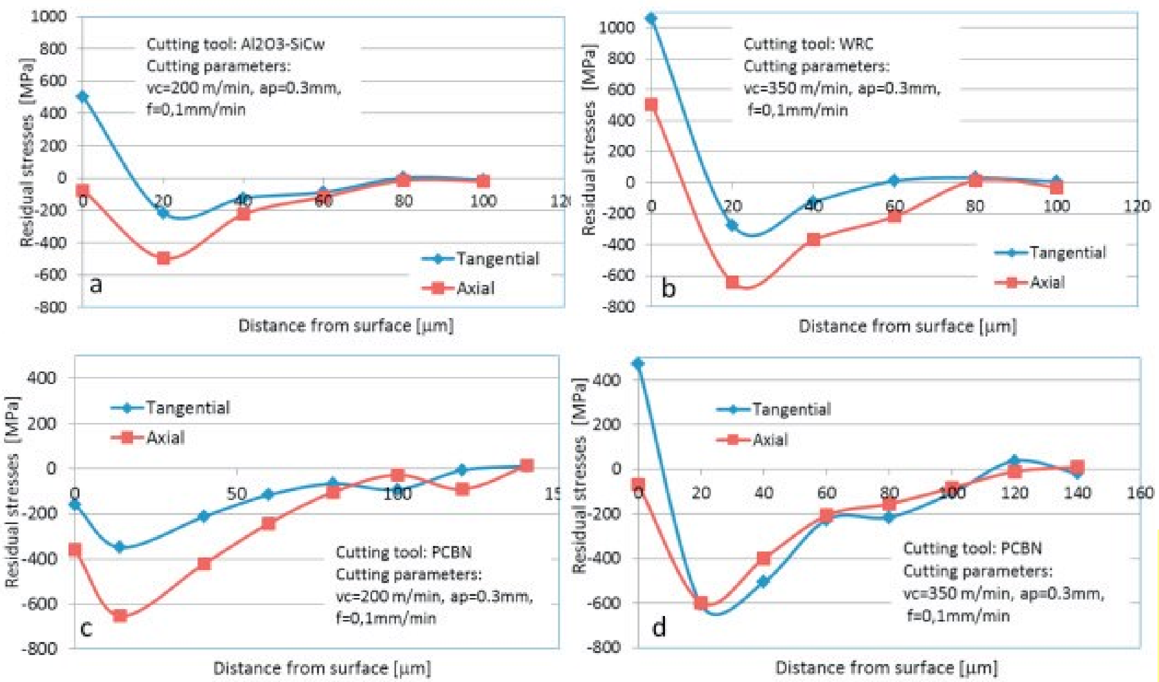
… An equivalent initial crack 0.03" radius has been used to simulate the effects of residual compressive stresses induced with machine driven fasteners …"

Industry Trends (*in RS context*)

- **Moving towards more aggressive design and manufacturing practices**
  - ***Faster, hotter, lighter, lower cost…***
- **Development of RS *measurement* technologies**
- **Development of RS *modeling* technologies**
- **Development of ICME frameworks**
- **Digital twin / digital thread**
- **…**

Residual Stress – Friend or Foe…

- ***Unfavorable*** **near-surface RS resulting from machining may significantly reduce component's LCF life (by 10x or more)…**



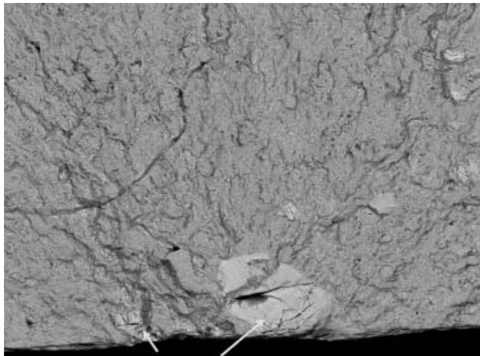
Challenge:
Magnitude (and even sign) of RS can be a function of:

- ***Cutting speed***
- ***Cutting tool / insert***
- ***Cutting direction***
- ***Etc.***

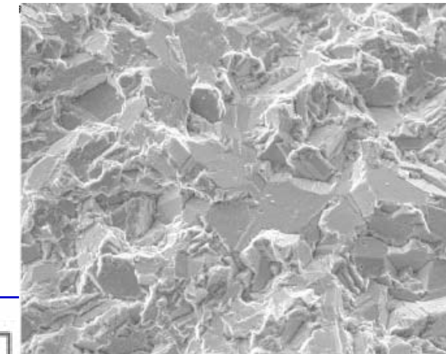
Reference: J. Zhou et al, "*Analysis of Subsurface Microstructure and Residual Stresses in Machined Inconel 718 with PCBN and Al2O3SiCw Tools*", 2014, Procedia CIRP, (13), 150-155.

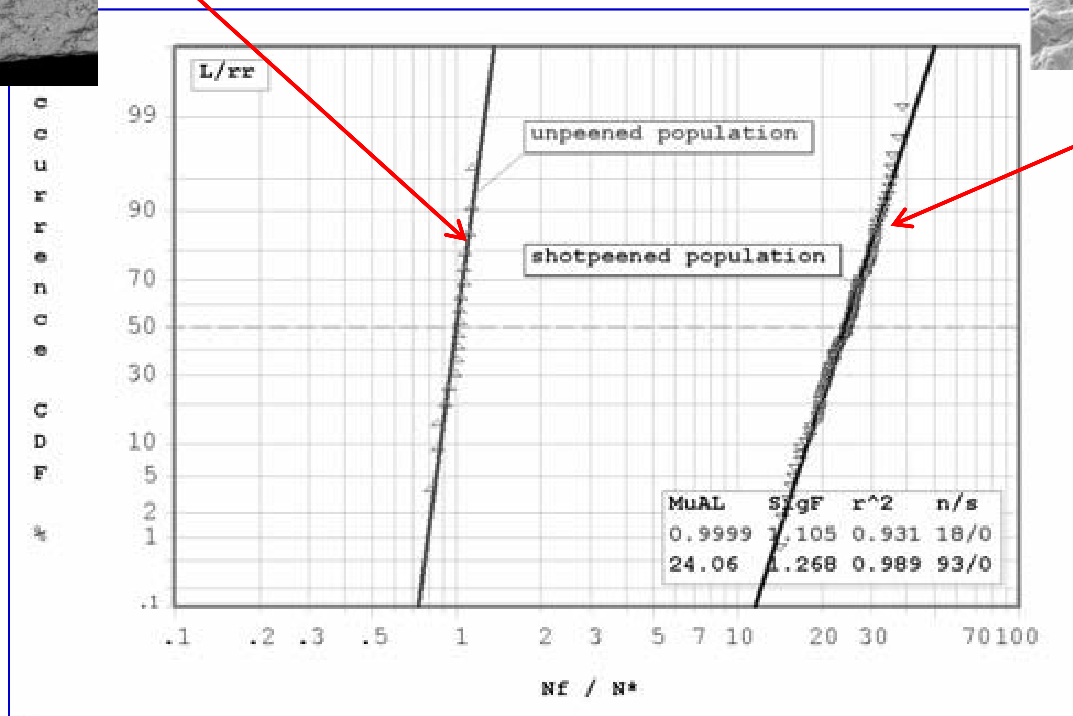
- ***Favorable*** **(machining-induced or engineered) RS may improve component's LCF life (by 10x or more) → *see next slide***

Example: Mitigating Effect of Material Inclusions with Shotpeening



Reference: M. Gorelik et al, "***Role of Quantitative NDE Techniques in Life Management of Gas Turbine Components***", GT2006-91337, Proceedings of TurboExpo 2006, Barcelona, Spain, May 8-11, 2006.

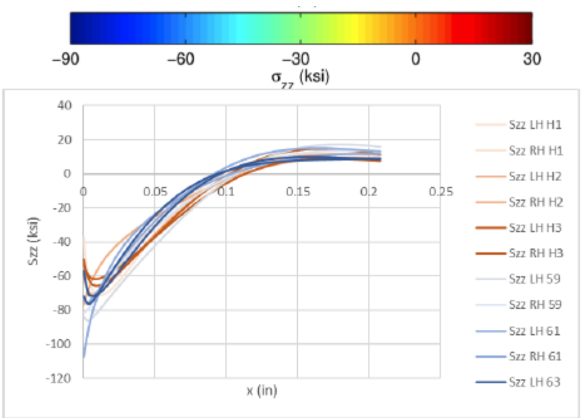




RS Measurement vs. Modeling

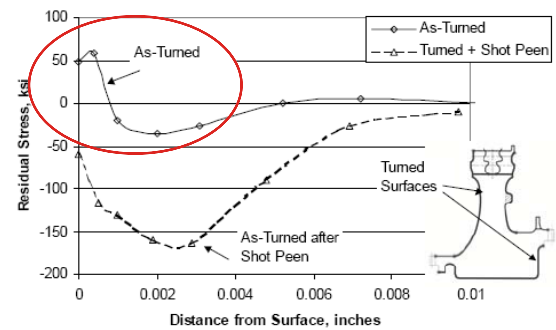
Measurement / modeling capabilities for beneficial ***engineered residual stresses*** continue to advance

Modeling Techniques



Unfavorable residual stresses ***resulting from manufacturing process*** may significantly reduce component's safe life (by 10x or more), as well as DT capabilities

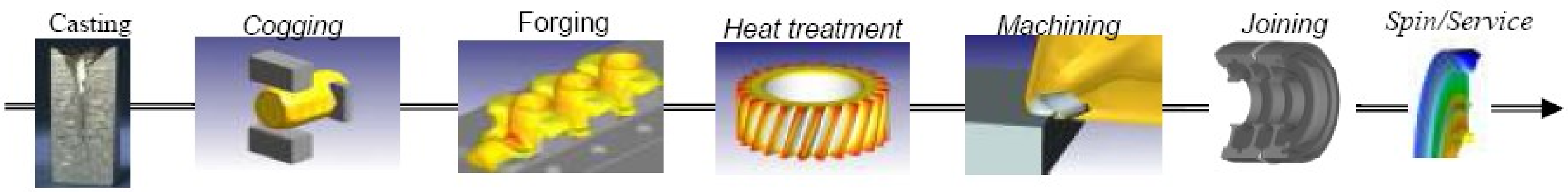
Measurement Techniques



Near surface residual stress gradient for a turned surface before and after shot peening.

Fatigue predictions (LCF) in the presence of RS in general represent a more significant challenge than DT assessment

Integration with Manufacturing
Process Simulation



Link DEFORM output with DARWIN input

- Finite element geometry (nodes and elements)
- Finite element stress, temperature, and strain results
- Residual stresses at the end of processing / spin test
- Location specific microstructure / property data
- Tracked location and orientation of material anomalies

DEFORM™

Design Environment for FORMing

<u>Reference</u>: C. McClung, "*Structural Integrity Assessment for Aviation Parts with Inherent or Induced Material or Manufacturing Anomalies*", presented at the 2nd FAA – AFRL AM Workshop, Aug. 30-Sept. 1, 2016, Dayton, OH.

Influence of Location-Specific Residual Stress and Microstructure on Life & Risk

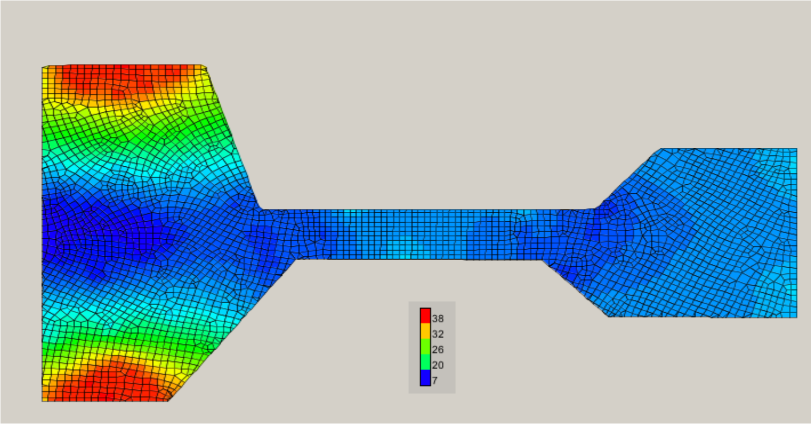
ANSYS
ABAQUS
DEFORM

Stress Results Files

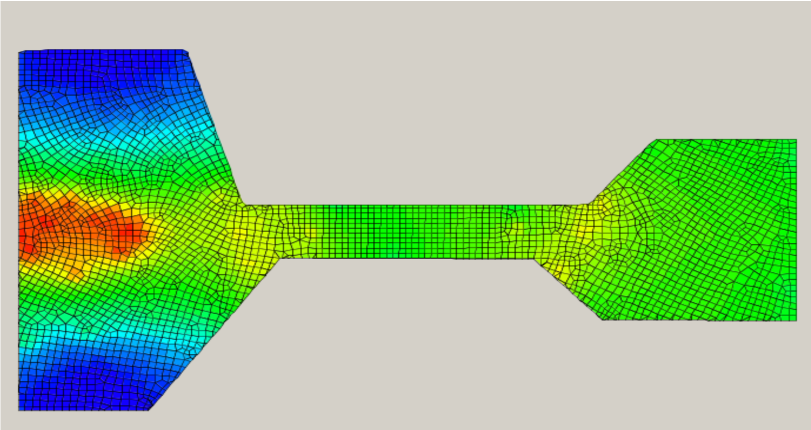
DARWIN

DEFORM

Grain Size Results File



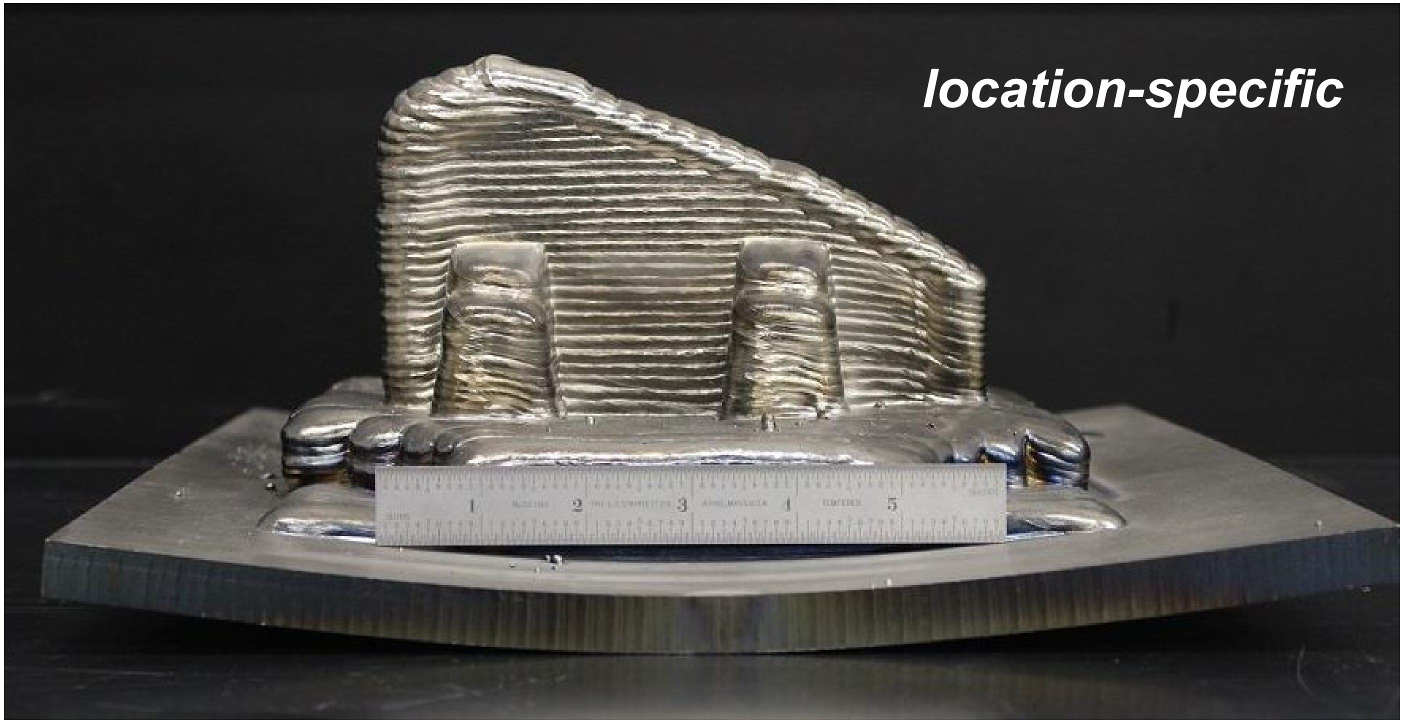
grain size contours



crack growth rate multiplier

Reference: C. McClung, "***Structural Integrity Assessment for Aviation Parts with Inherent or Induced Material or Manufacturing Anomalies***", presented at the 2nd FAA – AFRL AM Workshop, Aug. 30-Sept. 1, 2016, Dayton, OH.

New Tech - RS in AM Parts

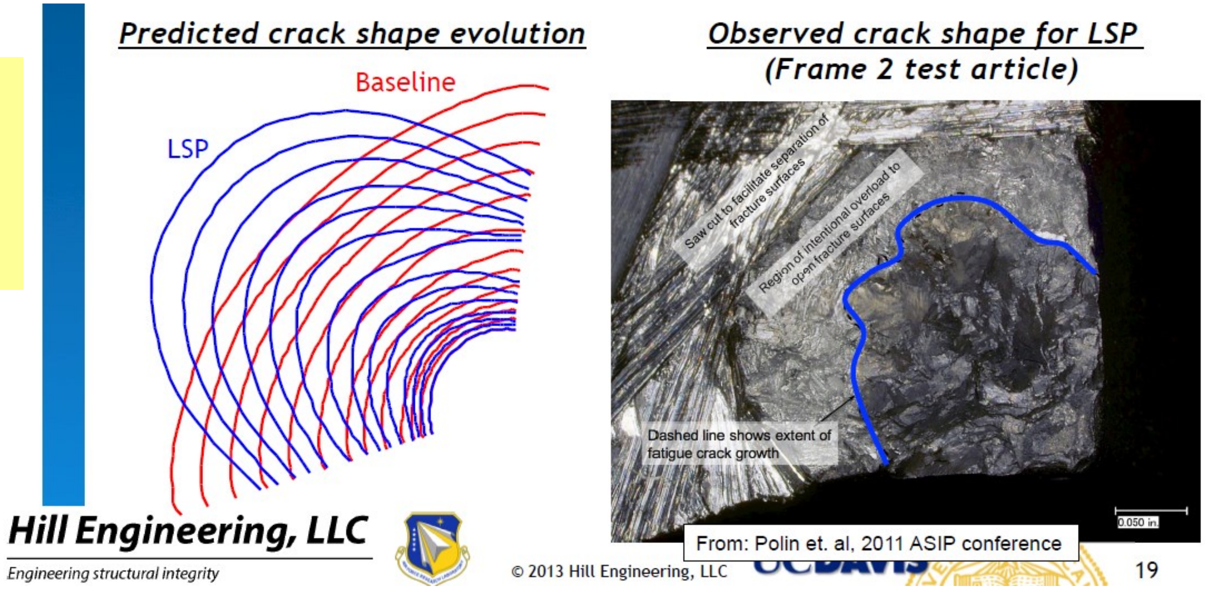


Crack Initiation (LCF)

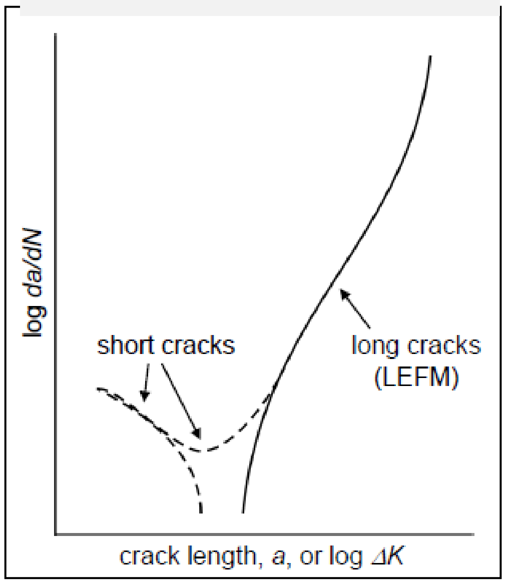
Crack Propagation (DT)

Fracture Mechanics Considerations

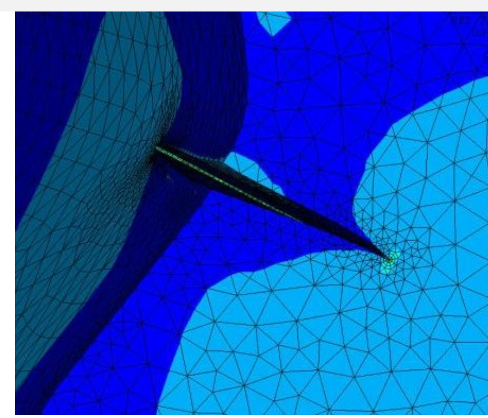
Reference: M. Hill et al, "***Correlation of 3D fatigue crack growth in residual stress bearing materials***", AFGROW Workshop, Sept. 10-11, 2013.



Short Crack Behavior



3D Fracture Mechanics



Complex geometries and stress fields, and small scales (e.g. near-surface RS gradients) require application of advanced Fracture Mechanics concepts *such as 3-D FM and short crack behavior*.

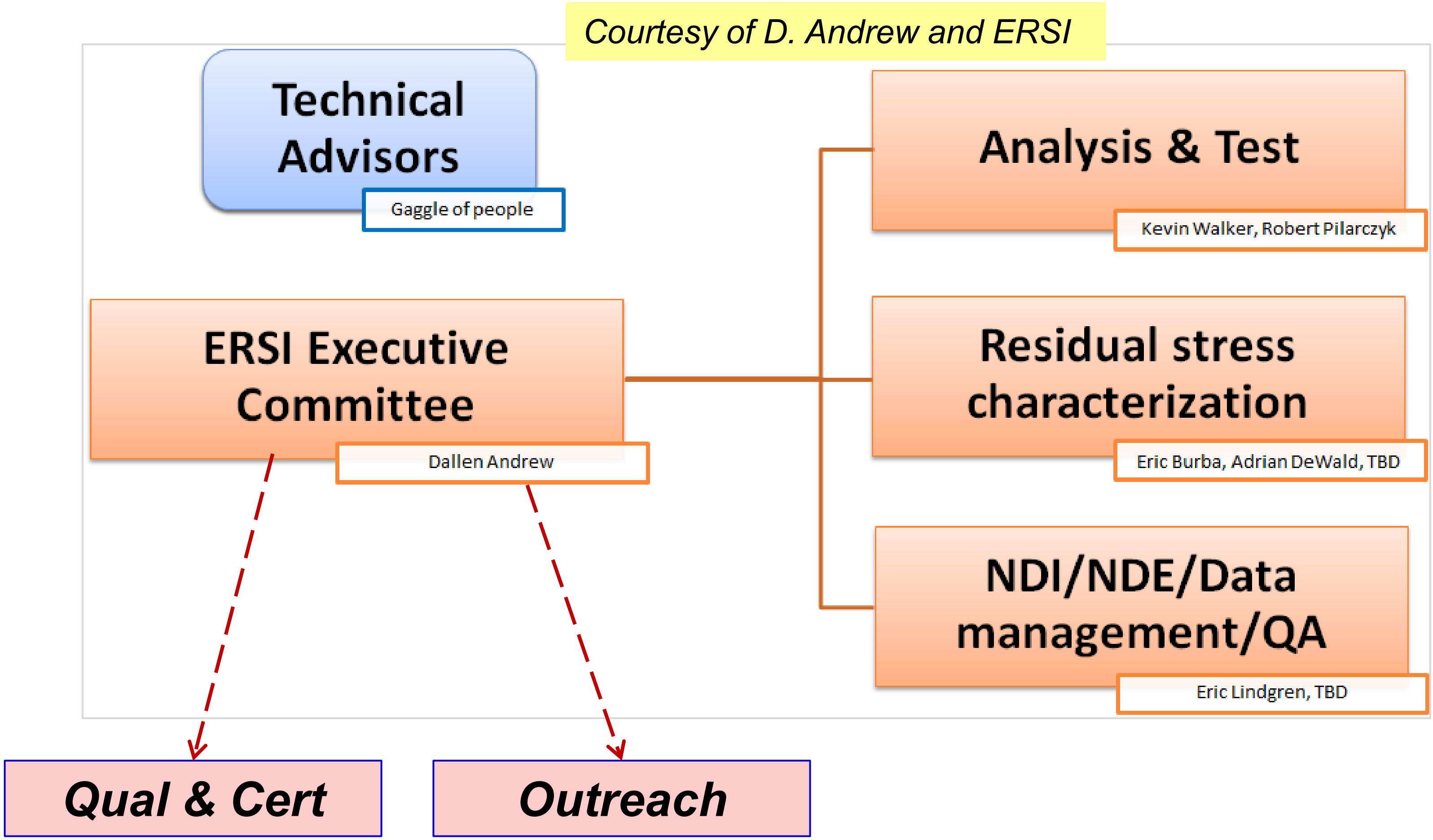
Fracture Mechanics Considerations (cont.)

- **Accurate fracture mechanics analysis (in the absence of RS) is a highly complex discipline that has many attributes, including (*but not limited to*) –**
  - ***Account of 3-D stress state***
  - ***Account of elastic-plastic material behavior***
  - ***Hold time effects***
  - ***Peak overload effects***
  - ***Complex 3-D part geometry and 3-D crack geometry / path***
  - ***Small crack behavior***

A "challenge" question –

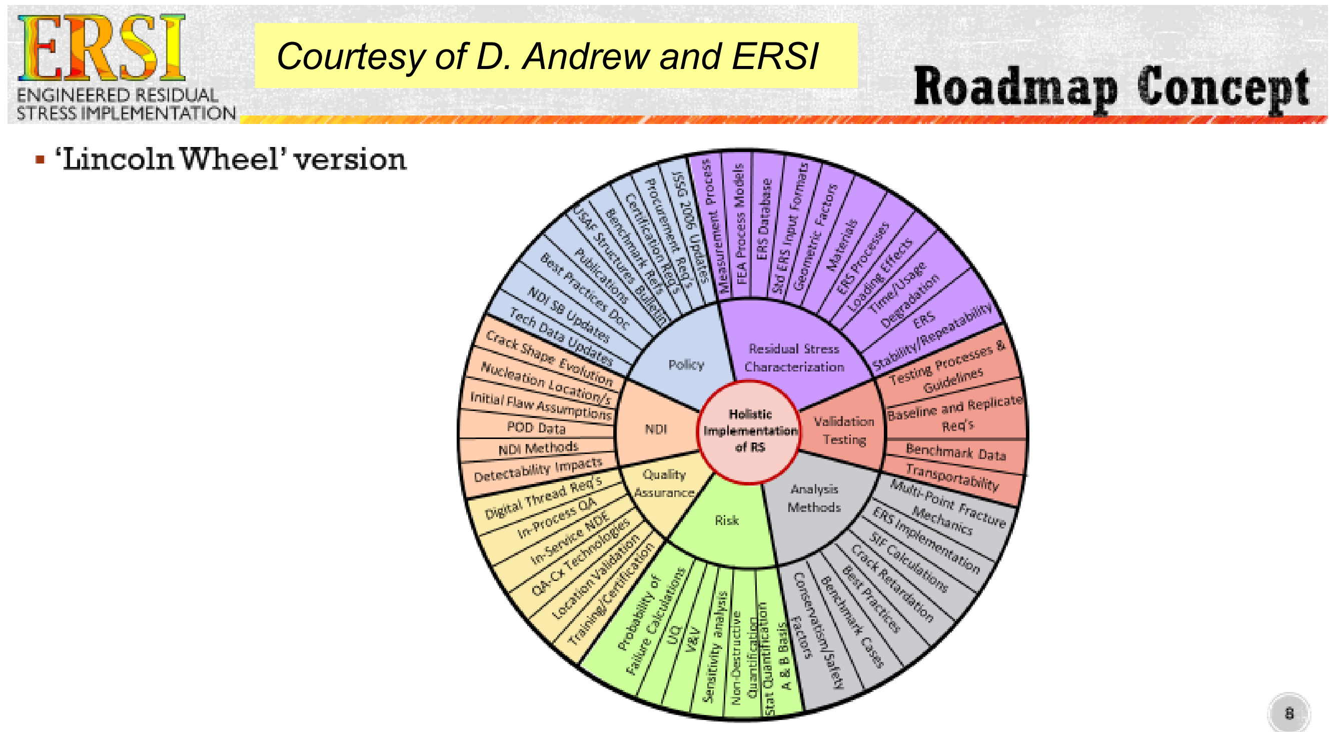
- ***Can we define a simplified FM framework that can be used to characterize the key beneficial effects of residual stresses as a "figure of merit" that can be linked to meaningful design or certification criteria***
  - **Note: have examples of successful applications from other F&DT areas**

Potential Expansion of the ERSI Structure



Regulatory Considerations

Roadmap Considerations

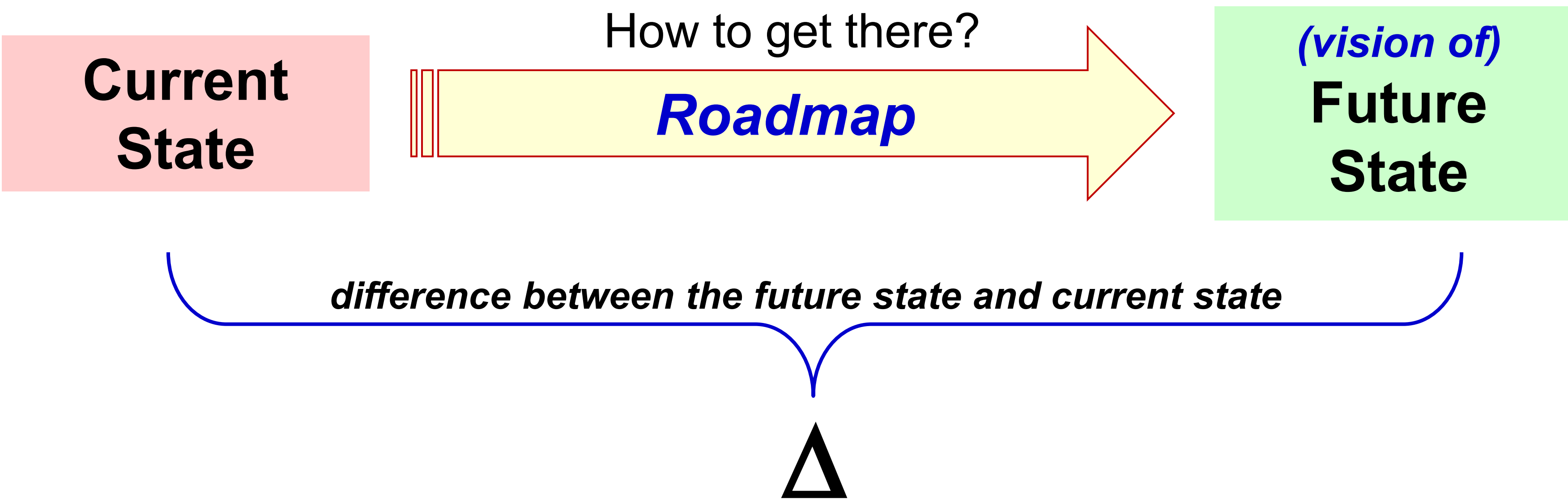


- **A very thorough list of relevant categories**
- **However, does not provide the current status or prioritization considerations for implementation**

Roadmap Considerations (cont.)

"Roadmap" means different things to different people

One interpretation →



ERSI – *Future* Scope Considerations

- **Military vs. Civil Aviation (?)**
- **Product types – airframe structures / propulsion systems / rotorcrafts / … (?)**
- **Engineered vs. manufacturing-induced (?)**
- **For engineered RS – type of technology (?)**
  - **Cx of holes / shot peening / LPB / LSP / …**
- **Primary use (?)**
  - More accurate life prediction / credits
  - Safety enhancements
  - Part of manufacturing QA
  - *Other..?*

Discussion…

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