Wednesday, 19 April 2023	
U.S. Air Force Academy, Colorado Springs, CO	
7:15 AM to 7:30 AM	***Executive Committee Arrive, Check-in***
7:30 AM to 10:00 AM	***Executive Committee Discussion*** |*Director's Conference Room*|
9:45 AM to 10:15 AM	**Arrive, Check-in**
10:15 AM to 10:30 PM	**USAFA Welcome & Overview** |*Main Forum*|
10:30 AM to 12:00 PM	**CAStLE Laboratory Tour**
12:00 PM to 1:30 PM	**Lunch break**
1:30 PM to 4:00 PM	**Committee Updates, Session 1** |*Main Forum*|
1:30 PM to 2:00 PM	ERSI Welcome, Announcements, Around the room
2:00 PM to 4:00 PM	Analysis Methods & Testing

Thursday, 20 April 2023	
U.S. Air Force Academy, Colorado Springs, CO	
7:15 AM to 7:30 AM	**Arrive**
7:30 AM to 10:45 AM	**Committee Updates, Session 2** |*Main Forum*|
7:30 AM to 9:00 AM	Residual Stress Measurement
9:00 AM to 9:30 AM	NDE/NDI/QA/Data Management
9:30 AM to 9:45 AM	Break
9:45 AM to 10:15 AM	Residual Stress Process Simulation
10:15 AM to 10:45 AM	Risk Analysis and Uncertainty Quantification
10:45 AM to 11:30 AM	**Discussion: ERSI Path Forward** |*Main Forum*|
11:30 AM to 1:00 PM	**Lunch break**
1:00 PM to 2:00 PM	**Open Discussion**
2:00 PM to 3:30 PM	**Committee Break-out Meetings** Analysis Methods & Testing |*Main Forum*| Residual Stress Measurement |*East Seminar*| Residual Stress Process Simulation |*West Seminar*| NDE/NDI/QA/Data Management | *Director's Conference Room* | Risk Analysis and Uncertainty Quantification |*Collaboration Room A*|
3:30 PM to 4:00 PM	**Regroup & Dismiss** |*Main Forum*|

2023 ERSI Workshop: Welcome!

19 April 2023

Dallen Andrew

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Agenda

- ERSI Purpose
- ERSI Organization
- Who is who
- EZ-SB-17-001 update
- RS Best Practices Document
- ‘Lincoln Wheel’ Roadmap
- USAF Academy Testing
- ERSI Communications
- Questions

Agenda

- **ERSI Purpose**
- ERSI Organization
- Who is who
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- RS Best Practices Document
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- ERSI Communications
- Questions

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

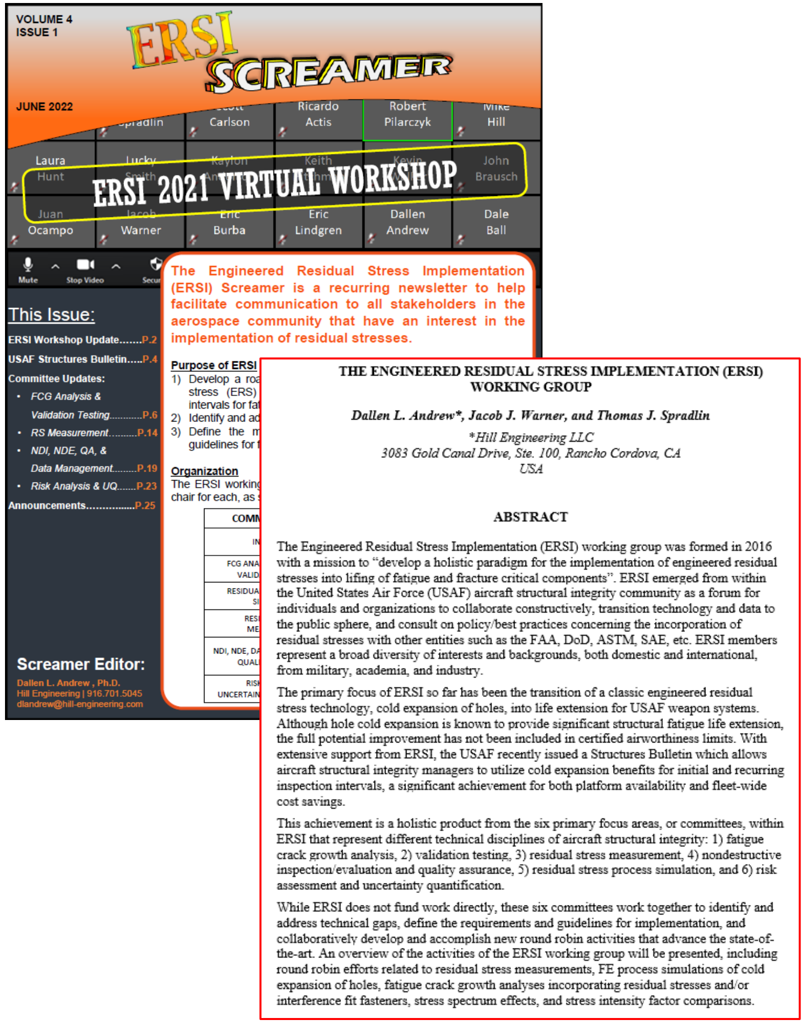
ERSI Key Objectives

- 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

ERSI purpose: Where does ERSI add value?

ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

- **Fatigue crack growth analysis methods / Validation 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 process simulation**
  - 2017: 2x2 material modeling data
  - 2019: 2x2 process simulation analysis
- **Residual stress measurement**
  - 2017: 2x2 Cx Coupons
  - 2017: Contour method inter-laboratory reproducibility uncertainty
  - 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]
- **Risk analysis / Uncertainty quantification**
  - x



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.

ERSI purpose: Where does ERSI add value?

- James B. Castle, D.Sc., Boeing Research & Technology
  - Engineered residual stresses provide a significant opportunity to extend the life of existing DoD platforms. With the increased number of assets grounded for maintenance, the ability to develop engineered residual stress techniques to extend airframes and lengthen intervals between inspections is essential technology. However, **it has been demonstrated repeatedly that the ability to properly analyze, apply, and measure engineered residual stresses requires advanced knowledge to ensure appropriate application**. Typically this has been accomplished through an extensive test and analysis program on each individual case with significant cost. **This working group provides the opportunity to share the best practices** the community has experienced in individual case by case insertions **enabling tools and processes to be developed** for the general cases that benefits all stakeholders especially the DoD which will benefit in improved platform availability at less investment per insertion.

Agenda

- ERSI Purpose
- **ERSI Organization**
- Who is who
- EZ-SB-17-001 update
- RS Best Practices Document
- ‘Lincoln Wheel’ Roadmap
- USAF Academy Testing
- ERSI Communications
- Questions

ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Organization: Committees (current)

- **Integrator**
  - TJ Spradlin
  - Dale Ball
- **Fatigue crack growth analysis methods / Validation testing**
  - Kevin Walker
  - Robert Pilarczyk
- **Residual stress process simulation**
  - Keith Hitchman
- **Residual stress measurement**
  - Eric Burba
  - Adrian DeWald
- **NDI/NDE / Data management / Quality assurance**
  - Eric Lindgren
  - John Brausch
  - Kaylon Anderson
- **Risk analysis / Uncertainty quantification**
  - Laura Hunt
  - Juan Ocampo

"We need to rethink how we collaborate so that the data generators have more talk with the data analyzers."

Organization: Committees (updated)

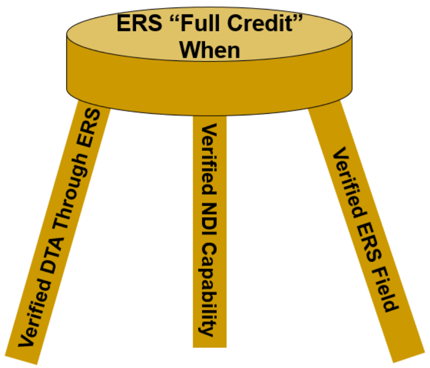
Technical Advisors
Gaggle of people

ERSI Executive Committee
Dallen Andrew

Analysis & Test
Kevin Walker, Robert Pilarczyk

Residual stress characterization
Eric Burba, Adrian DeWald, TBD

NDI/NDE/Data management/QA
Eric Lindgren, John Brausch, TBD



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Who am I?

- Original Bio
  - Dallen started his career off working with the A-10 team under Dr. Mark Thomsen where he learned how to be personable. 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. 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 4 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)

ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Who are you?

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

Ricardo	Actis	ESRD
Dallen	Andrew	Hill Engineering
Ana	Barrientos	Northrop Grumman
Daniel	Bavaro	USAF
Michael	Brauss	Proto
Dave	Breuer	Curtiss Wright
Eric	Burba	USAF
Joe	Cardinal	SwRI
Scott	Carlson	Lockheed Martin
Aditya	Chattopadhyay	Boeing
George	Crosthwaite	USAF
Adrian	DeWald	Hill Engineering
AJ	Flusche	Boeing
Jim	Greer	USAF
Tyler	Gruters	USAF
Jim	Harrison	Proto
Jason	Hawks	Boeing
Mike	Hill	Hill Engineering
Keith	Hitchman	FTI
Haydn	Kirkpatrick	Boeing
Eric	Lindgren	USAF
Adrian	Loghin	Simmetrix
Dean	Madden	FTI
Craig	McClung	SwRI
Robert	McGinty	MERC
Matt	McSwiggen	Lockheed Martin
Adam	Morgan	Northrop Grumman
Doyle	Motes	TRI-Austin
Mark	Obstalecki	USAF
Moises	Ocasio-Latorre	Boeing
Robert	Pilarczyk	Hill Engineering
James	Pineault	Proto
Scott	Prost-Domasky	APES
Evan	Ryker	TRI-Austin
Sandeep	Shah	Boeing
Greg	Shoales	USAF
Lucky	Smith	SwRI
TJ	Spradlin	USAF
Michael	Stivers	Lockheed Martin
Mike	Steinzig	Los Alamos National Lab
Hiram	Vega	Boeing
Jesse	Vickers	Sabreliner
Josh	Ward	UDRI
Jacob	Warner	USAF
Kevin	Gibbons	Sabreliner
Jude	Restis	PartWorks

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Structures Bulletin

AFLCMC/EZ
Bldg. 28, 2145 Monahan Way
WPAFB OH 45433-7101
Phone: 937-255-5312

Number: EZ-SB-17-001, Revision A

Date: December 2021

Subject: Requirements to Establish the Beneficial Effects of Cold Expanded Holes in Development of Damage Tolerance Initial and Recurring Inspection Intervals

References:

1. JSSG-2006, “Joint Service Specification Guide Aircraft Structures,” 30 Oct 1998
2. MIL-A-83444, “Airplane Damage Tolerance Requirements”, 2 Jul 1974
3. AFI 20-106, “Management of Aviation Critical Safety Items”, Department of the Navy, Air Force, Army, Defense Logistics Agency, and Defense Contract Management Agency, 27 January 2020
4. MIL-STD-1530D, “Aircraft Structural Integrity Program (ASIP)”, Department of Defense Standard Practice, 31 Aug 2016
5. EN-SB-08-012 Rev. D, “In-Service Inspection Flaw Assumptions for Metallic Structures”, Apr 2018
6. EZ-SB-14-003, “Durability Test Programs to Validate Aircraft Structure Service Life Capability for Repairs, Modifications, and Materials & Processes Changes”, 9 Apr 2014
7. Barter, S.A., et al., “Marker Loads for Quantitative Fractography of Fatigue Cracks in Aerospace Alloys”, 25th ICAF Symposium, May 2009
8. EZ-SB-13-002, “Correlating Durability Analysis to Unanticipated Fatigue Cracks in Metallic Structure”, 26 Feb 2013
9. ASTM E 647, “Standard Test Method for Measurement of Fatigue Crack Growth Rates”, AD1070087

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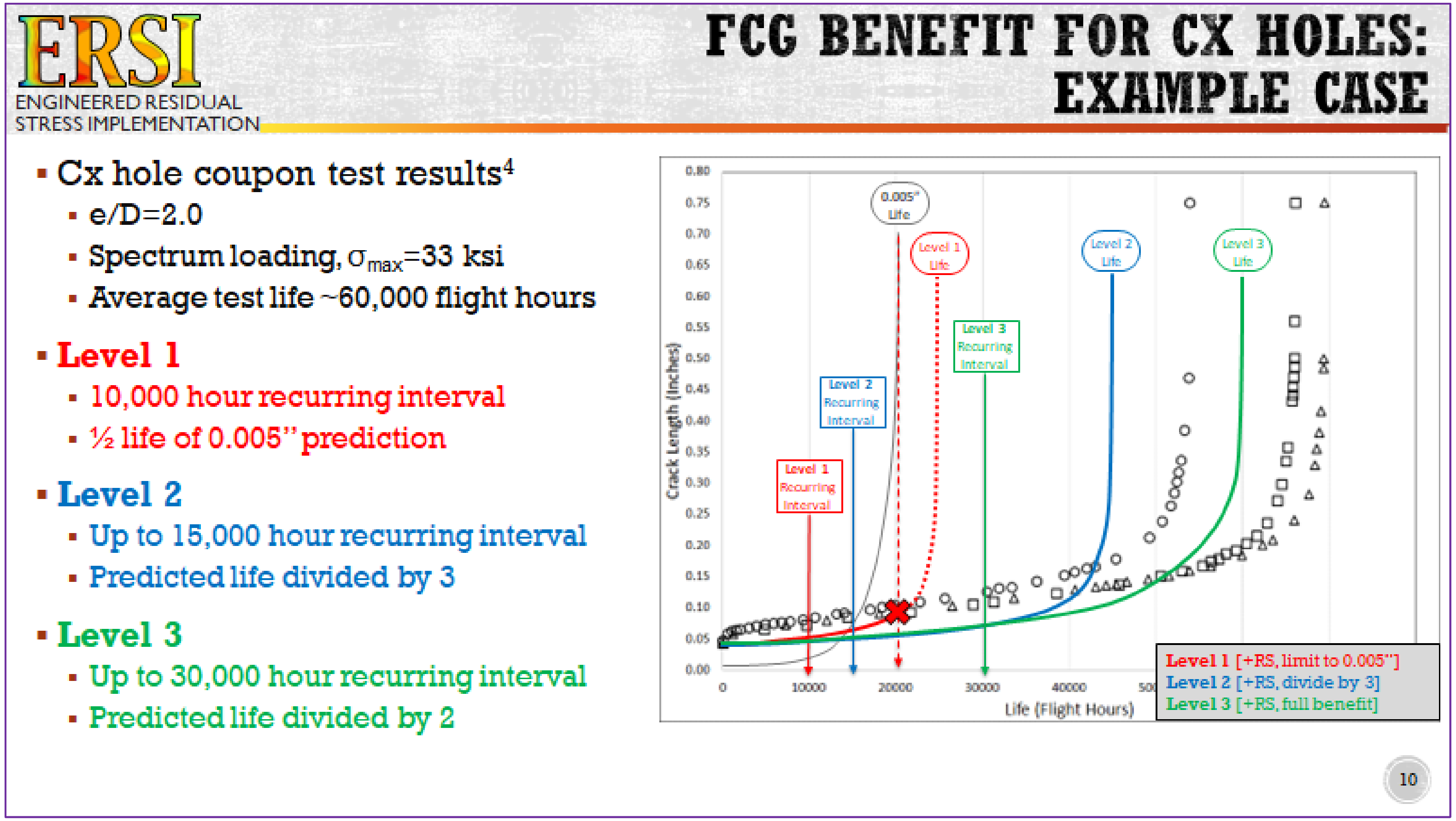
EZ-SB-17-001 Rev. A, Page 1 of 13

- Example Case



ERSI
ENGINEERED RESIDUAL
STRESS IMPLEMENTATION

EZ-SB-17-001 update

- Revision A
  - Includes Level 1 benefit (explicit RS, limit to 0.005" life)
- Revision B in-work
  - Targeting Level 2 benefit

ERSI
ENGINEERED RESIDUAL
STRESS IMPLEMENTATION

FCG Benefit for Cx Holes: Tier Summary

+RS = Explicit incorporation of residual stress field in FCG analyses

- Level 0 *[current state]*
  - Current use of 0.005" for initial inspection, no benefit for recurring inspections
- Level 1 *[+RS, limit to 0.005"]*
  - Include RS explicitly in analysis with traditional initial crack size of 0.05"
  - Same test and validation requirements as Level 0
  - Limit life benefit to match 0.005" approach (permits benefit for recurring inspections)
- Level 2 *[+RS, divide by 3]*
  - Include RS explicitly in analysis with traditional initial crack size of 0.05"
  - Prediction validated by at least 5 FCG test replicates
  - RS field validated by direct determination or validated FEA
  - Definitive verification Cx was performed within specification limits
  - Benefit limited to dividing by 3
- Level 3 *[+RS, full benefit]*
  - Include RS explicitly in analysis with traditional initial crack size of 0.05"
  - Prediction validated by at least 5 FCG test replicates
  - RS field validated by direct determination or validated FEA
  - Definitive verification Cx was performed within specification limits
  - Load interaction effects permitted

6

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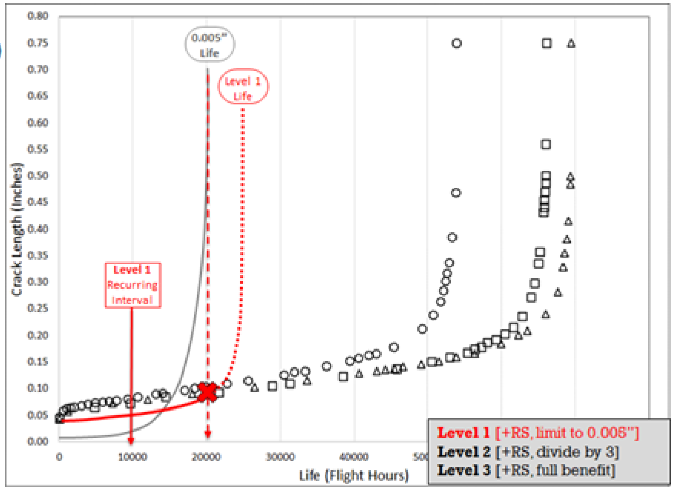
ENGINEERED RESIDUAL
STRESS IMPLEMENTATION

FCG Benefit for Cx Holes: Level 1 Requirements

- RS explicitly included in DTA using standard assumed crack size (0.05")
- Recurring & initial inspections limited to 0.005" life divided by 2
- User may define RS field and implementation approach
- Test requirements per EZ-17-SB-001[6] (or other acceptable justification)
- Recurring inspection benefit with no significant increased risk



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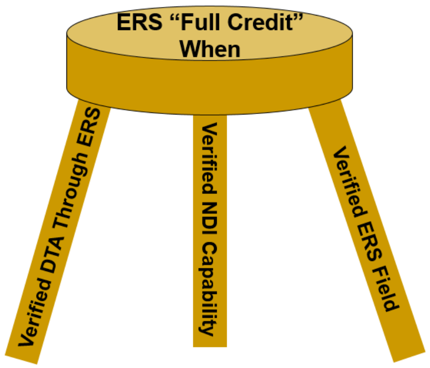
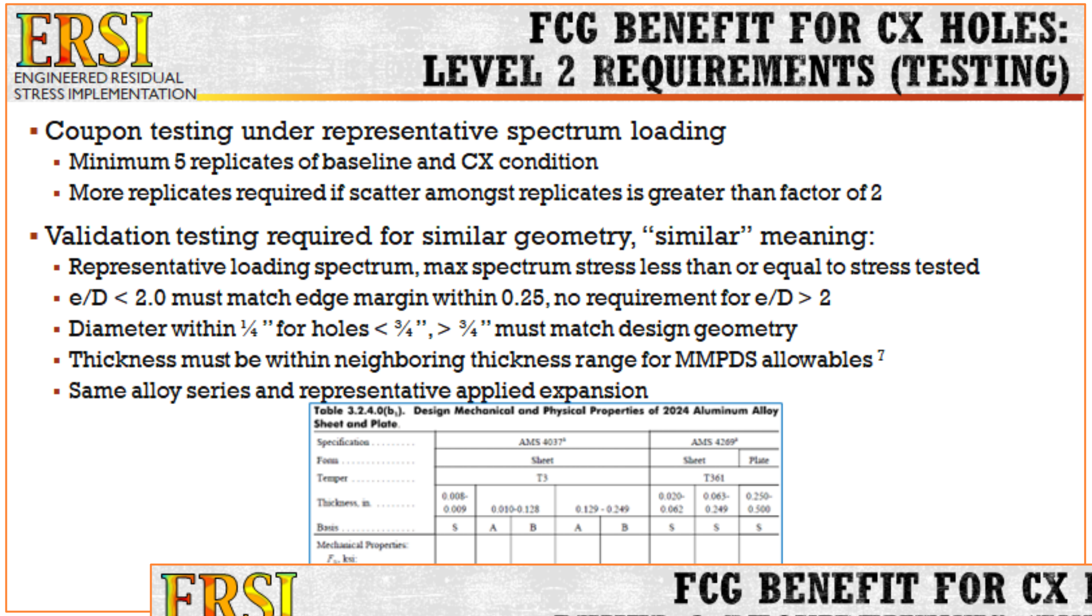
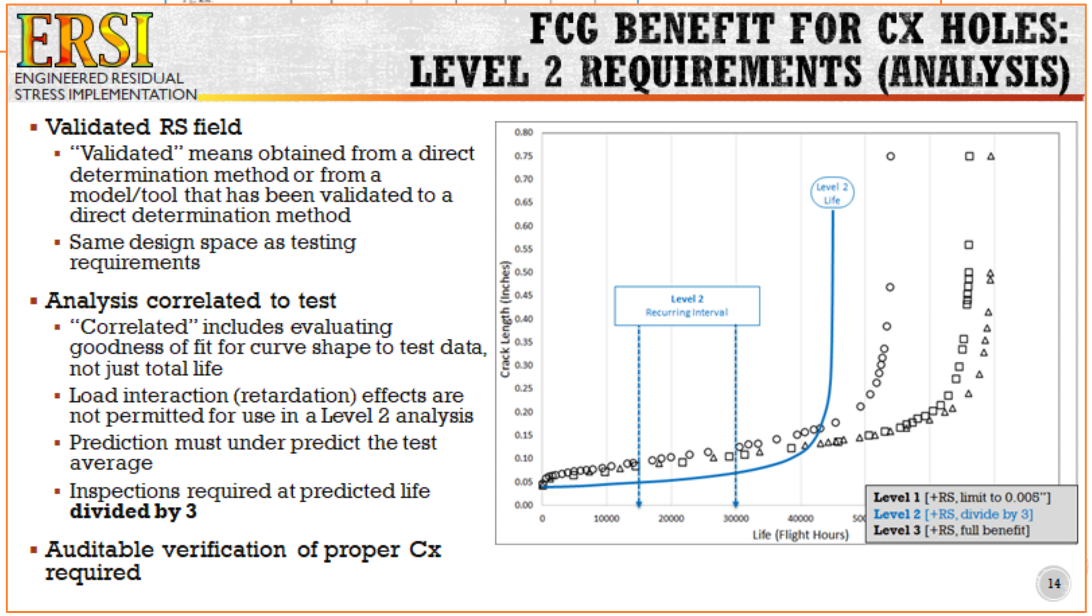
EZ-SB-17-001 update

- Revision B in-work
  - Targeting Level 2 benefit
  - Major challenges
    - Defining/prescribing the MPFM analysis process & associated details
    - Defining/prescribing requirements for RS field
  - Other challenges
    - Verifying Cx was done & was in-spec
    - Include benefit for interference fit fasteners







ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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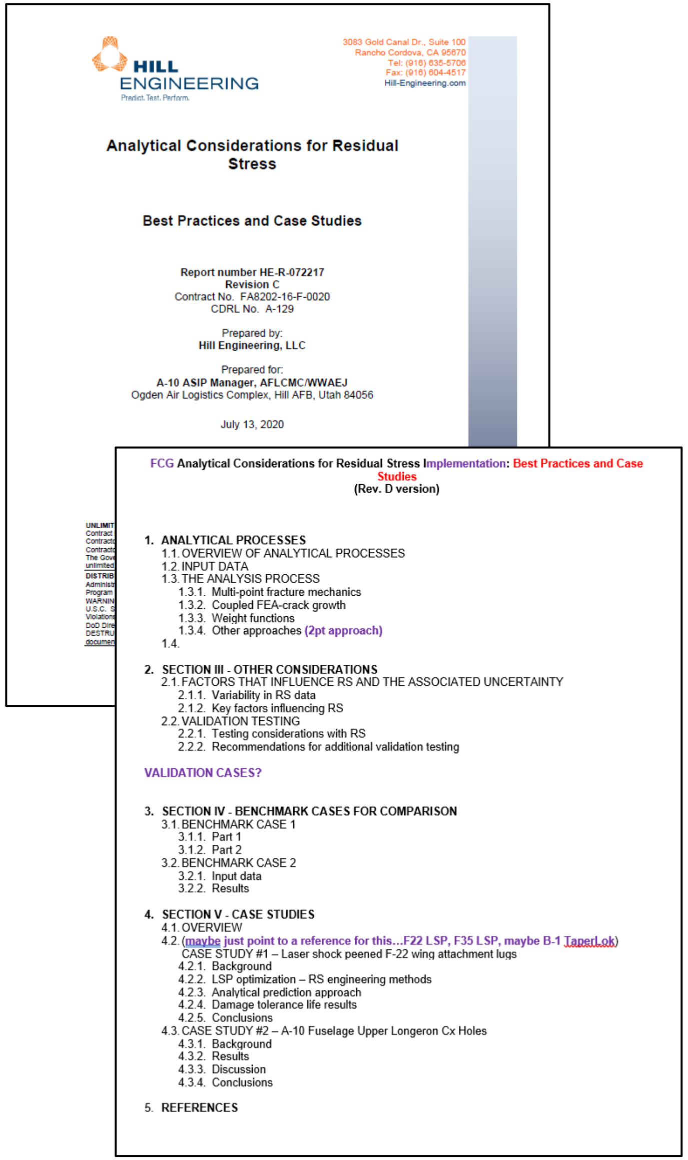
RS Best Practices Document

- 2 reasons people are asking for this
  - How do we do it (analysis steps; best practices; guide)
  - How has it been done in the past (case studies; lessons learned)
- If XYZ comes to you and wants to use RS, what are the step by steps we go through to help them
  - So you want to do RS in your analysis, how do you do it? (we hand them this document);
    - 1: get RS field from source you believe
    - 2: applying RS to FEA model
    - 3: doing MPFM
- Maybe add section on other sources for RS process models, instrumented puller, SpARS, Ball closed-form, marks math model, etc. (“sources of RS”)
- RS inducing processes as appendix
- Maybe ref DT design handbook for ‘how to do DTA’



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Rancho Cordova, CA 95670
Tel: (916) 635-5706
Fax: (916) 604-4517
Hill-Engineering.com

Analytical Considerations for Residual Stress

Best Practices and Case Studies

Report number HE-R-072217
Revision C
Contract No. FA8202-16-F-0020
CDRL No. A-129

Prepared by:
Hill Engineering, LLC

Prepared for:
A-10 ASIP Manager, AFLCMC/WWAEJ
Ogden Air Logistics Complex, Hill AFB, Utah 84056

July 13, 2020

FCG Analytical Considerations for Residual Stress Implementation: Best Practices and Case Studies
(Rev. D version)

1. **ANALYTICAL PROCESSES**
   - 1.1. OVERVIEW OF ANALYTICAL PROCESSES
   - 1.2. INPUT DATA
   - 1.3. THE ANALYSIS PROCESS
     - 1.3.1. Multi-point fracture mechanics
     - 1.3.2. Coupled FEA-crack growth
     - 1.3.3. Weight functions
     - 1.3.4. Other approaches **(2pt approach)**
   - 1.4.
2. **SECTION III - OTHER CONSIDERATIONS**
   - 2.1. FACTORS THAT INFLUENCE RS AND THE ASSOCIATED UNCERTAINTY
     - 2.1.1. Variability in RS data
     - 2.1.2. Key factors influencing RS
   - 2.2. VALIDATION TESTING
     - 2.2.1. Testing considerations with RS
     - 2.2.2. Recommendations for additional validation testing

VALIDATION CASES?

3. **SECTION IV - BENCHMARK CASES FOR COMPARISON**
   - 3.1. BENCHMARK CASE 1
     - 3.1.1. Part 1
     - 3.1.2. Part 2
   - 3.2. BENCHMARK CASE 2
     - 3.2.1. Input data
     - 3.2.2. Results
4. **SECTION V - CASE STUDIES**
   - 4.1. OVERVIEW
   - 4.2. **(maybe just point to a reference for this…F22 LSP, F35 LSP, maybe B-1 TaperLok)** CASE STUDY #1 – Laser shock peened F-22 wing attachment lugs
     - 4.2.1. Background
     - 4.2.2. LSP optimization – RS engineering methods
     - 4.2.3. Analytical prediction approach
     - 4.2.4. Damage tolerance life results
     - 4.2.5. Conclusions
   - 4.3. CASE STUDY #2 – A-10 Fuselage Upper Longeron Cx Holes
     - 4.3.1. Background
     - 4.3.2. Results
     - 4.3.3. Discussion
     - 4.3.4. Conclusions
5. **REFERENCES**

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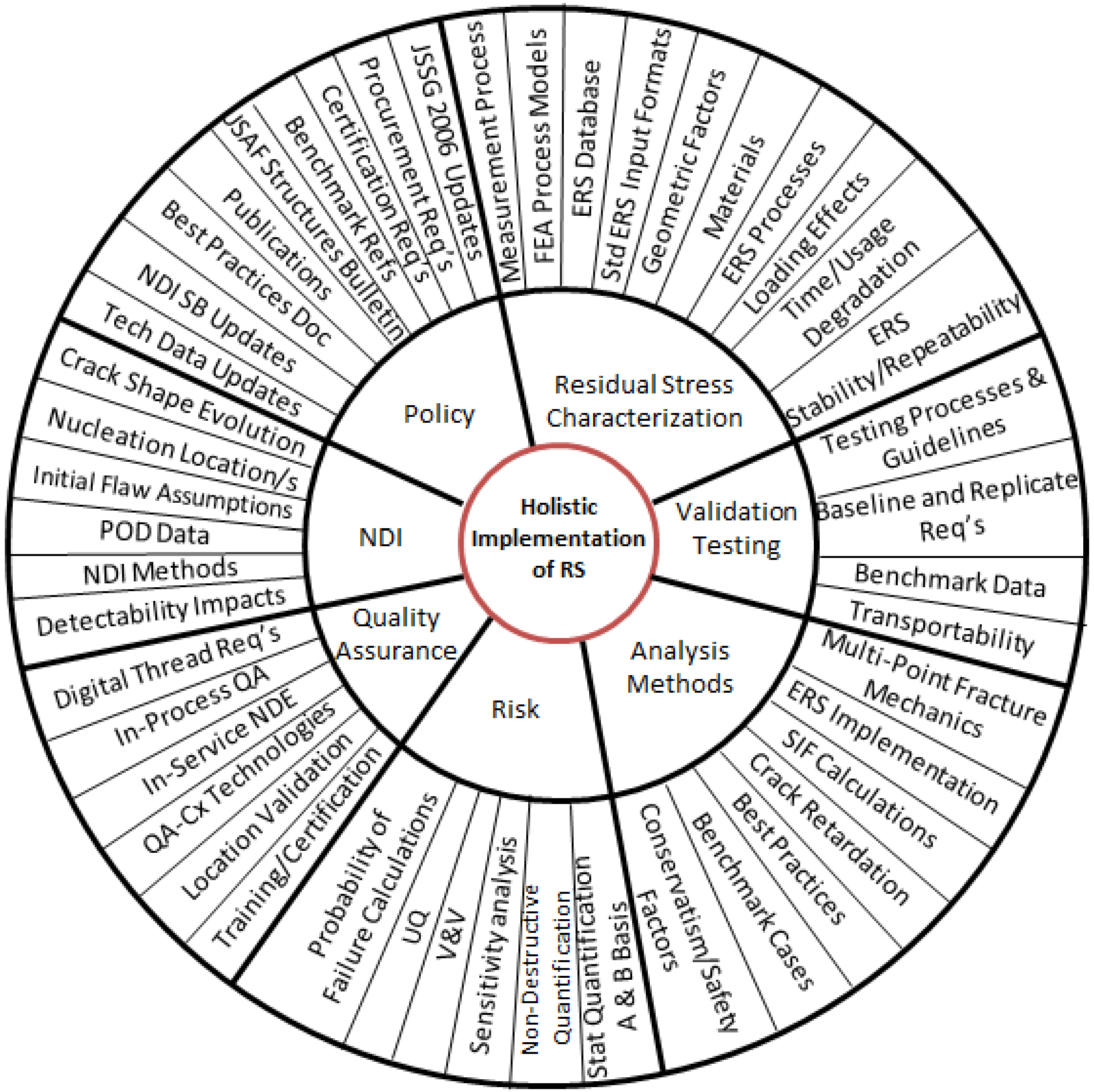
'Lincoln Wheel' Roadmap



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UNITED STATES AIR FORCE ACADEMY

Agenda

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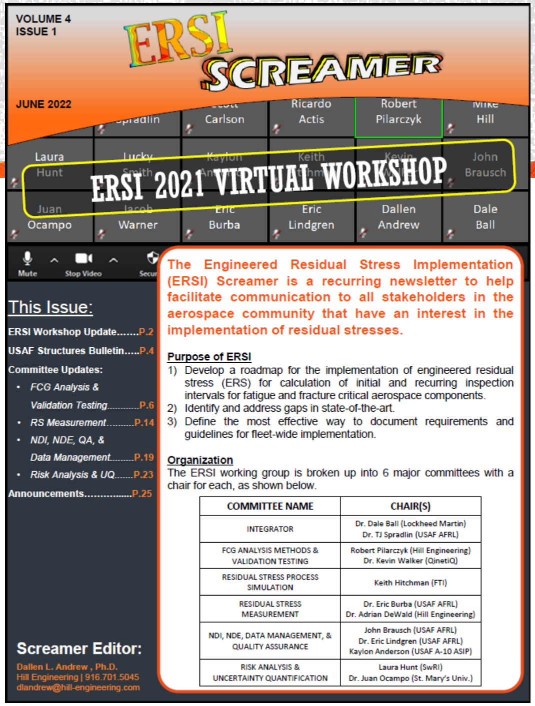


VOLUME 4
ISSUE 1

ERSI SCREAMER

JUNE 2022

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.

This Issue:

Purpose of ERSI

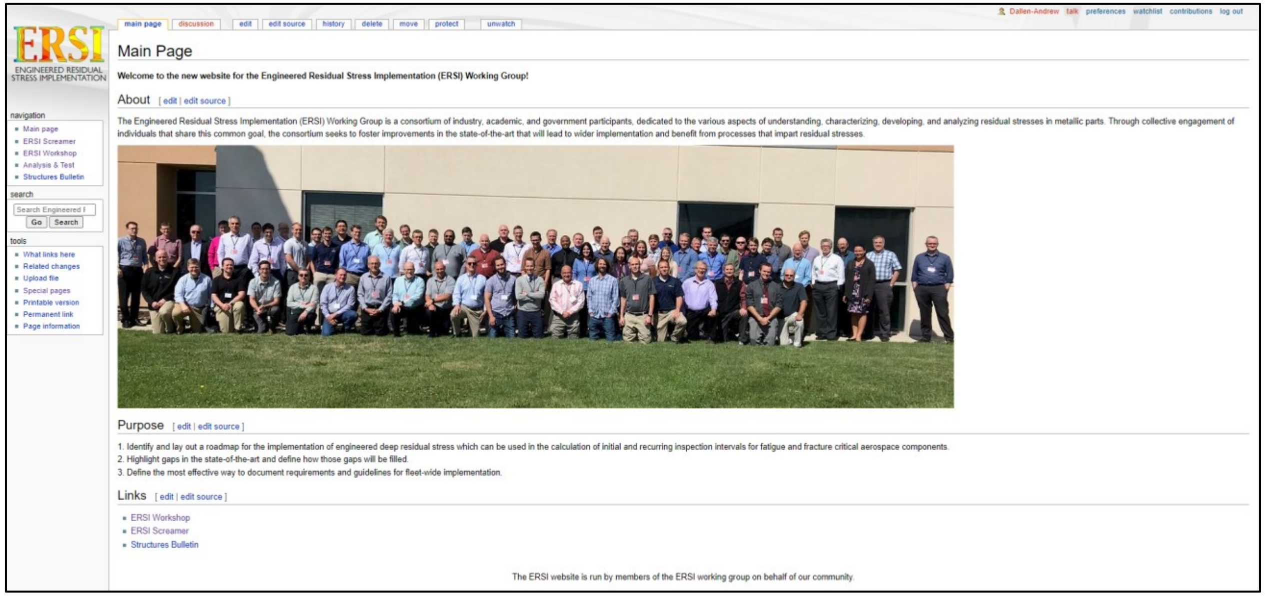
1) Develop a roadmap for the implementation of engineered residual stress (ERS) for calculation of initial and recurring inspection intervals for fatigue and fracture critical aerospace components.
2) Identify and address gaps in state-of-the-art.
3) Define the most effective way to document requirements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

Organization

The ERSI working group is broken up into 6 major committees with a chair for each, as shown below.

COMMITTEE NAME	CHAIR(S)
INTEGRATOR	Dr. Dale Ball (Lockheed Martin) Dr. TJ Spradlin (USAF AFRL)
FCG ANALYSIS METHODS & VALIDATION TESTING	Robert Pilarczyk (Hill Engineering) Dr. Kevin Walker (QinetiQ)
RESIDUAL STRESS PROCESS SIMULATION	Keith Hitchman (FTI)
RESIDUAL STRESS MEASUREMENT	Dr. Eric Burba (USAF AFRL) Dr. Adrian DeWald (Hill Engineering)
NDI, NDE, DATA MANAGEMENT, & QUALITY ASSURANCE	John Brausch (USAF AFRL) Dr. Eric Lindgren (USAF AFRL) Kaylon Anderson (USAF A-10 ASIP)
RISK ANALYSIS & UNCERTAINTY QUANTIFICATION	Laura Hunt (SwRI) Dr. Juan Ocampo (St. Mary's Univ.)

Screamer Editor:
Dallen L. Andrew , Ph.D.
Hill Engineering | 916.701.5045
dlandrew@hill-engineering.com



ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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Dallen-Andrew talk preferences watchlist contributions log out

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Main Page

Welcome to the new website for the Engineered Residual Stress Implementation (ERSI) Working Group!

About [edit | edit source]

The Engineered Residual Stress Implementation (ERSI) Working Group is a consortium of industry, academic, and government participants, dedicated to the various aspects of understanding, characterizing, developing, and analyzing residual stresses in metallic parts. Through collective engagement of individuals that share this common goal, the consortium seeks to foster improvements in the state-of-the-art that will lead to wider implementation and benefit from processes that impart residual stresses.

Purpose [edit | edit source]

1. Identify and lay out a roadmap for the implementation of engineered deep residual stress which can be used in the calculation of initial and recurring inspection intervals for fatigue and fracture critical aerospace components.
2. Highlight gaps in the state-of-the-art and define how those gaps will be filled.
3. Define the most effective way to document requirements and guidelines for fleet-wide implementation.

Links [edit | edit source]

- ERSI Workshop
- ERSI Screamer
- Structures Bulletin

The ERSI website is run by members of the ERSI working group on behalf of our community.

ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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- **Questions**

Dallen Andrew

dlandrew@hill-engineering.com | 916.701.5045

Fatigue Crack Growth & Testing Committee

2023 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**

Roster Summary

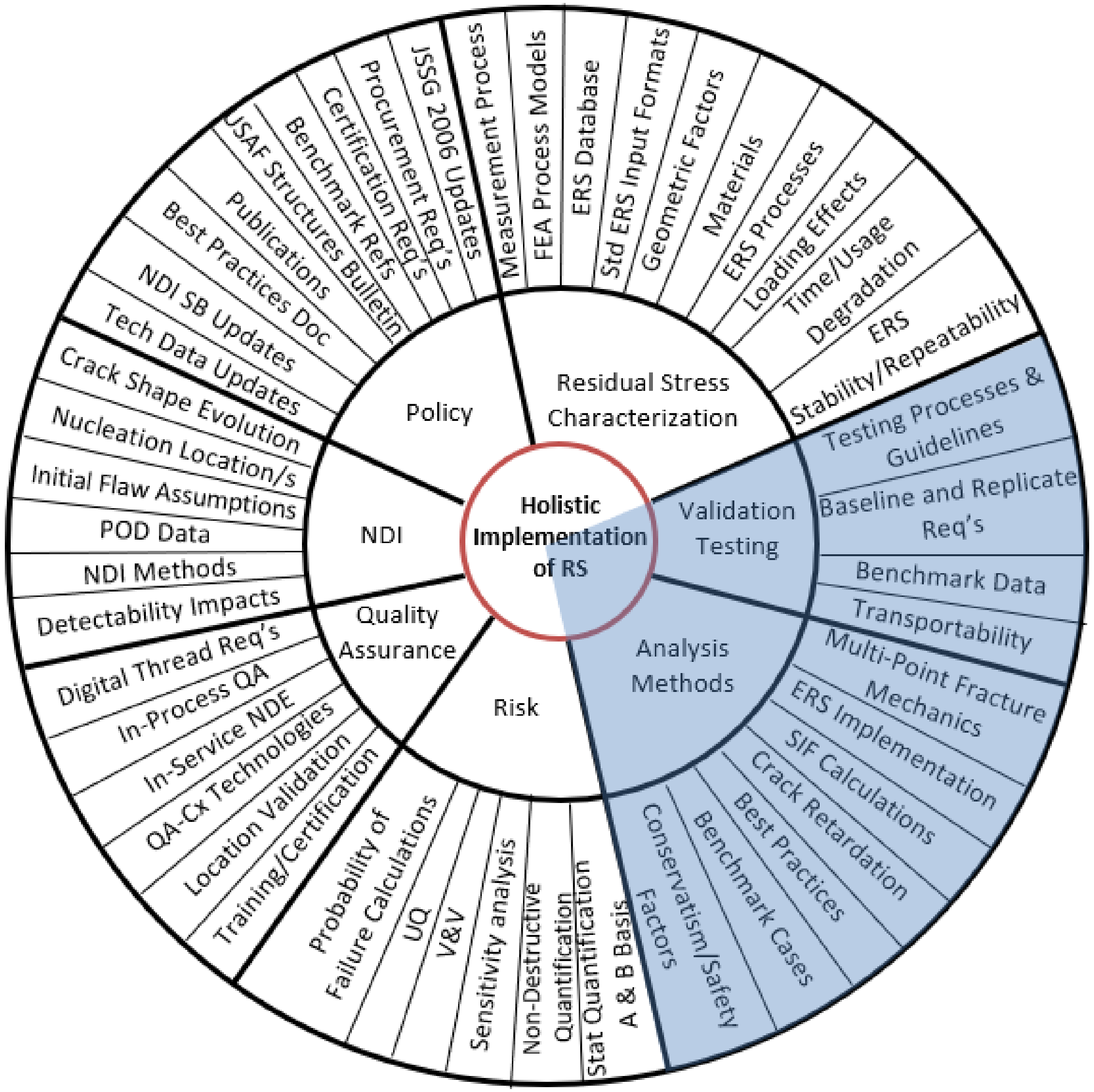
- **Committee members**
  - 68 members
  - Diverse participation from government, OEMs, small businesses, and academia
- **Active participants**
  - ~20-25 participants in monthly meetings
- **Working groups**
  - Two primary working groups
    - Spectrum loading
      - Leads – Moises, Walker, Newman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

Vision

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

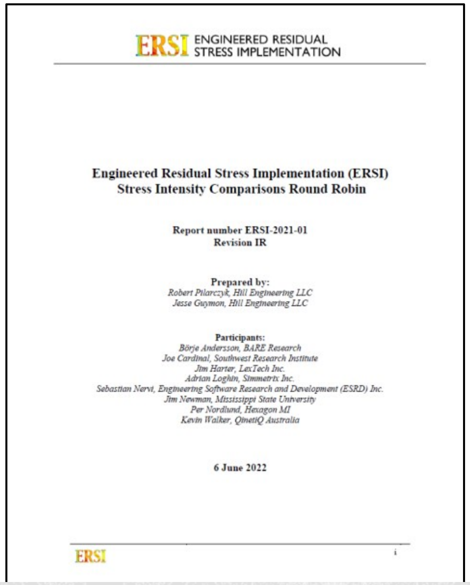
Implementation Roadmap

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



Accomplishments

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


ERSI ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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

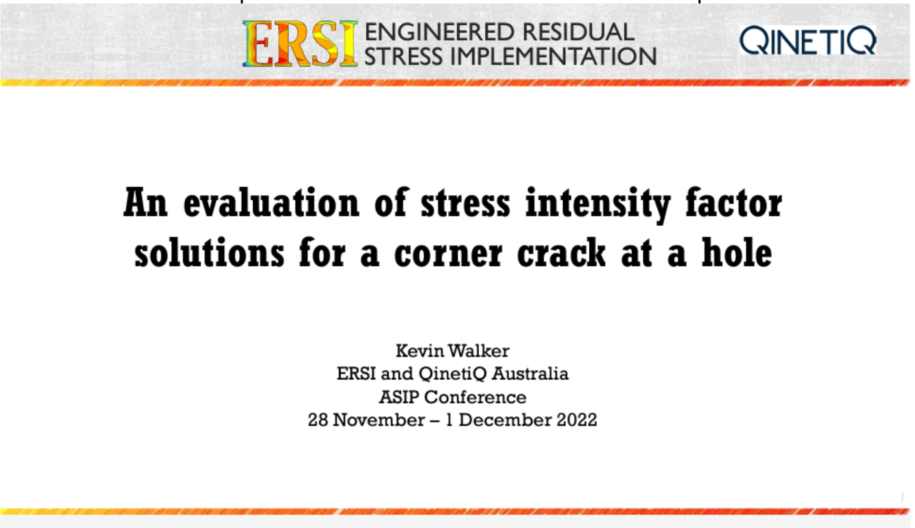
Report number ERSI-2021-01
Revision IR

Prepared by:
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

ERSI i



Accomplishments

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

Focus Areas

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

Spectrum Loading Working Group

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

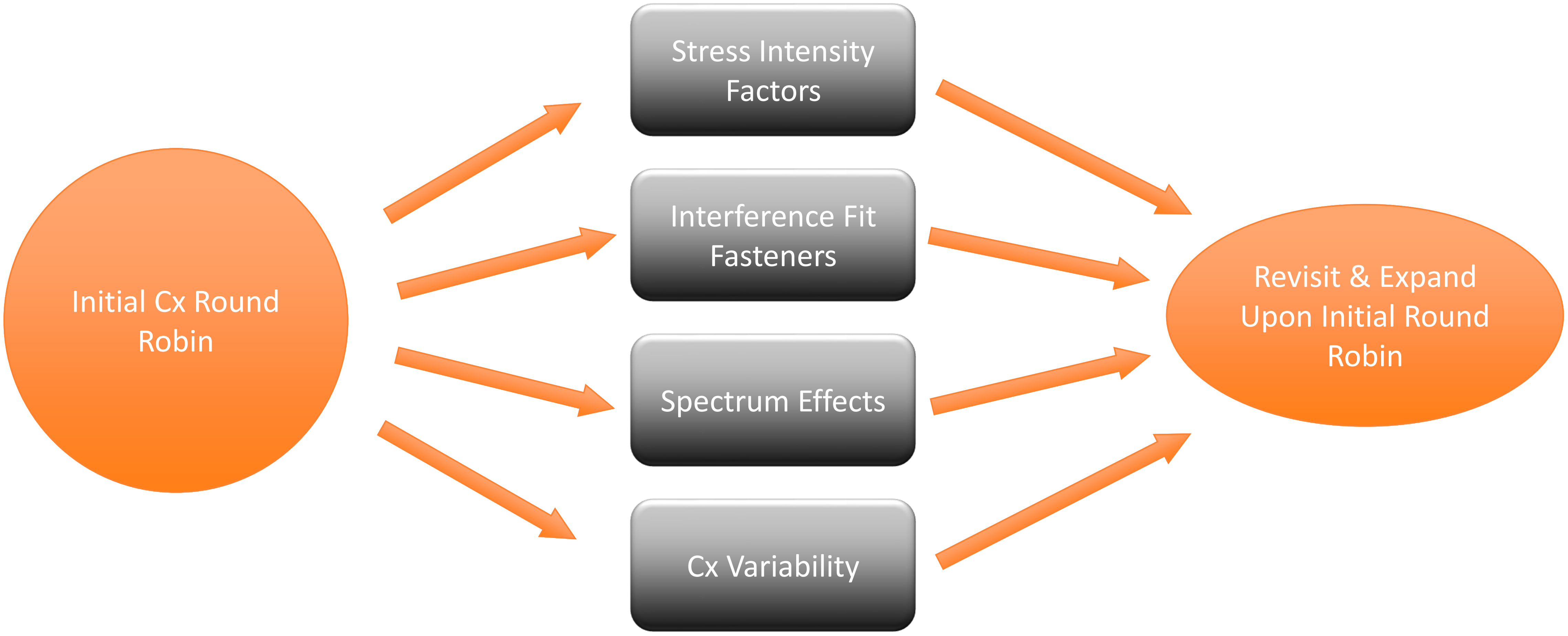
IFF Working Group

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

Breakout Presentations

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

Committee Goals



Past	Present	Future

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Future Plans

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

Revisit 2018 CW Hole Round Robin

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

Interference Fit Fasteners

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

Spectrum Loading

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

Summary

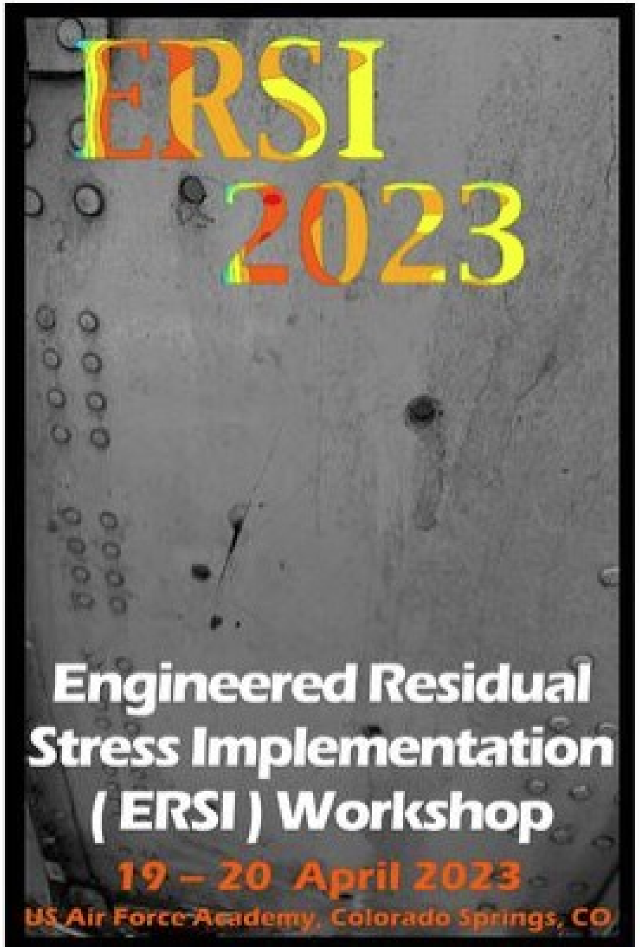
- **Diverse, active committee focused on key aspects for accurate analytical predictions with supporting validation data**
- **Topic areas have expanded beyond Cx since the original round robin**
  - Areas are critical for practical application
- **Refocusing on Cx cases is important moving forward**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

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

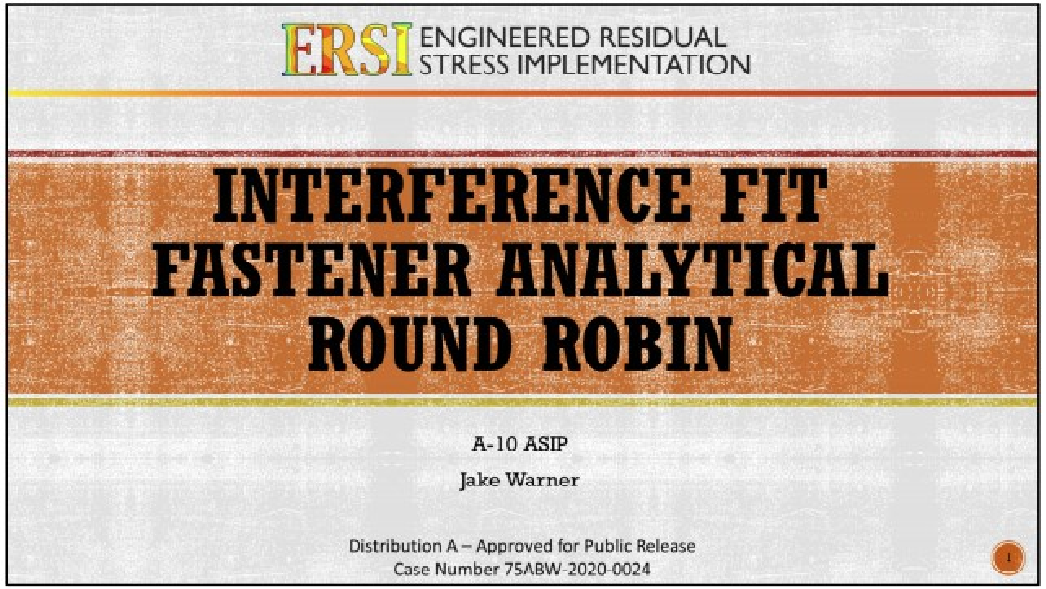
Adrian Loghin

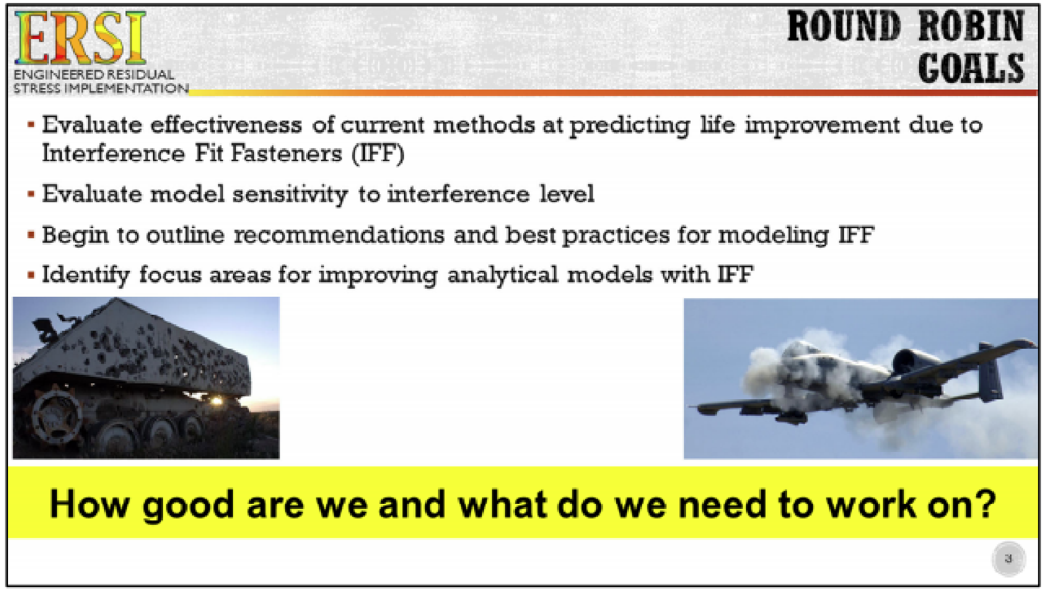
Simmetrix Inc.

Clifton Park, NY



IFF Round Robin Challenge: V&V Opportunity





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

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

IFF Round Robin Challenge: Problem Statement

Interference Fit Fastener Prediction Challenge

Analysis Methods Subcommittee

Round-Robin Life Prediction Invitation for Interference Fit Holes

Purpose:

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

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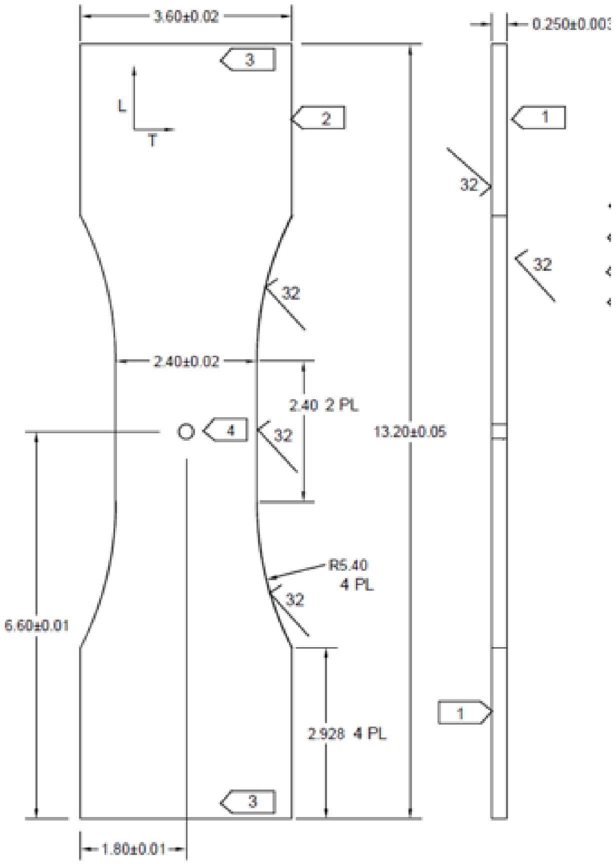
Conditions:

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

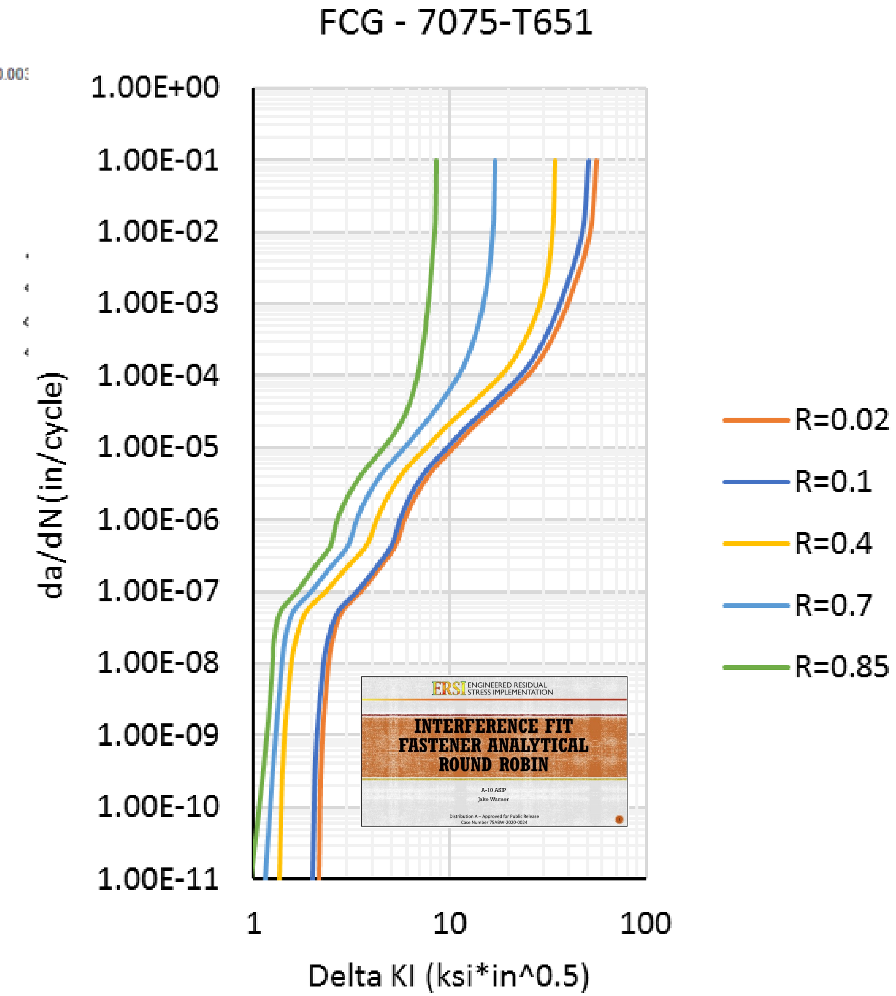
Table 1. Round-robin analysis conditions

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

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

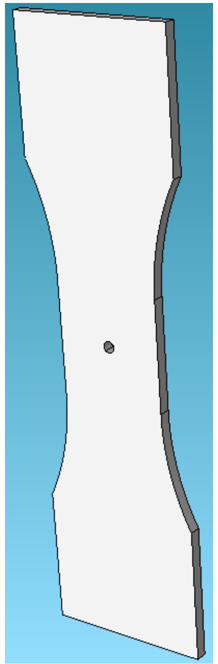


Length unit system: Imperial

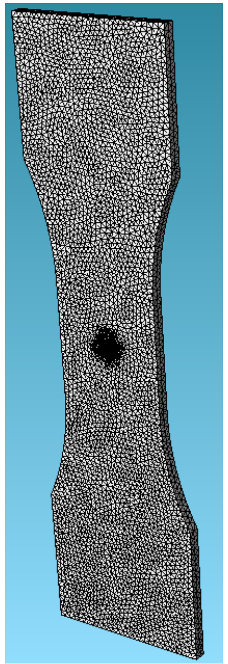


IFF Round Robin Challenge: 3D Modeling

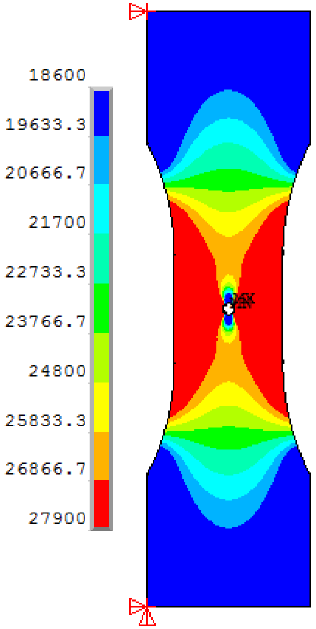
3D Geometry



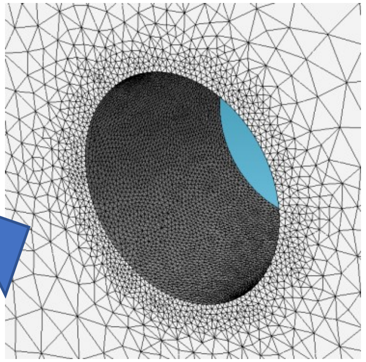
Mesh



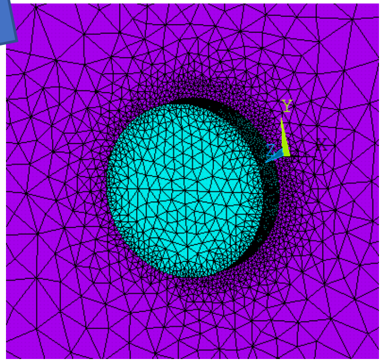
FE Model

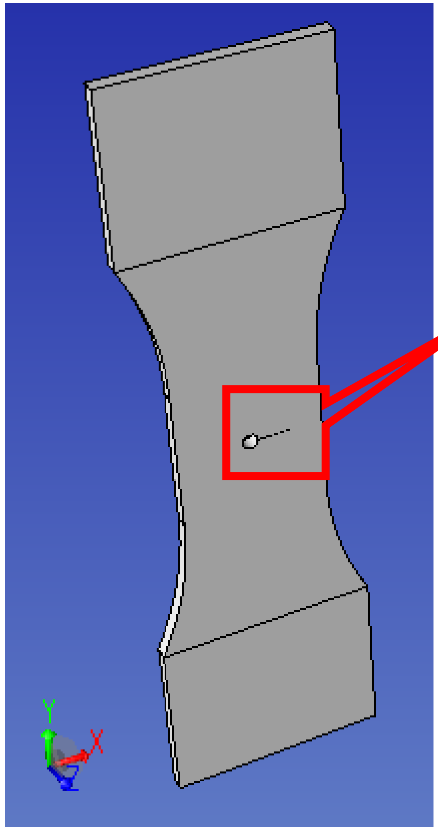


Open Hole Condition

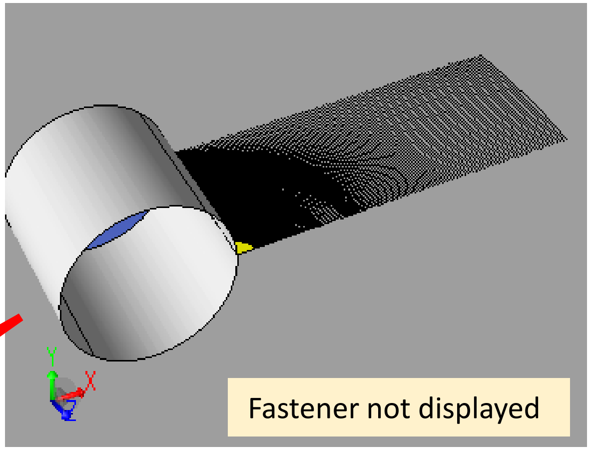


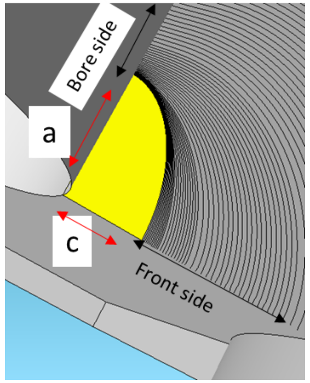
IFF Condition

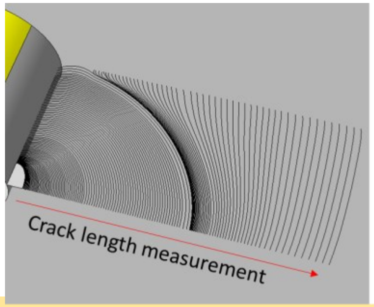




Typical solution: crack front increments





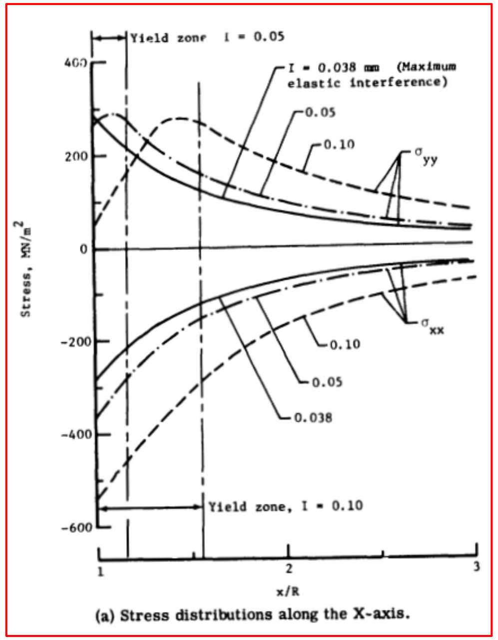


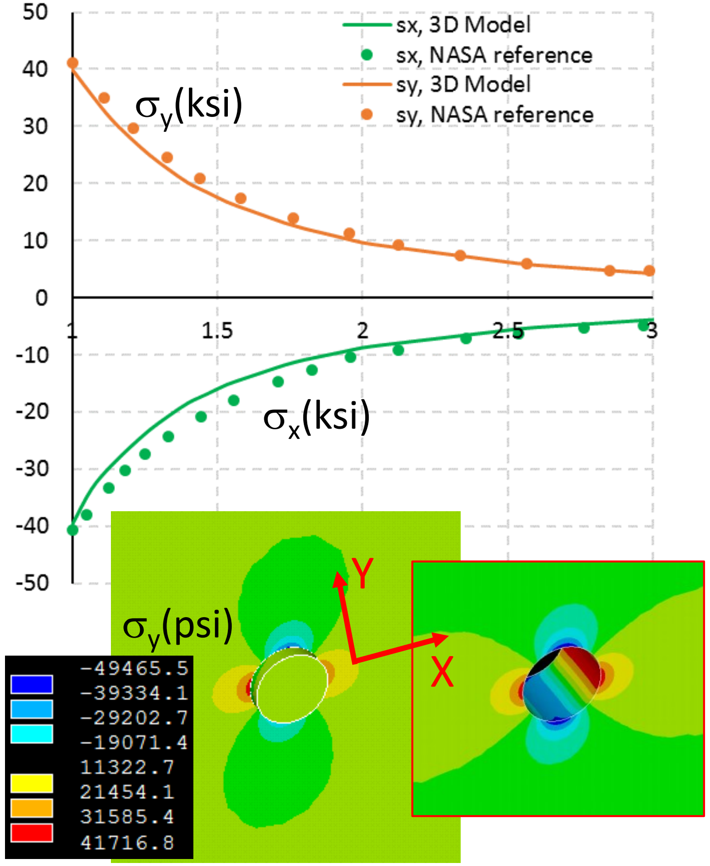
- Only 3D models are used in this assessment. The overall mesh pattern is maintained for all simulations
- Nominal bore and fastener diameters as provided in the challenge were used to create the 3D models for each condition.
- IFF stress levels are captured by solving the fastener-specimen bore contact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

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

3D Model Verification

Stress gradient comparison for different IFF values



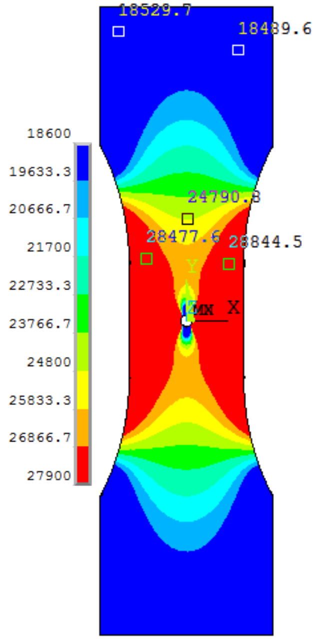


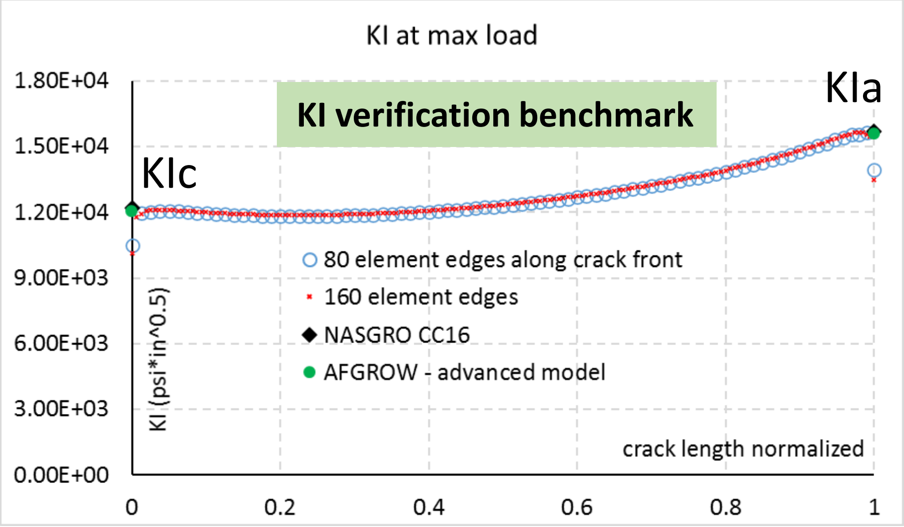
Reference: **John Crews, An elastoplastic analysis of a uniaxially loaded sheet with an interference-fit bolt, NASA, 1974.**

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

3D IFF stress gradients verification

K_I benchmark at max load (18.6 ksi grip section)





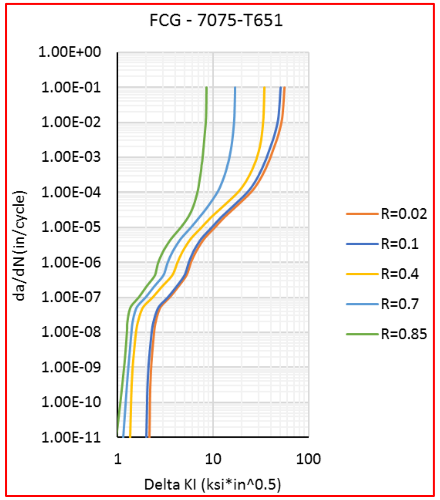
- Very good agreement between the 3D model prediction, AFGROW's advanced model and NASGRO's CC16
- Both NASGRO and AFGROW solutions are based on a geometry representative of the gauge section under uniform tension
- AFGROW (advanced model) solution was provided by Jim Harter
- NASGRO (CC16) solution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

Stress intensity factor (K_I) calculation is verified

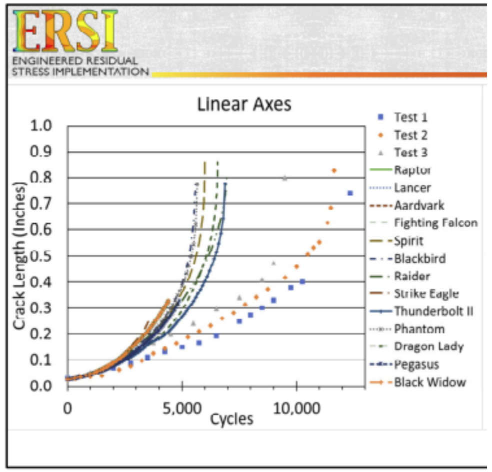
Open Hole solutions

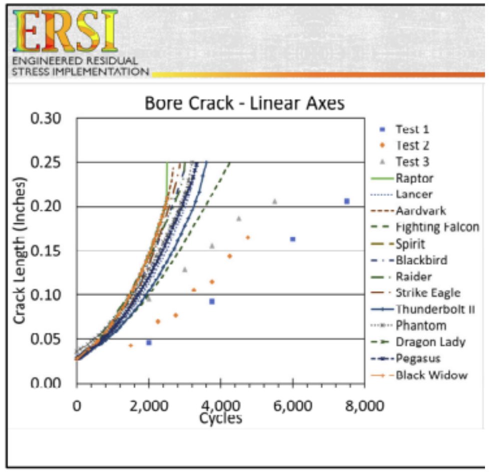
Engineered Residual Stress Implementation (ERSI) Workshop
19 – 20 April 2023
US Air Force Academy, Colorado Springs, CO

FCGR data 7075-T651 provided in the Round robin challenge

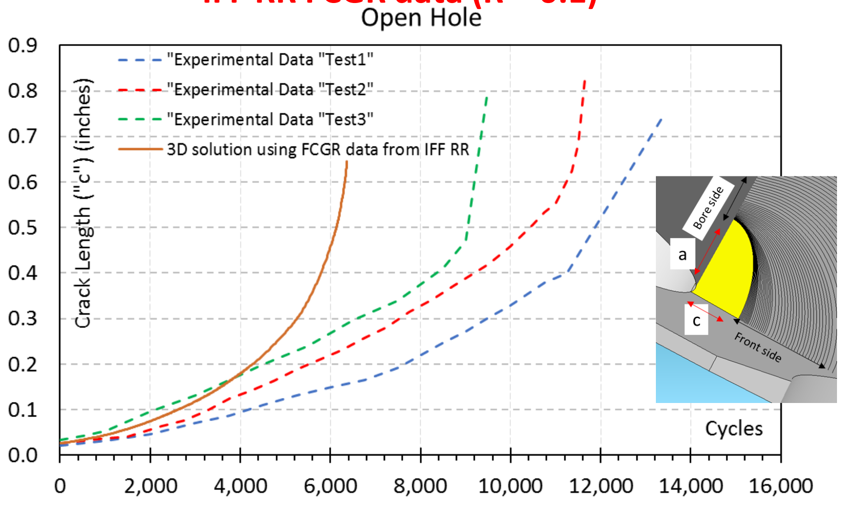


Interference Fit Fastener Analytical Round Robin, Jake Warner, 2020, AFGROW workshop.

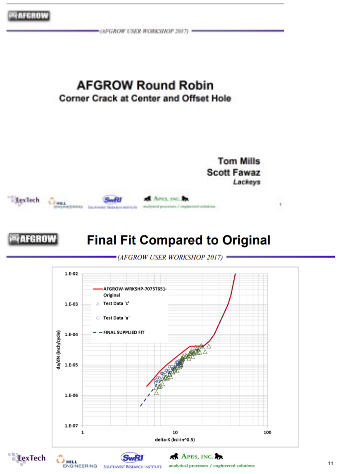


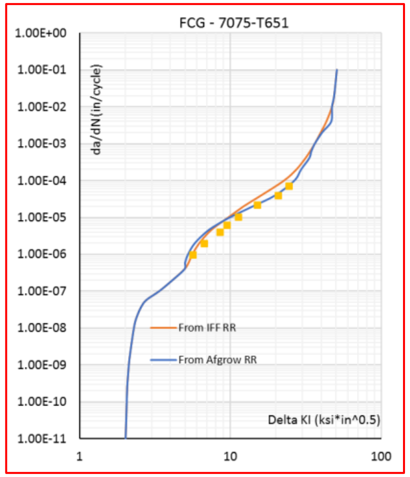


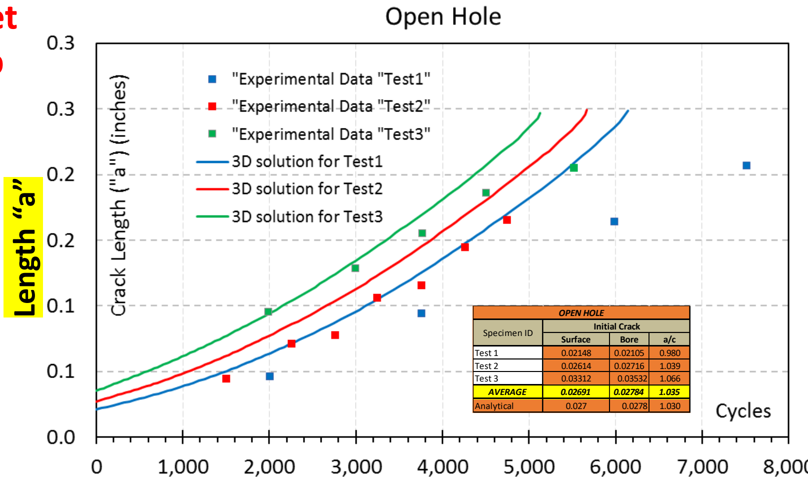
3D solution vs. experimental measurement using IFF RR FCGR data (R = 0.1)



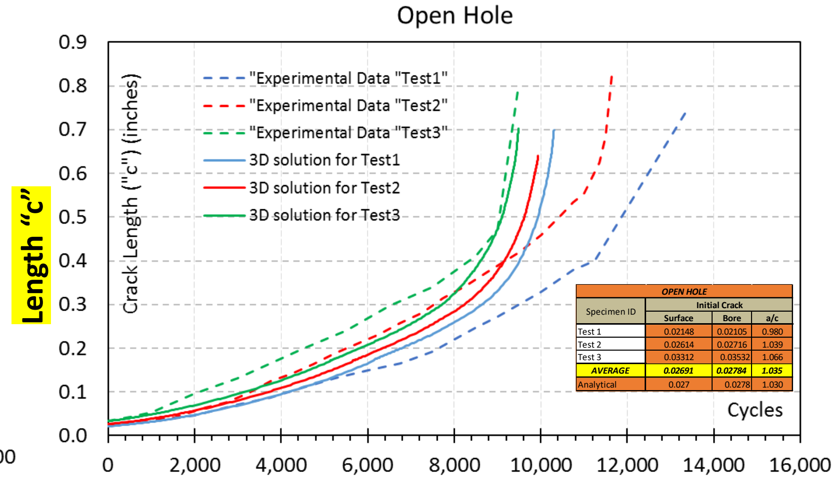
AFGROW Round Robin – Corner Crack at Center and Offset Hole, Tom Mills & Scott Fawaz, 2017 AFGROW Workshop







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



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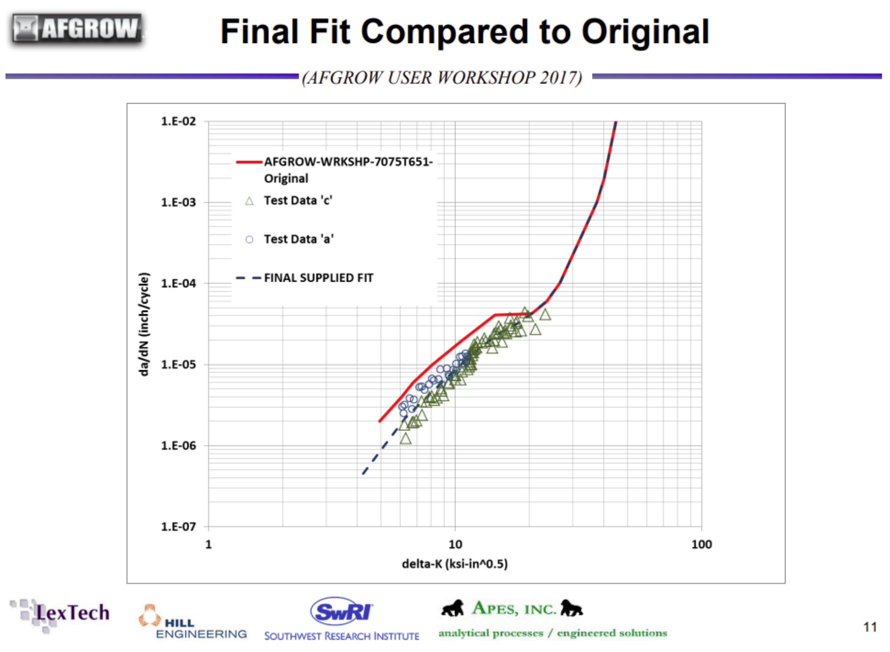
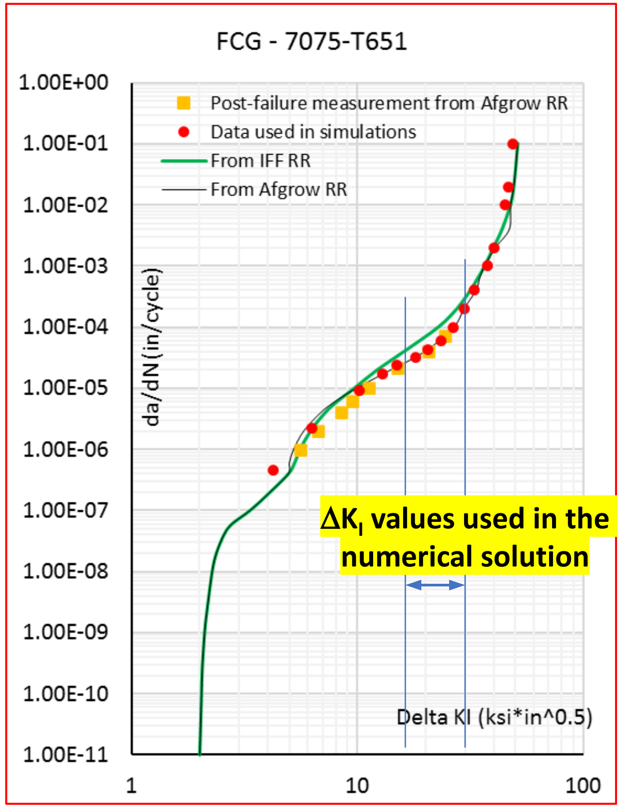
Analytical	0.027	0.0278	1.030

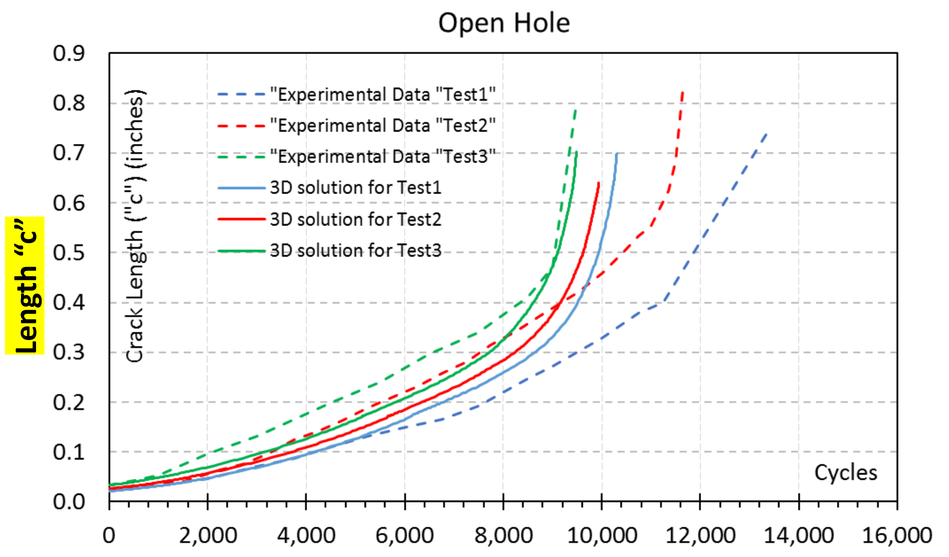
Numerical solutions are very sensitive to the FCGR data

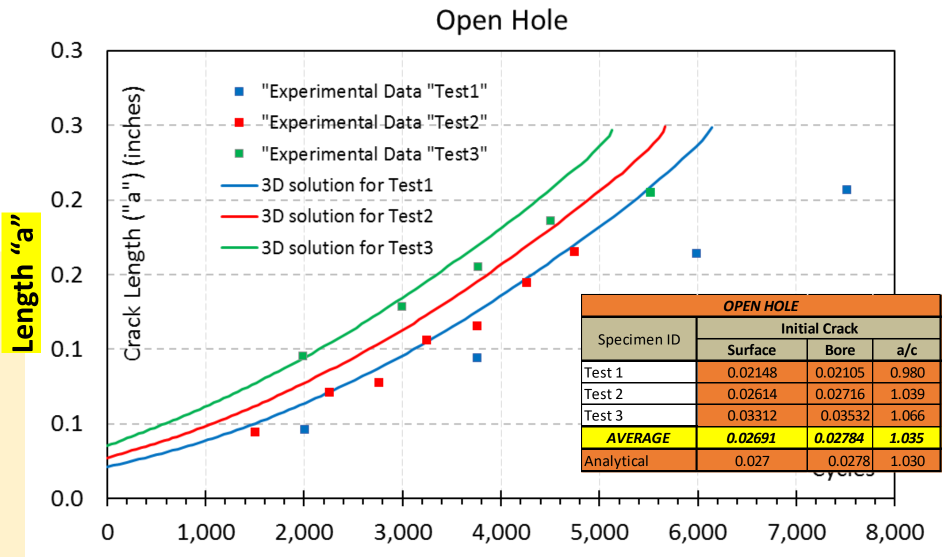
Open Hole solutions: FCGR sensitivity

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









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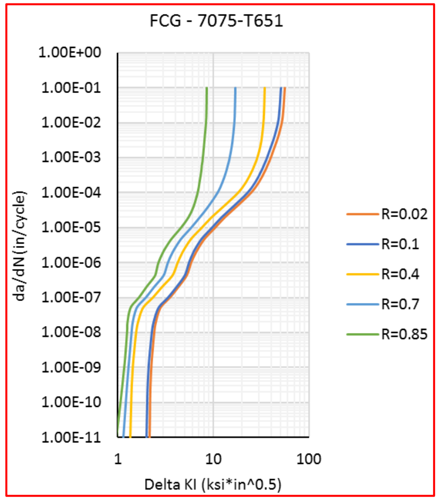
Specimen ID	Initial Crack		
	Surface	Bore	a/c
Test 1	0.02148	0.02105	0.980
Test 2	0.02614	0.02716	1.039
Test 3	0.03312	0.03532	1.066
AVERAGE	***0.02691***	***0.02784***	***1.035***
Analytical	0.027	0.0278	1.030

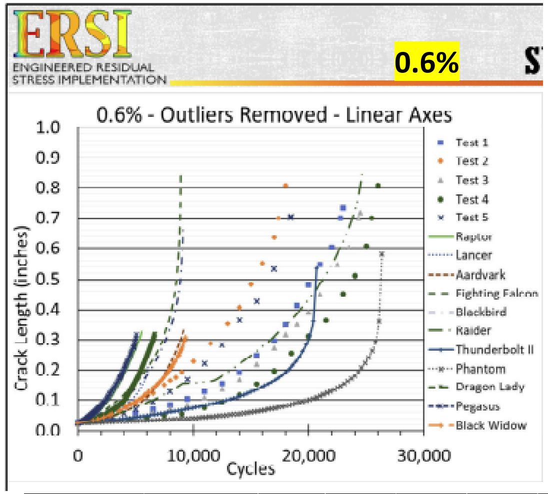
- **There are different sources of uncertainty that were not addressed in the round robin challenge. In general, additional instrumentation data is necessary to assess modeling solution sensitivity due to different sources of uncertainty.**
- **In this example, solution sensitivity due to FCGR scatter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

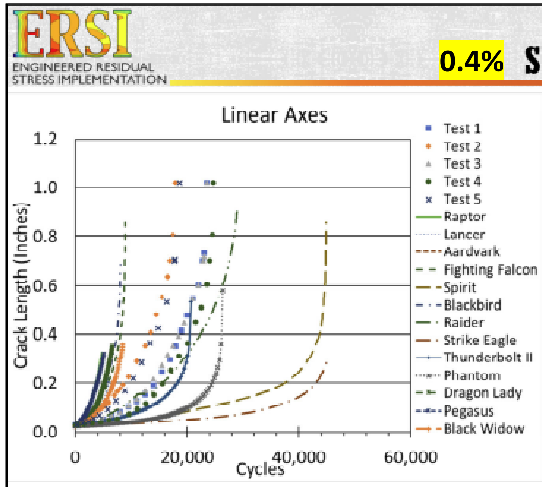
IFF 3D Crack Growth Solutions presented at AA&S 2021

FCGR data 7075-T651 provided in the Round robin challenge



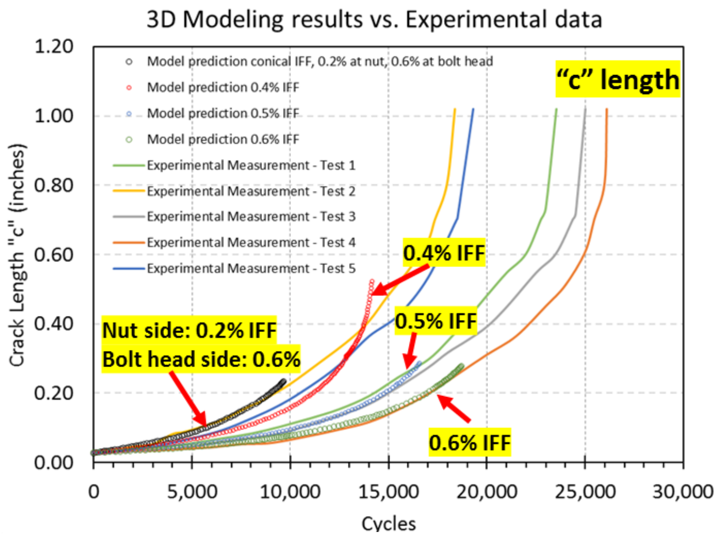
Interference Fit Fastener Analytical Round Robin, Jake Warner, 2020, AFGROW workshop.

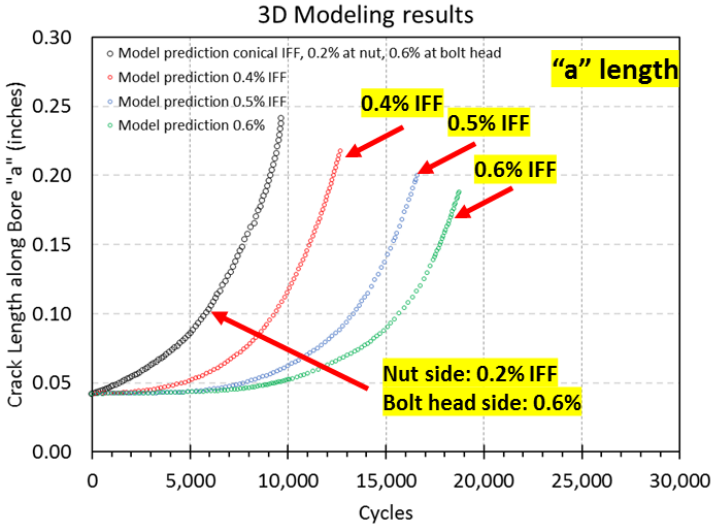




FILLED HOLE											
Specimen	Hole Diameter	Fastener Diameter			Interference			Fatigue Life	Initial Crack		
		MAX	AVE	MIN	MAX	AVE	MIN	Total	Surface	Bore	a/c
7D3-16-Da-2480	0.24786	0.24932	0.24884	0.24841	0.589%	0.397%	0.222%	23545	0.02978	0.04504	1.512
7D3-17-Da-2480	0.24784	0.24932	0.24884	0.24841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

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



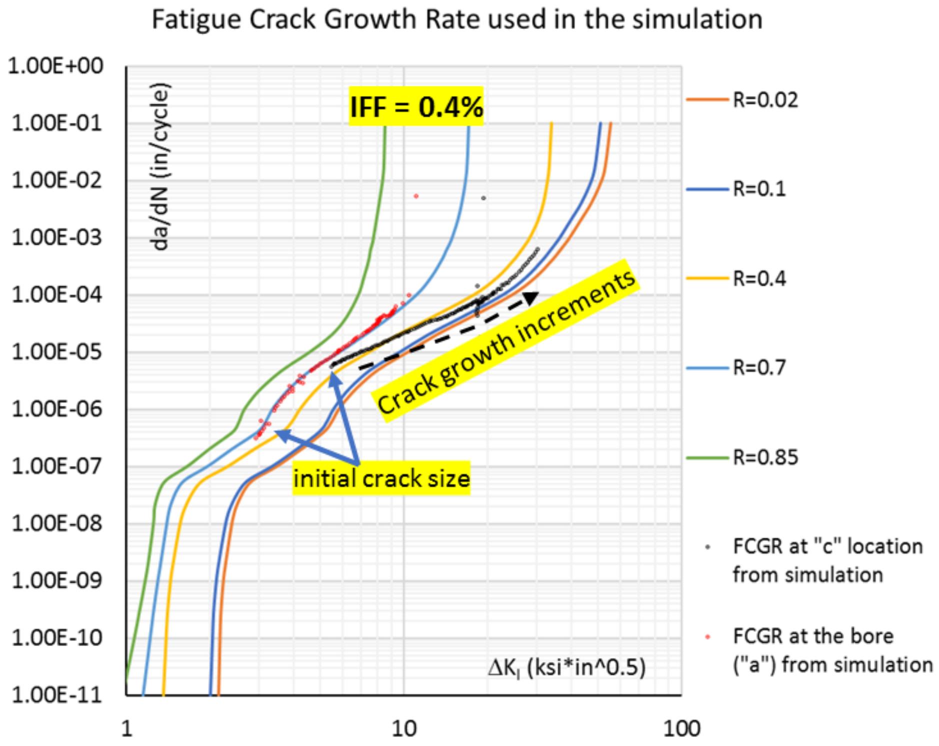


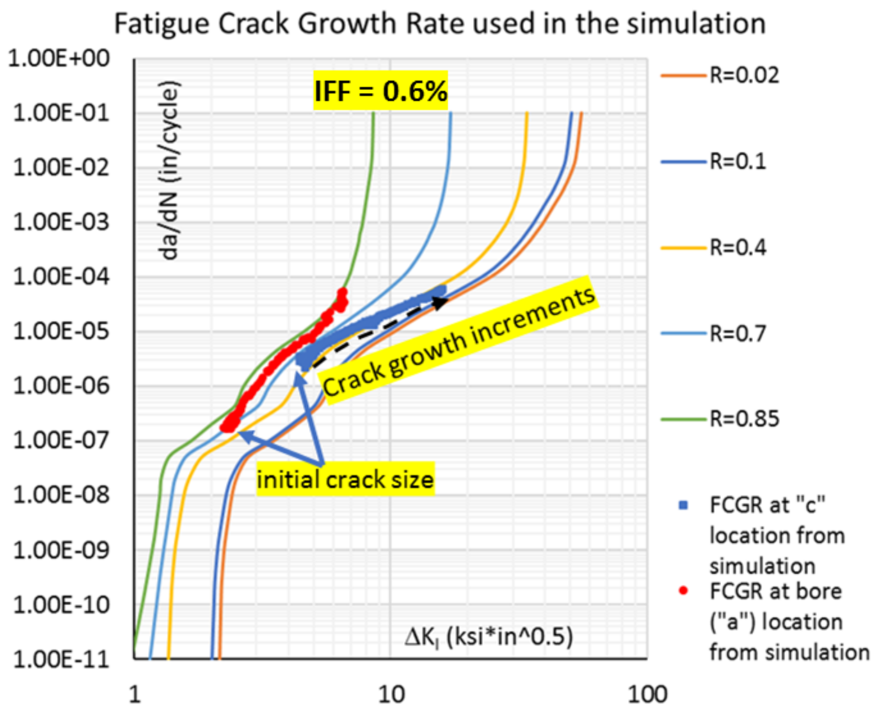
- **There is a discrepancy between the submitted solutions and the recorded measurement.**
- **Modeling details/tools that can lead to a scatter among the submitted solutions is currently addressed in the follow-up Round Robin challenge (stress gradient comparison among different numerical implementations).**
- **Using different IFF levels, the 3D FEA based approach seems to capture quite well the experimental measurement at least in the initial 50% of RUL.**
- **The numerical procedure relies on interpolation between the R curves since the R values along each crack front varies from the bore to the front side of the specimen. This can be a major contributor to the modeling uncertainty.**

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

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

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

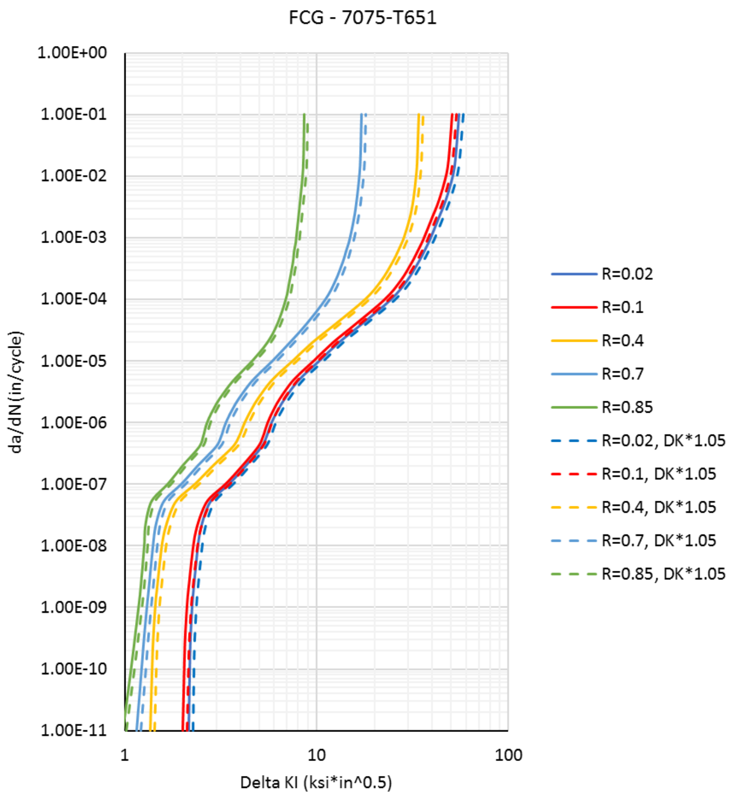


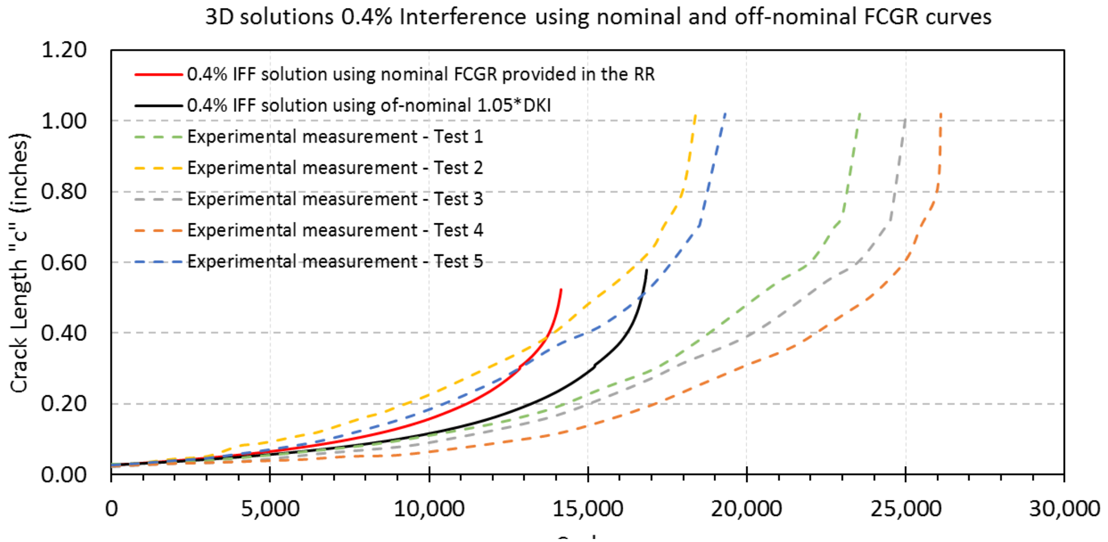


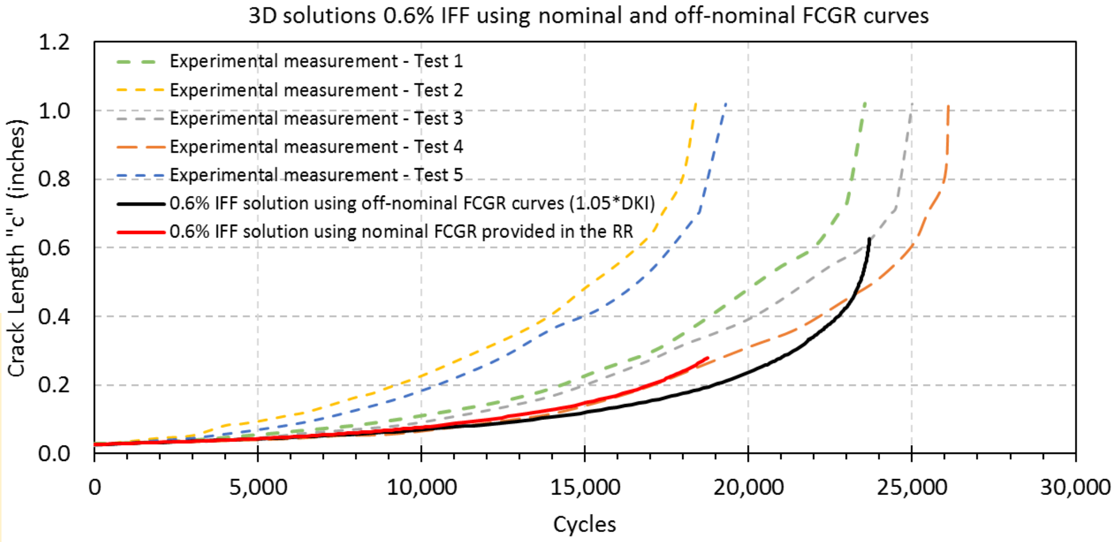
- **The 3D model does capture the evolution of the R values along each crack front increment**
- **The modeling uncertainty increases for da/dN values close to Region 3**
- **Adding FCGR curves for more R ratios should increase the accuracy of the numerical solutions especially for larger cracks where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

IFF 3D FEA based Crack Growth Solutions: FCGR sensitivity

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





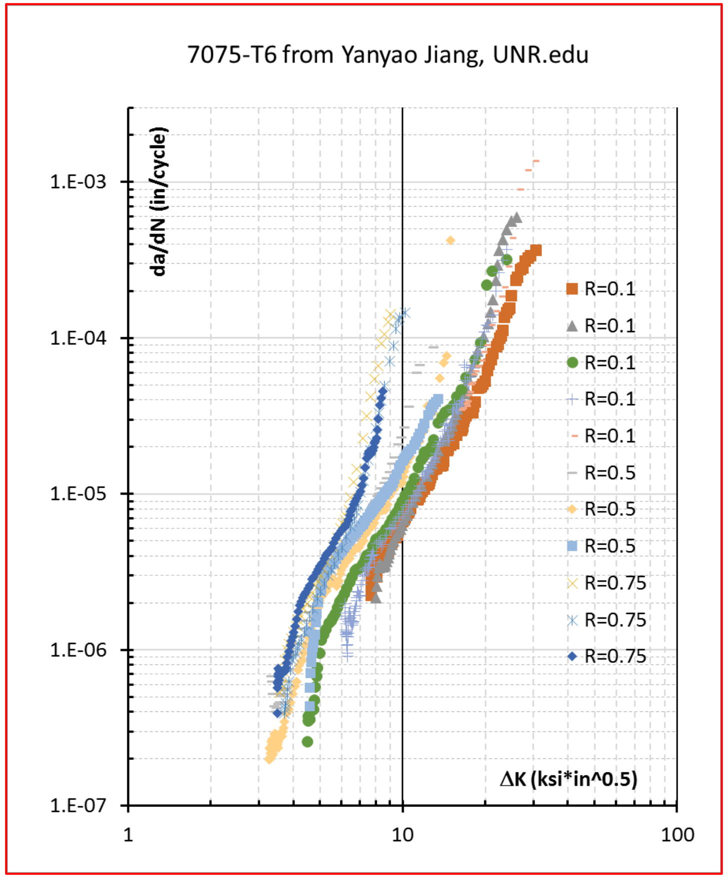


- **A simple study is performed to evaluate the sensitivity of the 3D solution to an eventual FCGR scatter.**
- **A slight modification of nominal FCGR curves (ΔKI*1.05 which is within the FCGR scatter bounds) can lead to ~20% RUL shift.**
- **Average and bounds of each FCGR curve (different R values)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

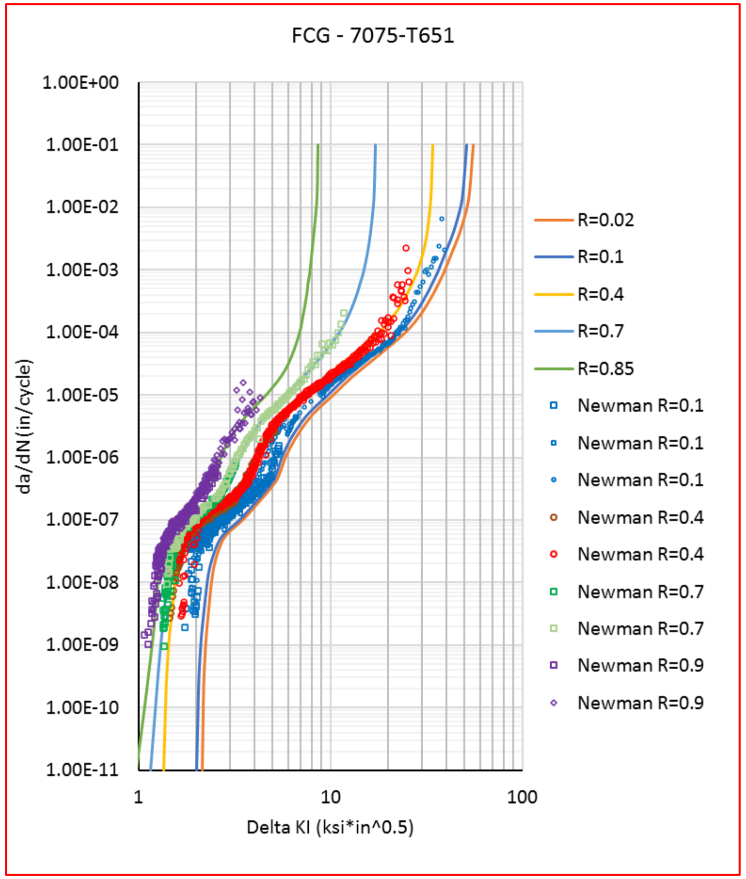
7075-T651 FCGR Data

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

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



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



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

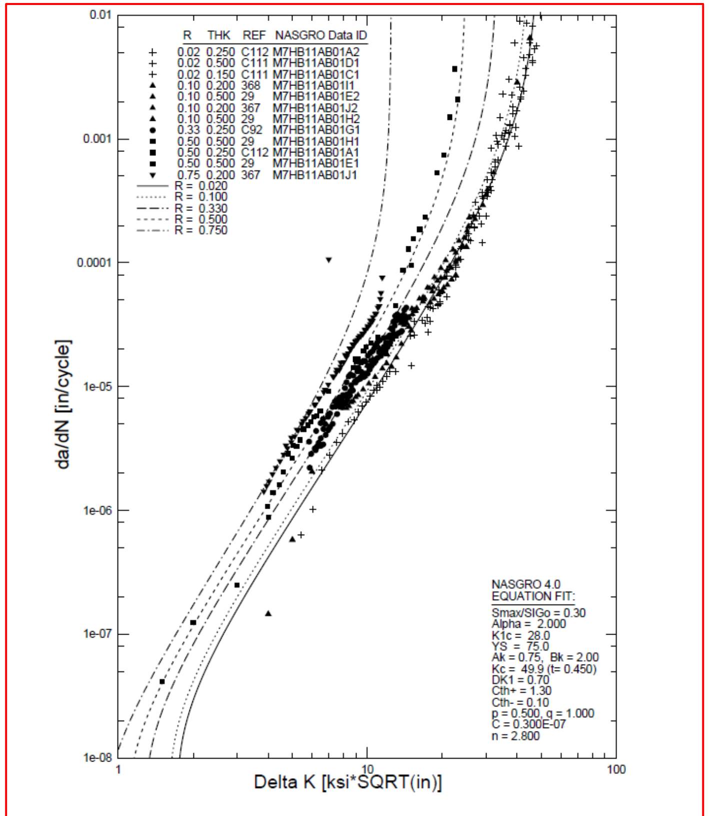


FIGURE B-25. NASGRO EQUATION FIT FOR 7075-T651 PLATE, L-T (M7HB11AB1)

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

Conclusions

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

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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

Life Analysis & Test Methods Committee

Organizer: T. Spradlin (AFRL/RQVS)

BOTTOM LINE UP FRONT

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

BACKGROUND

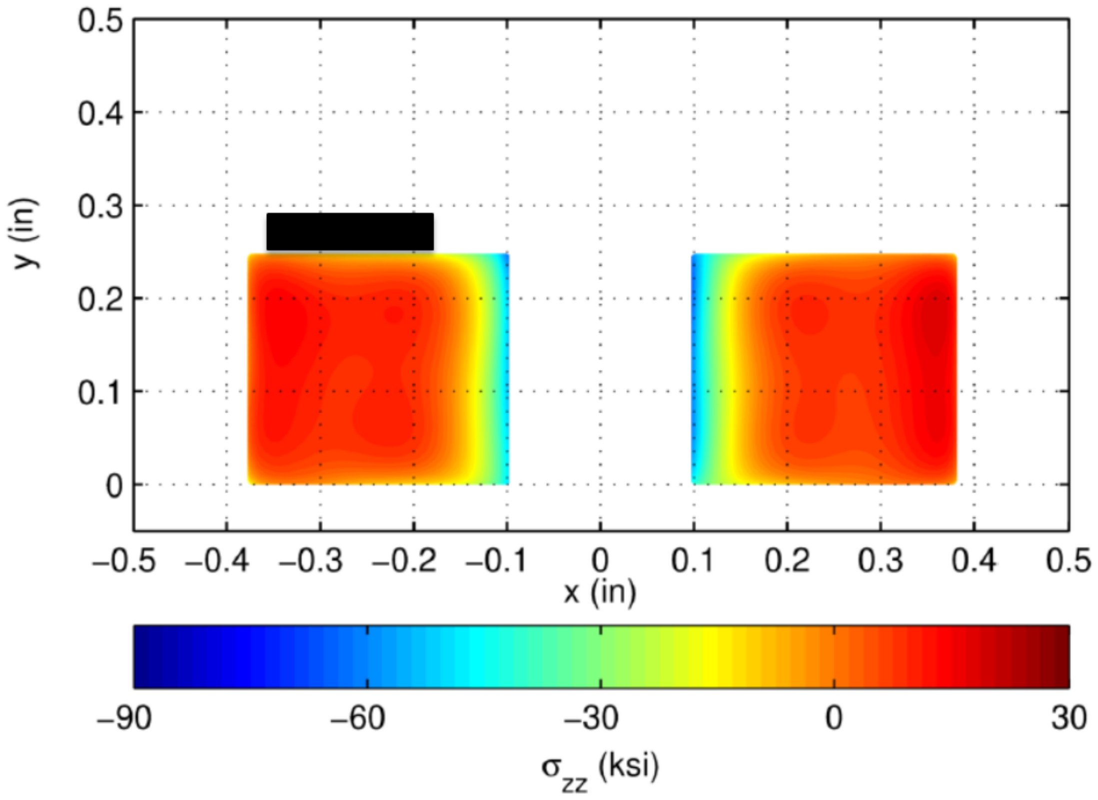
ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

WHAT DROVE THIS RR: TIER LEVELS

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

Level 3+

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



ROUND ROBIN:
RESULTS AND COMPARISONS

SOFTWARES REPRESENTED (Q1)

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

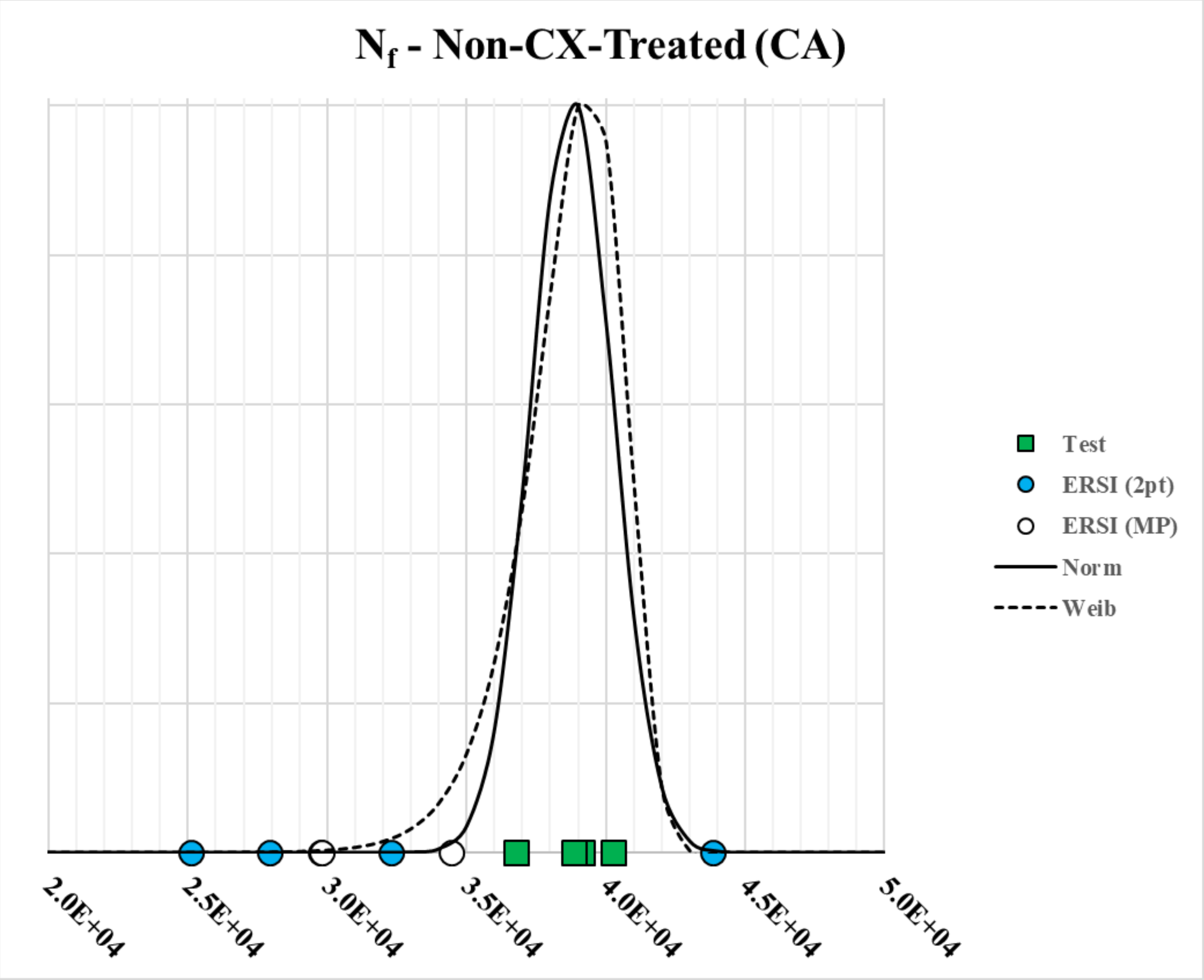
INCORPORATION OF RESIDUAL STRESS (Q3-5)

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

ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

CYCLES TO FAILURE: NON-CX (CA)

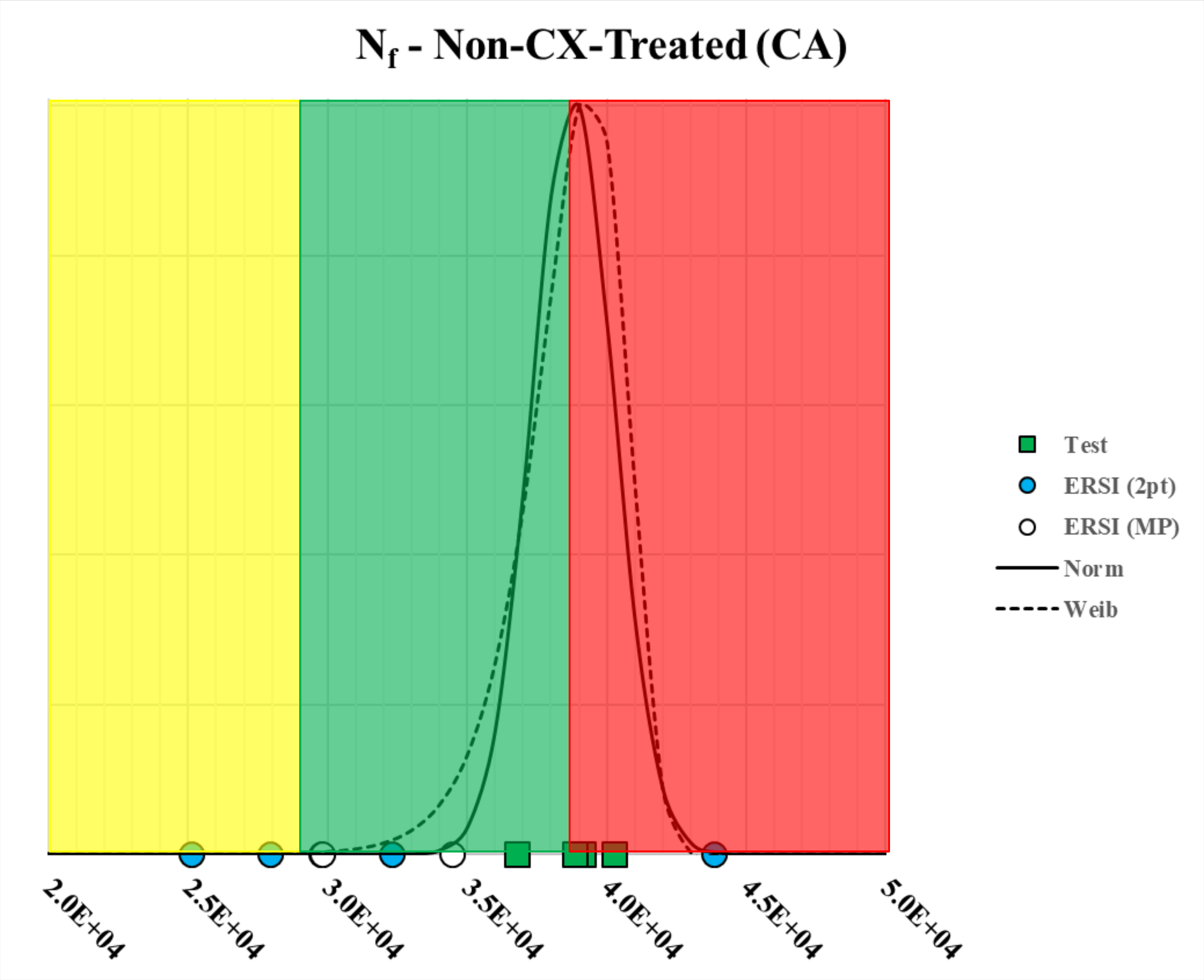
	N_f
Test (Mean)	38769
Entrant 1	27942
Entrant 2	25128
Entrant 3	43834
Entrant 4	32283
Entrant 5	29746
Entrant 6	34461
Entrant 7	29810



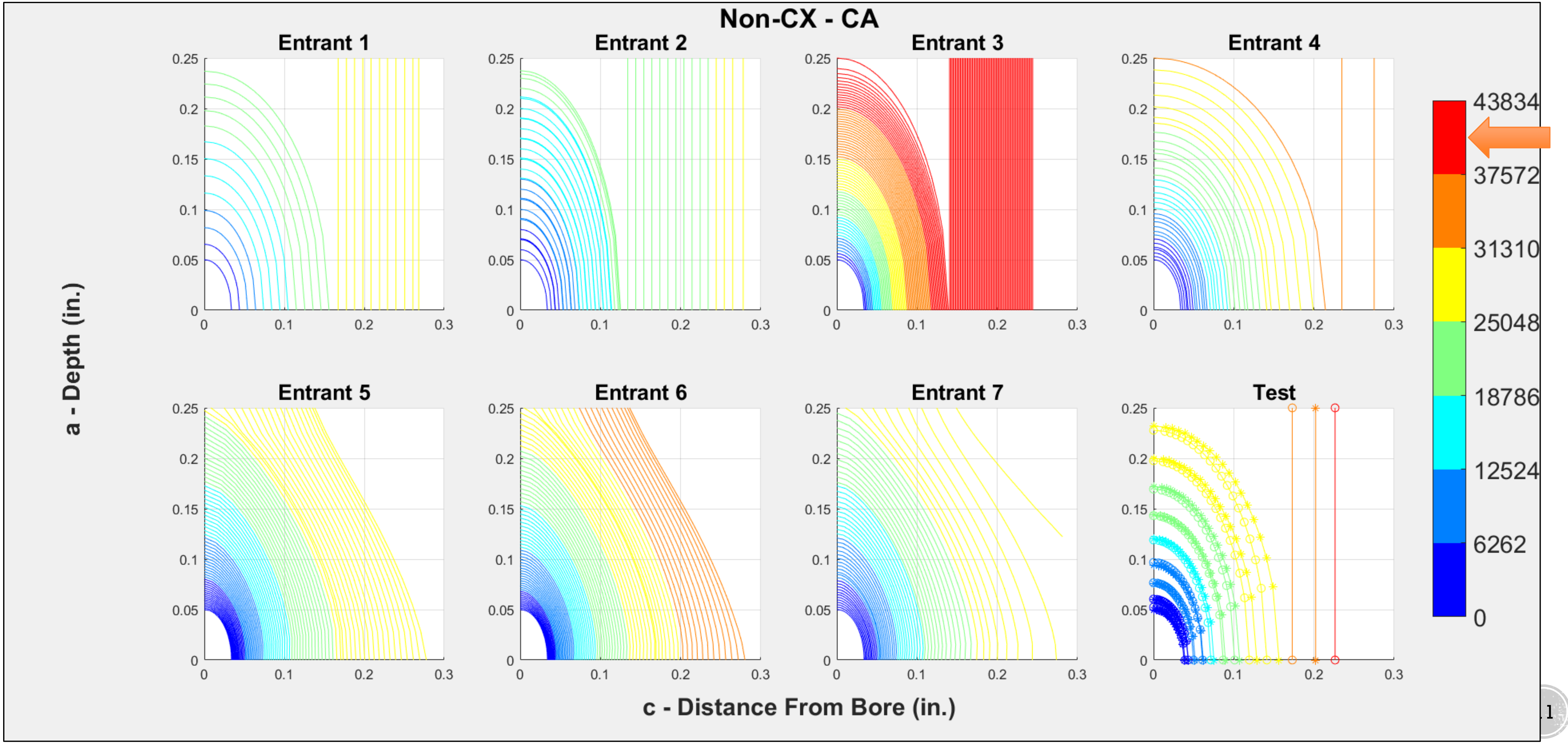
CYCLES TO FAILURE: NON-CX (CA)

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

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

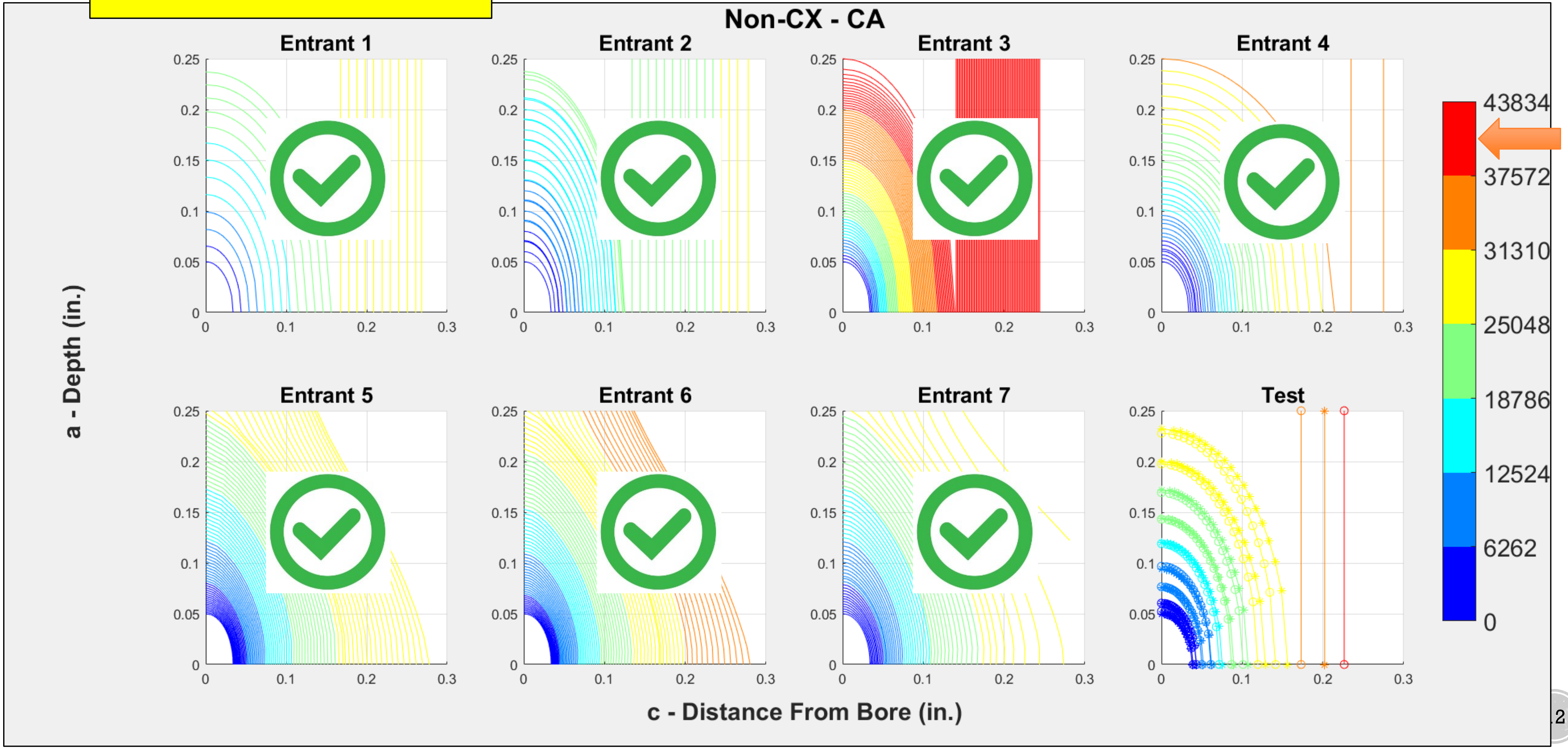


CRACK MORPHOLOGY: NON-CX (CA)



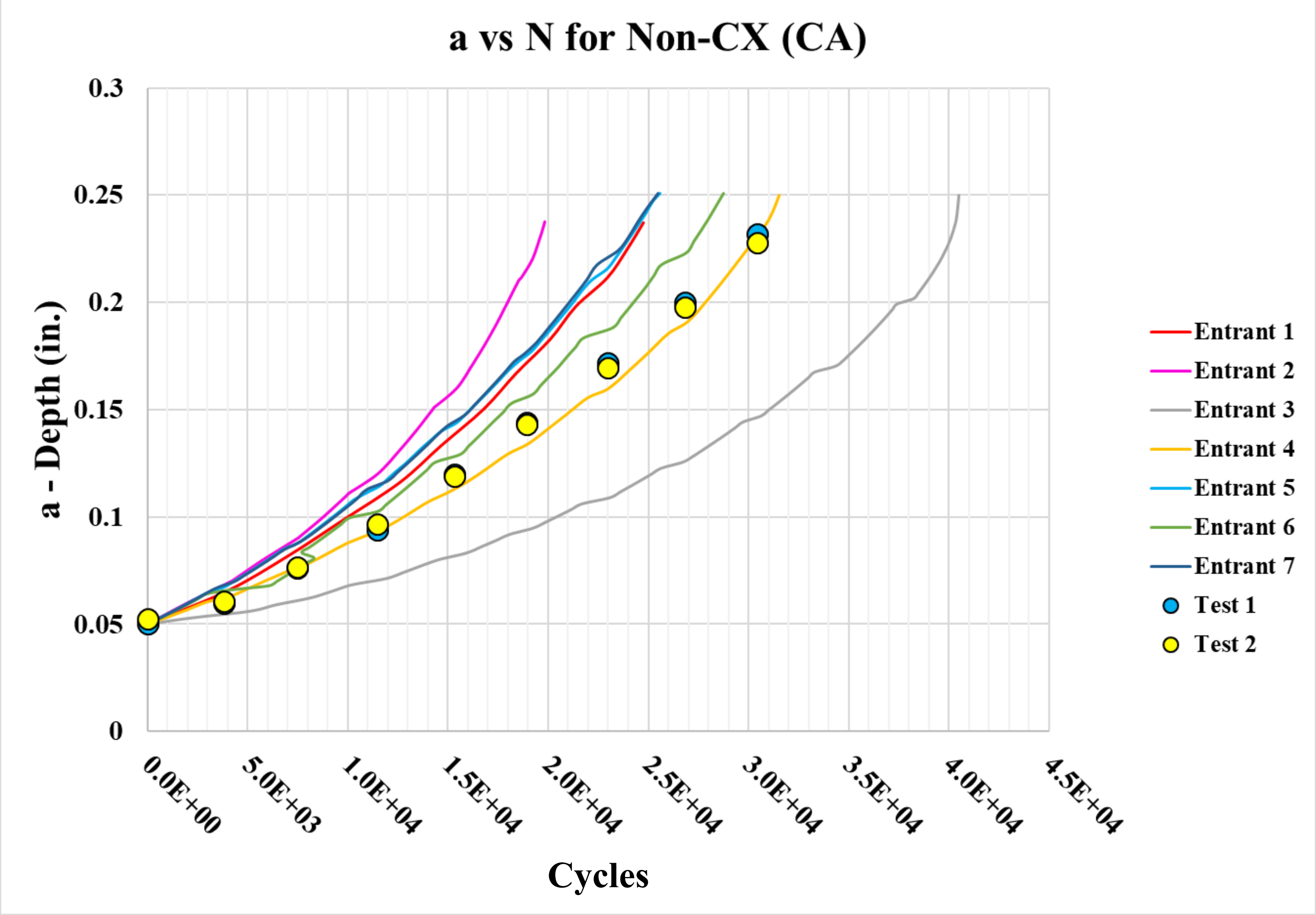
CRACK MORPHOLOGY: NON-CX (CA)

Did it break through?

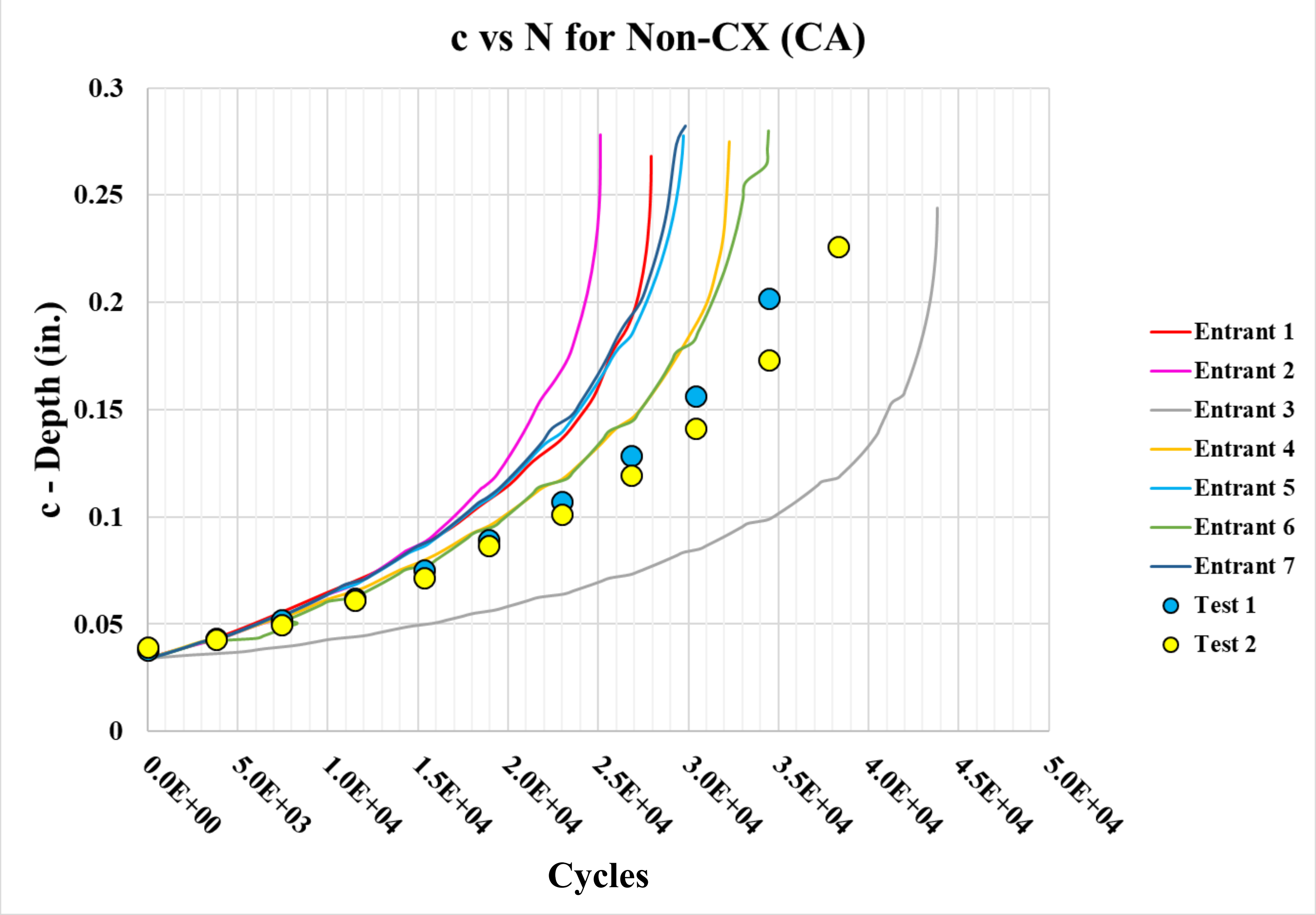


ENGINEERED RESIDUAL STRESS IMPLEMENTATION

CRACK PROGRESSION: NON-CX (CA)



CRACK PROGRESSION: NON-CX (CA)



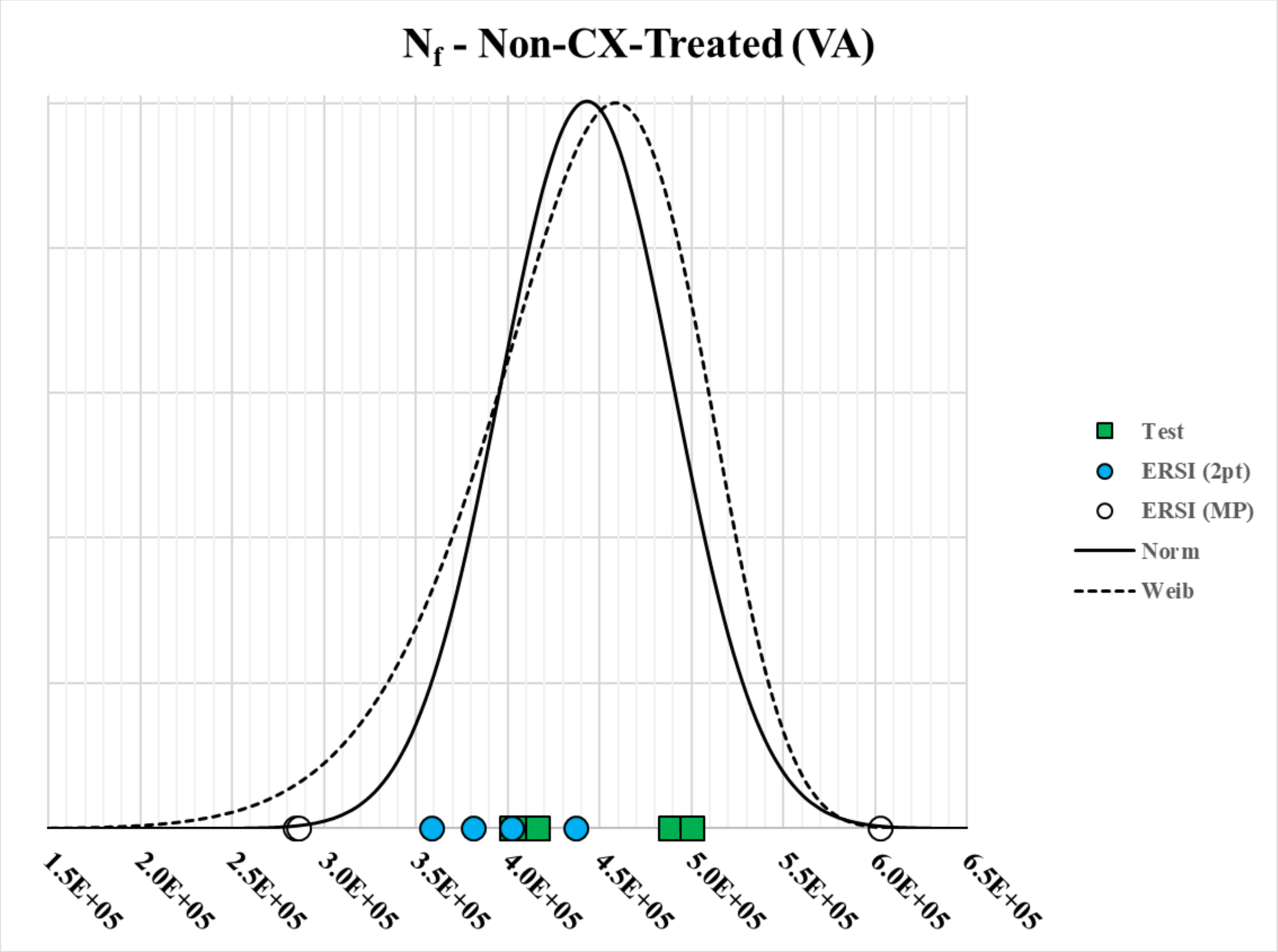
SCORE CARD: NON-CX (CA)

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

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

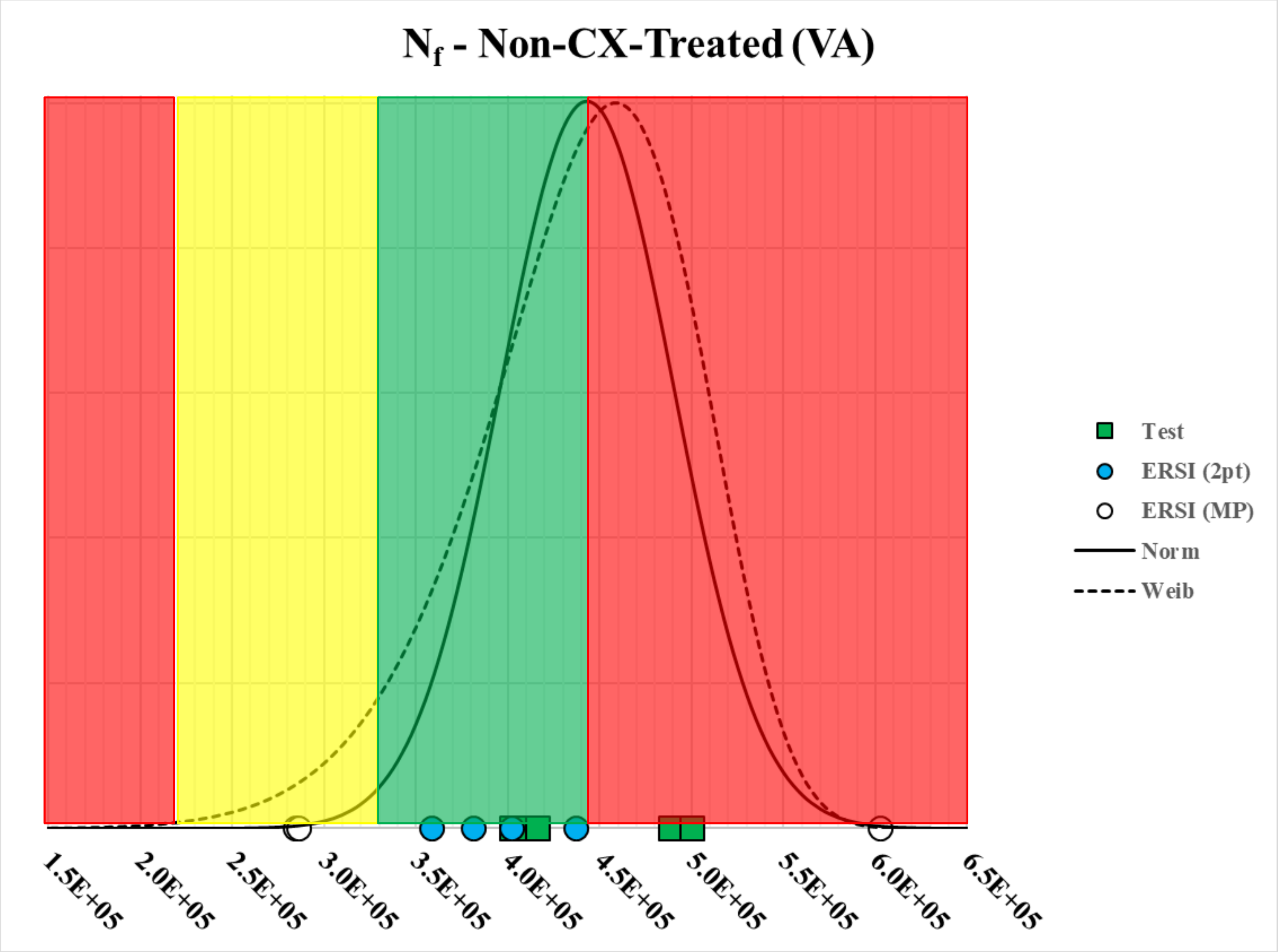
CYCLES TO FAILURE: NON-CX (VA)

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

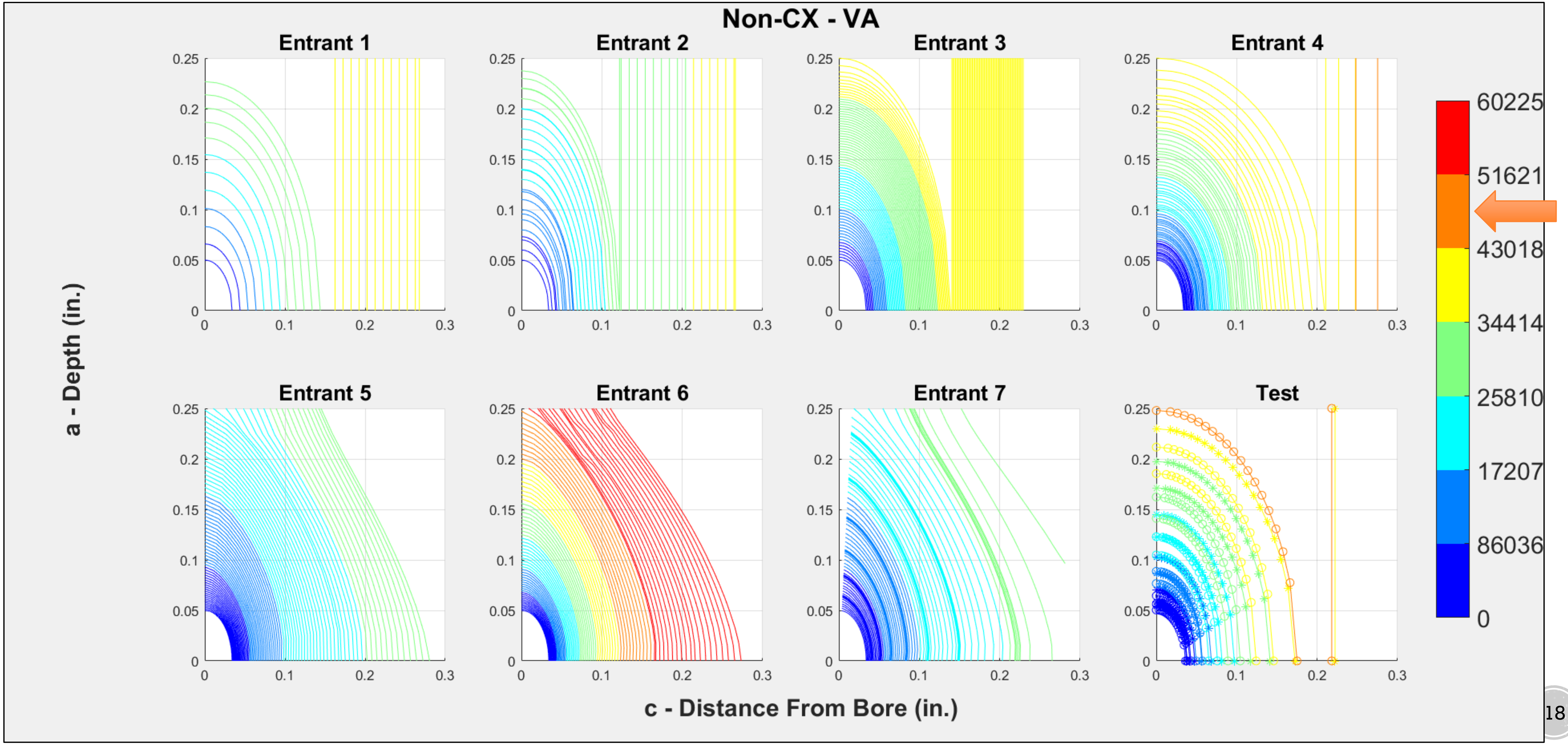


CYCLES TO FAILURE: NON-CX (VA)

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

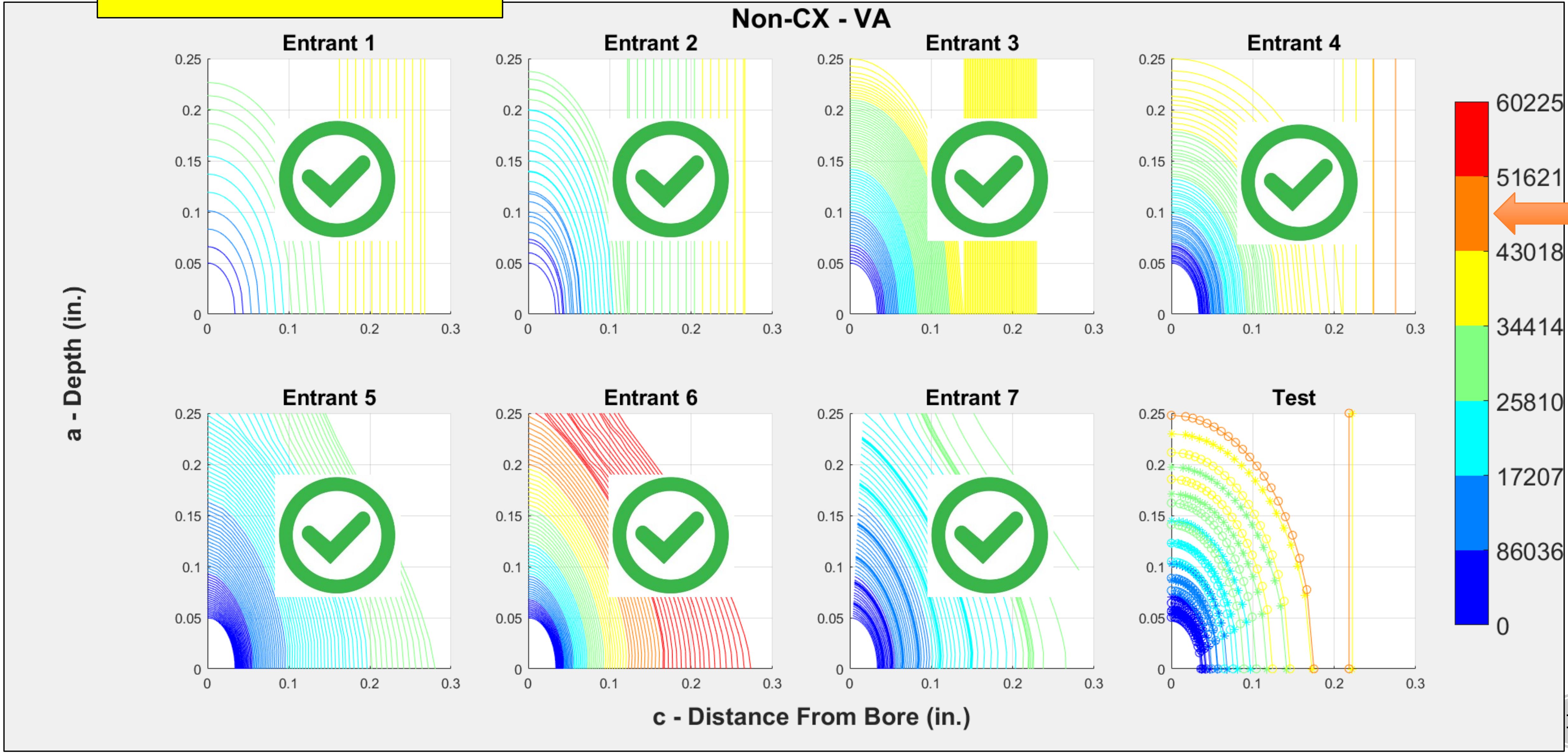


CRACK MORPHOLOGY: NON-CX (VA)

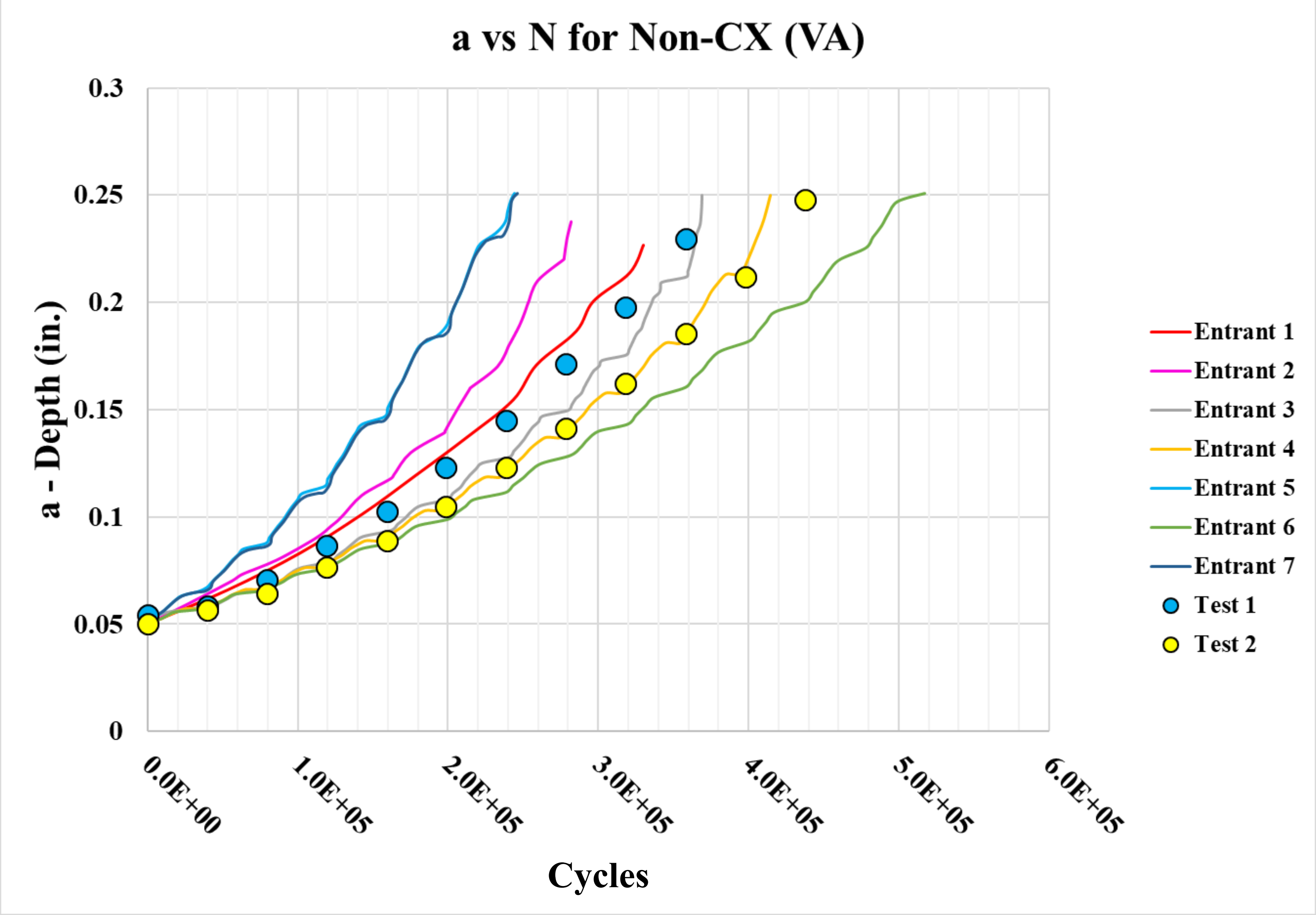


CRACK MORPHOLOGY: NON-CX (VA)

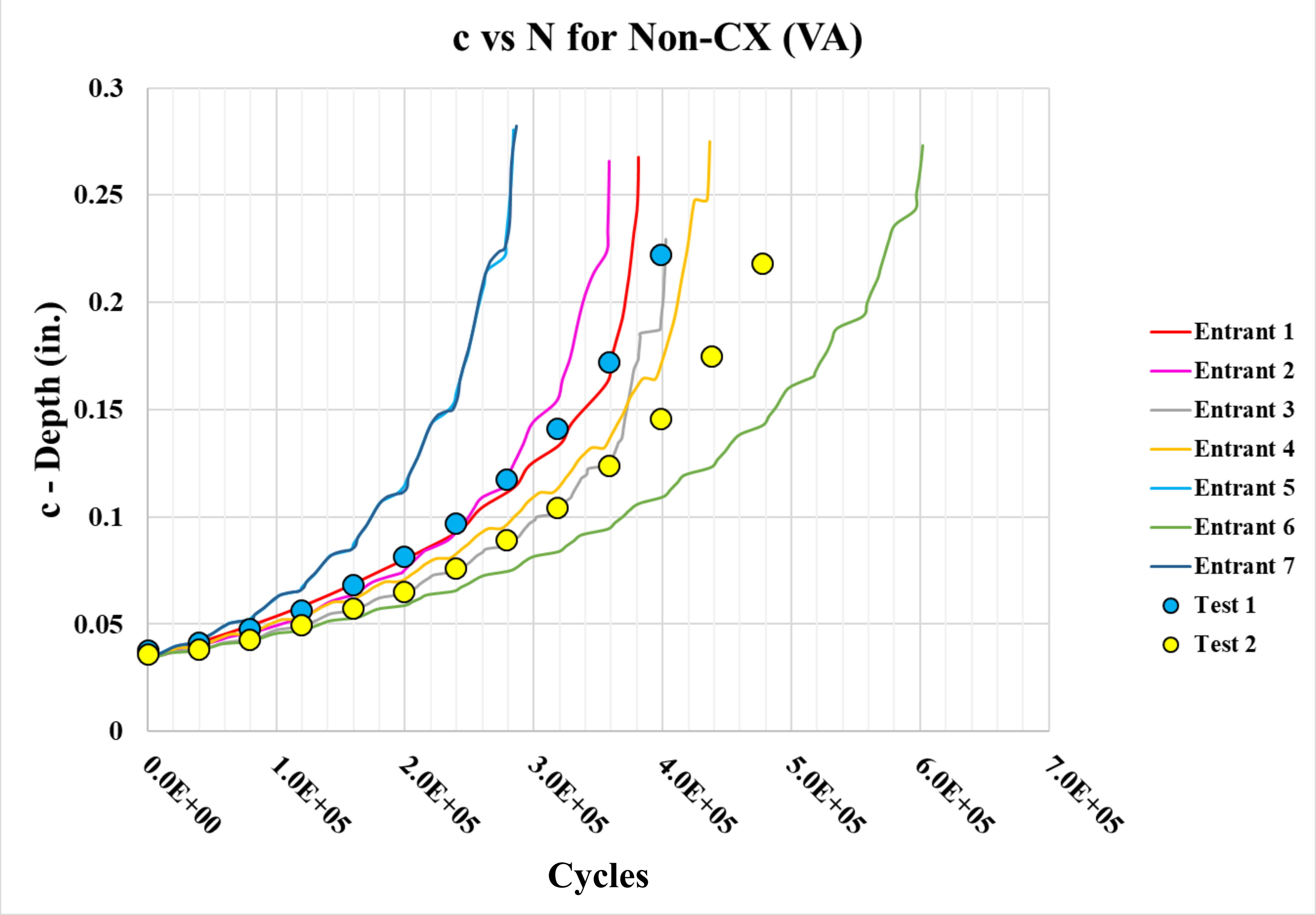
Did it break through?



CRACK PROGRESSION: NON-CX (VA)



CRACK PROGRESSION: NON-CX (VA)

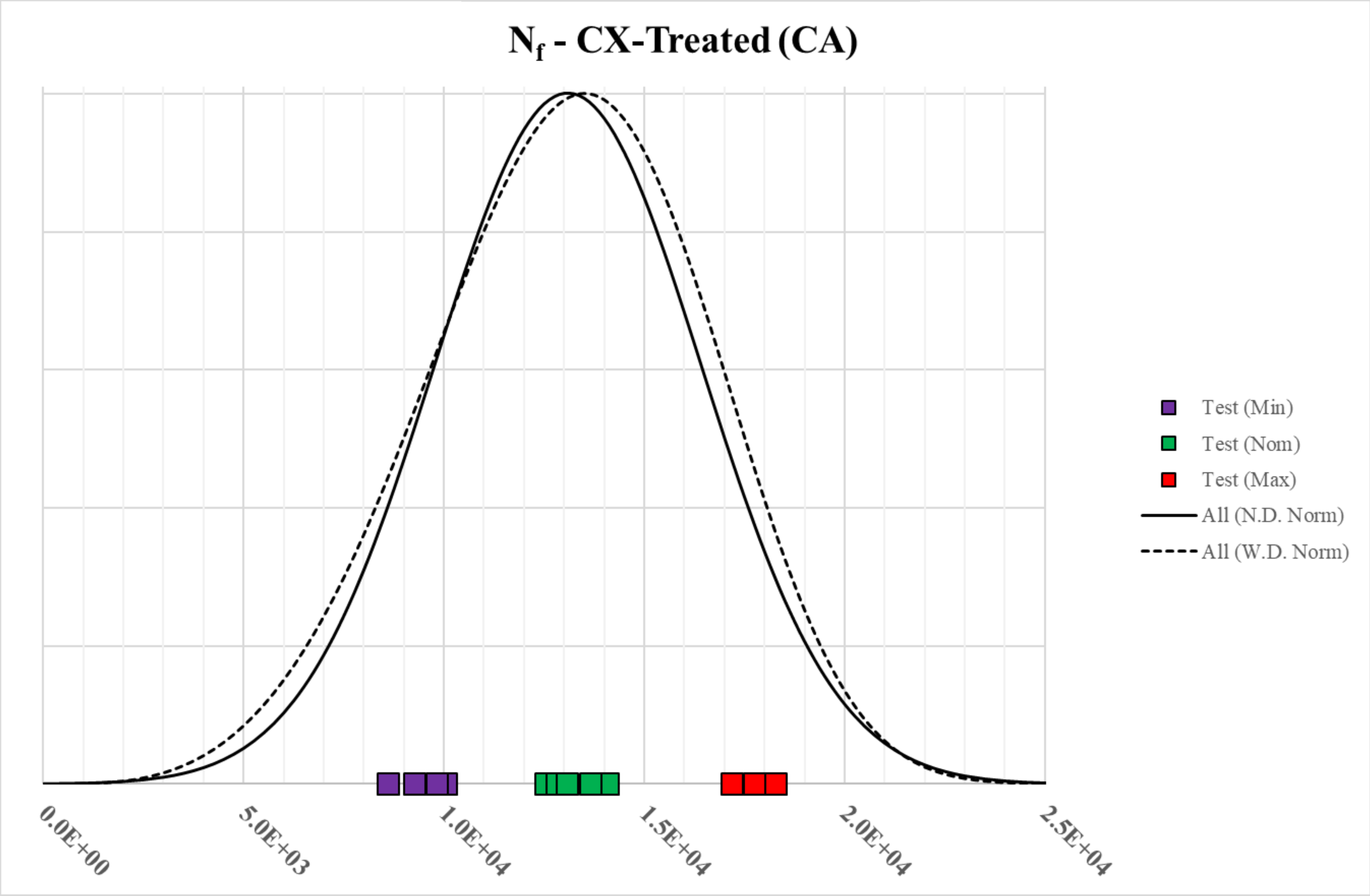


SCORE CARD: NON-CX (VA)

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

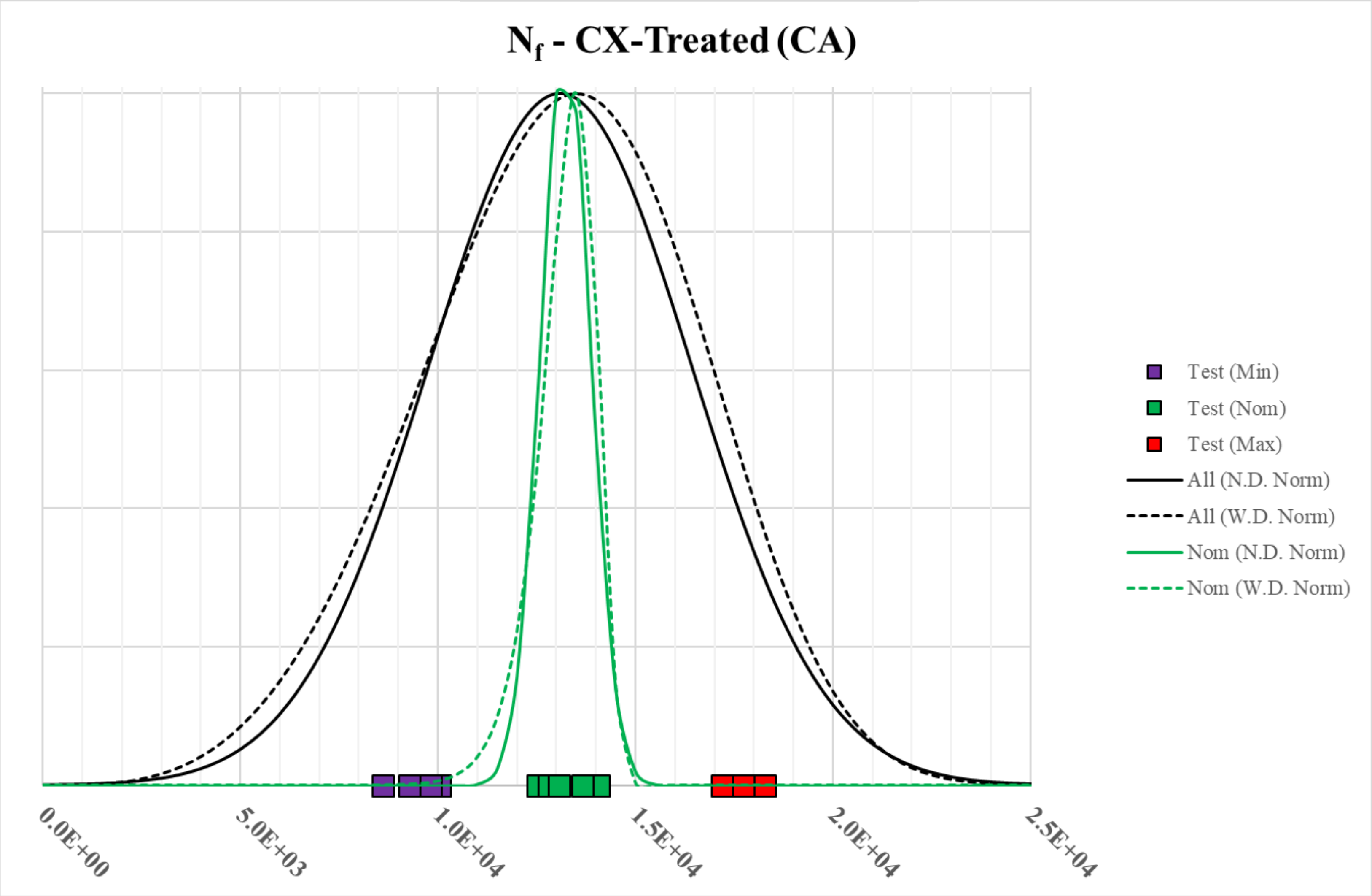
CYCLES TO FAILURE: CX (CA)

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



CYCLES TO FAILURE: CX (CA)

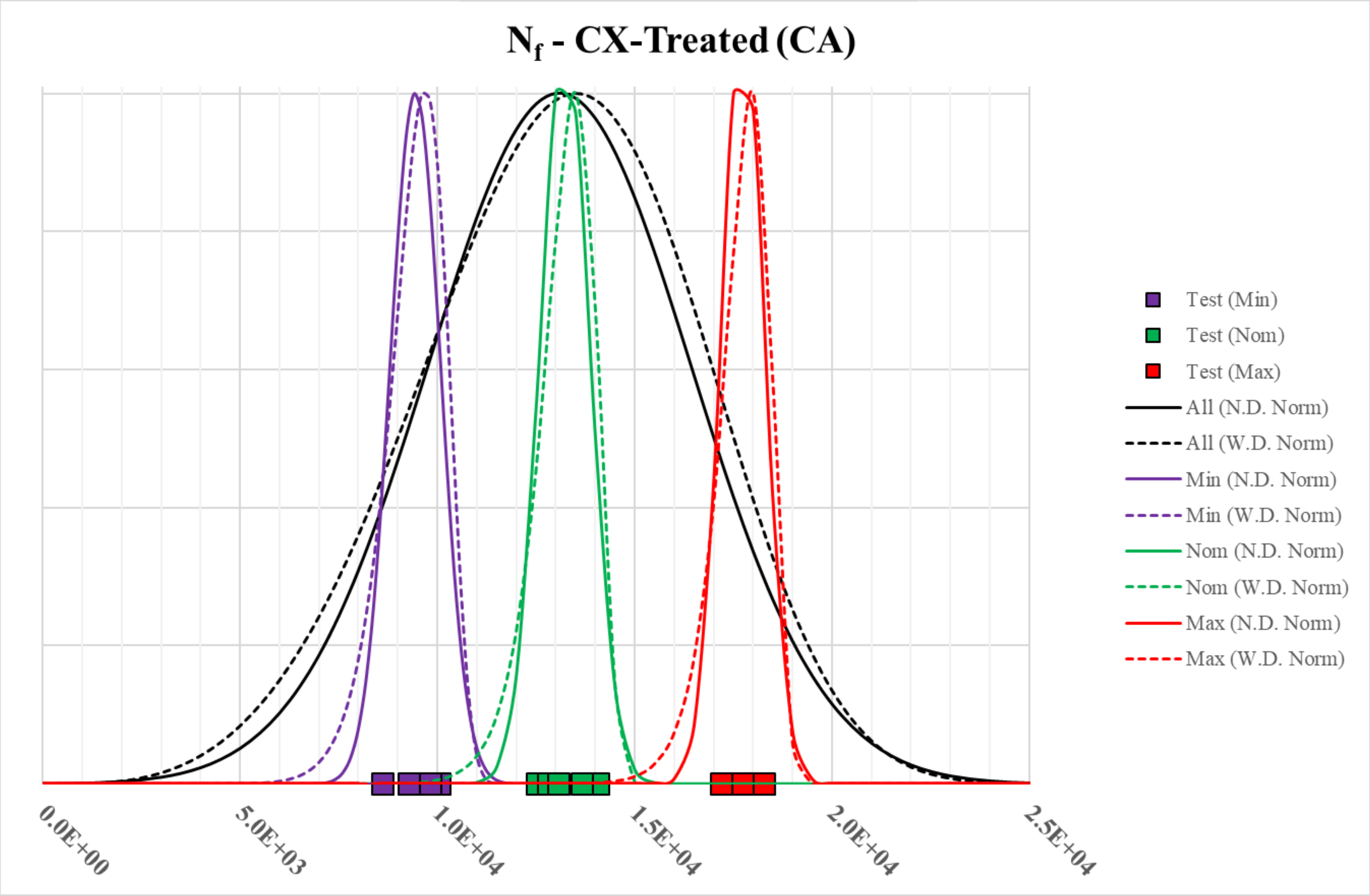
- First, let's isolate the nominal treatment



ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

CYCLES TO FAILURE: CX (CA)

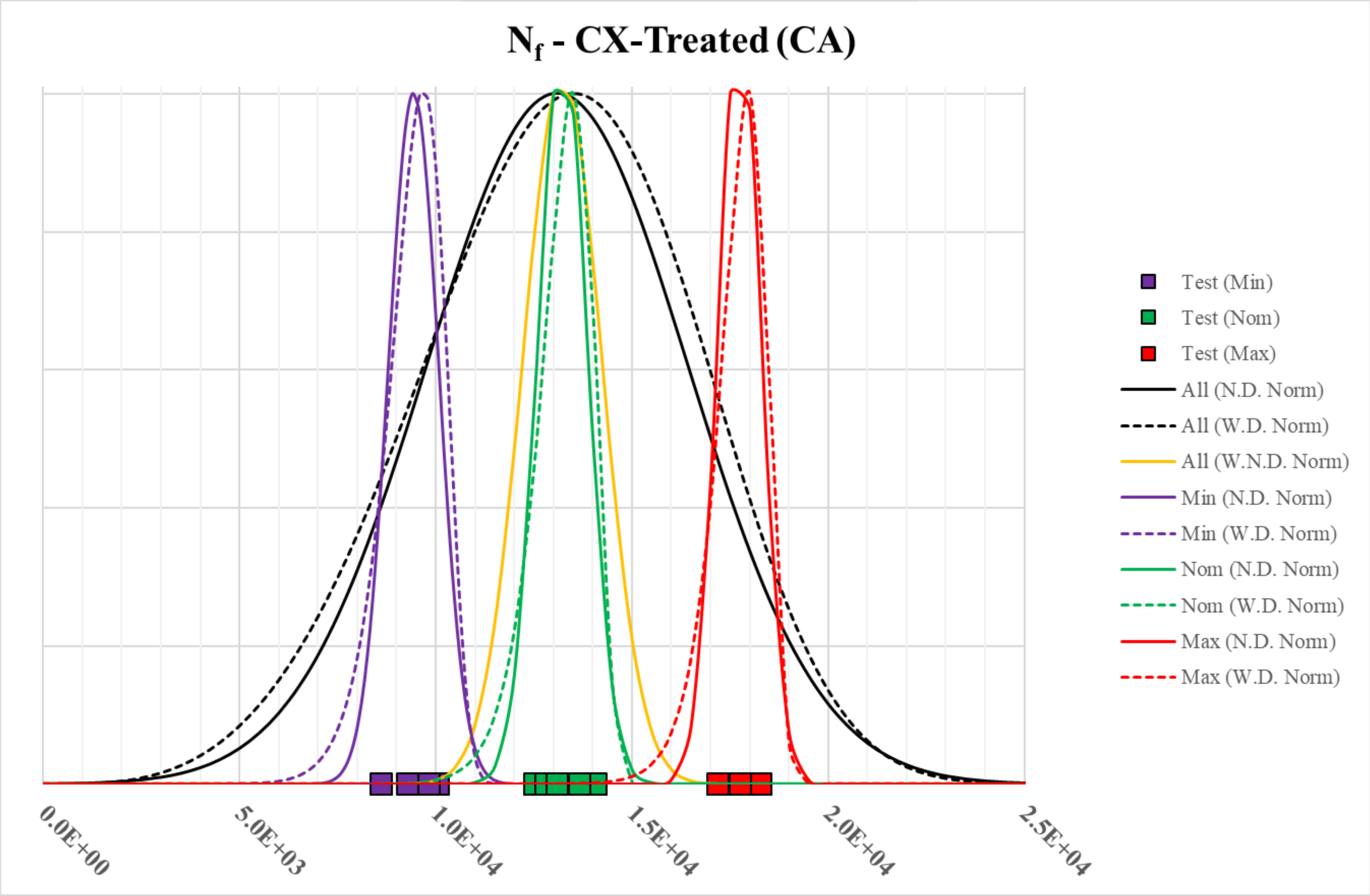
- Now the extrema
- Very clearly dealing with three disctinct populations
- Confirmed with single factor ANOVA
  - Alpha = 0.05
  - P-value ~1e-6



CYCLES TO FAILURE: CX (CA)

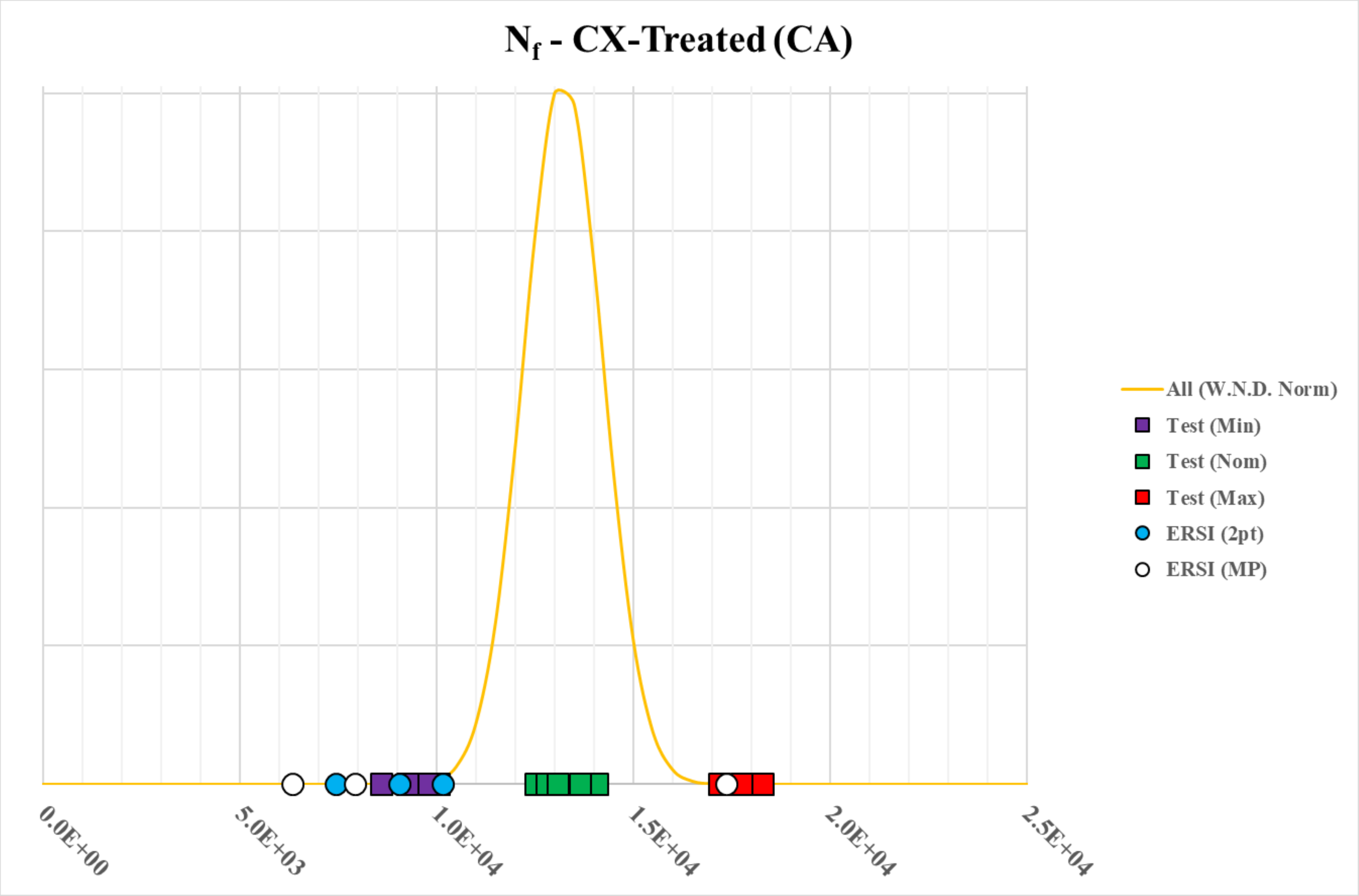
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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



CYCLES TO FAILURE: CX (CA)

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



ENGINEERED RESIDUAL STRESS IMPLEMENTATION

CYCLES TO FAILURE: CX (CA)

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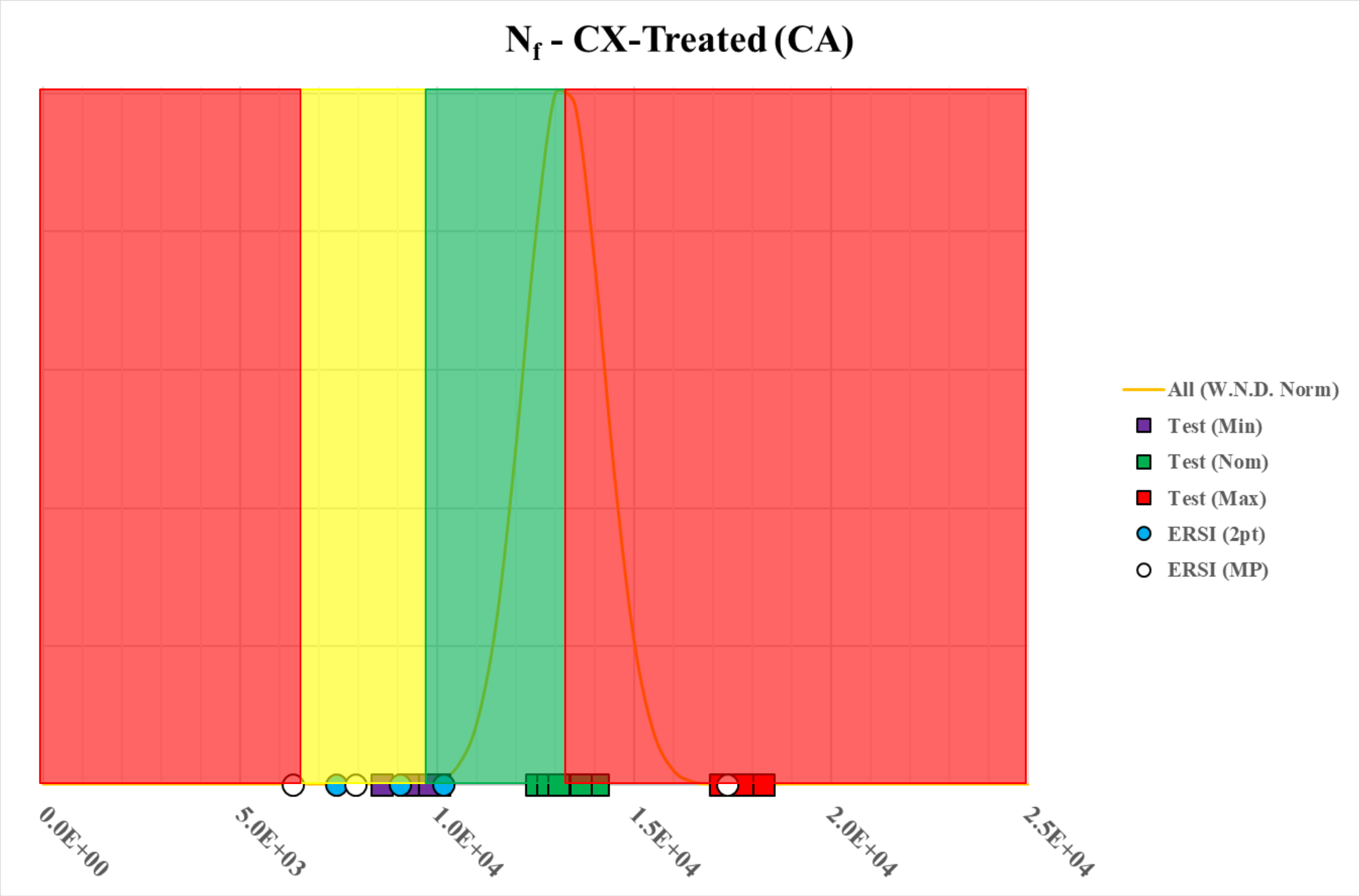
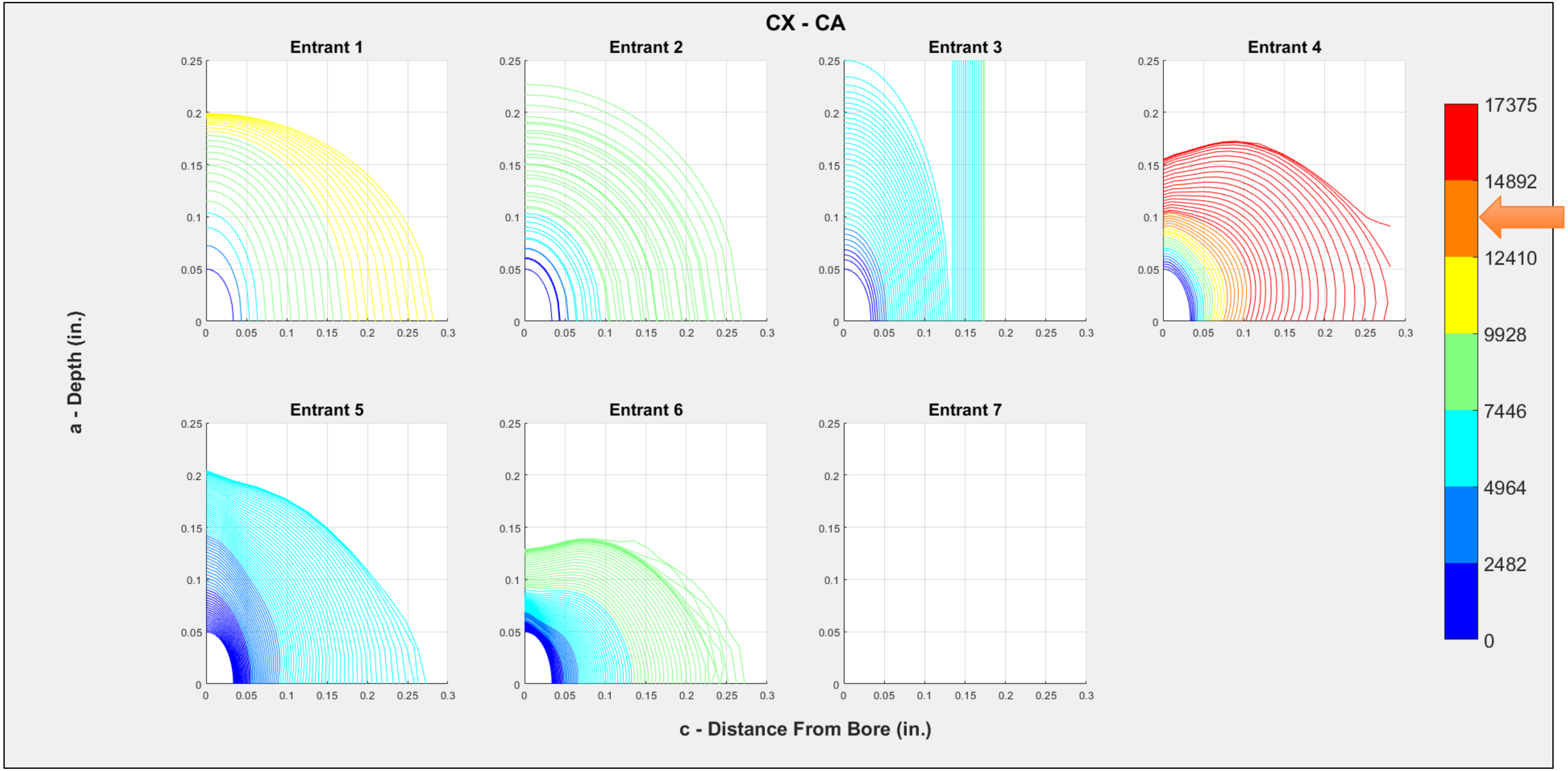
Entrant 3	7451
Entrant 4	17375
Entrant 5	6348
Entrant 6	7926
Entrant 7	N/A



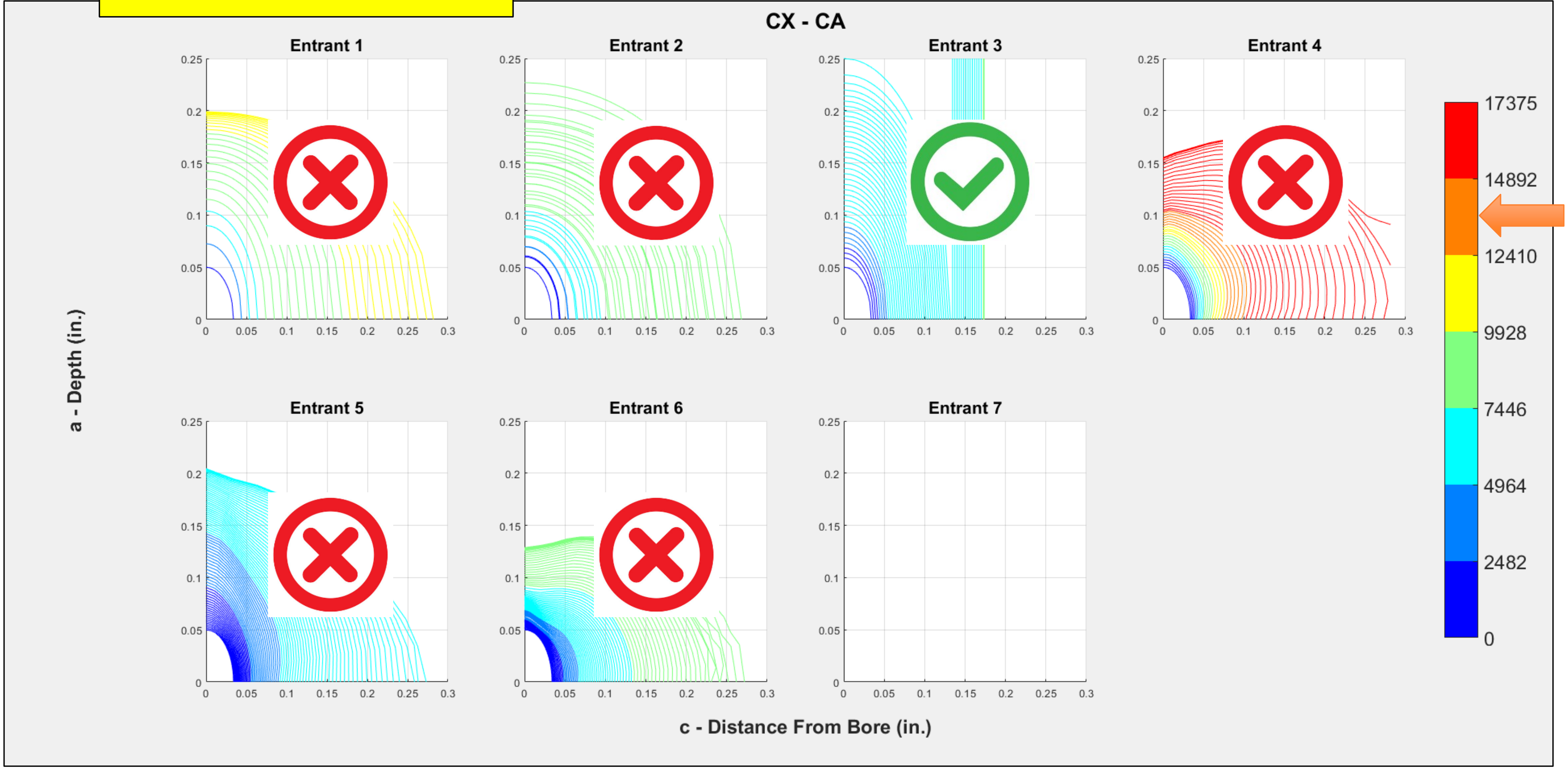
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

CRACK MORPHOLOGY: CX (CA)

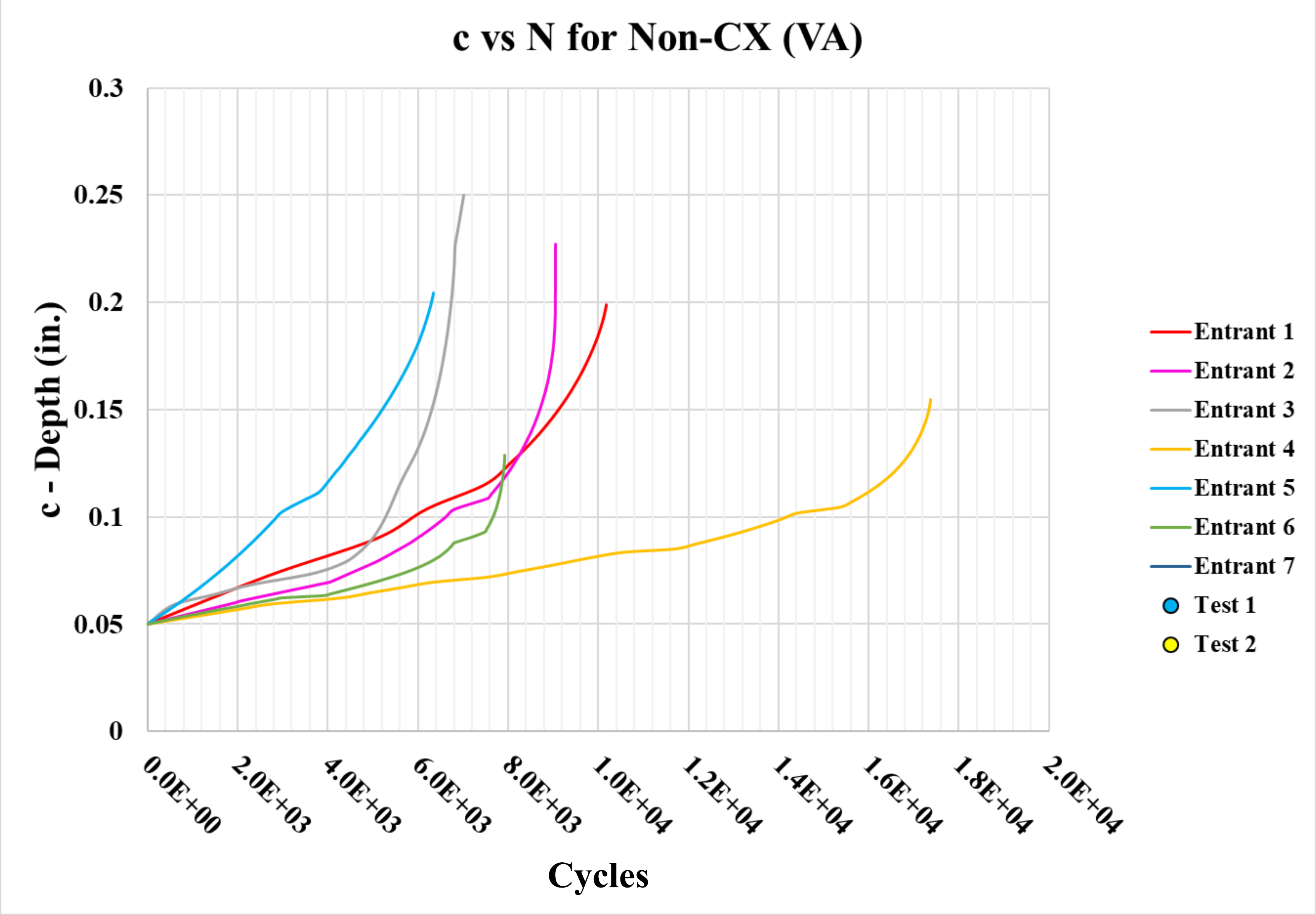


Did it break through?

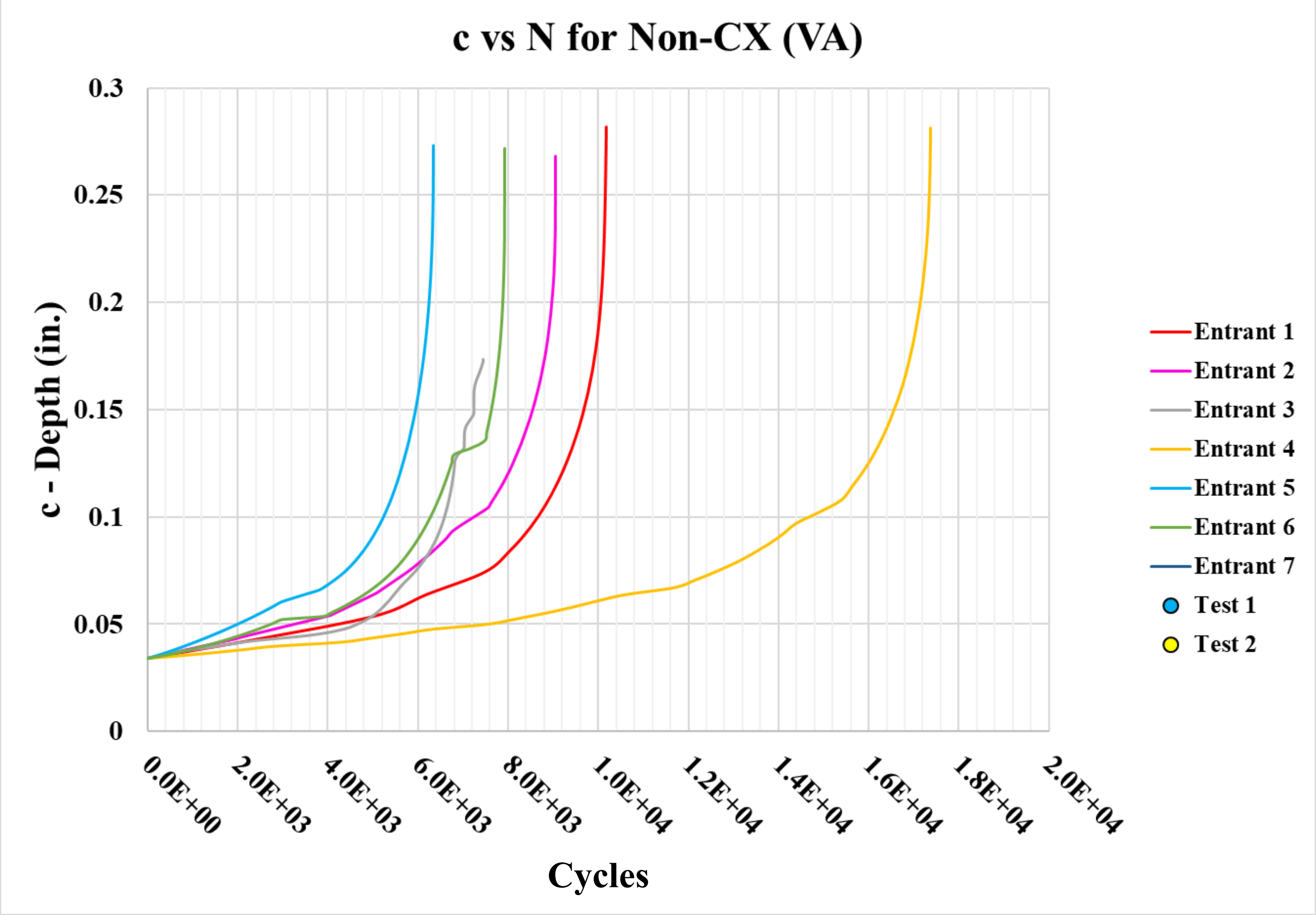
CRACK MORPHOLOGY: CX (CA)



CRACK PROGRESSION: CX (CA)



CRACK PROGRESSION: CX (CA)

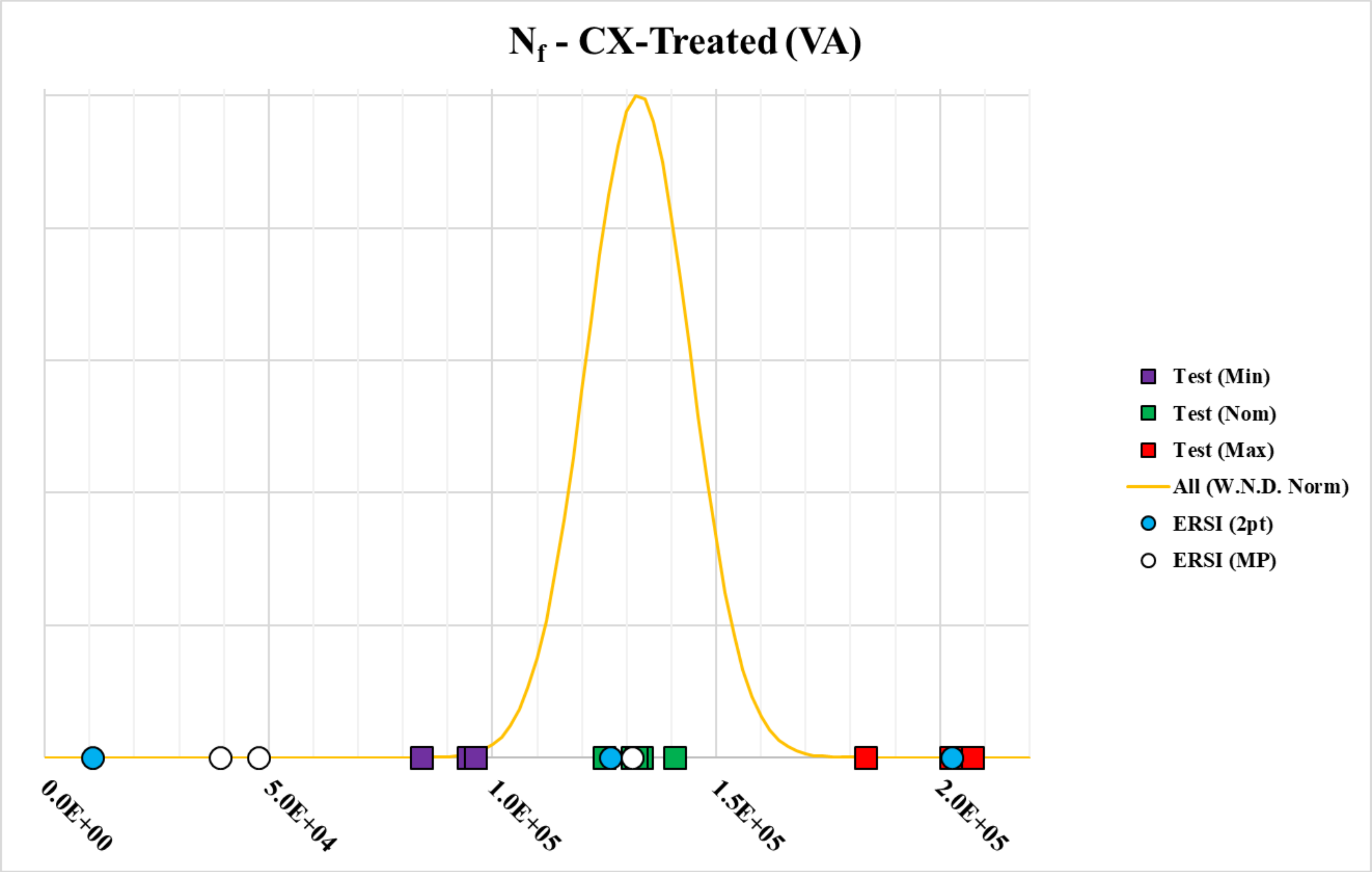


SCORE CARD: CX (CA)

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

CYCLES TO FAILURE: CX (VA)

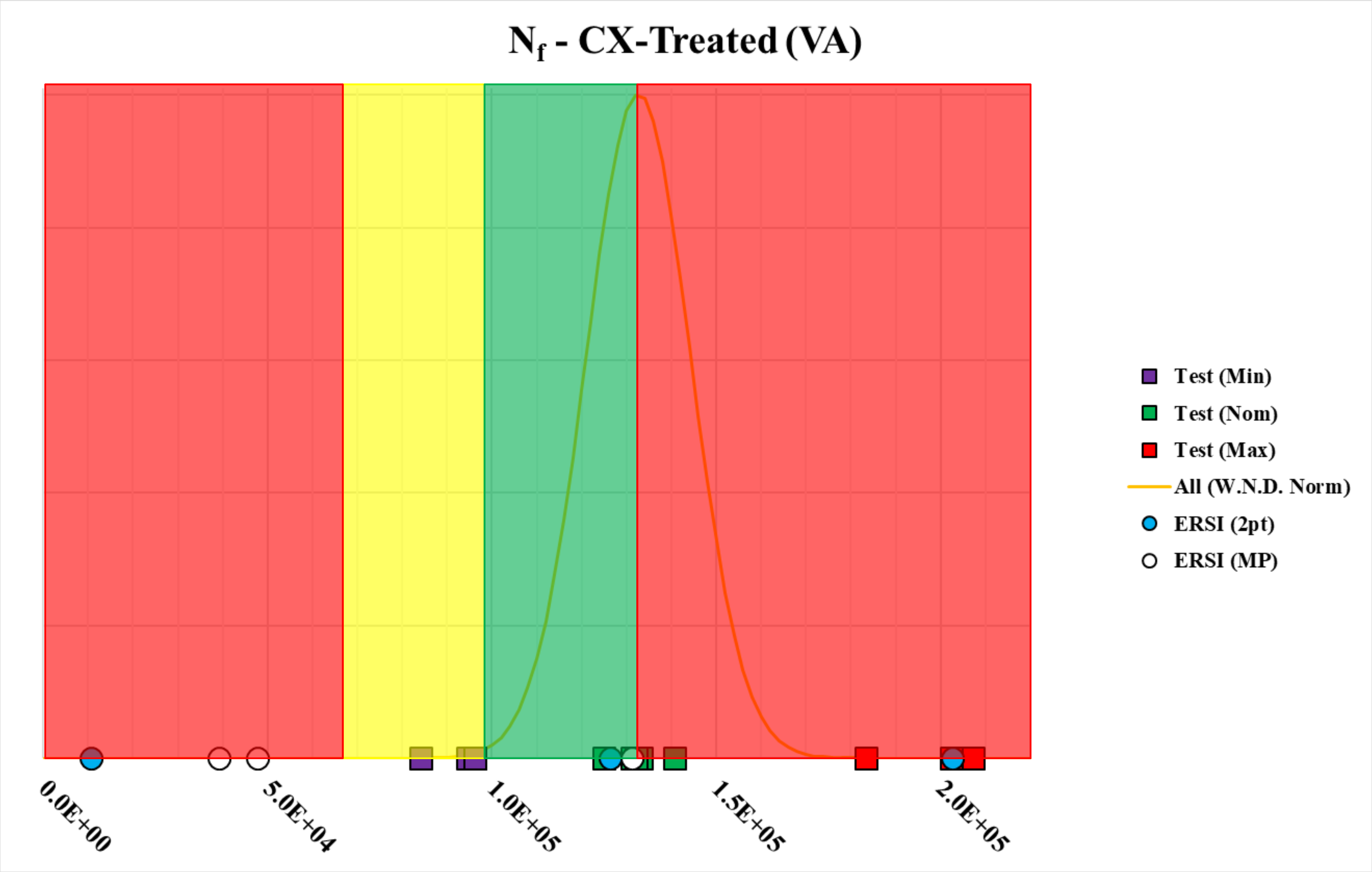
	N_f
Test (Mean)	132626
Entrant 1	202570
Entrant 2	126434
Entrant 3	10693
Entrant 4	131191
Entrant 5	39232
Entrant 6	47824
Entrant 7	N/A



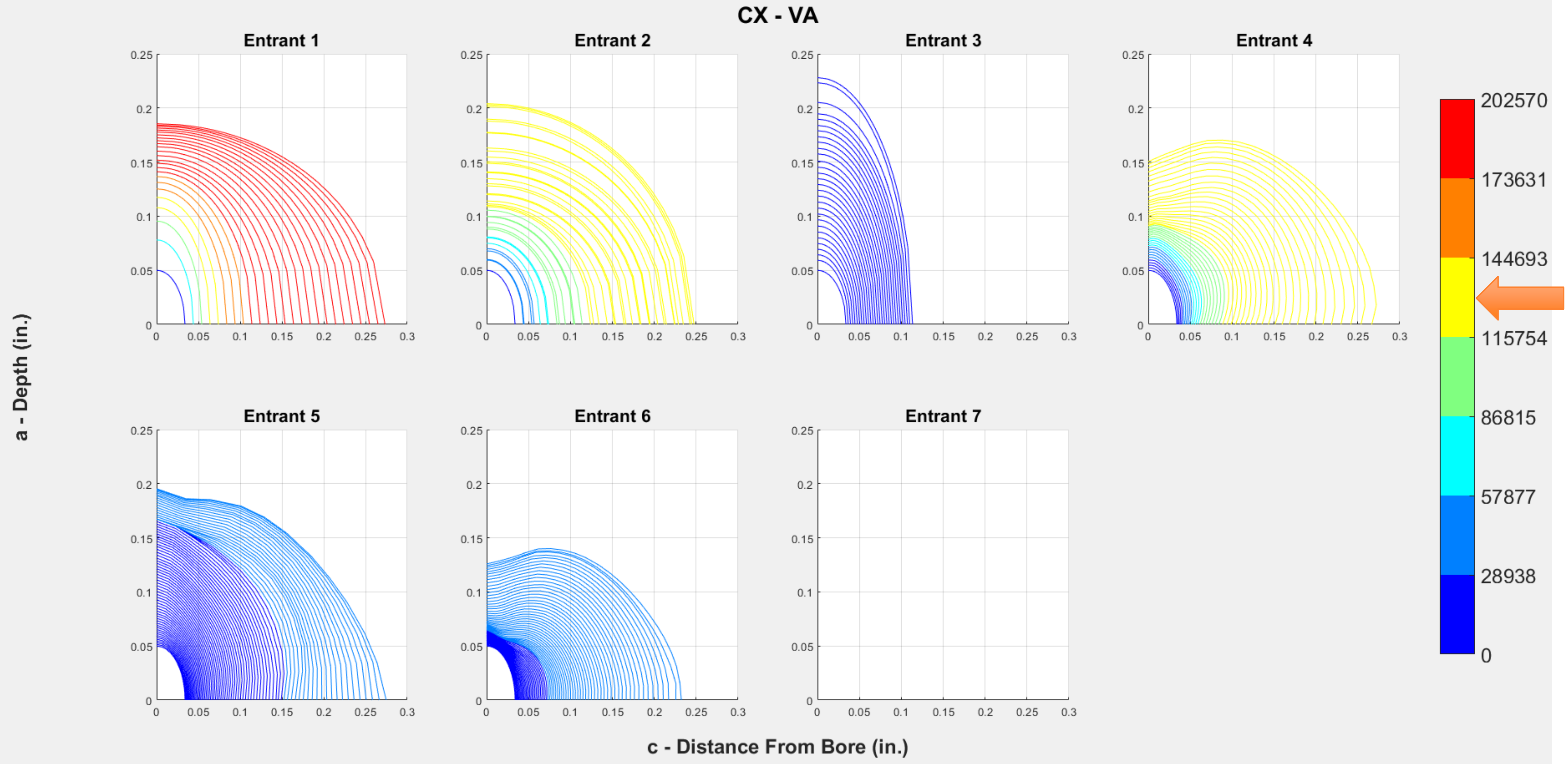
CYCLES TO FAILURE: CX (VA)

ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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

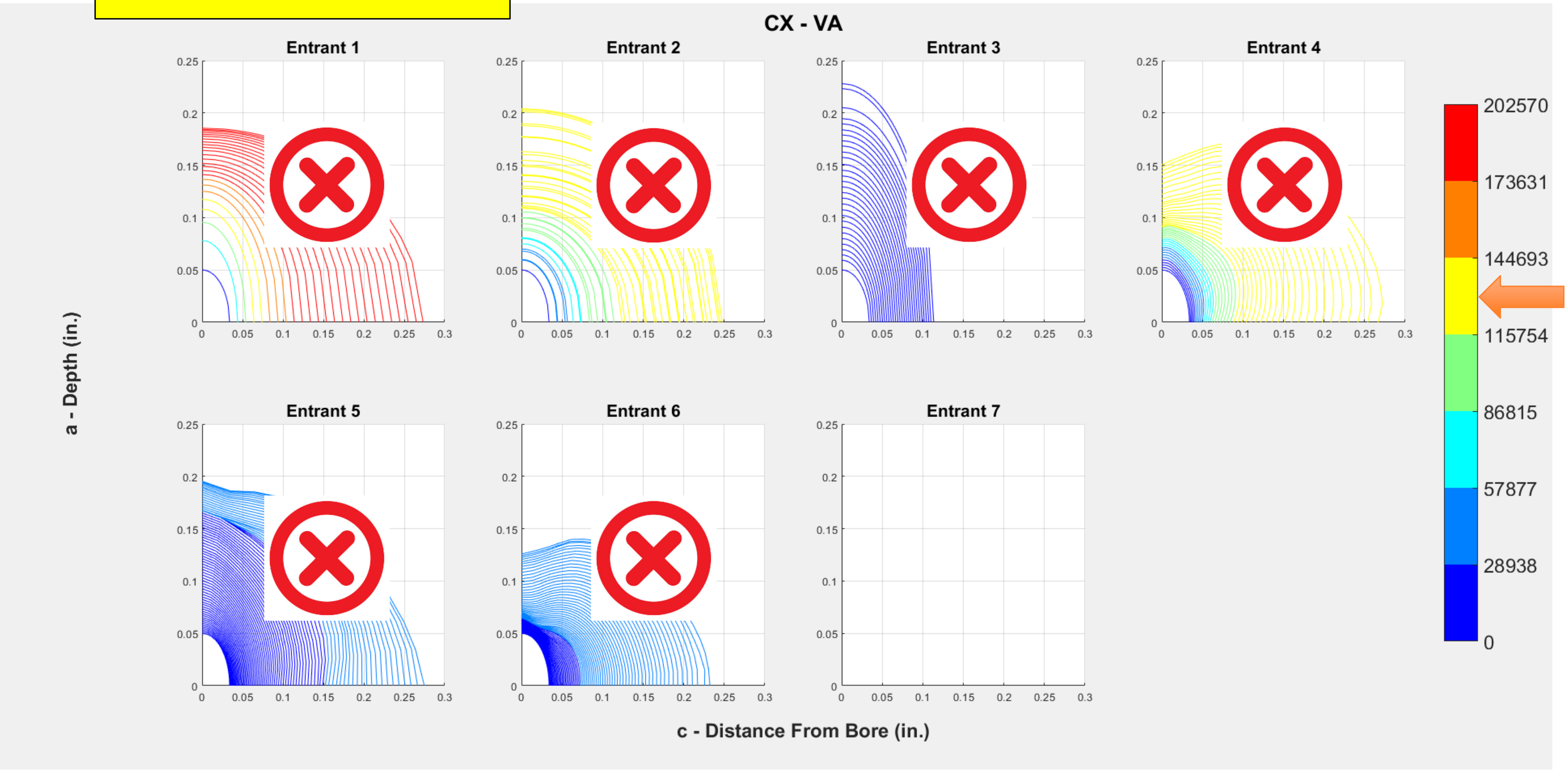


CRACK MORPHOLOGY: CX (VA)



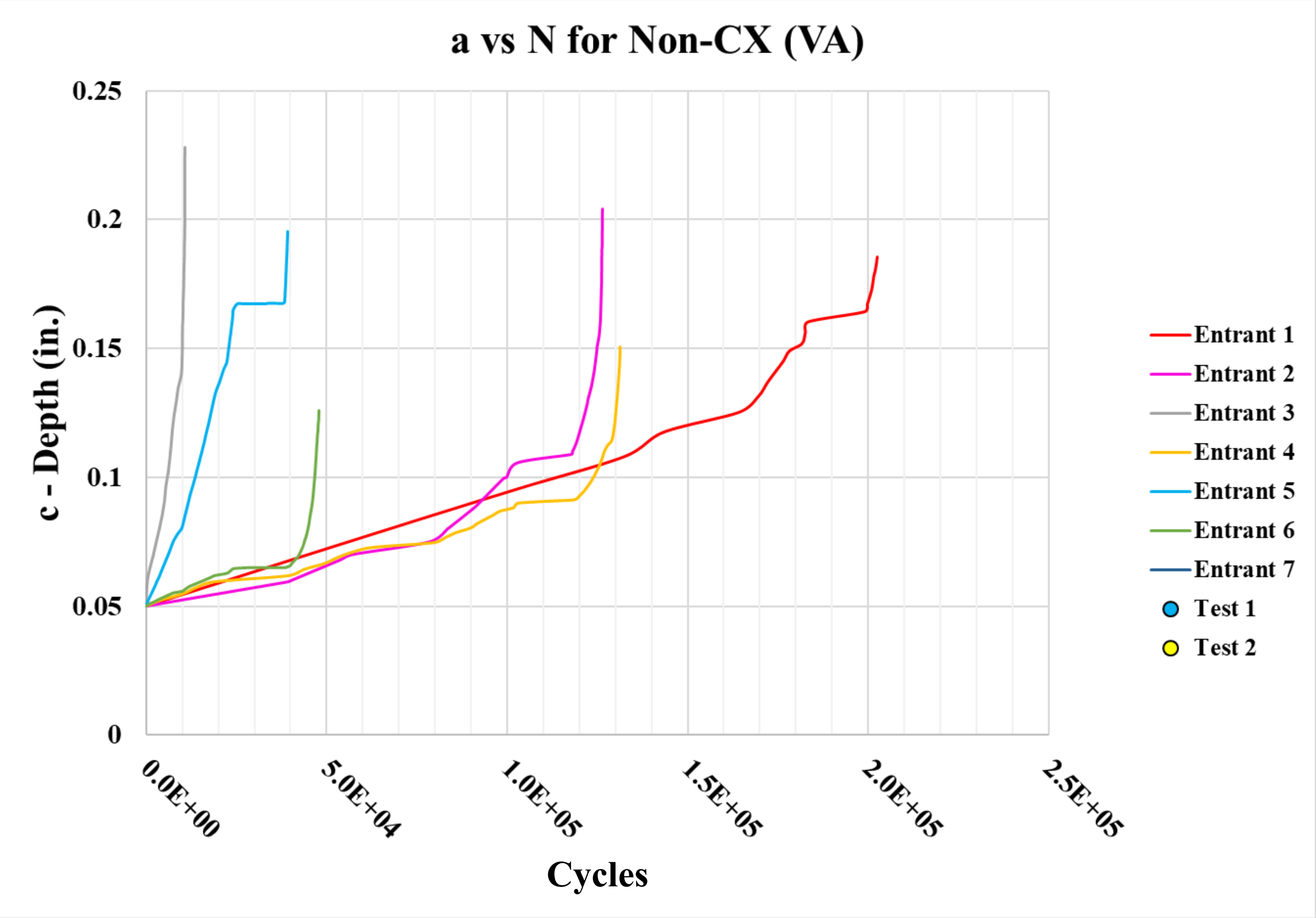
CRACK MORPHOLOGY: CX (VA)

Did it break through?

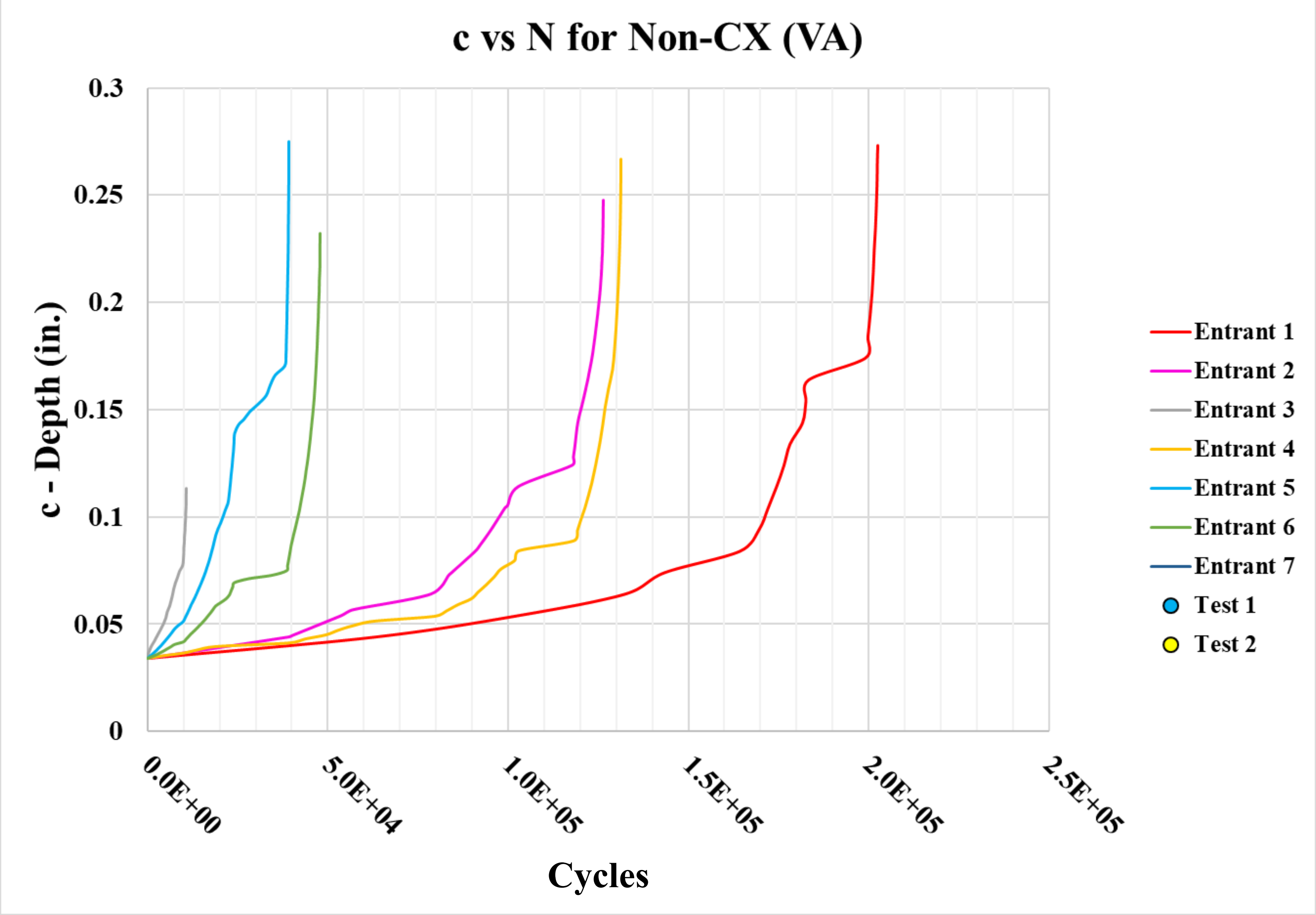


CRACK PROGRESSION: CX (VA)

ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION



CRACK PROGRESSION: CX (VA)



ERSI
ENGINEERED RESIDUAL
STRESS IMPLEMENTATION

SCORE CARD: CX (VA)

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

CONCLUSIONS AND NEXT STEPS

Conclusions & Next Steps

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

Backup

Spectrum Loading Efforts:
Spike Overload and Spectrum Testing

Kevin Walker

Moises Y. Ocasio

Agenda

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

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

Fatigue Life Enhancement

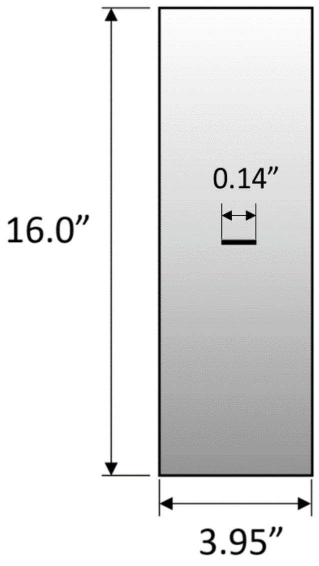
- Direct (e.g. Cold Work, IFF)
- Indirect (e.g. Local Plasticity)

Current Spectrum Efforts

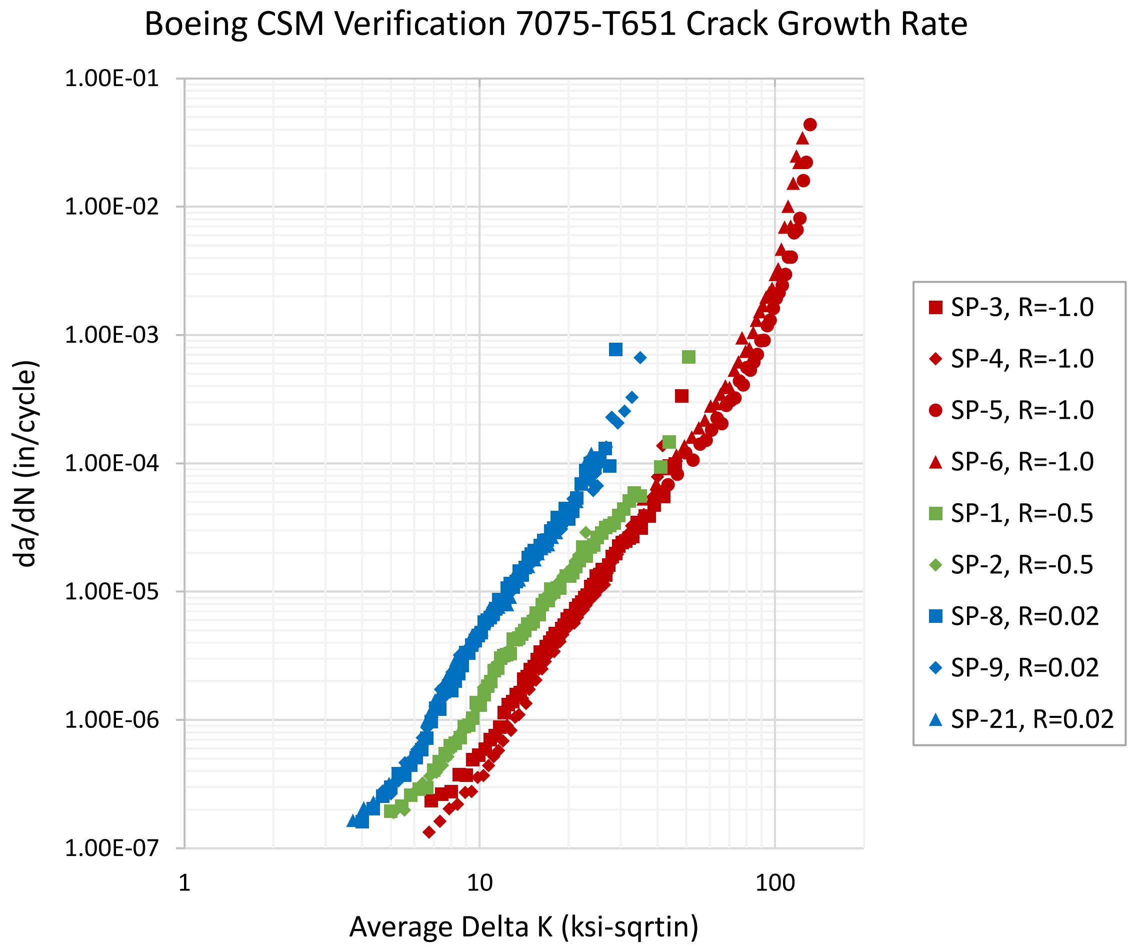
ERSI requires this complimentary approach to understand gaps in our methods, learn from each other and where possible deliver industry-wide guidelines (e.g. Structures Bulletin)

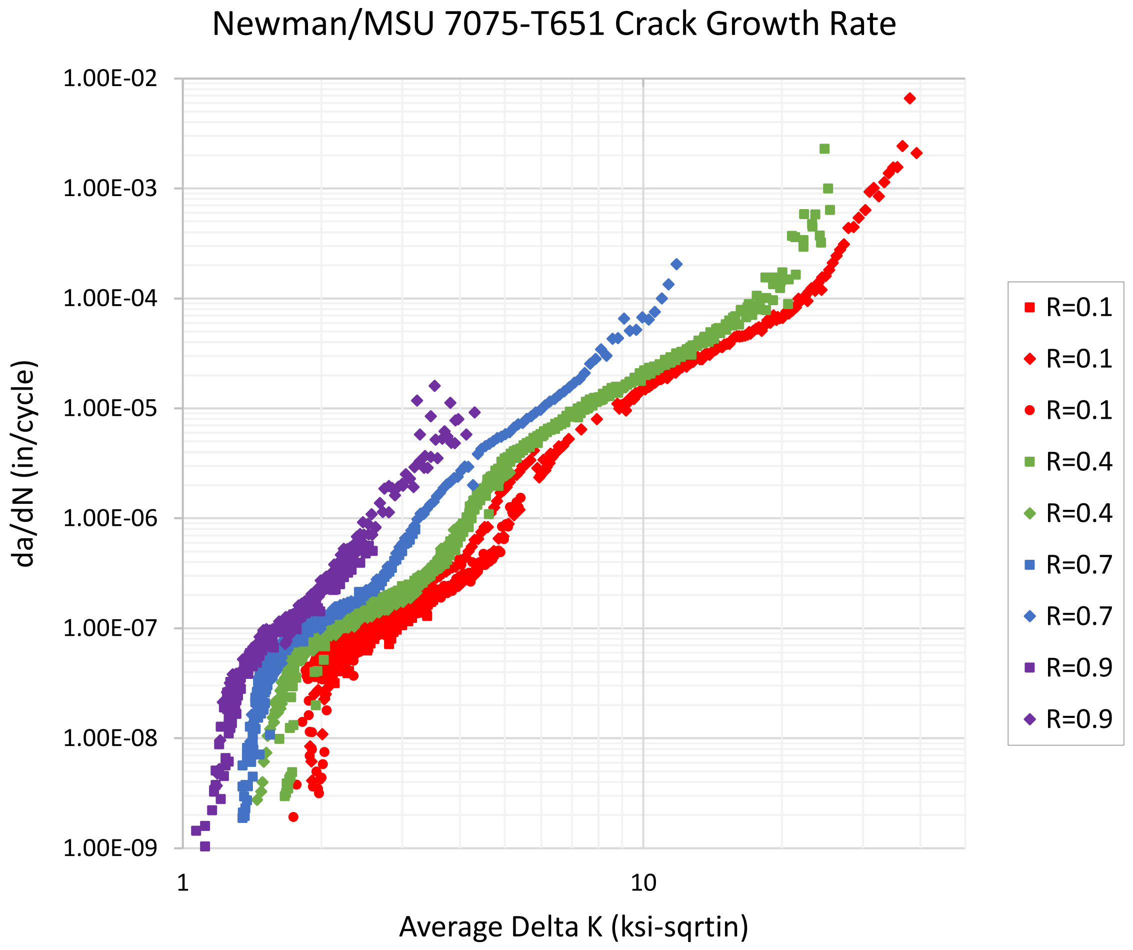
Summary

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



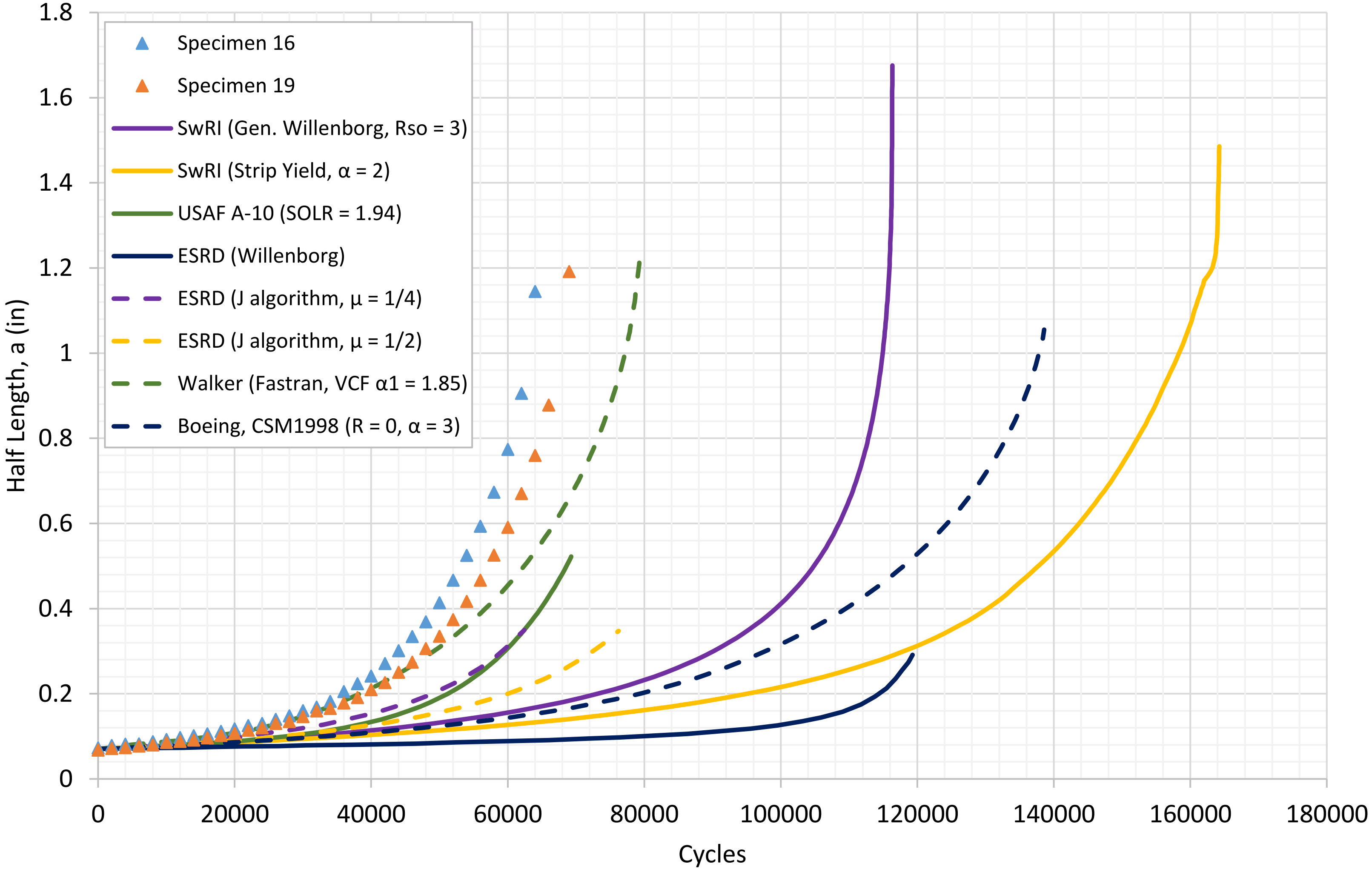
Round Robin Growth Rate Data Provided





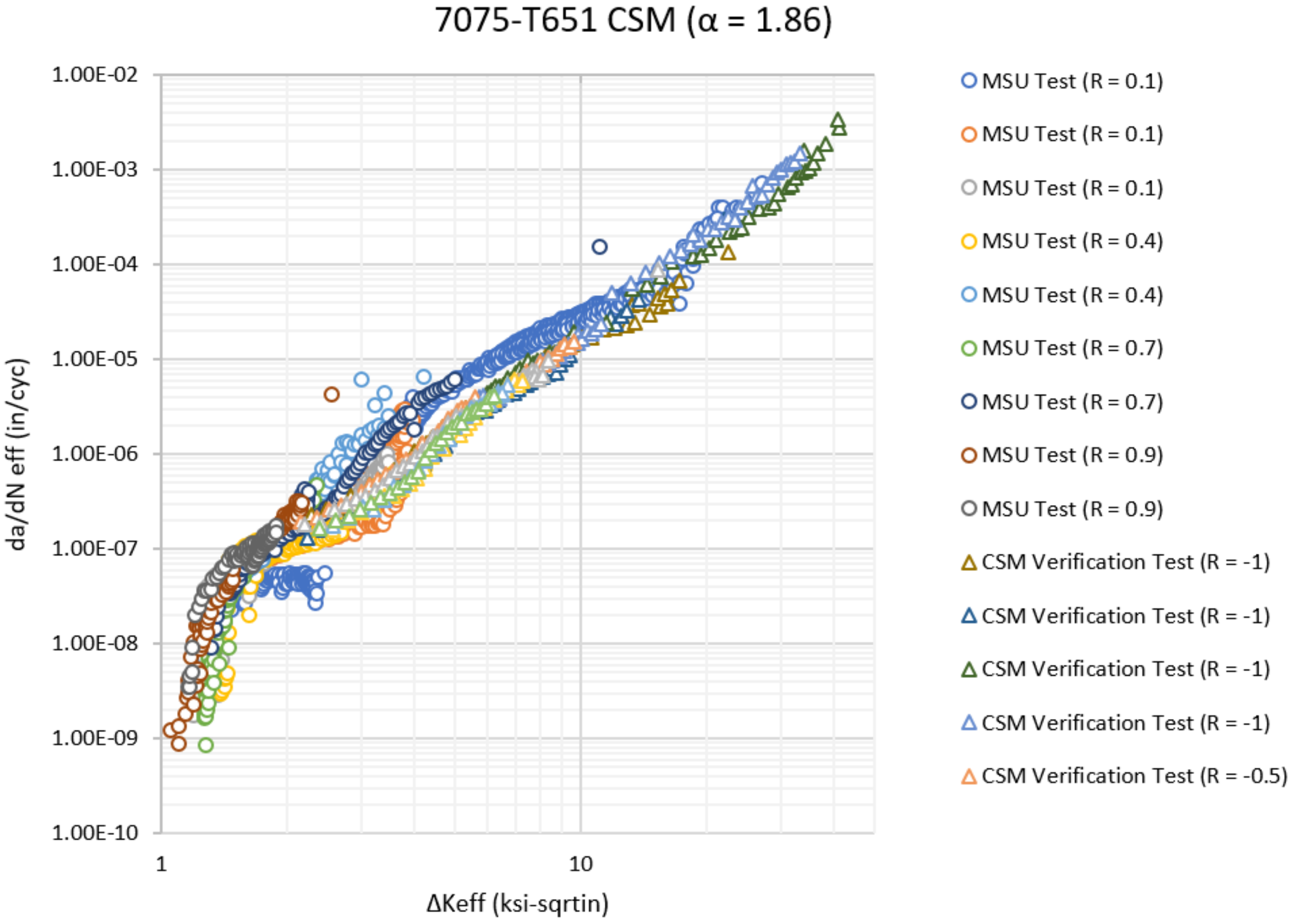
Task A: Constant Amplitude with Spike Overloads Prediction

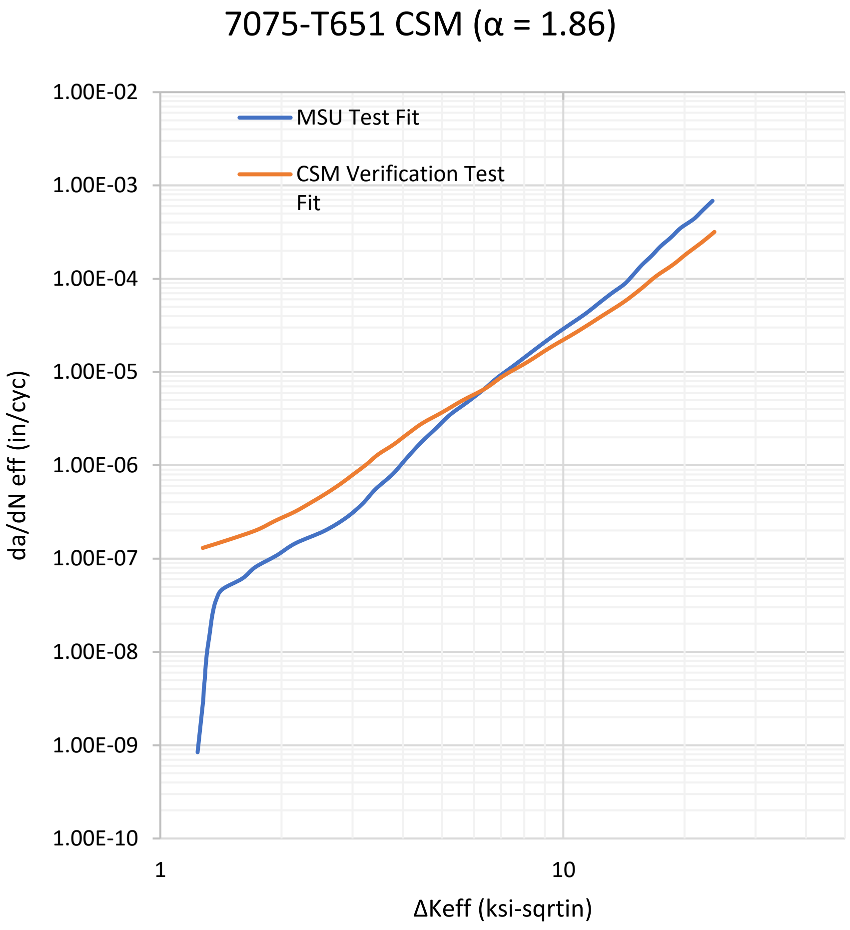
Configuration	Specimen Thickness (in)	Specimen Width (in)	Stress Level (ksi)	Stress Ratio	Test Type
A	0.245	3.950	15.0	0.0	Overload



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

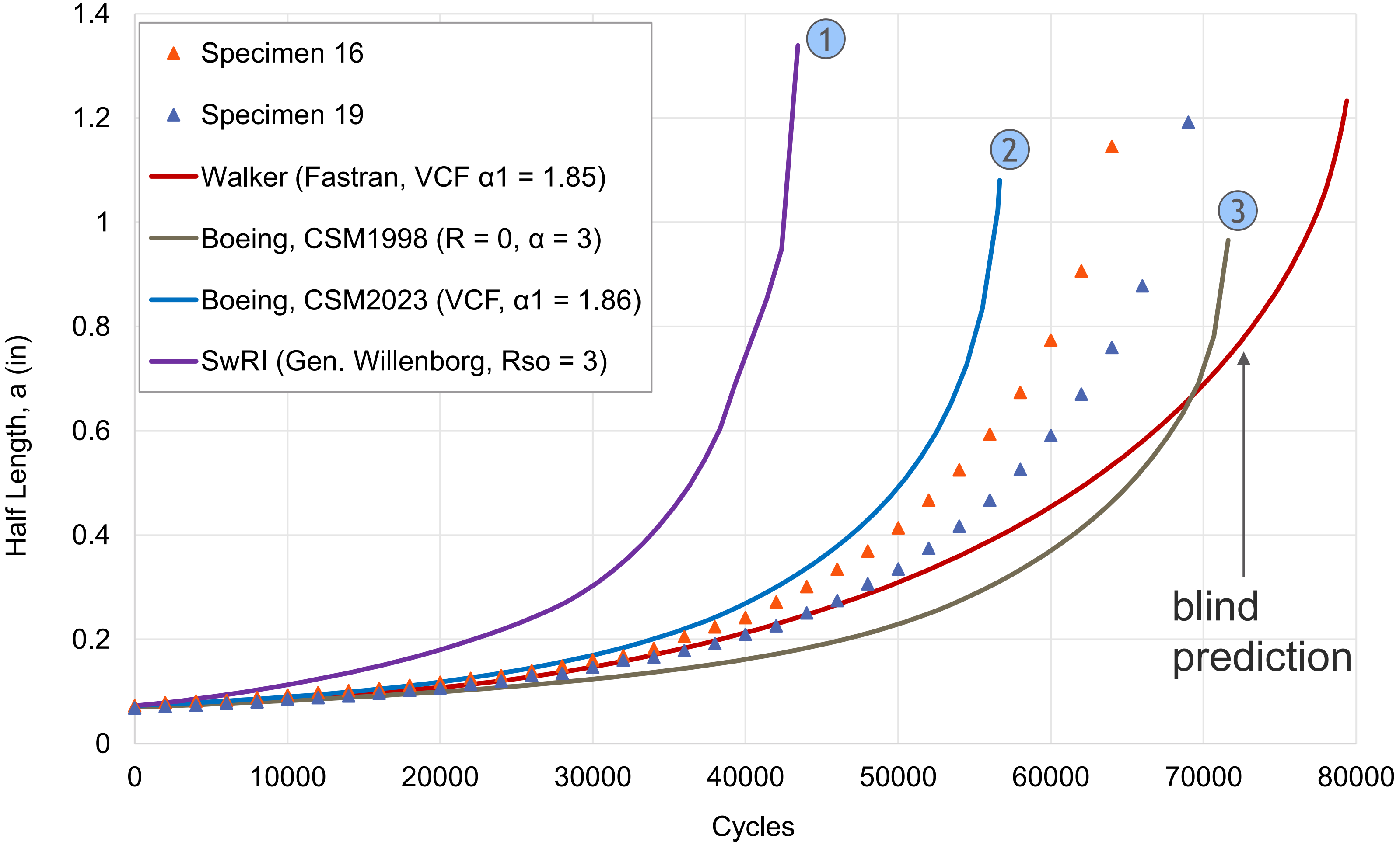
Crack Growth Rate Model





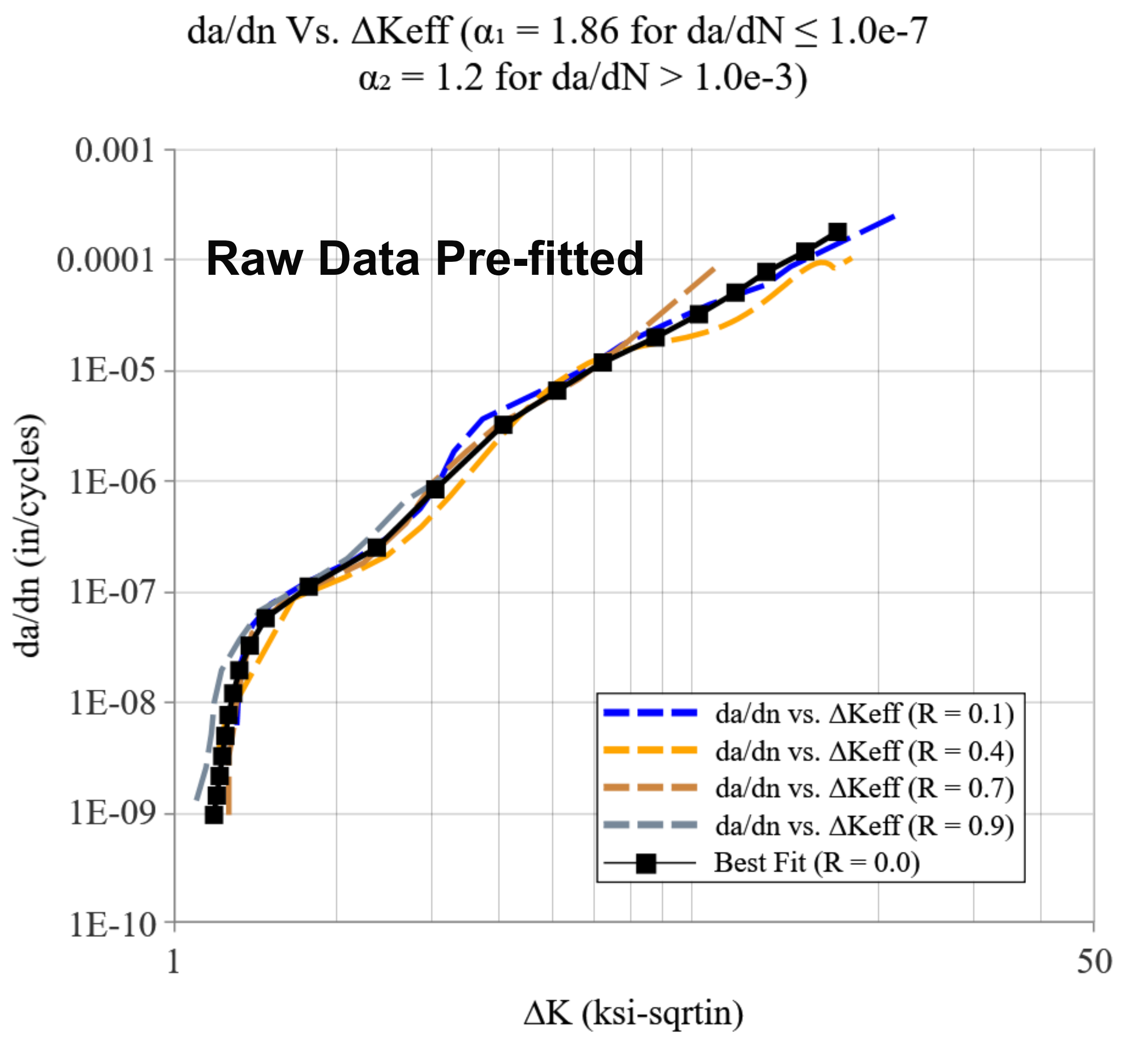
- CSM data: MT specimens, pre-cracked using load-shedding method. No Region I.
- MSU data: CT specimens, pre-cracked following CPCA method.

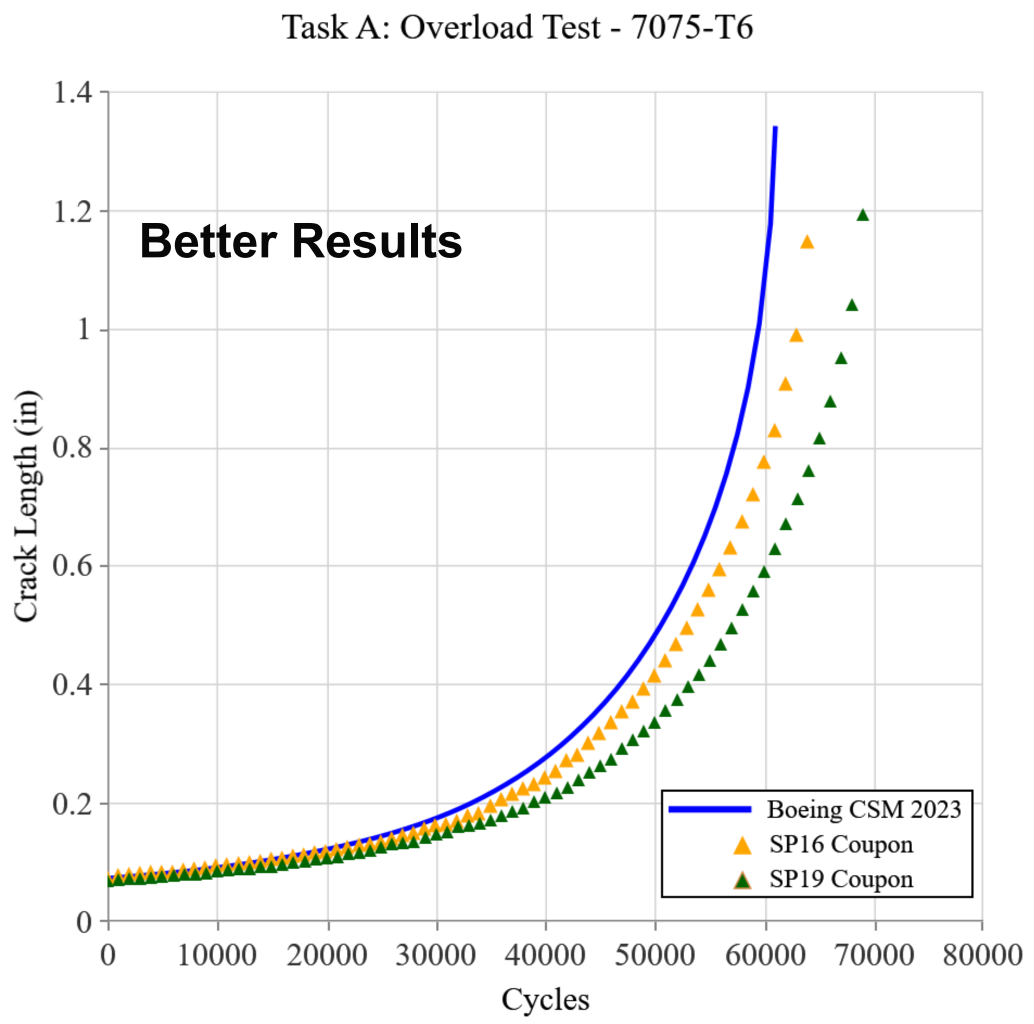
Task A: Constant Amplitude with Spike Overloads Lessons Learned



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

Crack Growth Rate Constraint Factor and Overload Test Prediction

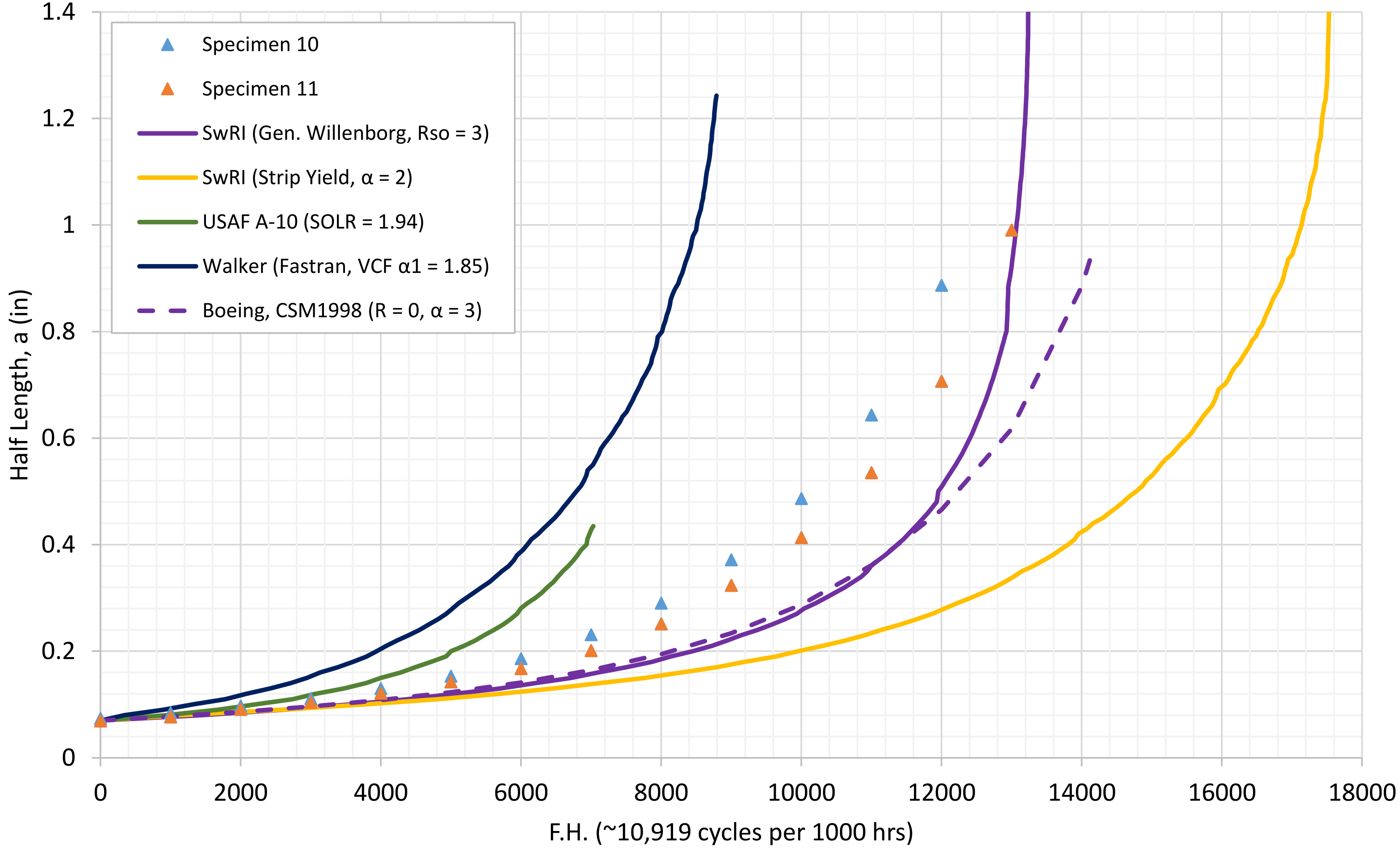


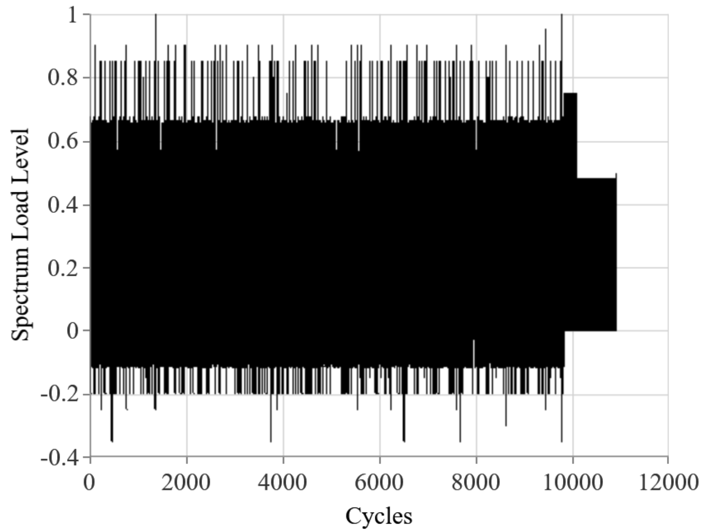


Task B: Fighter Lower Wing Spectrum Prediction

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

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





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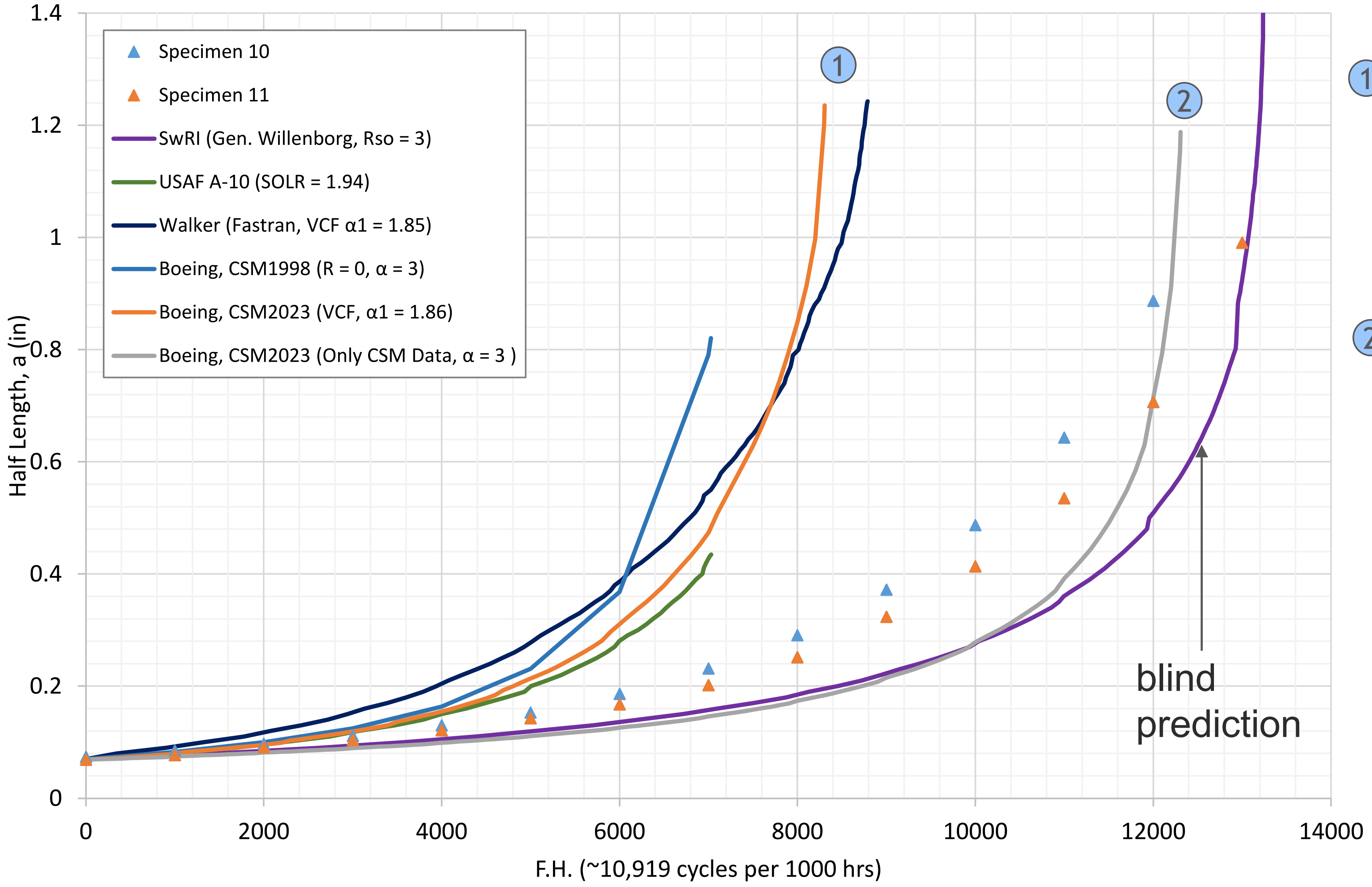
Task B: Fighter Lower Wing Spectrum Lessons Learned

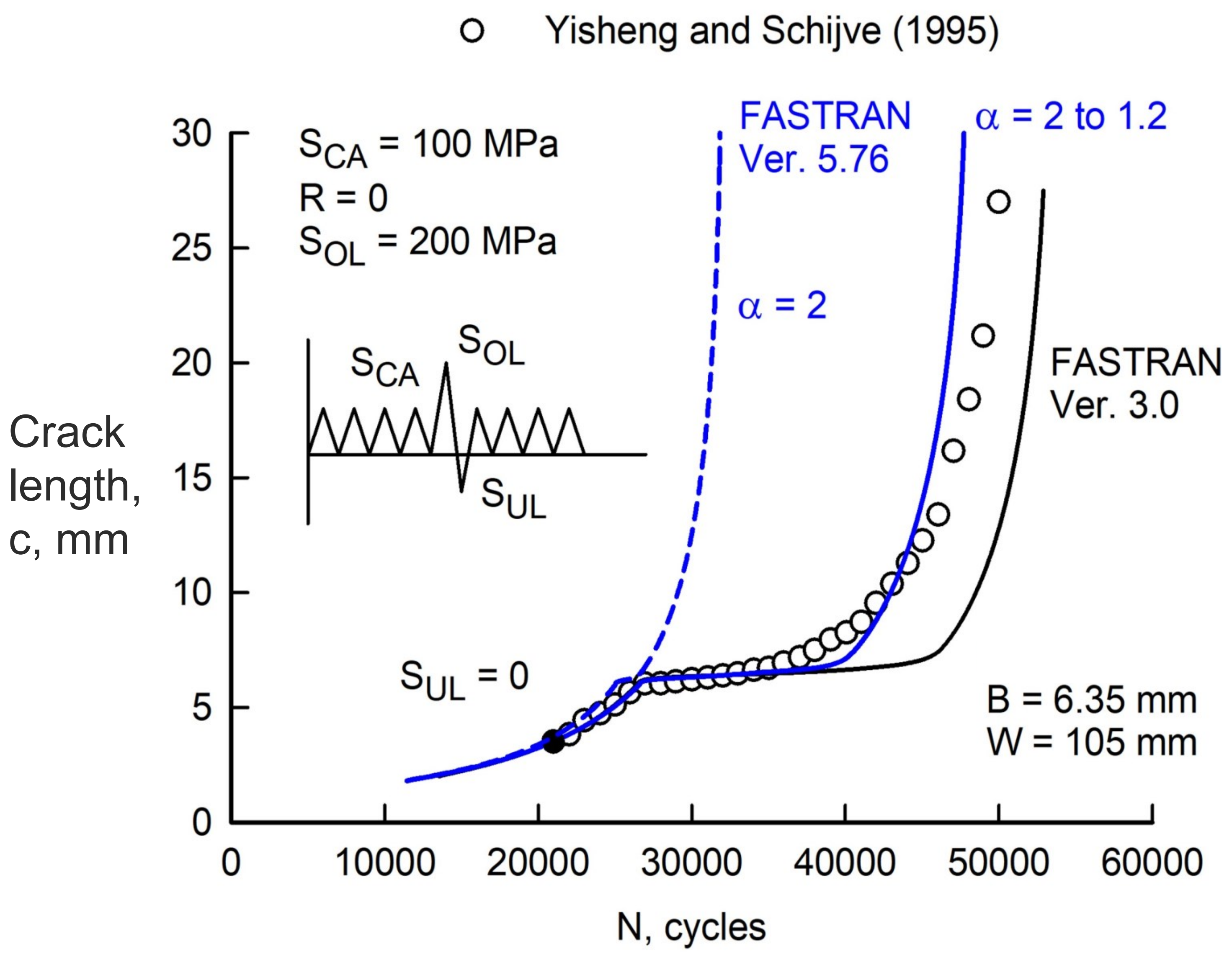


1. Strip-yield models (and Generalized Willenborg with SOLR correlation) produce conservative predictions due to higher Region II slope in MSU 7075-T651 data.
2. Using only CSM R=0 data improves final life prediction.

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

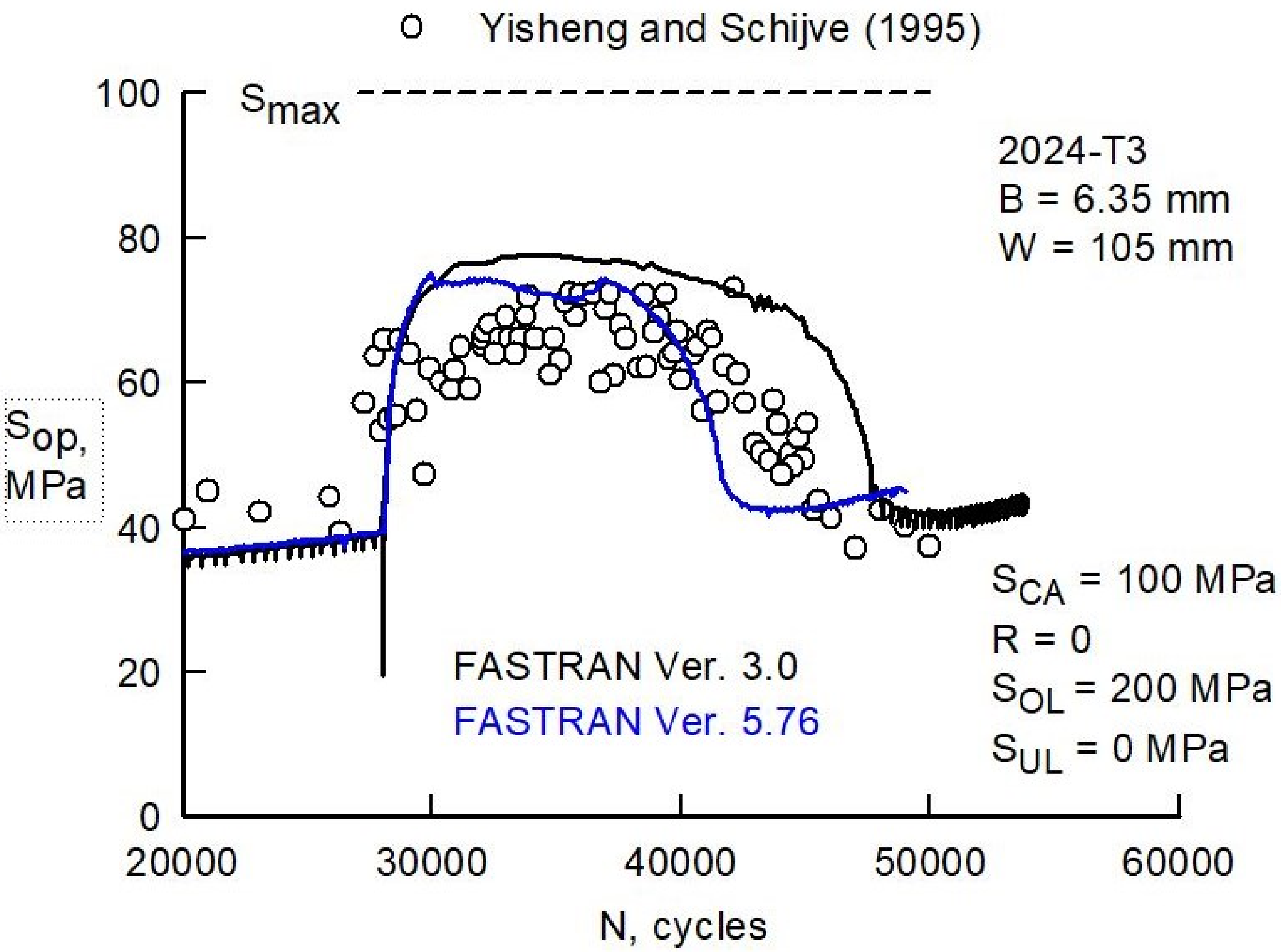
QinetiQ Sponsored Test and Analysis (Kevin Walker and Jim Newman)

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

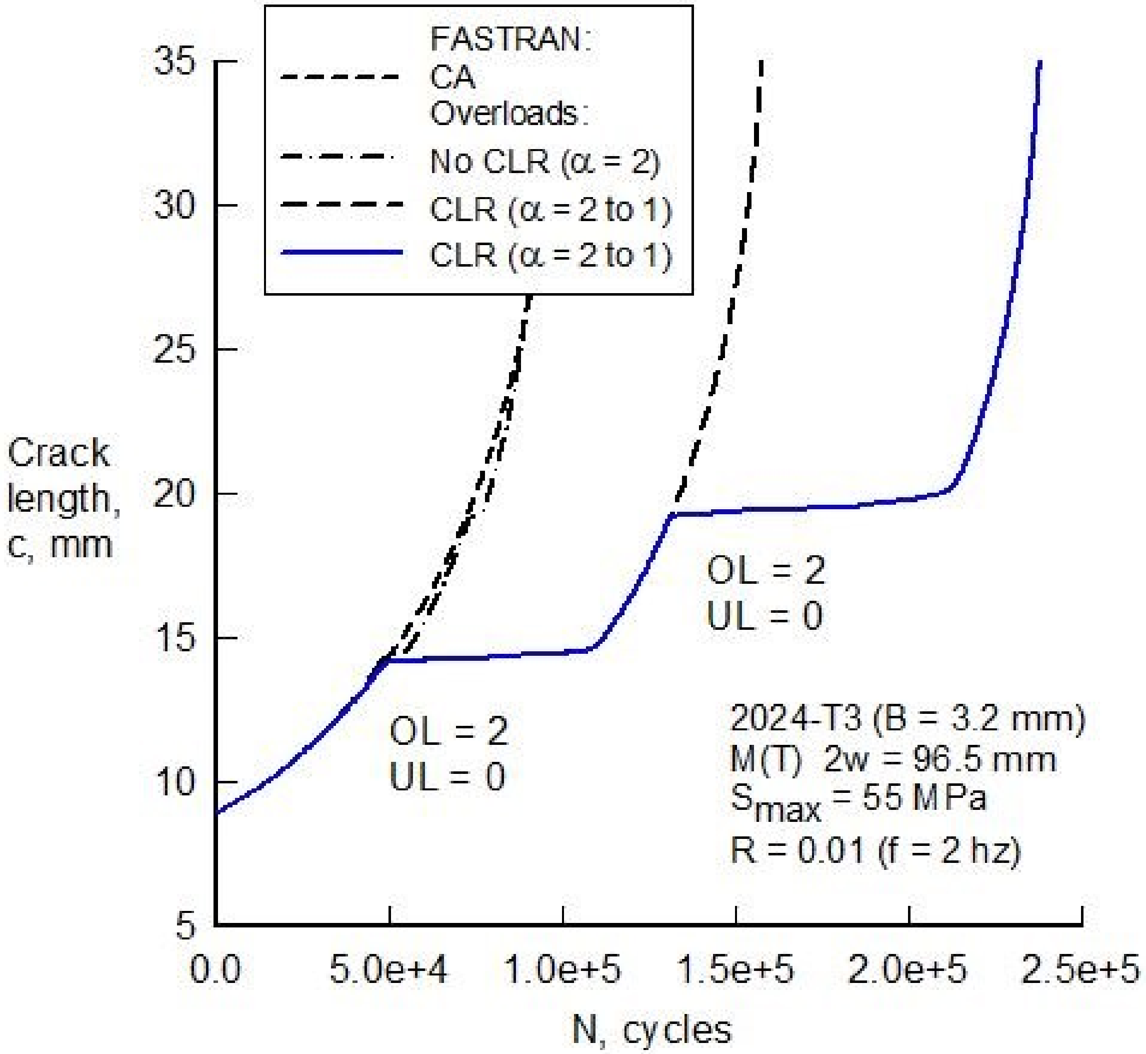


Test and Analyses of a Single-Spike Overload on 2024-T351 Plate

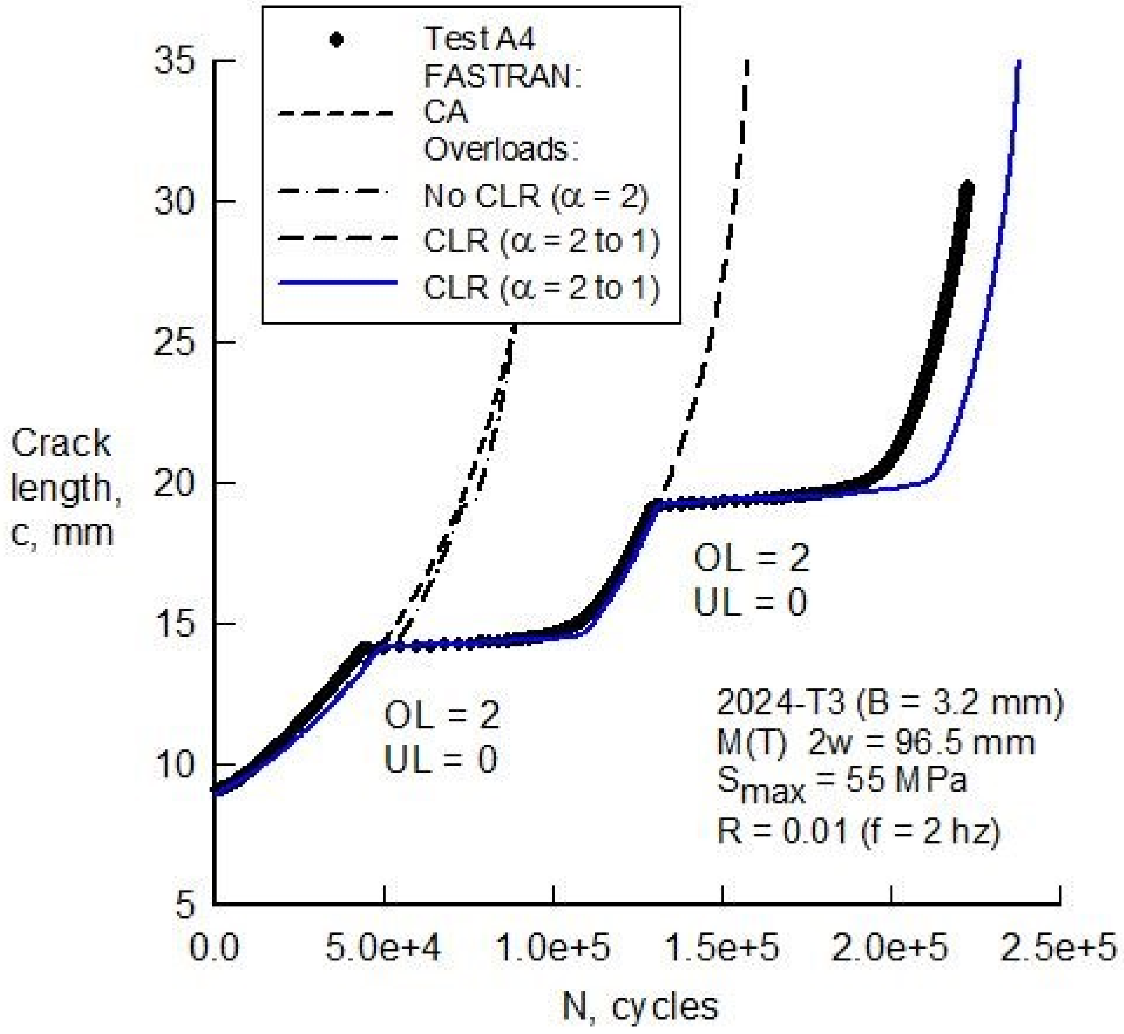
Measured and Calculated Crack-Opening Stress after a Single-Spike Overload on 2024-T351 Plate

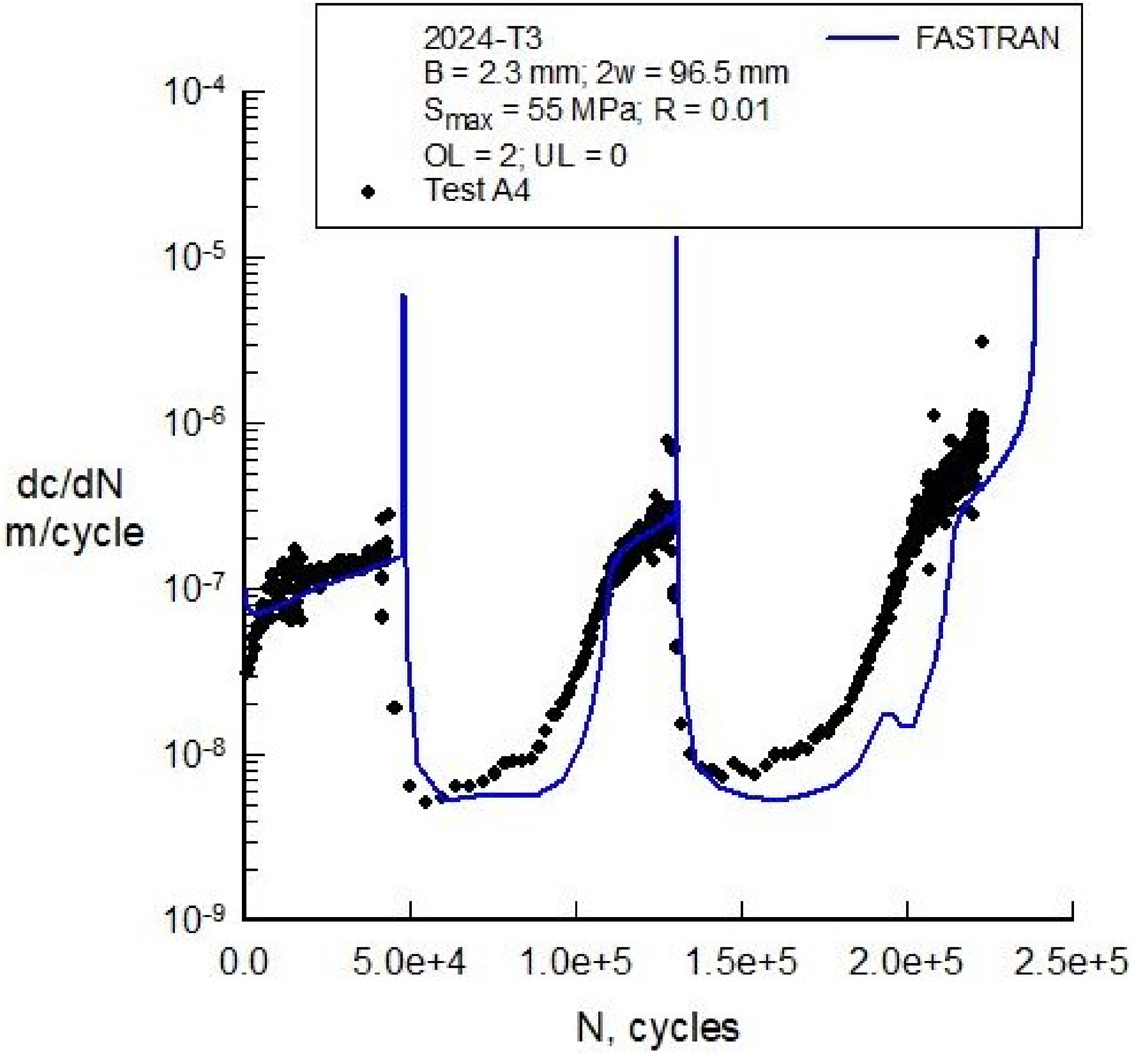


Predicted Crack-Length against Cycles under Repeated Single-Spike Overloads in 2024-T3 Sheet

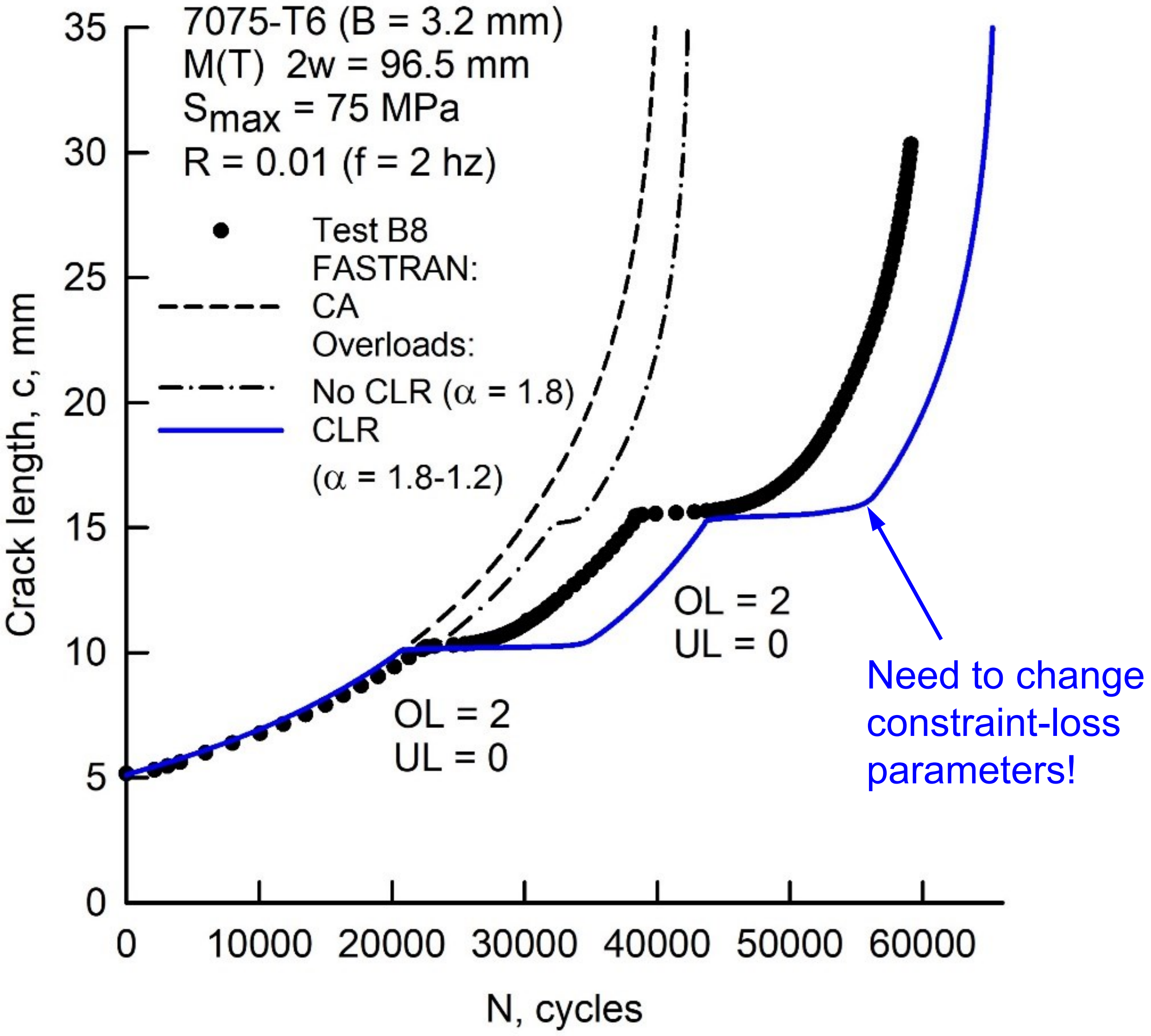


Measured and Predicted Crack-Length against Cycles under Repeated Single-Spike Overloads in 2024-T3 Sheet





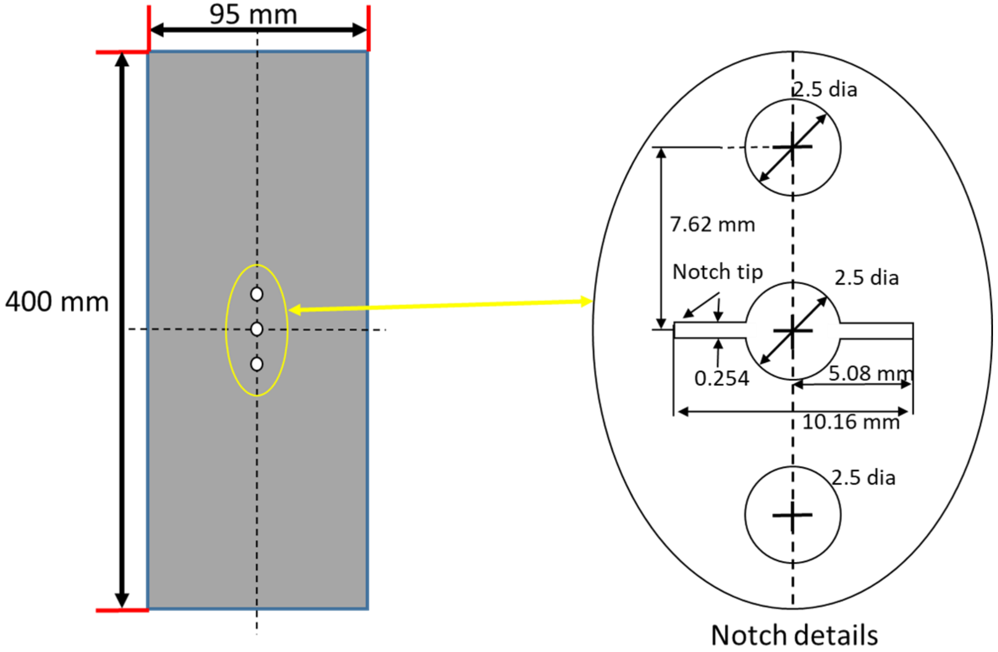
Measured and Predicted Crack-Growth-Rate against Cycles under Repeated Single-Spike Overloads in 2024-T3 Sheet



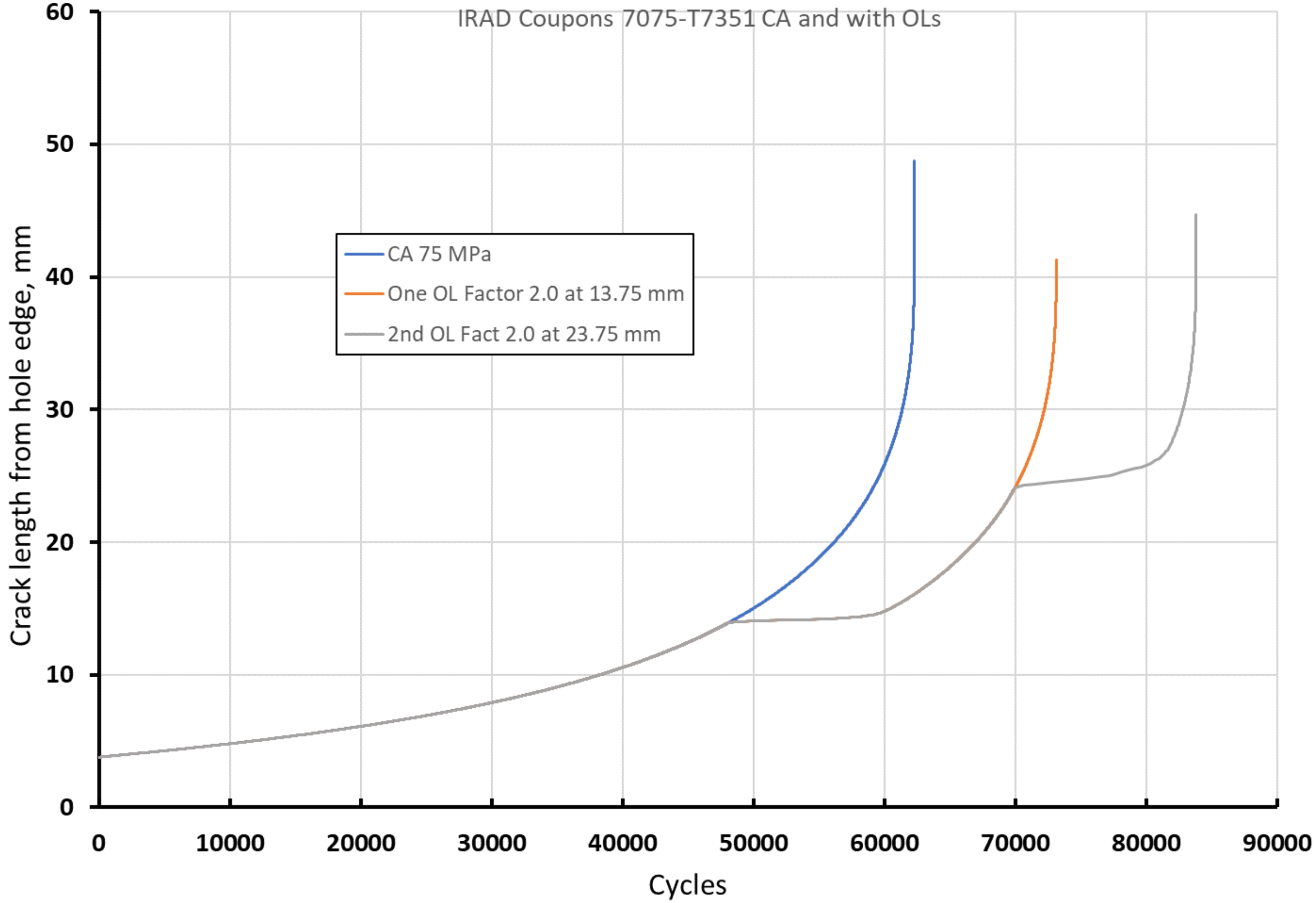
Measured and Predicted Crack-Length against Cycles under Repeated Single-Spike Overloads in 7075-T6 Sheet

IRAD Coupons 7075-T7351

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

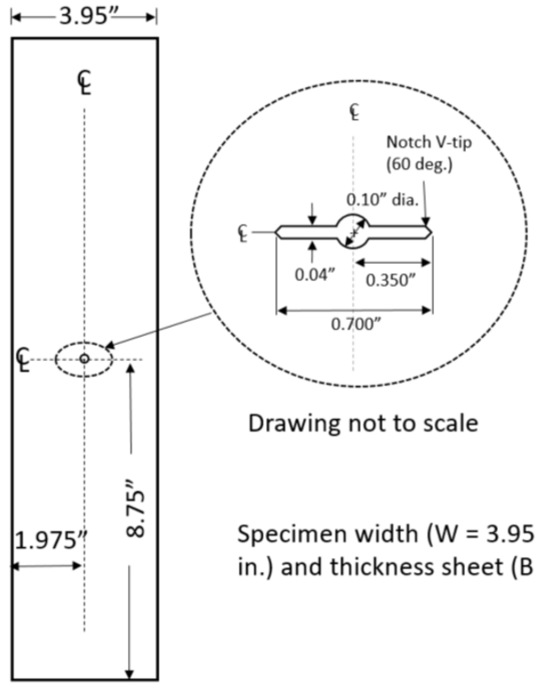


Example of predictions before tests



Spike Overload Testing (Boeing)

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



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

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

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

Kevin Walker PhD
Senior Principal Engineer
QinetiQ Pty Ltd
Level 3, 210 Kingsway
South Melbourne VIC 3205
Australia

Pronouns: He/His

D +61 3 9230 7271
M +61 457 002 775
KFWalker@QinetiQ.com.au

Moises Y. Ocasio
BDS SDT Fatigue Lead
Boeing Building 305, Level 3
163 James S. McDonnell Blvd,
Hazelwood, MO 63042

Work: 314-563-6661
moises.y.ocasio-latorre@boeing.com

Working Group on Engineered Residual Stress Implementation

Interference Fit Fastener

Working Group

Robert Pilarczyk
rtpilarczyk@hill-engineering.com

Adrian Loghin

loghin@simmetrix.com

Renan Ribeiro

rlribeiro@hill-engineering.com

IFF Working Group

Composition

- 13 participants

Objective

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

Approach

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

Key collaboration areas

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

IFF Implementation Plan

Phase I: Baseline Stress Analysis Verification

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

Phase II: Stress Intensity Factor Comparisons

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

Phase III: Crack Growth Analyses

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

IFF Phase I: Baseline Stress Analysis

Objectives

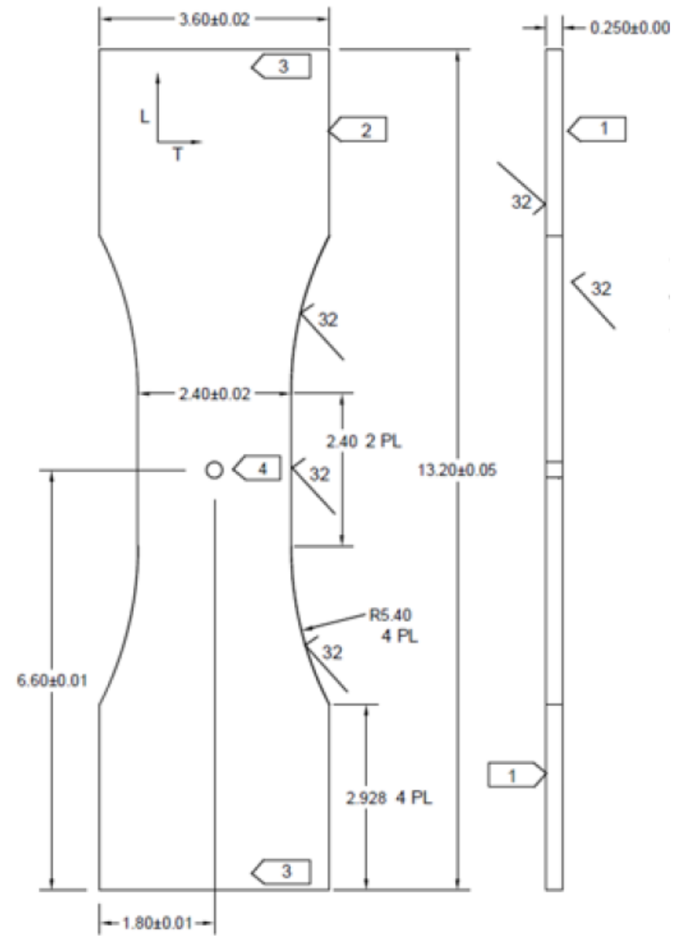
- The accuracy of SIFs and crack growth predictions for IFF conditions is highly dependent on the accuracy of the stress analysis
- The primary objective of Phase I is to establish a set of reference stress analyses agreed upon by the working group
- These analyses will establish the baseline stress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

IFF Phase I: Baseline Stress Analysis

Analysis Inputs

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

No Cracks for Phase I



IFF Phase I: Baseline Stress Analysis

Analysis Inputs, cont.

✓

Table 1. Round-robin analysis conditions, group 1

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

✓

Table 2. Round-robin analysis conditions, group 2

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

INW

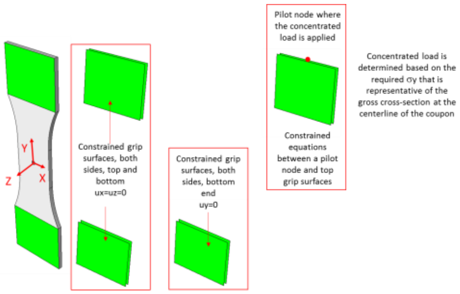
Table 3. Round-robin analysis conditions, group 3

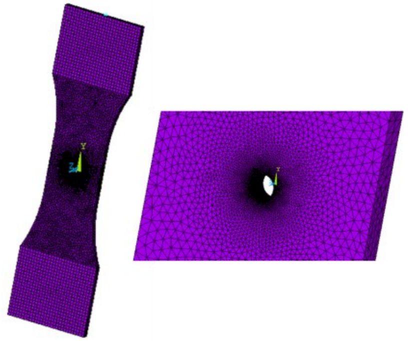
Group	Condition	Sequence Step	Interference Condition	Applied (ksi)
3	1	1 – Installed Fastener 2 – Apply Remote Stress 3- Unload 4 – Remove Fastener	Neat Fit	-10, 10, 20, 30
	2		0.3% IFF	
	3		0.6% IFF	
	4		1.2% IFF	

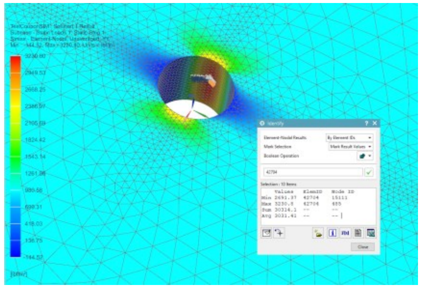
Group 1 – Open Hole Results

Summary of Submissions

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







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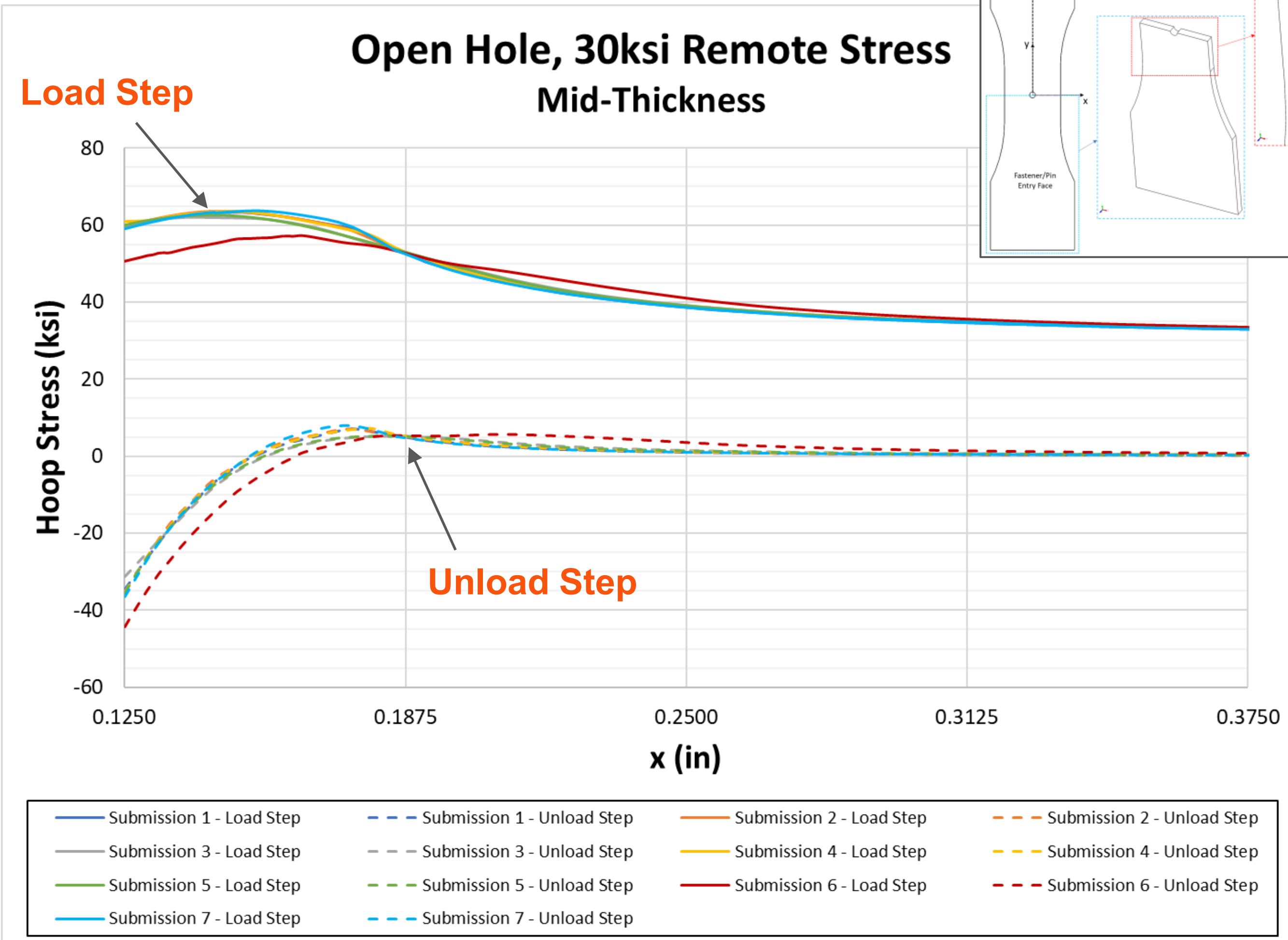
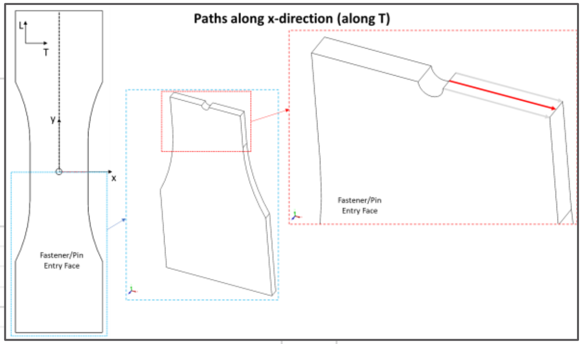
Group 1 – Open Hole Results

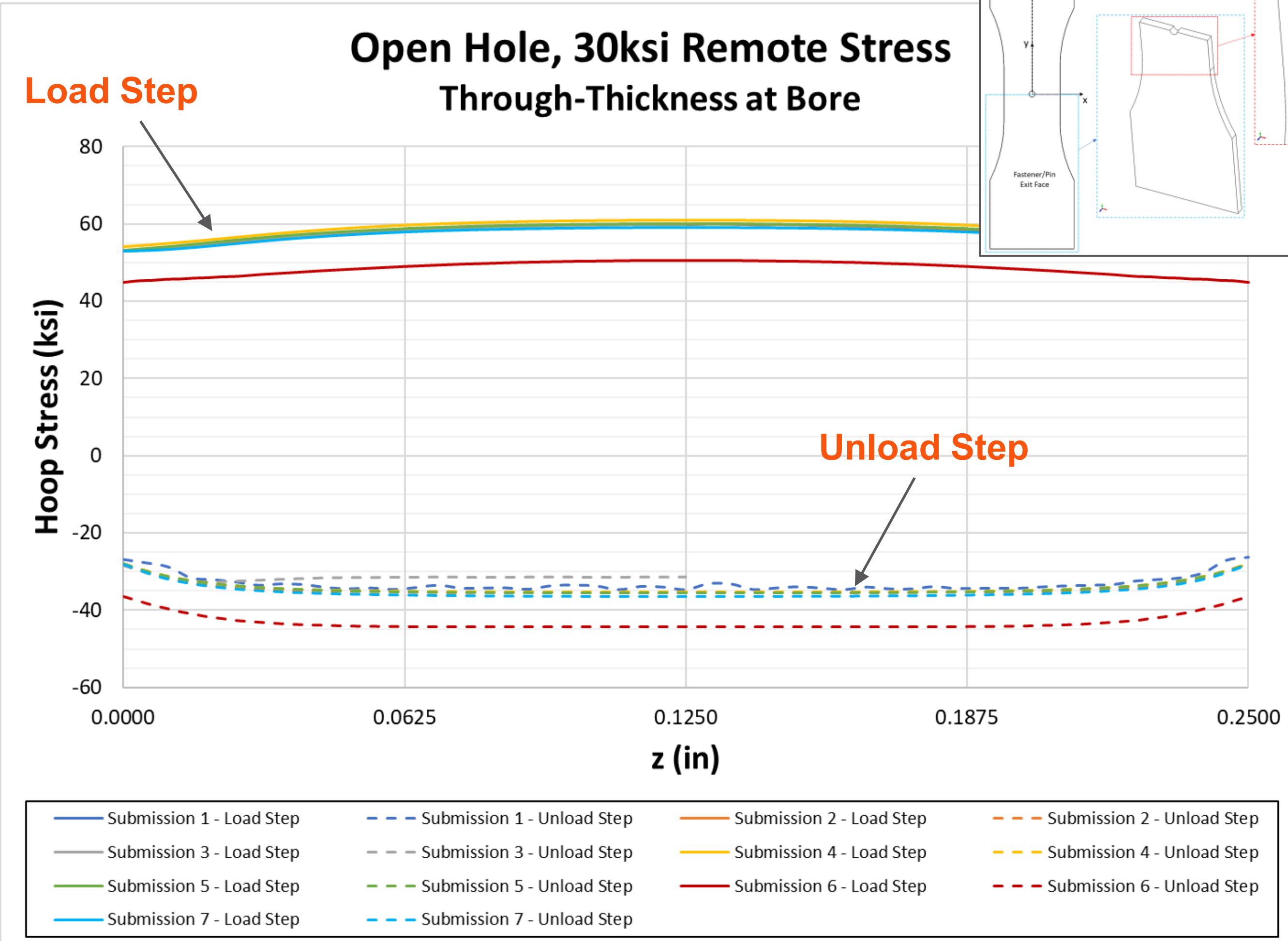
Summary of Results

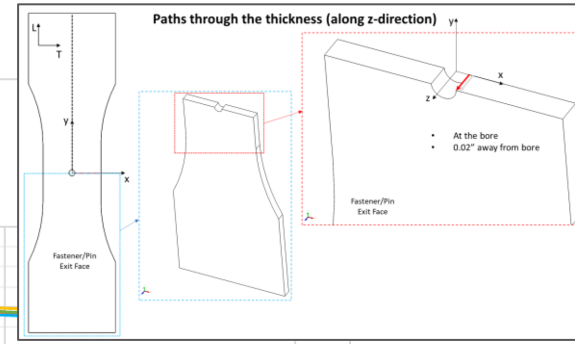




Group 1 – Open Hole Results

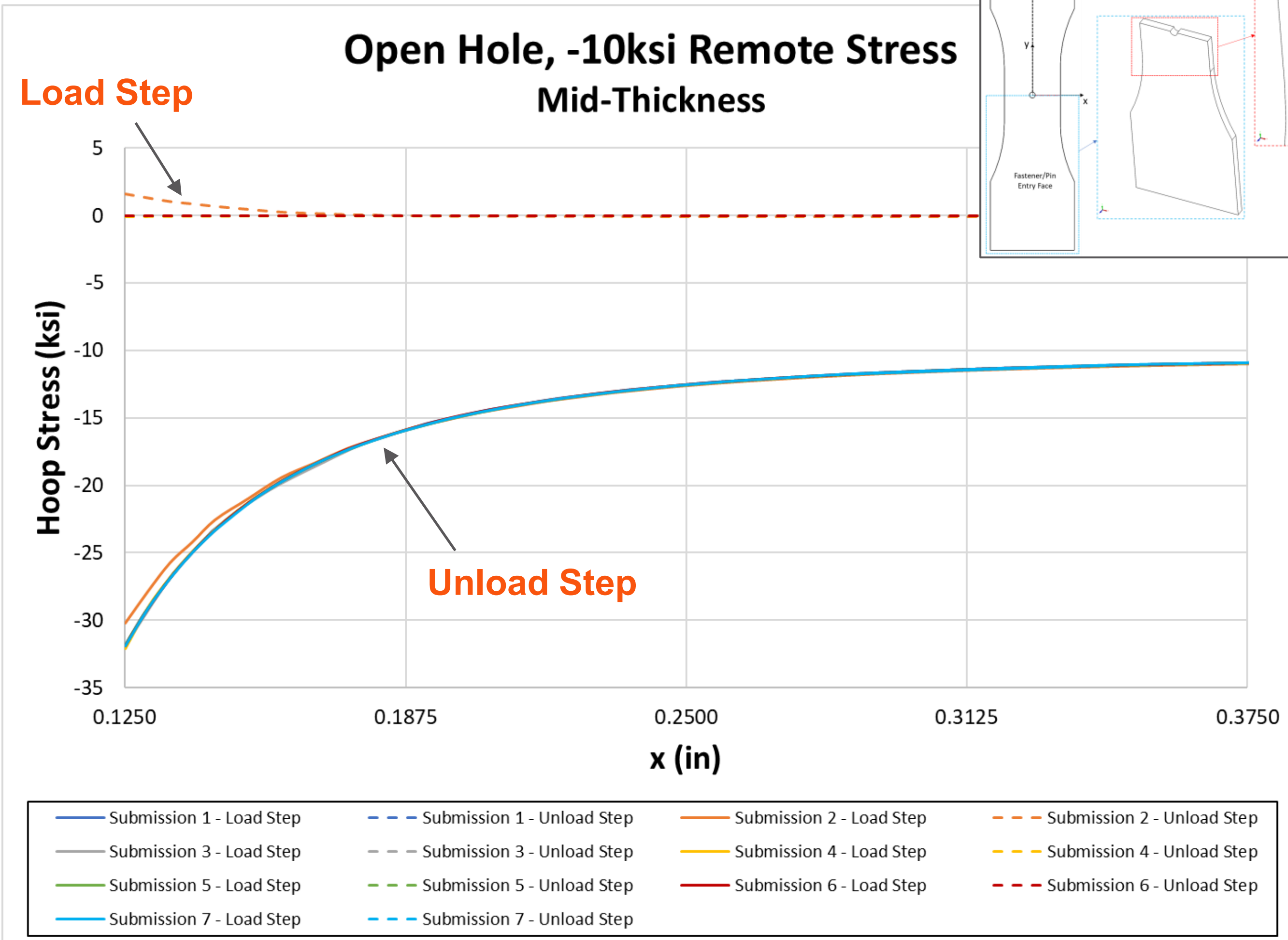
Summary of Results

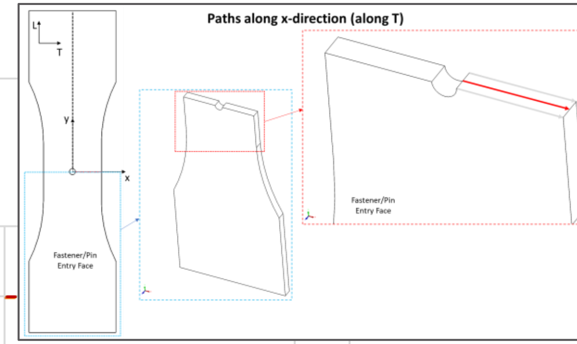




Group 1 – Open Hole Results

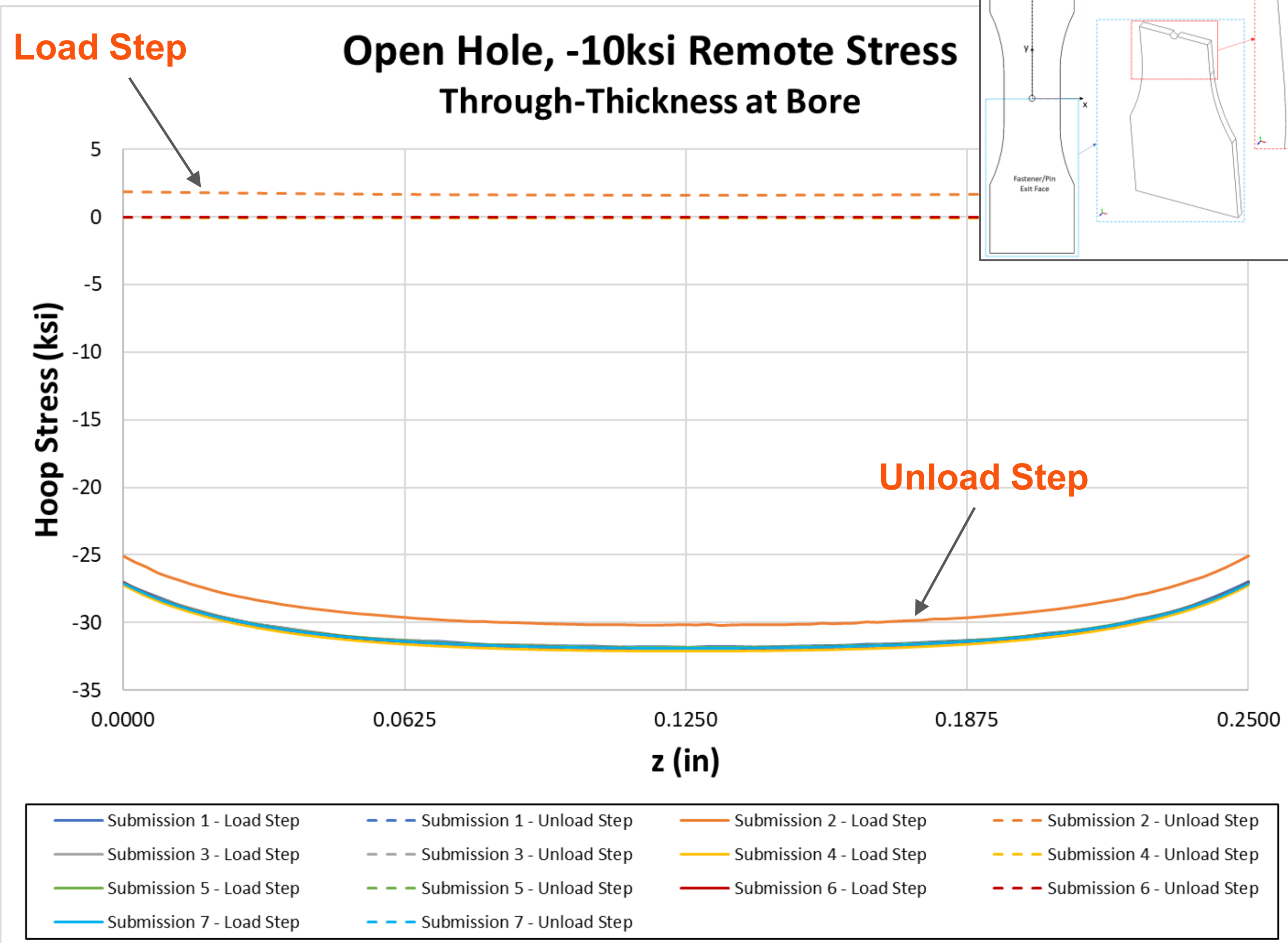
Summary of Results

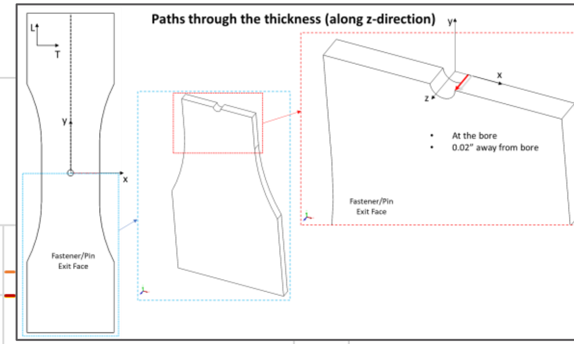




Group 1 – Open Hole Results

Summary of Results





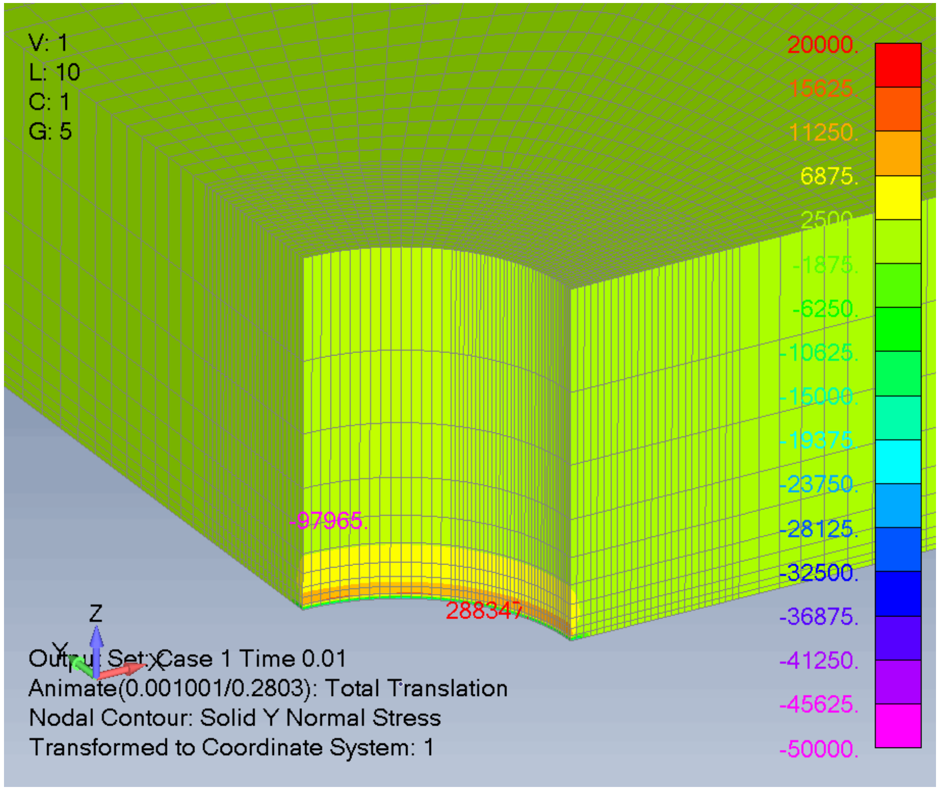
Group 2 – Fastener Install and Removal Results

Summary of Submissions

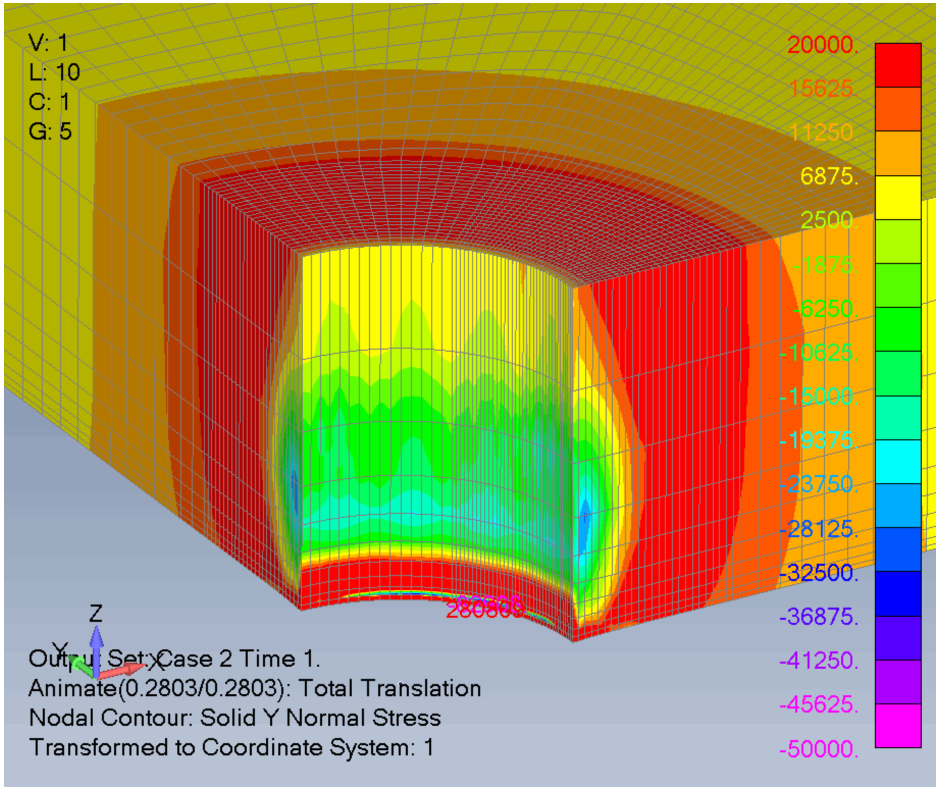
Sub ID	Analysis Software	General Setup	Boundary Conditions: Constraints	Boundary Conditions: IFF Modeling	Material Model
1	Ansys 2021 R2 w/ SimModeler Mesher	Full geometry model	Constrained grip surfaces both sides, top and bottom, ux=uz=0 Constrained grip surfaces, both sides, bottom end, uy=0	A cylindrical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

Group 2 – Fastener Install and Removal Results

Summary of Submissions



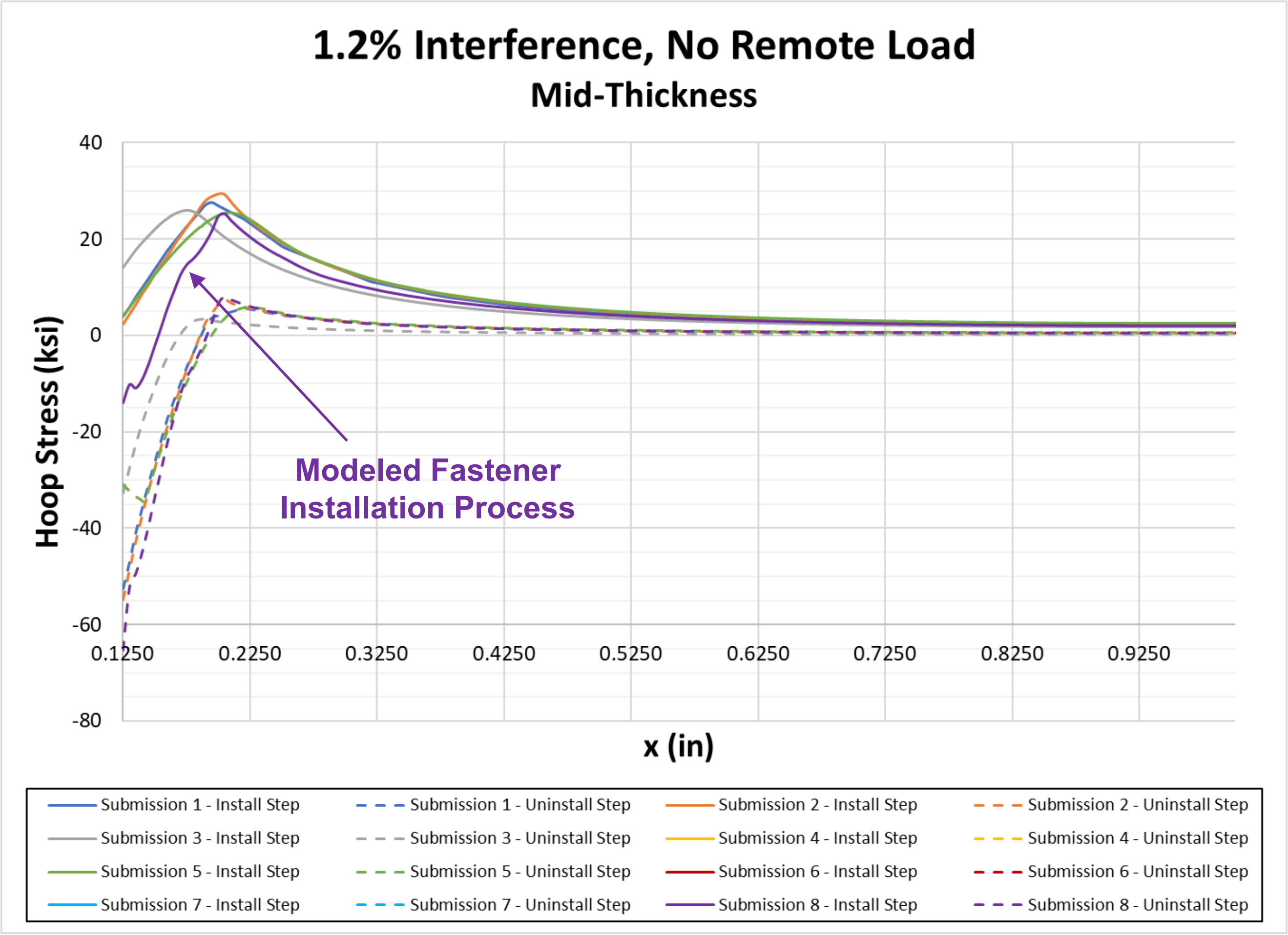
Pin Inserted



Pin Removed

Group 2 – Fastener Install and Removal Results

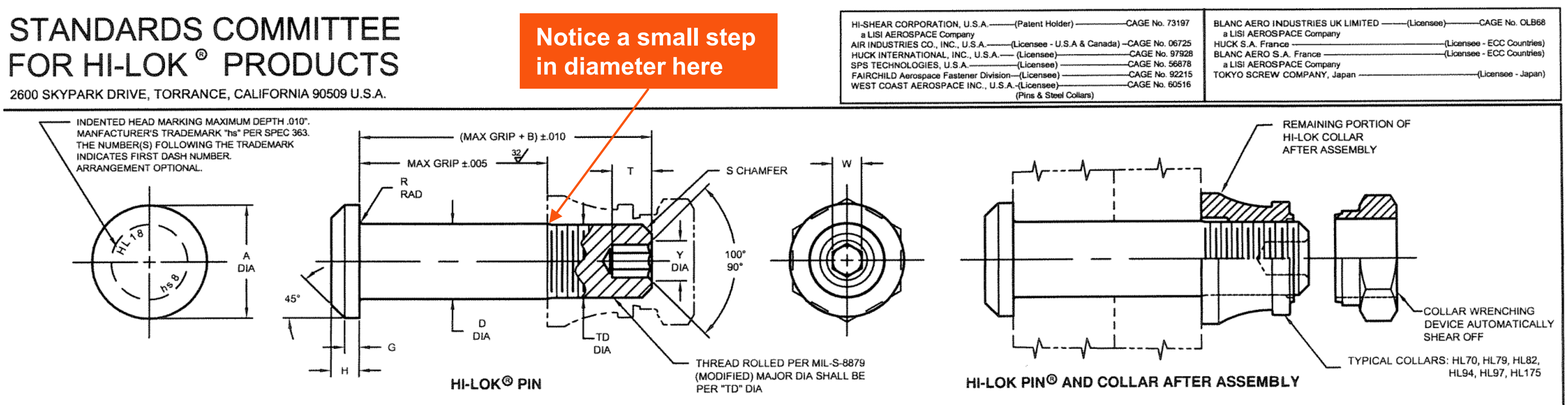
Summary of Results



Fastener Geometry and Installation

Fasteners have a transition region

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

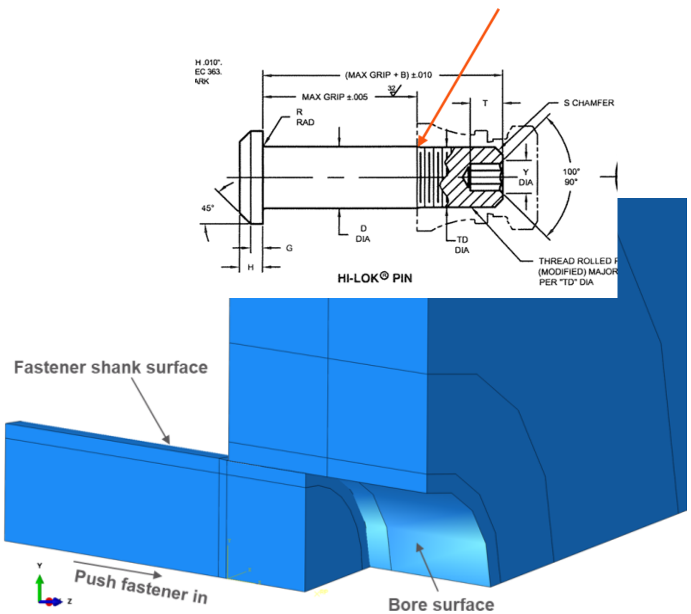


http://www.jet-tek.com/hi-lok-pins/hl18.pdf

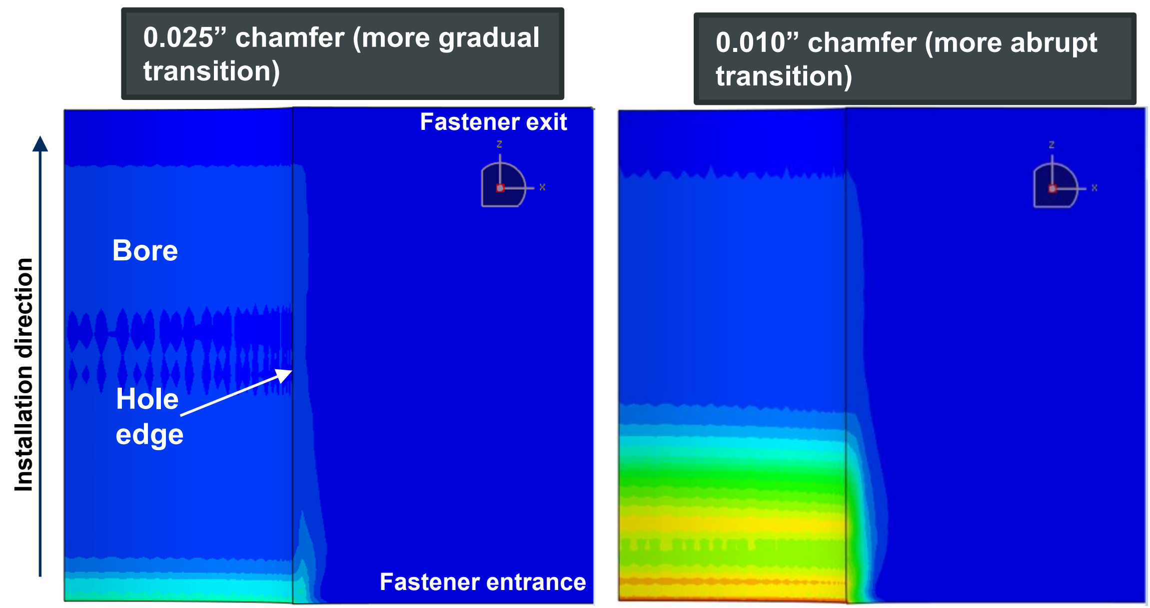
Fastener Geometry and Installation

FE modeling shows a significant influence of the chamfer geometry

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



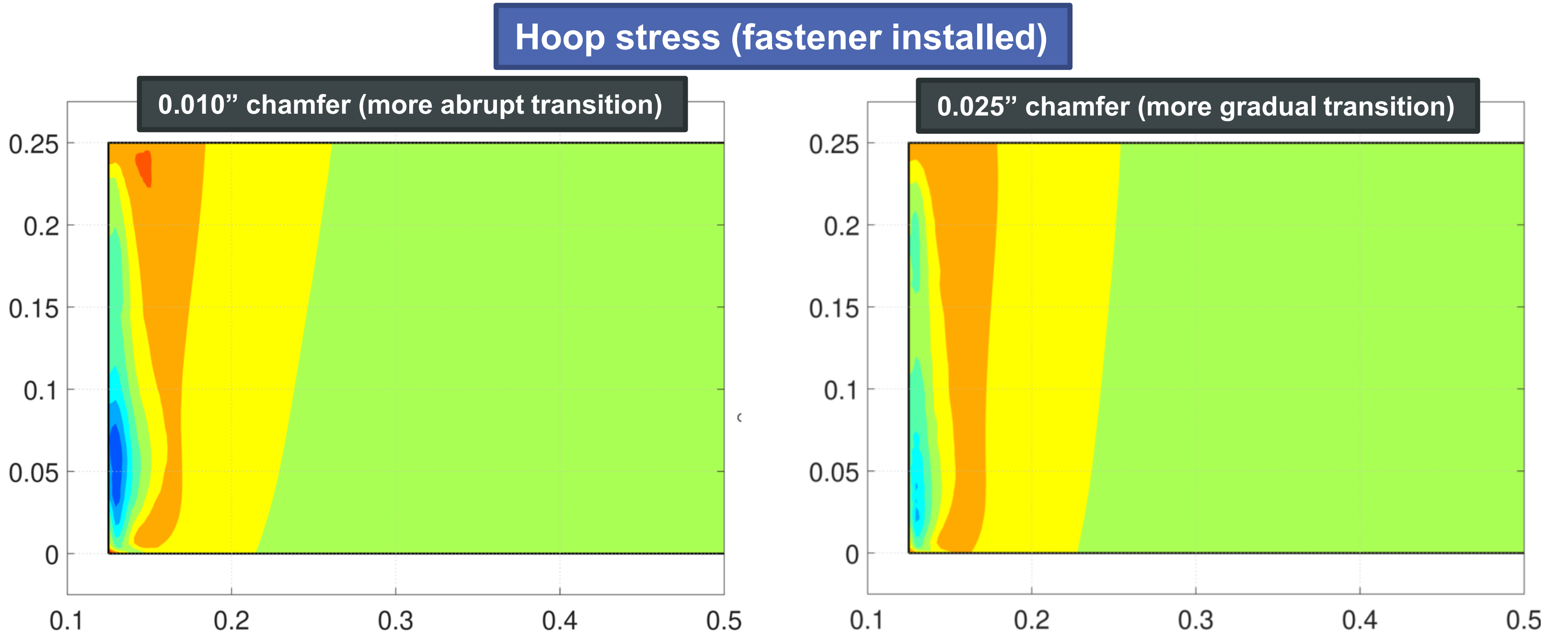
Equivalent plastic strain (PEEQ)



Fastener Geometry and Installation

FE modeling shows a significant influence of the chamfer geometry

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



Fastener Geometry and Installation

3D scanned Hi-Lok fasteners

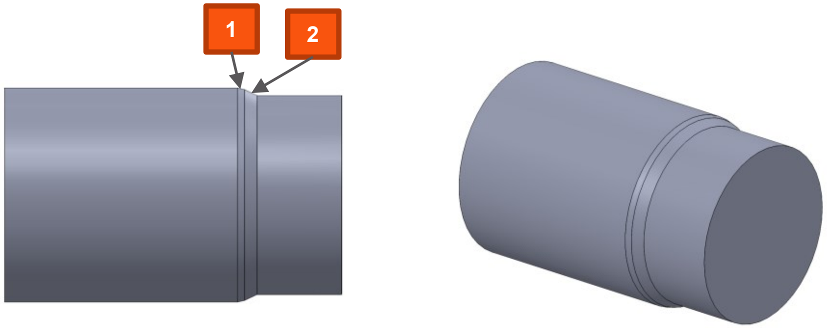
- 4 0.25” fasteners (HL18PB8-6)
- 4 0.50” fasteners (H118PB16-6)
- Png images with cross section measurements
- .stl files

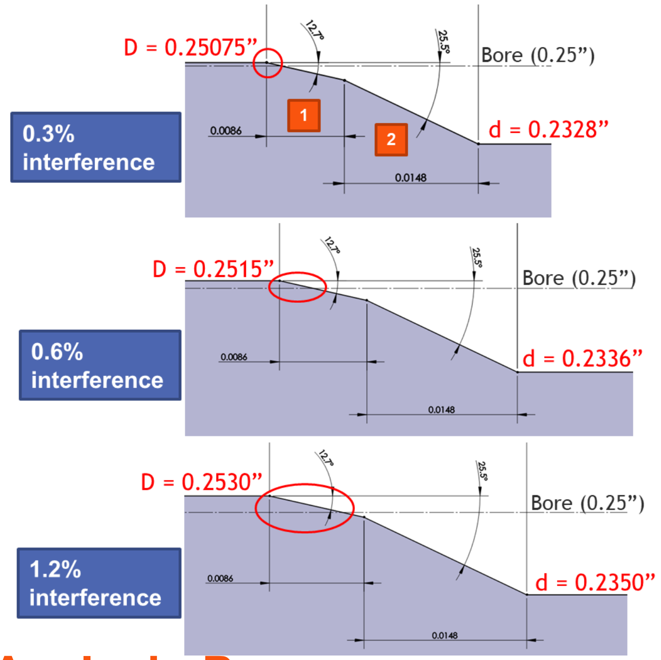
Funded by A-10 IFF Test and Analysis Program

Fastener Geometry and Installation

Pin geometry for each interference level

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





Funded by A-10 IFF Test and Analysis Program

A-10 IFF Testing & Analysis Program

Overview

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

Objective

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

Current Status

- Test plan in progress
  - Currently working on coupon manufacturing

Timeline

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

A-10 IFF Testing & Analysis Program

Phased approach with increasing complexity

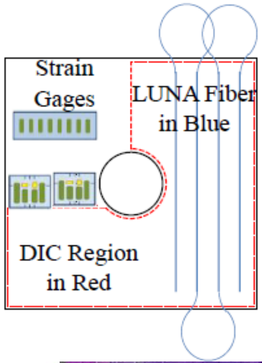
- Phase 1: assessment of as-installed state
  - Simulate and empirically quantify the strain and stress state near a hole in the presence of an interference fit fastener
    - 3 levels of interference
    - 3D nonlinear FE process modeling; DIC and strain gages for surface strain measurements
- Phase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

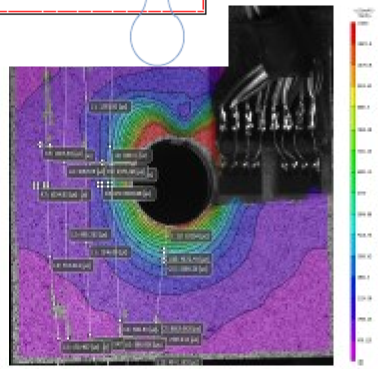
Parameter	Levels
Coupon material	2024-T351 plate
Pin material	52100 steel pin
Coupon thickness	0.25 inch
Nominal hole size	0.25 inch
Interference conditions	Open hole
	Neat fit
	0.3% interference
	0.6% interference
	1.2% interference
Strain monitoring	DIC (all specimens)
	Strain gage (initial specimen)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

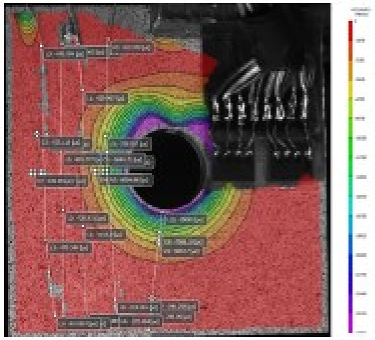
A-10 IFF Testing & Analysis Program

Verification Tests

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







Summary

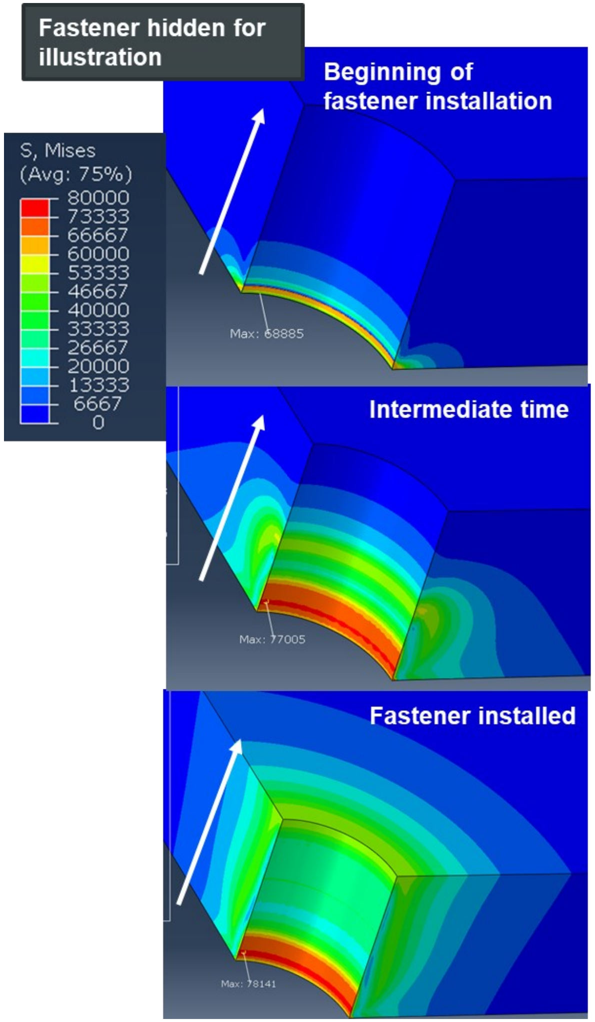
Complimentary efforts

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

Phased building block approach

Results

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



Working Group on
Engineered Residual
Stress Implementation

Residual Stress Measurement Committee Annual Summary

20 April 2023

(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 and Goals
- Monthly Meeting Framework
- Roster and Attendance

Update on Current Projects

- 2inch Cx Residual Stress Determination for Process Simulation Validation (Presenter: Dr. Scott Carlson, Lockheed Martin)
- Bulk RS Measurements in Cx Geometrically Large Holes (Presenter: Dr. Mike Hill, UC Davis)
- Texture and Anisotropy Sub-Team (Presenter: Mr. Josh Ward, UDRI)

Summary and Future Opportunities

Mission Statement

ERSI – RSM Committee has experts in a wide range of residual stress measurement techniques that are available to help ERSI stakeholders (e.g., end users and aircraft programs) design and implement fit-to-purpose residual stress measurement efforts

Established group of residual stress measurement professionals available to review, define, engage, and/or document:

- 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)
- UQ/Statistical methods relative to residual stress data (connect to inter-method as well as model-measurement)

Committee Goals - 2022

- Support the drafting of the Air Force Structures Bulletin, “Analytical Methods, Validation Testing, and Process Compliance Record Requirements for Explicit Utilization of Residual Stresses at Cold Expanded Fastener Holes in the Damage Tolerance Analysis of Metallic Structure”
- Review and provide feedback on the residual stress measurement section of the A-10 Best Practices document
- Assess/Quantify/Define effects of texture and anisotropy on residual stress measurement, document, and seek means to improve
- Develop and document exemplar datasets (leverage prior work and drive new work). Experimental residual stress datasets that have been implemented and published (use of 2x2 Cx hole dataset)

Committee goals for 2023-2024 to be established – see Future Opportunites

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 contract Burba or DeWald if you would like to attend

Typical Meeting Agenda

Other ERSI Committee Updates

- Process Modeling Committee Update (DeWald)
- Risk Committee update (Ocampo)

Measurement Committee Projects & Updates

- 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

Roster and Attendance

✓	Jeferson	Araújo de Oliveira	StressMap - Director	44 (0) 1908 653 452	Jeferson.Oliveira@stressmap.co.uk
✓	David	Backman	National Research Council Canada / Government of Canada	(613) 993-4817	david.backman@nrc-cnrc.gc.ca
	Ana	Barrientos Sepulveda	Northrup Grumman Aerospace Systems	321-361-2049	Ana.BarrientosSepulveda@ngc.com
	John	Bourchard	Professor of Materials Engineering Open University - Director of StressMap	44(0)7884 261484	john.bouchard@open.ac.uk
	Michael	Brauss	Proto Manufacturing Inc.	(734) 946-0974	mbrauss@protoxrd.com
✓	Dave	Breuer	Curtiss-Wright, Surface Technologies Division	(262) 893-3875	Dave.breuer@cwst.com
✓	Eric	Burba	U.S. Air Force (AFRL - RXC - Materials & Manufacturing Directorate)	(937) 255-9795	Micheal.Burba.1@us.af.mil
✓	Scott	Carlson	Lockheed Martin Aero (F-35 Service Life Analysis Group)	(801) 695-7139	SCarlson01@gmail.com
	James	Castle	The Boeing Company (Associate Technical Fellow BR&T Metals and Ceramics)	(314) 563-5007	james.b.castle@boeing.com
	David	Denman	Fulcrum Engineering, LLC. (President & Chief Engineer)	(817) 917-6202	david@fulcrumengineers.com
✓	Adrian	DeWald	Hill Engineering, LLC	(916) 635-5706	atdewald@hill-engineering.com
	Daniele	Fanteria	Dipartimento di Ingegneria Civile e Industriale	(+)39.050.2217266	daniele.fanteria@unipi.it
✓	Mike	Hill	Hill Engineering, LLC	(530) 754-6178	mrhill@hill-engineering.com
	Laura	Hunt	Southwest Research Institute (SwRI)		laura.hunt@swri.org
	Andrew	Jones	U.S. Air Force (B-52 ASIP Structures Engineer)		andrew.jones.79@us.af.mil
✓	Eric	Lindgren	U.S. Air Force (AFRL - Materials and Manufacturing Directorate)	(937) 255-6994	Eric.Lindgren@us.af.mil
✓	Marcias	Martinez	Clarkson University (Department of Mechanical & Aeronautical Engineering)	(315) 268-3875	mmartine@clarkson.edu
	Teresa	Moran	Southwest Research Institue (SwRI)	(801) 777-0518	teresa.moran@swri.org
✓	Mark	Obstalecki	U.S. Air Force (AFRL - RXCM)	(937) 255-1351	mark.obstalecki@us.af.mil
✓	Juan	Ocampo	St. Mary's University		jocampo@stmarytx.edu
	Robert	Pilarczyk	Hill Engineering, LLC	(801) 391-2682	rtpilarczyk@hill-engineering.com
✓	James	Pineault	Proto Manufacturing Inc.	(313) 965-2900	xrdlab@protoxrd.com
	Mike	Reedy	U.S. Navy (NAVAIR - Compression Systems Engineer)	(301) 757-0486	michael.w.reedy1@navy.mil
	Steven	Reif	AFLCMC/EZFS	937-656-9927	steven.reif@us.af.mil
✓	TJ	Spradlin	U.S. Air Force (AFRL - Aerospace Systems Directorate)	(937) 656-8813	thomas.spradlin.1@us.af.mil
✓	Marcus	Stanfield	Southwest Research Institute (SwRI)	(801) 860-3831	marcus.stanfield@swri.org
✓	Mike	Steinzig	Los Alamos National Labs - Weapons Engineering Q17	(505) 667-5772	steinzig@lanl.gov
	Kevin	Walker	QinetiQ	+61457002775	kfwalker@qinetiq.com.au
✓	Josh	Ward	University of Dayton Research Institute (UDRI)		joshua.ward.29.ctr@us.af.mil

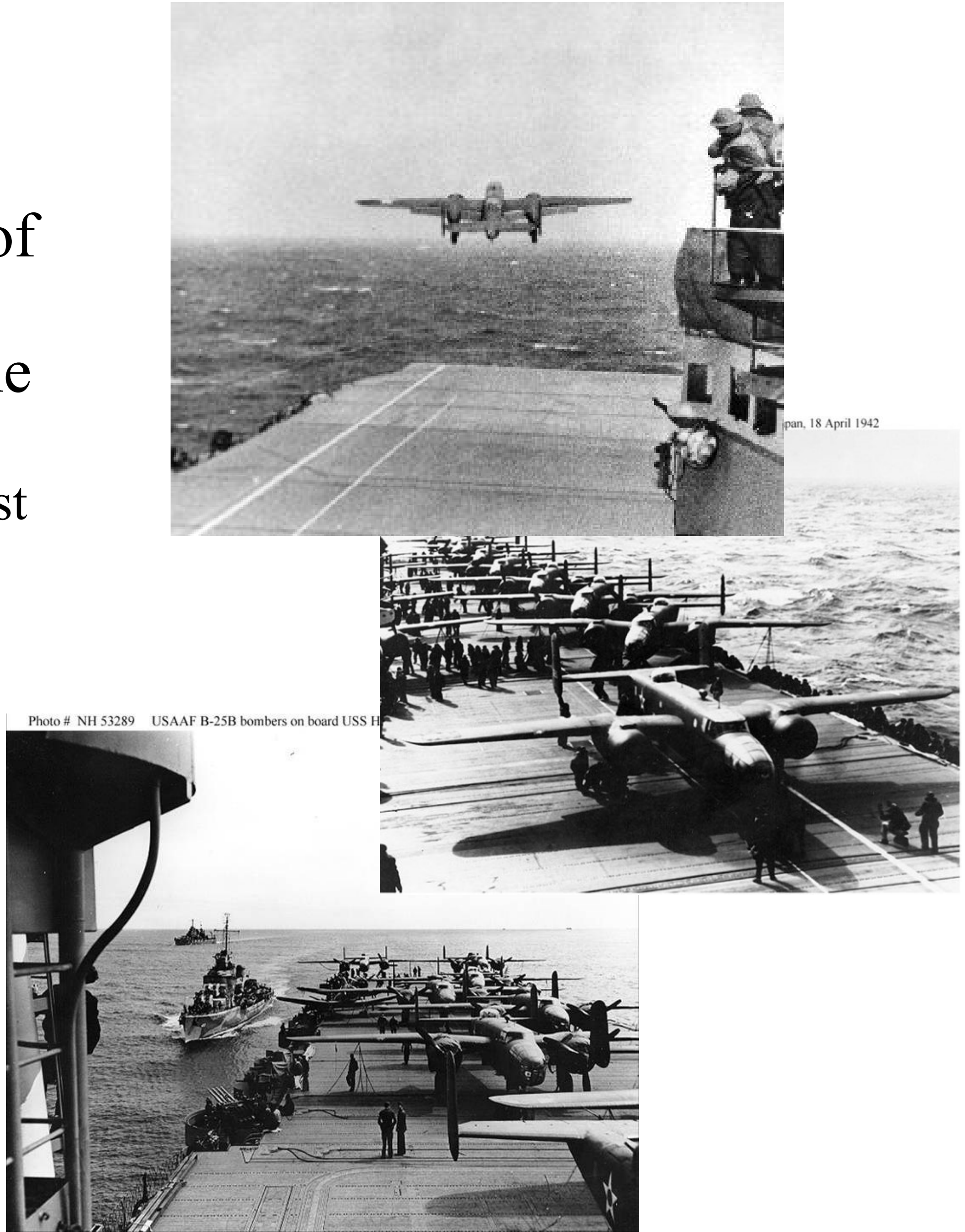
Please contact Burba or DeWald if you would like to be added or removed from this rosters

Residual Stress Determination for Cx Process Simulation Validation

Presented at the 2023 ERSI Workshop – USAF Academy, Colorado Springs, CO USA

A Little Air Force History

- On April 18, 1942 the Doolittle Raiders Took off from the USS Hornet
  - 16 B-25s were deployed to the USS Hornet
  - Raider 1 (Jimmy Doolittle's airplane) had only 467ft. of deck to take off on
  - All 16 Doolittle Raiders left Japanese air space after the bombing
    - 13 aircrews crash landed or bailed out along the Chinese coast
    - 1 aircrew landed on neutral Soviet Union soil
    - 2 aircrews were captured by the Japanese
      - Of the 10 aircrew members
        - 2 died in the crash landing
        - 3 were executed by the Japanese
        - 1 died during captivity
        - 4 were liberated in 1945
- Doolittle Raiders Continue to have a Significant Impact on the USAF



2inch Cx Project Overview

- 2024-T351 & 7075-T651 0.25inch Thick Aluminum Plate
  - 0.25inch thick
  - 0.50inch diameter hole
  - 2inch wide

- Coupons Cxed Using Split Sleeve Cold Expansion (SsCx™) Tool Kit to the Max & Min of the Applied Expansion Range per the FTI Spec
  - 3.2% and 4.2%
  - High precision starting hole size
- One Set of Each Condition was Final Reamed for Future Use as a "Standard"
- During the Cx Process Surface Strain Measurements were Taken in "Real-Time"
  - Strain gauges installed – Installed by FTI
  - LUNA Fiber optical strain gauge – Installed and monitored by Clarkson University
  - Digital Image Correlation – Installed and monitored by SwRI

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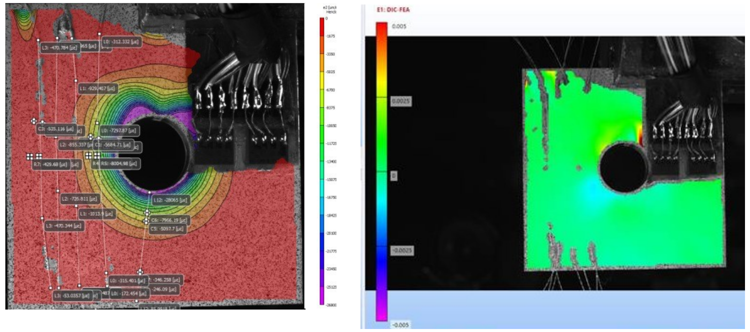
History of Program

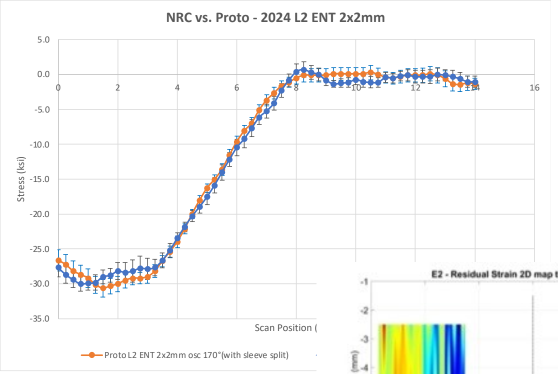
- **No Central Funding Source for all Work**
  - All Work provided at cost to the process/data owning organization – data “owned” by the group that processed the coupons
- 2016 NRC, FTI and SwRI Developed a FEA Round Robin Exercise
  - Goal was to compare state-of-the-art FEA process simulation methods and results
  - Compare results to contour method results
  - Presented at the 1st ERSI Workshop in Ogden Utah, Sept. 2016
- 2017 HOLSIP Dr. Spradlin, Dr. Martinez, Keith Hitchman and Scott Carlson Defined a Cx Process Validation Experimental Coupon Condition
  - Summer of 2017 Dr. Martinez and Marcus Stanfield performed the Cx process on 8 Aluminum coupons
- Fall of 2017 Dr. Spradlin and Carlson Traveled to Argonne NL to Perform ED-XRD on 4 of the 8 Coupons
- 2018 Through Transmission Neutron Diffraction was Performed at Coventry in UK
- Summer of 2018 Dr. Spradlin had 1 7075 Cx Coupon Processed at the CHESS EDXRD Facility
- 2019 Proto and NRC (James Pineault and Dr. David Backman) Performed an Inter-laboratory Round Robin using Surface XRD
- 2020 Neutron Diffraction was Performed on the 2024-Low Cx Coupon at JPAC (Dr. Richard Moat and Dr. Paddea)
- 2021 Neutron Diffraction was Performed on the 2024-High Cx Coupon at JPAC (Dr. Richard Moat and Dr. Paddea)
- 2021 2024-Low Cx Coupon Contour Cut at Stress-Space in UK (Prof. Bouchard)
- 2022 Neutron Diffraction of Both 7075 Cx Coupons at Oakridge National Labs (Payzant, Moat, Bouchard)
- 2023 2024-High Cx Coupon Contour Cut at 2 Difference Orientations at Stress-Space in UK (Prof. Bouchard)
- 2023 Submitted Abstracts for Surface Stress DIC Data for Process Simulation Material Model Validation and XRD Round Robin

Work Completed

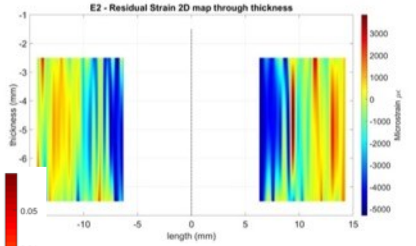
- Surface Strain Measurements During Cx Process ✓
  - Journal paper in draft form for release (focused on 2024-Low Cx level)
  - Utilizing MatchID for FEA-to-DIC comparison

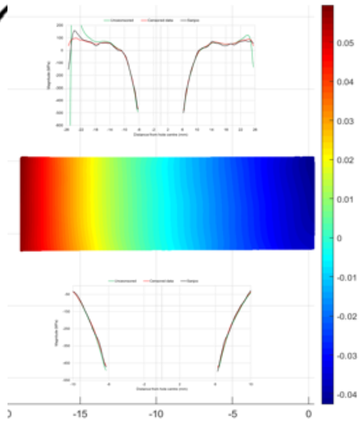


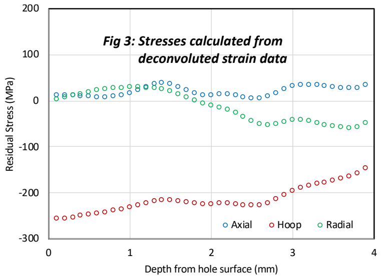
- Surface XRD Inter-Laboratory Comparison and Method Development ✓
  - Journal paper in draft for final review (All configurations presented)



- Through Thickness Measurements
  - Argonne National Lab's Synchrotron (All coupons processed) ✓
  - CHESS Synchrotron (7075 coupons processed – need data) ✓
  - JPARC and Oakridge National Lab's Neutron Diffraction (All coupons will be processed) ✓
  - Stress-Space - Contour Method (All coupons will be processed)
    - 2024 High and Low ✓







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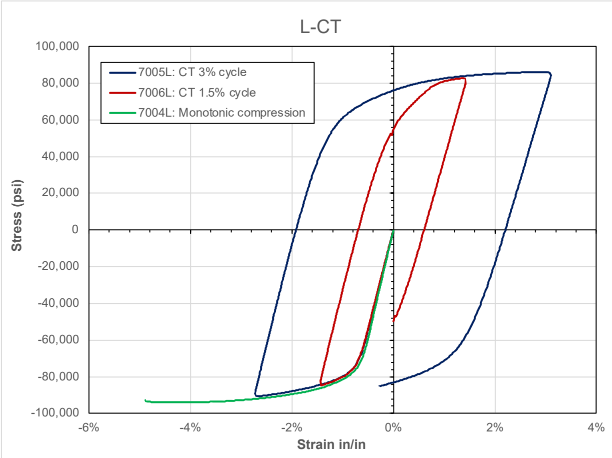
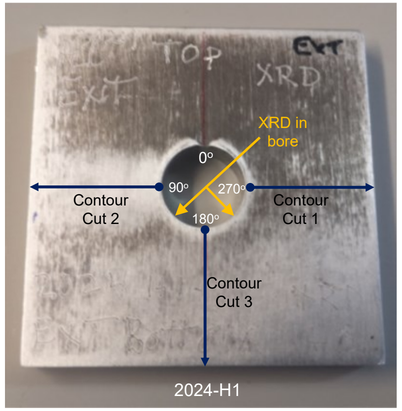
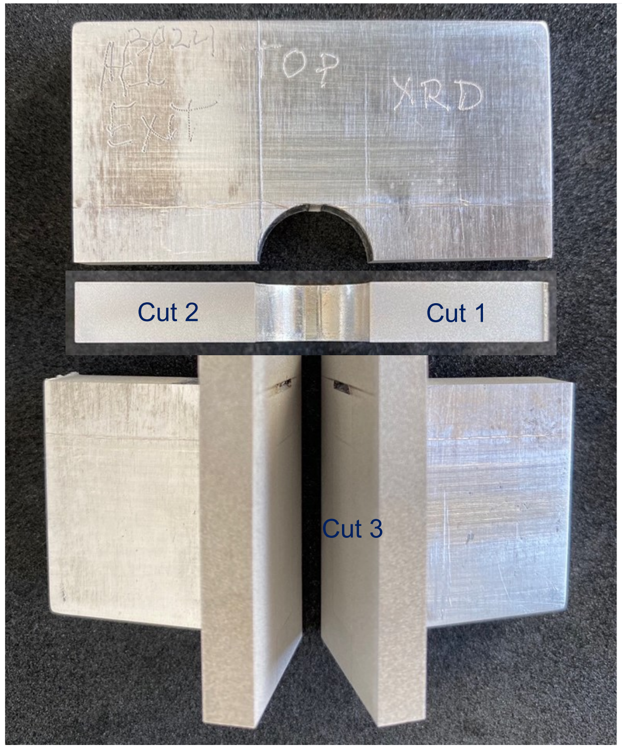
Work In Progress

- Review Plasticity Models for FEA Simulation of Cx Process
  - Combine work from the Process Simulation round robin paper
- Processing of Neutron Diffraction Data for:
  - 2024 “High” expansion
  - Both 7075 coupons
- Contour Method for Both 7075 Cx Coupons
  - Perform FEA for cutting technique
  - Perform multiple cuts on each coupon
- Develop Thru-Thickness Combination of RS Data
  - Surface XRD with Contour and Neutron Diffraction results
- Define Future Requirements for Cutting-Induced Plasticity
  - Effects of edge margin, yield strength and thickness
  - Define which side of the hole has results that are accurate







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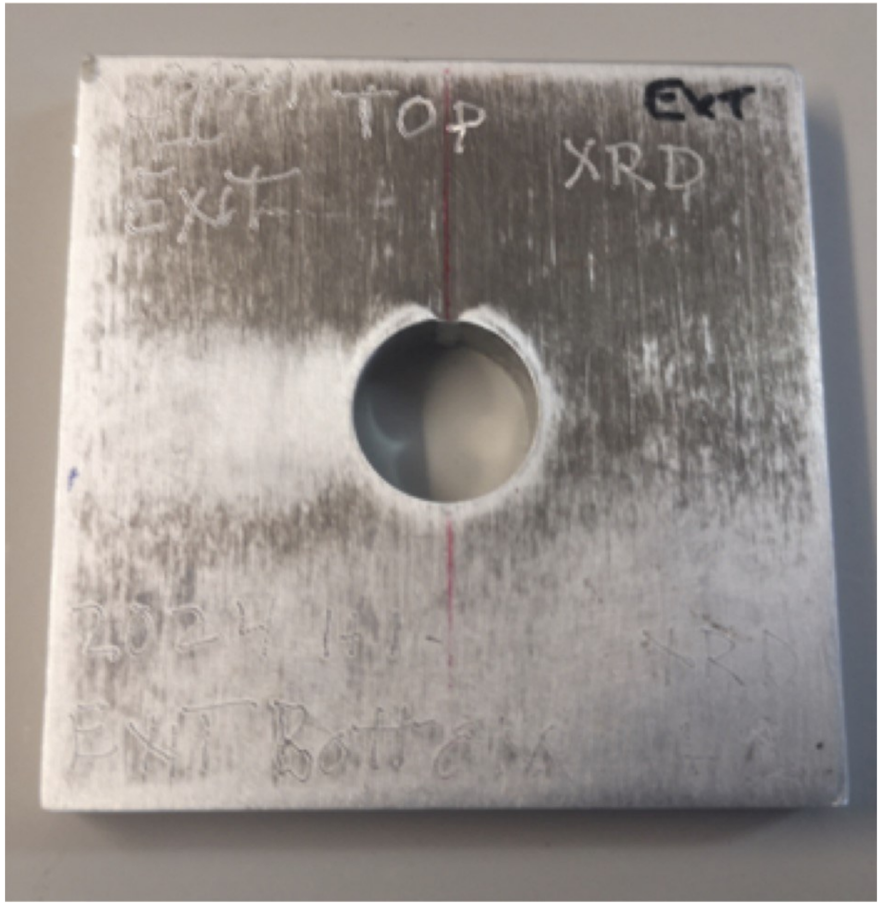
Different Data Sets for Same Case

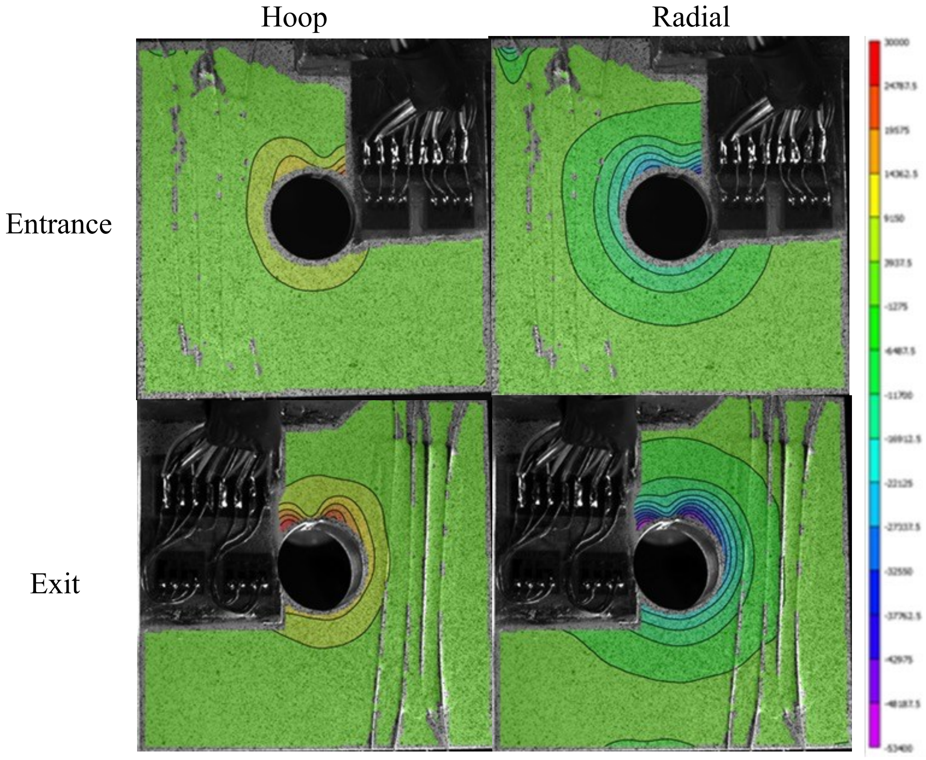
- The 2024-H1 Conditions has Completed all Residual Stress Determination Methods, which Include:
  - Surface DIC
  - Surface XRD
    - Proto & NRC
  - Thru-Thickness Neutron Diff.
    - JPARC
  - Contour Method
    - 2 Planes
  - Hole Drilling for Rolling Stresses
  - XRD into the Hole Bore
- What Do These Data Sets Look Like?
- How Can we Use them for FEA Process Simulation Validation?

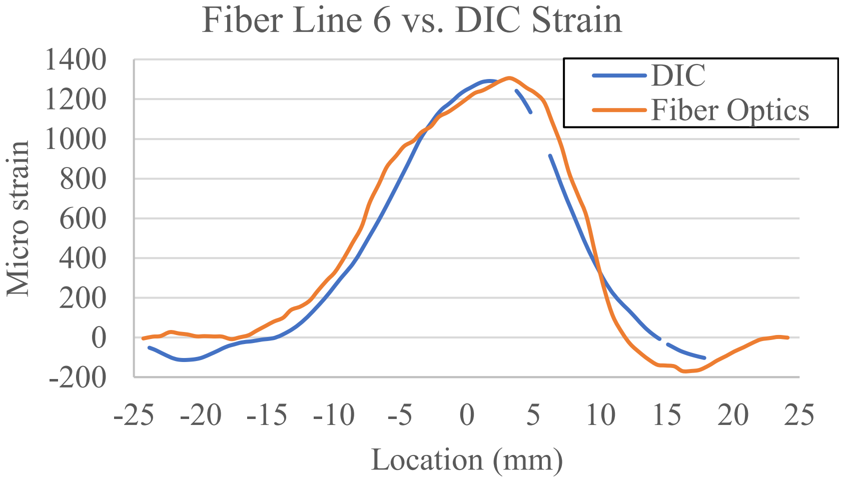


Cx Processing DIC Data vs. Strain Gauge

- During Cx Processing Real-Time DIC, LUNA Fiber Optics and Strain Gauges Captured Full-Field Strains
  - Limited ability to capture strains “at the edge of the hole” due to DIC and Cx processing factors
  - Goal was to validate DIC as the “standard” for surface strain results for FEA validation purposes

Strain Comparison: Gage vs. DIC			
Location	**Gage**	**DIC**	**%Diff**
1	0.003571	0.003573	0.05%
2*	-0.005699	-0.005684	0.26%
3	0.000984	0.000969	1.54%
4	-0.000459	-0.000430	6.43%
*Adjusted for 13.6 degree split rotation			





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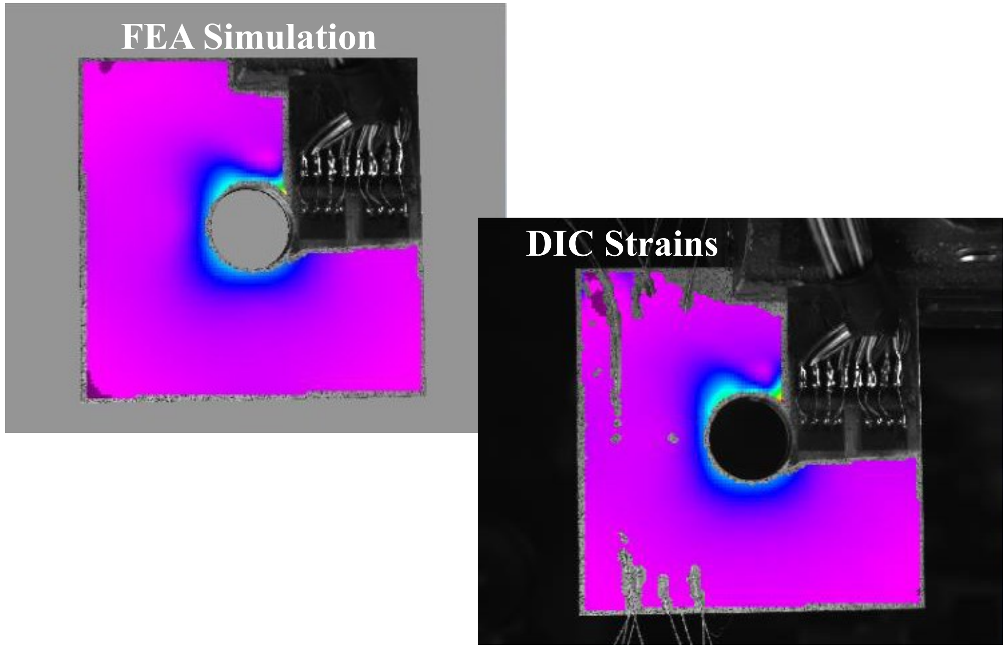
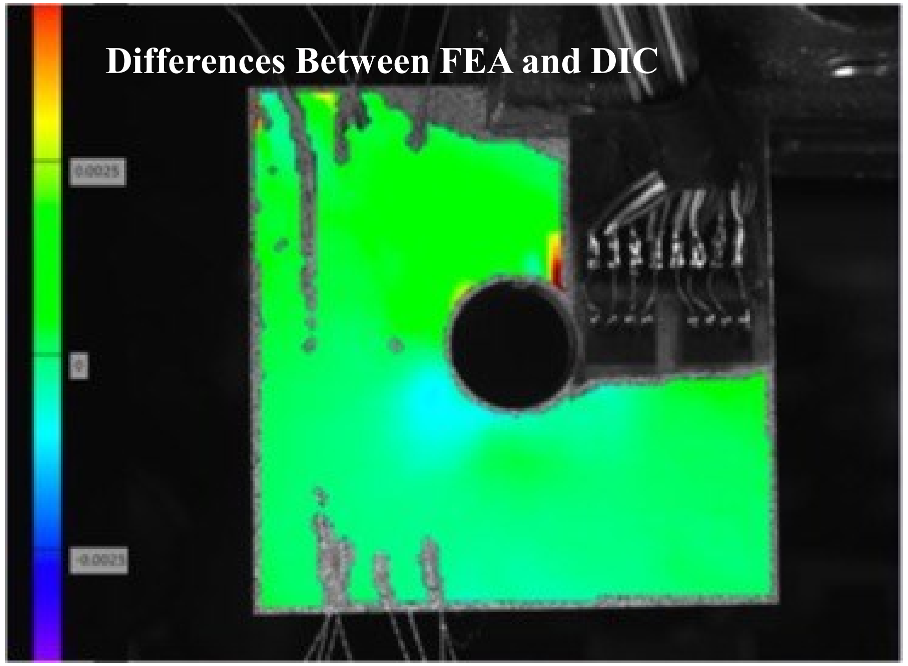
Application of MatchID

- MatchID Allows for the Alignment and Direct Nodal Comparison of DIC Data to FEA Surface Stresses
  - FEA process simulations were performed by FTI using 3 different material models
    - Kinematic
    - Isotropic
    - Combined
  - MatchID was performed at NRC to comparison of DIC strain measurement data to FEA simulations





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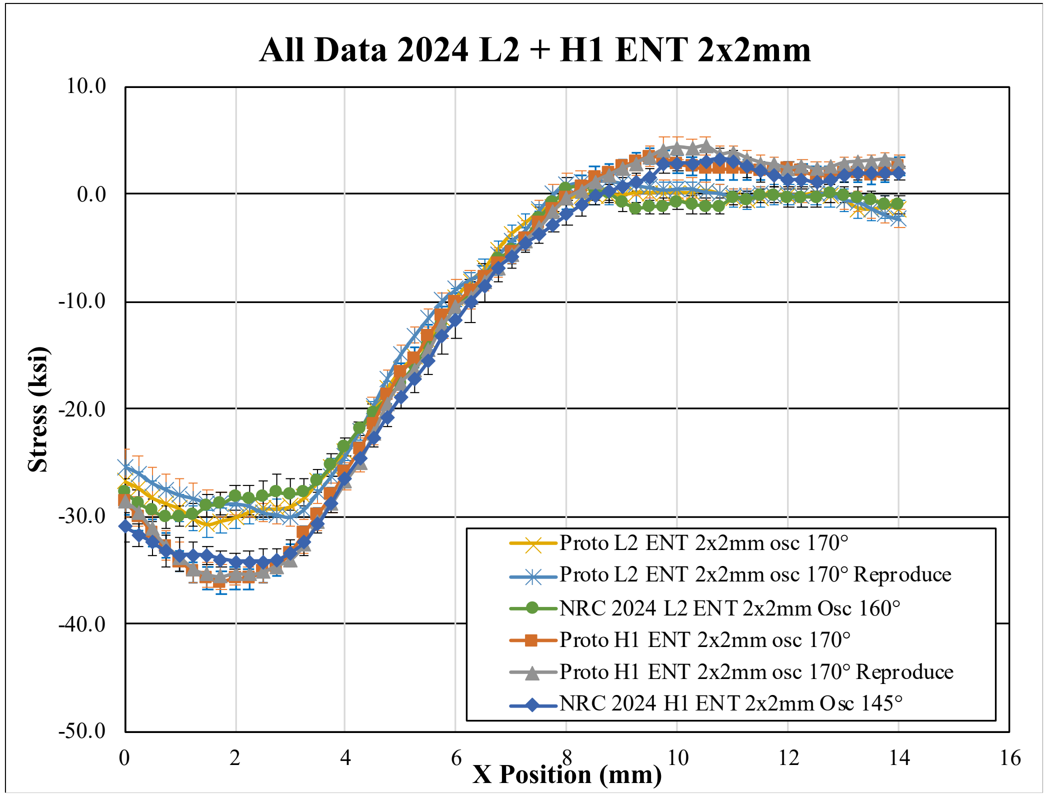
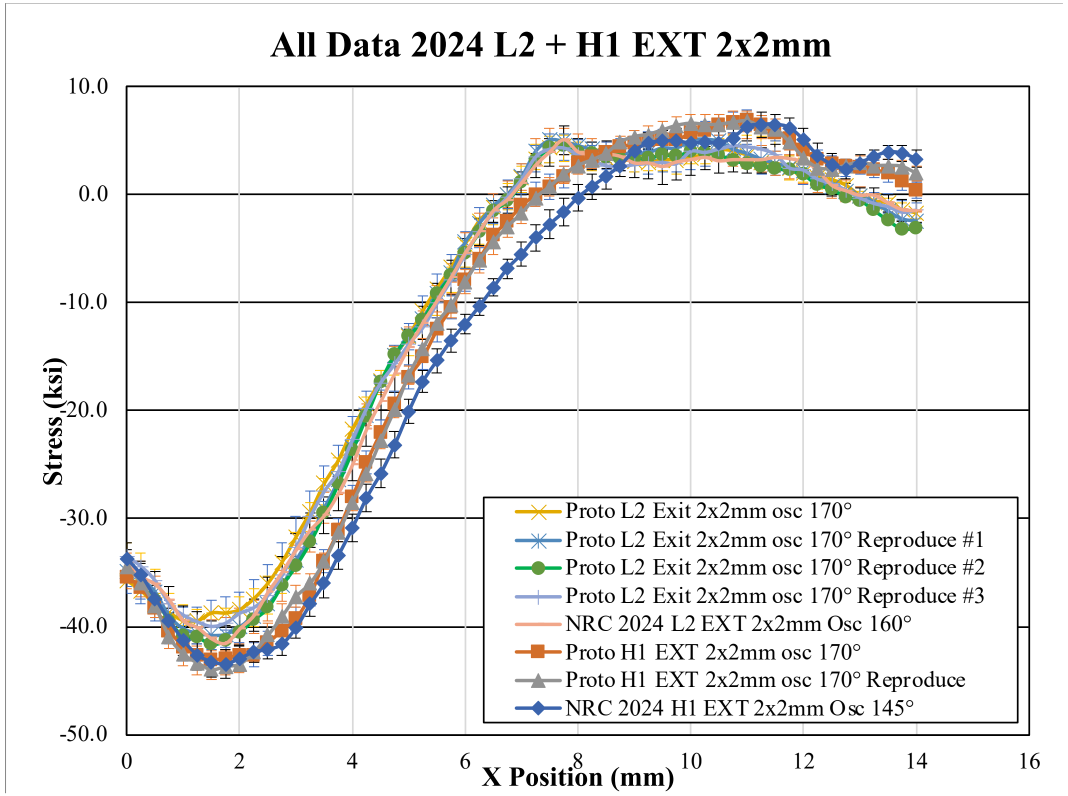
Surface XRD Round Robin Results

- Proto and NRC Performed Independent XRD Experiments on All 2inch Cx Un-Reamed Test Coupons (2024-High & Low + 7075 High & Low)
  - Development of state-of-the-art methodology for more accurate XRD measurements at Cx holes through the rotation of the coupon around the center of the hole
  - Allows for the capture of more grains but within the same stress gradient





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Neutron Diffraction Preliminary Results

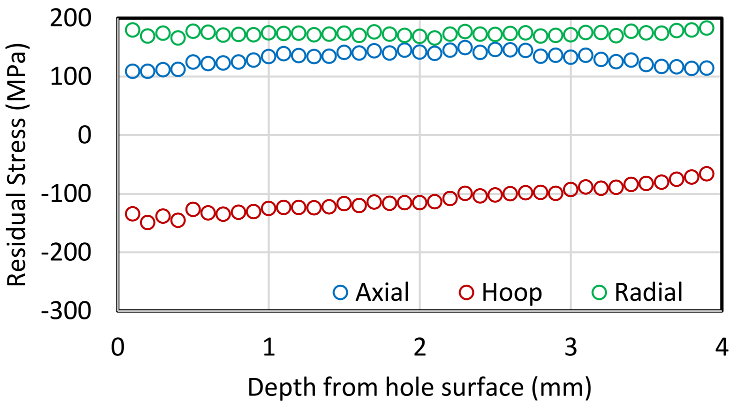
- Dr. Richard Moats Oversaw all Experiments with Deconvolution Data Analysis Approach Being Validated Prior to Application to Cx Data
  - 2024 Coupons at JPARC
  - 7075 Coupons at Oak Ridge NL

Neutron diffraction doesn't have the spatial resolution to reliably resolve much below ~1mm.

Using a step size smaller than the gauge size presents a complex convolution of spatially smoothed stresses and the nonuniform strain response of different regions of the gauge volume.

To deconvolute the raw data collected using a 100μm step size with a 2x2mm gauge size, the following steps are required.

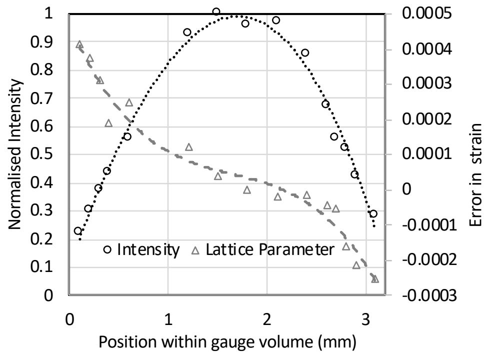
1. Collect lattice strains in 3 orthogonal direction with a step size of 100μm positioned at the centre of the thickness



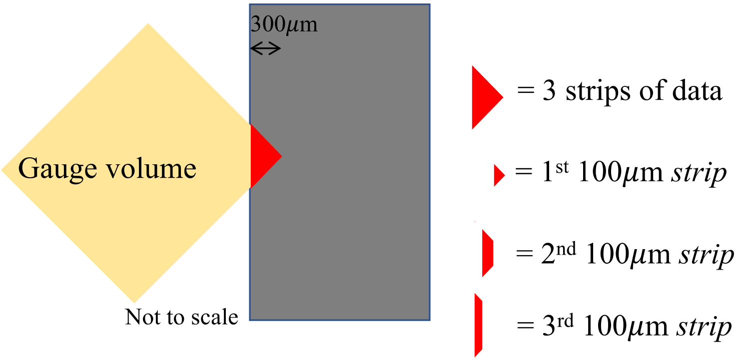
This yields highly smoothed, but clearly incorrect results (radial direction must be close to 0 MPa at the surface)

2. Map the contribution and effective error in strain across the gauge volume by scanning a 100µm thick foil

Fig 2: Intensity & error in lattice strain for 100µm slices of gauge volume



3. For each 100µm slice of gauge volume calculate the contribution & effective shift in strain by fitting polynomials to the above curve



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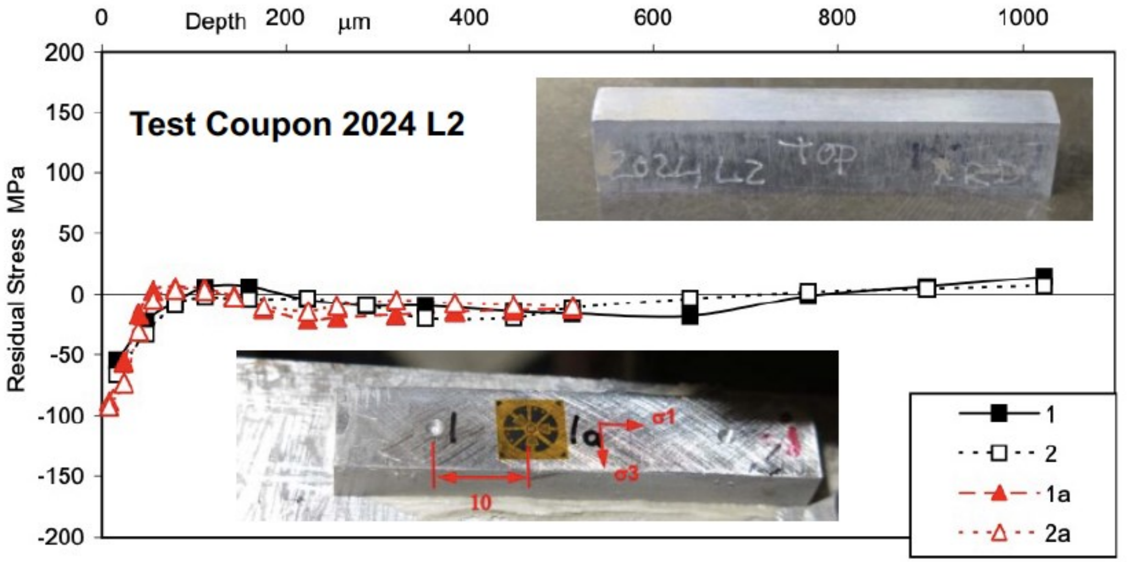
Questions Asked About Rolling Stresses

- Both Materials were Manufactured from Rolled 0.25inch Plate
  - Rolling process introduces compressive residual stresses at the surface
  - Could these impact the accuracy of other residual stress determination methods

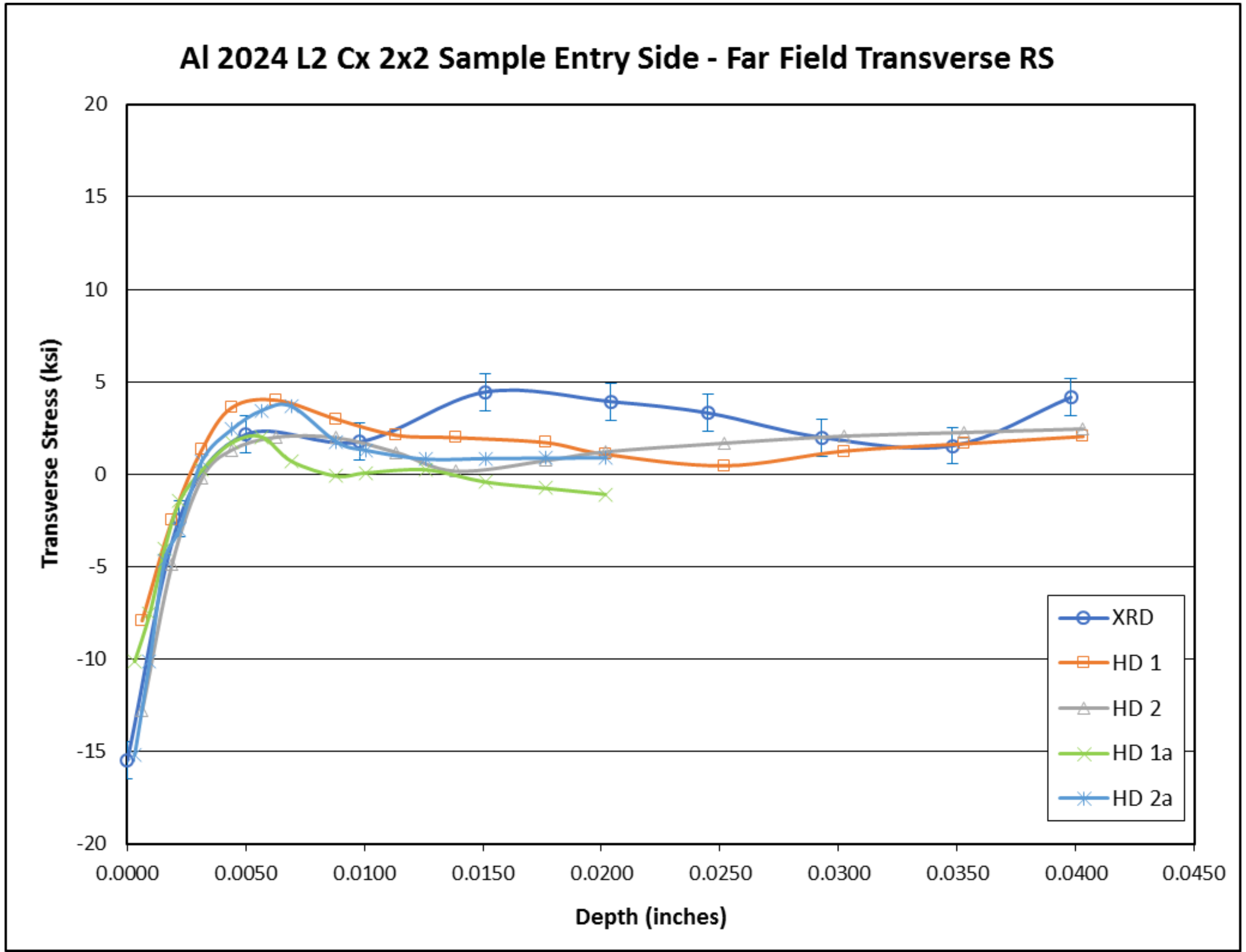


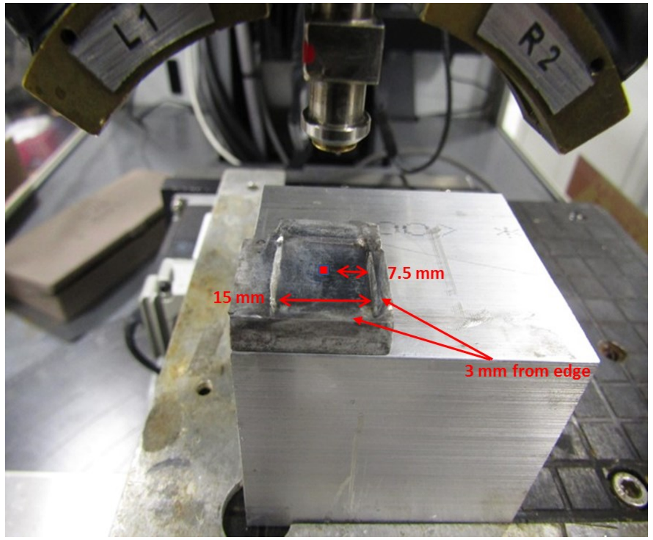
Distributions of longitudinal stresses vs depth

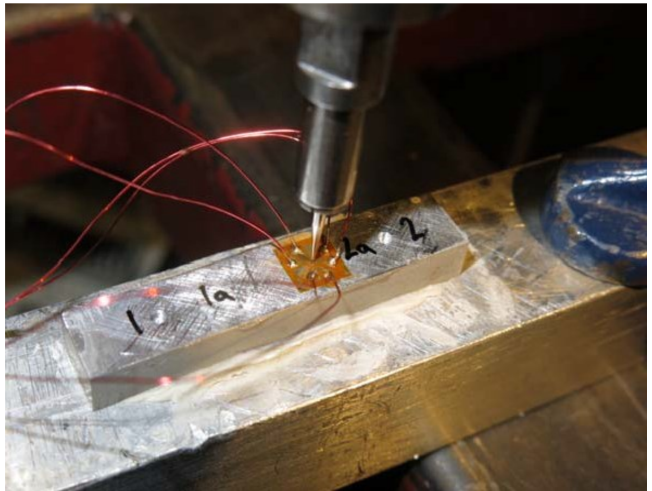
- HD Showed Compressive RS of Approx. -100MPa (-14.5ksi) at the Surface and Fall to 0ksi at Approx. 100 microns (0.004inch)
  - These rolling stresses interact with the Cx process at the surface
  - These stresses may be one reason why XRD and Contour results are different since Contour can't capture these gradients

Rolling Stresses Answered

- Confirmation of Rolling Stresses via XRD
  - Proto performed in-depth XRD via electro-polishing to confirm Holl Drilling results

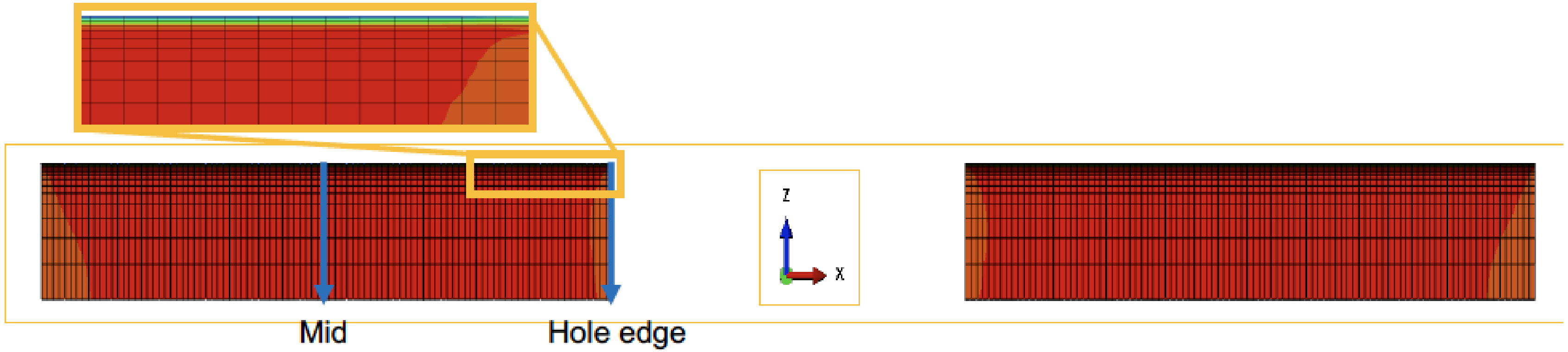


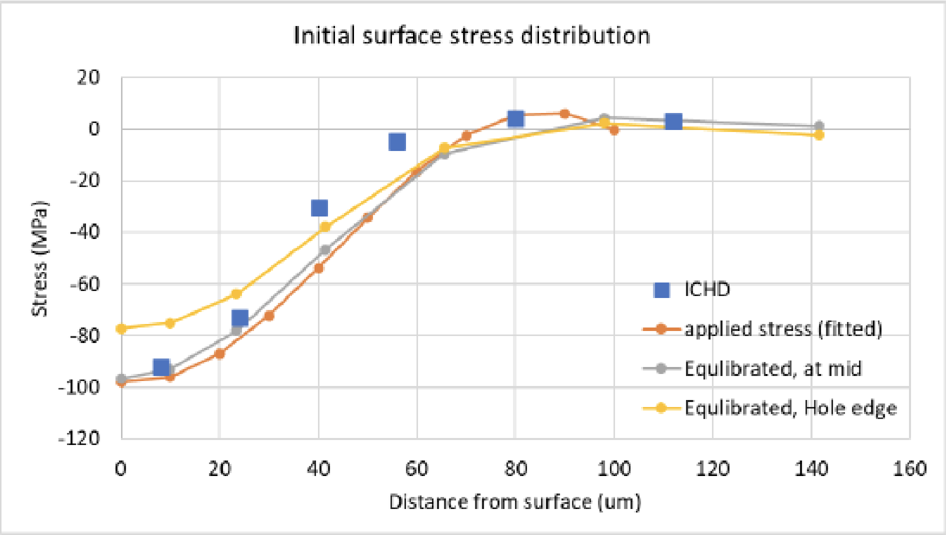




Initial Method for Combining RS Data

- Stress-Space and Open University Developing Methodology for Combining RS Data for the 2024-H1 Condition
  - Surface XRD + HD





- Single bias mesh along the z direction from 0.01 mm at top surface to 0.8 mm at the bottom surface (with applied z symmetry boundary condition)
- The measured stress data were fitted to a function which was applied as an initial stress to a depth of 100 microns from the top surface.
- Then an equilibrium step was applied.

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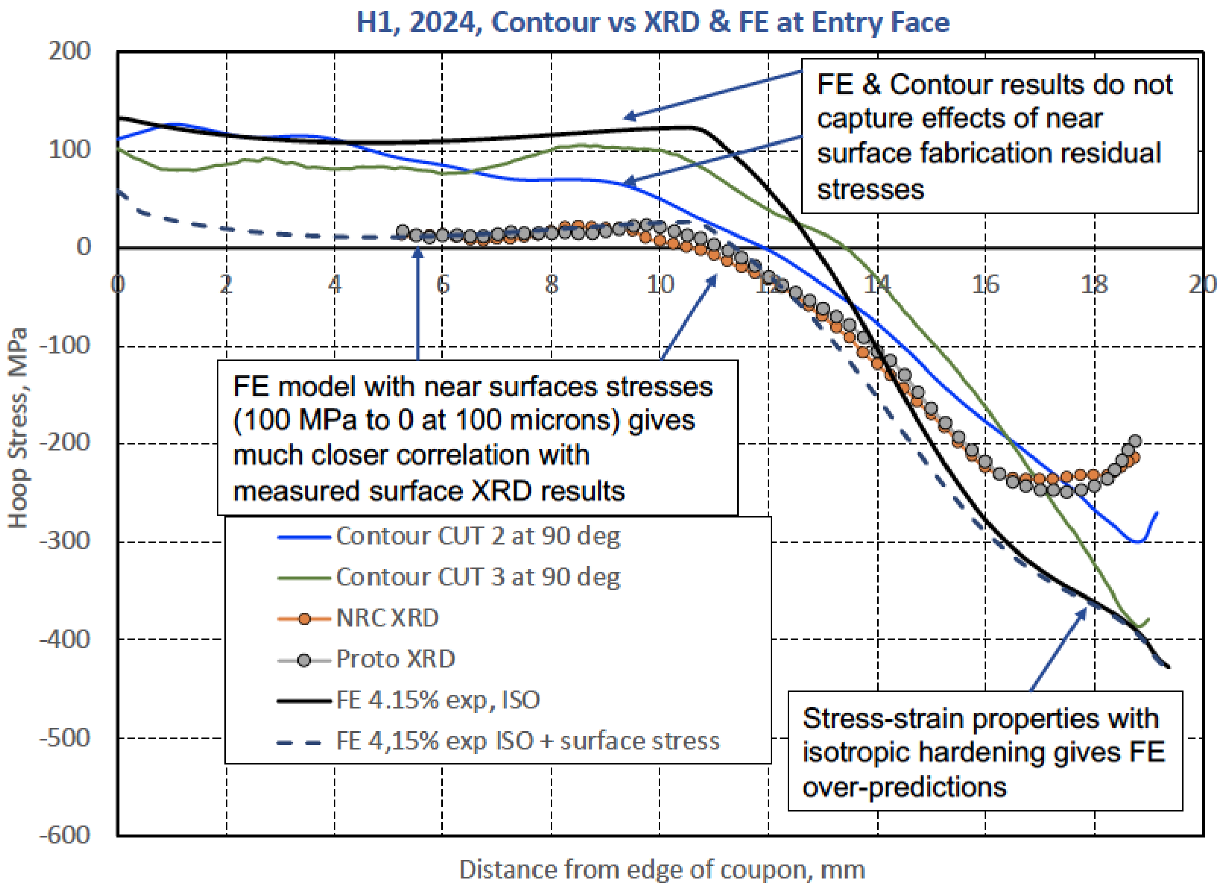
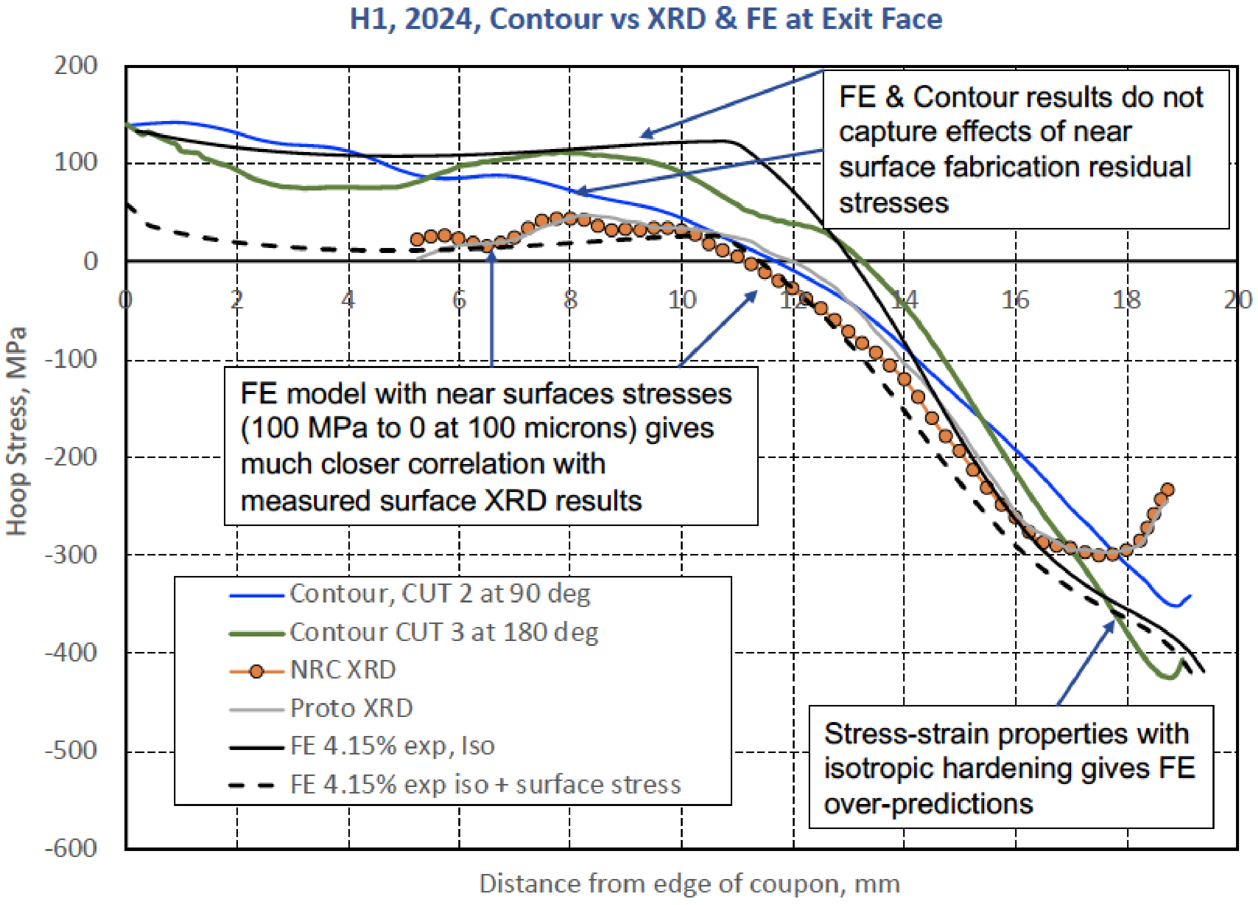
Initial Method for Combining RS Data

- Rough 1st Cut at FEA Process Simulation Validation via Combined RS Data





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Effect of Cutting Sequence for Contour Data

- Learning that Cutting Sequence Can Have Dramatic Influence on Residual Stress State
  - Residual Stress Database used an average of the "Left" and "Right" side of the hole
    - This is likely introducing significant errors into the residual stress data used at the edge of the hole
  - One 1 side of the hole will have "accurate" residual stresses due to cutting induced plasticity at the edge of the hole
- Recommend Performance of a Cutting Induced Plasticity FEA Simulation Prior to Cutting Cx Holes
  - In 7085 and 7050 we have learned that the cutting sequence may need to be changed due to:
    - Edge margin
    - Thickness
    - Material yield strength
- Recommend Review of the Residual Stress Database to Remove Incorrect Data and Perform Averaging Again
  - May need to perform FEA simulation to determine which side is most accurate

Future Work

- Complete and Submit Surface Strain & XRD Round Robin Papers to ASM Mat. Eng. and Processes Special Edition
  - Abstracts were accepted, time to "Band Together"
- Complete Data Processing of Neutron Diffraction Experiments
  - Richard Moats and Prof. Bouchard working through data reduction of all 4 Neutron Diff. data
- Complete Contour Method on 7075 "Low" and "High" Test Coupons
- Develop Journal Papers on Through-Thickness Comparisons
  - Neutron vs. Contour
- Develop Method for Coupling Residual Stress Methods for Near-Surface and Away-from-Surface Stress Fields
  - Potential to use Neutron or XRD data near the bore of the hole and Contour data away from the hole

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Questions??


Carlson Fam 2016


Carlson Fam 2023

Not Sure Which Looks More Tired

What happens after 6 years of work and:

- Traveling to 4 Countries
- Being Shot with High Energy X-rays (ED-XRD)
- Surface X-rays (XRD)
- Neutrons (Neutron Diff)
- Sectioned with a Wire EDM, 3 times (Contour)
- Electro-Polished and Shot with X-rays in the hole (XRD)

ERSI

Working Group on
Engineered Residual
Stress Implementation

Bulk RS Measurements in Cx Geometrically Large Holes

Presenter: Dr. Mike Hill, UC Davis

Mechanical and Aerospace Engineering
University of California, Davis

Determination of Residual Stress and Strain Fields During Cold Expansion Processing Using Complementary Diffraction Techniques

Nicholas A. Bachus, Donald W. Brown, Chris Budrow, Micheal E. Burba, Bjørn Clausen, Adrian T. DeWald, J.Y. Peter Ko, Kelly E. Nygren, Mark Obstalecki, Robert T. Pilaczyk, Renan L. Ribeiro, Paul A. Shade, Matthew Shultz, Michael R. Hill

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Challenge with Air Force Legacy Aircraft

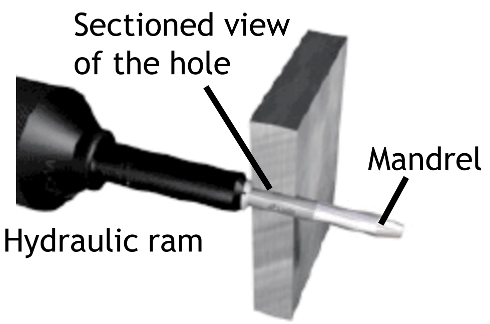
- The current airframes are aging, and solutions must be developed to extend their life expectancy
- Fatigue crack growth is a leading cause for airframe retirement and is why decelerating crack growth is so attractive
- Careful engineering implementation of residual stress can help decelerate crack growth
  - Residual stress is an equilibrium stress field (2nd order tensor) within a component in the absence of external loading

https://www.flickr.com/photos/usairforce/

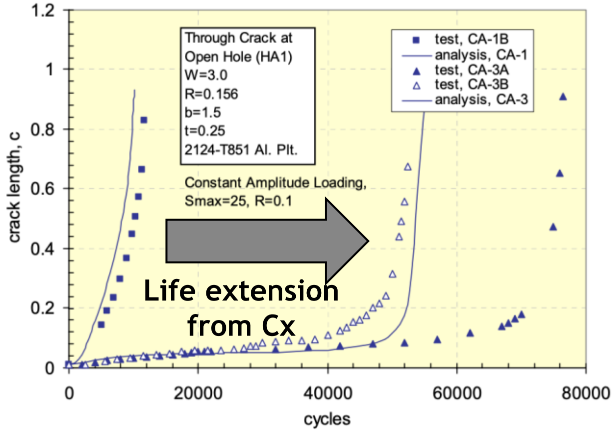
Defense.gov

Cold Expansion Process

- The Engineering Residual Stress Implementation (ERSI) group was formed to validate the Cold Expansion (Cx) process as a means of extending the fatigue life of structural components containing fastener holes
- The Cx process forces an oversized mandrel through an undersized hole causing plastic deformation which induces compressive residual stress near the hole bore
- Compressive residual stress slows crack growth (well documented in the literature)

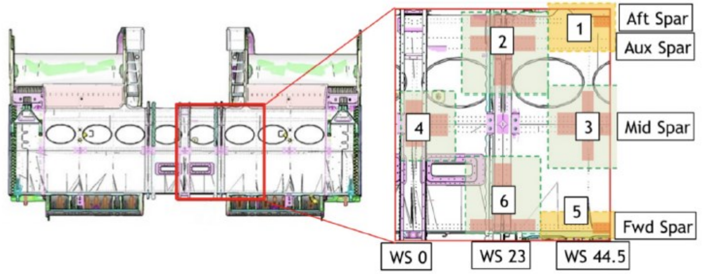


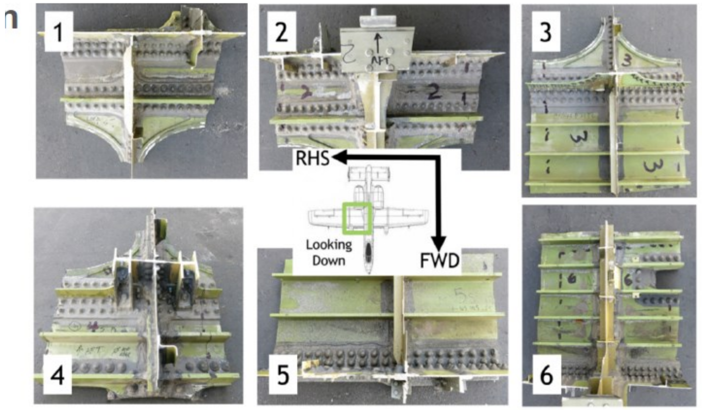
Fatigue Technology



D. Ball and M. Doerfler 2003

Wing bulkhead sections containing numerous fastener holes processed with Cx



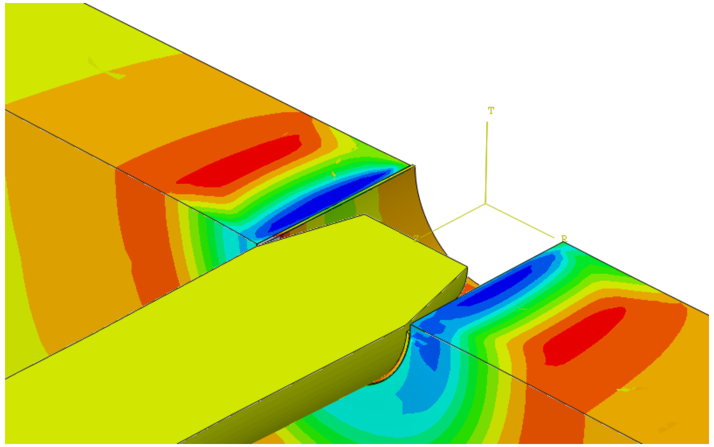


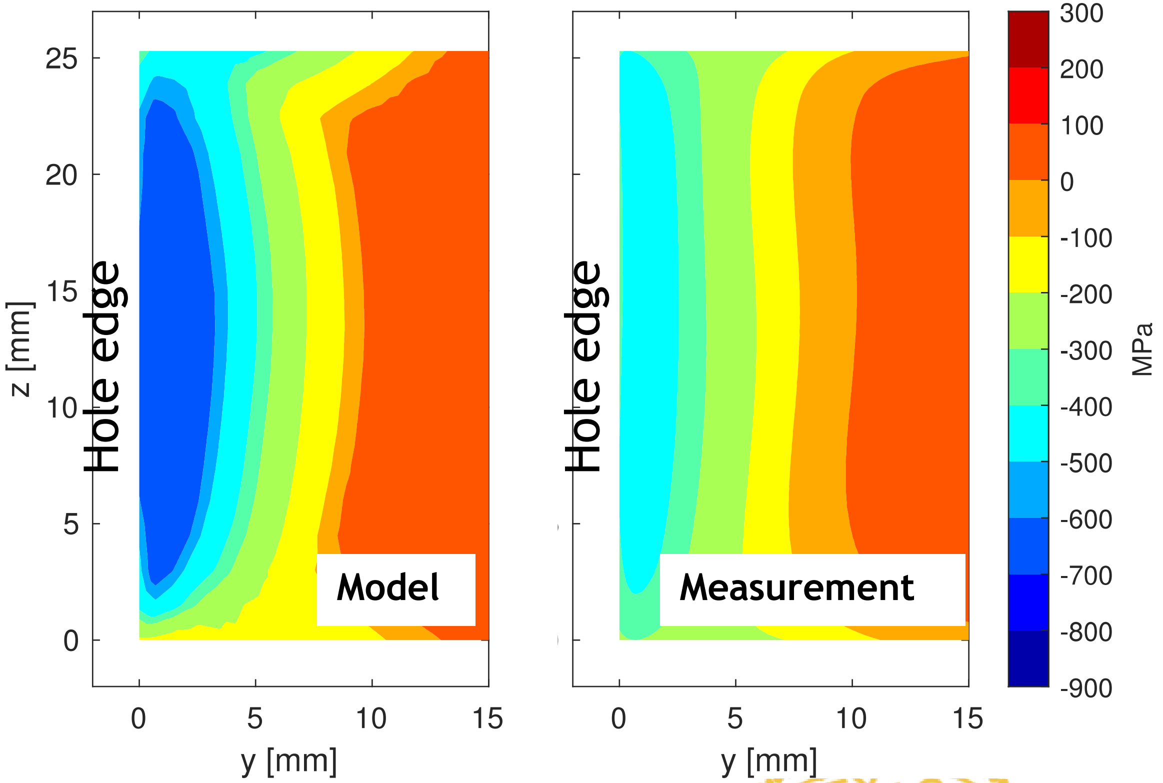
Pilarczyk, ASIP Conference 2018

Process Modeling and Historical Measurements

- To explicitly credit Cx with airframe life extension, engineers need accurate models to predict residual stress fields
- An elastic-plastic process model was previously developed using finite element software to incrementally displace the mandrel through the hole and observe the resulting residual stress state
- A prior validation campaign showed an over estimation of compressive residual stress near the hole edge
  - Overestimate of roughly 50% of maximum measured residual stress would lead to gross overestimation of Cx process benefit if used to predict structural fatigue life
- A lot of work has been published on modeling, residual stress measurements, and comparisons, but we believe an exemplar data set is required to encourage further model development

Sectioned view of the process model at a late time step





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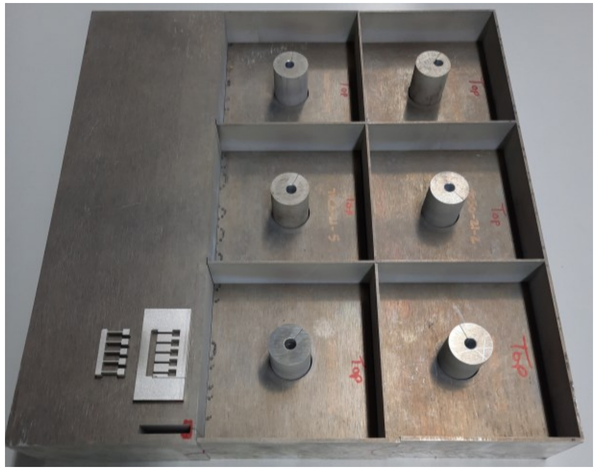
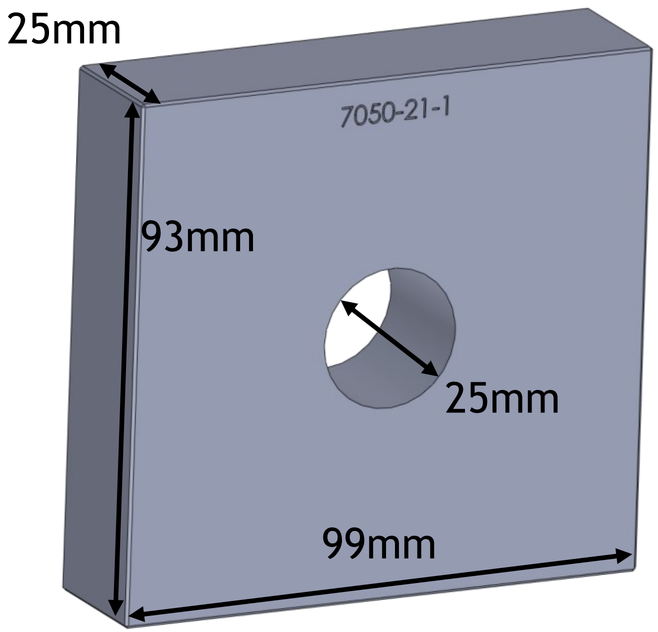
Specimen Preparation

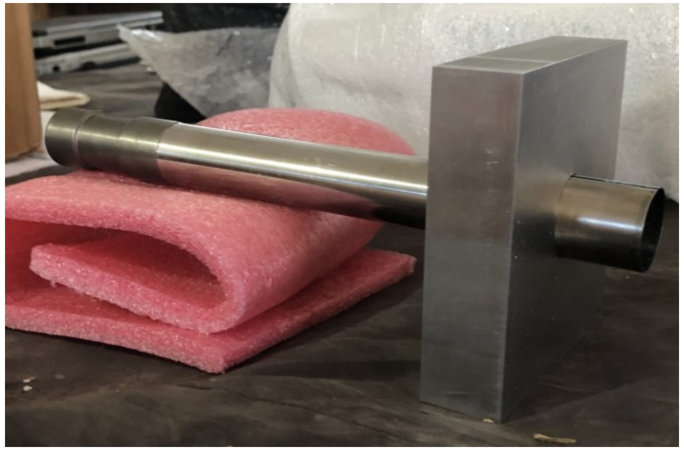
- Multiple specimens were extracted from a single 50mm thick rolled AA7050-T7451 plate (solution heat treated, stretch stress relieved, artificially aged)
- Extracted specimen dimensions were 99mm (L) x 93mm (LT) x 25mm (ST)
- To qualify models at multiple Cx processing time step, two processed conditioned were developed for this initial study
  - 100% Cx processed specimen
  - 50% Cx processed specimen, where the mandrel was held in place by friction



100% Cx processed



50% Cx processed

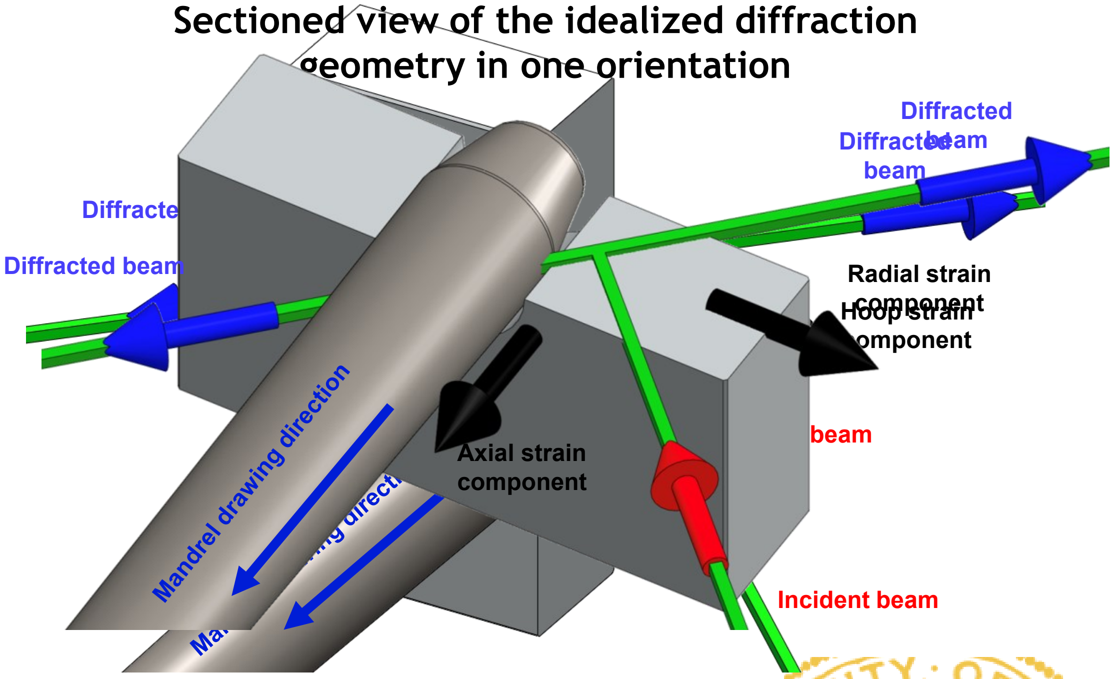


Neutron Diffraction Measurements

- Neutron diffraction measurements were conducted on the SMARTS instrument at the Los Alamos National Laboratory
- SMARTS capabilities include
  - Two detector banks at ± 90 degrees for typical engineering strain component determination
  - $0.5 - 7.5\text{Å}$ incident neutron spectrum for full diffraction pattern analyses
  - 250KN load frame, a vacuum furnace with in-situ loading capabilities, Leica laser absolute tracking system and Romer laser scanner, back scatter detector banks dislocation density measurements from line profile analysis
- Determined 3 orthogonal normal strain components along the axial, hoop, and radial directions
- Isotropic Hooke's law was then used to compute the normal residual stress components

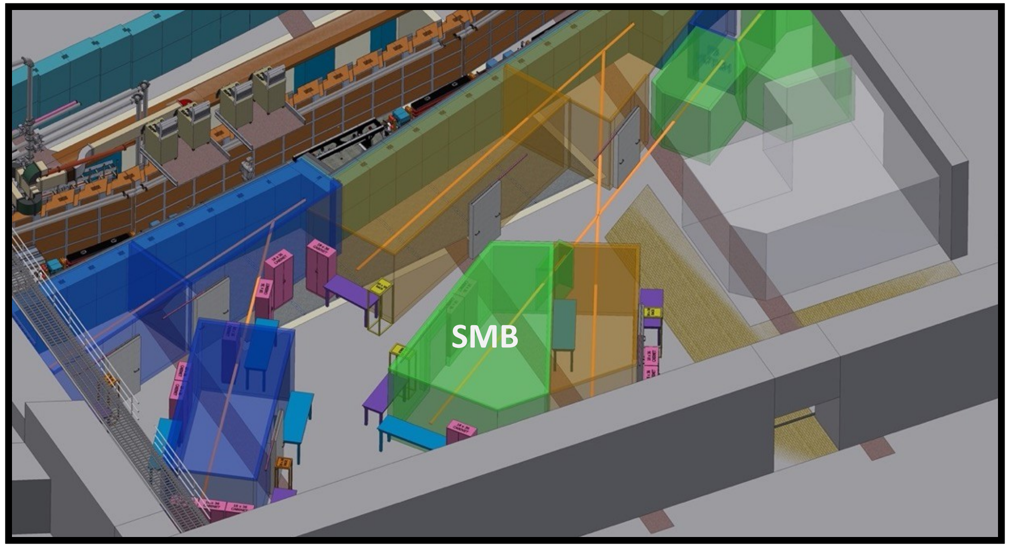
OSTI.gov

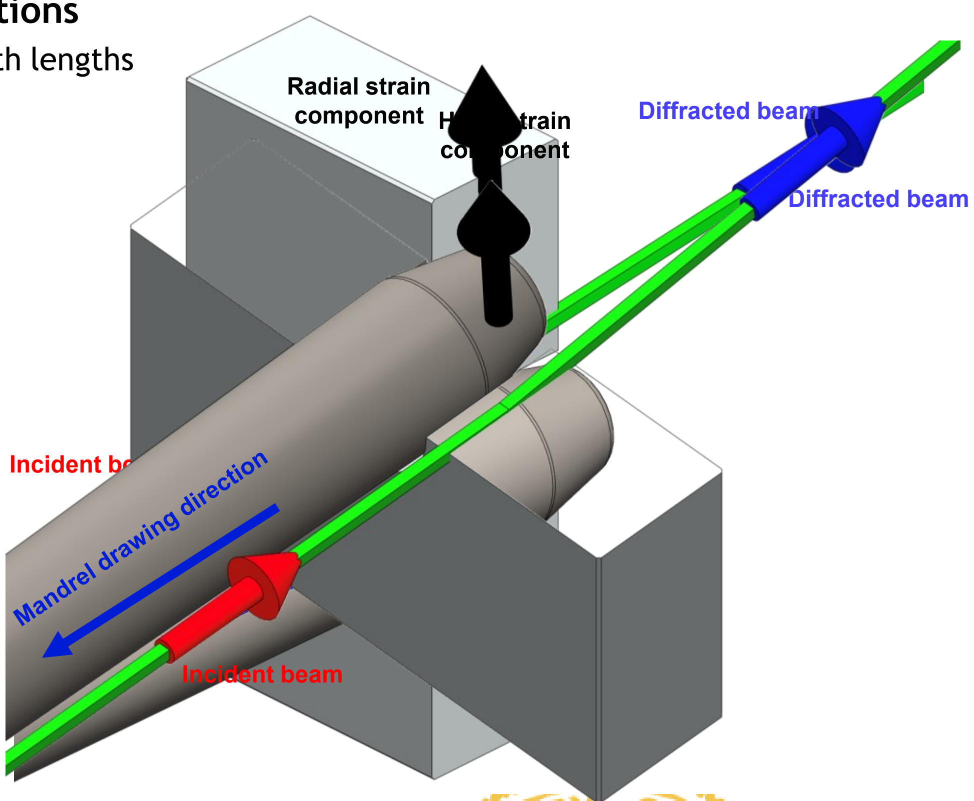
Sectioned view of the idealized diffraction geometry in one orientation



X-ray Energy Dispersive Diffraction Measurements

- X-ray energy dispersive diffraction measurements were conducted at the CHESS Structural Materials Beamline which is currently sponsored by the Air Force Research Laboratory (AFRL)
- Structural Materials Beamline capabilities include
  - Single detector bank at $2\theta = 6.46$
  - White beam incident X-ray spectrum
  - Kuka 6-axis robot arm for sample positioning
- Determined 2 normal strain components along the hoop and radial directions
  - Axial strain component measurements were not conducted due to the extreme path lengths

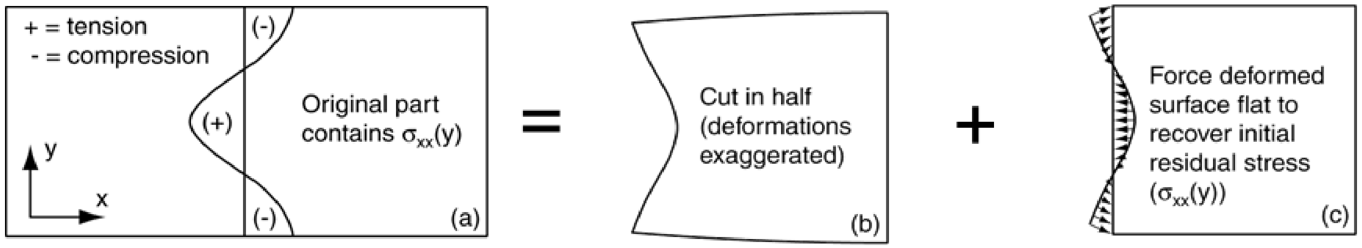




Contour Method Measurements of Residual Stress

- **A single hoop stress measurement was made along the same plane as the neutron and X-ray diffraction measurements**
- **The contour method determines a single component of residual stress normal to a plane of interest**
- **Comprises cutting a part along a plane of interest and measuring the resulting normal deformation**
  - Cutting a residual stress bearing body introduces a traction free surface and to satisfy equilibrium the residual stress field redistributes resulting in deformation
  - The normal deformation is applied to a linear elastic finite element analysis as a boundary condition to compute the residual stress field within the plane
  - Provides a 2D map of residual stress normal to the plane of interest

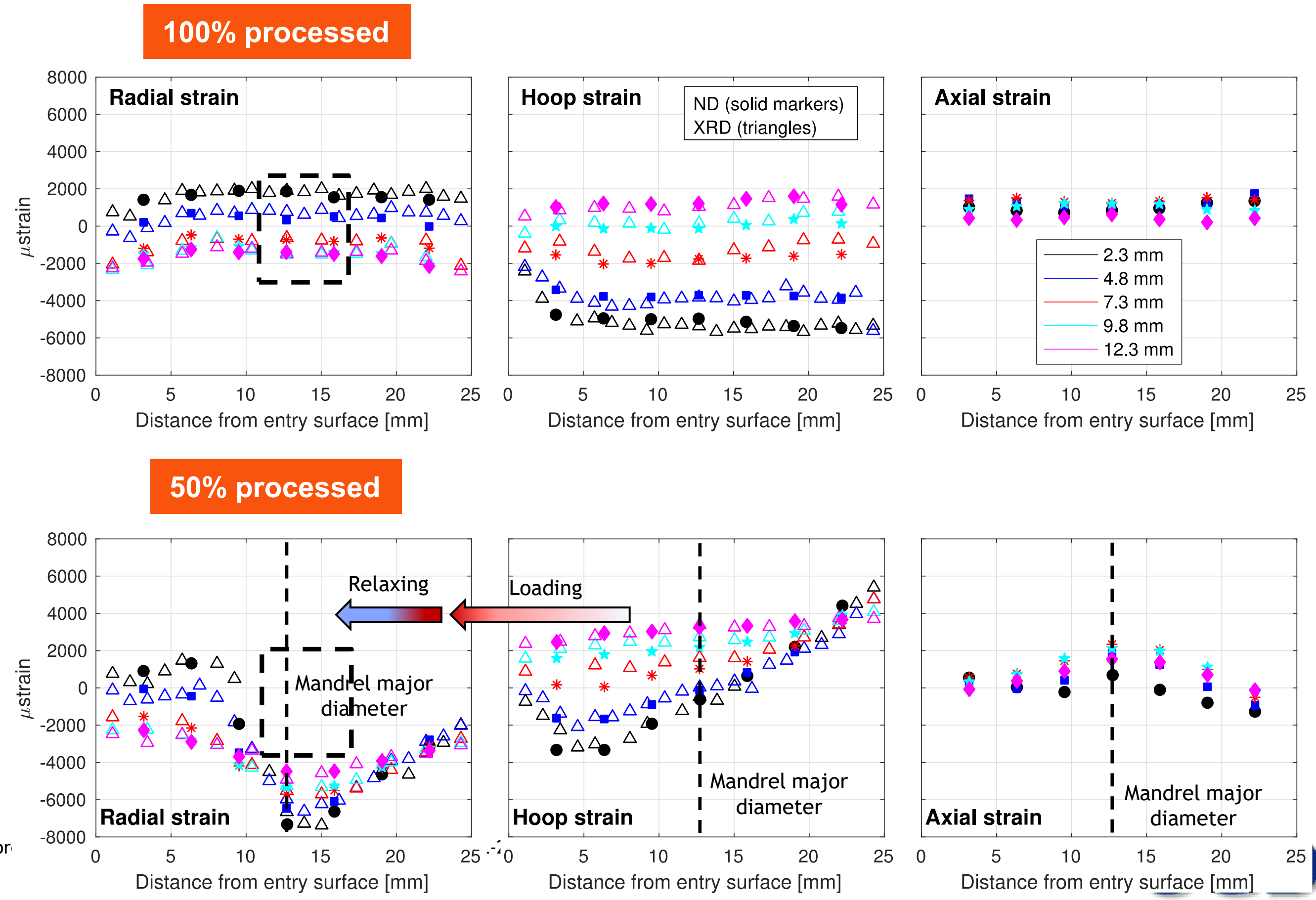
Contour method

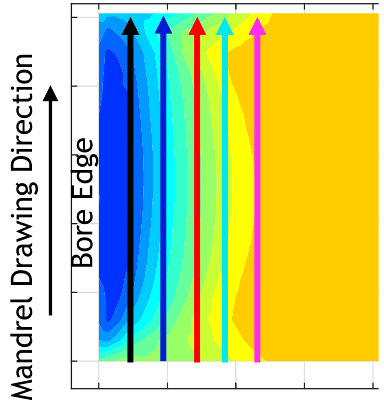


Prime 2001

Elastic Residual Strain Comparison

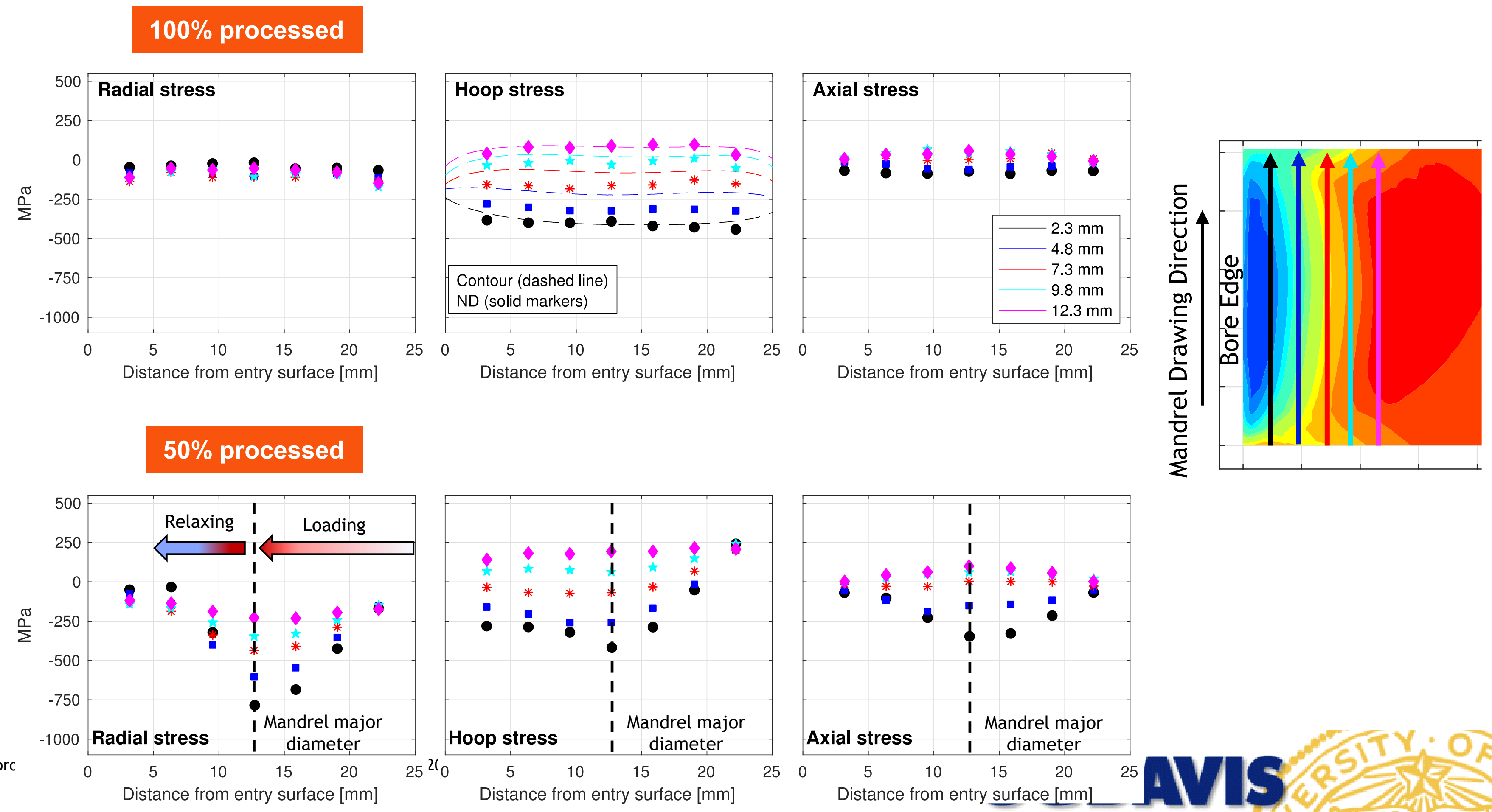
- Excellent agreement is seen between the XRD (triangles) and the ND (circles) elastic strain measurements
- The 100% Cx sample shows high magnitudes of hoop compressive strain near the hole bore edge in addition to slight tensile radial strain (typical to published results). The axial strain is near zero and slightly tensile
- The 50% Cx sample also shows exceptional agreement between XRD and ND measurements especially near the sharp gradients present in the radial strain field
  - This agreement if vital for furth qualifying the process model (please stick around for the following presentation from Professor Michael R. Hill for discussion of the modeling results)





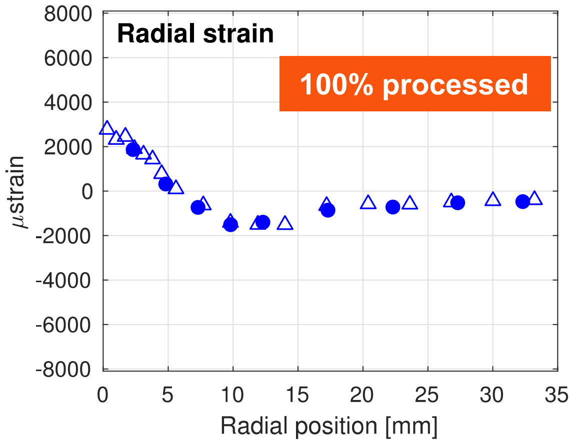
Residual Stress Comparison

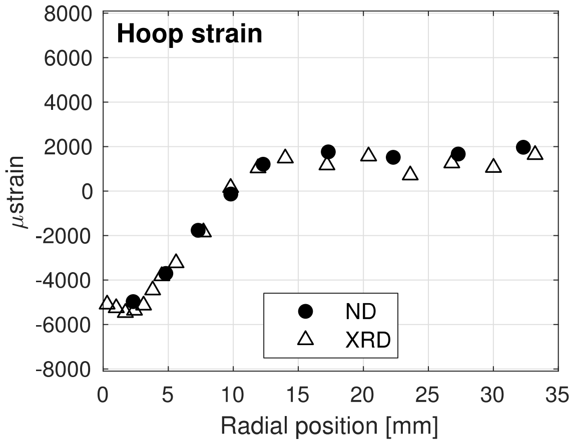
- Good agreement is seen between the ND and and CM measurements of the hoop residual stress component in the 100% Cx sample
- The 50% Cx sample displays a nearly hydrostatic stress state near the hole bore edge at the position of the mandrel major diameter (12.7 mm)

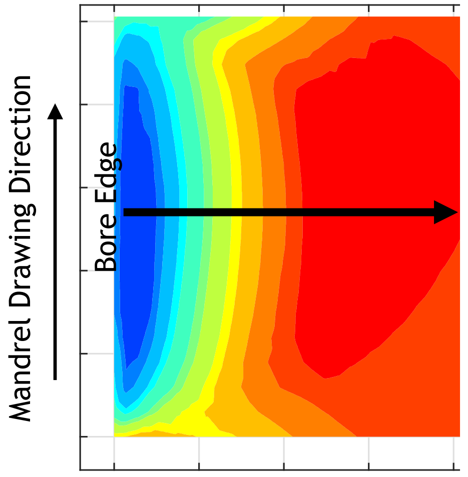


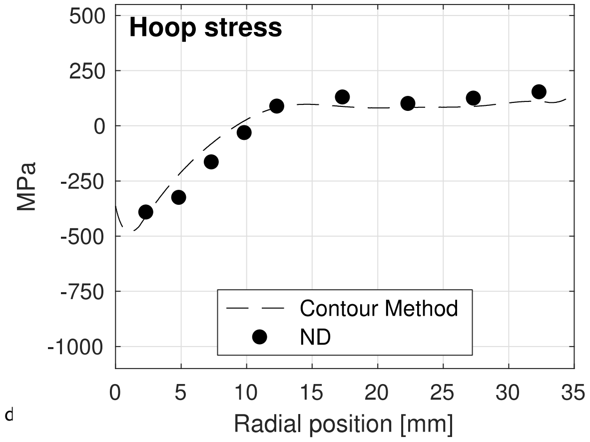
Comparing measurement techniques

- The elastic strain measurements compare well within measurement uncertainty near the bore and bulk regions
- Residual stress measurements techniques are just outside each uncertainties, with better correlation in the bulk region
  - We think this is due to the finite ND measurement volume over high stress gradients



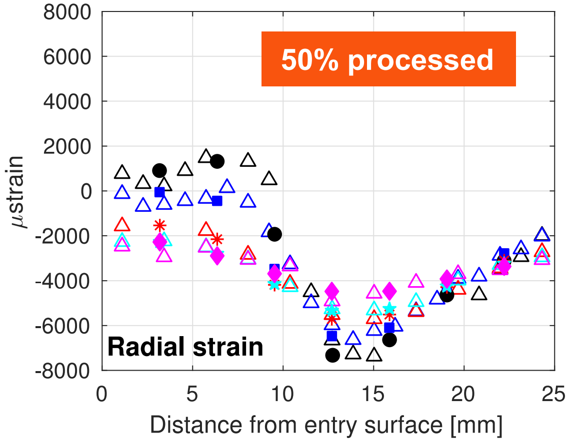


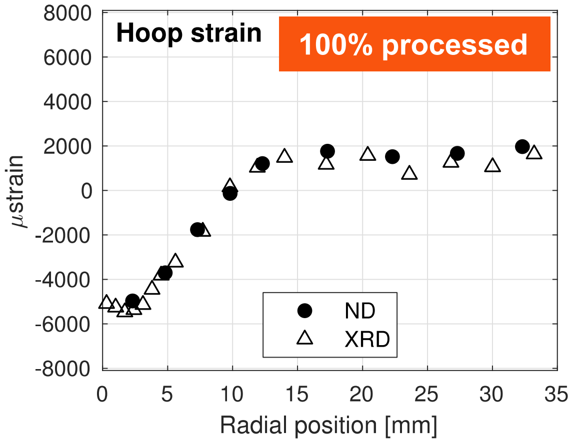


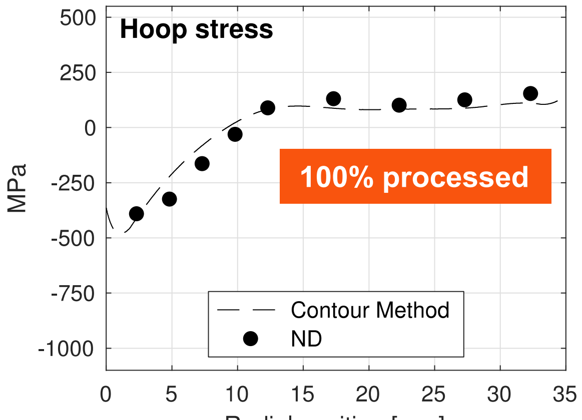


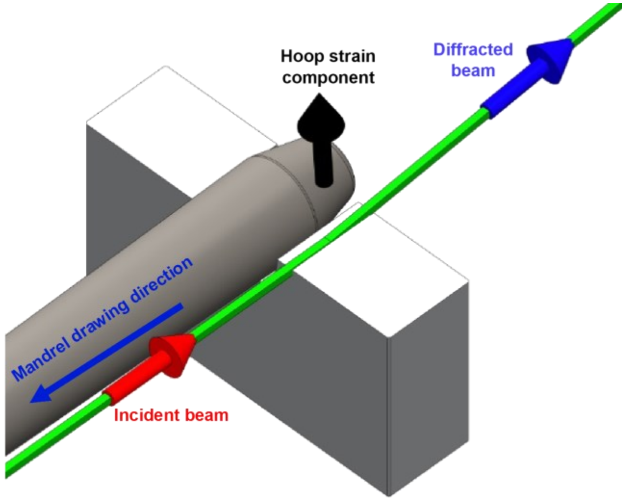
Concluding remarks

- ❑ **Comparable results are seen between the diffraction and mechanical based measurement techniques in the 50% and 100% Cx processed samples giving confidence in the residual elastic strain and stress fields for future model validation**
- ❑ **Diffraction techniques offer indispensable perception into the Cx process through the 50% processed sample**
  - ➢ Neutron diffraction allows for simple stress determination
  - ➢ XRD's reduced measurement gage volume offers higher spatial resolution near the hole bore









10:35 AM

Bulk Residual Stress and Strain Measurements Near Geometrically Large Holes for Improving Cold Expansion Process Models: *Michael Hill*[1]; Nicholas Bachus[1]; Donald Brown[2]; Chris Budrow[3]; Michael Burba[4]; Bjørn Clausen[2]; Adrian DeWald[5]; J.Y. Peter Ko[6]; Kelly Nygren[6]; Mark Obstalecki[4]; Robert Pilarczyk[5]; Renan Ribeiro[5]; Paul Shade[4]; Matthew Shultz[7]; [1]University of California Davis; [2]Los Alamos National Laboratory; [3]Budrow Consulting LLC; [4]Air Force Research Laboratory; [5]Hill Engineering, LLC; [6]Cornell High Energy Synchrotron Source; [7]Fatigue Technology, Inc

Thank you for your attention

Any questions?

Bulk Residual Stress and Strain Measurements Near Geometrically Large Holes for Improving Cold Expansion Process Models

ERSI

Working Group on Engineered Residual Stress Implementation

Michael R. Hill[1], Nicholas A. Bachus[1,2], Donald W. Brown[2], Chris Budrow[3], Michael E. Burba[4], Bjørn Clausen[2], Adrian T. DeWald[5], J.Y. Peter Ko[6], Kelly E. Nygren[6], Mark Obstalecki[4], Robert T. Pilarczyk[5], Renan L. Ribeiro[5], Paul A. Shade[4], Matthew Shultz[7]

[1] Mechanical and Aerospace Engineering, University of California, Davis
[2] Los Alamos National Laboratory
[3]Budrow Consulting LLC
[4] Air Force Research Laboratory
[5] Hill Engineering LLC
[6]Cornell High Energy Synchrotron Source
[7] Fatigue Technology Inc

(14 authors from 7 organizations)

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Team

Organized under ERSI Residual Stress Measurement Subgroup

Contributors:

- Hill Engineering (HE)
  - Renan Ribeiro, Bob Pilaczyk, Adrian DeWald
- US Air Force Research Lab (AFRL)
  - Eric Burba, Mark Obstalecki, Paul Shade
- Fatigue Technologies (FTI)
  - Matt Shultz
- Los Alamos National Lab (LANL)
  - Don Brown, Bjørn Clausen
- Cornell High Energy Synchrotron Source (CHESS)
  - Chris Budrow, Kelly Nygren, Peter Ko
- University of California, Davis (UC Davis)
  - Nick Bachus, Mike Hill

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Background and Objectives

Background:

- Existing prior data for large (D = 25.4 mm) Cx holes in 7075-T651
  - Residual stress measurements (contour)
  - Residual stress outputs from nonlinear process model
- Disagreement between measurement results and model outputs

Objectives:

- Fabricate coupons for measurements in D = 25.4 mm Cx holes
  - Samples cut from 7050-T7451 50.8 mm (2 inch) thick plate (AFRL)
  - 100% processed and 50% processed (FTI)
- Develop process model outputs for coupon conditions (Hill Engineering)
- Assess bulk RS in coupons
  - Neutron Diffraction (ND) at SMARTS (LANL, UCD)
  - Synchrotron X-ray Diffraction (EDXRD) (CHESS, AFRL, UCD)
  - Contour (Hill Engineering)
- Compare model outputs to measurement data (UCD and all)

Expected outcomes:

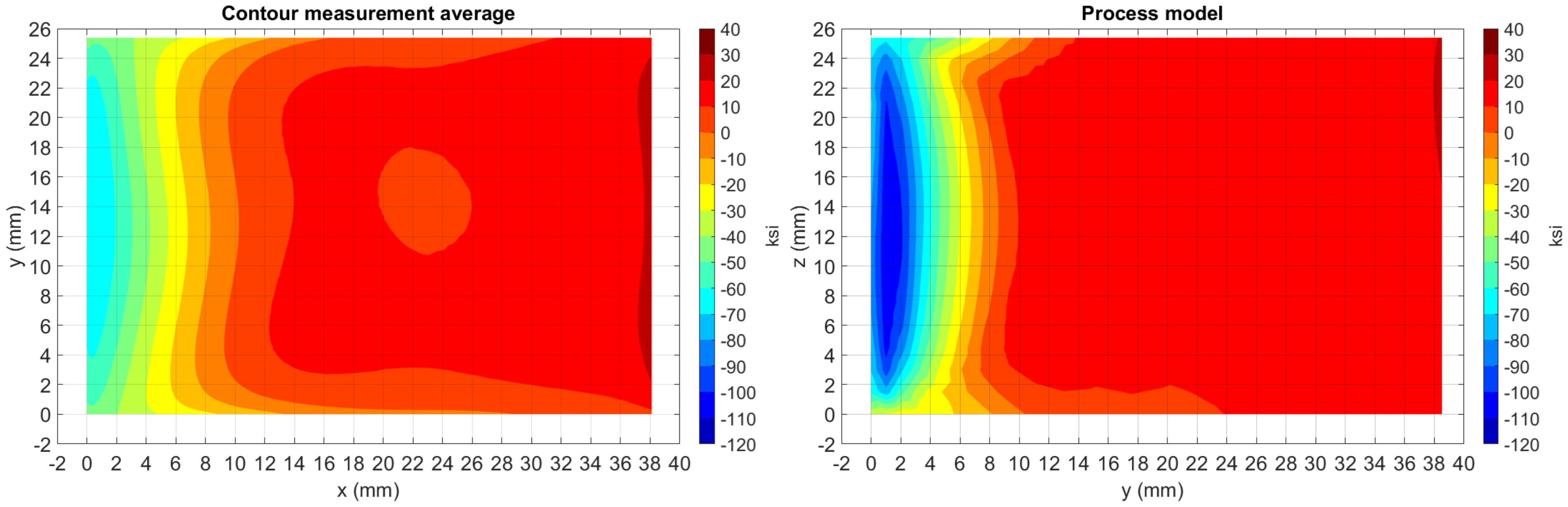
- Use data for process model improvements
- Share data with community (Conference presentation, Journal publication)

Prior work: Measurement and model comparisons

Contour maps of the hoop residual stress below

- Results shifted to start at the hole edge
- Dimensions in mm, stress in ksi (same color scale)
- Significantly higher magnitude of residual stress from model compared to measurement average

7075-T651



Samples for experiments

Samples reflect the conditions in the prior charts, but are in a new material and geometry

Material is AA7050-T7451 plate, 50.8 mm (2 inch) thick

- Widely used high-strength aluminum alloy

Sample geometry (mm)

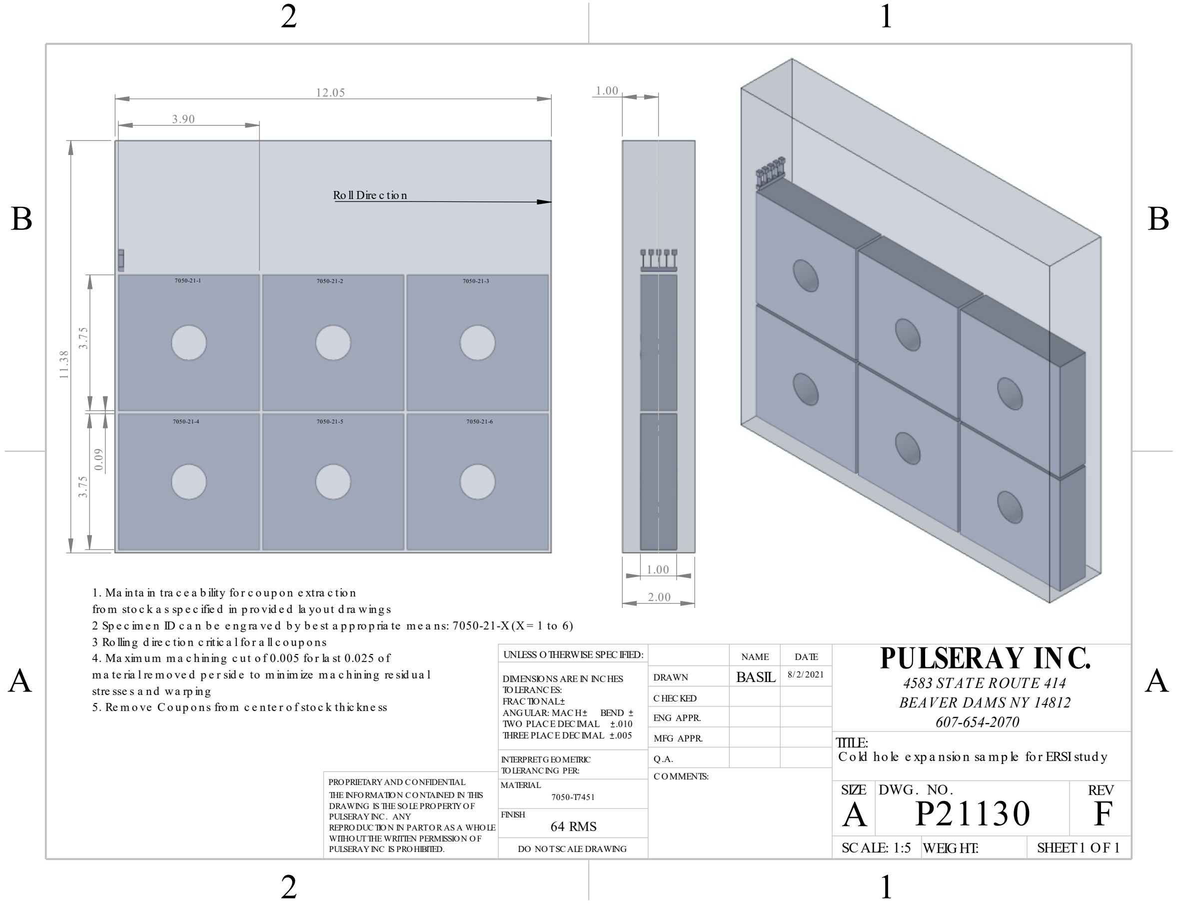
- Plates, L = 99 (along L), W = 95 (along LT), and T = 25.4 (along ST)
  - 25.4 dimension at plate mid-thickness to reduce texture
- Centered hole, D = 25.4

Fabricated 6 samples (AFRL)

- 7050-21-1 to 7050-21-6

Processing (FTI)

- Cx to 3.43 to 3.45% (see data)
- 7050-21-1: 100% Cx (ND complete)
- 7050-21-2: 100% Cx
- 7050-21-3: 50% Cx (ND complete)



Processed samples upon arrival at LANL

7050-21-1 – 100% CX (ND, EDXRD, Contour)

7050-21-2 – 100% CX (Spare)

7050-21-3 – 50% CX (ND, EDXRD)

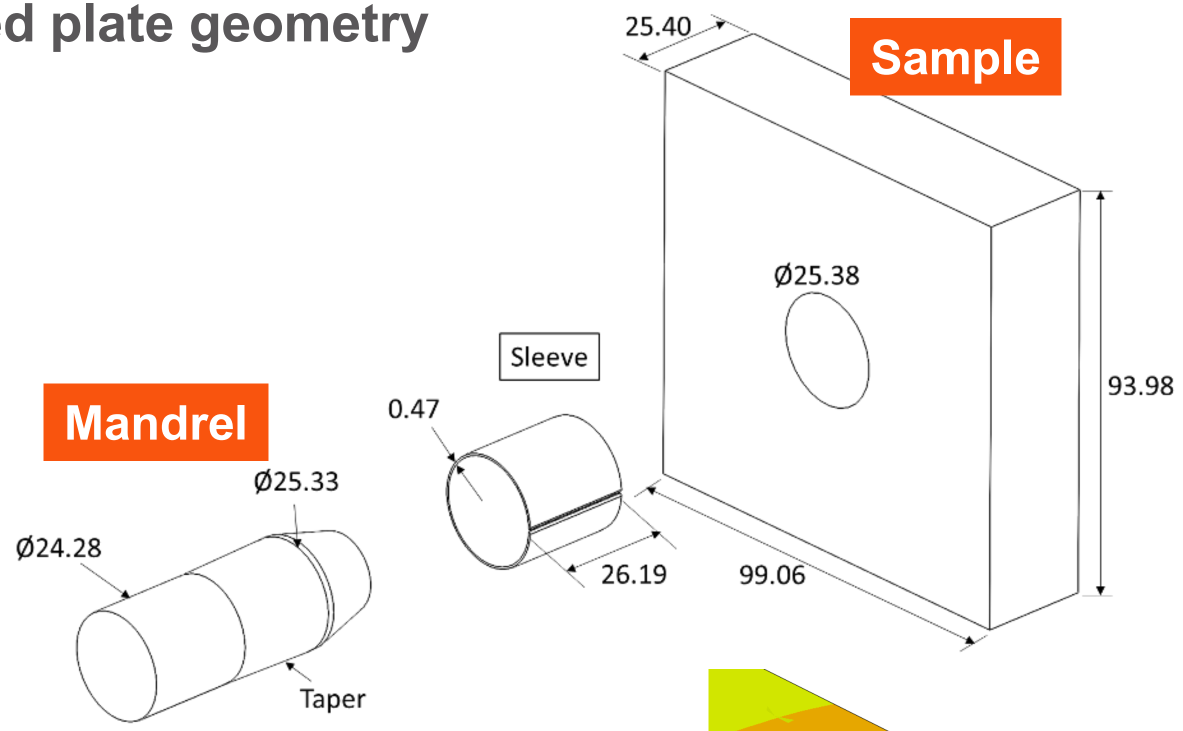
Numerical Simulation of Cx

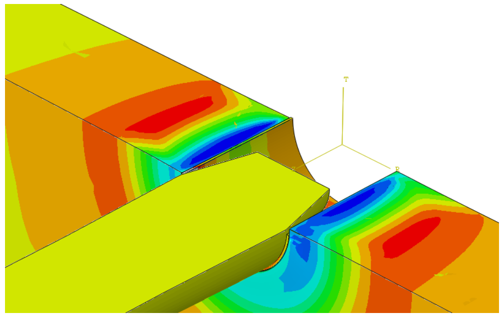
Samples: well-known material, tightly controlled plate geometry

Used finite element method

- Three bodies: sample, sleeve, mandrel
- Non-linear contact with friction
- Elastic plastic model for the sample material
  - Typical isotropic metal plasticity model
    - J_2 yield criterion and associative flow rule
    - Isochoric plasticity
    - Isotropic hardening
- Small time steps to follow the development of deformation, strain, and stress fields with mandrel motion

Note: prior work shows that these models tend to over-predict retained residual stress





Section view of the process model at a late time step

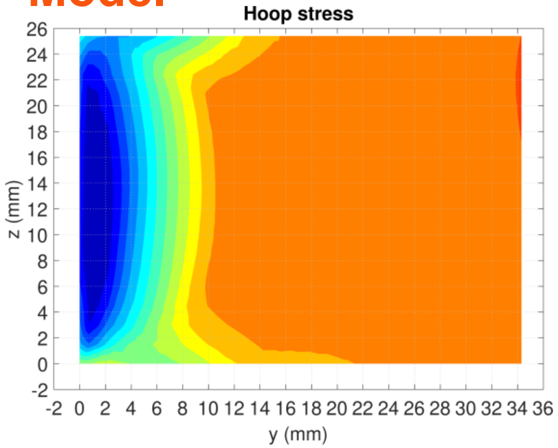
Comparisons at 100% (process complete) (Stress vs. r, z = T/2)

Model vs Contour measurement

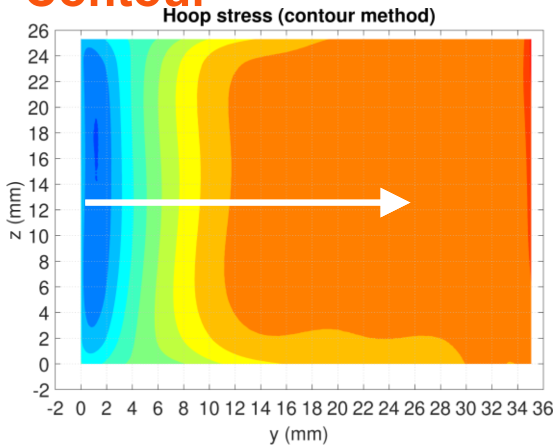
Line plots for Model, Contour, ND measurements below

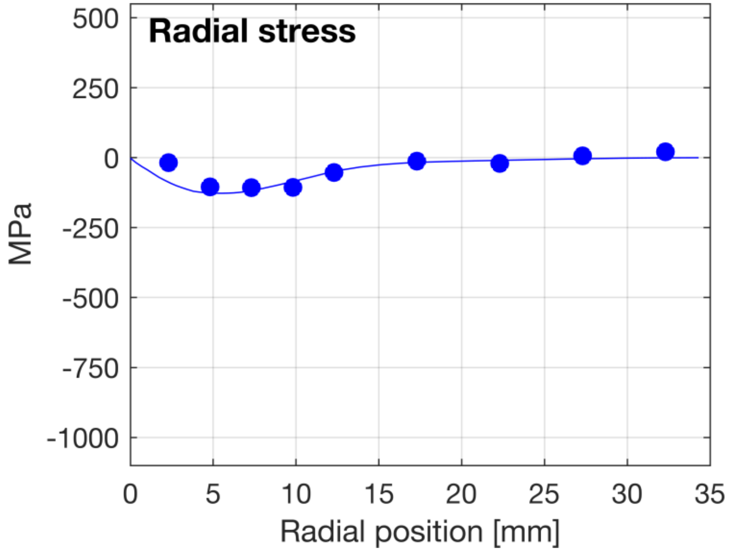
- Radial, hoop, and axial stress components

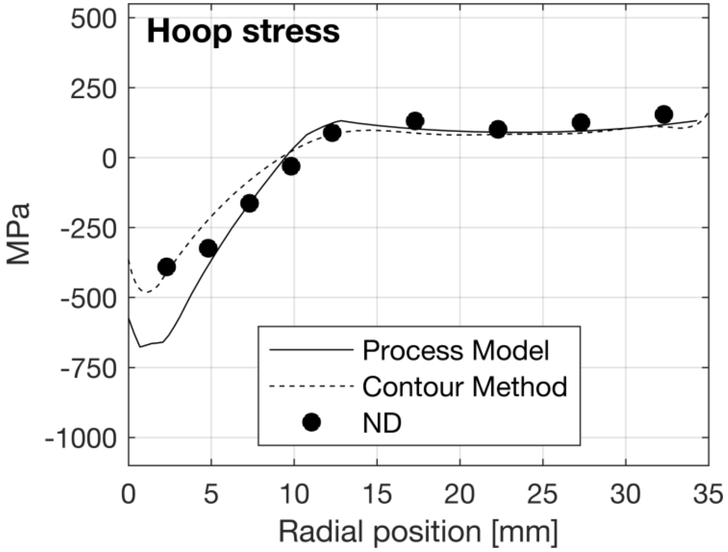
Model

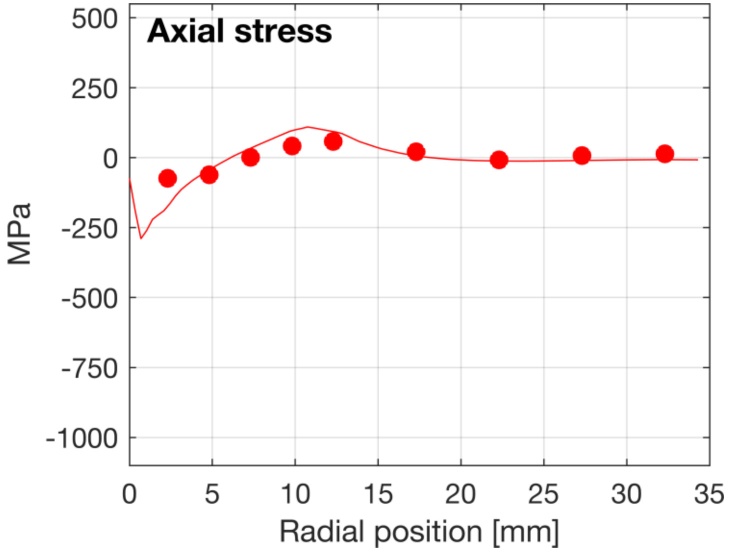


Contour









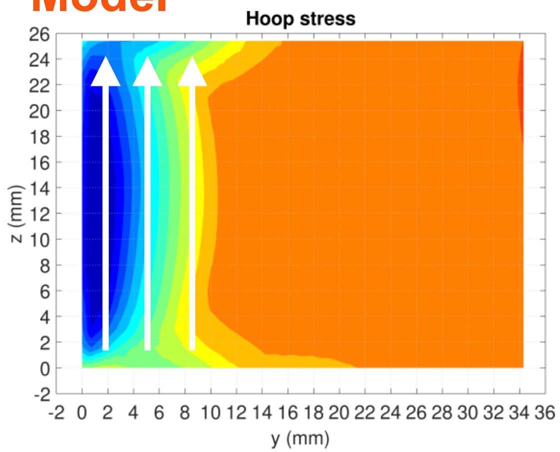
Comparisons at 100% (process complete) (Stress vs z, various r)

Model vs Contour measurement

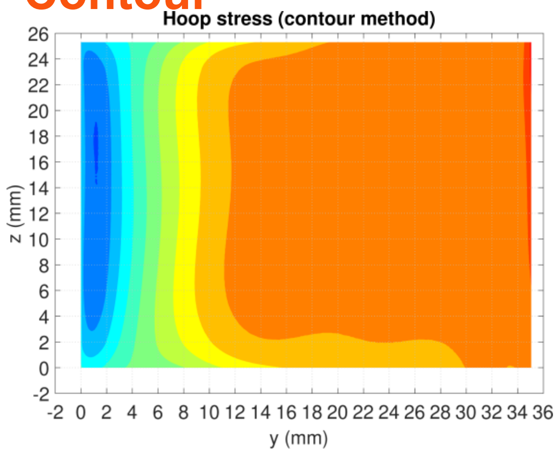
Line plots for compare Model, Contour, ND data

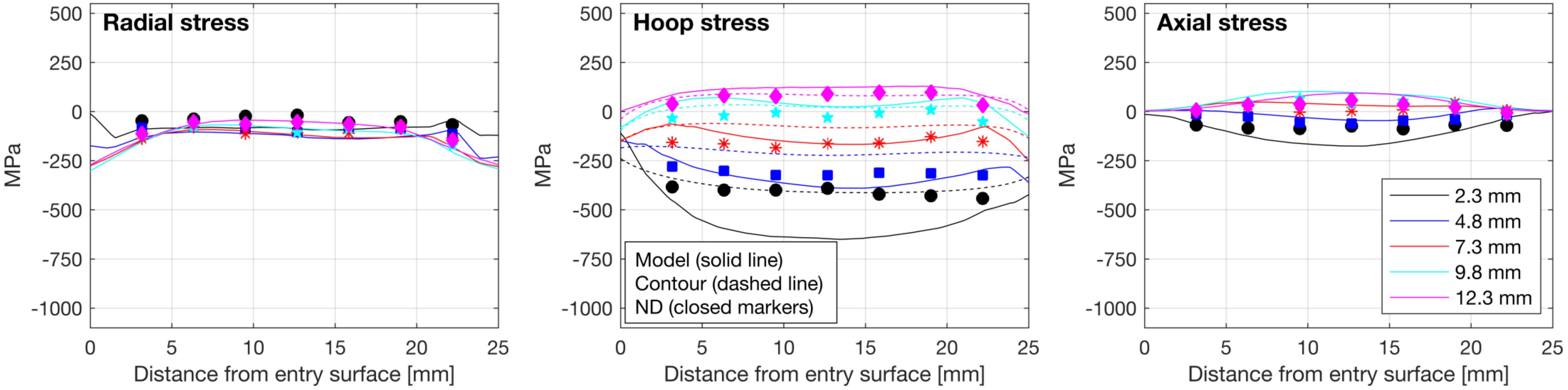
- Radial stress
- Hoop stress
- Axial stress

Model



Contour



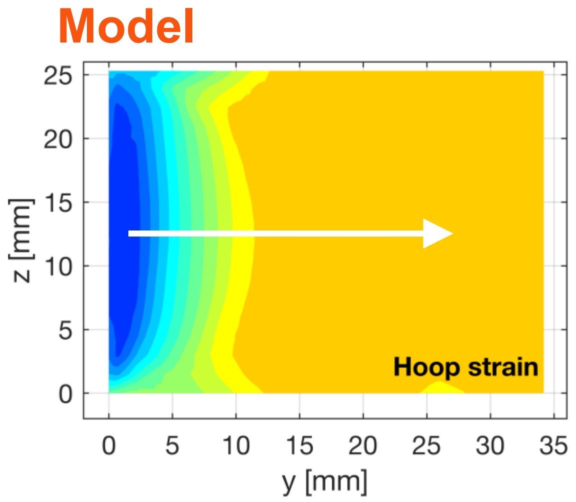


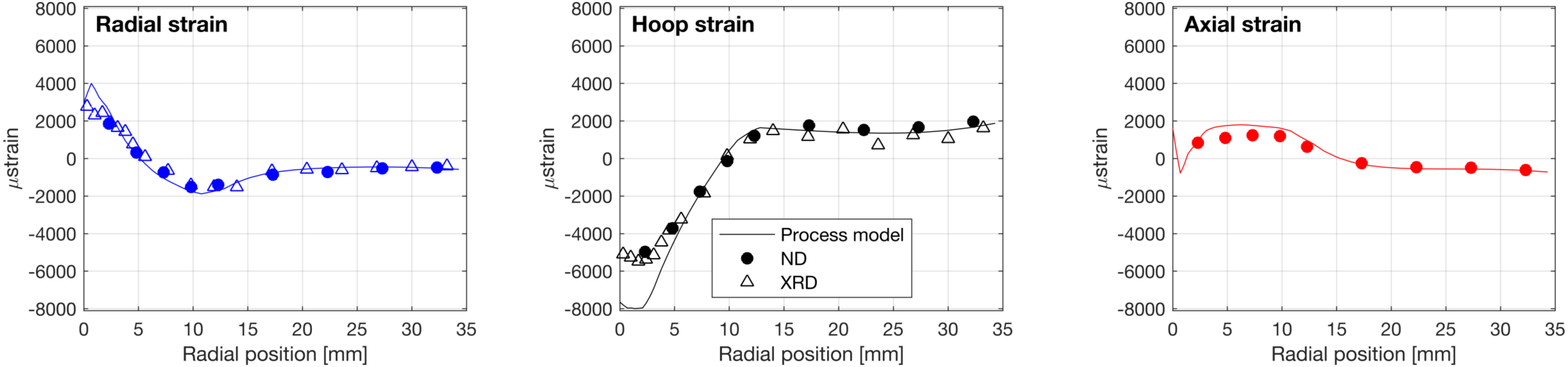
Comparisons at 100% (process complete) (Strain vs. r, z = T/2)

Model shows hoop strain field

Line plots for Model, ND, and EDXRD measurements below

- Radial, hoop, and axial stress components



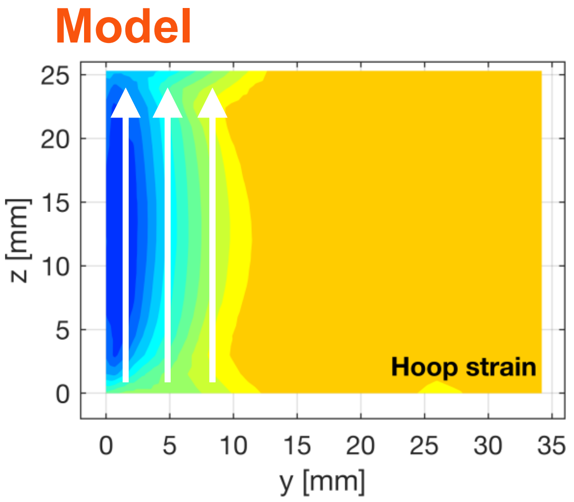


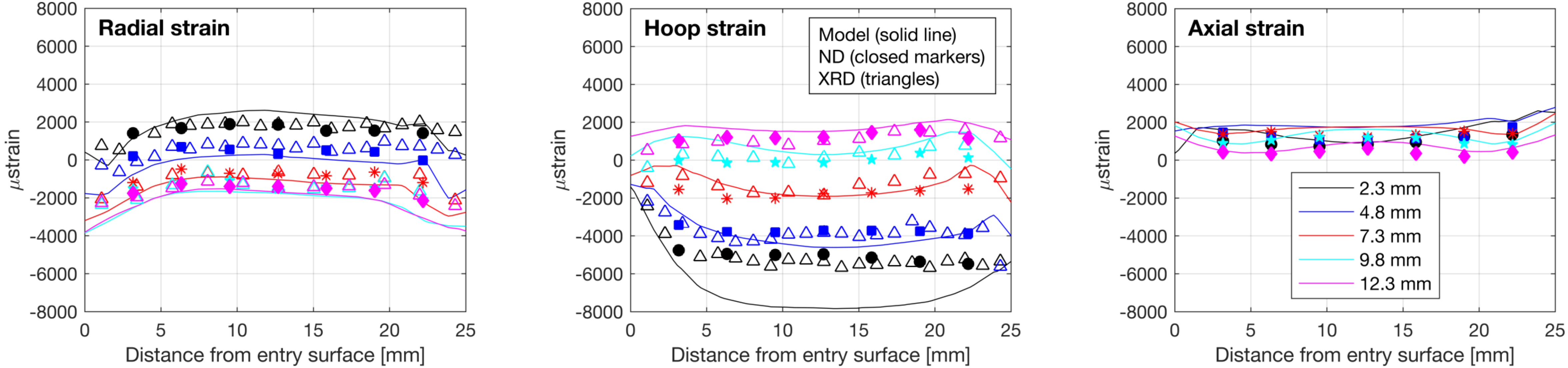
Comparisons at 100% (process complete) (Strain vs z, various r)

Model shows hoop strain field

Line plots for Model, ND, and EDXRD measurements below

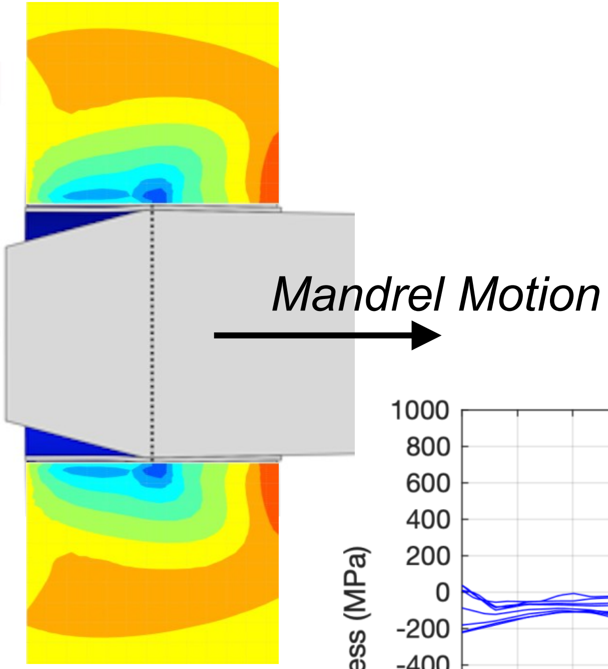
- Radial, hoop, and axial stress components

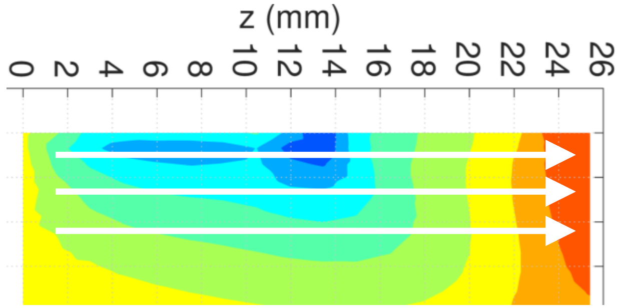


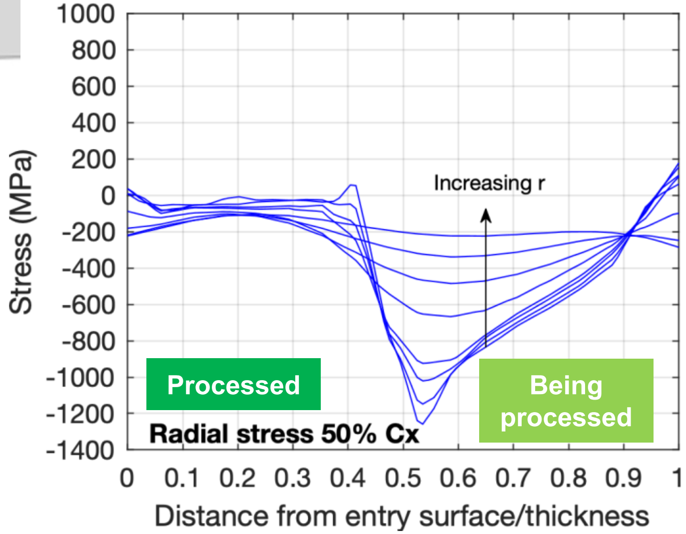


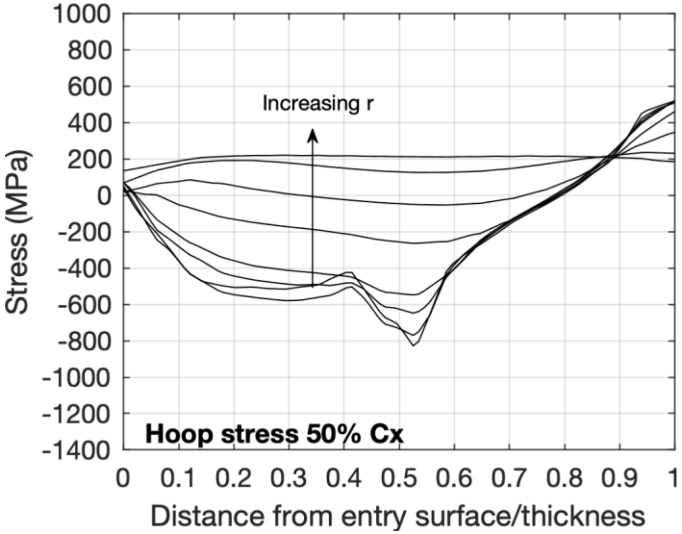
Model output spatial field at 50% processed (fixed time)

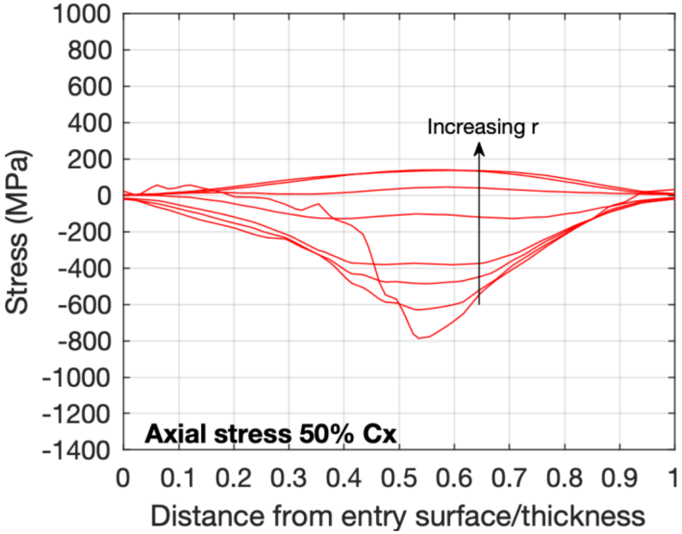
Stress field versus axial position, lines for range of radial positions





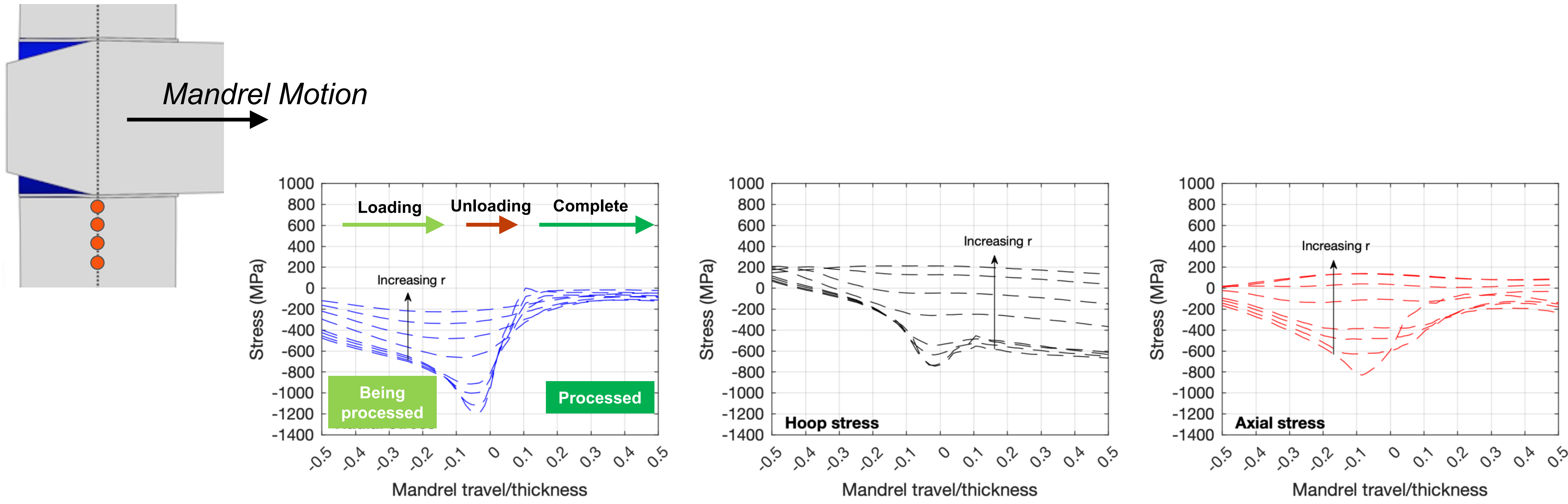




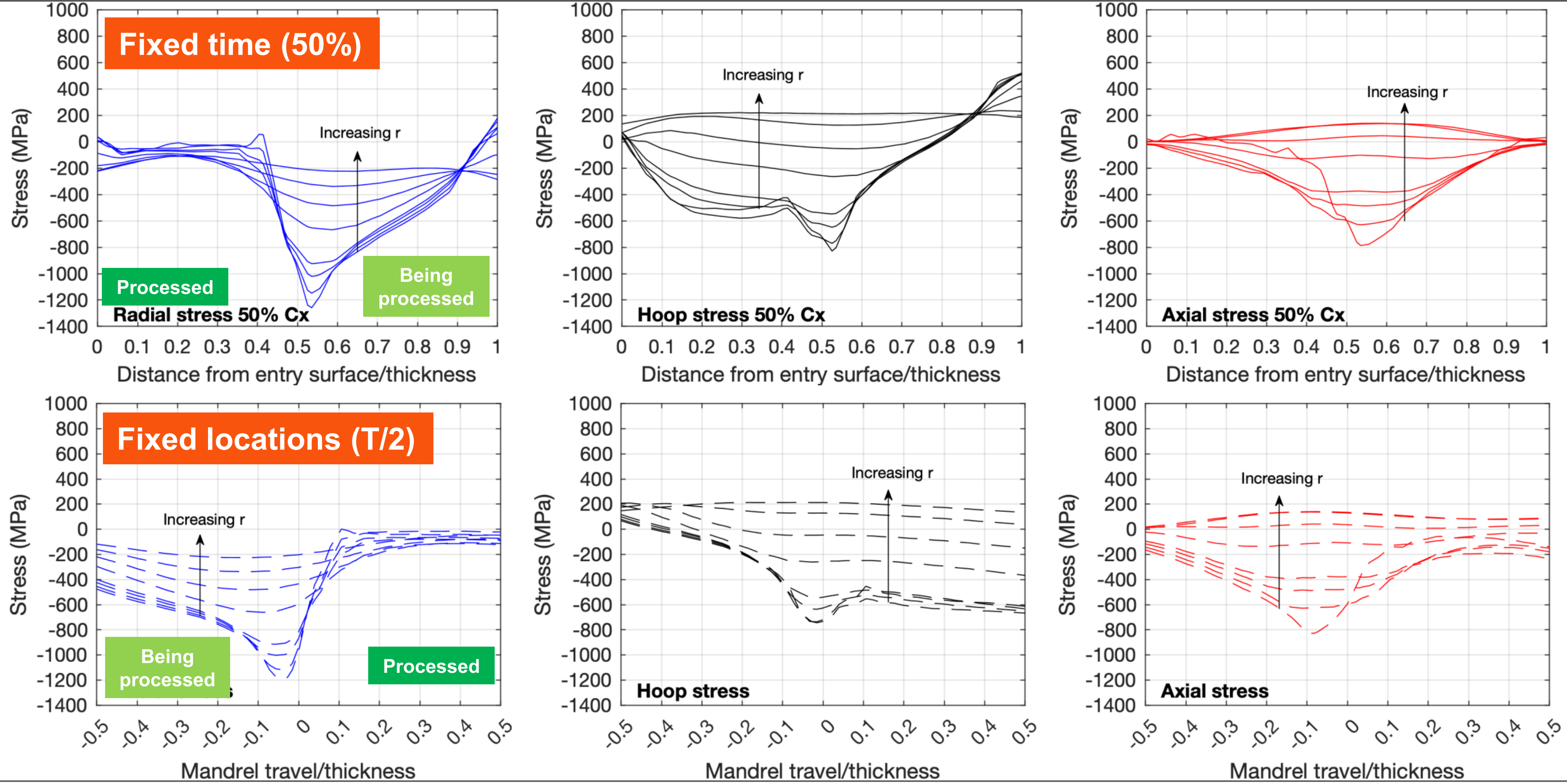


Model output versus time at z = T/2 (fixed locations, various r)

Stress field versus mandrel travel, lines for range of radial positions



Model outputs at 50% time compared to time variation at T/2



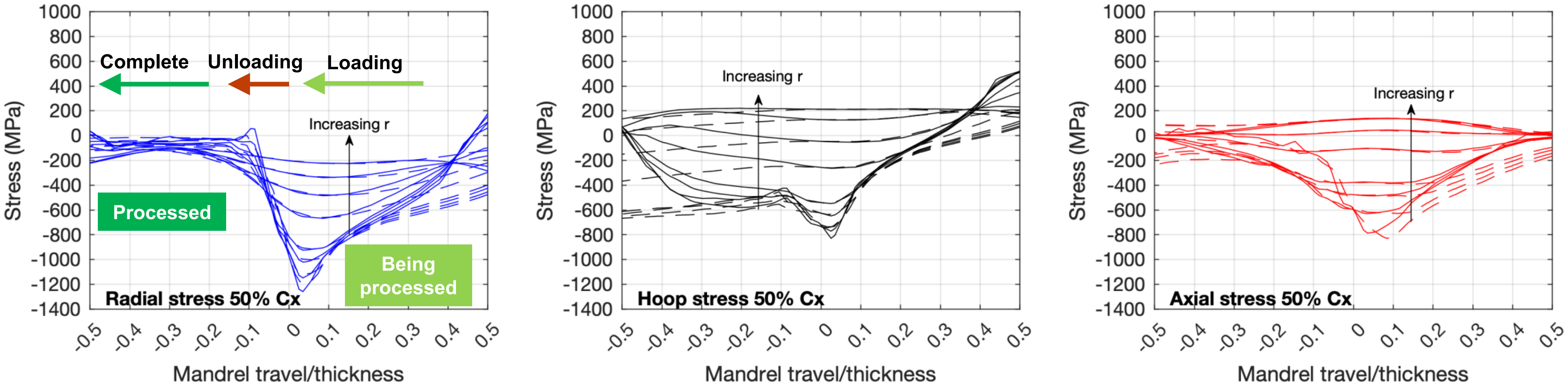
Model output overlay: at 50% time and versus time at T/2

Solid lines are at fixed time: spatial variation at 50% processed

Dashed lines are at fixed locations: temporal variation at z = T/2 (plotted backward)

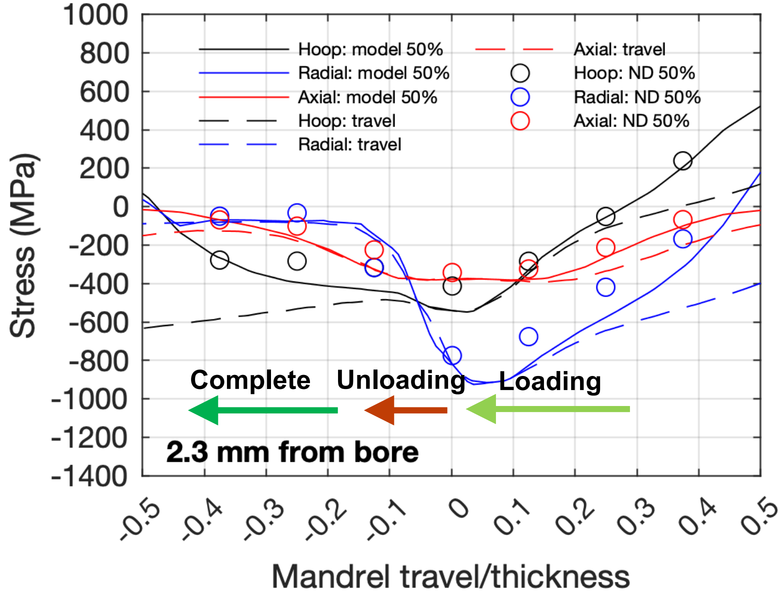
Region near mid-thickness where the two sets of trends are very similar

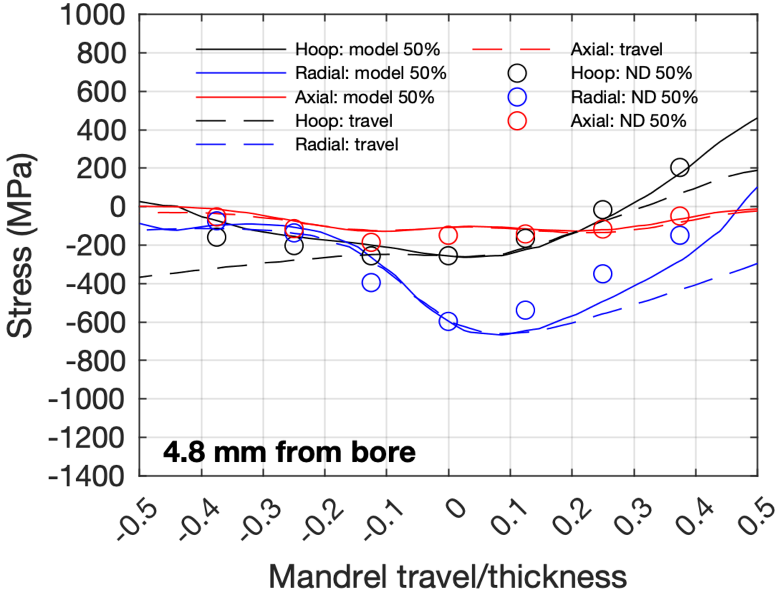
- Measurement at 50% time almost as good as a time-resolved test (*in situ* process experiment)

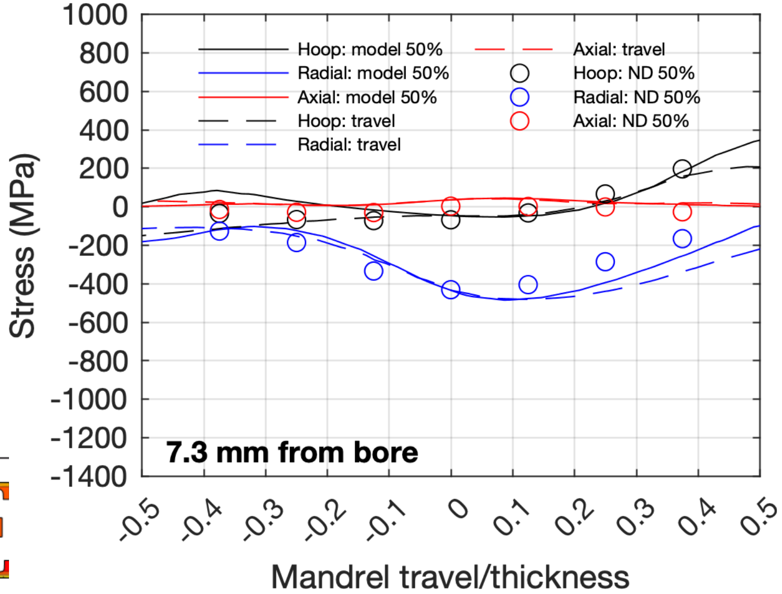


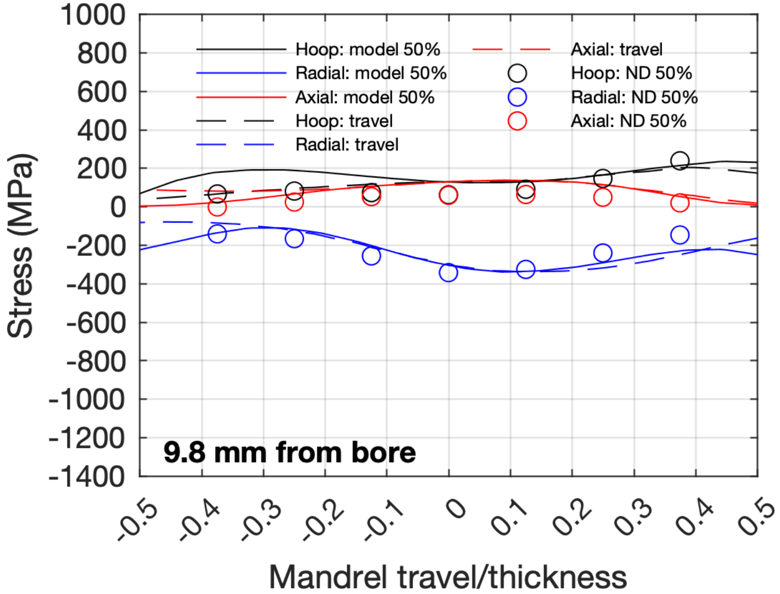
Comparisons of model outputs to 50% measurement data (Stress)

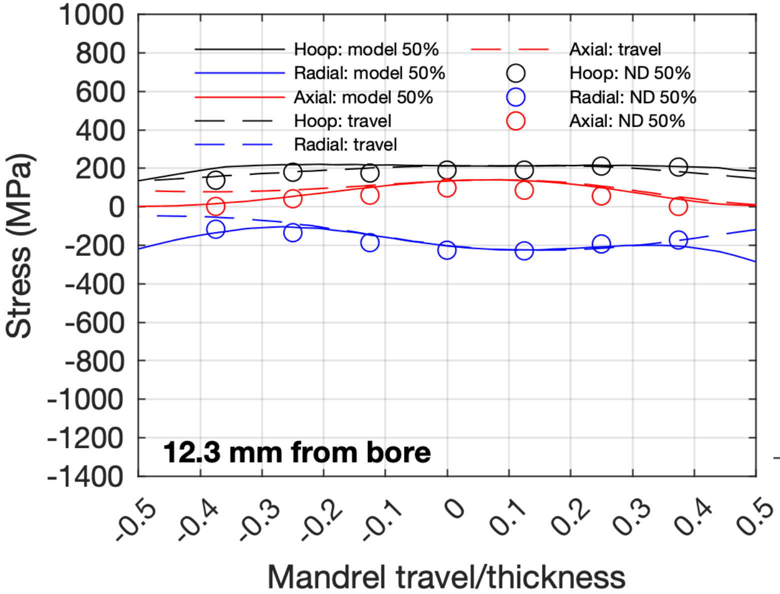
——— Fixed time (50%)
– – – Fixed location (T/2)
o ND (50%)
Hoop Radial Axial



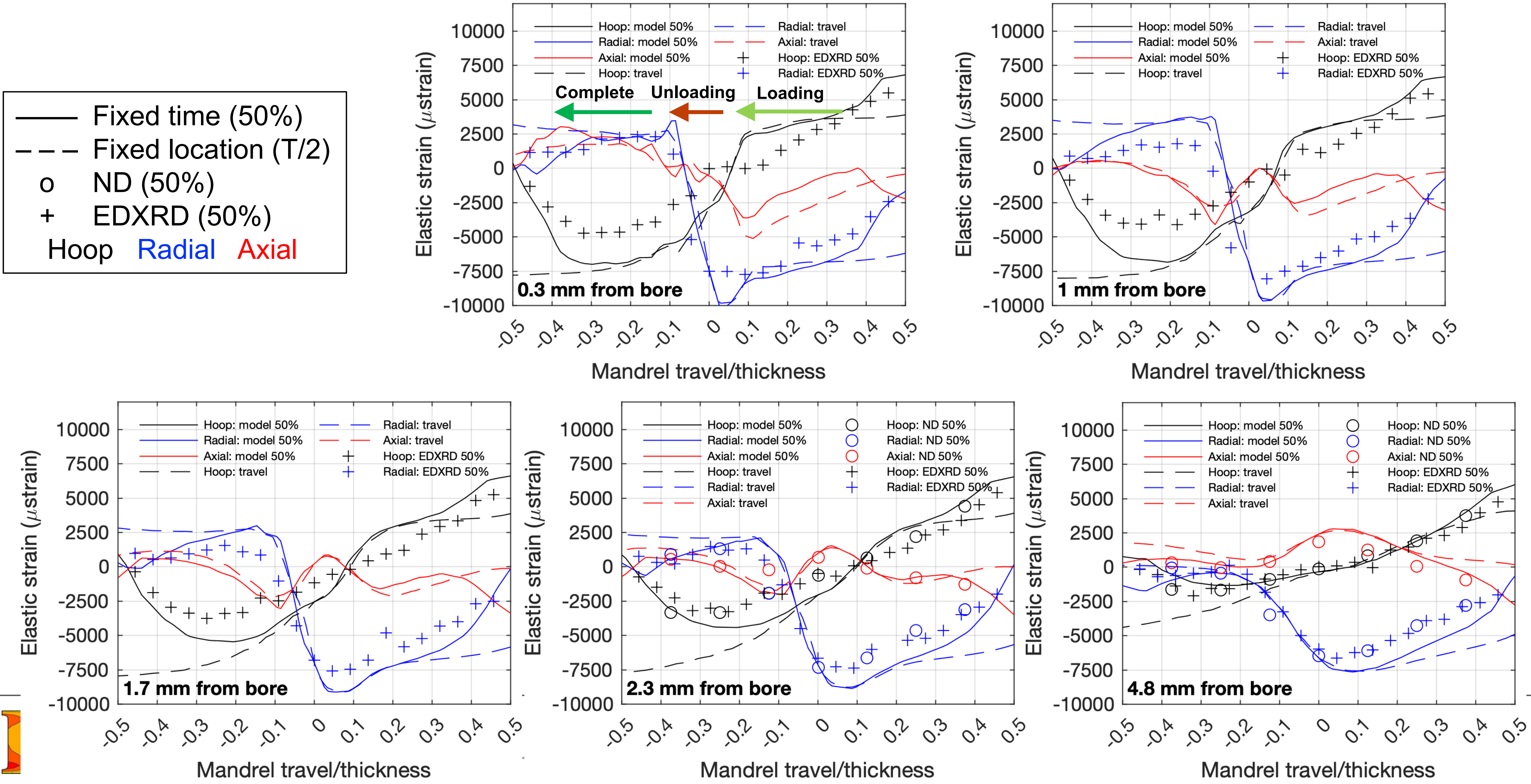








Comparisons of model outputs to 50% measurement data (Strain)



Summary

A set of samples were made to support model validation for cold expanded (Cx) holes

- Two configurations were assessed, a fully processed sample (100%), and a half-processed sample (50%)

Measurements of residual stress were performed using three diverse techniques

- Neutron diffraction (ND), Energy dispersive x-ray diffraction (EDXRD), and Contour method (CM)

Measurement data are consistent across all techniques

- Residual strains from ND and EDXRD are in agreement
  - For both 100% and 50% processed samples
- Residual stresses from ND and CM are in agreement
  - For 100% processed samples

Each technique had particular advantages

- ND provided three orthogonal strain and stress components (radial, hoop, and axial)
- EDXRD enabled high spatial resolution and data near the free surface (0.3 mm from edge)
- CM provided a 2D map of the hoop residual stress across the entire plane of measurement

Model outputs exhibit discrepancy compared to the measurement data

- Close to the hole bore, hoop stress and strain from the model are 40% higher than from measurement

Data for the 50% sample showed that discrepancies appear during the loading phase of Cx and then persist during unloading and at process end

- Material behavior appears to differ from the assumed plasticity model (isochoric, J_2 flow theory) during Cx loading

The present data can support development of an improved constitutive model applicable to Cx

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)
Kyle Johnson (Sandia)
Philip Reu (Sandia)
D. Michael Autenrieth (Sandia)
Dan Moser (Sandia)

Mission Statement & Background

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

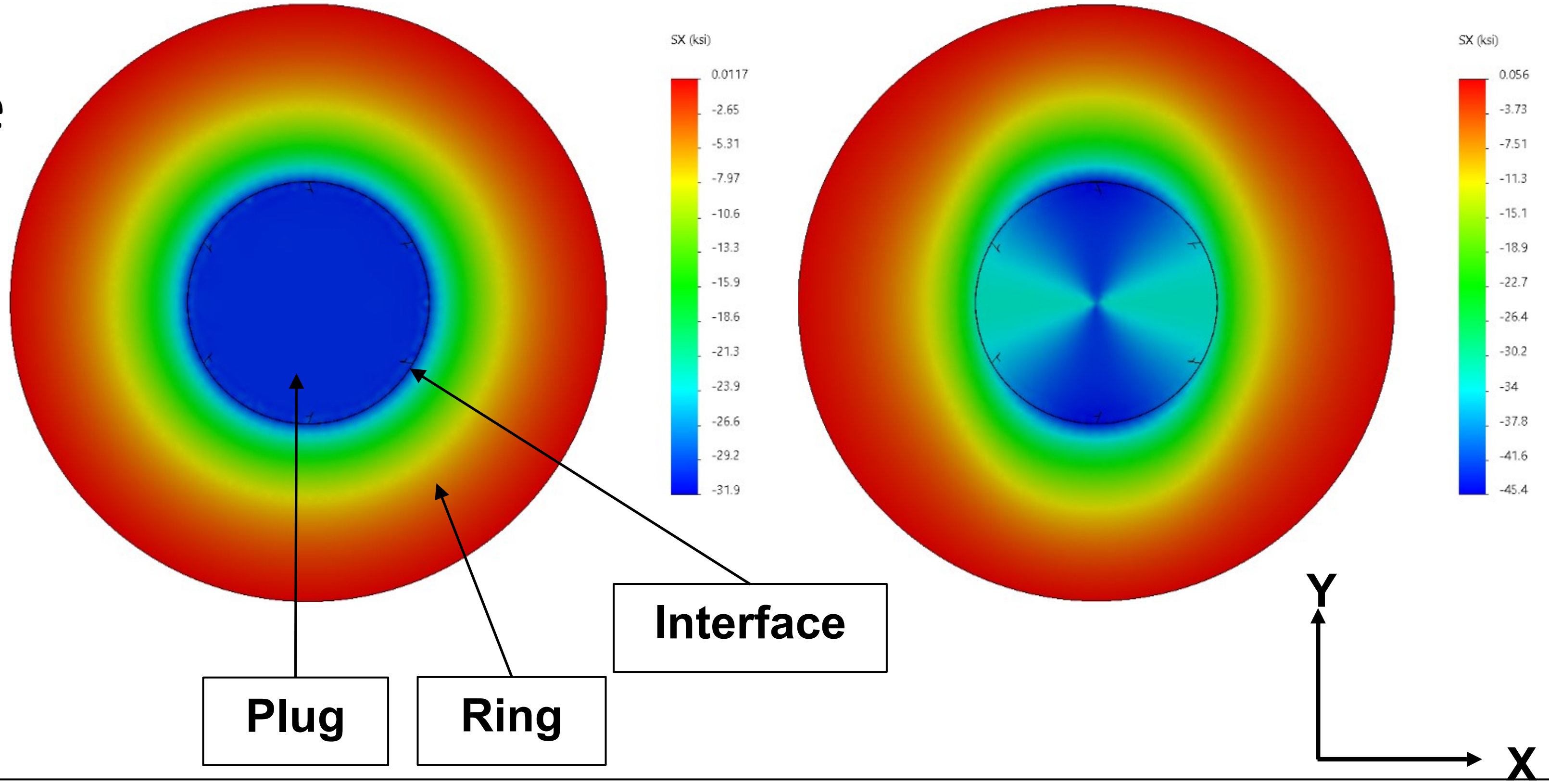
- Focused on RS hole drilling
- Ring and Plug sample

$$\begin{bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \sigma_{23}\\ \sigma_{13}\\ \sigma_{12}\end{bmatrix} = \begin{pmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0\\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0\\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0\\ 0 & 0 & 0 & C_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & C_{44} & 0\\ 0 & 0 & 0 & 0 & 0 & C_{44}\end{pmatrix} \begin{bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ 2\varepsilon_{23}\\ 2\varepsilon_{13}\\ 2\varepsilon_{12}\end{bmatrix}$$

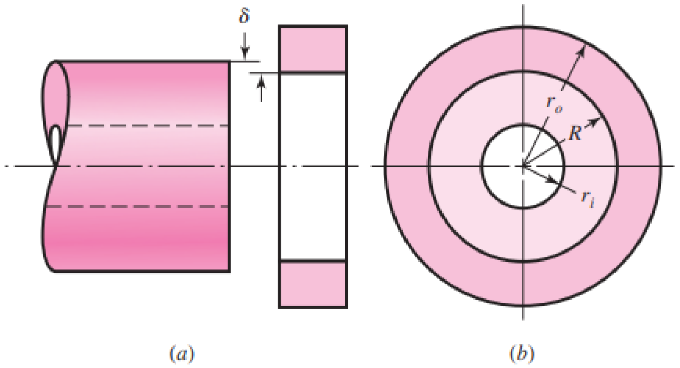
where $C_{44} = 0.5(C_{11}-C_{12})$

$$\begin{bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \sigma_{23}\\ \sigma_{13}\\ \sigma_{12}\end{bmatrix} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16}\\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26}\\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36}\\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46}\\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56}\\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66}\end{pmatrix} \begin{bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ 2\varepsilon_{23}\\ 2\varepsilon_{13}\\ 2\varepsilon_{12}\end{bmatrix}$$

$E_x = E_y = 28{,}000$ ksi **$E_x = 28{,}000$ ksi $E_y = 36{,}400$ ksi**



Ring and Plug Sample Definition



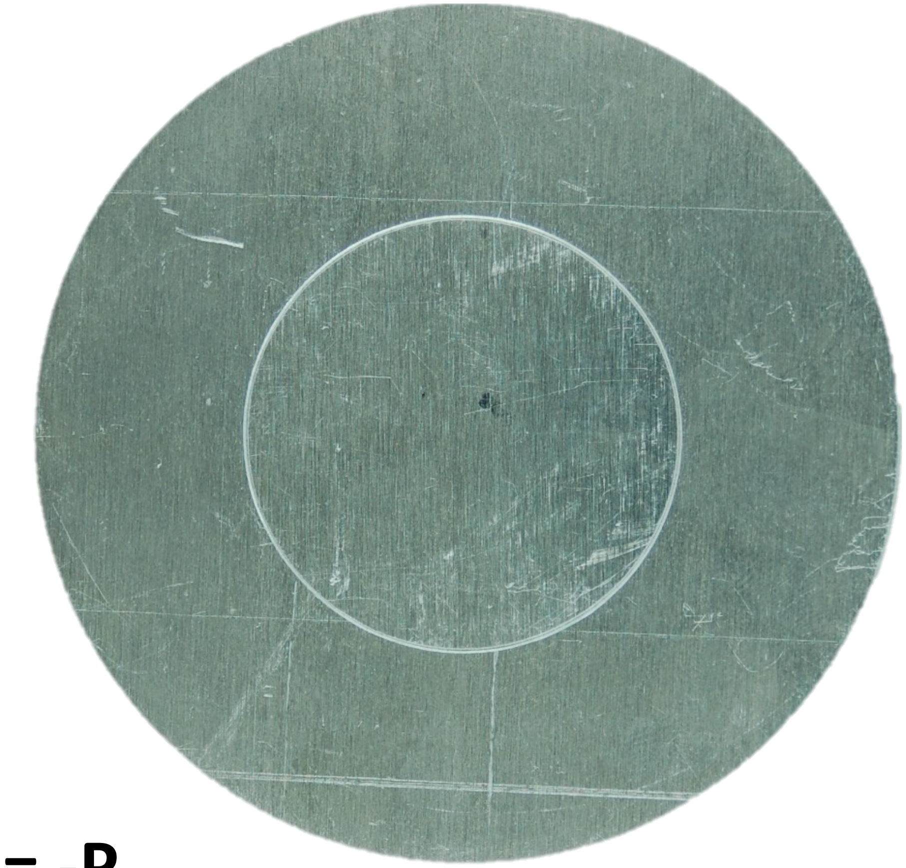
$$\sigma_h = \frac{P_i {r_i}^2 - P_o {r_o}^2 - {r_i}^2 {r_o}^2 \frac{P_o - P_i}{R^2}}{{r_o}^2 - {r_i}^2}$$

$$\sigma_r = \frac{P_i {r_i}^2 - P_o {r_o}^2 + {r_i}^2 {r_o}^2 \frac{P_o - P_i}{R^2}}{{r_o}^2 - {r_i}^2}$$

$$P = \frac{\delta}{R\left[\frac{1}{E_o}\left(\frac{{R_o}^2 + R^2}{{R_o}^2 - R^2} + v_o\right) + \frac{1}{E_i}\left(\frac{{R_i}^2 + R^2}{{R_i}^2 - R^2} + v_i\right)\right]}$$

Inside the plug, assuming $R_i = P_i = 0$

$\sigma_h = \sigma_r = -P$



- $E_o = E_i = 10{,}600$ ksi
- $V_o = V_i = 0.28$
- $R = 1''$
- $R_o = 2''$
- $\delta = 0.00355''$

$\sigma_{Analytical} = -13.2$ ksi

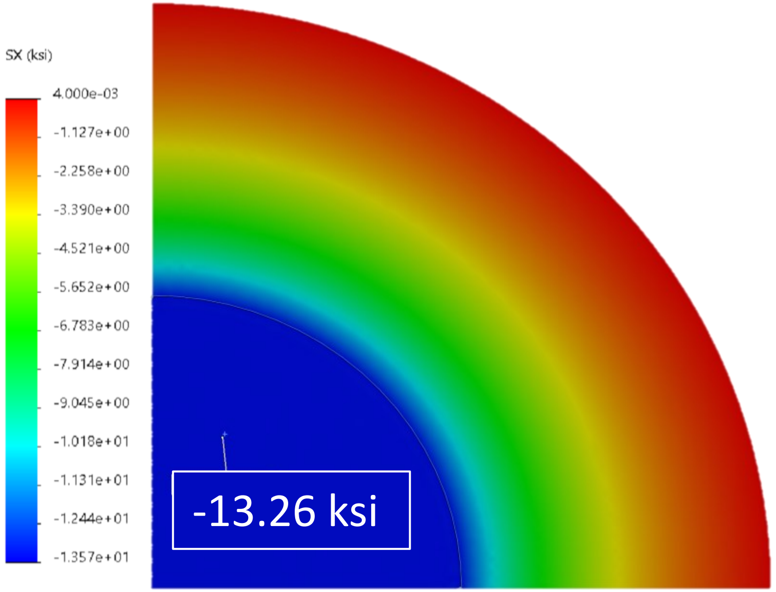
Residual Stress Measurement Technique Comparison

- Round Robin Measurements
  - Residual Stress Hole Drilling (HD) (ASTM E837)
  - X-Ray Diffraction (XRD) (ASTM E915, E1426, and SAE H5784)
  - Electronic Speckle Pattern Interferometry (ESPI)
- Aluminum 2024-T351, assumed to be elastically isotropic

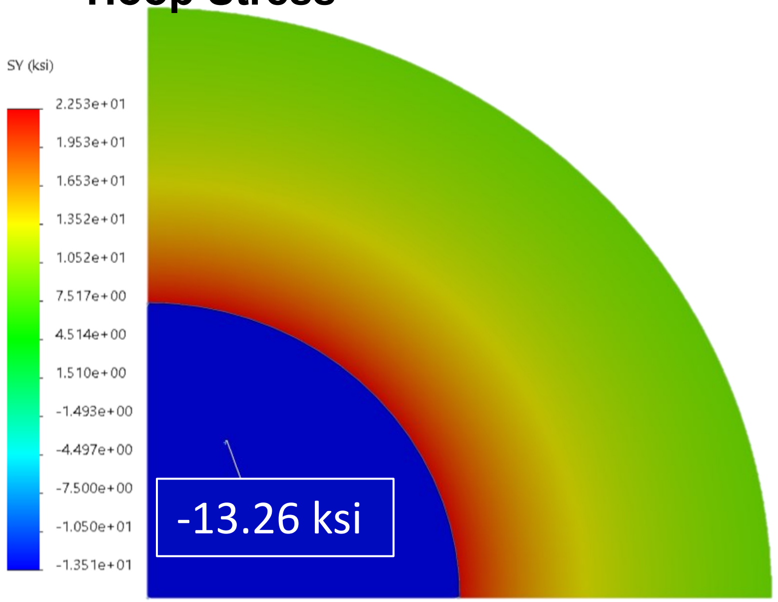
$\sigma_{Simulated}$ = -13.26 ksi

Technique	Elastic Constant	Value
HD / ESPI	E	10,600 ksi
	v	0.33
XRD	XEC_{RD}	7,832 ksi
	XEC_{TD}	7,907 ksi

Radial Stress

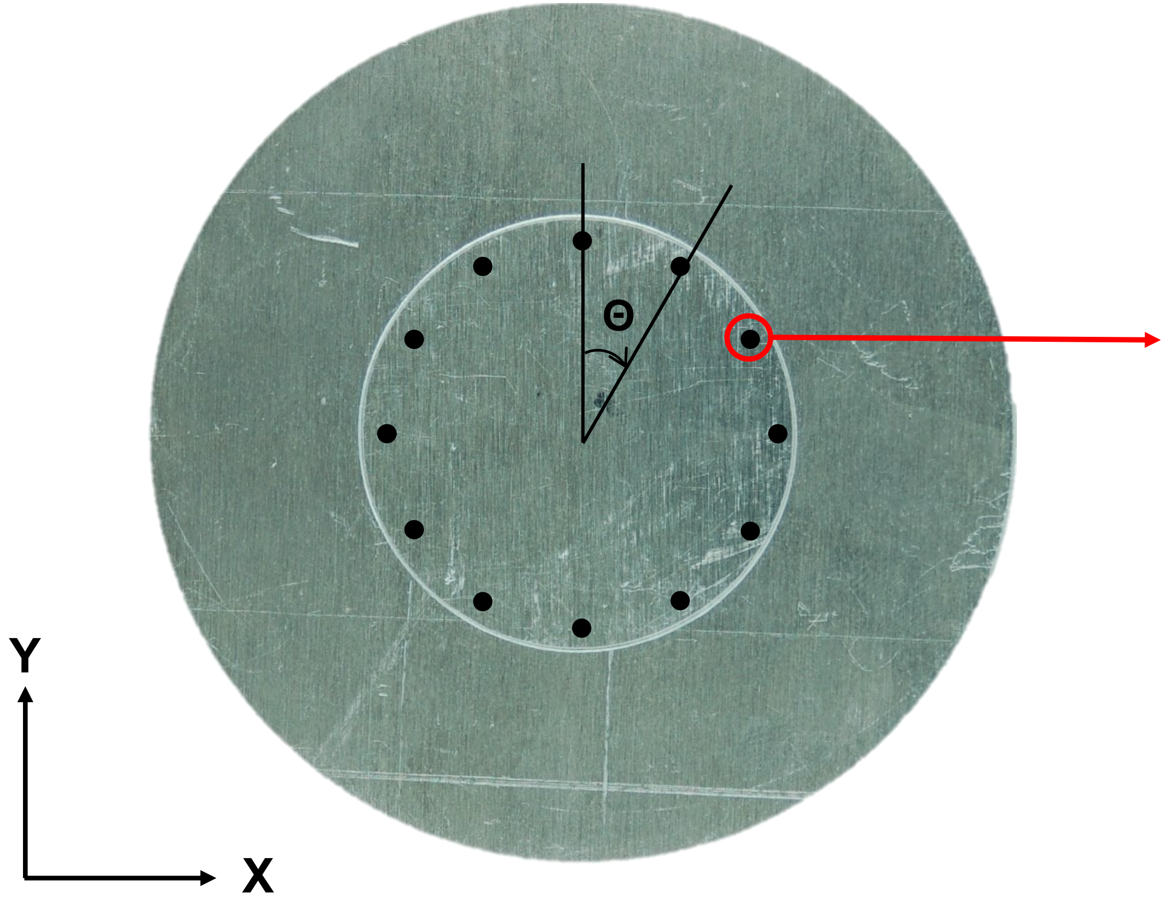


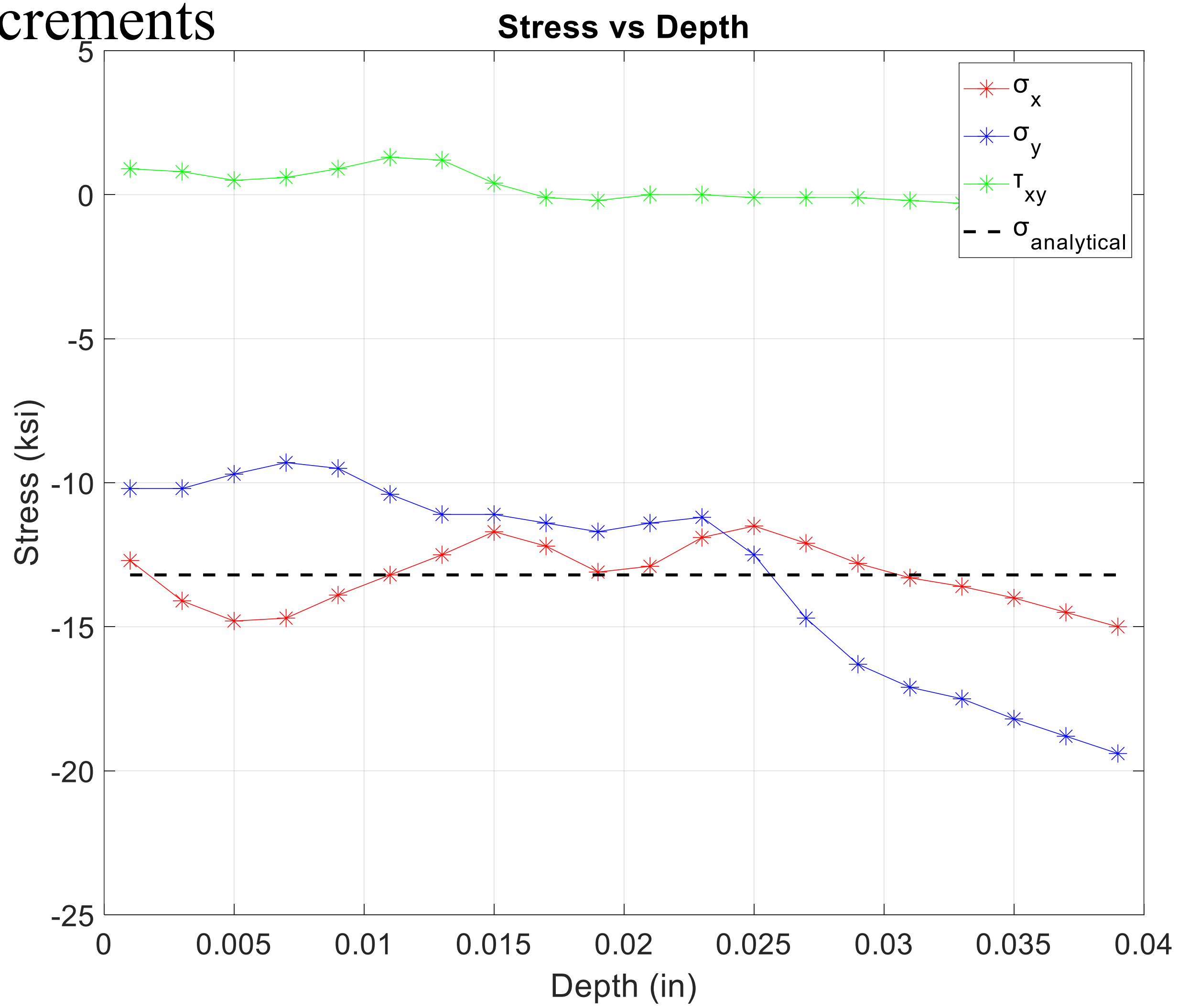
Hoop Stress



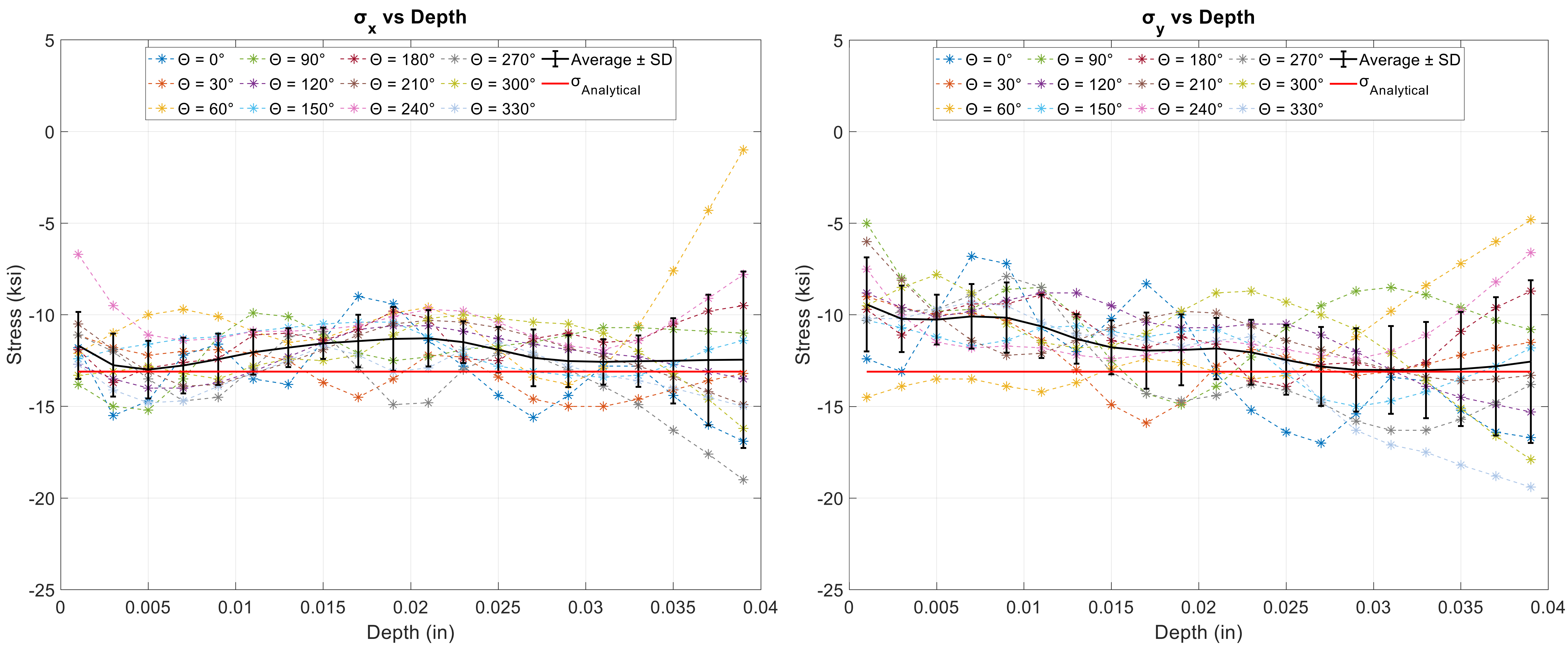
Hole Drilling Method - AFRL

- Measurements made using DART (US Patent 10,900,768) (Appendix A)
- Total of 12 measurements made at 30° increments



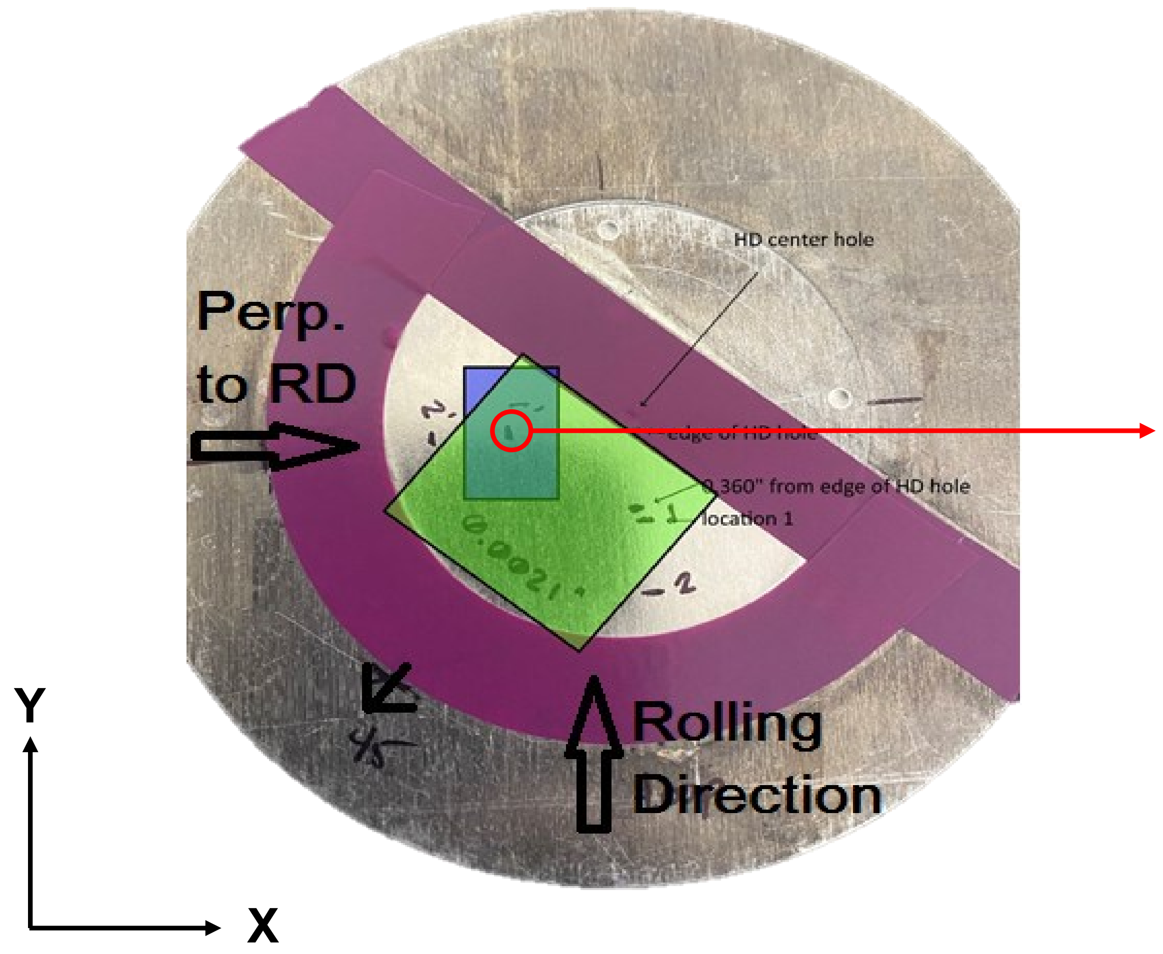


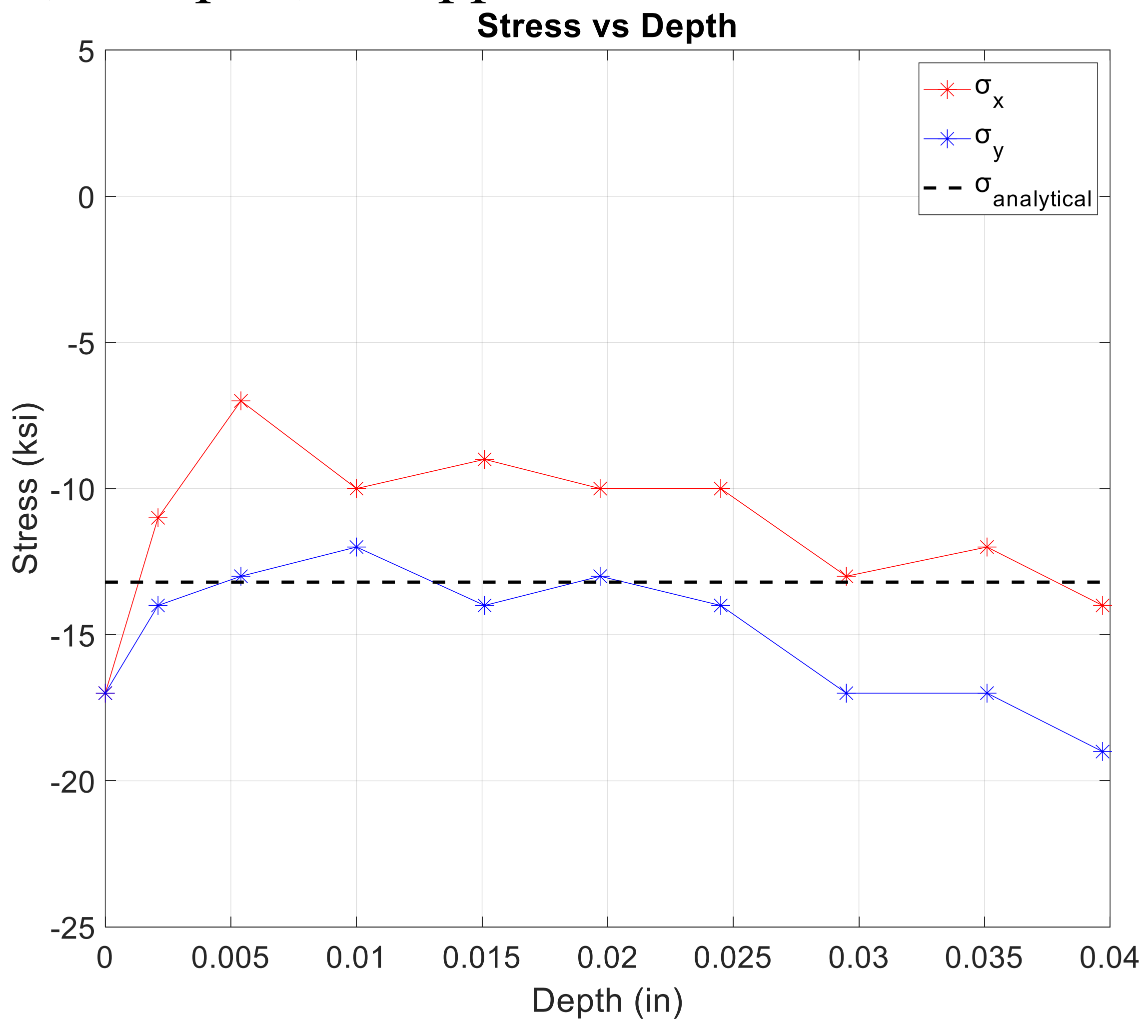
All 12 Hole Drilling Stress Profiles



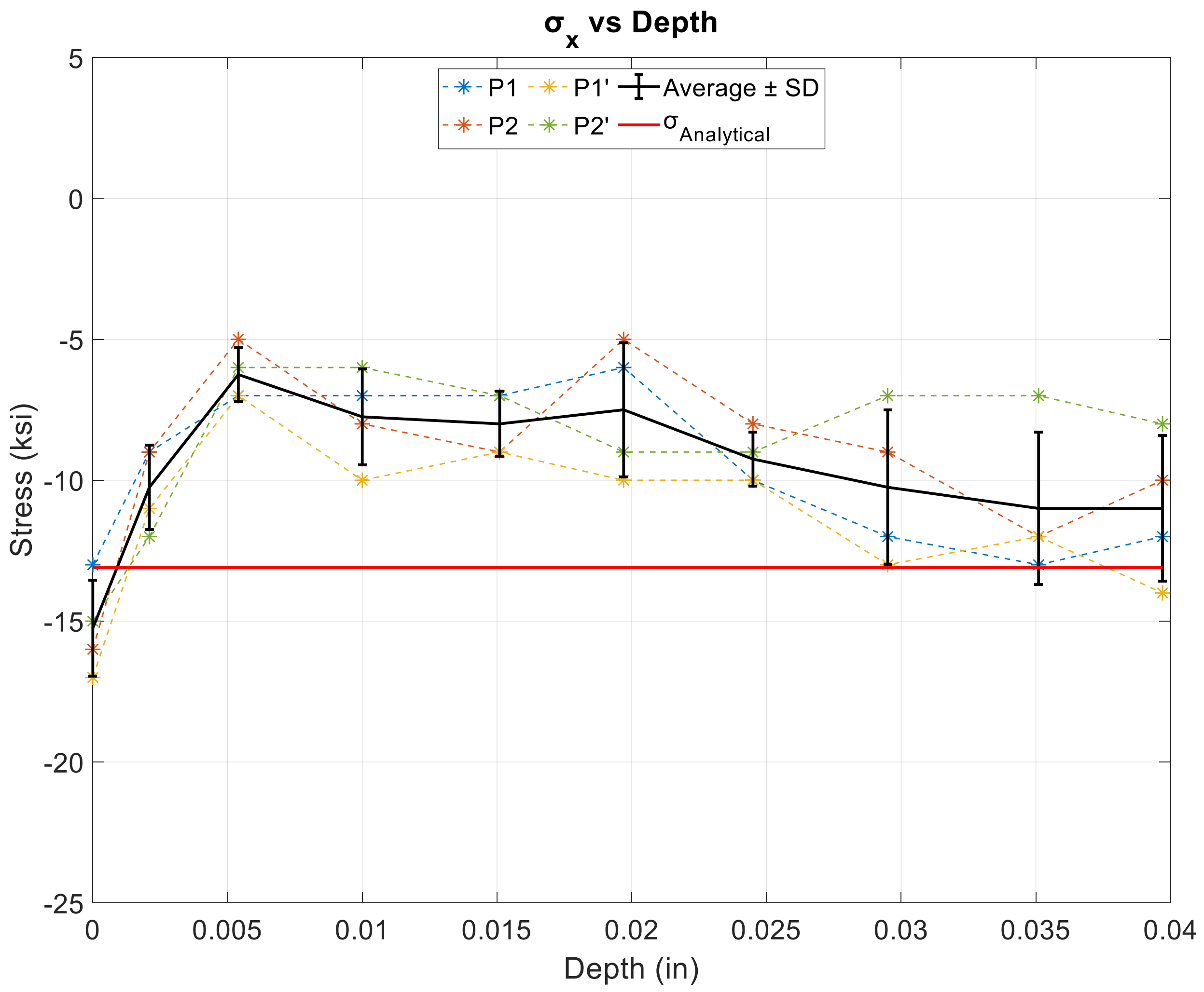
X-Ray Diffraction – Proto Manufacturing

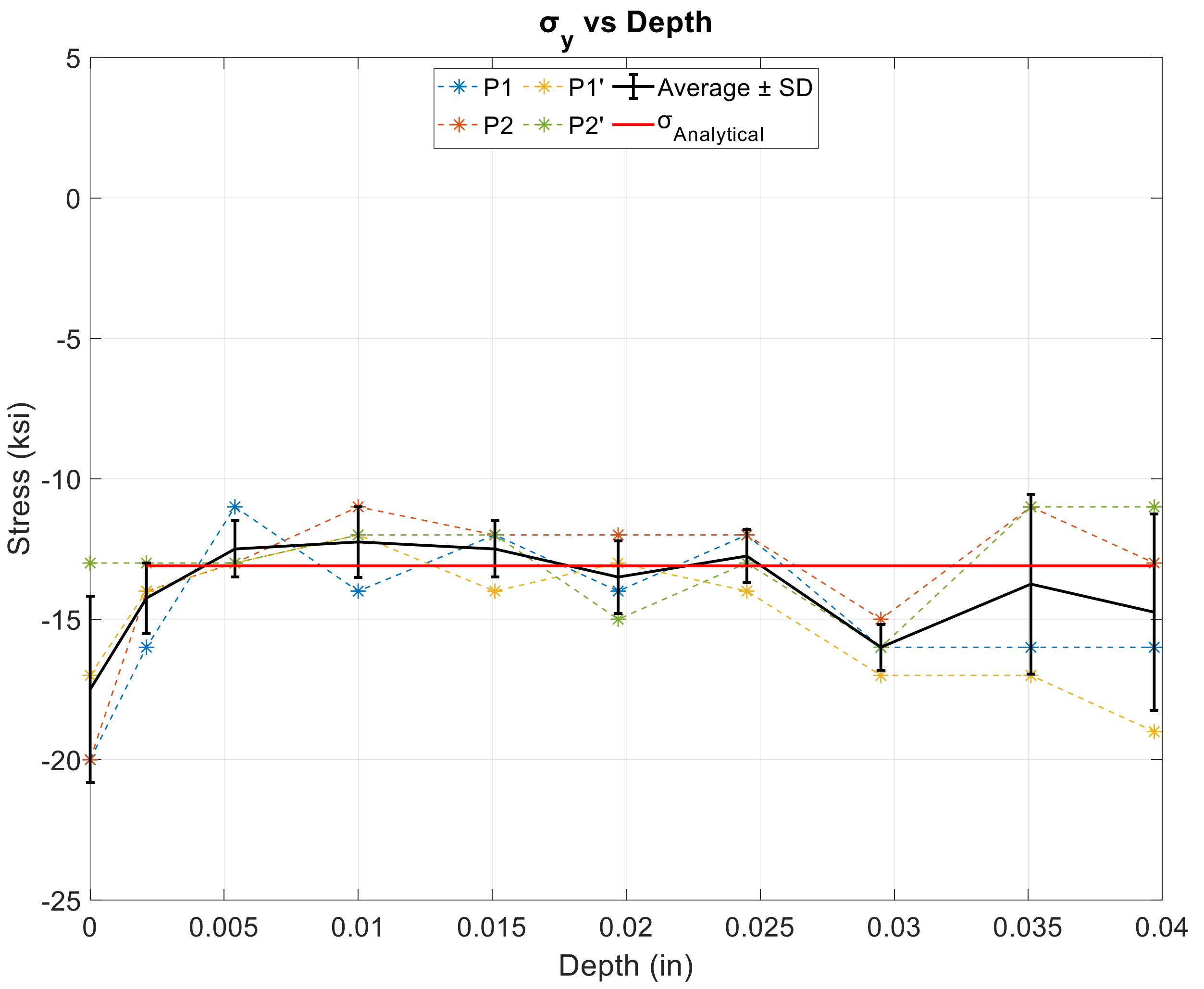
- 4 locations at 2 different radii, 90°apart, on opposite face as HD





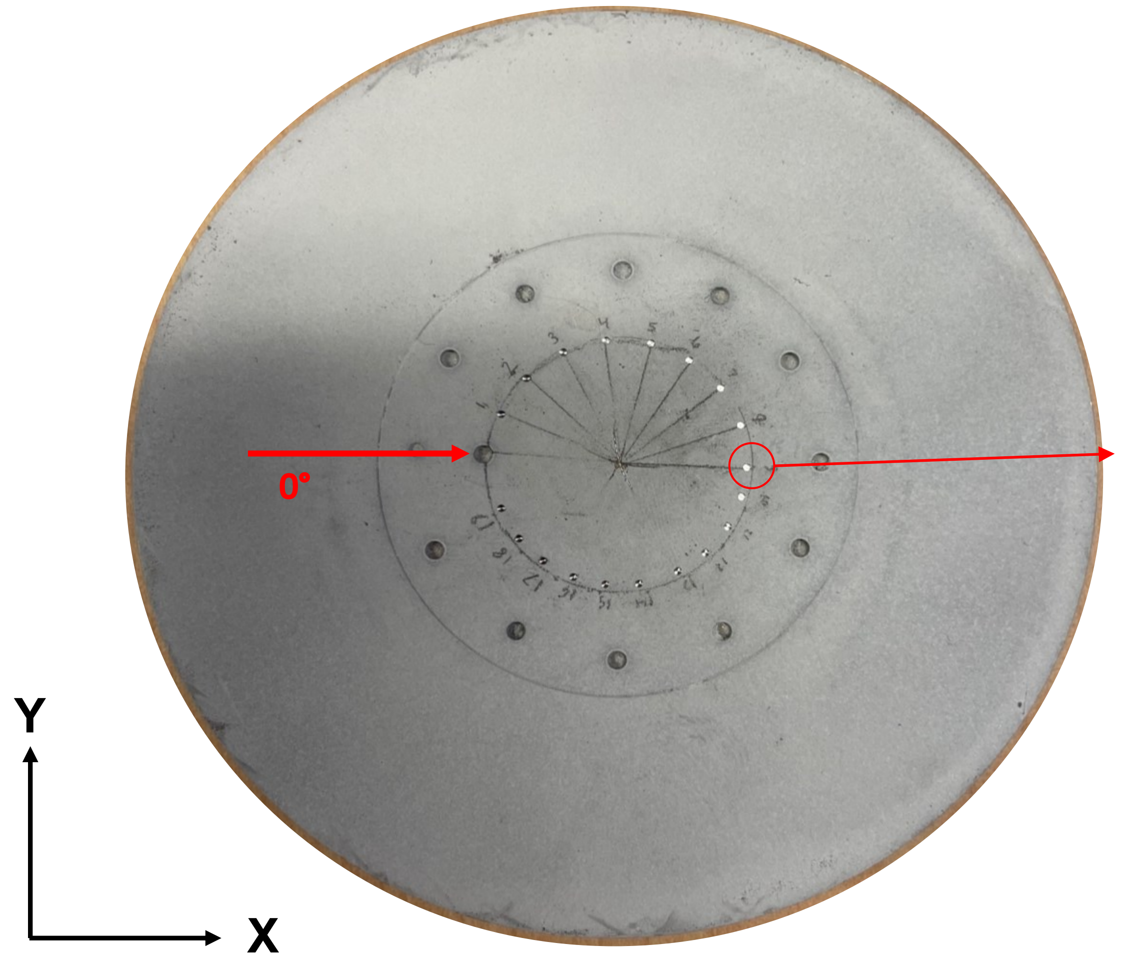
All 4 X-Ray Diffraction Stress Profiles

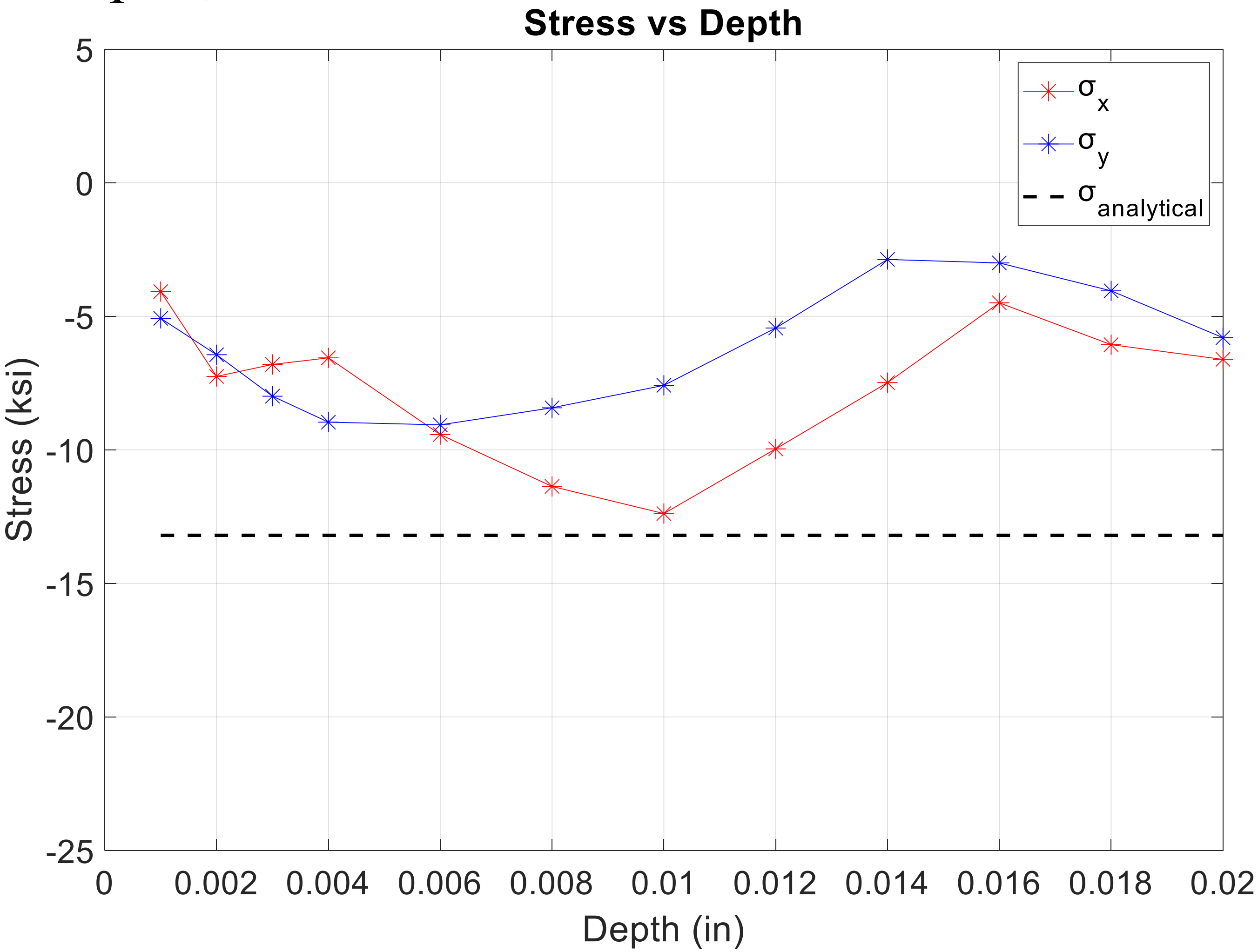




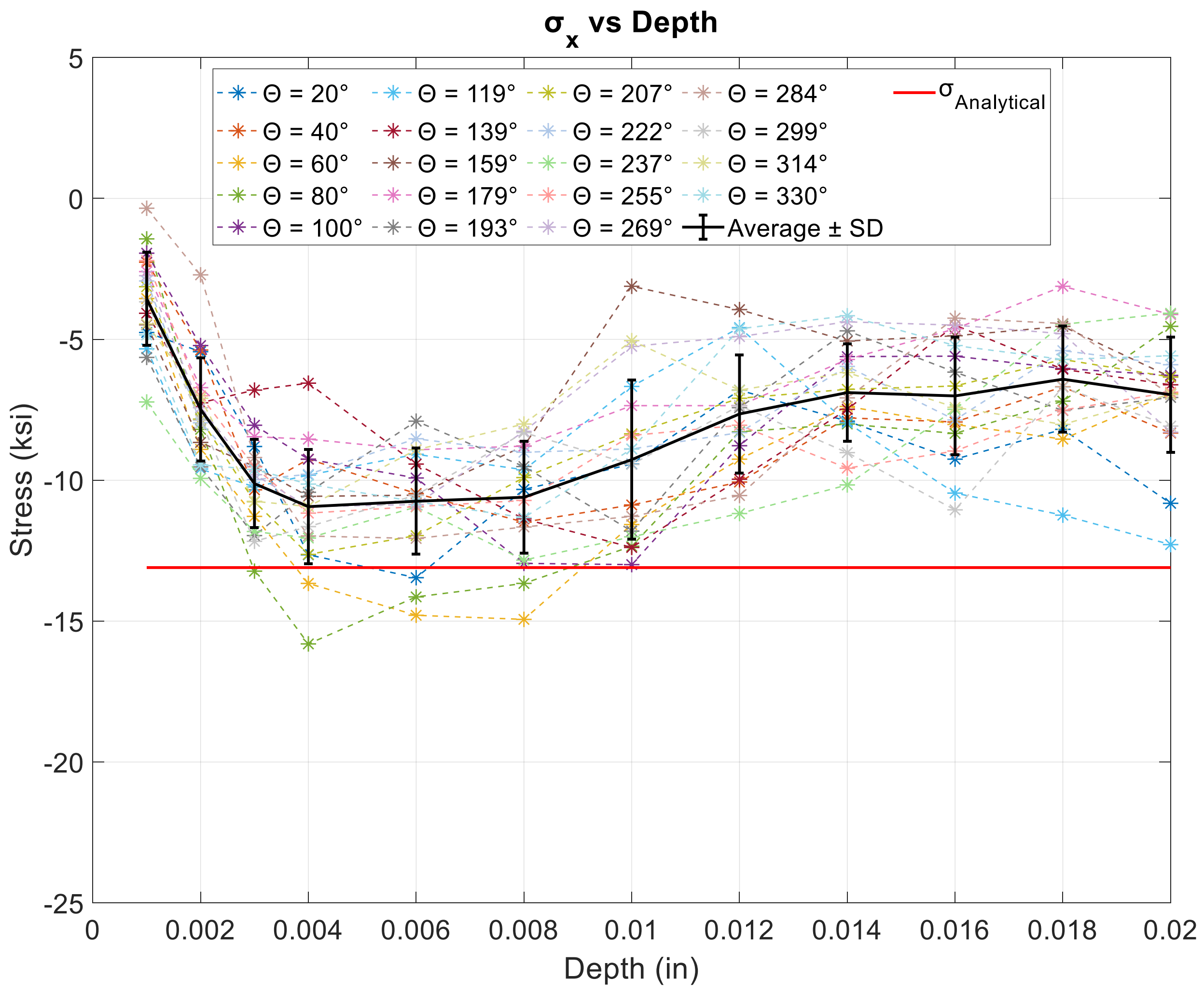
ESPI (Prism) – Sandia National Laboratories

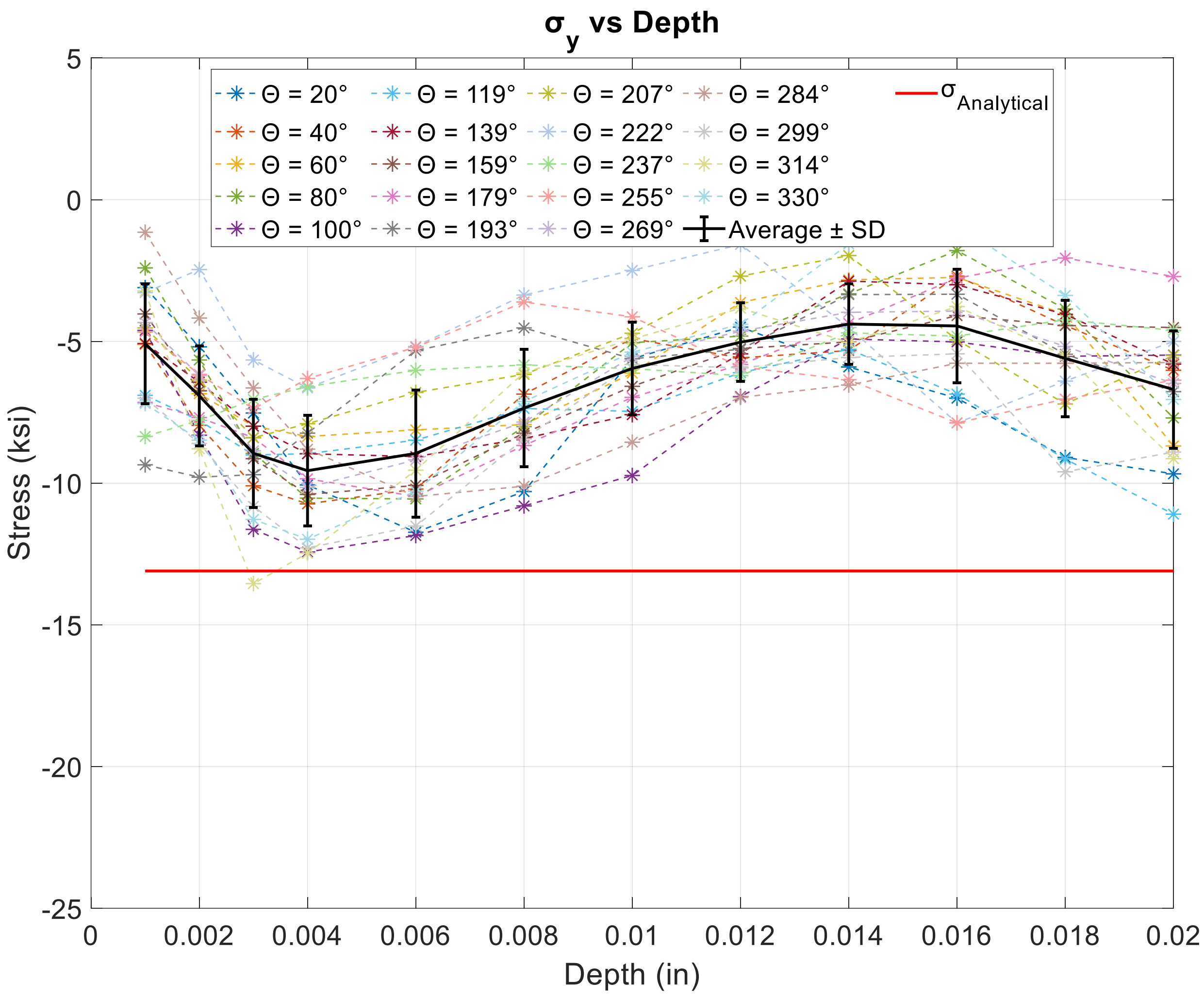
- 19 locations between 14-20°apart, made on same face as HD



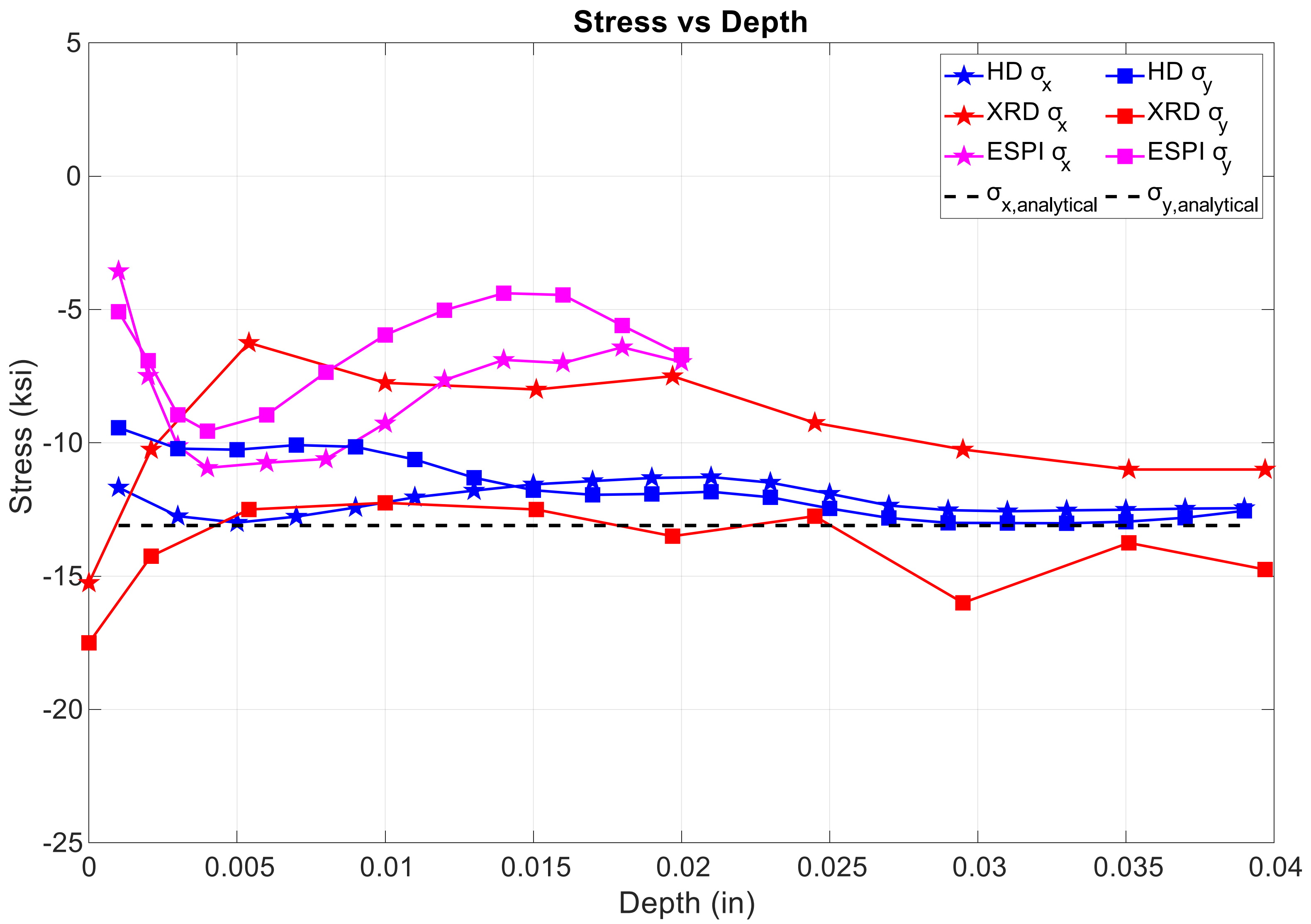


All 19 ESPI Stress Profiles





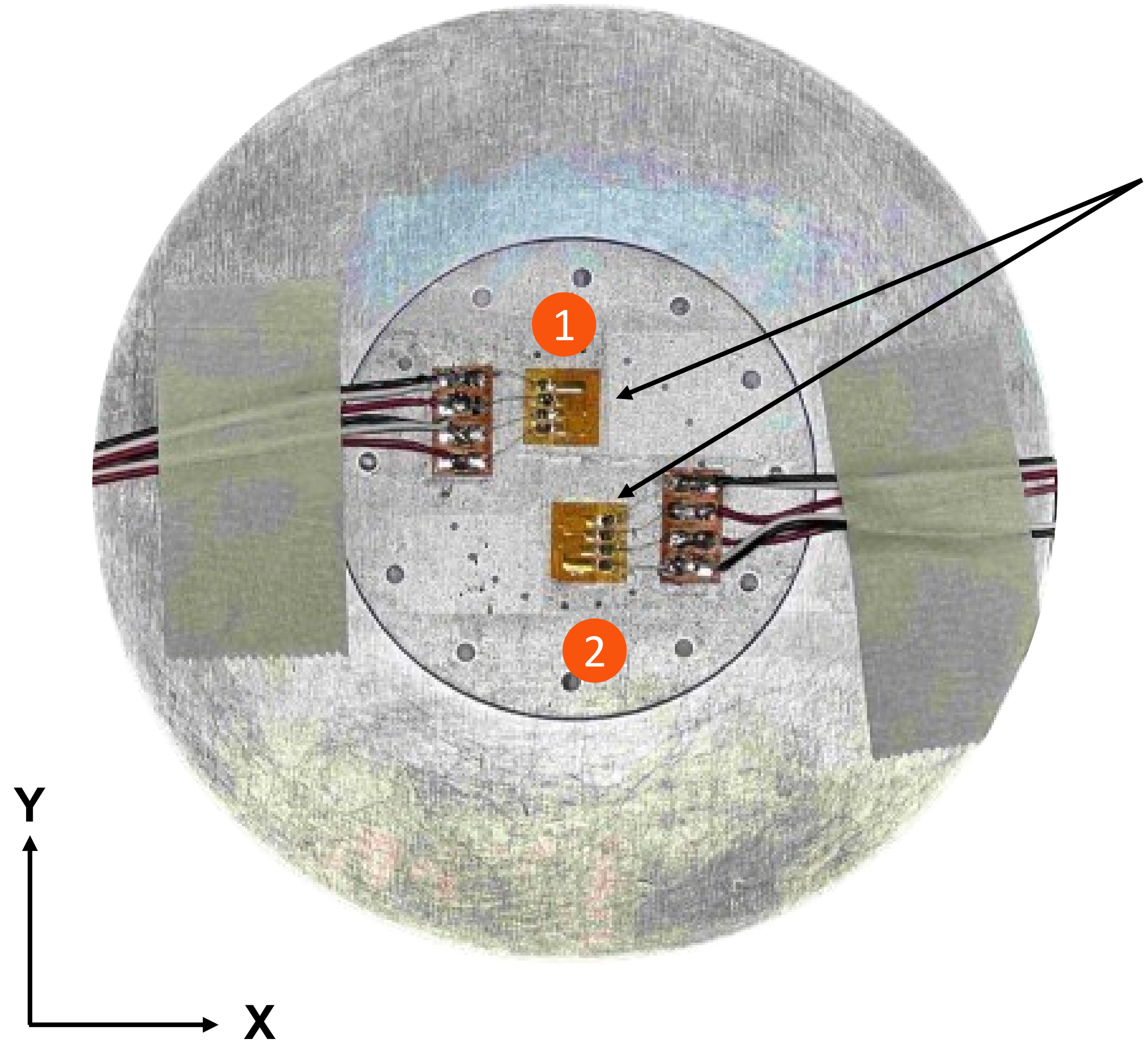
Round Robin Summary

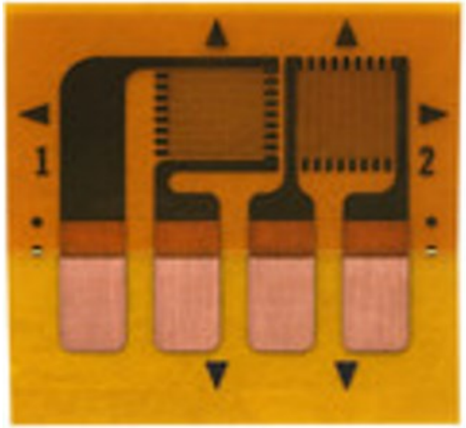


$$\Delta\sigma = \sigma_{analytical} - \bar{\sigma}$$

Method	σ	Δσ (ksi)
HD	σ_x	1.0
	σ_y	1.4
XRD	σ_x	3.5
	σ_y	0.9
ESPI	σ_x	5.0
	σ_y	6.5

Stress Measured from Ring Removal





Gage #	$\Delta\varepsilon_x$ (με)	$\Delta\varepsilon_y$ (με)
1	773.2	789.8
2	748.3	750.4

Method	Ring Removal	HD	XRD	ESPI
σ_x (ksi)	-12.1	-12.1	-9.7	-8.1
σ_y (ksi)	-12.1	-11.7	-14.0	-6.6

Summary

- Highlighted the variability of residual stress measurement techniques
- Comparable results for the three techniques
- Elastically isotropic samples provide a good baseline for the development and comparison of elastically anisotropic samples

Future Work

- Utilizing RUS quantify anisotropic elastic constants of textured brass for ring and plug assembly design
- Conduct residual stress measurements on ring and plug sample manufactured of elastically anisotropic material
- Build framework to simulate incremental hole drilling for experimental comparison
- Conducting similar round robin measurements for steel ring and plug sample
- For more information regarding this work check out "Effects of Elastic Anisotropy on Residual Stress Measurements Performed Using the Hole-Drilling Technique" being published this summer

Appendix A

Device for

Automated

Residual Stress

Test

Courtesy of:

Hill Engineering

Appendix A

LXRD

Stress Analyzer

Courtesy of:

Proto Manufacturing

Future Opportunities

Bring us your problems!

Continuation of active work

New! Residual Stress Characterization Committee

- RS Measurement
- RS Process Simulation
- Uncertainty Quantification

Nondestructive Evaluation for Quality Assurance and Surveillance of Cold-worked Fastener Holes

Eric Lindgren

Materials State Awareness Branch

Materials and Manufacturing Directorate

April 20, 2023

Acknowledgments – Contractor Team

Hill Engineering

- Josh Hodges
- Bob Pilarczyk
- Dallen Andrew
- Adrian DeWald

Southwest Research Institute

- Clint Thwing
- Adam Cobb
- Nathan Richter
- Nikolay Alimov

HILL ENGINEERING

SwRI®

Outline

- Motivation / Impact
- Challenges
- Technical Approach
- Testing
- Results
- Summary
- Way Forward

Photograph by author

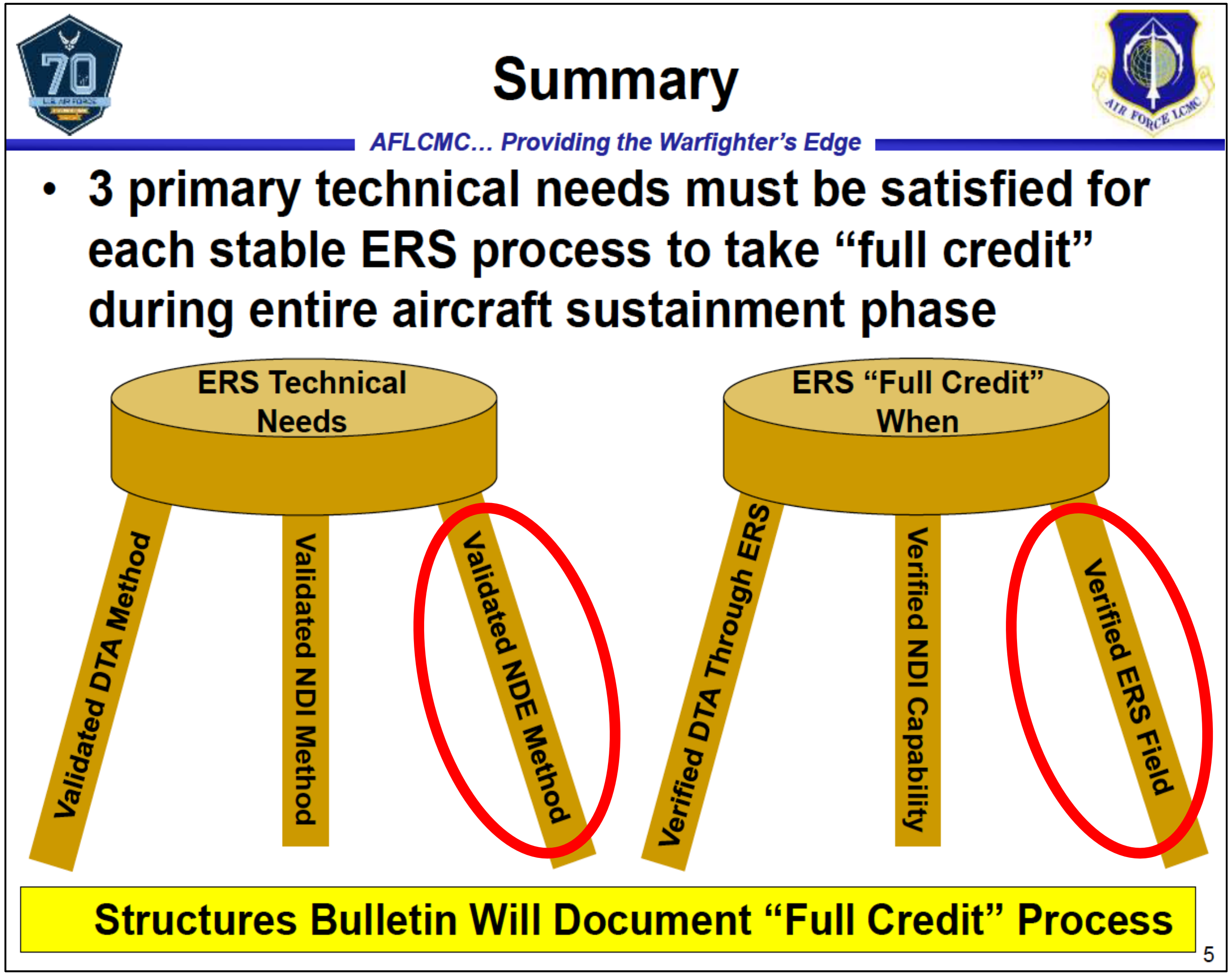
Motivation / Impact

Motivation

- QA of Cx process to ensure residual stresses are present
- Verification residual stresses remain present during life

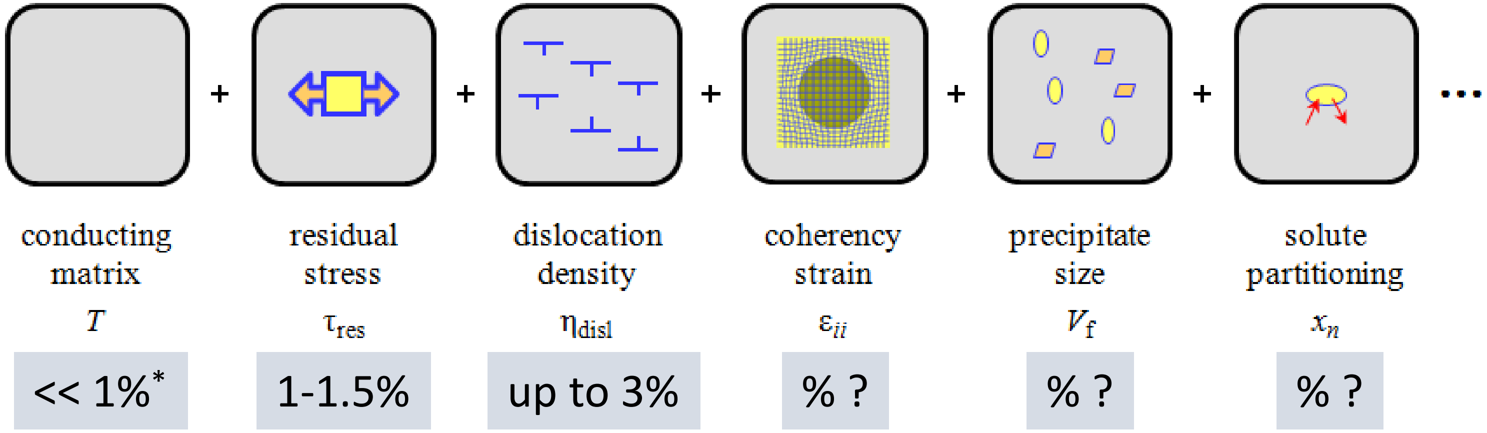
Impact

- Enhanced life management
- Extended inspection intervals



Briefing chart from Charles Babish, available at: http://www.meetingdata.utcdayton.com/agenda/asip/2017/proceedings/presentations/P13677.pdf

NDE of Residual Stress: Challenges



* Temperature controlled environment

- **Lots of factors affect measurement in addition to residual stress**
  - **Microstructural complications simplified with aluminum alloys**
  - **Macro-scale considerations: temperature and geometry**
  - **USAF considerations: manufacturing (e.g. fit-up stresses), maintenance, modification, repair, use**
- **Deconvolve or control as much as possible**
- **Maximize sensitivity analysis**

Technical Approach

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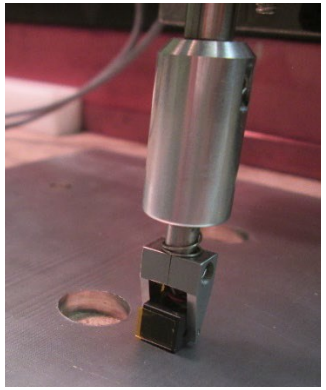
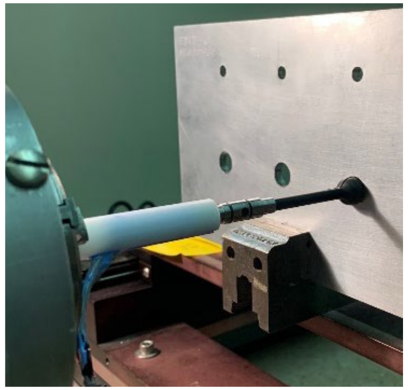
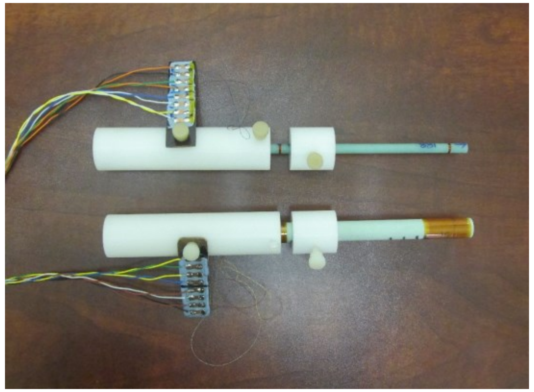
- Develop NDE techniques for quantifying the residual stress state at Cx holes
- Evaluate and rank NDE techniques for quantifying the residual stress state at Cx holes
- Investigate key confounding factors and their influence on NDE response
- Optimize NDE techniques for evaluation Cx holes
- Demonstrate the NDE techniques for evaluation of Cx holes
- Verify the NDE techniques for evaluation of Cx holes
- Sensing approaches explored:



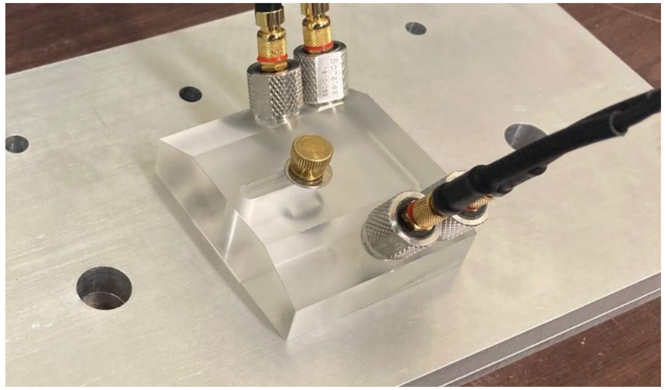
Eddy Current Surface Probe



Low Frequency Eddy Current



Four Coil In-hole Eddy Current Probe



Ultrasonic Longitudinal Critically Refracted Wave Probe

Program Goals

Desired performance:

- Geometry: open holes – 0.25” and 0.5”
- Materials: aluminum alloys: 2024-T351 and 7075-T651
- Environment: field and Depot (plus manufacturing)
- Surface condition: minimal preparation
- Rapid data acquisition: prefer less than one minute
- Equipment: minimize specialize equipment
- Sensitivity: 90% detection of detect cold-worked holes (applied expansion of 3%)

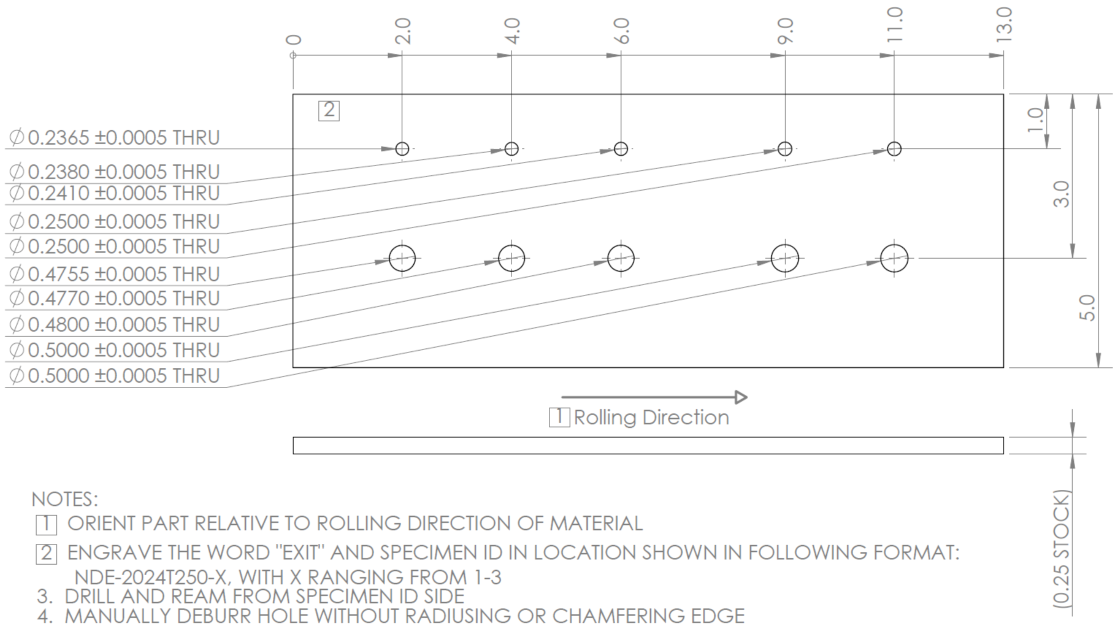
Representative Depot Maintenance

Representative Manufacturing

Testing (Lots of Testing!)

Testing matrices included:

- Levels of cold work
- Hole diameters
- Confounding factors
- Variability
- Coupons
- Extracted components
- In-Depot demonstration



Representative multi-hole coupon machining drawing (0.250” thickness)

Evaluated Confounding Factors

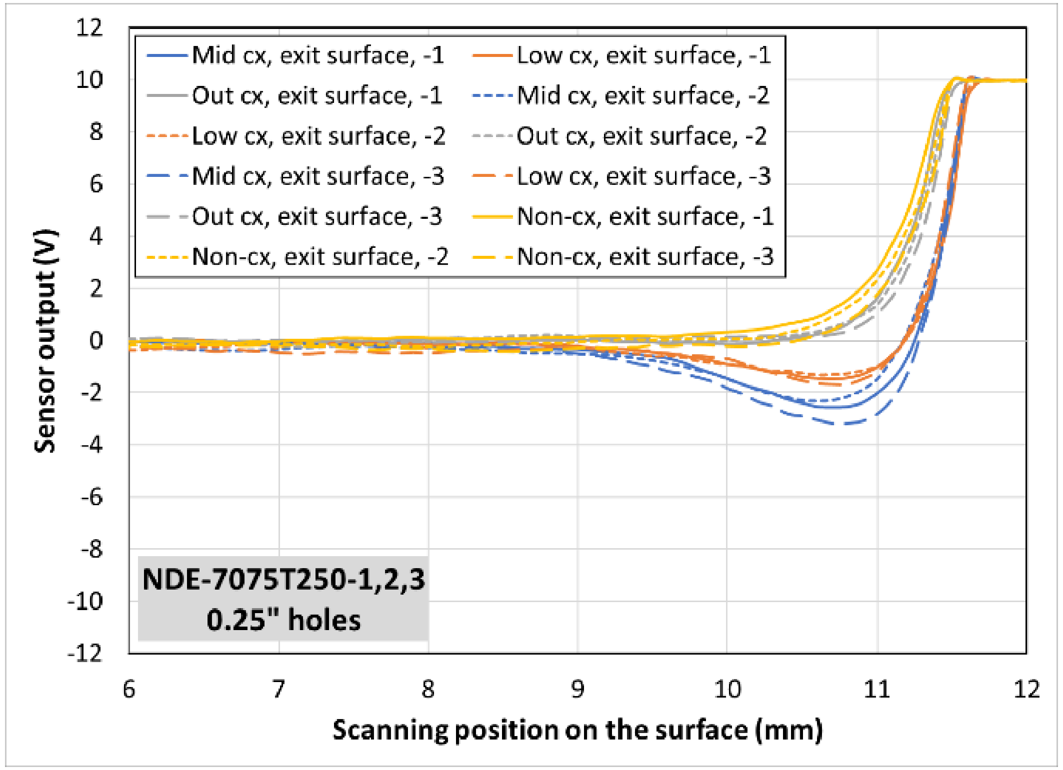
- **Eddy Current centric**

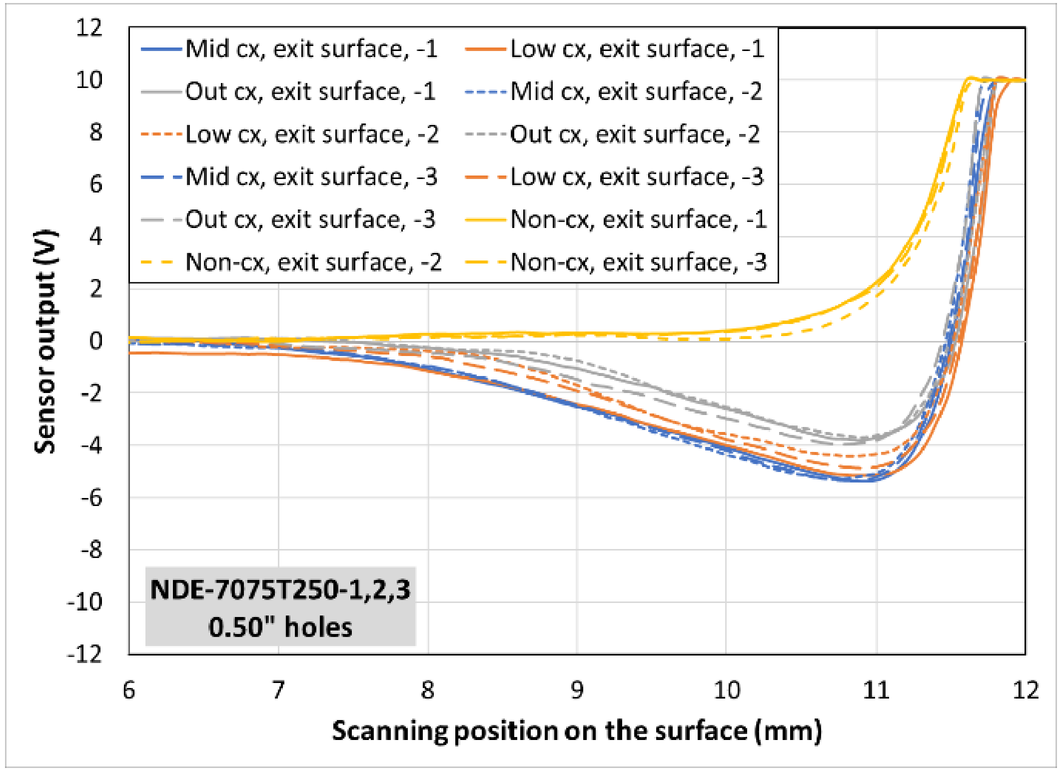
Factor	Influence on NDE response – ET
Electrical Conductivity: Global	High
Electrical Conductivity: Through Thickness Variation	Medium
Hole Diameter	Medium
Plastic Strain	Medium
Coatings/Paint	Medium
Hole Skew	Medium or Low
Operational Overloads	Medium or Low
Temperature Variation – Long Term Changes	Medium or Low
Temperature Variation – Short Term Fluctuation	Medium or Low
Acoustoelasticity	Low
Chemical Composition	Low
Cross-Section Changes	Low
Hole Edge Margin	Low
Hole Pitch	Low
Hole Roundness	Low
Microstructure – Global	Low
Microstructure – Local	Low
Static Loads	Low
Surface Corrosion	Low
Surface Flatness	Low
Surface Roughness	Low
Surface Treatment	Low
Thermal Conductivity	Low
Thermal Exposure	Low

- **Ultrasound centric**

Factor	Influence on NDE response – UT
Acoustoelasticity	High
Coatings/Paint	High or Low
Chemical Composition	Medium
Hole Diameter	Medium
Hole Edge Margin	Medium
Hole Pitch	Medium
Microstructure – Global	Medium
Microstructure – Local	Medium
Operational Overloads	Medium
Surface Corrosion	Medium
Surface Flatness	Medium
Temperature Variation – Long Term Changes	Medium
Temperature Variation – Short Term Fluctuation	Medium
Cross-Section Changes	Medium
Thermal Conductivity	Low
Electrical Conductivity: Global	Low
Electrical Conductivity: Through Thickness Variation	Low
Hole Roundness	Low
Hole Skew	Low
Plastic Strain	Low
Static Loads	Low
Surface Roughness	Low
Surface Treatment	Low
Thermal Exposure	Low

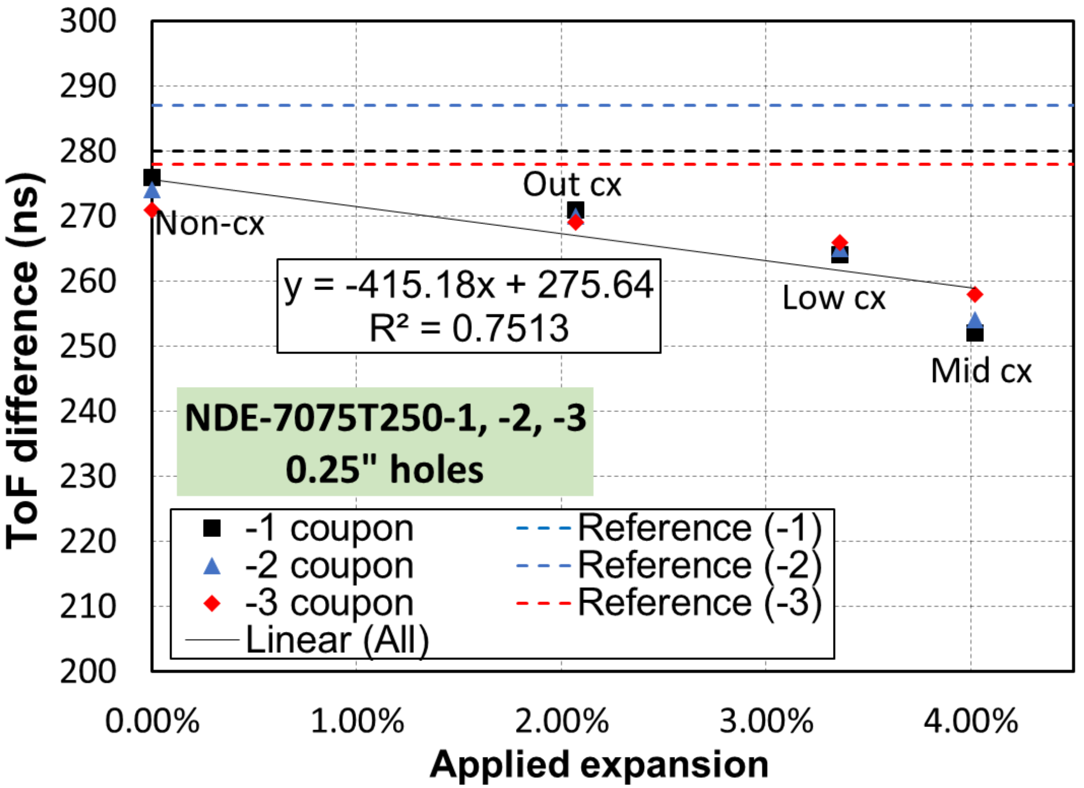
Representative Result: Eddy Current Surface Probe

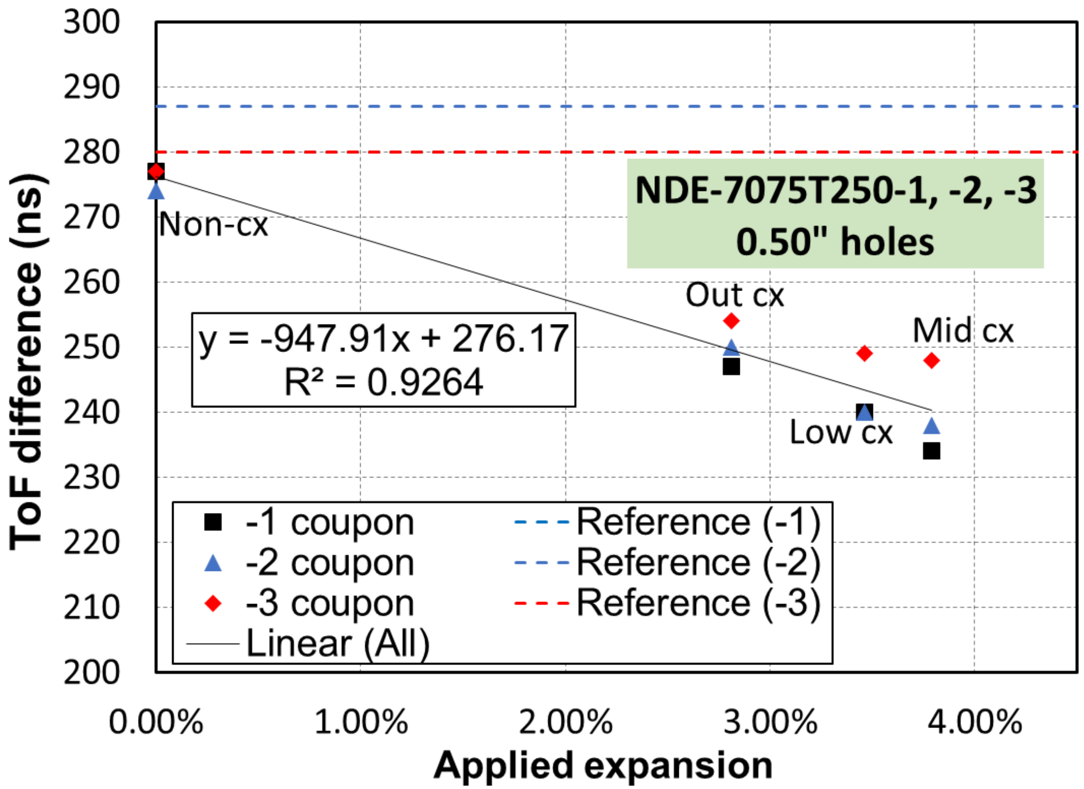




- **Left: 7075 coupons with 0.250 inch thickness, 0.25 inch holes**
- **Right: 7075 coupons with 0.250 inch thickness, 0.50 inch holes**

Representative Result: Ultrasound LCR Probe





- **Left: 7075 coupons with 0.250 inch thickness, 0.25 inch holes**
- **Right: 7075 coupons with 0.250 inch thickness, 0.50 inch holes**

Way Forward – Remaining Challenges

- Address effect of cold-work volcano
  - Impact of surface eddy current results
  - Potential effect on LCR time-of-flight
- Probe optimization
  - Frequency, geometry, durability, fixturing
- May need both approaches
  - Eddy current for QA post cold work of fastener hole
  - Ultrasound for quantitative surveillance during in-service
- Validation study
- Simplified integration into current NDE practice
- Data capture and storage (other programs underway to address this capability)

Summary

Current 6.2 funded effort realized objectives

- Leveraged NDE experience detecting residual stress

Two potential approaches identified

- Surface scanning eddy current with differential coil
- Longitudinal critically refracted (LCR) ultrasound probe

Lots of testing to support identified approaches

- Confounding factors, e.g. surface and sub-surface
- Reproducibility: repeated measures on similar conditions
- Variability: hole diameter, magnitude of cold work, and material

Solutions look favorable, but more development required:

- Probe optimization
- Volcano effect
- Validation

} Need for follow-on program

Discussion

Caelum Domenari

THE AIR FORCE RESEARCH LABORATORY

Photograph by Author

ERSI

The IMx+: A Digital Thread Tool to Enable Effective ASIP

Presented by: Dallen L. Andrew, Ph.D.

Co-Authors: Robert Pilarczyk & Josh Hodges

Hill Engineering LLC

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4/20/2023

Digital Thread Definition

What is a Digital Thread?

- Two-way line connecting engineering and maintenance (Mx) in a common data stream
- Required to extend from Mx action through Aircraft Structural Integrity Program (ASIP) engineering processes to development of an inspection interval published in tech data

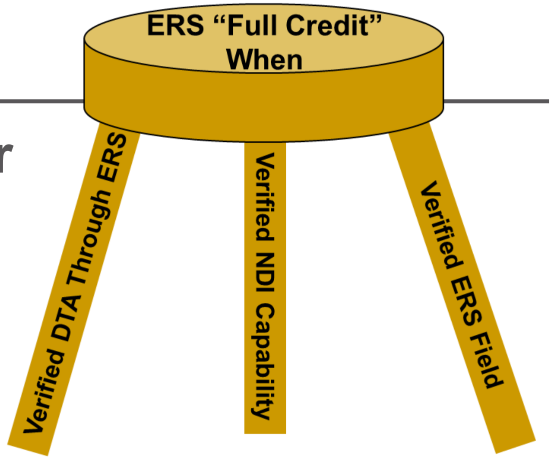
What does a digital thread look like?

- *It depends…*
- Different scenarios require different levels of need for data capture
- Customized Data Fidelity Level (DFL) should be developed for different levels of need

Category	Source	Data Description
Cold Expansion	DigitalEx	Correlation to residual stress
		Pressure profile
		Go/No-Go indication (in/out spec)
NDE	UT/ET Probe	Cx Applied % Expansion
		UT/ET response data
		Go/No-Go indication (in/out spec)
NDI	NORTEC	Screen capture
		Probe settings
		Clock position
		% screen height
		Final cleanup indication
Location	iGPS	(xyz) coordinates for each device

DFL 1: One-off type repairs
DFL 2: Depot-level repairs
DFL 3: Major modification programs

Digital Thread Definition



For cold expansion (Cx) of fastener holes, digital thread data must answer critical ASIP questions to qualify for full credit:

1. *Was Cx accomplished at the correct location?*
2. *Was Cx accomplished (go/no-go)?*
3. *Is the ERS validation traceable?*
4. *Has NDI/NDE been accomplished?*
5. *What are analysis requirements for full credit?*

For NDI process, digital thread data must provide essential data for evaluating inspection:

- Automatically capture and store inspection data (not just pass/fail) to support NDI and engineering
- Identify critical layers and crack locations for stack-ups
- Identify correct location of Mx in aircraft coordinates

Category	Source	Data Description
Cold Expansion	DigitalEx	Correlation to residual stress
		Pressure profile
		Go/No-Go indication (in/out spec)
NDE	UT/ET Probe	Cx Applied % Expansion
		UT/ET response data
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NDI	NORTEC	Screen capture
		Probe settings
		Clock position
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Location	iGPS	(xyz) coordinates for each device

DFL 1: One-off type repairs
DFL 2: Depot-level repairs
DFL 3: Major modification programs

Digital Thread Tools to Enable Effective ASIP

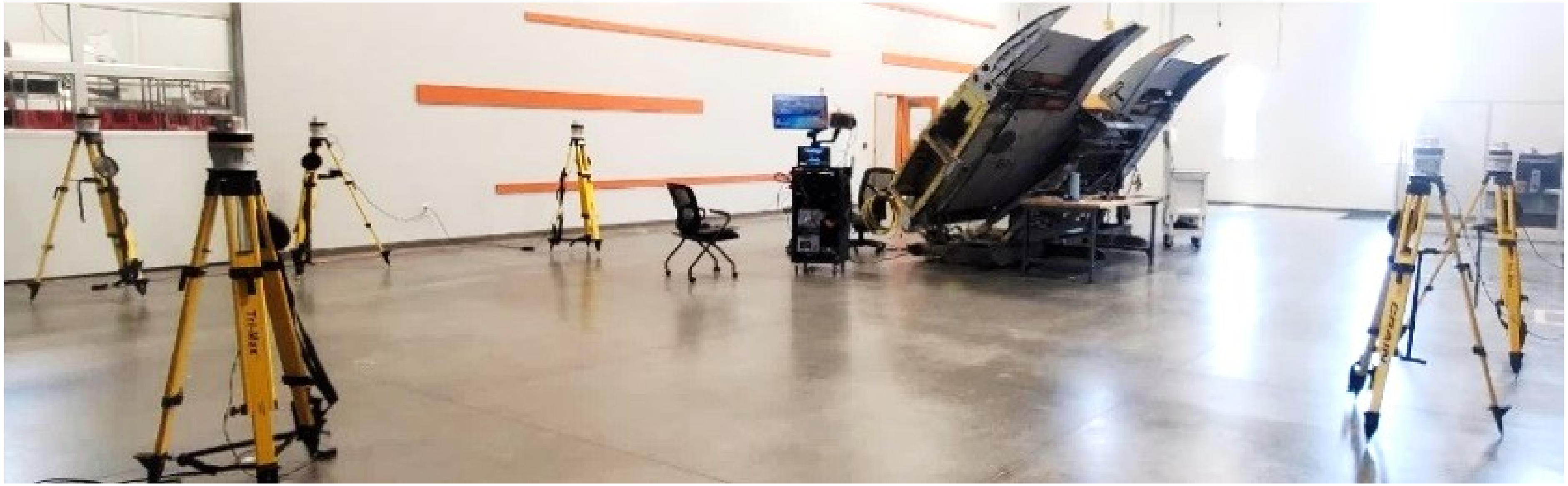
Hill Engineering continues to support multiple USAF-sponsored programs targeted to support digital thread tools to enable an effective ASIP

- Data Spatial Positioning → Integrated Maintenance System (IMx+)
- Digital Thread Tools for NDI Applications of IMx+
- Spatial Registration of NDE Sensors in Enclosed Locations

Digital Thread Tools to Enable Effective ASIP

IMx+

Integrated Maintenance System+



Digital Thread Tools: IMx+ System

Stated Need

“Current challenges include an automated method for digital procedural compliance, importing digital NDI equipment outputs & interfacing with legacy maintenance processing systems. In terms of capturing maintenance data, an automated integrated system doesn’t exist.”

-Lt. Col Gary Steffes, 76 CMXG/CR, ASIP Conference 2020

Objectives

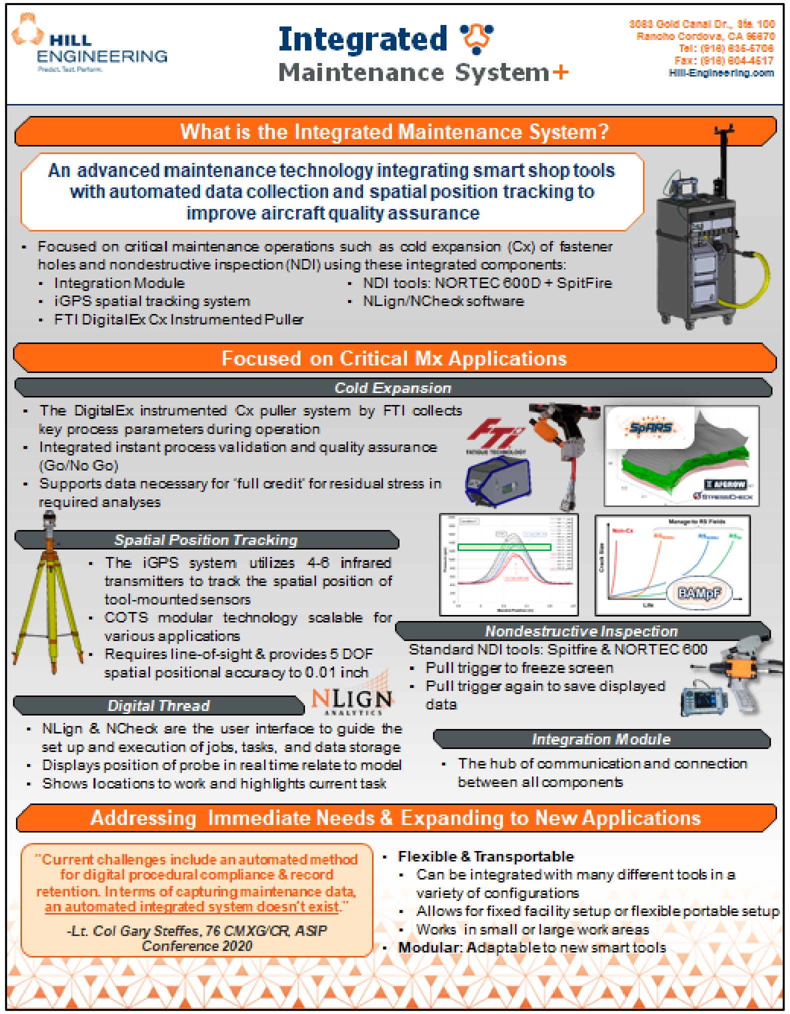
- Create a digital thread for fastener holes that builds & maintains process records for NDI & Cx using commercial Data Spatial Positioning (DSP) technologies to leverage in structural integrity management
- Assist maintainer with real-time position feedback
- Digitally capture NDI and Cx results and submit results automatically
- Cybersecurity accreditation to integrate with the USAF NIPRNet
- **Simplify the maintenance, inspection and reporting process**

Mx being performed → Live tool location → Live inspection results

Digital Thread Tools: IMx+ System

Introduction to the IMx+ system

- An advanced maintenance technology integrating smart shop tools with automated data collection and spatial position tracking to improve aircraft quality assurance
- Focused on critical maintenance operations such as Cx of fastener holes and NDI using these integrated components:
  - **Integration Module**
  - **iGPS spatial tracking system**
  - **FTI DigitalEx Cx Instrumented Puller**
  - **NDI tools**
  - **NLign/NCheck software**



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Digital Thread Tools: IMx+ System

Integration Module [Hill Engineering]

- The hub of communication and connection between all components
- All the physical and digital signals are combined and managed
- Integrates location and maintenance/inspection results for upload to the digital thread directly from within the USAF network
- Adaptable to new smart tools

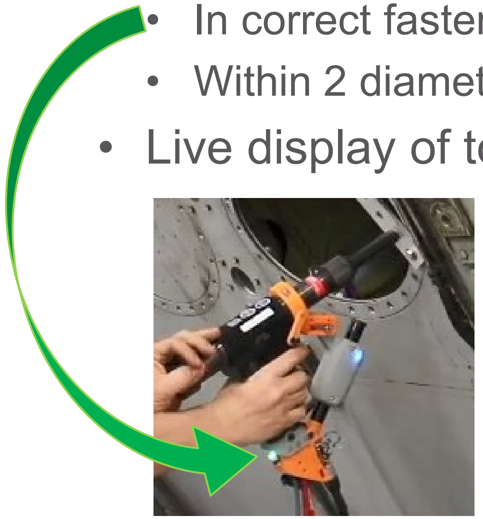
Digital Thread Tools: IMx+ System

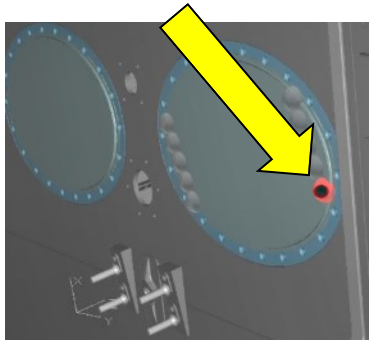
Spatial Position Tracking [7D Kinematic Metrology]

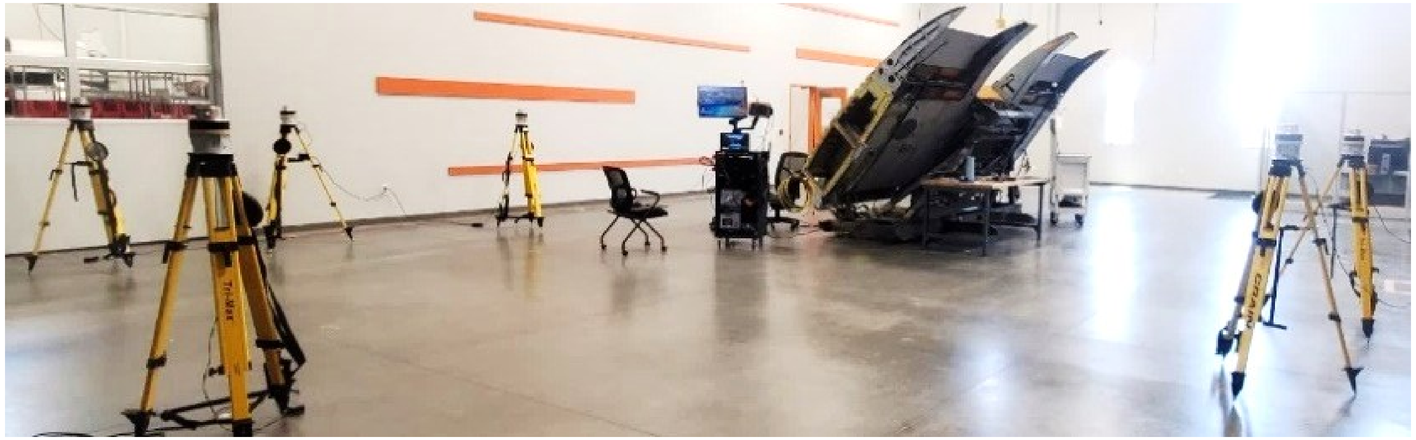
- iGPS infrared laser off-the-shelf modular technology
- Coverage area: Scalable for small to large production facilities
- Utilizes 4-6 infrared transmitters to track the spatial position of tool-mounted sensors
- Requires line-of-sight & provides 5 DOF spatial positional accuracy down to 0.01 inch

Add-on: Integrated Feedback to Maintainer

- LED lights indicate if tool is:
  - In correct fastener hole (green)
  - Within 2 diameters of correct hole (yellow)
- Live display of tool location







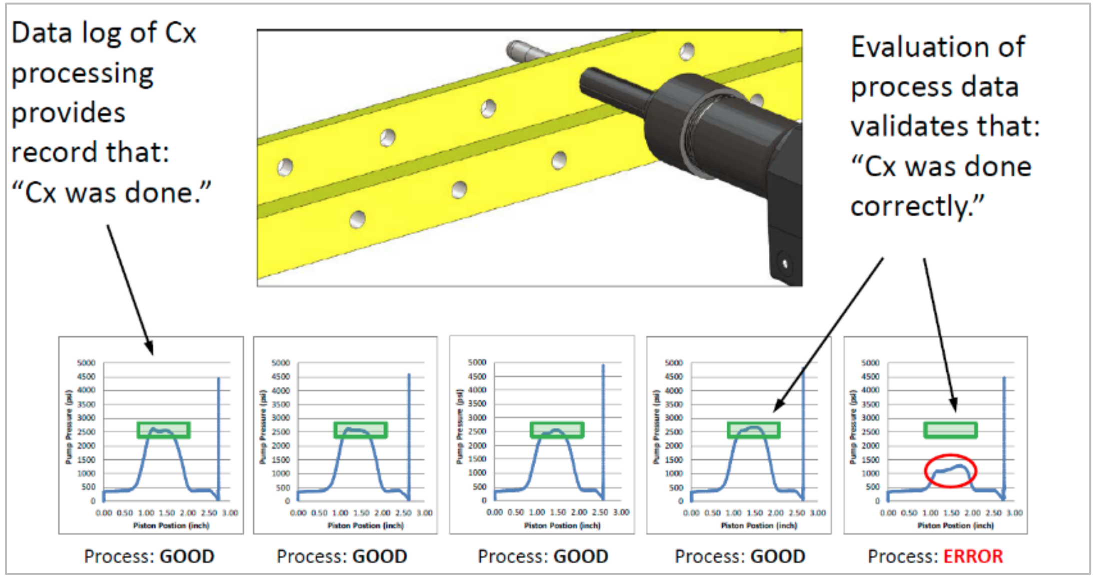
Inclusion of additional modular spatial position tracking technologies

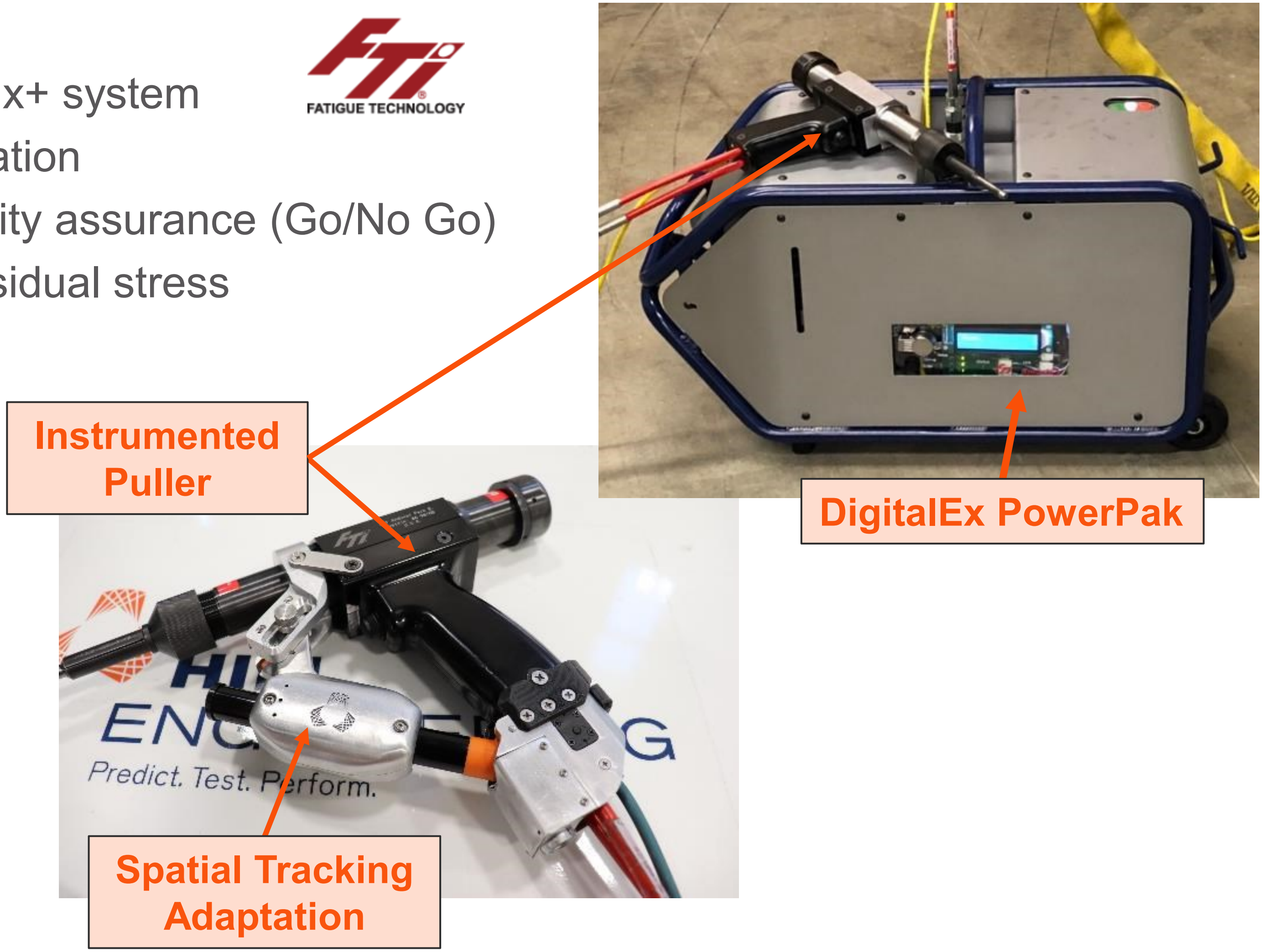
Digital Thread Tools: IMx+ System

DigitalEx Instrumented Cx Puller [FTI]

FATIGUE TECHNOLOGY

- DigitalEx physical and digital interface with IMx+ system
- Collects key process parameters during operation
- Integrated instant process validation and quality assurance (Go/No Go)
- Supports data necessary for 'full credit' for residual stress





Digital Thread Tools: IMx+ System

NDI Tools

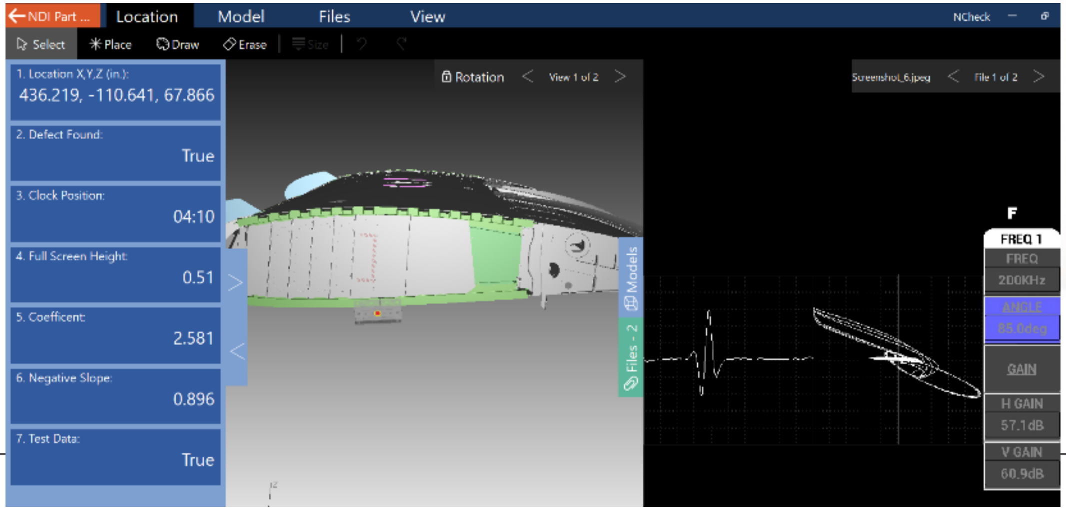
- NORTEC + SpitFire + MiniMite
- EVi + ECS-3 + ECS-5
- EPOCH 650
- Physical and digital interface between NDI tool and IMx+ system
- NDI data stream capture
  - Screenshot automatically saved to hole location with trigger pull
  - Automatically tracks/saves defect layer
  - Automatically populates inspection data based on screenshot

Spatial Tracking Adaptation

Spitfire BHEC Scanner

NORTEC 600D Instrument

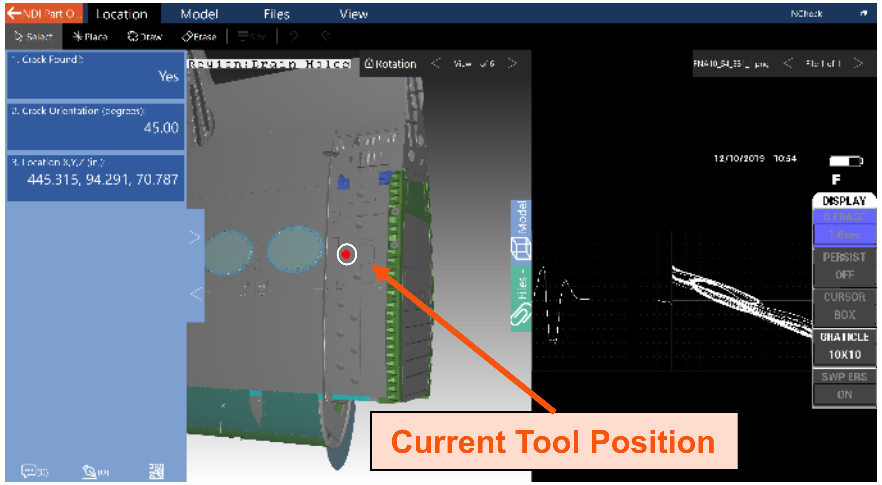
NO MORE SNEAKERNET TO CAPTURE NDI DATA!

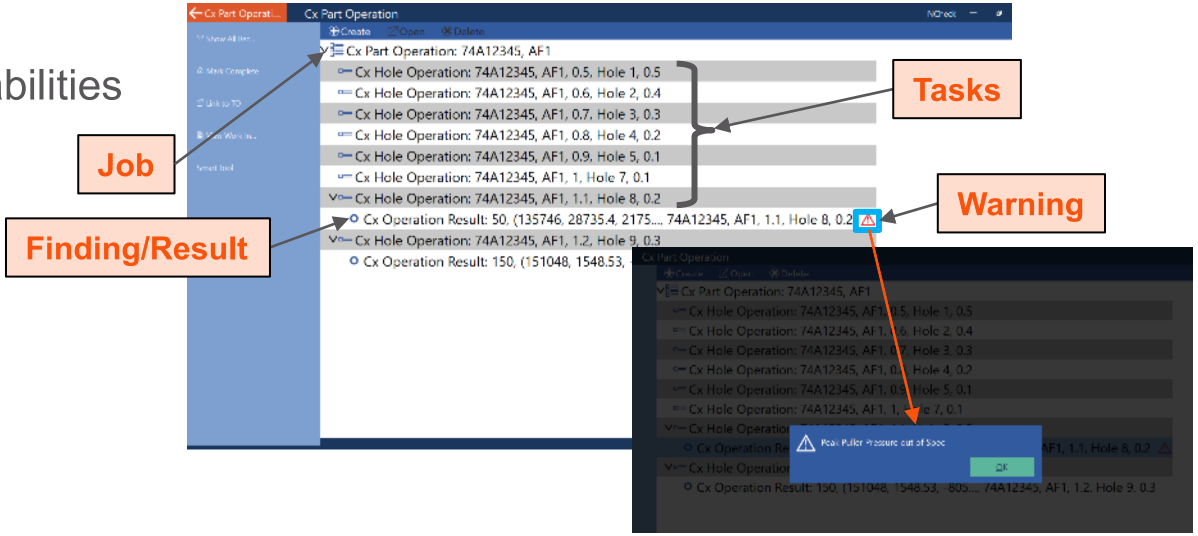


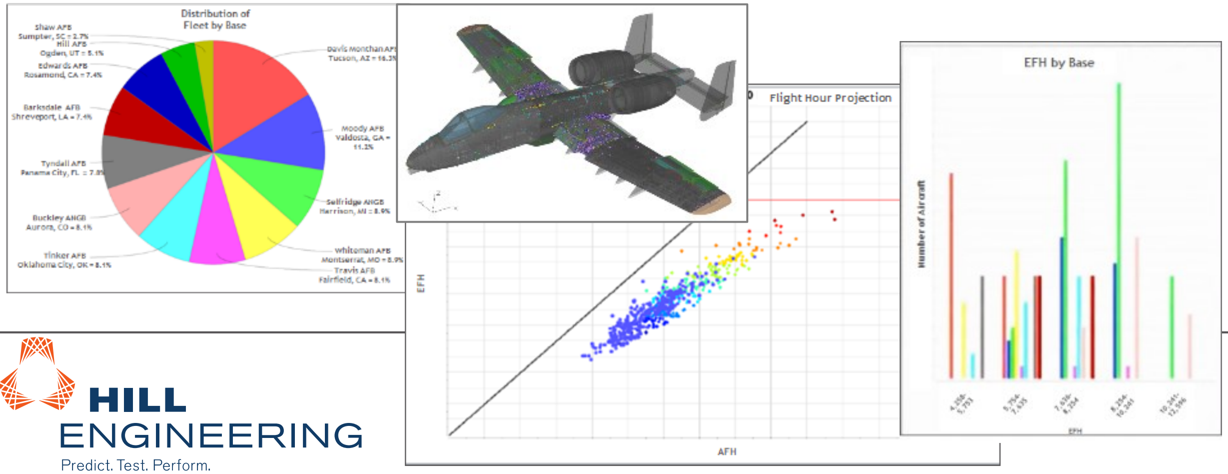
Digital Thread Tools: IMx+ System

User Interface and Digital Thread [NLign Analytics]

- NCheck
  - User interface for maintainers for the execution of jobs and tasks
  - Shows locations to be worked and highlights current task
  - Displays what operations have been completed and the results
  - Captures location and operation results automatically
- NLign
  - User interface for engineering to guide the set up of jobs and tasks
  - Digital thread and full data repository
  - Extensive data analytics, visualization, and mapping capabilities
  - Trending of fleet statistics based on user inputs







Digital Thread Tools: IMx+ System

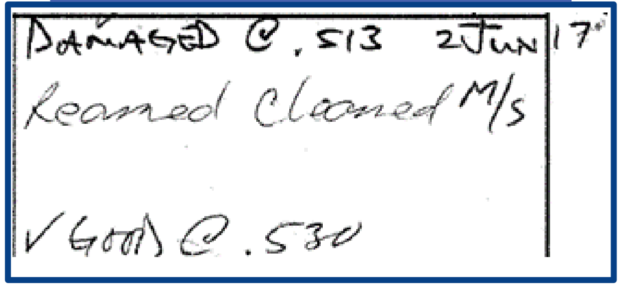
Why IMx+ for NDI?

- Automatically capture critical data to support NDI and engineering
- Identify critical layers and crack locations for stack-ups
- Estimated 50% reduction in time to document inspection results
- Estimated 20% reduction in inspection time through real time feedback

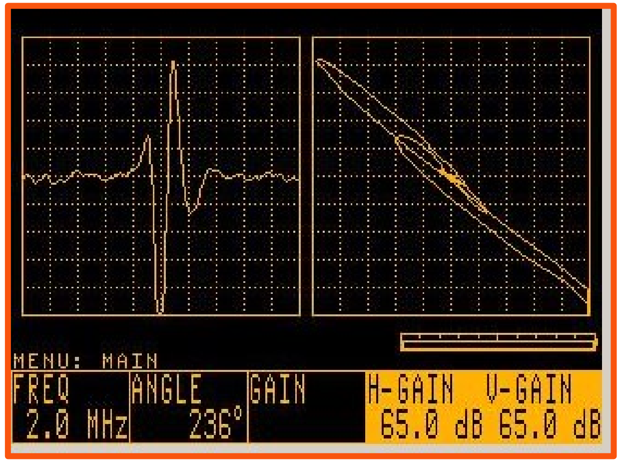
A-10: Why do we want IMx+? ▸ ▸ ▸

- Meets MIL-STD-1530D requirements
- Automates data entry and upload (faster and easier for inspector)
- Improves inspection value by saving inspection data, not just pass/fail
- Includes Mx location in aircraft coordinates
- Identifies correct location of Mx

Logbook: Data capture



IMx+: Data capture



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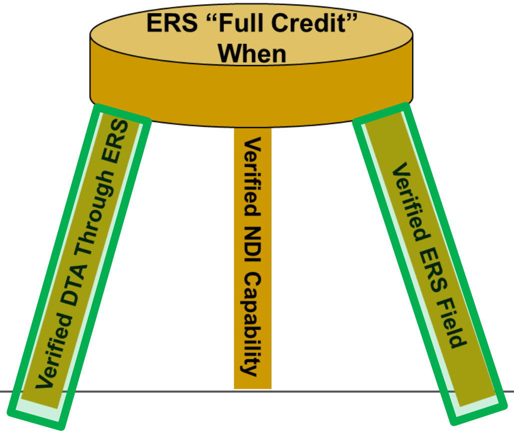
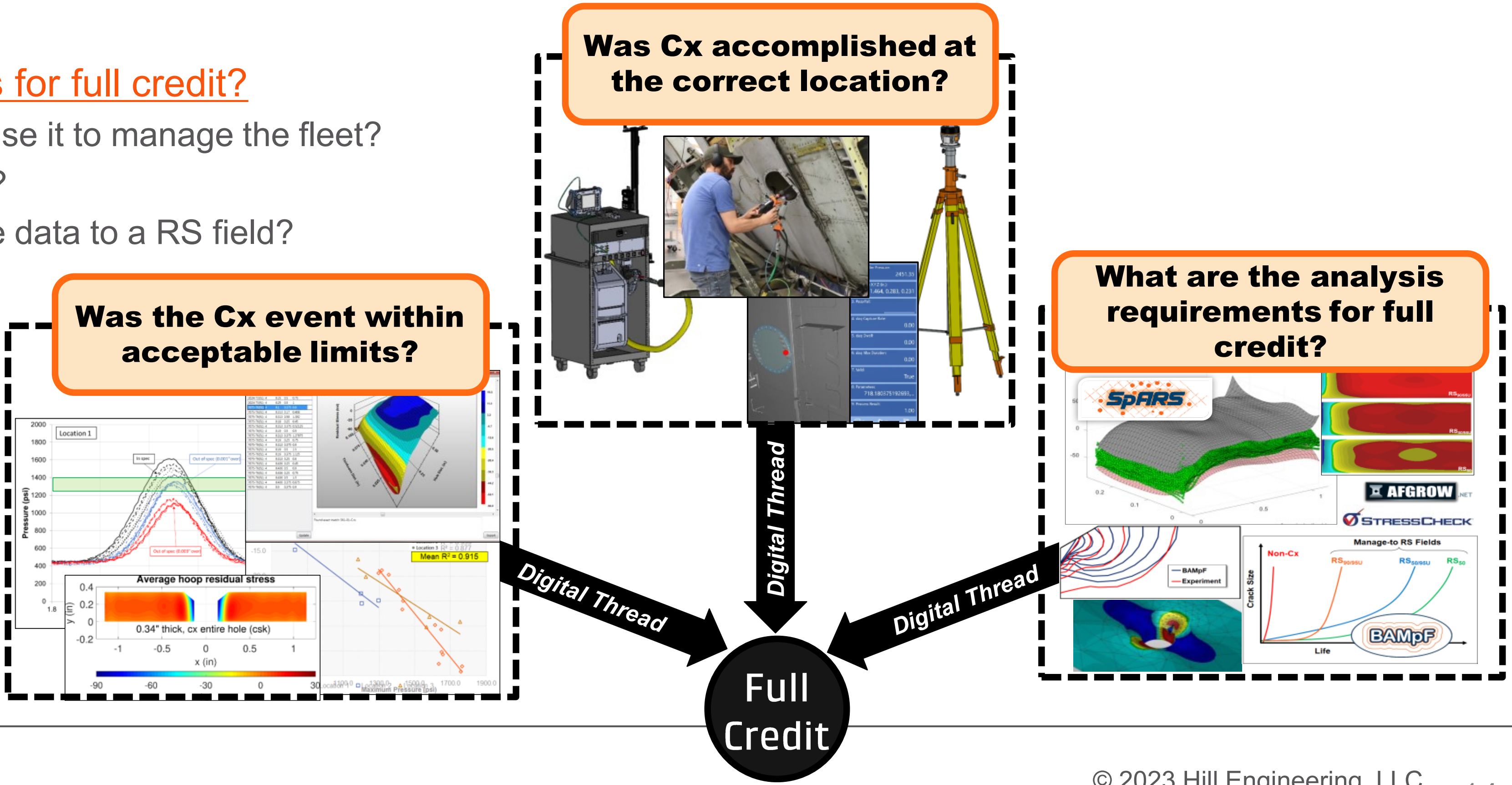
Digital Thread Tools: IMx+ System

Why IMx+ for Cx? ▸▸ Establishing the Cx digital thread ▸▸

Required to extend from Mx action through ASIP engineering processes to development of an inspection interval to be published in tech data

- Address next-step-questions faced by ASIP to develop inspection intervals & answers critical questions required for RS full credit
  - Was Cx accomplished at the correct location?
  - Was Cx accomplished (go/no-go)?
  - What are the analysis requirements for full credit?
    - What do I do with this data and how use it to manage the fleet?
    - What data is needed to perform DTA?
    - How do I correlate Cx pressure profile data to a RS field?
    - How statistically characterize RS field to use explicitly in DTA?

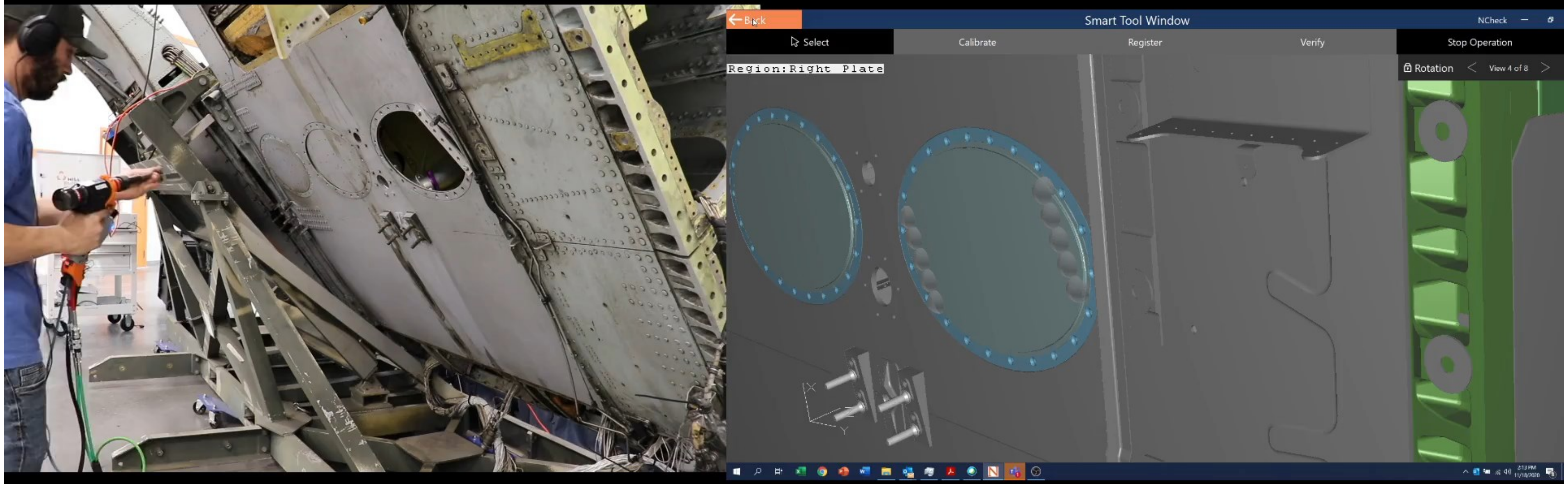




Digital Thread Tools: IMx+ System ▸▸ Cx Demo

Technician working

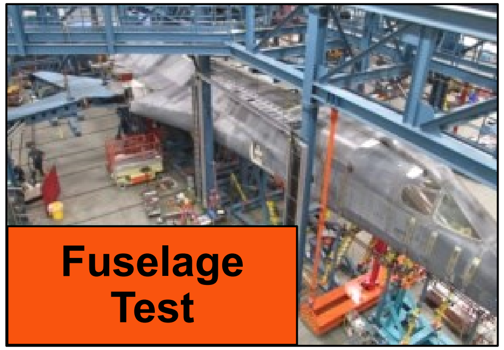
Live display on Integration Module

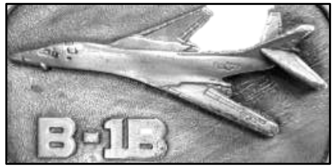


Digital Thread Tools: NDI Applications of IMx+

Design, develop, test, and demonstrate adaptations of USAF standard NDI tools for use with IMx+

- Automate data capture from the NDI tool
- Retrofit current USAF NDI tools with a spatial tracking sensor
- Output captured NDI data to user-defined database
- Update user interface for expanded use for all users
- Perform on-site demonstrations of NDI automated data capture capabilities and deliver IMx+ system
  - Candidate 1: Hill AFB & A-10 application
  - Candidate 2: B-1 Full Scale Fatigue Test





Integrated Maintenance System+

Integration and Validation Testing

EVi testing

- Spatial position tracking functioning with ECS-3 and ECS-5

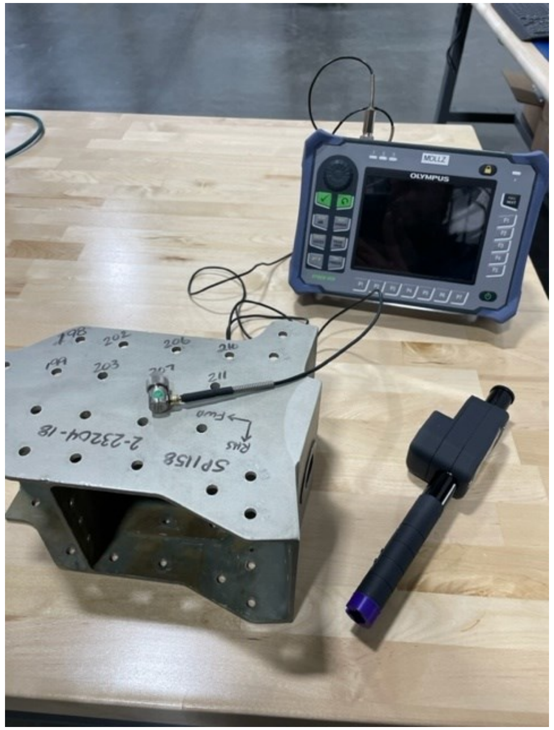
Integration and Validation Testing

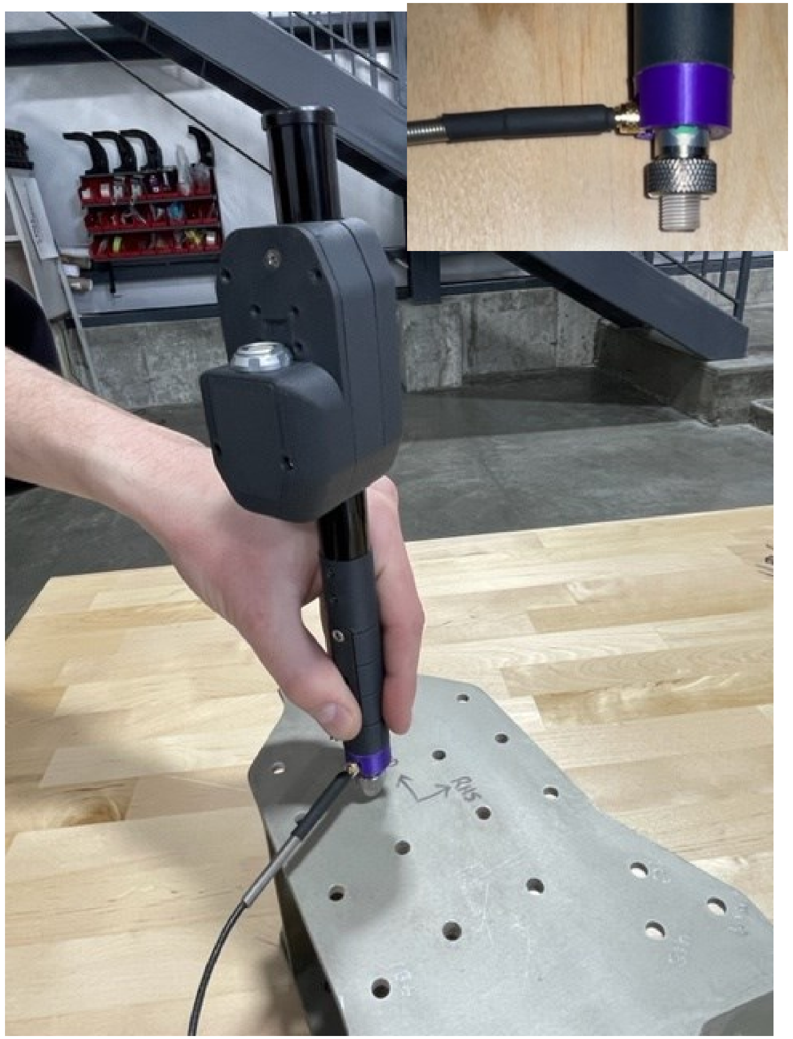
Digital bore gauge testing

Integration and Validation Testing

EPOCH 650 development

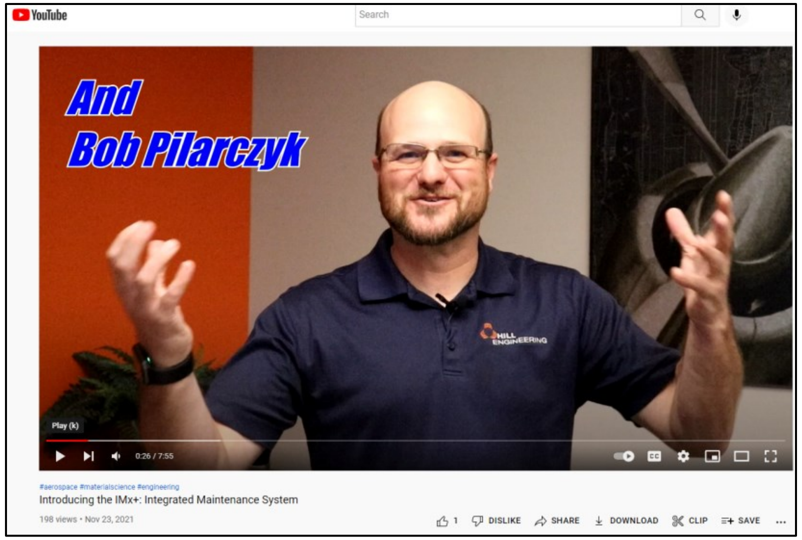
- Leverage existing Space Pencil for spatial tracking
- Adaptable tips for various UT probes
- Real-time tracking of position
- Video and dataset of position of data from EPOCH





Digital Thread Tools to Enable Effective ASIP

QUESTIONS?



https://hill-engineering.com/our-work/introducing-the-imx/

Residual Stress Summit

Mike Steinzig

RS Summit history

- Originally conceived as a North American conference on Residual Stress (to compete with ICRS and ECRS)
- First instance held in Los Alamos, 2003
- Six total Summits have been held
  - Los Alamos, NM 2003 (Hytec, Inc)
  - Vancouver, BC 2005 (University of British Columbia)
  - Oak Ridge, TN 2007 (ORNL facilities)
  - Lake Tahoe, CA 2010 (conference center)
  - Idaho Falls, ID 2013 (at a hotel)
  - Dayton, OH 2017 (University of Dayton Research Institute)
- Attendance has been 40-80 people

Our cadence is getting slower (as are the organizers)

Non-traditional conference ideas

- *The central objective of the meeting is to bring together residual stress users (who have "problems" and are in search of "solutions") and developers (who have "solutions" and are in search of "problems").*
- Single track, with all participants attending each talk
    - Identify a facility with suitable capability
- Facilitate discussion amongst participants
    - long lunches on site, scheduled breaks, poster sessions
- Themed topics where possible (multiple speakers on one topic)
- All speakers are invited to maintain specific focus points
- Typically longer talks than standard conference (30 minutes)
- If an industrial facility, then involve local technical support for topic and tours

Other Efforts

- Honoring our community: Iain Finnie Award
  - Wayne Kroenke 2007
  - Wylie Cheng 2010
  - Bob Bucci 2013
  - Lyndon Edwards 2017
- Demonstrations and Instruction
  - Round robin in Titanium
  - Hole drilling workshop
- Organizers
  - Steinzig/Schajer/Prime (03/05)
  - Hill Noyan (2007)
  - Local organizers from the site location

2003 Summary

- Two industrial applications sessions (RS problems in industry)
- Standards and comparison studies
- One full day on measurement techniques and demonstrations
- ~30 attendees

Participants

- ALCOA
- American Stress Technologies
- ATK Thiokol Propulsion
- Bettis/Bechtel Atomic Power Laboratory
- Boeing Company, St Louis
- Boeing Integrated Defense Systems
- Boeing A/F-22
- Caterpillar
- Dana Corp
- Don Bray Engineering
- Hill Air Force Base
- Hydro-Quebec
- JENTEK Sensors Inc.
- John Deere Tech Center
- Los Alamos Nat. Laboratory
- National Physical Laboratory
- NIST
- Pella Windows
- PROTO Manufacturing
- Sandia National Laboratory
- Savannah River Company
- StressTech Oy
- SUNY, Binghampton
- TEC
- Texas Tech University
- University of Alabama
- University of British Columbia
- University of California, Davis

2003 stated objectives

- To provide a forum where developers and practitioners can share practical RS information
  - Developers: to learn the practical needs and challenges of industry
  - Practitioners: to learn how to choose and use appropriate measurement methods
- To facilitate personal connections between the two groups

- Most attendees liked the format and the result, and said they would attend others
- Mix of highly technical and concentrated material with practical bent

2005 Summary - UBC

Technology¶

"Requirements of a Practical Residual Stress Measurement Technique" *Cevdet Noyan* Columbia University¶
"Engineered Residual Stresses" *Michael R. Hill* University of California, Davis¶
"Heat Treating and Quenching Stresses and Distortion" *George Totten* and *Victor Li* Portland State University¶
"The Recent Development of the Global Industrial Approach for Residual Stress Consideration: Measurement, Process Simulation and Design Issues" *Jian Lu* LASMIS, University of Technology of Troyes, France¶
"Direct Measurements of the Effect of RS on Fatigue Crack Growth Using Thermoelasticity", *Eann Patterson* Michigan State¶
"Modeling of Residual Stress in Machined Workpieces and its Effect on Part Distortion" *Luis Zamorano* Third Wave Systems¶
"Residual Stresses, Fatigue Crack Growth, and Life Prediction", *R. Craig McClung* Southwest Research Institute¶
"Stress Measurement in Nonmetallic materials: Applications to Measurement in the Earth" *Douglas R. Schmitt* University of Alberta¶
"Overview and Developments in Destructive Measurement Techniques" *Mike Prime* LANL, *Gary Schajer UBC*¶
"Overview and Developments of Nondestructive Measurement Techniques" *Clayton Ruud* Penn State¶
¶

Industrial Experience¶

"Industrial Experiences", *James Pillers* The Boeing Company, Seattle¶
"Residual Stresses and Failures in Railroad Rail and Wheels: Experimental andAnalytical Techniques" *Jeff Gordon*, U.S. DoT¶
"Industrial Welding Residual Stress Problems, Measurements, and Predictions" *Pingsha Dong* Battelle¶
"RS distribution in chilled face, cast iron calendar rolls" + "RS development in A356 Automotive heels" *Steve Cockcroft UBC*¶
"Recent Residual Stress Activities at ALCOA" *R.W. Schultz and P.A.Vranka* ALCOA Technical Center¶
"Industrial Case Studies in Residual Stress: Putting Neutrons to Work for Industry" *Ronald Rogge*, NRC, Chalk River, Canada¶
"The Challenge of Computer Modeling the Effects of Fillet Rolling for Automotive Crankshafts" *Clifford Grupke* DaimlerChrysler¶

- 17 speakers, poster session
- Two non-technical, local speakers (lunch and dinner)
- Foreign travel may have reduced attendance

2007 summary - ORNL

2007 RESIDUAL STRESS SUMMIT
ENGINEERED RESIDUAL STRESSES

October 2-4, 2007
OAK RIDGE NATIONAL LABORATORY
OAK RIDGE, TN, USA

- THE 3RD BIENNIAL RESIDUAL STRESS SUMMIT
- OVER 20 INVITED TALKS on RESIDUAL STRESS
- FOCUS on *ENGINEERED RESIDUAL STRESSES*
- TOUR of the VULCAN NEUTRON FACILITY
- POSTERS and DEMONSTRATIONS

The Residual Stress Summit is a bi-annual meeting of researchers and practitioners interested in residual stress. The central objective of the meeting is to bring together residual stress users, (who have "problems" and are in search of "solutions") and developers (who have "solutions" and are in search of "problems"). The format of the Summit is designed to facilitate technical interchange among practicing engineers and researchers. The 2007 Summit has a theme of *Engineered Residual Stresses*, which encompasses methods for inducing, measuring, and predicting the effects of residual stresses. A coherent sequence of topics has been chosen related to new technologies, practical needs, and proven applications of engineered residual stresses. To keep the focus of the meeting, all talks are by invitation only. A demonstration and poster session will be held during the Summit to allow additional information to be conveyed to Summit participants. Additional information at www.rssummit.org

$400 registration fee includes a welcome reception/poster session, 3 exhibitor continental breakfasts, 2 working lunches, and a dinner/awards banquet.
$325 early bird registration fee until August 15.

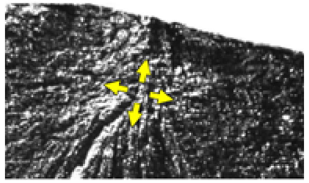
SPEAKERS:

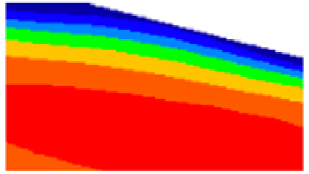
Michael Shepard, *Air Force Research Lab*
Paul Domas, *GE Aviation*
Dean Jones, *Rolls Royce, PLC*
Bob Morris, *Pratt & Whitney*
John Cammet, *Cam-Met, Inc.*
David Lahrman, *LSP Technologies*
T. Gnaeupel-Herold, *NIST Center for Neutron Research*
Paul Prevey, *Lambda Technologies*
Lloyd Hackel, *Metal Improvement Company*
Steven Thompson, *Air Force Research Lab*
Gary Schajer, *University of British Columbia*
Michael Lance, *Oak Ridge National Laboratory*
Mark Croft, *Rutgers University*
David Smith, *Bristol University, UK*
Dale Ball, *Lockheed Martin Aeronautics Company*
Adrian DeWald, *Hill Engineering, LLC*
Lynn Ferguson, *Deformation Control Technologies*
Cam Hubbard, *Oak Ridge National Laboratory*
Xun-Li Wang, *Oak Ridge National Laboratory*
Richard Burguete, *Airbus UK Ltd.*
Aladar Csontos, *Nuclear Regulatory Commission*
Roger England, *Cummins Engine*
Troy Marusich, *Third Wave Systems, Inc.*
Len Reid, *Fatigue Technologies, Inc.*

Work up front in advertising is key!
1/2 of the attendees are speakers (demos/posters included)

2010 Summary

- 71 attendees, 3 days
- Isolated conference center worked well
- Revisited measurement techniques
- 29 speakers +





Residual Stress Summit 2010

Tahoe City, California, September 26-29, 2010

The 2010 Residual Stress Summit continues the central objective of the Residual Stress Summit series, which is to bring together residual stress users (who have "problems" and are in search of "solutions") and developers (who have "solutions" and are in search of "problems").

First organized in 2003, the Summit is specifically designed to stimulate practical technical interchange among working engineers and researchers. A coherent sequence of topics has been chosen to focus on practical needs and applications. Three major thrusts in the 2010 agenda are welding residual stress, forging residual stress, and residual stress measurements. Experts in these fields are being specifically invited to speak and to share their knowledge and experience. To keep the focus of the meeting, all talks are by invitation only.

Summit participants are invited to give voluntary poster presentations. Also included are demonstration areas where residual stress related equipment and materials will be on display. Informal conference proceedings will be distributed following the event.

The 2010 Residual Stress Summit will be held Sunday to Wednesday, September 26-29, 2010 at the Granlibakken Conference Center and Lodge, Tahoe City, California.

For further details, see:

www.rssummit.org

2013 summary - INL

Industrial Talks
P. John Bouchard, Open University, *Residual Stress Driven Creep in Nuclear Power Plants*
Mark James, Alcoa, *Forging Residual stress (Follow-up from 2010 RS Summit)*
Brian Leitch, Chalk River Laboratories, *Residual Stresses in the NRU Vessel Weld Repair*
Iuliana Cernatescu, Pratt and Whitney, *Residual Stress Measurements on Bulk Residual Stress in Nickel Base Superalloy Aeroen*
S. Chandrasekar, Purdue University, *TITLE? (Mike Prime)*
Tony Parker, University of Cranfield, *Gun Tube Residual Stresses - Known Knowns, Known Unknowns, Best Guesses and Outstar*

Residual Stress Failure Case Studies and Forensics (Organized by Mike Prime)
Lyndon Edwards, Australian Nuclear Science & Technology Organisation, *How understanding RS can help solve industrial and f*
Michael Brauss, Proto Manufacturing, *X-Ray Diffraction Residual Stress Measurement in Failure Analysis*
Pete McKeighan, Exponent Failure Analysis Associates, *Broke Bits & Pieces: Self Stresses & Failure Analysis*
Michael Prime, Los Alamos National Laboratory, *Forensic determination of residual stress from fracture surfaces*

Residual Stresses in Shipbuilding (Organized by Mike Steinzig)
T.D. Huang, Ingalls Shipbuilding, *Solving residual stress induced distortion problems in ship structures*
Bud Brust, Engineering Mechanics Corporation of Columbus, *Residual stress in oil rig platforms*
Luke Brewer, Naval Postgraduate School, *Measurements of RS in ship repairs*

Short Updates (Organized by Mike Hill)
Mitch Olson, Hill Engineering, *Contour Method repeatability and potential for round robin*
John Broussard, DEI, ASME Codes-*potential for residual stress effects*
Phillip Withers, Manchester University, *BP International Center and associated RS work*

Recommended Practices and Future Extensions (Organized by Gary Schajer)
Gary Schajer, University of British Columbia, *Hole-drilling and ring-coring*
Ed Kingston, Veqter, *Deep Hole Drilling*
Michael hill, UC Davis, *Slitting*
Adrian DeWald, Hill Engineering, *Contour Method*
Cevdet Noyan, *Columbia University, X-Ray Diffraction*
Phillip Withers, *University of Machester, Synchrotron Diffraction*
Ron Rogge, NRC, *Neutron Diffraction*
Drew Nelson, Stanford University, *Optical Measurement Techniques*
Michael Prime, Los Alamos National Laboratory, *Overview and Comparison*

- First time at a hotel – worked pretty well

2017 summary - Dayton OH

- 3 day session
- Central location with great tours
- 28 talks + posters and demos

Mark your calendars for the 6th Residual Stress Summit, to be held on Monday-Thursday October 23-26, 2017 at the University of Dayton Research Institute, in Dayton, Ohio, USA. The Welcome Reception is on Monday evening, October 23, followed by the technical sessions Tuesday-Thursday October 24-26. The Summit will showcase invited talks from acknowledged experts, topical updates, poster sessions and equipment demonstrations. The Residual Stress Summits are organized on a non-profit basis so as to be affordable and accessible meetings, see registration page.

The central objective of the Residual Stress Summit series is to bring together residual stress users, (who have "problems" and are in search of "solutions") and developers (who have "solutions" and are in search of "problems"). The Summit is designed to have a tightly focused format by choosing in advance a coherent sequence of topics directed at practical needs and applications. Experts in these fields are then invited to speak and to share their knowledge and experience. *All talks are by invitation only.*

Also included in the meeting are demonstration sessions where residual stress related equipment and materials are displayed. In addition, RS Summit participants are invited to give voluntary poster presentations and/or equipment demonstrations. The informal conference proceedings will include a list of attendees, demonstrators and affiliations, as well as the presentations from the speakers and poster presenters.

An optional Short Course on the Hole-Drilling Method for measuring residual stresses will be given immediately before Summit, on Monday morning, October 23, 2017.

The Summit Banquet will be held at the The Engineers' Club of Dayton, at which the Iain Finnie Memorial Award will be presented. Dr. Tom Crouch, Senior Curator, National Air and Space Museum, Washington DC, will give an after-dinner talk on early aviation history.

The organizers warmly thank the University of Dayton Research Institute for assisting with meeting coordination and organization of the v

We look forward to welcoming you to the 6th Residual Stress Summit, 2017 !

Michael Hill (University of California, Davis), 530-754-6178   Michael Prime (Los Alamos National Lab), 505 667 1051
Michael Steinzig (Los Alamos National Lab), 505-667-5772   Gary Schajer (University of British Columbia), 604-822-6004
Ismail Cevdet Noyan (Columbia University), 212-854-8919   Kristina Langer (Air Force Research Laboratory), 937-241-5717
Stefano Coratella (University of Dayton Research Institute), 937-212-9399

RS Summit 2024

- Fall would be a good time (ECRS in May of 2024)
- Location (location, location)
  - An industrial site with tours and RS work ongoing
  - Support for organizing the venue AND the technical content
- Volunteers/organizers for this and future Summits
  - Current organizers have tentatively agreed to do 1 more
- Sessions
  - Revisit past sessions (measurement techniques?)
  - Other industrial problems (casting RS, airplane industry)

Questions/Interest: Contact Mike, Mike, Mike, Cev, Gary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