ERSI 2020 Virtual Workshop

Date: 8-10 December, 2020
Location: Zoom

Agenda (All Times EST)

8 December:
13:00 – Opening Remarks and Overview (Spradlin)
13:05 – Non-Destructive Inspection + Quality Assurance & Data Management (Brausch/Anderson)
13:35 – Residual Stress Measurement (Hill)
14:05 – Risk Analysis and Uncertainty Quantification (Hunt/Ocampo)
14:35 – Residual Stress Process Simulation (Hitchman)
15:05 – Break
15:20 – Fatigue Crack Growth Analysis Methods + Validation Testing (Pilarczyk/Warner)
16:10 – Open Discussion
17:00 – Adjourn

9 December:
13:00 – Committee Leads Discussion
15:00 – Adjourn

10 December:
13:00 – Committee Leads De-Brief Group
14:00 – Town Hall Discussion
16:00 – Closing Remarks and Adjourn

Notes:

- Committees are strongly encouraged to hold meetings the week immediately preceding the workshop to aggregate viewpoints and update committee membership; this will take the place of the breakout sessions that typically occur the afternoon of the first day.
- Committee leads should disseminate read-ahead materials for their presentations to the entire ERSI membership by 27 November.

USSF

AFRL

Nondestructive Inspection (NDI) Nondestructive Evaluation (NDE) Quality Assurance (QA) & Data Management (DM) Committee Overview

Engineered Residual Stress Implementation (ERSI) Workshop

8 December 2020

Subcommittee Leads

John Brausch[1], Dr. Eric Lindgren[1], Kaylon Anderson[2]

[1]Materials and Manufacturing Directorate, Air Force Research Laboratory, [2]A-10 Program Office, Hill AFB UT

Overview

- NDI/NDE/QA/DM Committee Membership
- Subcommittee Updates
  - Nondestructive Inspection (NDI) – John Brausch
    - Damage detection in residual stress fields
  - Nondestrutive Evaluation (NDE) – Eric Lindgren
    - Detection and quantification of residual stress fields
  - Quality Assurance (QA), Data Management (DM) – Kaylon Anderson

Committee Members

First Name	Last Name	Company/Organization
Kaylon	Anderson	U.S. Air Force (A-10 ASIP Analysis Group)
Dallen	Andrew	Hill Engineering, LLC
John	Brausch	U.S. Air Force (AFRL - NDE Lead Engineer, Systems Support)
Nicholas	Brunnell	Engineer, NDI SME AFSC/ENRB OL Robins
Dave	Campbell	U.S. Air Force (Tinker AFB NDI Program Office Lead)
Brandon	Dierschke	L3 MID (Sustainment Engineering)
Teodor	Dogaru	Southwest Research Institue (SwRI)
Ward	Fong	U.S. Air Force (Hill AFB NDI Program Office Lead)
Dave	Forsyth	Texas Research International (TRI) - Austin, Inc.
Leo	Garza	L3 Communications (RC-135 Fleet Manager)
Scott	Geller	GTC Machining
Tyler	Gruters	US. Air Force (F-15 Structures)
Bryce	Harris	U.S. Air Force (F-16 ASIP Manager)
Ian	Hawkings	US Navy (PAX river)
Mike	Hill	Hill Engineering, LLC
Joshua	Hodges	Hill Engineering, LLC
Phil	Hoefert	L3 Harris Aerospace Systems Division - Sustainment Engineering
Kim	Jones	U.S. Air Force (F-16 ASIP)
Chris	Kirkpatrick	L3 Harris Aerospace Systems Division - Sustainment Engineering
Eric	Lindgren	U.S. Air Force (AFRL - Materials and Manufacturing Directorate
Carl	Magnuson	Texas Research International (TRI) - Austin, Inc.
Doyle	Motes	Texas Research International (TRI) - Austin, Inc.
Mike	Reedy	U.S. Navy (NAVAIR - Compression Systems Engineer)
David	Rusk	U.S. Navy - NAVIAR Structures, AIR-4.3.3.5
Hazen	Sedgwick	U.S. Air Force (A-10 ASIP Analysis Group Manager)
Gregory	Shoales	Center for Aircraft Structural Life Extention, US Air Force Acad
Clint	Thwing	Southwest Research Institue (SwRI)
Jacob	Warner	U.S. Air Force (A-10 ASIP Analysis Group Lead)
David	Wilkinson	U.S. Air Force (C-5 ASIP Manager)
Sam	Zimmerman	Fatigue Technology Incorp. (FTI) - A PCC Company
Jude	Restis	PartWorks
Ian	Hawkings	US Navy
Edward	Bajeck	US Navy

33 Members

Nondestructive Inspection Sub-Committee

NDI Subcommittee Priorities

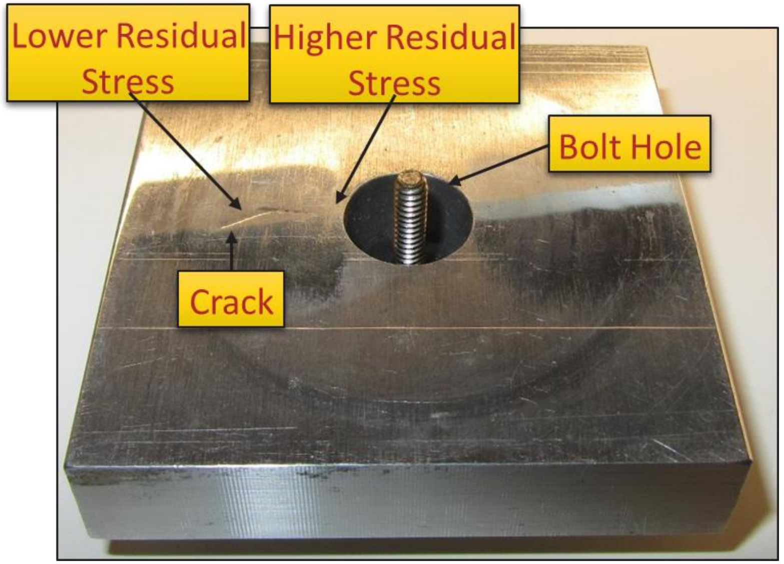
I. **Quantify ultrasonic dead zone in Cx holes**

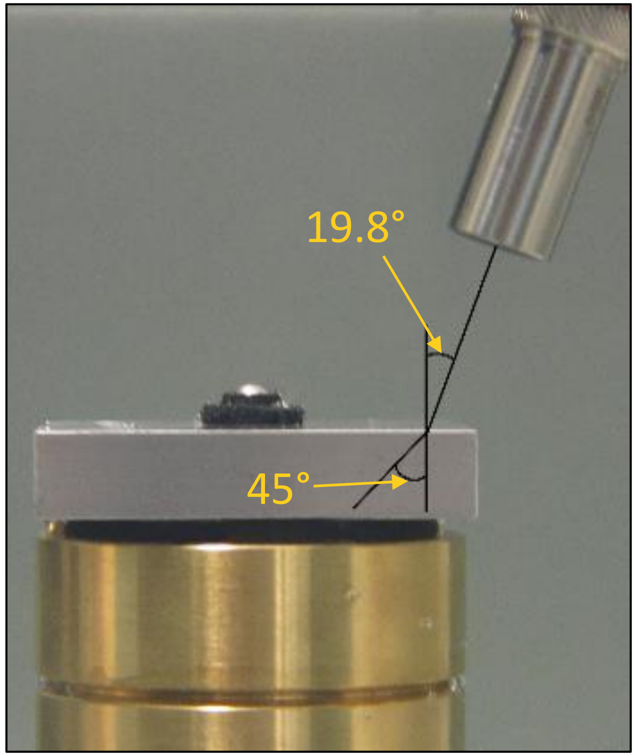
II. Evaluate Phased Array UT for inspection of Cx holes

III. Characterize impact of laser-peening of Titanium on eddy current, penetrant and eddy current detectability

Ultrasonic Dead Zone Characterization in Cx Holes

- Round Robin Testing
- Characterize effect of residual stresses on detectability of fatigue cracks with ultrasound
- 117 Specimens, 4% cold work holes – Courtesy of Apes Engineering
    - 3 hole diameters (0.278 inch D, 0.418 inch D, 0.538 inch D)
    - 3 plate thicknesses (0.100 inch, 0.313 inch, 0.500 inch)
    - Fatigue cracks: 0.020 inch – Thru-Thickness



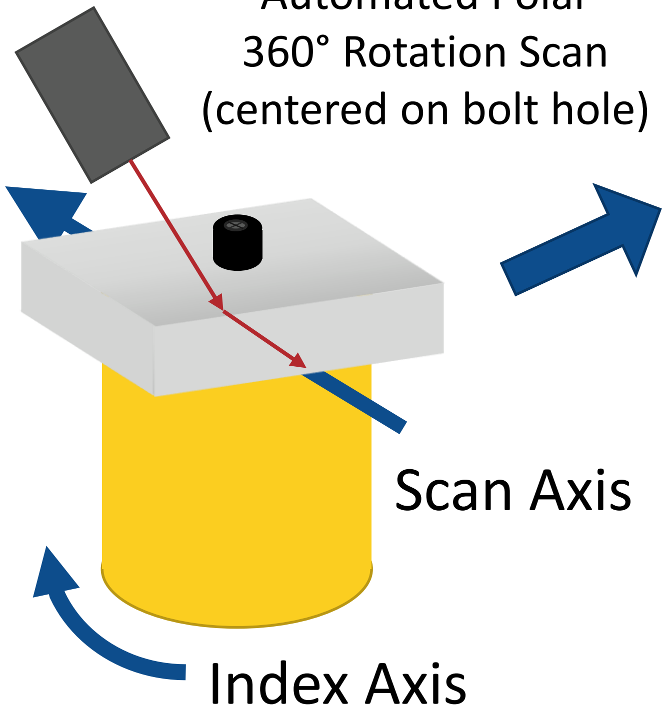


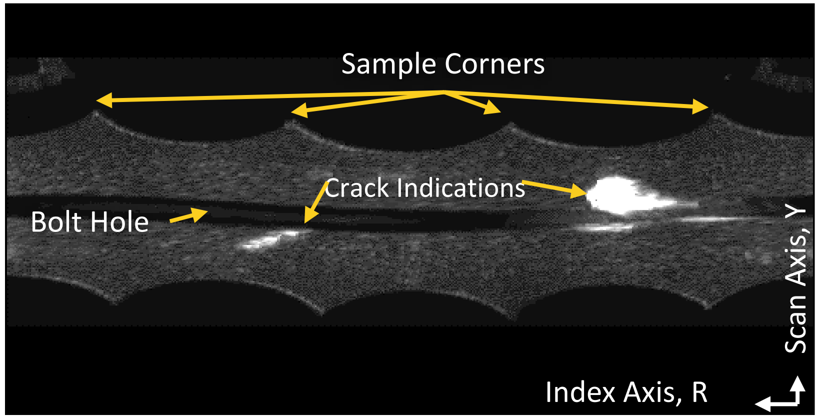
Research performed UDRI On-Site Personnel (Tyler Lesthaeghe, David Zainey & Tineka Witt)

Ultrasonic Dead Zone Characterization in Cx Holes

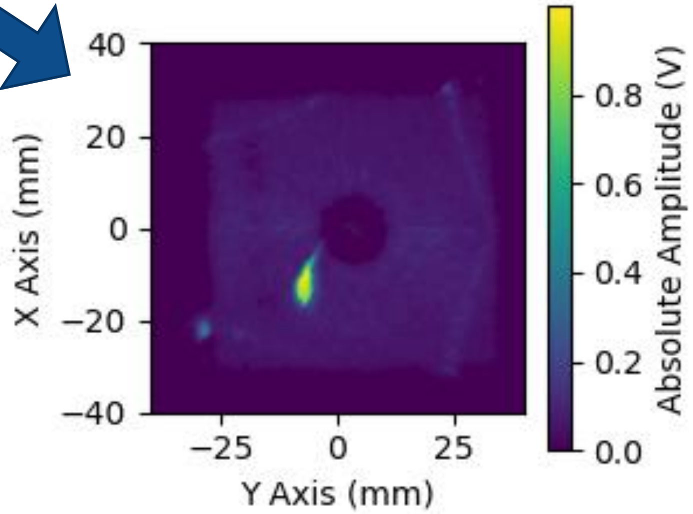
Sample Screening using Polar Scanning Process

Automated Polar
360° Rotation Scan
(centered on bolt hole)





Warping Procedure To
Create C-scan Image For
Easier Interpretation

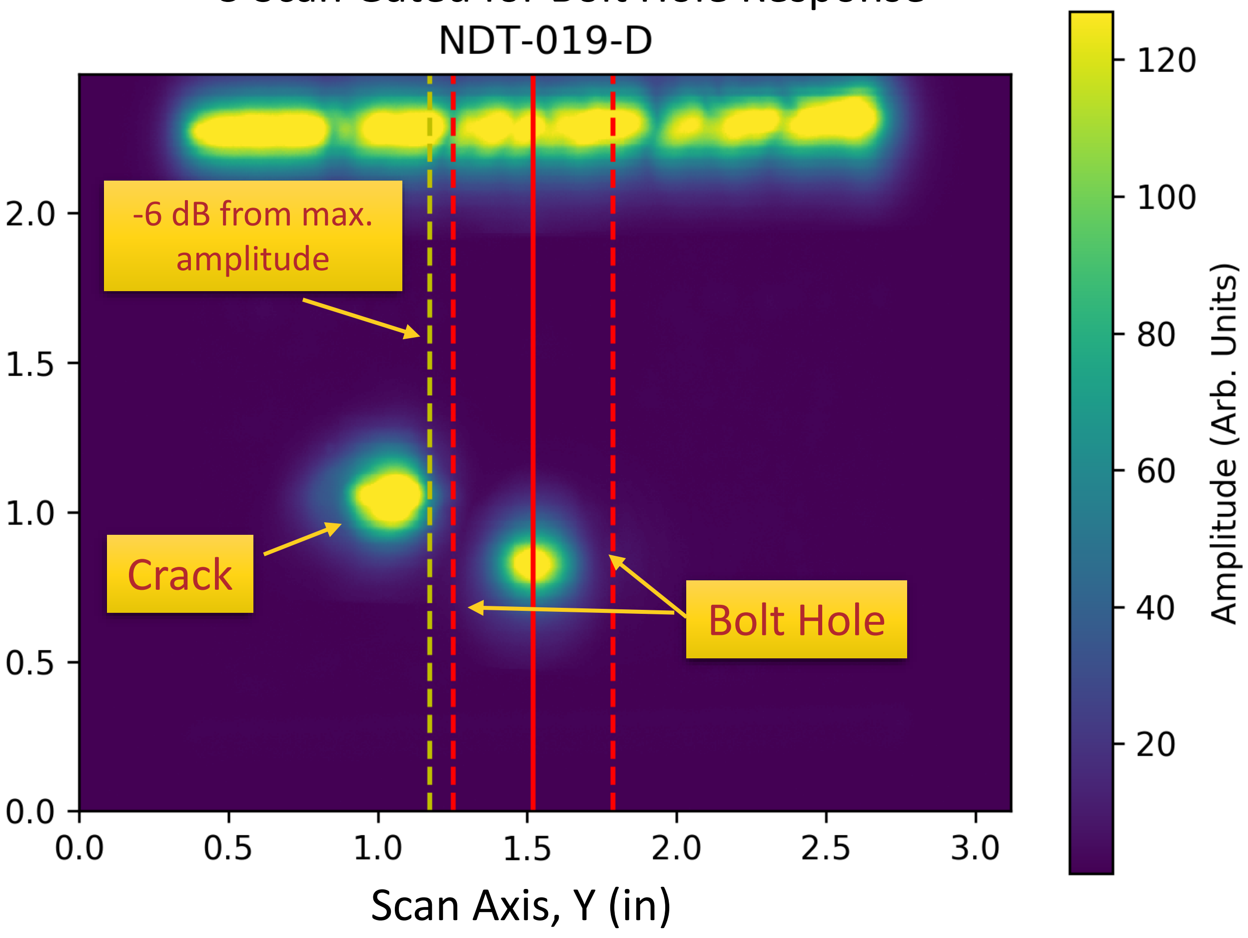


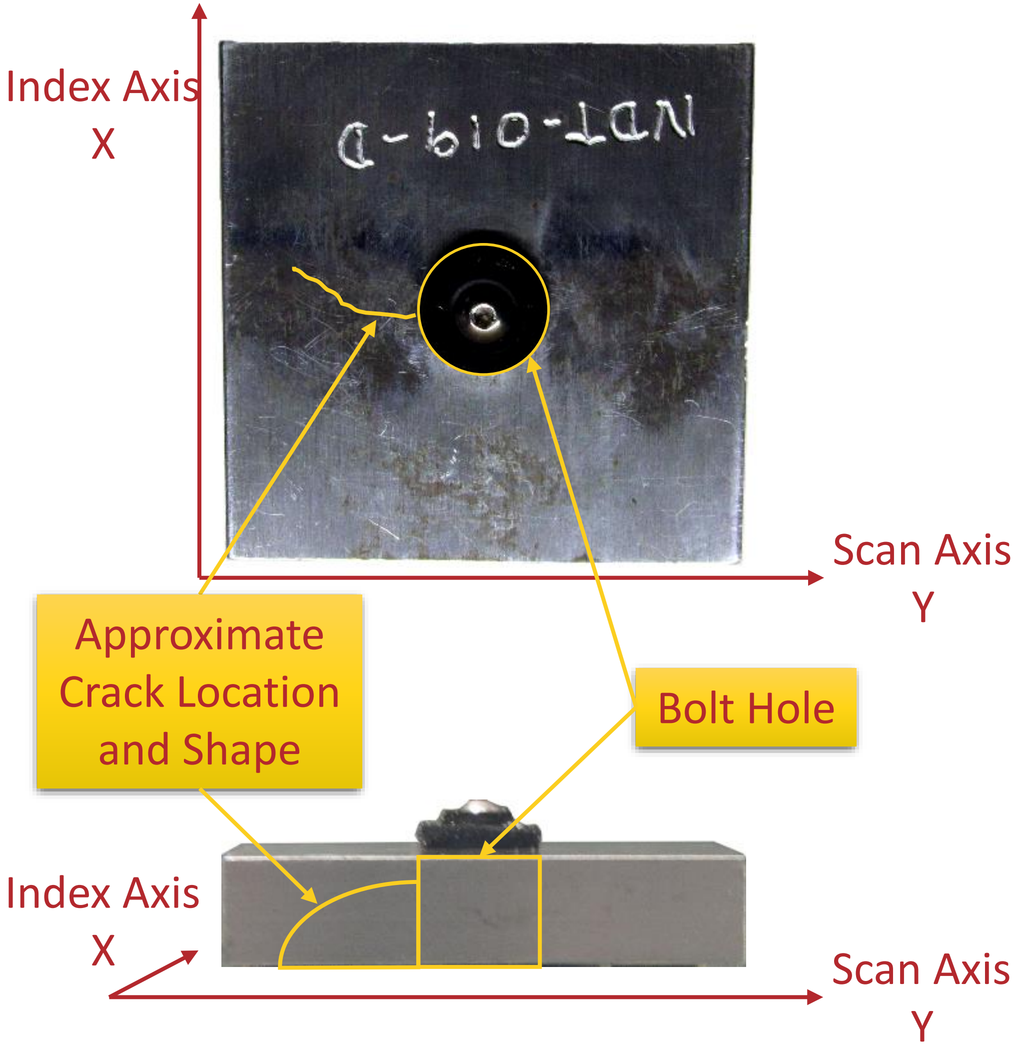
Employed automated scanning to screen for samples with detectable cracks

- 117 Samples, most did not have detectable cracks

Procedure for Dead Zone Measurement

C-Scan Gated for Bolt Hole Response
NDT-019-D



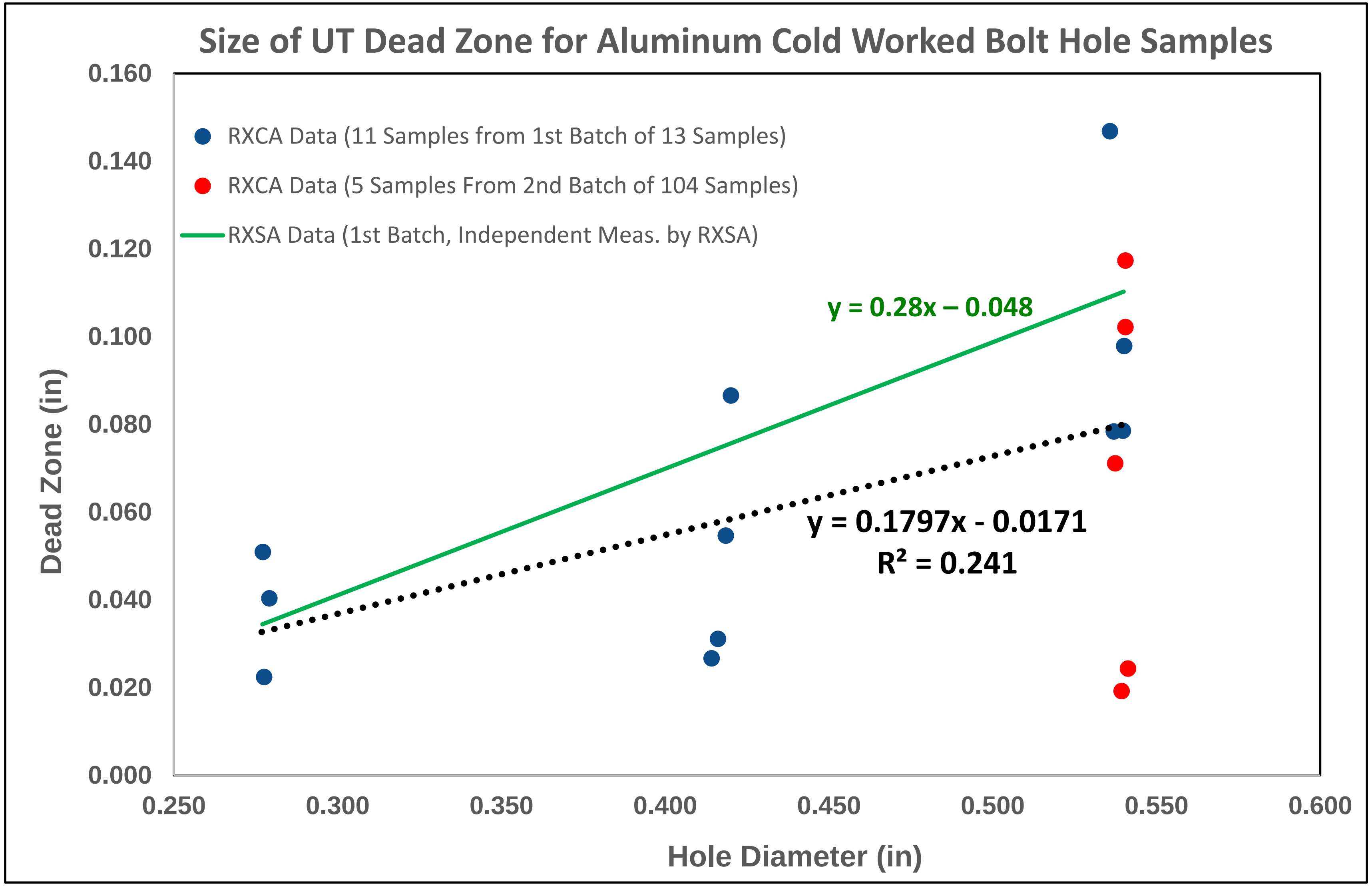


Python Scripts used to Semi-Automate Dead Zone Measurements

Summary of RXCA Results

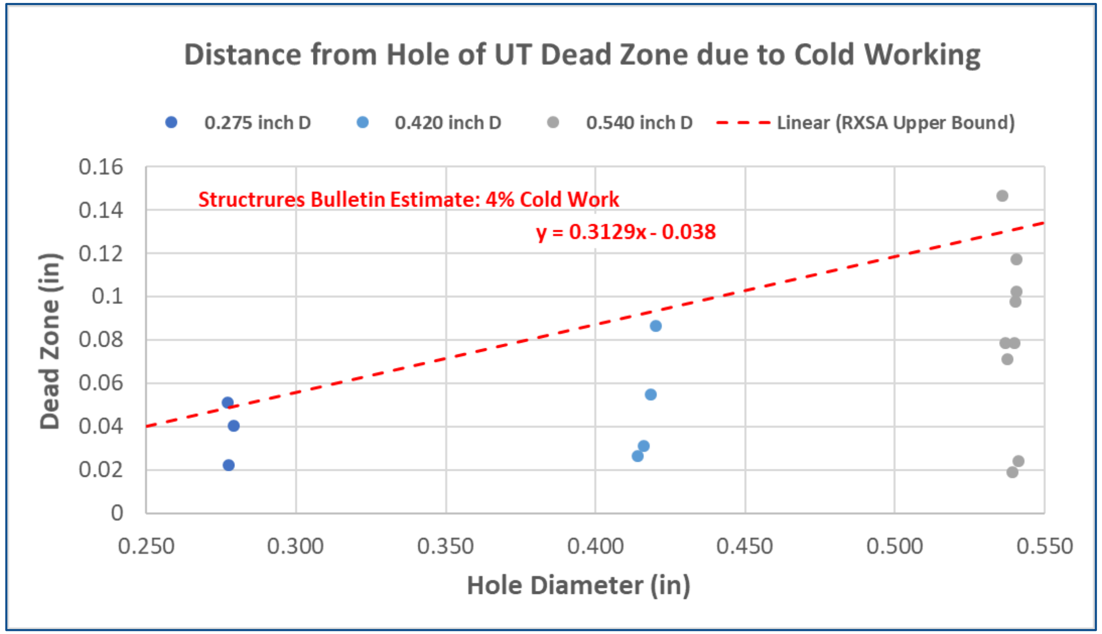
- 117 Samples Examined
- Measurable Dead Zone in only 16 samples
  - Used similar procedure as RXSA to size dead zone
  - Samples with no dead-zone not shown
- Similar trend of Dead Zone Size Proportional to Hole Dia. as found by RXSA

  - On average, RXCA results report smaller dead zone compared to RXSA measurements



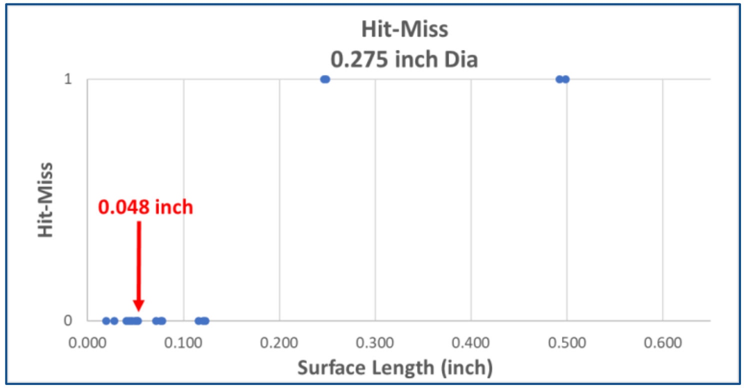
Comparison to Current Assumptions

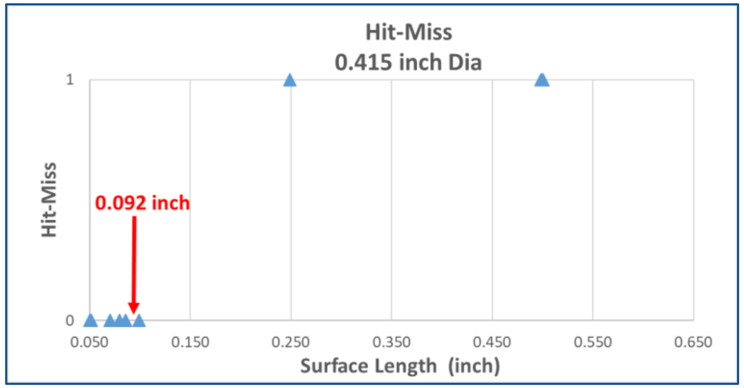
Data for Detectable Cracks (16 samples)

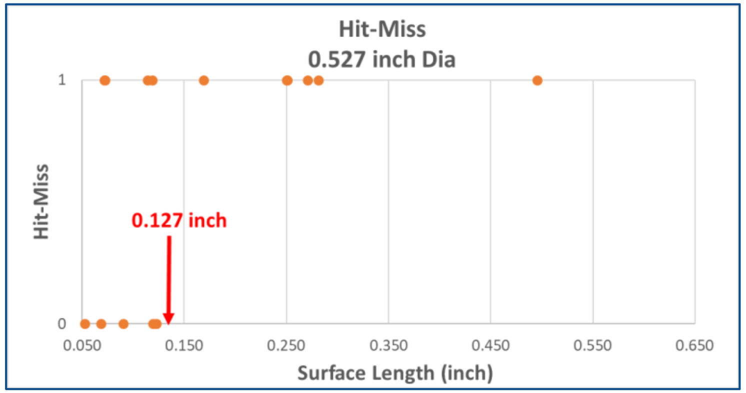


- Considerable variability in results
- Missed cracks greater than prediction are concerning
  - Further analysis of 0.275 in diameter hole samples initiated
- Next: Correlate dead zone estimates to residual stress profiles – collaboration required

All Cracks (56 samples)







NDI Implementation Strategy

- Capability impacts documented in EN-SB-008-012
- Impacts incorporated into ultrasonic probability of detection models
- Inspection limitations to be documented in ERSI Best Practices
- Documentation of inspection process best practices in general procedures of T.O. 33B-1-2 where applicable

Nondestructive Evaluation Sub-Committee

AFRL

Nondestructive Evaluation to Detect and Quantify Residual Stress Fields in Cold Worked Holes

Eric Lindgren

Materials State Awareness Branch
Materials and Manufacturing Directorate

December 8, 2020

Objective / Motivation / Impact

Objective

- **Nondestructive Evaluation (NDE) to quantify residual stress field at cold worked fastener holes**
  - **Verify Engineered Residual Stress (ERS) is present**
  - **After in-service and possibly for quality assurance**

Motivation

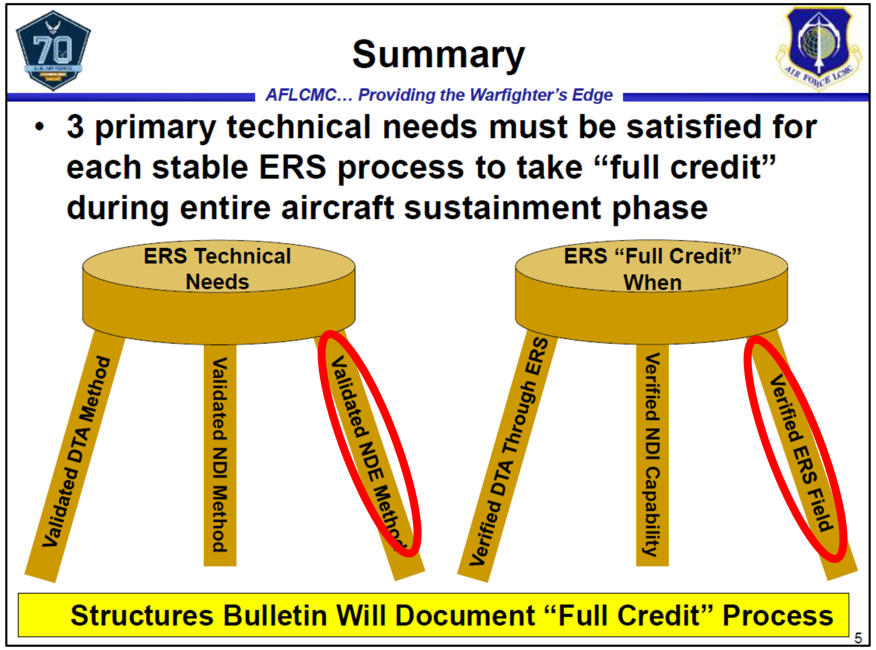
- **One of three primary technical needs to take full credit during entire sustainment phase**

Impact

- **Enables enhanced life management**
- **Enables life extension**
- **Both while not compromising safety**

ERSI

Engineering Residual Stress Integration



Summary

AFLCMC… Providing the Warfighter's Edge

- **3 primary technical needs must be satisfied for each stable ERS process to take "full credit" during entire aircraft sustainment phase**

Structures Bulletin Will Document "Full Credit" Process

From "ASIP Perspective on Accounting for Engineered Residual Stress (ERS) in Damage Tolerance Analysis," C.A. Babish, ASIP Conference 2017

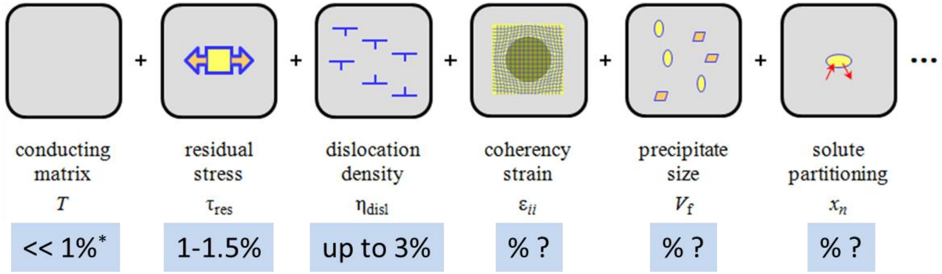
Background / Challenges

Background

- Multiple NDE-based methods sensitive to residual stress
  - X-ray diffraction, ultrasound, eddy current, neutron diffraction
- Previous research addresses predominantly shot-peened metals
  - Multiple for turbine engine applications

Challenges

- Confounding factors can exceed residual stress effect on NDE measurements
- In service: manufacturing (e.g. fit-up stresses), maintenance, repair, usage
- Macro-scale: temperature, geometry, material
- Micro-scale: dislocation density, coherency strain, precipitates, solute positioning



*Temperature controlled environment

Approach

Develop comprehensive inversion methodology:

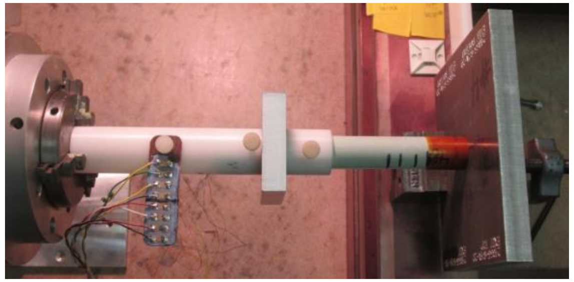
- **Focus: cold worked fastener holes**
- **Includes: multi-frequency, multi-probe approaches**
  - **Initial focus on eddy current methods**
  - **Ultrasonic techniques being evaluated**
- **Leverages modeling: macro and micro effects in aluminum alloys first**
- **Integrates uncertainty quantification:**
  - **Required to provide quantitative answer**
- **Year one of four year program complete**

HILL ENGINEERING
Predict. Test. Perform.

SwRI®

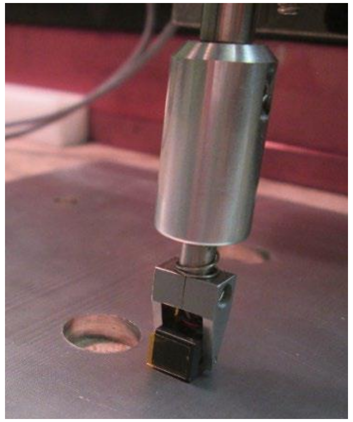
ERSI

Progress to Date



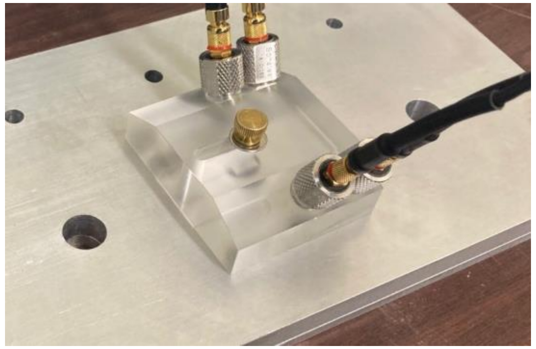
Initial Exploration:

- In-hole eddy current probe
- Specialized eddy current surface probe
- Ultrasonic probes



Structured Approach:

- Confounding factor assessment
- Rigorous test matrices
- Initial sample sets
- Will integrate structural variability



Preliminary Results:

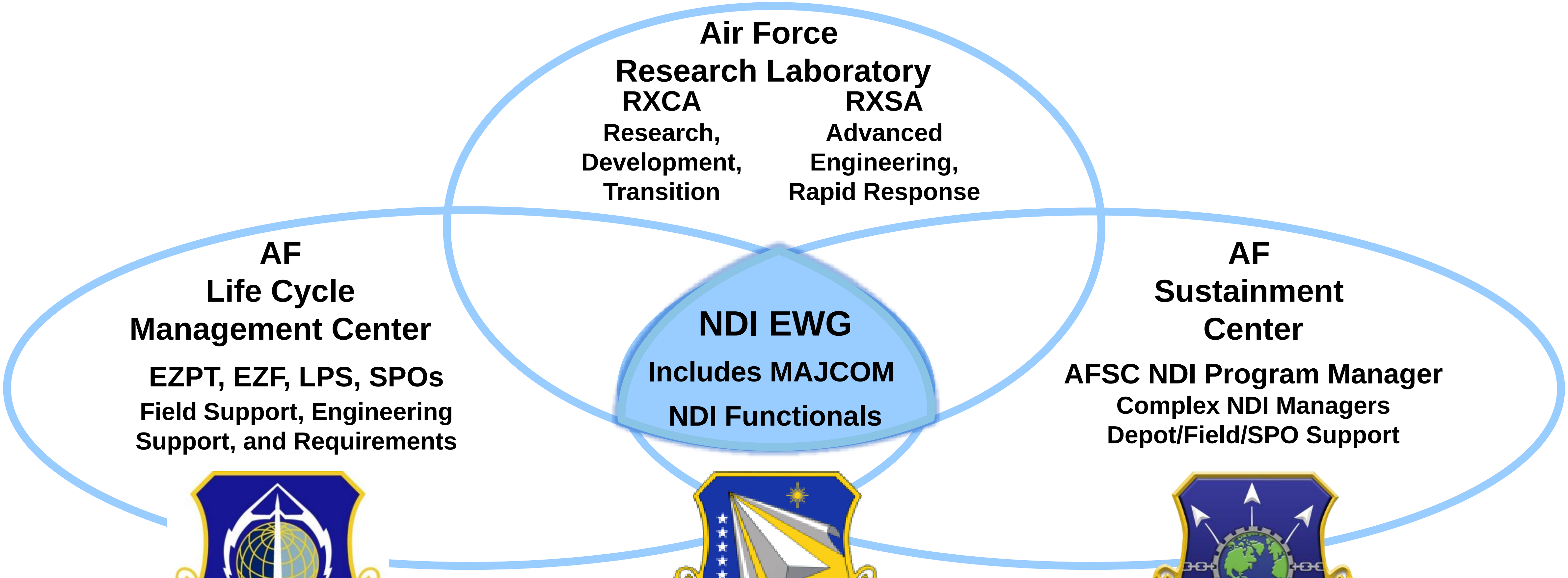
- All methods sensitive to controlled residual stresses
- Changes measured are small – promising for QA
- Start to address hard problem: quantification

Summary

- Quantitative NDE methods required for “full credit” for ERS
    - QA and Surveillance
- Extensive past R&D focused on NDE
    - Multiple methods can measure ERS
    - Success limited to differential measurements
    - Quantitative results hindered by confounding factors: there are many!
- New program leveraging past experience
    - Ambitious objectives
    - Eddy current and ultrasonic based approaches
    - Addresses QA and surveillance
    - Includes components with 10 and 20 year service life

AIRCRAFT STRUCTURAL INTEGRITY PROGRAM
ASIP
EST. 1958

Nondestructive Inspection Executive Working Group



Air Force Research Laboratory

RXCA
Research,
Development,
Transition

RXSA
Advanced
Engineering,
Rapid Response

AF Life Cycle Management Center

EZPT, EZF, LPS, SPOs
Field Support, Engineering
Support, and Requirements

NDI EWG

Includes MAJCOM
NDI Functionals

AF Sustainment Center

AFSC NDI Program Manager
Complex NDI Managers
Depot/Field/SPO Support

Material Assessment for Integrity Assurance

Quality Assurance and Data Management Sub-Committee

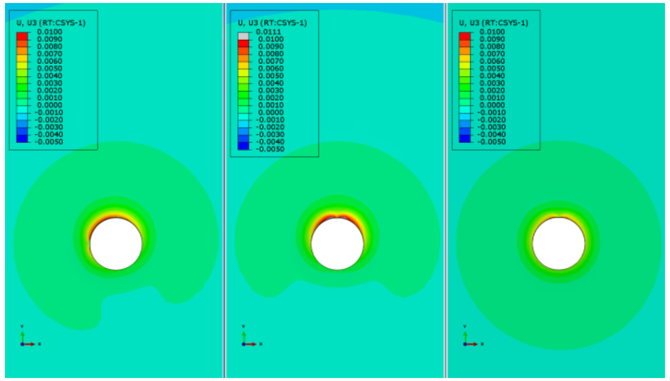
FastenerCam for QA/QC of Cold-Expanded Fastener Holes – 2020 ERSI Update and Summary

Doyle Motes,
Texas Research Institute (TRI) Austin, Inc.

8 December 2020

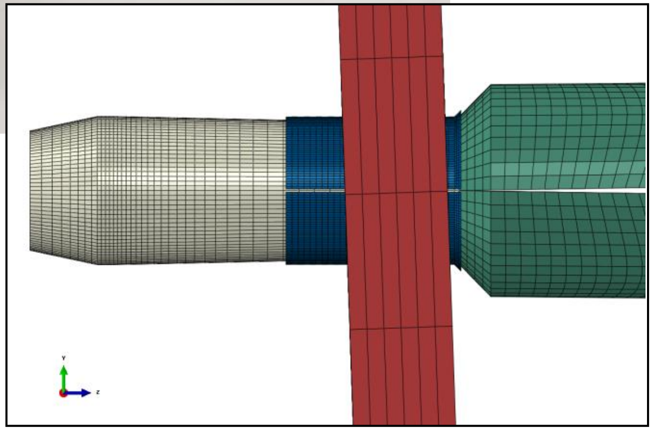
What is FastenerCam™?

- Developed out of RIF and subsequent SBIR efforts
- Handheld laser profilometer and software package (open source Python)
- Measures cold expansion around cold-worked fastener holes (quality assurance)
  - New install
  - Legacy analysis
  - What is unique to our approach
- Provides options for:
  - Good/Bad (Green light/red light)
  - Full data capture (entire set of profile data)
  - Interfaces with NLign for reporting



Current Status of FastenerCam™

- Ruggedized manufacturing prototype has been developed (TRL 6)
- Positioned to start LRIP for fieldable units
- Use cases include:
  - Straight shank holes
  - Multiple layers
  - Off-angle pulls
  - 2024 and 7075 Al alloys
- Meets MIL-STD-810F, -1472F, - 461G
- 8 hr battery, 2 TB HD, integrated touchscreen tablet



Next Steps to Develop FastenerCam™

- Develop and implement profilometry capabilities (scanning and analysis) for countersunk CX holes
- Manufacture an upgraded FastenerCam™ (for straight and countersunk holes)
- Repeatability and reliability (R&R) study to integrate FastenerCam™ into tech orders for aircraft of interest

Digitalex background

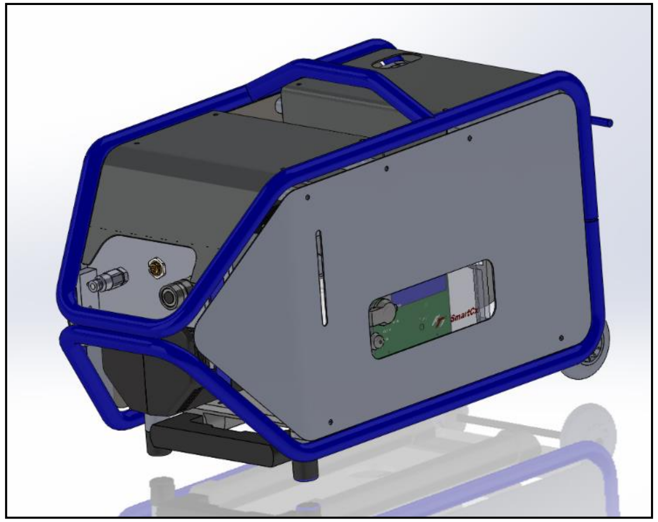
Sam Zimmerman,
Fatigue Technologies, Inc.

8 December 2020

Next-generation split sleeve instrumented Cx tooling

New Hydraulic Puller and PowerPak integrating instrumentation with proprietary data analysis

- Fully electric operation,
- Monitors load vs piston stroke data,
- Integrated process validation (Go/No Go),
- Process data logging for archive records,
- Allows tool life tracking, lockout and other digitized tool management
- Integration to networked factory (IoT),
- Compatible with legacy FTI processes,
- Compatible with Data Spatial Positioning (DSP) systems.



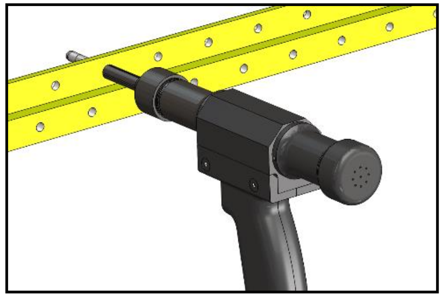
Vision for digitized cold expansion tools

QUALITY

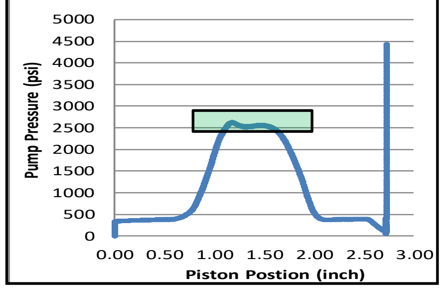
- Increased process confidence and reduced quality risk
- Integrated process check (“Instant” Go/No Go)

PLANNING

- Pre and Post Cx process data sharing
- Active monitoring of KPI’s and advanced analytics



FTI Instrumented SsCx Tooling



PROCUREMENT

- Real-time tooling and consumables data
- Advanced tool tracking

ENGINEERING

- Greater confidence in design allowables
- Traceable digital Cx data records (Digital Twin)

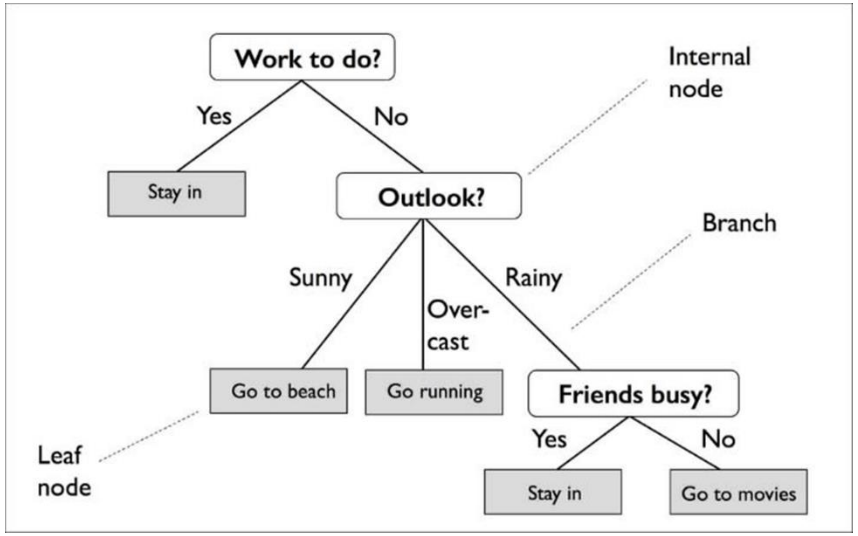
CUSTOMER SATISFACTION

- Increased quality at higher rates
- Potential for extended PM schedules
- Traceability and advanced data

Decision Tree Go/No-go

Process description

- Data is curve fit to both a flat-top Gaussian and a skew Gaussian
- Curve fit parameters are fed into decision tree classifier
- Planned schedule: Available on DSP program unit
  June 2020



In-depth method – Curve Fit

- Two curve fit equations:

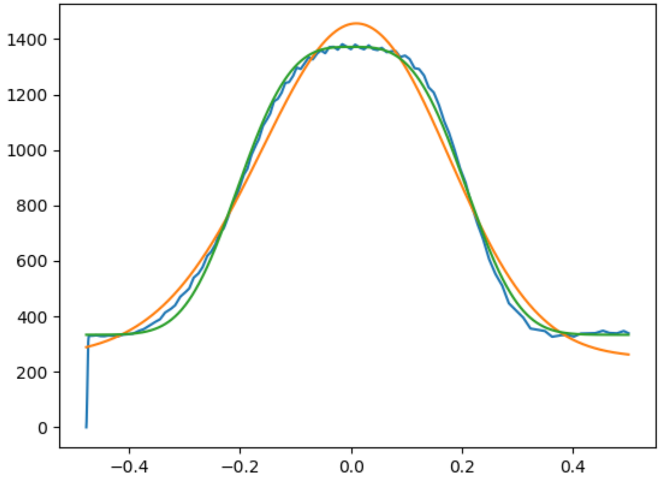
$$PDF(x) = \frac{1}{\sqrt{2\pi}} e^{-x^2/2}$$

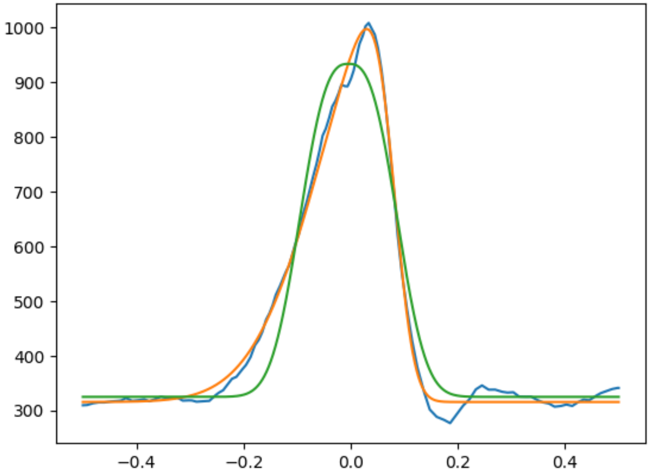
$$CDF(x) = \frac{1 + \operatorname{erf}\left(x/\sqrt{2}\right)}{2}$$

Equations:

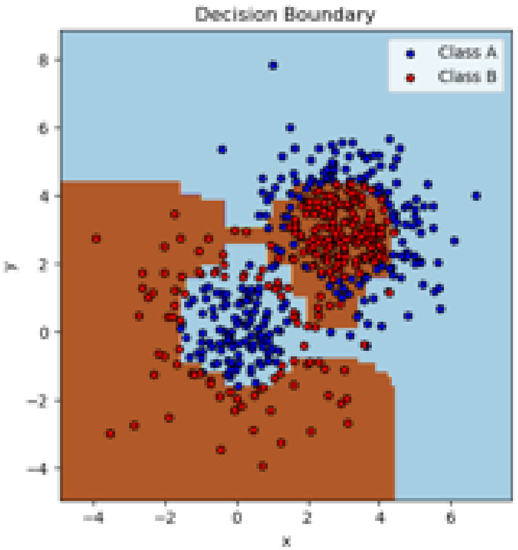
$$S(x) = \alpha\left(PDF\left(\frac{x-m}{\sigma}\right) CDF\left(\frac{\beta(x-m)}{\sigma}\right)\right) + \gamma$$

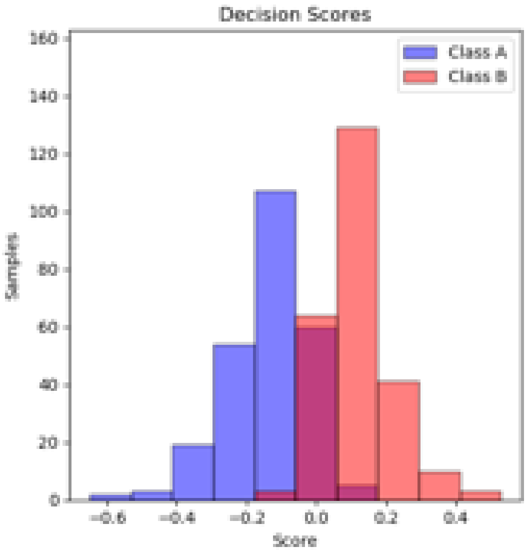
$$F(x) = \alpha\left(PDF\left(\left(\frac{x-m}{\sigma}\right)^{\varphi}\right)\right) + \gamma$$





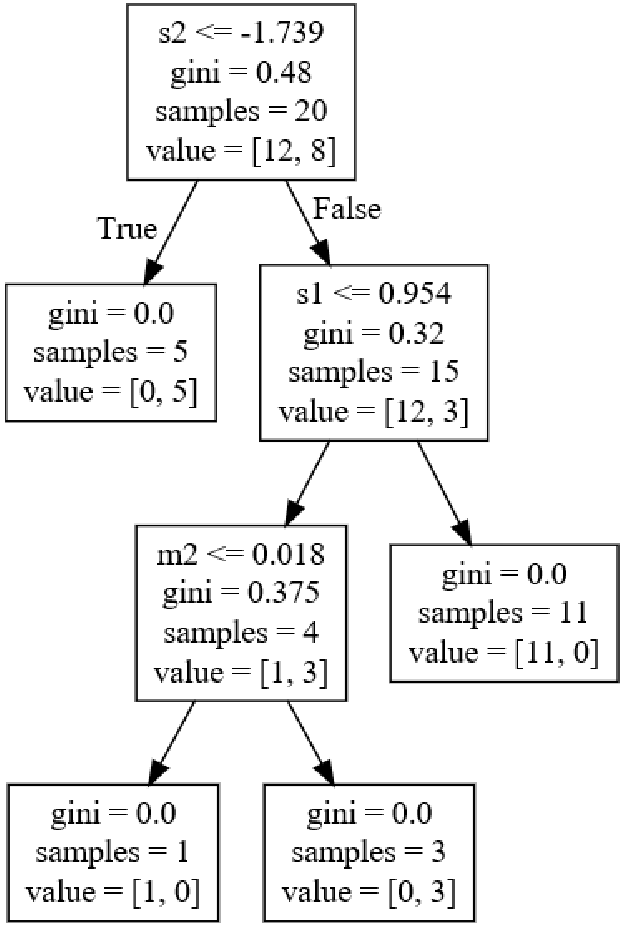
In-depth method – Decision Tree Classification





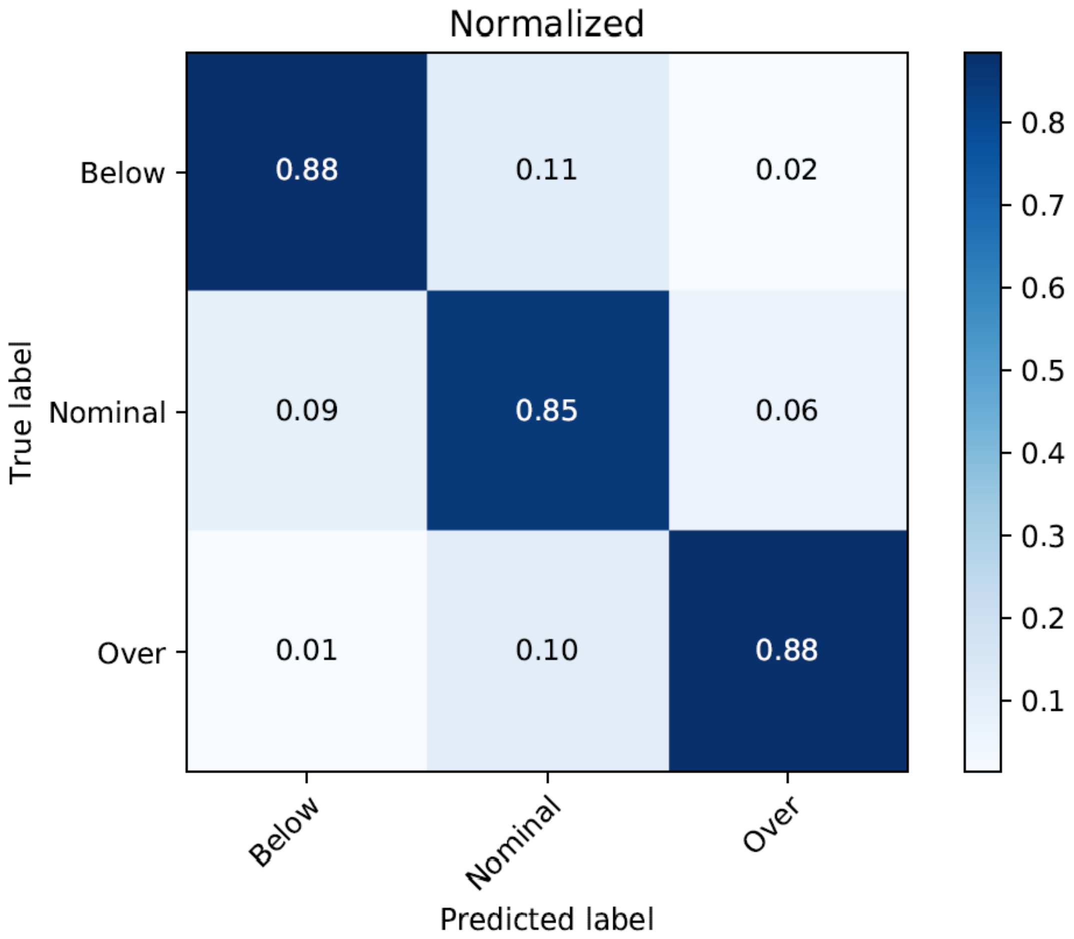
- Separate parameter space into rectangular "regions" split by branches
- Regions are continually split into smaller and smaller rectangles at each branch

Optimization process



- At each branch, minimize Gini index.
  - Gini measures how “pure” each category is
- Pruning
  - After building tree, remove unnecessary branches
- Bootstrapping
  - Build multiple trees and take the median of all of them

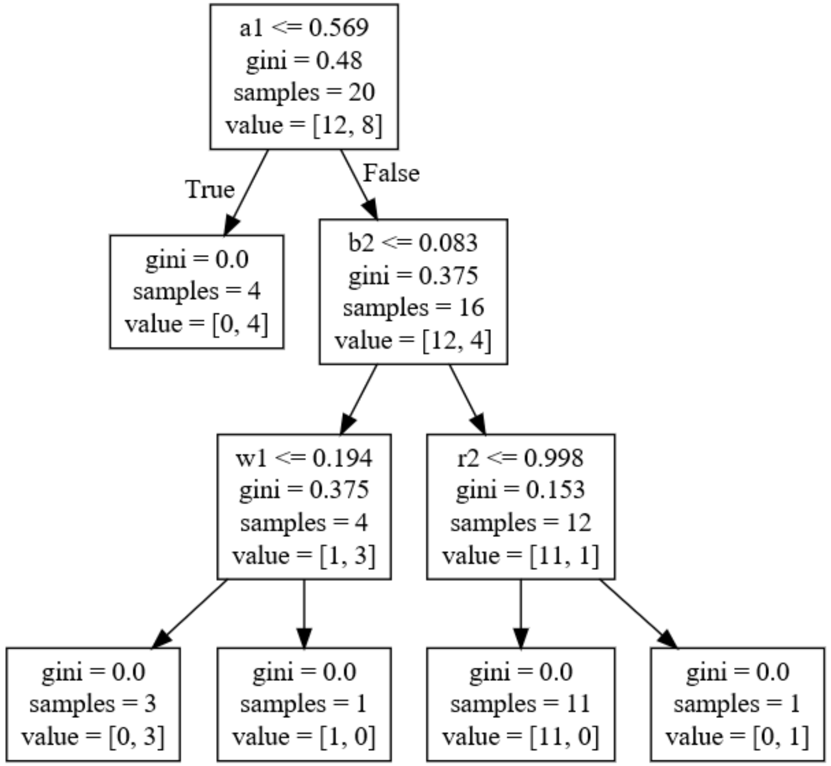
Results



Classification rate with built-in 90% confidence interval

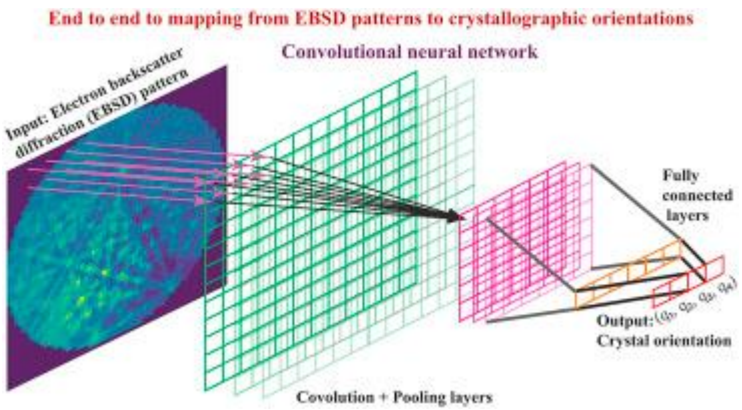
Discussion

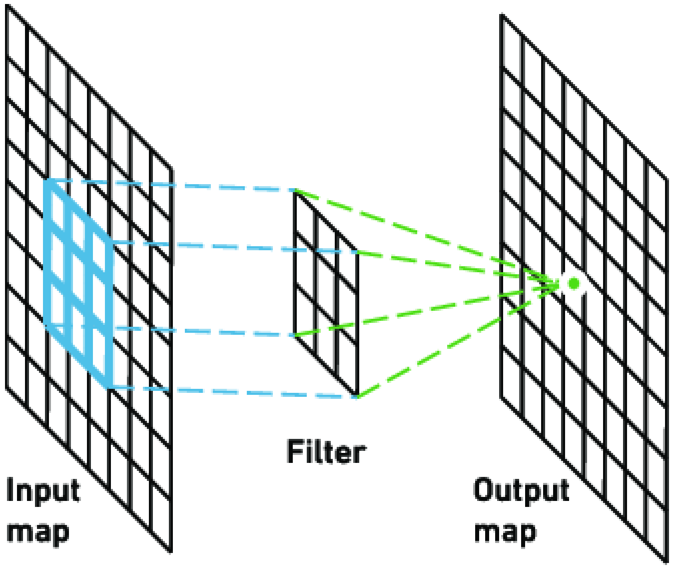
- Process can account for lots of different data configurations and styles
- Better configuration with LOTS more data
- Need to fine-tune pruning options to help clean up excessively large trees



Machine Learning
Applied Expansion Estimation

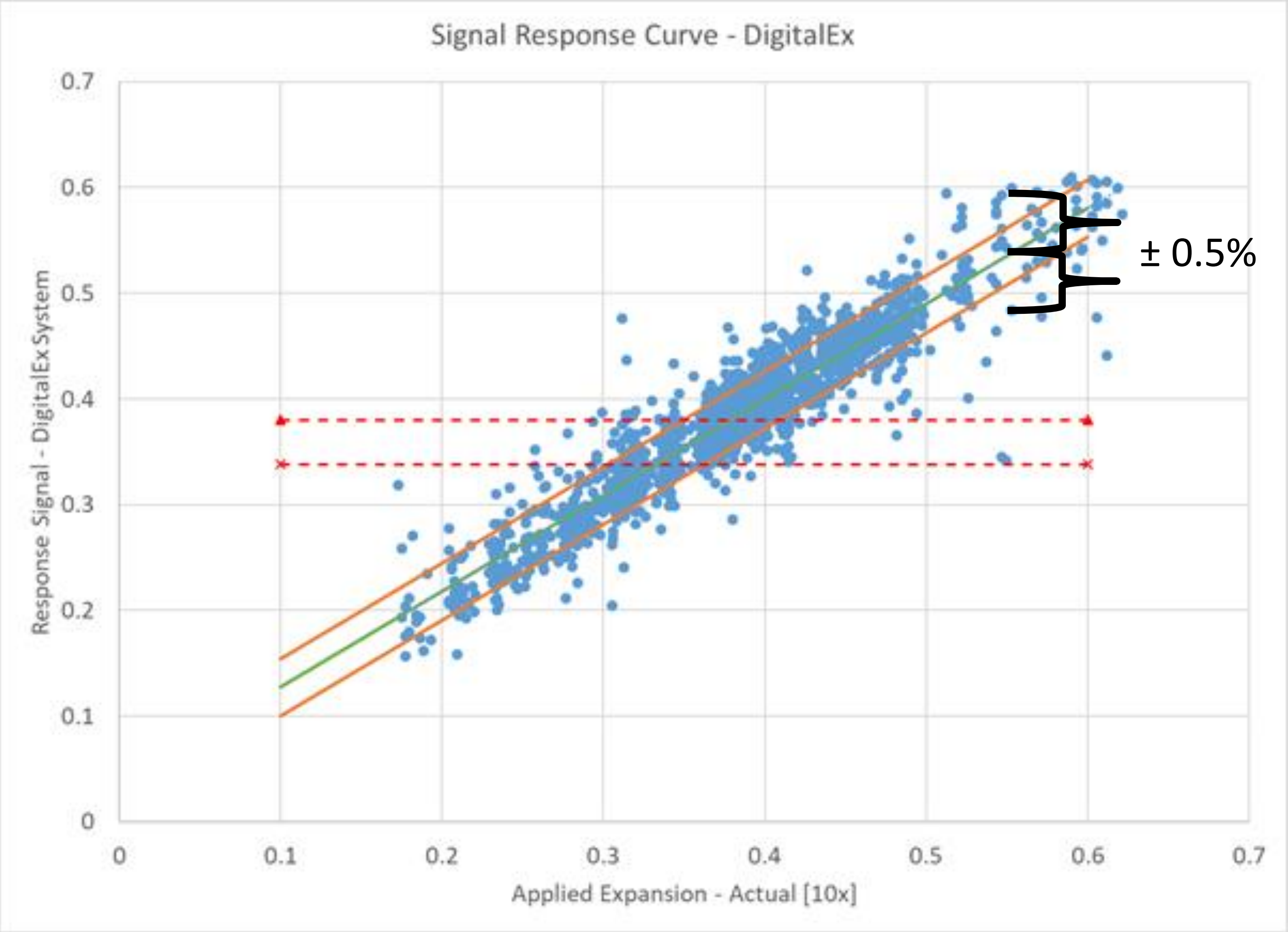
Convolution Network





- Convolution NN iteratively determines filters
- Filters are optimized using error back-propagation
- Consecutive layers detect important combinations of features

Results


Signal Response Curve - DigitalEx
Response Signal - DigitalEx System
Applied Expansion - Actual [10x]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

± 0.5%

Discussion

- Present capabilities are useful but not universal
  - Needs significantly more testing before final roll-out
- Better for processing prediction, not as useful for QA control
  - Since QA is not driven by expansion, cannot *currently* use expansion as true QA metric
- Expected timeline – May/June 2021

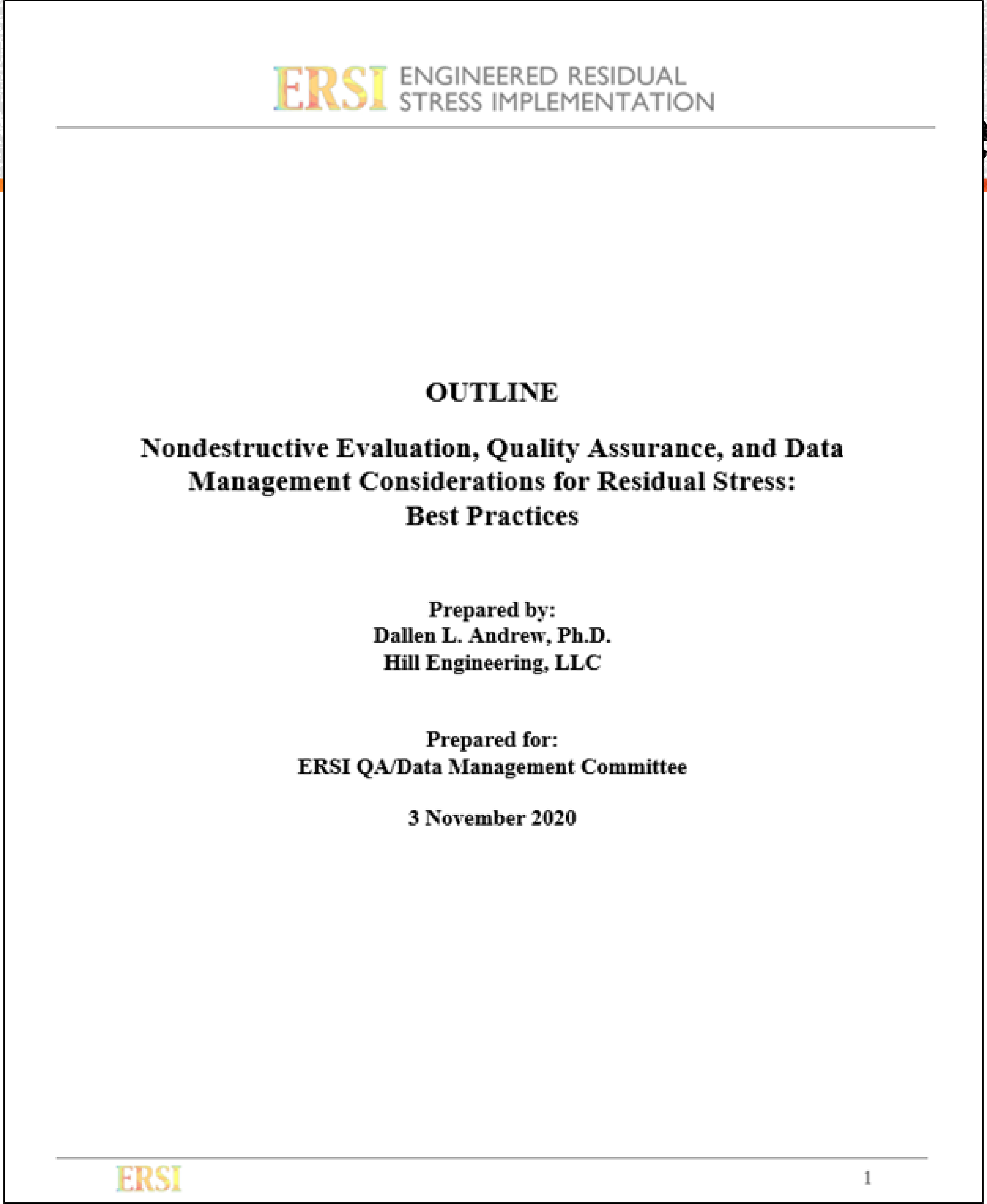
Update on Best Practices Document

Dallen L. Andrew, Ph.D.
Hill Engineering LLC

8 December 2020

s Update

- Significant progress was made to the NDI/NDE/QA/Data Management Best Practices document
- Feedback has been gathered from ERSI committee members and revisions are in-work
- An outline of the revised sections is included for reference



ERSI ENGINEERED RESIDUAL
STRESS IMPLEMENTATION

OUTLINE

Nondestructive Evaluation, Quality Assurance, and Data Management Considerations for Residual Stress: Best Practices

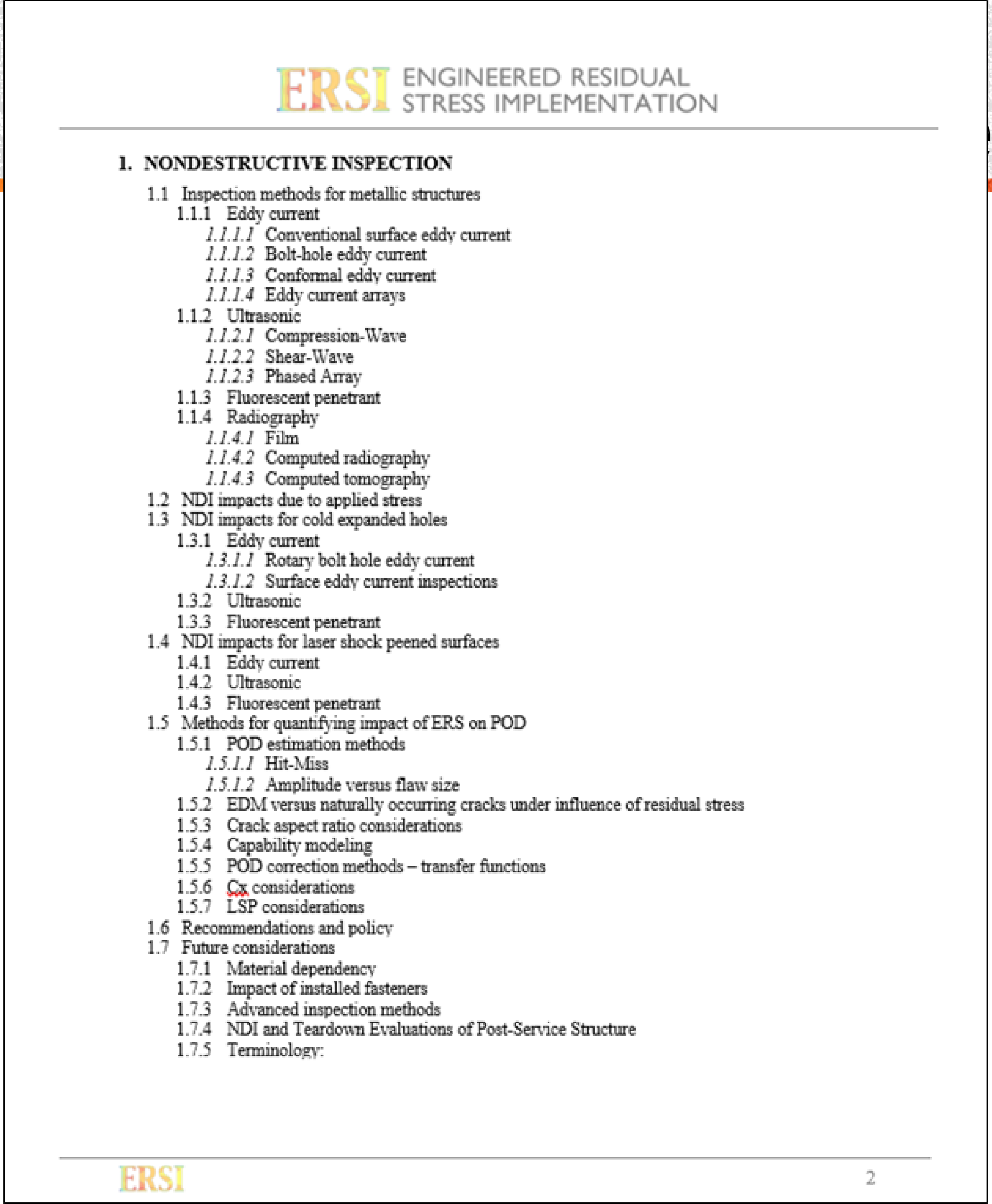
Prepared by:
Dallen L. Andrew, Ph.D.
Hill Engineering, LLC

Prepared for:
ERSI QA/Data Management Committee

3 November 2020

ERSI 1

s Update

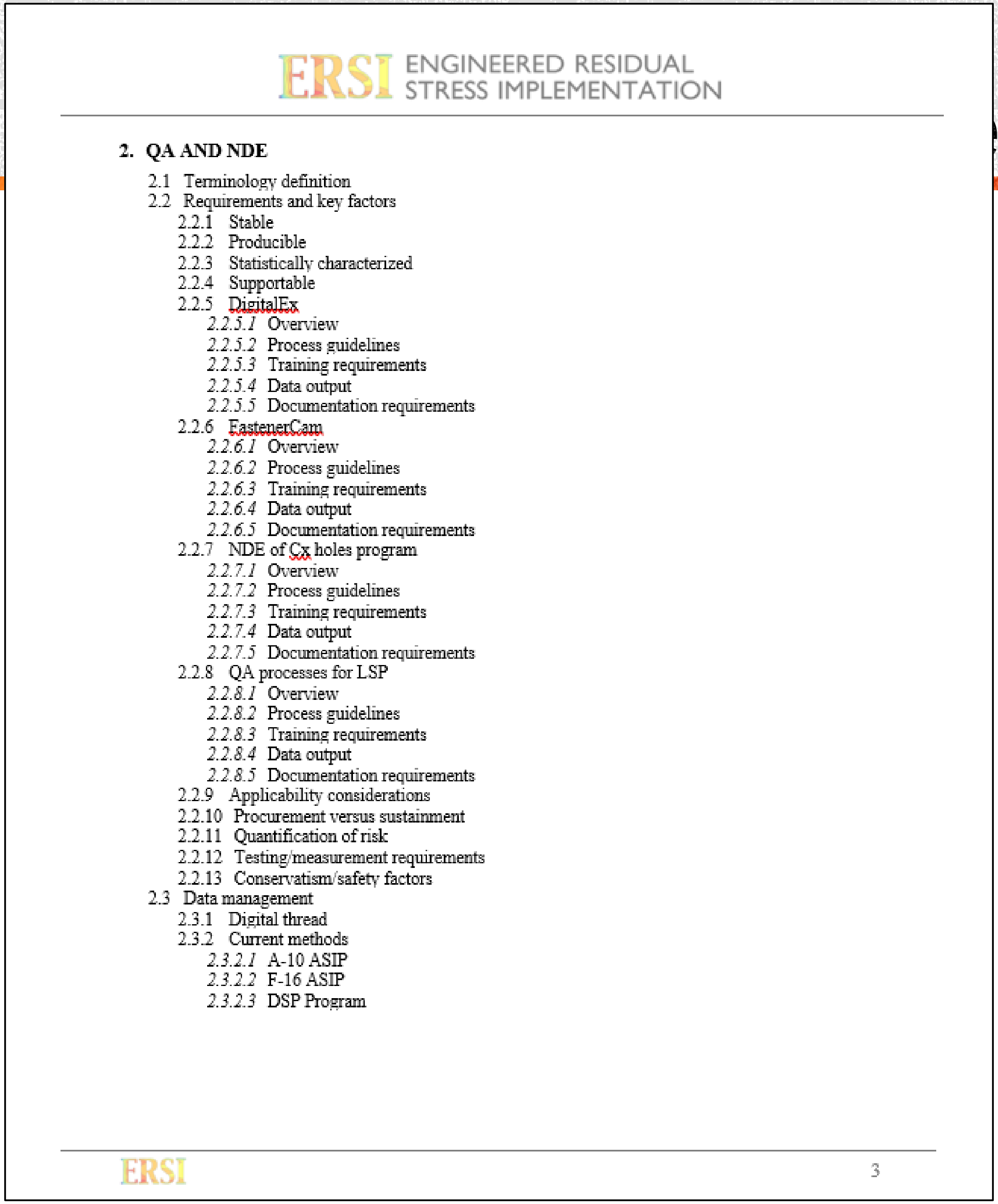


1. NONDESTRUCTIVE INSPECTION

- 1.1 Inspection methods for metallic structures
  - 1.1.1 Eddy current
    - *1.1.1.1* Conventional surface eddy current
    - *1.1.1.2* Bolt-hole eddy current
    - *1.1.1.3* Conformal eddy current
    - *1.1.1.4* Eddy current arrays
  - 1.1.2 Ultrasonic
    - *1.1.2.1* Compression-Wave
    - *1.1.2.2* Shear-Wave
    - *1.1.2.3* Phased Array
  - 1.1.3 Fluorescent penetrant
  - 1.1.4 Radiography
    - *1.1.4.1* Film
    - *1.1.4.2* Computed radiography
    - *1.1.4.3* Computed tomography
- 1.2 NDI impacts due to applied stress
- 1.3 NDI impacts for cold expanded holes
  - 1.3.1 Eddy current
    - *1.3.1.1* Rotary bolt hole eddy current
    - *1.3.1.2* Surface eddy current inspections
  - 1.3.2 Ultrasonic
  - 1.3.3 Fluorescent penetrant
- 1.4 NDI impacts for laser shock peened surfaces
  - 1.4.1 Eddy current
  - 1.4.2 Ultrasonic
  - 1.4.3 Fluorescent penetrant
- 1.5 Methods for quantifying impact of ERS on POD
  - 1.5.1 POD estimation methods
    - *1.5.1.1* Hit-Miss
    - *1.5.1.2* Amplitude versus flaw size
  - 1.5.2 EDM versus naturally occurring cracks under influence of residual stress
  - 1.5.3 Crack aspect ratio considerations
  - 1.5.4 Capability modeling
  - 1.5.5 POD correction methods – transfer functions
  - 1.5.6 Cx considerations
  - 1.5.7 LSP considerations
- 1.6 Recommendations and policy
- 1.7 Future considerations
  - 1.7.1 Material dependency
  - 1.7.2 Impact of installed fasteners
  - 1.7.3 Advanced inspection methods
  - 1.7.4 NDI and Teardown Evaluations of Post-Service Structure
  - 1.7.5 Terminology:

ENGINEERED RESIDUAL
STRESS IMPLEMENTATION

s Update



2. QA AND NDE

- 2.1 Terminology definition
- 2.2 Requirements and key factors
  - 2.2.1 Stable
  - 2.2.2 Producible
  - 2.2.3 Statistically characterized
  - 2.2.4 Supportable
  - 2.2.5 DigitalEx
    - *2.2.5.1* Overview
    - *2.2.5.2* Process guidelines
    - *2.2.5.3* Training requirements
    - *2.2.5.4* Data output
    - *2.2.5.5* Documentation requirements
  - 2.2.6 FastenerCam
    - *2.2.6.1* Overview
    - *2.2.6.2* Process guidelines
    - *2.2.6.3* Training requirements
    - *2.2.6.4* Data output
    - *2.2.6.5* Documentation requirements
  - 2.2.7 NDE of Cx holes program
    - *2.2.7.1* Overview
    - *2.2.7.2* Process guidelines
    - *2.2.7.3* Training requirements
    - *2.2.7.4* Data output
    - *2.2.7.5* Documentation requirements
  - 2.2.8 QA processes for LSP
    - *2.2.8.1* Overview
    - *2.2.8.2* Process guidelines
    - *2.2.8.3* Training requirements
    - *2.2.8.4* Data output
    - *2.2.8.5* Documentation requirements
  - 2.2.9 Applicability considerations
  - 2.2.10 Procurement versus sustainment
  - 2.2.11 Quantification of risk
  - 2.2.12 Testing/measurement requirements
  - 2.2.13 Conservatism/safety factors
- 2.3 Data management
  - 2.3.1 Digital thread
  - 2.3.2 Current methods
    - *2.3.2.1* A-10 ASIP
    - *2.3.2.2* F-16 ASIP
    - *2.3.2.3* DSP Program

Questions

- NDI: J. Brausch committed to fill-in any of this chapter?
- QA and NDE: Does anyone want to help fill-in any of this chapter?
  - Will likely need support at least from:
    - FTI (Sam?) for instrumented puller
    - TRI-Austin (Doyle?) for FastenerCam

Working Group on
Engineered Residual
Stress Implementation

Measurement Committee Summary

(These charts are a team product.)

Dec 08, 2020

Mike Hill, committee lead
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530-754-6178 (work)

Eric Burba, committee co-lead
Micheal.Burba.1@us.af.mil
(937) 255-9795 (work)

Topics for Today

Committee Logistics:

- Typical Meeting Agenda
- Roster and Attendance

Topics of Note

- Active work items
- Status and accomplishments
- Summary of technical elements

Opportunities Ahead

- Applications at CHESS
  - Large hole coupons
- Continuation of active work
- Interactions with other ERSI Committees
- Interactions with field challenges

Meeting Agenda

Example slide, typical meeting

X:00-X:05 Welcome and agenda (Mike H)

X:05-X:10 Update from Process Modeling committee (Adrian)

X:10-X:15 Update from 2x2WG (Marcus)

X:15-X:40 Old Business

- Project updates
  - Texture/Orientation/Anisotropy update (Mark, Mike S)
  - Exemplar Data Sets (Eric)
  - Large Hole Effort (Mike H and James)
- Potential activities at CHESS (Mark)
  - EDD for Large Hole coupons
- Documentation updates
  - Discussion of Best Practices Document updates

X:40-X:55 New business

- Quick updates (All)
- Open discussion (All)
- ERSI 2020 Virtual Meeting: Nov 17-19, 2020
- RS Measurement goals discussion

X:55-X:58 Action items

X:58-X:59 Closing

Committee roster (recent changes in color)

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Kevin	Walker	QinetiQ	+61457002775	kfwalker@qinetiq.com.au

Summary of Meeting Attendance

Example slide, typical meeting

Nov 18, 2020

- Breuer, Burba, DeWald, Lindgr [illegible] Obstalecki, Oliveira, Pineault, Sp [illegible] Hill

Oct 14, 2020

- Backman, Breuer, Pineault, Oliveira, Bouchard, Burba, Martinez, Obstalecki, Hill

Sep 9, 2020

- Pineault, Burba, Obstalecki, DeWald, Harrison, Hill

Aug 19, 2020

- Burba, Pineault, Stanfield, DeWald, Obstalecki, Hill

July 8, 2020

- Lindgren, Burba, Bouchard, Carlson, DeWald, Pineault, Hill

June 10, 2020

- Lindgren, Burba, Bouchard, DeWald, Obstalecki, Pineault, Spradlin, Oliveira, Hill

May 13, 2020

- Burba, Obstalecki, Carlson, DeWald, Pineault, Hill, Backman, Steinzig, Bouchard, Harrison

April 8, 2020

- Harrison, Pineault, Burba, Hill, Hitchman (from Modeling group), Dave Breuer (CWST, guest of Harrison)

March 11, 2020

- [illegible]llin, DeWald, Carlson, Pineault, Obstalecki, [illegible]dgren, Burba, Hill

Sep 12, 20[illegible] ([illegible]kshop)

- Pearce, Nyugen-Quoc, Barrientos, Greuner, Stanfield, Carlson, Bouchard, Dubberly, A Jones, Hitchman, DeWald, Steinzig, T Thompson, Pineault, Hill

March 13, 2019

- Spradlin, Lindgren, Pineault, Brauss, Steinzig, DeWald, Carlson, Grodzicki (guest), Hill

Feb 6, 2019

- Steinzig, Carlson, Penault, Grodzicki (guest), Pilarczyk, DeWald, Hill

Jan 9, 2019

- Spradlin, Carlson, Pilarczyk, Burba, Obstalecki, Lindgren, Martinez, Hill

Update from Process Modeling Committee

Adrian DeWald is point person fostering interaction with the Process Modeling Committee

New items (Adrian)

- Notes from last meeting (9/17/20):
  - Planning to finish the summary of the first round robin modeling activity
    - Results to be presented at December ERSI general meeting
  - Holding on second round robin until after feedback from the December ERSI general meeting

Example slide, typical meeting

From prior discussions

- First simulation round-robin is to be reported 9/25
  - Publication being considered
  - New round-robin activity is planned, but on hold pending feedback
- There is an opportunity to work with other ERSI Groups on methods for data comparison and data assessment
  - Basic questions:
    - When we have different 2D stress fields from given sources (e.g., measurements of different types, and/or models of different types) what are useful ways to compare them?
    - What are ways to assess uncertainty of 2D stress fields?
  - All groups have a stake in this area, but maybe these are key:
    - Data Management and Quality Assurance (Kaylon Anderson)
    - Risk Analysis and Uncertainty Quantification (Laura Hunt)
    - Residual Stress Measurement (Mike Hill)
    - Residual Stress Process Simulation (Keith Hitchman)

Update from 2x2 working group

Marcus Stanfield is point person fostering interaction with the 2x2 working group (2x2WG)

New items (Marcus)

Example slide, typical meeting

- Synchrotron data from APS needs to be processed (need a p[illegible])
- XRD needs elastic constant (XEC) determined
- Neutron data from Japan is complete, Prof Bouchard preparing a publication
  - Post-meeting question: can this data be shared (to be held in the Committee)?
- 2x2WG priority is publication

From prior discussions

- Detailed update (Marcus, 19 Aug 20; see charts in email)
  - Opportunity to measure non-reamed CX holes (contact Marcus)
    - + Limited to nondestructive measurements
    - + Potential opportunity with at CHESS (USAF has a funded program)
  - Opportunity to help with analysis of prior EDXRD data (contact Scott C)
- Updates at July meeting (Bouchard, Pineault)
  - XRD data being worked on
  - Additional ND measurements active
  - Marcus Stanfield is current lead for this activity

Old business

On-going project updates

Example slide, typical meeting

- Texture/Orientation/Anisotropy (Mark/Mike S)
  - Current status
- Exemplar Data Sets (Eric)
  - Current status
    - Mike and Eric will develop a workflow for open publication of residual stress measurement data using DRYAD
      - Mike: data presented to the committee on June 10, 2020
      - Eric: USAF data to be identified (likely for shot peened materials)
    - DRYAD as opportunity for sharing data
      - https://datadryad.org/
- Large Hole Effort (Mike H)
  - Current status
    - James and Mike to provide update on recent measurement data in November

Potential activities at CHESS (Mark)

- Potential application of Energy Dispersive Diffraction (EDD) to the A-10 Large Hole coupons (good tie in to standing work)
  - Mark and Eric have the action on this?

Old business (continued)

Example slide, typical meeting

Documentation updates

- Current updates
  - Please provide feedback on best practices documents ([illegible])
  - Received some detailed feedback (thanks, James!) on the A-10 [illegible]ocument (see below)
    - Mike H and Eric will review, then feedback to Committee for consensus [illegible] to A-10
    - Watch for an action item on this by email
- Prior notes
  - New journal publication related to ERSI: Andrew, DL, Han, H-C, Ocampo, J, Alaeddini, A, Thomsen, M. Characterization of residual stresses from cold expansion using spatial statistics. *Fatigue Fract Eng Mater Struct*. 2020; 1–14. https://doi.org/10.1111/ffe.13334
  - New journal paper on contour method reproducibility
    - Available for all to read at https://rdcu.be/b4KpF
  - USAF Best Practices document being opened for updates (A-10 program) "Analytical Considerations for Residual Stress Best Practices and Case Studies"
    - Prior release available here: https://apps.dtic.mil/sti/citations/AD1084445
    - Feedback and suggestions are welcome
      - Provide comments back to Mike Hill for relay to program
  - ASTM Task Group writing industry guidance document
    - TG E08.04.06 - Residual Stress in Structural Design and Sustainment (T.J. Spradlin, TG Chair)
  - Forthcoming USAF Structures Bulletin
    - T.J. Spradlin accepting input
  - ERSI NDE/QA Committee is circulating a document framework for feedback
    - Send input to Mike Hill, Eric Burba, or Kaylon Anderson kaylon.anderson@us.af.mil

Active work items

Communications and collaboration within ERSI

- 2x2 Working Group (2x2WG)
- Process Simulation Committee

Exemplar RS data sets

Large hole RS measurements

Anisotropy and preferred orientation

- Assess how residual stress measurement techniques perform in processed metals (typical and atypical material conditions)

Outward facing documents

- Develop measurement-specific documents
- Support overall ERSI documentation efforts
  - SB, A-10 Best Practices, ASTM, ASM
  - Focus currently on A-10 Best Practices
- List relevant publications and reports

Status and accomplishments

Established interfaces with other activities

- 2x2WG
- Process Simulation

Developed plan for posting exemplar data sets in open data repository

Developed RS data in large hole coupons

- Being discussed within Committee

Developed plan for studying anisotropic materials

Contributed to outward facing documents

- Engaged in developing draft material or revisions (ASTM, A-10 Best Practices)
- Noted relevant publications
  - Andrew, DL, et al., “Characterization of residual stresses from cold expansion using spatial statistics”. *Fatigue Fract Eng Mater Struct*. 2020; 1-14. https://doi.org/10.1111/ffe.13334
  - D’Elia, CR, et al., “Interlaboratory Reproducibility of Contour Method Data Analysis and Residual Stress Calculation”. *Experimental Mechanics*, 2020, https://rdcu.be/b4KpF

Summary of technical elements

2x2 working group (2x2WG)

- Contact Marcus Stanfield

Exemplar data sets: near surface stress profiles

- Contact Eric Burba

Large hole experimental work

- Contact Mike Hill

Anisotropy and preferred orientation

- Contact Mark Obstalecki

2x2 Working Group Overview

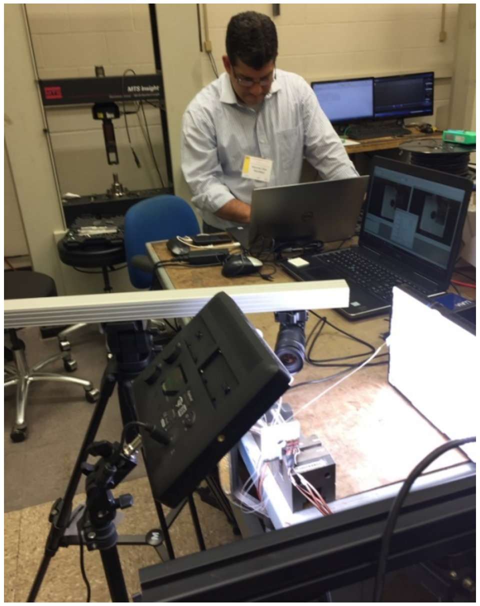
Schedule: 2016 - Ongoing

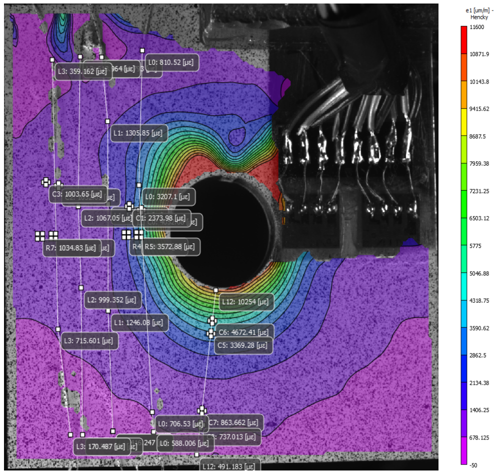
Members

- Research, Industry, Academia
- Multiple committee participation

Purpose

- Cx multiple aluminum alloys (2024-T351 & 7075-T651) at “Low” and “High” expansion levels for reamed and un-reamed configurations
- Characterize the residual stress/strain using multiple measurement techniques
  - Strain gauge, LUNA fiber optics, DIC
  - XRD, EDD, ND
  - Contour Method
- Develop a validation data set and framework for process simulations and NDI/QA
- Develop input data for FCG validation





ERSI Working Group on Engineered Residual Stress Implementation

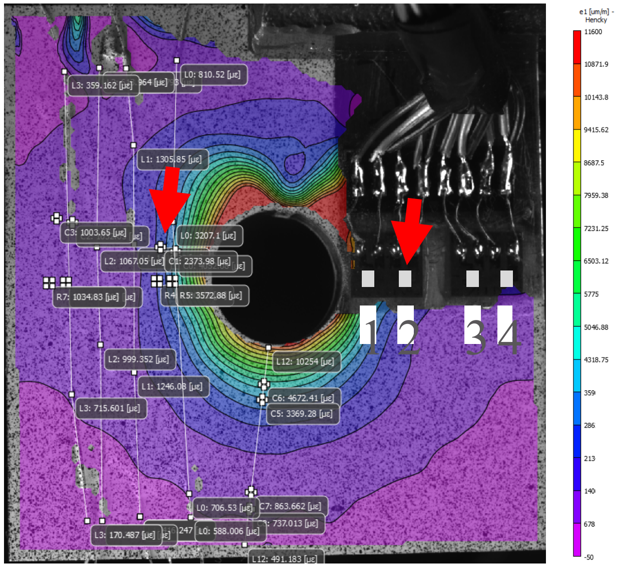
Surface Strain Highlights

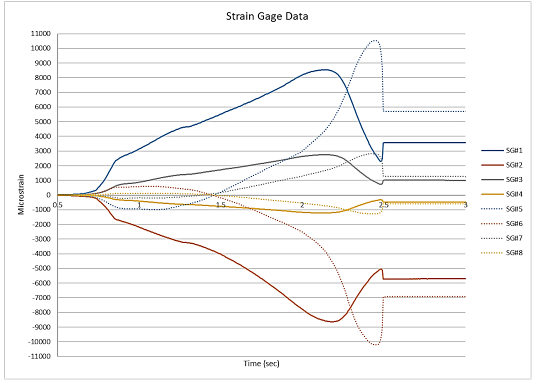
Multiple measurement cross validation

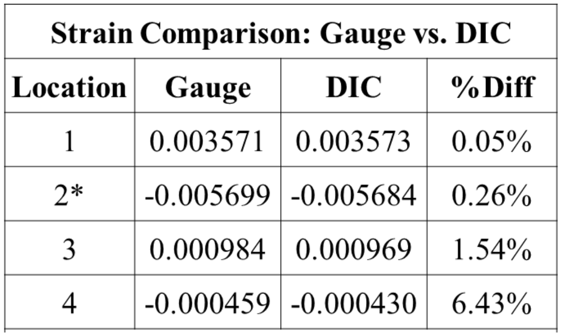
DIC/FEM comparison using MatchID

Validation metrics established (Zimmerman)

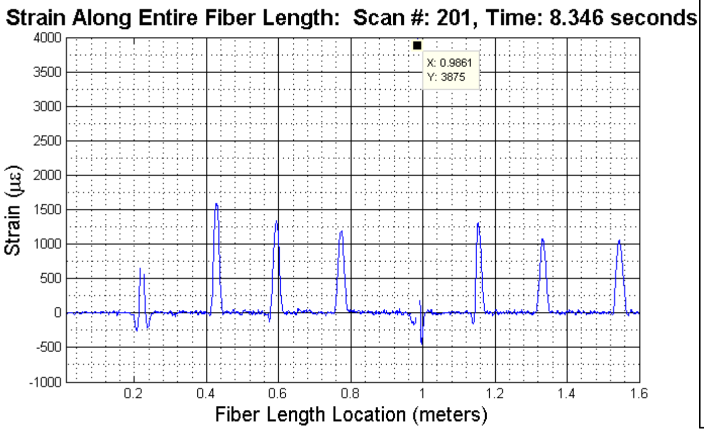
Multiple process simulation models (FTI/NRC)

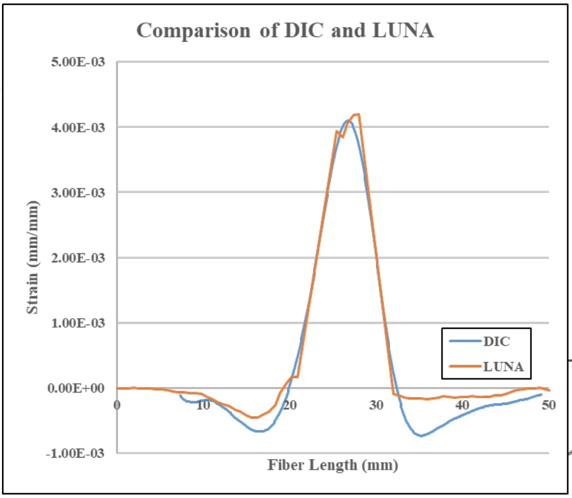



Strain Gage Data


Strain Comparison: Gauge vs. DIC

Location	Gauge	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%


Strain Along Entire Fiber Length: Scan #: 201, Time: 8.346 seconds

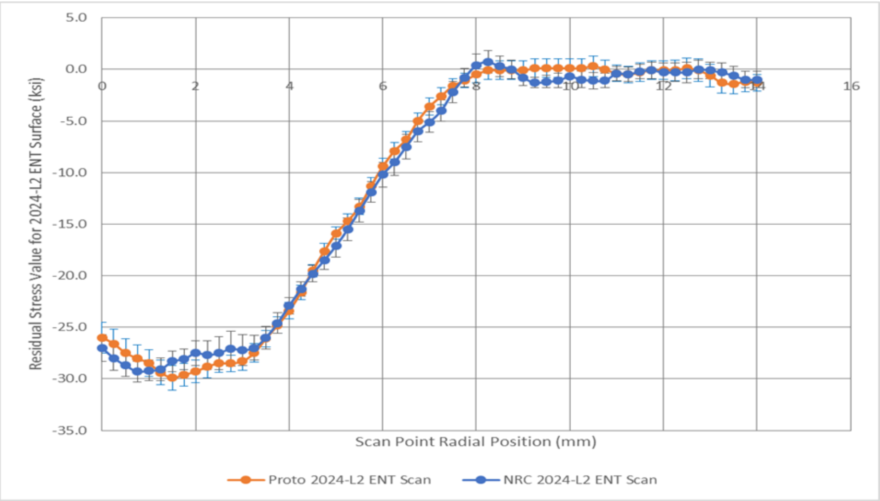

Comparison of DIC and LUNA

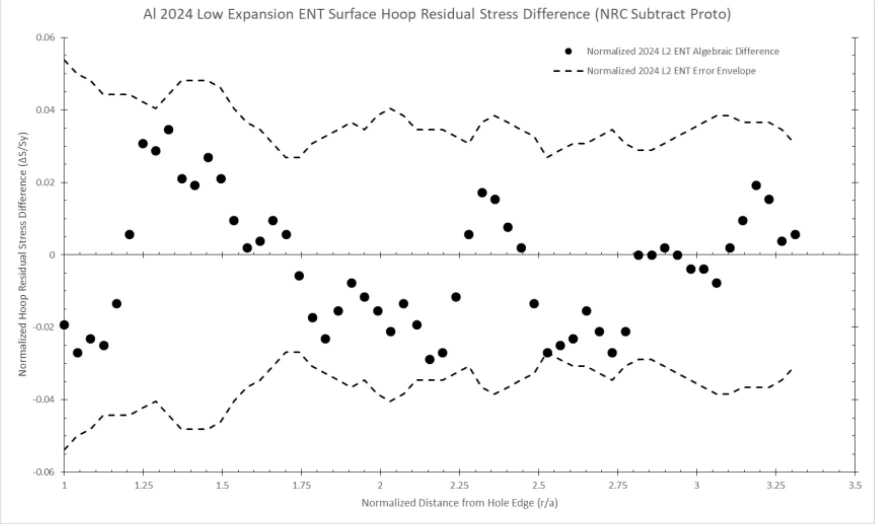
XRD Highlights

Inter and Intra laboratory studies (NRC & Proto Mfg.)

Optimize data collection parameters and take advantage of circumferential strain fields around CX holes to further improve measurement accuracy & precision

XEC determination for the specific 2024-T351 & 7075-T651 product forms studied is currently in progress



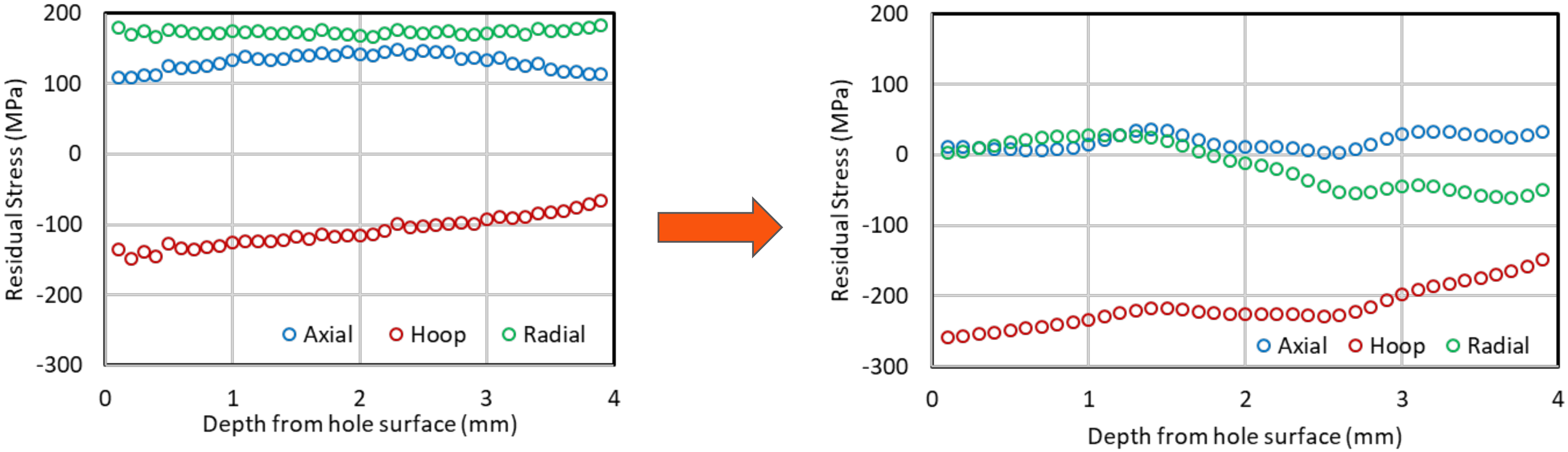


ND Highlights

Work performed by OpenU, Stress Space Ltd., CEAM, JAEA

Increased spatial resolution using a deconvolution algorithm

- Requires a thin foil for calibration
- Longer beam time



Status

Progress made

- Validation metrics and framework for simulation to data comparisons
  - Still to be discussed in committee
- XRD and ND “lessons learned” can be applied to similar applications
  - Accuracy improvements observed

Work planned

- Additional ND and Contour Method measurements in Q1 & Q2 of 2021
- Residual stress data sets for FCG inputs should be established by Q4 2021
- Reamed coupons reserved for NDI and QA techniques
- Multiple journal papers in work

Exemplar data sets: near-surface stress profiles

Exemplar data sets objective:

- Identify examples of residual stress measurement data that are typical of good practice in aerospace materials
- Seek data showing comparisons of different experimental methods applied to the same parts or samples
- Post these data to an open repository for access by the community

Methods:

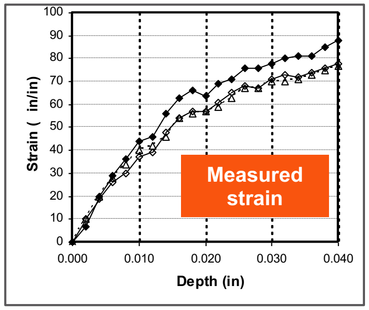
- Identify data through committee members and their networks
  - Prior publications, contract reports, ERSI studies, et cetera
- Employ open data sharing platform
  - DRYAD https://datadryad.org/
    - Any field. Any format. Quality control and assistance. Community-led.
    - Currently developing posting workflow

First example: near-surface stress profiling

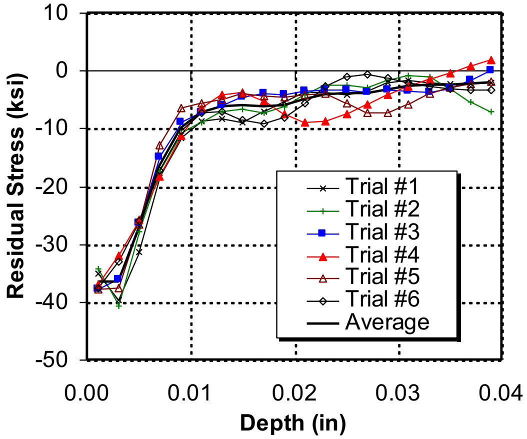
- Inter-method comparison of near-surface stress profiling
  - *Ref: "Measurement of residual stresses near the surface of metals," M.R. Hill, A.T. DeWald, T.A. Wong, 10th European Conference on Residual Stresses, Leuven BE*

Near-surface stress profiling methods

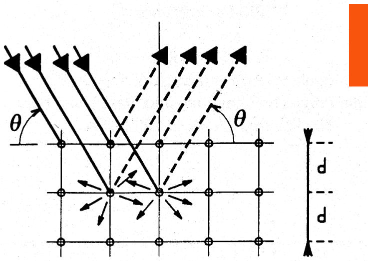
Hole-drilling



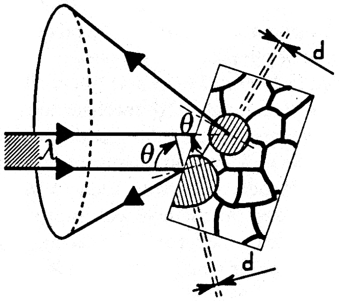
3 stress components

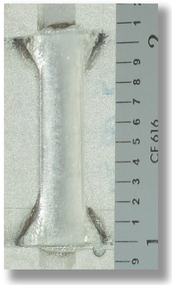


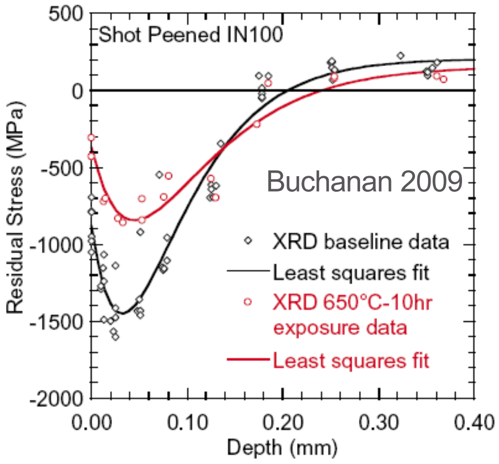
XRD



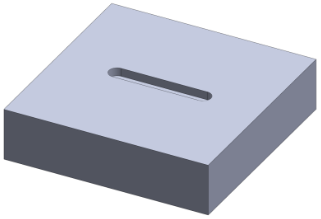
J. Lu, Handbook of Meas. of RS, 1996.

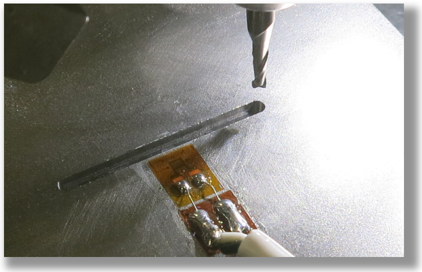


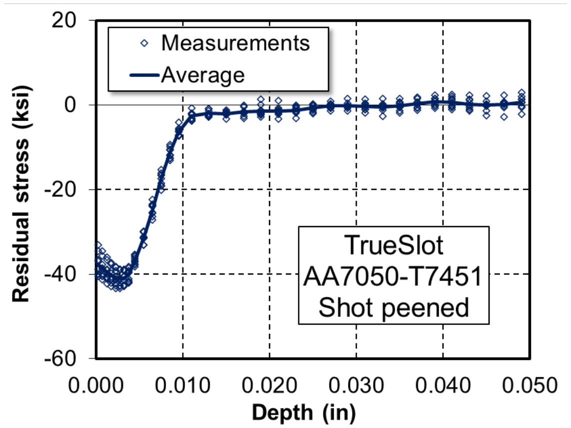




Slotting (TrueSlot®)



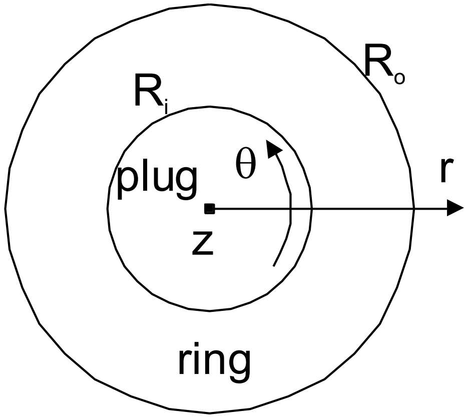


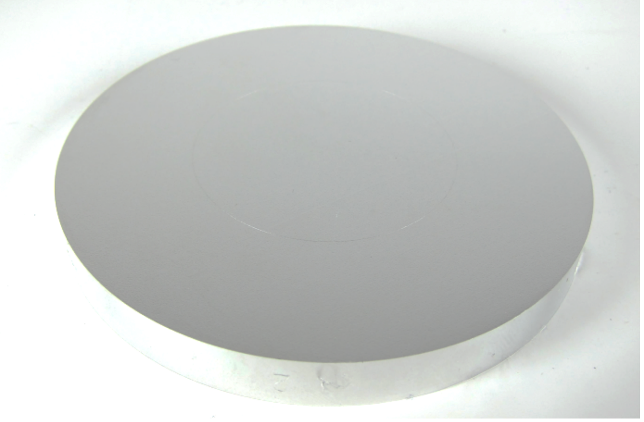


Sample type 1: Ring and plug

Ring and plug specimen

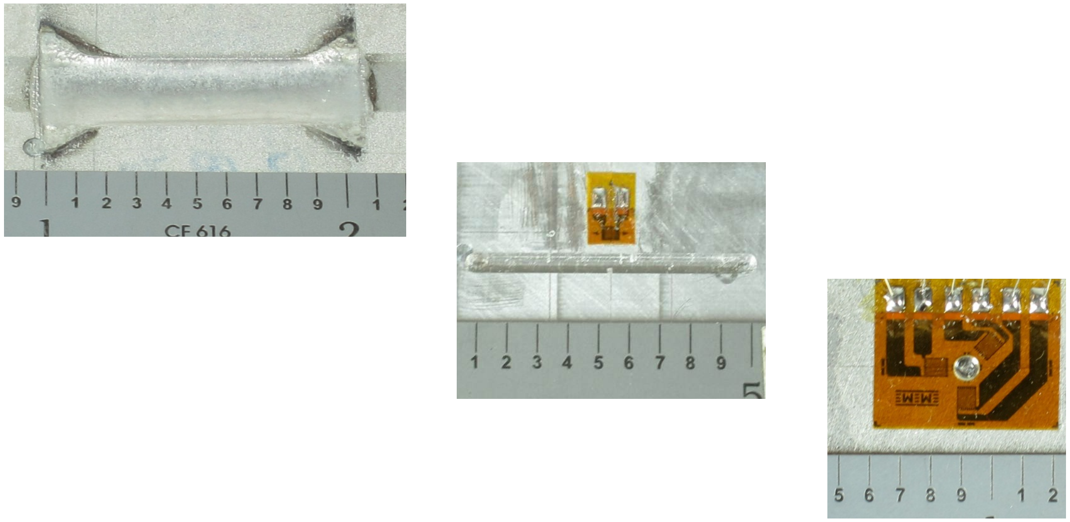
- 2.0 inch diameter plug
- 4 inch diameter ring





Material properties:

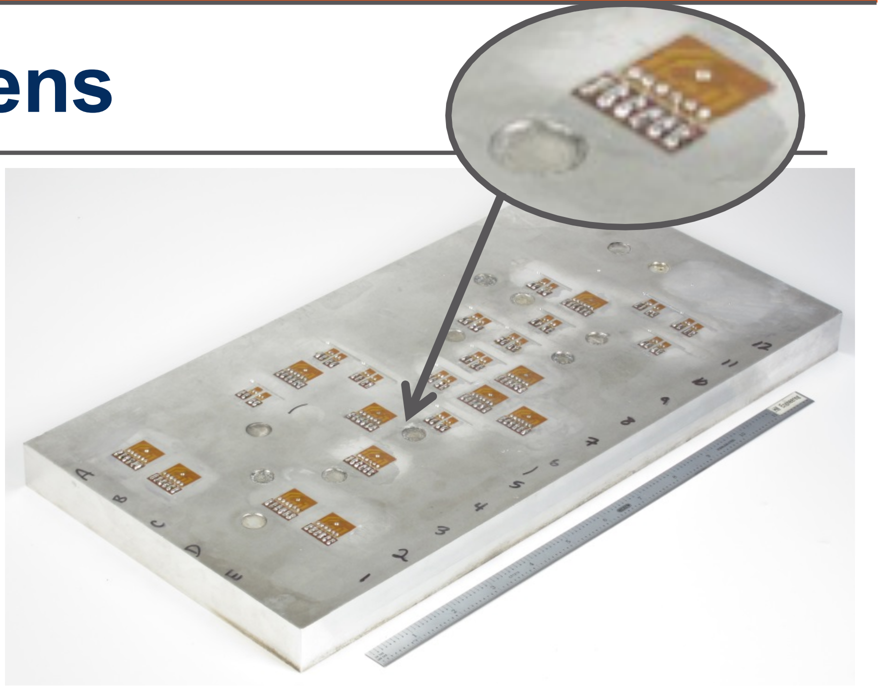
- AA2024-T351
- E = 10,400 ksi
- $\nu = 0.33$
- Expect -6.0 ksi stress in the plug equibiaxial



Measurement order

- First: XRD
- Second: HD
- Third: slotting

Sample type 2: Plate specimens



Nominally 15 x 7.5 x 1 inch (380 x 190 x 25.4 mm)

Three plate conditions

- Shot peened AA7050-T7451
  - SAE 230-280 cast steel shot, 6 A, 200%
- Shot peened Ti-6Al-4V (mill-annealed)
  - SAE 170 cast steel shot, 6-9 A, 100%
- Quenched AA7050-T74

12 replicate measurements

- Randomize locations

Measurement order

- First: XRD
- Second: HD
- Third: slotting

Description	Material Properties
Shot peened Al plate	Aluminum alloy 7050-T7451 E = 10,400 ksi $\nu = 0.33$
Shot peened Ti plate	Titanium alloy Ti-6Al-4V E = 16,500 ksi $\nu = 0.34$
Quenched Al plate	Aluminum alloy 7050-T74 E = 10,400 ksi $\nu = 0.33$

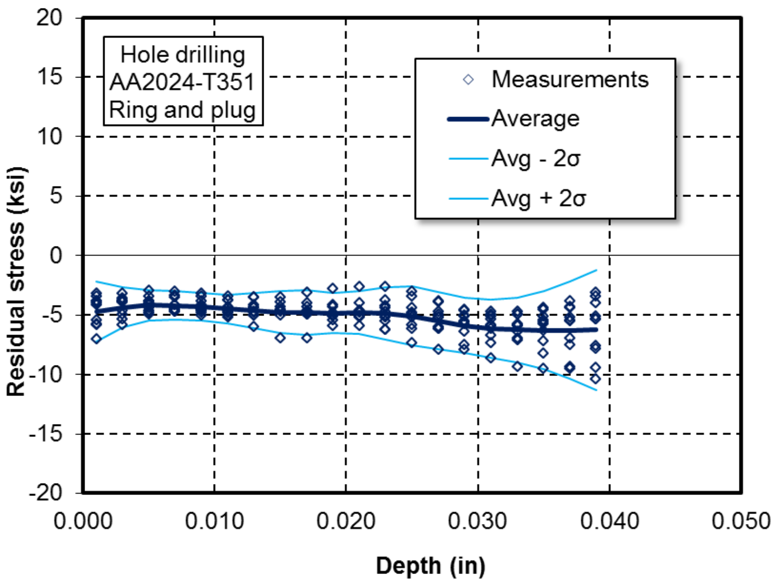
Ring and plug results

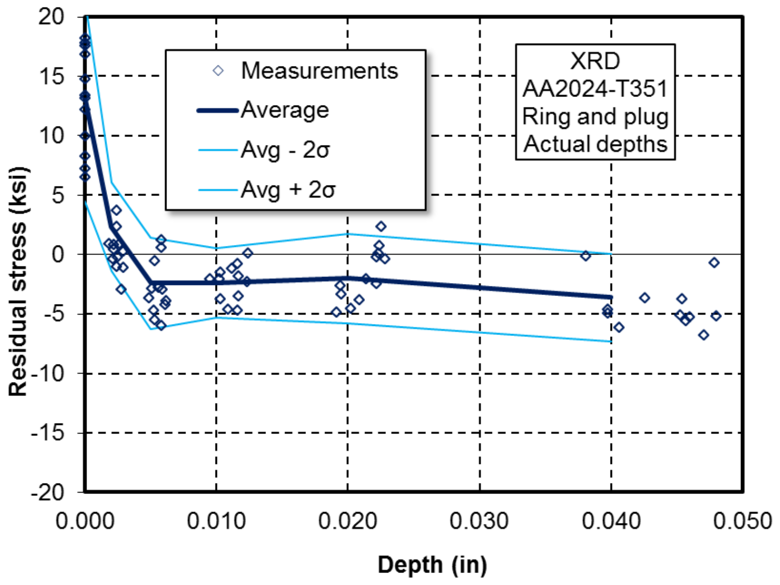
Summary of results

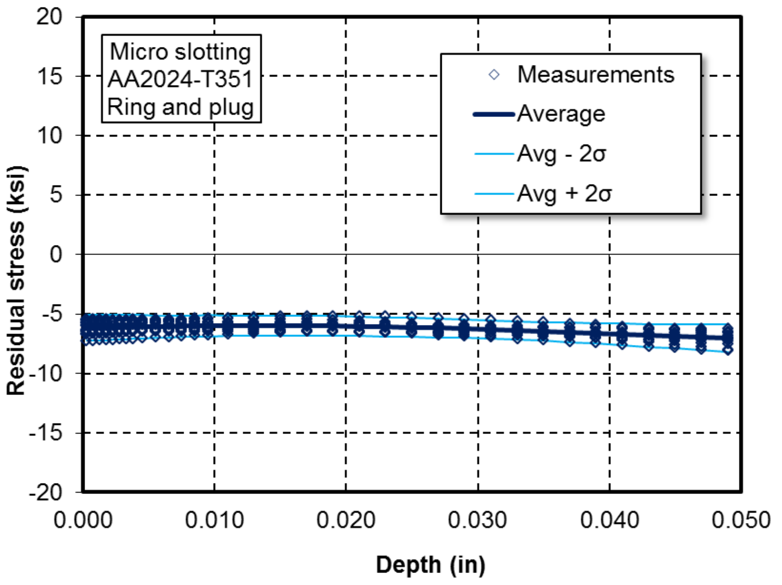
- Near uniform compressive RS
- Similar to expected value of -6 ksi

Data analysis

- Compute average and standard deviation at set of depths
- Use linear interpolation to consistent depths







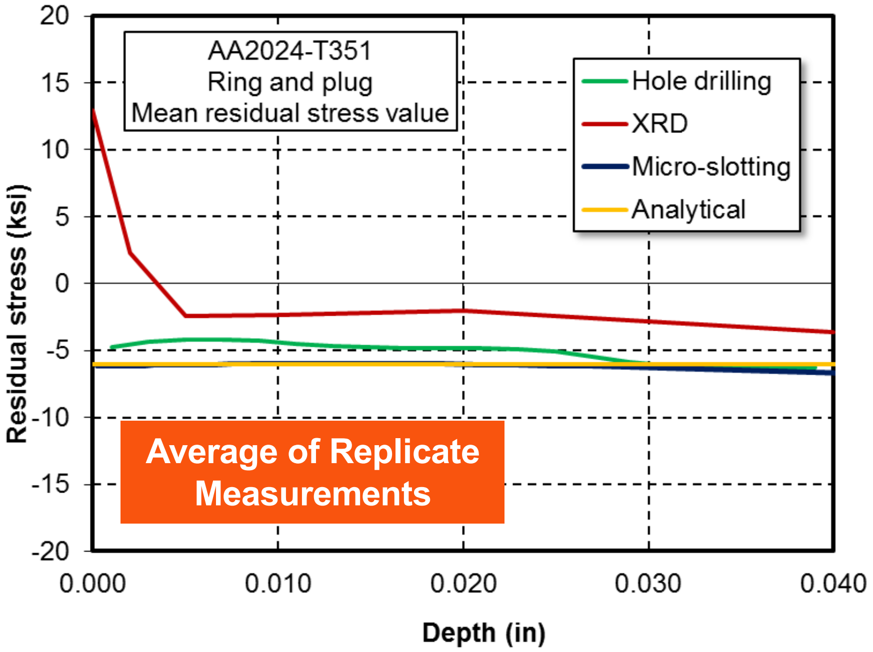
Ring and plug results

Comparison of average residual stress

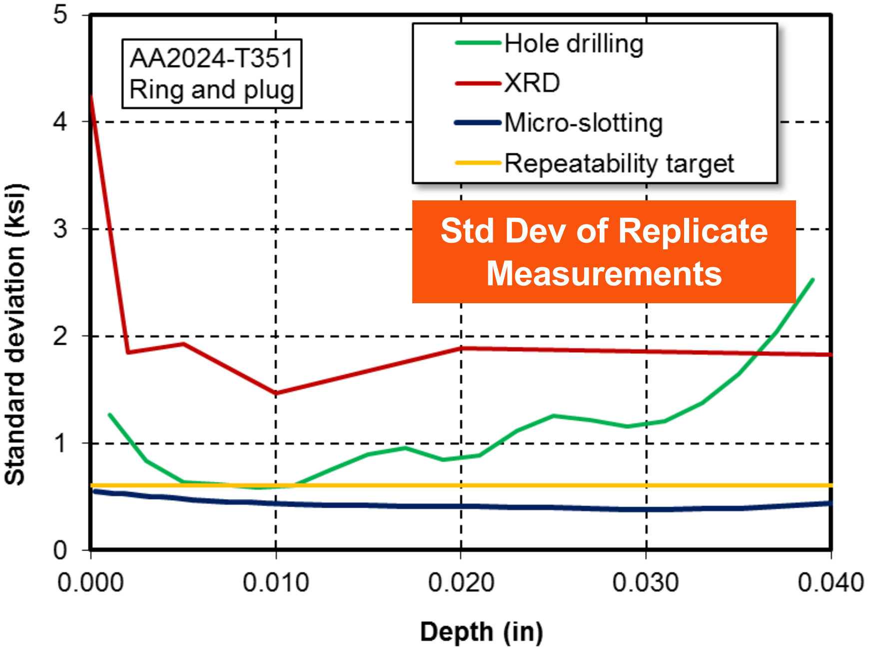
- Slotting closely matches expected residual stress
- Hole-drilling has similar shape, slightly different magnitude
- XRD has different surface value and sub-surface bias (different value)

Residual stress repeatability (standard deviation) versus depth

- Slotting repeatability better than 0.5 ksi (average); hole-drilling somewhat higher, and XRD largest



Average of Replicate Measurements



Std Dev of Replicate Measurements

Near-surface profiling study summary

Documented repeatability of residual stress measurement

- In relevant materials and stress states
- Summary data are tabulated below
- Full data to be posted on DRYAD

Results show hole-drilling, XRD, and slotting provide similar results, with differences in bias and precision

- Results dependent on specific materials, geometry, stress state, and methods

	Repeatability Std Dev (ksi) Average 0.00 to 0.04 inch			**Repeatability Std Dev Normalized by Slotting**		
Specimen	**XRD**	**HD**	**Slotting**	**XRD**	**HD**	**Slotting**
Aluminum ring and plug	2.2	1.1	0.4	5.5	2.7	1.0
Shot peened aluminum	2.5	3.0	1.1	2.3	2.7	1.0
Shot peened titanium	8.7	3.7	4.1	2.1	0.9	1.0
Quenched aluminum	2.0	1.4	1.0	2.0	1.4	1.0

Large Hole CX Evaluation

Objective

- Develop a coupon that scales-up the stress field
- Develop and interrogate residual stress measurement data
  - Full configuration
  - Split configuration (split along 10” dimension)
- Develop crack growth data in split configuration

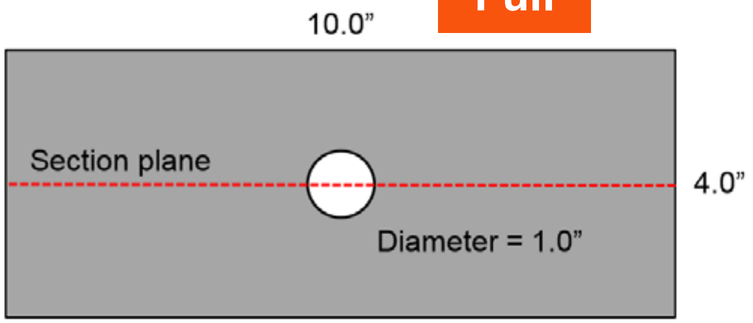
Coupon attributes

- Large diameter
  - Maximize length scale of “near-surface” and “near-bore” regions
- Long enough to facilitate fatigue testing
- Wide enough to minimize edge margin effects

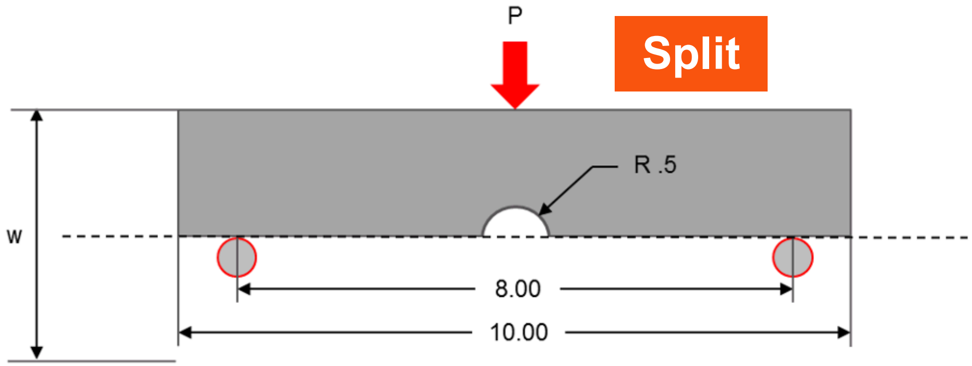
Material types

- 7075-T651
- 2024-T351

Full



Split



Large Hole Status

Study design

- Complete (HE and A-10)

Coupon fabrication

- Complete (HE)

Planned residual stress measurements

- Contour: complete (HE)
- Hole drilling: complete (HE)
- XRD: complete (Proto)
- Comparison and assessment: in-process (Team)

Fatigue crack growth testing of split samples

- Straight bend: complete (A-10)
- Corner bend: unknown

Reporting

- To be defined

ERSI Texture & Anisotropy Team

Objective: Incorporate elastic anisotropy into standard industry residual stress measurement workflows

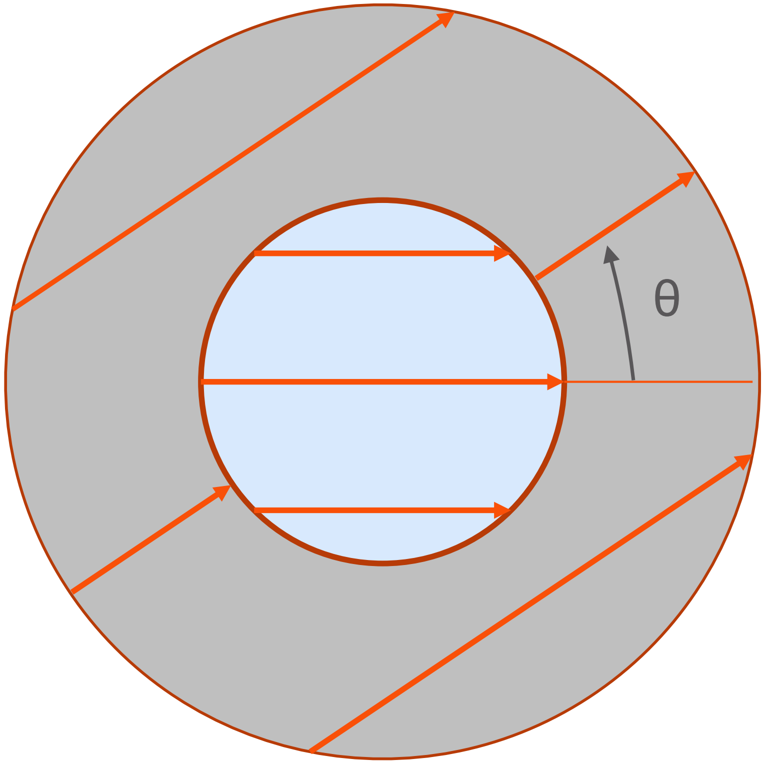
Methods: Develop combined modeling and experimental approach to (1) demonstrate impact of elastic anisotropy on current RS measurement techniques, (2) enable incorporation of microstructure into existing workflows, and (3) support round robin sample sharing

Schedule:

- Nov 2020 – First ‘official’ biweekly meeting
- Dec 2020 – LANL prepares ring/plug samples
- Jan 2021 – AFRL begins hole drilling measurements
- FY21 – Anisotropic FE ring/plug model development
- FY21 – Measurement of ‘optimized’ anisotropic ring/plug samples

Team:

- Mike Steinzig & Zac Sanchez Archuleta – LANL
- Mike Hill – Hill/UC Davis
- Mark Obstalecki & Eric Burba – AFRL



- Arrows indicate the dominate texture direction in each component
- Model anisotropic material properties to determine theta with the greatest effect on plug/ring interaction

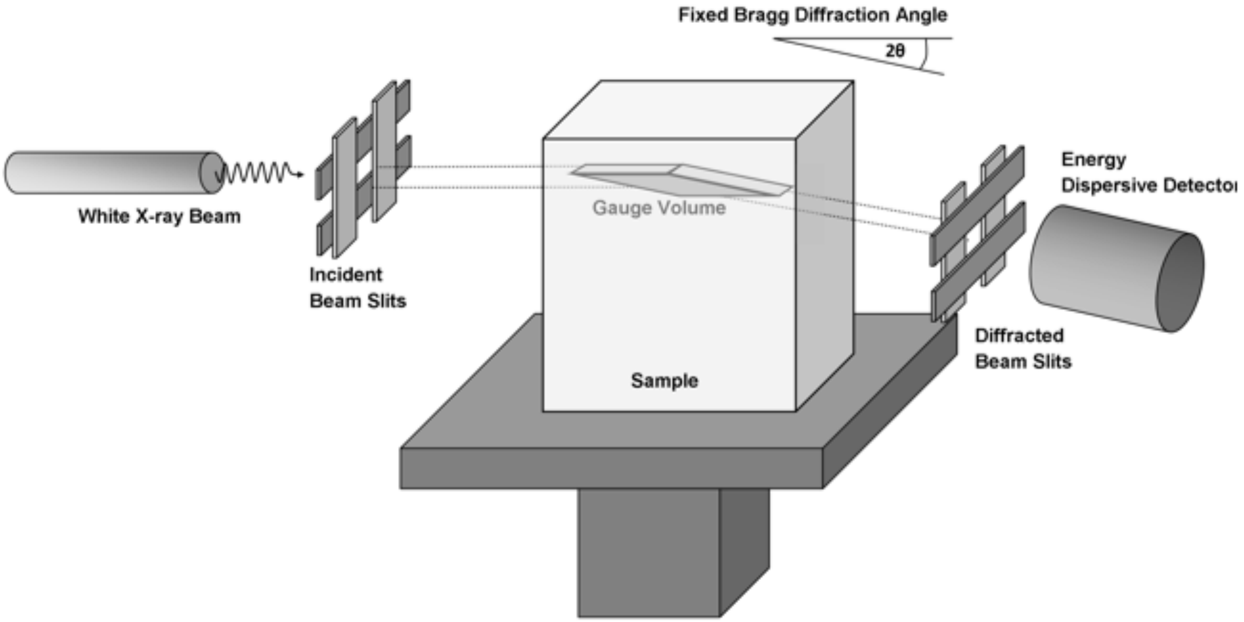
Cornell High Energy Synchrotron Source

Cornell University
Ithaca, NY

Synchrotron X-ray Menu

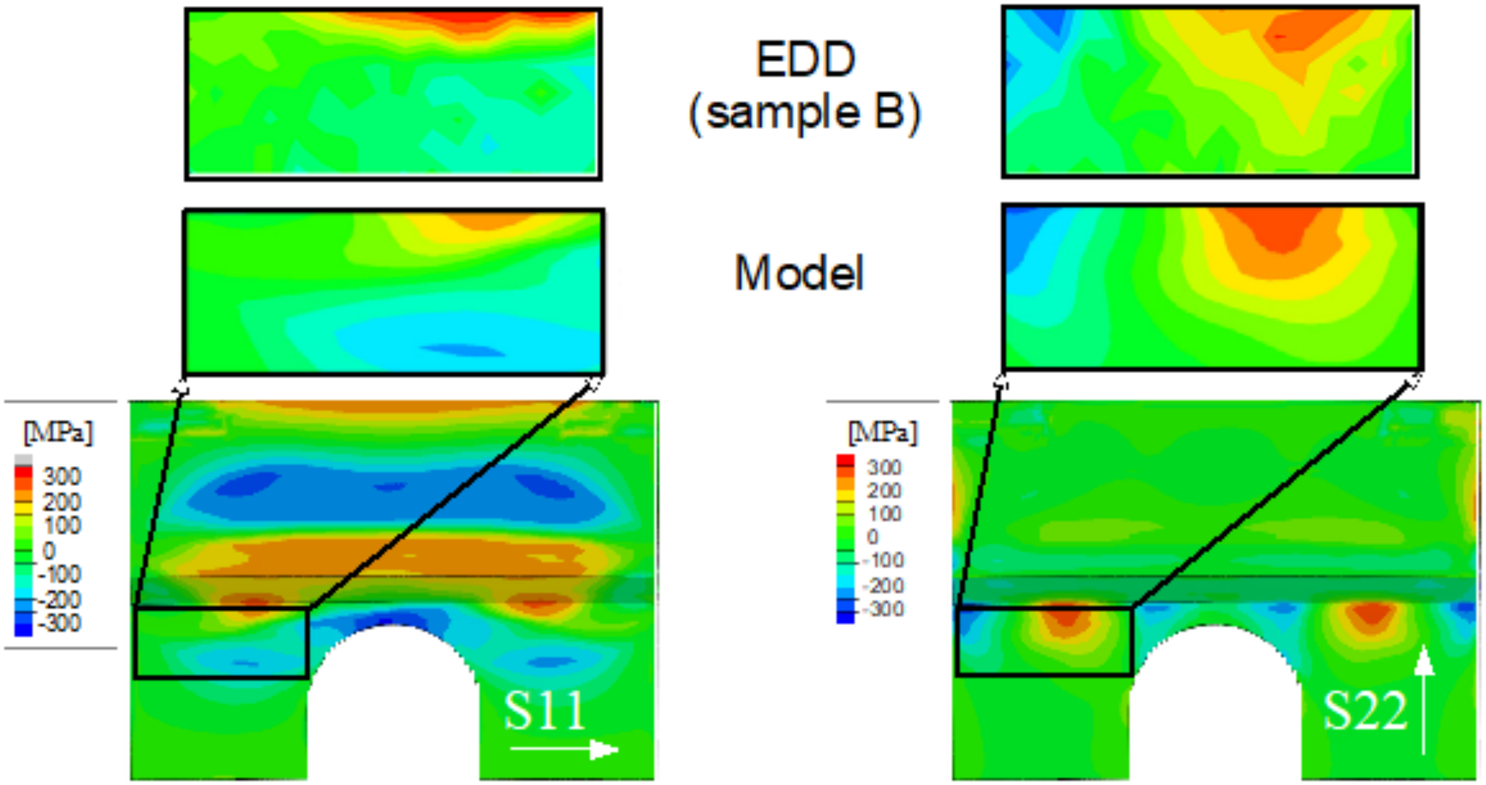
- **High Energy Diffraction Microscopy (HEDM)**
  - **Far-field:** grain average orientation, position, and strain
  - **Near-field:** grain orientation map
- **Transmission Powder Diffraction**
  - texture and strain pole figures
- **Energy Dispersive Diffraction**
  - volume averaged strain

Energy Dispersive Diffraction (EDD)



- EDD enables measurement of spatially resolved distributions of strain in large volumes (in)
- Polychromatic x-rays ranging from 50-200 keV
    - Can penetrate through bulky samples & sample environments
- Measurement time: 60 sec to 30 min per point
- Works best with fine grained materials, but heavily textured materials can be problematic
- Energy sensitive point detector

Residual Stress Mapping Example



Mach, et. al., JOM, (2017)

Summary and Future Opportunities

Committee logistics

Active work

Opportunities in store

- Applications at CHESS
    - Large hole samples
- Continuation of active work
    - Communications and collaboration within ERSI
    - Exemplar RS data sets
    - Large hole RS measurements
    - Anisotropy and preferred orientation
    - Outward facing documents
- Interactions with other ERSI committees
    - Leverage ERSI member experience
- Interactions with field challenges
    - AFRL Multi-point Fracture Mechanics program (MAI)
    - Bring us your problems!

ERSI

ERSI RISK AND UQ SUBCOMMITTEE ACTIVITIES

Virtual ERSI Workshop

December 2020

Committee Members

- Co-chairs: Juan Ocampo (StMU) and Laura Hunt (SwRI)
- Participating Organizations
  - Analytical Processes/Engineering Solutions (AP/ES)
  - Booz Allen Hamilton
  - Hill Engineering
  - Lockheed Martin
  - NRC Canada
  - SmartUQ
  - Southwest Research Institute
  - St. Mary’s University (TX)
  - University of Pittsburgh
  - USAF

Committee Overview

- **GOAL**: Investigate and implement UQ methods that enhance the overall understanding of how residual stress affects life prediction analyses
  - Uncertainty Quantification
    - How do we understand and describe the uncertainty and variability in the relevant parameters?
  - Sensitivity Analysis
    - What are the most significant variables in the ERS process?
    - How can we maximize/minimize the benefits/damages of these variables?

Outline

- Risk and UQ Subcommittee Overview

- Short Presentations of Current Activities
  - **“Residual Stresses Activities at StMU”** Juan Ocampo, StMU
  - **“Residual stress characterization for cold expansion utilizing spatial statistics: The SpARS Methodology”** Dallen Andrew, Hill Engineering
  - **“Stress Gradient Surrogate Model Using PCA”** SwRI
- Future Activities

Residual Stresses Activities at St. Mary's University

ERSI

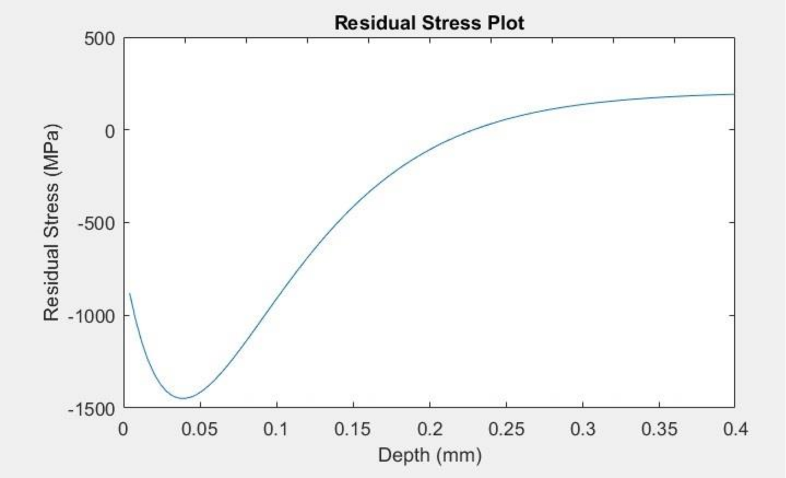
Juan D. Ocampo
St. Mary's University

1852

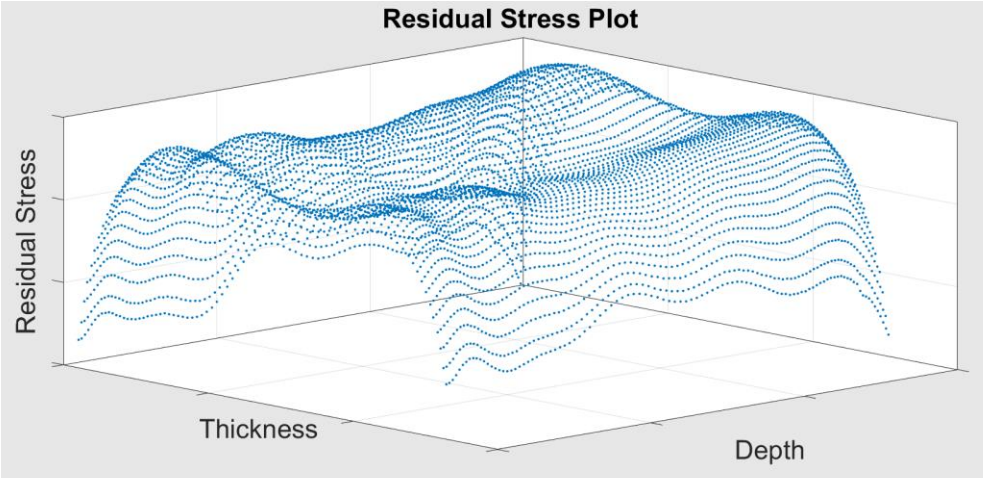
Engineered Residual Stress Implementation

Residual Stress Modeling Software

- Standalone executable to read experimental/ simulated data and find the best deterministic and probabilistic fit parameters.
  - 2 Models Available (Expandable)
  - 2D (Stress vs Depth) and 3D (Stress vs Depth vs Thickness).
  - Read input data in .txt & .csv format



2D



3D

Models

- **Model I***

$$\sigma(x) = (ss - si + C_1 x)Exp(-C_2 x) + si$$

$$C_1 = \frac{\{(ss - si)\big(1 - Exp(-C_2 B)\big) + siBC_2\}C_2}{(C_2 B + 1)Exp(-C_2 B) - 1}$$

- **Model II****

$$\sigma(x) = Asin(Bx + C)Exp\left(-\frac{x}{\lambda}\right)$$

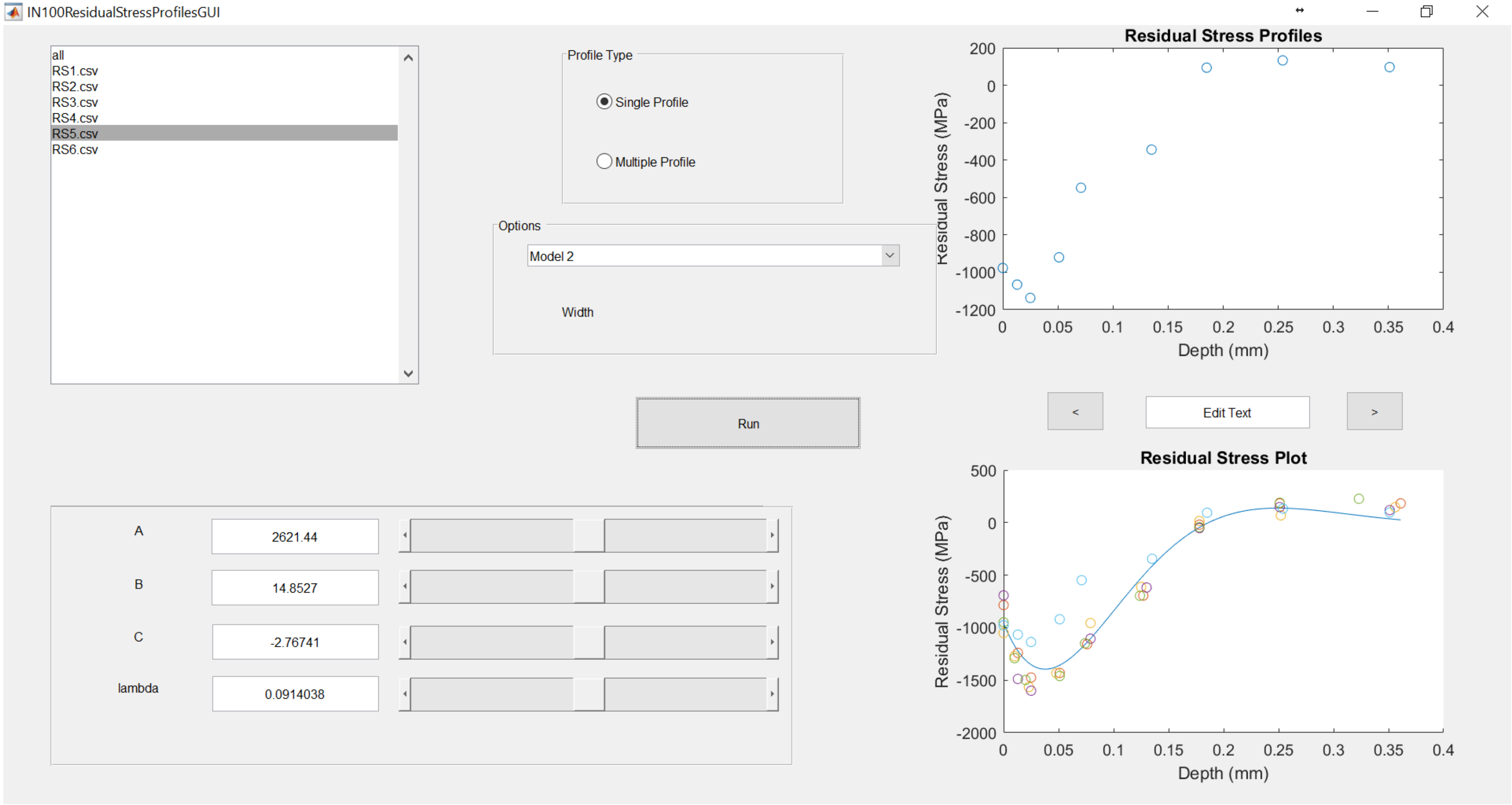
Working to include Kriging to the GUI

* *User Manual for ZENCRACK™ 7.1*, Zentech International Ltd., Camberley, Surrey, UK, September, 2003.

** R. VanStone, “F101-GE-102 B-1B Update to Engine Structural Durability and Damage Tolerance Analysis Final Report (ENSIP), Vol. 2,” General Electric, p. 5-2-2.

ERSI

Single Profile Model I & II



IN100ResidualStressProfilesGUI

all
RS1.csv
RS2.csv
RS3.csv
RS4.csv
RS5.csv
RS6.csv

Profile Type

● Single Profile

○ Multiple Profile

Options

Model 2

Width

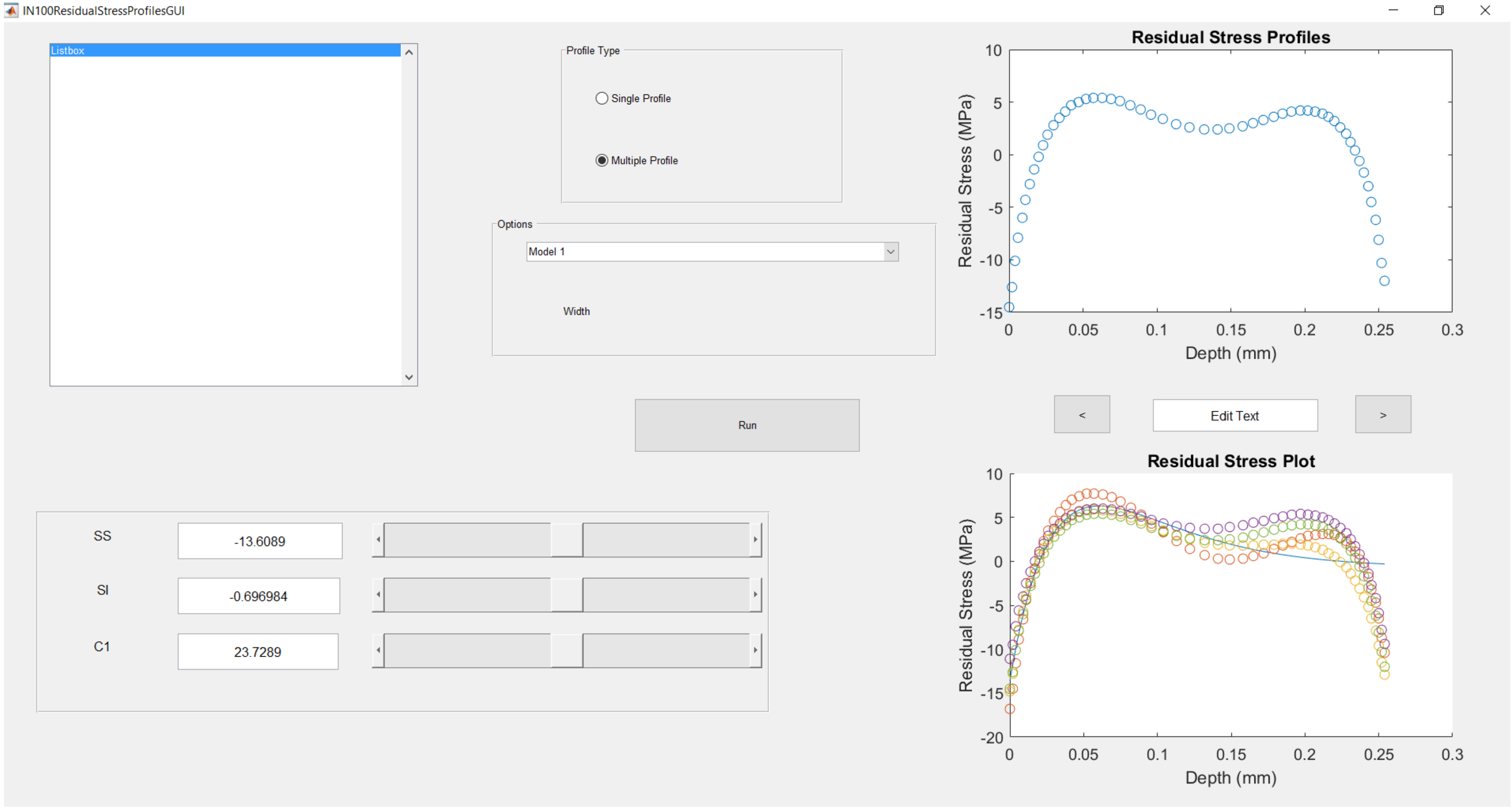
A: 2621.44

B: 14.8527

C: -2.76741

lambda: 0.0914038

Mult. Profile Model I



IN100ResidualStressProfilesGUI

Listbox

Profile Type

○ Single Profile

● Multiple Profile

Options

Model 1

Width

SS -13.6089

SI -0.696984

C1 23.7289

Variogram Selection

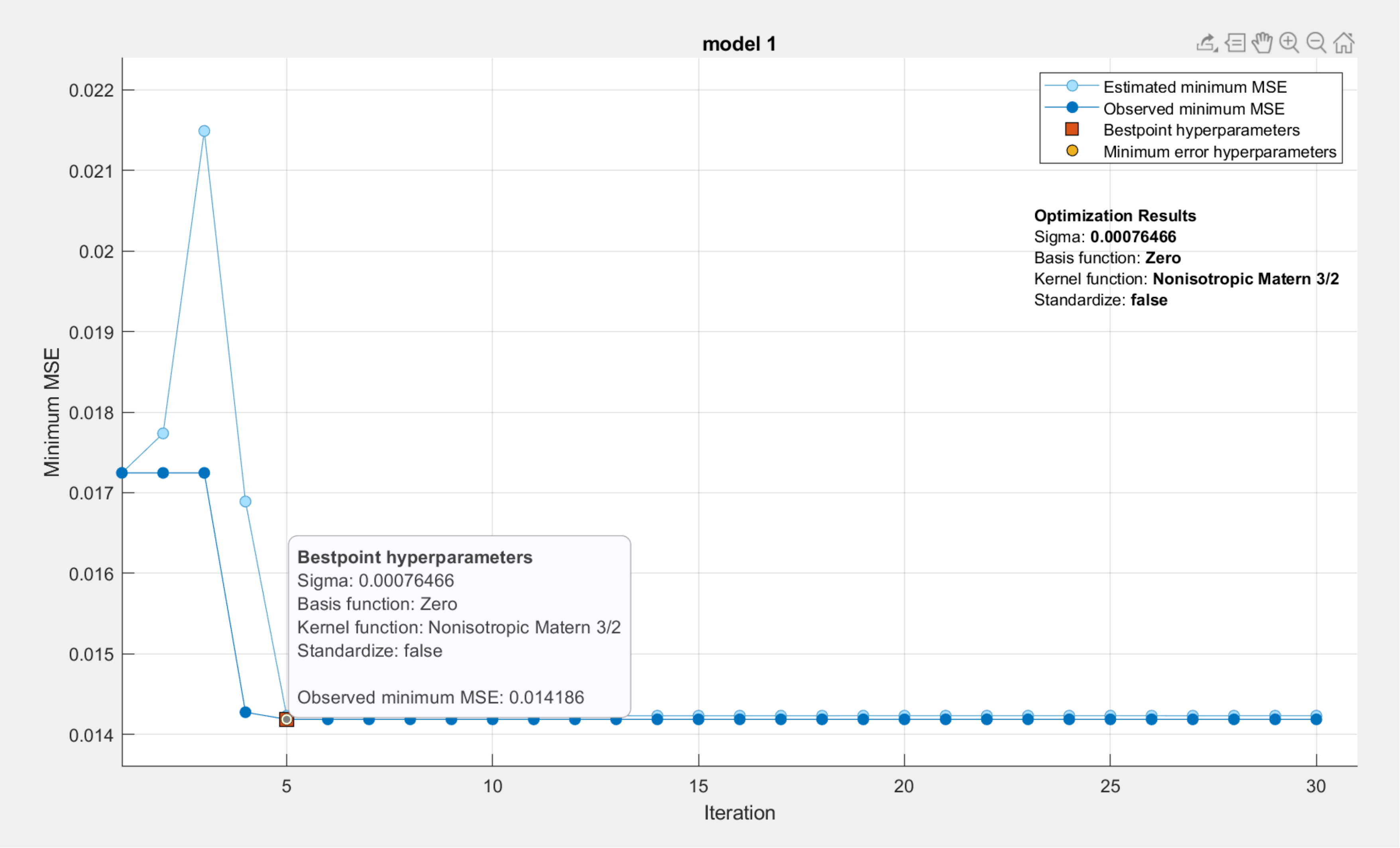
Study to find best Kriging Variogram for our data
Initial study performed with data provided by Carlson. I Need more data to have better conclusions

Variogram Selection

Kernel function – The software searches among:

- Nonisotropic Rational Quadratic
- Isotropic Rational Quadratic
- Nonisotropic Squared Exponential
- Isotropic Squared Exponential
- Nonisotropic Matern 5/2
- Isotropic Matern 5/2
- Nonisotropic Matern 3/2
- Isotropic Matern 3/2
- Nonisotropic Exponential
- Isotropic Exponential

Optimization Tool



Optimization Results
Sigma: **0.00076466**
Basis function: **Zero**
Kernel function: **Nonisotropic Matern 3/2**
Standardize: **false**

Bestpoint hyperparameters
Sigma: 0.00076466
Basis function: Zero
Kernel function: Nonisotropic Matern 3/2
Standardize: false

Observed minimum MSE: 0.014186

RS – Force Equilibrium

$$\int_{o}^{Thickness} \sigma(x)dx = 0$$

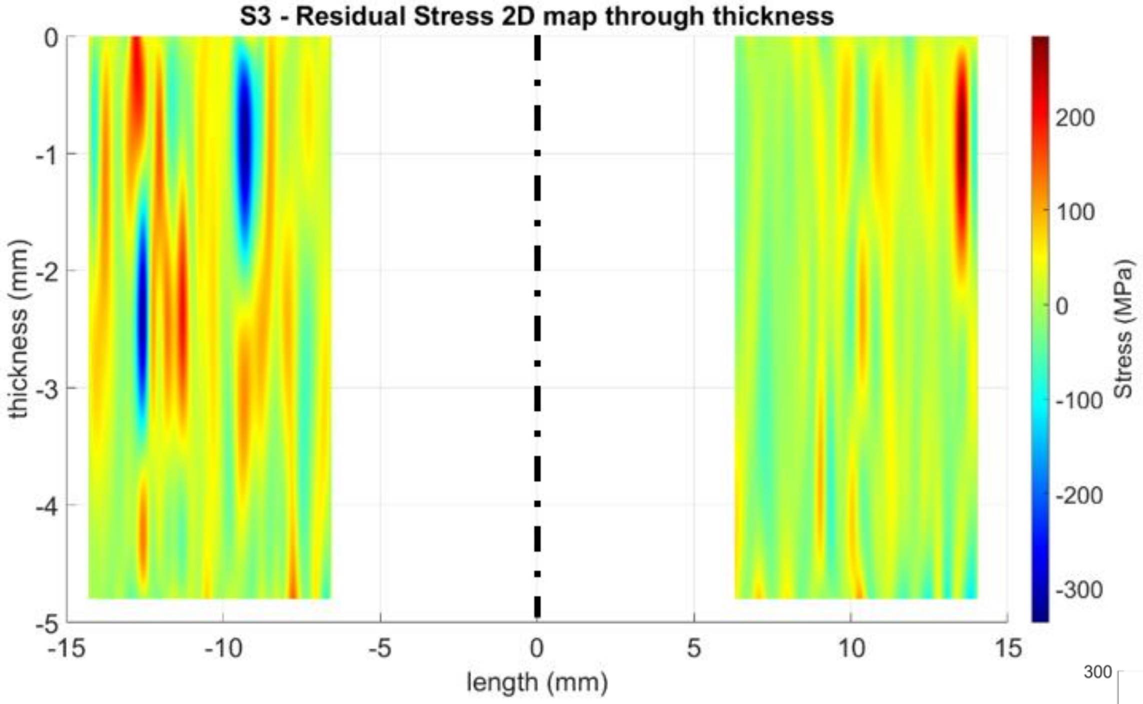
Our residual stresses models (Deterministic or Probabilistic) need to Account for force equilibrium.

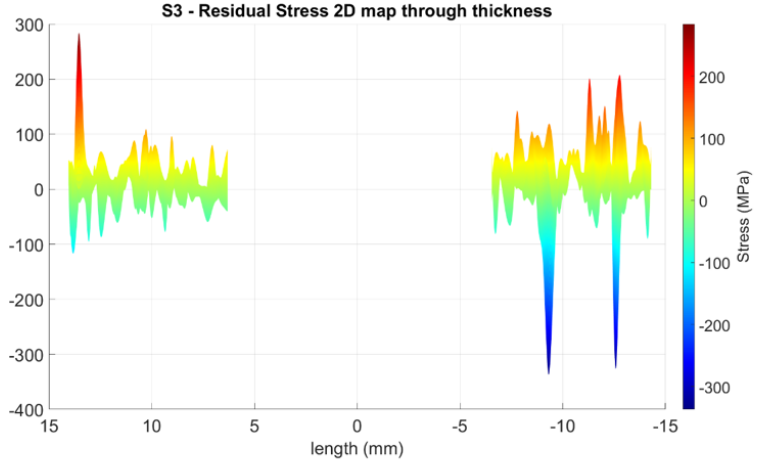
How this group is planning to incorporate equilibrium.

- Constrained Kriging?

ERSI

Reduce Variation





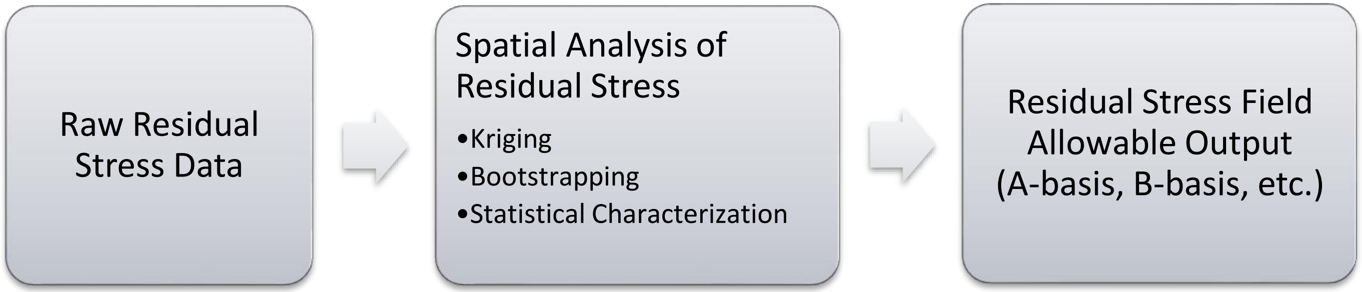
Residual stress characterization for cold expansion utilizing spatial statistics: The SpARS methodology

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

ERSI 2020 Virtual Workshop

Spatial Analysis of Residual Stress (SpARS)

- Purpose
  - Develop process to statistically quantify RS fields from Cx by utilizing spatial statistical methods, then quantify impact on analytical fatigue crack growth life

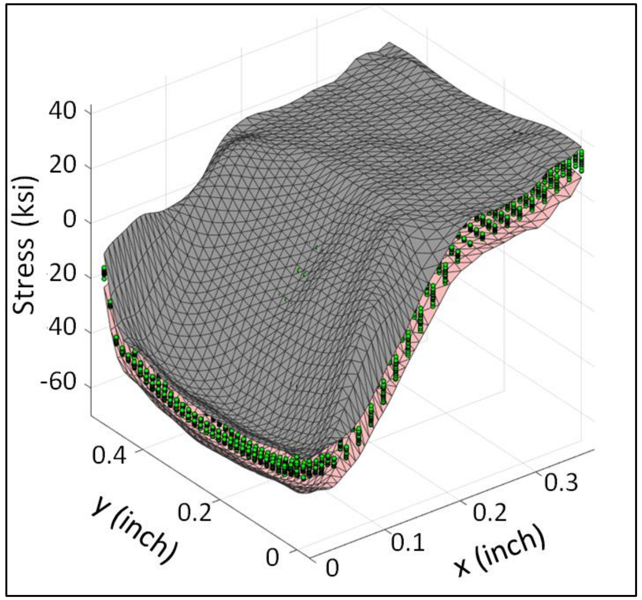


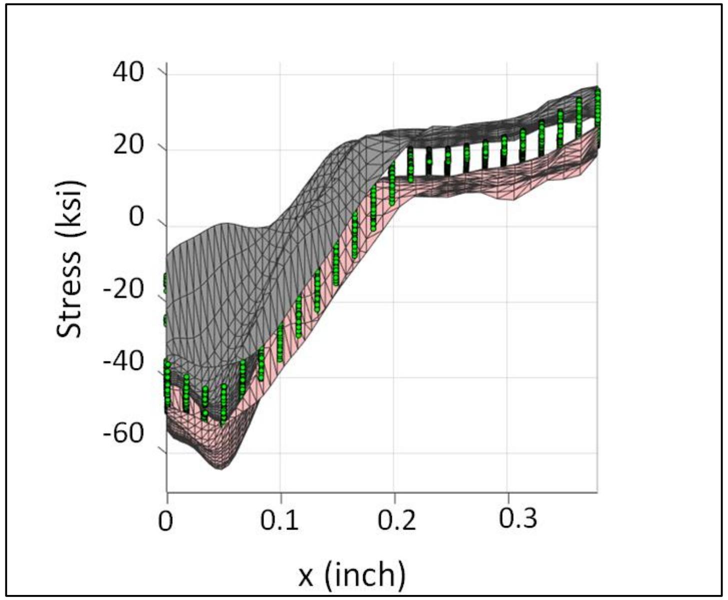
Raw Residual Stress Data

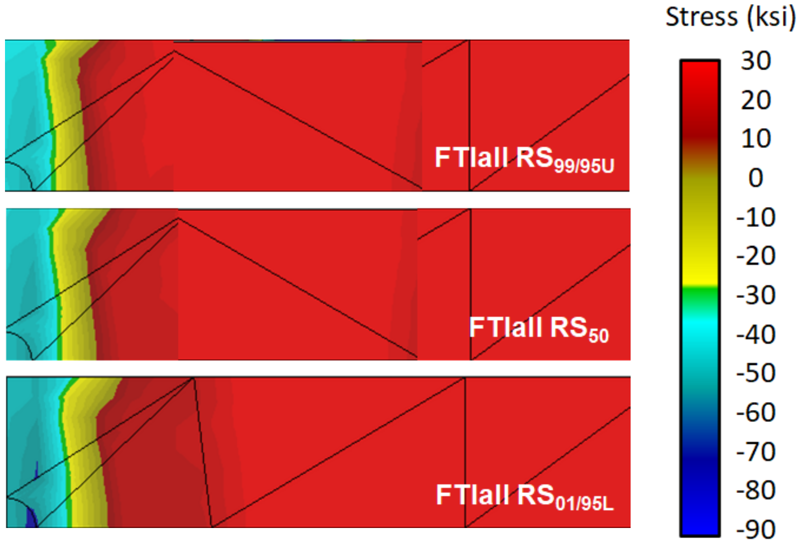
Spatial Analysis of Residual Stress
- Kriging
- Bootstrapping
- Statistical Characterization

Residual Stress Field Allowable Output (A-basis, B-basis, etc.)

- Results: Residual Stress
  - Upper and lower tolerance bound surfaces created from RS data



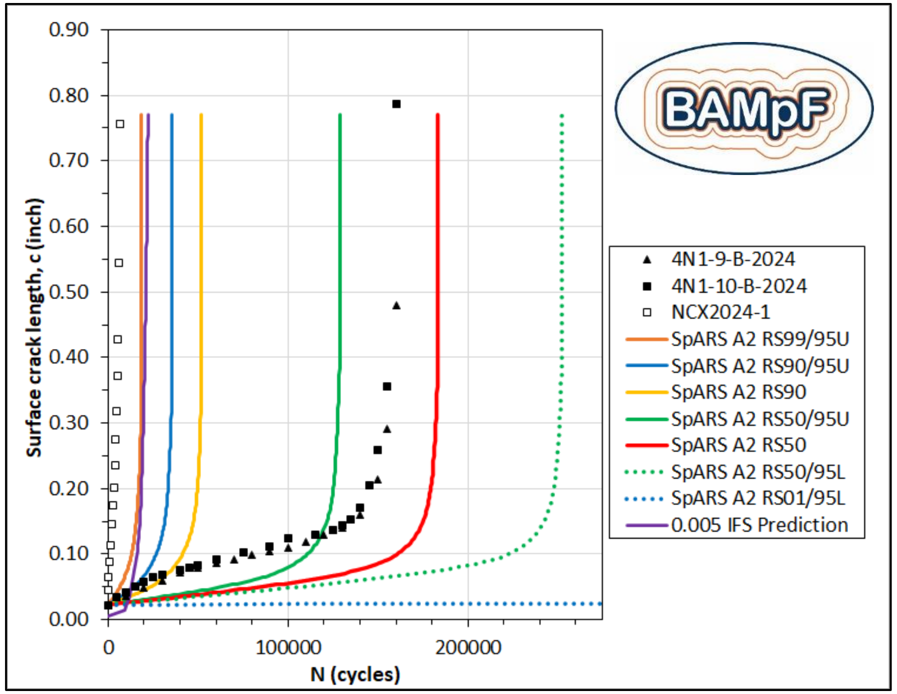


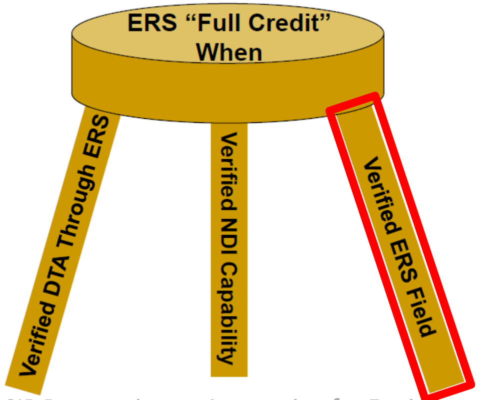


Andrew et al. Characterization of residual stresses from cold expansion using spatial statistics. Fatigue Fract Eng Mater Struct. 2020; 1– 14.

Spatial Analysis of Residual Stress (SpARS)

- Results: Crack Growth
  - 2024-T351, D=0.5", t=0.25", min %Cx
  - Analyses performed using BAMpF
  - Benefit from SpARS allowable RS fields compared to 0.005" approach
  - Selected upper tolerance bound was $RS_{50/95U}$
- Conclusion:
  - SpARS addresses one leg of stool and is an acceptable means of compliance for the draft structures bulletin:
    - "Multiple residual stress field characterizations must be used to generate a statistical representation that quantifies the cold expansion…variability, with the less compressive 95% upper bound statistical representation…to be utilized in all crack growth analyses utilized for fleet management."





ERS "Full Credit" When

Verified DTA Through ERS

Verified NDI Capability

Verified ERS Field

Babish C. ASIP Perspective on Accounting for Engineered Residual Stress in Damage Tolerance Analysis. Paper presented at: Aircraft Structural Integrity Program Conference. 2017; Jacksonville, FL.

Stress gradient surrogate model using Principal Components Analysis (PCA)

SOUTHWEST RESEARCH INSTITUTE®

John McFarland, David Riha, Laura Hunt

This presentation was from the NASA Layered Pressure Vessel Project dealing with weld residual stresses – the method is currently being demonstrated on ERS-type profiles

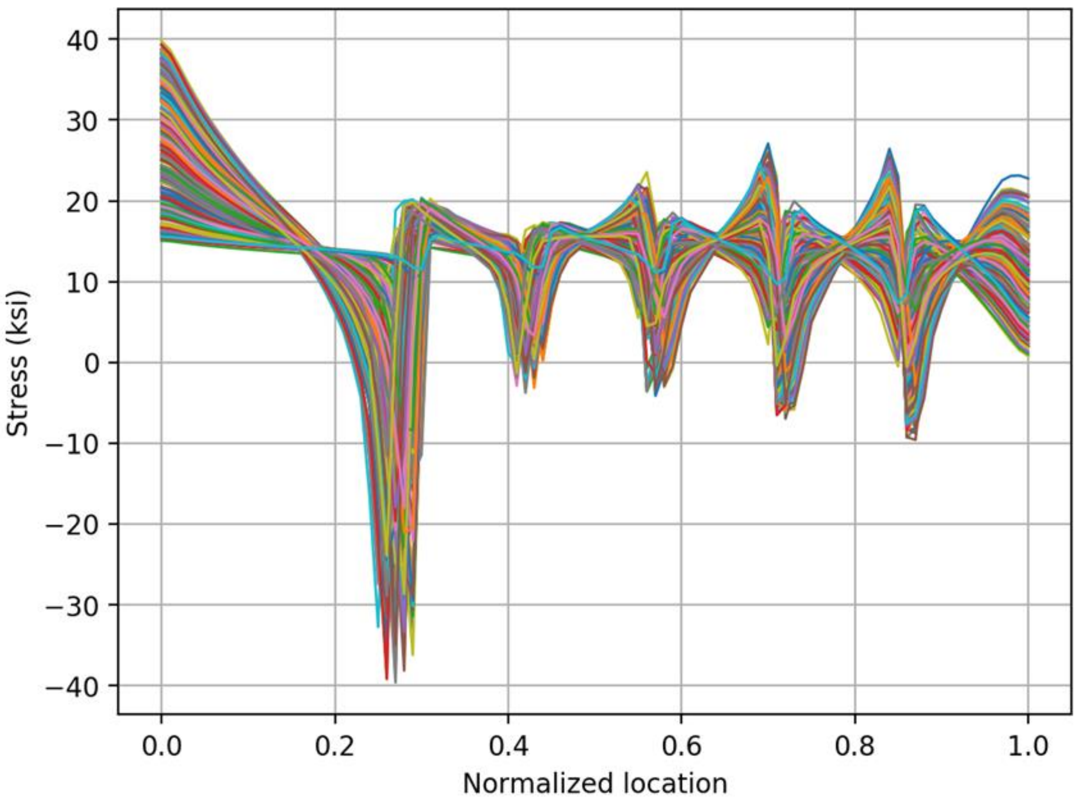
Overview

Objective

- Create a fast-running surrogate model that is capable of predicting stress gradient (in given direction and at particular location) as a function of a set of selected variables

Approach

- Use Latin Hypercube DOE to generate surrogate model training data over range of values for input variables
- Use Principal Components Analysis (PCA) to express stress gradient using a reduced set of coordinates
- Fit Gaussian Process (GP) regression models to predict PC scores, which can be used to reconstruct full stress gradients



- 250 axial stress gradients in a pressure vessel weld based on 7-variable DOE
- 101 points along each gradient

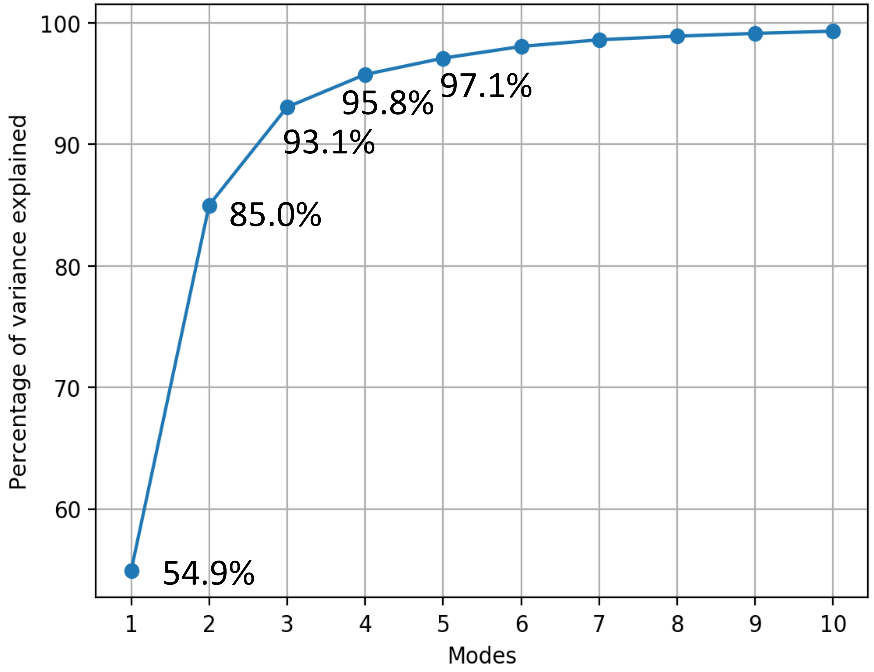
PCA variance explained

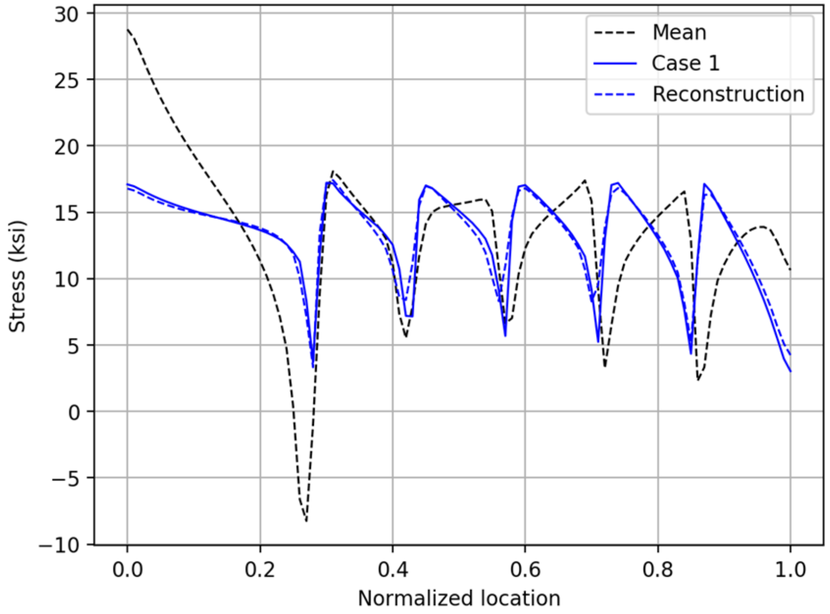
- Singular values from PCA decomposition are related to amount of variance explained by each mode
- For these data, between 4 and 10 modes can capture majority of variation in the stress gradients
- The bottom figure shows the reconstructed stress gradient for Case 1 using only the first four modes

$$\boldsymbol{Y} = \boldsymbol{U\Sigma V}^T$$

RS fields / Shape Vectors / Singular Values

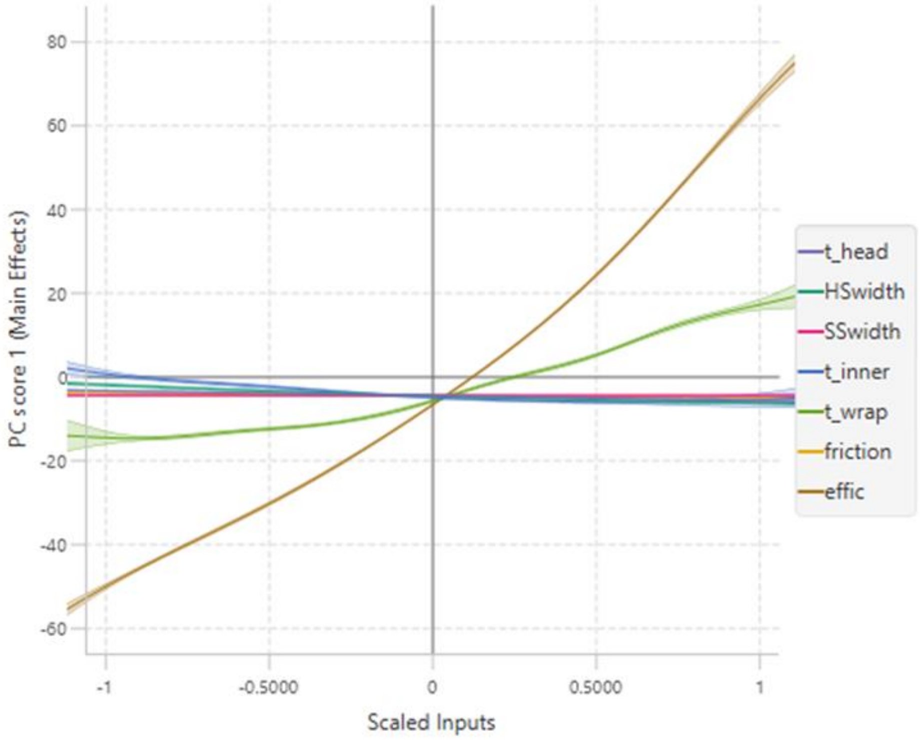
$$\begin{bmatrix} Y_{1,1} & \cdots & Y_{1,n} \\ \vdots & \ddots & \vdots \\ Y_{m,1} & \cdots & Y_{m,n} \end{bmatrix} = \begin{bmatrix} U_{1,1} & \cdots & U_{1,n} \\ \vdots & \ddots & \vdots \\ U_{m,1} & \cdots & U_{m,n} \end{bmatrix} \begin{bmatrix} \Sigma_{1,1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \Sigma_{n,n} \end{bmatrix} \boldsymbol{V}^T$$





Surrogate model for stress gradient prediction

- PCA represents the variations in the high-dimensional stress field (101 locations) using a smaller number of coordinates (the principal components)
- Then use response surface models to relate the input variables to the principal components (sensitivity analysis)
- Equilibrium is naturally enforced to a degree. Incorporating an optimization formulation can improve it further



Efficiency and wrap thickness have the strongest influence on mode 1 variation in the stress gradient

Activities for Upcoming Year

- Compile literature review on existing UQ studies
- Discuss and exercise USAF-funded Residual Stress Database (currently being organized by AP/ES)
  - 200 total RS profiles of varying completeness
- Provide support to other subcommittees as needed

Questions?

Residual Stress Process Simulation Committee Progress Report

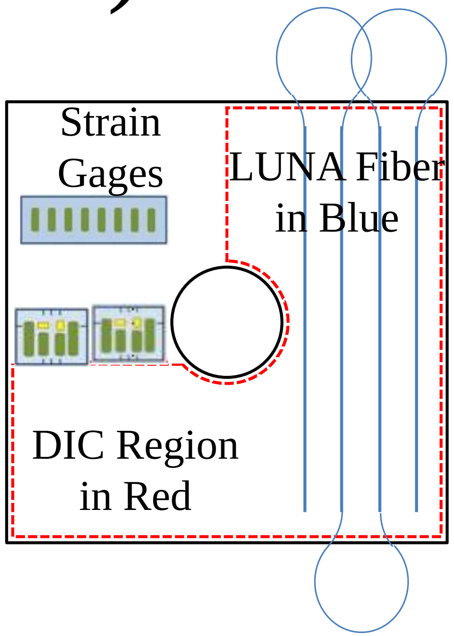
Engineered Residual Stress Implementation Virtual Workshop 2020

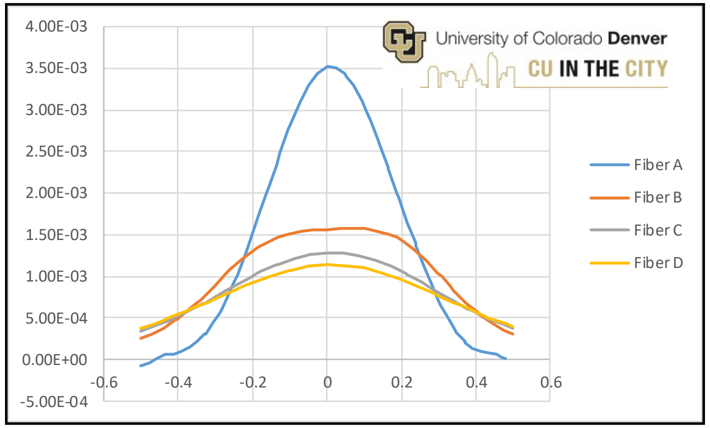
Location: The Ether

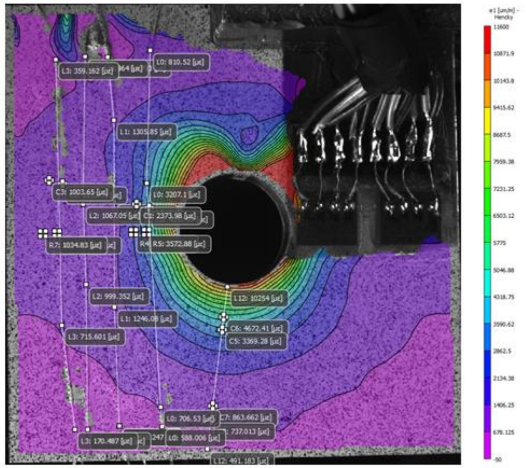
December 2020

Outline

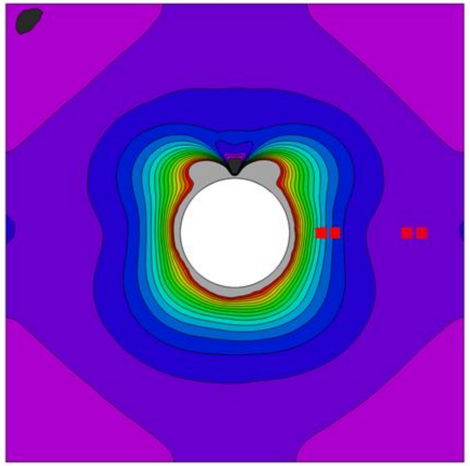
- Committee Activity
- Material Testing Update – 7075
- Process Simulation Round Robin Update
- Other items of interest (2x2 specimen status, future RR plans)







DIC Hoop strains



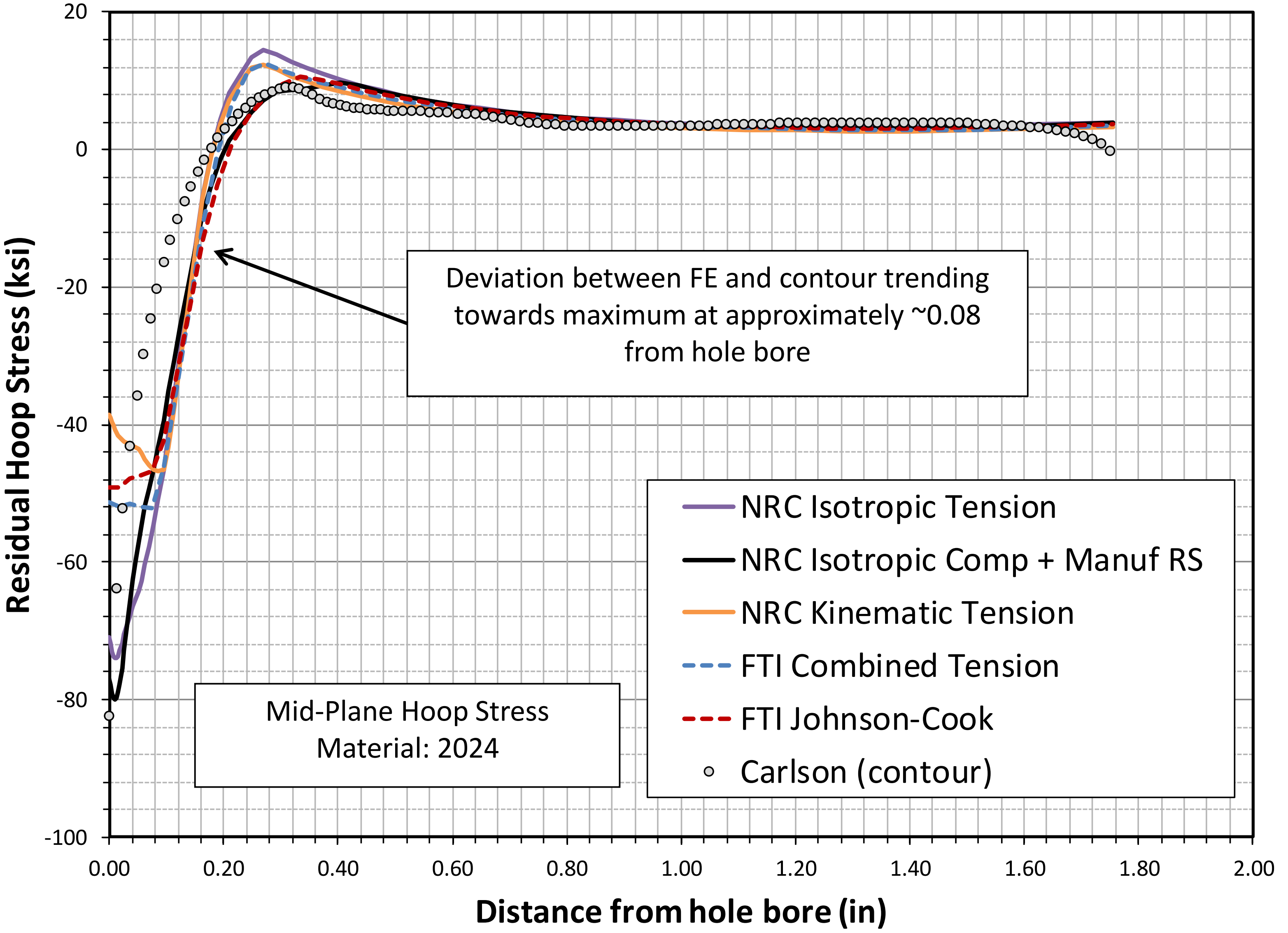
FEA Hoop strains
Chaboche Hardening

Committee Activity & Roster Updates

- Excellent Participation
  - Monthly Meeting 3rd Friday of each month, all are welcome!
  - Total of 13 monthly meetings
- Round Robin Data Reduction Crew
  - Gavin Jones
  - Scott Prost-Domasky
  - Keith Hitchman
  - Total of three sidebar meetings

Material Model Testing - Purpose of Program

Which constitutive model is most appropriate?



Deviation between FE and contour trending towards maximum at approximately ~0.08 from hole bore

Mid-Plane Hoop Stress
Material: 2024

Material Model Testing - Purpose of Program

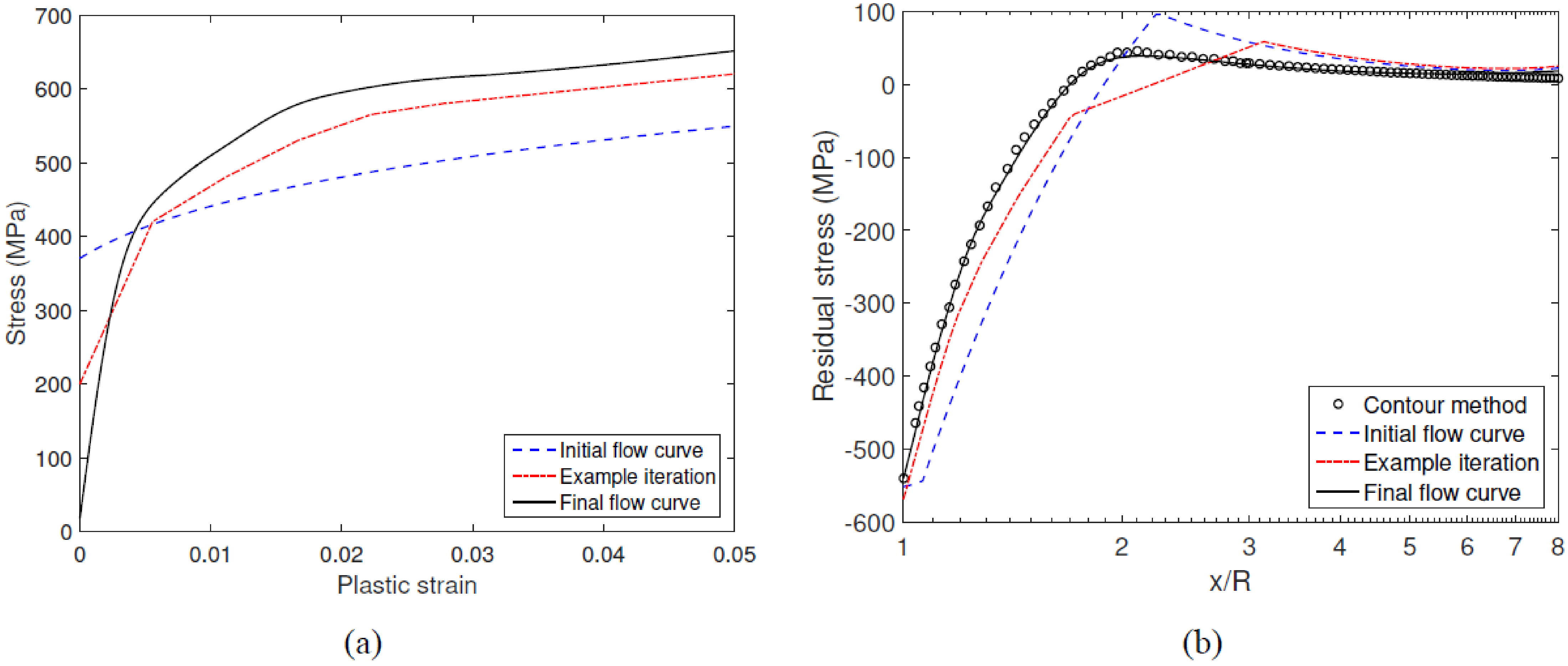
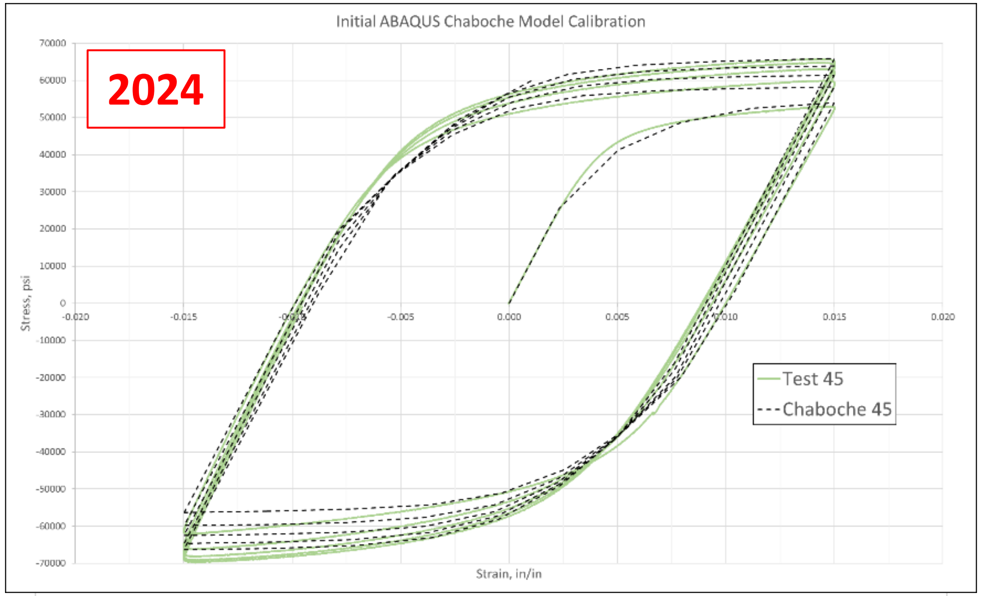


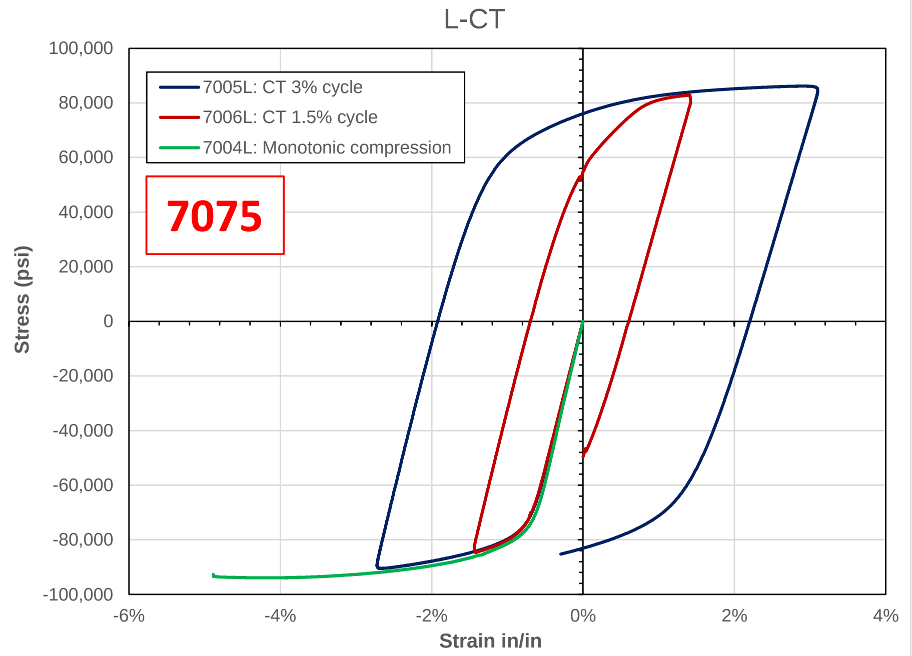
Figure 7 – (a) Flow curves tested, (b) resulting hoop residual stress ($\sigma_{\theta\theta}$); note log scale on x/R

Ribeiro, Renan L., and Michael R. Hill. "Residual Stress From Cold Expansion of Fastener Holes: Measurement, Eigenstrain, and Process Finite Element Modeling." Journal of Engineering Materials and Technology 139.4 (2017): 041012. https://doi.org/10.1115/1.4037021

Material Model Testing – General Plan

- Based upon E606 LCF, up to ±4% in./in., reduced to ±1.5%
- Isolating current investigation to orthotropy
- 2024 testing complete 2018
- 7075 testing complete 2020





Material Model Testing – Previous Results, 2024

Chaboche Parameter	NRC·CNRC Long.	NRC·CNRC Trans.	NRC·CNRC 45°	NRC·CNRC Avg.	Clausen, et. al.*
σ_{ys}, psi	30281	28942	32786	30670	31894
C, psi	7.35e6	8.69e6	8.19e6	8.08e6	9.74e6
Υ	346.88	412.96	399.09	386.31	412.0
Q, psi	21202	21042	20526	20923	23637
b	3.37	3.85	5.53	4.70	7.00
E, psi	10.56e6	10.36e6	11.10e6	10.67e6	10.62e6
ϵ	0.33	0.33	0.33	0.33	0.33

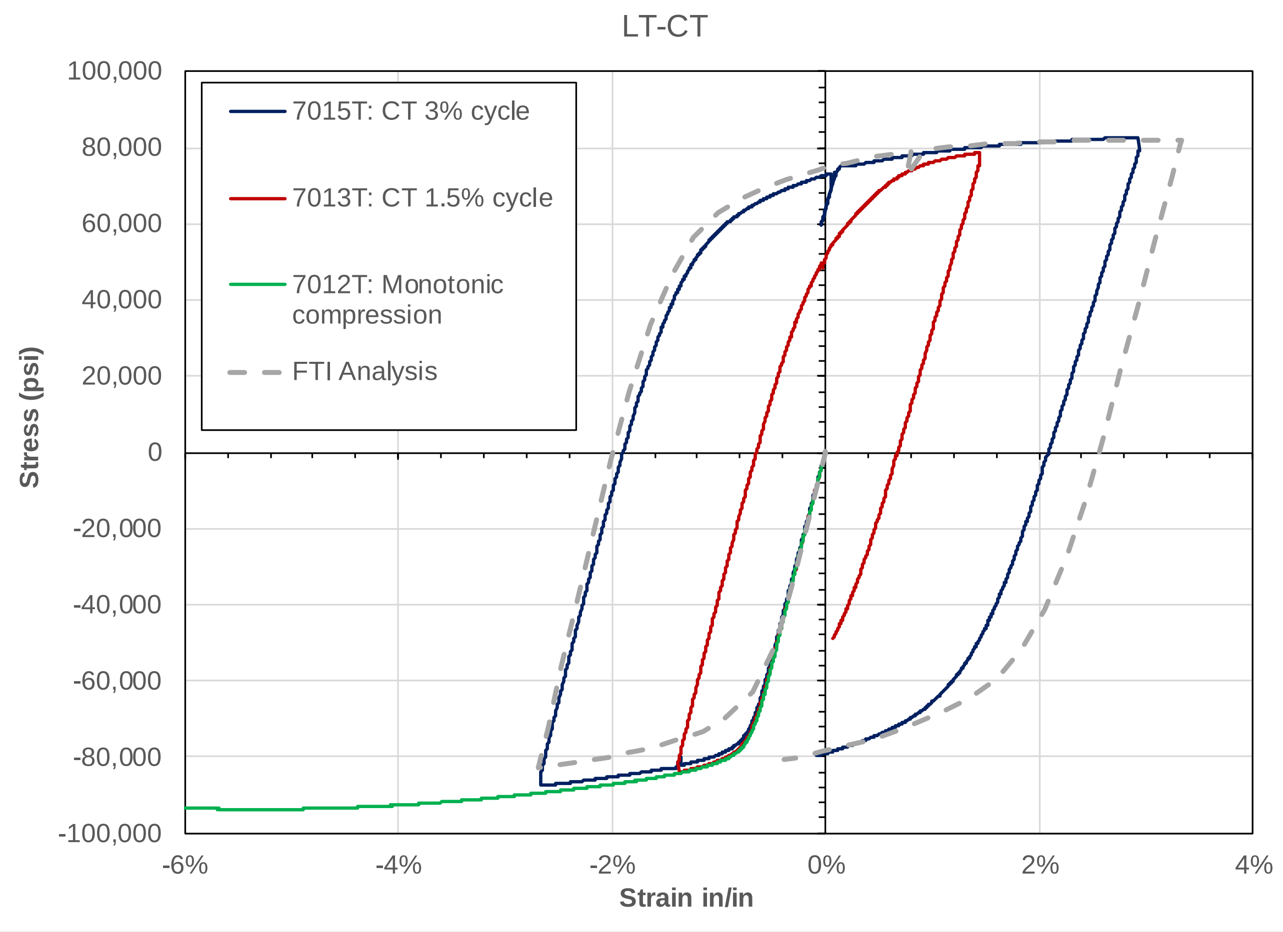
* public.lanl.gov/clausen/Clausen_et_al_PrePrint_SEM_2009.pdf

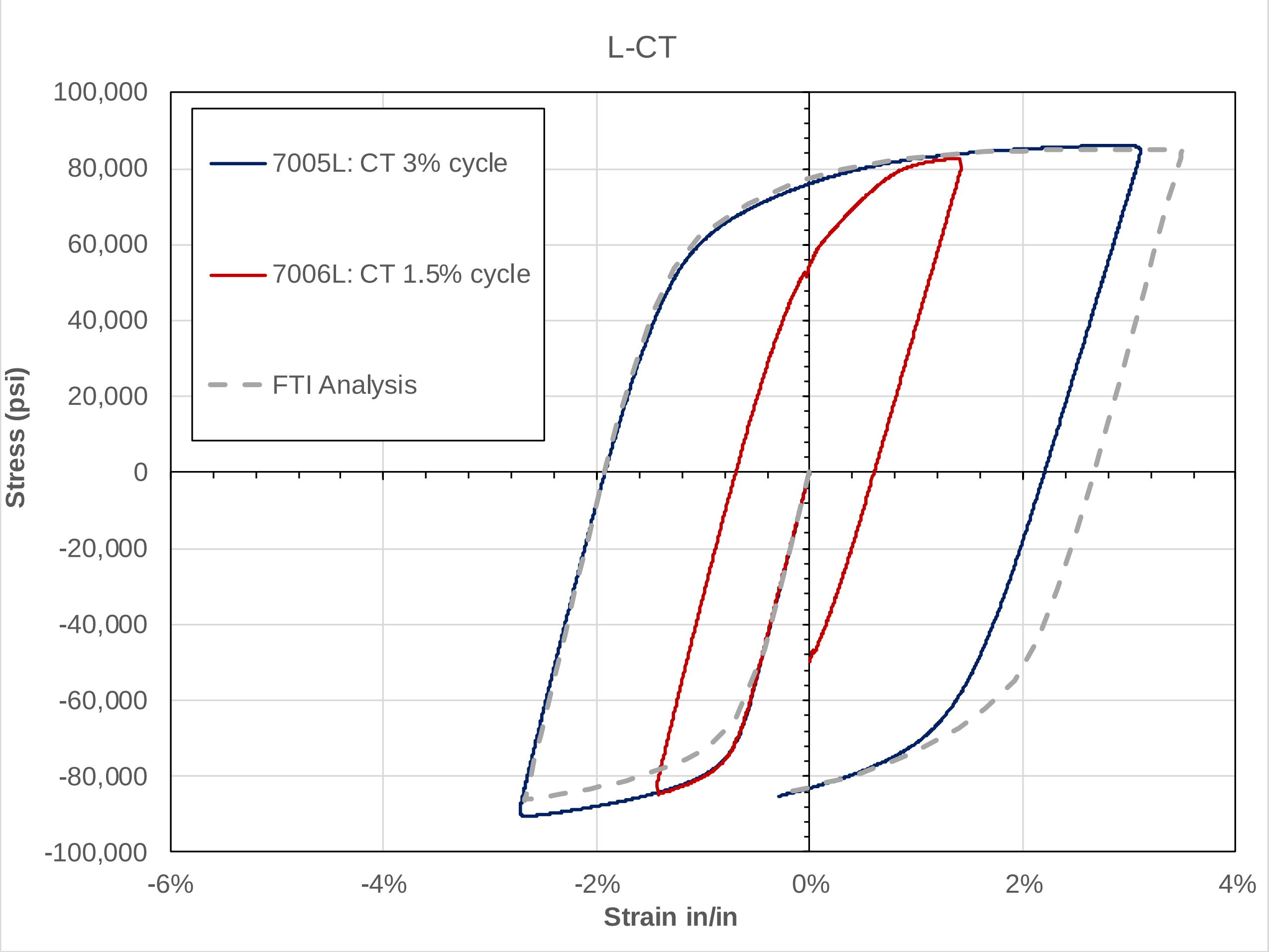
Material Model Testing – New Results, 7075

Chaboche Parameter	NRC 3% L-TC		NRC 3% L-CT		NRC 3% LT-CT			Zehsaz, et. al.*
σ_{ys}, psi	49993		45720		42321			60000
C, psi	1.99e6	3.50e7	2.21e6	3.25e7	3.65e7	1.32e7	1.52e6	7.72e5
ϒ	95.57	1795.80	113.79	1546.80	4845.10	782.45	90.37	31.06
Q, psi	1226		866		2574			19957
b	209.09		56.68		25.68			6.82
E, psi	9.992e6		1.149e7		1.128e7			1.06e7
ϵ	0.33		0.33		0.33			0.33

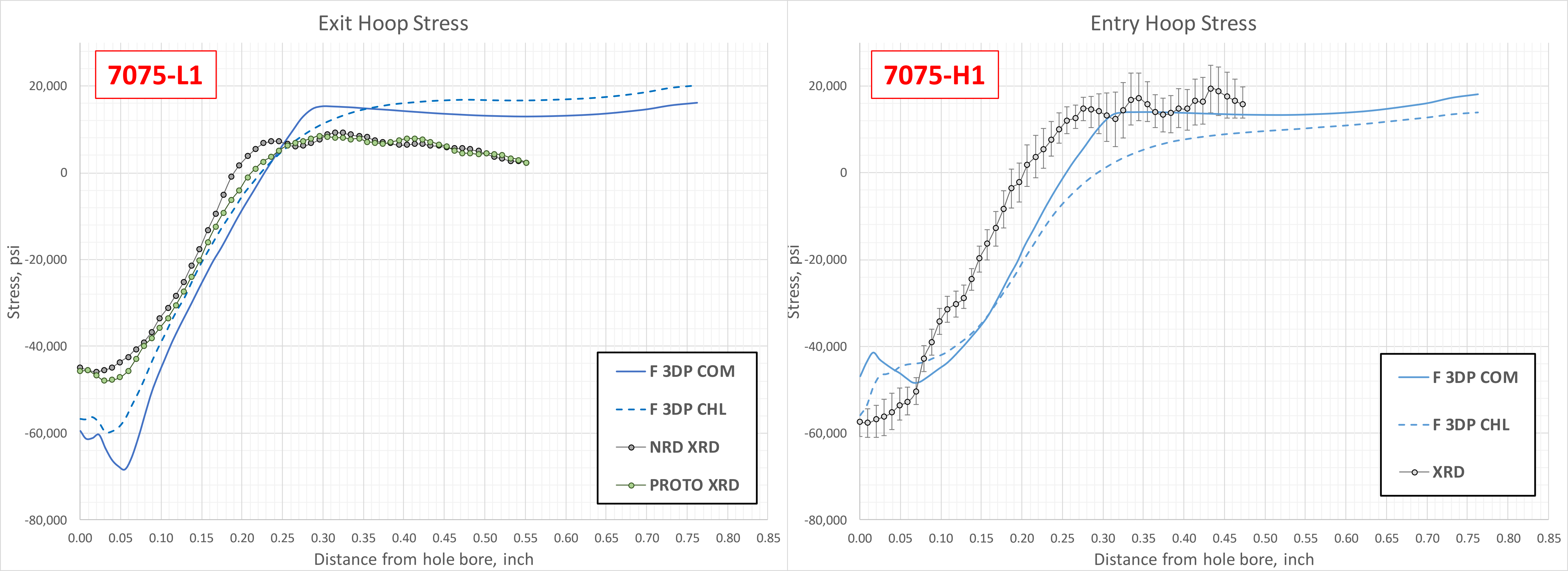
* 7075-T6 @ RT, see https://paginas.fe.up.pt/~m2d/Proceedings_M2D2017/data/papers/6567.pdf

Material Model Testing – New Results, 7075





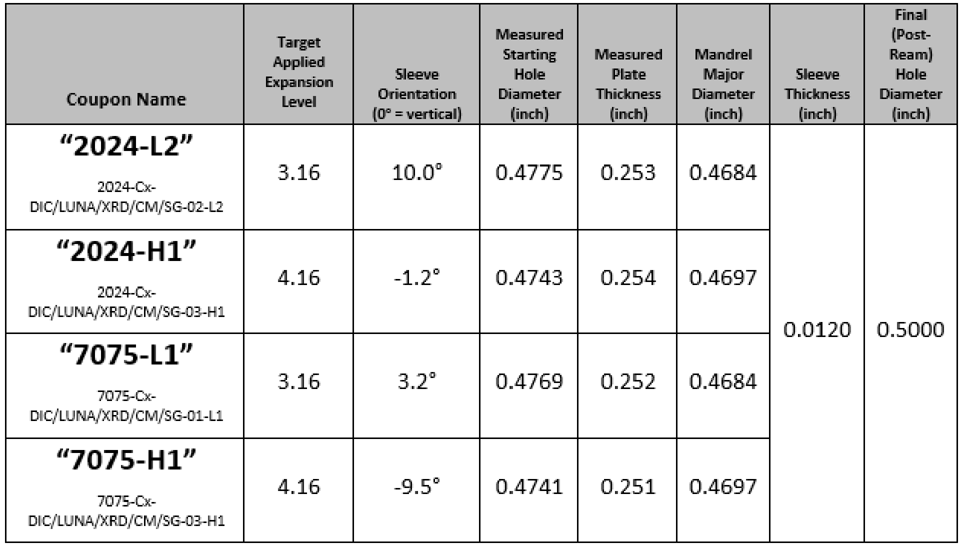
Material Model Testing – New Results, 7075



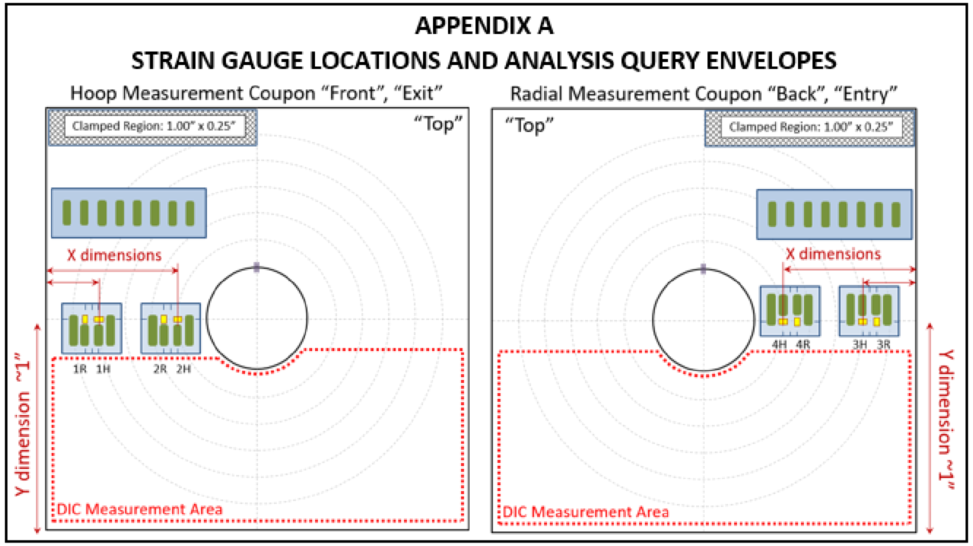
Comparisons: Combined Hardening, new Chaboche (L-TC), and XRD data

RS Process Simulation Round Robin

- Multiple submissions from seven participants
  - Abaqus
  - MARC
  - Nastran
  - StressCheck
- Analysis of the 2”x2” coupon cold expansion
  - Model matrix shown at right
  - Presentation limited to 2024-L2 discussion
- Multiple measurement techniques offer a unique opportunity for process simulation validation and correlation.
- Paper presenting round robin comparisons in work, lead by R. Ribeiro (Hill Engineering).



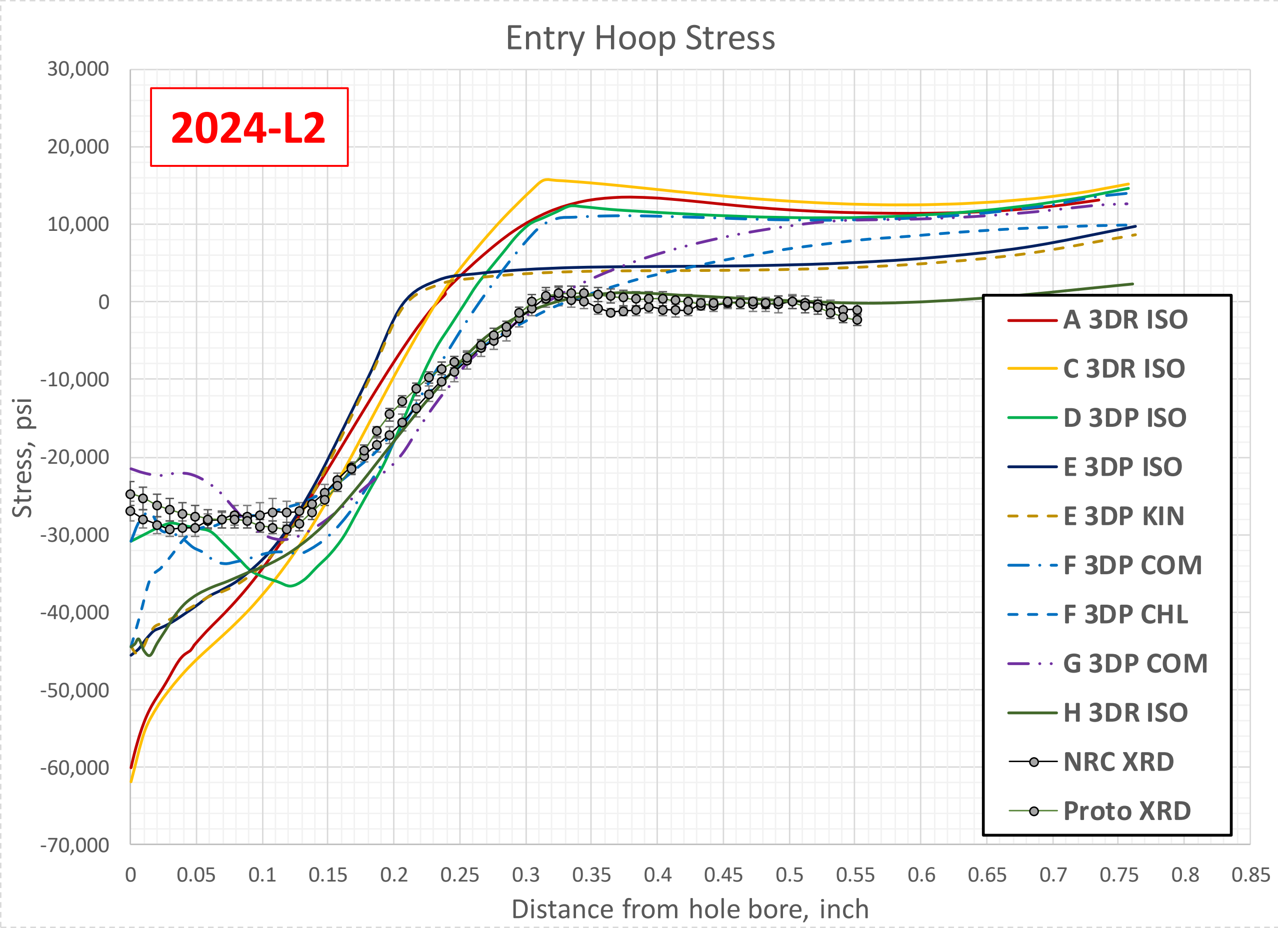
Coupon Name	Target Applied Expansion Level	Sleeve Orientation (0° = vertical)	Measured Starting Hole Diameter (inch)	Measured Plate Thickness (inch)	Mandrel Major Diameter (inch)	Sleeve Thickness (inch)	Final (Post-Ream) Hole Diameter (inch)
“2024-L2” 2024-Cx-DIC/LUNA/XRD/CM/SG-02-L2	3.16	10.0°	0.4775	0.253	0.4684	0.0120	0.5000
“2024-H1” 2024-Cx-DIC/LUNA/XRD/CM/SG-03-H1	4.16	-1.2°	0.4743	0.254	0.4697		
“7075-L1” 7075-Cx-DIC/LUNA/XRD/CM/SG-01-L1	3.16	3.2°	0.4769	0.252	0.4684		
“7075-H1” 7075-Cx-DIC/LUNA/XRD/CM/SG-03-H1	4.16	-9.5°	0.4741	0.251	0.4697		

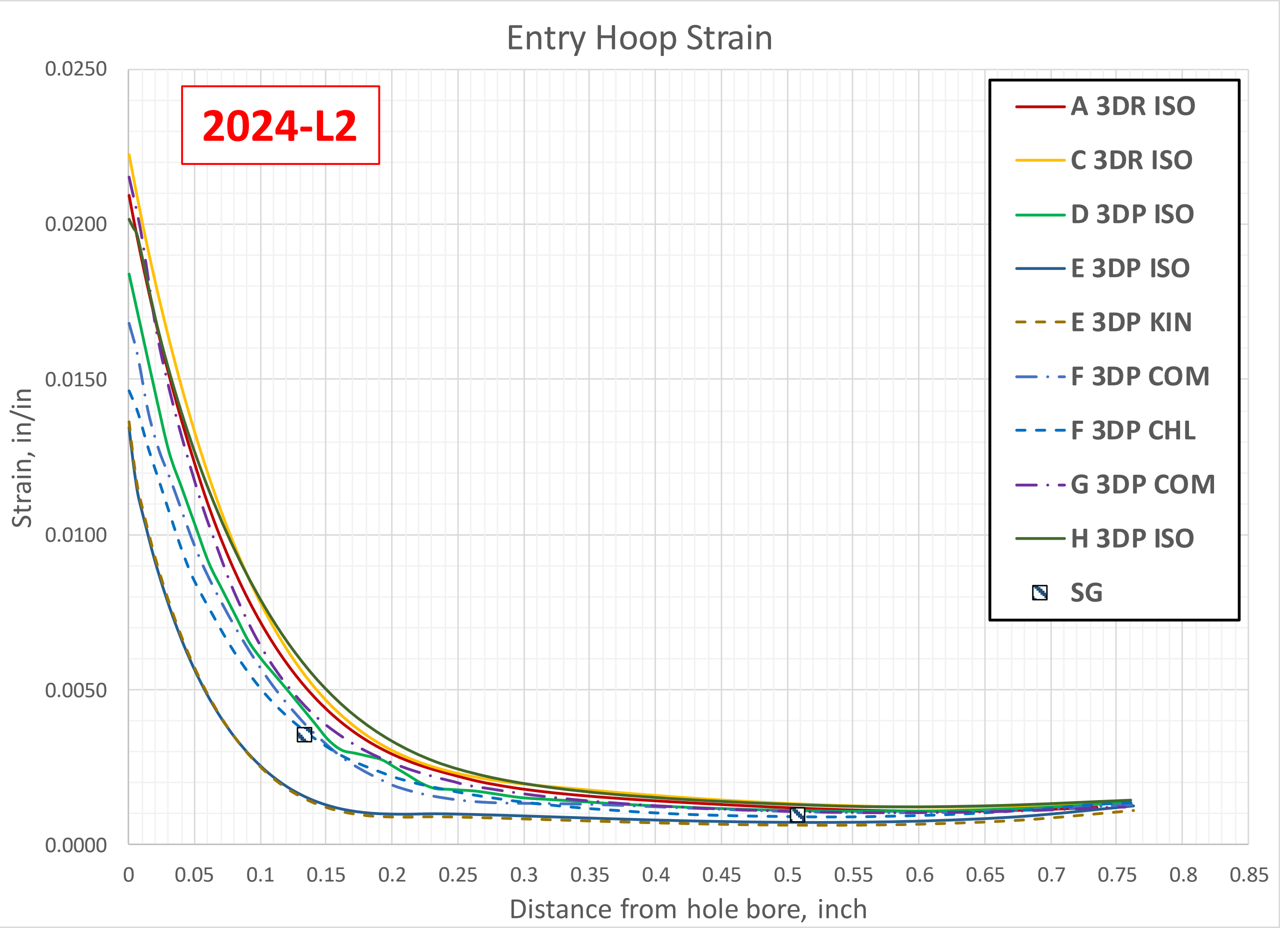


APPENDIX A

STRAIN GAUGE LOCATIONS AND ANALYSIS QUERY ENVELOPES

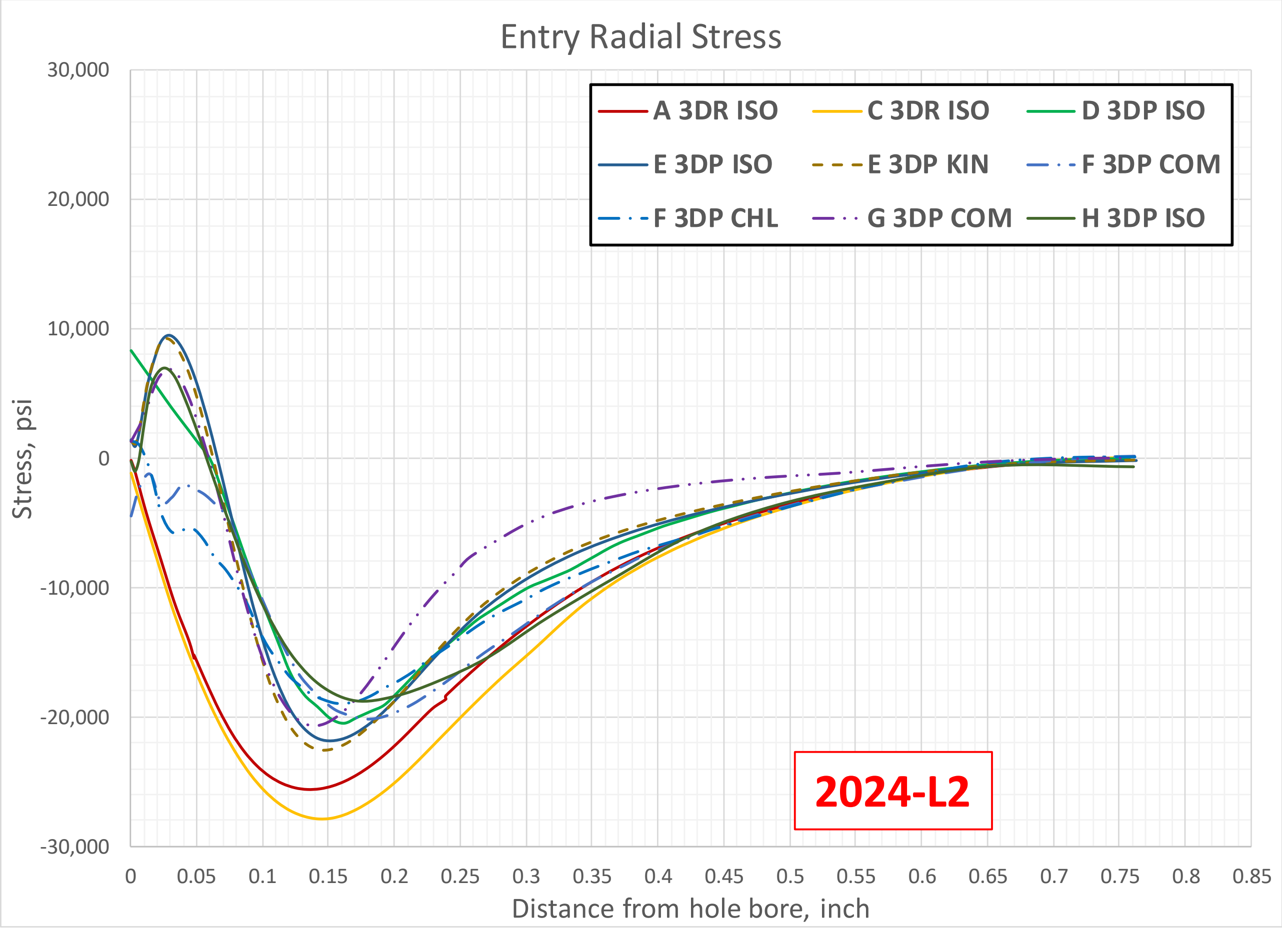
RS Process Simulation Round Robin – Results v SG

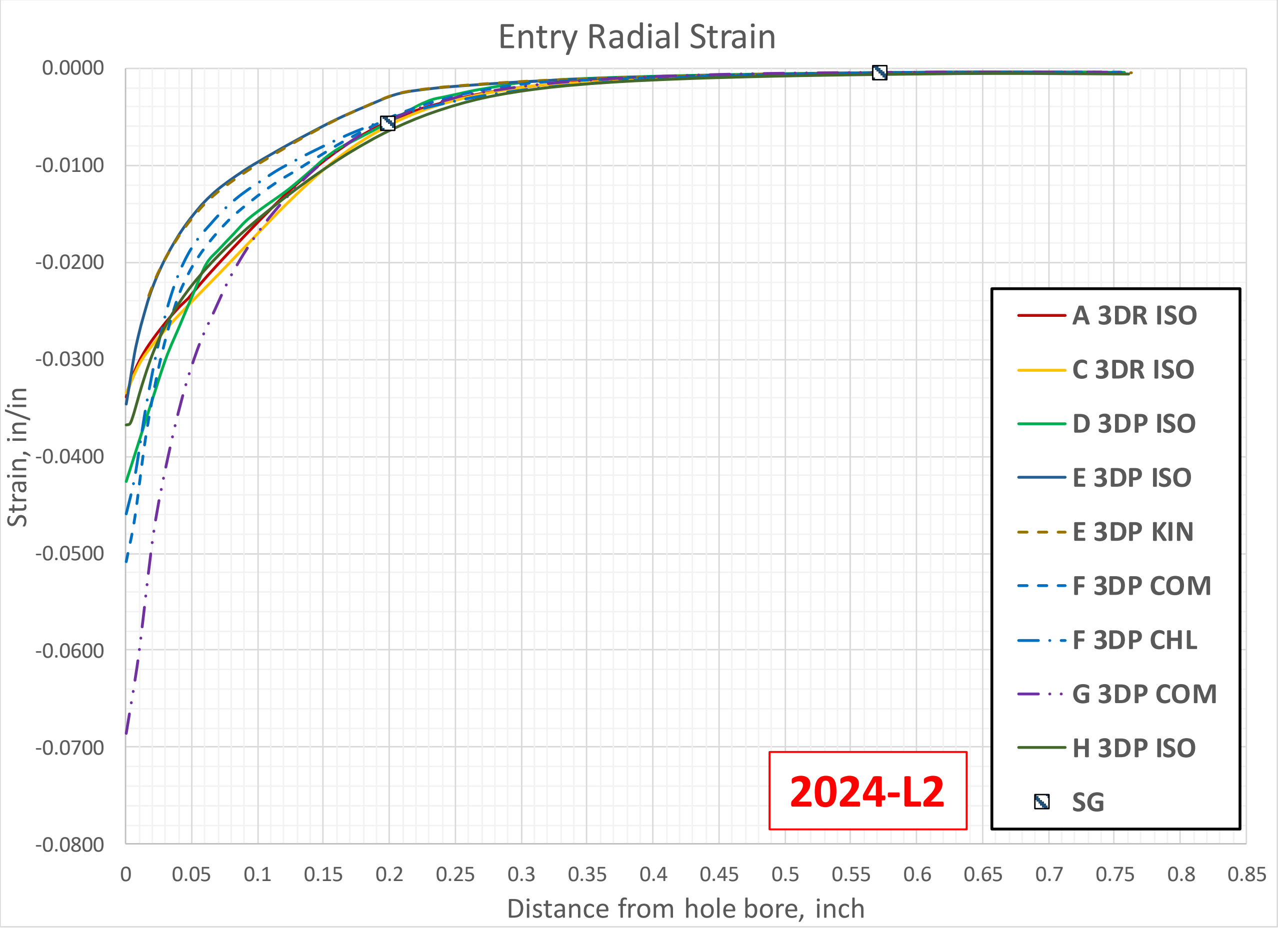




3DR – 3D Radial Displacement
3DP – 3D Mandrel Pull Through
ISO – Isotropic Hardening
COM – Combined Hardening
KIN – Kinematic Hardening
CHL – Chaboche, Longitudinal

RS Process Simulation Round Robin – Results v SG





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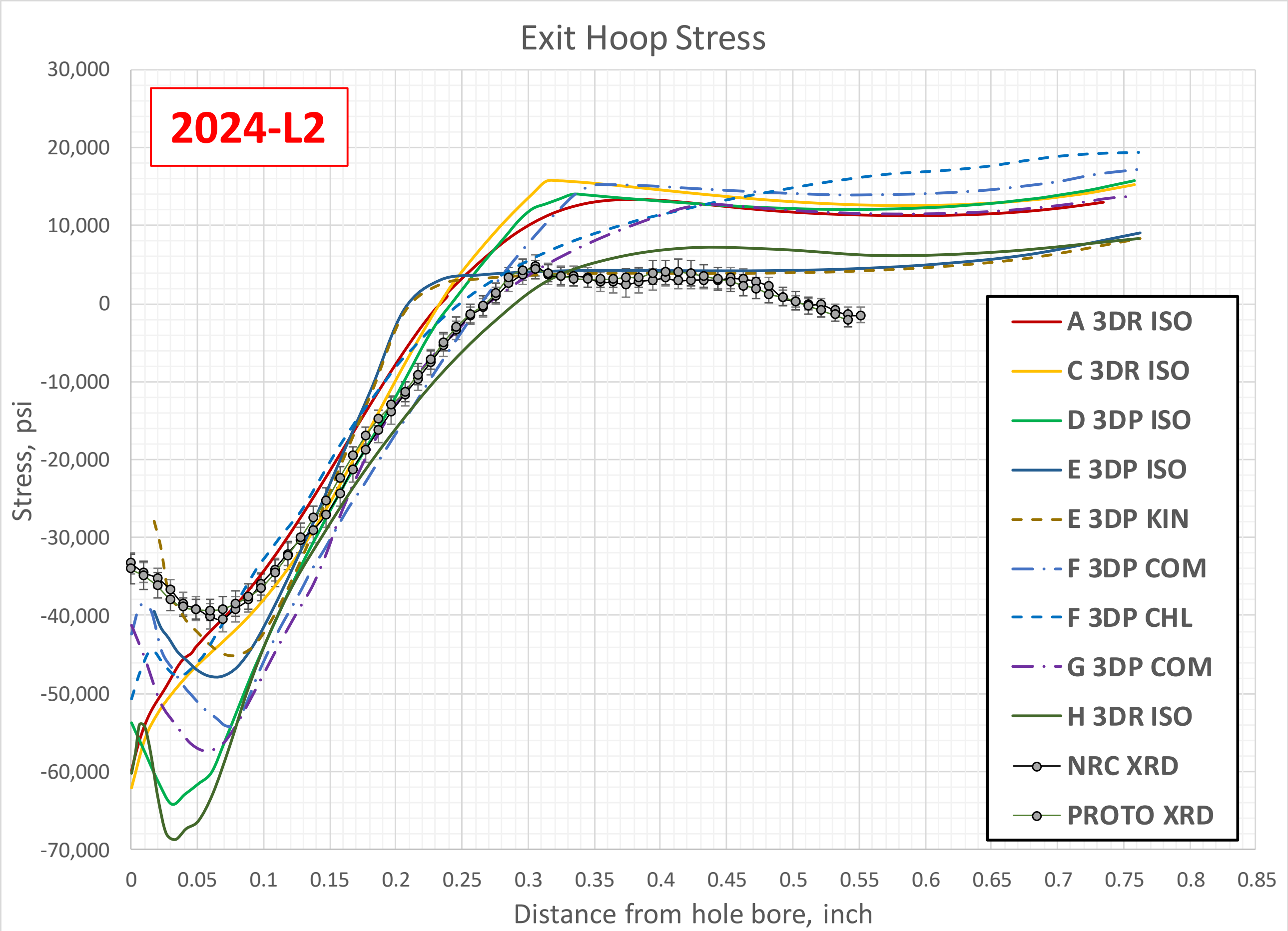
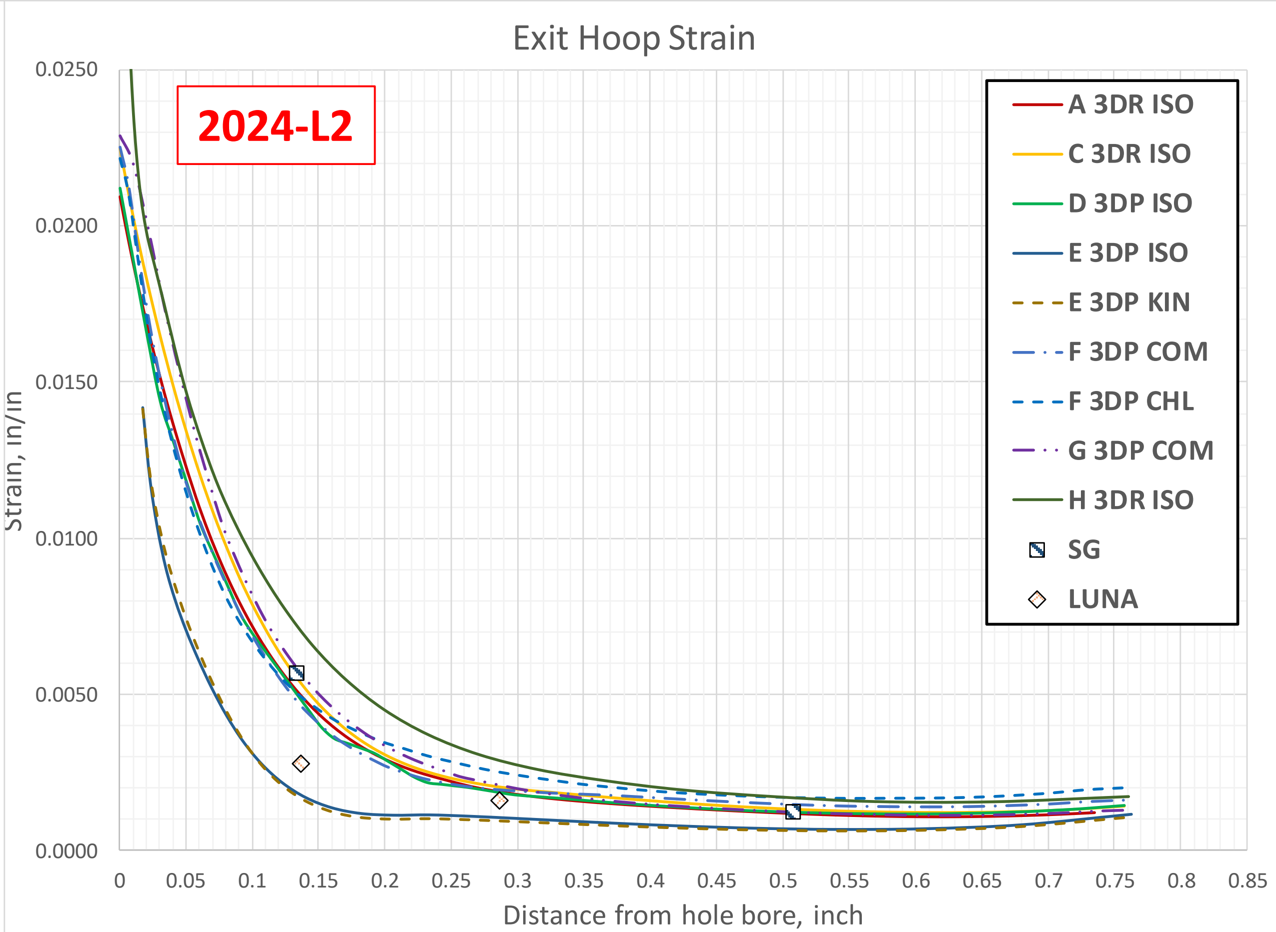
RS Process Simulation Round Robin – Results v SG





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3DP – 3D Mandrel Pull Through
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KIN – Kinematic Hardening
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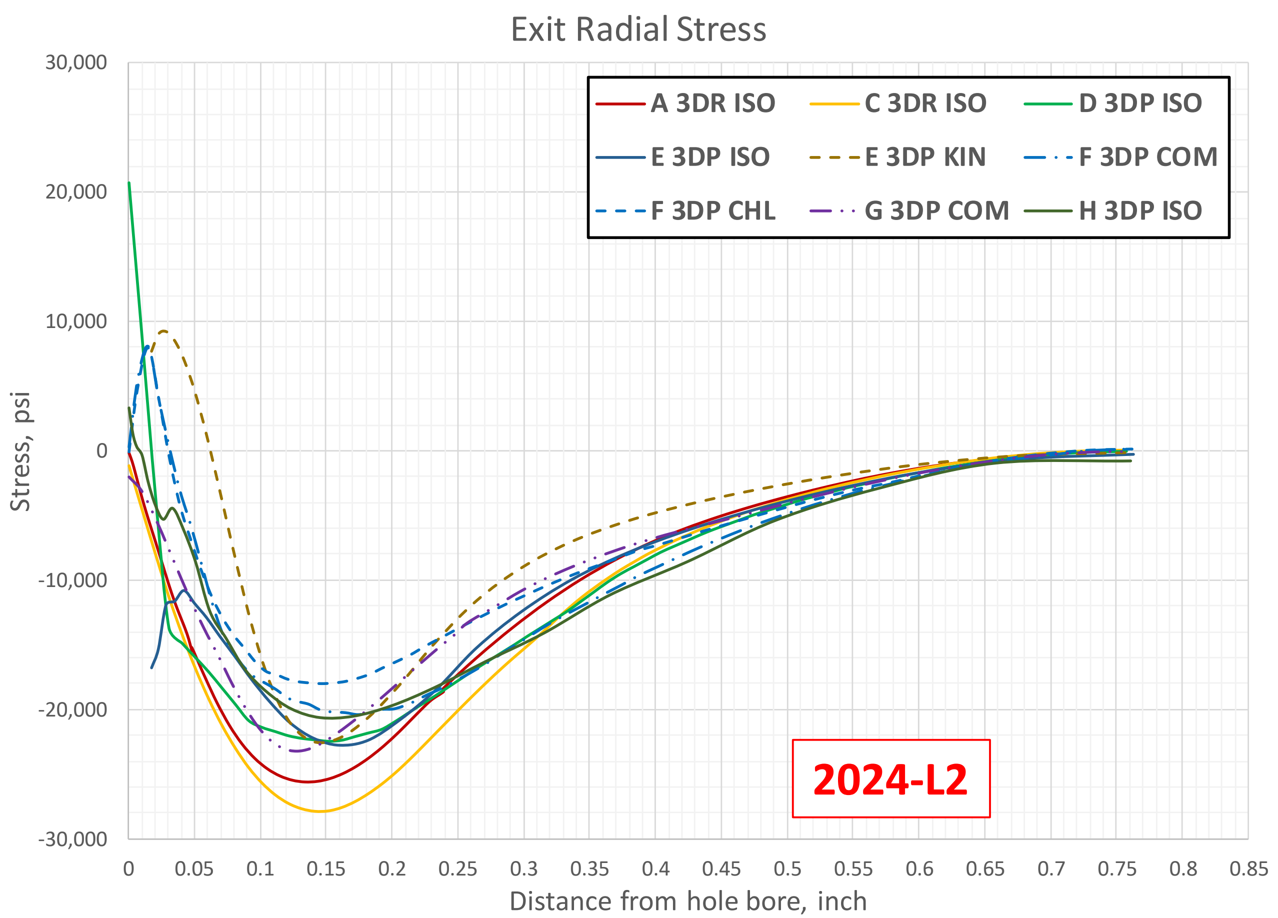
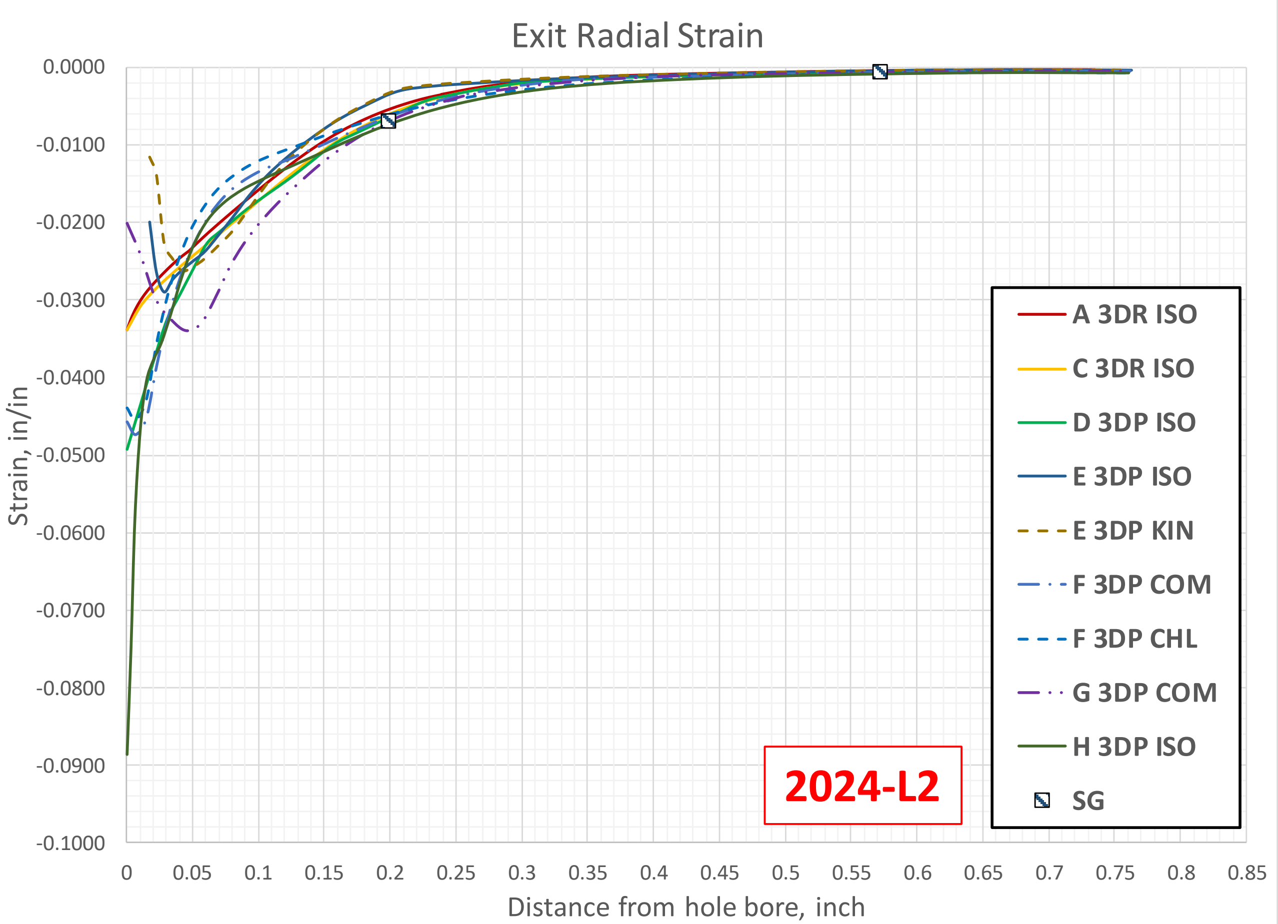
RS Process Simulation Round Robin – Results v SG


Exit Radial Stress


Exit Radial Strain

3DR – 3D Radial Displacement
3DP – 3D Mandrel Pull Through
ISO – Isotropic Hardening
COM – Combined Hardening
KIN – Kinematic Hardening
CHL – Chaboche, Longitudinal

RS Process Simulation Round Robin – Results v SG

Process Simulation Residual Strains – averaged over area subtended by strain gage.

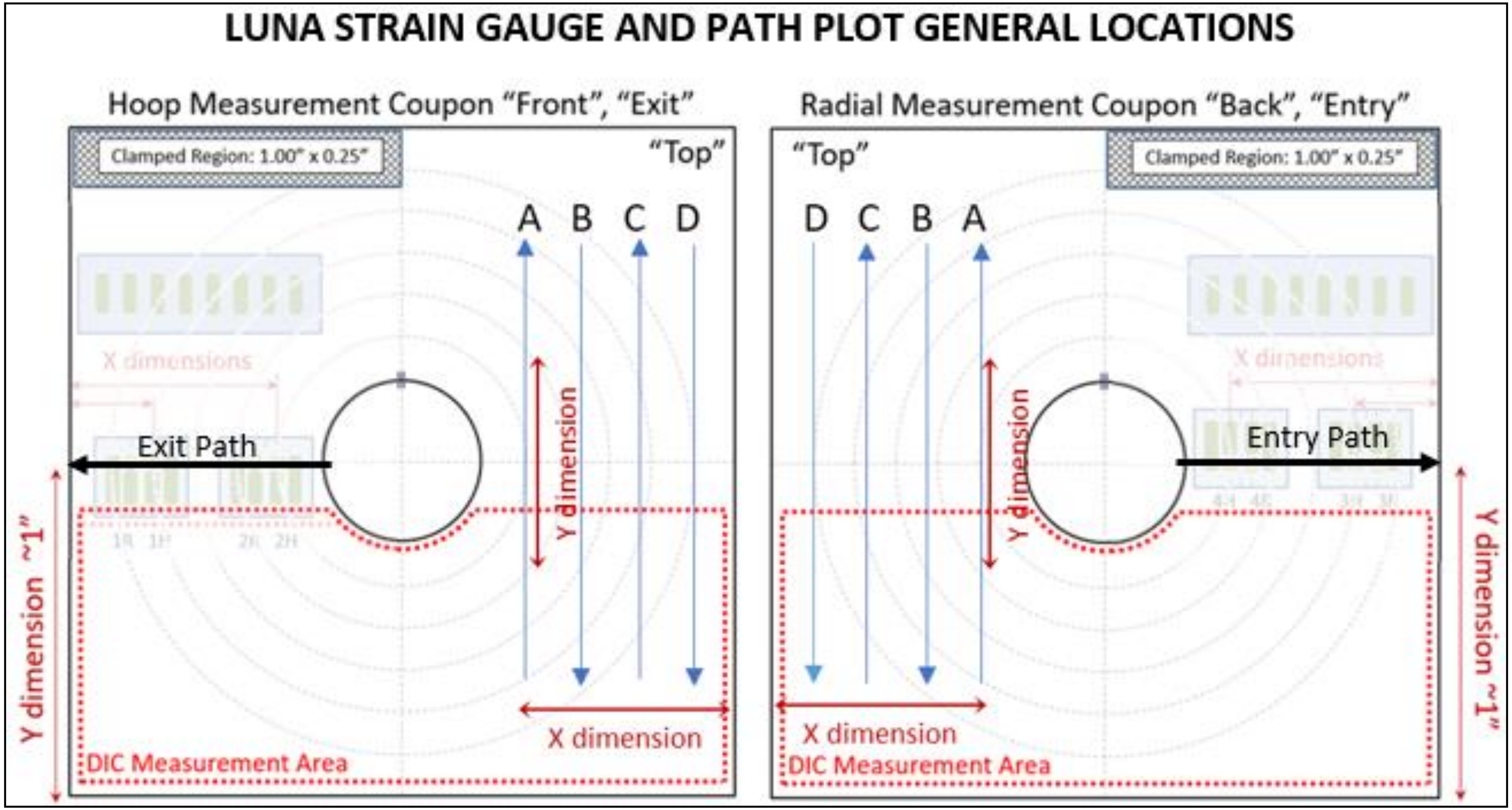
2024 - L2			SG Value	A 3DR ISO		B 2DR KIN		C 3DR ISO		D 3DP ISO		E 3DP KIN	
			Residual	Residual	% Error	Residual	% Error	Residual	% Error	Residual	% Error	Residual	% Error
Entry	Hoop	Inner	**3570**	4436	24.2%	5316	48.9%	5659	58.5%	4341	21.6%	1407	-60.6%
		Outer	**982.8**	1187	20.8%	1529	55.6%	1306	32.9%	1089	10.8%	656	-33.2%
	Radial	Inner	**-5699**	-4417	-22.5%	-4657	-18.3%	-6042	6.0%	-5530	-3.0%	-2543	-55.4%
		Outer	**-460.8**	-487	5.7%	-733	59.1%	-567	23.0%	-467	1.3%	-386	-16.2%
Exit	Hoop	Inner	**5703**	4436	-22.2%	5316	-6.8%	5712	0.1%	5078	-11.0%	1632	-71.4%
		Outer	**1238**	1187	-4.1%	1529	23.5%	1312	6.0%	1247	0.7%	641	-48.2%
	Radial	Inner	**-6906**	-4417	-36.0%	-4657	-32.6%	-6096	-11.7%	-6402	-7.3%	-2882	-58.3%
		Outer	**-570.6**	-487	-14.6%	-733	28.5%	-570	-0.1%	-579	1.5%	-427	-25.2%

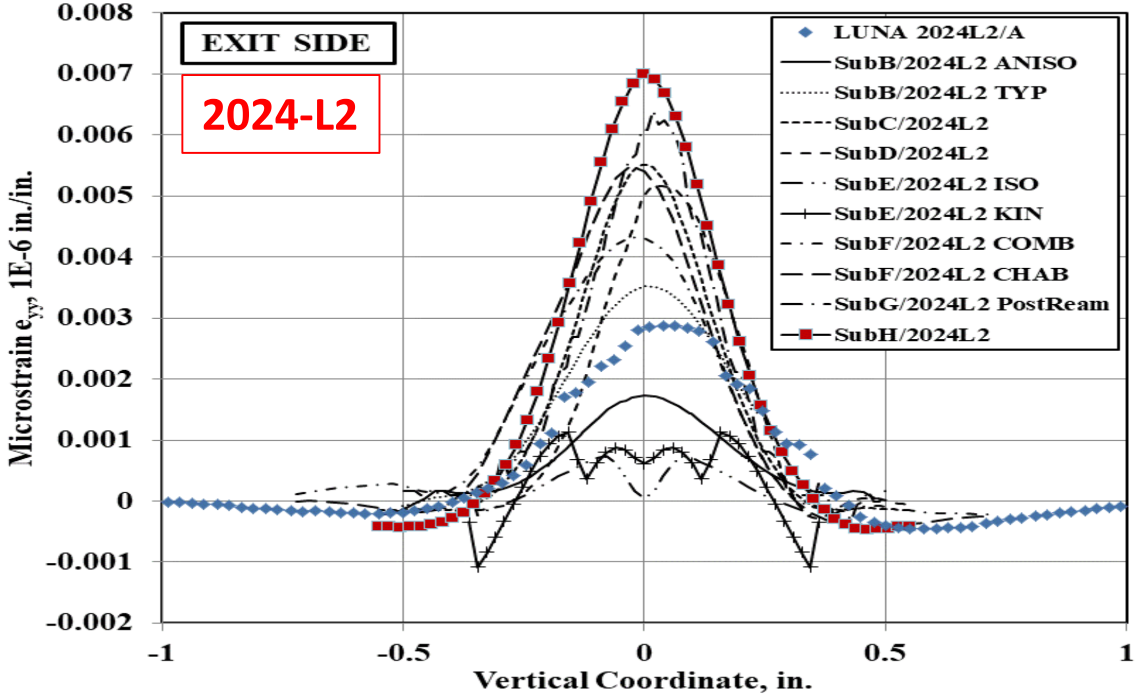
2024 - L2			SG Value	F 3DP COM		F 3DP CHA		G 3DP COM		H 3DP ISO		E 3DP ISO	
			Residual	Residual	% Error	Residual	% Error	Residual	% Error	Residual	% Error	Residual	% Error
Entry	Hoop	Inner	**3570**	3775	5.7%	3664	2.6%	4598	28.8%	5723	60.3%	1455	-59.2%
		Outer	**982.8**	1073	9.2%	836	-14.9%	1053	7.1%	1275	29.7%	721	-26.6%
	Radial	Inner	**-5699**	-5318	-6.7%	-5333	-6.4%	-5567	-2.3%	-6273	10.1%	-2595	-54.5%
		Outer	**-460.8**	-500	8.5%	-458	-0.6%	-405	-12.1%	-561	21.7%	-416	-9.7%
Exit	Hoop	Inner	**5703**	4640	-18.6%	5010	-12.2%	5948	4.3%	7121	24.9%	1757	-69.2%
		Outer	**1238**	1446	16.8%	1826	47.5%	1225	-1.0%	1698	37.2%	708	-42.8%
	Radial	Inner	**-6906**	-6506	-5.8%	-9342	35.3%	-7069	2.4%	-7090	2.7%	-3110	-55.0%
		Outer	**-570.6**	-669	17.3%	-803	40.7%	-555	-2.7%	-765	34.1%	-481	-15.7%

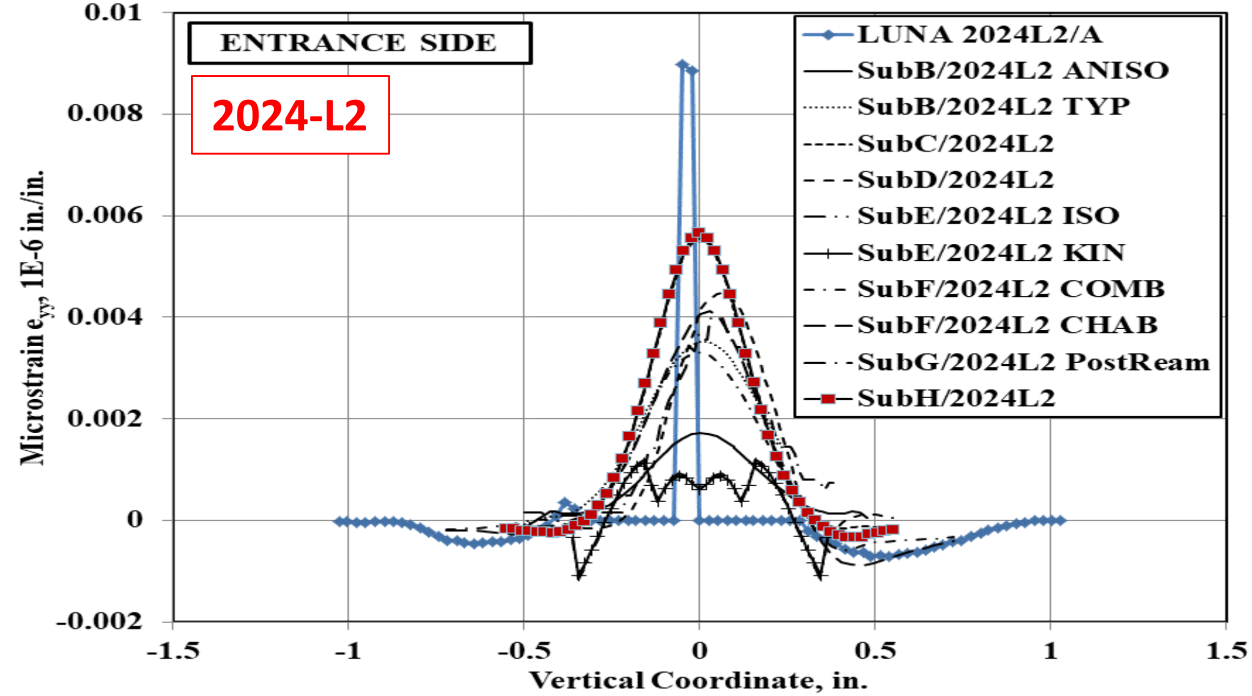
All values in µinch/inch. Green: less than ±10% Red: more than ±30%

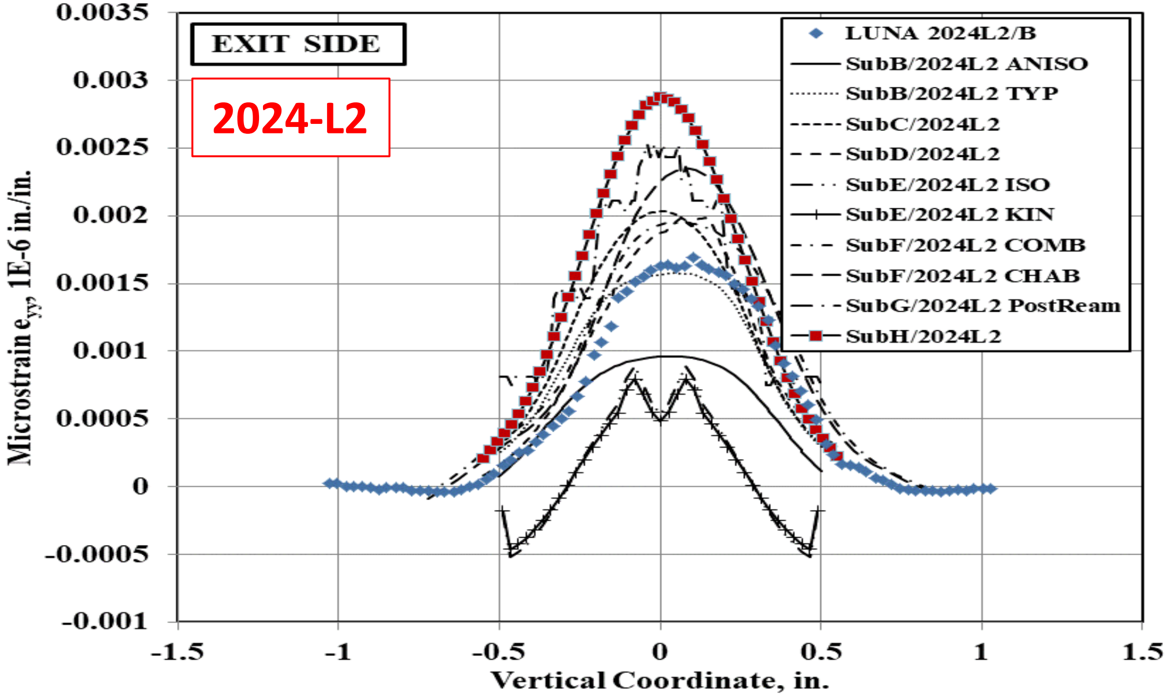
3DR – 3D Radial Displacement
3DP – 3D Mandrel Pull Through
ISO – Isotropic Hardening
COM – Combined Hardening
KIN – Kinematic Hardening
CHL – Chaboche, Longitudinal

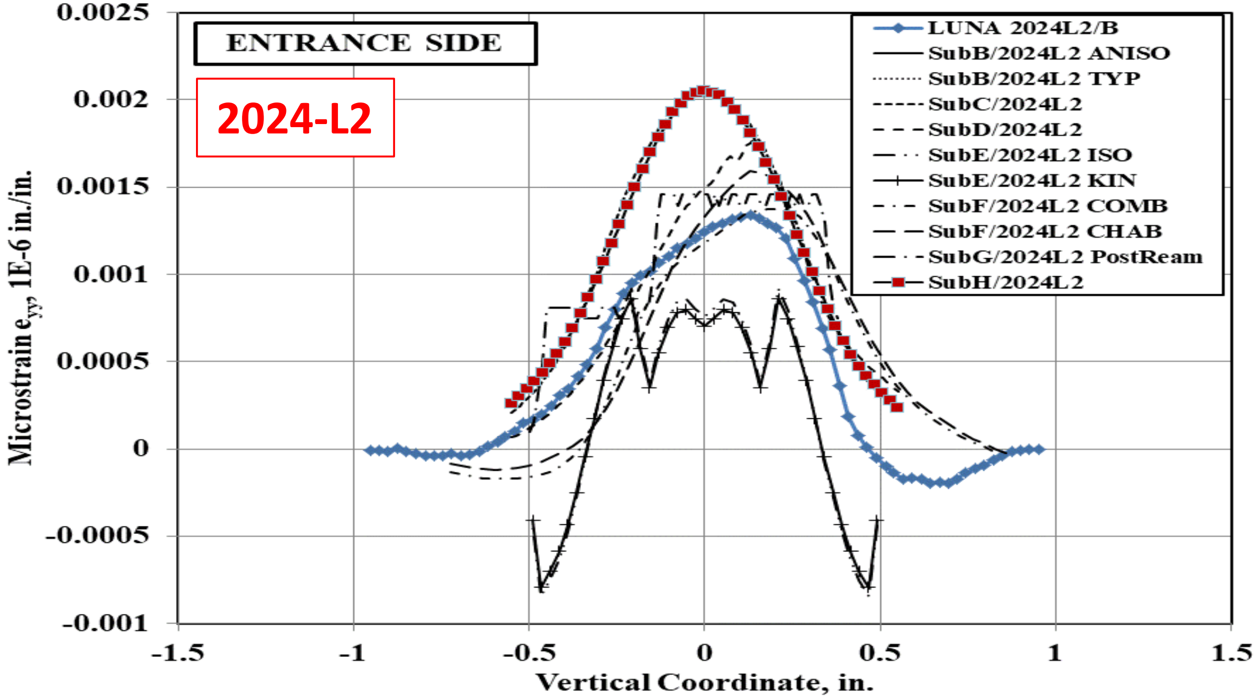
RS Process Simulation Round Robin – Results v Luna




EXIT SIDE
2024-L2
LUNA 2024L2/A
SubB/2024L2 ANISO
SubB/2024L2 TYP
SubC/2024L2
SubD/2024L2
SubE/2024L2 ISO
SubE/2024L2 KIN
SubF/2024L2 COMB
SubF/2024L2 CHAB
SubG/2024L2 PostReam
SubH/2024L2
Microstrain e_{yy}, 1E-6 in./in.
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-1
-0.5
0
0.5
1
Vertical Coordinate, in.


ENTRANCE SIDE
2024-L2
LUNA 2024L2/A
SubB/2024L2 ANISO
SubB/2024L2 TYP
SubC/2024L2
SubD/2024L2
SubE/2024L2 ISO
SubE/2024L2 KIN
SubF/2024L2 COMB
SubF/2024L2 CHAB
SubG/2024L2 PostReam
SubH/2024L2
Microstrain e_{yy}, 1E-6 in./in.
0.01
0.008
0.006
0.004
0.002
0
-0.002
-1.5
-1
-0.5
0
0.5
1
1.5
Vertical Coordinate, in.


EXIT SIDE
2024-L2
LUNA 2024L2/B
SubB/2024L2 ANISO
SubB/2024L2 TYP
SubC/2024L2
SubD/2024L2
SubE/2024L2 ISO
SubE/2024L2 KIN
SubF/2024L2 COMB
SubF/2024L2 CHAB
SubG/2024L2 PostReam
SubH/2024L2
Microstrain e_{yy}, 1E-6 in./in.
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
-0.0005
-0.001
-1.5
-1
-0.5
0
0.5
1
1.5
Vertical Coordinate, in.


ENTRANCE SIDE
2024-L2
LUNA 2024L2/B
SubB/2024L2 ANISO
SubB/2024L2 TYP
SubC/2024L2
SubD/2024L2
SubE/2024L2 ISO
SubE/2024L2 KIN
SubF/2024L2 COMB
SubF/2024L2 CHAB
SubG/2024L2 PostReam
SubH/2024L2
Microstrain e_{yy}, 1E-6 in./in.
0.0025
0.002
0.0015
0.001
0.0005
0
-0.0005
-0.001
-1.5
-1
-0.5
0
0.5
1
1.5
Vertical Coordinate, in.

Other Items of Interest

- 2x2 Specimen (Stansfield)
  - Surface Paper
  - Final Measurements
- Round Robin Last Steps
  - Complete Report Out
  - Paper Submittal
- Round Robin: GLS

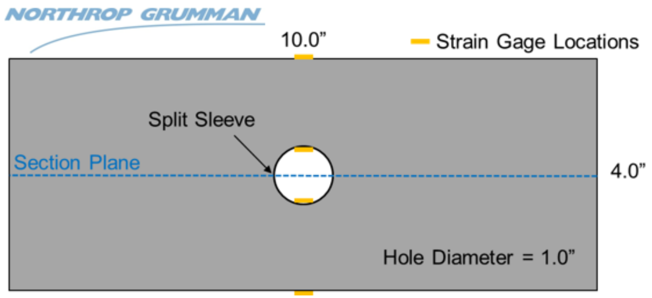


Figure 1 Geometrically “large” test coupon illustration

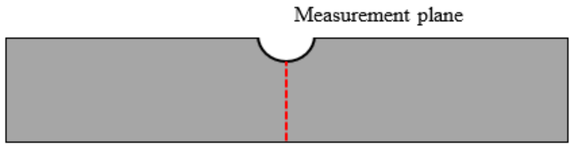
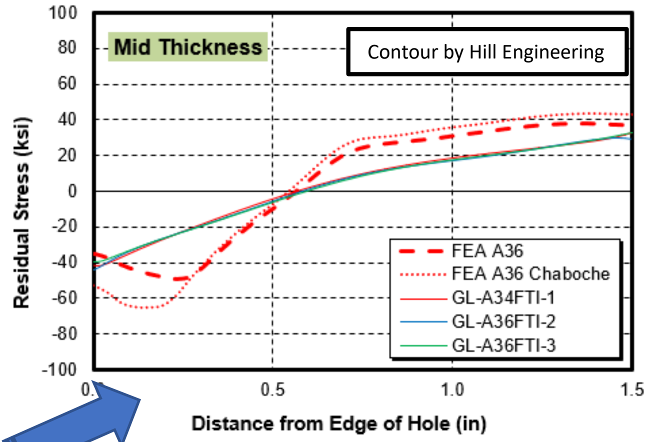
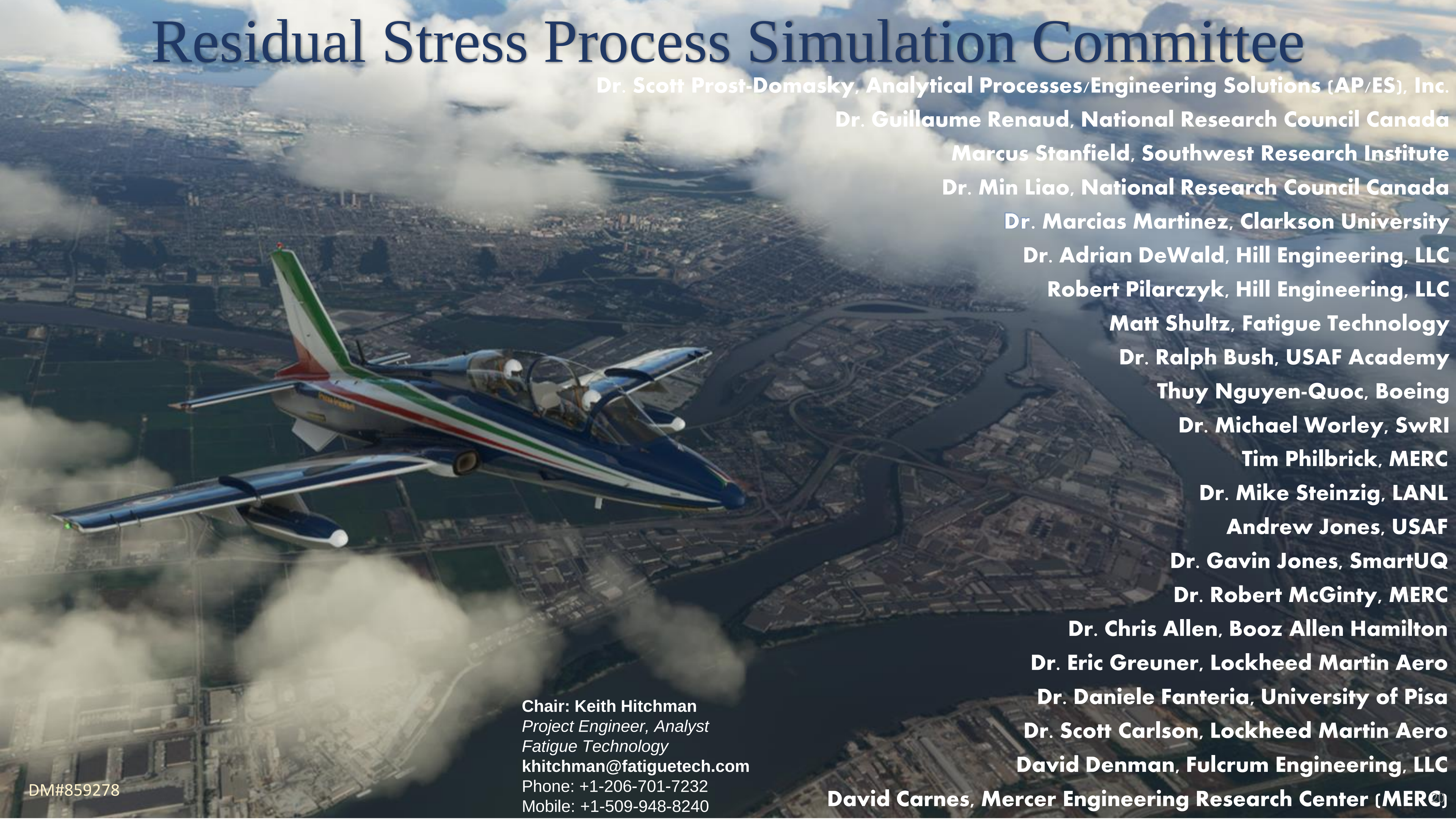


Figure 2 Illustration of contour measurement plane



Residual Stress Process Simulation Committee



Dr. Scott Prost-Domasky, Analytical Processes/Engineering Solutions (AP/ES), Inc.
Dr. Guillaume Renaud, National Research Council Canada
Marcus Stanfield, Southwest Research Institute
Dr. Min Liao, National Research Council Canada
Dr. Marcias Martinez, Clarkson University
Dr. Adrian DeWald, Hill Engineering, LLC
Robert Pilarczyk, Hill Engineering, LLC
Matt Shultz, Fatigue Technology
Dr. Ralph Bush, USAF Academy
Thuy Nguyen-Quoc, Boeing
Dr. Michael Worley, SwRI
Tim Philbrick, MERC
Dr. Mike Steinzig, LANL
Andrew Jones, USAF
Dr. Gavin Jones, SmartUQ
Dr. Robert McGinty, MERC
Dr. Chris Allen, Booz Allen Hamilton
Dr. Eric Greuner, Lockheed Martin Aero
Dr. Daniele Fanteria, University of Pisa
Dr. Scott Carlson, Lockheed Martin Aero
David Denman, Fulcrum Engineering, LLC
David Carnes, Mercer Engineering Research Center (MERC)

Chair: Keith Hitchman
Project Engineer, Analyst
Fatigue Technology
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Phone: +1-206-701-7232
Mobile: +1-509-948-8240

Analytical Methods & Testing Committee: Breakout Session

Engineered Residual Stress Implementation Group

Robert Pilarczyk
Group Lead – Structural Integrity
Hill Engineering, LLC

Jacob Warner
A-10 ASIP Engineering
USAF

Agenda

- Round Robin Efforts
  - Round Robin #1 (Pilarczyk)
  - Round Robin #2 (Warner)
- Modeling Efforts
  - Cyclic Redistribution (Pilarczyk, Mills)
  - Multi-Point MAI Program (Spradlin, Morgan)
  - AFGROW Advanced Model Predictions (Prost-Domasky)
  - Surface Corrections for Multi-Point Analyses (Hodges, Pilarczyk)
  - FCG Testing of Complex Coupons with Quench Induced Residual Stress (Ribeiro)
  - 7075 Prediction Comparisons (Pilarczyk)
- Validation Testing
  - Closure Images (Ross)
- Weapon System Applications
  - B-1 Taper-Lok Analysis & Testing (Pilarczyk, Lee, Smith)
- Misc. Other
  - Kt Free Coupons (Warner, Greer)
  - USAF Draft Structures Bulletin (Andrew, Warner, Spradlin)
  - Literature Review (Pilarczyk)

ROUND ROBIN EFFORTS

Round Robin #1 Wrap-up

- Follow-on efforts
  - Collaborating with Jim Newman, Kevin Walker, Jim Harter, and others to understand SIF comparisons for RR cases
- Publications
  - Presented at 19th International ASTM/ESIS Symposium on Fatigue and Fracture Mechanics (42nd National Symposium on Fatigue and Fracture Mechanics), May 2019
  - Presented at the 2019 USAF ASIP Conference
  - Published in Special Issue on Fatigue and Fracture Mechanics for Materials Performance and Characterization

ASTM INTERNATIONAL

Materials Performance and Characterization

Robert Pilarczyk,[1] Ricardo Actis,[2] Joseph Cardinal,[3] Scott Carlson,[3] James Harter,[4] Joshua Hodges,[5] Scott Prost-Domasky,[6] and Guillaume Renaud[7]

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Successful Round Robin Analyses Resulting from the Engineered Residual Stress Implementation Working Group

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  - ➢ Ricardo Actis, Engineering Software Research & Development Inc, St. Louis, MO, USA
  - ➢ Joseph Cardinal, Southwest Research Institute, San Antonio, TX, USA
  - ➢ Scott Carlson, Lockheed Martin - Aeronautics, Ft. Worth, TX, USA
  - ➢ James Harter, LexTech Inc, Dayton, OH, USA
  - ➢ Joshua Hodges, Hill Engineering LLC, Rancho Cordova, CA, USA
  - ➢ Millard Kwan, Aviation Engineers Pty Ltd, Arundel, QLD, Australia
  - ➢ Scott Prost-Domasky, Analytical Processes/Engineered Solutions Inc, St. Louis, MO, USA
  - ➢ Guillaume Renaud, National Research Council Canada, Ottawa, Ontario, Canada
- ☐ Engineered Residual Stress Implementation (ERSI) Working Group

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ERSI

INTERFERENCE FIT FASTENER ANALYTICAL ROUND ROBIN

A-10 ASIP

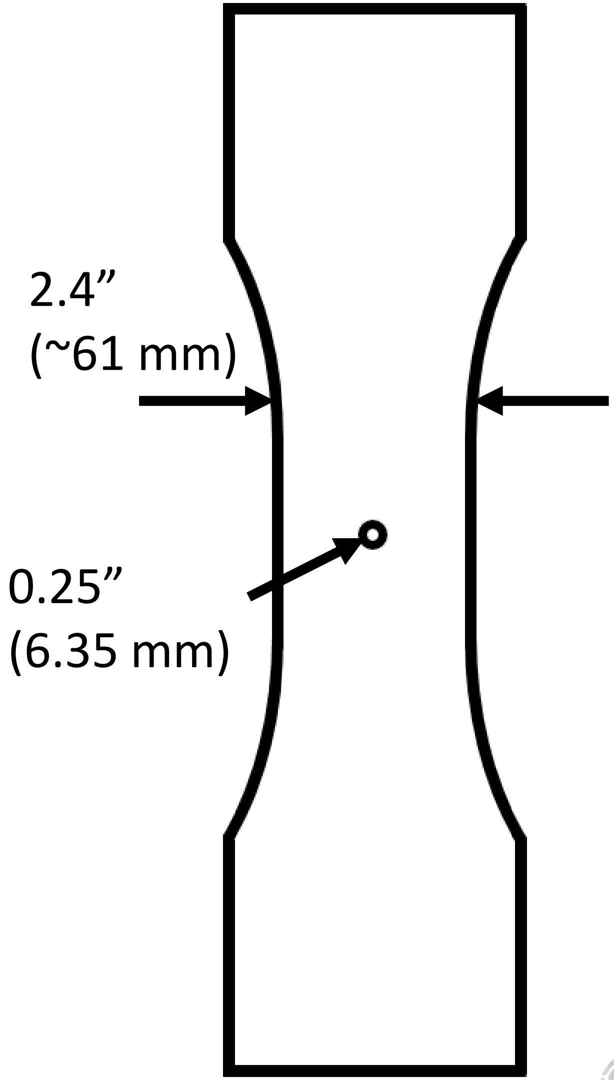
Jake Warner

LOADING AND GEOMETRY

- Constant amplitude, R = 0.1, 27.9 ksi (192.4 Mpa)
- 7075-T651, 0.25" (6.35 mm) thick
- 0.027" (~0.69 mm) precrack
- Hi-Lok (steel) fastener, target 0.4% interference

- Two (2) conditions tested
  - Open hole
  - 0.4% interference Hi-Lok (not torqued)

- Three (3) conditions predicted
  - Open hole
  - 0.4% interference
  - 0.6% interference



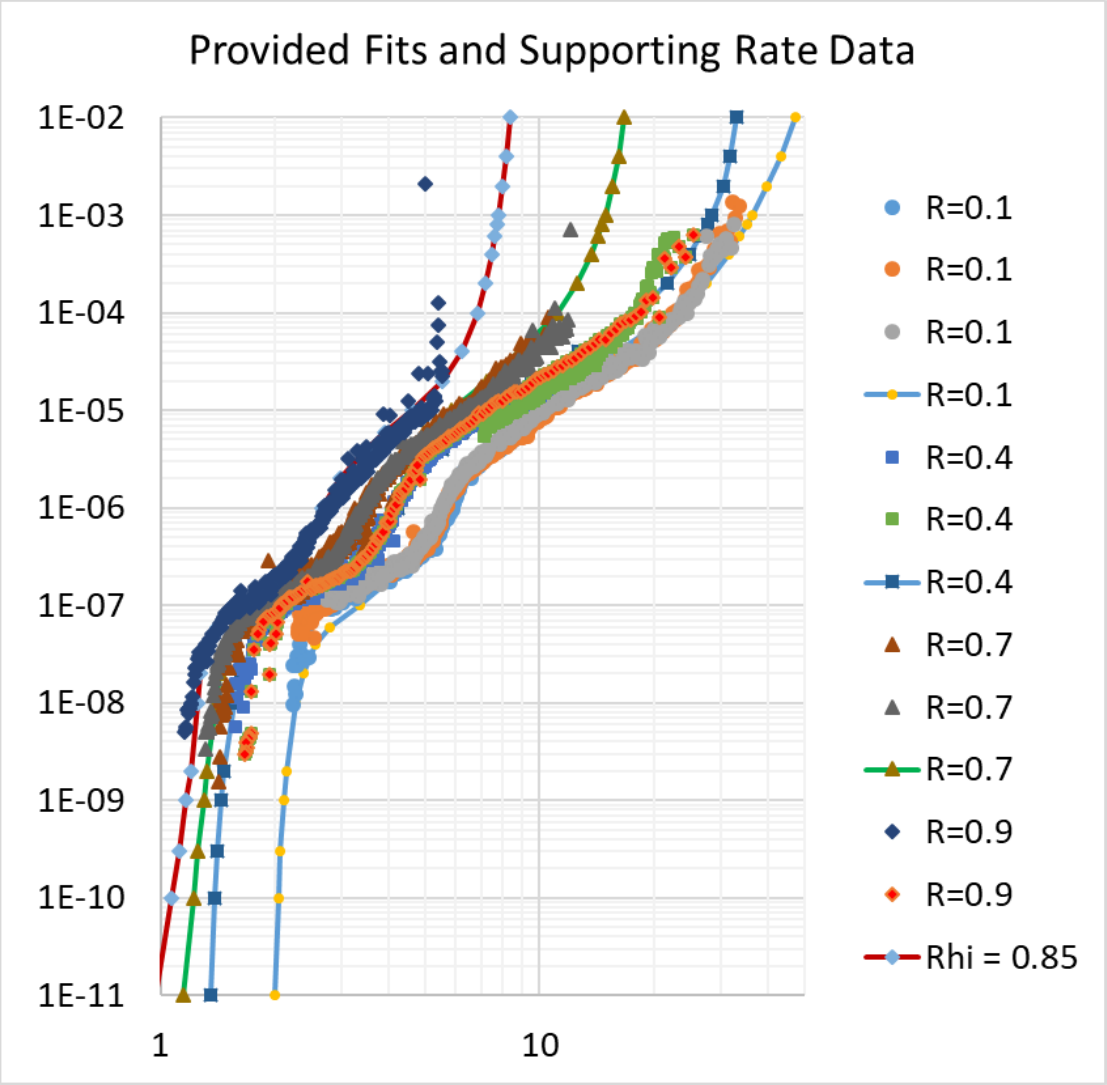
SUBMISSION DIVERSITY

- 12 Participants
- 13 Submissions
- Crack Growth Engine
  - 6 AFGROW
  - 3 FASTRAN
  - 4 Others
- Stress Intensity Solution
  - 7 StressCheck
  - 3 FASTRAN
  - 3 Others

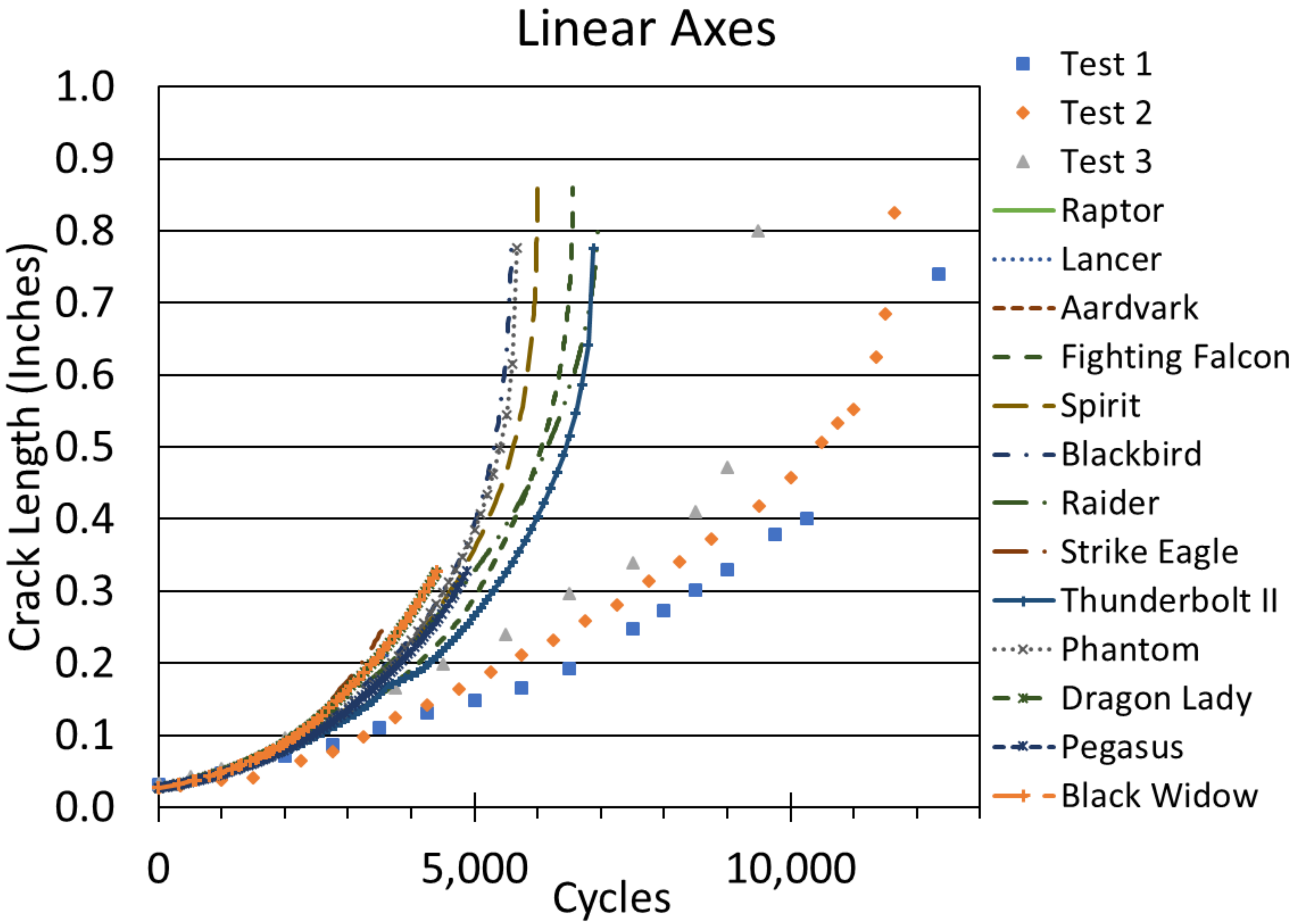
	Crack Growth Engine	FEA Tool
P-61 Black Widow	AFGROW	MSC Marc 2019
U-2 Dragon Lady	AFGROW	StressCheck
KC-46 Pegasus	AFGROW	StressCheck
B-1 Lancer	AFGROW/ MS Excel	StressCheck
F-111 Aardvark	AFGROW	StressCheck
F-22 Raptor	AFGROW	StressCheck
SR-71 Blackbird	CPAT	StressCheck
F-16 Fighting Falcon	LifeWorks	StressCheck
A-10 Thunderbolt II	FASTRAN v 5.70	N/A
F-4 Phantom	FASTRAN v 5.70	N/A
B-21 Raider	FASTRAN v 5.42	N/A
B-2 Spirit	NASGRO	NASTRAN
F-15 Strike Eagle	SimModeler Crack	ANSYS

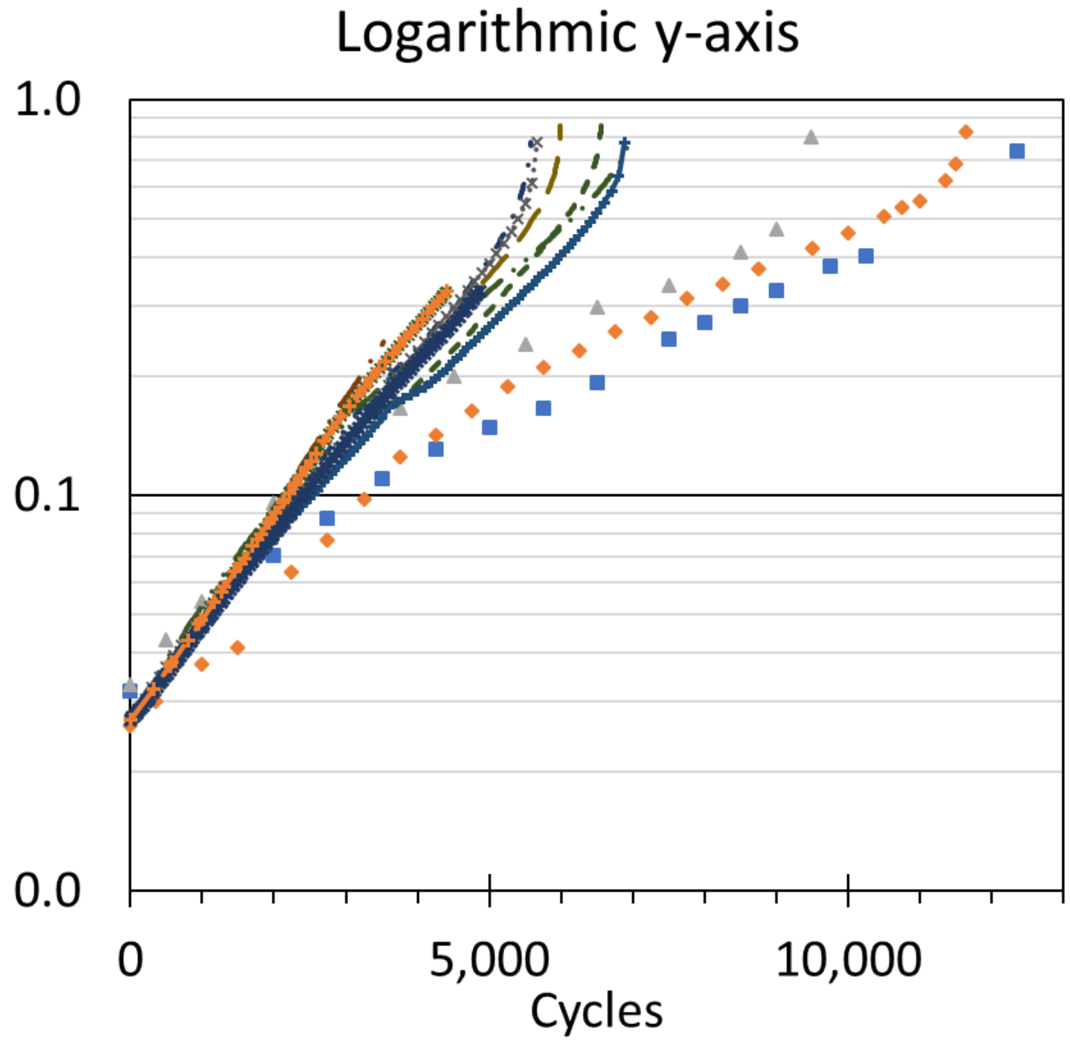
PROVIDED RATE DATA

- Material lookup file provided
  - Based on tests from multiple (4+) entities, material lots and timeframes
  - Good agreement across test data
  - Rate data *not* generated from same lot as test specimens
  - Rate data provided for 6 stress ratios
  - R = -0.15, 0.02, 0.1, 0.4, 0.7, 0.85



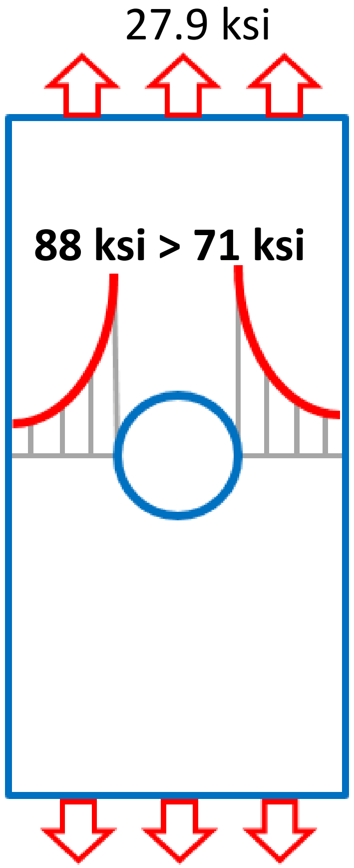
OPEN HOLE RESULTS SURFACE CRACK


Linear Axes

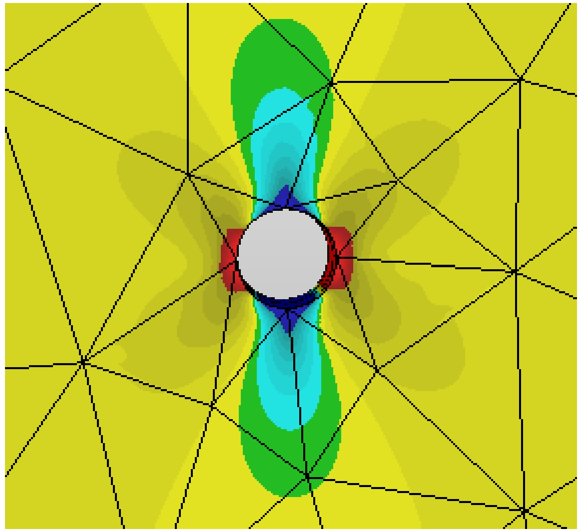

Logarithmic y-axis

SPECIMEN YIELDING

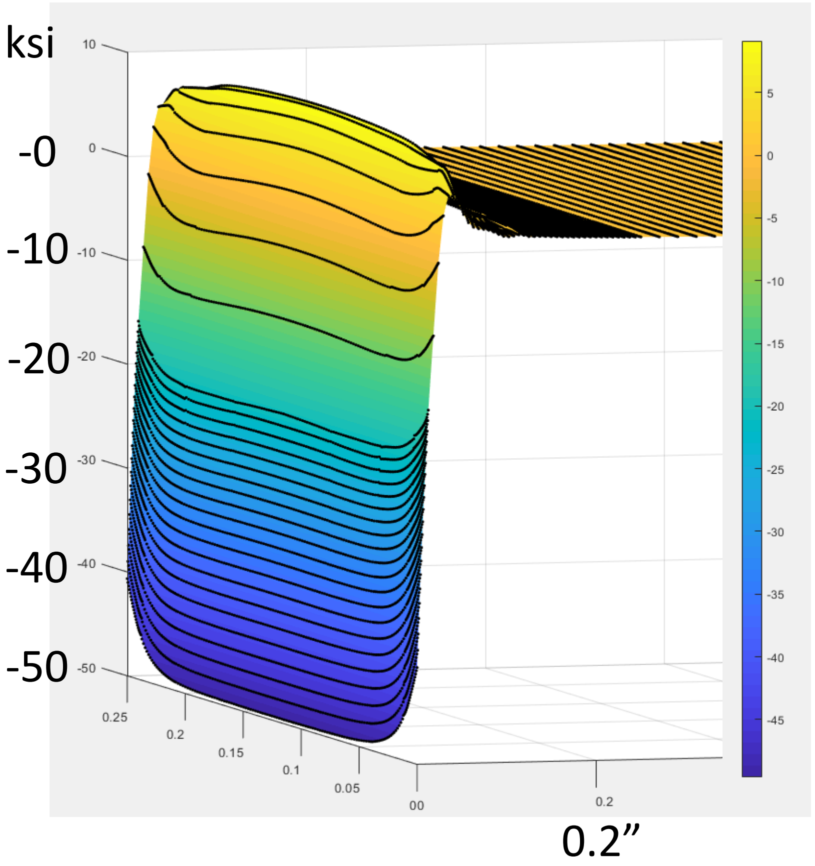
- Yield strength = 71 ksi (Reference MMPDS-15)



Yielding at hole edge

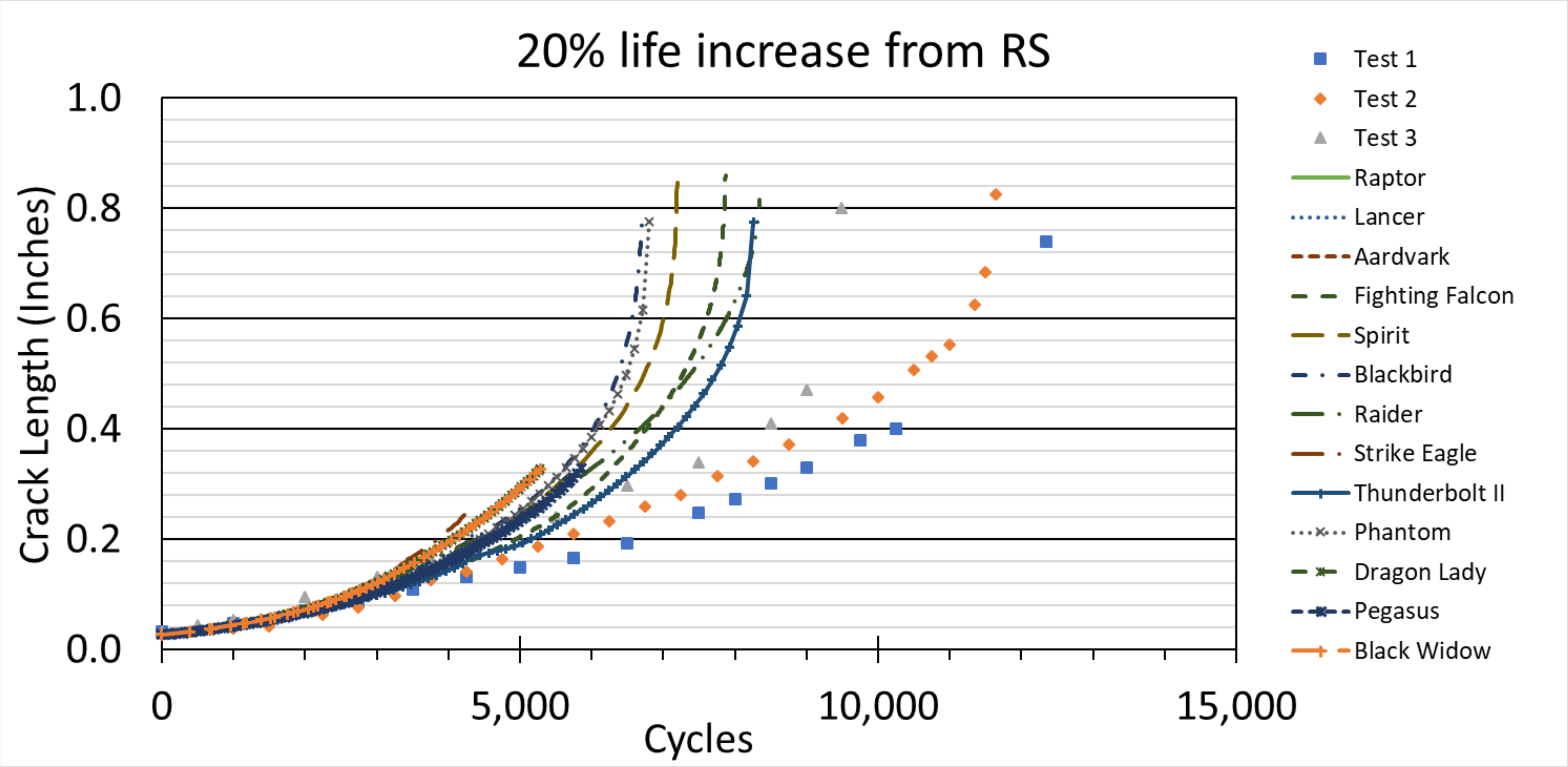


Residual stress from yielding



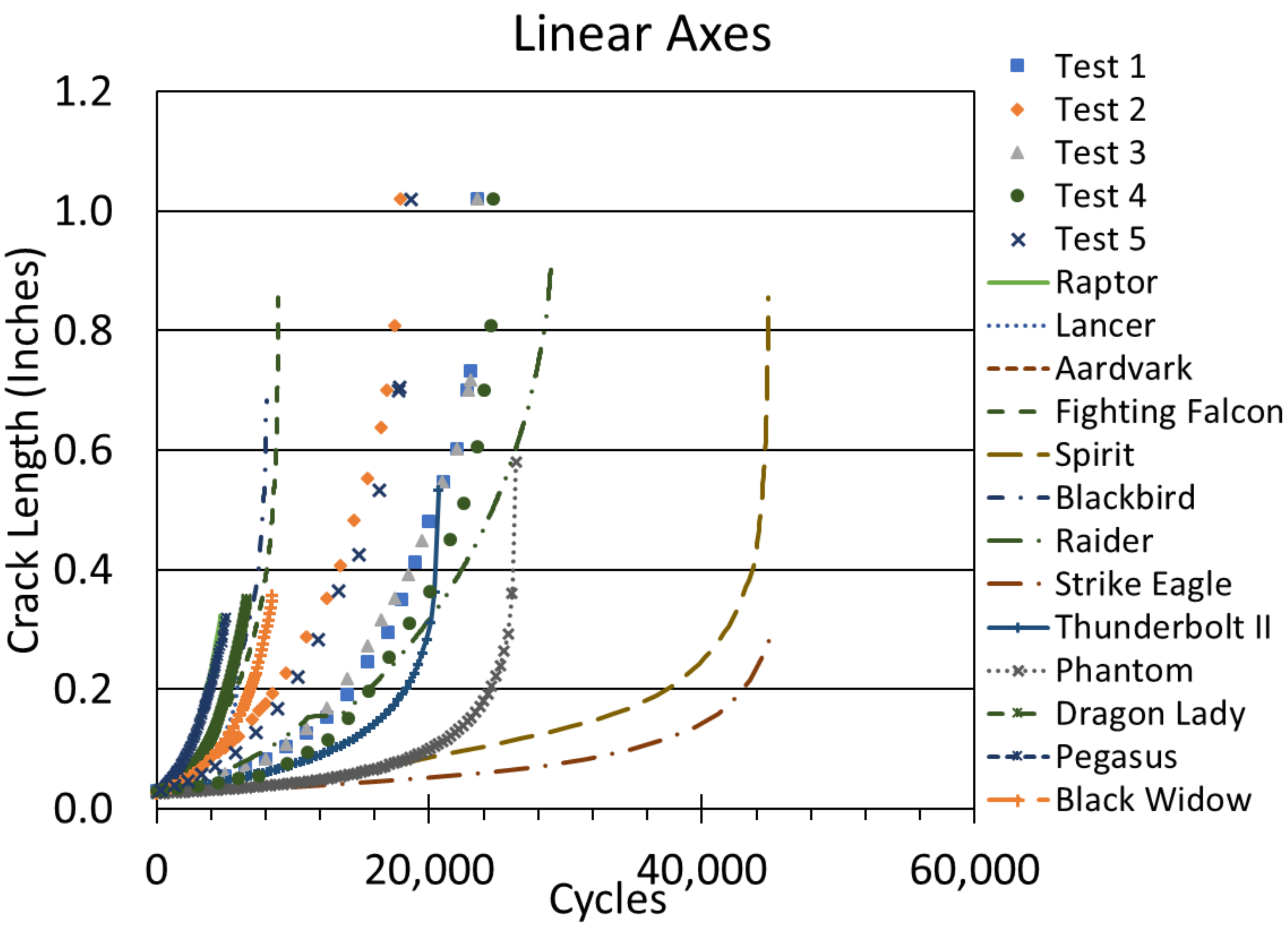
SPECIMEN YIELD RS INFLUENCE

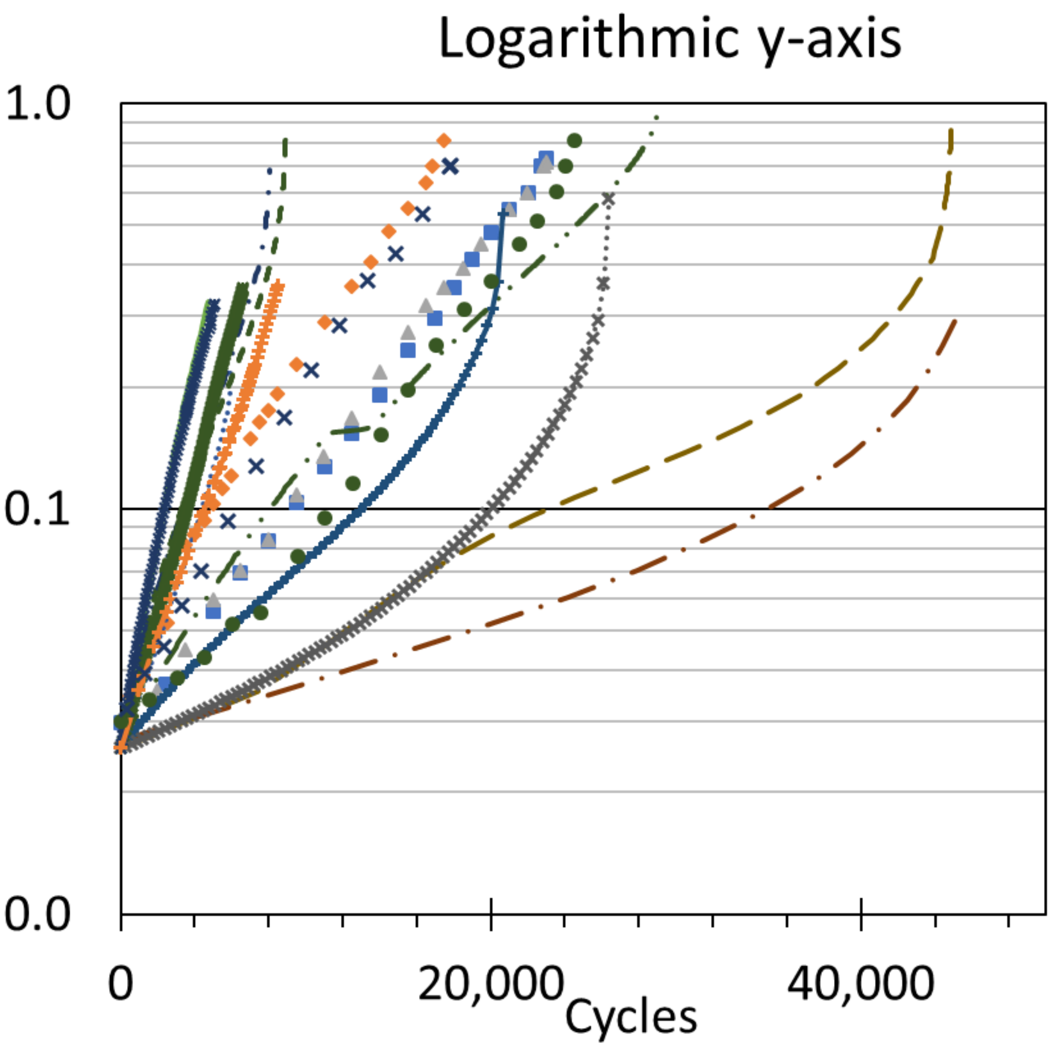
- Residual Stress from yield provided ~20% life increase
- Applying a 20% life increase to all predictions appears encouraging



ENGINEERED RESIDUAL
STRESS IMPLEMENTATION

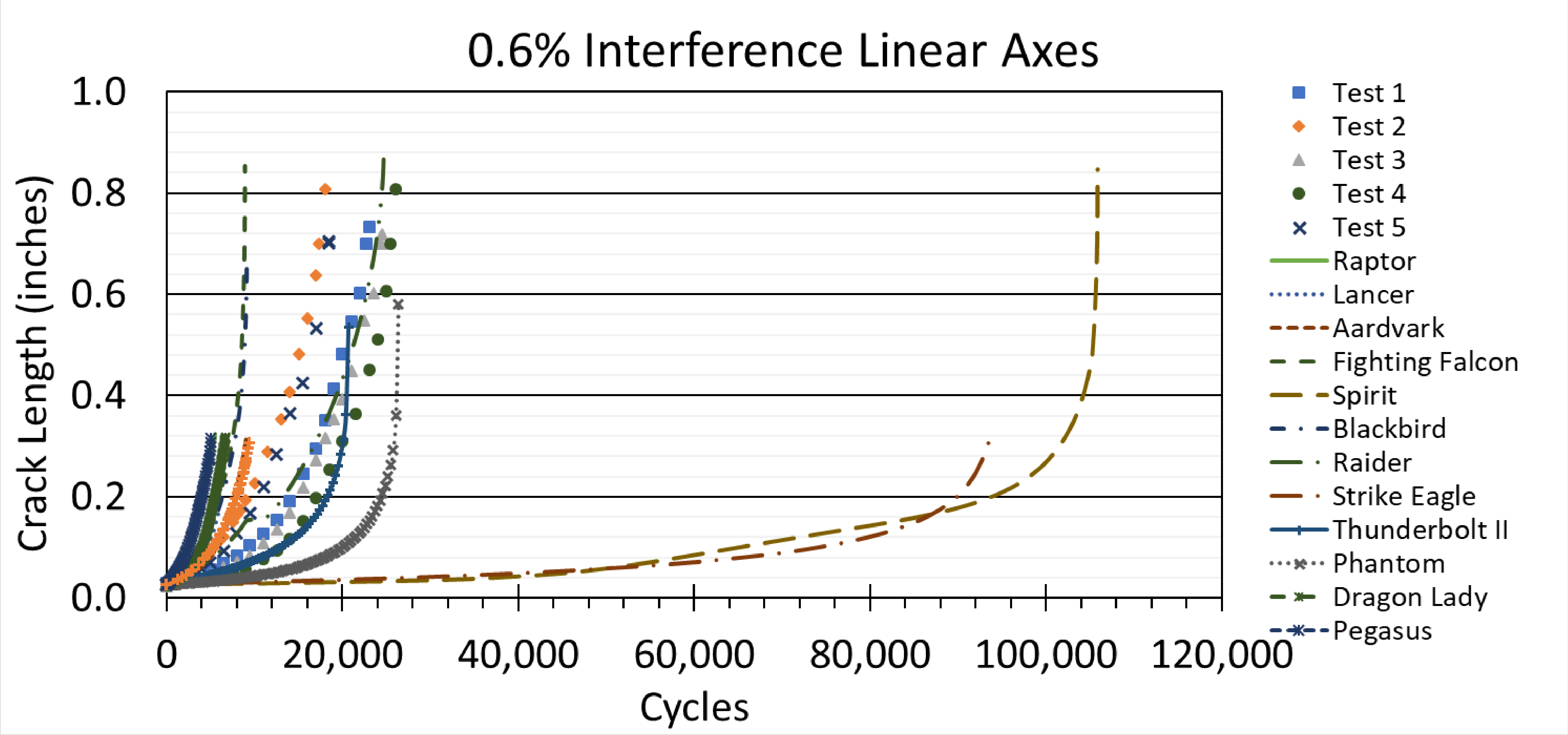
0.4% INTERFERENCE SURFACE CRACK GROWTH


Linear Axes


Logarithmic y-axis

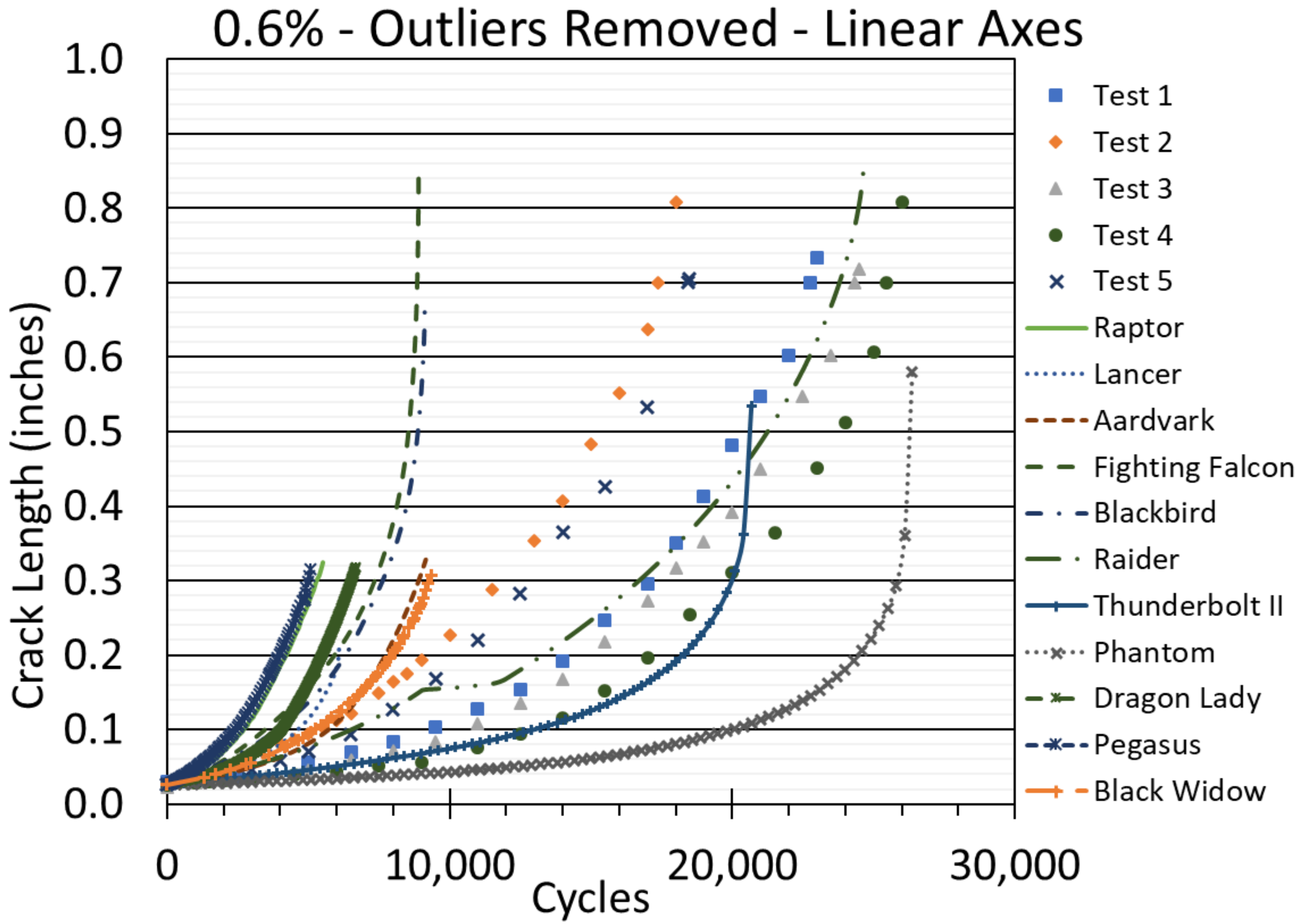
ERSI
ENGINEERED RESIDUAL
STRESS IMPLEMENTATION

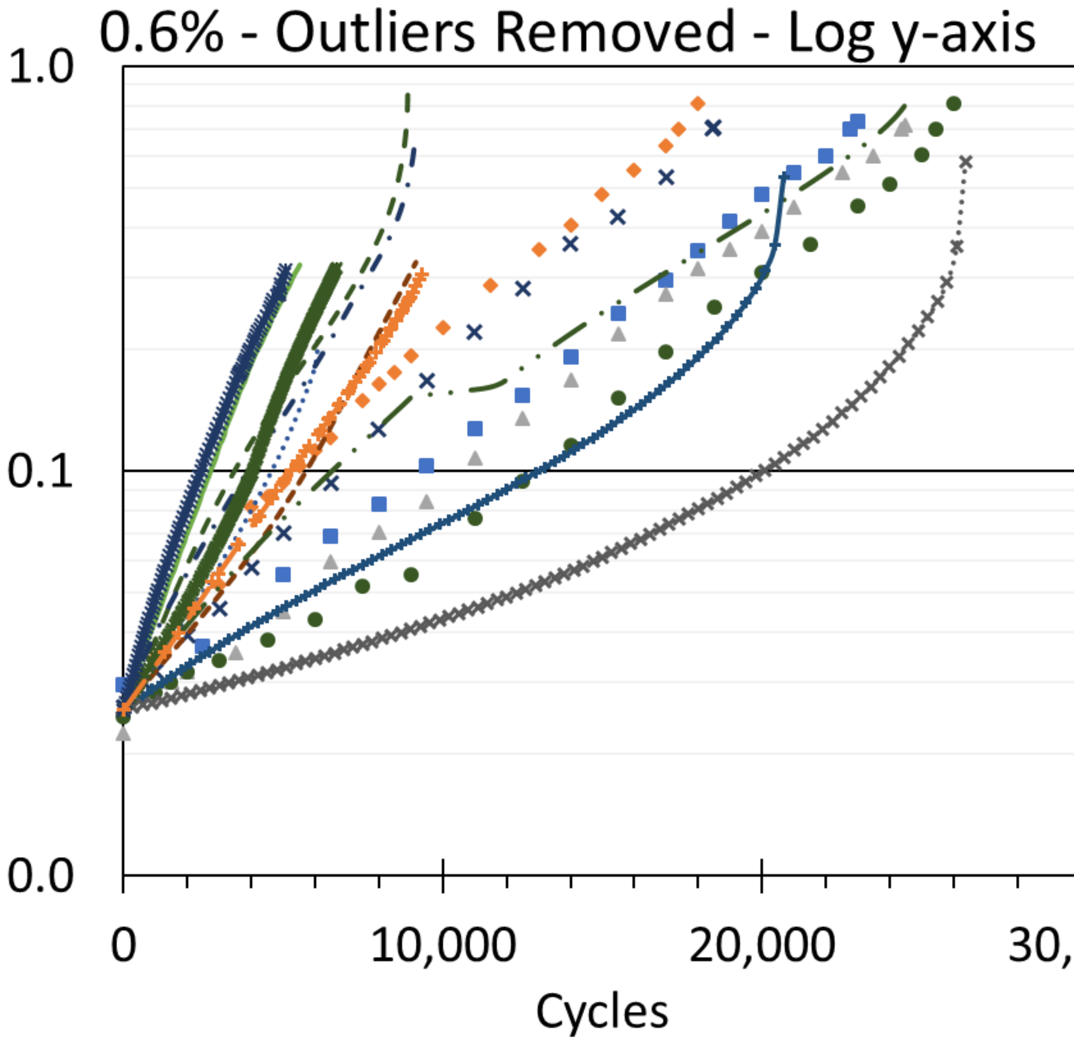
0.6% INTERFERENCE SURFACE CRACK GROWTH



ERSI
ENGINEERED RESIDUAL
STRESS IMPLEMENTATION

0.6% INTERFERENCE SURFACE CRACK GROWTH

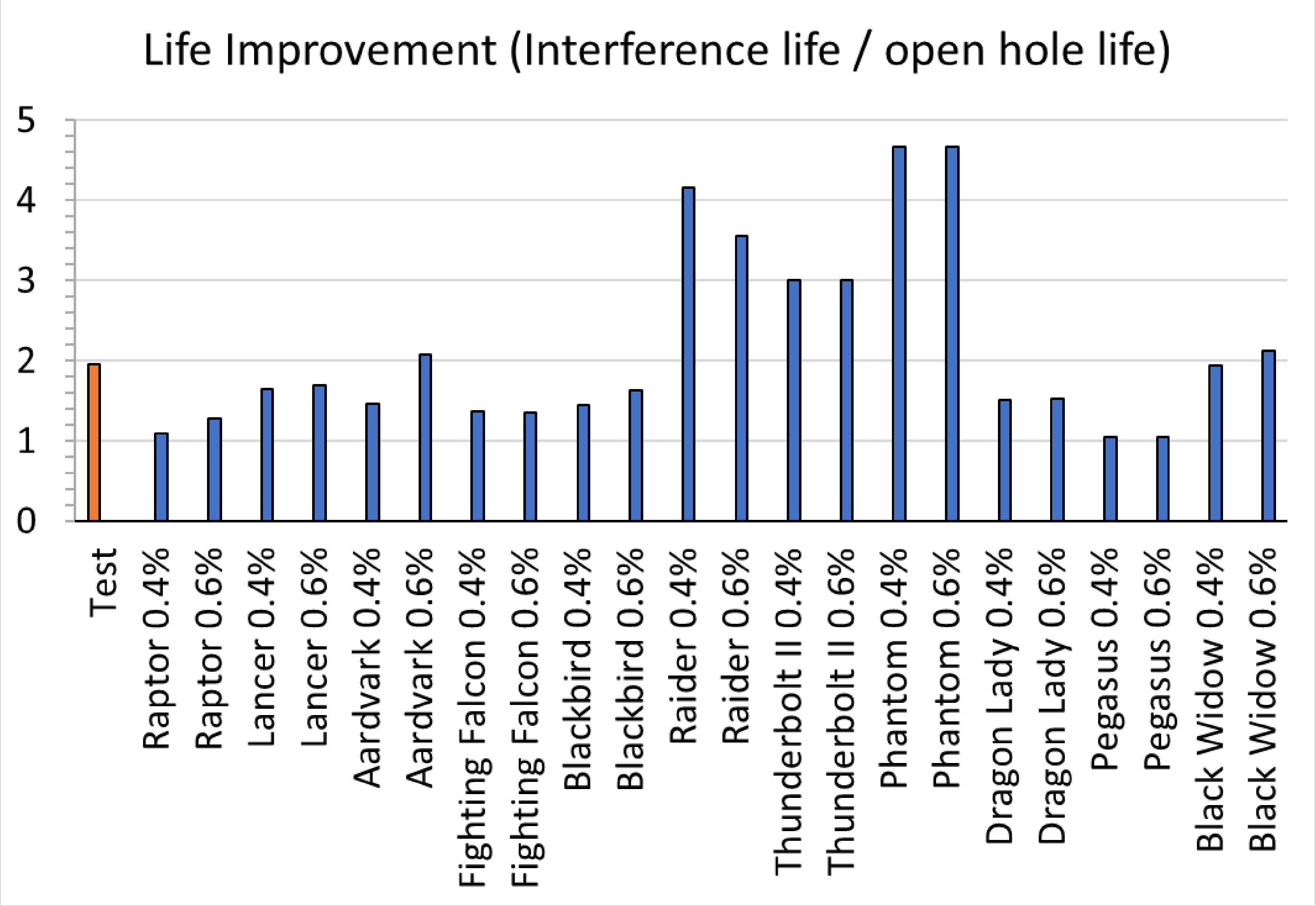




ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

INTERFERENCE FIT LIFE IMPROVEMENT

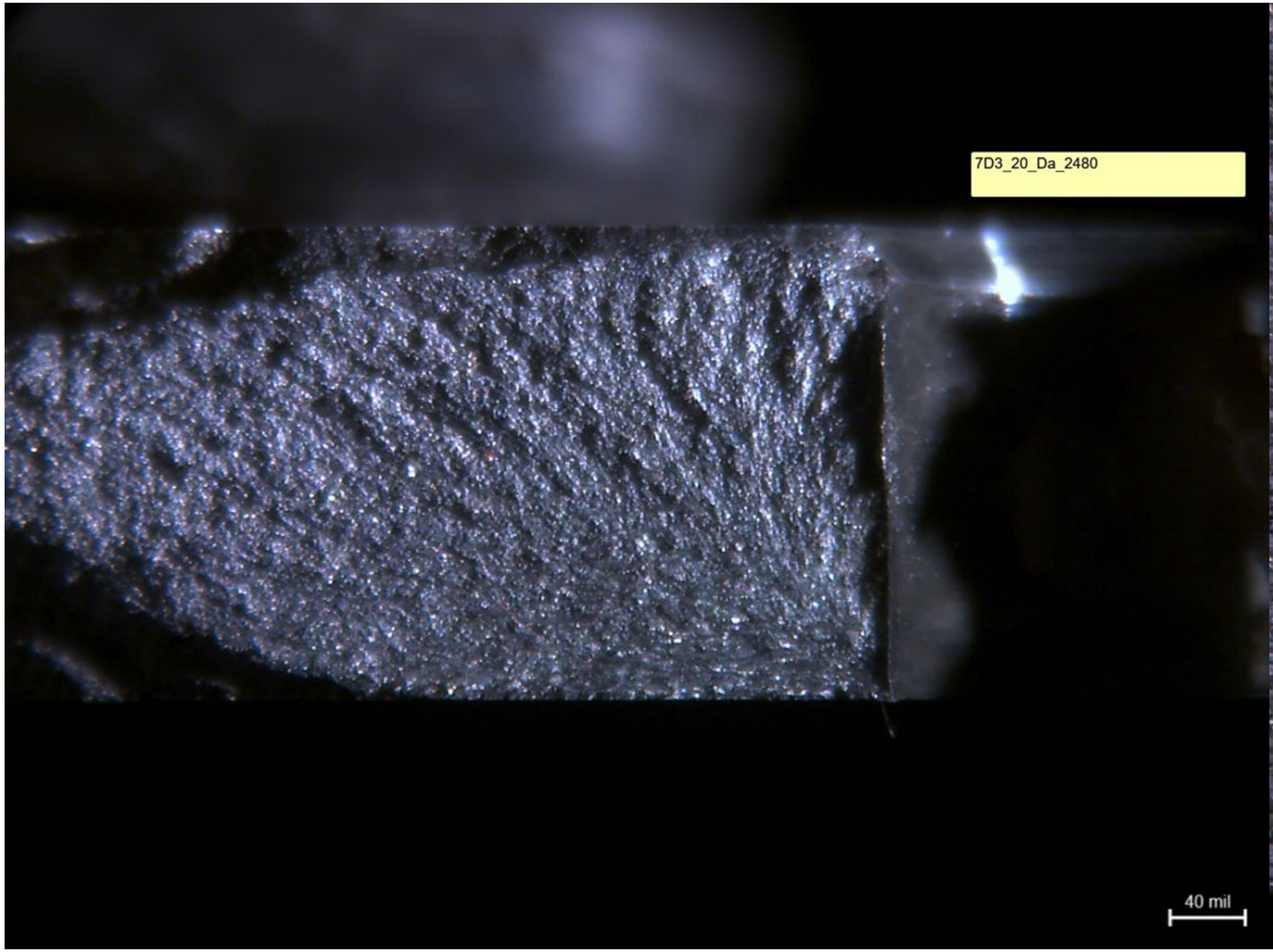
- Test life improvement = 1.96
- Average predicted life improvement = 2.15 (Outliers removed)
- 3 submissions over predict life improvement (5 with outliers)
- 8 submissions under predict life improvement
- Black Widow submission has life improvement nearest to test data

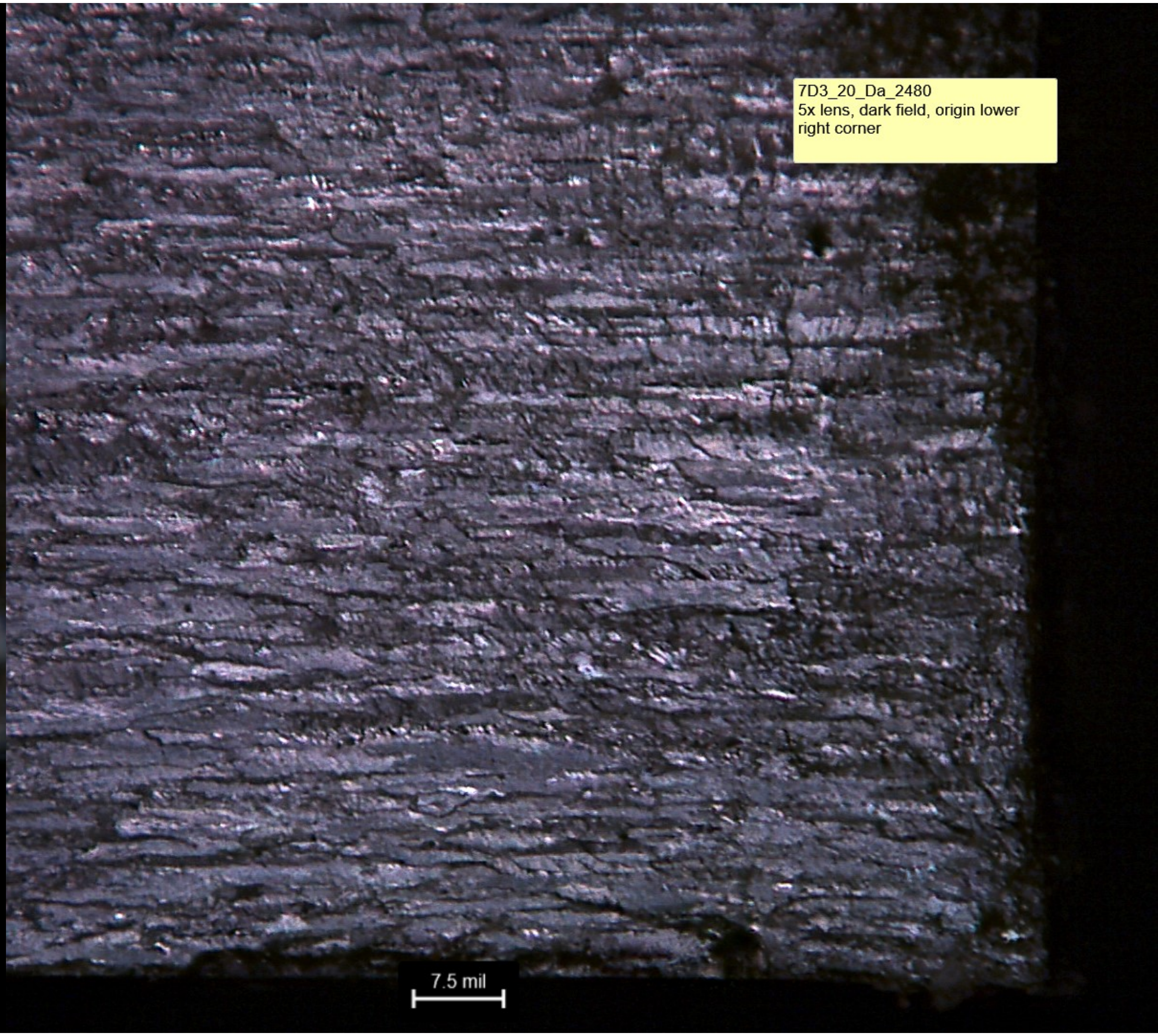


CONCLUSIONS

- Need to understand disparity between open hole predictions and test results
  - Residual stress from overload appears promising
  - Are other plasticity effects compounding issue?
- Factor of two (2) life improvement despite high stress scenario
- Most submissions under predicted life improvement
- Loading scenarios that avoid yielding should be evaluated
- Generally small difference between 0.4% and 0.6% predictions

QUESTIONS?


7D3_20_Da_2480

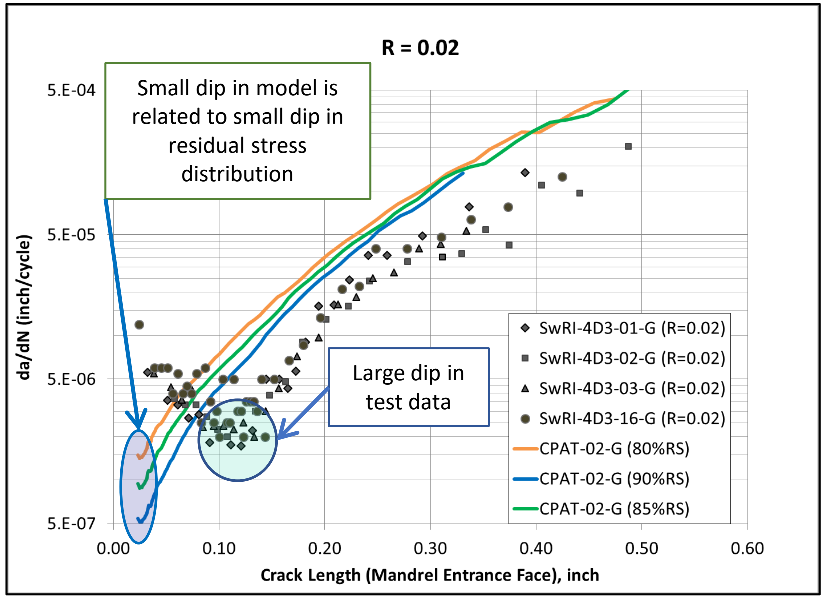

7D3_20_Da_2480
5x lens, dark field, origin lower
right corner

MODELING EFFORTS

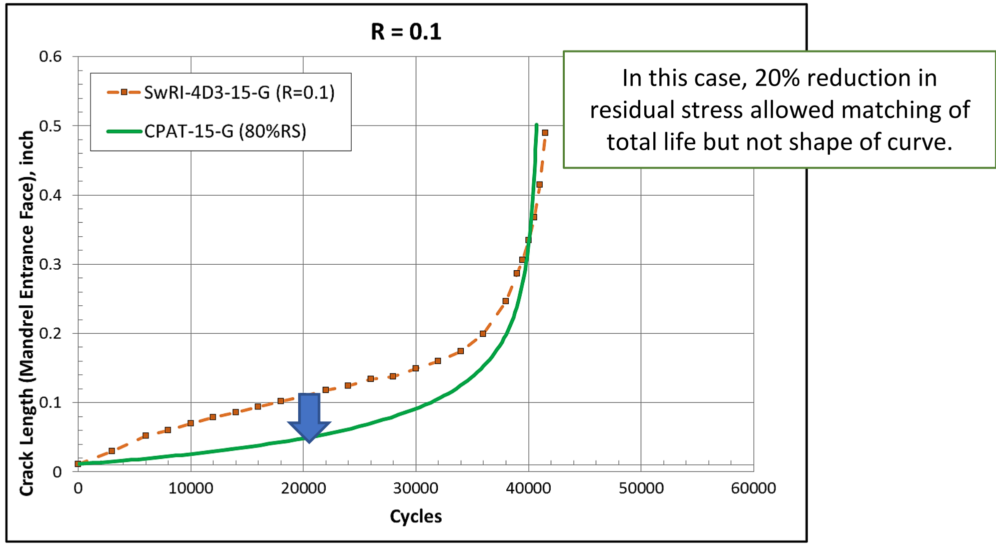
Cyclic Redistribution

Refresher from 2018: Key Observations

- Most fatigue crack growth testing at CX holes has traditionally focused on lower stress ratios (e.g. applied R = 0.1)
- These data sets show a **characteristic dip** in crack growth rates
    - Crack propagation modeling efforts of the last several years do not capture this behavior
- Dip only occurs when $R_{tot} < 0$
    - Hypothesis of crack closure
- Dip leads to inaccuracy in modeling solutions


Small dip in model is related to small dip in residual stress distribution

Large dip in test data


In this case, 20% reduction in residual stress allowed matching of total life but not shape of curve.

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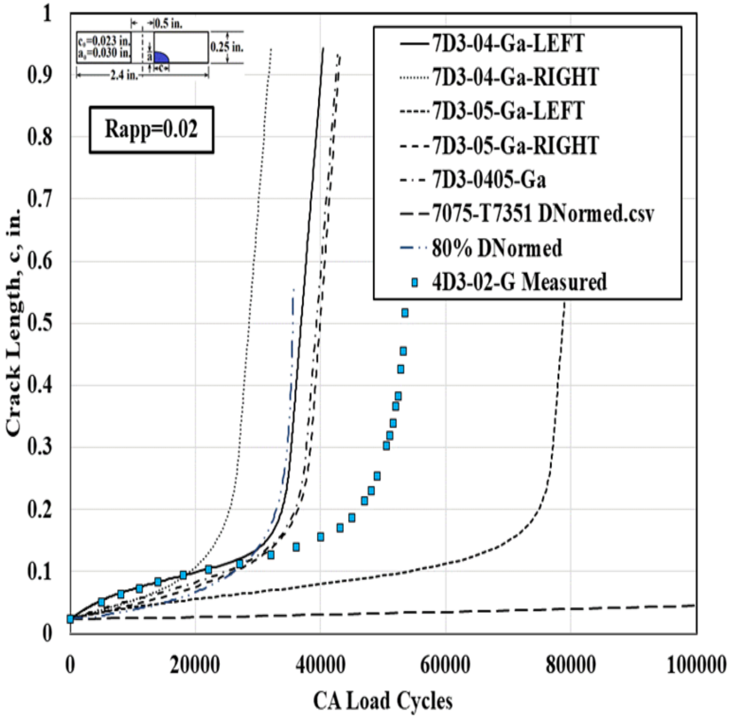
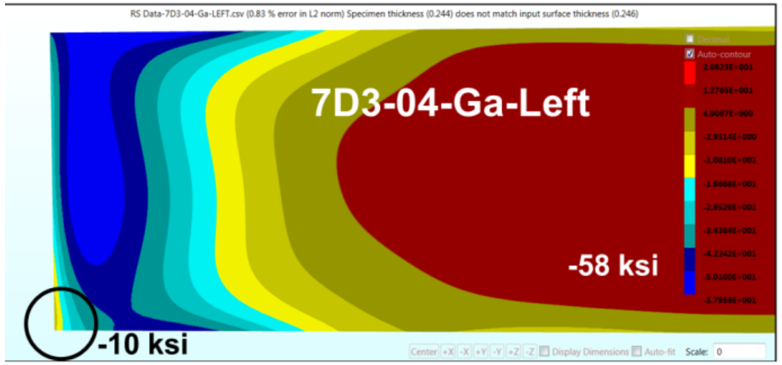
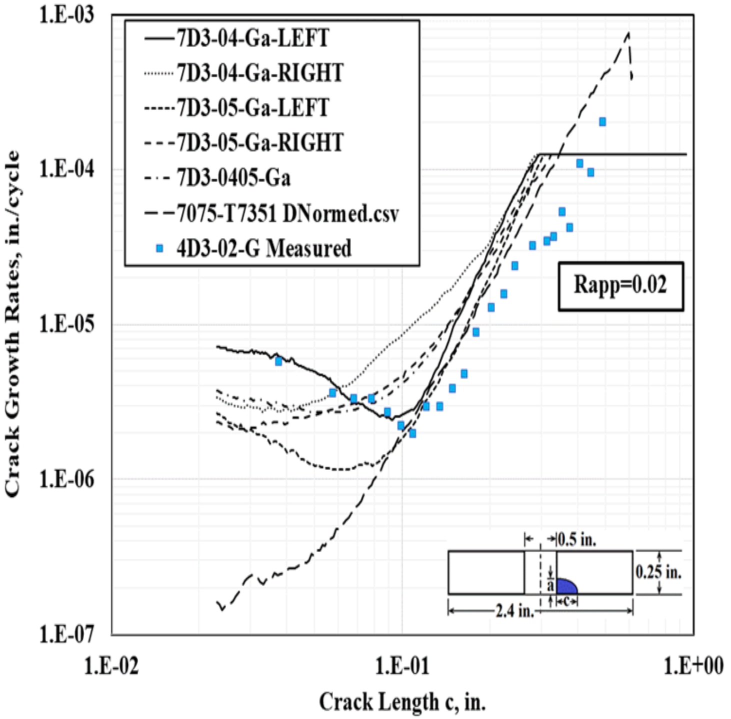
Redistributed Residual Stress Leads to Improved Modeling

- Open hole CX specimens pre-cycled 2000 cycles at test stress
  - “shakedown” of RS
- Results in much less compression at the bore surface than in past data that was not pre-cycled





RS Data-7D3-04-Ga-LEFT.csv (0.83 % error in L2 norm) Specimen thickness (0.244) does not match input surface thickness (0.246)



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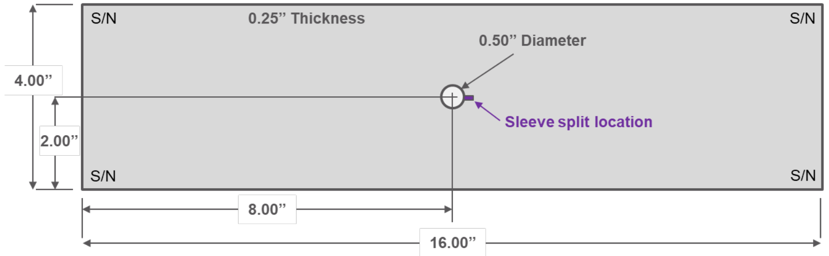
Cyclic Redistribution

- New Program to Investigate Behavior
- Approach
  - Investigate differences between:
    - non-cycled coupons
    - open hole cycled coupons
    - filled hole cycled coupons
- Scope
  - Coupon configurations (18 total)
  - Material: 2024-T351 and 7075-T651
  - Diameter: 0.50-inch
  - Hole Offset: centered
  - Thickness: 0.25-inch
  - Applied expansion: mean

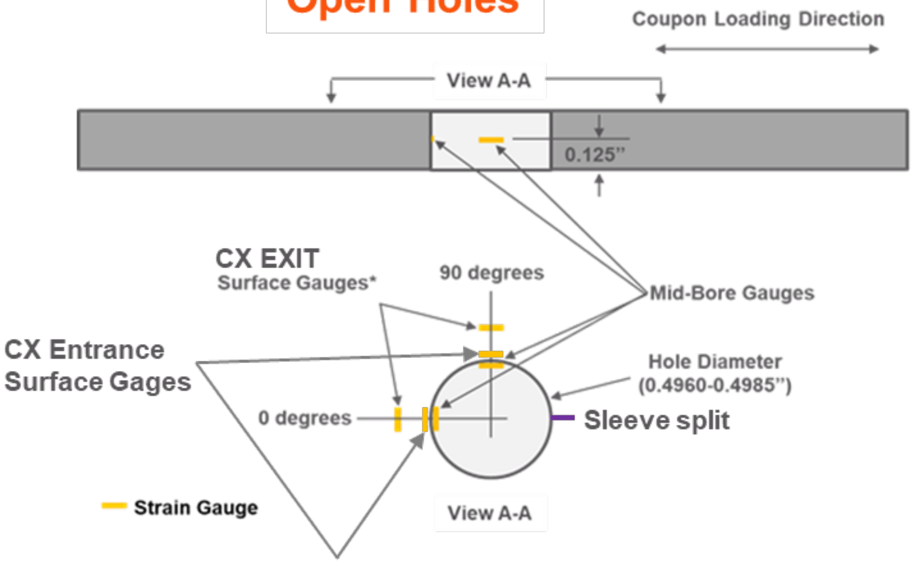


Condition	Material	Thickness (in)	Width (in)	Hole Edge Margin	Pre-Cx Ream Diameter (in)	Applied Expansion	Post-Cx Ream Diameter (in)	Replicates
Non-Cycled	2024-T351	0.25	4.00	Centered	0.4755+/-0.0005	Mid	0.4960-0.4985	3
Open Hole Cycled								3
Filled Hole Cycled								3
Non-Cycled	7075-T651							3
Open Hole Cycled								3
Filled Hole Cycled								3

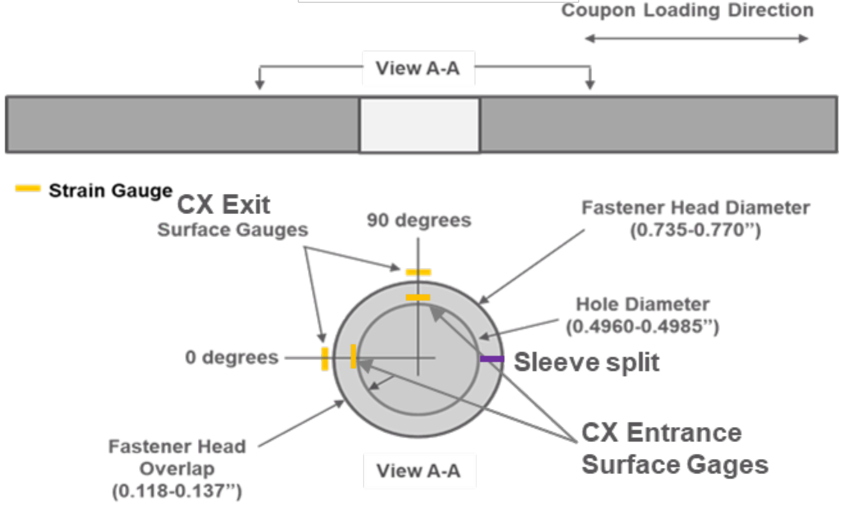
Cyclic Redistribution

- Pre-cycling
  - Strain gauging of (1) coupon per condition

Open Holes



Filled Holes

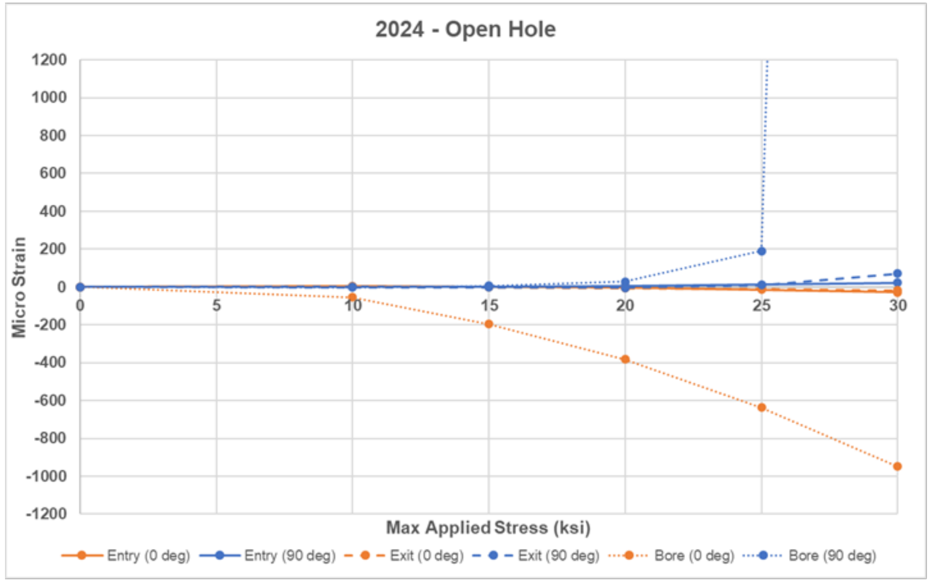


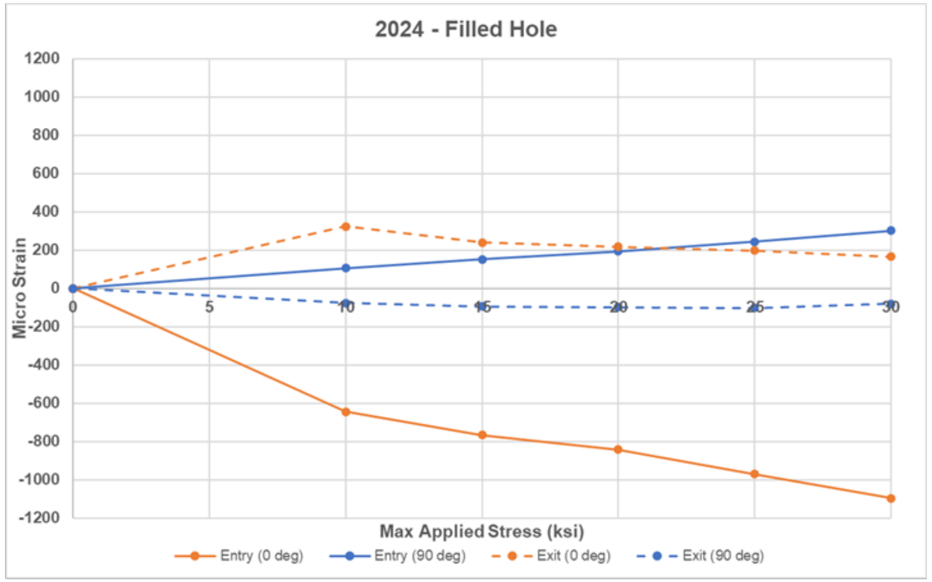
Condition	Loading	Strain Monitoring	Gauge Location	Max Stress (ksi)	Cycles	Replicates (each material)
Open Hole Cycled	CA R=0.1	Yes	Bore & Surface	10, 15, 20, 25, 30	2000/each	1
		No	N/A	30	2000	2
Filled Hole Cycled		Yes	Surface	10, 15, 20, 25, 30	2000/each	1
		No	N/A	30	2000	2

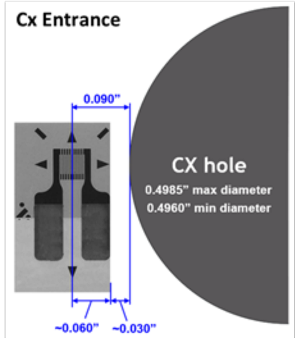
Cyclic Redistribution

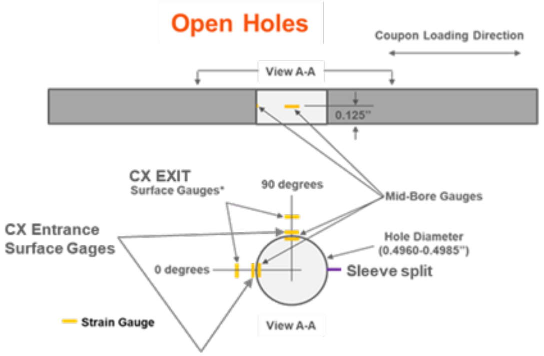
- 2024 strain gauge results
  - 100 microstrain ~ 1ksi

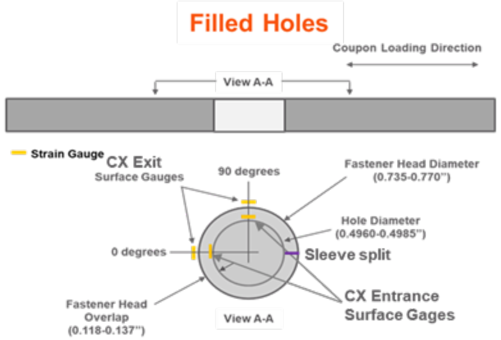
HILL ENGINEERING
Predict. Test. Perform.

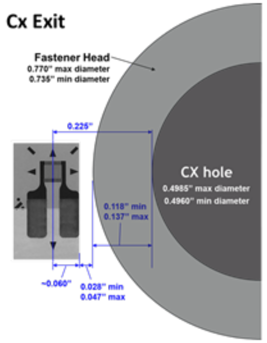






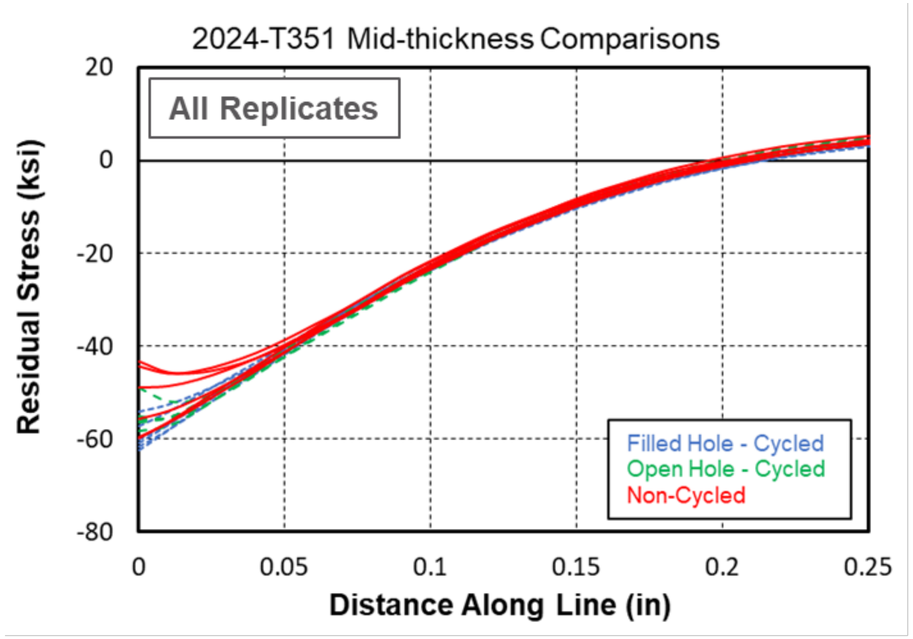


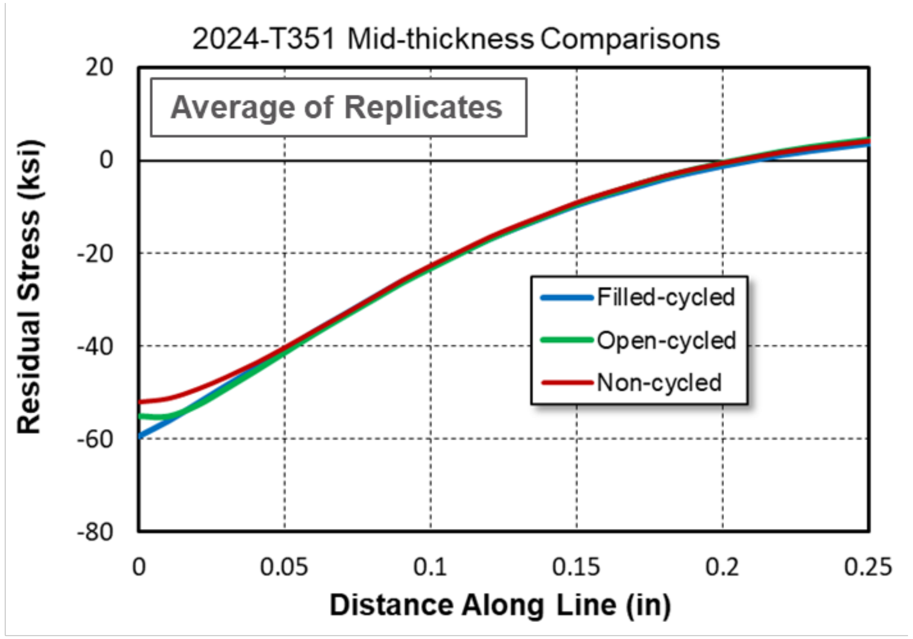




Cyclic Redistribution

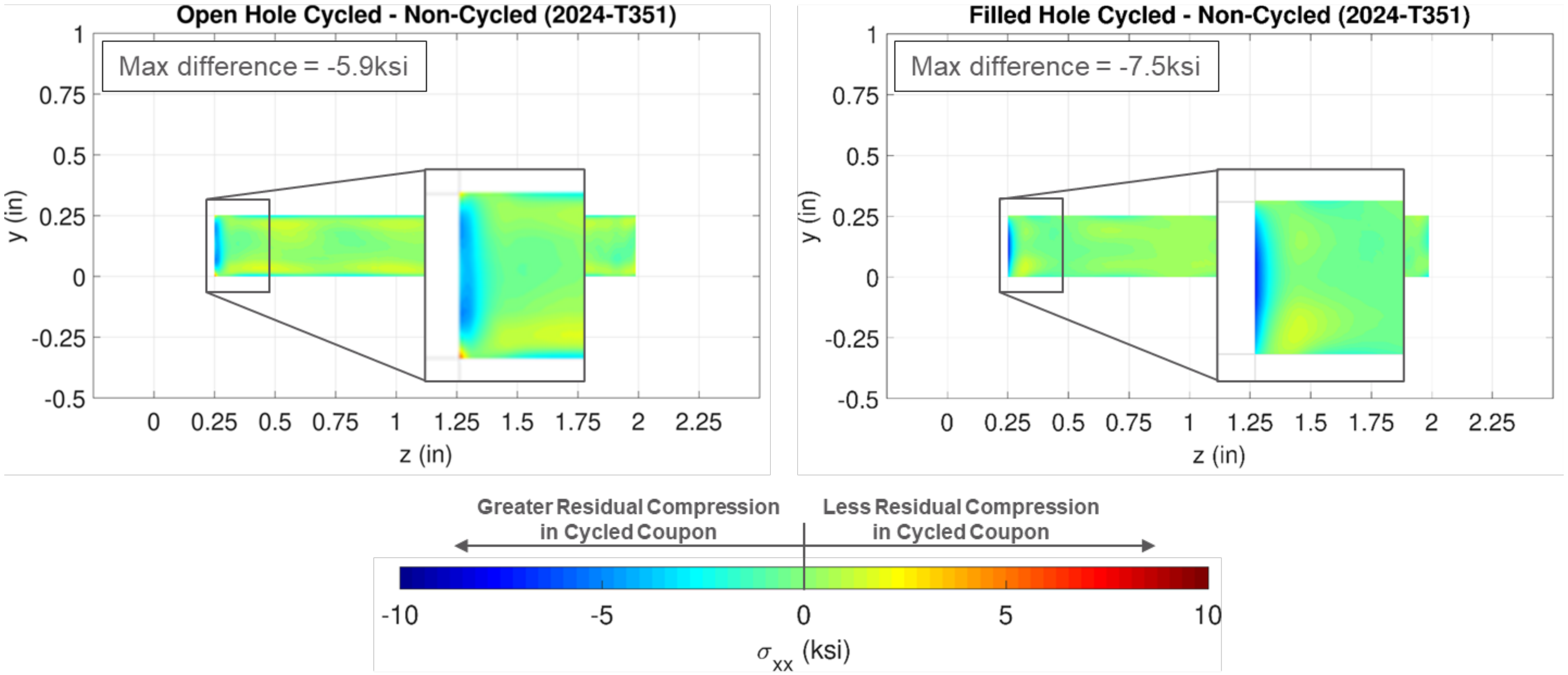
- Residual stress measurements – 2024 comparisons





Cyclic Redistribution

- Residual stress measurements – 2024 comparisons



Cyclic Redistribution

- Summary & conclusions
  - Pre-cycled open and filled hole coupons did not result in appreciable changes in surface strains or residual stress relative to non-cycled coupons
  - Surface and bore strain gauges were generally within 400 microstrain
  - Residual stress changes were within 8ksi
    - Typically higher for cycles coupons near the bore
  - Redistribution of stress, as observed by APES in 7D3-04-Ga coupons, was not evident in measurement results
  - Still reviewing data, however, additional investigation is necessary to understand details for 7D3-04-Ga coupons and any underlying keys to resulting residual stresses

Multi-Point MAI Program

MAI III
NG-11 Program Overview

Verification, Validation, and Demonstration of Multi-Point Fracture Modeling (MPFM) Codes

Adam Morgan
Senior Principal Engineer

8th December, 2020

Program Team

NG-11 is being performed as part of the Metals Affordability Initiative and is being performed cooperatively with a team of government and industry participants.

Air Force Research Laboratory

ATI
ADVANCED TECHNOLOGY INTERNATIONAL ®

NORTHROP GRUMMAN

HILL ENGINEERING

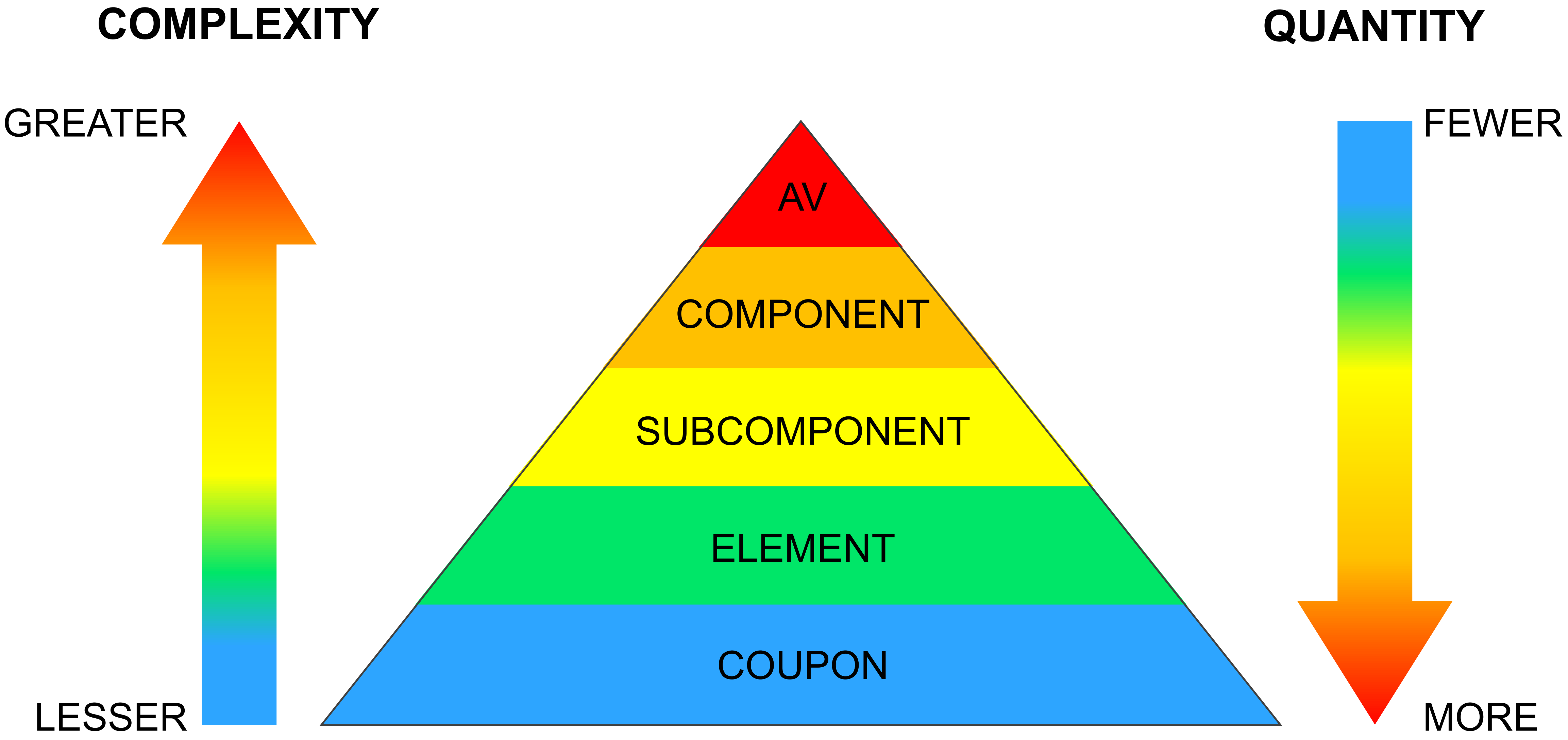
Fracture Analysis Consultants, Inc

Overall Program Objectives

"*Validate and assess capability of commercial off-the-shelf (COTS) and proprietary multi-point fracture mechanics (MPFM) codes as applied to the linear elastic fracture mechanics (LEFM) analysis of cold-expanded (Cx) holes.*"

- Task 3 – V&V of MPFM against analytical solutions and test data
  - Building Block Approach
  - '*Blind*' Predictions
- Task 4 – Demonstrate MPFM on Defense Aerospace Application
- Task 5 – Document and Out Brief

Building Block Approach



COMPLEXITY

QUANTITY

GREATER

LESSER

AV

COMPONENT

SUBCOMPONENT

ELEMENT

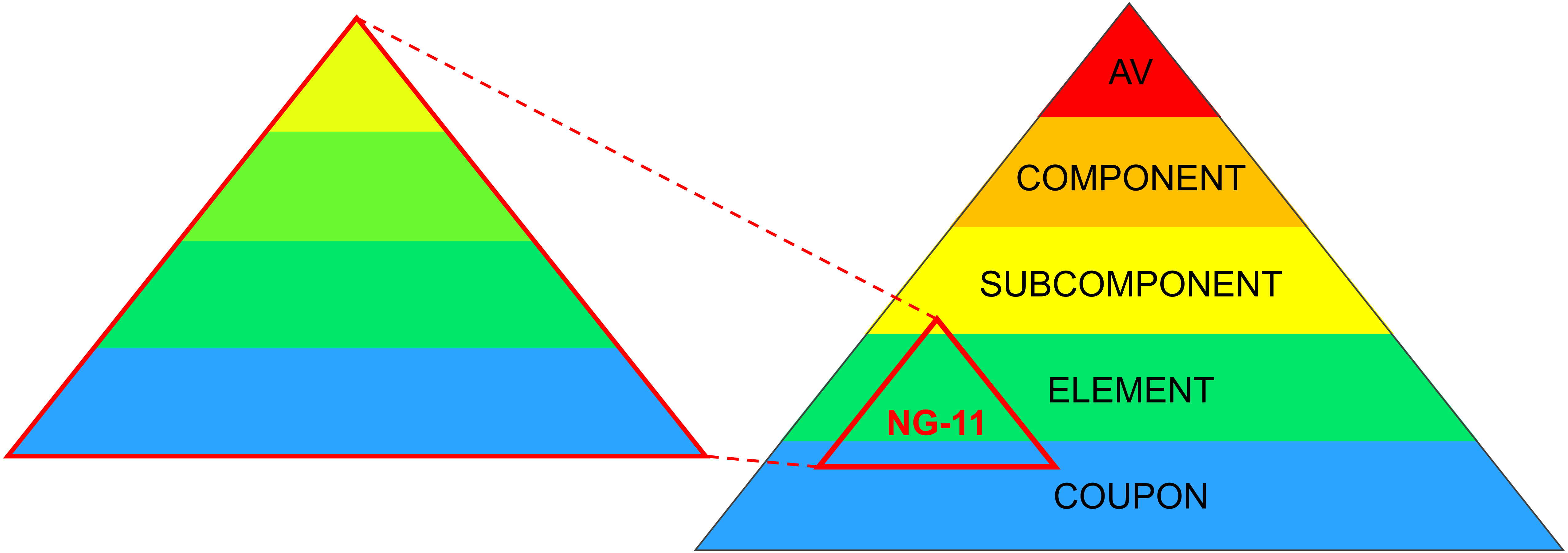
COUPON

FEWER

MORE

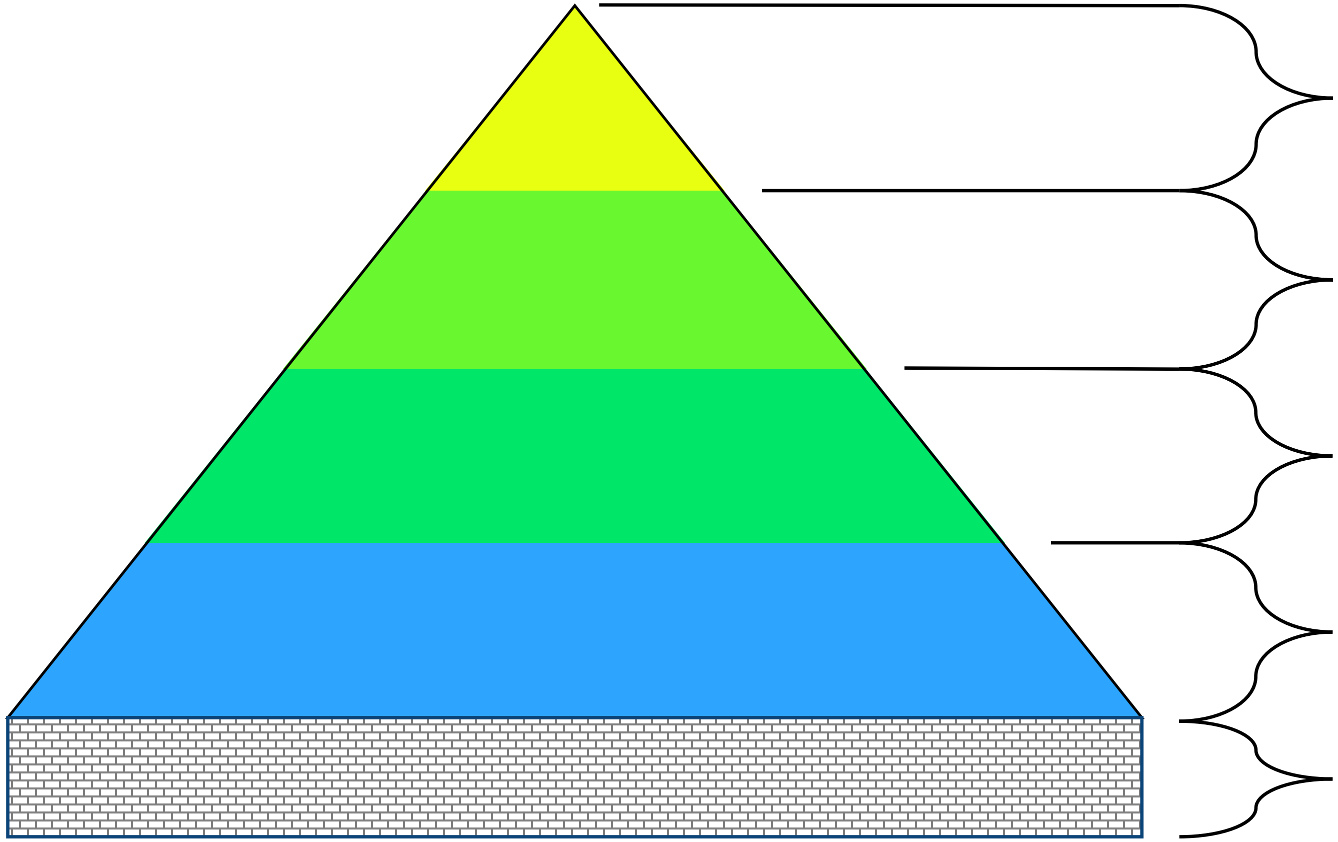
Building Block Approach

- NG-11 is primarily element-level tests (of increasing complexity) with limited coupon-level test.



Building Block Approach

- NG-11 is primarily element-level tests (of increasing complexity) with limited coupon-level test.



Element-to-Subcomponent Level – FCL *(Task 4)*
- AFRL Supplied
- Demonstrate on participating platform

Element Level *(Task 3.3)*
- AFRL Supplied – With residual stresses
- AFRL Supplied – With complex load
- Validate MPFM to level beyond traditional DTA methods

Element Level *(Task 3.2)*
- AFRL Supplied – No residual stresses
- Validate MPFM to level comparable to traditional DTA methods

Coupon Level *(Task 3.1 Continued)*
- *NG Legacy Data – Basis for material model*
- *Additional AFRL Data – Modify material models*
- Simulate to validate SIF + Analysis Code integration

Analytical Benchmark Case *(Task 3.1)*
- Verification of MPFM Solution
- Validation of modeling procedure/practices

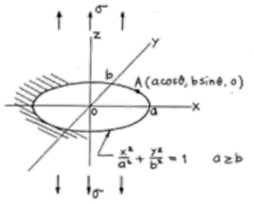
MPFM Codes

Three (3) Multi-Point Fracture Modeling Codes to be utilized:

1. Broad Application for Modeling Failure (BAMF)
   - COM interface to be developed by Hill Engineering LLC
     - Integrate with AFGROW through COM interface
     - Integrate with FASTRAN through scripting
2. Fracture Analysis Code 3D (FRANC3D)
   - Allows for development of Python based extensions
     - Integrate with AFGROW through COM interface
     - Integrate with FASTRAN through scripting
3. BEASY
   - BEM and MPFM capabilities already integrated

Benchmark-to-Sub-Component Analyses

Analytical
Benchmark



$$K_{I_A} = \frac{\sigma\sqrt{\pi b}}{E(k)}\left\{\sin^2\theta + \frac{b^2}{a^2}\cos^2\theta\right\}^{1/4} = \frac{\sigma\sqrt{\pi \ell}}{E(k)}$$

$$E(k) = \int_0^{\pi/2}\sqrt{1-k^2\sin^2\varphi}\,d\varphi$$

$$k^2 = 1 - b^2/a^2$$

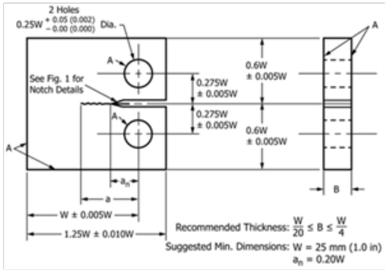
$$K_{I,max} = K_I(\theta = \pm\pi/2) = \frac{\sigma\sqrt{\pi b}}{E(k)}$$

$$K_I(a=b) = \frac{2\sigma}{\pi}\sqrt{\pi a}$$

$$K_I(a\to\infty) = \sigma\sqrt{\pi b}$$

Method: Integral Transform (3-D potential functions)
Accuracy: Exact
References: Sadowsky 1949, Green 1950, Irwin 1962b

Basic Coupon Level

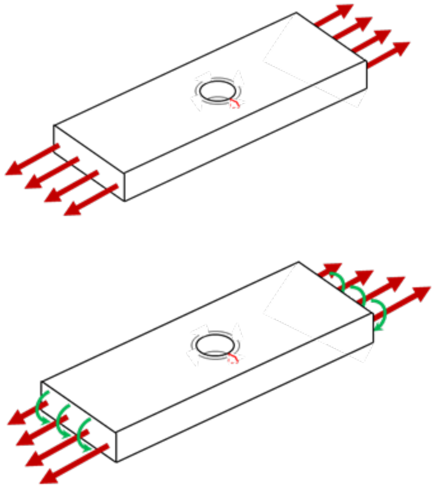


Recommended Thickness: $\frac{W}{20} \le B \le \frac{W}{4}$

Suggested Min. Dimensions: W = 25 mm (1.0 in)
$a_n = 0.20W$

$$K = \frac{P}{B\sqrt{W}}\frac{(2+{}^{a}/_{W})}{(1-{}^{a}/_{W})^{3/2}}\left(0.886+4.64({}^{a}/_{W})-13.32({}^{a}/_{W})^2+14.72({}^{a}/_{W})^3-5.6({}^{a}/_{W})^4\right)$$

Element Level



Sub-Component
Level

?

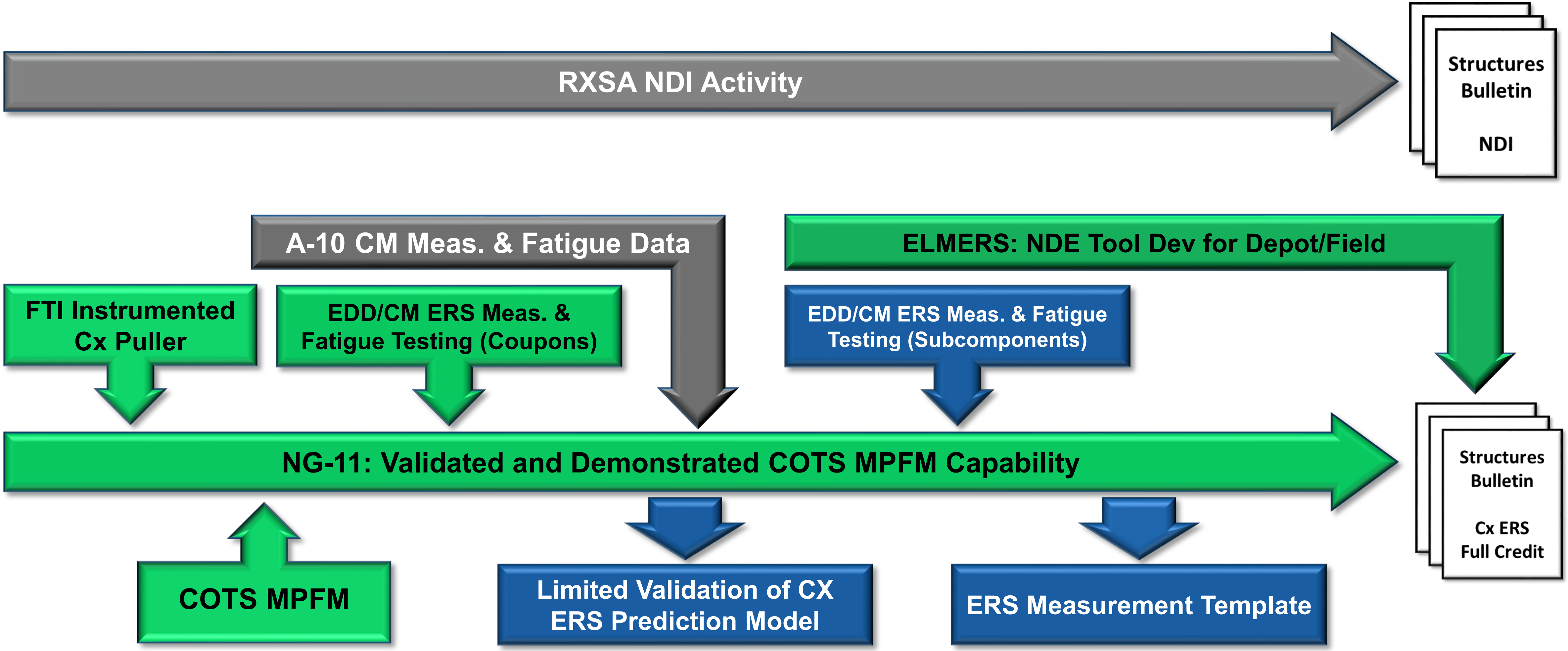
Fatigue Critical Location on Partner Weapons Platform *(AFRL to Define)*

Summary

Description	Analysis Configurations
Task 3.1 - Baseline Verification Specimens	
Analytical – Embedded Ellipse	2
Empirical – Compact Tension C(t)	1
Task 3.2 - Validation to level commensurate with traditional DTA methods	
Corner Crack at an Open Hole - Axial	4
Task 3.3 - Validation to level beyond traditional DTA methods	
Corner Crack at a Cold Worked Open Hole – Axial Load	8
Corner Crack at an Open Hole – Complex Load	2
Corner Crack at a Cold Worked Open Hole – Complex Load	2
Task 4 - Demonstration	
Fatigue Critical Location	1

MAI NG-11: Interrelated Activities

🟦 Planned 🟩 On Going ▨ Completed



RXSA NDI Activity

Structures Bulletin

NDI

A-10 CM Meas. & Fatigue Data

ELMERS: NDE Tool Dev for Depot/Field

FTI Instrumented Cx Puller

EDD/CM ERS Meas. & Fatigue Testing (Coupons)

EDD/CM ERS Meas. & Fatigue Testing (Subcomponents)

NG-11: Validated and Demonstrated COTS MPFM Capability

Structures Bulletin

Cx ERS Full Credit

COTS MPFM

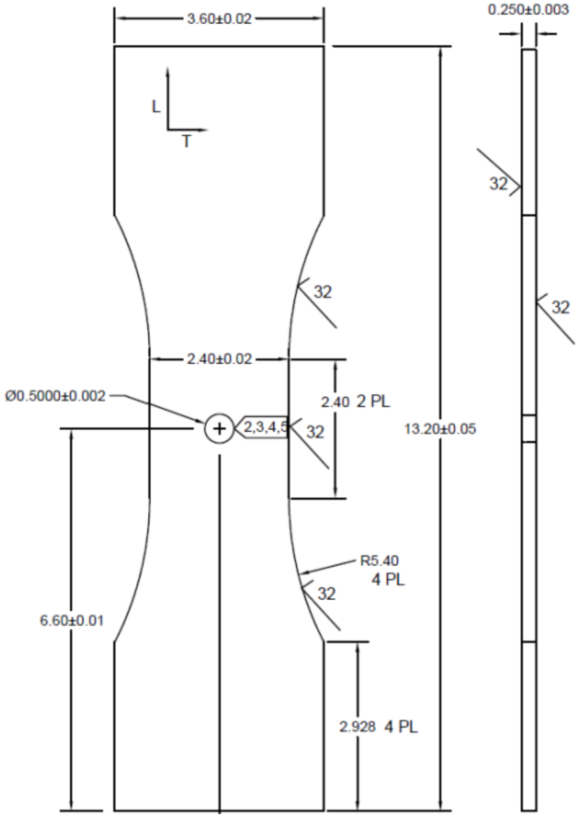
Limited Validation of CX ERS Prediction Model

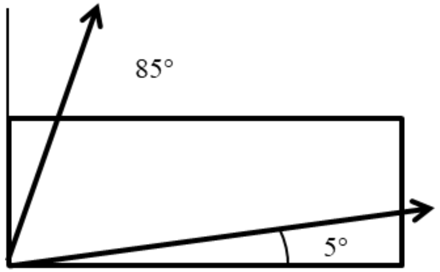
ERS Measurement Template

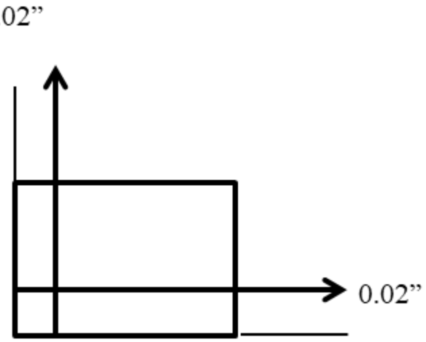
AFGROW Advanced Model Predictions

AFGROW Advanced Model Predictions

- Methods
  - AFGROW Advanced Models
  - Inputs
    - Materials (2): 7075-T7351, 2024-T3
    - Coupon Geometry: Central hole
    - Constant amplitude
    - AFGROW Residual stress "vectors"-1 vector each for adjusting "c" and "a" crack SIFs

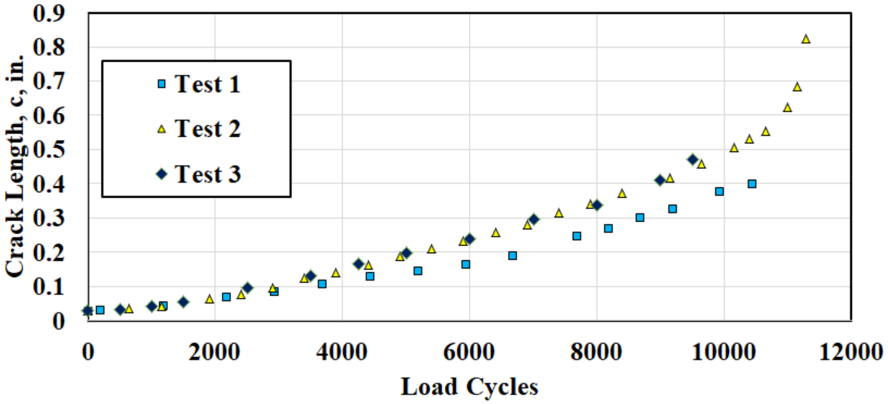




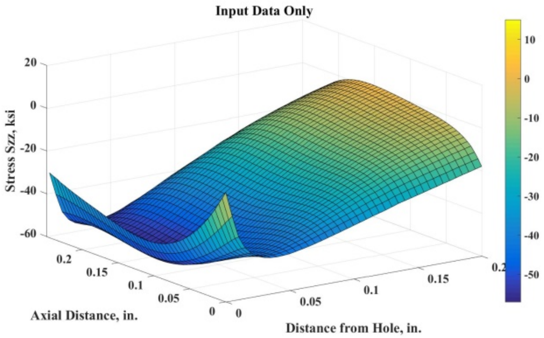


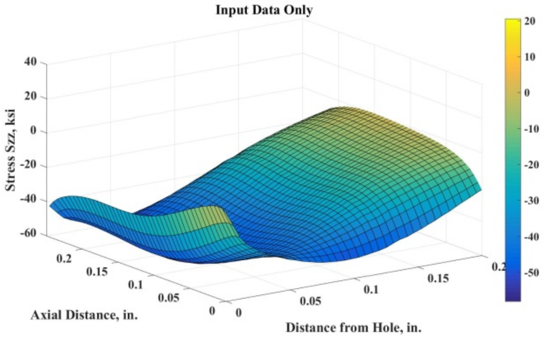
AFGROW Advanced Model Predictions

- Available Data for Validation
  - Experimental crack growth measurements



  - Residual stress measurements





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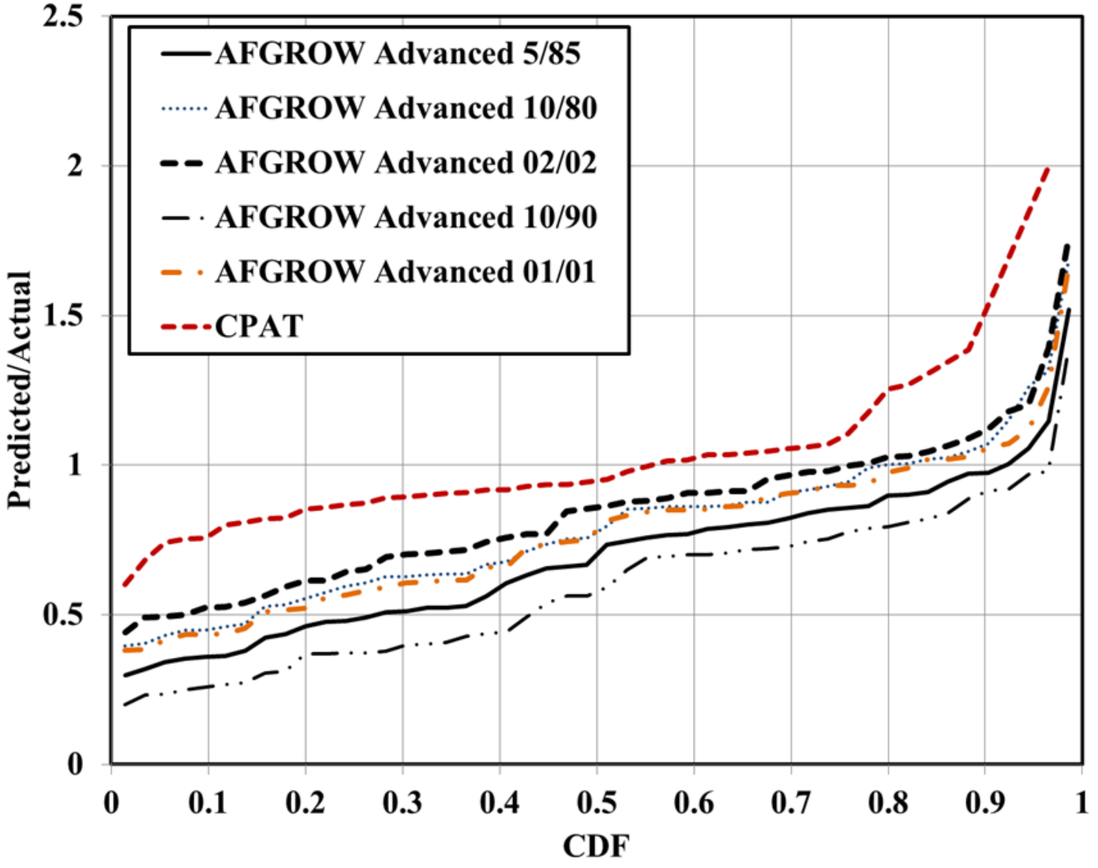
AFGROW Advanced Model Predictions

- Summary of Predictions – 7075-T7351



Ranking
1. CPAT (Best)
2. 02/02
3. 10/80
4. 01/01
5. 5/85
6. 10/90

Initial cracks are as-measured pre-crack. References (Actuals) are measured fatigue lives.

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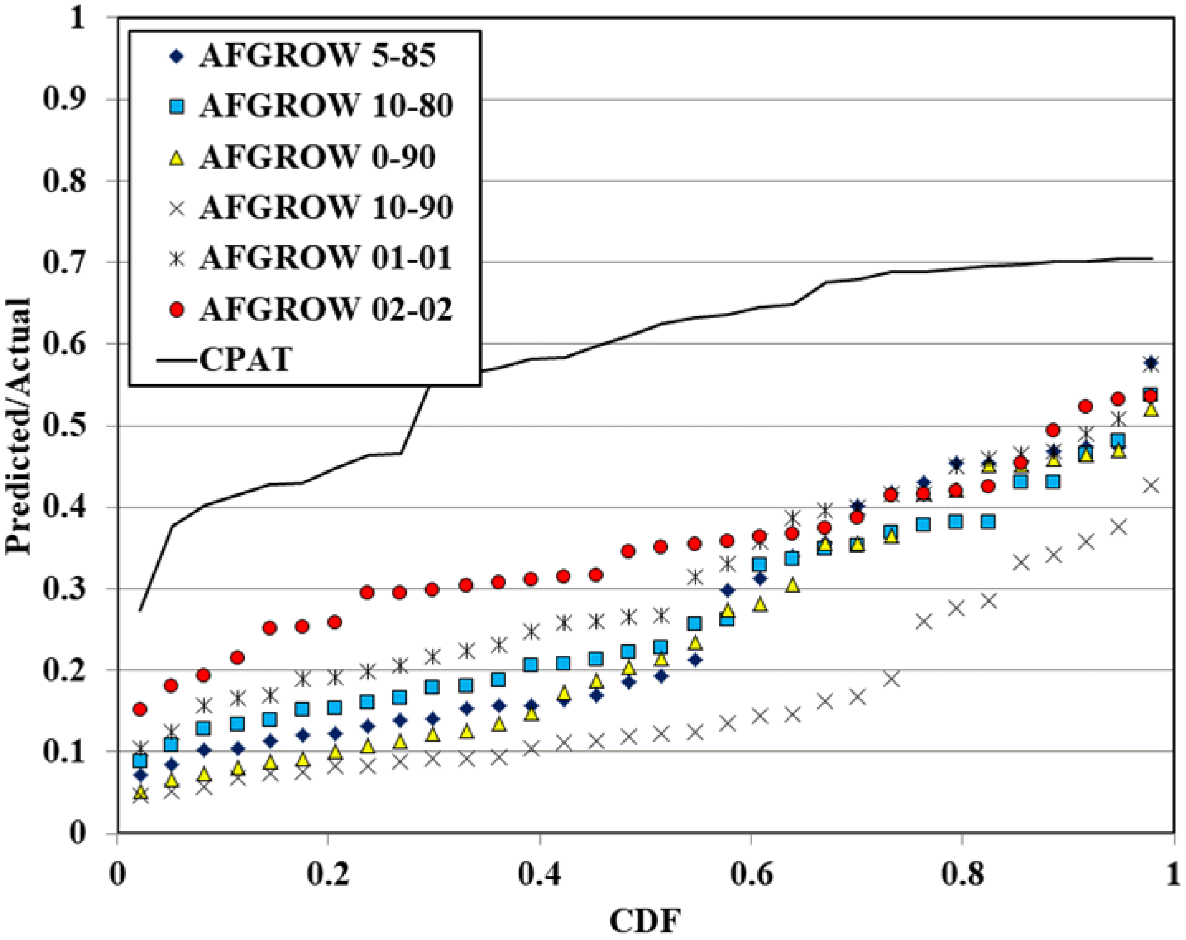
AFGROW Advanced Model Predictions

- Summary of Predictions – 2024-T3 Central Hole



Ranking

1. CPAT (Best)
2. 02/02
3. 01/01
4. 10/80
5. 5/85
6. 0/90
7. 10/90

Initial cracks are as-measured pre-cracks. References (Actuals) are measured fatigue lives.

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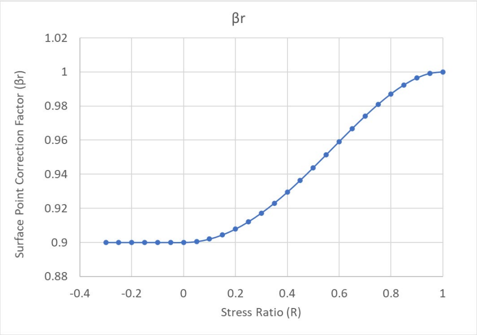
Distribution Statement A—Approved for public release. Approval Number 75ABW-2020-0038

Surface Correction for Multi-Point Analysis

Crack Closure

- SwRI investigated the AFGROW implementation of crack closure and its impacts on typical A-10 control point analysis
  - Surface crack growth showed moderate life improvements (2-6%) and decrease in a/c (2-5%)
  - Corner crack growth shows increased analytical predictions (2-37%) but very little change in aspect ratio
  - Crack closure factor not recommended for current A-10 Methods
    - Minimal difference from current method
    - Concerns of potential conservatism due to location of K extraction
    - Concerns of potential conservatism due to constraint variation with large and small load cycles
  - Methods utilizing multi-point analysis should consider investigating effects of closure factor
    - Recommend performance of analytical study to compare multi-point growth with and without beta corrections at the free surfaces of the crack face

$$\beta_R = 0.9 + 0.2\,R^2 - 0.1R^4 \; for \; R > 0$$
$$\beta_R = 0.9 \; for \; R \leq 0$$



Note: this implementation still forces an assumed elliptical crack shape

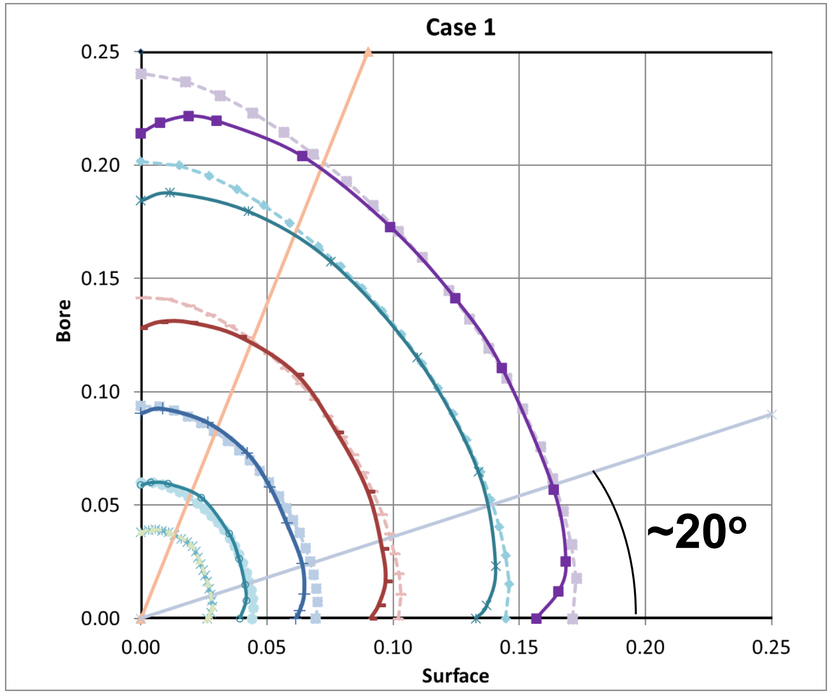
Approach

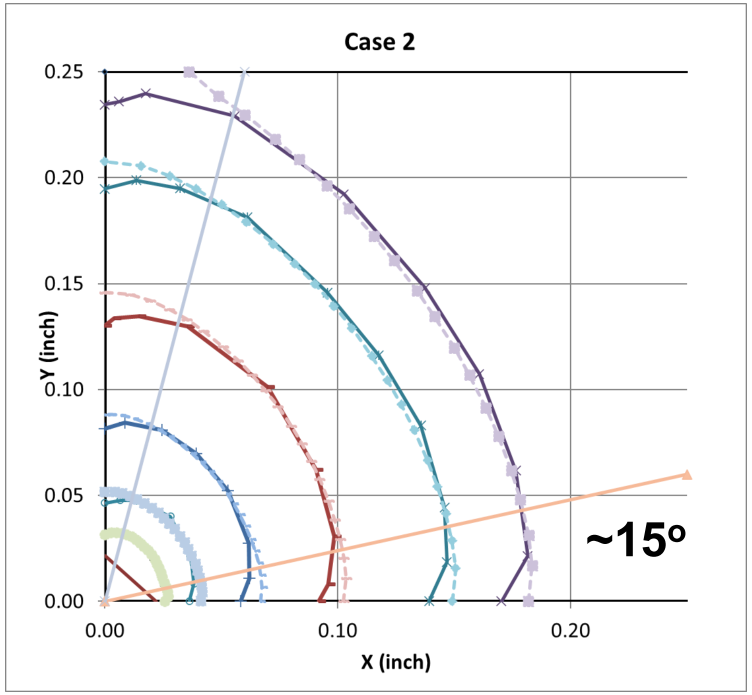
- Investigate differences in crack shape evolution from predicted shape
- Investigate effects modifying surface points have on crack shape
- Incorporate updates into BAMpF
- Complete predictions for defined conditions
  - AFGROW round robin
  - Other available data with good markerband and test correlation

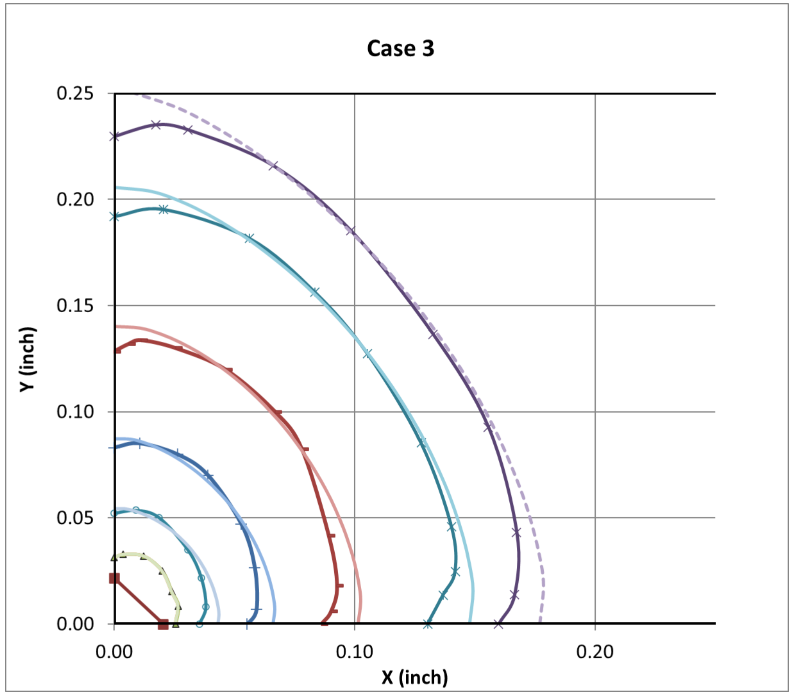
AFGROW Round Robin – BAMpF Comparisons

- BAMpF vs. markerband comparisons

▬ Markerbands
- - - Predicted Shape

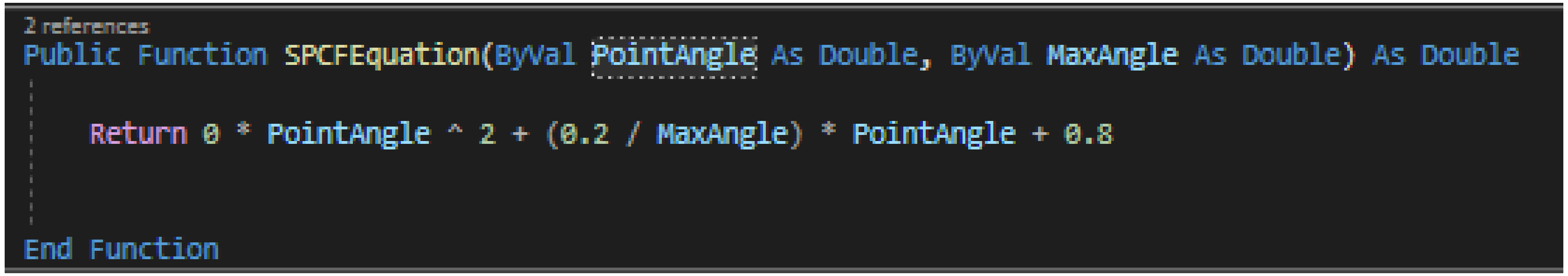






BAMpF Initial Implementation

- Initial approach
  - Implement function to modify K_{app} with a correction factor and an angle for both the surface and the bore
    - Implement capability to adjust angle utilizing BAMpF parameter features
  - Utilize an equation based on differences in crack growth profiles to determine correction factor and angle
    - Linearly interpolate correction factor from surface to defined angle
  - Utilize new functionality to determine effects the correction factor and angle have on life and crack shape



```
2 references
Public Function SPCFEquation(ByVal PointAngle As Double, ByVal MaxAngle As Double) As Double

    Return 0 * PointAngle ^ 2 + (0.2 / MaxAngle) * PointAngle + 0.8

End Function
```

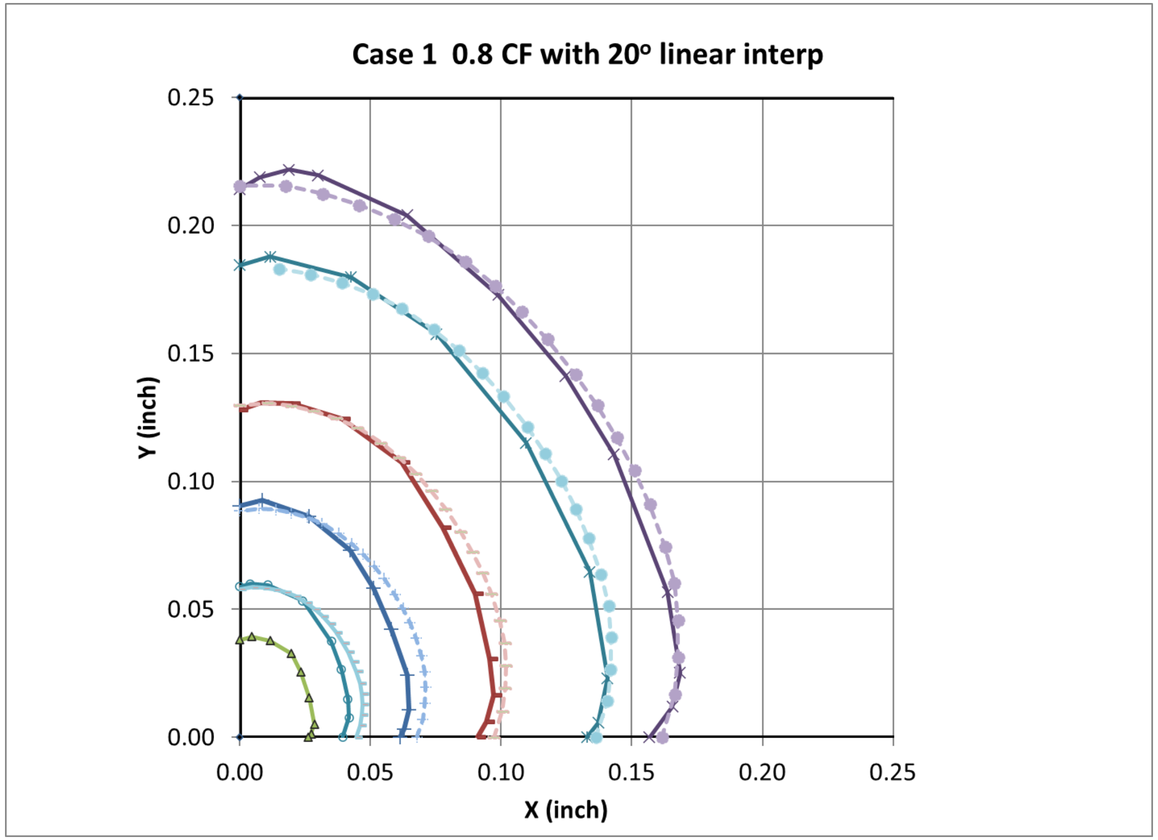
$$\beta_{surface\ correction} = \frac{(1 - CF)}{Max_{angle}}\phi + CF$$

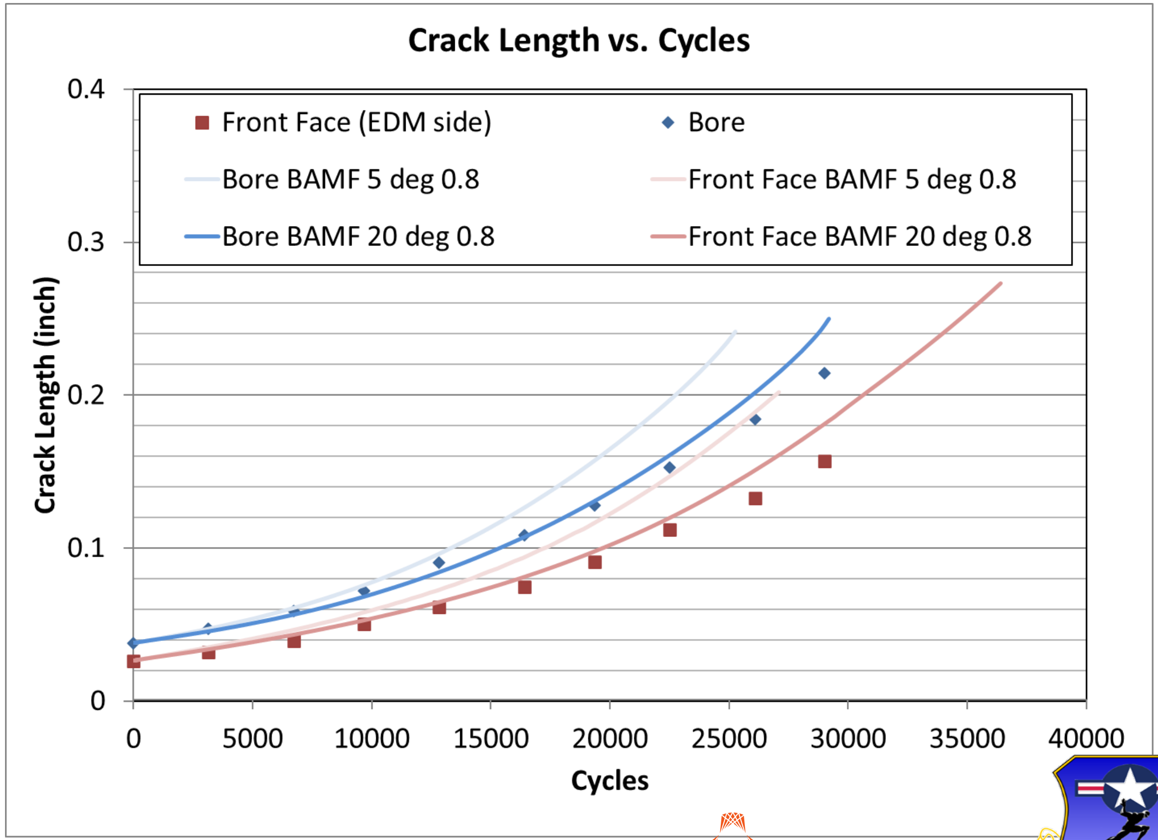
CF= Correction factor
Max Angle= Maximum angle the correction factor acts over
Φ=Angle from surface

BAMpF Predictions - AFGROW Round Robin with Updated Angle

- AFGROW RR Case 1
  - Updated AFGROW RR results with 0.8 CF and 20º max angle
  - Shape and life predictions are very consistent with test data

— Markerbands
- - - Predicted Shape

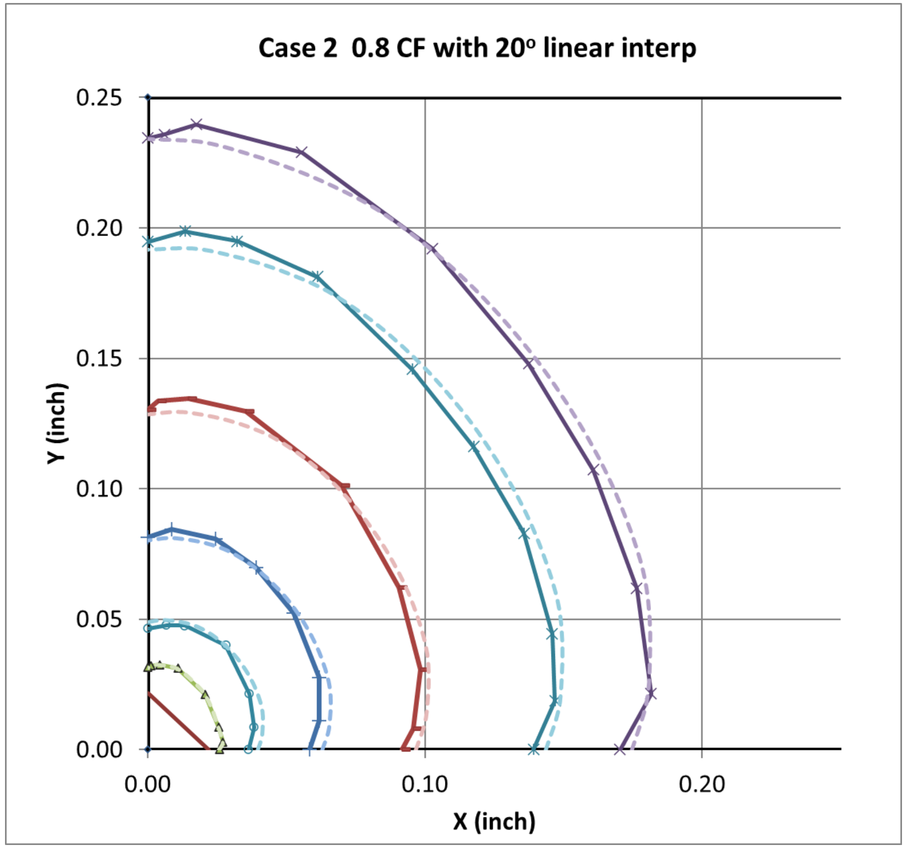


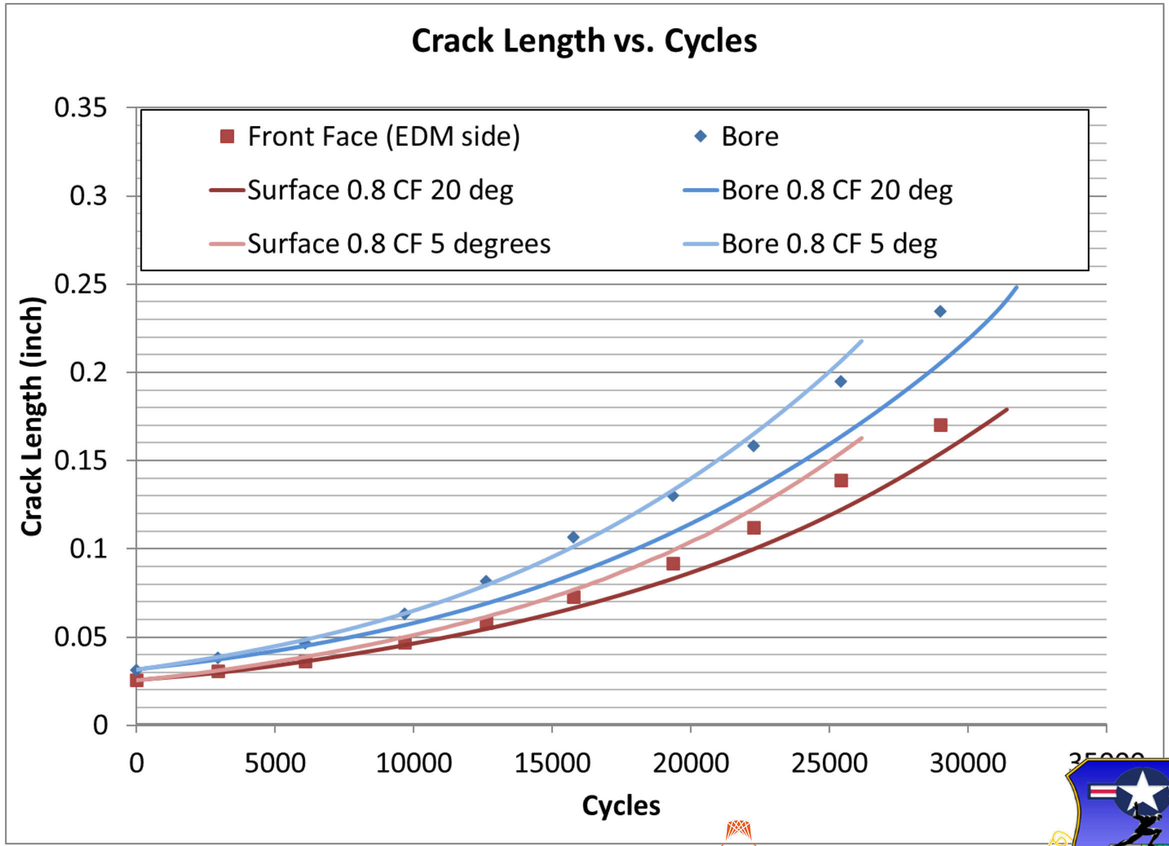


BAMpF Predictions - AFGROW Round Robin with Updated Angle

- AFGROW RR Case 2
  - Updated AFGROW RR results with 0.8 CF and 20^{o} max angle
  - Life is slightly long (5% slower in prediction)

━ Markerbands
- - - Predicted Shape





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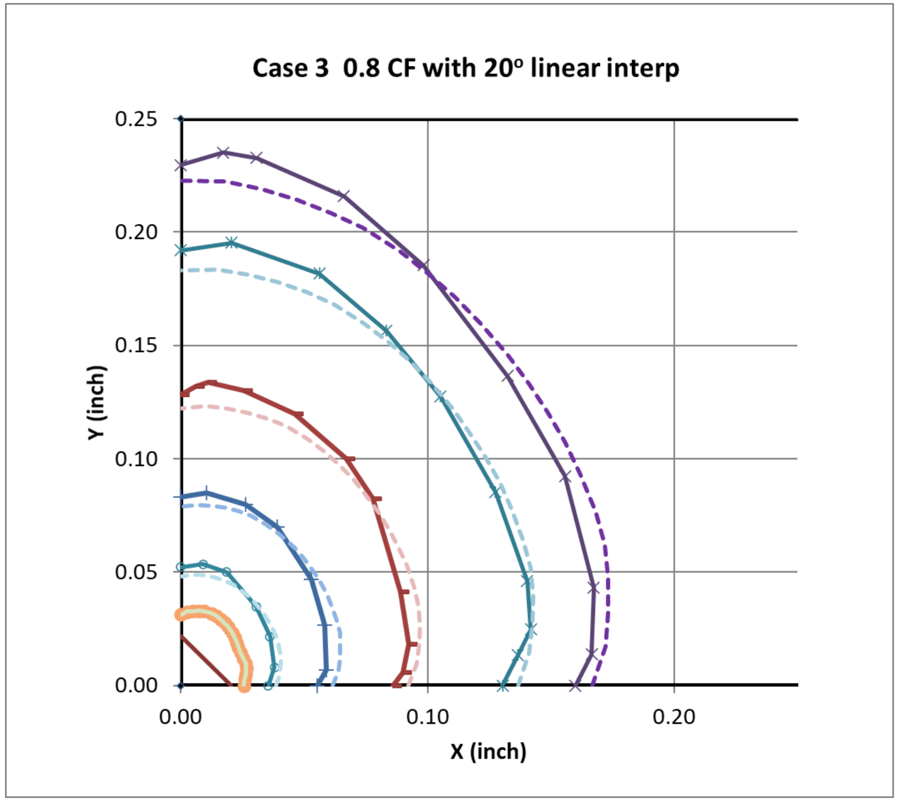
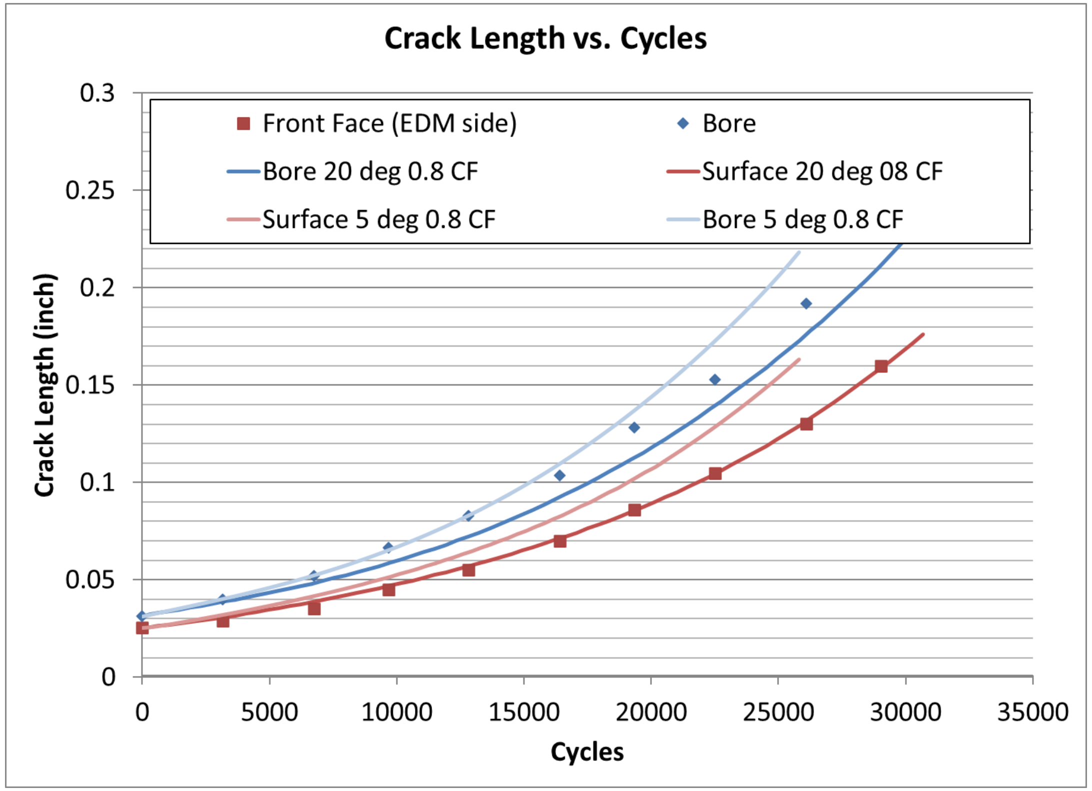
Predict. Test. Perform.

BAMpF Predictions - AFGROW Round Robin with Updated Angle

- AFGROW RR Case 3
  - Updated AFGROW RR results with 0.8 CF and 20^{o} max angle
  - Life looks pretty good! Crack shape isn't bad (bore grows faster in test)

▬	Markerbands
- - -	Predicted Shape


Case 3 0.8 CF with 20° linear interp


Crack Length vs. Cycles

Conclusions

- Method developed to implement surface corrections into BAMpF using a max angle and CF
  - Initial predictions indicate a correction factor of 0.8 and a max angle of 20 degrees correlates best to test data
  - Corrections appear to work for crack shapes in both CA and VA testing
  - Corrections resulted in good life correction for CA tests, however, VA tests showed life that was longer than test
  - Additional predictions completed for other conditions, materials, etc. with very good agreement
- So far, this is just experimentation to understand if we can consistently match observed test behavior
  - How do we move forward from here to understand the physics of the behavior and ensure the implementation isn't just a tuning knob (no self-licking ice cream cones)?
  - What is the correct implementation approach?
  - What data can we utilize to guide the approach?

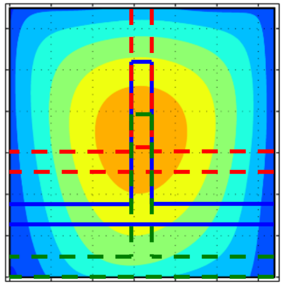
FCG Testing of Complex Coupons with Quench Induced Residual Stress

Renan Ribeiro – Hill Engineering

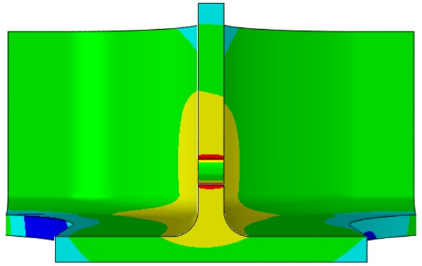
FCG in Coupons with Quench Residual Stress

- Motivation:
  - Residual stress from quench is inherent in the production of key high-strength aluminum alloys (typical post-quench stress level 50% S_y)
  - Residual stress relief processes leave some residual stress behind
    - Stretched plate can have very low peak stress levels (≈ 2% to 4% S_y)
    - Compressed die forgings can have higher peak stress (≈ 5% to 20% S_y)
  - Fatigue performance of finished parts is affected by residual stress
  - Finished parts have different residual stress than does parent stock
- Research questions:
  - Can residual stress from raw stock be used to predict stress in finished parts?
  - Can predicted residual stress improve prediction of fatigue crack growth in finished parts?

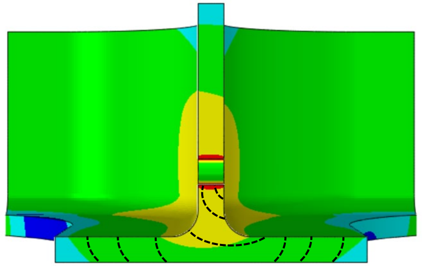
Renan L. Ribeiro,
UC Davis



Measure RS in
Raw Product Form



Predict RS in
Part Cut from
Raw Product Form



Predict Fatigue
Performance
Including RS

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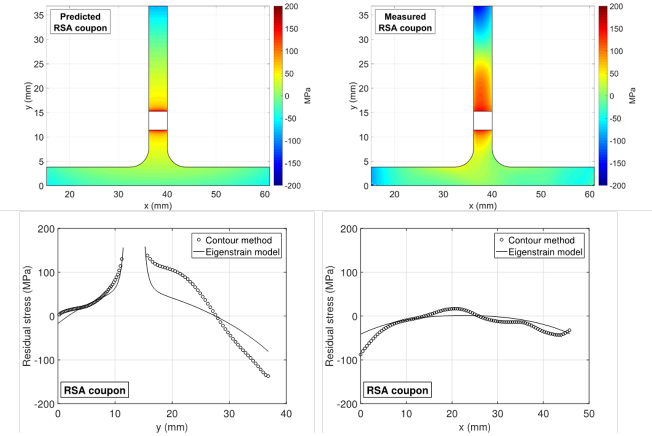
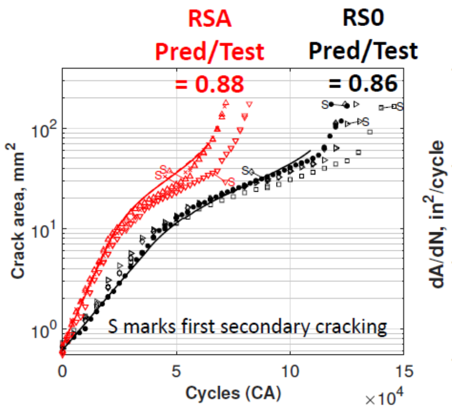
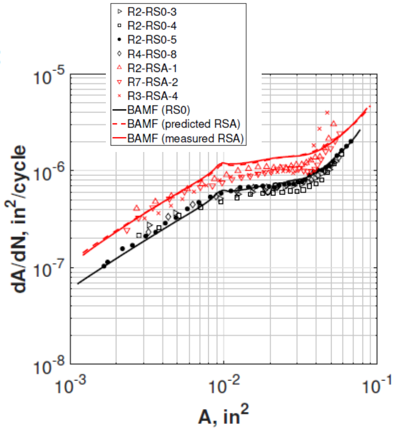
FCG in Coupons with Quench Residual Stress

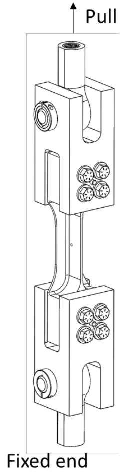
- Methods
  - Coupons manufactured from rectangular quenched bars (representative of airframe detail)
  - Eigenstrain method for prediction of residual stress based on raw stock measurements
  - Contour method for measurements of residual stress for validation
  - Fatigue crack growth testing
    - Pull-pull configuration, DCPD, marker banding, quantitative fractography, digital photogrammetry
  - Fatigue crack growth modeling
    - Multi-point fracture mechanics analysis (BAMpF)
    - Residual stress (predicted and measured) included

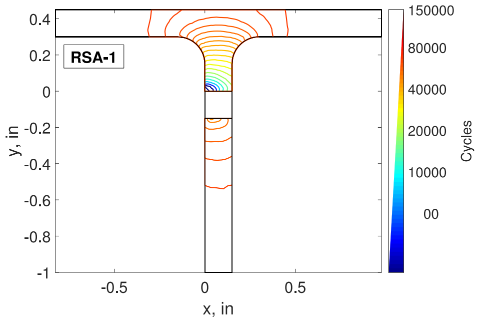
- Results
  - Can residual stress from raw stock be used to predict stress in finished parts? **(Journal paper 1 in progress)**
    - Yes, but with some discrepancy
    - This study showed point-wise accuracy to better than 70 MPa
  - Can predicted residual stress improve prediction of fatigue crack growth in finished parts? **(Journal paper 2 in progress)**
    - Yes, with good fidelity (better than 20% on crack growth life)
    - This study showed
      - Ignoring tensile RS caused anticonservative error of about 1.5X on life
      - Accuracy of crack growth prediction for RS bearing material (RSA) was comparable to that for low RS material (RS0)











Acknowledgements
Helpful advice from Dale Ball (LM Aero), TJ Spradlin (AFRL), and Kevin Walker (DST Group)
MPFM analyses with BAMpF by Josh Hodges (Hill Engineering, LLC)
Technical interchange with Jim Newman, Jr (MS State)
Prior collaborations with Mark James (Arconic)

7075-T651 Predictions

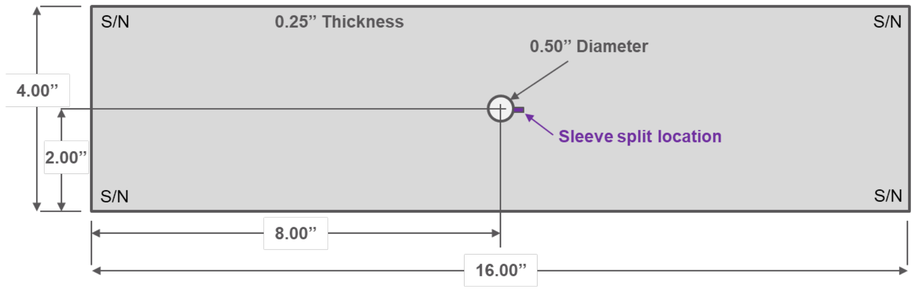
Robert Pilarczyk – Hill Engineering

Classic 0.005-inch IFS Comparisons

- Background
  - Reduced IFS has been and currently is the established method for Cx credit, recently referred to as “partial credit”
  - “Full credit” approaches would explicitly incorporate residual stress in the DTA
  - Comparisons between these approaches for 2024-T351 were completed during the A-10 Cx Teardown program and presented at the ASIP conference in 2018 and 2019
    - These results were directly compared to Warner’s thesis and demonstrated reasonable correlation between predictions and experimental results
- Current effort
  - Repeat comparisons, however, focus on 7075-T651 aluminum as well as constant and variable amplitude loading
  - Compare to available experimental results as well as life improvement factors for 2024-T351

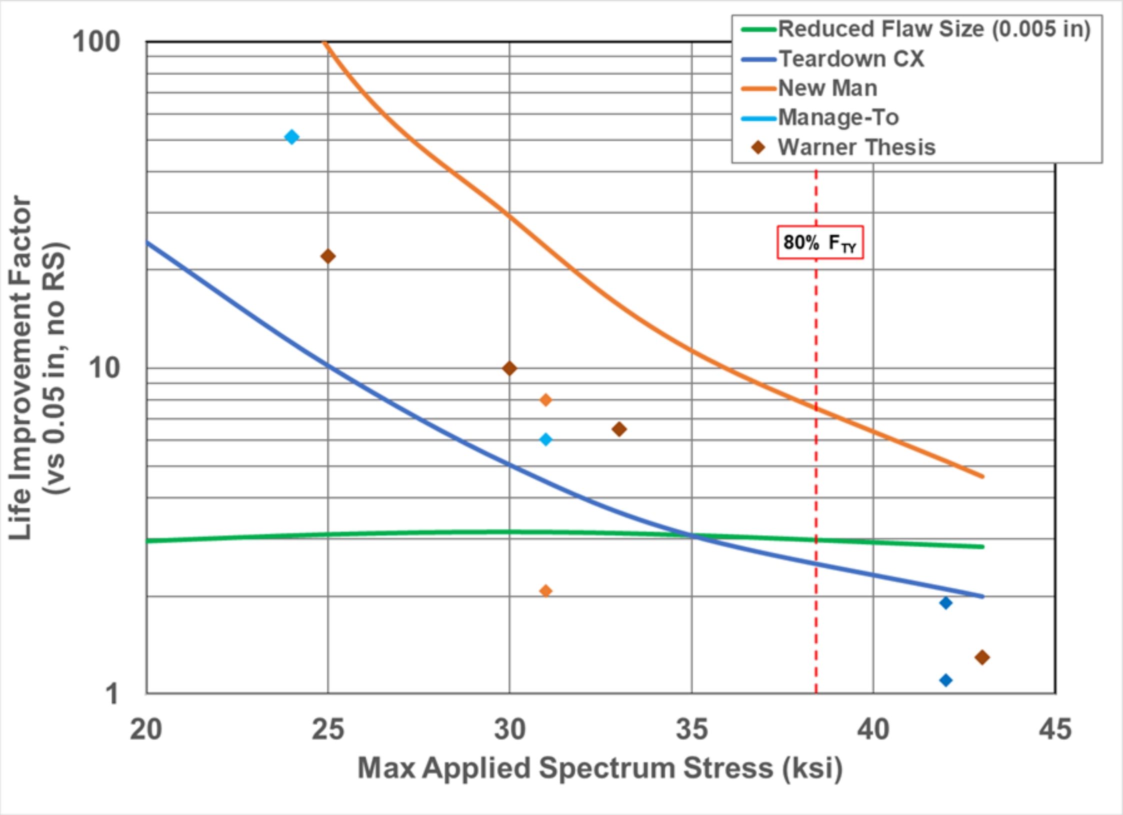
Classic 0.005-inch IFS Comparisons

- Approach
  - Maintain consistency with Pilarczyk's thesis
  - Inputs:
    - Geometry:
      - Width: 4-inch
      - Thickness: 0.250-inch
      - Hole diameter: 0.500-inch
      - Hole Offset: Centered hole
      - Applied expansion: mid
    - Loading:
      - Constant Amplitude, R=0.1
        - Peak stress: 20, 25, 30, 35ksi
      - Spectrum, A-10 RPDS DTRCP7
        - Peak spectrum stress: 20, 25, 30, 35ksi
    - Spectrum retardation:
      - Constant amplitude predictions: N/A
      - Reduced IFS predictions: A-10 ground rules for 7075-T6
      - Explicit residual stress predictions: No retardation
    - Residual stress:
      - Average of OY2 varying thickness coupons (0.250-inch thick) was utilized for residual stress

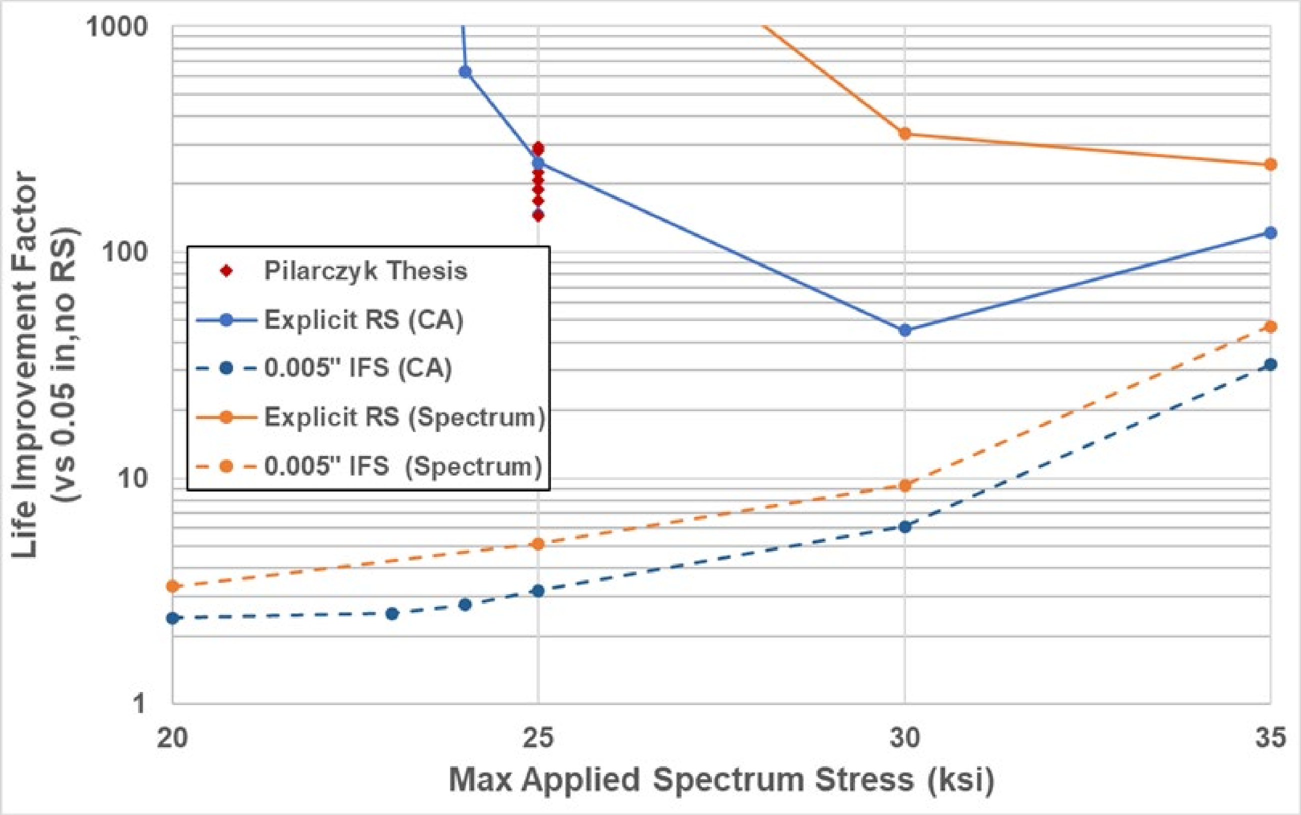


Classic 0.005-inch IFS Comparisons

Previous 2024-T351 Comparisons



New 7075-T651 Comparisons



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Classic 0.005-inch IFS Comparisons

- Summary & conclusions
  - Significant life improvements were observed for “full credit” analyses for 7075-T651, with the minimum improvement of 45x
    - Appreciably higher improvements relative to 2024, however, additional test data is necessary to validate trend
  - Comparable life improvement was observed for experimental results and predictions at 25ksi peak stress
  - Similar improvements were observed for constant and variable amplitude
  - Life improvements above 30ksi are somewhat skewed due to limited baseline life (less than 500 cycles and 2000 hours for constant and variable amplitude loading, respectively)
  - Overall, results indicate “full credit” analyses for Cx would result in a terminating action (no follow-on inspections) for 7075-T651 aluminum
- Recommendations
  - Complete additional validation testing to substantiate life improvement for Cx in 7075 aluminum

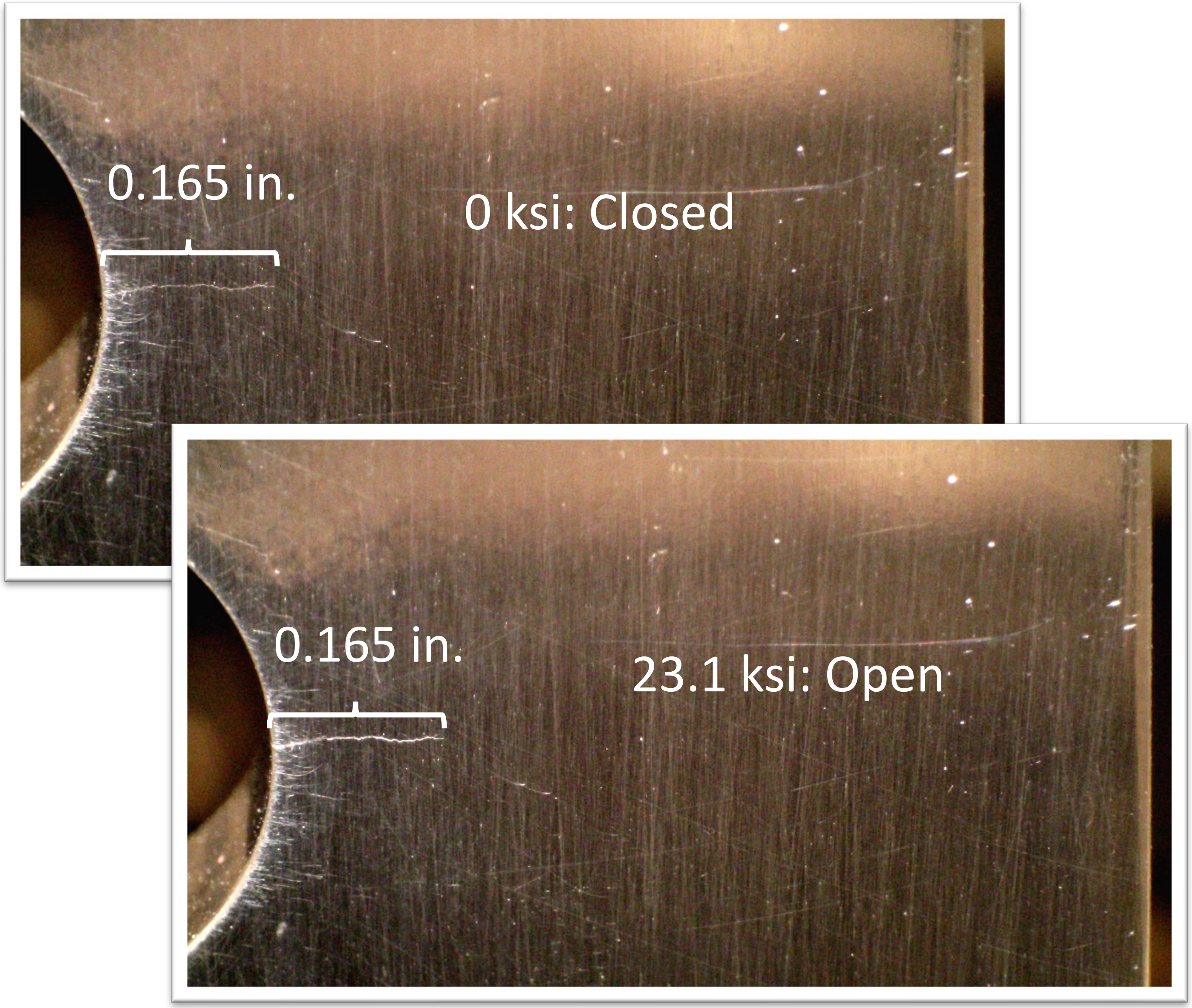
VALIDATION TESTING

Closure Images

Evan Ross - USAF

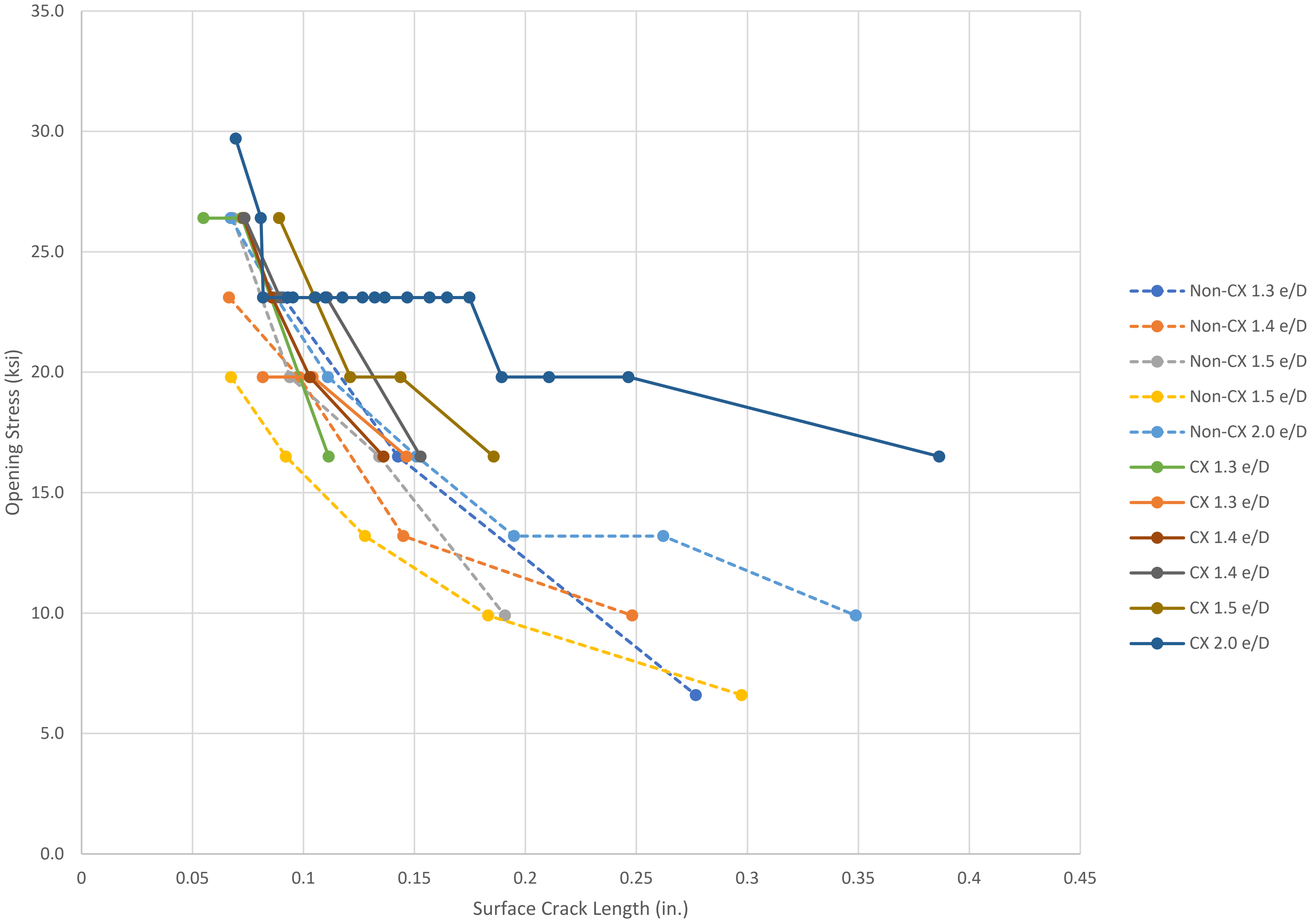
Crack Closure Imaging

- Cracks in 2024-T351 plate from 0.5” holes with short e/D (1.3, 1.4, 1.5, 2.0)
- Various crack lengths
- Images at 0 to 33 ksi with 3.3 ksi increments



Crack Closure Imaging

- Crack length vs opening stress
- Combined Non-CX (dashed) and CX (solid) holes
- All e/D



WEAPON SYSTEM APPLICATIONS

B-1 Taper-Lok Analysis & Testing

B-1 Taper-Lok Background

- Taper-Lok Fasteners
  - Taper-Lok fasteners are known to produce high levels of interference and residual stress within the host material. As a result, details with Taper-Lok fasteners display increased fatigue and damage tolerance lives.
  - Limited methods exist to quantify the benefit of Taper-Lok installations
    - All require testing and coupons unique to the detail geometry being analyzed
    - These methods are known as partial-credit because they do not capture the full benefit
  - Currently, an analytical methodology does not exist to quantify the benefit of Taper-Lok installations
- B-1 Taper-Lok Locations
  - Common to wing rear spar structure (Al material)
  - Common to wing carry through structure (Ti material)

B-1B Wing Assembly at Avco (Chatanooga, TN)

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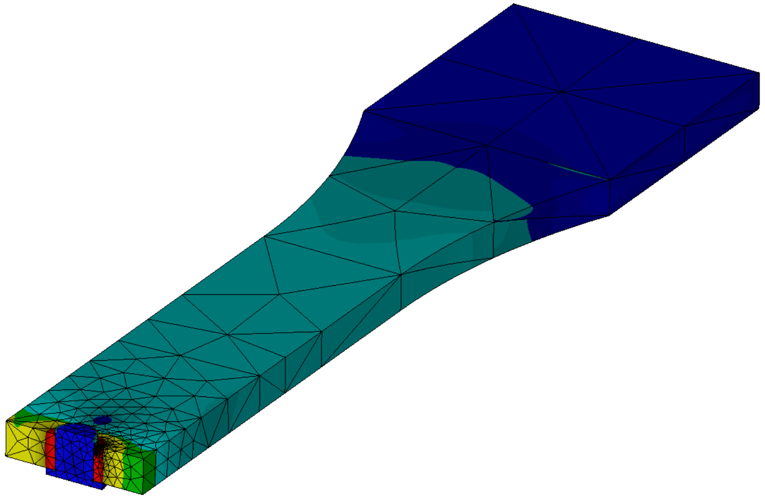
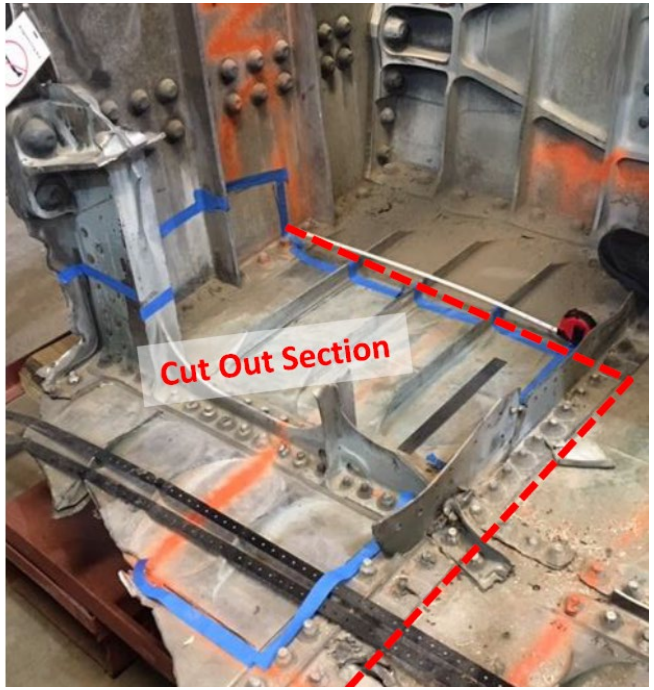
Program Objectives



- Develop a robust analytical approach to predict the damage tolerance life at B-1 Taper-Lok fastener holes
- Perform measurements to quantify interference and residual stress at Taper-Lok fastener holes
- Perform fatigue tests for representative Taper-Lok fastener hole conditions
  - Representative coupon and excised component tests
- Perform fatigue crack growth analyses for representative Taper-Lok fastener hole conditions
- Perform damage tolerance assessments and assess inspection requirements for B-1 Taper-Lok fastener hole locations



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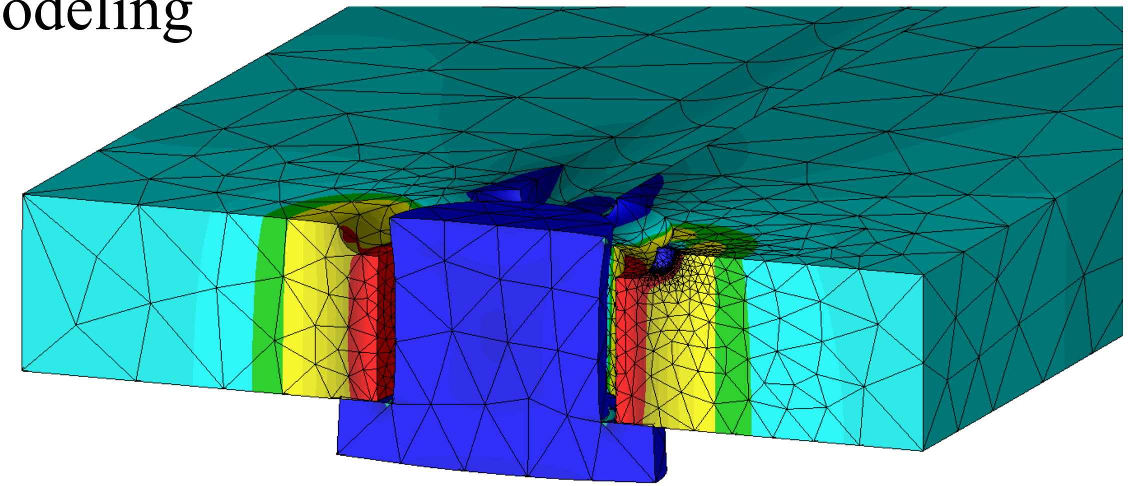
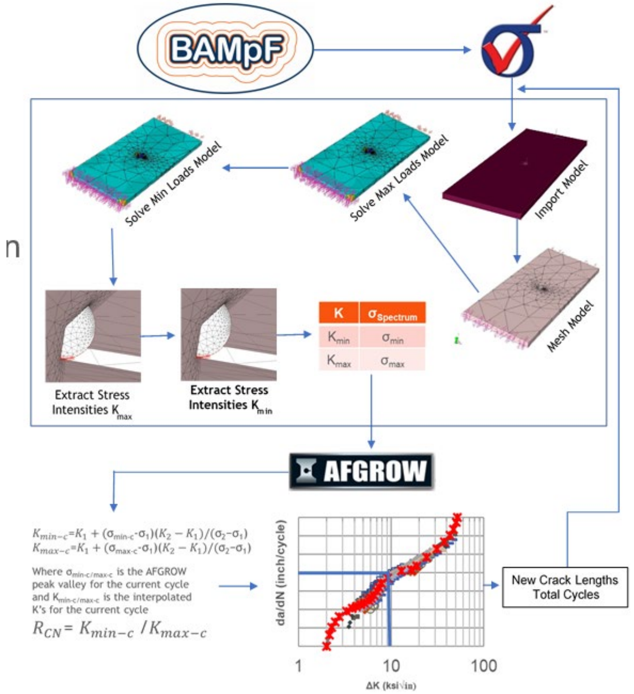
Analytical Approach

- Investigate Key Factors for Explicit Taper-Lok Modeling
  - Hole propping/interference and residual stress
- Modeling Approach
  - Multi-point fracture mechanics
    - Explicit model geometry, loading, etc.
    - Enables natural crack shape evolution
  - Fastener hole propping/interference
    - Multi-body contact
  - Residual stress
    - Crack face traction
  - Explicit modeling of fastener interference and residual stresses
- Sensitivity Studies
  - Investigate variations in key factors and their influence on damage tolerant life
- Tool Updates
  - Incorporated ability to pass tabular lookup (SIF vs. remote applied stress) instead of alpha to AFGROW from BAMpF to address non-linearity of SIFs from interference





Preliminary Results

- Combination of Process Simulations and Residual Stress Measurements
  - Comparisons between model predictions and measurements look good and promising
- Validation Testing for Baseline and Taper-Lok Conditions
  - Results look consistent
- Analysis vs. Test Comparisons
  - Wing process model prediction results show very well with test measurements, including baseline open hole and Taper-Lok configurations
- Extracted WCT Structure Test Specimens
  - Completed residual interference, protrusion measurements, fastener & hole diameter measurements and residual stress characterizations
  - Fatigue test pending

Remaining Effort

- Fatigue Testing
  - Coupon fatigue testing
  - Component fatigue testing
- Residual Stress Measurements
  - Non-cycled coupons
- Test vs. Analysis Comparisons
- Best Practices and Lessons Learned
- Updated B-1 DTAs

MISC. OTHER

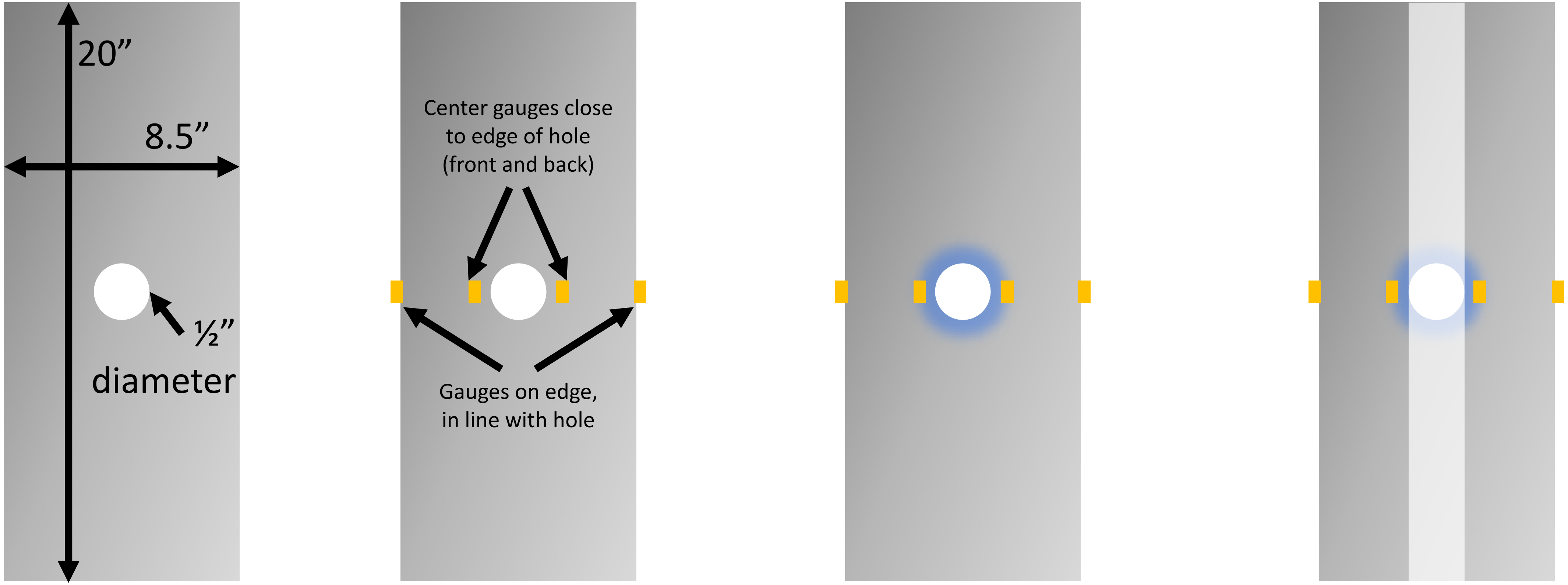
K_t-Free Coupons

Jacob Warner, James Greer - USAF

Coupon Development

- Objective: Eliminate the effect of the hole K_t while preserving the RS field created by Cx

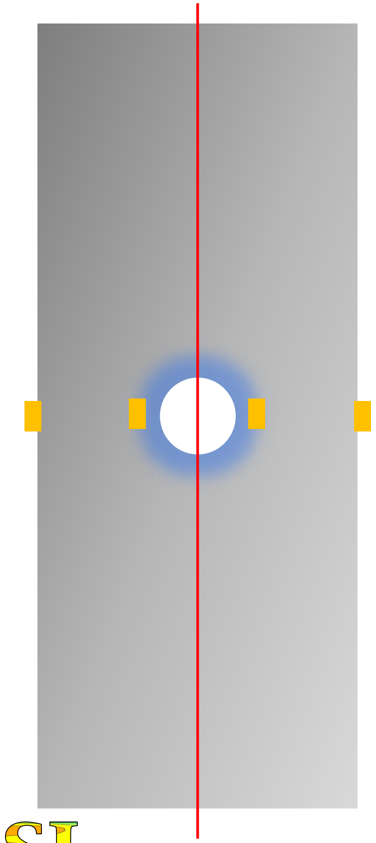
1. Machine ¼" thick Specimen
2. Install Strain Gauges (6)
3. CX Hole (record strain from CX) and final ream
4. Cut Specimen into two bars (measure strain to determine stress relaxation – next slide)



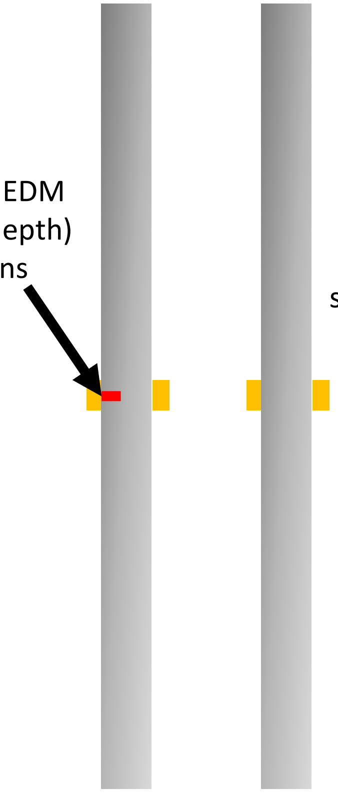
Cutting Process (step 4 of previous slide)

- Record strain at each step (either during process or before/after)

4a. After Cx and ream, bisect specimen with EDM



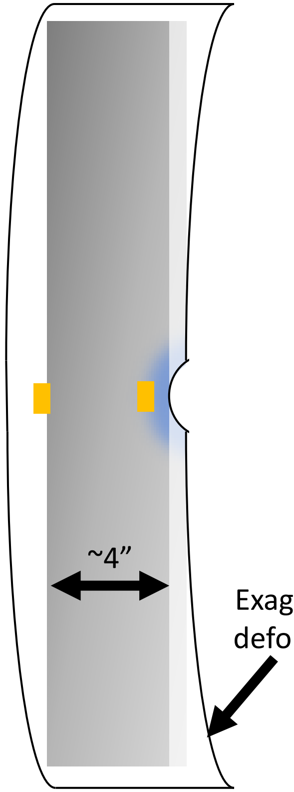
4b. EDM notch at hole corner (view rotated 90º)



0.030” corner EDM notch (target depth) x6 specimens

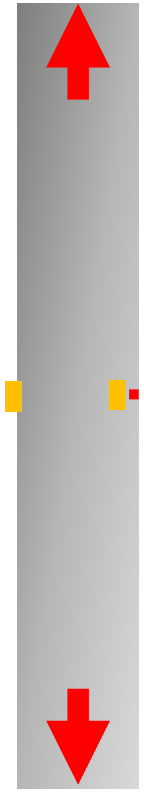
two unnotched specimens for RS evaluation

4c. Measure bow before and after milling square to tangency



Exaggerated deformation

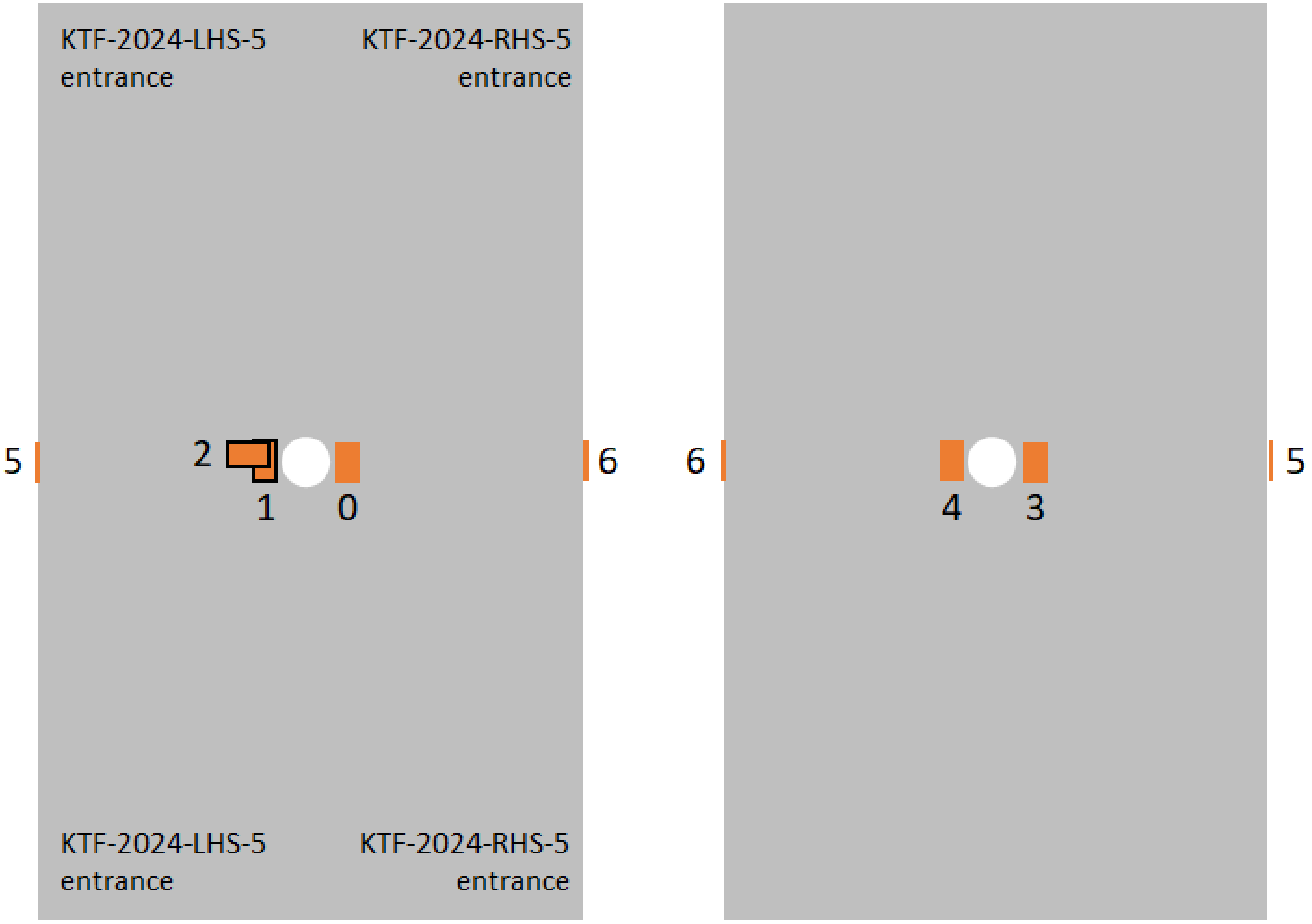
4d. Precrack specimen to 0.050” corner crack from notch



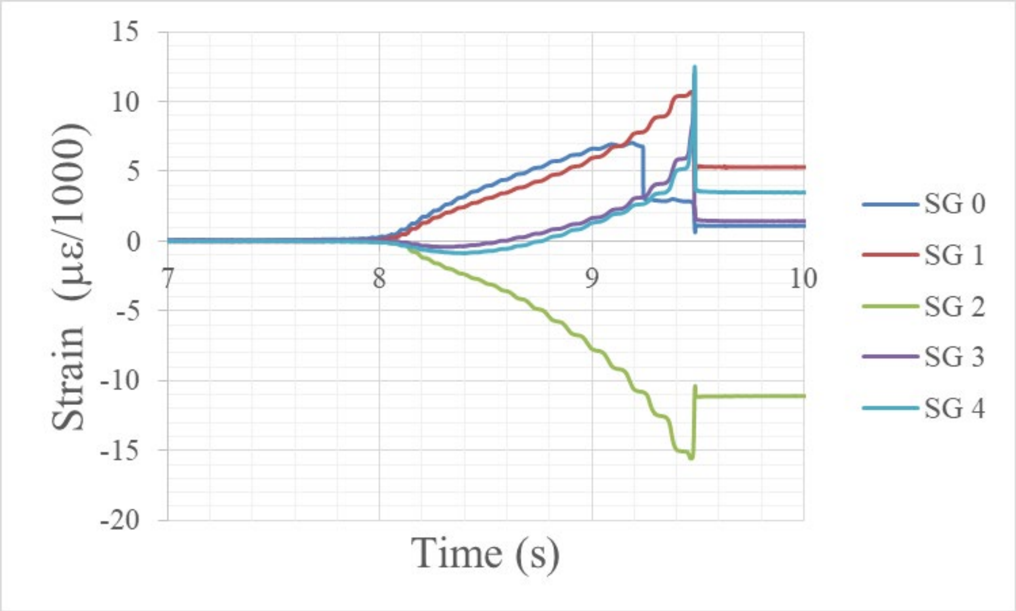
Test similar to ASTM E647 ESE specimen

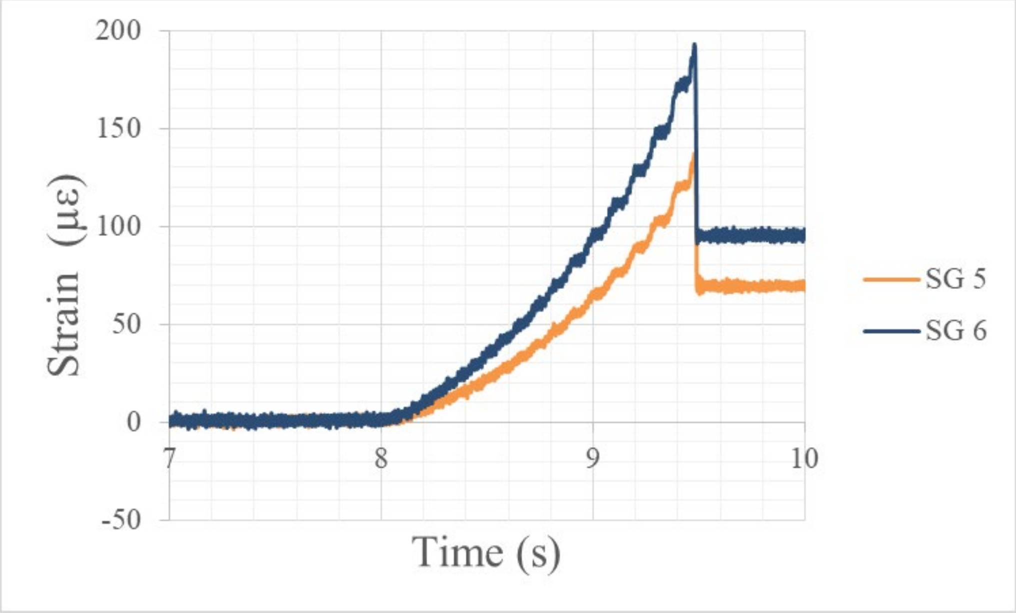
Strain Gage Data During Cx Mandrel Pull

Sample Data



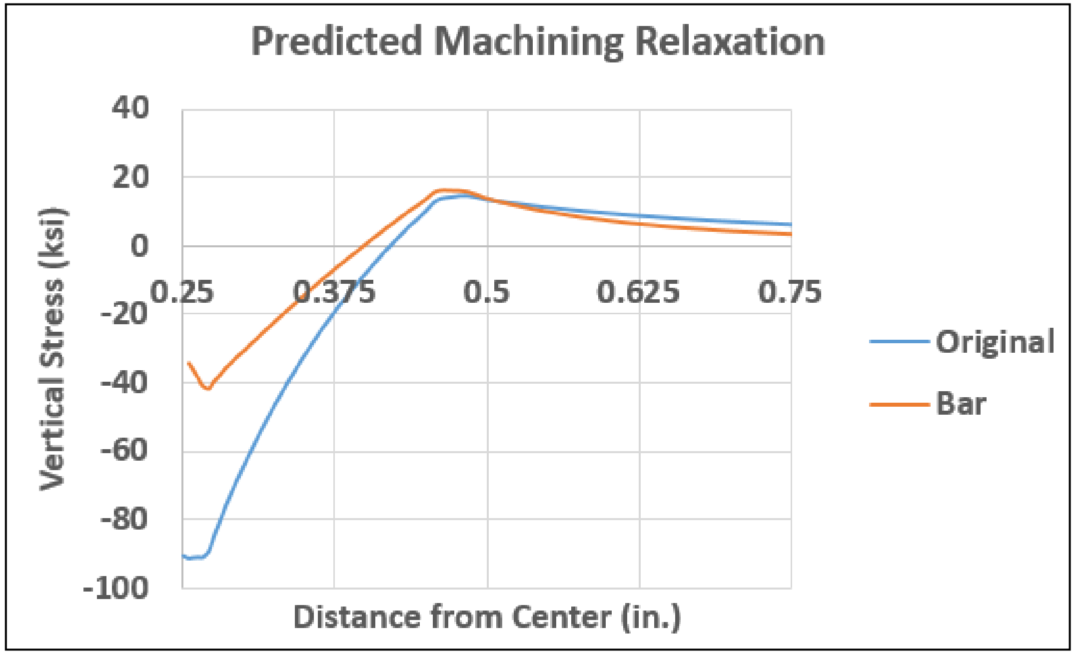
PANEL KTF-2024-XXX-5

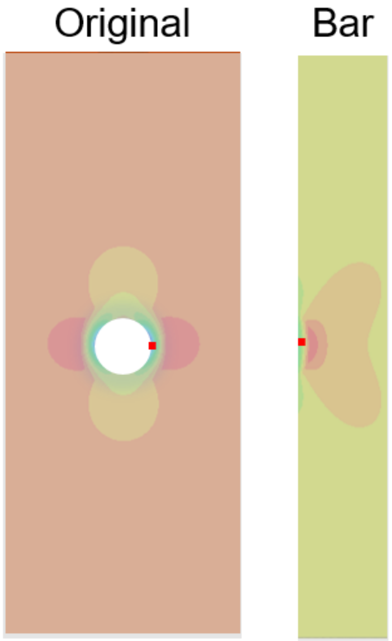




Summary

- FEA prediction indicates specimen with hole removed ("bar") has an RS stress field with the same characteristic shape as the specimen with the Cx hole.
  - Will be verified with RS analysis.
- Fatigue crack growth (FCG) behavior will be compared to existing FCG data for Cx hole coupons.





- Status
  - Specimen preparation complete
  - Testing of FCG specimens (x6) and RS analysis specimens (x2) to follow

USAF Draft Structures Bulletin

(Andrew, Warner, Spradlin)

CX IN ANALYSIS IMPLEMENTATION

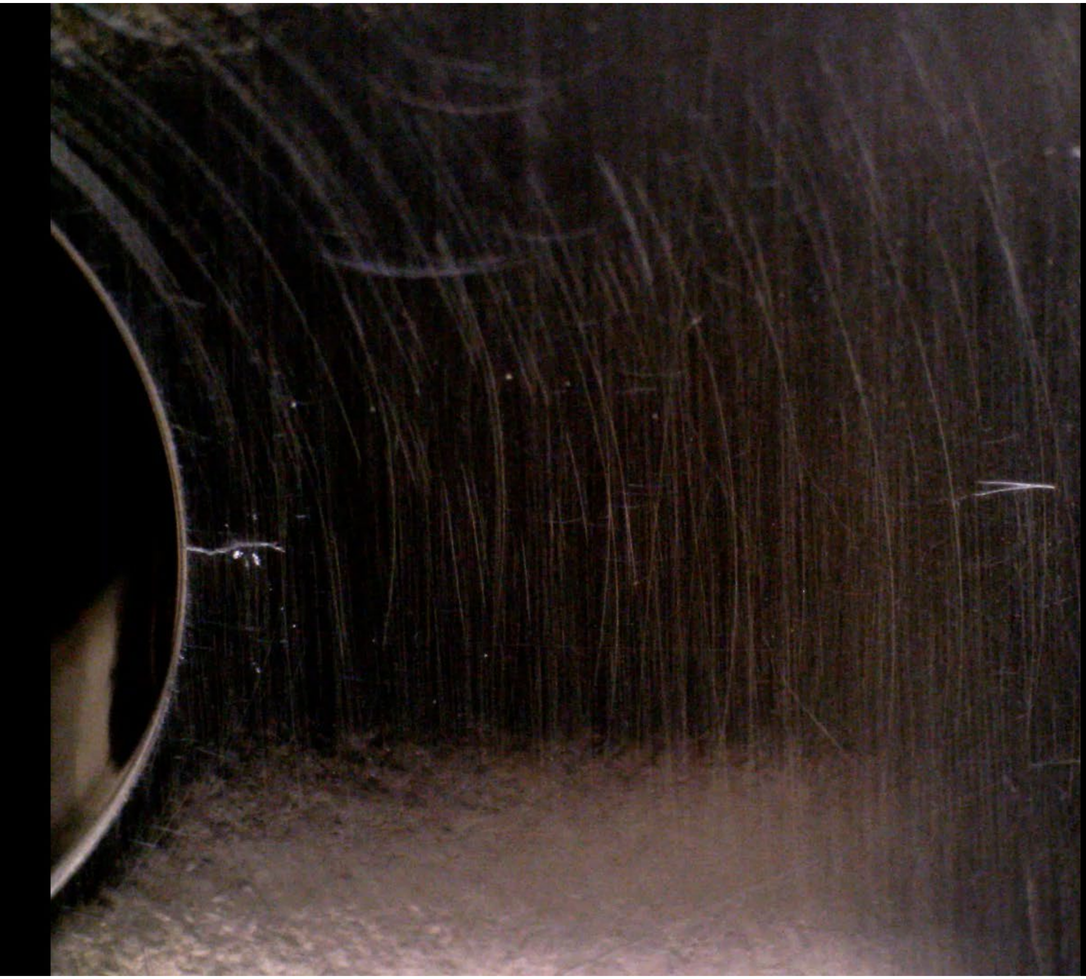
A-10 ASIP

Jake Warner

Distribution A: Approved for public release. Case number 2020-02-12-034_75ABW-2020-0004

WHY CX

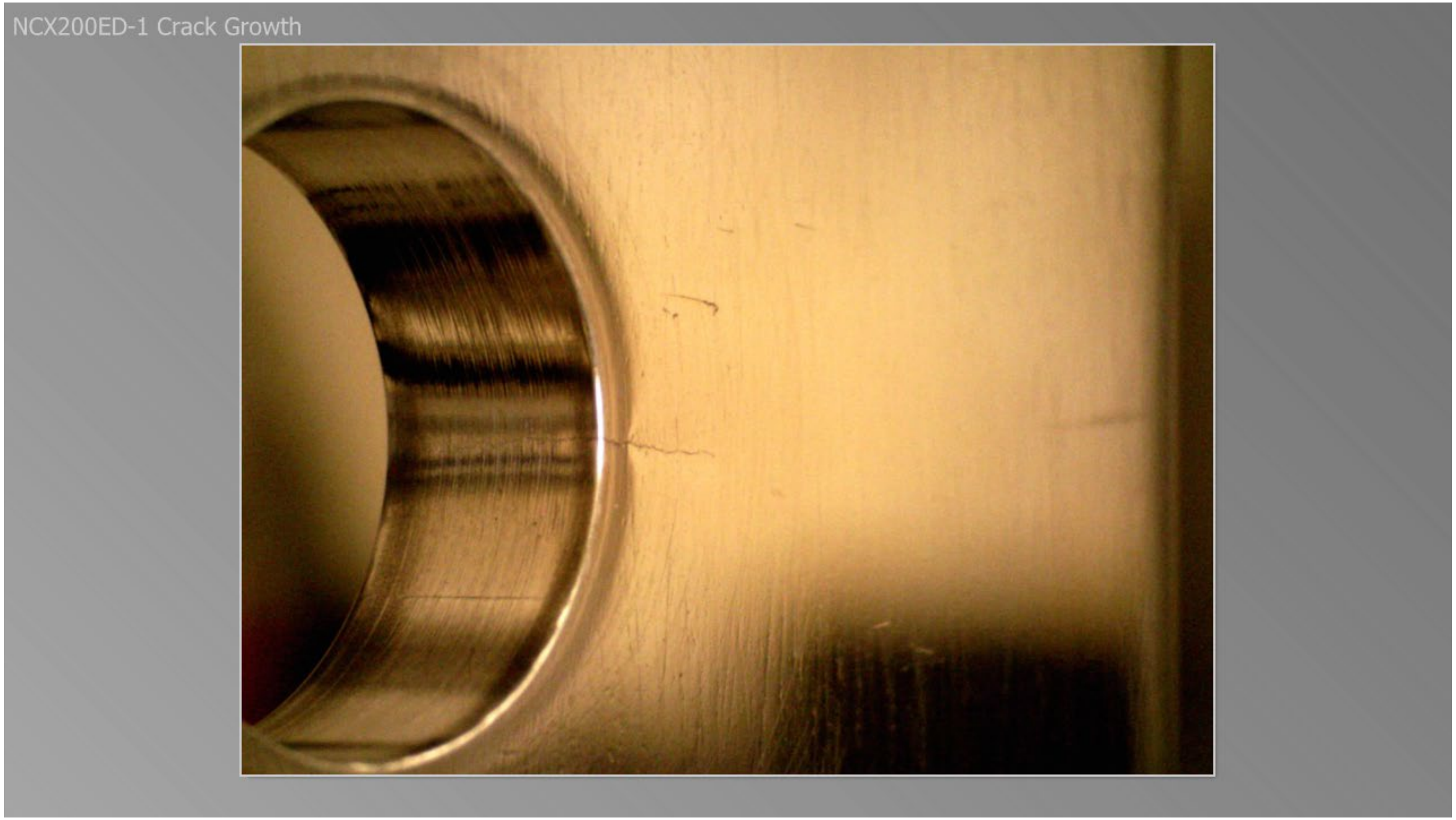
CX



Non CX

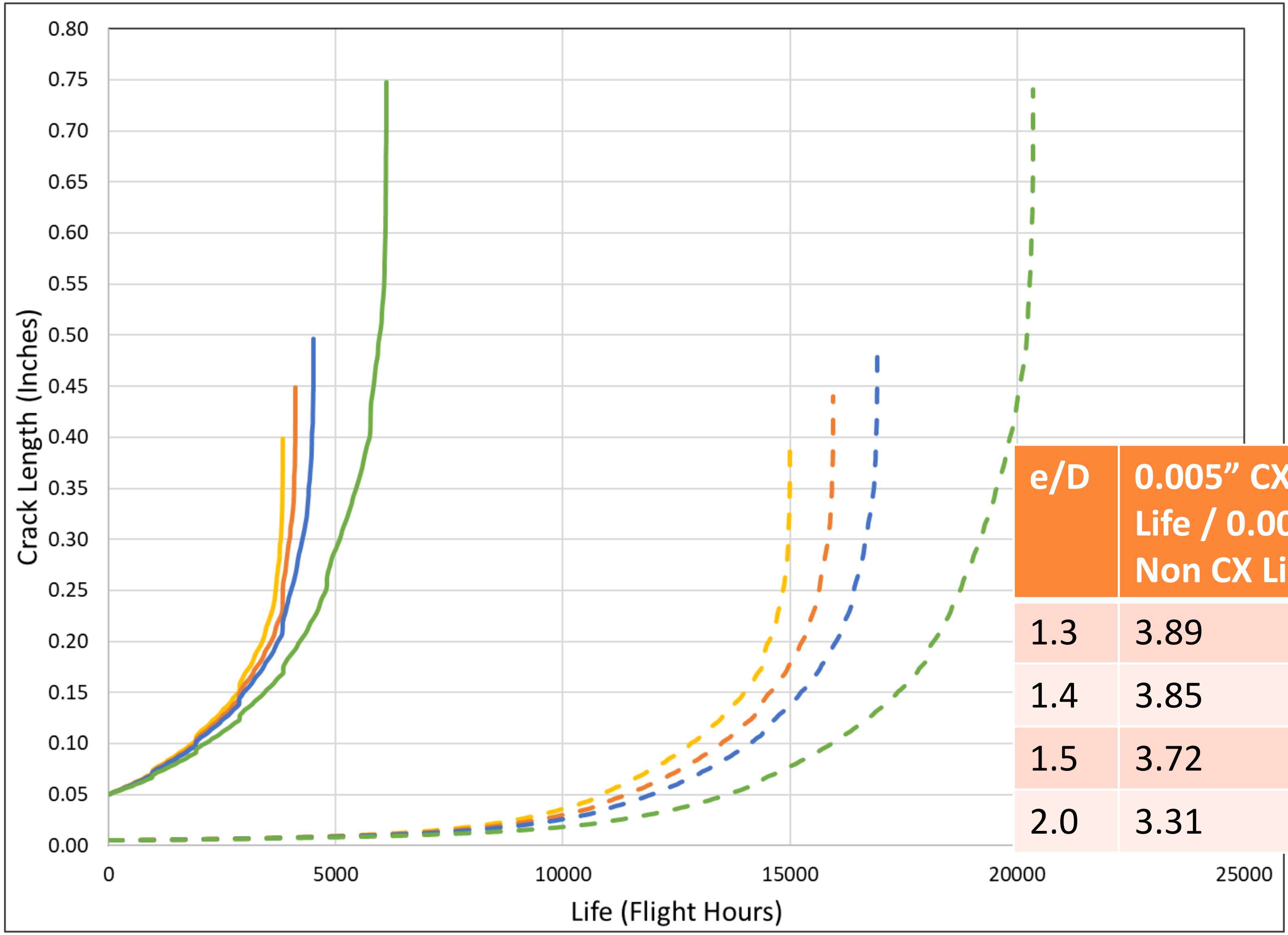
RECENT EXAMPLE
SHORT EDGE MARGIN TESTS

- Spectrum loaded – 33 ksi (227 Mpa) max spectrum stress
- e/D = 1.3, 1.4, 1.5, 2.0



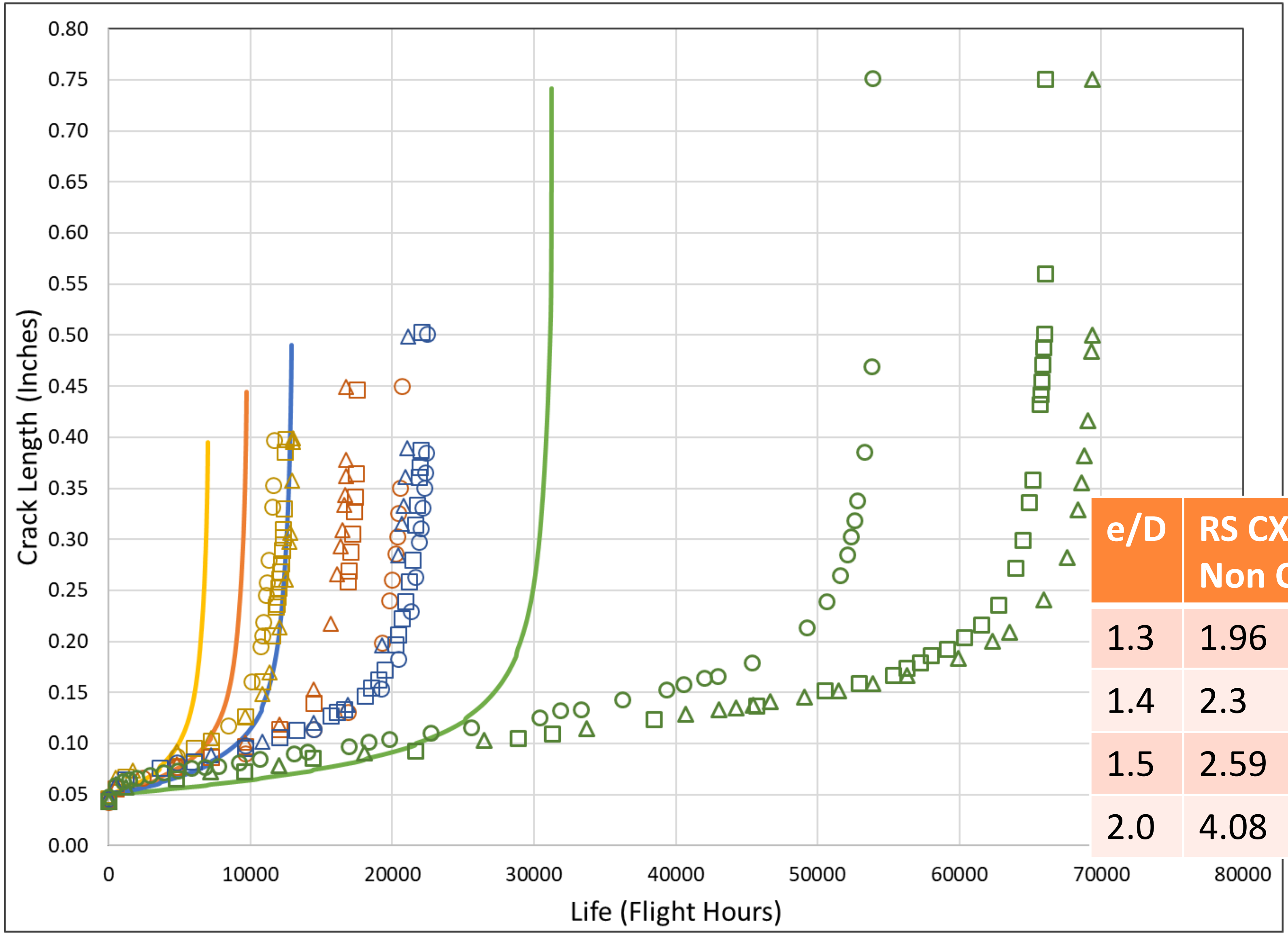
NCX200ED-1 Crack Growth

SHORT EDGE MARGIN TESTS 0.005" COMPARISONS

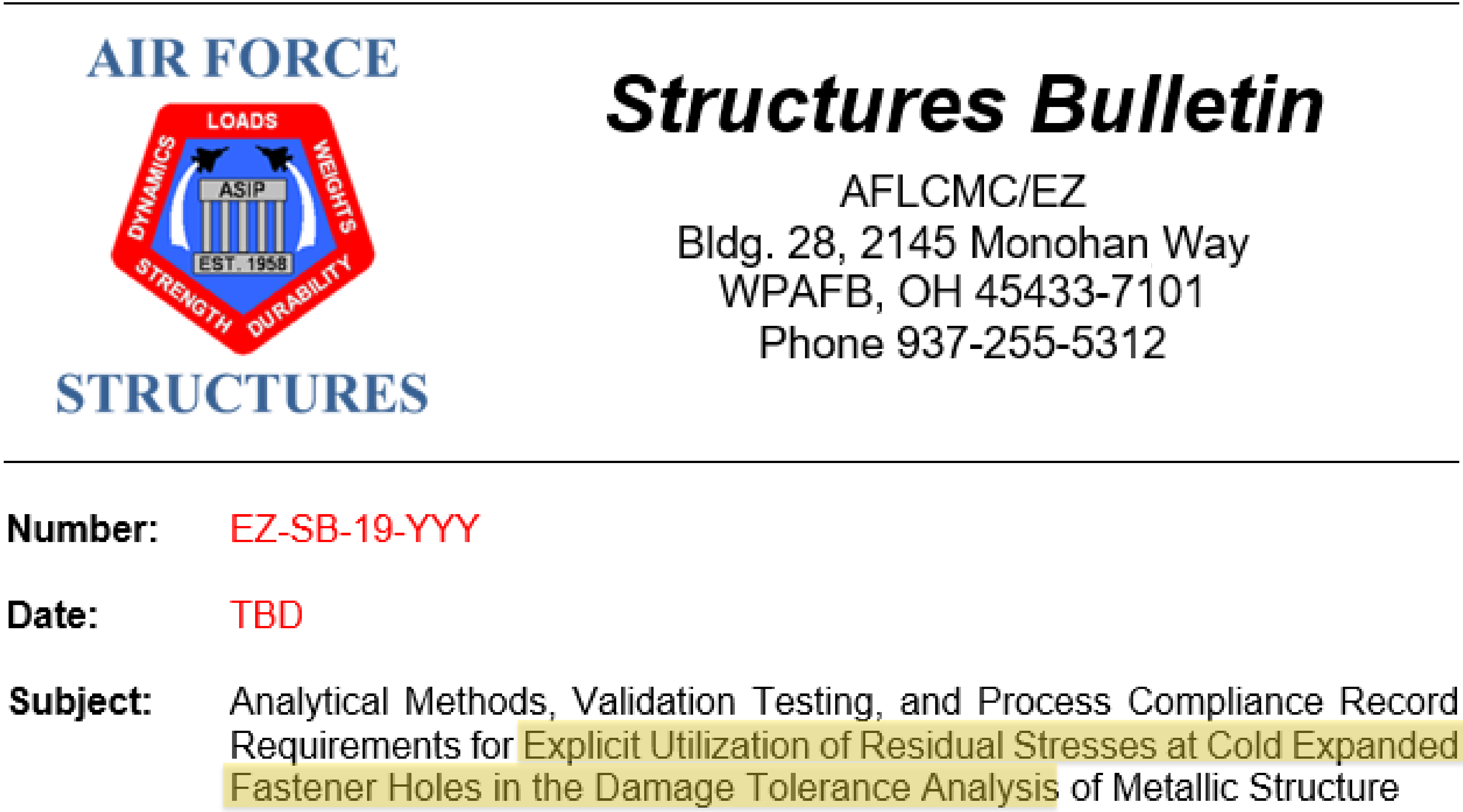


e/D	0.005" CX Life / 0.005" Non CX Life	Test CX Life / Test Non CX Life
1.3	3.89	3.44
1.4	3.85	4.3
1.5	3.72	4.39
2.0	3.31	8.22

SHORT EDGE MARGIN TESTS
BLIND EXPLICIT RS PREDICTIONS



e/D	RS CX Life / RS Non CX Life	Test CX Life / Test Non CX Life
1.3	1.96	3.44
1.4	2.3	4.3
1.5	2.59	4.39
2.0	4.08	8.22



AIR FORCE
STRUCTURES

Structures Bulletin

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

Number: EZ-SB-19-YYY

Date: TBD

Subject: 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

DEFINING SUCCESS CRITERIA

👍

👎

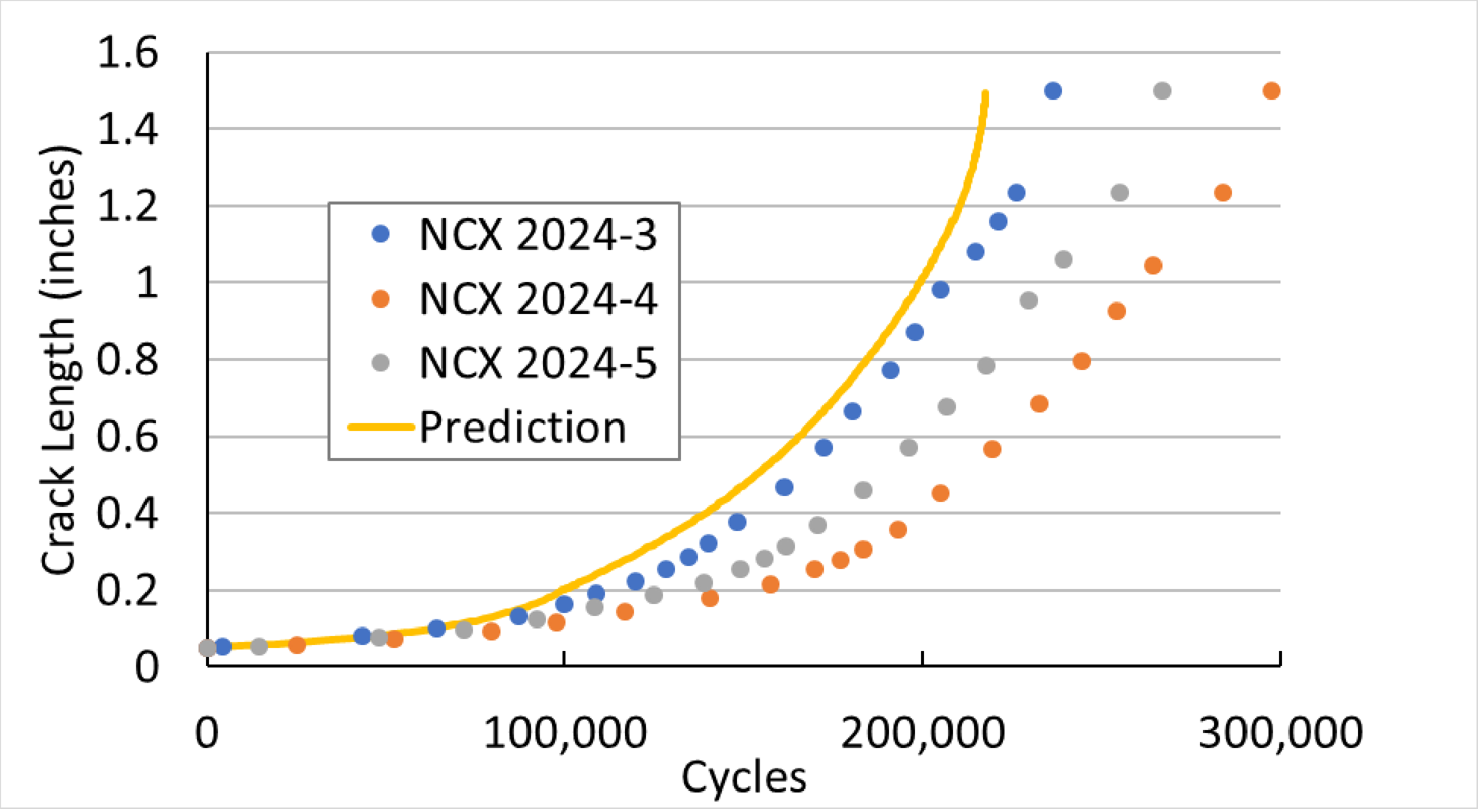
Creator: Rich Niewiroski Jr
Credit: Rich Niewiroski Jr.
Copyright: © Rich Niewiroski Jr. 2007

https://www.masstlc.org/alignment-the-key-to-high-growth/

1. Define Requirements
2. Offer Recommendations

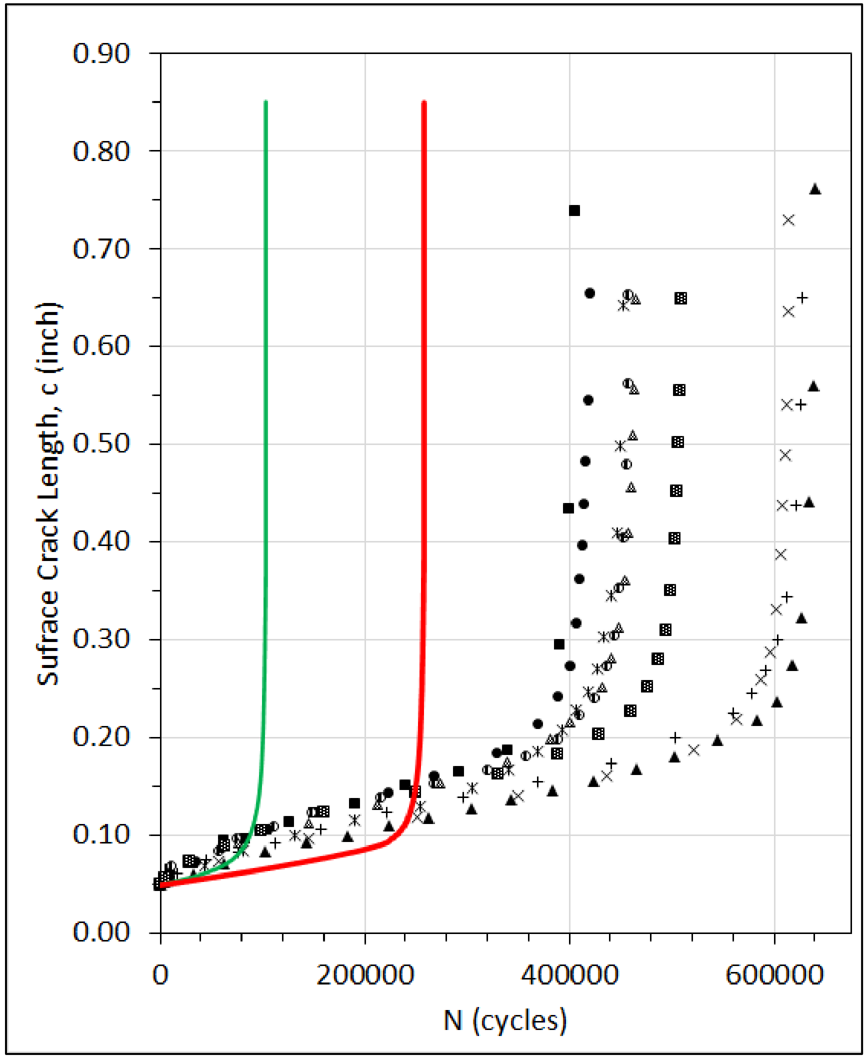
REQUIREMENT: CORRELATION TO TEST

- Require correlation to both CX and Non CX tests
  - Non CX
    - 3 test minimum
    - Prediction matches test average within 20%
    - Prediction matches each test within 50%



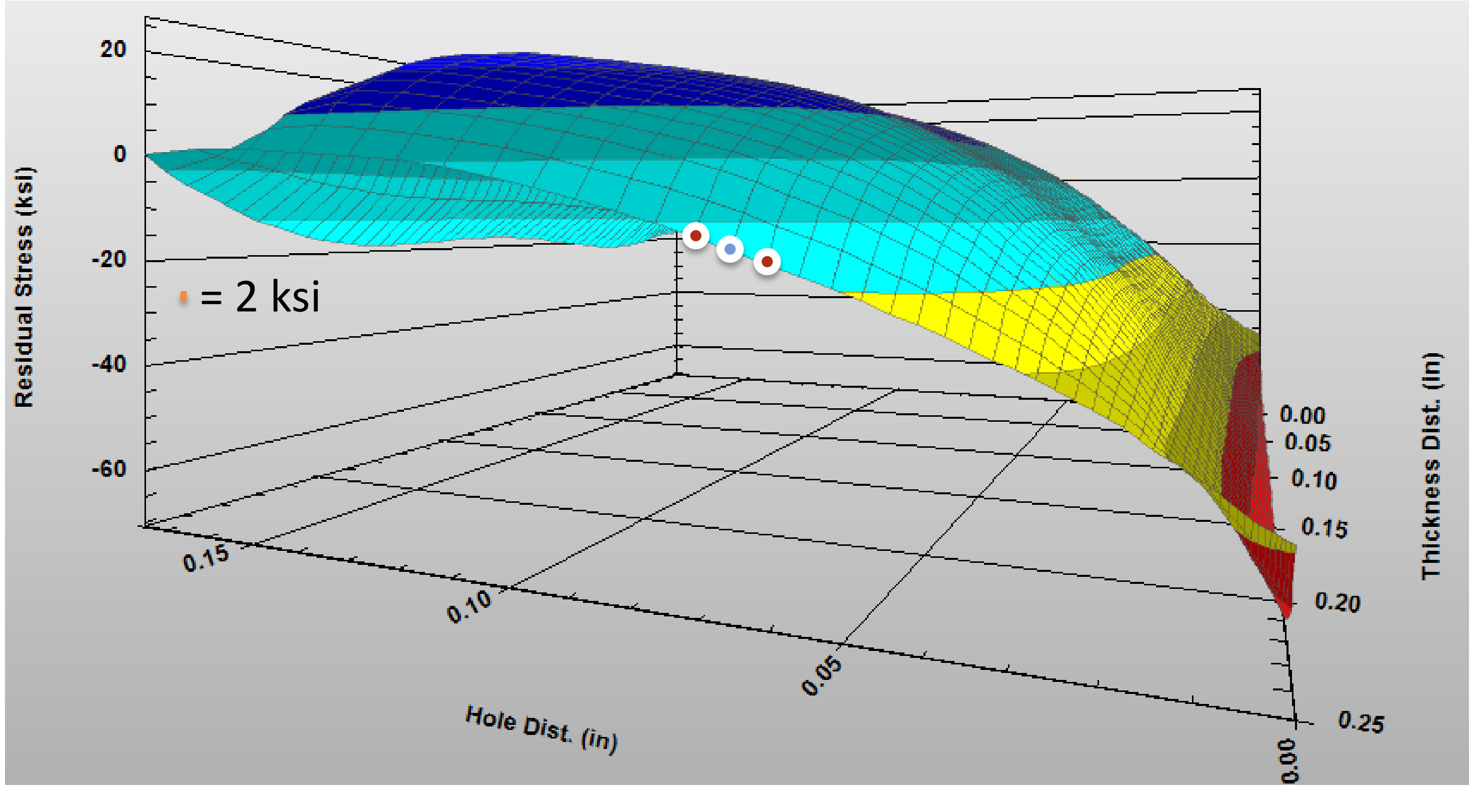
REQUIREMENT: CORRELATION TO TEST

- Require correlation to both CX and Non CX tests
  - Non CX
    - 3 test minimum
    - Prediction matches test average within 20%
    - Prediction matches each test within 50%
  - CX
    - 5 test minimum
    - Two predictions required
      - Mean expected life
        - 0.5 * Test Average < Prediction < 1.2 * Test Average
      - Min expected life
        - Prediction < 0.8 * Test min



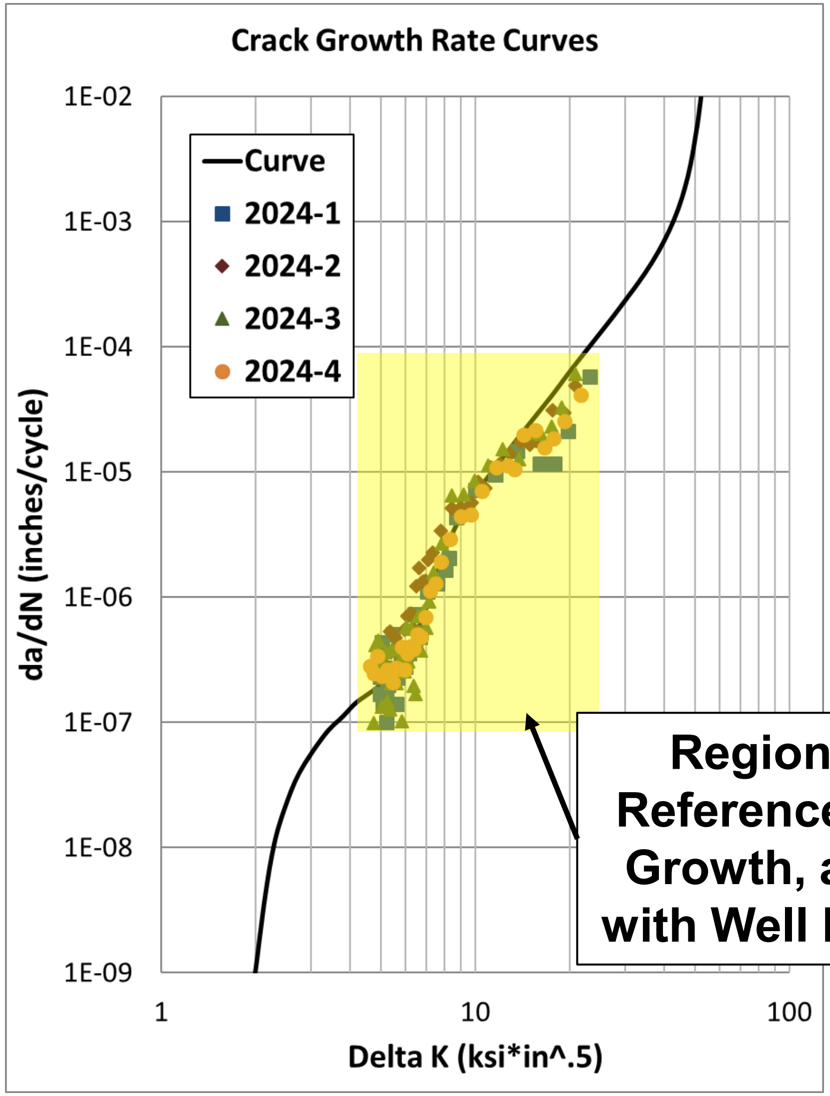
RECOMMENDATION: SPATIAL RESOLUTION

- Correlation to test is *requirement*
- *Recommendation* to resolve residual stress field within ~2-5 ksi (14-35 Mpa)



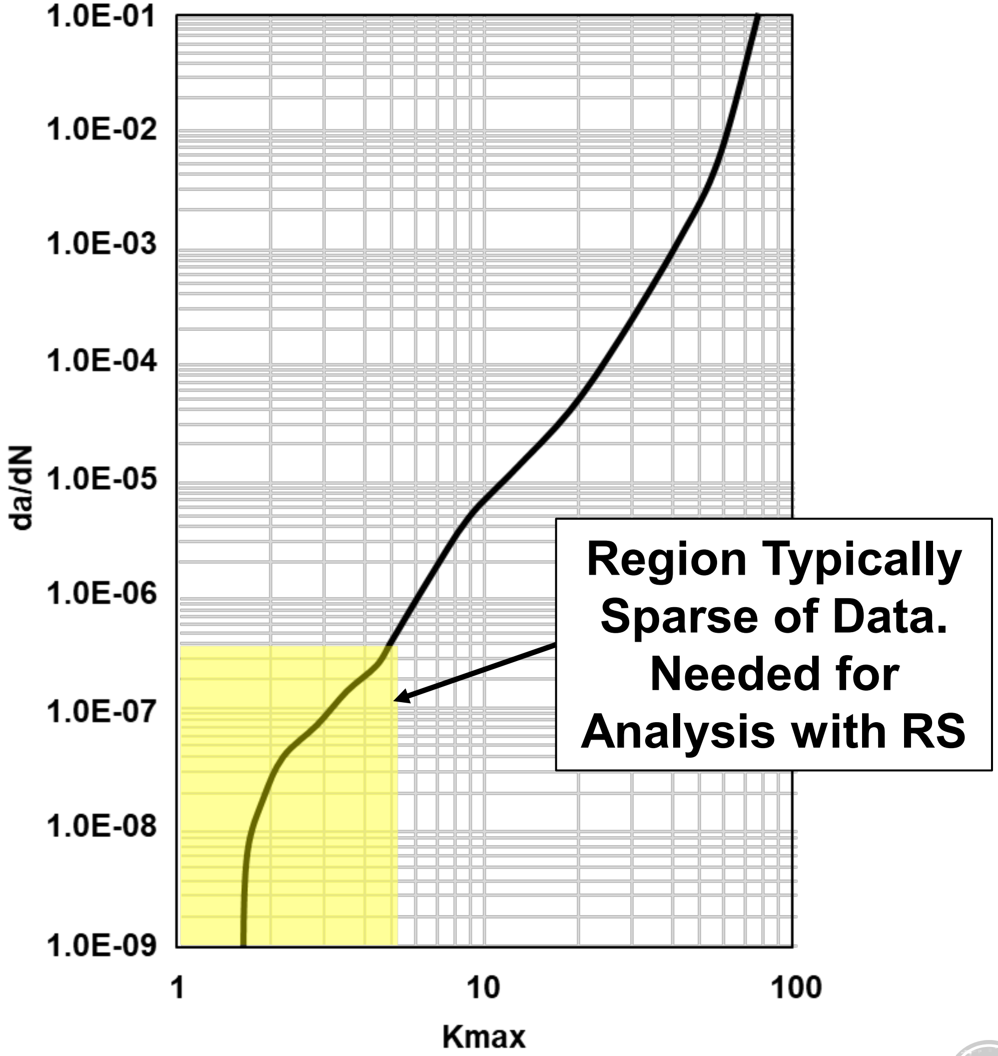
2024-T351
e/D = 1.2
D = 0.25
t = 0.25
3% CX

RECOMMENDATION: RATE DATA EVALUATION



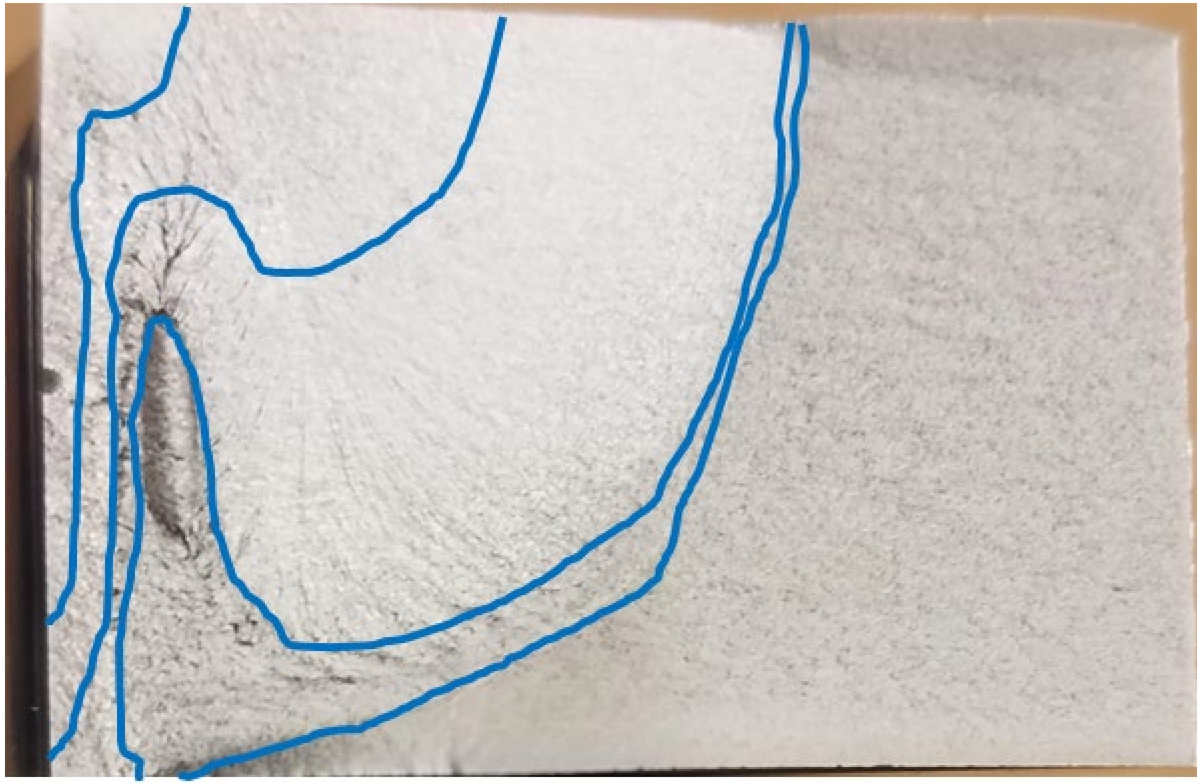
Region Typically Referenced for Crack Growth, also Region with Well Defined Data

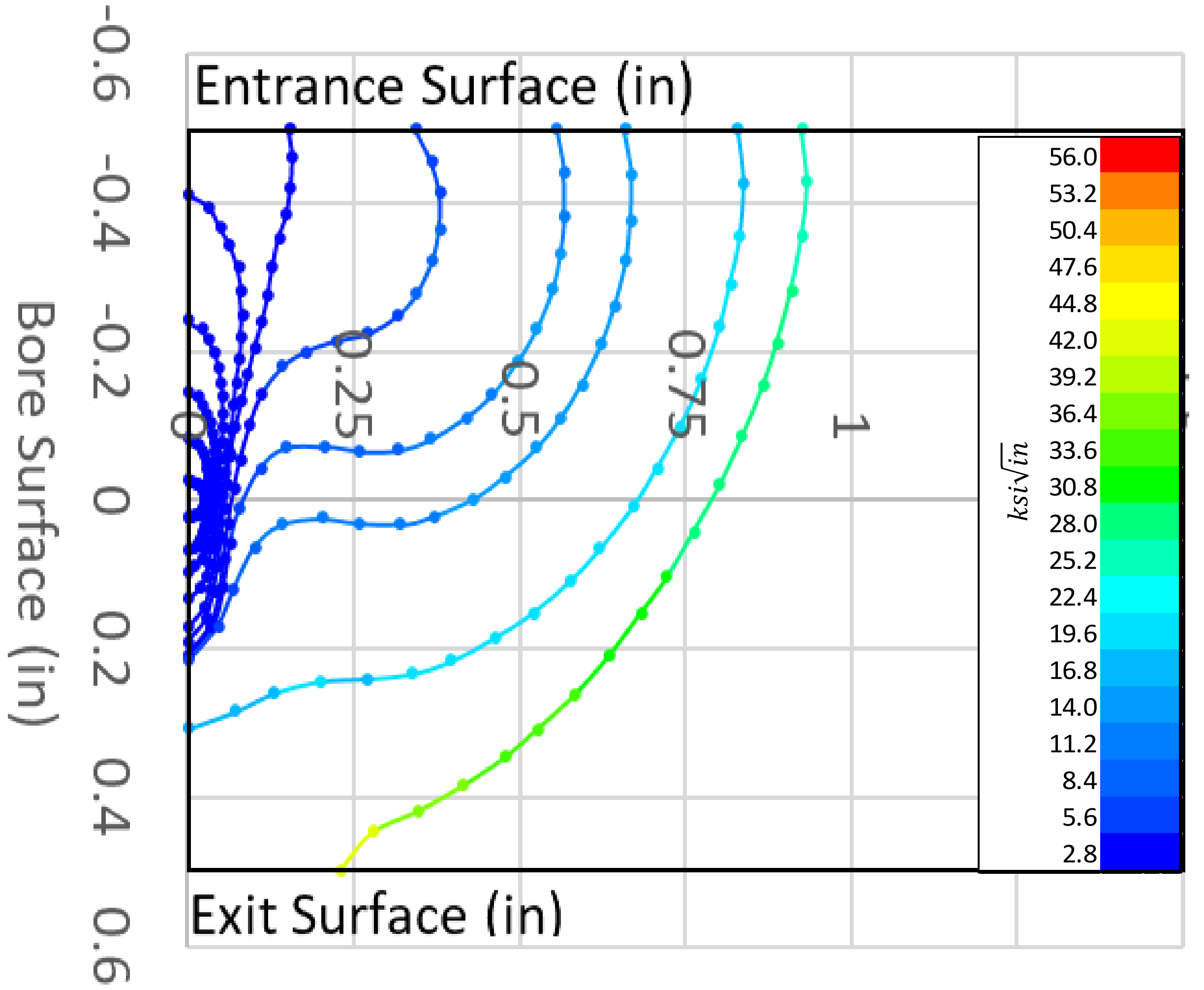
Superimpose Residual Stress



Region Typically Sparse of Data. Needed for Analysis with RS

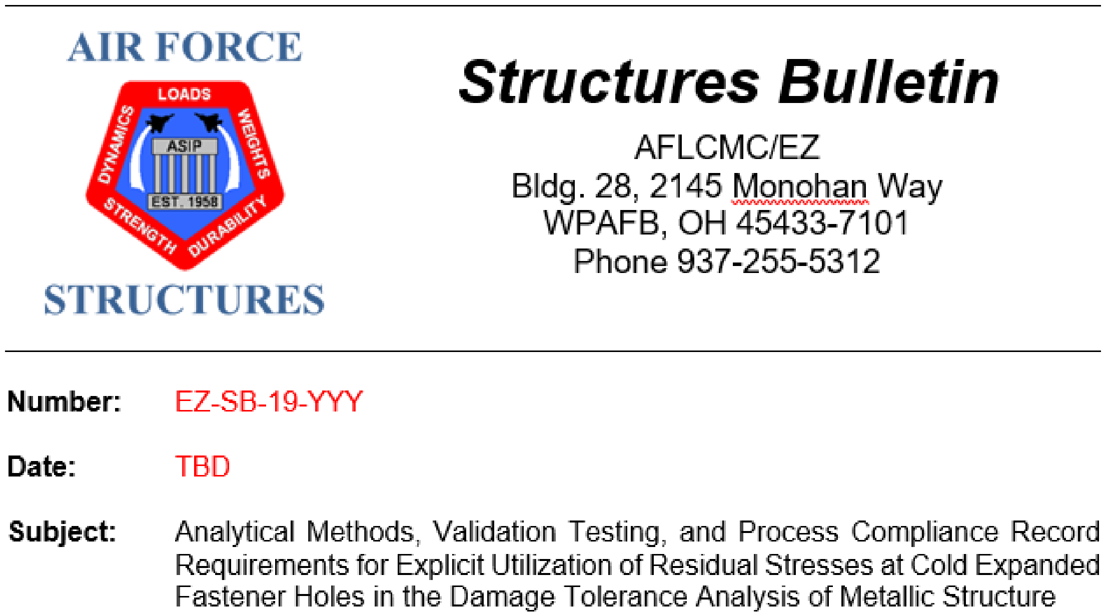
RECOMMENDATION: POINTS ALONG CRACK FRONT





CONCLUSIONS

- *Requirement* is correlation to test
- *Recommendations* can help meet the requirement



AIR FORCE STRUCTURES

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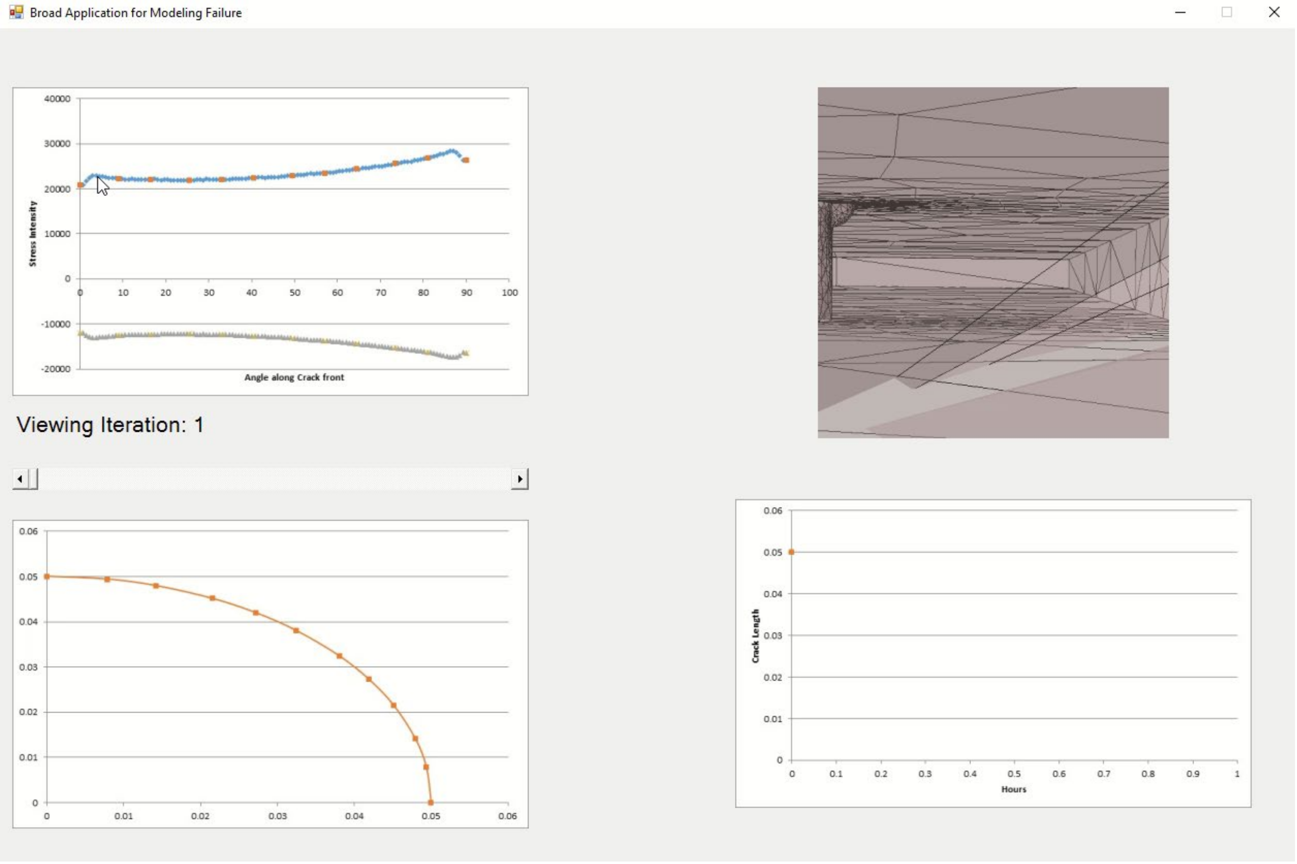


Viewing Iteration: 1

Literature Review

Literature Review

- Objective
  - Develop a consolidated summary of Cx references for the community
  - Increase visibility of existing Cx references
- Status
  - Developed a template to identify key parameters
  - Divvied out responsibility to populate amongst community

Source Information						Scope			Geometric Details					Cx Details				Testing Details	
Title	**Source**	**Date published**	**Author**	**DOI link**	**Reference POC**	**Goal/Abstract Summary**	**Type of data (Analysis/Testing)**	**Compare to reduced IFS approach?**	**Material/s**	**Final Hole Diameter**	**Edge Margin (e/D)**	**Hole (Straight/Csk)**	**Hole Fill (Open/Filled/Interference)**	**Cx Level**	**Cx Order (Before/After Crack)**	**Final Ream (Y/N)**	**Residual Stress Measurement Data?**	**Loading (CA/VA)**	**Crack Formation (Natural/Notched)**
Experimentally derived beta corrections to predict fatigue crack growth at cold expanded holes in 7075-T651 aluminum alloy	MS Thesis; University of Utah	Aug-08	Pilarczyk		Pilarczyk	Quantify life benefit of CX and derive beta corrections to accurately model life in 7075-T651	Both	Y	7075-T651	0.5	Center	Straight	Open	Nom	After	Y	N	CA	Notched
Experimentally derived beta corrections to accurately model the fatigue crack growth behavior at cold expanded holes in 2024-T351 aluminum alloys	MS Thesis; University of Utah	Aug-08	Carlson		Carlson	Quantify life benefit of CX and derive beta corrections to accurately model life in 2024-T351	Both	Y	2024-T351	0.5	Center	Straight	Open	Nom	After	Y	N	CA	Notched
Investigation of cold expansion of short edge margin holes with preexisting cracks in 2024-T351 aluminum alloy	MS Thesis; University of Utah	Dec-11	Andrew		Andrew	Quantify life benefit of short edge margin (e/D=1.2) CX holes under constant amplitude and fighter wing root bending spectrum loading	Both	Y	2024-T351	0.5	1.2	Straight	Open	Nom	Both	Y	N	Both	Notched
Cold Expansion Effects on Cracked Fastener Holes under Constant Amplitude and Spectrum Loading in the 2024-T351 Aluminum Alloy	MS Thesis; University of Utah	May-12	Warner		Warner	Quantify life benefit of precracked CX hole and compare to 0.005" IFS for fighter wing root bending spectrum at multiple stress levels	Both	Y	2024-T351	0.5	Center	Straight	Open	Nom	Before	Y	N	Both	Notched
Integrating Residual Stress Analysis of Critical Fastener holes into USAF depot maintenance	Rapid Innovation Fund	Feb-14	Mills		Mills	Quantify residual stress field and benefit at CX process tolerance extremes as well as nominal conditions	Both	Y	7075-T6 7075-T651 7075-T7351 2024-T3 2024-T351	0.25 0.375 0.5	Center	Straight	Open	High Middle Low	Both	Y	Y	Both	
Cold Expanded Hole Testing Summary	USAF Contract F34601-88-C-0392	Sep-90	Boeing		Warner	Summarize CX test data for CX application recommendations on B-52 and KC-135	Testing	N	7075-T411 7178-T651 7079-T6 7075-T6	0.375 0.5 0.875	Center 2.0 1.5 1.25 1.2 1.0	Both	Open	Nom	Both	Y	N	VA	Notched
Effects of Variations in Coldworking Repair Procedures on Flaw Growth and Structural Life (AFWAL-TR-82-3030)	AFWAL	Apr-84	J. M. Pearson-Smith, Lt		Warner	Quantify CX benefit in light of a final or starting hole diameter larger than permitted by CX process	Testing	N	7075-T651	0.25	Center	Straight	Open	Low	After	Both	Y	VA	Natural
Stress Analysis of Coldworked Fastener Holes (AFML-TR-74-44)	AFML	Jul-74	William F. Adler		Warner	Quantify residual stress/strain from CX and redistribution from tensile overloads analytically and experimentally	Both	N/A	7075-T6	0.25	Center	Straight	Open	Nom	N/A	Y	Y	N/A	N/A

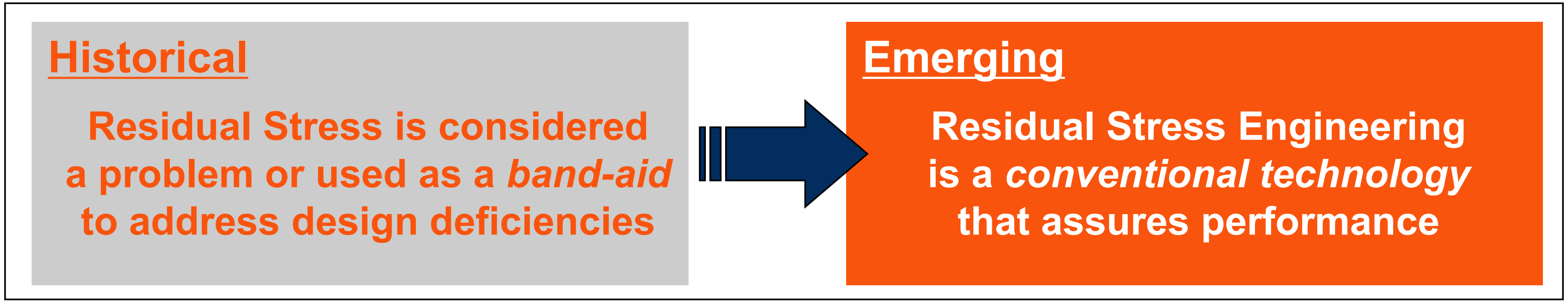
ERSI

Timeline of Research Efforts Related to the Application of Residual Stresses into Damage Tolerance Analysis for USAF weapon systems

U.S. AIR FORCE

Conclusions/Summary

- Incrementally, we are making progress within the Analysis Methods and Validation Testing Committees
  - Thanks to those individuals that have contributed
- We must continue to push forward with a focus on refining our analytical capability and addressing technical gaps



Historical

Residual Stress is considered a problem or used as a *band-aid* to address design deficiencies

Emerging

Residual Stress Engineering is a *conventional technology* that assures performance

Questions?