ENGINEERED RESIDUAL STRESS IMPLEMENTATION (ERSI) WORKSHOP 2019

Wednesday, September 11, 2019	
USTAR Innovation Center | 633 Falcon Hill Drive, Clearfield, UT 84015	
SPECIAL SESSION FOR: ***ERSI Committee Leads & ERSI Executive Committee***	
4:30 PM to 5:00 PM *Wednesday, September 11, 2019*	**Arrive and Greeting**
5:00 PM to 8:00 PM *Wednesday, September 11, 2019*	**Group Discussion of ERSI Vision, Strategic Vision, Technology Gaps, and Structures Bulletin** *Dinner will be served*

Thursday, September 12, 2019	
Weber State University Center for Continuing Education *775 University Park Blvd, Clearfield UT 84015*	
8:00 AM to 8:30 AM *Thursday, September 12, 2019*	**Arrive and Breakfast**
8:30 AM to 8:45 AM *Thursday, September 12, 2019*	**Welcome** *Mr. Dallen Andrew, Dr. Scott Carlson, Mr. Robert Pilarczyk*
8:45 AM to 10:40 AM *Thursday, September 12, 2019*	**Presentations by Leads Covering Progress, Session 1** *(25 minute presentations, 15 minutes discussion)*
8:45 AM to 9:15 AM	Executive Committee Review – Programmatic Overview, Strategic Vision, and Structures Bulletin Update *Dr. Scott Carlson (Lockheed Martin)*
9:15 AM to 9:55 AM	Residual Stress Process Simulation *Mr. Keith Hitchman (FTI)*
10:00 AM to 10:40 AM	Residual Stress Measurement *Dr. Mike Hill (Hill Engineering)*
10:40 AM to 10:50 AM *Thursday, September 12, 2019*	**BREAK**
10:50 AM to 12:10 PM *Thursday, September 12, 2019*	**Presentations by Leads Covering Progress, Session 2** *(25 minute presentations, 15 minutes discussion)*
10:50 AM to 11:30 AM	Fatigue Crack Growth Analysis Methods *Mr. Robert Pilarczyk (Hill Engineering)*
11:30 AM to 12:10 PM	Validation Testing *Mr. Jacob Warner (USAF A-10 ASIP)*
12:10 PM to 12:30 PM *Thursday, September 12, 2019*	**WORKING LUNCH** *(Served at the Workshop)*

Thursday, September 12, 2019 (continued)	
12:30 PM to 2:30 PM *Thursday, September 12, 2019*	**Presentations by Leads Covering Progress, Session 3** *(25 minute presentations, 15 minutes discussion)*
12:30 PM to 1:10 PM	Non-Destructive Inspection *Mr. John Brausch (USAF AFRL)*
1:10 PM to 1:50 PM	Quality Assurance and Data Management *Mr. Kaylon Anderson (USAF A-10 ASIP)*
1:50 PM to 2:30 PM	Risk Analysis and Uncertainty Quantification *Mr. Lucky Smith (SwRI) | Ms. Laura Hunt (SwRI)*
2:30 PM to 3:00 PM ***Thursday, September 12, 2019***	**Open Discussion**
3:00 PM to 5:30 PM ***Thursday, September 12, 2019***	**Breakout Discussions, Session 1**
Room (as assigned):	*Fatigue Crack Growth Analysis Methods & Validation Testing*
Room (as assigned):	*Residual Stress Process Simulation*
Room (as assigned):	*Quality Assurance and Data Management*

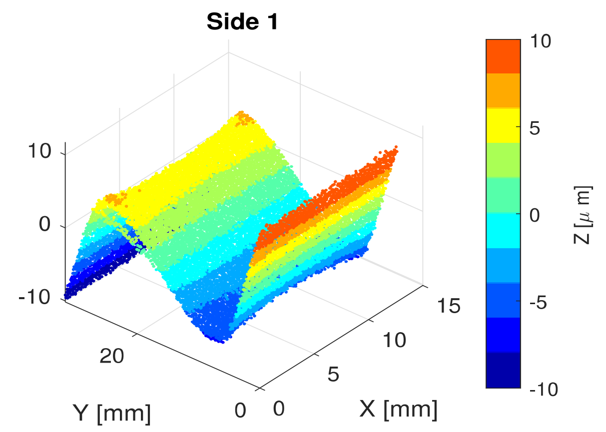
Friday, September 13, 2019	
Weber State University Center for Continuing Education ***775 University Park Blvd, Clearfield UT 84015***	
8:00 AM to 8:30 AM ***Friday, September 13, 2019***	**Arrive and Breakfast**
8:30 AM to 10:30 AM ***Friday, September 13, 2019***	**Breakout Discussions, Session 2**
Room (as assigned):	*Fatigue Crack Growth Analysis Methods & Validation Testing*
Room (as assigned):	*Residual Stress Measurement*
Room (as assigned):	*Non-Destructive Inspection*
Room (as assigned):	*Risk Analysis and Uncertainty Quantification*
10:30 AM to 1:00 PM ***Friday, September 13, 2019***	**Open Discussion and Lunch** (*Lunch provided by Hill Engineering)* Topics: Review, Future Planning, Governance, Funding
BY INVITATION ***Friday, September 13, 2019***	***SPECIAL SESSION FOR USAF ONLY*** *Dr. TJ Spradlin (USAF AFRL)*

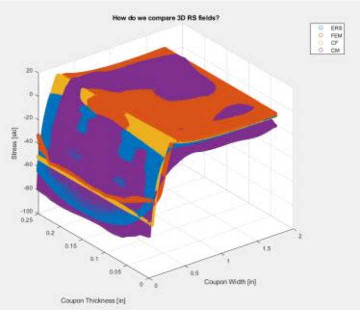
2019 Engineered Residual Stress Implementation (ERSI) Workshop 2019

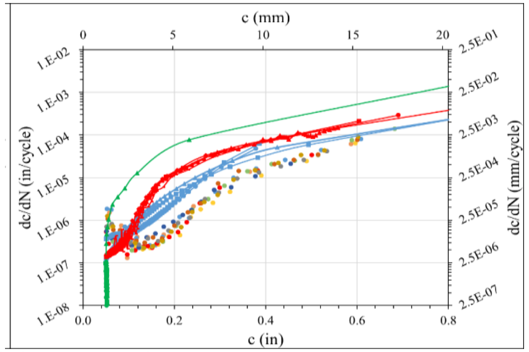
Announcements

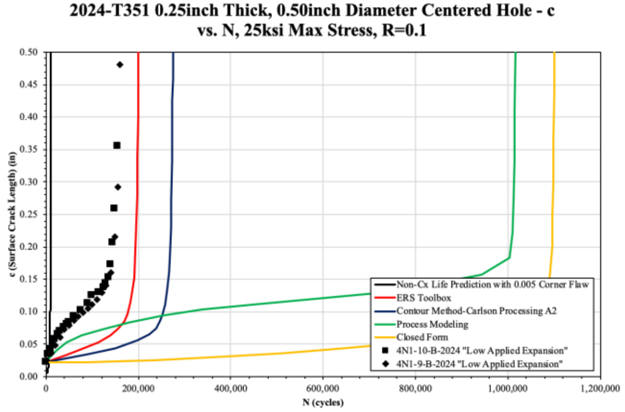
- Welcome to the 4th Annual ERSI Workshop
- Agenda is Flexible but Should Follow the one that was Printed/Provided
- Wi-Fi Information Provided on the Board
- Please Provide Presentations to Organizers (Carlson, Pilarczyk, Andrew)
- Lunch will be Provided both Days – Donations are welcome this year
- **Presentation are to Encourage Discussion – Please Ask Questions**

- **THANK YOU FOR COMING AND ENJOY!**









ERSI

Overview of Working Group Structure

Total Individuals within the Working Group - 78

- Countries Involved - 4
- DoD Organizations - 3 + FAA
- National Laboratory - 2
- Universities - 8
- OEMs - 4
- Industry Partners - 18
- Weapon Systems - 13

ERSI Executive Committee
Dr. Dale Ball (Lockheed Martin)
Dr. TJ Spradlin (USAF AFRL)

Mr. Dallen Andrew (Hill Engineering)
Dr. Scott Carlson (Lockheed Martin)
Mr. Robert Pilarczyk (Hill Engineering)

Integrator Committee

Technical Advisors
Mr. Chuck Babish (USAF ASIP)
Dr. Michael Gorelik (FAA)

Validation Testing
Mr. Jacob Warner
(USAF A-10 ASIP)

Fatigue Crack Growth Analysis Methods
Mr. Robert Pilarczyk
(Hill Engineering)

Residual Stress Process Simulation
Mr. Keith Hitchman
(FTI)

Data Management & Quality Assurance
Mr. Kaylon Anderson
(USAF A-10 ASIP)

Non-Destructive Inspection (NDI)
Mr. John Brausch
(USAF AFRL)

Residual Stress Measurement
Dr. Mike Hill
(Hill Engineering)

Risk Analysis & Uncertainty Quantification
Ms. Laura Hunt
Mr. Lucky Smith
(SwRI)

Purpose of the ERSI Workshop

1. To identify and **lay out a road map for the implementation of engineered deep residual stress** which can be used in the calculation of initial and recurring inspection intervals for fatigue and fracture critical aerospace components.
2. To **highlight gaps in the stat-of-the-art** and define how those gaps will be filled.
3. Then to define the most **effective way to document requirements and guidelines** for fleet-wide implementation.

ERSI

Vision of ERSI Working Group - 2016

Within 3-7 years have developed a framework for fleet-wide implementation of a more holistic, physics-based approach for taking analytical advantage of the deep residual stresses field, induced through the Cold Expansion process, into the calculations of initial and recurring inaspection intervals for fatigue and fracture critical aerospace components. Then move from there to other deep residual stress inducing processes, like Laser Shock Peening , and Low Plasticity Burnishing.

ERSI

Residual Stress Process Simulation Committee Progress Report

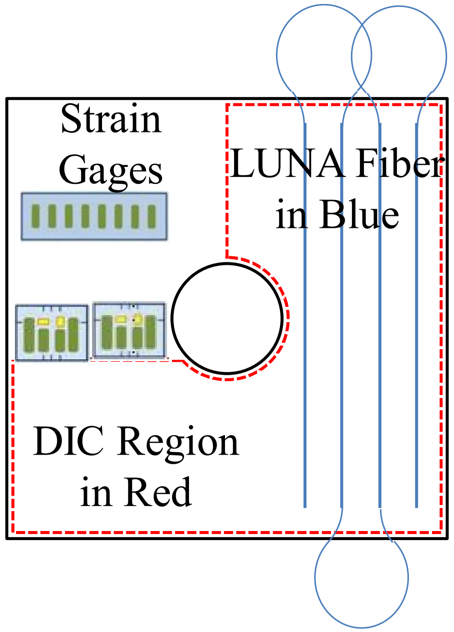
Engineered Residual Stress Implementation Workshop 2019

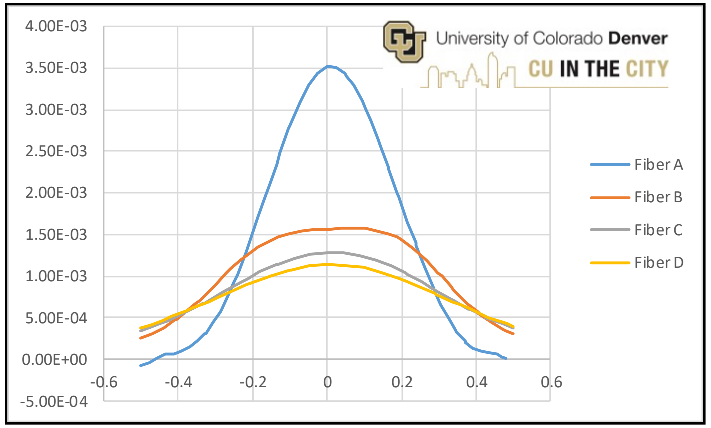
Layton, Utah, USA

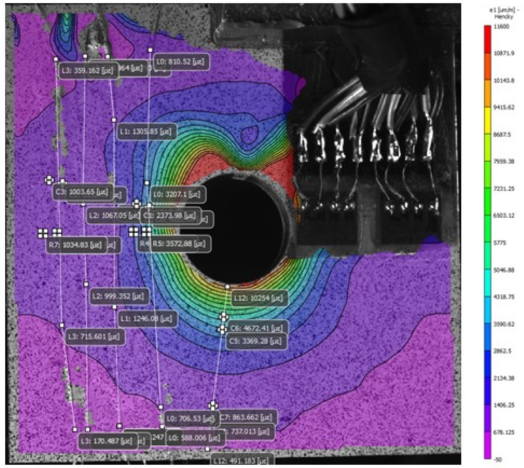
September 12, 2019

Outline

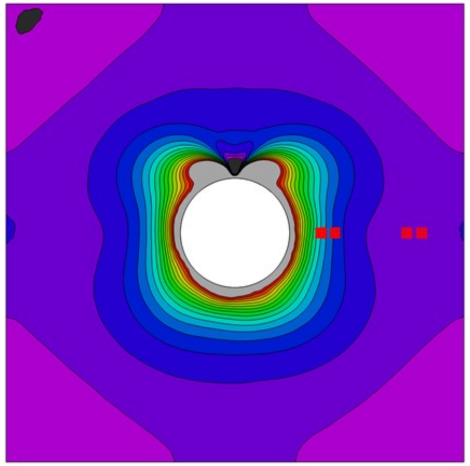
- Committee Activity and Roster Updates
- Material Testing Update – 7075
- Process Simulation Round Robin







DIC Hoop strains



FEA Hoop strains
Chaboche Hardening

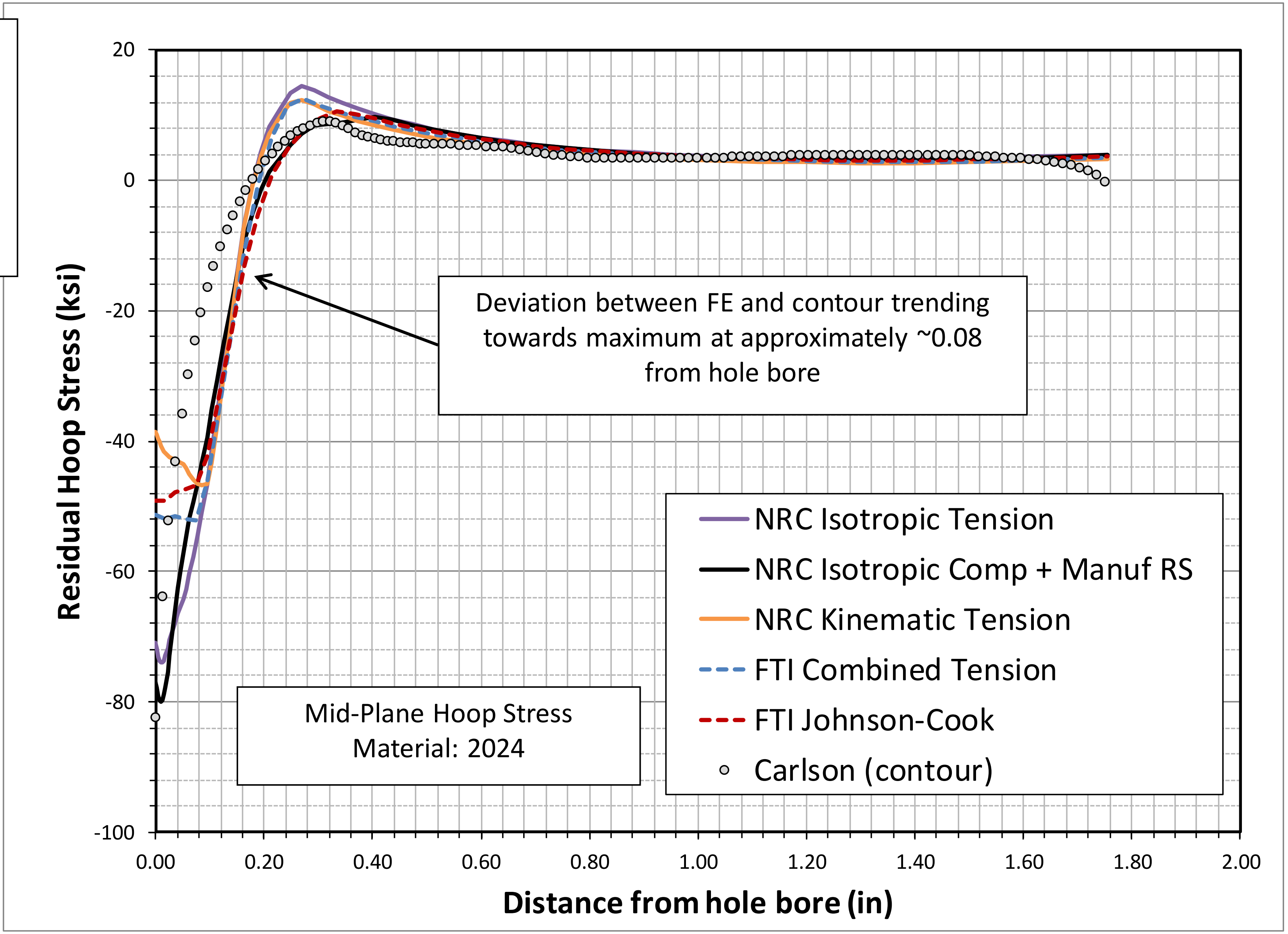
Committee Activity & Roster Updates

- Survey December 2018
  - Set Monthly Meeting to 3rd Friday of each month
  - Move forward with round robin
- Monthly Meetings – thank you for participation
- Welcomed a number of new committee members

    Chris Allen, Booz Allen Hamilton
    Eric Greuner, LM Aero
    Andrew Jones, USAF
    Gavin Jones, SmartUQ
    Thuy Nguyen-Quoc, Boeing
    Dr. Mike Steinzig, LANL
    Michael Worley, SwRI

Material Model Testing - Purpose of Program

Which constitutive model is most appropriate?



Material Model Testing - Purpose of Program

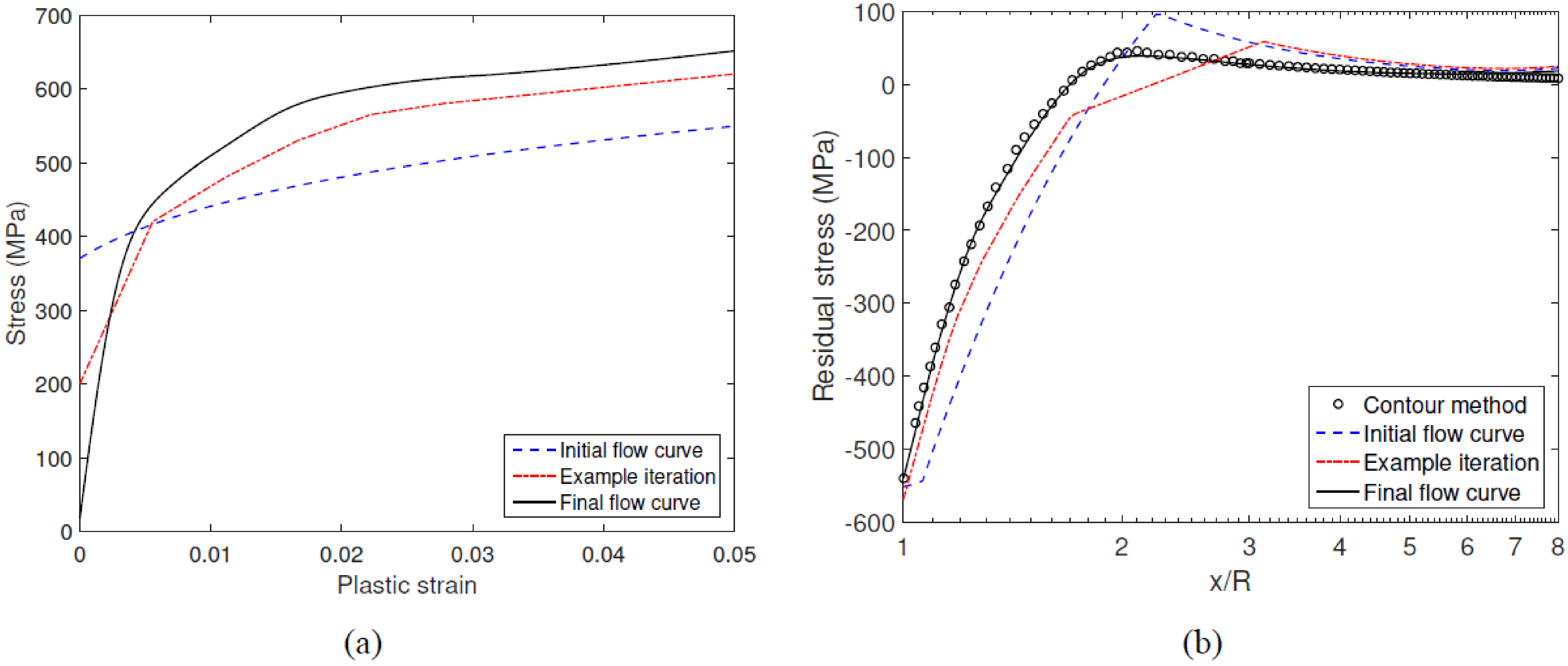
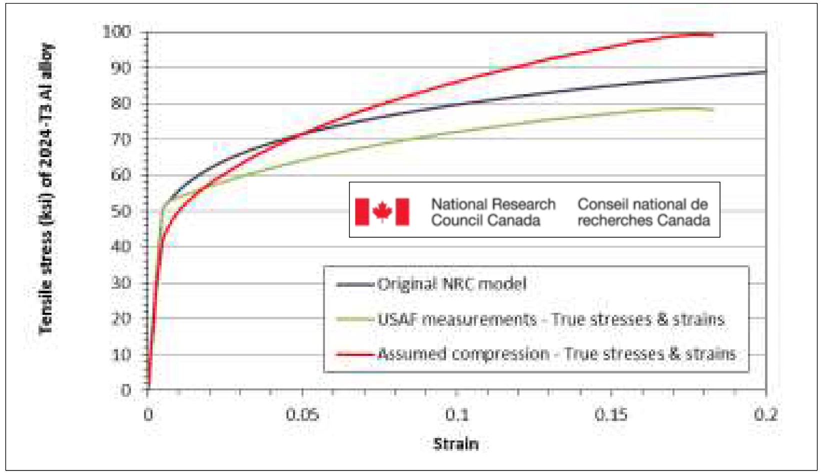


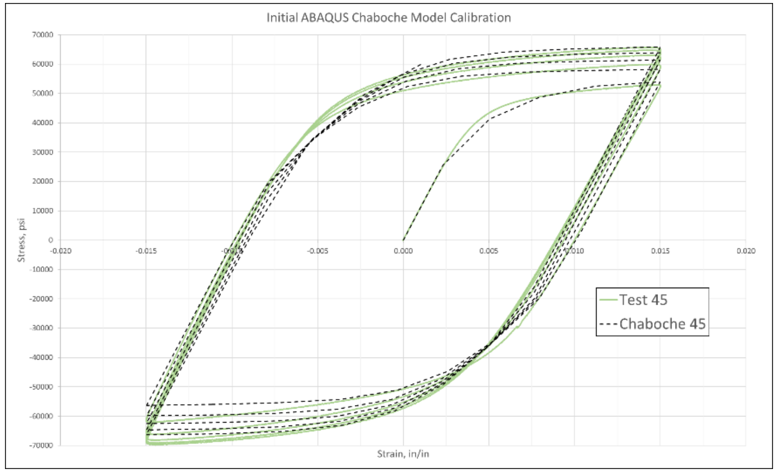
Figure 7 – (a) Flow curves tested, (b) resulting hoop residual stress ($\sigma_{\theta\theta}$); note log scale on x/R

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
- Currently testing 7075, complete early fall 2019





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

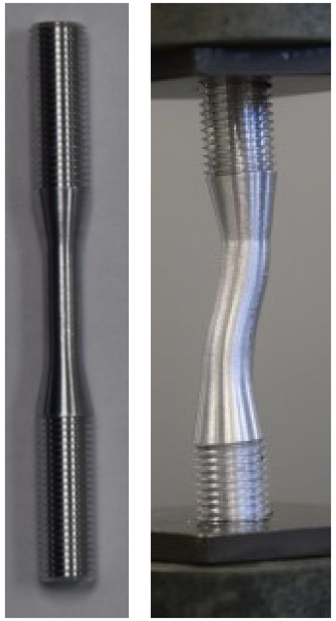
Material Model Testing – Lessons Learned: 2024 to 7075

2024 coupons

- Typical ASTM 606 cylindrical design
- Started to rotate/bend at compressive strains of ~ 1%
- Rotation of the cross-section was detected using a video camera

7075 coupons

- Thick rectangular cross-section to ease detection of bending or rotation
- Dual clip gauge to monitor strain on both surfaces



2024

7075

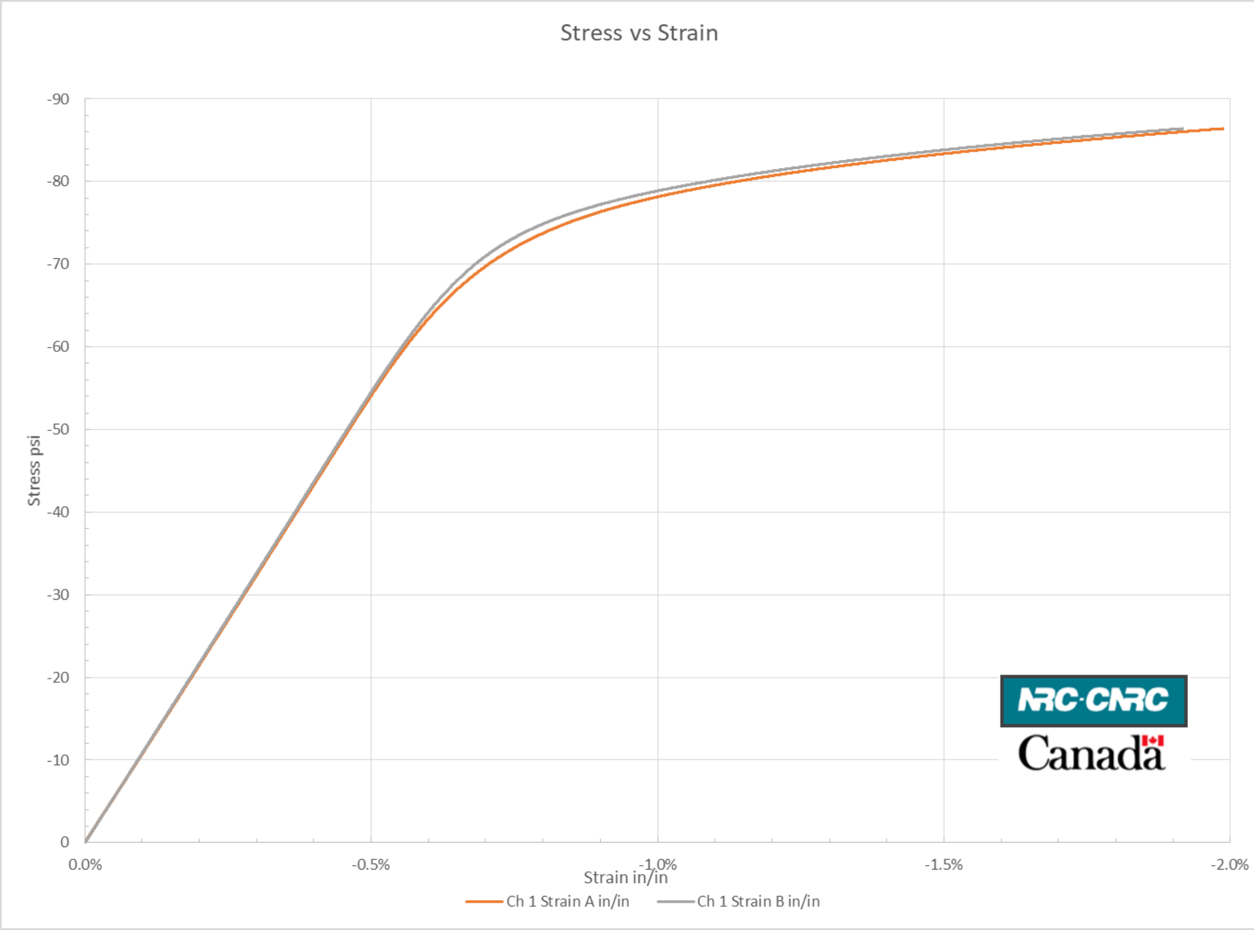
Material Model Testing – 7075 Modifications

- Initial trials showed strain measurement start diverging at approx. 1.5% strain
- Can we still use the average of the two strains to generate material data □ to be verified with FE modeling
- Modifications were made to improve the results:
- The coupons were shortened
- A piston guide for compressive loads was designed and manufactured

NRC·CNRC Canada

Material Model Testing – Current 7075 Status

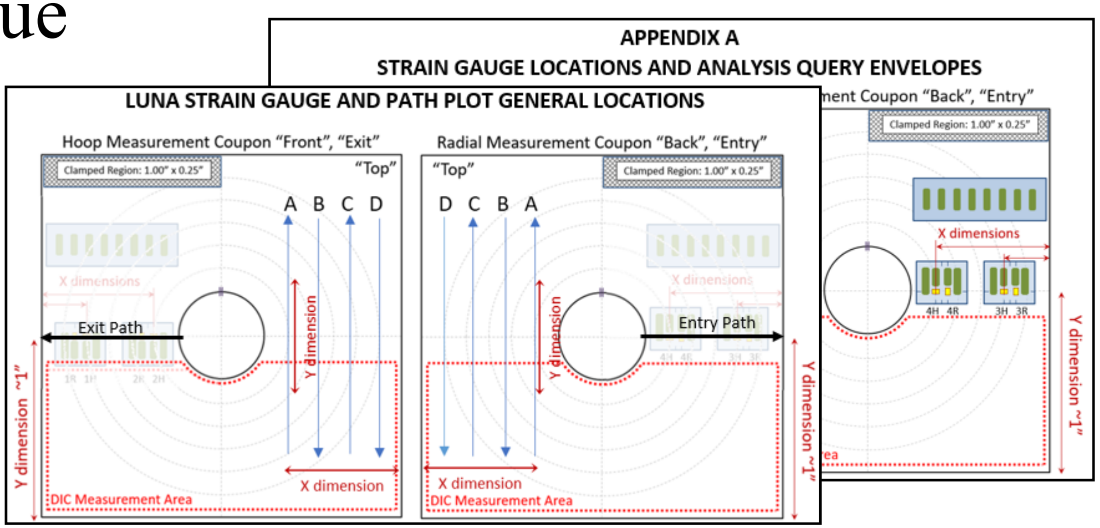
- Relatively uniform compressive strains up to 2% (limit of the current clip gauges) can now be measured.
- Clip gauge that can go up to 10% strain are currently being installed. Will be tested soon.
- Methods to avoid clip gauge slipping will be tested.
- Once the max uniform measurable compressive load is known, discussion will take place with the committee about the test levels and 1-cycle tests will be performed.



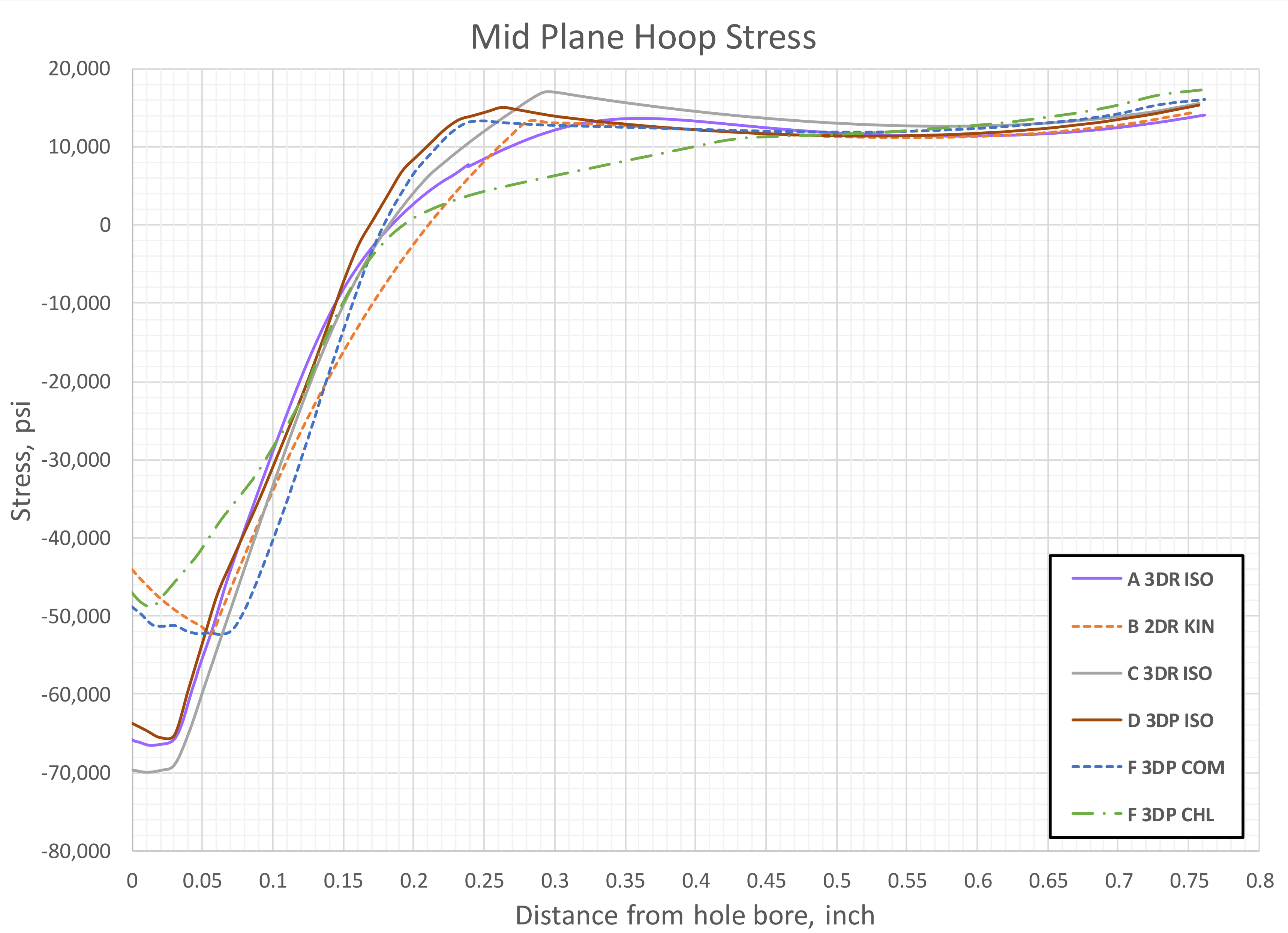
RS Process Simulation Round Robin

- Open to anyone, high interest!
  - Abaqus, StressCheck
  - Pending from MARC, closed form
- Analysis of the 2”x2” coupon cold expansion
  - See right for coupons of interest
  - Current compilation limited to 2024-L2
- Multiple measurement techniques offer a unique opportunity for process simulation validation and correlation.

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		



RS Process Simulation Round Robin – Results



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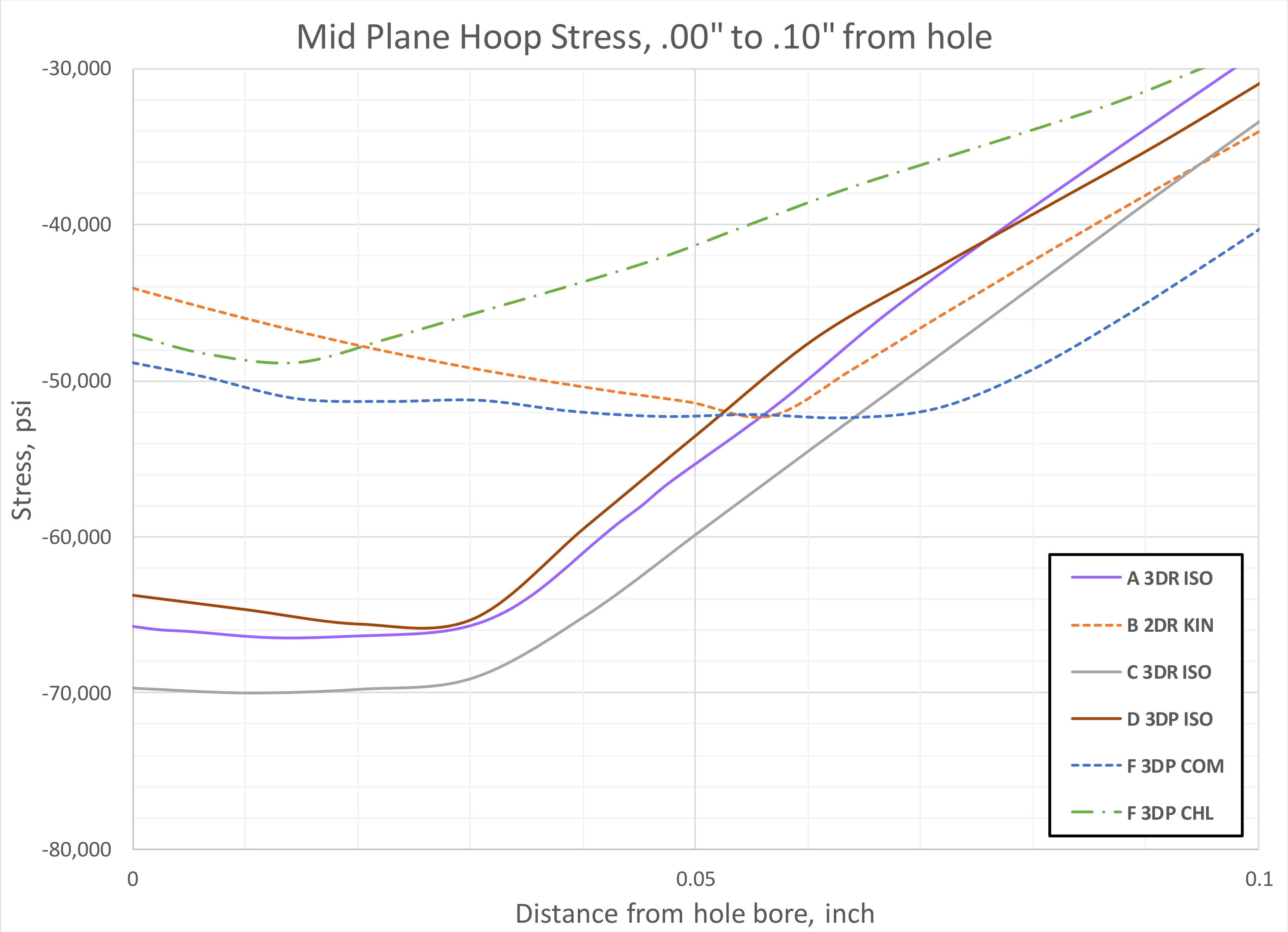

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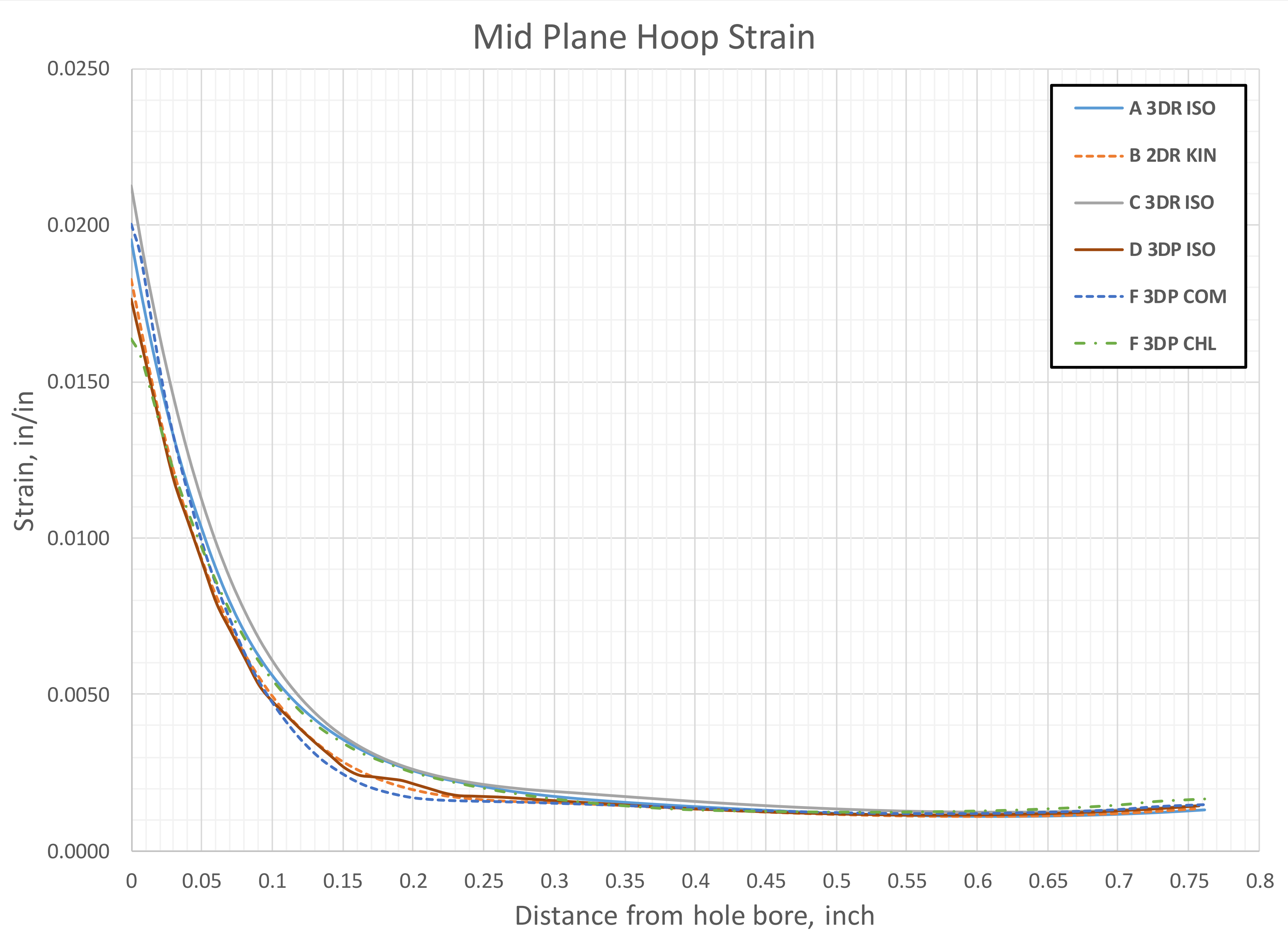

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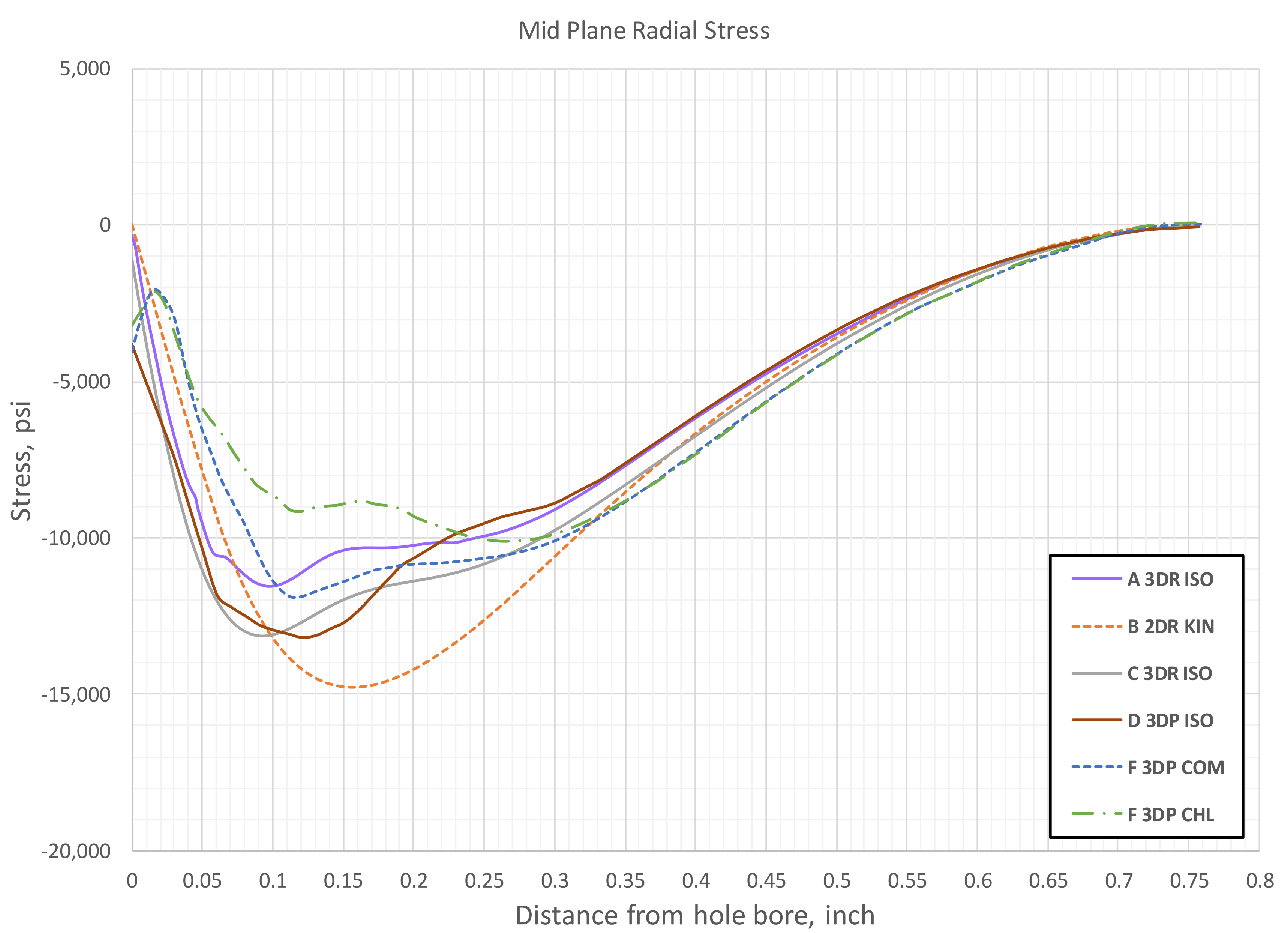
RS Process Simulation Round Robin – Results



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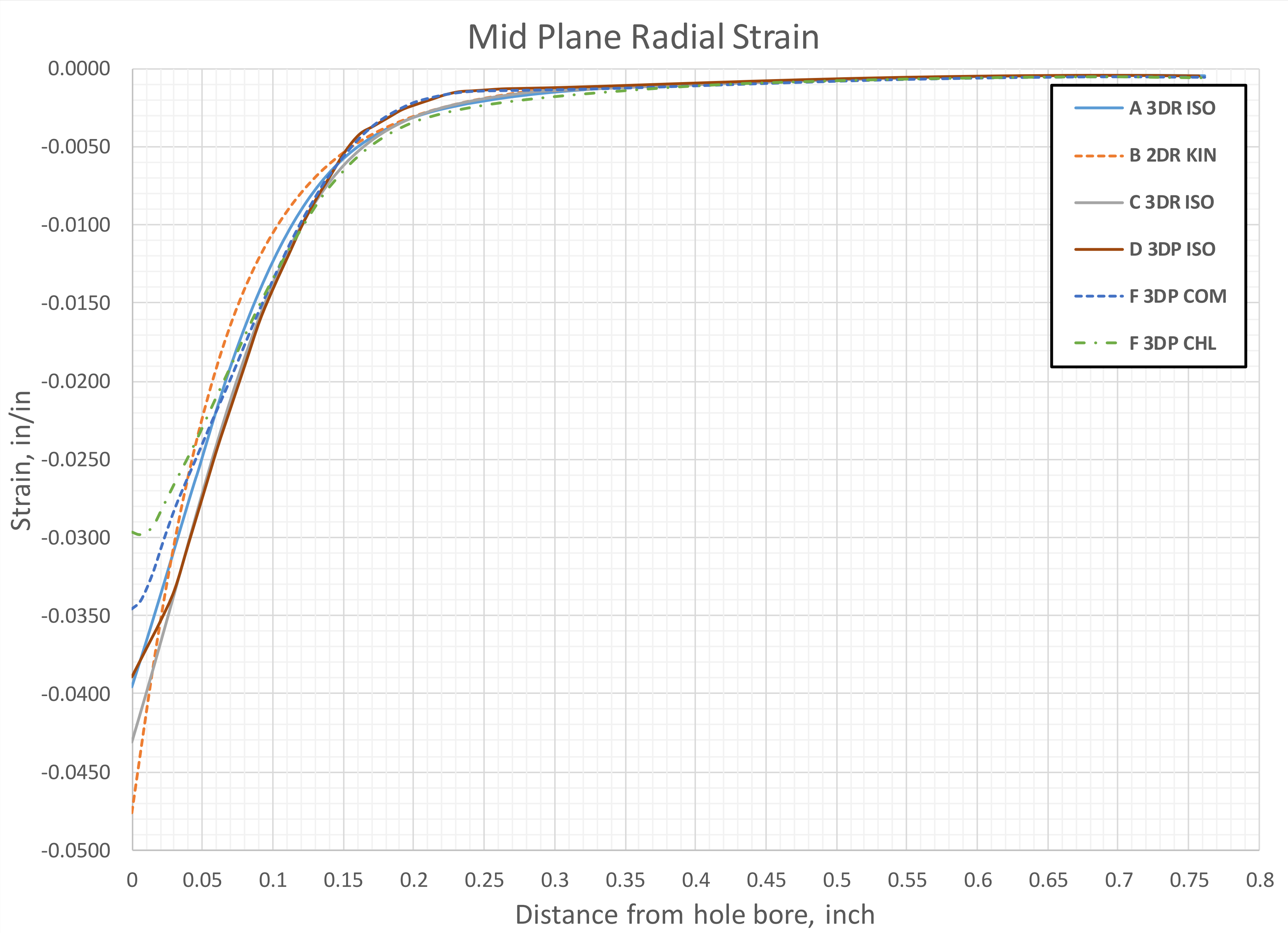

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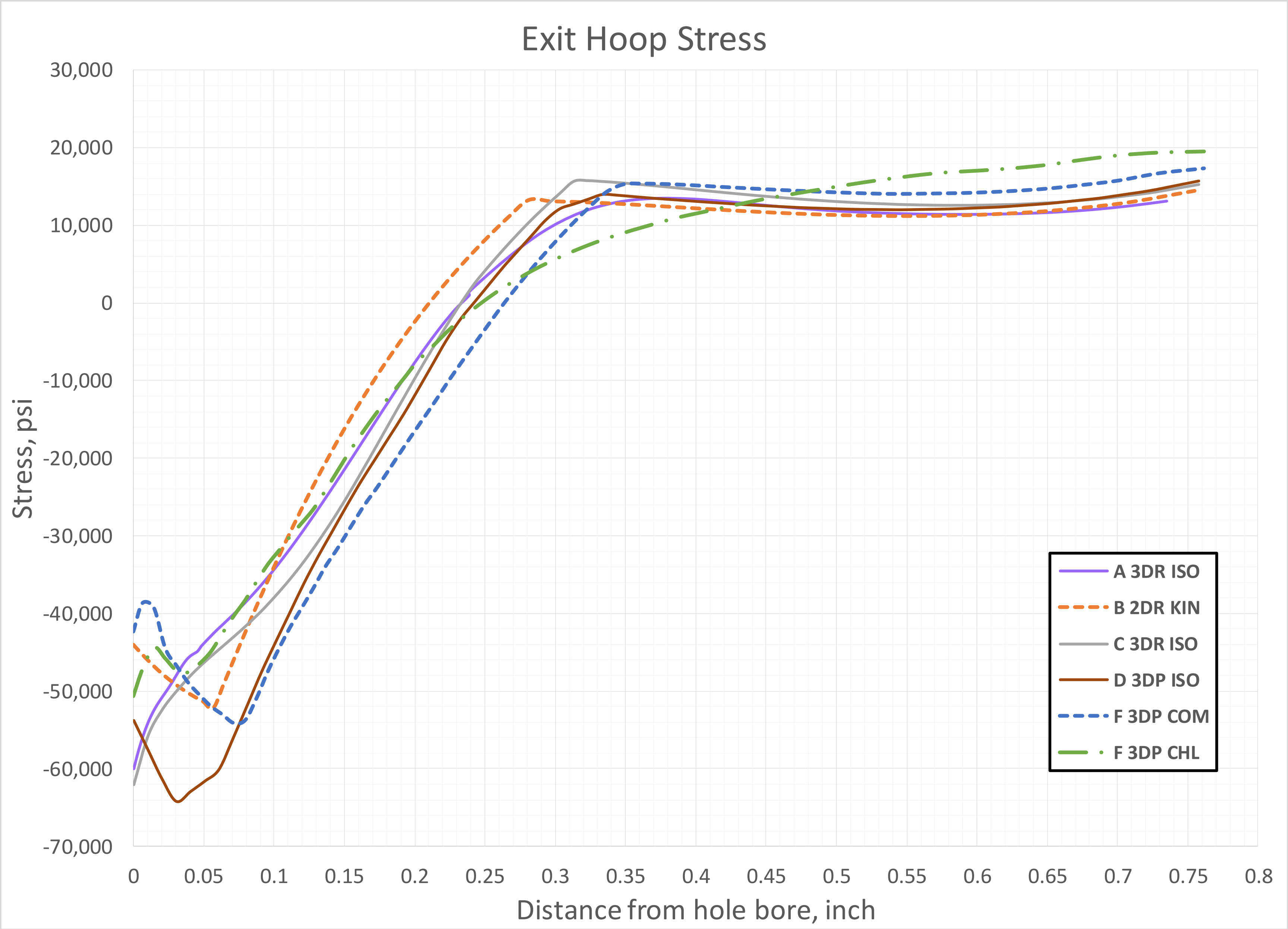

RS Process Simulation Round Robin – Results

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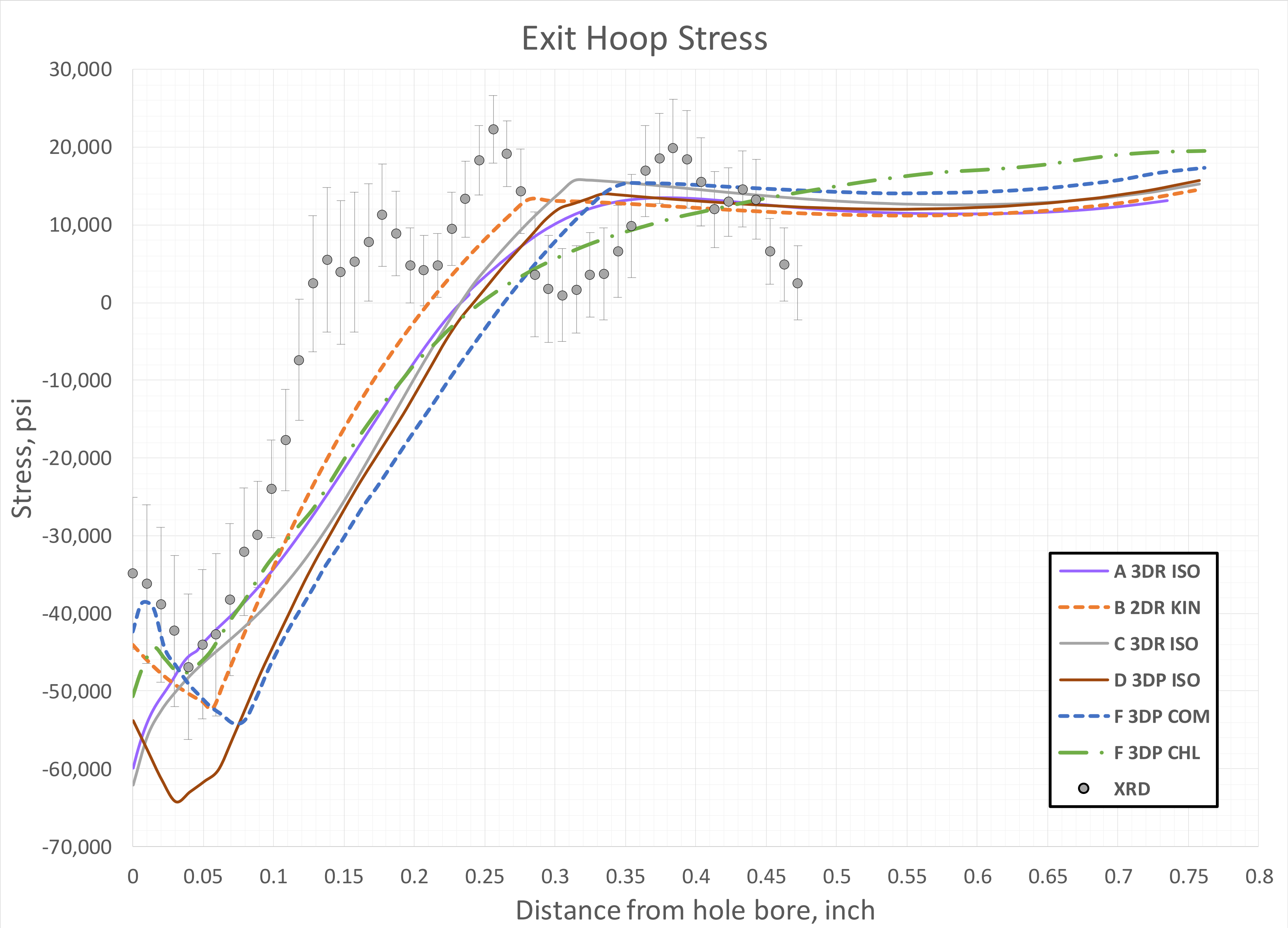
RS Process Simulation Round Robin – Results

	L norm	Cosine
A 3DR ISO	0.7461	0.2223
B 2DR KIN	0.5904	0.1415
C 3DR ISO	0.8338	0.2700
D 3DP ISO	0.6500	0.1824
F 3DP COM	0.9030	0.3140
F 3DPCHL	0.6703	0.1920



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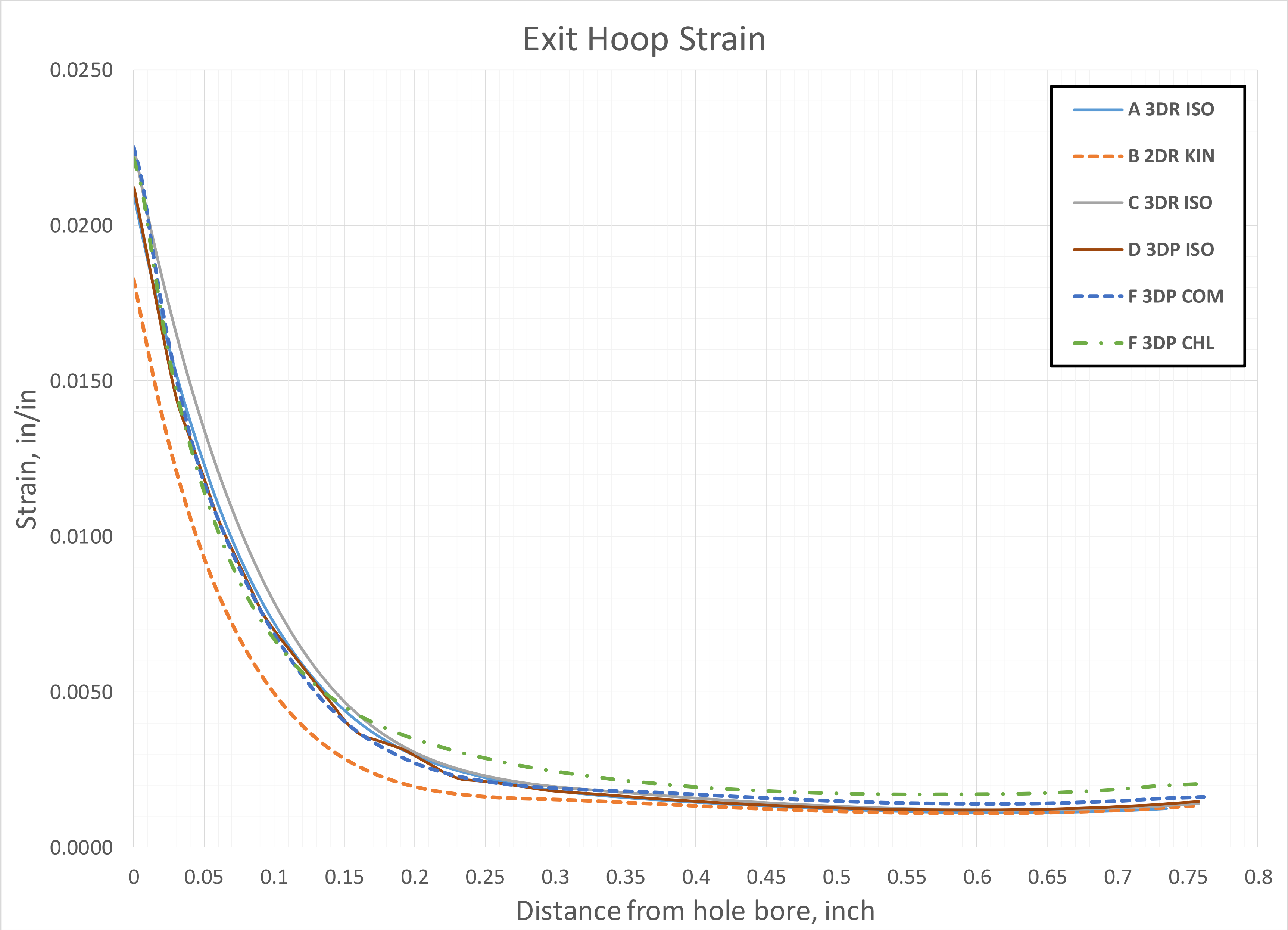

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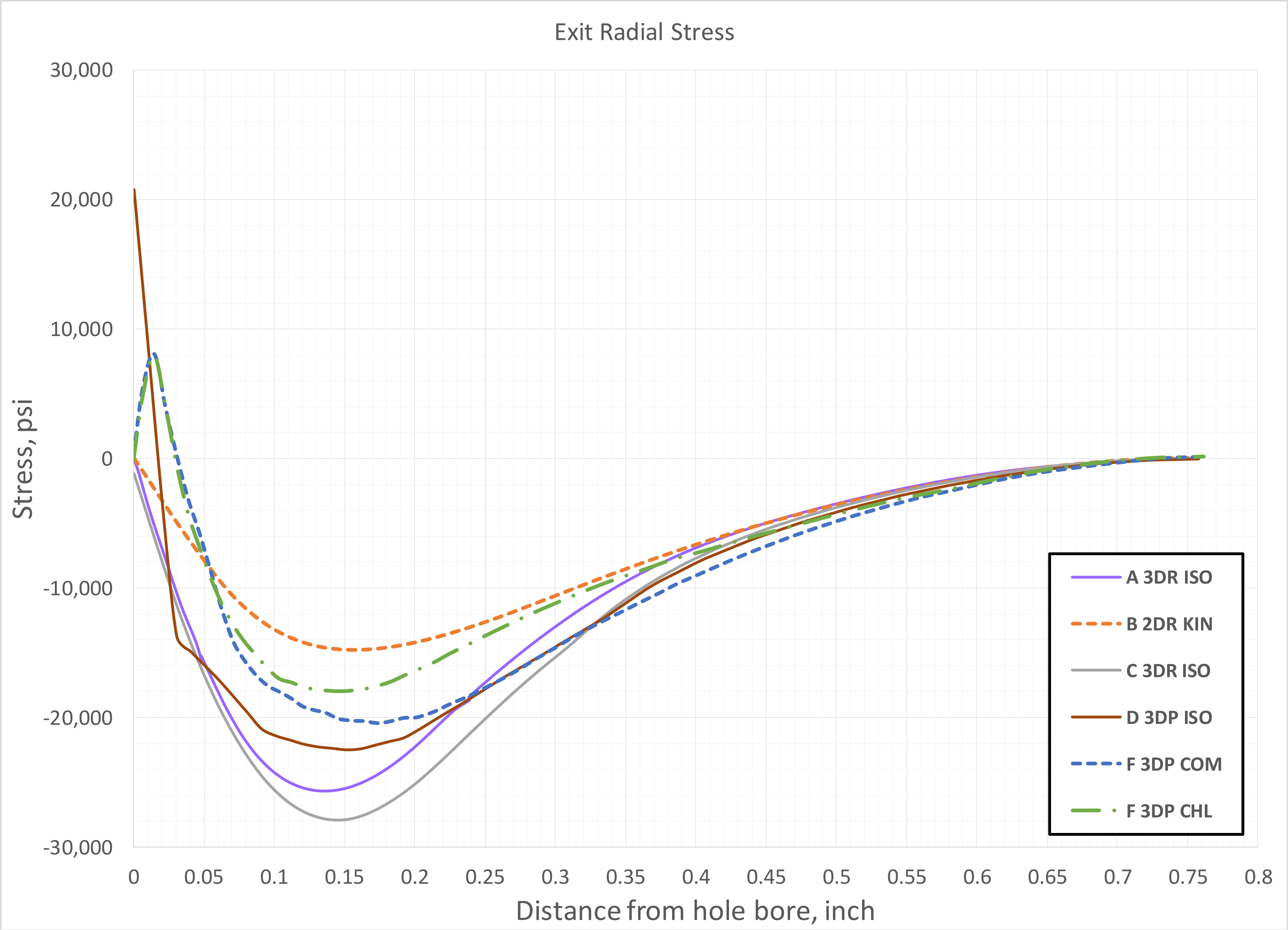

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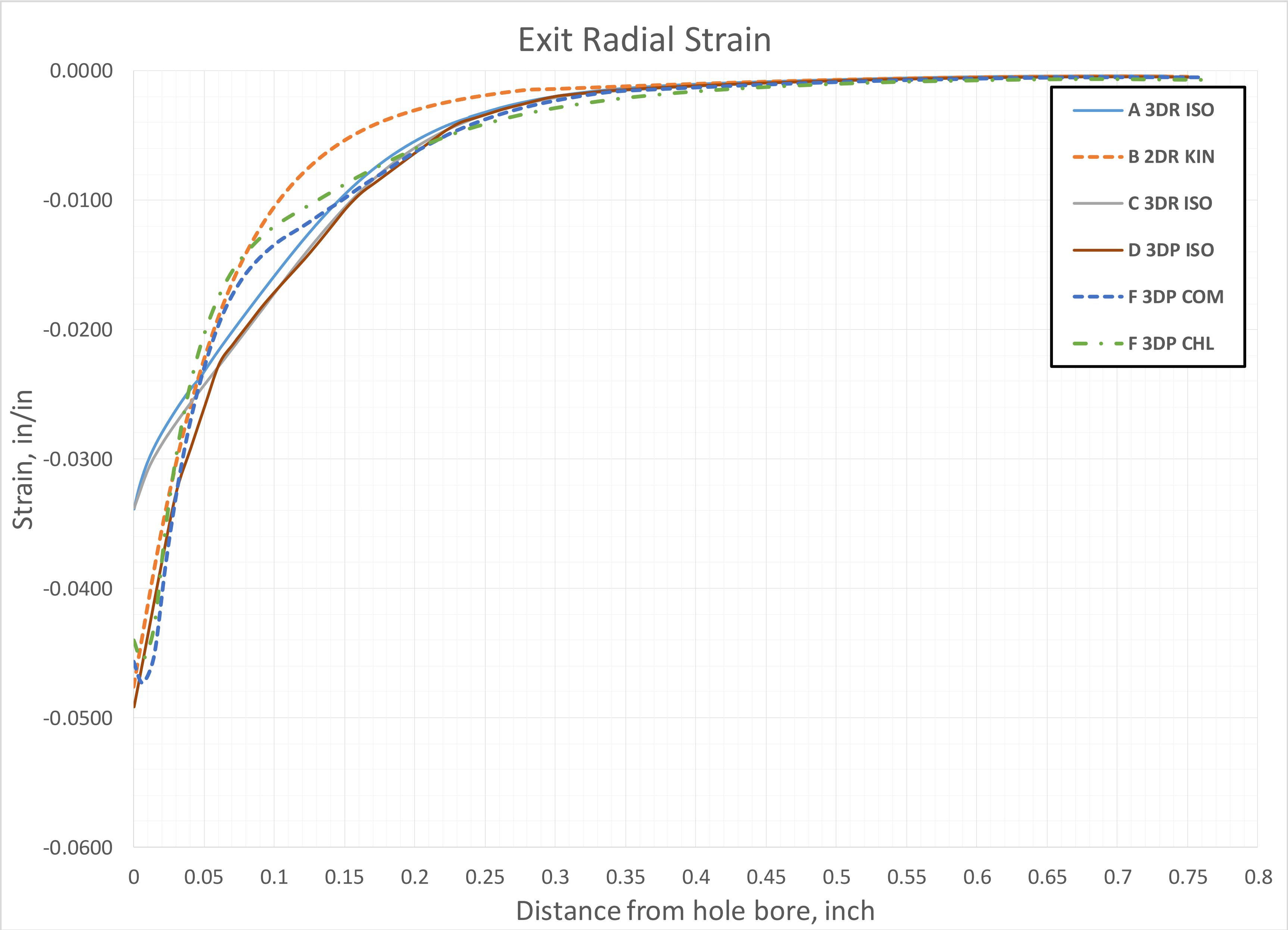

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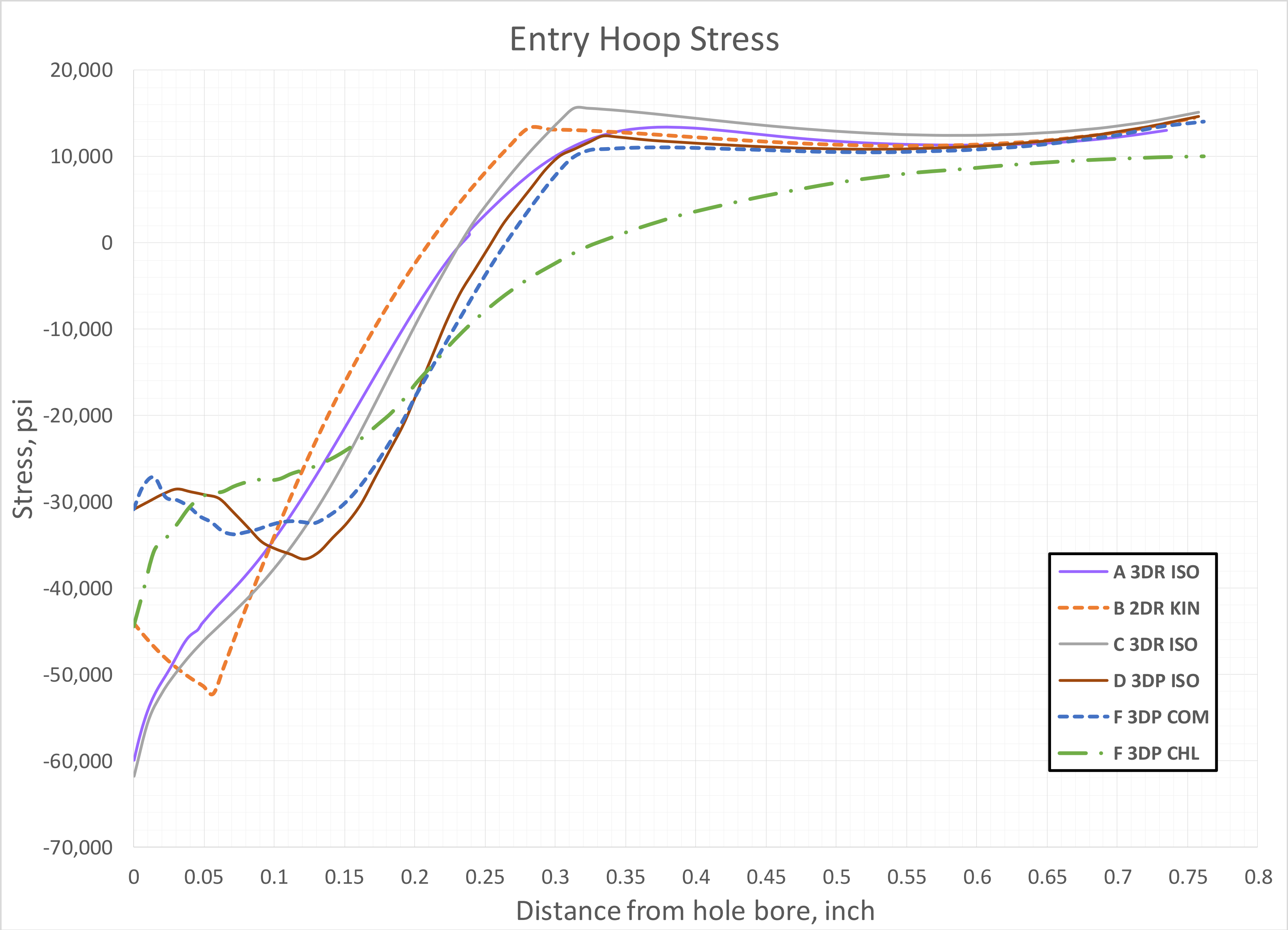

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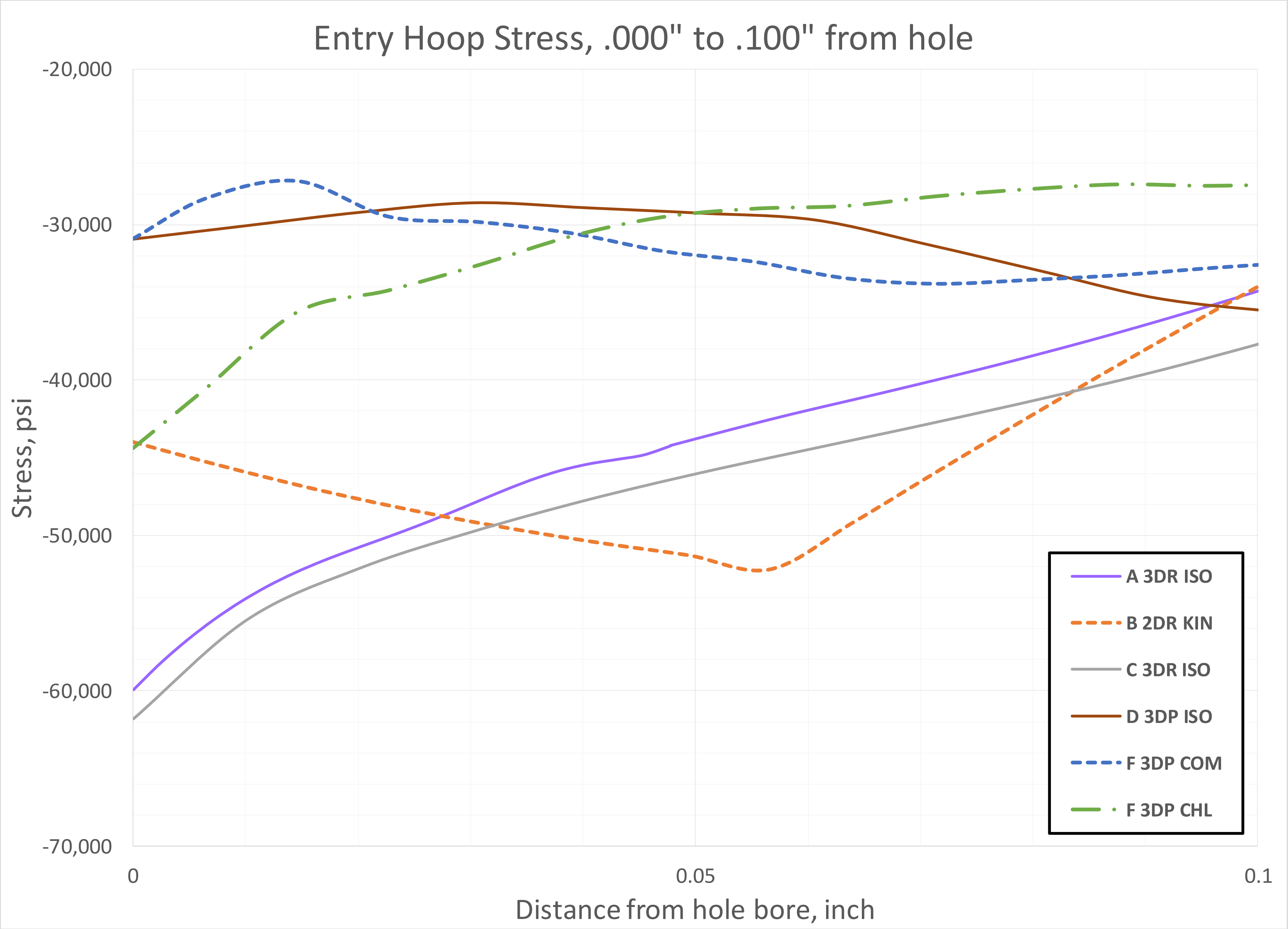

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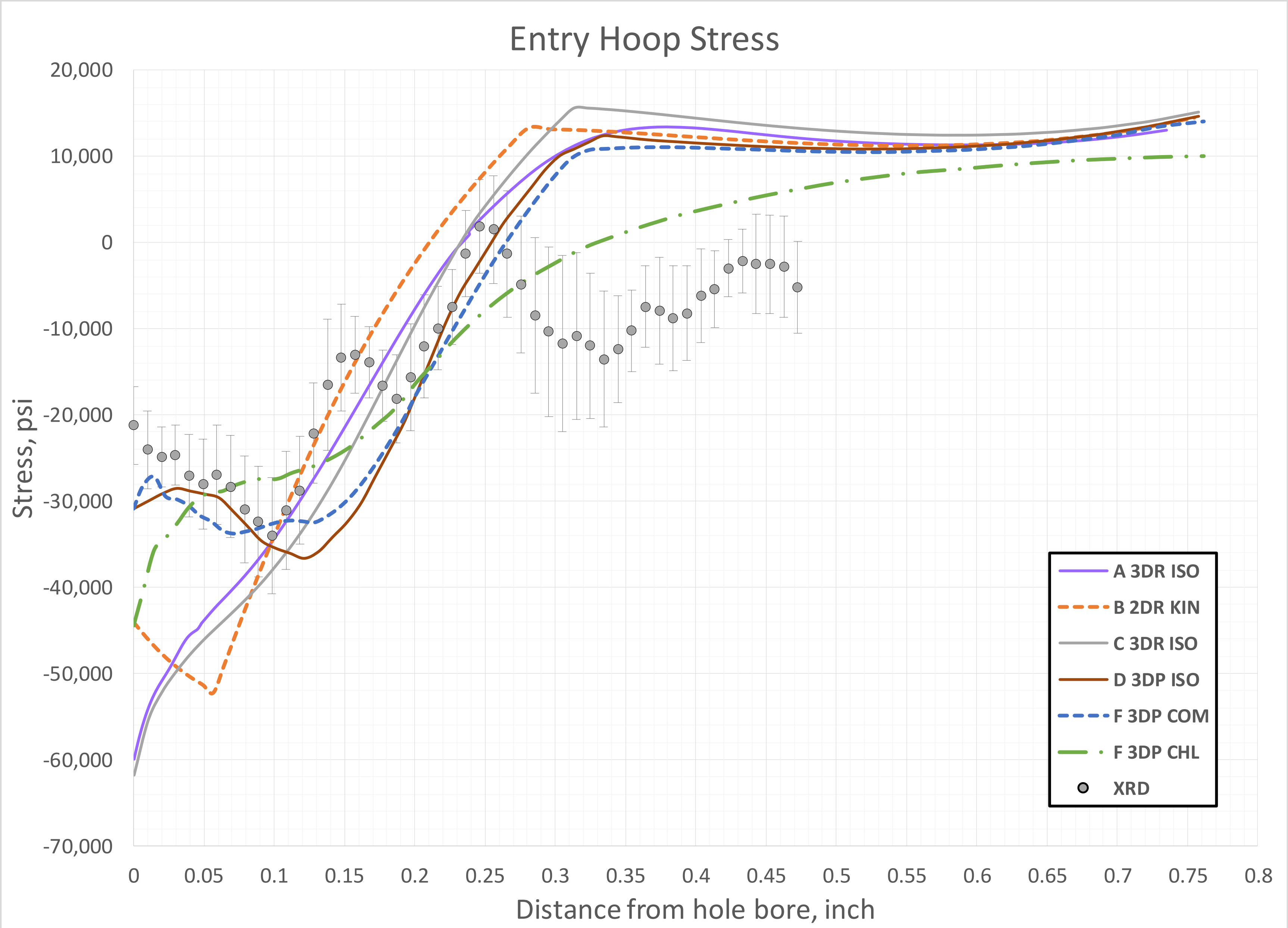

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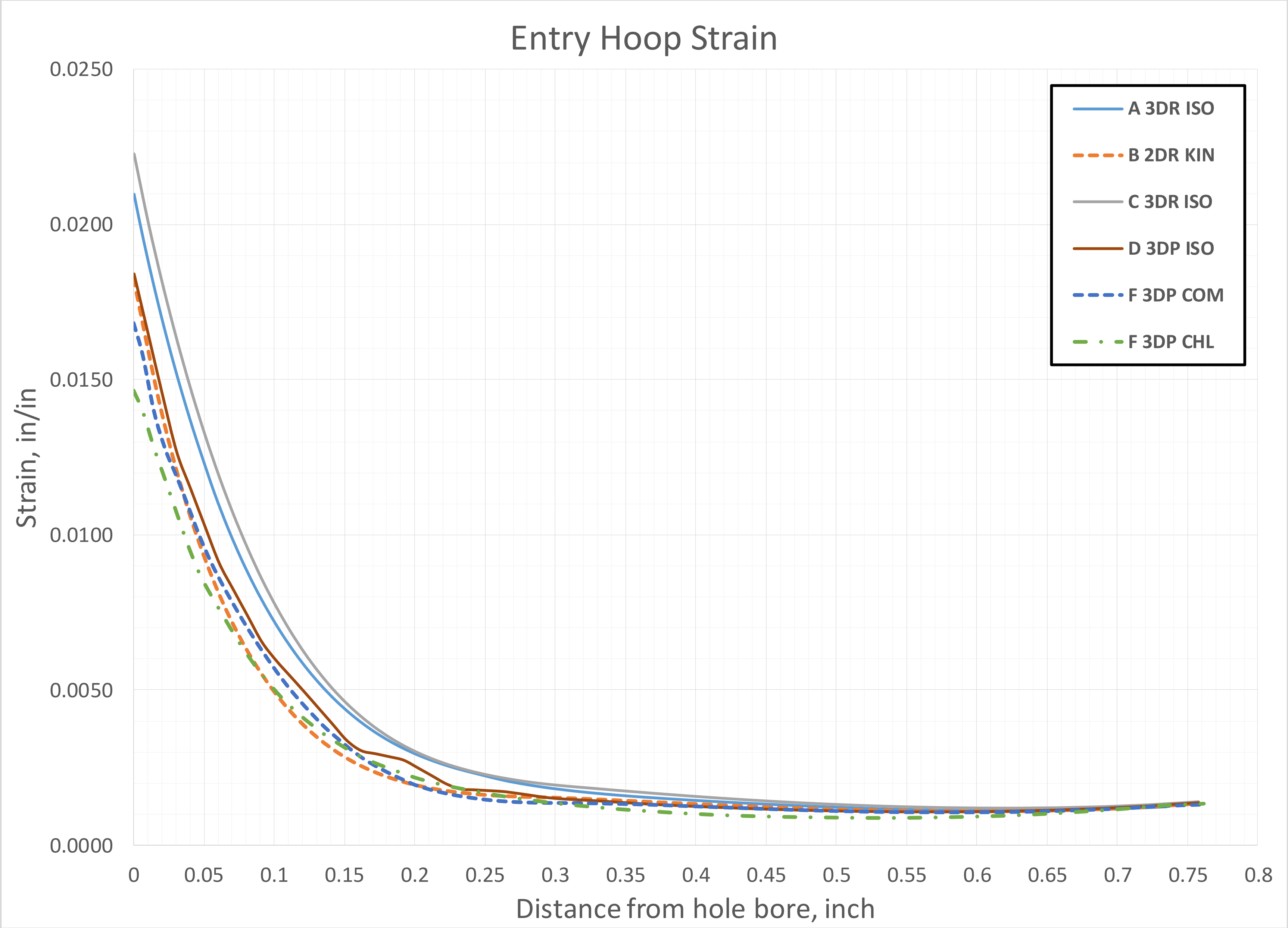

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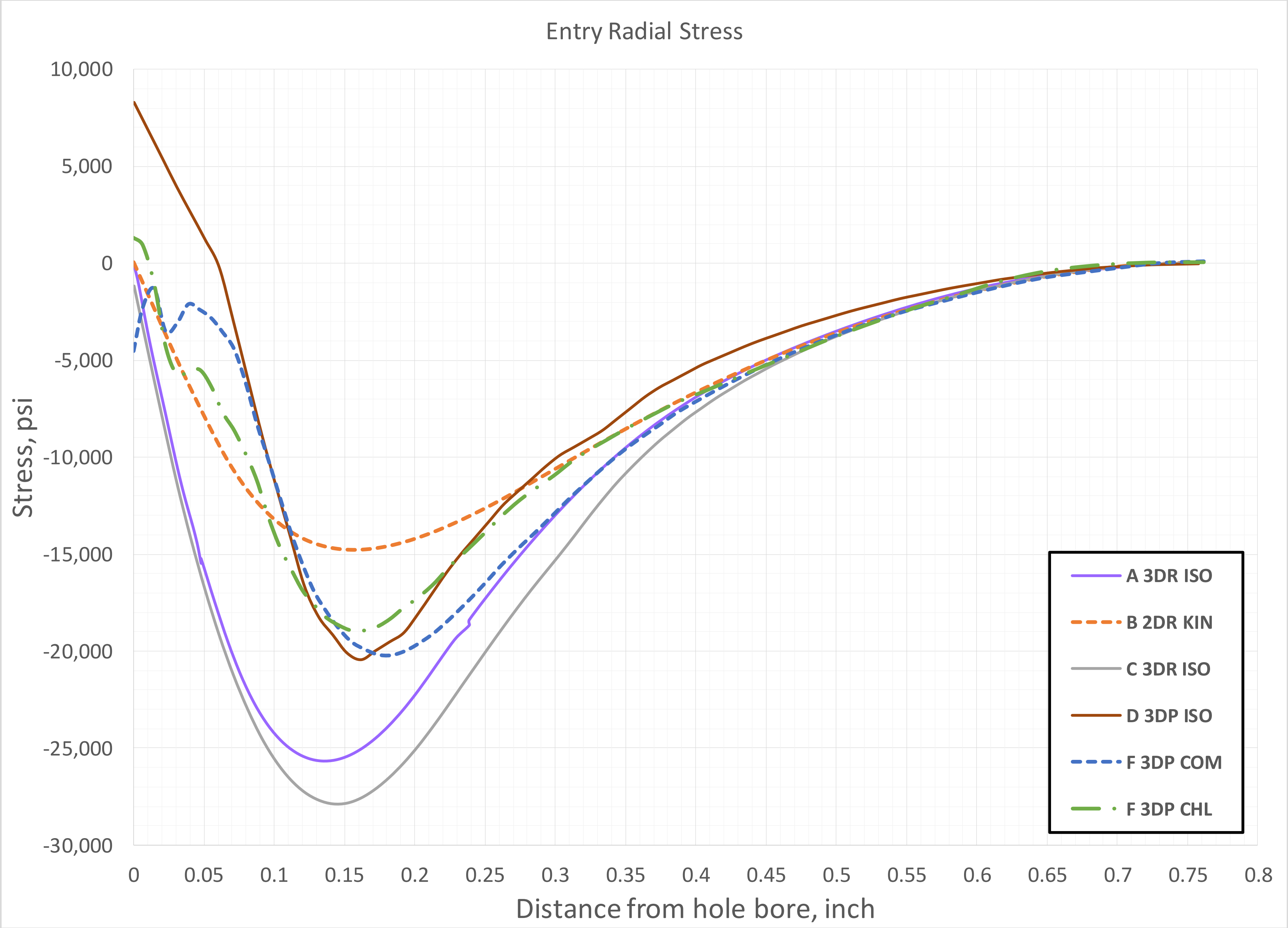

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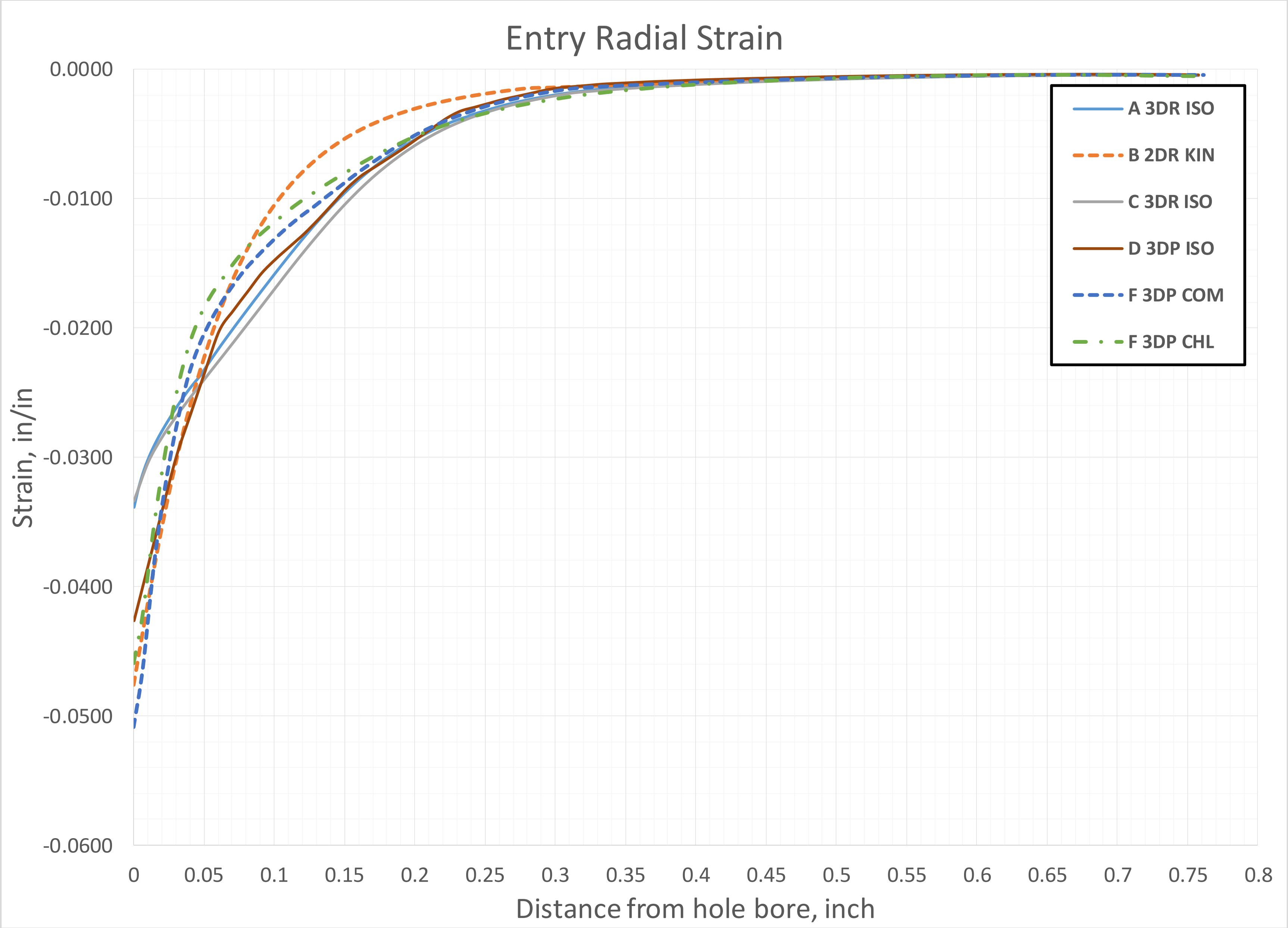

RS Process Simulation Round Robin – Results

Process Simulation Residual Strains – averaged over area subtended by strain gage.
All values in microinch/inch.
Green: less than ±10%
Red: more than ±30%

2024 - L2			SG Value	A 3DR ISO		B 2DR ISO		C 3DR ISO		D 3DP ISO		F 3DP COM	
			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%	**3761**	**5.3%**
		Outer	**982.8**	**1187**	20.8%	**1529**	55.6%	**1306**	32.9%	**1089**	10.8%	**801**	-18.5%
	Radial	Inner	**-5699**	**-4417**	-22.5%	**-4657**	-18.3%	**-6042**	**6.0%**	**-5530**	**-3.0%**	**-5454**	**-4.3%**
		Outer	**-460.8**	**-487**	**5.7%**	**-733**	59.1%	**-567**	23.0%	**-467**	**1.3%**	**-433**	**-6.1%**
Exit	Hoop	Inner	**5703**	4436	-22.2%	5316	**-6.8%**	**5712**	**0.1%**	**5078**	-11.0%	**5004**	-12.3%
		Outer	**1238**	1187	**-4.1%**	1529	23.5%	**1312**	**6.0%**	**1247**	**0.7%**	**1804**	45.7%
	Radial	Inner	**-6906**	-4417	-36.0%	-4657	-32.6%	**-6096**	-11.7%	**-6402**	**-7.3%**	**-6778**	**-1.9%**
		Outer	**-570.6**	-487	-14.6%	-733	28.5%	**-570**	**-0.1%**	**-579**	**1.5%**	**-768**	34.6%

RS Process Simulation Round Robin – Wrap Up

INITIAL FINDINGS

- Different modeling techniques provide broadly comparable results for similar material models
- Bore hoop stress ranges from -30 to -70 ksi over all material models and locations
- Comparisons to XRD appear to diverge in far field
- Need to evaluate radial strain discrepancies

NEXT STEPS

- Receive additional entries – at least two more on the way
- Complete compilation of remaining results
  - Time based strain gage
  - LUNA fiber strain measurements
  - Three other cases (2024-H1, 7075-L1, 7075-H1)

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
Michael Worley, SwRI

Tim Philbrick, MERC
Mike Steinzig, LANL
Andrew Jones, USAF
Gavin Jones, SmartUQ
Dr. Robert McGinty, MERC
Chris Allen, Booz Allen Hamilton
Eric Greuner, Lockheed Martin Aero
Dr. Daniele Fanteria, University of Pisa
Dr. Scott Carlson, Lockeed Martin Aero
David Denman, Fulcrum Engineering, LLC
David Carnes, Mercer Engineering Research Center (MERC)

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

Sincere thanks to all active committee members!

DM#833665

Working Group on
Engineered Residual
Stress Implementation

RS Measurements Group Overview
Sep 12, 2019

Mike Hill, group lead
mrhill@ucdavis.edu
530-754-6178 (work)

TBD, group co-lead

Topics for Today

Group roster

Group Goals (still in development)

Related on-going programs

Stimulating inter-group interactions

Summary

Committee roster (please confirm and correct)

David	Backman	National Research Council Canada / Government of Canada	(613) 993-4817	david.backman@nrc-cnrc.gc.ca
Jeferson	Araújo de Oliveira	StressMap - Director	44 (0) 1908 653 452	Jeferson.Oliveira@stressmap.co.uk
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Ana	Barrientos Sepulveda	Northrup Grumman Aerospace Systems	321-361-2049	Ana.BarrientosSepulveda@ngc.com
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Meetings and Attendance

Sep 12-13, 2019

-
-
-

Feb 6, 2019

- Mike Steinzig
- Scott Carlson
- James Pineault
- Gabe Grodzicki (guest of J Penault)
- Bob Pilarczyk
- Adrian DeWald
- Mike Hill

March 13, 2019

- TJ Spradlin
- Eric Lindgren
- James Pineault
- Mike Brauss
- Gabriel Grodzicki (guest of J Penault)
- Mike Steinzig
- Adrian DeWald
- Scott Carlson
- Mike Hill

Jan 9, 2019

- TJ Spradlin
- Scott Carlson
- Bob Pilarczyk
- Eric Burba
- Mark Obstalecki
- Eric Lindgren
- Marcias Martinez
- Mike Hill

Brief statement of Goals (subject to concurrence)

"A good goal is Quantitative, Realistic, and has a Useful end-state"

- Define and document *repeatability* of residual stress measurement data (in-lab variability)
- Define and document *reproducibility* of residual stress measurement data (lab-to-lab variability)
- Develop residual stress *inter-method comparisons* (e.g., ND to x-ray to contour)
- Develop *measurement-model comparisons* (e.g., for CX holes)
- Engage UQ/statistical methods relative to residual stress data
- Document *exemplar* datasets (leverage prior work and drive new work)
- Assess/Quantify/Define *effects of texture and anisotropy* on residual stress measurement
- Develop a summary of relevant past work (recent and historical)
- Develop a compendium of relevant on-going or recent work

Discussion of goals

Goal: Repeatability of residual stress data (precision)

- Make repeated measures of residual stress in identical parts with one method, in one lab, by one operator, in short intervals of time
- Past work has evaluated repeatability for
  - Surface XRD (no depth profile, just surface)
  - Depth profiling (stress vs depth)
    - Hole drilling, Slotting, Slitting, and XRD + layer removal
  - 2D stress mapping (contour method)
- Focus new work on relevant materials, processes, and measurement techniques

Goal: Reproducibility of residual stress data (precision)

- Make repeated measures of residual stress in identical parts with one method, in multiple labs, following a defined protocol or standard
- Some examples in the literature for hole drilling and XRD + layer removal
  - A few prior published studies show large lab-to-lab variability

Goal: Inter-method comparisons (bias)

- Use multiple techniques to establish residual stress in specific parts
- Uncovers potential for systematic error and bias

Discussion of goals

Goal: Measurement-model comparisons

- How well do model outputs and experimental data correlate?
- Comparisons support model validation

Goal: Engage UQ/statistical methods

- Measurements have uncertainty and potential for bias
- UQ and statistical methods can assess impact of uncertainty and bias on downstream analyses and decision making

Goal: Exemplar data sets

- Document cases where residual stress measurement data are
  - Enabling in the solution of structural integrity challenges (success cases)
  - Or otherwise (negative cases: not helpful, misleading, problematic)

Discussion of goals

Goal: Effects on texture and anisotropy

- Directionality of mechanical properties can lead to errors in residual stress measurements
  - Elastic anisotropy affects diffraction and mechanical techniques equally
  - Texture can affect diffraction methods, but not mechanical techniques
  - Document these effects in relevant materials

Goal: Summary of past work

- Develop a summary of past efforts
  - Use prior test data to address new challenges
  - Avoid repeating prior work

Goal: Summary of recent or on-going work

- See following charts

Goal: Summary of recent or on-going work

Motivation

- ERSI is a volunteer/unfunded initiative
- It is difficult to make significant progress in a timely manner with this constraint
- Opportunities may exist to build on or utilize existing funded programs to further the goals and objectives of the Residual Stress Measurements Sub-group

Objective

- Develop compendium of ongoing (recently complete okay) programs related to ERSI Residual Stress Measurements Sub-group

Approach

- Requested self-report of on-going programs using a simple template

Results

- On following pages

Template

Program name/title: < enter name/title >

Program schedule: < start date > to < end date >

Funding organization: < enter funding organization >

Team members:

- < Enter first team member >
- < Enter second team member >

< Enter program graphic >

Program objectives:

- < Enter first objective >
- < Enter second objective >

Relationship to ERSI goals and objectives:

- < Describe how this efforts relates to one or more of the ERSI Residual Stress Measurements Sub-group goals and objectives listed on the following slide >

Summary of outputs to be shared with ERSI:

- < Enter brief description of first item that can be shared and when it should be expected >

Summary of responses

Requests to RS Measurement Group members (21 ppl)

Responding organizations – 3

Programs – 10

Yielded ring and plug

Program schedule: June 2019 to December 2019

Funding organization: LANL

Team members:

- LANL

Program objectives:

- Create residual stress standard with quantified RS
- Demonstrate RS standard with near yield and yielded regions

Relationship to ERSI goals and objectives:

- Standards can be used to test lab to lab variability

Summary of outputs to be shared with ERSI:

- Product will be made available for measurement. Method will be made available for duplication

Textured ring and plug

Program schedule: June 2019 to December 2019

Funding organization: LANL

Team members:

- LANL

Program objectives:

- Create residual stress standard with quantified RS
- Demonstrate RS standard in characterized textured material

Relationship to ERSI goals and objectives:

- Standards can be used to test lab to lab variability

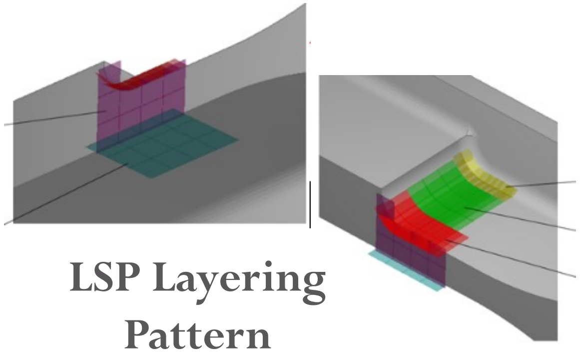
Summary of outputs to be shared with ERSI:

- Product will be made available for measurement. Method will be made available for duplication

LSP of 7085 Forgings

Program schedule: 2015 to 2020

Funding organization: F-35 Joint Program Office



LSP Layering Pattern Development

Team members:

- Lockheed Martin - Aeronautics

Program objectives:

- Determine optimal LSP parameters to eliminate subsurface cracking
- Enhance crack formation/nucleation and crack growth performance of 7085 forgings

Relationship to ERSI goals and objectives:

- Through this effort over 60 different measurements have been made using the contour method
  - Many of these had multiple replicates
  - Provides a robust residual stress database for a range geometries
  - Fatigue tests of almost all conditions has been performed with crack front shapes developed via marker banding

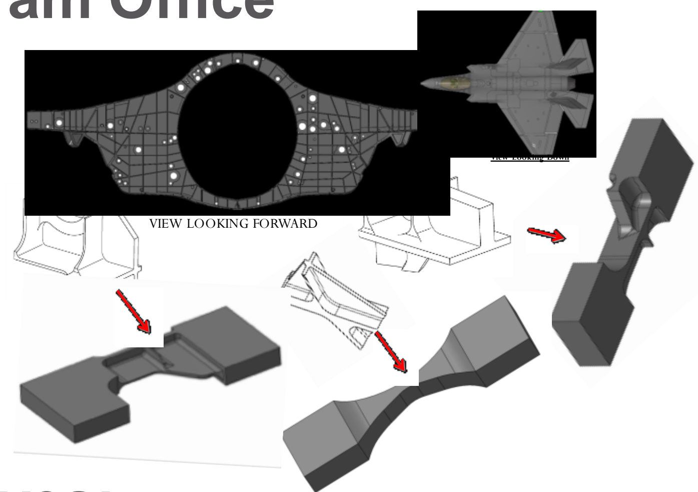
Summary of outputs to be shared with ERSI:

- It is hoped that residual stress data can be shared for a range of conditions

LSP of Ti6Al4V BA ELI Forgings

Program schedule: 2017 to 2020

Funding organization: F-35 Joint Program Office



Team members:

- Lockheed Martin - Aeronautics

Program objectives:

- Determine optimal LSP parameters to eliminate subsurface cracking
- Enhance crack formation/nucleation and crack growth performance of Ti6Al4V BA ELI forgings

Relationship to ERSI goals and objectives:

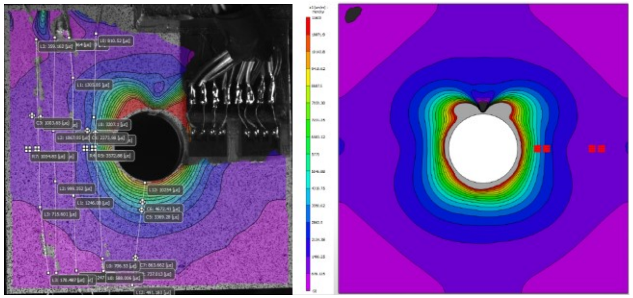
- This effort will quantify the residual stress in 3 different geometries via the contour method
- Fatigue testing of these conditions will also be performed
  - No replicate fatigue tests will be performed

Summary of outputs to be shared with ERSI:

- It is hoped that residual stress data can be shared for a range of conditions

2inch x 2inch Cold Expanded Coupons

Program schedule: 2016 - 2020



Funding organization: A-10 ASIP, FTI, NRC, AFRL

Team members:

- Many individuals and companies

Program objectives:

- Perform the Cold Expansion process on simple geometry in 2024-T351 and 7075-T651 plate at ”Low” and “High” applied expansion levels
  - Use multiple methods to quantify surface residual stresses while performing the Cx process
  - Have coupon sets interrogated by many different residual stress determination/quantification techniques to include:
    - + Strain gauge
    - + DIC
    - + LUNA fiber optics
    - + Surface XRD
    - + ED XRD (APES, CHESS)
    - + Neutron Diffraction
    - + Neutron Emission
    - + Contour Method

Relationship to ERSI goals and objectives:

- Investigate multiple techniques to quantify differences in results
- Use as a validation dataset for FEA simulation

Summary of outputs to be shared with ERSI:

- Residual stress/strain data from all the different techniques
- A set of the coupons is also final reamed but this set has had a smaller set of techniques applied to it

Residual stress quality system

Program schedule: May 2017 to July 2018

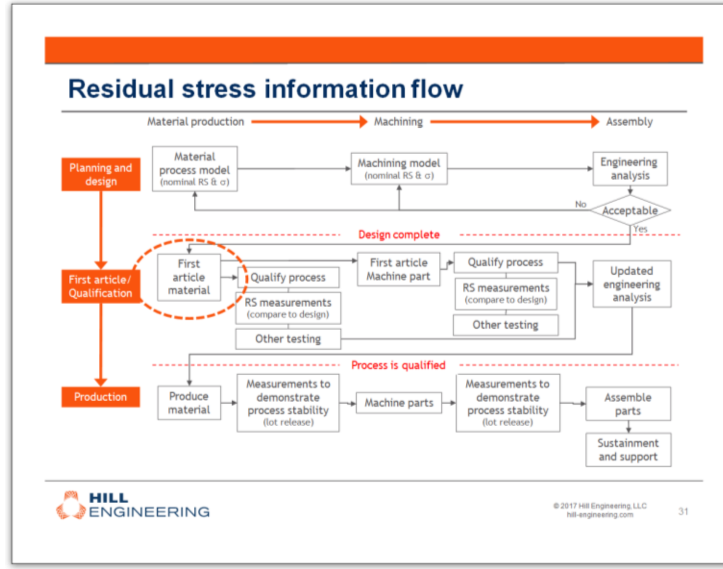
Funding organization: AFRL (SBIR and MAI)

Team members:

- Hill Engineering, Arconic, Lockheed Martin, AFRL

Program objectives:

- Quantify residual stress in large aluminum bulkhead forgings
- Estimate expected part-to-part residual stress variability for large aluminum bulkhead forgings
- Develop comparisons between residual stress measurements and process models
- Prepare a draft residual stress quality system specification for large aluminum bulkhead forgings



Relationship to ERSI goals and objectives:

- Develop inter-method residual stress comparisons
  - Hole drilling to ring core, Contour to neutron diffraction
- Develop measurement-model comparisons
  - Cold worked aluminum die-forgings
- Engage UQ/statistical methods relative to residual stress data
  - Statistical methods used to process results

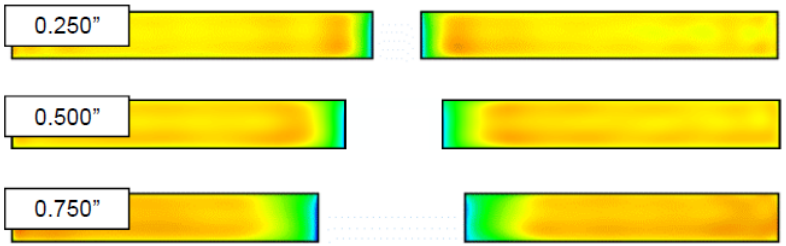
Summary of outputs to be shared with ERSI:

- Comparison between residual stress measurement results and residual stress process models
- Inter-method residual stress comparisons
  - Hole drilling to ring core
  - Contour to neutron diffraction

A-10 ASIP Modernization

Program schedule: November 2016 to June 2020

Funding organization: A-10 ASIP



Team members:

- A-10 ASIP
- Hill Engineering

Program objectives:

- Experimentally measure residual stress magnitudes & distributions and develop models
- Develop analytical methods for damage tolerance analysis accounting for residual stress effects
- Validate analytical methods and/or tools through fatigue testing
- Demonstrate the benefits compared to the existing methodology

Relationship to ERSI goals and objectives:

- Develop benchmark datasets
  - Residual stress measurements for select Cx hole conditions

Summary of outputs to be shared with ERSI:

- Residual stress measurement results for Cx holes

Regularization uncertainty

Program schedule: January 2018 to December 2019

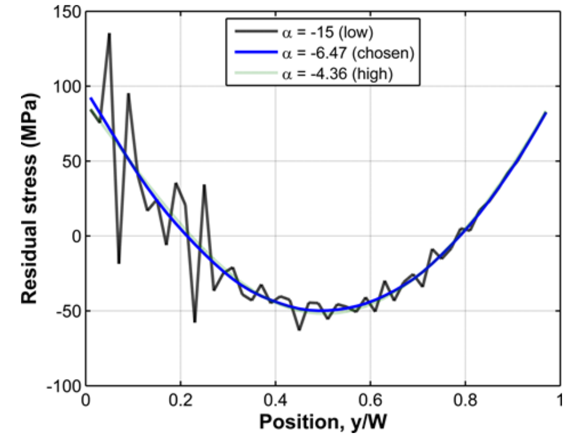
Funding organization: Hill Engineering

Team members:

- Hill Engineering

Program objectives:

- Develop a method to estimate the uncertainty associated with regularization used in the integral method of stress calculation



Relationship to ERSI goals and objectives:

- Engage UQ/statistical methods relative to residual stress data
  - Using UQ/statistical methods to improve uncertainty estimates

Summary of outputs to be shared with ERSI:

- Improved uncertainty estimates for hole drilling and slitting – December 2019

Bulk residual stress measurement

Program schedule: June 2014 to March 2017

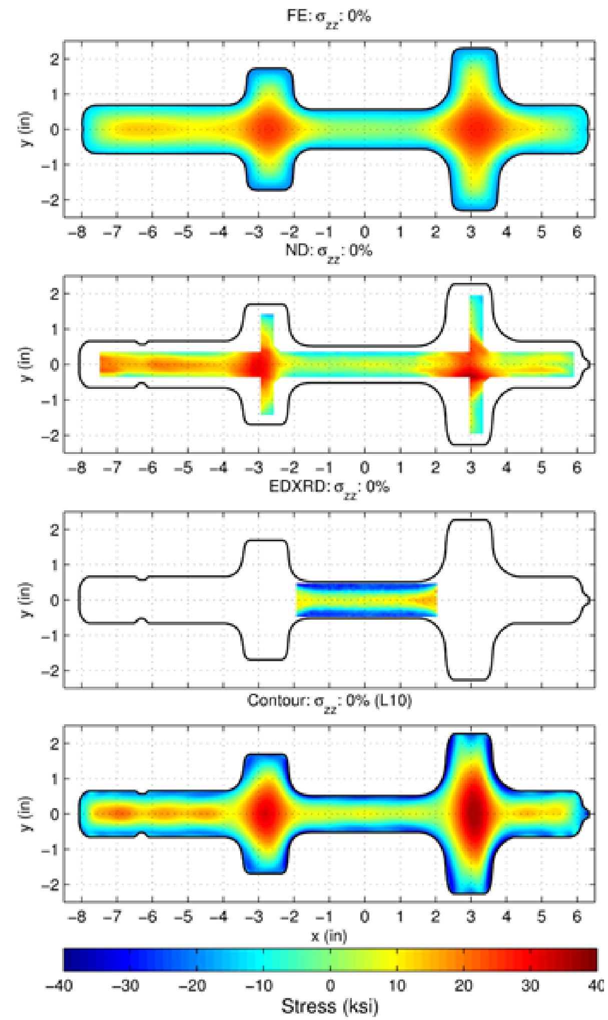
Funding organization: AFRL (SBIR)

Team members:
- Hill Engineering
- AFRL

Program objectives:
- Standardize the uncertainty estimate for contour method measurements
- Quantify the repeatability (precision) of contour method measurements
- Refine the approach for mapping multiple residual stress components
- Validate the results from multiple residual stress components mapping using independent measurements

Relationship to ERSI goals and objectives:
- Develop intra-laboratory repeatability
- Develop inter-method residual stress comparisons
  - Residual stress measurements for a variety of specimens using different techniques
    - + Contour method vs. slitting vs. neutron diffraction vs. high-energy x-ray diffraction

Summary of outputs to be shared with ERSI:
- Contour method repeatability data (5-10 replicates, 5 different parts)
- Inter-method residual stress comparison summary



Steel Cx holes

Program schedule: May 2018 to December 2019

Funding organization: FTI and Hill Engineering

Team members:

- FTI
- Hill Engineering

Program objectives:

- Quantify residual stress in steel Cx specimens
- Compare residual stress measurement results to process model

Relationship to ERSI goals and objectives:

- Develop measurement-model comparisons (e.g., for CX holes)
  - Comparison between contour method and process model for steel Cx hole

Summary of outputs to be shared with ERSI:

- Summary of residual stress measurement to model comparison – December 2019

Stimulating inter-group interactions

We want to promote interaction with other ERSI groups

- RS measurement would like to link up with:
  - Simulation
  - Quality Assurance and Data Management
  - NDE
- Motivations
  - Facilitate cross-talk
  - Define and work joint efforts
  - Define and deliver outputs that feed overall ERSI objectives
- Do we want to define a format for such interactions?

Summary of Topics for Today

Group roster

Group Goals (still in development)

Related on-going programs

Stimulating inter-group interactions

Summary

Thank You

Analytical Methods & Testing Committee: Overview of Recent Efforts

Engineered Residual Stress Implementation Workshop 2019

September 12, 2019

Robert Pilarczyk
Group Lead – Structural Integrity
Hill Engineering, LLC

Jacob Warner
A-10 ASIP Engineering
USAF

Acknowledgements

- USAF Structural Integrity Teams
- Air Force Research Lab
- Analysis Methods & Testing Committee Participants
- ERSI Working Group

Historical

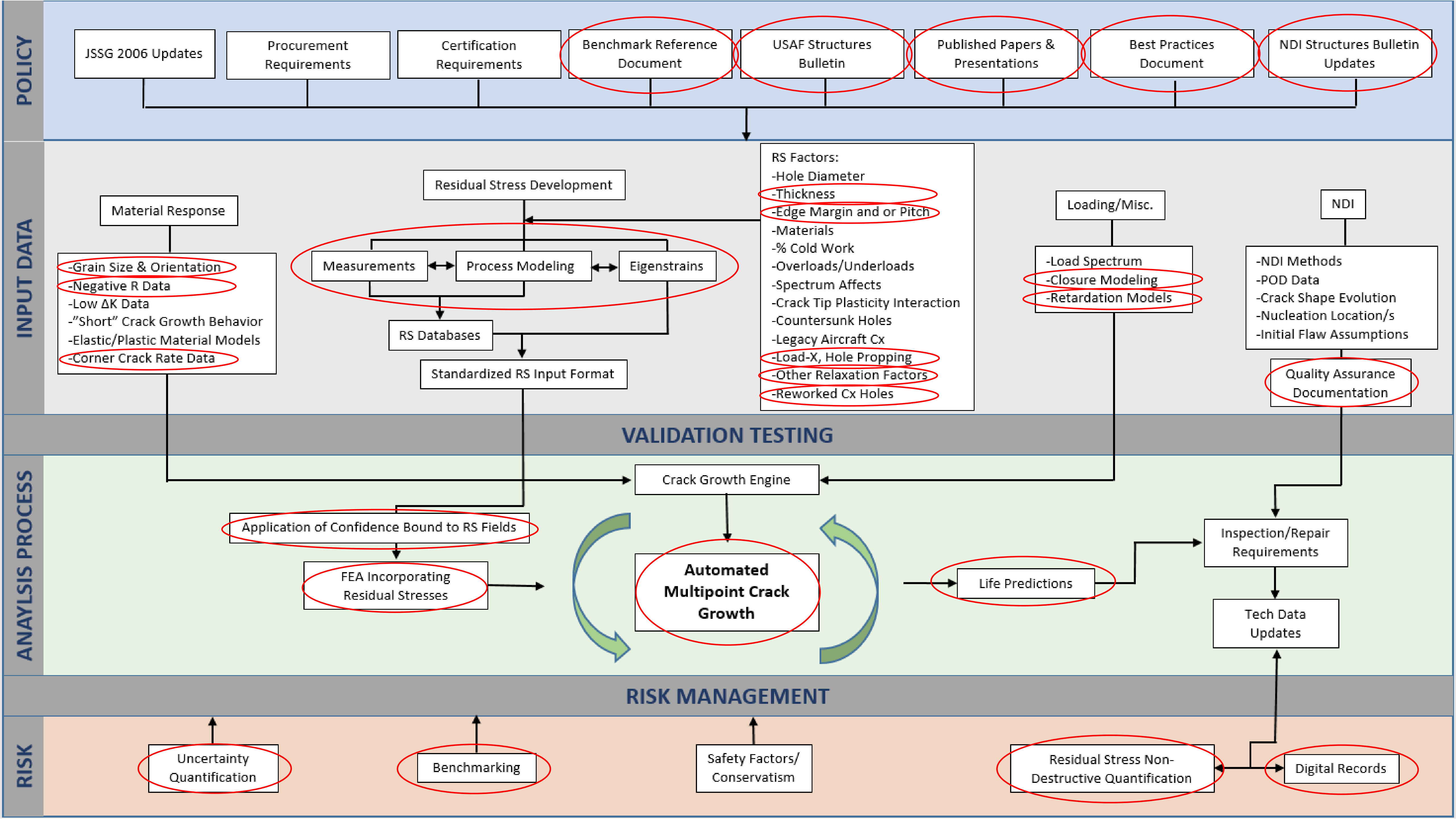
Residual Stress is considered a problem or used as a *band-aid* to address design deficiencies

Emerging

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

Agenda

- Round Robin Efforts
  - Round Robin Wrap-Up (Pilarczyk)
  - Round Robin #2 Plan (Warner)
- Modeling Efforts
  - Residual Stress Source Comparisons w/ Test Data (Carlson)
  - Multi-directional material properties (Pilarczyk)
  - Closure Modeling (Mills)
  - Closure Images (Ross)
  - Shakedown (Mills, Pilarczyk)
  - Notch Plasticity (Keller)
  - FCG Testing of Complex Coupons with Quench Induced Residual Stress (Hill)
  - Fatigue Life Variability (Warner, Mills)
- Validation Testing
  - Short Edge Margin Evaluation (Ross)
  - Geometrically Large Coupons (Warner)
- Weapon System Applications
  - F-18 Wing Root Shear Tie Analyses (Walker)
  - A-10 Control Point Predictions (Pilarczyk, Warner)
  - B-1 Taper-Lok Analysis (Pilarczyk)
- Misc. Other
  - USAF Draft Structures Bulletin
  - Literature Review (Pilarczyk)


POLICY
JSSG 2006 Updates
Procurement Requirements
Certification Requirements
Benchmark Reference Document
USAF Structures Bulletin
Published Papers & Presentations
Best Practices Document
NDI Structures Bulletin Updates
INPUT DATA
Material Response
-Grain Size & Orientation
-Negative R Data
-Low ΔK Data
-"Short" Crack Growth Behavior
-Elastic/Plastic Material Models
-Corner Crack Rate Data
Residual Stress Development
Measurements
Process Modeling
Eigenstrains
RS Databases
Standardized RS Input Format
RS Factors:
-Hole Diameter
-Thickness
-Edge Margin and or Pitch
-Materials
-% Cold Work
-Overloads/Underloads
-Spectrum Affects
-Crack Tip Plasticity Interaction
-Countersunk Holes
-Legacy Aircraft Cx
-Load-X, Hole Propping
-Other Relaxation Factors
-Reworked Cx Holes
Loading/Misc.
-Load Spectrum
-Closure Modeling
-Retardation Models
NDI
-NDI Methods
-POD Data
-Crack Shape Evolution
-Nucleation Location/s
-Initial Flaw Assumptions
Quality Assurance Documentation
VALIDATION TESTING
ANAYLSIS PROCESS
Crack Growth Engine
Application of Confidence Bound to RS Fields
FEA Incorporating Residual Stresses
Automated Multipoint Crack Growth
Life Predictions
Inspection/Repair Requirements
Tech Data Updates
RISK MANAGEMENT
RISK
Uncertainty Quantification
Benchmarking
Safety Factors/ Conservatism
Residual Stress Non-Destructive Quantification
Digital Records

Round Robin Efforts

Round Robin #1 Wrap-up

- Follow-up Efforts
  - Replicate variance and its impact on life predictions
- Publications
  - Presented at 19th International ASTM/ESIS Symposium on Fatigue and Fracture Mechanics (42nd National Symposium on Fatigue and Fracture Mechanics), May 2019
  - Publication in upcoming Special Issue on Fatigue and Fracture Mechanics for Materials Performance and Characterization

ASTM INTERNATIONAL

Acknowledgements

- Co-Authors
  - Ricardo Actis, Engineering Software Research & Development Inc, St. Louis, MO, USA
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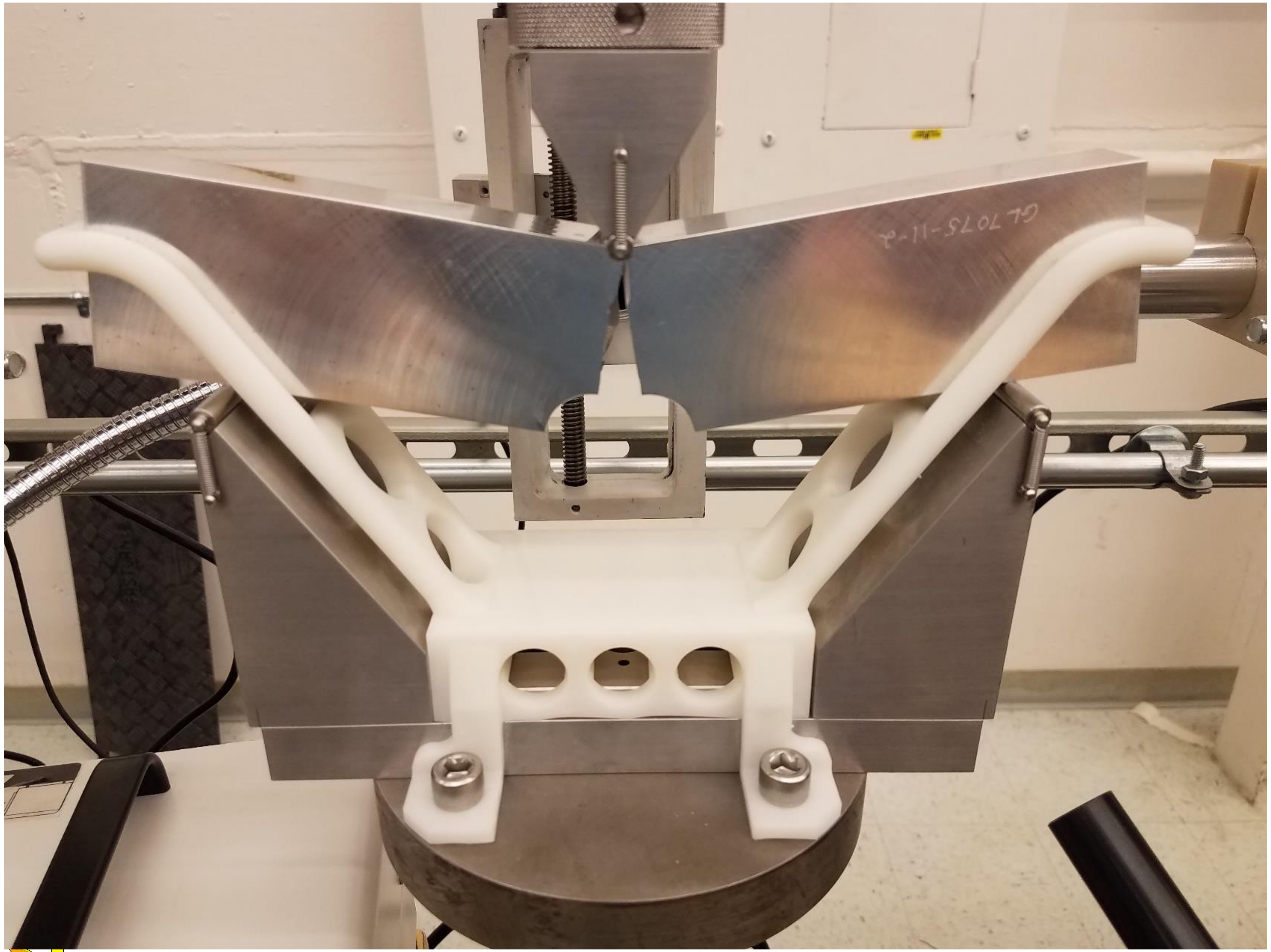
  - Joshua Hodges, Hill Engineering LLC, Rancho Cordova, CA, USA
  - Millard Kwan, Aviation Engineers Pty Ltd, Arundel, QLD, Australia
  - Scott Prost-Domasky, Analytical Processes/Engineered Solutions Inc, St. Louis, MO, USA
  - Guillaume Renaud, National Research Council Canada, Ottawa, Ontario, Canada
- Engineered Residual Stress Implementation (ERSI) Working Group

HILL ENGINEERING Predict. Test. Perform. ERSI 2

Round Robin #2 Planning

- Background
  - Initial Round Robin effort proved to be quite fruitful and facilitated collaboration amongst committee
  - Follow-on Round Robins should focus on investigating other areas of the analysis process to gain confidence in analysis methods, gather lessons learned, and define best practices
- Approach
  - Investigate available datasets to identify candidates
  - Smaller subcommittee review data to determine best case for next Round Robin

Round Robin 2 - Option 1

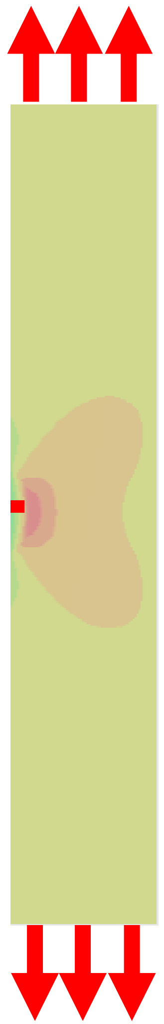


ERSI

Round Robin 2 - Options 2 and 3

- SEN(T) specimen with residual stress field
  - Pros:
    - RS prediction without stress concentration
    - Focus on crack growth fundamentals
  - Cons:
    - No practical application
    - Test data not yet generated
- Interference fit fastener in a plate
  - Pros:
    - Typically far broader application than CX
    - One step closer to aircraft structure from open hole
  - Cons:
    - Different life improvement mechanism than RS, though still relevant

SEN(T)



Round Robin 2

- Are there other relevant datasets to consider??
- Bring your ideas to our breakout session.

ERSI

Modeling Efforts

Assessing the State-of-the-Art Residual Stress Input Methods for Crack Growth Prediction vs. Test

Engineered Residual Stress Implementation Workshop 2019

September 12, 2019

Scott Carlson – LM-Aero

Marcias Martinez & Craig Merrett – Clarkson University

Keith Hitchman – FTI

Caleb Morrison – Hill Engineering, CA

Joshua Hodges – Hill Engineering, UT

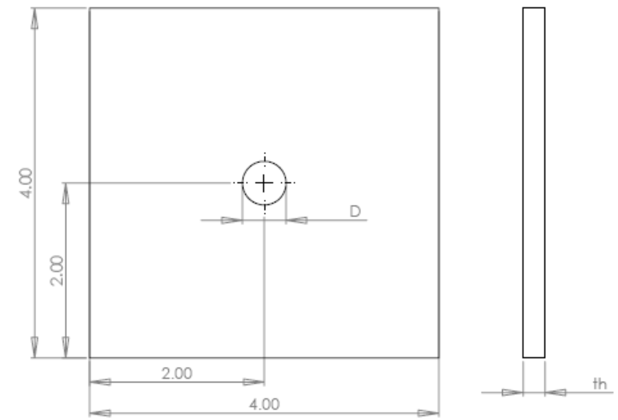
ERSI

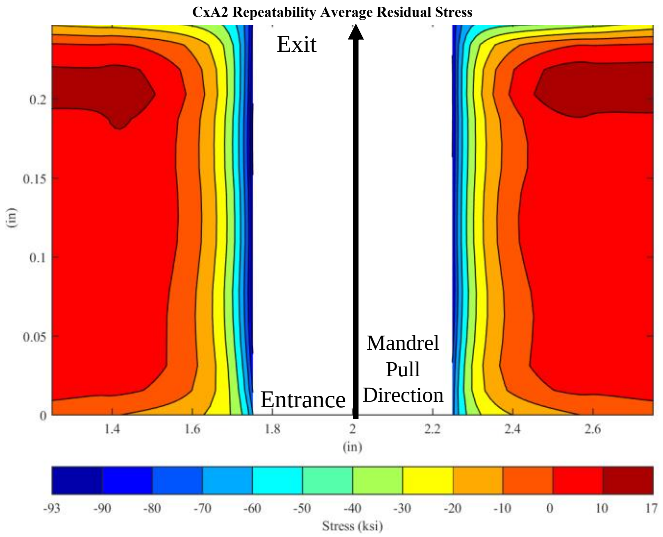
Problem Statement

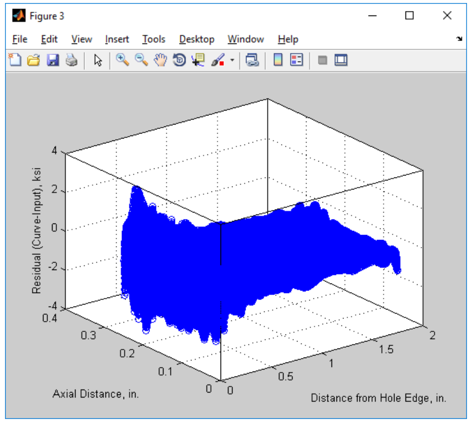
- Utilize Current State of the Art Residual Stress Inputs into a Crack Growth Prediction
  - Start with “simple” condition, 2024-T351
    - 0.25inch thick x 4inch wide with a “Low” applied expansion 0.5inch dia. hole
  - Residual stress inputs include
    - Contour method (Carlson)
    - Elastic-plastic process simulation (Hitchman)
    - Closed-form solution (Ball/Martinez/Merrett)
    - Eigenstrain fit (Morrison)
  - Include residual stresses into two crack growth engines
    - BAMF – multi-point FEA/LEFM tool
      - Residual stress included as a function
    - CGRO – LM’s 2-point LEFM tool
      - Residual stress included as a point-wise cloud
- Predict Life from a 0.03x0.03inch Initial Crack – Compare to Test

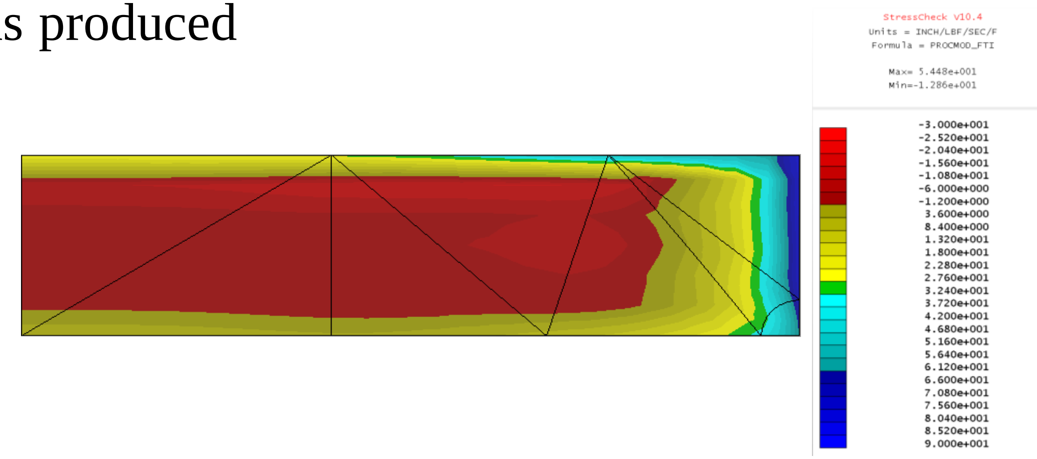
Residual Stress Input – Contour Method

- Contour Method for Determining Residual Stresses[1]
  - 5 Replicates were produced for the "Low" applied Cx
    - The "low" applied expansion represents 3.14-3.19%
    - Initial hole diameter = 0.4772-0.4774in
    - Mandrel diameter = 0.4684in with sleeve thickness = 0.0120in
    - Avg. post Cx diameter = 0.48783-0.48835inch
    - Residual expansion = 2.33%-2.34%
  - Average of left side of hole for all 5 replicates
  - Data was re-grid to a 0.001x0.001inch grid spacing
  - Data was fit using a 15th order polynomial for inclusion in BAMF
    - Residuals of fit to data was produced





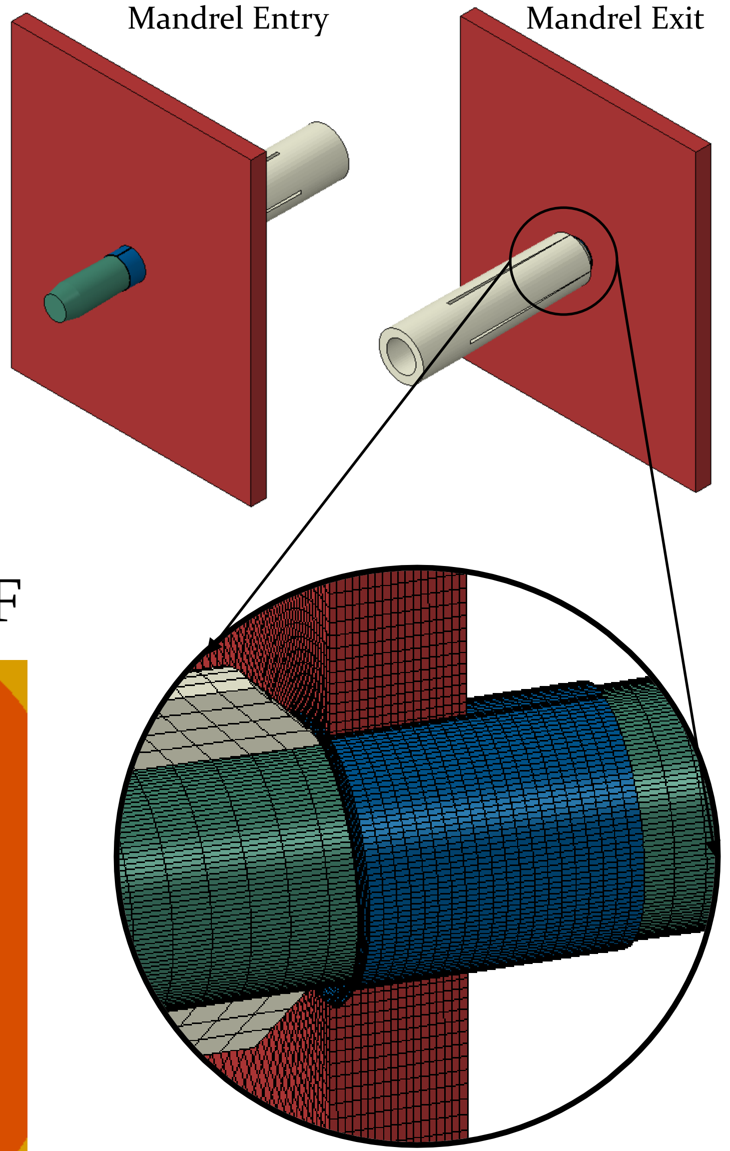


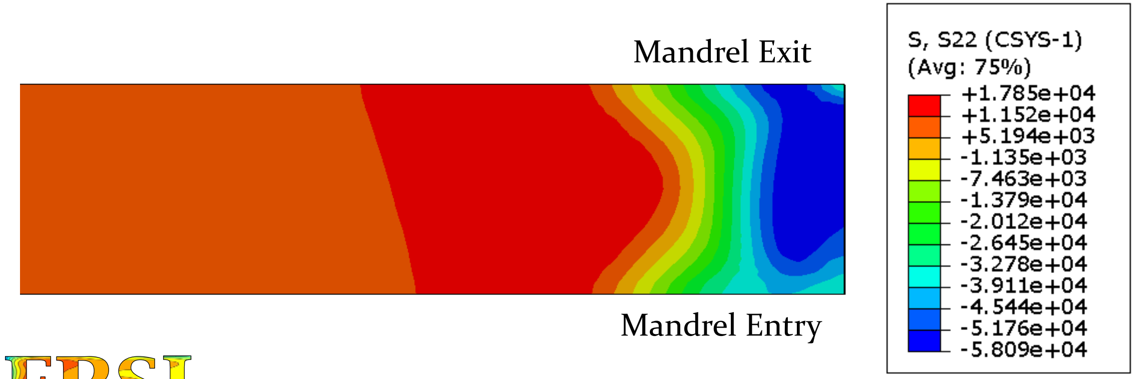


ERSI

Residual Stress Input – Elastic-Plastic FEA

- Finite Element Analysis using ABAQUS[2]
  - 3D, mandrel pull through
  - Reduced integration elements (.017” x .011” x .014” near hole)
  - Penalty Contact with appropriate friction for sleeve, etc.
  - Combined hardening material model (others evaluated)
  - Post-Cx Ream via element removal (results shown)
  - Data was re-grid to a 0.001x0.001inch grid spacing
  - Data was fit using a 15th order polynomial for inclusion in BAMF
    - Residuals of fit to data was produced





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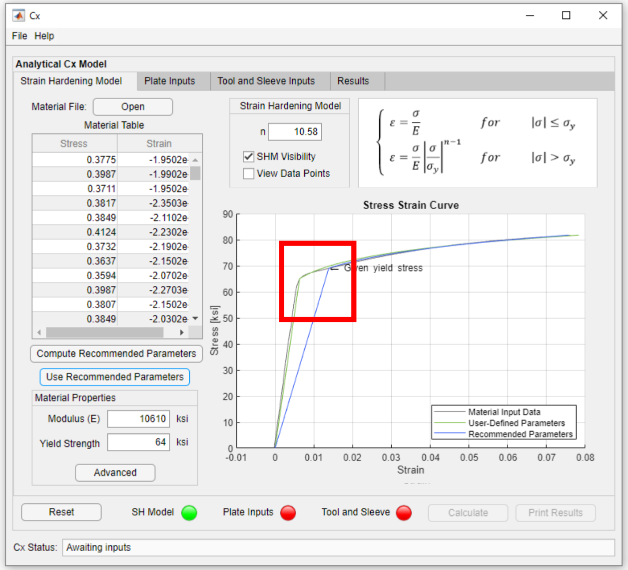
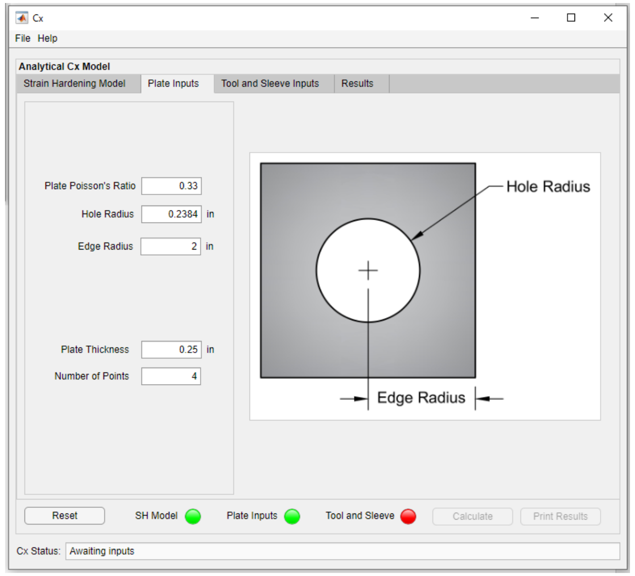
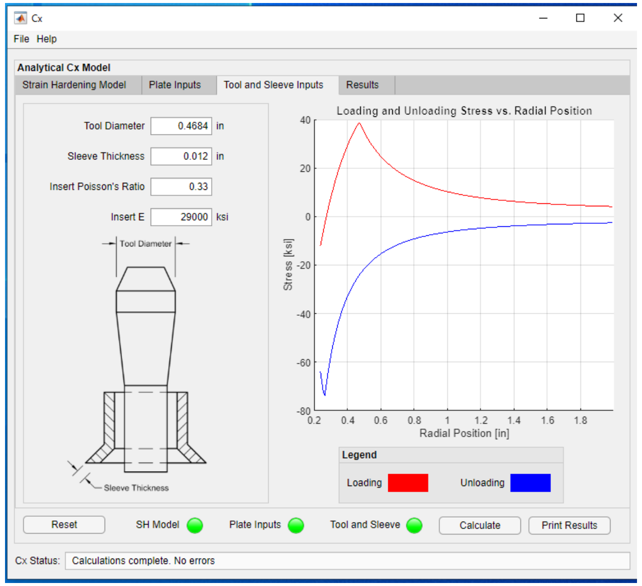
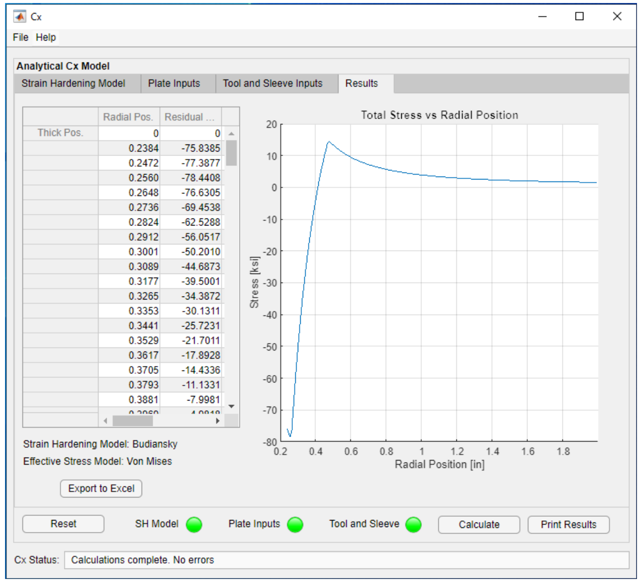
Closed Form Solution

- The closed form solution based on Dr. Ball's paper[3]
- Assumptions:
  - Radial expansion (no difference through material thickness)
  - Budiansky, elastic-plastic material model
  - Determination of elastic-plastic region based on an effective von Misses Stress
  - Process assumed to be quasi-static.
  - No strain rate dependencies included in the model
  - Isotropic material behavior
- Data was re-grid to a 0.001x0.001inch grid spacing
- Data was fit using a 15th order polynomial for inclusion in BAMF





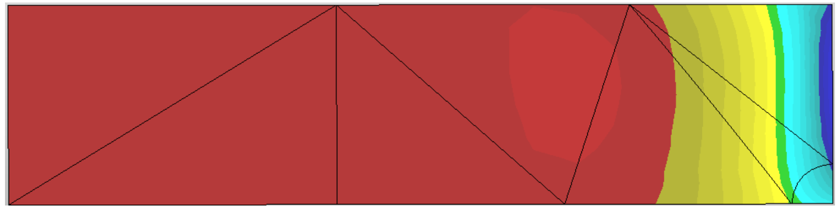


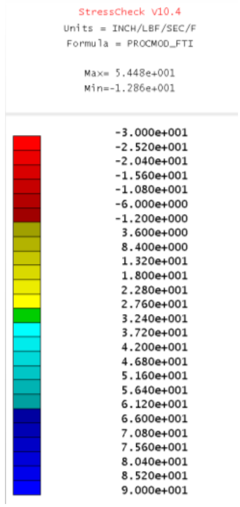


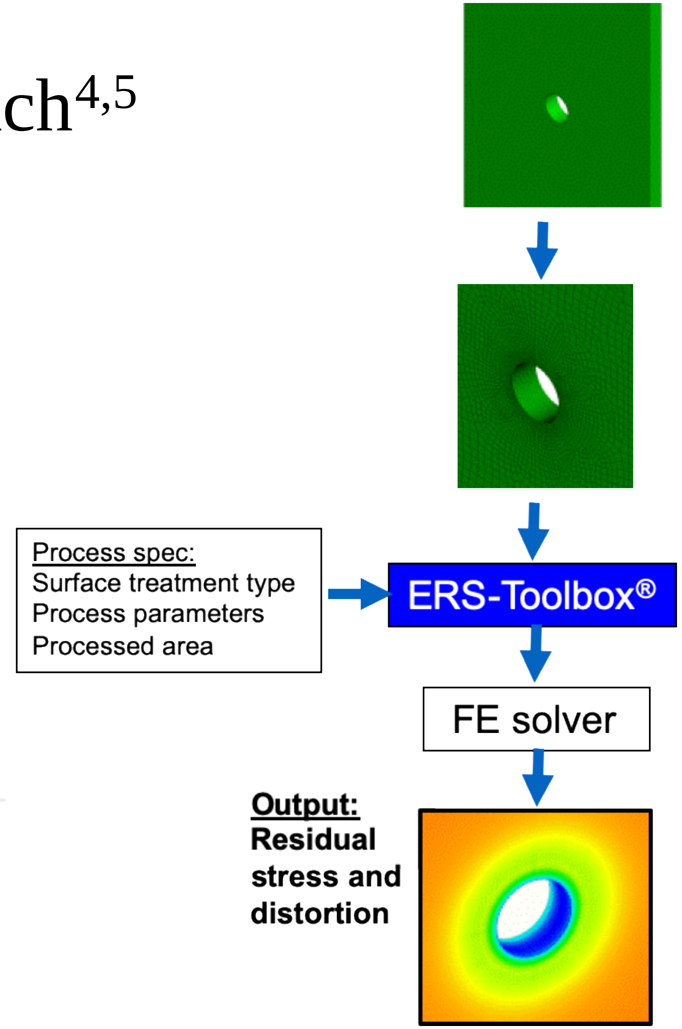
Residual Stress Input – Eigenstrain

- ERS-toolbox® software estimates full field residual stress and part distortion and implements the eigenstrain approach[4,5]
- Specifics of this case
  - Eigenstrain based on residual stress data for similar condition
    - Five coupons with CX spanning 3.14% to 3.23%
      - Coupon IDs are A2-1 to A2-5 from A-10 Mod III program
    - Eigenstrain model based on average of all coupon measurements
  - Residual stress output was interpolated on a 0.001x0.001inch grid
  - Fit to a 15th order polynomial for inclusion in BAMF

Residual stress input into BAMF







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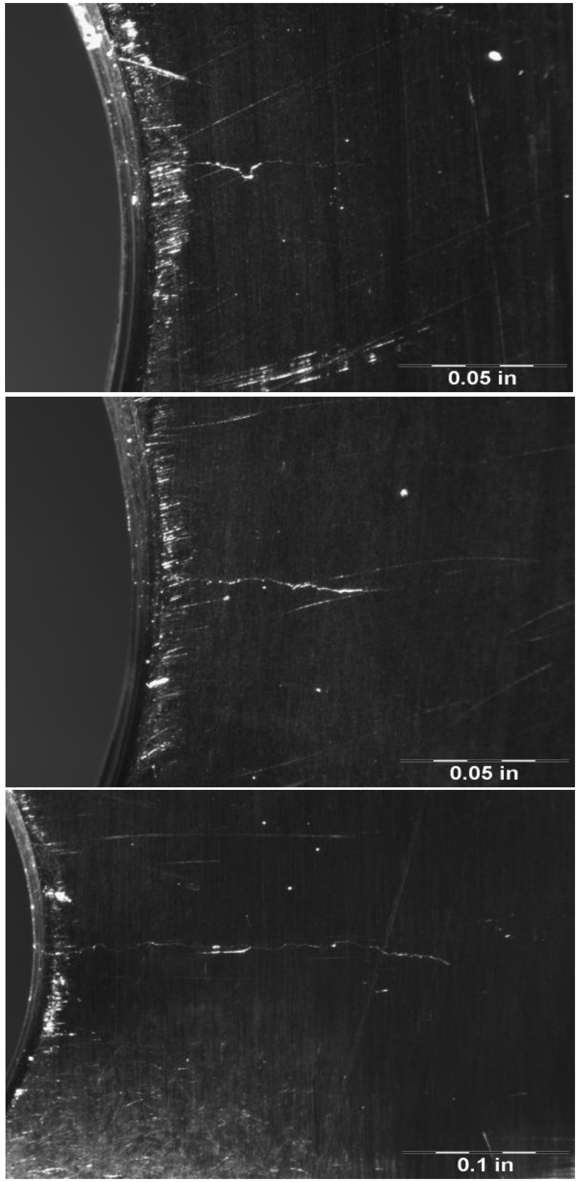
Fatigue Test Condition

- Fatigue Test Coupon Configuration
  - 4inch wide x 0.25inch thick x 16inch long
  - Avg. initial ream diameter = 0.4770inch
  - Std on initial ream = 0.0001inch
  - Applied expansion avg = 3.24%
  - Avg final ream = 0.4992inch
  - Std on final ream = 0.0006inch
- Testing Spectrum – Constant Amplitude
  - Max stress = 25ksi
  - Stress Ratio (R) = 0.1
  - Marker banding with 15% overload
- Fatigue Testing Performed at APES
  - Surface crack length measured via traveling microscopes



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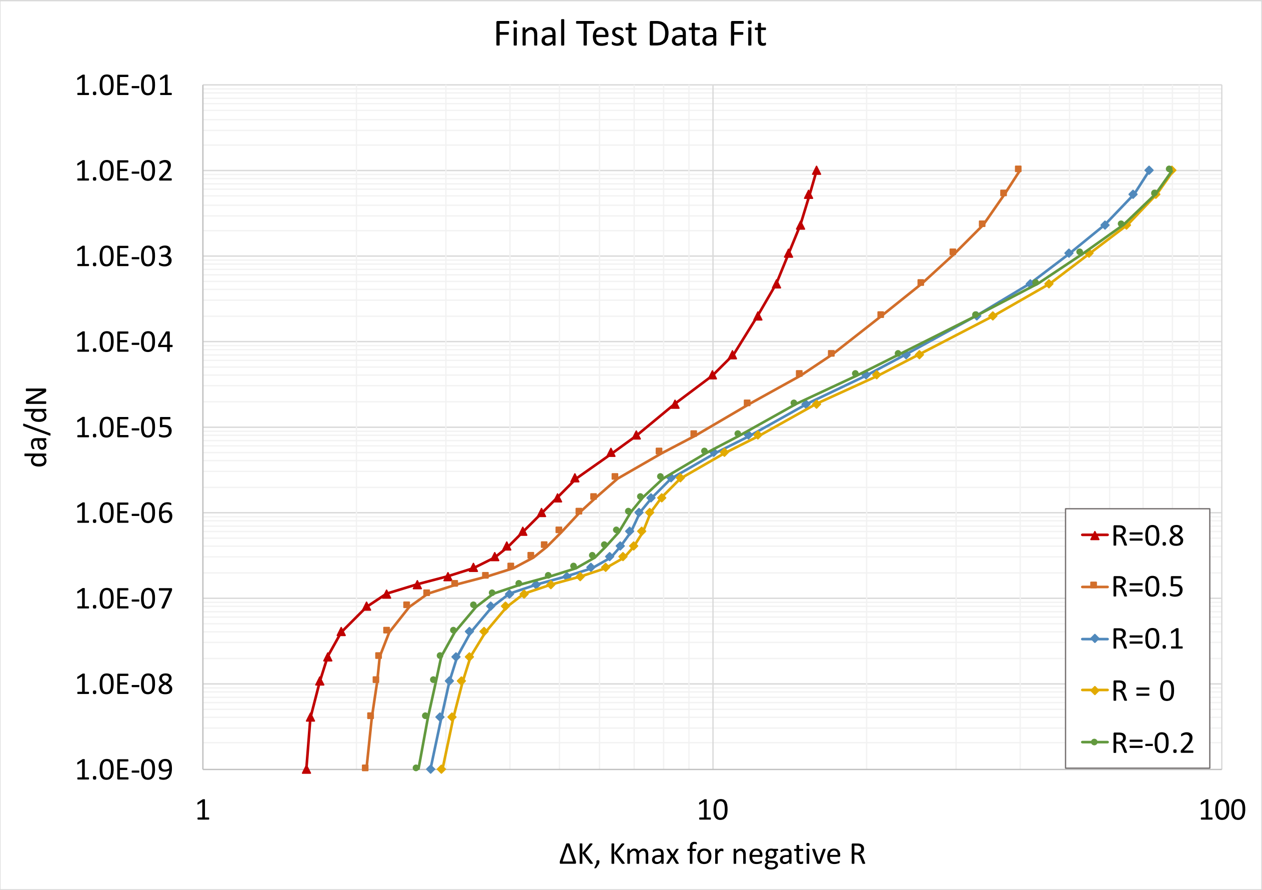
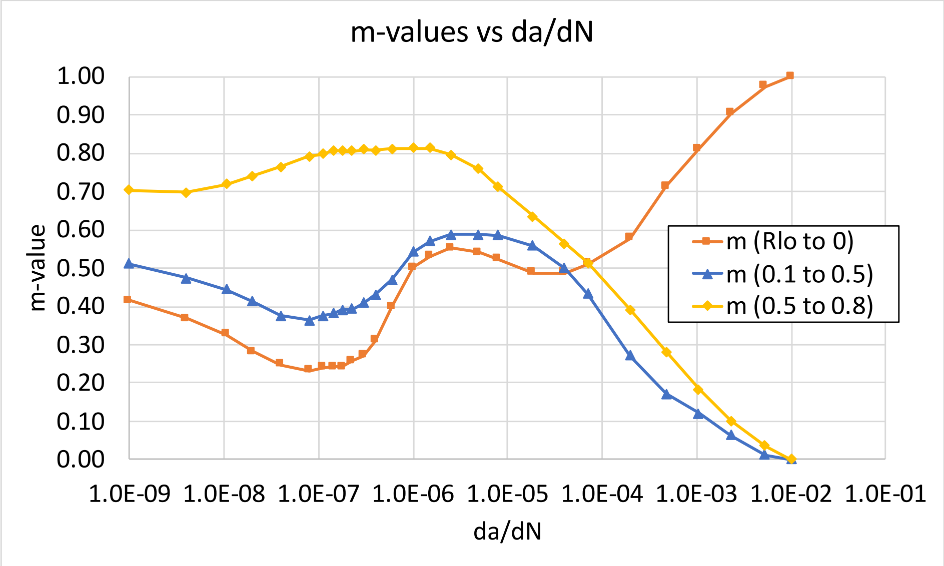
BAMF Predictions

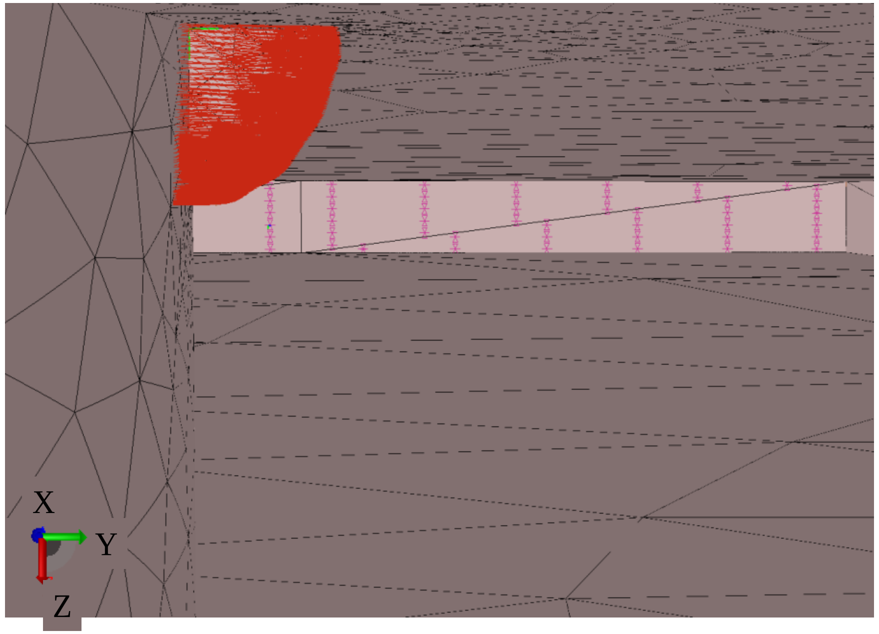
- Material File Input[6]
  - Material file same as ERSI Cx hole round robin and AFGROW round robin
  - 2024-T351, 4 Stress Ratios (R)
  - Material fit performed by Hill Eng. UT

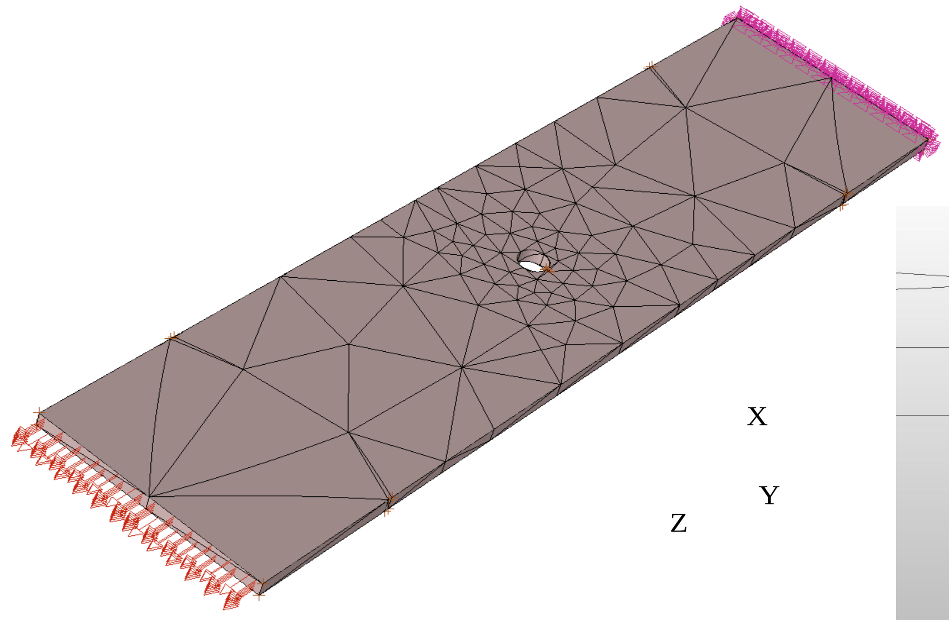


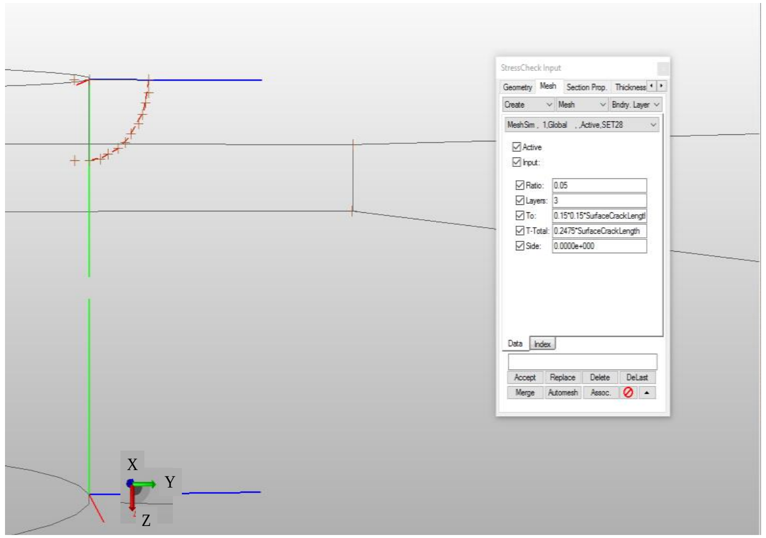


BAMF Predictions

- BAMF Set-up and Model Definition[7]
  - Size of initial crack in model = 0.03x0.03inch quarter elliptical
    - Size based on avg. initial crack size from marker banded coupons
  - Residual stress applied as crack-face traction
  - K_{total} solved at P-level = 5 with convergence checked







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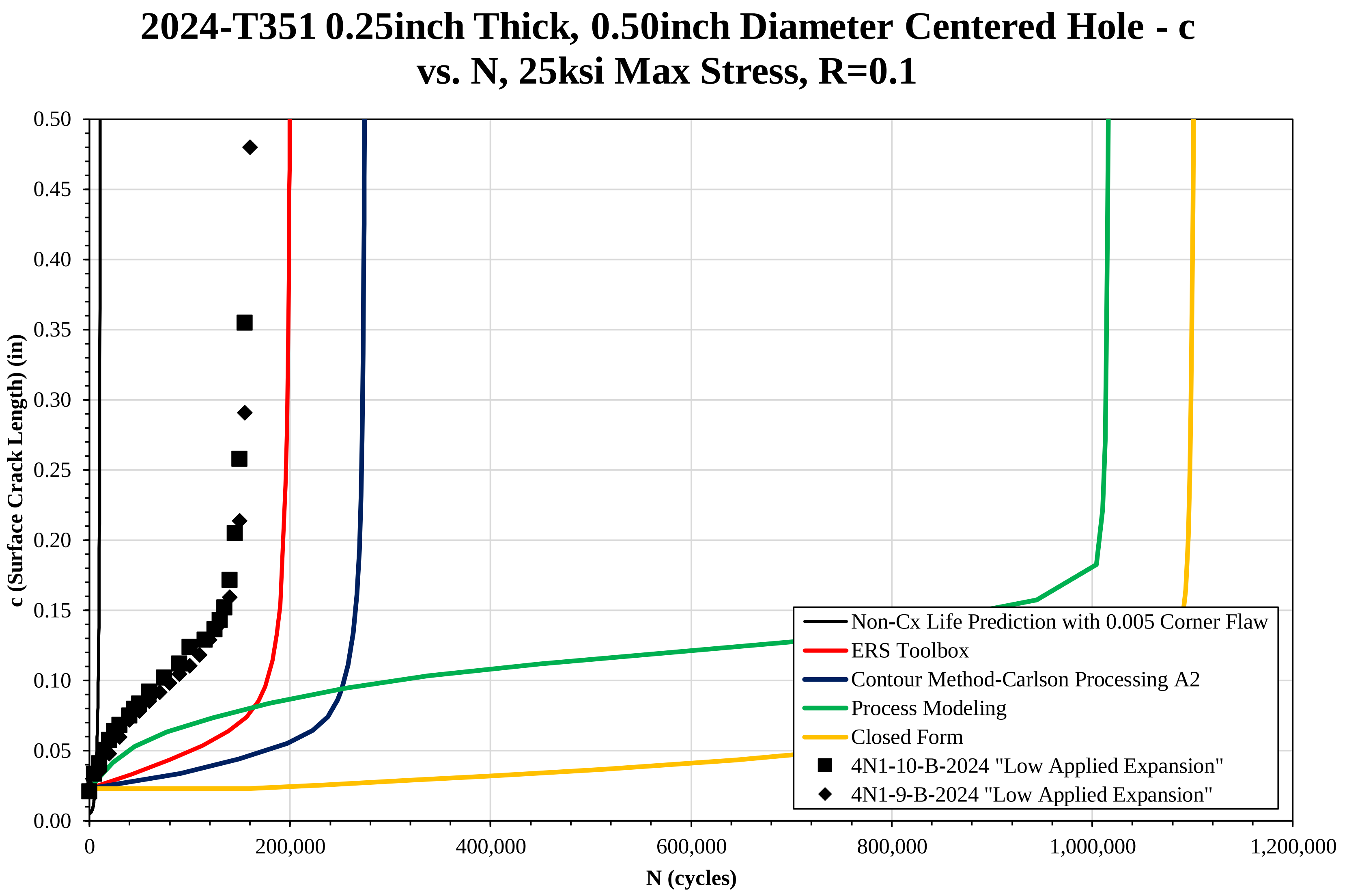
BAMF Predictions

- Life Predictions with Assessed Residual Stress Fields

Residual Stress Input	Life Predicted	Test Life Avg.
0.005x0.005 IFS Assumption	10,900	160,000
Contour Method	275,500	
Eigenstrain	201,000	
Process Simulation	1,017,000	
Closed Form	1,102,000	



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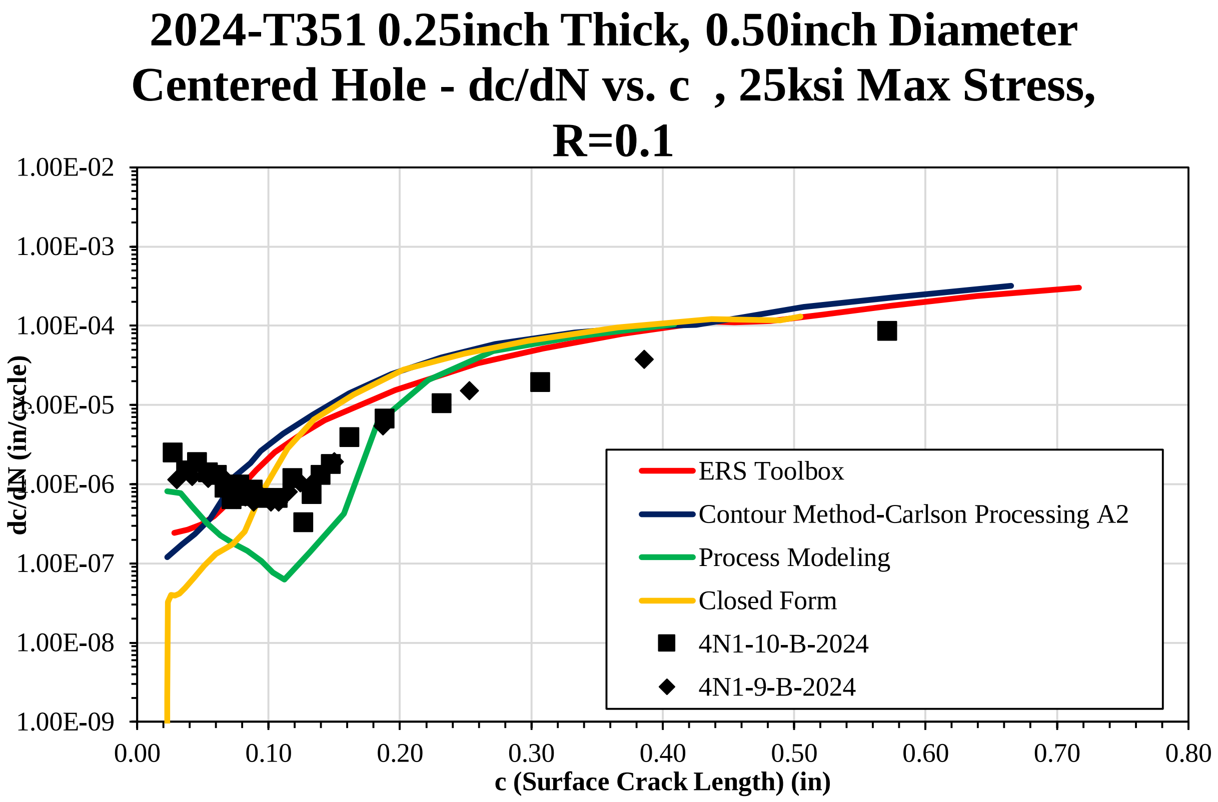
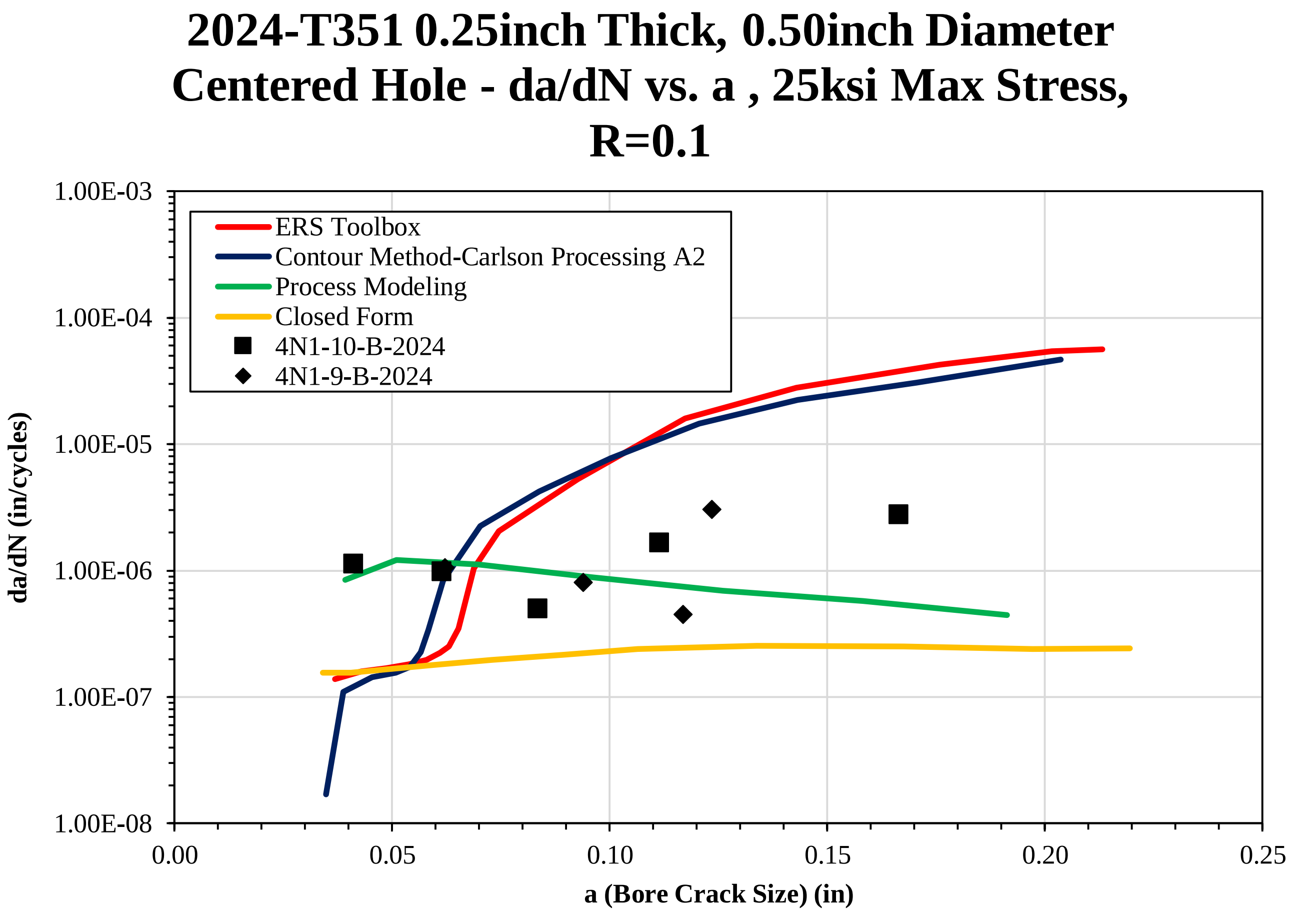
BAMF Predictions





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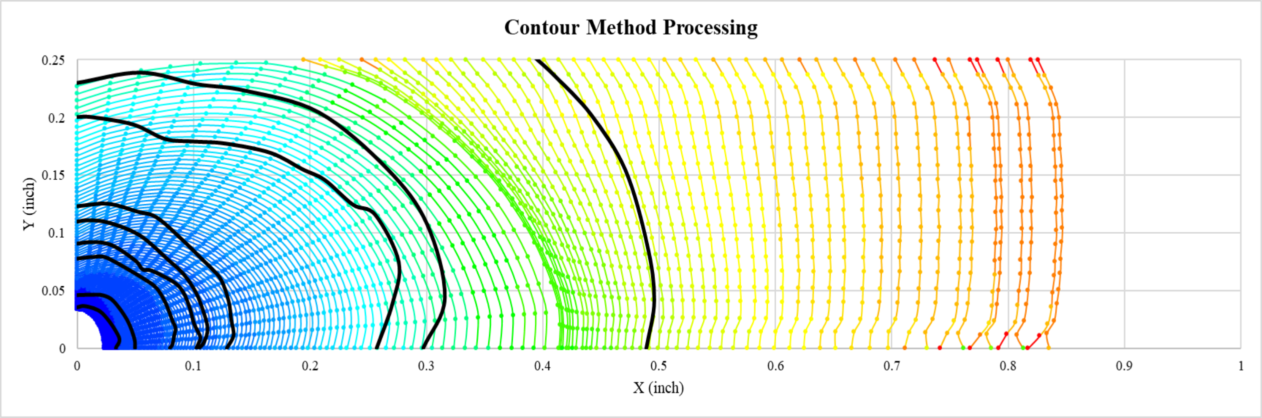
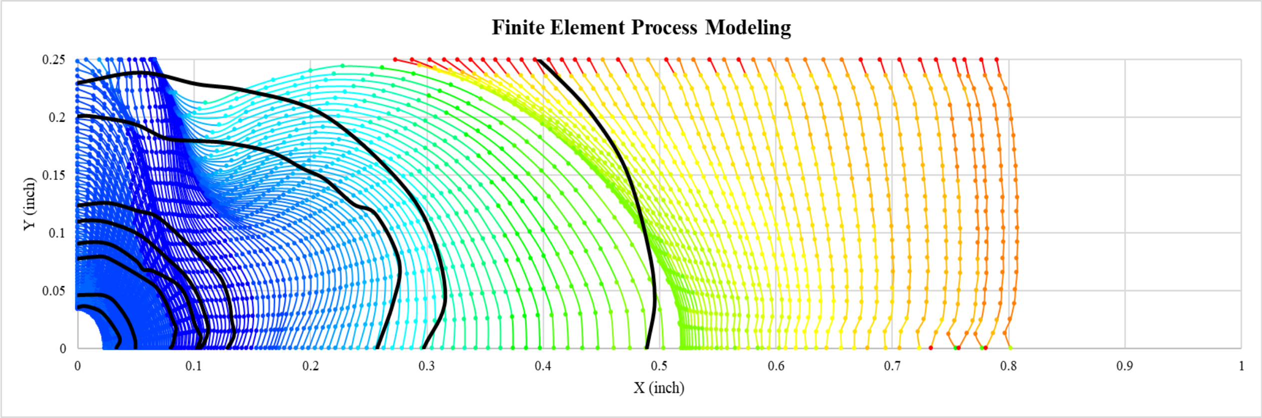
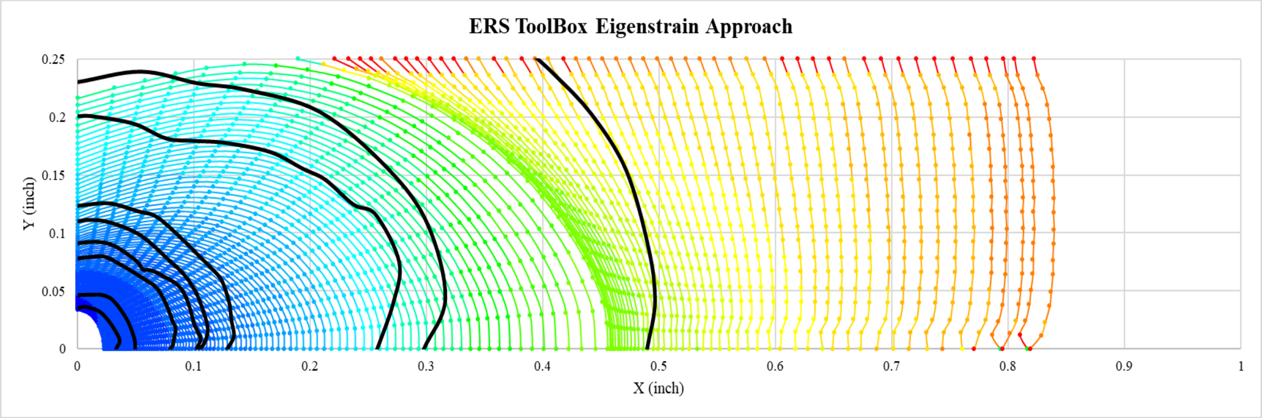
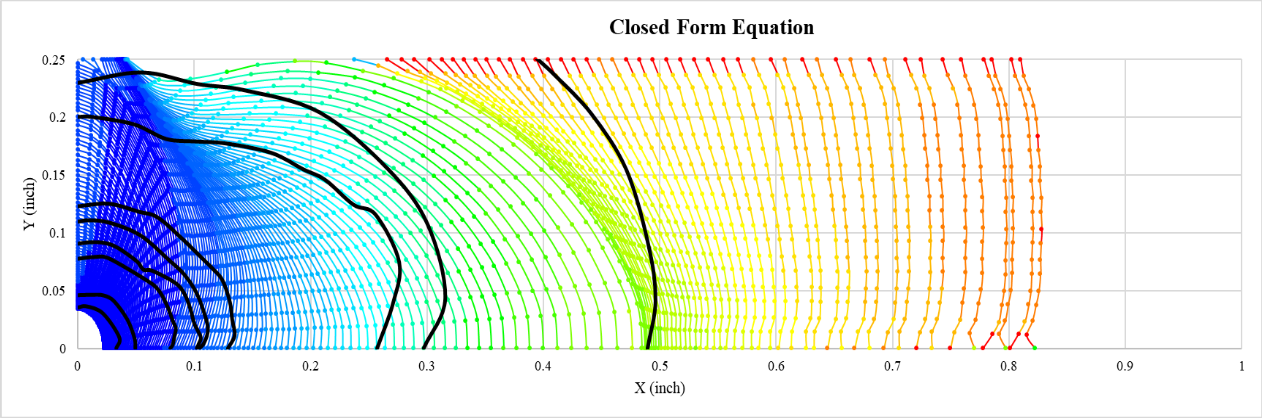
BAMF Predictions

- Predictions of Fatigue Crack Growth Shape vs. Test Marker Bands



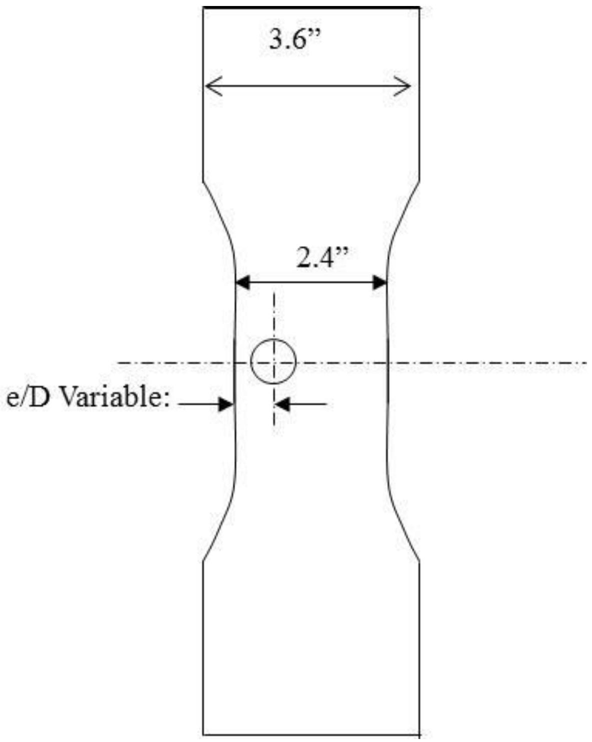






Phase II – ”Short” Edge Margin Hole

- Phase II
  - Move from a “centered” hole to a “short” edge margin hole (e/D = 1.8)
  - Material = 2024-T351
    - Thickness = 0.314inch
    - Final hole diameter = 0.375inch
  - Down select residual stress input from Phase I
    - Contour method
    - Eigenstrain-based ERS Toolbox®
  - Fatigue testing performed for condition via RIF Report[5]
    - Max stress = 22ksi
    - Stress ratio (R) = 0.1
    - Marker banding sequence = 15% overload
  - Perform crack growth prediction using BAMF and LM crack growth code



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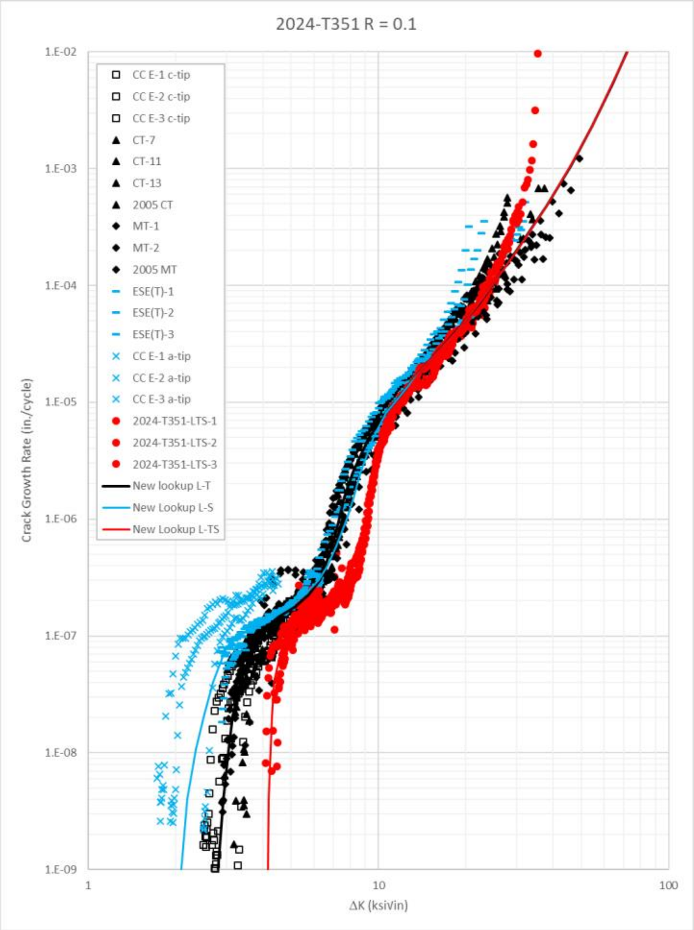
4. Morrison, C.M., Hill, M.R., DeWald, A.T., (2017), Prediction of Full Field Residual Stress in Arbitrary Bodies Using ERS-toolbox®, Proceedings of the 2017 AFGROW Workshop, Layton, UT, USA.
5. Mills, T.B., Honeycutt, K.T., Prost-Domasky, S.A., Brooks, C.L., (2015), Integrating Residual Stress Analysis of Critical Fastener Holes into USAF Depot Maintenance, Report Number A3G-2015-185420, Hill AFB, UT, USA.
6. Pilarczyk, R., (2016), Analytical Methods Subcommittee: Overview of Recent Efforts, Proceedings of the 2017 Engineered Residual Stress Implementation (ERSI) Workshop, Layton, UT USA.
7. Carlson, S., Hodges, J., Pilarczyk, R., Clark, P., (2014), 21st Century Crack Growth Analysis Methods & Tools – Building New Damage Tolerance Capabilities in the United States Air Force (USAF) Aircraft Structural Integrity Program (ASIP) Evolution, Proceedings of the NATO AVT-222 Workshop, Brussels, Belgium.

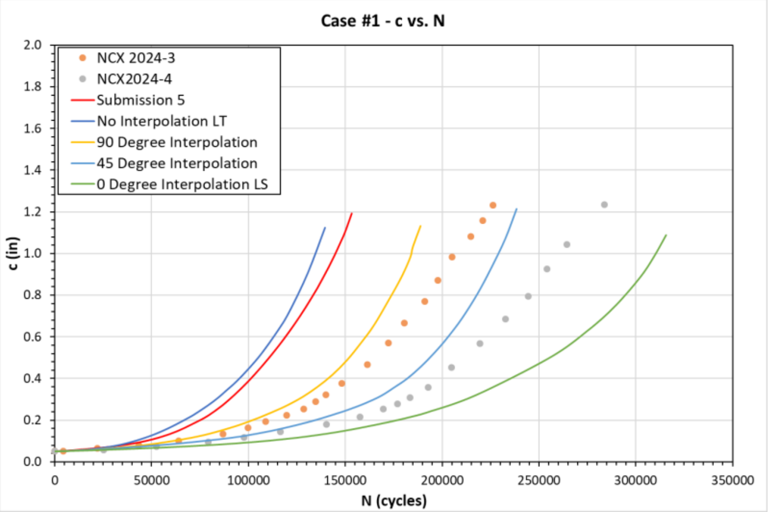
Multi-Directional Material Properties

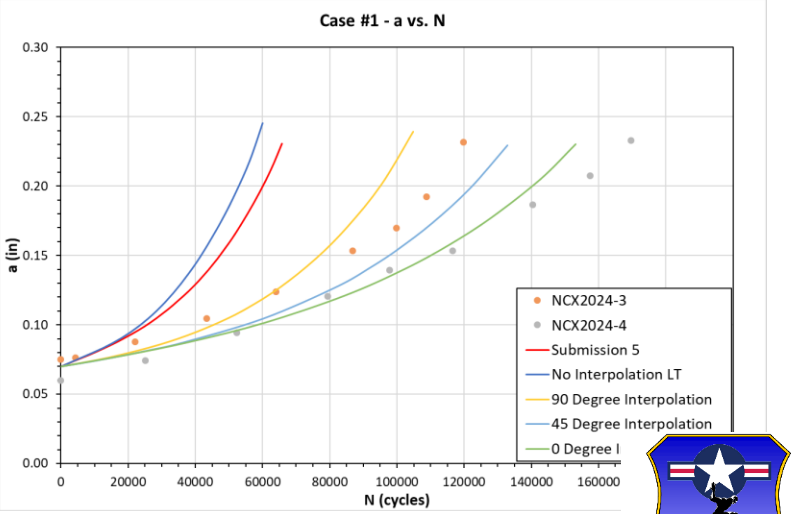
- Background
  - Inability to predict corner crack aspect ratio behavior has prompted recent interest to characterize FCG material properties in different orientations
  - SwRI has been generating data for the past few years
  - Analysis tools must be capably of handling FCG material properties in different orientations
- Approach
  - Incorporate multi-directional material property capability into multi-point fracture mechanics analyses (BAMF)
  - Develop routines (initial investigation) to interpolate between different directions
  - Evaluate new capability with comparisons to benchmarks

Multi-Directional Material Properties

- Results
  - Baseline analyses w/o Cx
    - AFGROW and ERSI Round Robins
  - Improved a/c trends
  - Mixed impacts for life prediction
- Next Steps
  - Investigate interpolation routines
  - Continue investigating and developing test data
  - New capability in upcoming release of BAMF







We're learning as we go…

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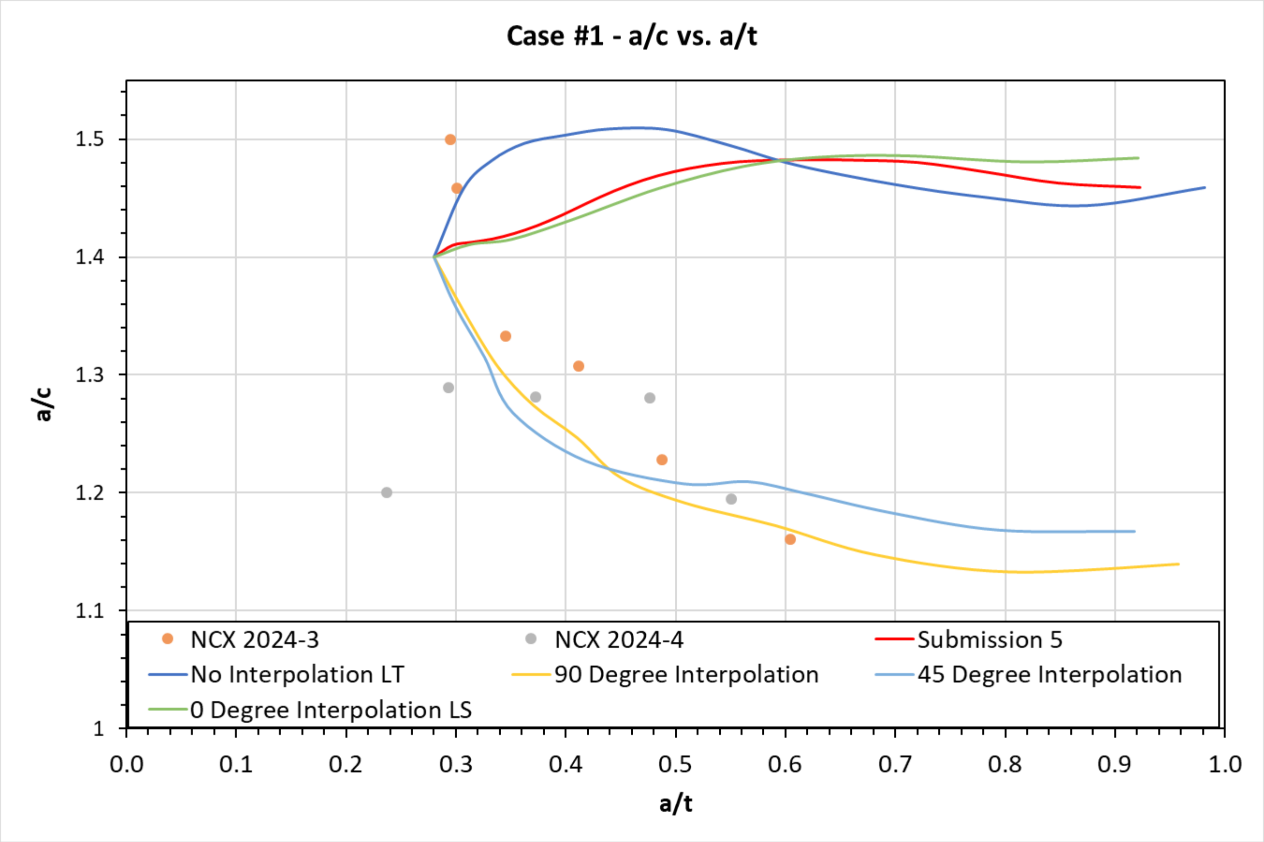
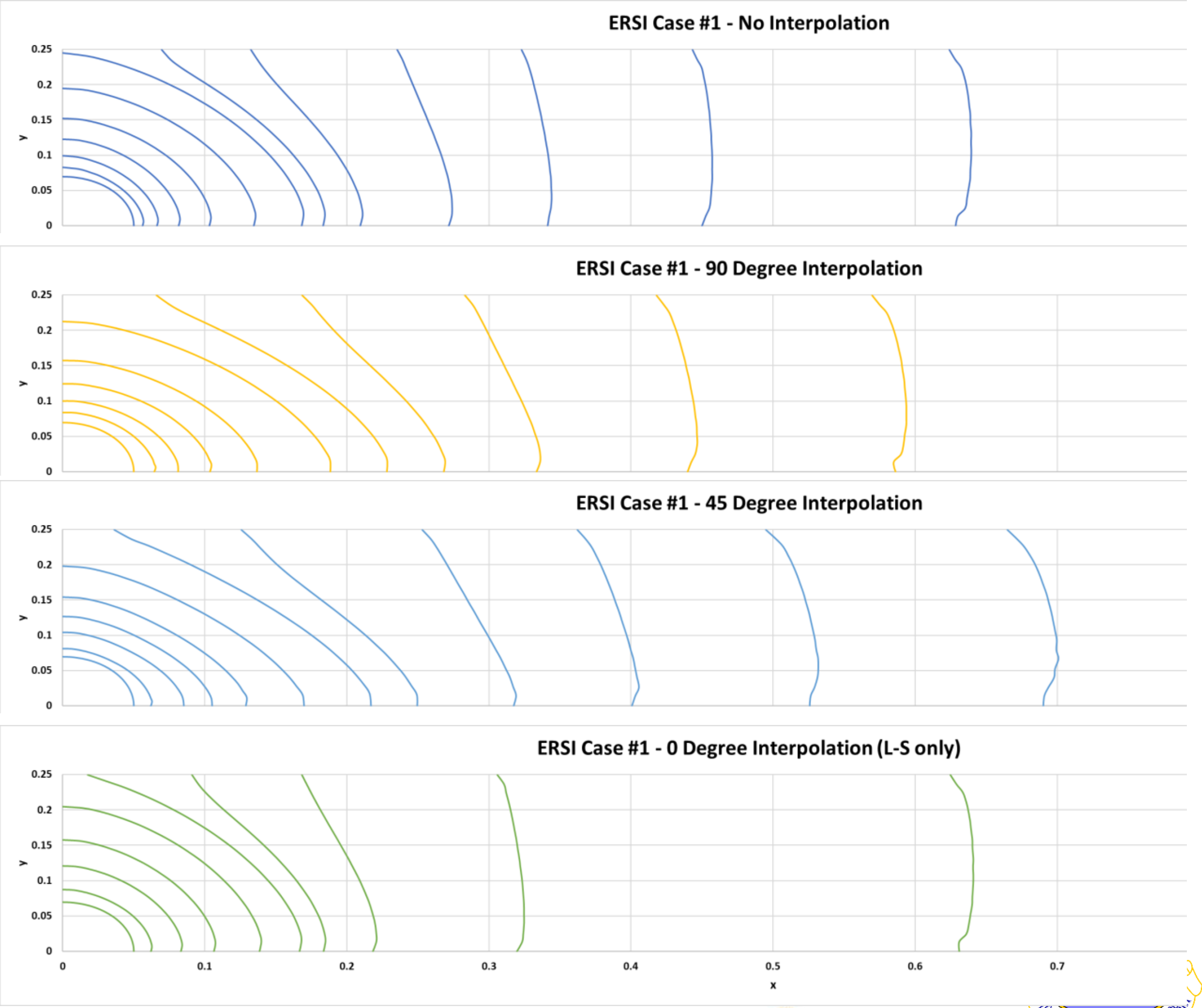
Multi-Directional Material Properties

- Results





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Closure Modeling

Seeking to understand and better model crack growth behavior at CX holes

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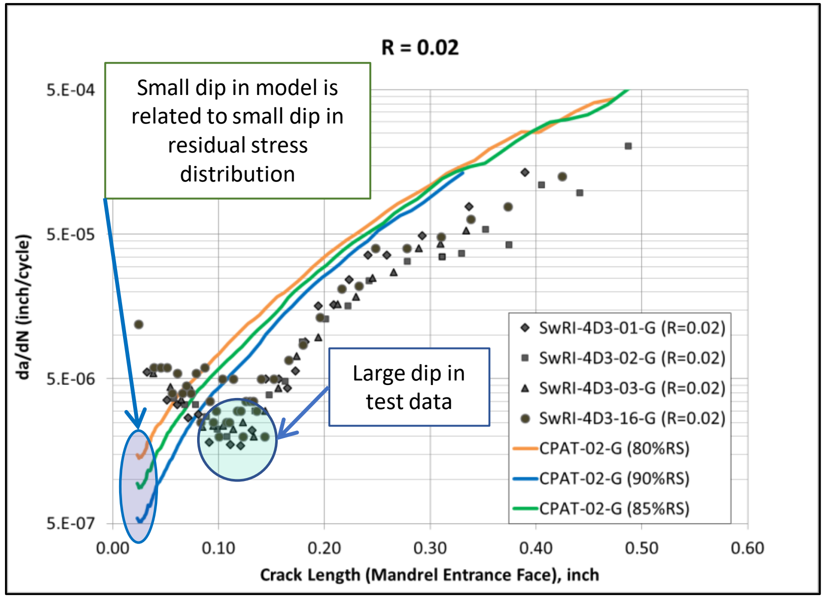
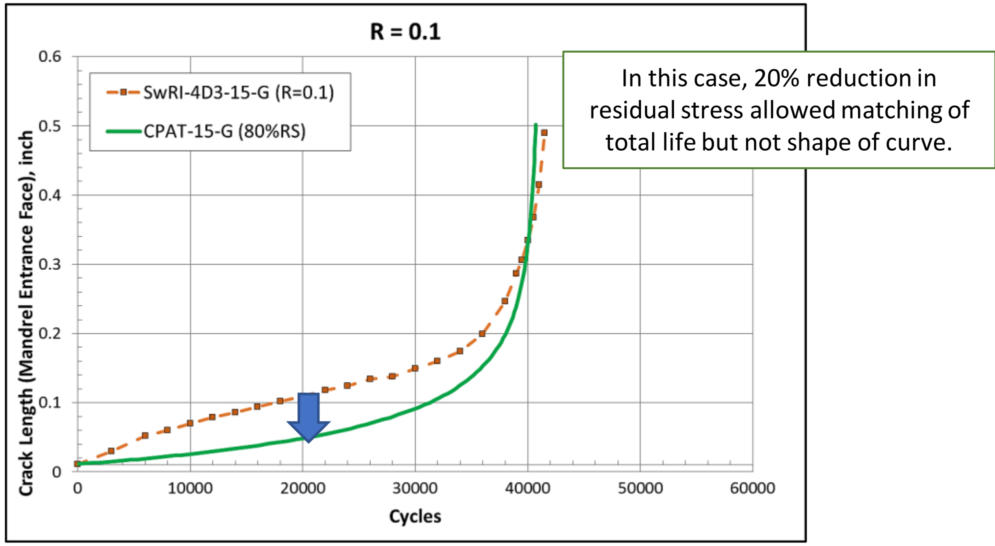
Refresher from 2018: Key Observations

- 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





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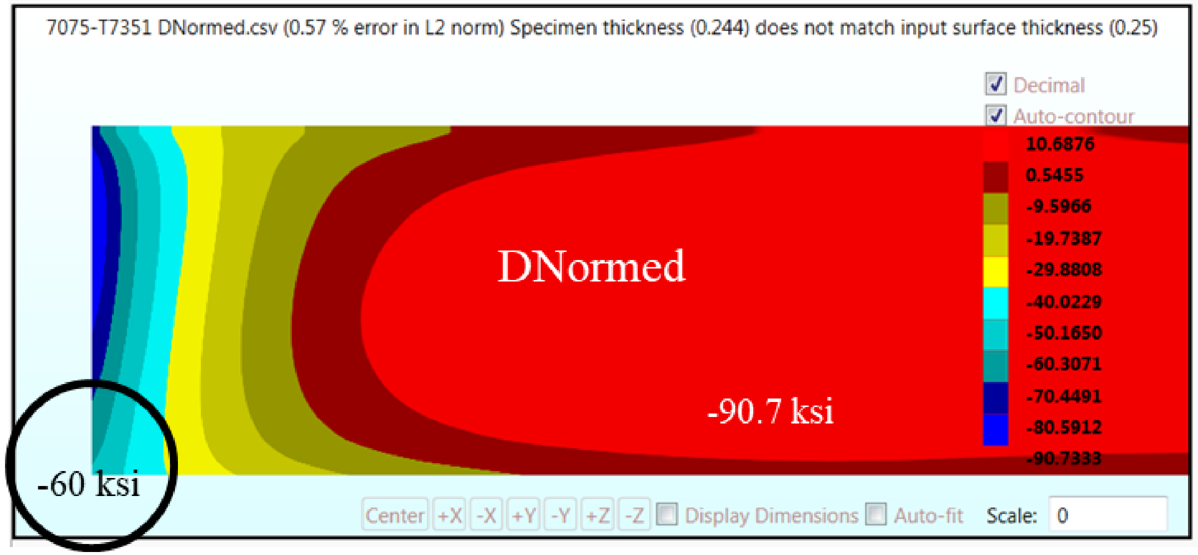
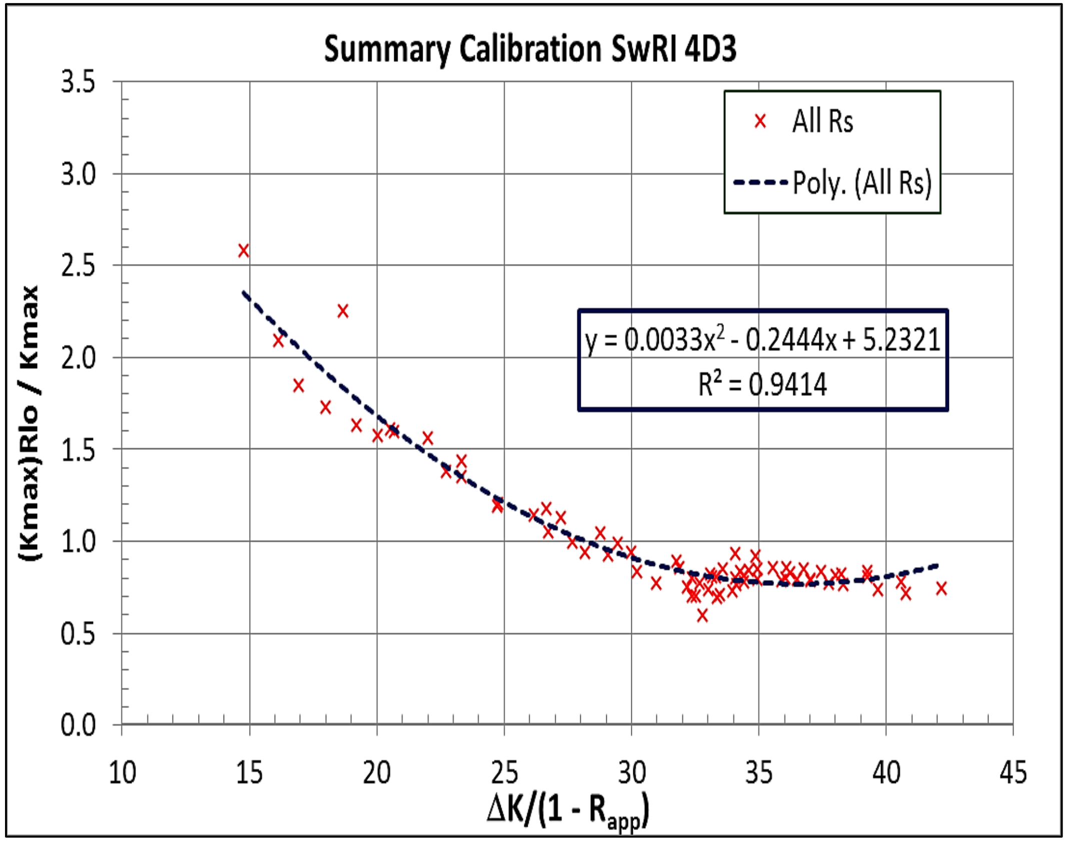
Data Analysis

- Calibration
  - Empirical study showed that Kmax as much as 2.5x higher than calculated was needed to correlate with early crack growth rates
  - Deeply negative RS





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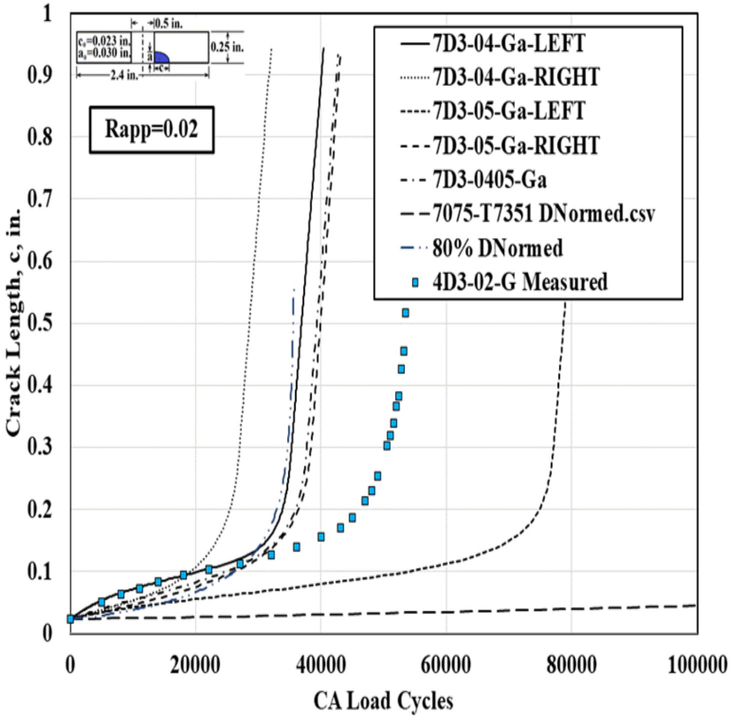
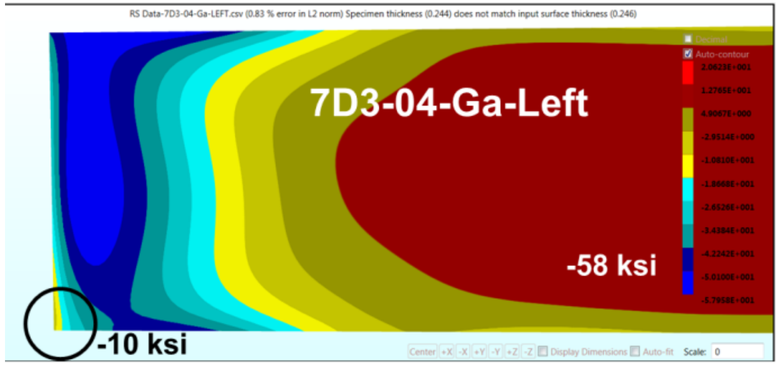
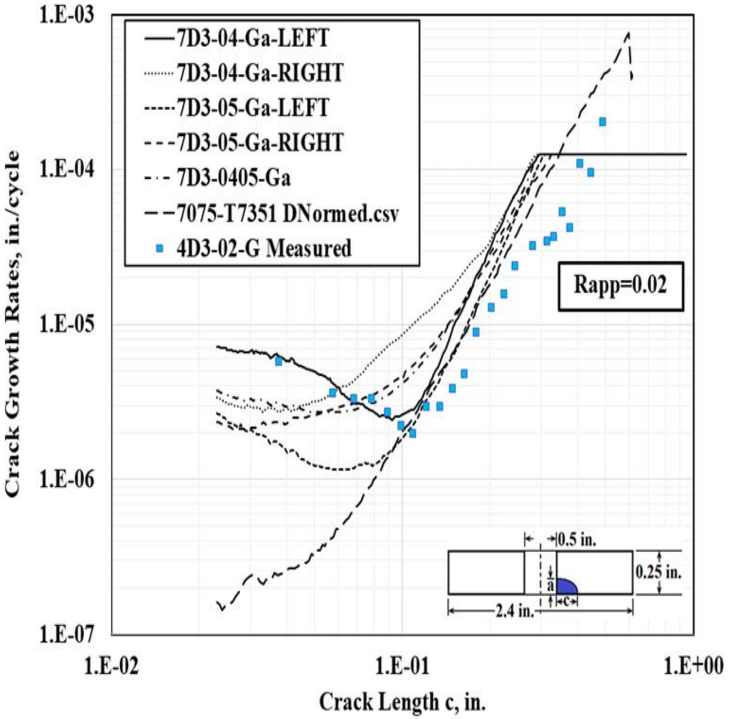
Redistributed Residual Stress Leads to Improved Modeling

- 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







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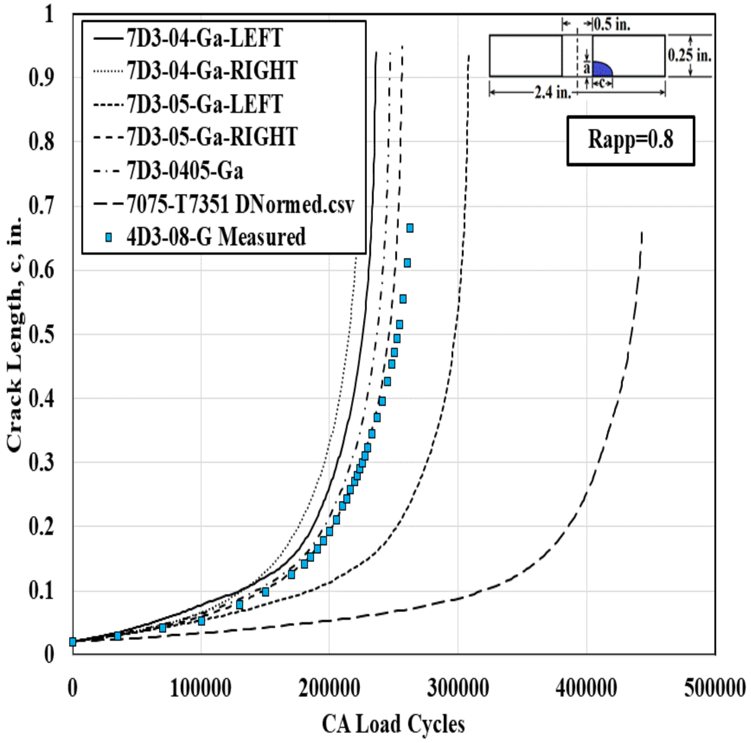
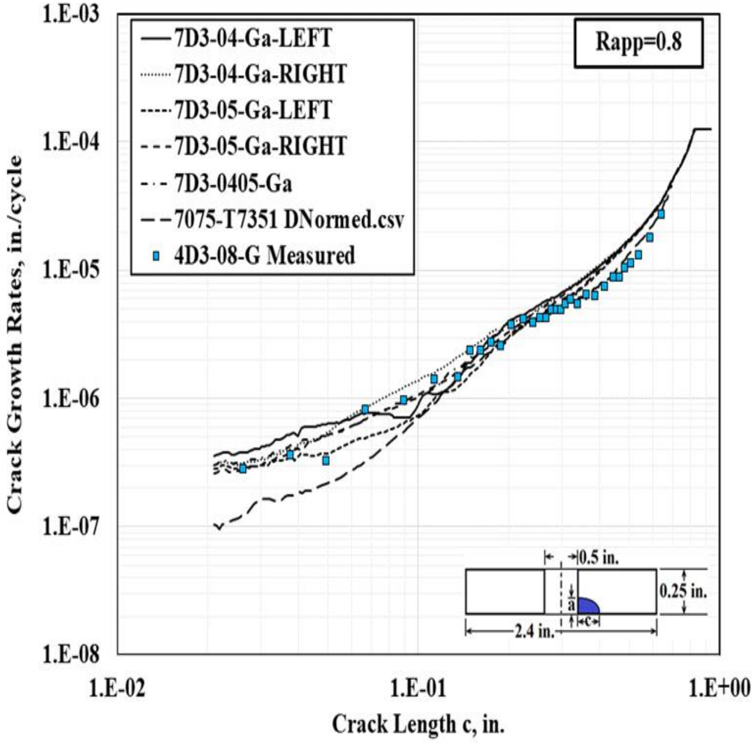
Redistributed Residual Stress Leads to Improved Modeling

- Same RS Correlates Well at $R_{app} = 0.8$ ($R_{tot} > 0$)
  - No dip in da/dN test data when $R_{tot} > 0$
  - New RS captures this behavior as well





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Residual Stress Shakedown

- Why is the behavior not evident in teardown assets?

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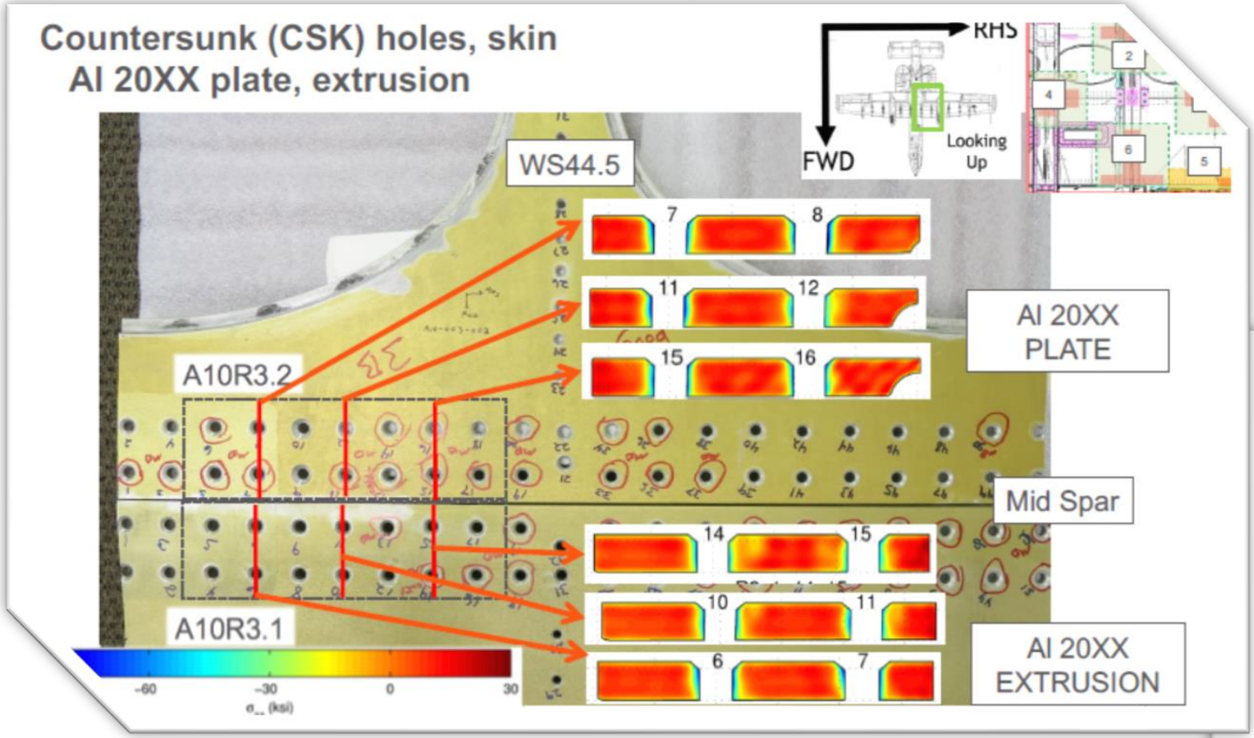

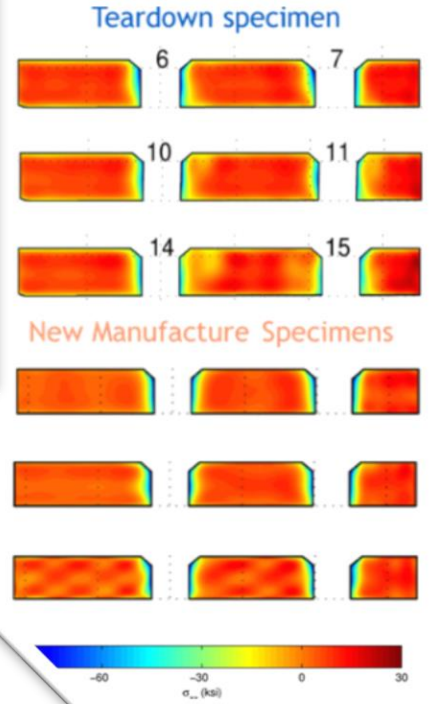

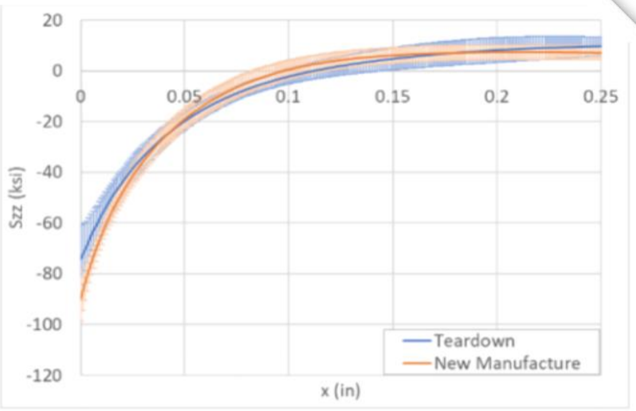

Sample ID	Midthickness 0.125*rad (ksi)	Midthickness 0.25*rad (ksi)	Midthickness 0.5*rad (ksi)	Midthickness 0.75*rad (ksi)	Depth at crossover (midthickness) (in)	Point Value of Entrance (ksi)	Avg RS in 0.05" Radius Entrance (ksi)	Point Value CSK Knee (ksi)	Avg RS in 0.05" Radius CSK knee (ksi)
Mean	-47.15	-31.04	-12.29	-2.60	0.13	-51.30	-34.67	-77.92	-44.59
Stdev	5.17	4.10	2.71	2.99	0.04	21.61	6.68	16.67	10.37
Mean	-52.82	-32.95	-10.82	-0.19	0.10	-49.72	-31.57	-98.82	-55.33
Stdev	3.68	3.91	3.91	3.65	0.02	21.46	3.05	14.72	2.64
Residuals (Td-NM)	5.68	1.91	-1.46	-2.42	0.03	-1.58	-3.09	20.90	10.74
P Value	0.00	0.13	0.15	0.05	0.02	0.43	0.08	0.00	0.00
Significant	Yes	No	No	Yes	Yes	No	No	Yes	Yes

Filled Hole Effects?

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Residual Stress Shakedown

- Next Steps
  - Complete initial investigate for standard configurations
- Approach
  - Investigate differences between:
    - non-cycled coupons (utilize existing data)
    - open hole cycled coupons
    - filled hole cycled coupons
- Scope
  - Coupon configurations (12 total)
  - Material: 2024-T351 and 7075-T651
  - Diameter: 0.50-inch
  - Hole Offset: centered
  - Thickness: 0.25-inch
  - Applied expansion: mean

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Swift, Taylor. (2014), “Shake It Off”

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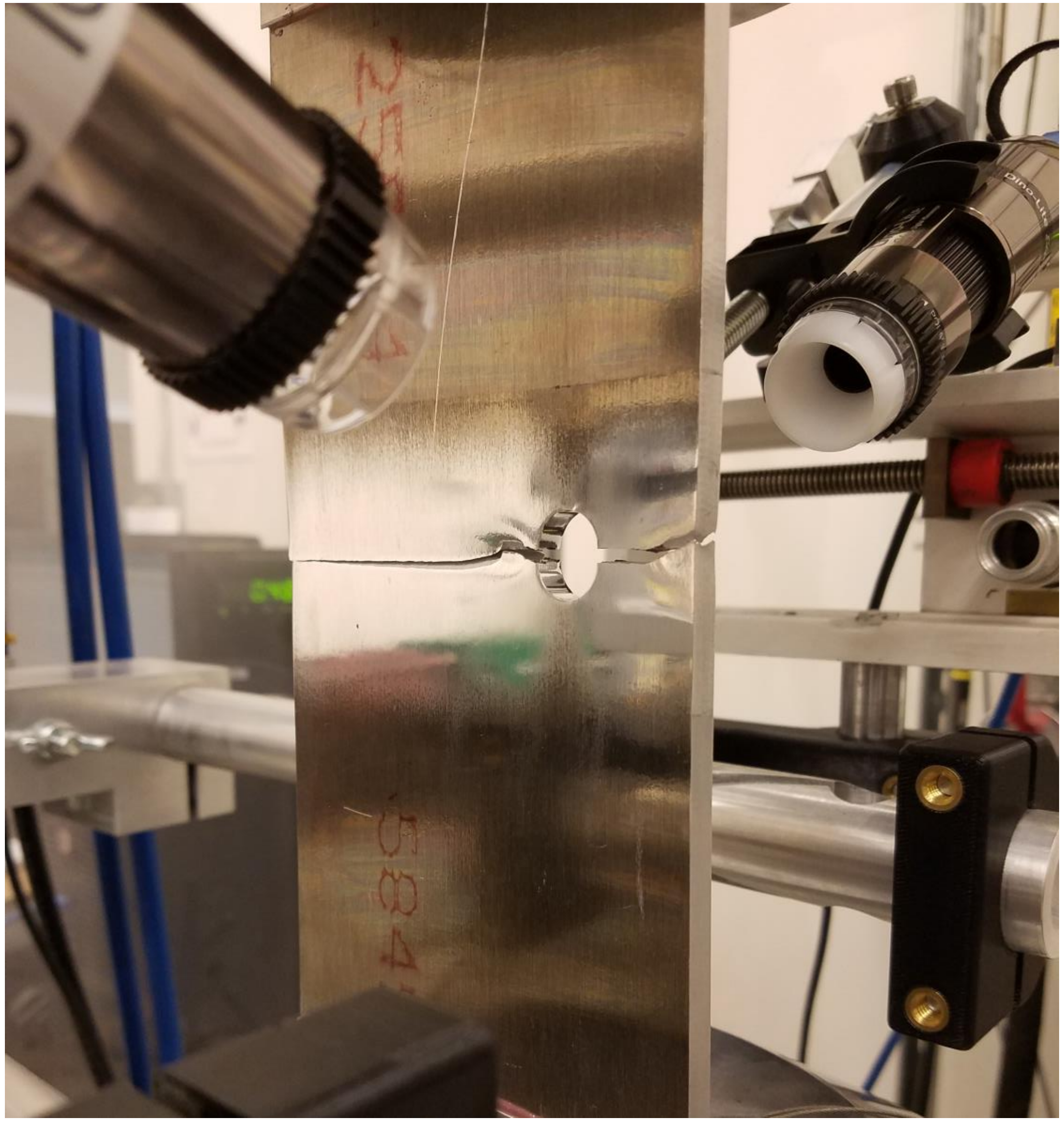
Crack Closure Imaging

- Objective
  - Capture images of cracks at CX holes
  - Determine stress level required to open crack
  - May be useful for validating closure models
- Approach
  - Digital microscope controlled by test software
  - Periodically stepped stress from 0 to 33ksi at 3.3ksi (10%) increments
  - Captured image at each stress level
  - Visually determine if crack is open



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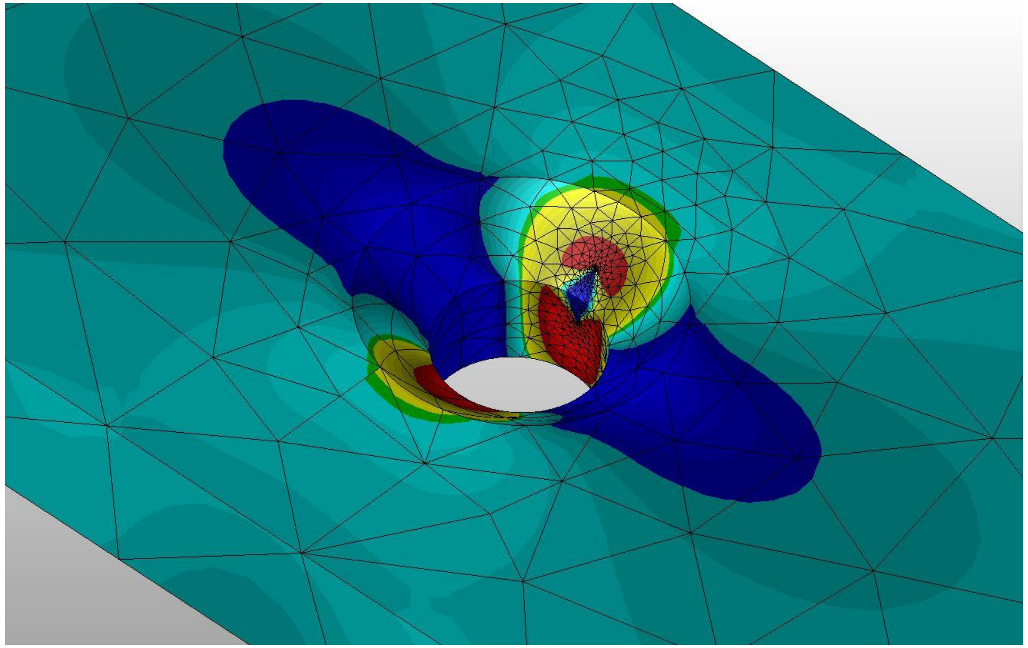
Notch Plasticity

- Objective
  - Investigate the notch plasticity and size of plastic zone at a non-Cx and Cx fastener hole
  - Answer question:
    - Does notch plasticity impact Cx residual stress locally at the hole?
- Approach
  - Investigate handbook solutions
  - Compare/contrast to linear and non-linear FEA
  - Investigate open and filled hole configurations
  - Build macros and plots to compare results



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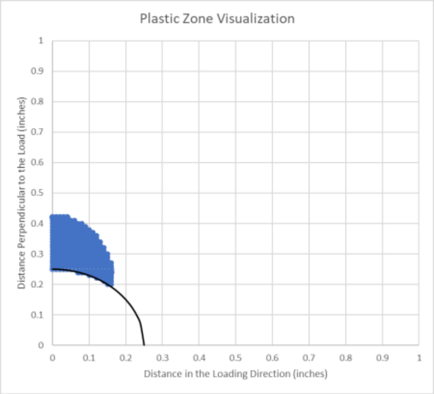
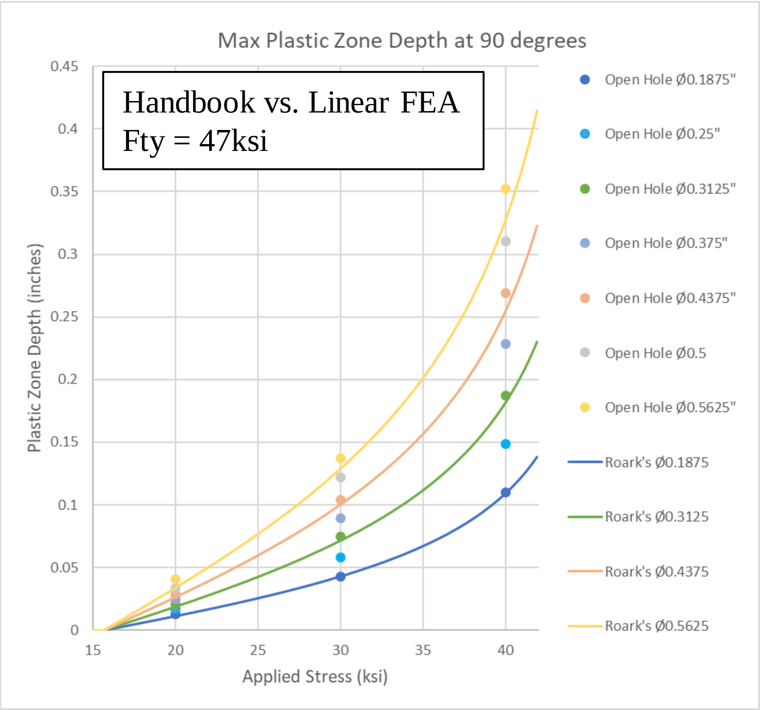
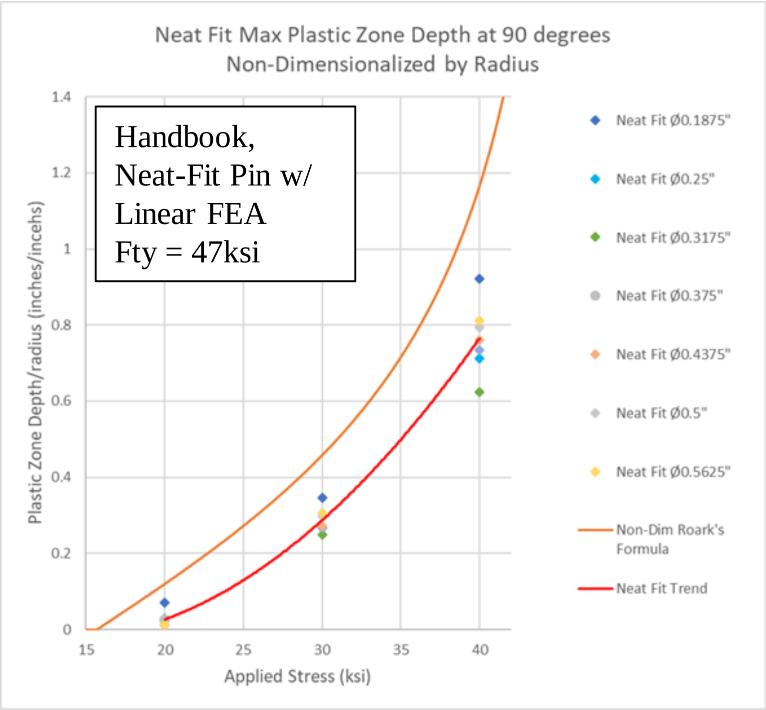
Notch Plasticity

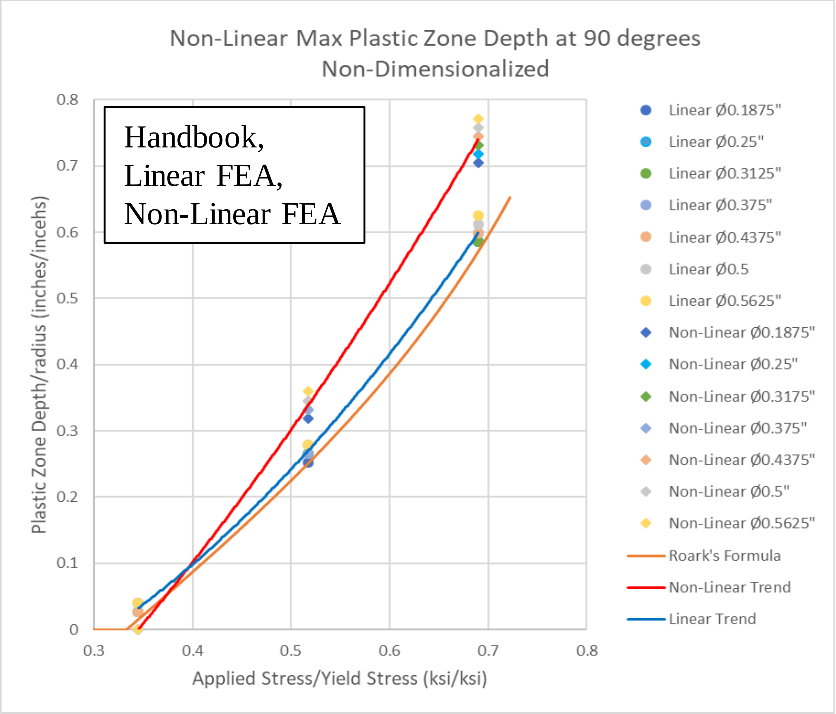
- Handbook Solutions
  - Roark’s Formulas for Stress and Strain, 7th edition
  - Linear Elastic solution
- FEA
  - Linear and non-linear predictions

$$\sigma_\theta = \frac{\sigma}{2}\left[1 + \frac{a^2}{r^2} - \left(1 + 3\frac{a^4}{r^4}\right)\cos 2\theta\right]$$







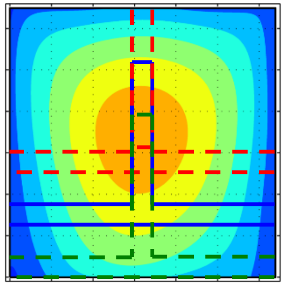


FCG in Coupons with Quench Residual Stress

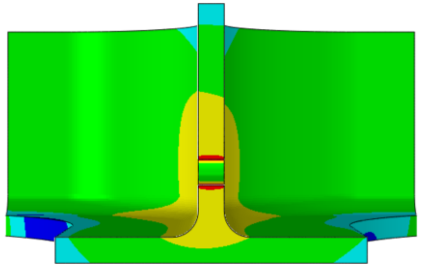
- Motivation:
  - Residual stress from quench is inherent in the production of key high-strength aluminum alloys (typical post-quench stress level 50% S_y)
  - Residual stress relief processes leave some residual stress behind
    - Stretched plate can have very low peak stress levels (≈ 2% to 4% S_y)
    - 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

Renan L. Ribeiro, UC Davis

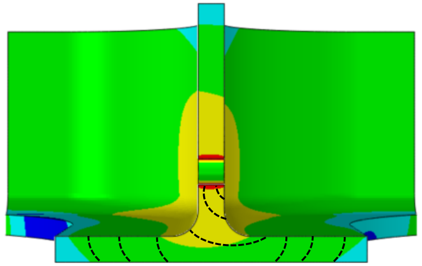
- Research questions:
  - Can residual stress from raw stock be used to predict stress in finished parts?
  - Can predicted residual stress improve prediction of fatigue crack growth in finished parts?



Measure RS in Raw Product Form



Predict RS in Part Cut from Raw Product Form



Predict Fatigue Performance Including RS

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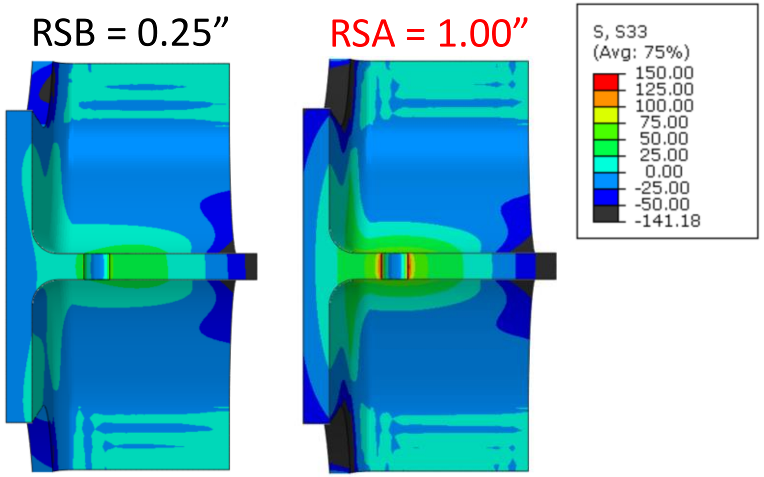
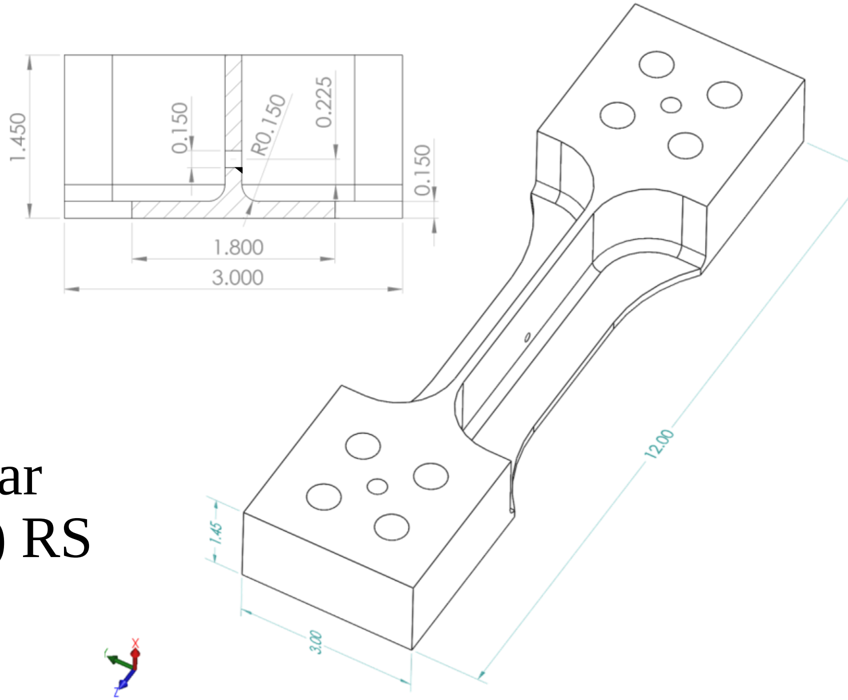
FCG in Coupons with Quench Residual Stress

- Coupon Design and Conditions
  - Geometry shown below (representative of airframe detail)
  - Produced coupons in 3 conditions:
    - RS0: low RS cut from AA7050 T7451 (stretched)
    - RSA: high RS, cut from AA7050 T74 (quenched)
    - RSB: moderate RS, cut from AA7050 T74 (quenched)
  - Corner crack starter milled at the edge of hole
    - Crack grows towards the base flange
- Residual Stress Prediction (eigenstrain)
  - Predict RS for coupons removed from different locations within bar
  - Chose two locations that provide moderate (RSB) and high (RSA) RS

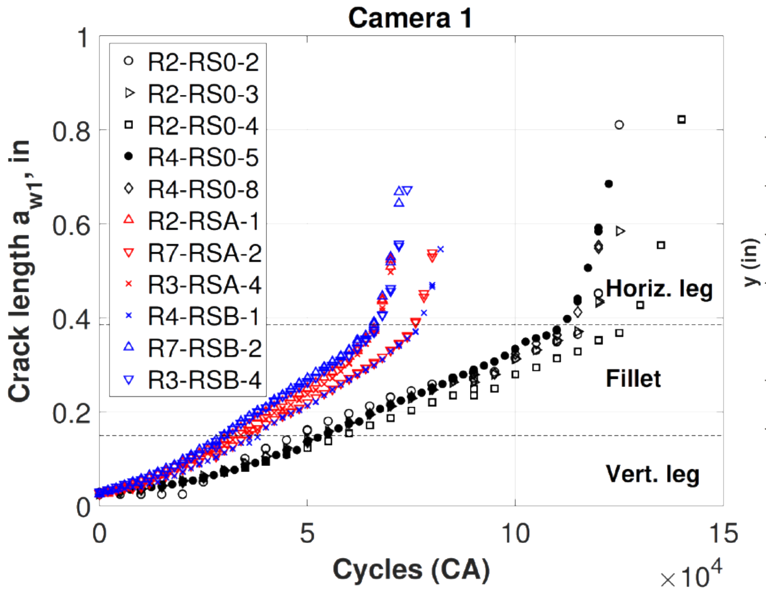


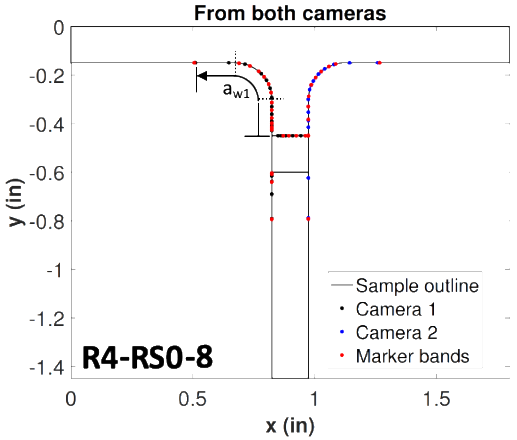


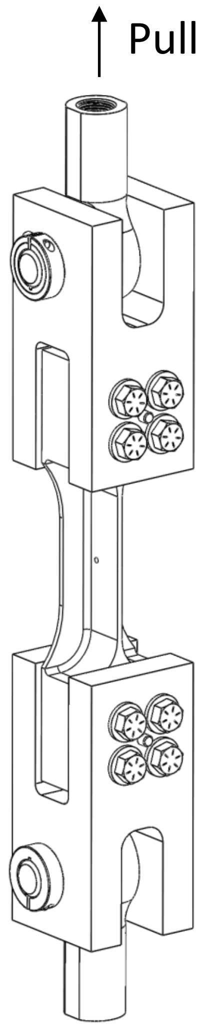
All dimensions in inches

FCG in Coupons with Quench Residual Stress

- Fatigue Crack Growth Testing
  - Test in pull-pull configuration, constant amplitude (CA) loading, R = 0.1
    - Fixture provides consistent load, known restraint
  - Monitor crack growth using three techniques
    - Direct Current Potential Drop (DCPD)
    - Digital photogrammetry (DP)
    - Quantitative fractography (QF), also called marker banding
      - Number of marker bands 13 to 41 per sample







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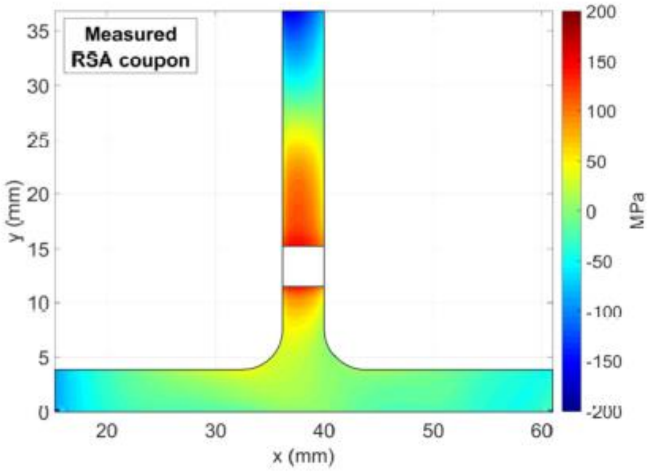
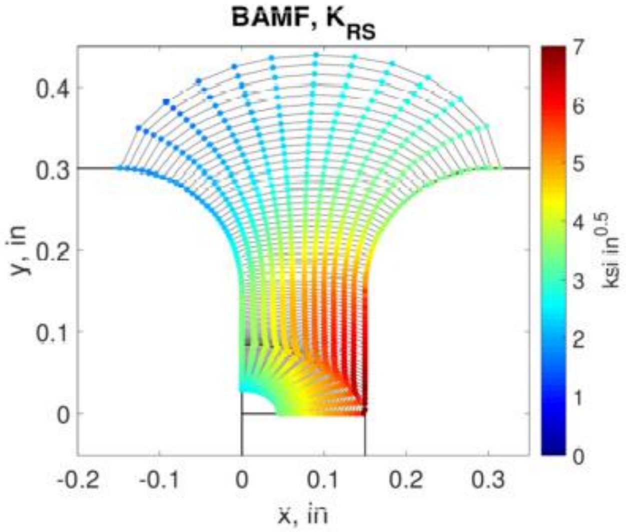
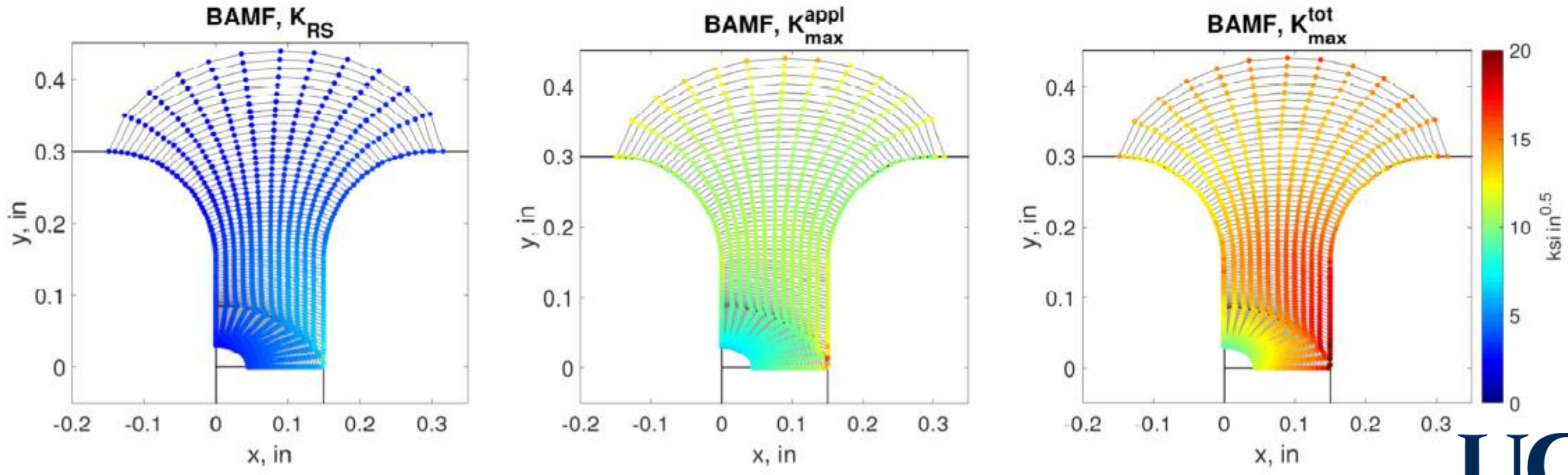
FCG in Coupons with Quench Residual Stress

- Fatigue Crack Growth Predictions







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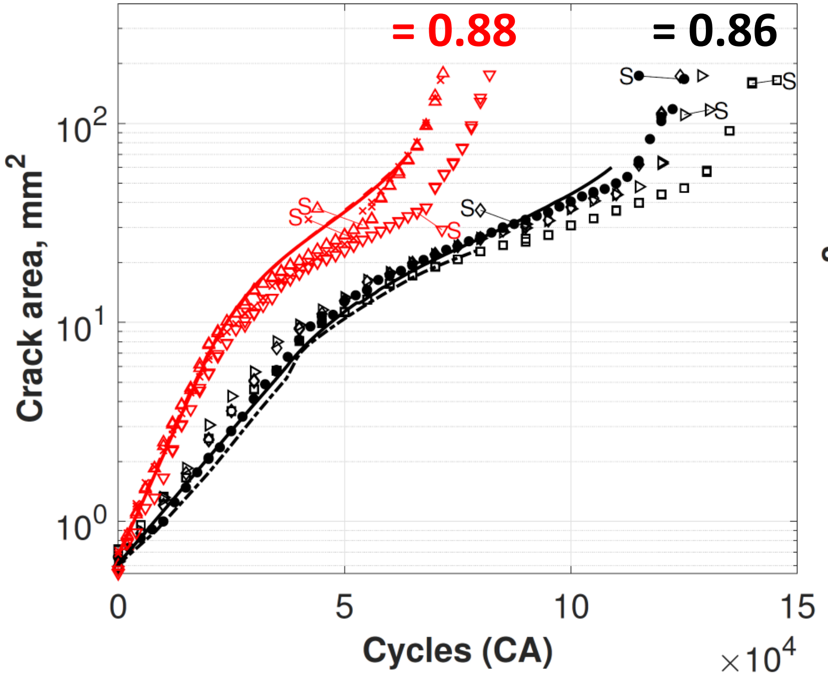
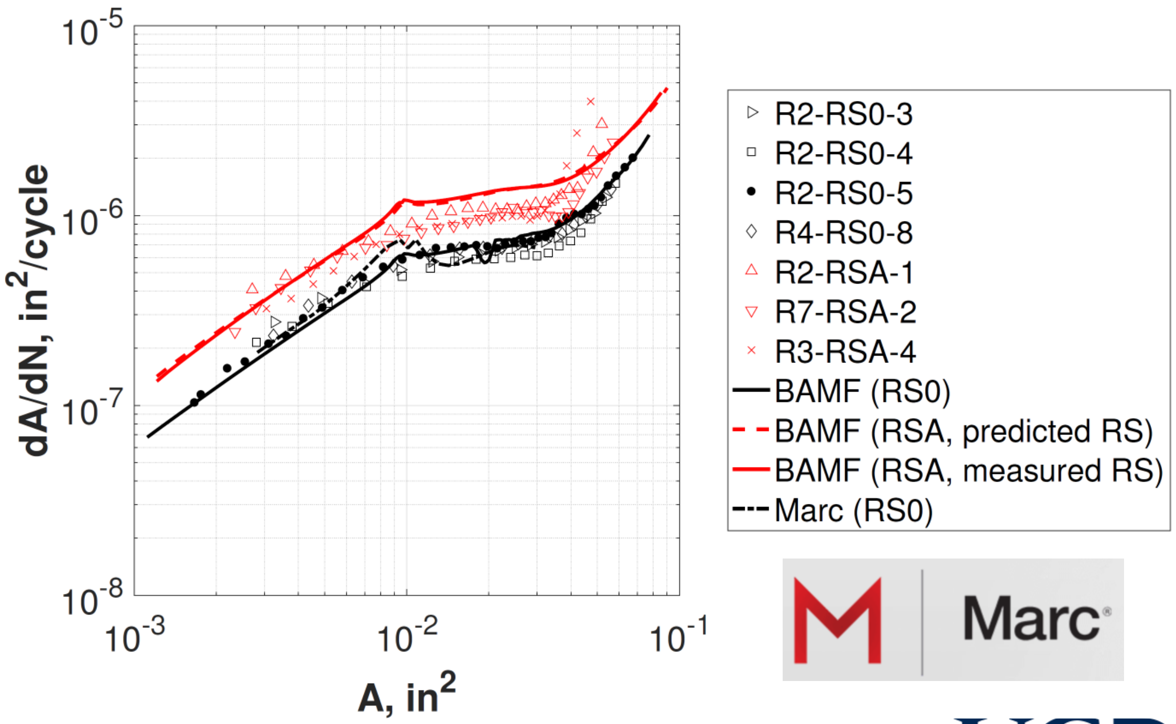
FCG in Coupons with Quench Residual Stress

- Fatigue Crack Growth Validation
  - Comparisons of MPFM model and test data below
  - Overall, crack growth is predicted accurately
    - Ignoring RS for the RSA condition is non-conservative at about 1.5X

RSA Pred/Test = 0.88 **RS0 Pred/Test = 0.86**





Marc

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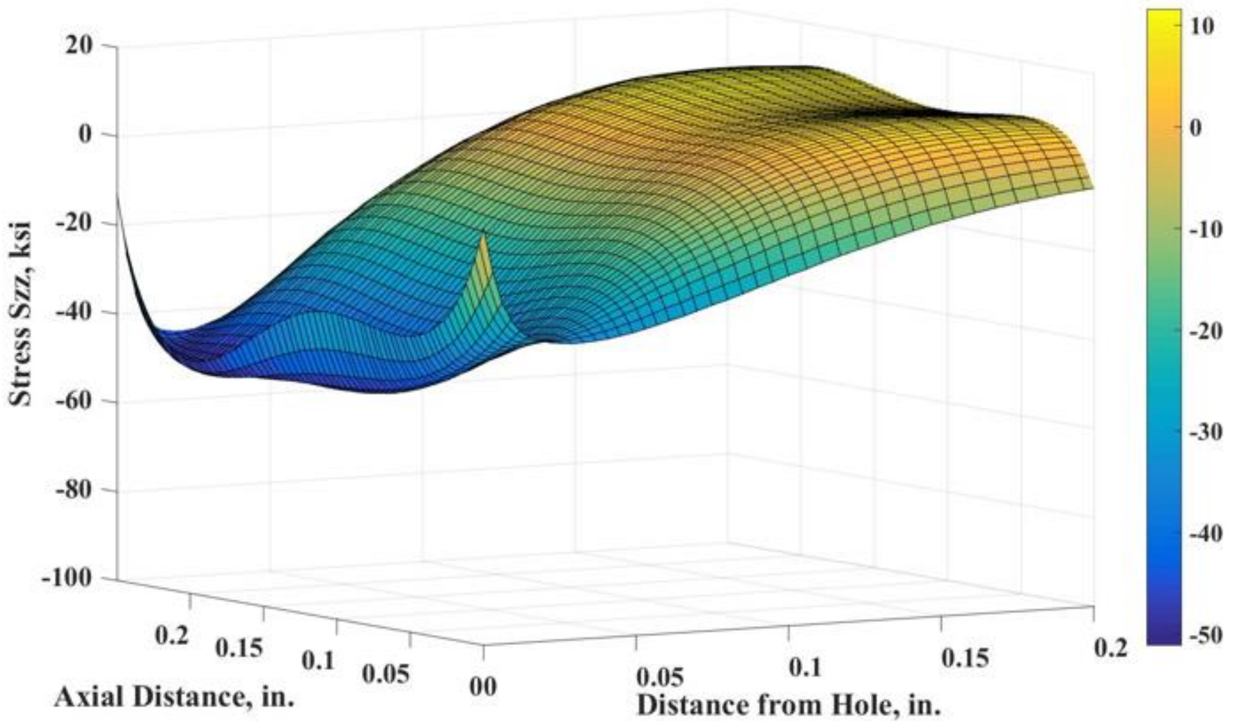
Fatigue Life Variability

- Background
  - Investigate sensitivity of fatigue life prediction with varying interference levels and replicates
- Specimen Geometry
  - 2024-T351,
  - 0.25 inch thick,
  - 0.5 inch hole
  - e/D = 4
- Three different interference levels
  - Low CX = 3.16%   (5 specimens – 10 replicates)
  - Mid CX = 3.67%   (5 specimens – 10 replicates)
  - High CX = 4.16%   (3 specimens – 6 replicates)



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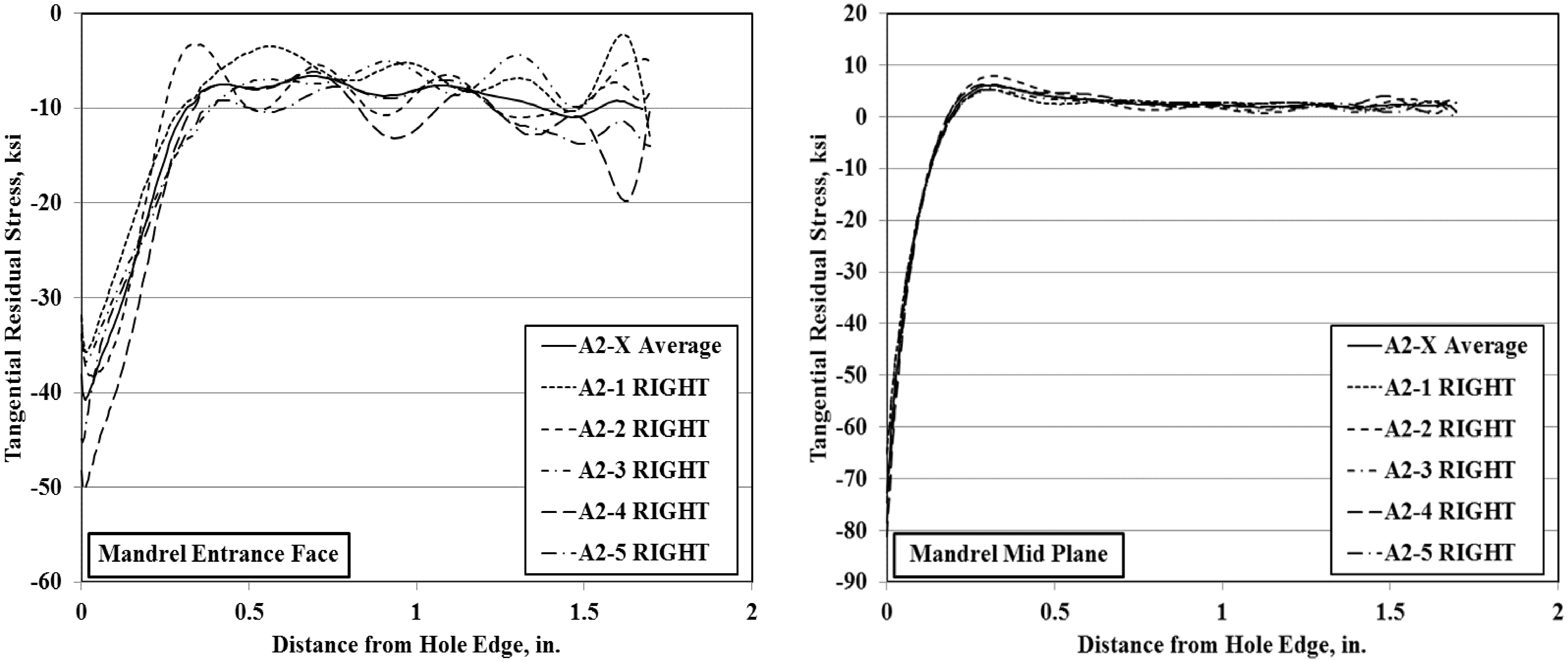
Fatigue Life Variability



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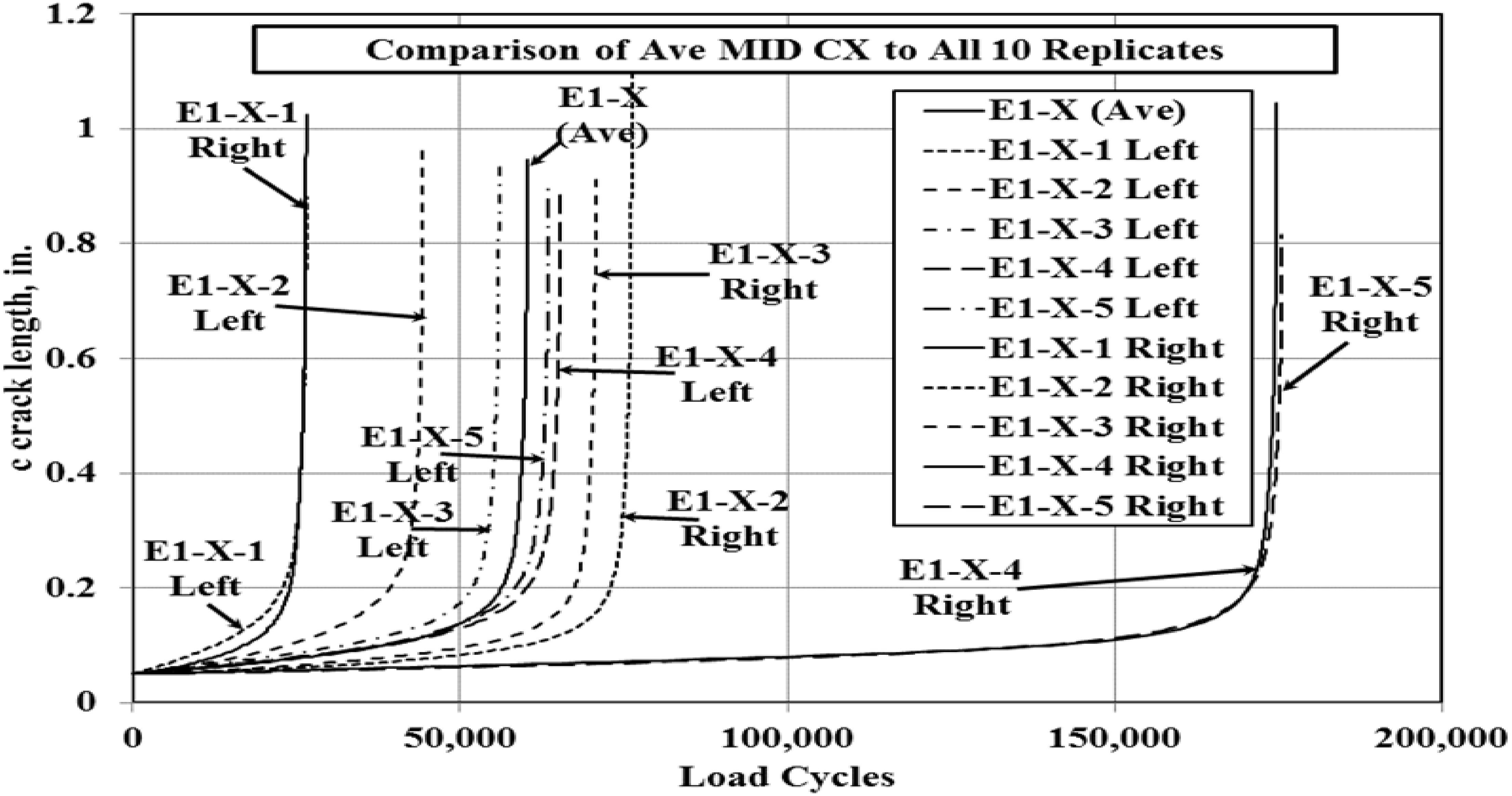
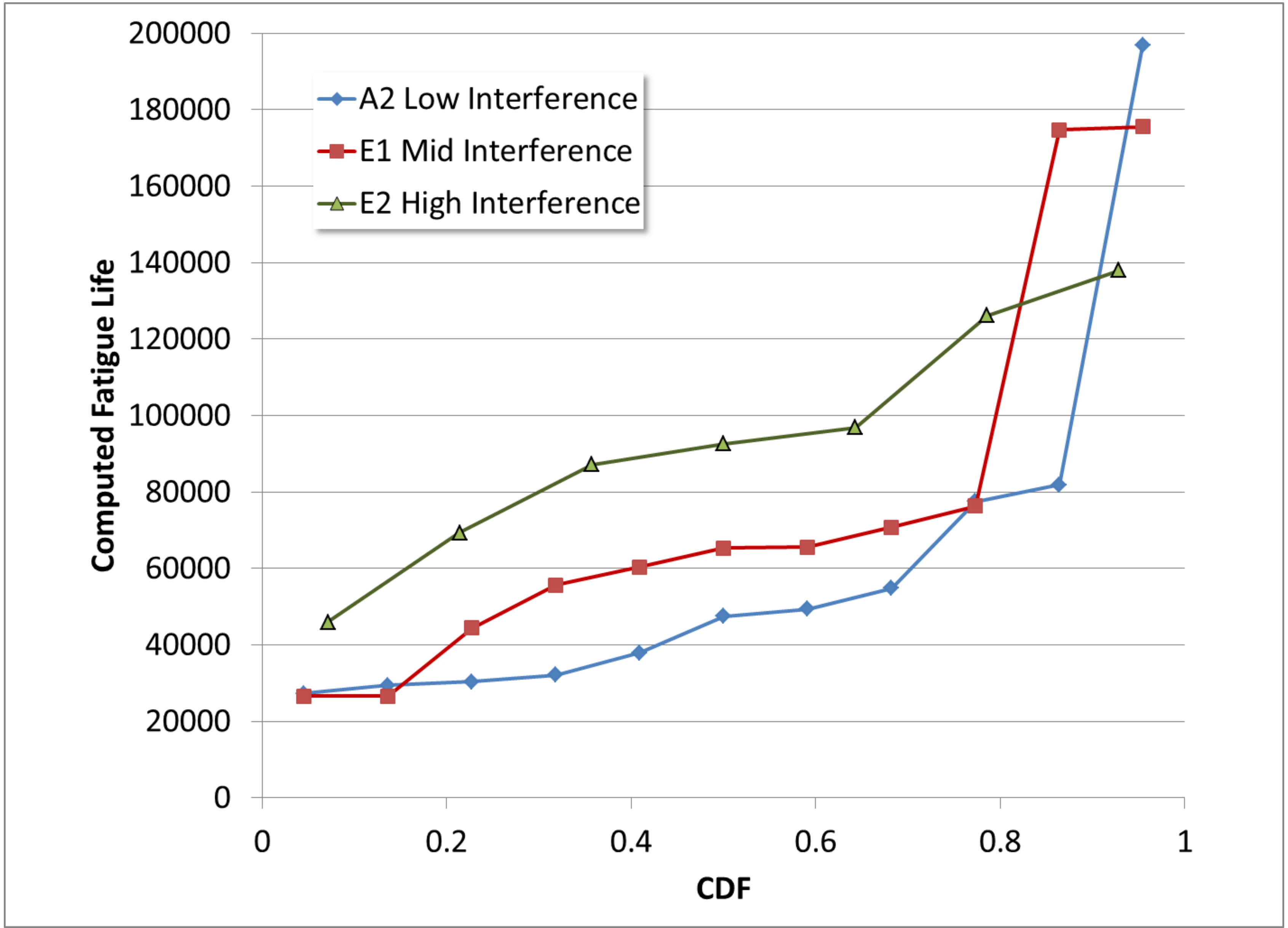
Fatigue Life Variability



Fatigue Life Variability

- Computed lives segregate as expected in the middle of the distributions.
- However, some curves cross at the extremes.
- Ratio of 7.5 Max/Min Life Computed in A2 data set



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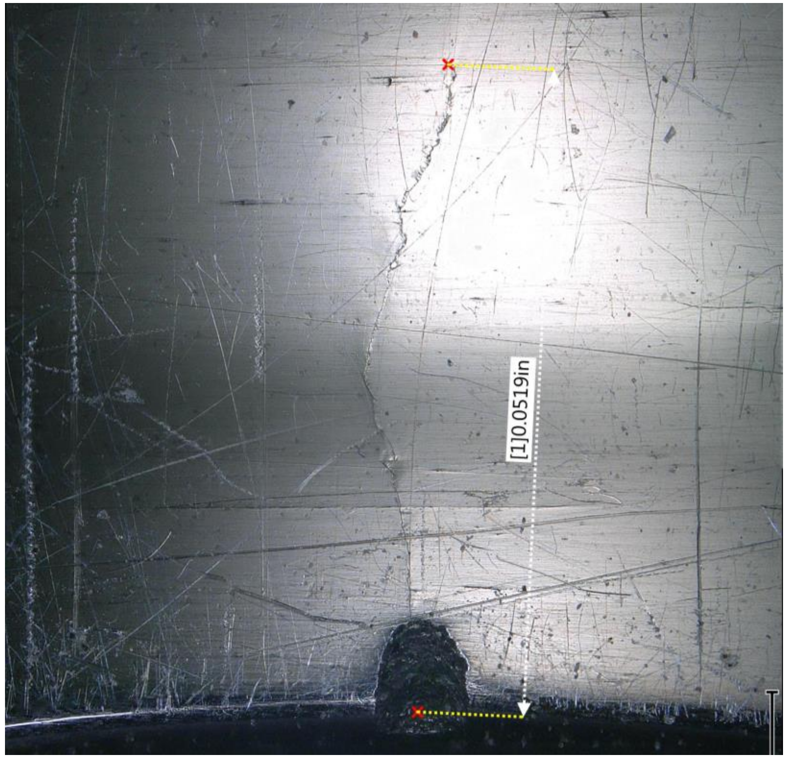
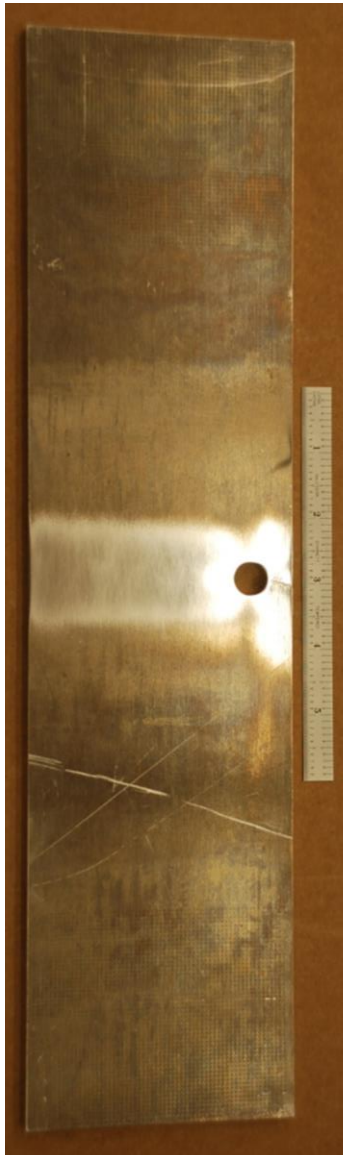
Validation Testing

Short Edge Margin Testing

- Objectives
  - Evaluating reduced IFS (0.005”) for short e/D (≤ 2.0)
  - 0.005” is unconservative for 1.2 e/D, 33 ksi max stress (Dallen Andrew)
  - When does 0.005” become unconservative?
  - Is explicitly modeling residual stress in BAMF conservative?
- Approach
  - e/D Tested:1.3, 1.4, 1.5, 2.0
  - 2024-T351 Aluminum
  - 0.05” precrack before CX
  - 33 ksi max stress spectrum
  - Compared tests to 0.005” IFS AFGROW
  - Compared tests to 0.05” BAMF
    - Residual Stress Toolbox (blind)





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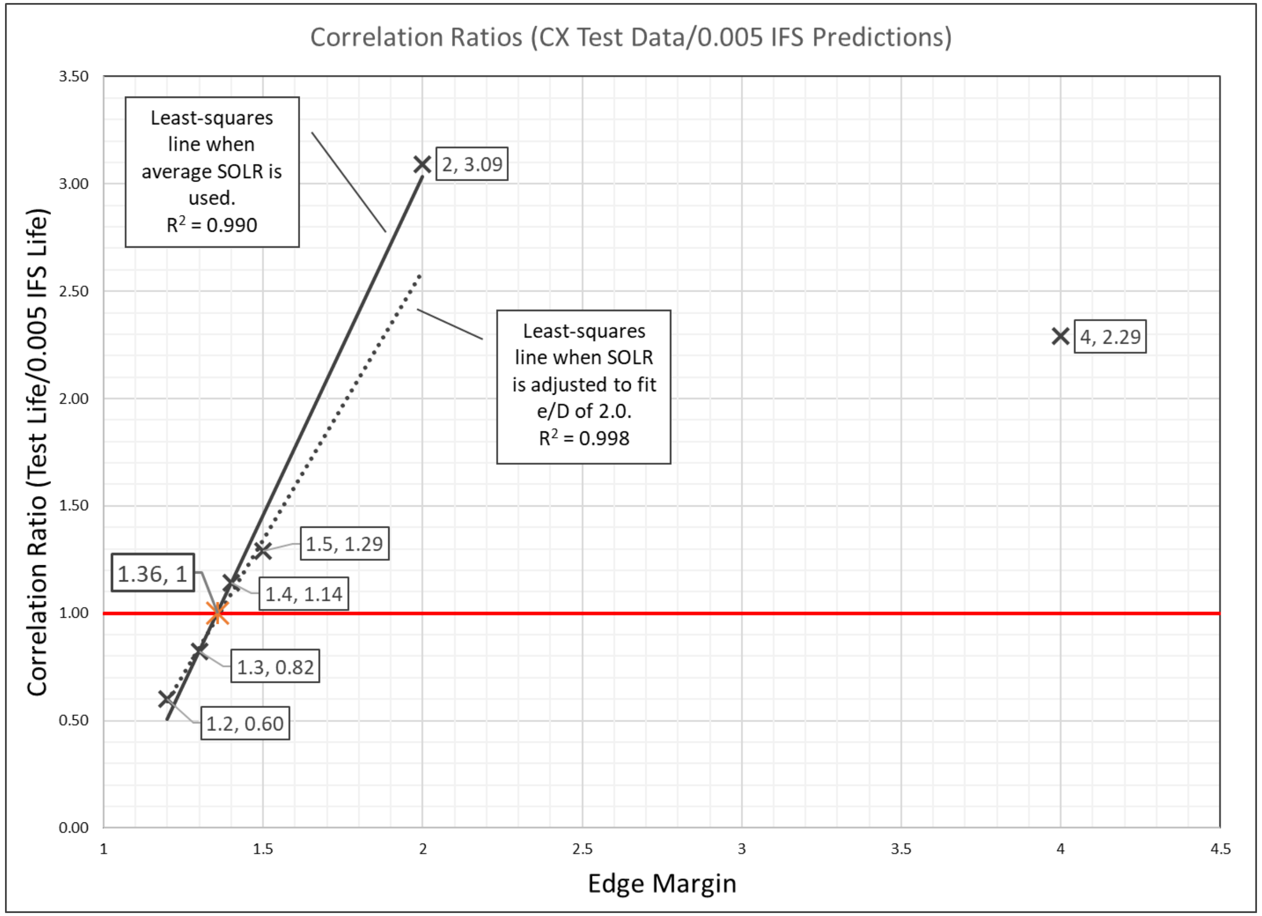
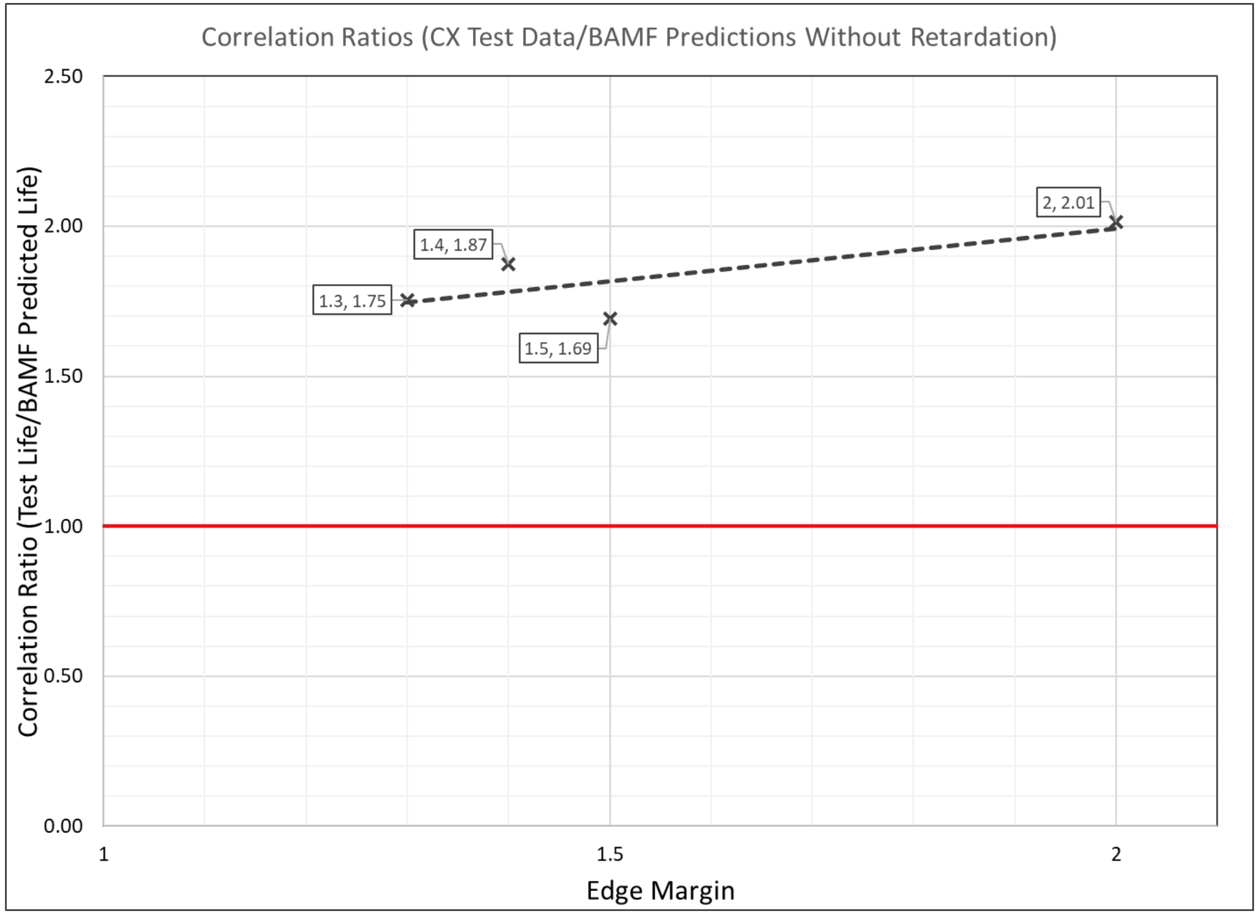
Short Edge Margin Testing

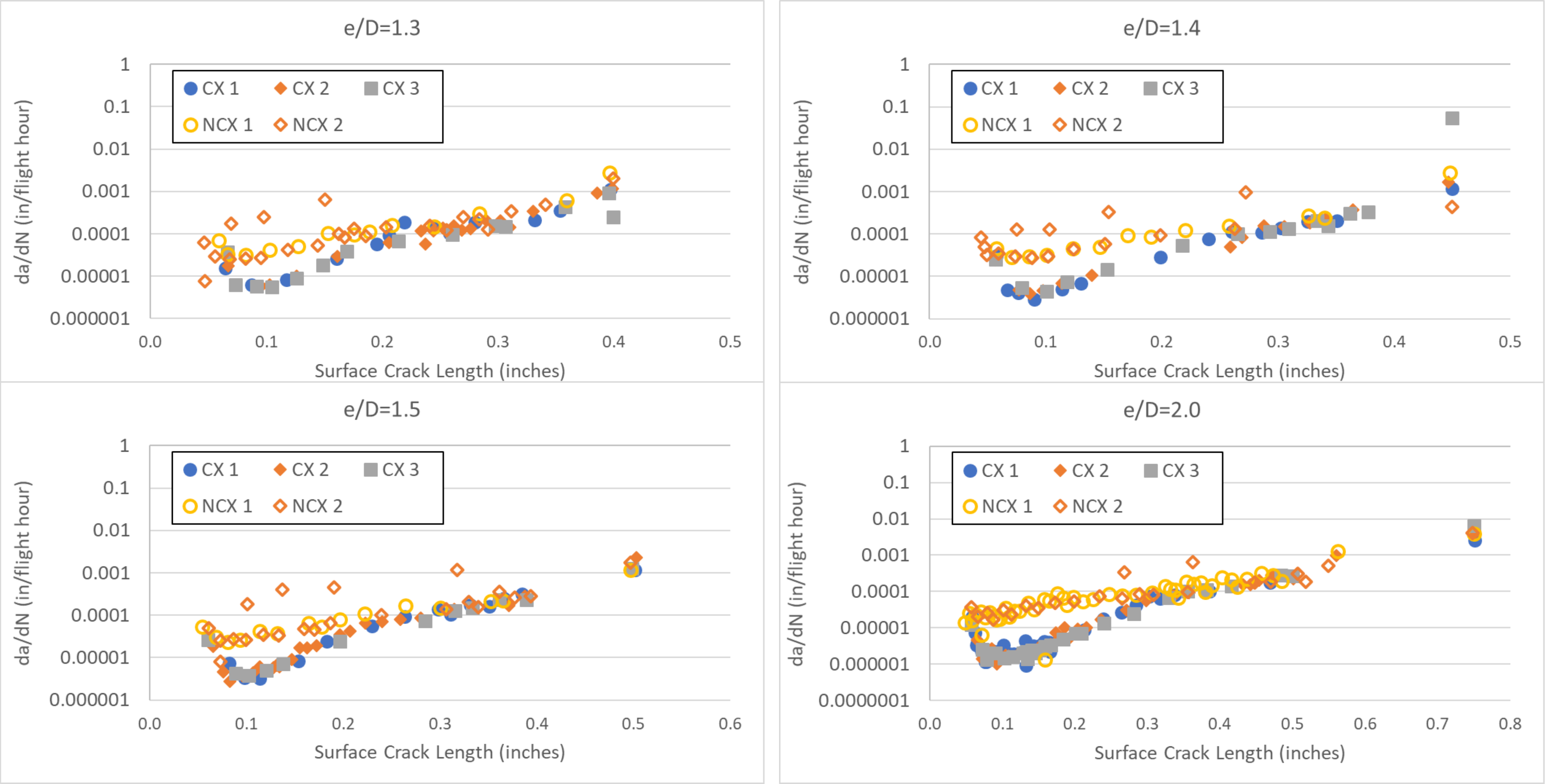
- Results
  - 0.005” IFS is not conservative……………………………….BAMF is





Short Edge Margin Testing

- Results



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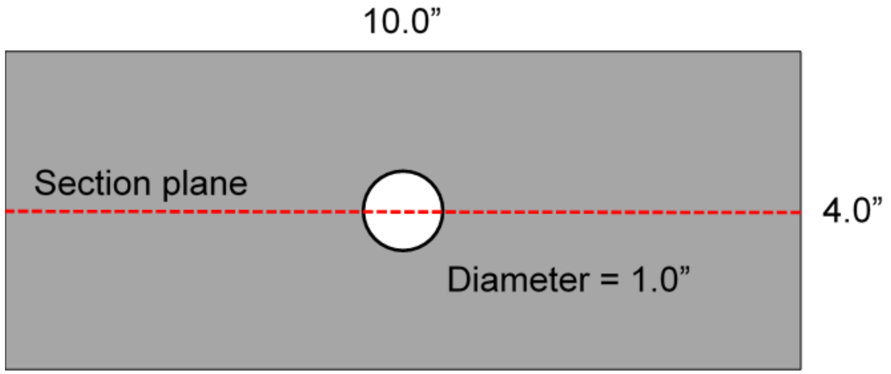
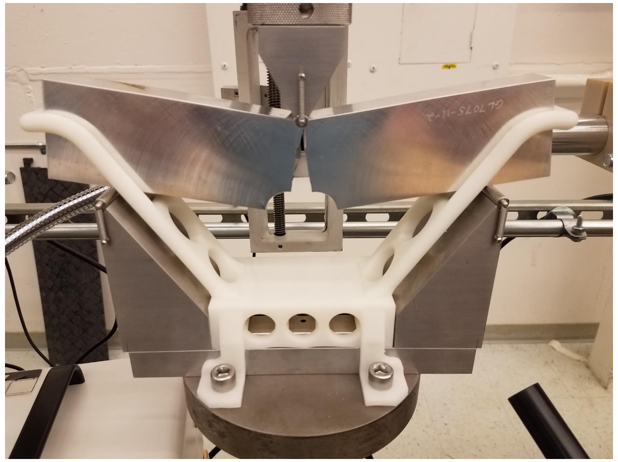
Short Edge Margin Testing

- Crack Videos

Geometrically "Large" Coupons

- Background
  - Part of the difficulty with the CX hole problem is the significance of the RS and applied stress gradients near the hole. Both gradients are very steep, which creates issues for measurements and life correlations. In an effort to minimize the impact of the gradients and increase the understanding of the RS near the hole, geometrically "large" coupons were developed to accomplish RS measurements and fatigue testing
- Approach
  - Year 1 – Manufacture coupons & contour measurements
  - Year 2 – Fatigue testing
  - Year 3 – Additional measurement refinement
- Coupon details:
  - Material: 2024-T351 Plate, 7075-T651 Plate
  - Thickness: 1.0 inch
  - Hole Diameter: 1.0 inch
  - Centered Hole, Baseline (no CX) and Mid CX





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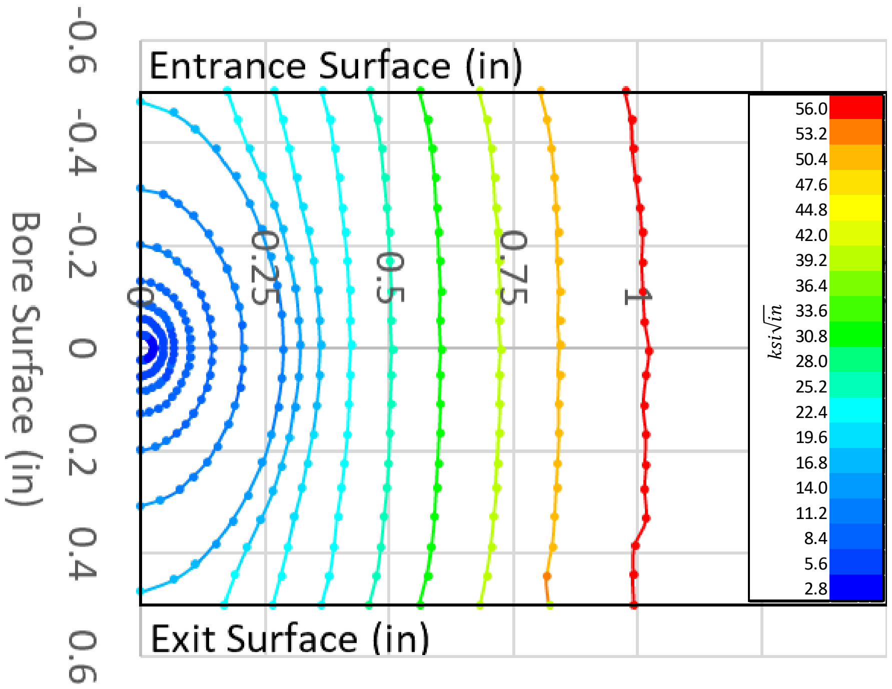
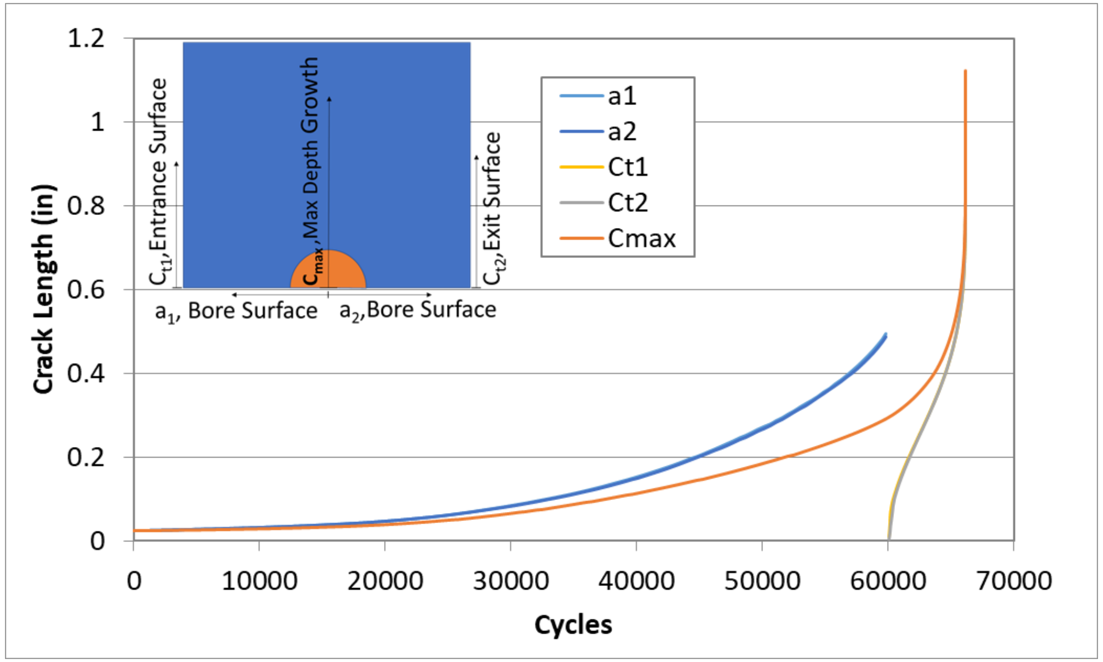
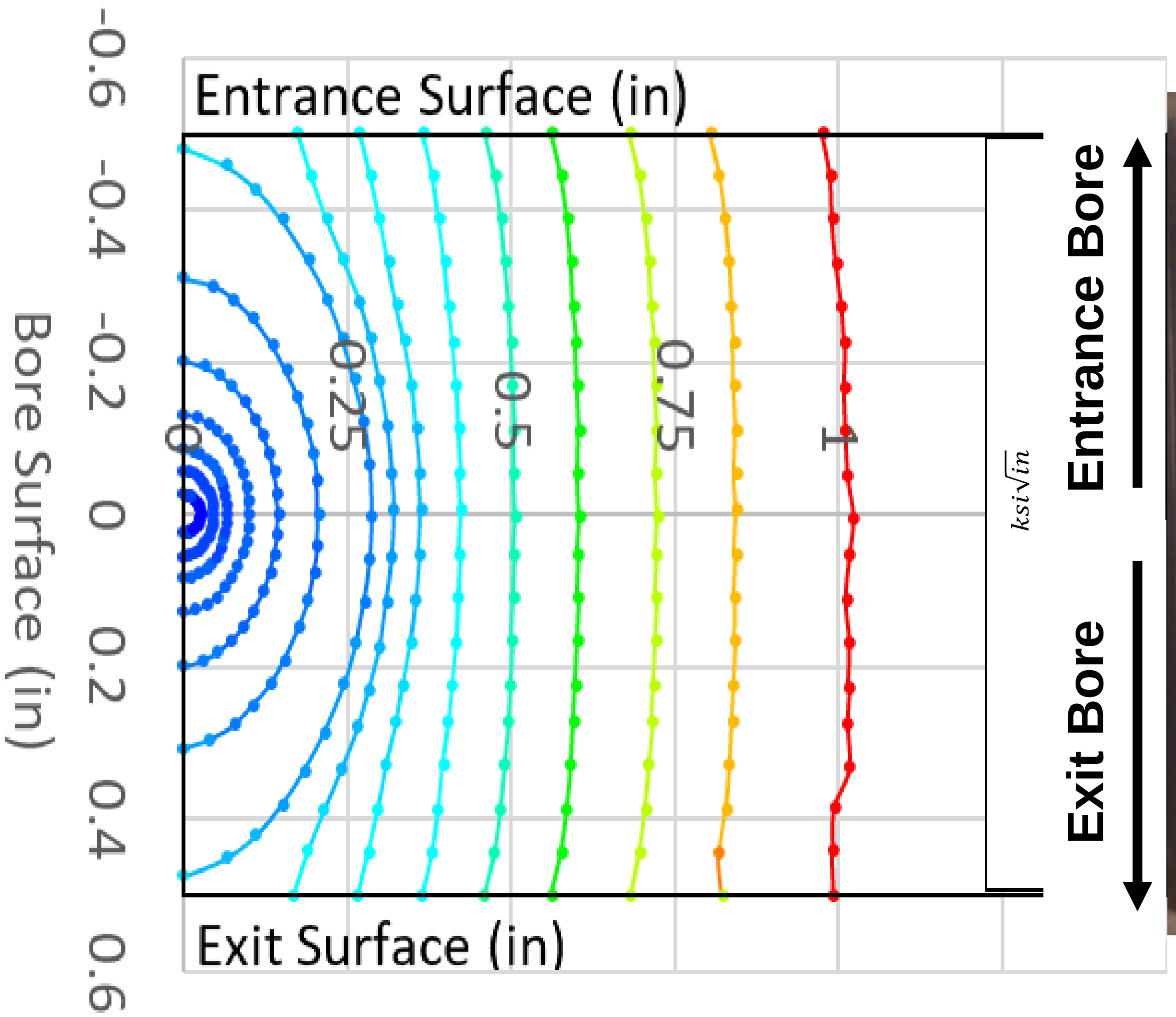
Geometrically "Large" Coupons

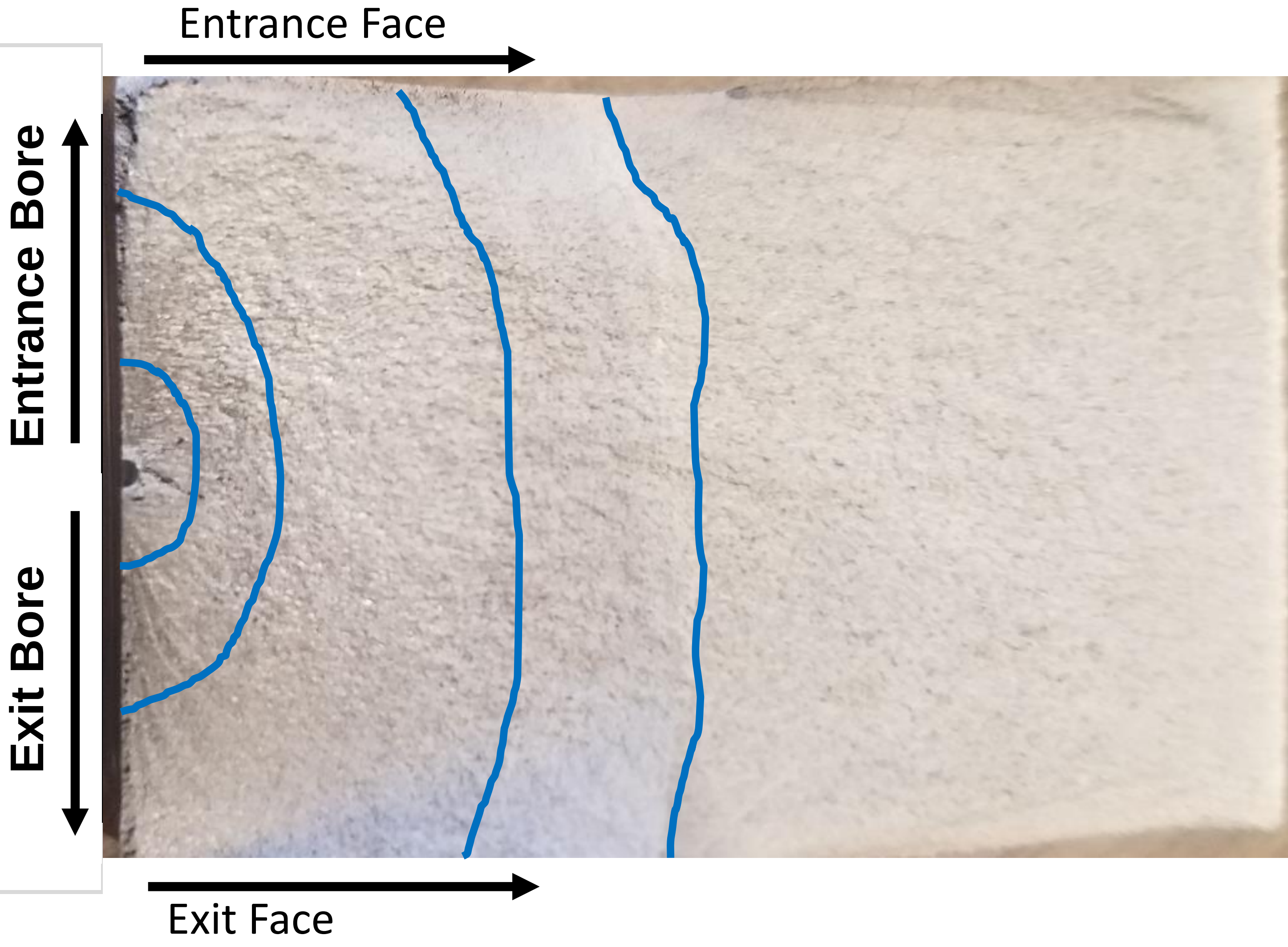
- 7075 Baseline NonCx Coupons
  - Applied Load - 3.5 kips
  - Material - 7075-T651
  - Starting flaw - 0.025" semi-circular





7075 NCX Prediction vs. Test





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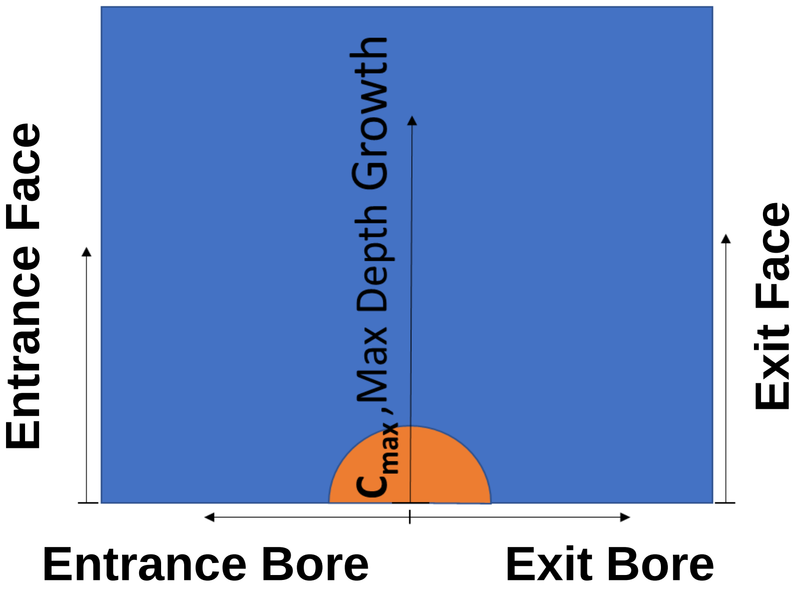
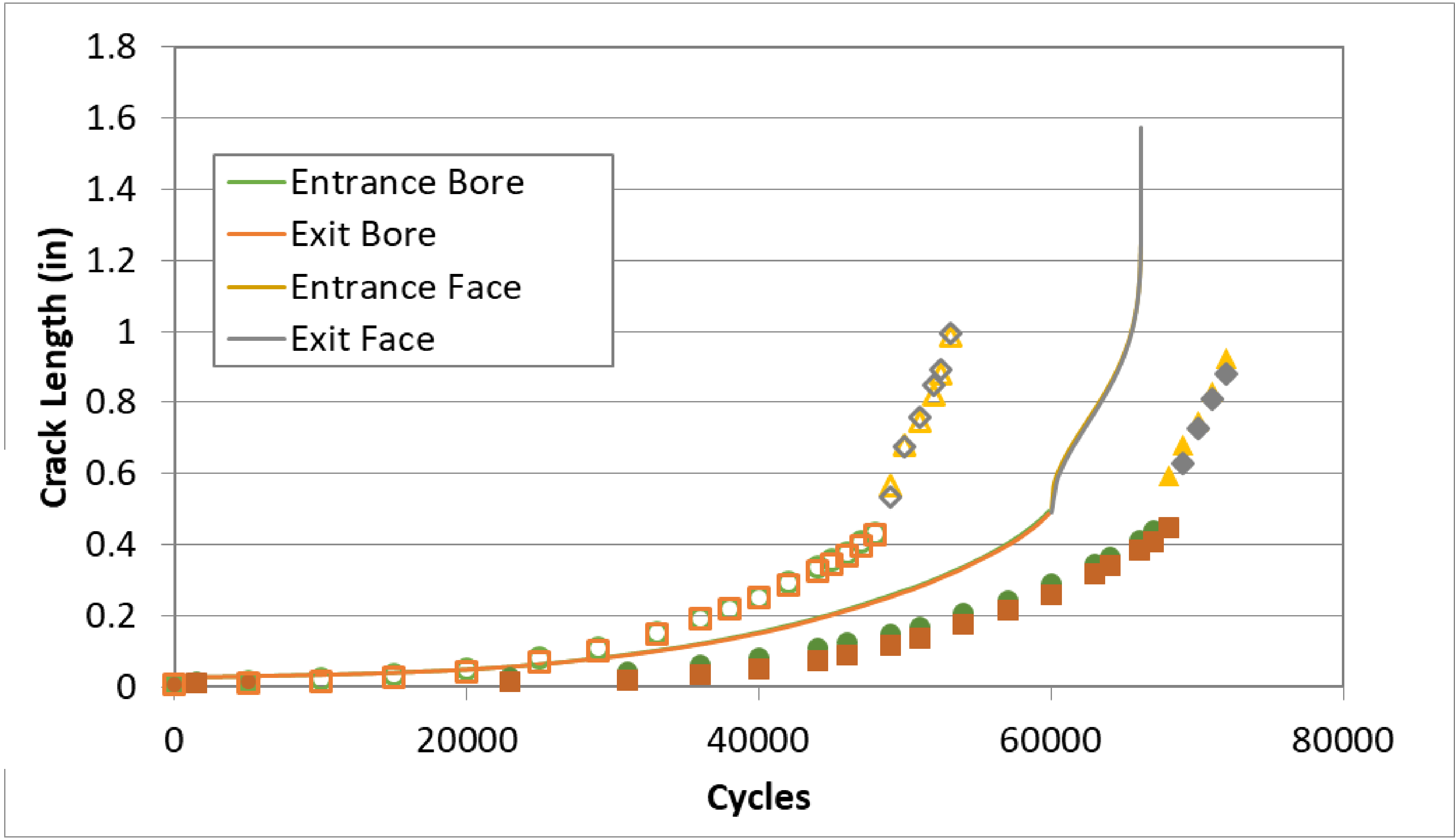
7075 NonCX Prediction vs. Test

- Prediction splits test
- Tests are halves of same coupon, same hole





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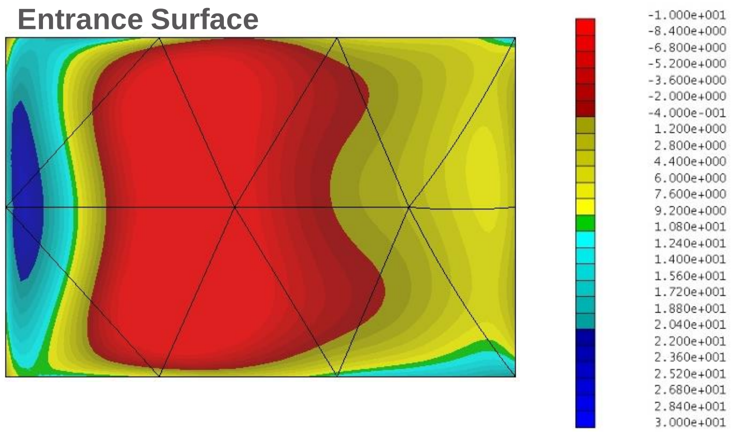
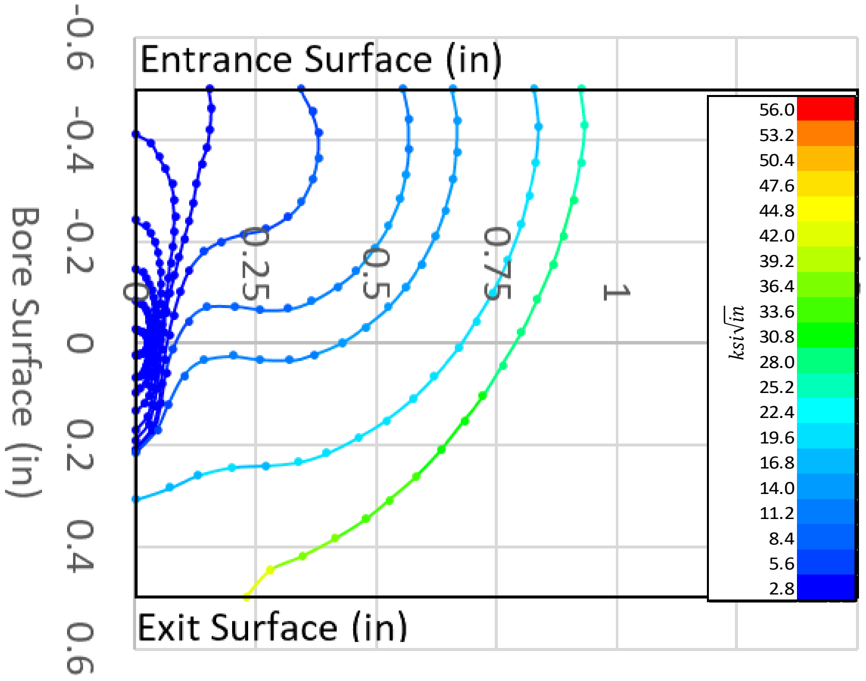
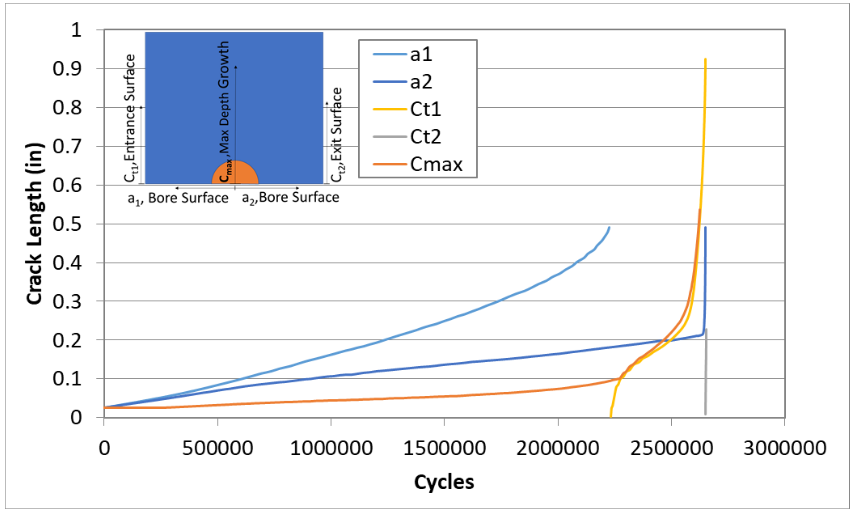
Geometrically "Large" Coupons

- Cx Coupons
  - Applied Load - 3.5 kips
  - Material - 7075-T651
  - Starting flaw - 0.025" semi-circular







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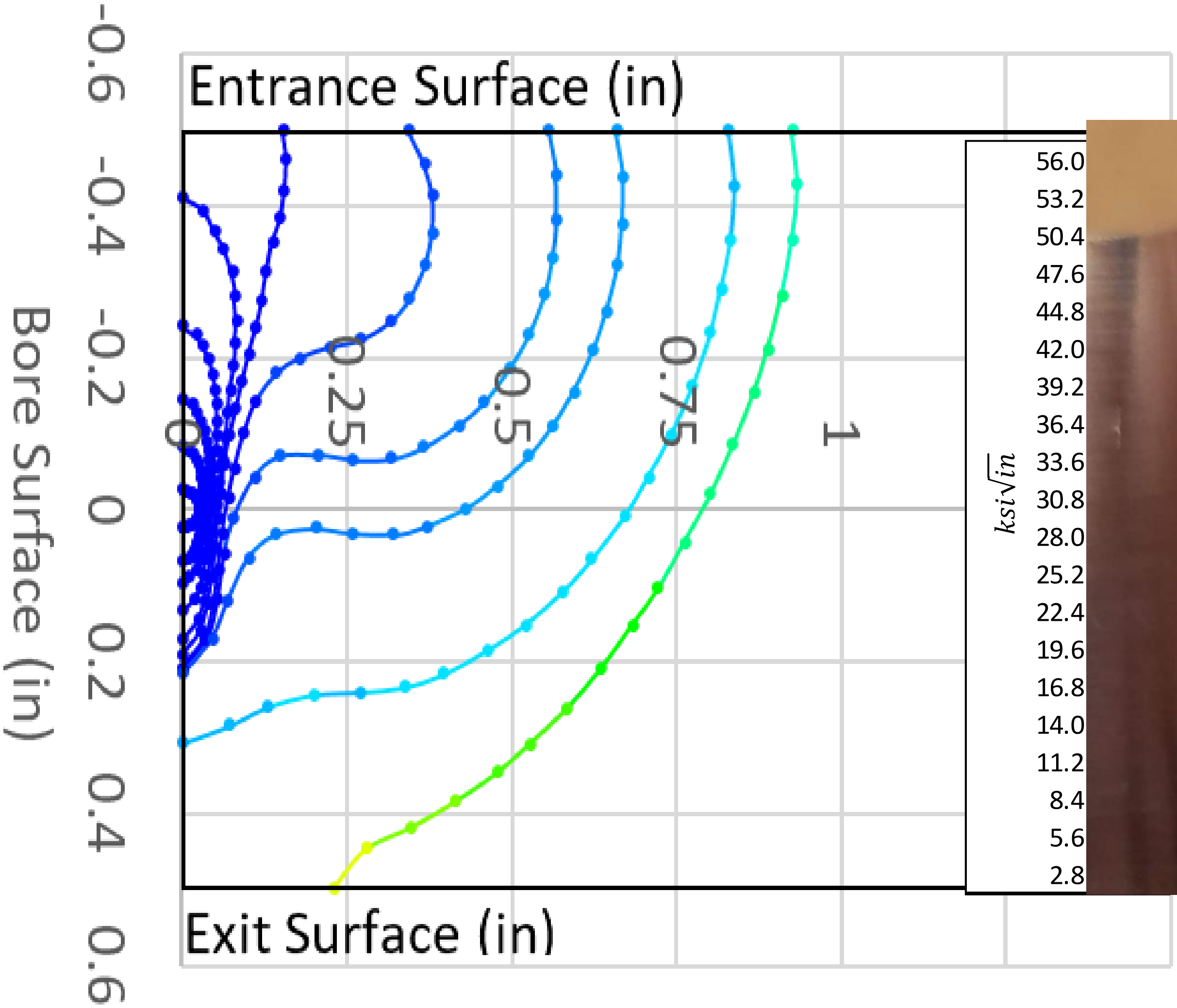
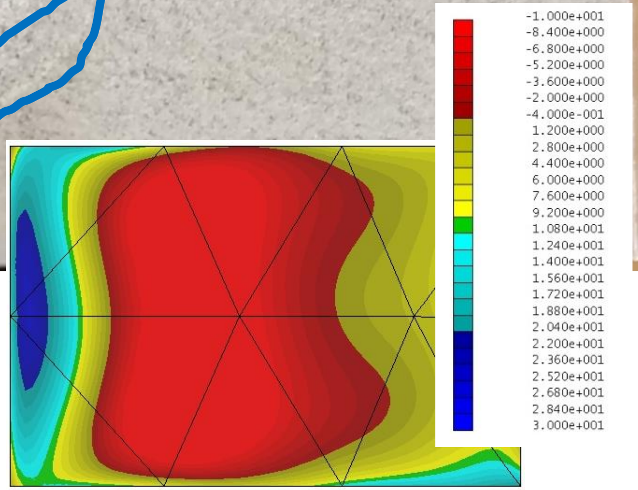
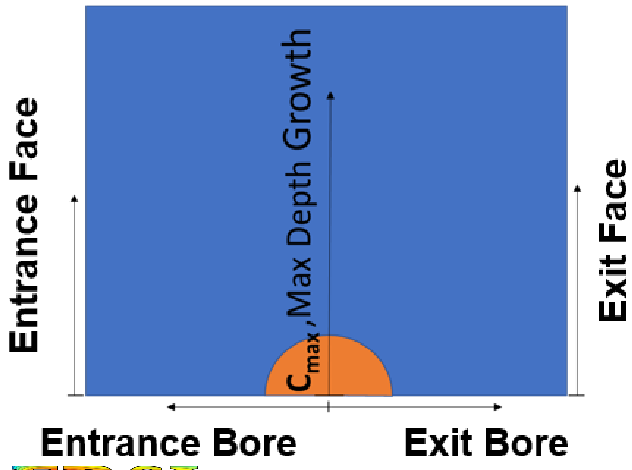
7075 CX Prediction vs. Test

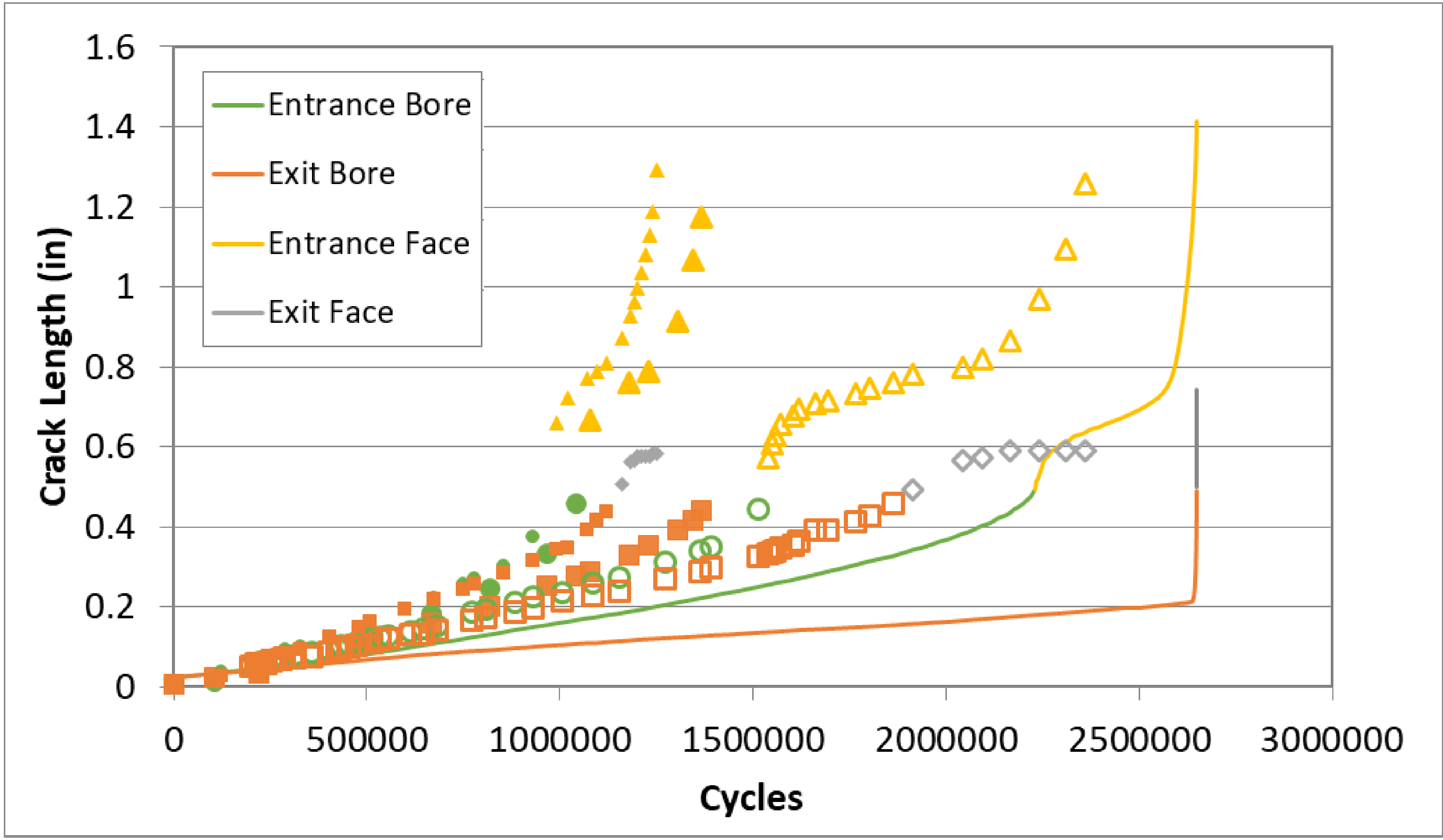




7075 CX Prediction vs. Test

- Blind predictions
- Unconservative, test scatter needs to be quantified





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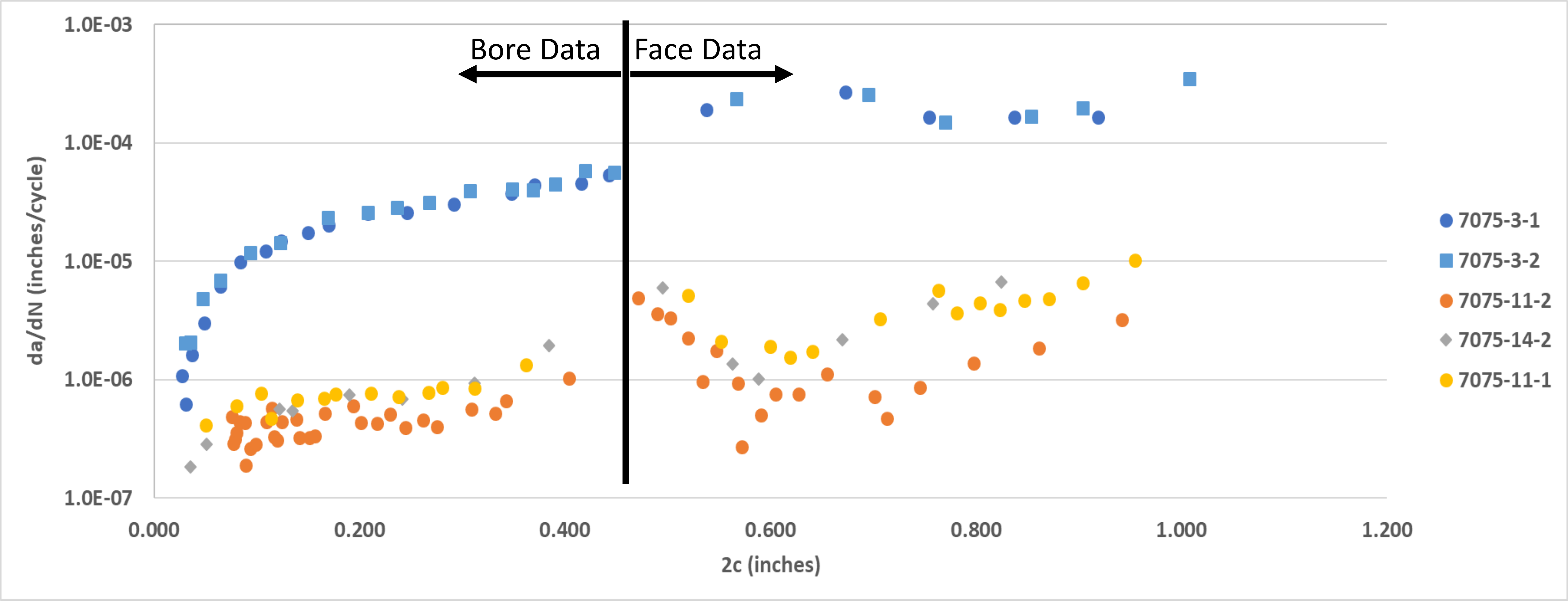
7075 Rate Data



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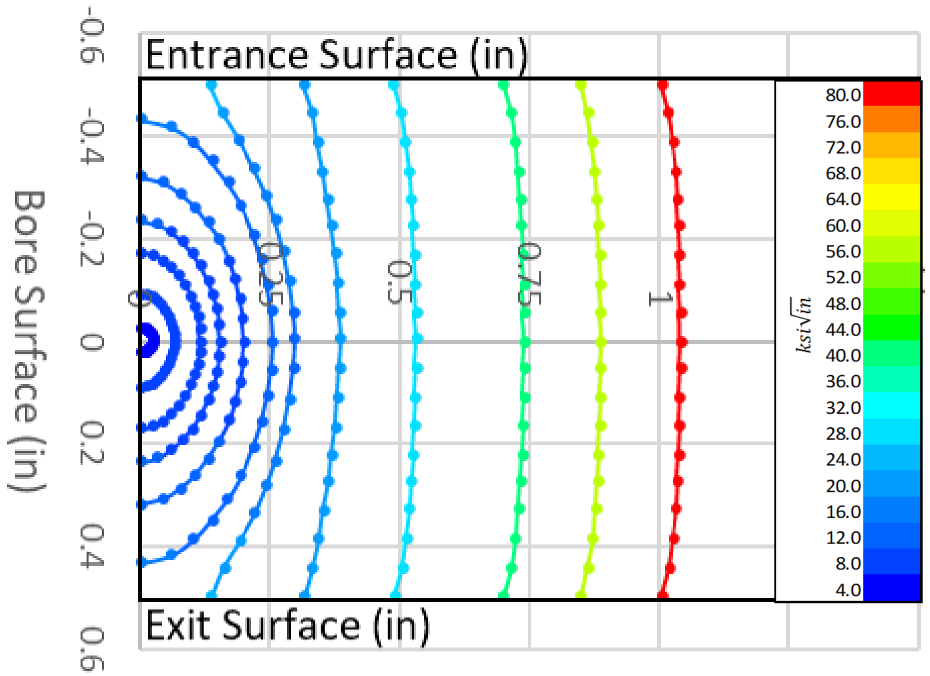
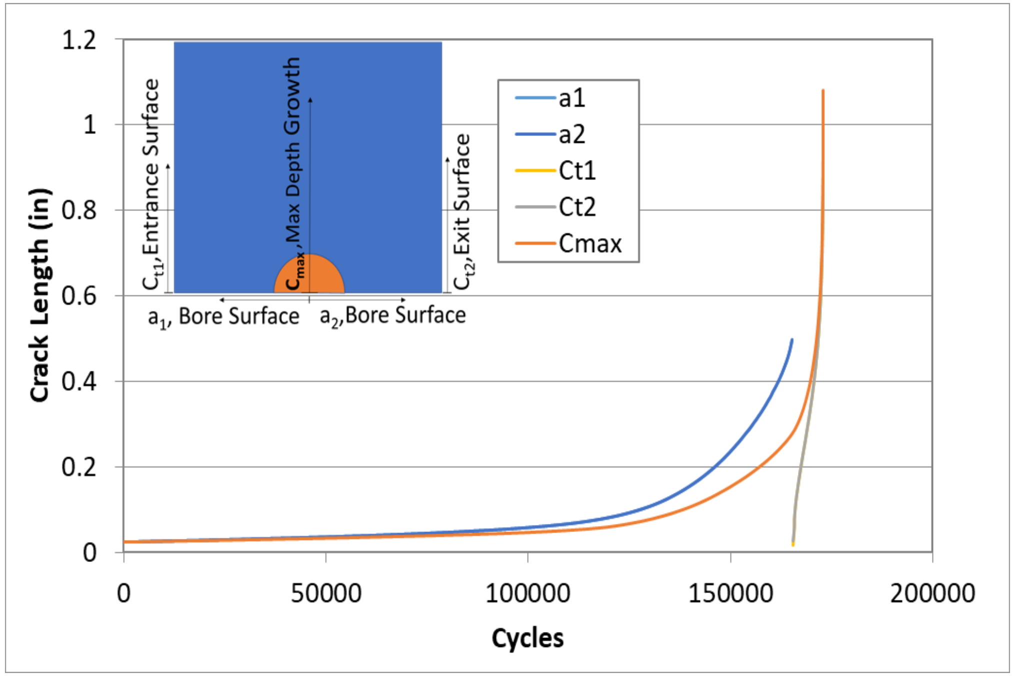
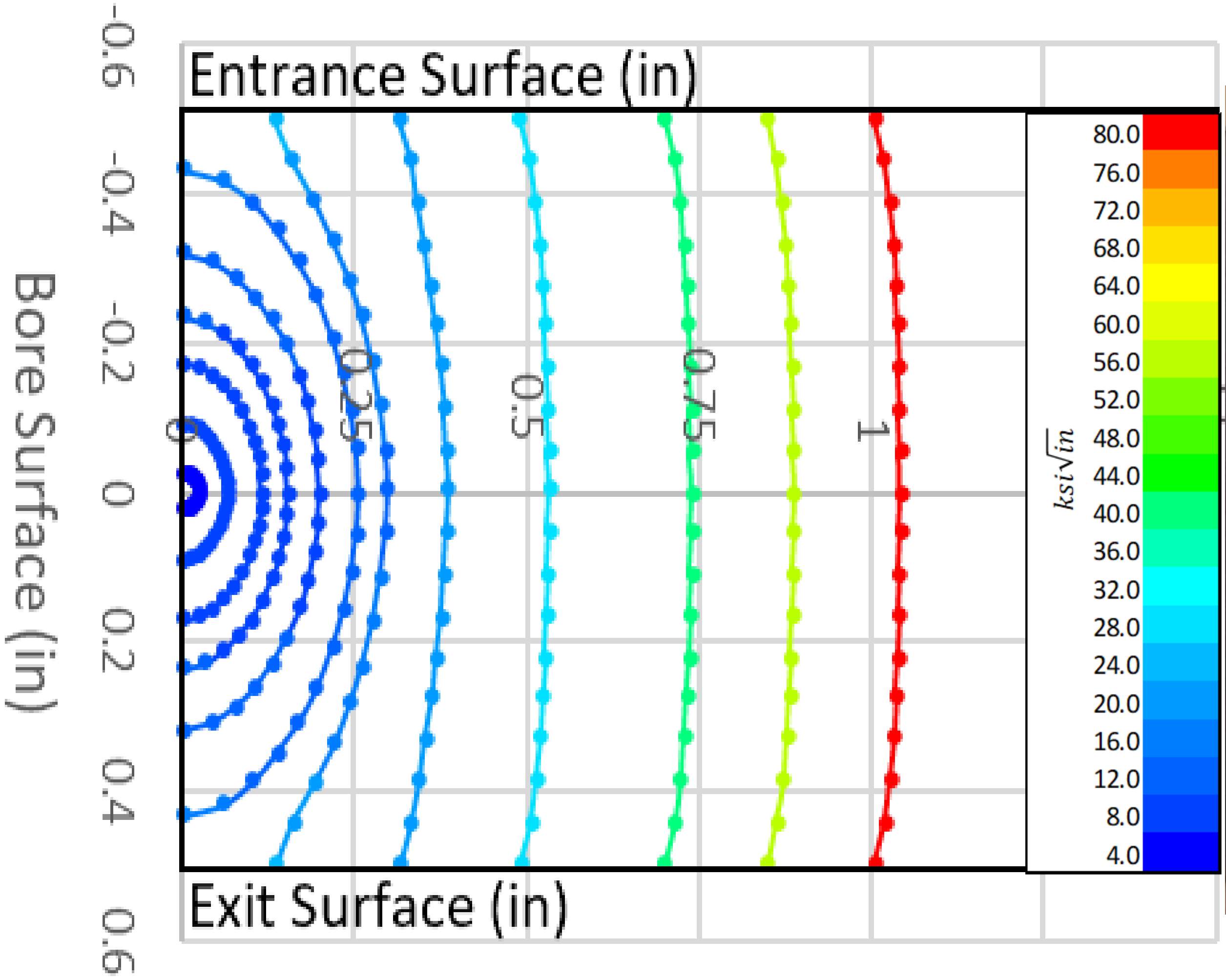
Geometrically "Large" Coupons

- Baseline NonCx Coupons
  - Applied Load - 3.5 kips
  - Material - 2024-T351
  - Starting flaw - 0.025" semi-circular





2024 NonCX Prediction vs. Test



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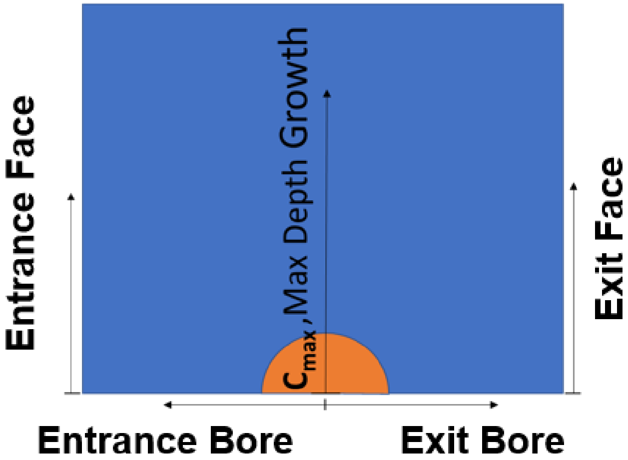
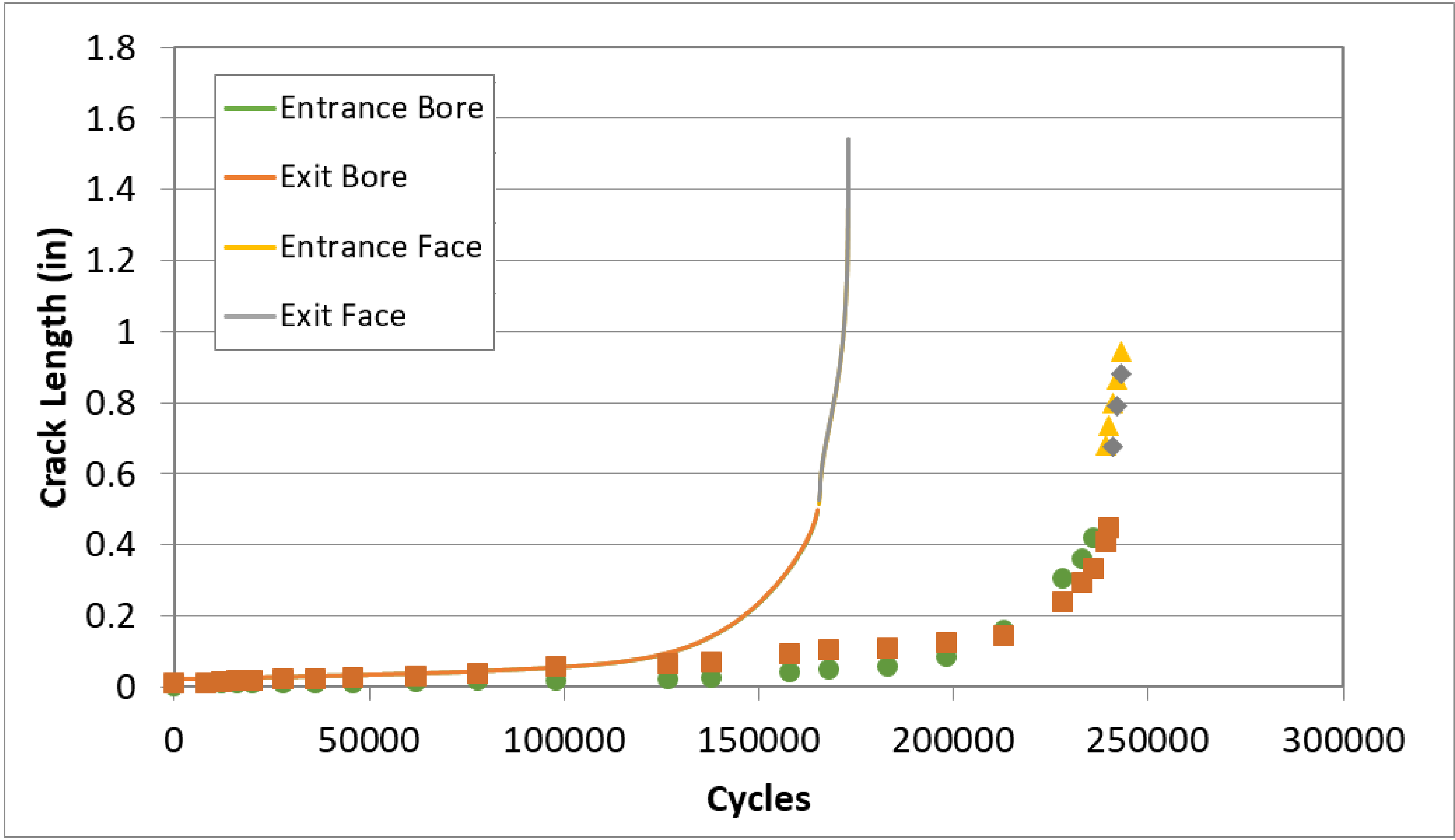
2024 NCX Prediction vs. Test

- Conservative prediction
- Essentially symmetric growth entrance and exit





Geometrically “Large” Coupons

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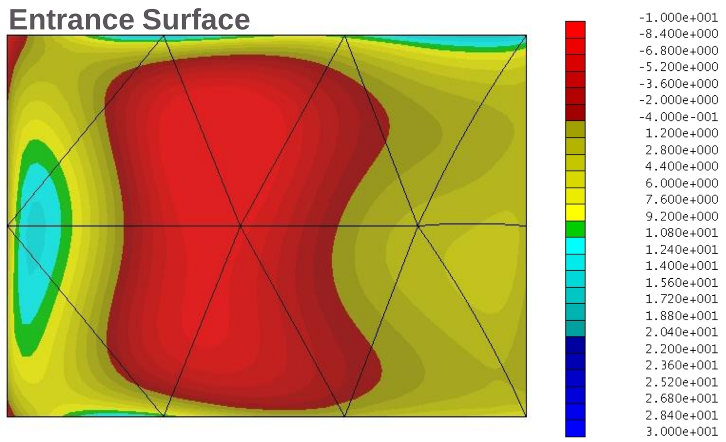

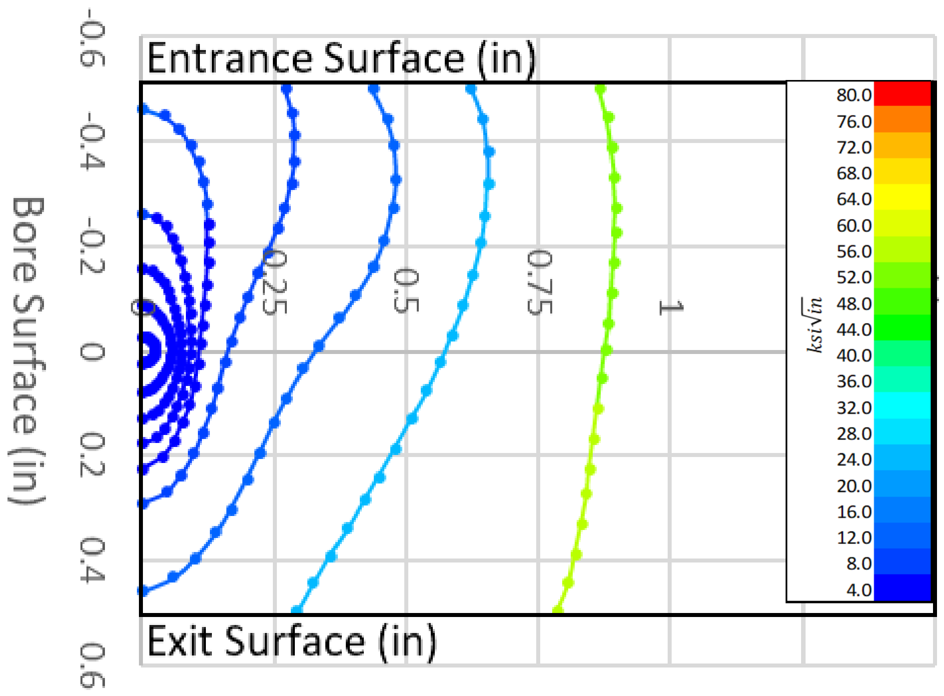

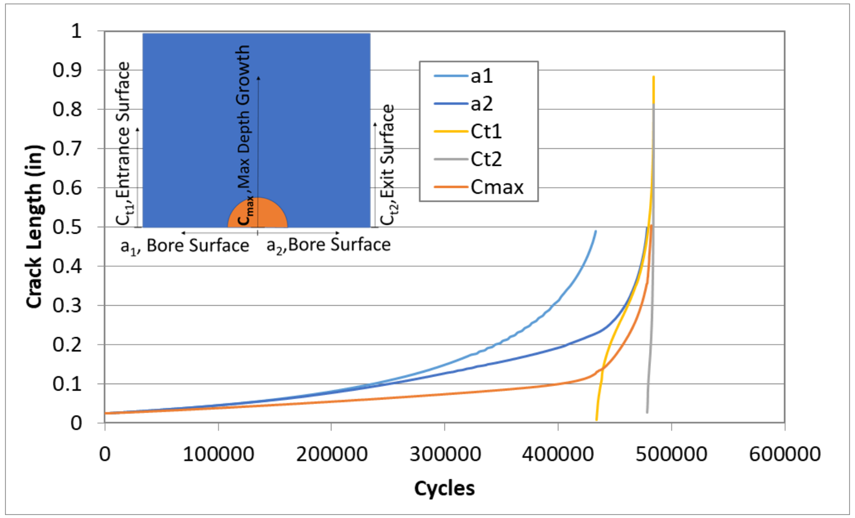

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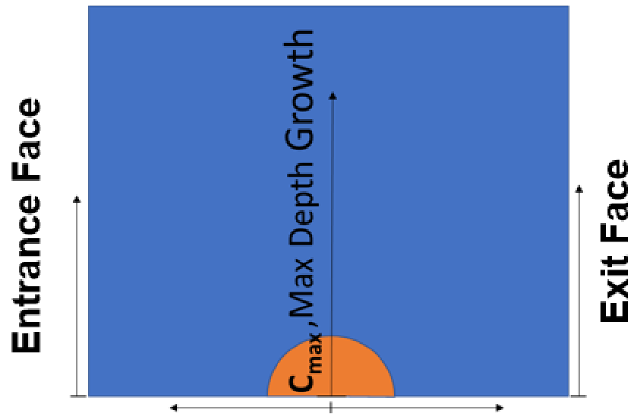
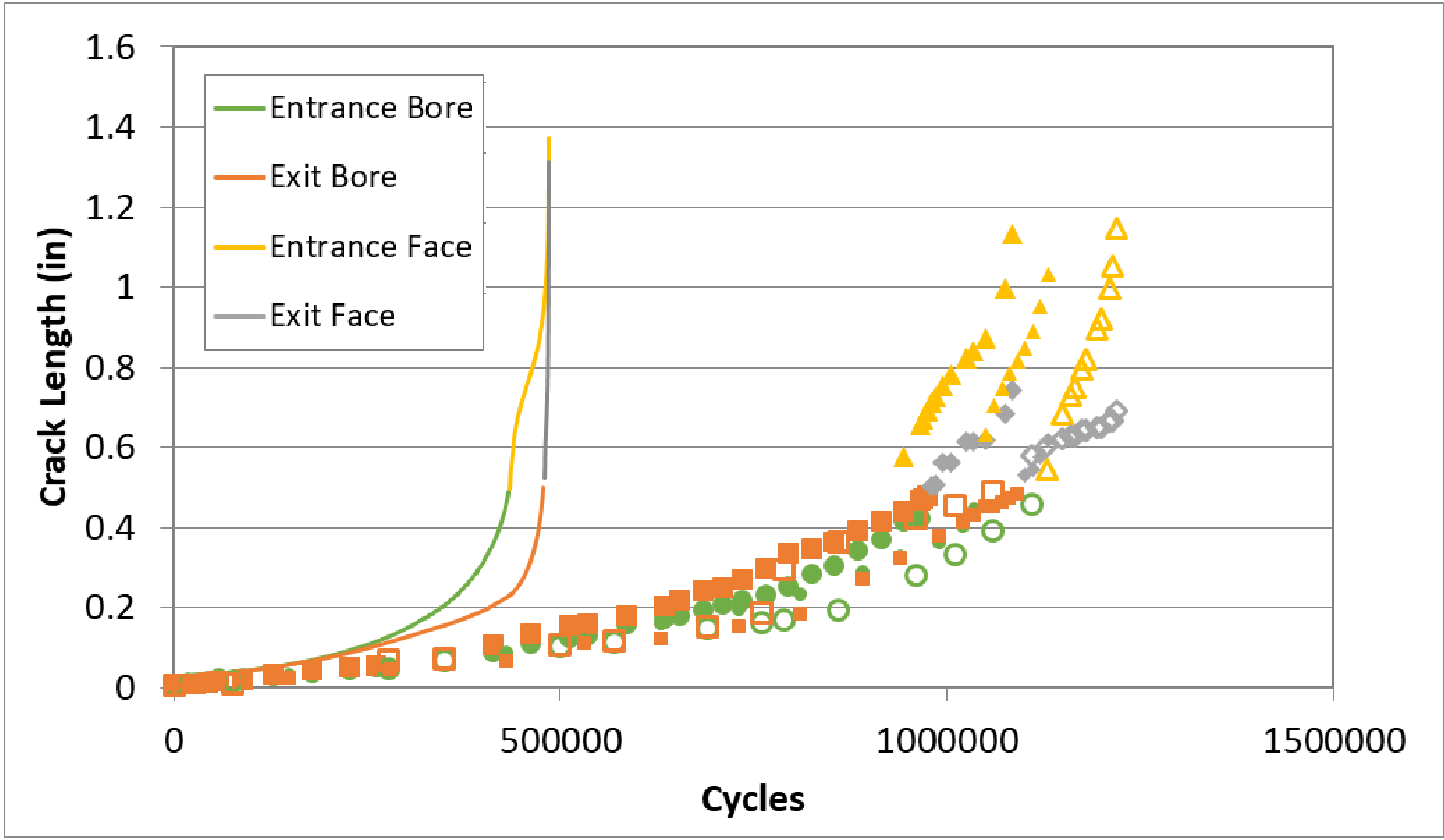
2024 CX Prediction vs. Test

- Prediction conservative
- Shape matches well on front face





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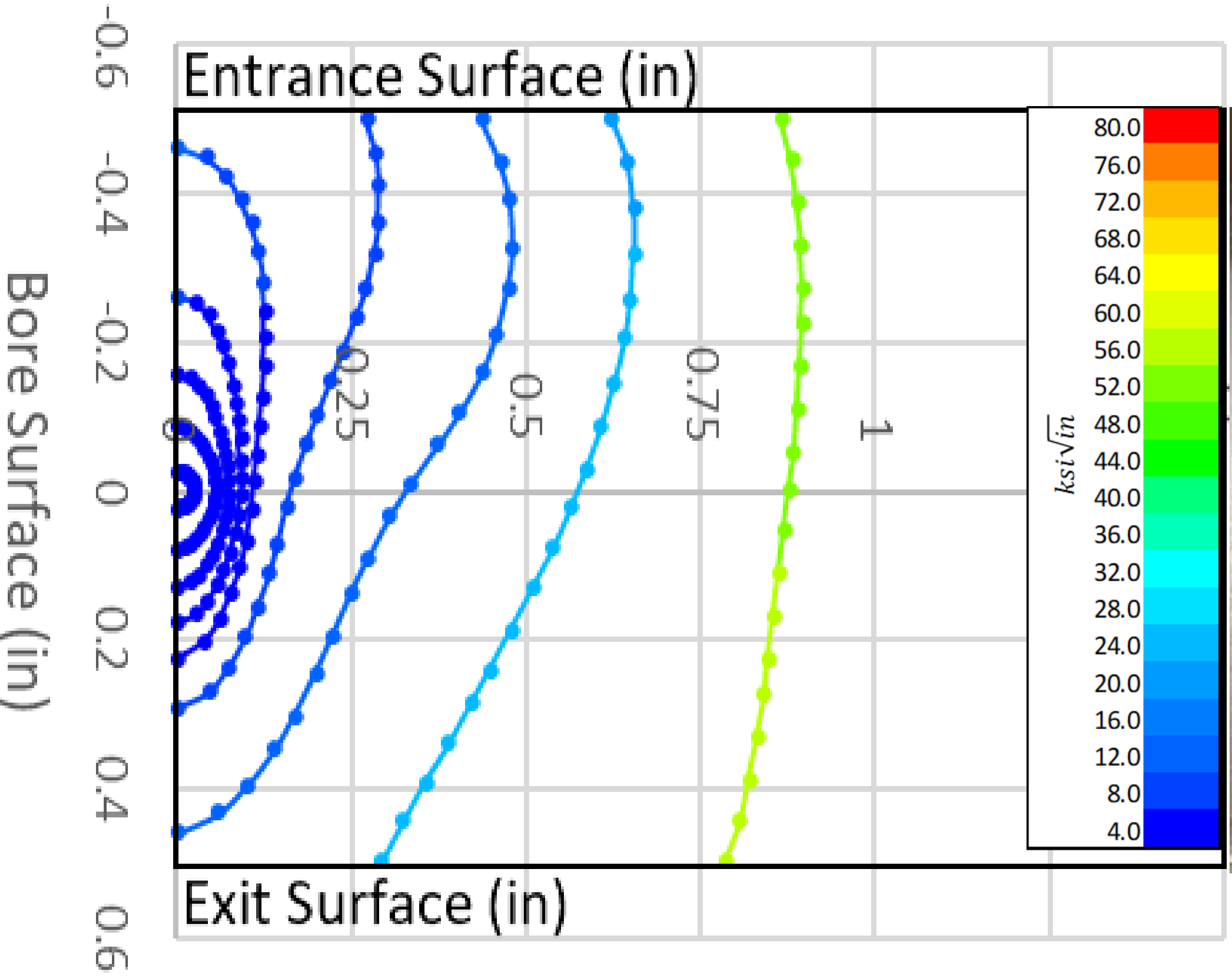
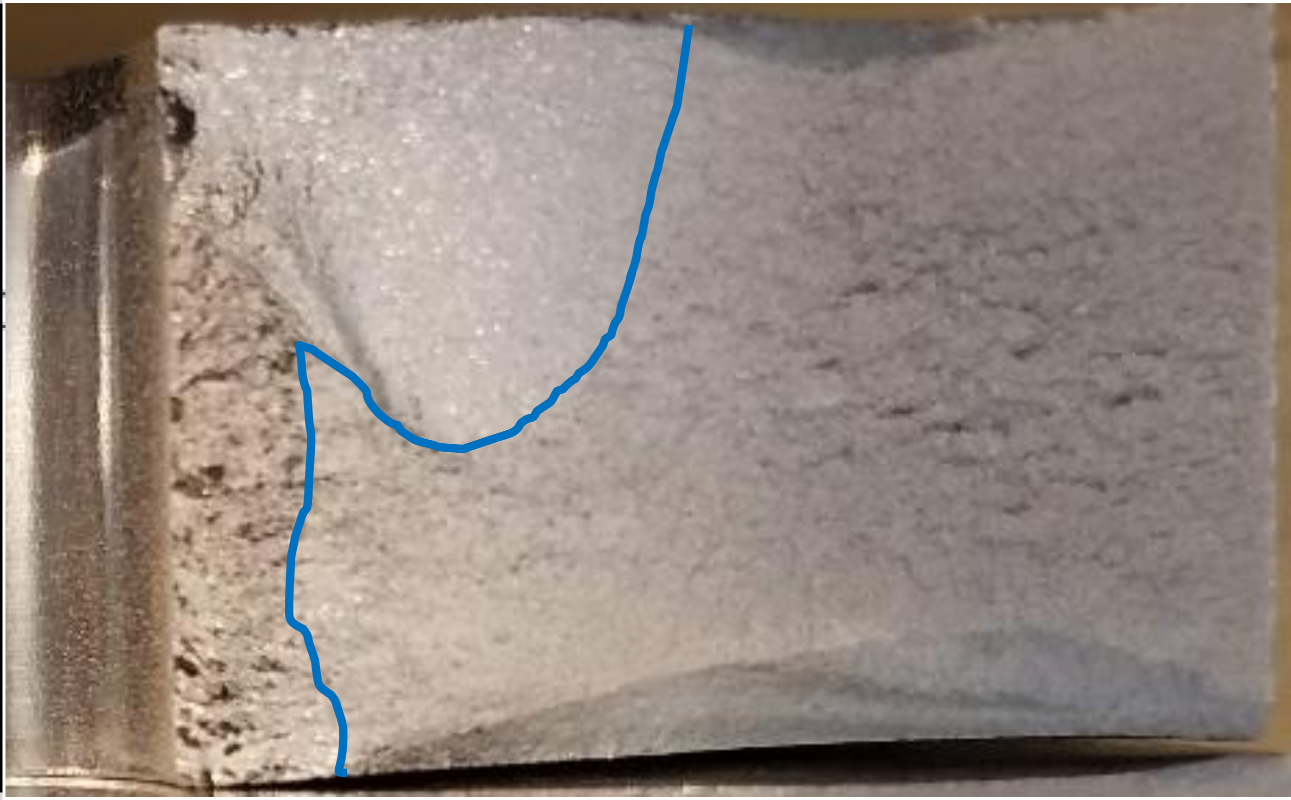
2024 CX Prediction vs. Test





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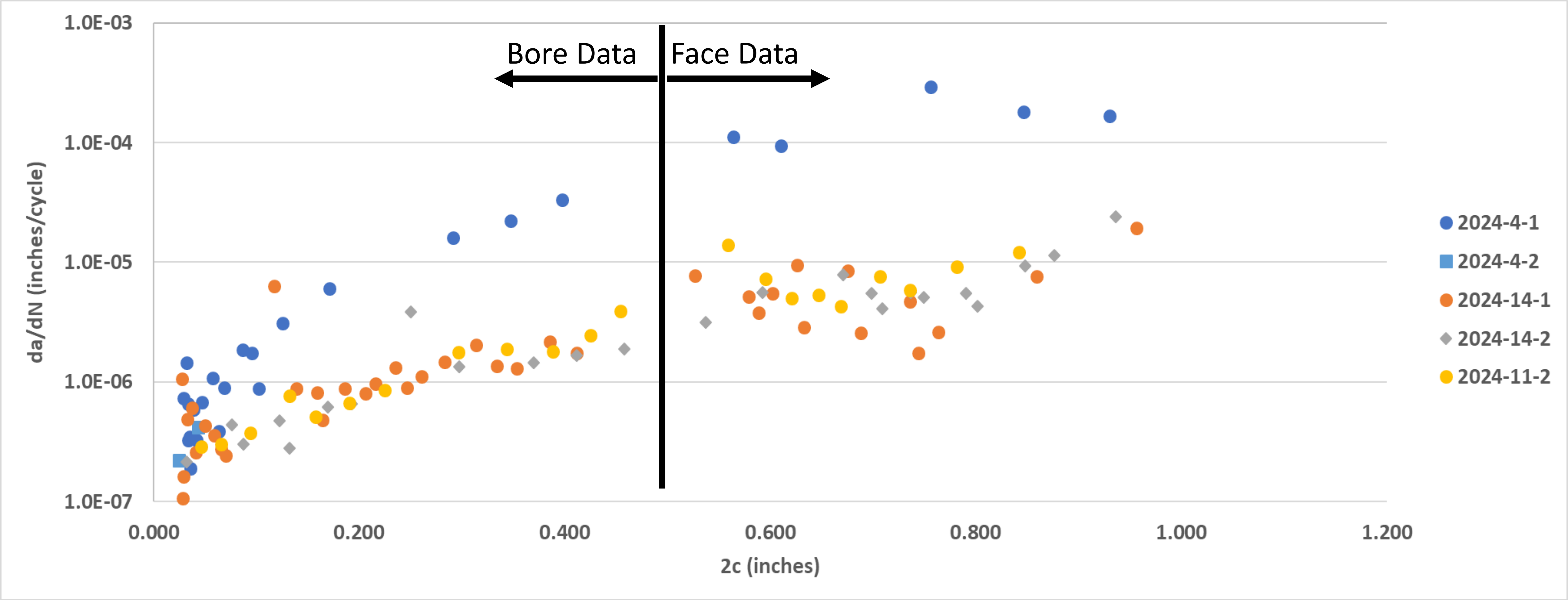
2024 Rate Data



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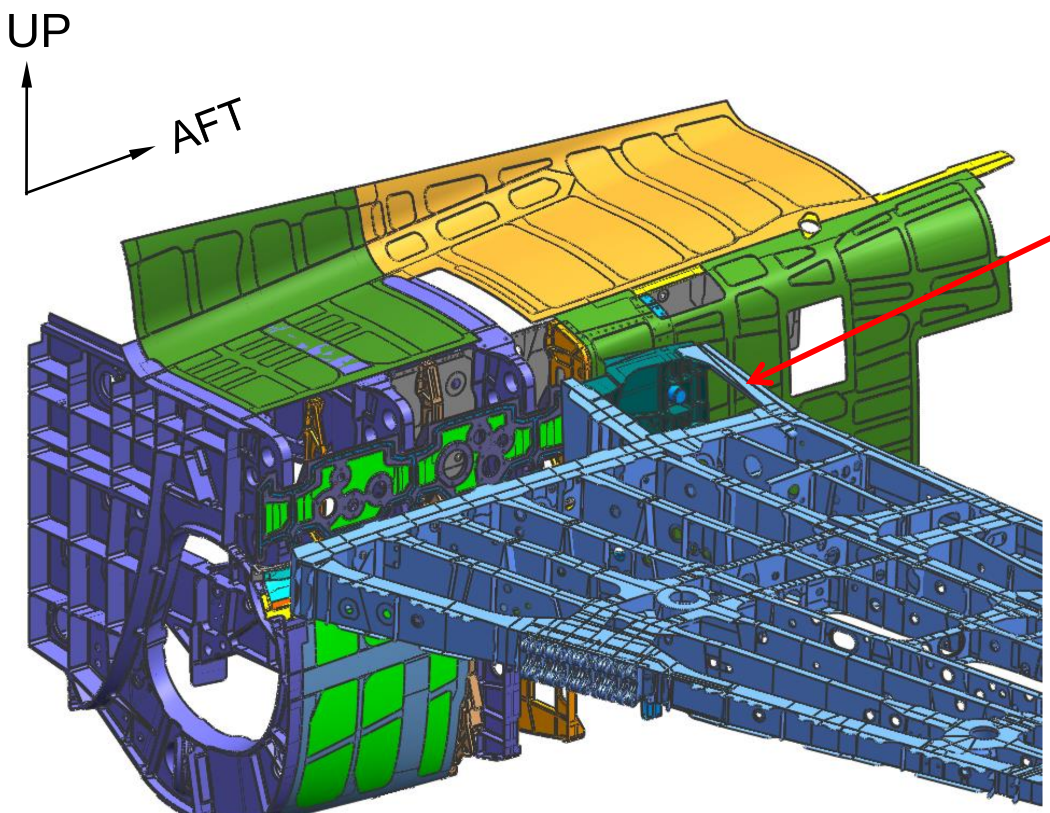
Weapon System Applications

Modelling fatigue cracking in F/A-18 Wing Root Shear Tie

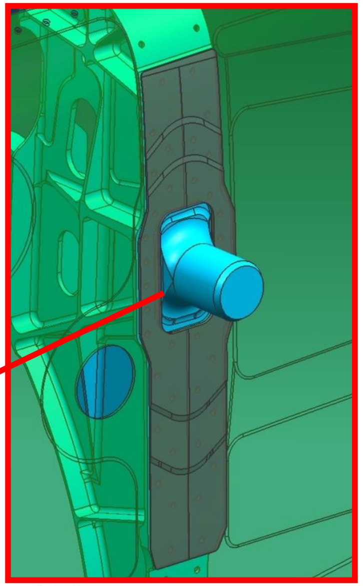
- Complex Geometry
- With and without Residual Stress
- Residual Stress due to shot peening
- Representative coupon testing under a known load spectrum gave the basis for comparison with analysis
- Analysis performed with BAMF which includes Stress Check and AFGROW
- Analysis results compared very well with the experimental data

Problem Description - F-18 Wing Root Shear Tie

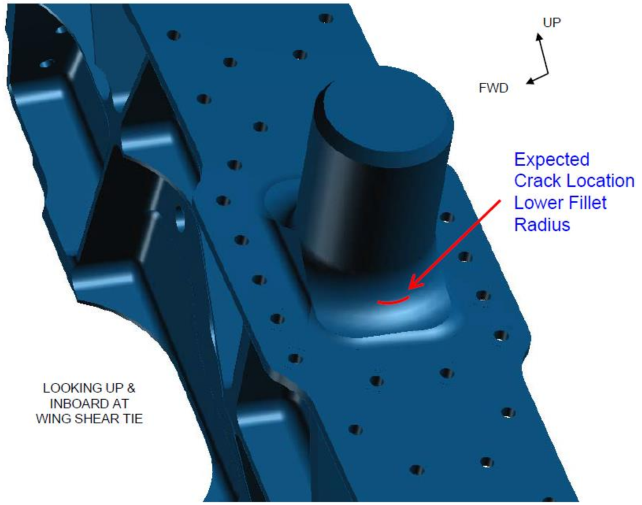
Flight Loads: Combination of Wing Root Shear and Trailing Edge Flap (TEF) Hinge Moment buffet introduced from the adjacent inboard TEF hinge and back-up structure.



FS508 Former Analysis Review (2010) *Northrup Grumman*



Materials and Surface Finish: Integral post machined from AA7050-T7451 plate. Pre-Ion Vapour Deposition (IVD) etched. Shot peened radius (steel shot) at production.



AFB-728 (2011) *Naval Air Systems Command (NAVAIR)*

Acknowledgement: Parts of this slide adapted from : Main, B. etal., “Component Testing of the F/A-18 A/B Y508 Wing Root Shear Tie”, ASIP Conference November 27-30 2017, Jacksonville, FL, USA

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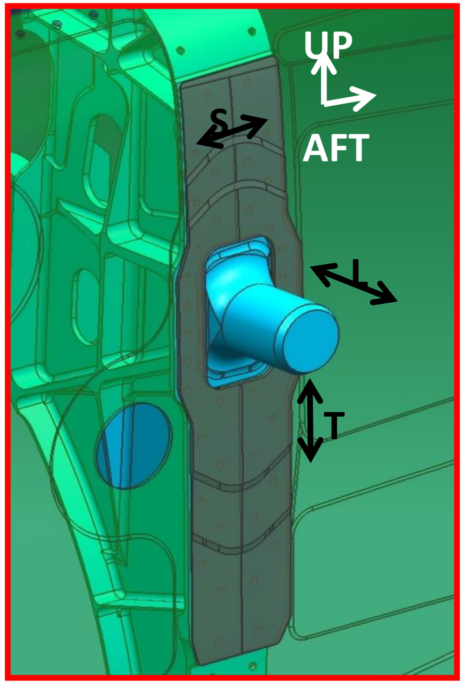
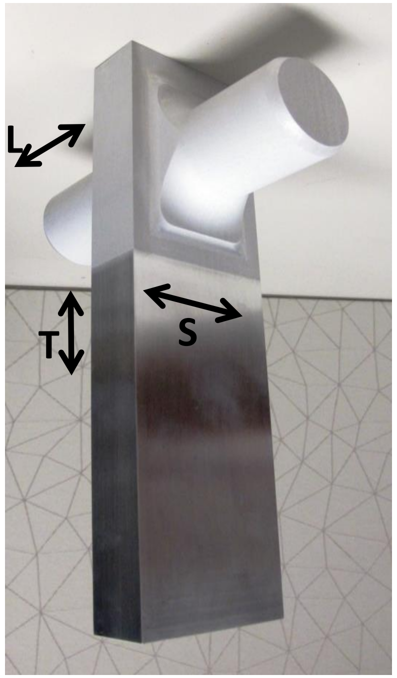
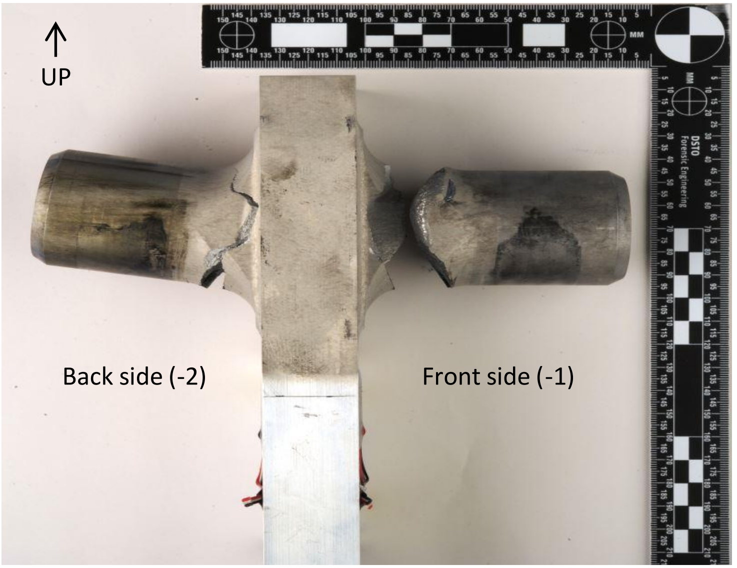
Science and Technology

Representative Coupon Design and Production

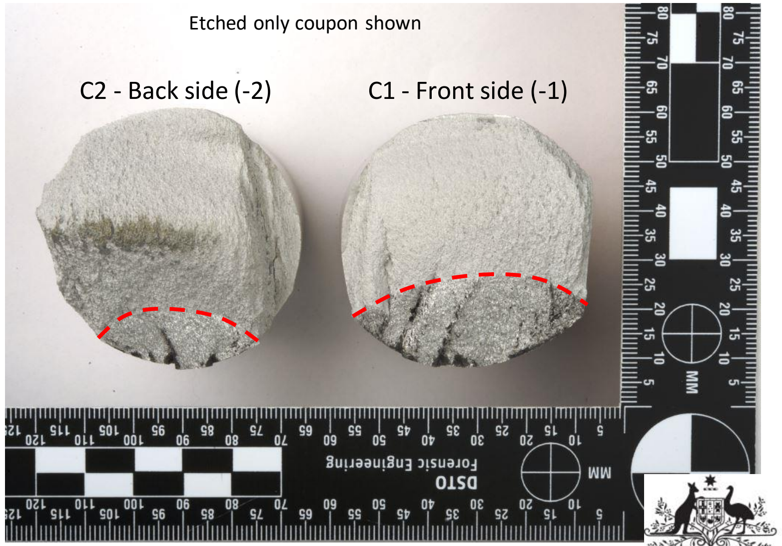




Etched only coupon shown



Etched only coupon shown



20 coupons machined from AA7050-T7451 plate. As machined finish and where noted:

- nitric acid etched per PS 13143 (1980) *McDonnell Douglas*
- steel shot peening to 0.001A per PS 14023 Rev G (1980) *McDonnell Douglas*

Acknowledgement: Parts of this slide adapted from : Main, B. etal., "Component Testing of the F/A-18 A/B Y508 Wing Root Shear Tie", ASIP Conference November 27-30 2017, Jacksonville, FL, USA

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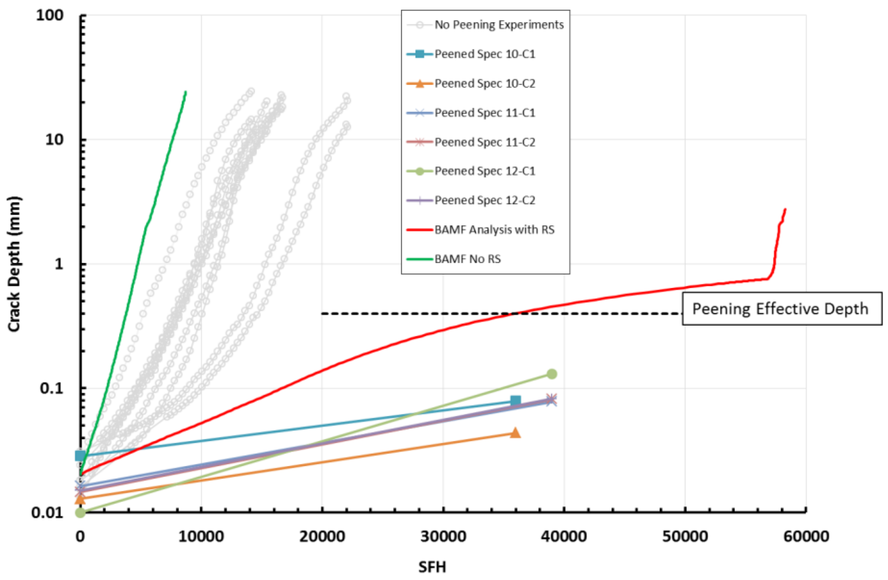
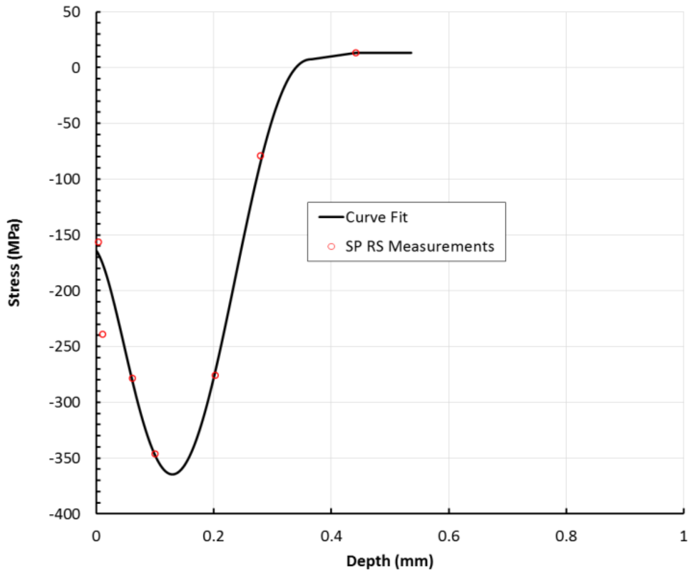
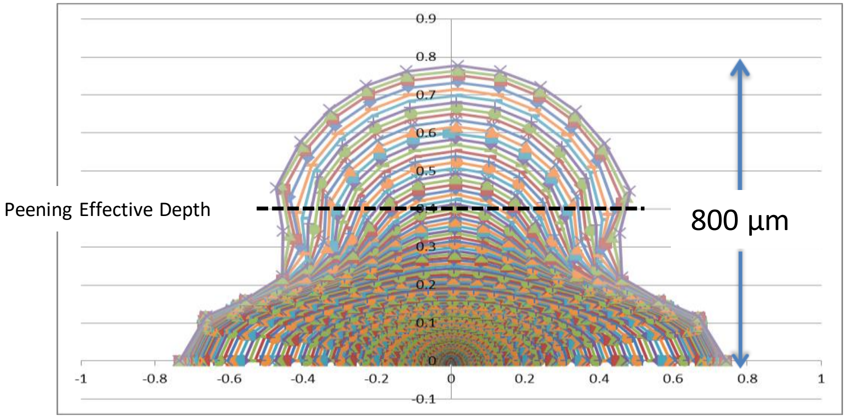
BAMF Results – With and without Shot Peening RS







Predicted crack shapes at 800 µm (0.8 mm) depth, beyond the effective peening range

<u>Observations</u>

- BAMF analysis and test results for no RS also shown for comparison
- BAMF analysis with RS compares very well against test observations
- Rapid growth predicted beyond the shot peening effective depth
- Predicted crack shape affected by the RS as expected

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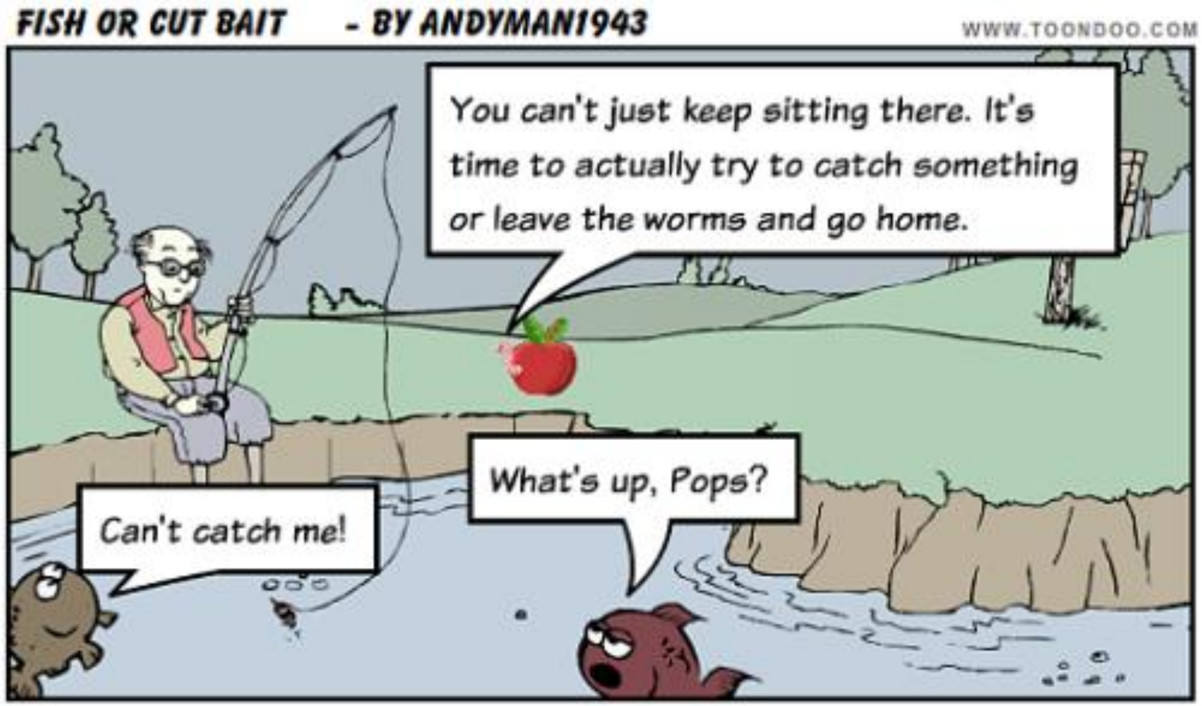
Control Point Analyses

- Objectives
  - Utilizing state-of-the-art methods and inputs, update DTAs for select Control Points (CPs), explicitly incorporating residual stress
  - Compare/contrast with reduced flaw size predictions (partial credit)
  - Identify gaps and refine best practices
  - Define initial ground rules
- Approach
  - Select candidate locations (3)
    - Typical & extreme locations
  - Review baseline input data/methods
  - Complete baseline analyses
  - Complete multi-point analyses w/ RS
  - Compare/contrast predictions
  - Provide conclusions and recommendations



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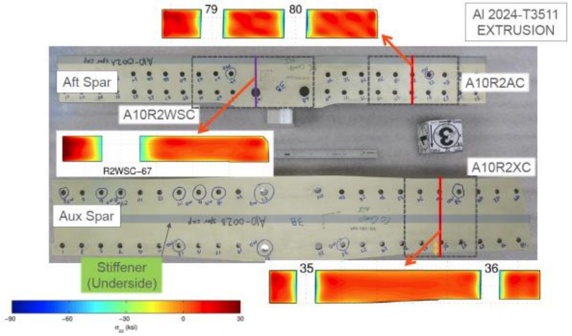
Control Point Analyses

- Inputs and Results
  - Oversized conditions
  - Variations in residual stress
  - Variation in stress spectrum



Location 1 residual stresses

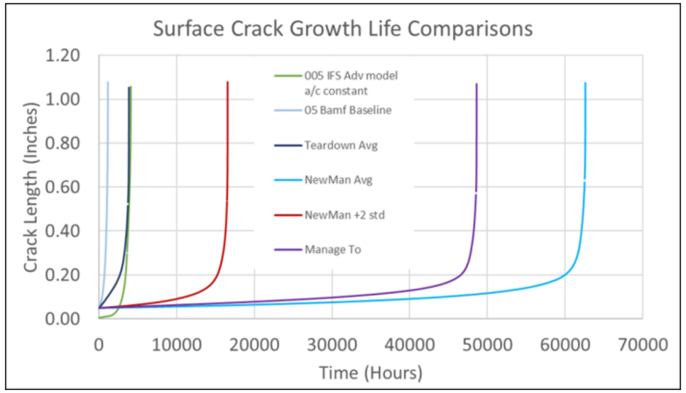
Analysis Details

Location	Description	Material	Thickness (in)	Hole Size (in)	Edge Margin (e/D)	Max Stress (ksi)
1	Lwr Fwd Skin, WS 23 (SLEP)	2024-T3511	0.300	0.625	2.256	31.2
2	Lwr Fwd Skin, WS 23 (Thick Skin)	2024-T3511	0.420	0.562	2.508	24.0
3	Lwr Wing Skin at Mid Spar, WS 23 (SLEP)	2024-T351	0.300	0.328	1.981	42.4

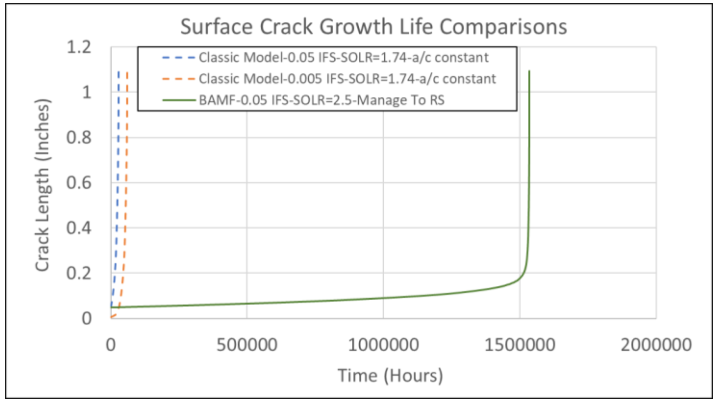
Residual Stresses

Location	New Manufacture Mean	Teardown mean	New Manufacture +2 Std	Teardown +2 Std	Manage To
1	x	x*	x		x
2		x			
3	x	x	x	x	

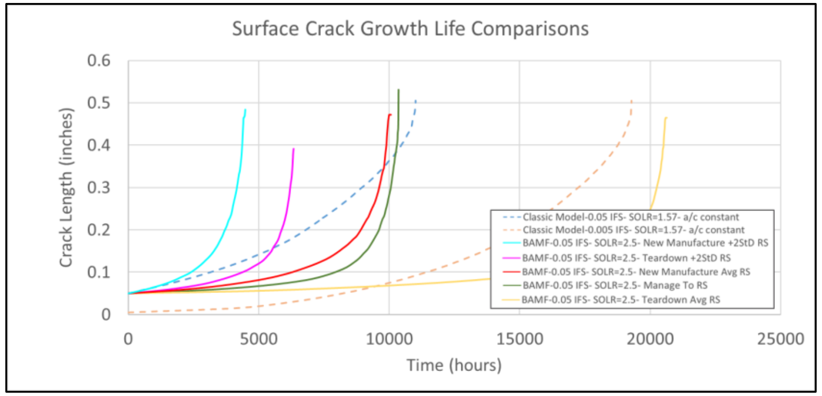
Location 1 Predictions



Location 2 Predictions



Location 3 Predictions



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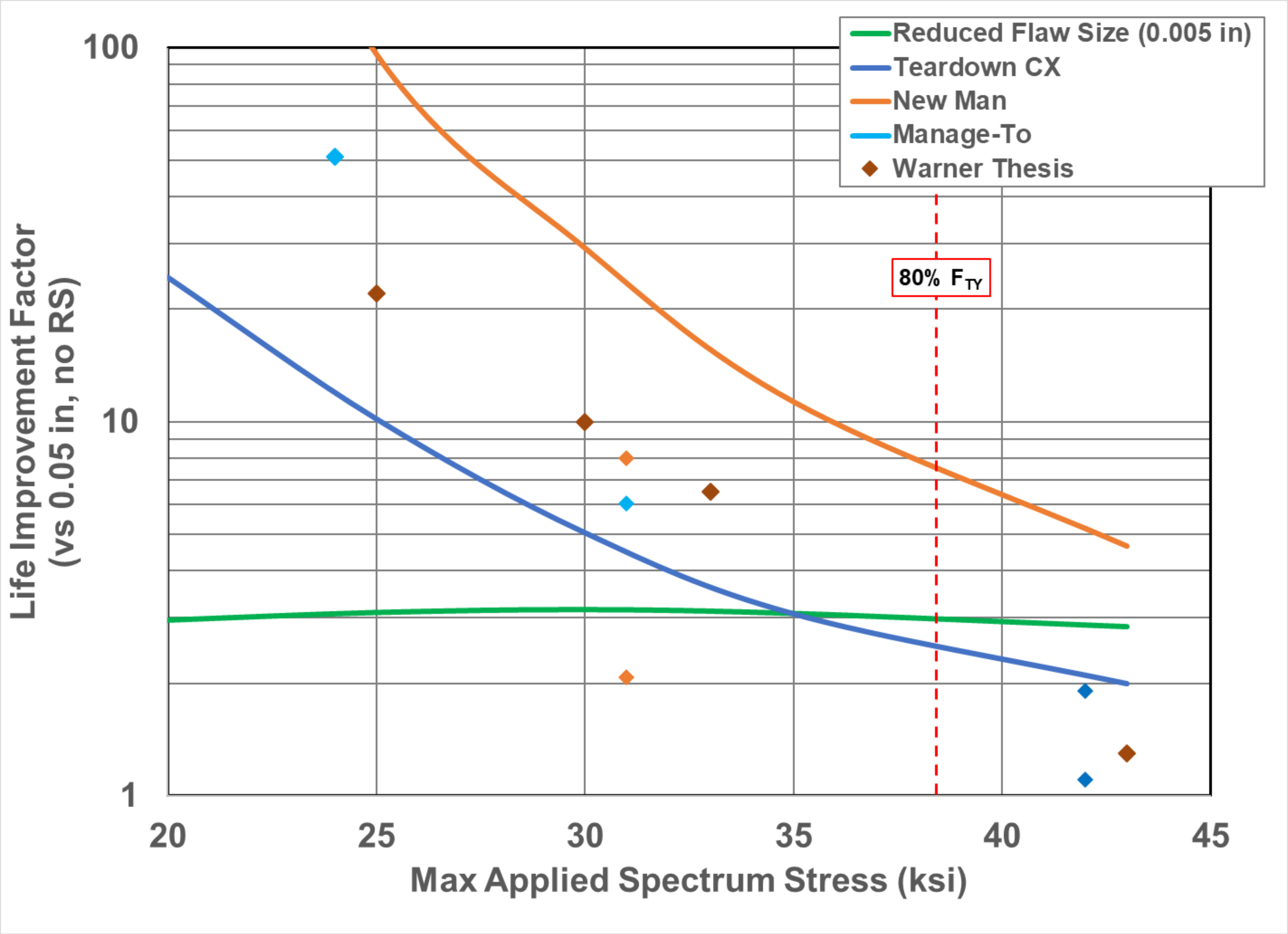
Control Point Analyses

- Conclusions
  - Peak spectrum stress has a key influence on the LIF at Cx holes
  - The LIF from traditional DTA methods, that also have high applied stresses and are account for the benefit of Cx, could be unconservative if utilizing 0.005” RIFS
  - Cx benefit is significantly reduced for locations with peak spectrum stresses greater than 85% of the yield strength. Experimental results demonstrate minimal benefit.
  - Appropriate crack retardation values with explicit residual stress range from 2.5-4.0 based on initial evaluations
    - Retardation parameters established from non-Cx holes should not be used for Cx hole analyses
    - Retardation values derived from 0.05” tests may not be appropriate for modeling RS with the RIFS assumption (0.005-inch)
  - The residual stress utilized for analyses is critical for the predictions and must be considered closely, considering the impacts of in-service degradation and statistical variation
  - The “Manage-To” approach results in a reasonable conservative prediction of the residual stress (as intended)

Control Point Analyses

- Results and Conclusions



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B-1 Taper-Lok Program Overview

- There are a number of current damage tolerance assessments requiring widespread initial inspections within the next 5 years
  - Removing Taper-Lok fasteners is difficult due to the interference fit of the fastener, and damage is often accrued
- The upcoming initial inspections are primarily based on testing data from the 1990’s and are considered to be conservative (partial-credit)
- The lack of a robust analytical approach requires costly testing and conservative methodologies to garner a benefit

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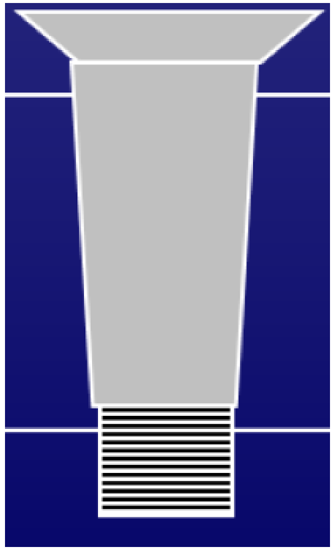
B-1 Taper-Lok Background

- 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
- Taper-Lok Locations
  - Hundreds of Taper-Loks common to wing rear spar and wing carry through



Taper-Lok Diagram

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

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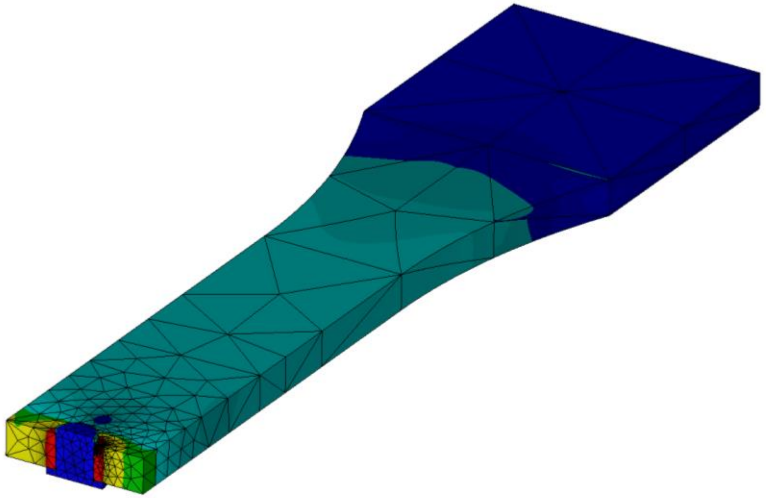
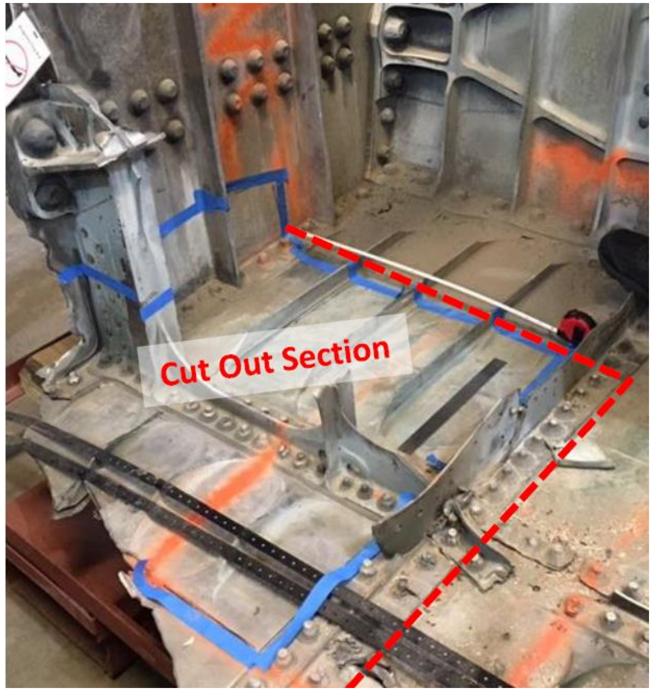
B-1 Taper-Lok Program Objectives

- Develop a robust analytical approach to predict the damage tolerance life at Taper-Lok fastener holes
- Perform measurements to quantify interference, elastic/plastic deformation, and stresses 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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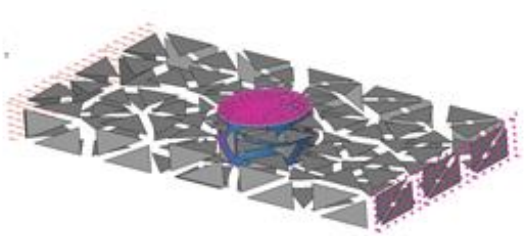
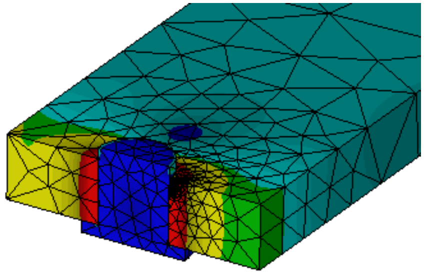
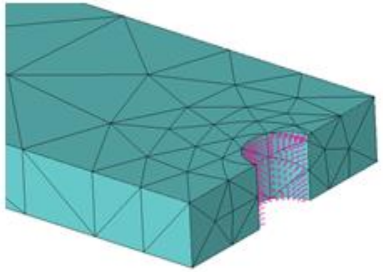
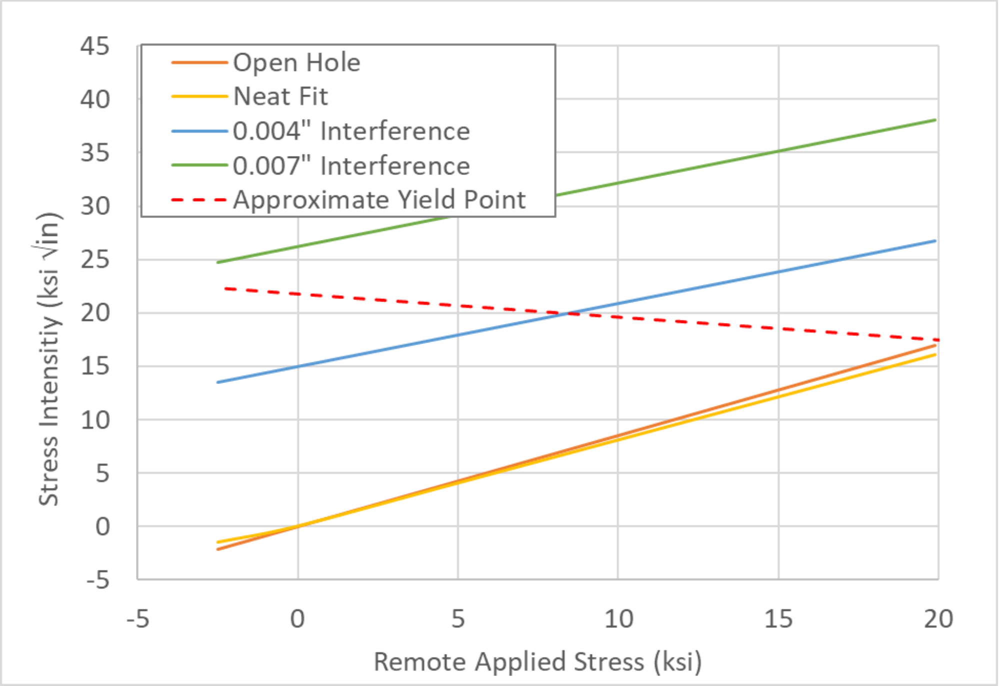
Analytical Approach

- Investigate Key Factors for Explicit Taper-Lok Modeling
  - Hole propping/interference, pre-stresses, and residual stress
- Modeling Approaches
  - Multi-point fracture mechanics
    - Explicit model geometry, loading, etc.
    - Enables natural crack shape evolution
  - Hole propping/interference
    - Multi-body contact
    - Springs
    - Pressure distributions
  - Pre-stresses
    - Reduced ΔK and R_{eff}
    - K vs. σ_{ref} characterization
  - Residual stress
    - Crack face pressures
    - Full-field residual stress
  - Characterize elastic and plastic response
  - Investigate variations in key factors and their influence on damage tolerant life
- Tool Updates
  - Incorporate ability to pass tabular lookup (K vs. σ_{ref}) instead of alpha to AFGROW from BAMF to address non-linearity of SIFs from interference









Misc. Other

USAF Structures Bulletin for ERS

- Objective
  - Provide guidance and requirements for “full credit”
- Approach
  - Considers the 5 factors for new materials, processes, joining methods and/or structural concepts in MIL-STD-1530D (para 5.1.7)
    - Stable: established process to impart ERS?
    - Producible: validated Quality Assurance (QA) or Non-Destructive Evaluation (NDE) method?
    - Characterized properties: known ERS field and known damage growth rates through ERS field?
    - Predictable performance: validated DT Analysis (DTA) method?
    - Supportable: validated QA/NDE and Non-Destructive Inspection (NDI) methods during sustainment phase?
- Initial Scope
  - Primarily focused on initial inspection benefit
  - NDE is required for recurring inspection interval benefit
- Status
  - Release for ASIP Manager review is imminent

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: Draft v2

Subject: Analytical Methods and Validation Testing Requirements for Explicit Utilization of Residual Stresses at Cold Expanded Fastener Holes in Damage Tolerance Analysis

References:

1. JSSG-2006, “Joint Service Specification Guide Aircraft Structures”, 30 October 1998
2. MIL-STD-1530D, “Aircraft Structural Integrity Program”, 13 August 2016
3. EN-SB-17-001, “Testing and Evaluation Requirements for Utilization of an Equivalent Initial Damage Size Method to Establish the Beneficial Effects of Cold Expanded Holes for Development of the Damage Tolerance Initial Inspection Interval,”, 24 April 2017
4. Northrop Grumman Corporation, “Analytical Considerations for Residual Stress, Best Practices and Case Studies, A-10 Thunderbolt Life-cycle Program Support (TLPS) ASIP Modernization VI, Crack Growth Analysis in Residual Stress Fields”, HE-R-072217 Revision B, 27 June 2018
5. Mills, T.; Honeycutt, K.; Prost-Domasky, S.; Brooks, C., “Integrating Residual Stress Analysis of Critical Fastener Holes into USAF Depot Maintenance”, A3G-2015-185420, 2 November 2014
6. Hill, M.; DeWald, A.; VanDalen, J.; Bunch, J.; Flanagan, S.; Langer, K., “Design and analysis of engineered residual stress surface treatments for enhancement of aircraft structure, 2012 ASIP Conference
7. EN-SB-08-012, “In-Service Inspection Crack Size Assumptions for Metallic Structures”, April 2018
8. Brausch, J.; Stubbs, D.; Fong, W., “Impact of Deep Residual Stress on NDI Methods”, Engineered Residual Stress Implementation Workshop, 21 September 2017

Literature Review

- Objective
  - Develop a consolidated summary of Cx references for the community
  - Increase visibility of existing Cx references
- Approach
  - Developed a template to identify key parameters
  - Divvy 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

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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

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Breakout Session Agenda

- Breakout Discussions, Session 1 (Thursday, 3-5pm)
  - Individual presentations
    - Closure (Mills)
    - Interference Fasteners (Mills)
    - FCG Testing of Complex Coupons with Quench Induced Residual Stress (Hill)
  - Re-Vectoring
    - Revisit our current focus areas and technology gaps
    - Discuss new focus areas for upcoming year
- Breakout Discussions, Session 2 (Friday, 8:30-10:30am)
  - Individual presentations
    - Short Edge Margin Evaluation (Ross)
  - Round Robin #2 Planning (Warner)
  - Open discussion and task assignments

Questions?

Nondestructive Inspection (NDI) Committee Overview

Engineered Residual Stress Implementation (ERSI) Workshop

12 September 2019

John Brausch[1], Ward Fong[2]

[1]Materials and Manufacturing Directorate, System Support Division

[2] Ogden NDI Program Office, Hill AFB, UT

- NDI Subcommittee Membership
- Summary of Current Knowledge
- Gaps
- Committee Priorities
- Progress to Date
- NDI Implementation Strategy

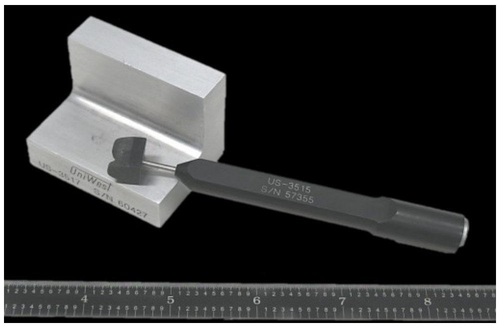
NDI Committee Members

Title	First Name	Last Name	Company/Organization
Mr.	Fred	Acosta	U.S. Marine Corp (F-5 NDI Lead)
Mr.	John	Brausch	U.S. Air Force (AFRL - NDE Lead Engineer, Systems Support)
Mr.	Nicholas	Brunnell	Engineer, NDI SME AFSC/ENRB OL Robins
Mr.	Dave	Campbell	U.S. Air Force (Tinker AFB NDI Program Office Lead)
Dr.	Teodor	Dogaru	Southwest Research Institue (SwRI)
Mr.	Ward	Fong	U.S. Air Force (Hill AFB NDI Program Office Lead)
Mr.	Dave	Forsyth	Texas Research International (TRI) - Austin, Inc.
Mr.	Leo	Garza	L3 Communications (RC-135 Fleet Manager)
Mr.	Bryce	Harris	U.S. Air Force (F-16 ASIP Manager)
Dr.	Kim	Jones	U.S. Air Force (F-16 ASIP)
Mr.	Doyle	Motes	Texas Research International (TRI) - Austin, Inc.
Mr.	Tommy	Mullis	U.S. Air Force (Warner Robins AFB NDI Program Office Lead)
Mr.	Mike	Reedy	U.S. Navy (NAVAIR - Compression Systems Engineer)
Dr.	Gregory	Shoales	U.S. Air Force (Center for Aircraft Structural Life Extension (CAStLE) - Director)
Mr.	Clint	Thwing	Southwest Research Institue (SwRI)
Mr.	Jacob	Warner	U.S. Air Force (A-10 ASIP Analysis Group Lead)
Mr.	David	Wilkinson	U.S. Air Force (C-5 ASIP Manager)

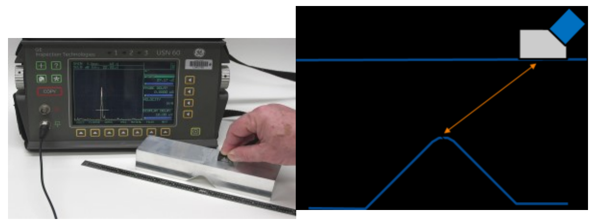
Summary of Current Knowledge

Laser Shock Peening

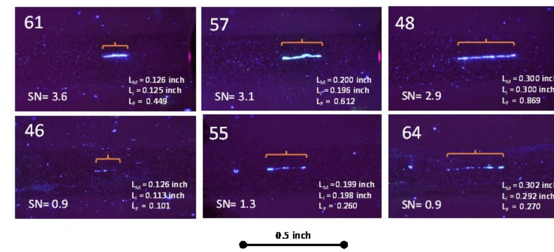
Eddy Current

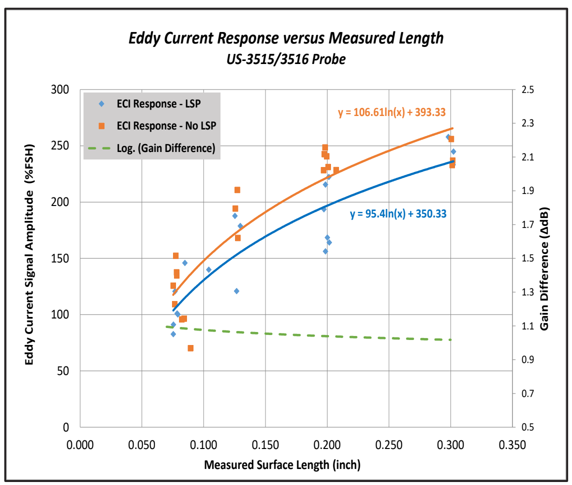


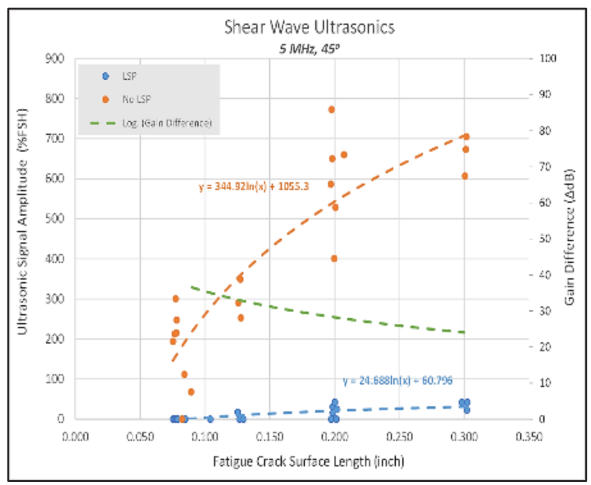
Ultrasonics

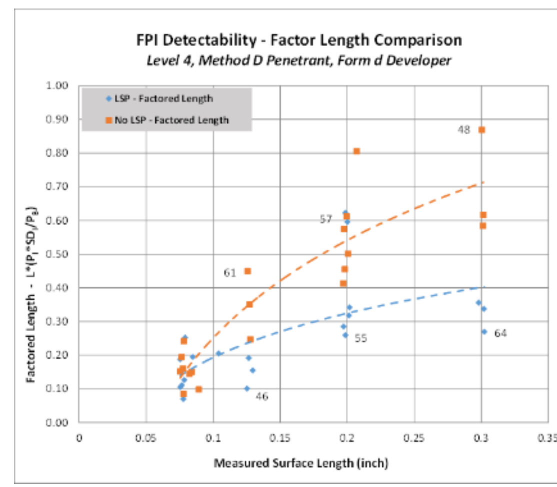


Fluorescent Penetrant









Minimal Impact

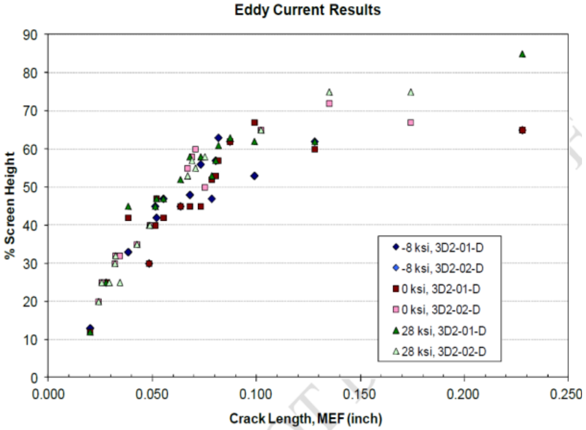
Significant Impact

Significant Impact

Distribution A: Approve for Public Release (Case #: 88ABW-2019-4193)

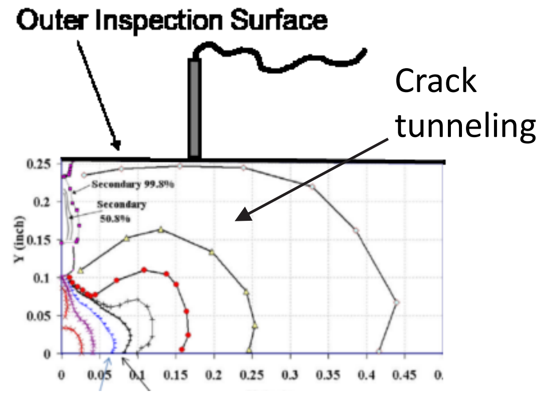
Hole Cold Working: Eddy Current, Ultrasonics

Rotary Hole Eddy Current

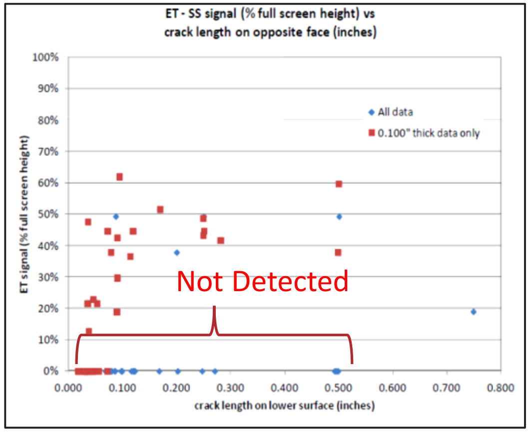


Minimal Impact

Surface Eddy Current

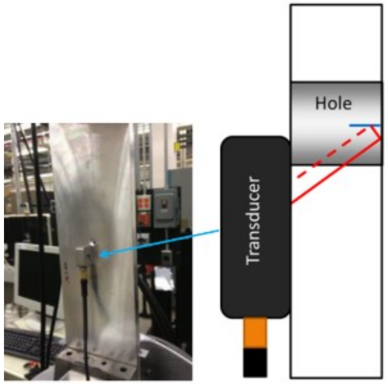


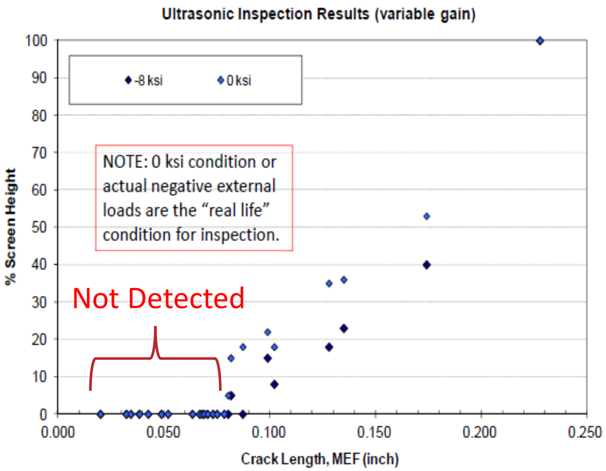
Forsythe, D., Mills, T. "Results of Study of Applied Stress and CX Process on Detectability of Fatigue Cracks"



Significant Impact

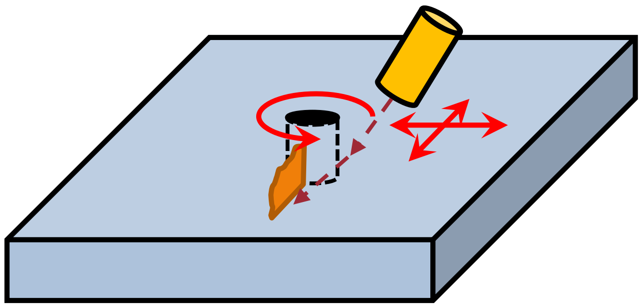
Ultrasonics

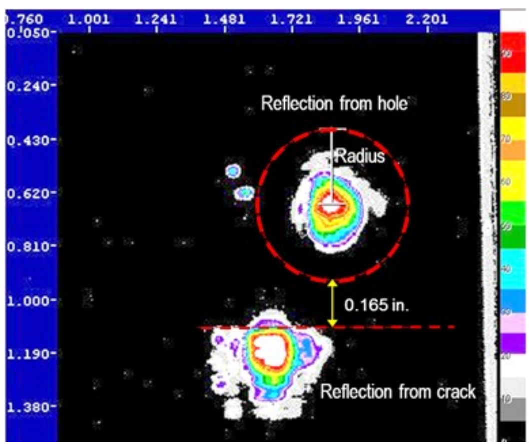


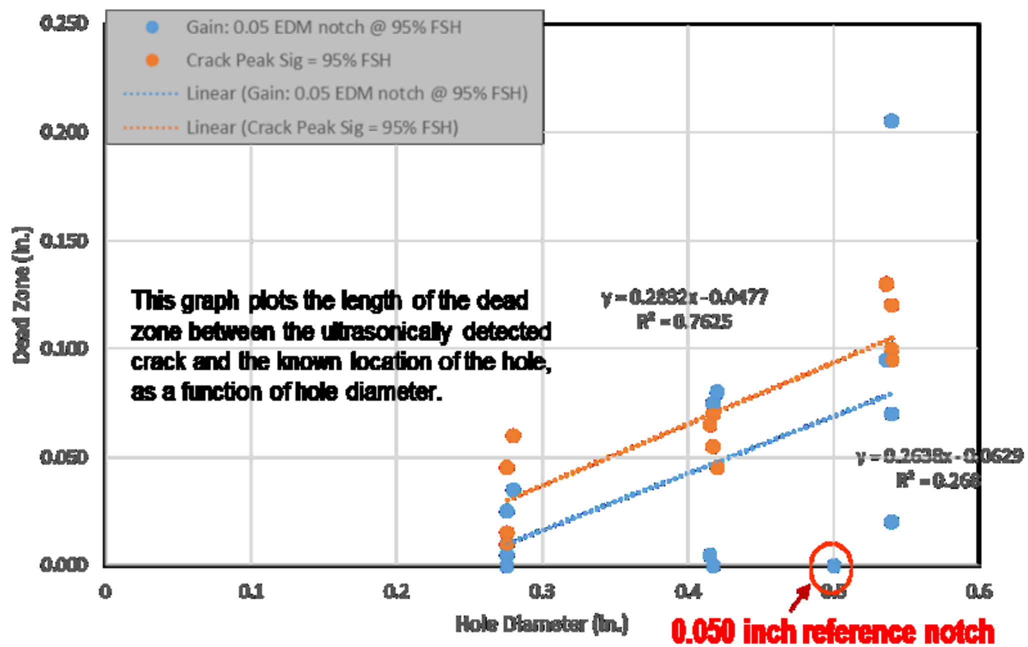


Significant Impact

Ultrasonic "Dead-Zone" in Cx Holes







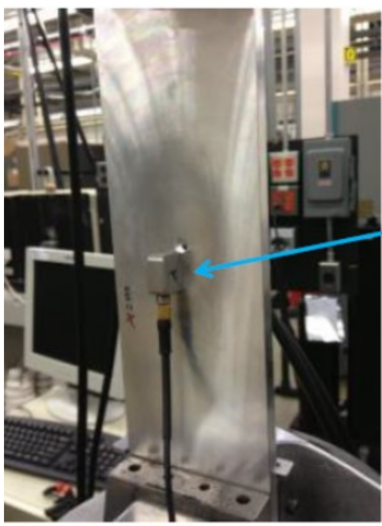
D. Stubbs, AFRL/RXSA - UDRI

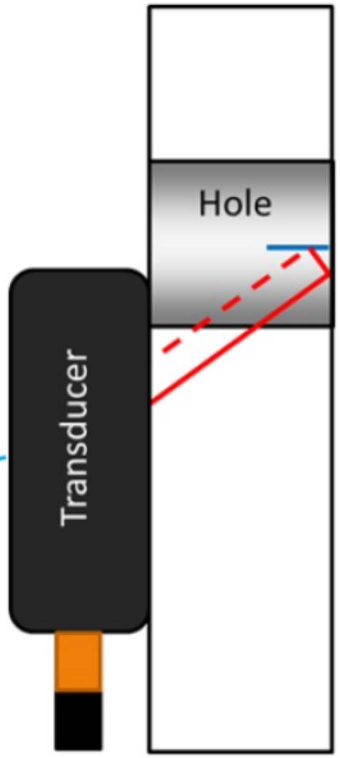
- *Dead zone proportional to hole diameter but scatter suggests other influencing factors*
- *Use upper bound of UT dead zone estimates to correct UT POD estimates for Cx holes*
- *Ultrasonic inspections must be designed to interrogate beyond the tangency of the hole*

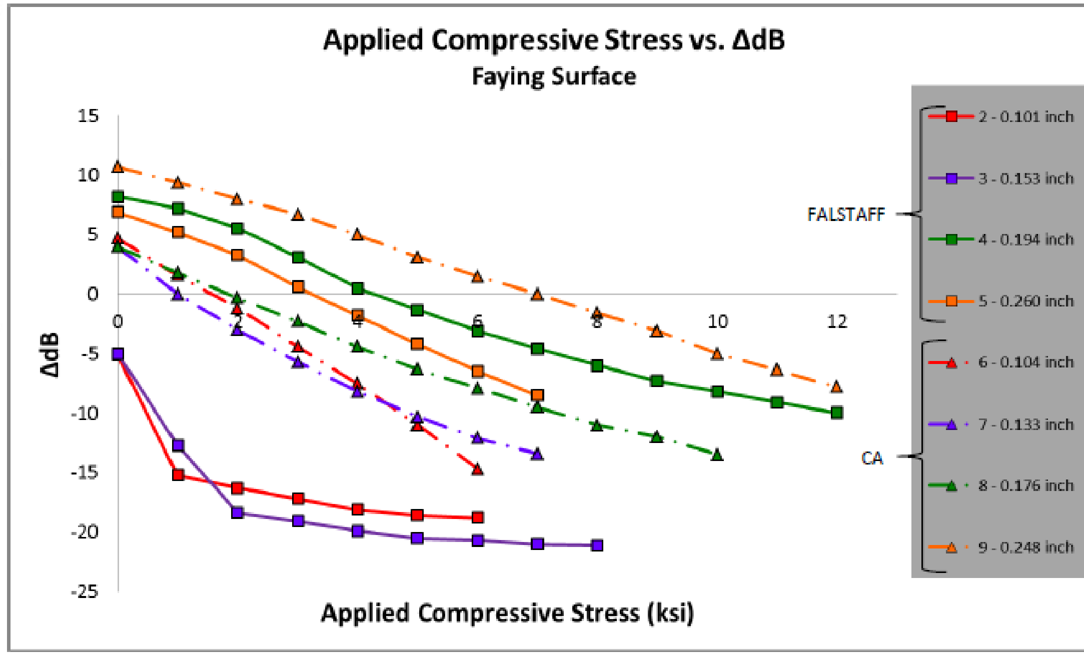
Ultrasonic "dead zone" proportional to hole diameter.

Applied Compressive Stress: Shear-Wave Ultrasonics

Ultrasonic response from fatigue cracks under applied compressive stress.





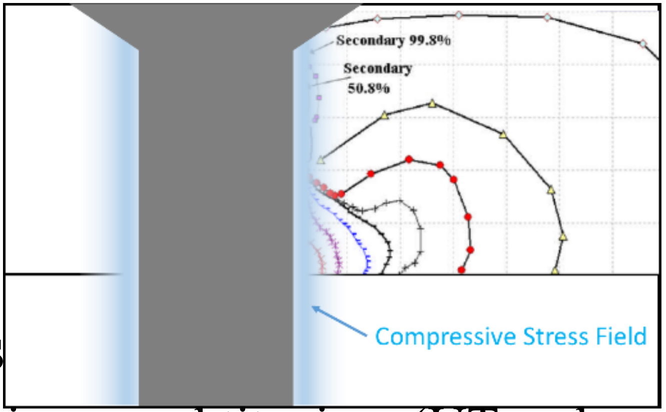


Henry, T. "Correlating Ultrasonic Responses of Fatigue Cracks Propagated Under Different Load Spectra."

Significant Impact
~6dB (50%) signal reduction per 4 ksi applied compressive stress.

Gaps

- Further Quantify Ultrasonic "Dead Zone" at Cx Holes
  - **Quantify UT "Dead Zone" for a range of Cx applied expansion ranges**
  - Investigate causes of "Dead Zone" variability
  - *Define UT POD correction factors for Cx holes*
    - ✓ ***Initial estimates documented in EN-SB-008-012***
  - *Define optimum UT system design for Cx holes*
- Fastener Installation on UT Detectability
  - Taper-Lok fasteners
  - Interference fit fasteners
- Other ERS Surface Treatments and Materials
  - Shot peening, low plasticity burnishing – on aluminum and titanium (UT and FPI focused)
  - **Laser Shock Peening (LSP) on titanium alloys**



Subcommittee Priorities

Priority I. Quantify UT dead zone in Cx holes. Correlate to hole D and T.

A. Round Robin - Map UT dead zone for Cx holes – selected specimens
- RXSA, RXCA, AFSC/ENSI Participating – In progress
- ✓ Stress profiles from Val/Ver Test Subcommittee – T. Mills

B. Impact of interference fit fasteners – repeat Round Robin

C. Evaluate Phased Array Ultrasonics
- Capture data w/ existing AFIS UT inspection system
- Build on SwRI body of knowledge

Priority II. Investigate impact of Taper-Lok fastener installation on ultrasonic fatigue crack detectability?

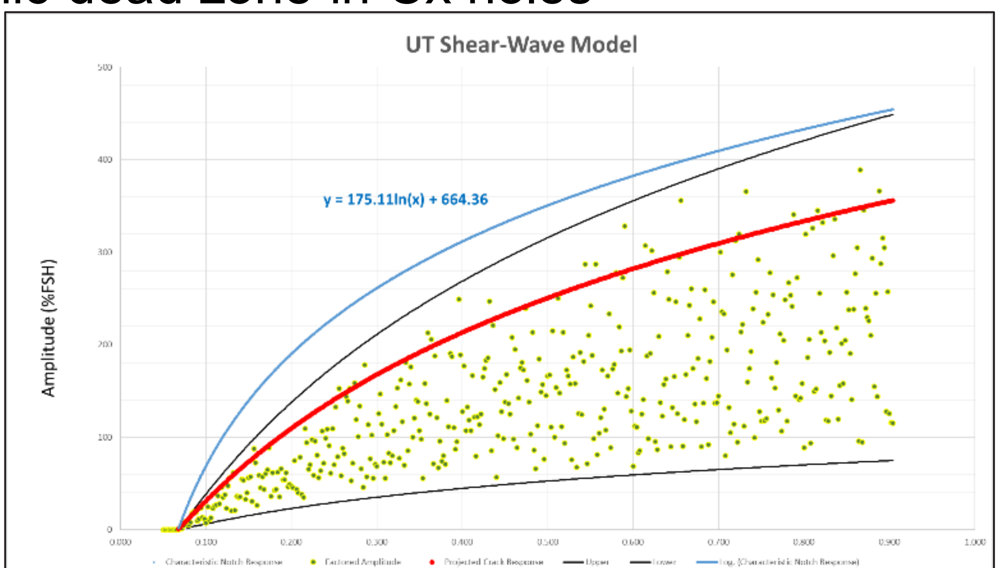
A. Model Taper-Lok stress field

B. Empirical measurements of UT response

Priority III. Characterize impact of laser-peening on titanium.
- Integrate measurements into planned a/c qual. Programs

Progress

- Published EN-SB-008-012 Rev D, April 2018
  - Impact of Cx on surface eddy current inspection
  - Impact of Cx on ultrasonic inspection of Cx fastener holes
    - Initial estimates of dead zone for POD correction
  - Guidance for FPI and UT on Laser Peened structures
- Incorporation of current knowledge into AFRL developed UT scatter model.
  - Applied compressive stress
  - Ultrasonic dead zone in Cx holes



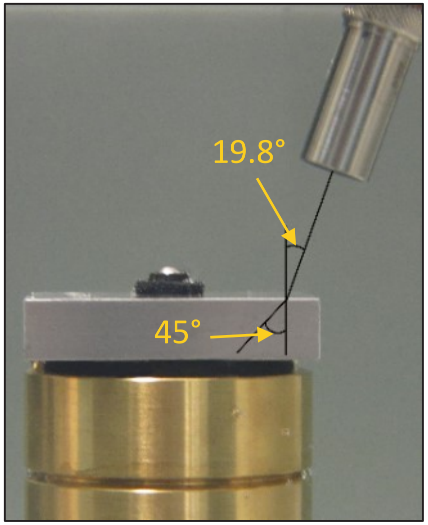
Progress: Priority I.A: Quantify UT Dead Zone

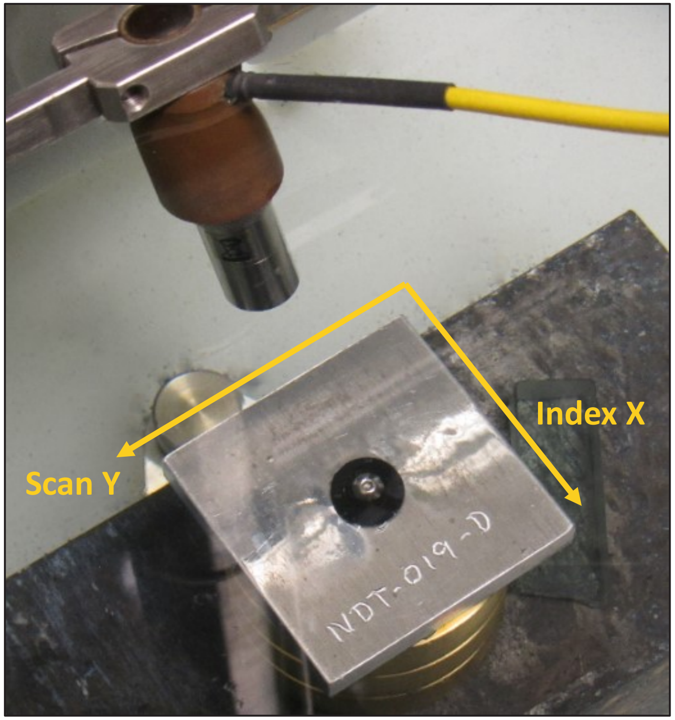
Round Robin Progress

- Test fixtures provided to AFSC/ENSI and AFRL/RXCA
- Initial setups established
- 118 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

Testing Setup Example

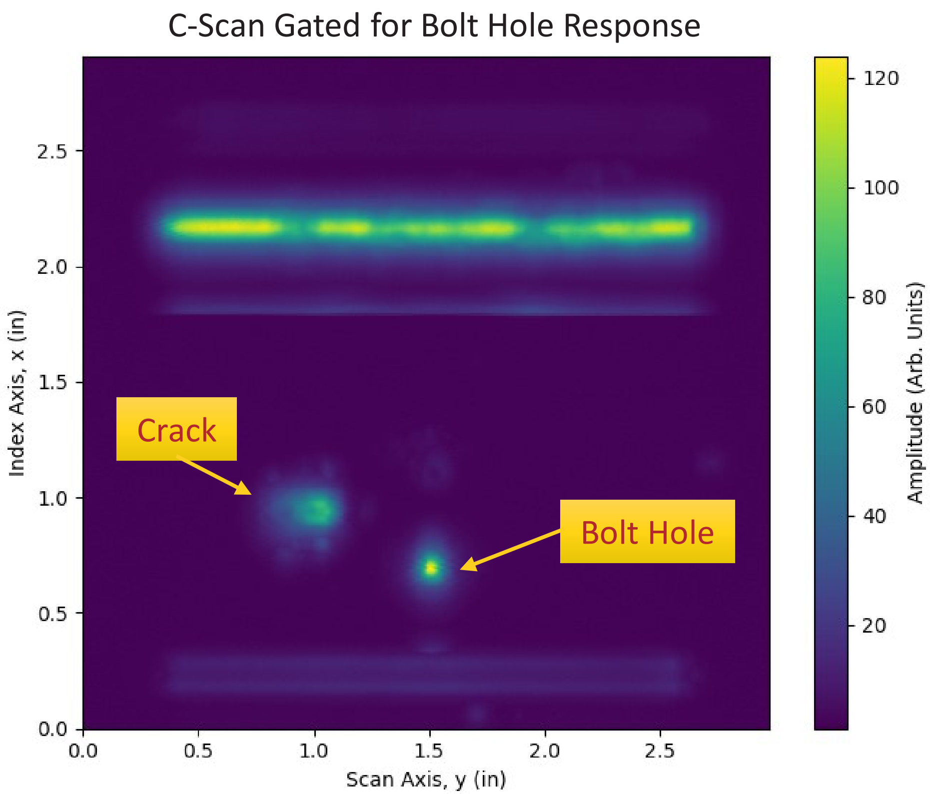
- Sample NDT-019-D (0.540 inch Dia. Hole)
- Calculated Incident Angle 19.8º
  - 45º shear angle in aluminum
- Scan Step Size: 0.006 inch
- Transducer Panametrics V327
  - 10MHz 0.375 inch Dia.
  - 3” Spherical Focal Distance
  - Approximate Mid Plane Focus

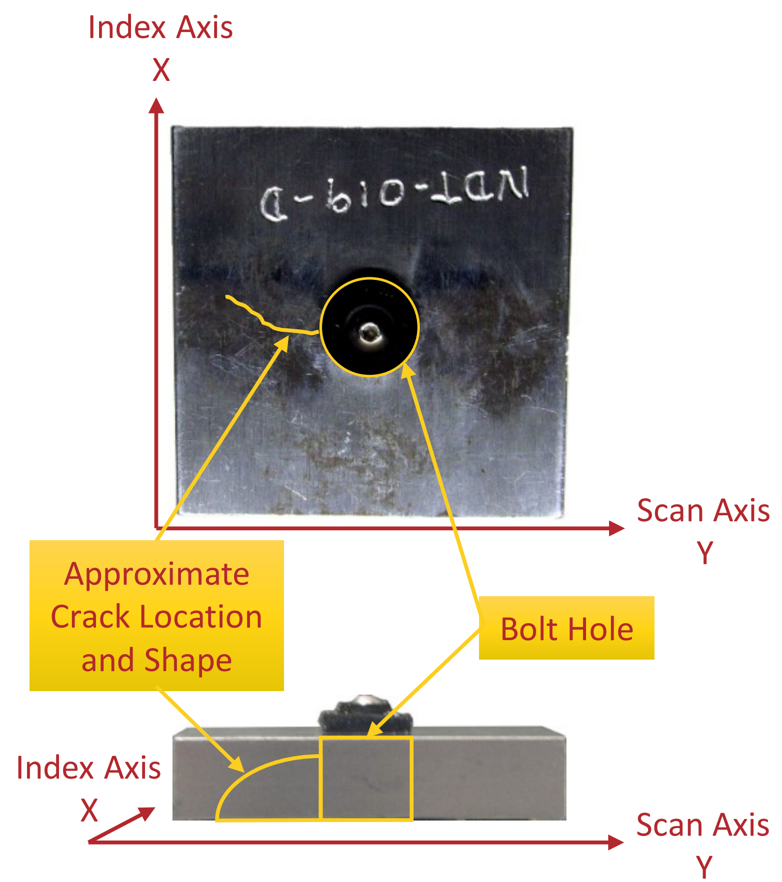




Courtesy of:
Mike Uchic – AFRL/RXCA
Tyler Lesthaeghe – University Dayton Research Institute
David Zainey - University Dayton Research Institute
Vicki Kramb - University Dayton Research Institute

Initial Test Results – AFRL/RXCA

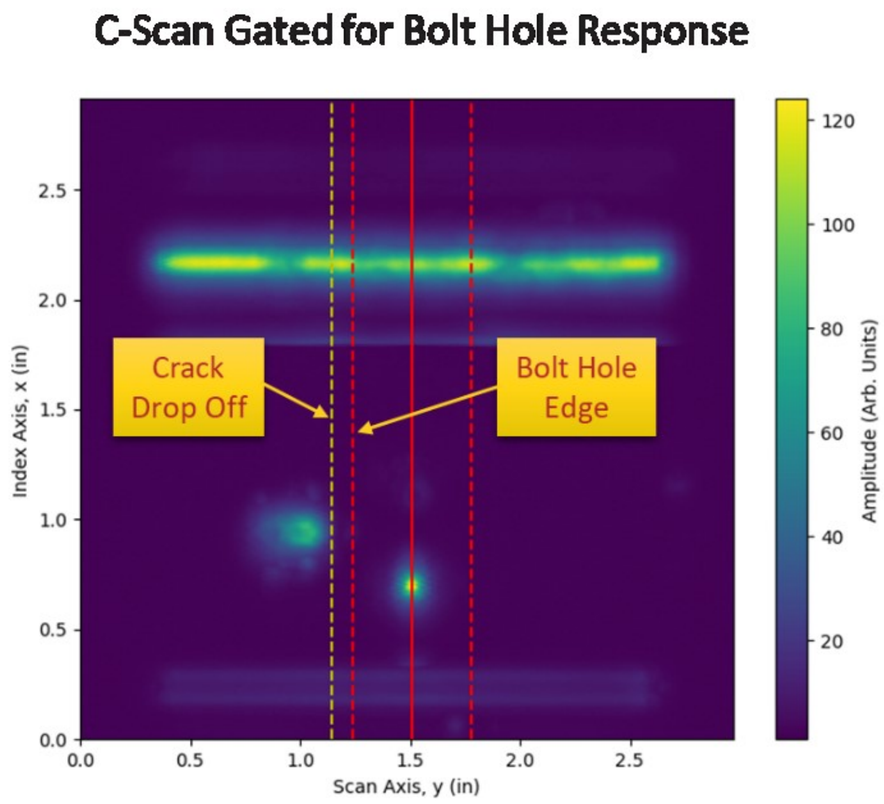




<u>Courtesy of</u>:
Mike Uchic – AFRL/RXCA
Tyler Lesthaeghe – University Dayton Research Institute
David Zainey - University Dayton Research Institute
Vicki Kramb - University Dayton Research Institute

Ultrasonic Dead Zone Measurement

- Dead zone measured by locating peak amplitude response from bolt hole and using known hole diameter to determine edge location
- Edge of dead zone determined from B-Scan drop off (-6dB) from the max crack response
- Estimated dead zone: 0.0985 inch
  - Consistent with RXSA findings
- Ready to test remaining 117 coupons



Courtesy of:
Mike Uchic – AFRL/RXCA
Tyler Lesthaeghe – University Dayton Research Institute
David Zainey - University Dayton Research Institute
Vicki Kramb - University Dayton Research Institute

Progress: Priority I.C: Evaluate Phased Array UT

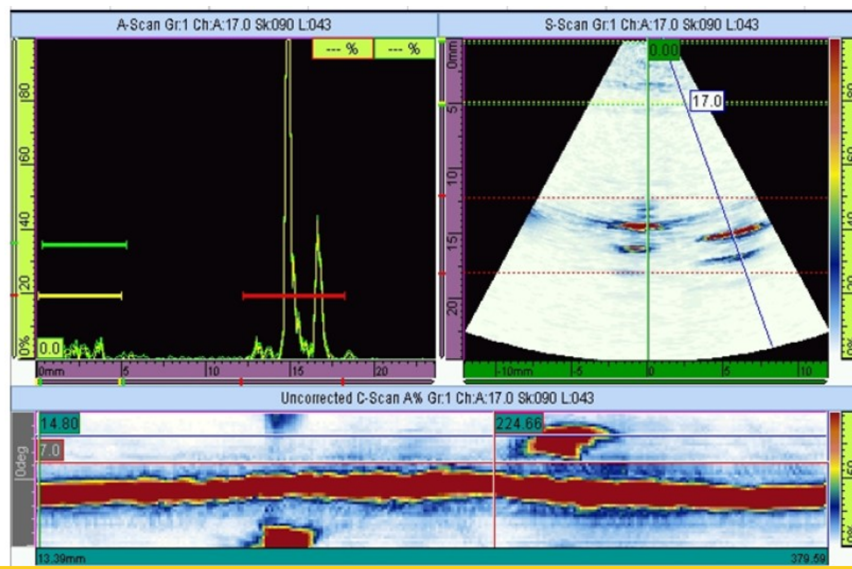
Non-Destructive Testing of cold Worked Fastener Holes

Dallen L. Andrew and Clint Thwing – SwRI and CAStLE

- Evaluation of 4% cold worked holes in lower wing skin structure and detectability of fatigue cracks via the Automated Fastener Inspection System (AFIS) and Rotoscan ultrasonic inspection systems.
  - 0.261 inch final diameter hole, 11 Coupons
  - 0.340 inch Thick 7075-T651 Plate

General Conclusions:

- Fatigue cracks >0.071 inch length detected (regardless of depth)
- Countersink cracks only detected when faying surface cracks >0.165 inch were present.



AFIS Result from 0.150 inch Faying Surface Crack

Progress: Priority III: Characterize Impact of Laser-Peening on Titanium.

- NDI characterization (FPI, ECI and UT) has been integrated into on-going Lockheed mechanical test program for laser peening of Ti-6-4
- Limited scope with limited number of subcomponents
- AFRL/RXSA is supporting these efforts
- POC: Scott Carlson, Lockheed Martin - Aerospace

NDI Implementation Strategy

- Capability impacts documented in EN-SB-008-012
- Inspection limitations could be documented in future ERSI SB
- Documentation of inspection process best practices in general procedures of T.O. 33B-1-2 where applicable

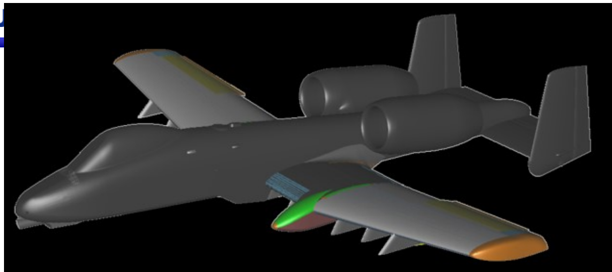
Questions?

Quality Assurance and Data Management

(Sept 12, 2019)

Kaylon Anderson
A-10 ASIP & Analysis, USAF
kaylon.anderson@us.af.mil

An Introduction to our Team



Harris
(USAF – F16)

am Zimmerman
(FTI)

Eric Lindgren
(USAF – AFRL)

Kaylon Anderson
(USAF – A10)

Dave Forsyth
(TRI-Austin)

Doyle Motes
(TRI-Austin)

Brandon Dierschke
(L3 MID)

Phil Hoefert
(L3 Harris)

Chris Kirkpatrick
(L3 Harris)

Kim Jones
(USAF – F16)

Hazen Sedgwick
(USAF – A10)

Josh Hodges
(Hill Engineering)

Taking Full Credit for Engineering Residual Stress

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Full Credit: being able to take advantage of the residual stress (RS) field in an analysis.

Quality Assurance **(QA)**:

Validating that the RS field is within spec. and imparted in the correct location.

Non Destructive Evaluation **(NDE)**:

Provides a qualitative description of the RS field.

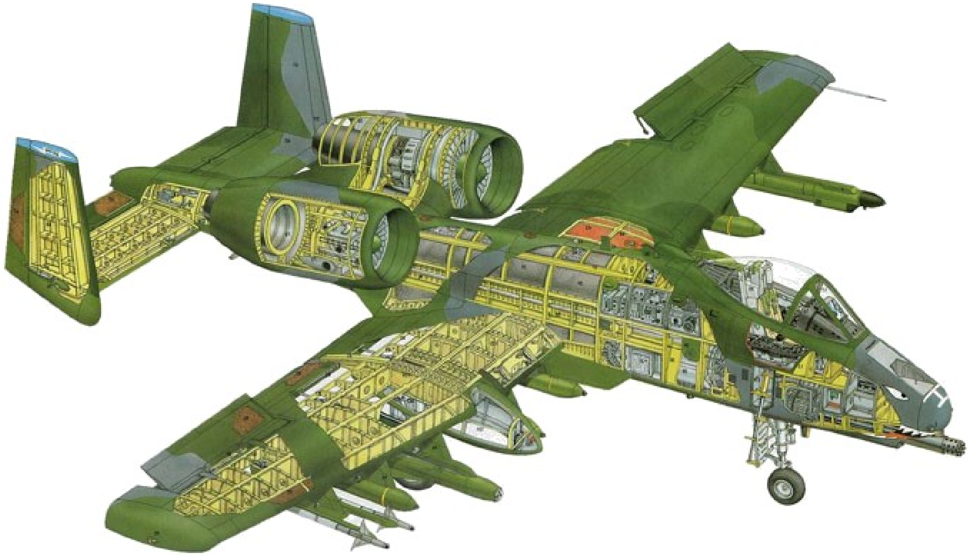
Validating where within the spec the residual stress field is.

QA/NDE World

QA / NDE Responsibilities

1. Validated QA/NDE method in Production & Sustainment
   a. I.e. An auditable trail to the imparted residual stress

2. QA/NDE needs to be documented such that it is Quantitative, Retained as a Permanent Record and Auditable.



Reference Slides from 2017 Residual Stress Summit, UDRI, C
Chuck Babish, "ASIP Perspective on Accounting for ERS in DTA"

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Validated QA/NDE method

Validated QA/NDE method
(Basic Requirements)

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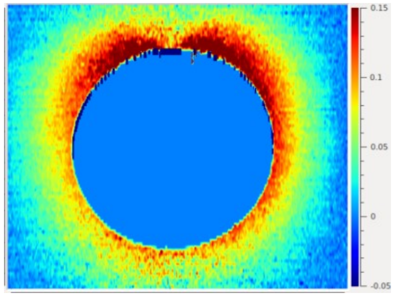
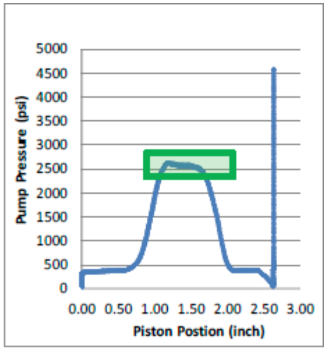
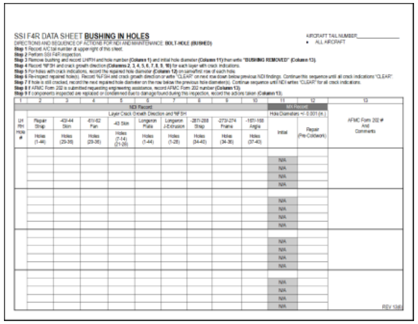
Two basic requirements:



1. <u>The Residual Stress Field is to be verified</u>
    a. Go No Go Gauge (FTI standard spec)
    b. Instrumented puller
    c. Volcano characterization
    d. Eddy Current NDE



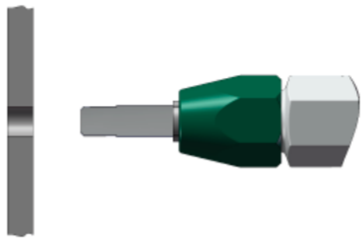
2. <u>The location of the RS is to be know</u>
    a. Manual entry
    b. Automated Locating



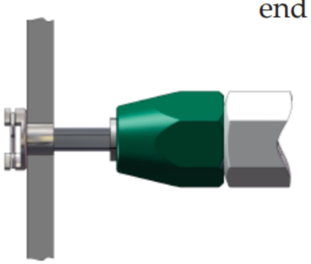
Validated QA/NDE method
(Go No Go Gauge)

A check to determine if the hole was expanded to the correct size.

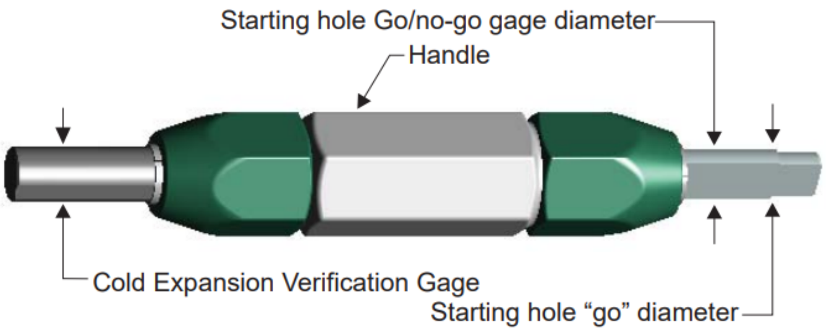
<u>For Full Credit the Residual Stress field correlated to the lower bound of FTI's spec would be used.</u>



Check the starting hole using blade end of the combination gage.



Check the final hole diameter using the round end of the combination gage.



Validated QA/NDE method
(Instrumented Cx Tools - FTI)

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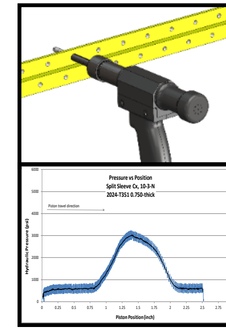
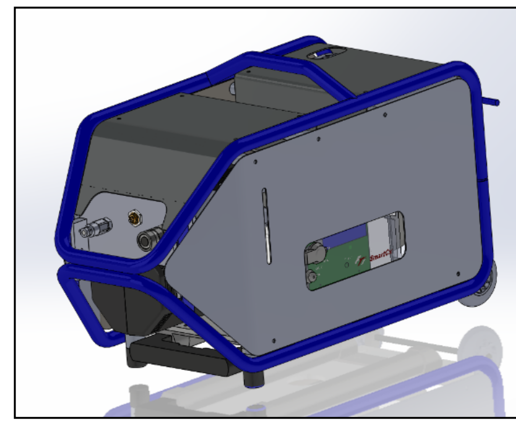
New Hydraulic Puller and PowerPak integrating instrumentation with proprietary data analysis



- 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.



Used by permission from FTI

Validated QA/NDE method
(Instrumented Cx Tools, FTI – Full Credit Road Map)

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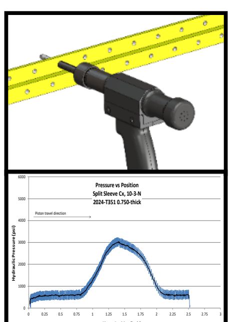
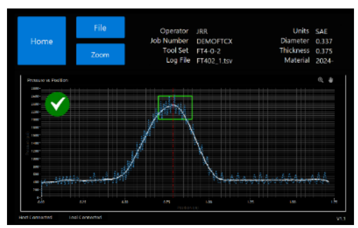
For Full Credit the Residual Stress field correlated to the puller force would be used.

Hole Cold Working

Next Gen Cx Tooling



FTI Smart Tablet



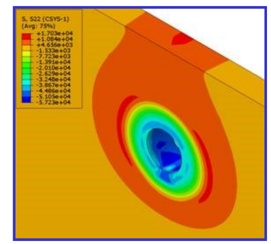
Cx Process Raw Data

- Unique "digital signature" of discrete Cx event
- Provides traceable, archival process data

Analysis & Measurement

Predicted E.R.S.

- Several methods and tools in use and under development

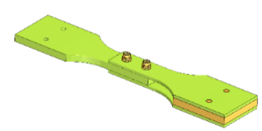


Cx Process Validation

- "Go/No Go" post-process evaluation
- Proprietary algorithms validate process

Fatigue Testing

Application-specific

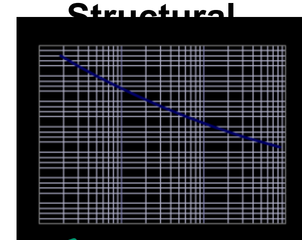


INCREASED CONFIDENCE

FCGA and other industry met hods

MAXIMUM CONFIDENCE

Predicted Structural



S-N Curve

Used by permission from FTI

Validated QA/NDE method
(TRI Austin's FastenerCam™)

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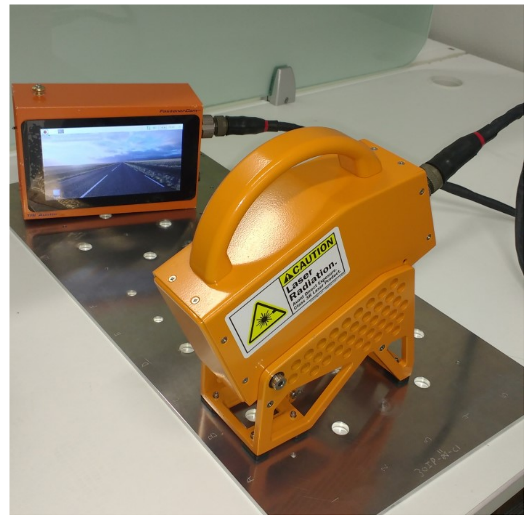
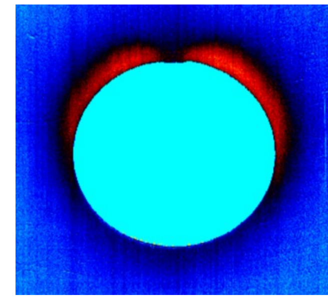
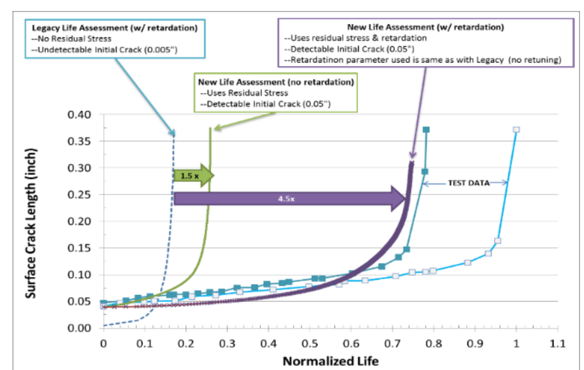
<u>For Full Credit the Residual Stress field correlated to the surface deflections would be used.</u>

1. **FastenerCam™ is designed to support the "third leg" of the ERSI "stool" - Q/A)**
2. **Characterizes the residual stress field by quantifying the surface deformation around a cold-expanded hole**
3. **<u>Features:</u>**
   1. **Easy to use, handheld, and lightweight (9 lbs total)**
   2. **Low power laser profilometer to verify and digitally document newly expanded aircraft fastener holes (assess the volcano)**
   3. **Provides an effective method of establishing Pass/Fail for cold expansion of straight shank holes**
4. **TRI has successfully produced a ruggedized, manufacturing prototype scanner (MRL 7) from Phase II SBIR**
5. **Next activity would be to complete a repeatability and reliability (R&R) study and integrate FastenerCam™ into TOs for an aircraft of interest**





TRI Austin's manufacturing prototype FastenerCam™

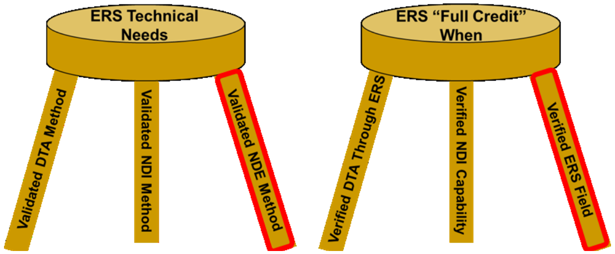


Used by permission from TRI Austin

Validated QA/NDE method
(NDE for QA)

- Background
  - Validated NDE methods are needed to achieve:
    - "Full credit" recurring inspection interval benefit for Cx holes
    - Additional tools for production Quality Assurance (QA)
  - Questions to resolve:
    - Was the ERS applied correctly (QA process step)?
    - What level of ERS is present?
    - Is the expected ERS still present after years of operational usage?
- Objective
  - Develop NDE techniques to quantify cold expanded (Cx) hole residual stress during in-process QA and in-service fleet surveillance applications

<u>Team:</u>
AFRL/RXC,
Hill Engineering,
Southwest Research Institute



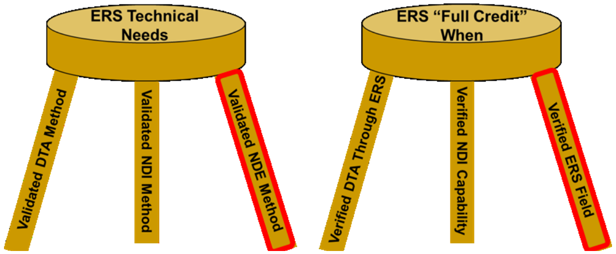
Babish, C., (2017). Aircraft Structural Integrity Program (ASIP) Perspective on Accounting for Engineered Residual Stress in Damage Tolerance Analysis, 2017 ASIP Conference, Jacksonville, FL.

Validated QA/NDE method
(Manual - Entry)

Location of RS is to be Know
(Automated – Data Spatial Positioning (DSP))

- **Background**
  - **Quality assurance methods are needed to achieve:**
    - **“Full Credit” for Engineered Residual Stress (ERS) at cold expanded (Cx) holes**
  - **Questions to resolve:**
    - **Has each critical hole been cold expanded?**
    - **Was the work performed properly?**
    - **Has NDI been accomplished at each critical hole?**
    - **Is the ERS validation traceable?**
- **New Rapid Innovation Fund (RIF) program establishes a digital thread for critical fastener holes that builds and maintains process records for NDI and Cx and makes them available in fleet management processes**

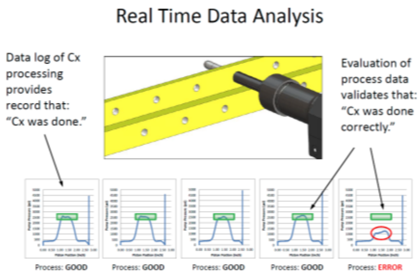
<u>Team:</u>
A-10 ASIP Team
Hill Engineering
Etegent Technologies, Ltd
Fatigue Technologies, Inc



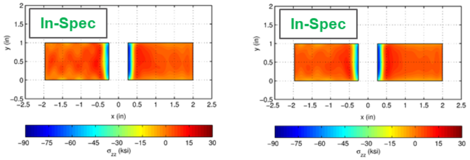
Babish, C., (2017). Aircraft Structural Integrity Program (ASIP) Perspective on Accounting for Engineered Residual Stress in Damage Tolerance Analysis, 2017 ASIP Conference, Jacksonville, FL.

Validated QA/NDE method
(NDE for QA)

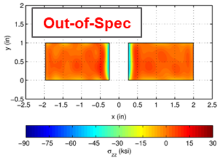
Approach



- Build on the <u>NLign tool for the digital thread</u>
- Adapt commercial <u>Data Spatial Positioning</u> (DSP) technologies
- Integrate DSP into smart tools for critical maintenance actions
  - <u>Cx process</u>
  - <u>NDI process</u>



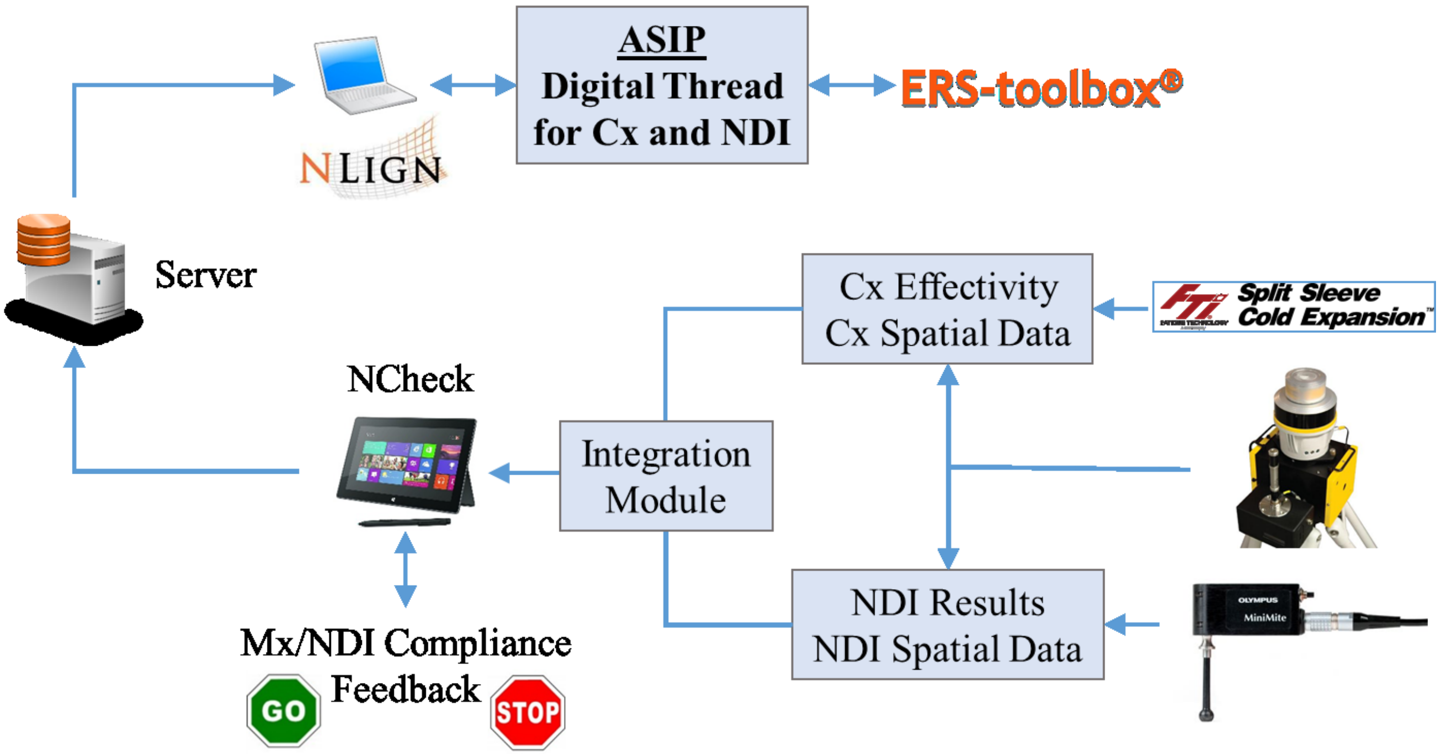
- Enable <u>compliance indicators</u> and <u>storage of process rec</u>
  - Real-time feedback indicator to Mx personnel
  - Storage of smart tool outputs and in-process data (NDI and Cx)
  - Feeds a digital thread for Cx holes and NDI



- Document Cx process effectivity
  - In-process Cx data, post-process Cx data
  - <u>Translate to residual stress</u> for use in fleet management

Validated QA/NDE method
(NDE for QA)

- **Conceptual technology integration**



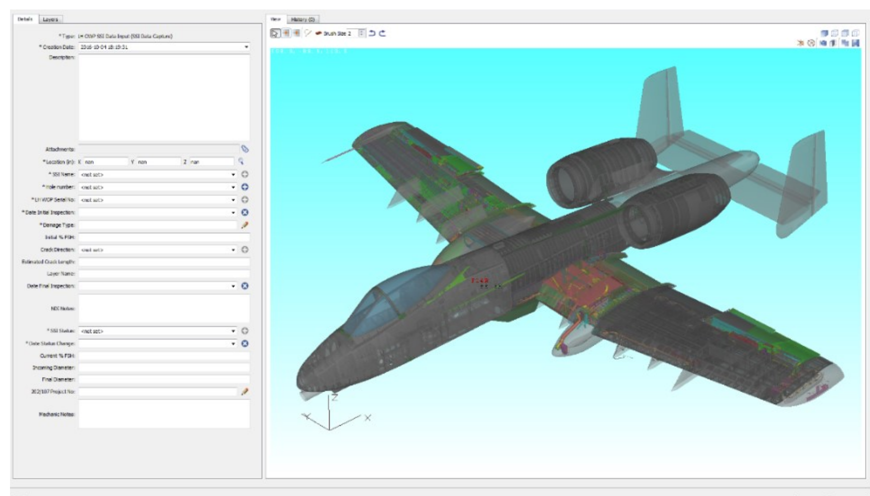
QA / NDE

Documentation of Data

QA/NDE needs to be documented
(Auditable Data)

Auditable Data

1. Requires data storage (NLign, FSS,SMXG, Blue Quartz, Teamcenter, etc)
2. Requires predetermined data format (figures, metadata fields, etc)
3. Required to be quantitative (values that can be searched, tracked, and trended)



Best Practice Guide (High Level Needs)

1. Outlines the method(s) to validate the ERS
2. Describes processes/guidelines necessary for the QA options
3. Describes the required data to be documented
4. Provides insight into the RS that can be used, which is associated with the QA option. Provides probably of missing the correct hole
    a. *For example manual location entry would have a probability of not entering the correct location vs automated location entry.*
5. Provides examples for validating the ERS accomplished by different weapon systems

QA/NDE
(Summary Table)

Document QA Options similar to the DFS values in EN-SB-08-012

QA Option (RS Field, how much?)	Process / Guideline	Data Requirements	RS field Used
Go No Go Gauge	Paragraph x.xx	• Yes/No	Low end of Spec
Instrumented Puller	Paragraph x.xx	• Pull Force	Correlated to pull force
Volcano Characterization	Paragraph x.xx	• Surface Deformation • %Cx	Correlated to Surface Deformations
Eddy Current NDE	Paragraph x.xx	• Measured Profile	

QA Option (Location of RS, where?)	Process / Guideline	Data Requirements	Prob of Missing
Manual Location Entry	Paragraph x.xx	• Hole Number • Spatial Coordinates	
Automatic Location Entry	Paragraph x.xx	• Hole Number • Spatial Coordinates	

QA / NDE

Points of Consideration

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ERSI Full Credit

Points of Consideration

ERSI

As we consider QA options the following points should be considered:

- Some platforms do not have Periodic Depot Maintenance (PDM)
- Some platforms are located in numerous places around the world.
  - Any requirement for new field-level tooling / processes / procedures has to have a slam-dunk return on investment
- For some platforms using partial credit is currently sufficient.
- The time constraints to set up tooling on the shop floor.
- Access to areas in or around the aircraft
- Cost to the depot to purchase tooling
- training for new tooling
- Etc.

In summary, will the result of using “full credit” be sufficient to offset the costs (time and money) to capture the data needed for “full credit”.

Summary of Programs in Work

Validated QA / Documentation Process

Work Accomplished or being Accomplished

Instrumented puller – *FTI*

1. Records puller force and provides a go/no-go for maintainer

Data Collection / Documentation – *NLign, F-16 product, SMXG, Blue Quartz, etc.*

1. Data Collection for maintainer
2. Documentation for engineering

Data Spatial Positioning System (RIF) – *Summer 2019*

1. Provide real time location compliance feedback
2. Connect to instrumented Cx puller
3. Associate puller outputs to measured residual stress
4. Data will go directly from the puller to data collection system

NDE for QA and Surveillance of CX Fastener Holes (AFRL/RXC) – *Summer 2019*

1. Develop NDE methods to measure residual stress at a CX fastener hole

Thank you!

Backup Slides

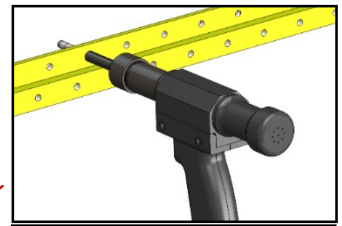
Vision for Digitized Cold Expansion Tools

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

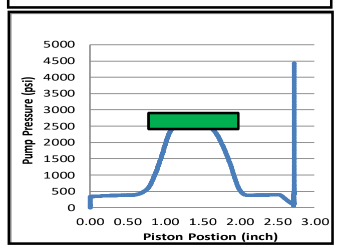
Automated Quality Assurance

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

Data Sharing



FTI Instrumented SsCx Tooling



Networking within Modern Factory

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

Advanced Data Analysis

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

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Maintenance Data Spatial Positioning (DSP) Program

ERSI

- Objectives
  - Develop methodology, technology, hardware, and software for:
    - Smart NDI tool with sensor outputs that document inspection effectiveness
    - Smart Cx tool with sensor outputs that can be used to quantify process effectiveness
    - Integrating DSP with smart tools for Cx and NDI processes
      - Capture positional data
      - Associate data to aircraft coordinates
      - Push data to digital thread
    - Translating Cx tool outputs to process effectiveness (i.e., residual stress)
    - Defining maintenance flow by location and providing feedback for compliance
  - Mesh individual technology elements into a complete system for advanced maintenance practices
  - Validate the performance of the integrated system showing the ability to:
    - Quantify process effectiveness
    - Assign it to the correct spatial location
    - Populate the digital thread
    - Demonstrate use of the Cx digital thread for structural integrity evaluation
  - 2-year effort to demonstrate the performance of the integrated system

Non-Destructive Evaluation for Quality Assurance and Surveillance of Cold Expanded Fastener Holes

U.S. AIR FORCE

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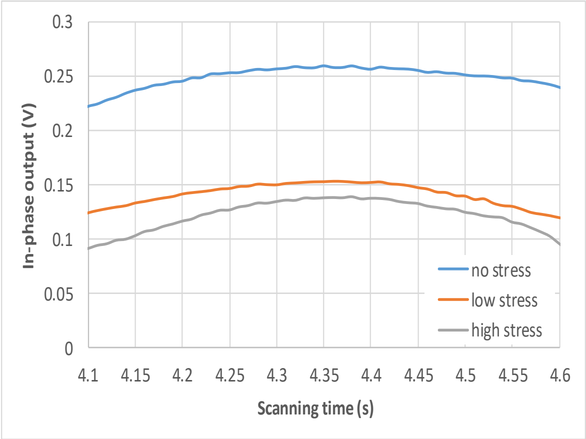
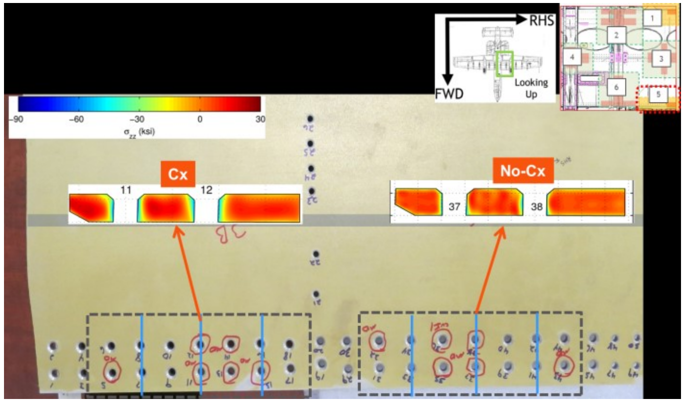
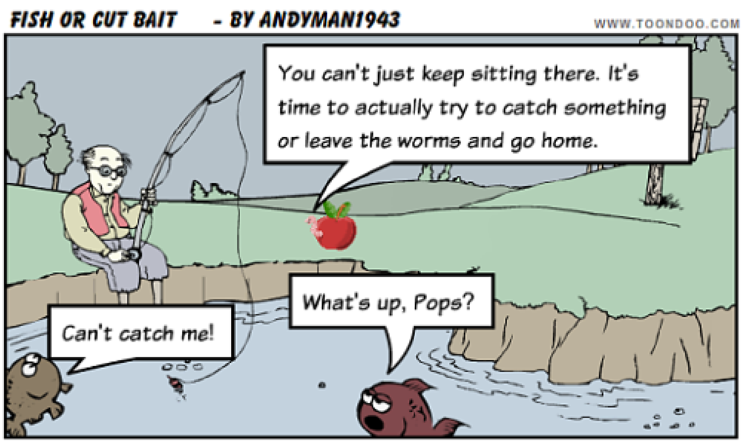
- **Approach**
  - Assess/develop NDE techniques for QA of Cx
    - Leverage existing technology and tailor to the unique characteristics of Cx holes
  - Evaluate NDE techniques across Cx process bounds
  - Develop in-process QA/NDE for in- vs. out-of-spec Cx
  - Investigate confounding factors and NDE response impacts
  - Develop NDE for in-service Cx holes
  - Validate QA and NDE for Cx holes
- **Challenges**
  - Confounding factors complicate the NDE response making the segregation of residual stress difficult





Control Point Analyses

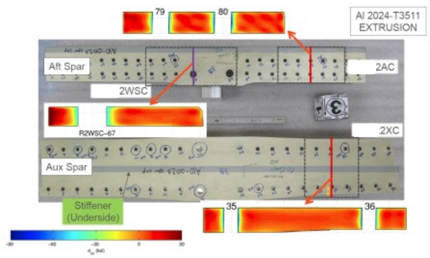
- Objectives
  - Utilizing state-of-the-art methods and inputs, update DTAs for select Control Points (CPs), explicitly incorporating residual stress
  - Compare/contrast with reduced flaw size predictions (partial credit)
  - Identify gaps and refine best practices
  - Define initial ground rules



- Approach
  - Select candidate locations (3)
    - Typical & extreme locations
  - Review baseline input data/methods
  - Complete baseline analyses
  - Complete multi-point analyses w/ RS
  - Compare/contrast predictions
  - Provide conclusions and recommendations

Control Point Analyses

- Inputs and Results
  - Oversized conditions
  - Variations in residual stress
  - Variation in stress spectrum



Location 1 residual stresses

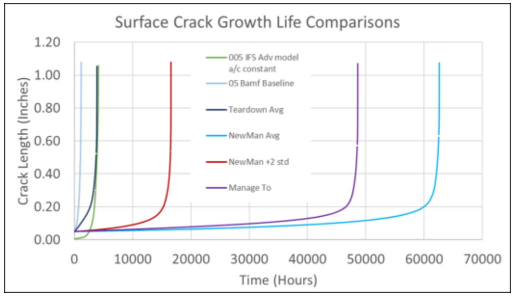
Analysis Details

Location	Description	Material	Thickness (in)	Hole Size (in)	Edge Margin (e/D)	Max Stress (ksi)
1	Lwr Fwd Skin, Repair config	2024-T3511	0.300	0.625	2.256	31.2
2	Lwr Fwd Skin, Redesign config	2024-T3511	0.420	0.562	2.508	24.0
3	Lwr Fwd Skin at Mid Spar, Repair config	2024-T351	0.300	0.328	1.981	42.4

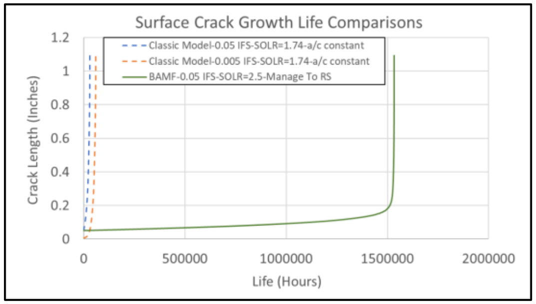
Residual Stresses

Location	New Manufacture Mean	Teardown mean	New Manufacture +2 Std	Teardown +2 Std	Manage To
1	x	x*	x		x
2		x			
3	x	x	x	x	

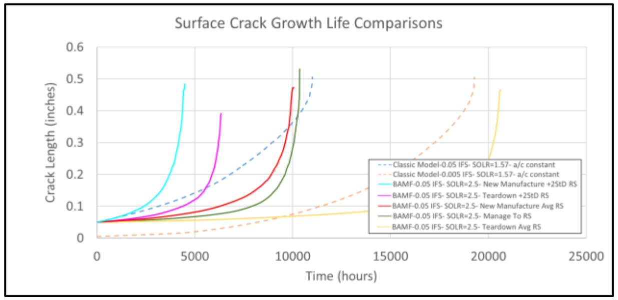
Location 1 Predictions



Location 2 Predictions



Location 3 Predictions

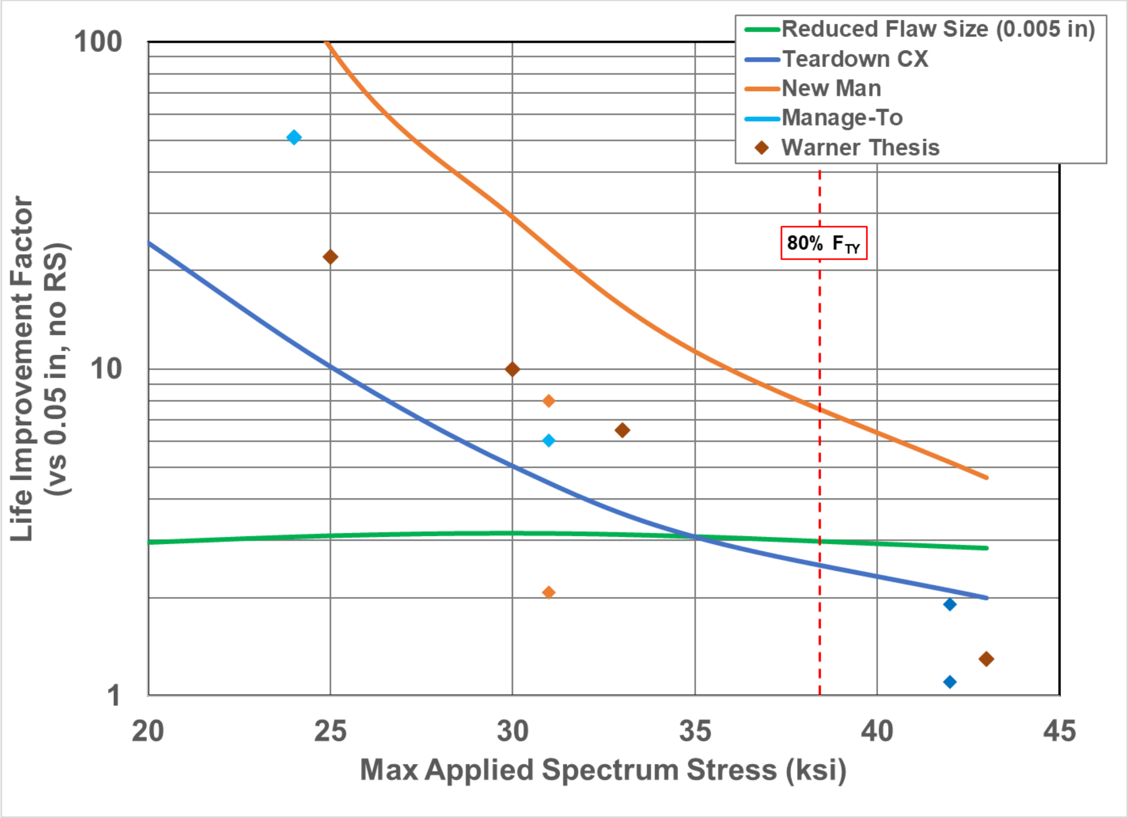


Control Point Analyses

- **Conclusions**
  - Peak spectrum stress has a key influence on the LIF at Cx holes
  - The LIF from traditional DTA methods, that also have high applied stresses and are account for the benefit of Cx, could be unconservative if utilizing 0.005” RIFS
  - Cx benefit is significantly reduced for locations with peak spectrum stresses greater than 85% of the yield strength. Experimental results demonstrate minimal benefit.
  - Appropriate crack retardation values with explicit residual stress range from 2.5-4.0 based on initial evaluations
    - Retardation parameters established from non-Cx holes should not be used for Cx hole analyses
    - Retardation values derived from 0.05” tests may not be appropriate for modeling RS with the RIFS assumption (0.005-inch)
  - The residual stress utilized for analyses is critical for the predictions and must be considered closely, considering the impacts of in-service degradation and statistical variation
  - The “Manage-To” approach results in a reasonable conservative prediction of the residual stress (as intended)

Control Point Analyses

- **Results and Conclusions**



ERSI RISK AND UQ SUBCOMMITTEE ACTIVITIES

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Outline

- Risk and UQ Subcommittee Overview
- Short Presentations of Current Activities
  - **"A spatial statistics approach for utilizing 2D residual stress fields in a fatigue crack growth analysis**," Dallen Andrew, Hill Engineering
  - **FTI Coldworking Simulation Data Analysis**
    - Gavin Jones, Smart UQ
    - Joseph Yurko, University of Pittsburgh

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?

A spatial statistics approach for utilizing 2D residual stress fields in a fatigue crack growth analysis

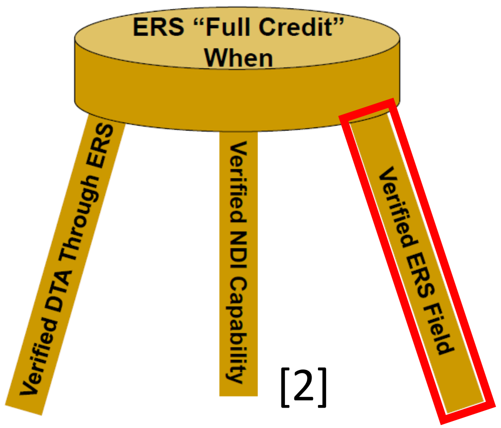
Dallen Andrew

Hill Engineering, LLC

dlandrew@hill-engineering.com

Objective

- Develop an analytical methodology to:
  - Characterize 2D spatial field of residual stresses from the Cx process using spatial statistical methods
    - Focus on determining the appropriate 'binning' method for the residual stresses in a model (i.e. is a 2 ksi to 3 ksi bin sufficient or should it be a 2.5 ksi to 2.6 ksi bin)
    - Focus on determining the appropriate filtering or sub-sampling method for the residual stress data prior to developing the response surface model, as the data density is essentially continuous
  - Utilize the characterized residual stress field in FCG analyses to meet airworthiness requirements
    - Perform deterministic FCG analysis that utilizes the statistically characterized residual stress field, analyzing both the mean response surface and the 5% lower bound "manage to" response surface (such as $RS_{90/95}$) [3]
      - Focus on method to ensure each response surface used still meets physical static equilibrium requirements
    - Perform probabilistic FCG analysis and risk assessment using the statistically characterized response surface
- Fatigue crack growth testing and residual stress measurements of Cx holes have been performed to verify and validate the analysis methodology



[2]

Preliminary Work

- Data is representative of RS field at Cx hole
  - Objective is to calculate the Kriging response at x=0.4
- Given the training points, the next step is to compute the experimental semivariogram γ(h)

$$\hat{\gamma}(h) = \frac{1}{2|N(\boldsymbol{h})|}\sum_{N(h)}\left[Z(s_i) - Z(s_j)\right]^2$$

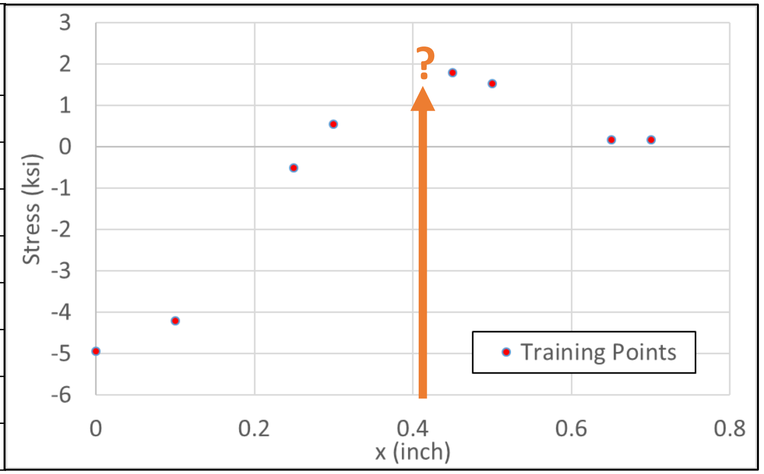
- When experimental semivariogram is estimated a semivariogram model is selected

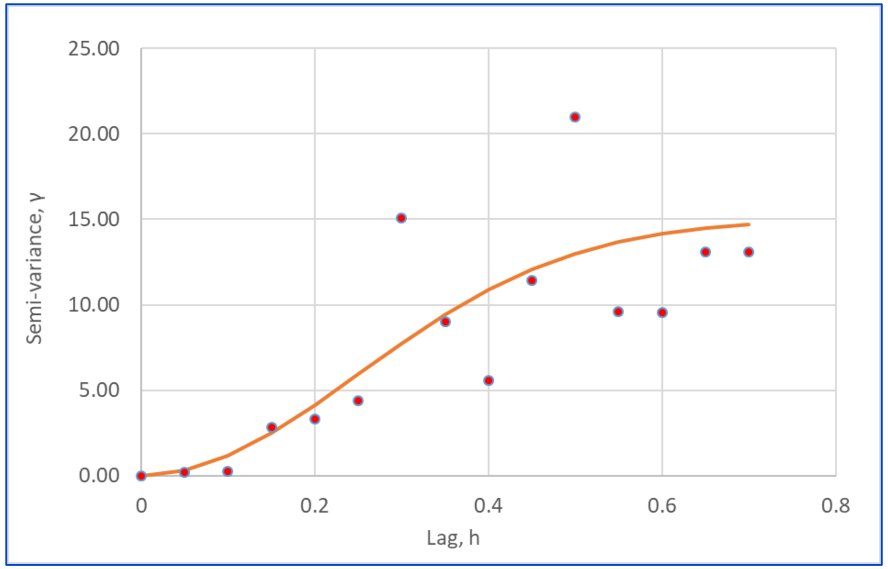
$$\gamma(h) = c \cdot \left(1 - exp\left(-\frac{h^2}{\theta^2}\right)\right)$$

- Having the semivariogram matrix and vector, the Kriging weights (λ) can be computed

$$\gamma\lambda_0 = \gamma_0$$

Training Point	x (inch)	Stress (ksi)
1	0	-4.95
2	0.1	-4.21
3	0.25	-0.52
4	0.3	0.54
5	0.45	1.78
6	0.5	1.53
7	0.65	0.17
8	0.7	0.16





Preliminary Work

- Response at $x = 0.4$ is:

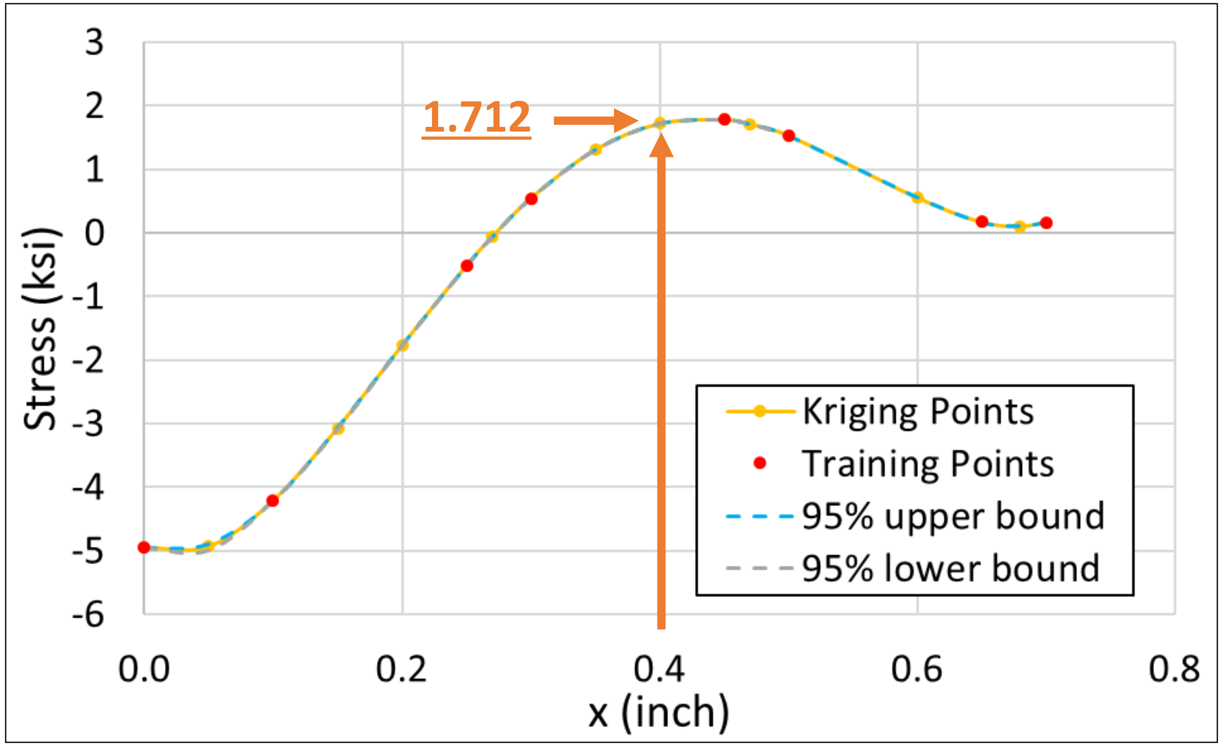
$$\hat{Z}(0.4) = \lambda^t Z = 1.712$$

- Error in terms of the variance computed at x=0.4:

$$\sigma_e^2(x = 0.4) = \boldsymbol{\lambda}_0^t \cdot \boldsymbol{\gamma}_0 = 7.7\text{E-}7$$

- The 95% confidence bound at x=0.4 from the prediction can be computed:

$$(Z(x_0)-1.96\sigma_e(x_0),\ Z(x_0)+1.96\sigma_e(x_0)) = (1.710,\ 1.714)$$

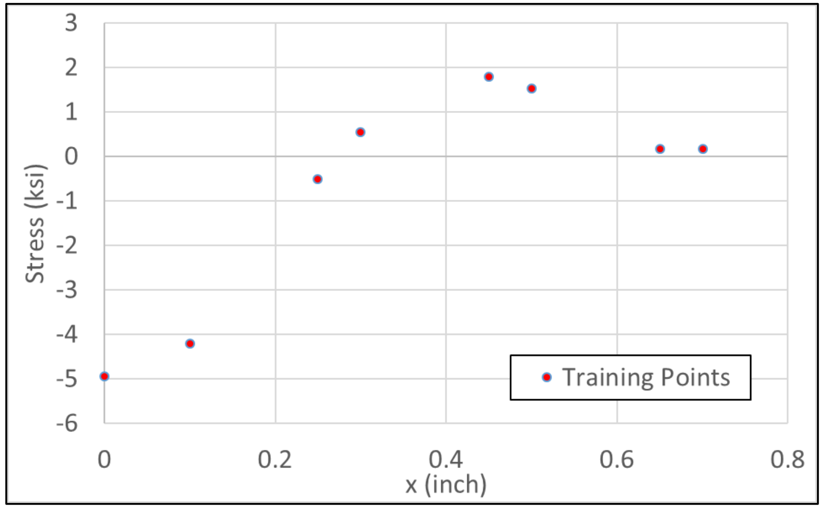


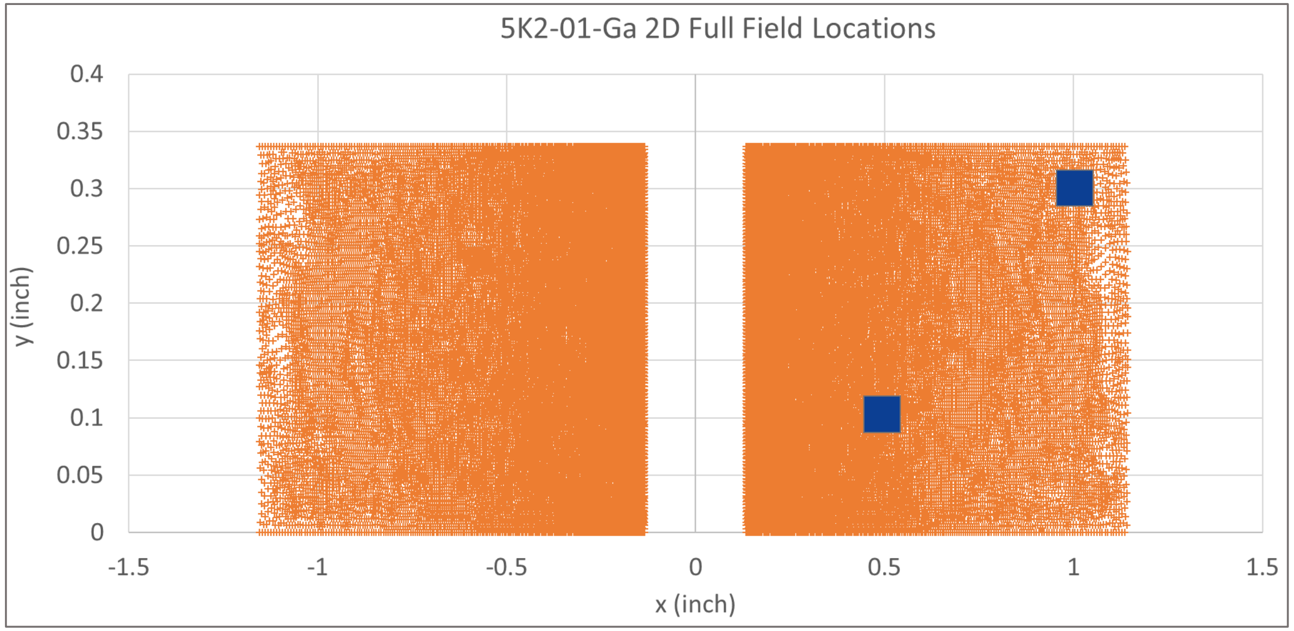
Methodology

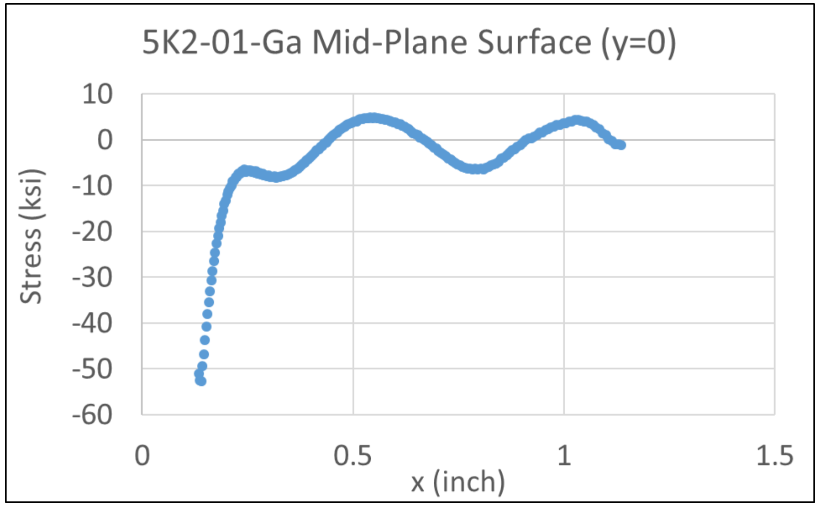
- The same process used for the simple 1D example will be implemented and expanded to apply to full 2D spatial residual stress field through the following steps:
  - Determine which fitting method is most appropriate for the 2D residual stress spatial data (i.e. polynomial, response surface model, etc.) then expand previous work for 1D line (single coupon) to 2D field (single coupon)
  - Develop method to incorporate multiple sample reps for 1D line (multi-coupon) then expand to 2D field (multi-coupon) using probabilistic methods
  - Determine and implement method for quantifying uncertainty and goodness of fit for 1D line then expand to 2D field and assess validity of static equilibrium of predicted response surface
  - Perform FCG analysis with predicted response surface

Methodology: RS Characterization

- Compute experimental semivariogram beginning with a 1D line then expand methodology for 2D surface, focusing on:
- - Binning Methods
- - Sub-sampling Methods
  - Output resolution of (x,y) coordinates is relatively high (# points >34,000)







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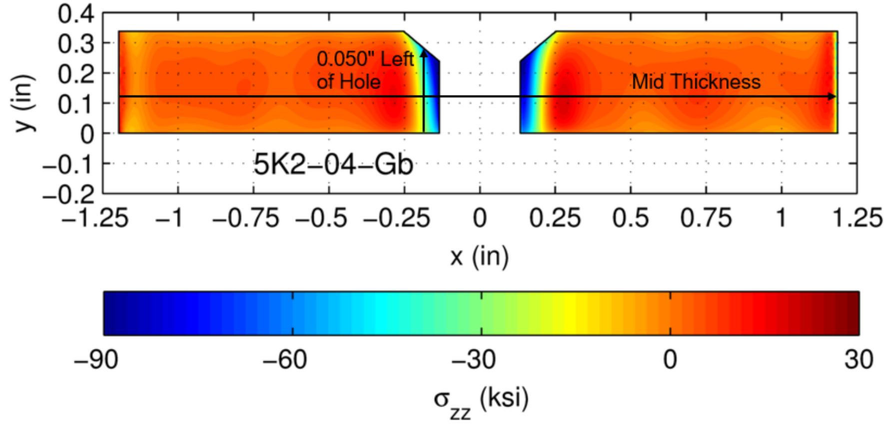
Methodology: RS Characterization

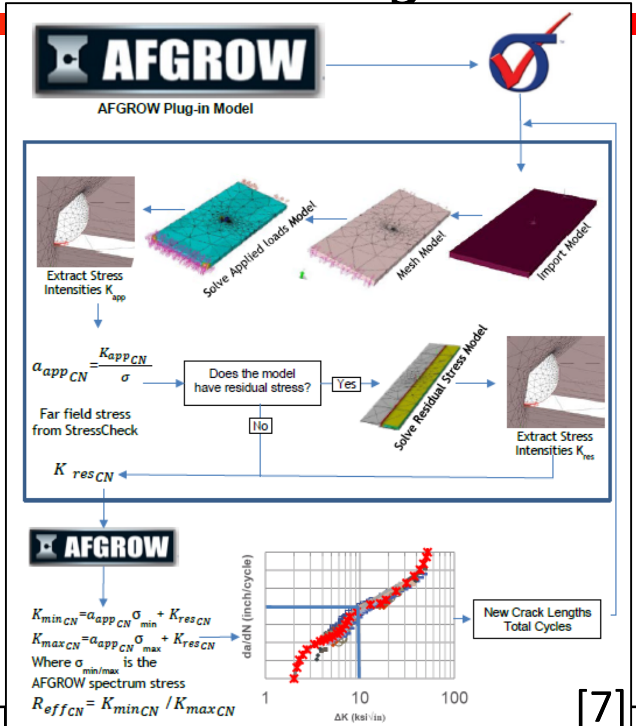
- - Probabilistic Analysis
  - Use replicate samples to develop a distribution of response surfaces and Cumulative Distribution Function (CDF)
  - Available Cx hole test data from contour method has up to 5 replicate samples for a given Cx condition
  - RS process simulation data replicates from varying Cx parameters is also available
- - Uncertainty Quantification
  - Uncertainty introduced by a response surface model
    - Can calculate variance with Kriging
  - Uncertainty of the RS from the contour method
    - Can use published UQ methods for
      - Repeatability uncertainty associated with Cx process variation [5]
      - Single measurement uncertainty from contour method [6]
  - Assess validity of static equilibrium of any predicted response surface

Coupon Type	Material	Loading	Hole Type	Thickness	CX method	Reps
Residual Stress	7075-T7351	N/A	Straight	0.34	CX Hole	3
			CSK		CX Hole	5
					CsCx	3
					CX Bore	3
			Straight	0.2	CX Hole	3
			CSK		CX Hole	3
					CsCx	3
					CX Bore	3
					TOTAL:	26



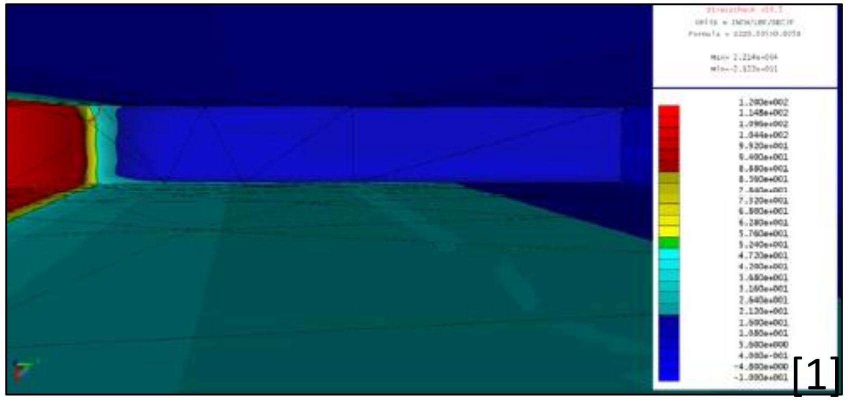
Methodology: Fatigue Crack Growth Analysis

- Perform deterministic FCG analysis with response surface
  - Mean surface & "manage to" surface [3], such as $RS_{90/95}$
  - Validate analytical method by comparing model predictions to countersunk Cx hole fatigue test data
- Perform probabilistic FCG analysis and risk assessment with predicted response surface
  - Using SMART [8] and/or PROF
  - Ocampo, AA&S 2017: "There is a need for a methodology…to model probabilistic residual stress [and] incorporate them into Probabilistic Damage Tolerance Analysis" [9]



[7]

Coupon Type	Material	Loading	Hole Type	Thickness	CX method	Reps
Fatigue	7075-T7351	CA	CSK	0.34	NonCX	3
					CX Hole	5
					CsCx	3
					CX Bore	3
				0.2	NonCX	3
					CX Hole	3
					CsCx	3
					CX Bore	3
		CA + MB		0.34	NonCX	1
					CX Hole	1
					CsCx	1
					CX Bore	1
					Total:	30


[1]

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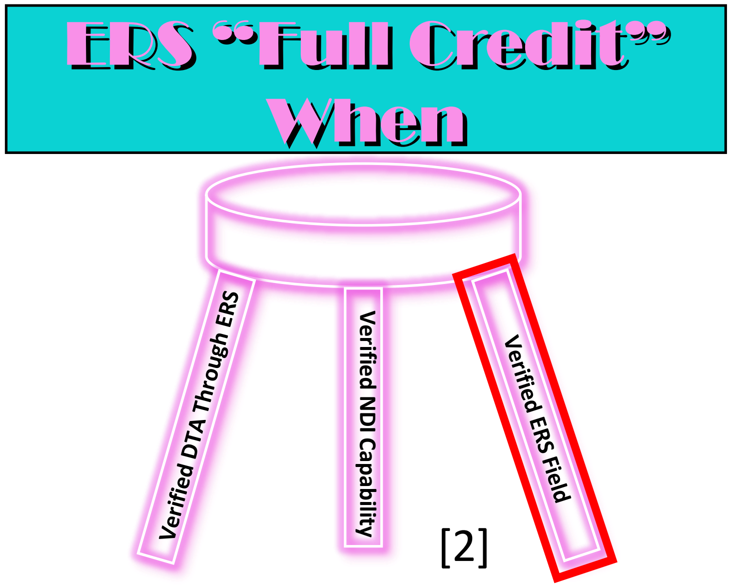
Summary

- The main contribution of this research is to produce an allowables-based methodology for utilizing residual stress in FCG analyses
  - Enhances the current analysis method to match other aircraft structural methods that rely on the use of allowable values to ensure structural safety and certification requirements for “full credit” of the fatigue life benefit from the Cx process



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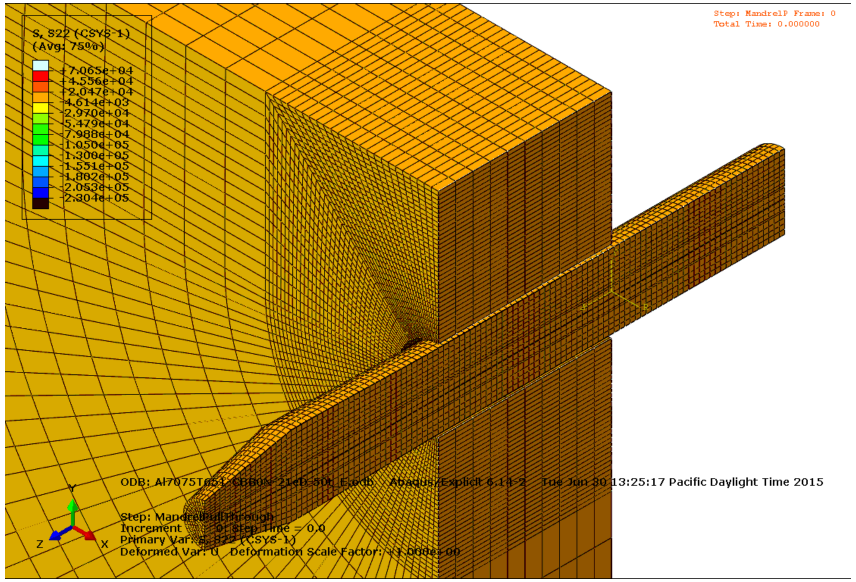
References

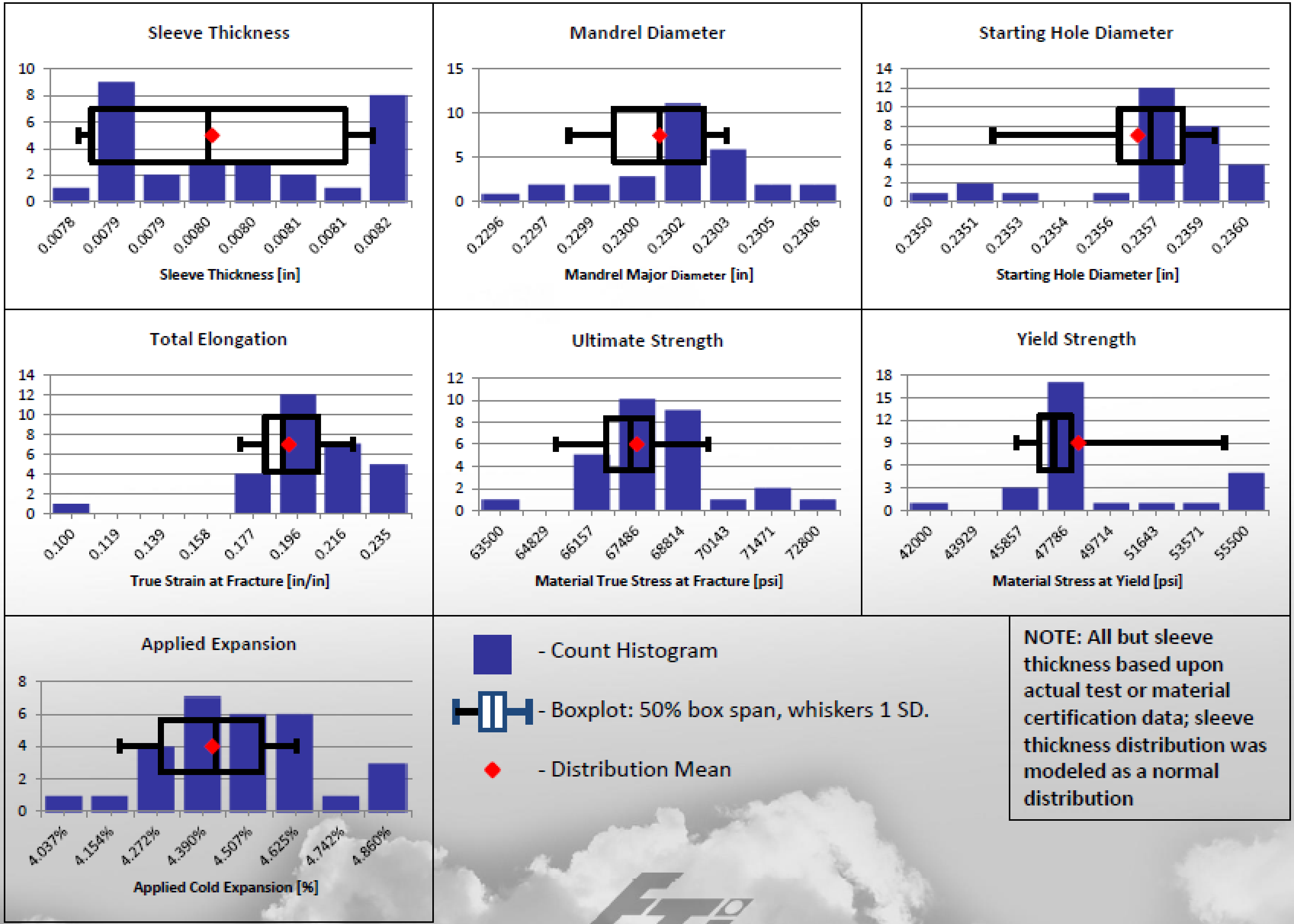
1. Carlson, S.S., “Quantifying the effect of a fatigue crack on the residual stress field induced by the split sleeve cold expansion process in 2024-T351 and 7075-T651 aluminum alloys,” Doctoral Dissertation, University of Utah, May 2018.
2. Babish, C., “ASIP Perspective on Accounting for Engineered Residual Stress in Damage Tolerance Analysis,” Proceedings of the Aircraft Structural Integrity Program Conference, Jacksonville, FL, November 2017.
3. Thomsen, M.L., “Incorporation of Residual Stresses into Aircraft Design and Sustainment: An ASIP Manager Perspective,” Proceedings of the Aircraft Structural Integrity Program Conference, Jacksonville, FL, November 2017.
4. Riha, D., McFarland, J., Thacker, B., Bichon, B., and Enright, M., “Short Course on Probabilistic Analysis and Uncertainty Quantification for Engineering Design – Methods and NESSUS® Training,” Southwest Research Institute, San Antonio, TX, September 2014.
5. Hill, M.R. and Olson, M.D., “Repeatability of the contour method for residual stress measurement,” Experimental Mechanics, Vol. 54, pgs. 1269-1277, 2014.
6. Olson, M.D., DeWald, A.T., Prime, M.B., Hill, M.R., “Estimation of Uncertainty for Contour Method Residual Stress Measurements,” Experimental Mechanics, 55, pgs. 577-585, 2014.
7. Hill Engineering, LLC., “Broad Application for Modeling Failure (BAMF) User’s Guide,” Release 5.0, Rancho Cordova, CA, January 2018.
8. Reyer, M., Millwater, H., Ocampo, J., Crosby, N., Gamble, B., Hurst, C., and Nuss, M., “Training using the SMART|DT software,” Proceedings of the Aircraft Airworthiness & Sustainment Conference, Grapevine, TX, March 2016.
9. Ocampo, J., Carlson, S., Smith, L., Millwater, H., and Crosby, N., “Incorporating residual stresses into Probabilistic Damage Tolerance Analysis,” Proceedings of the Aircraft Airworthiness & Sustainment Conference, Phoenix, AZ, May 2017.

Preliminary FTI UQ Study

- FTI provided the committee access to stress results from their cold expansion process models
  - Hitchman and Zimmerman, "Development and Use of an FEA Script for Variance and Correlation Studies of Analytical Predictions of Cold Expansion Residual Stress Fields," HOLSIP 2016.
- A total of 29 models with varying input parameters were provided (inputs on next slide)
- Stresses extracted from short ligament crack plane, after coldworking and reaming
- **Purpose of showing these preliminary results is to demonstrate available techniques, NOT necessarily to draw conclusions on RS process modeling**



Step 3: Input distributions

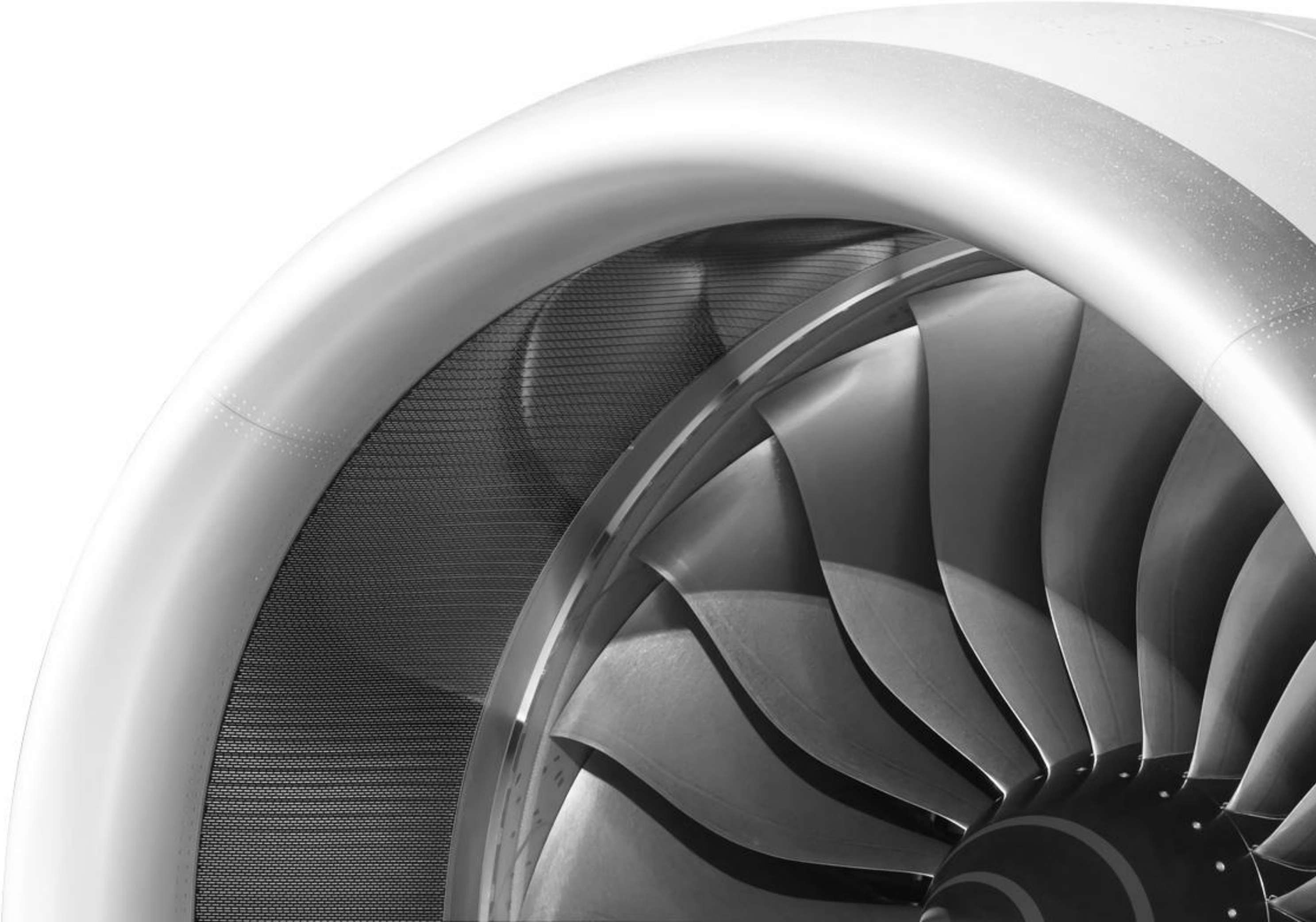


NOTE: All but sleeve thickness based upon actual test or material certification data; sleeve thickness distribution was modeled as a normal distribution

FATIGUE TECHNOLOGY

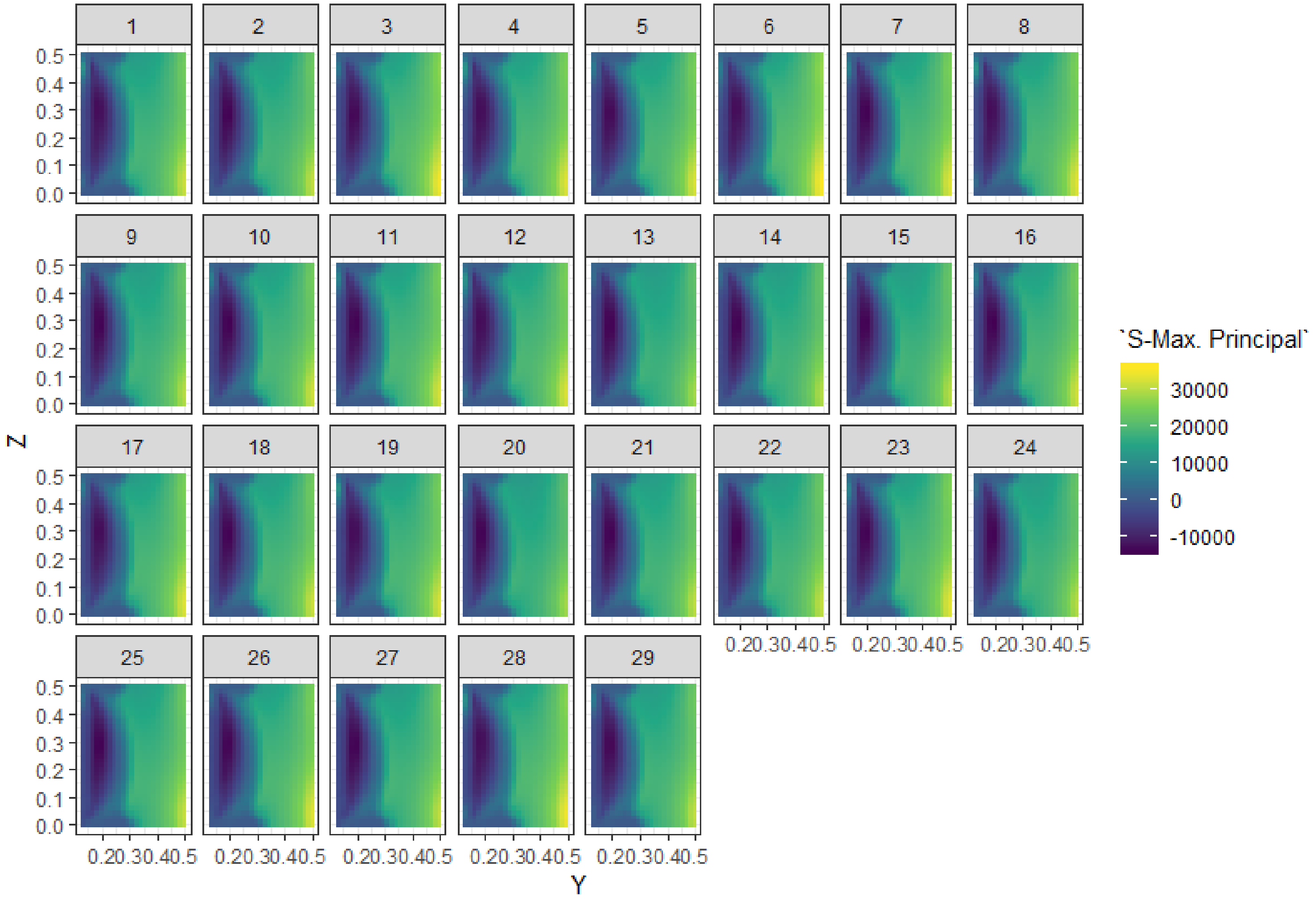
Ream Simulation EDA

Joe Yurko Arconic ATC

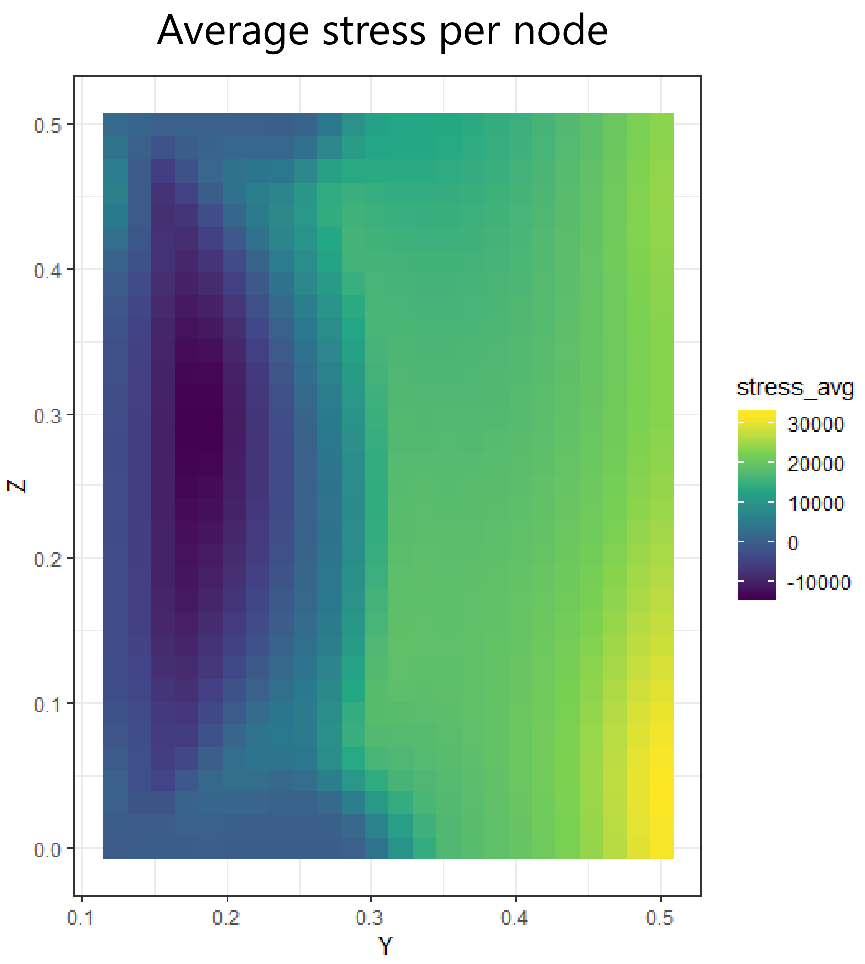


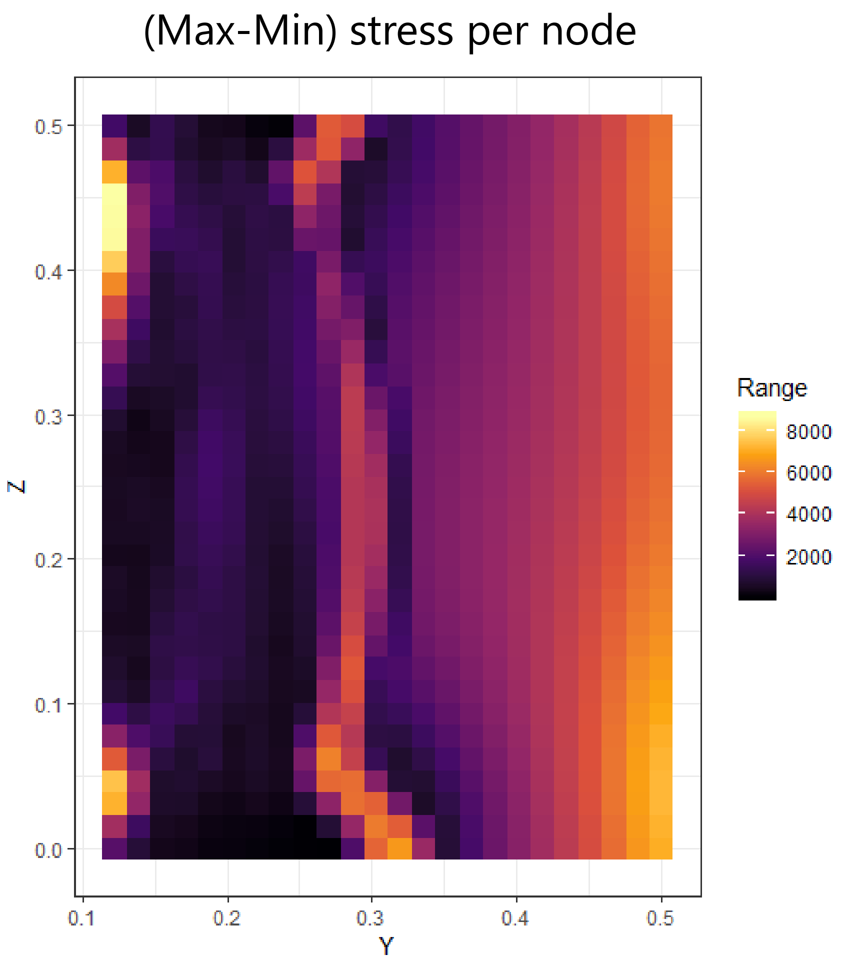
ARCONIC
Innovation, engineered.

Ream simulation results across all 29 runs

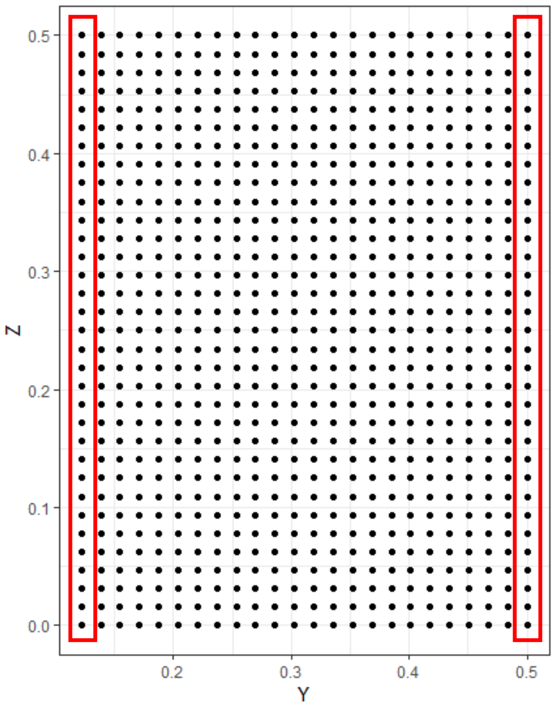


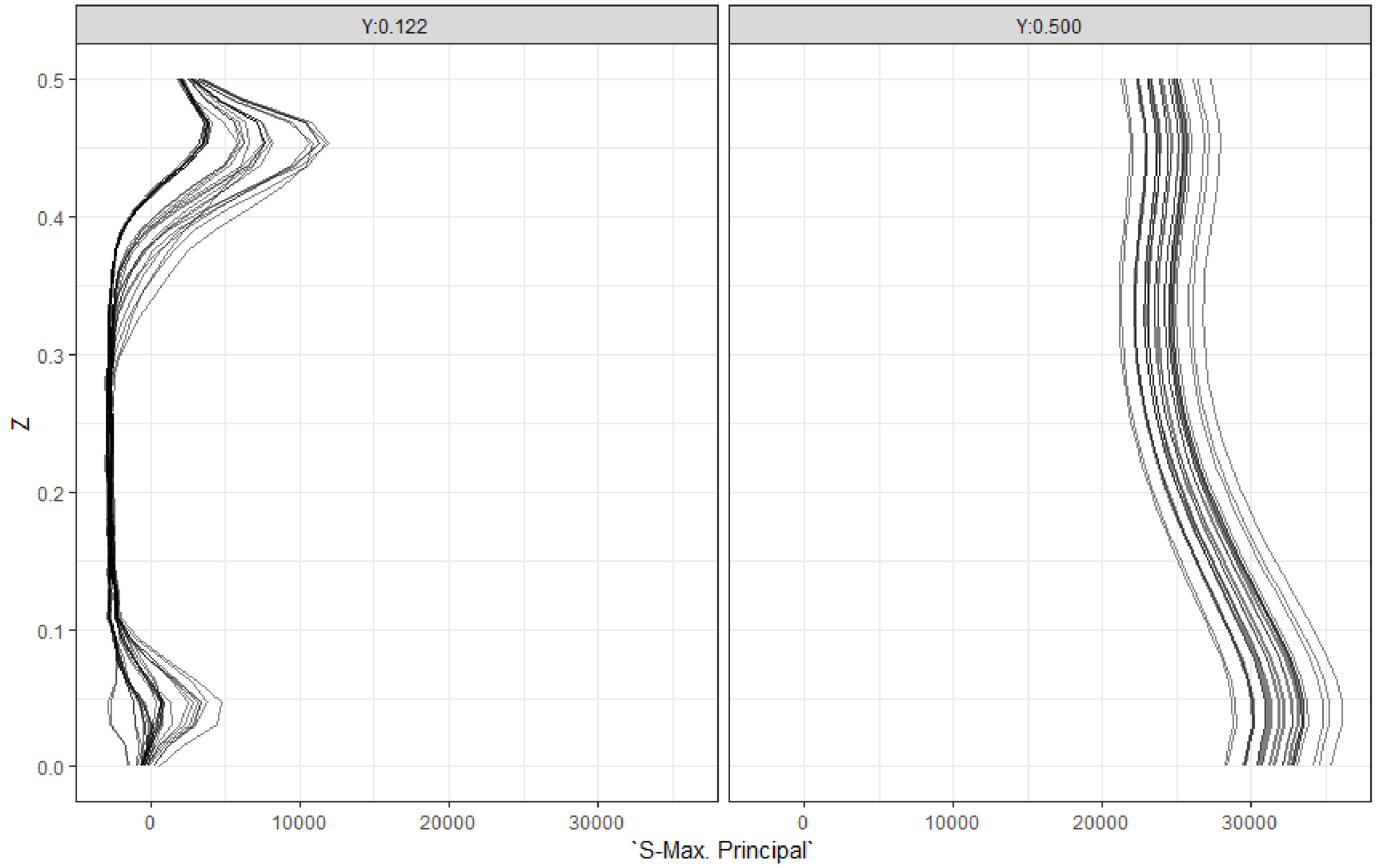
Summarize each stress at each node across the 29 runs



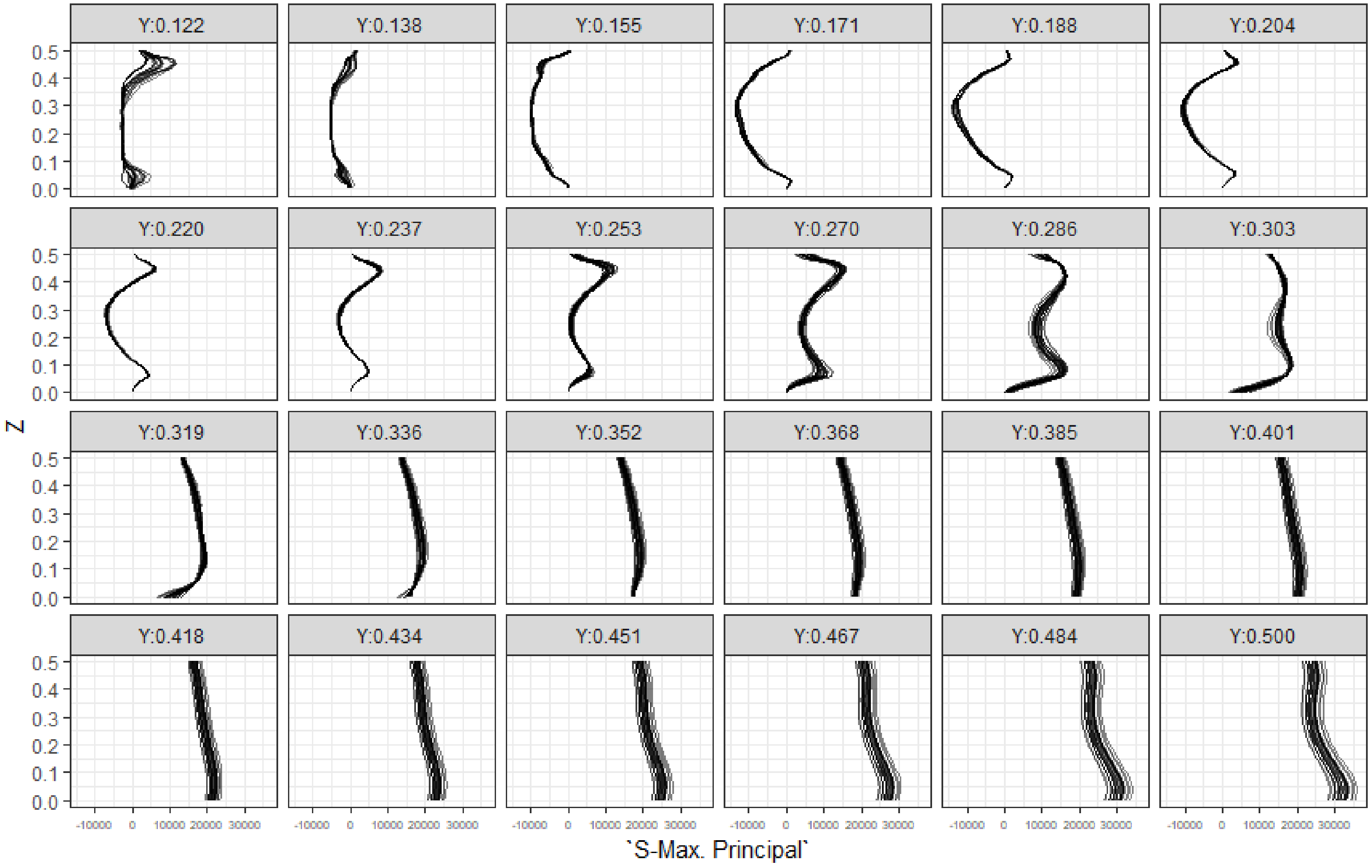


Line style plots for the `S-Max. Principal` wrt the z-direction at two y-locations, across all 29 runs

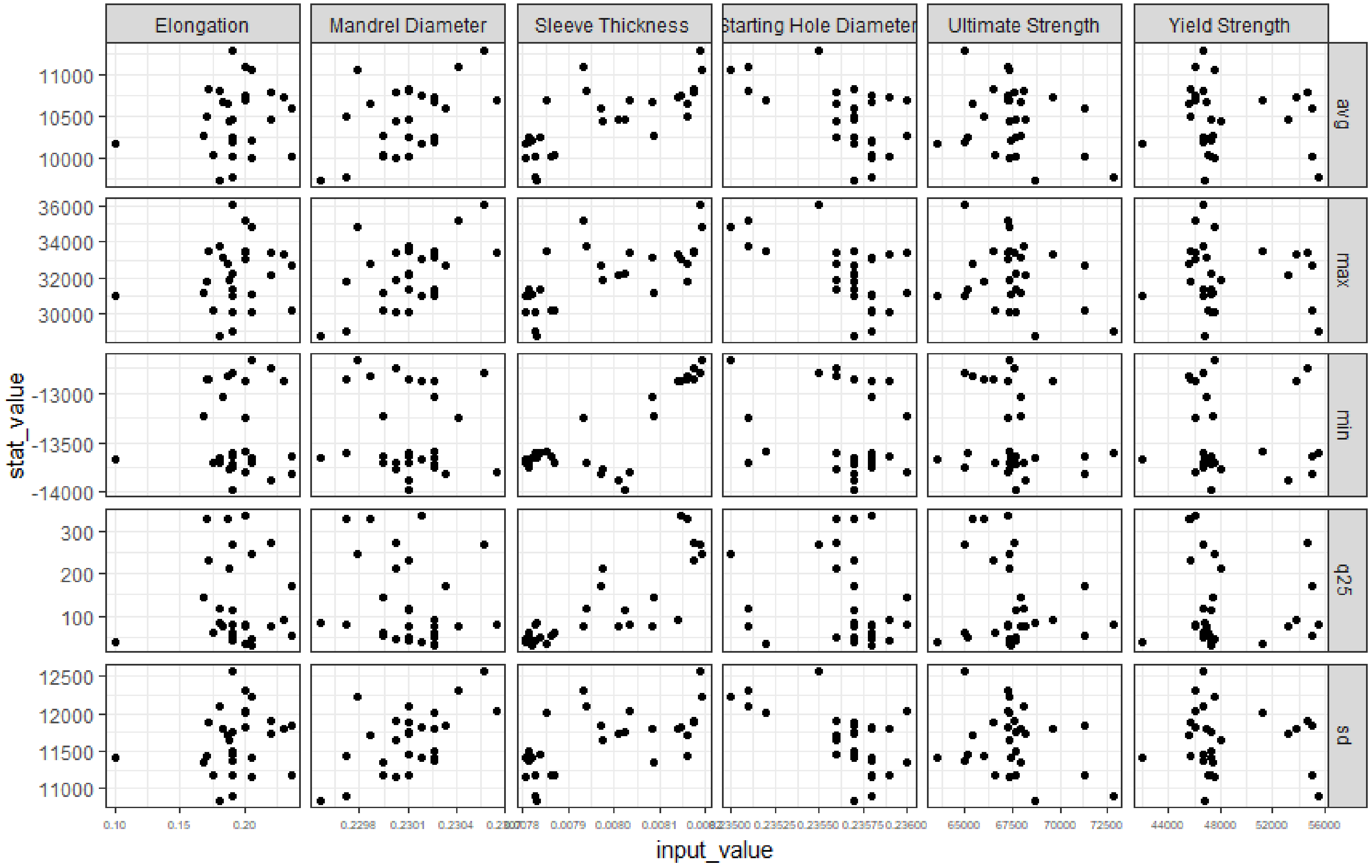




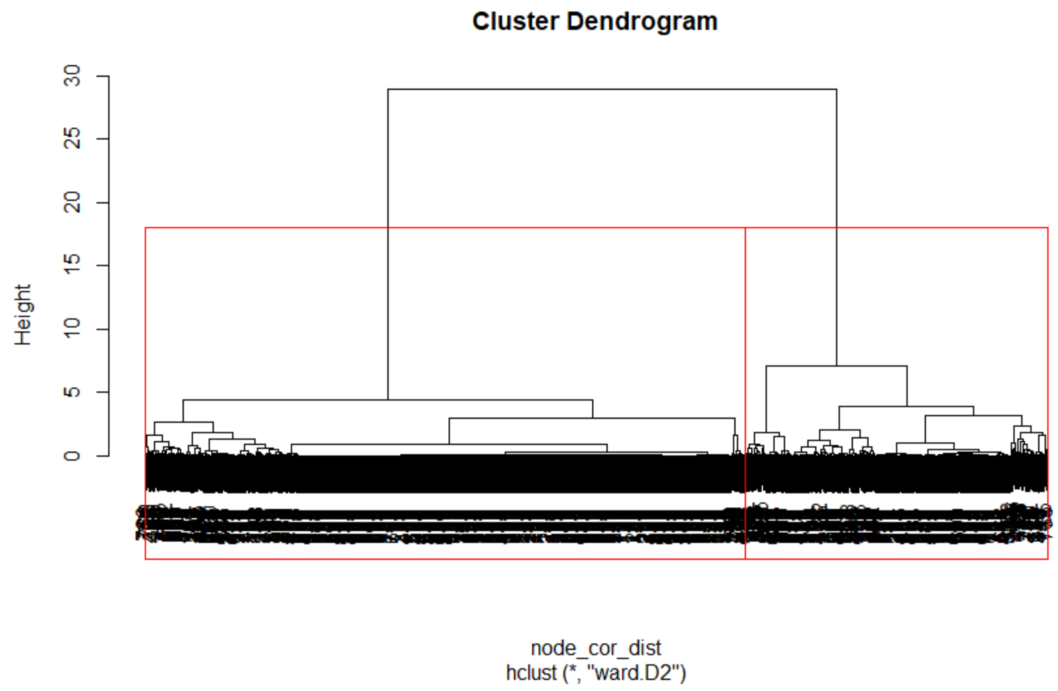
Line style plots at all y-locations across all runs

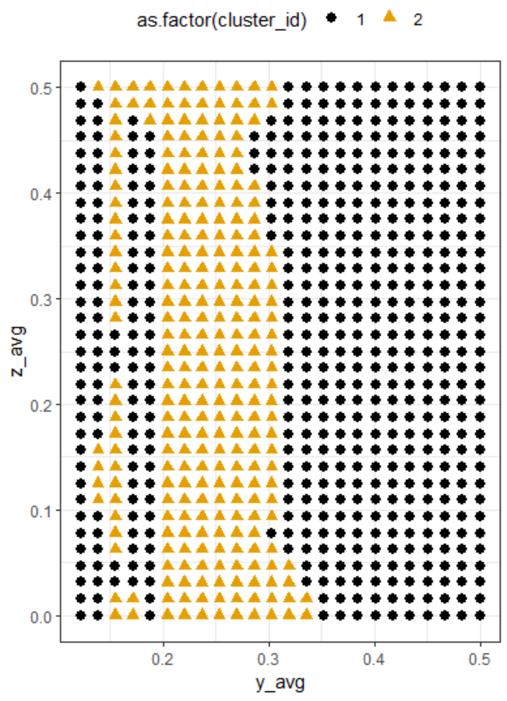


Scatter plots between the run summary stats and the inputs



Cluster nodes together based on their correlation





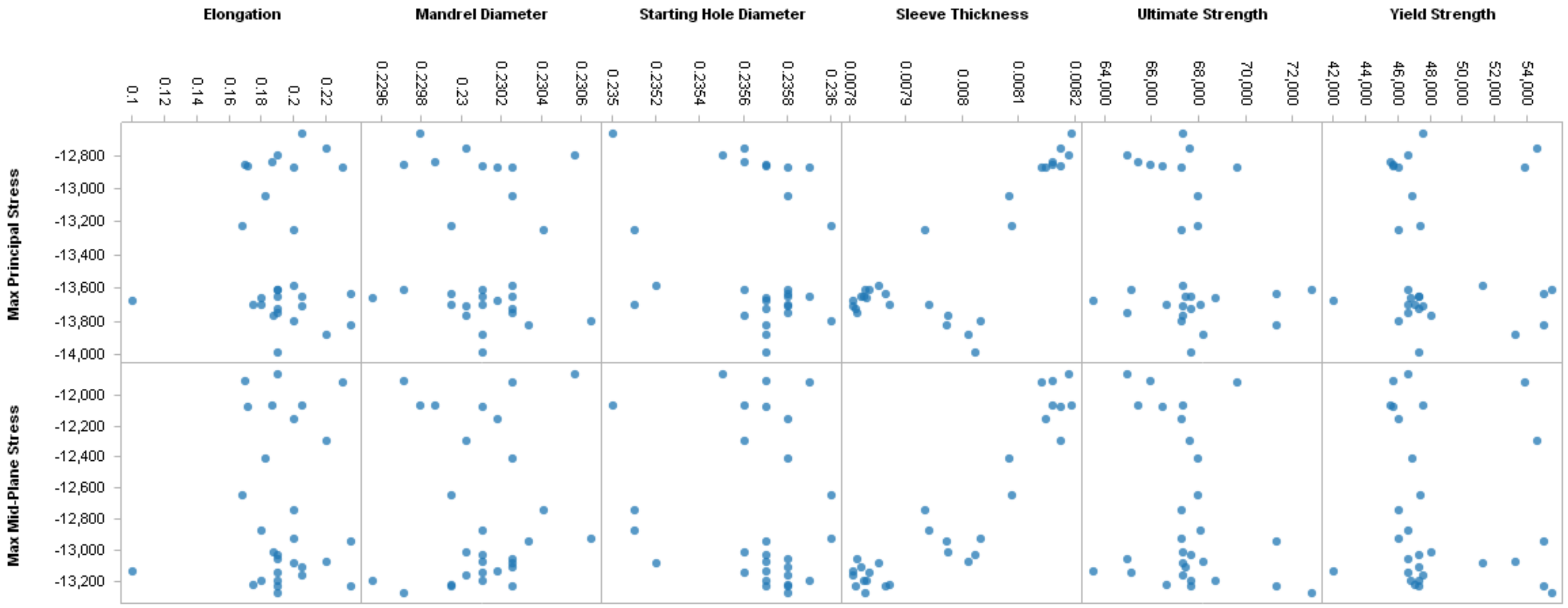
FTI Preliminary Data Analysis

ERSI Risk and UQ Subcommittee Teleconference
July 25, 2019

Gavin Jones
Sr. Application Engineer
SmartUQ, Madison, WI
Gavin.Jones@smartuq.com

Data Preprocessing

- Python script to extract
  - Most negative stress value from each of the 29 Ream files, i.e. largest max compressive stress
  - Most negative stress value at thickness = 0.25 coordinate for max mid-plane stress
- Data looks very uncorrelated except for sleeve thickness



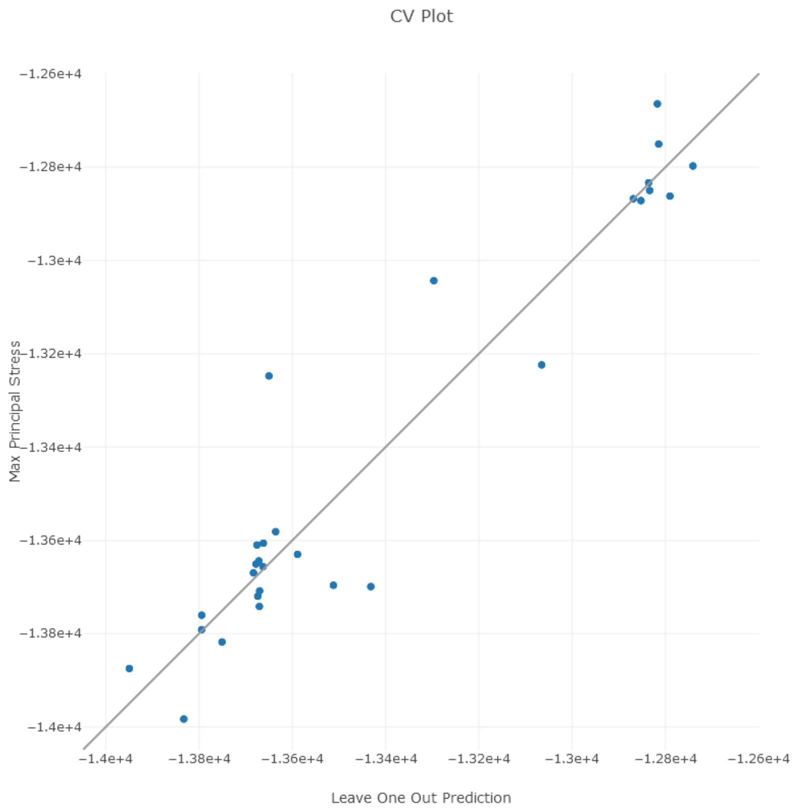
SMARTUQ®

Initial Model Fitting

- Built Gaussian Process (GP) Surrogate Model for Maximum Principal Stress and Maximum Midplane Stress using all 29 data points (Ream Data)
- Built linear regression model for comparison

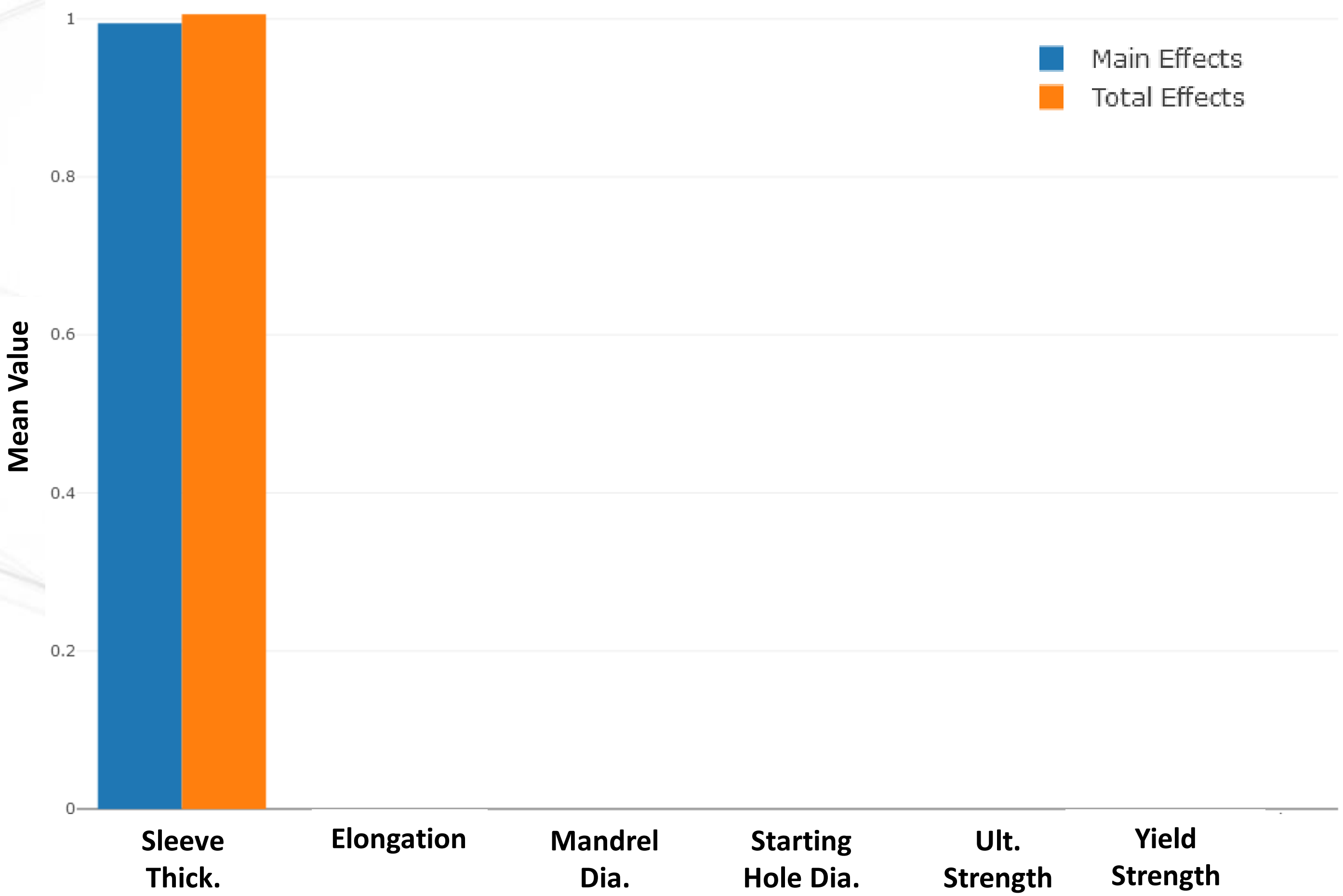
	Std CV (GP Model)	R^2 Equivalent	Linear Model R^2
Max Principal Stress	0.2968	0.9119	0.6887
Max Mid Plane Stress	0.2712	0.9265	0.8638

Maximum Principal Stress



Sensitivity Analysis

- Used GP Emulator for Global Sensitivity Analysis
- Sensitivity analysis shows response is completely dependent on sleeve thickness

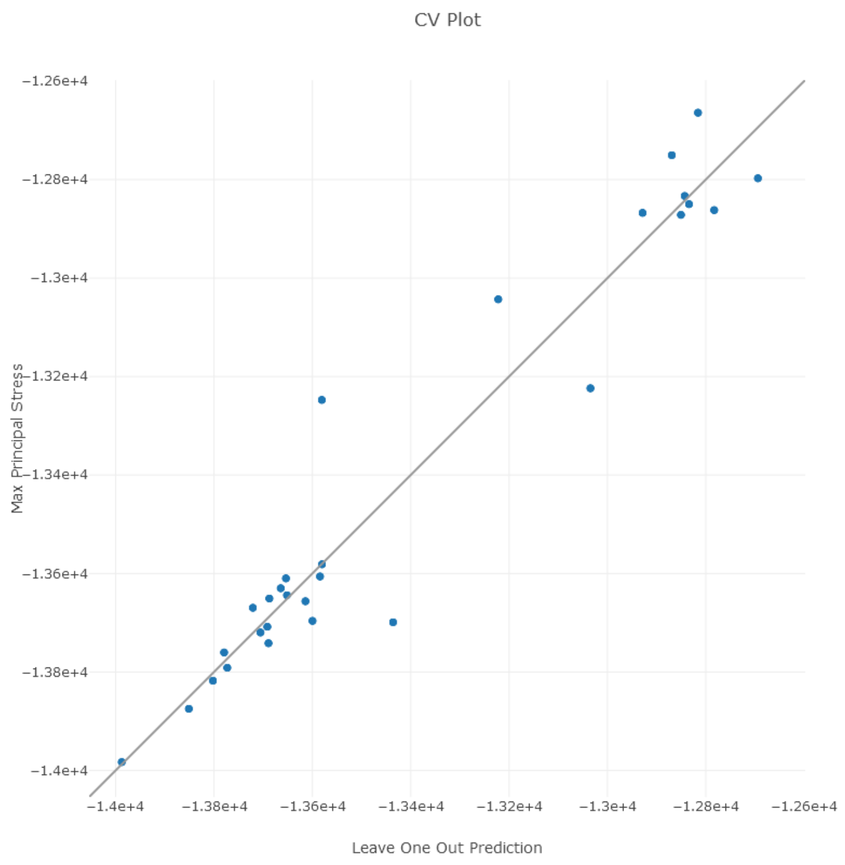


Reduced Input Set Model Fitting

- Rebuilt GP Surrogate Model only using the sleeve thickness input.
- Tried other input combinations, based on assumed correlations, e.g. yield and ultimate strength being correlated, but could not achieve better results.

	Std CV (GP Model)	R^2 Equivalent	Linear Model R^2
Max Principal Stress (All Inputs)	0.2968	0.9119	0.6887
Max Mid Plane Stress (All Inputs)	0.2712	0.9265	0.8638
Max Principal Stress (Sleeve Thickness Only)	0.2543	0.9353	0.6420
Max Mid Plane Stress (Sleeve Thickness Only)	0.2704	0.9269	0.8425

Maximum Principal Stress



Model Validation

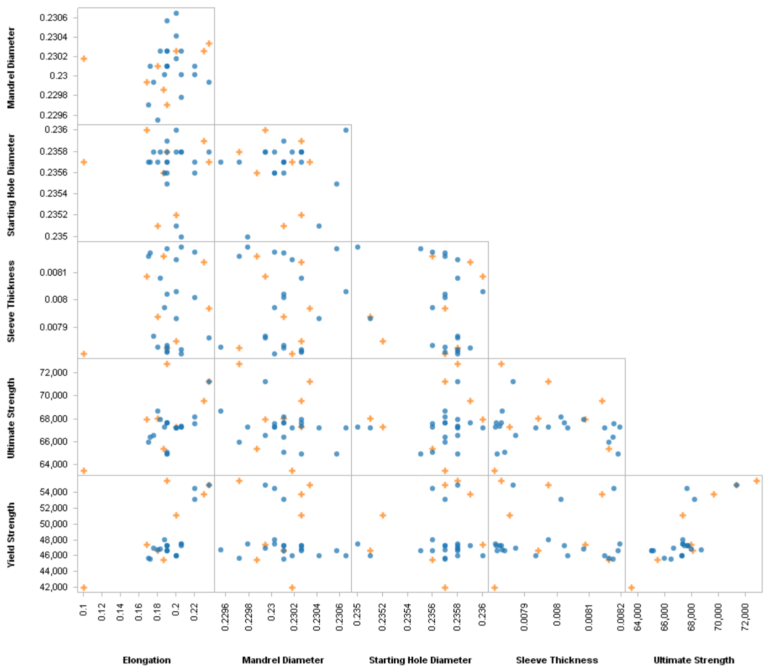
- Subsampled 8 points from original 29 to use as validation set via 2 separate methods
- Built GP emulators with remaining 21 points
- Results seem promising in suggesting an accurate GP model could be trained given more (and better space-filling) data. Making further conclusions or comparisons between Std CV and Std RMSE results is risky as the datasets are small and standard deviations will vary.

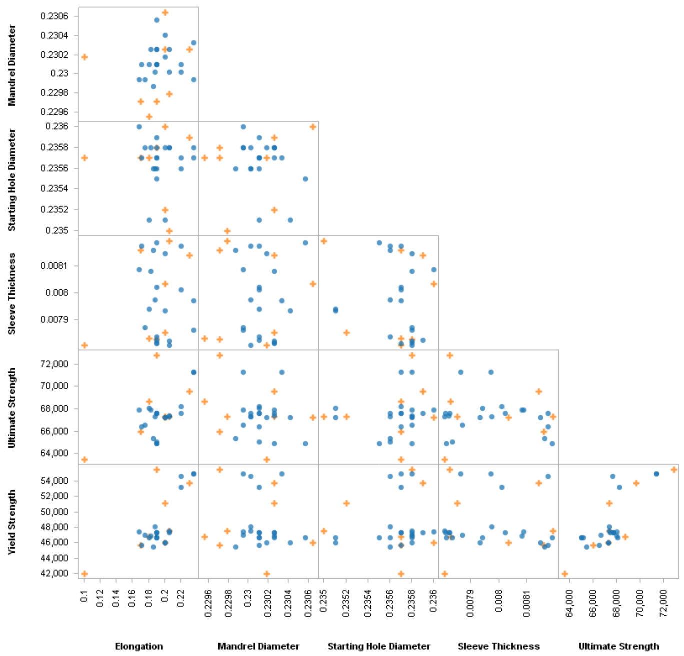
Subsample Method 1

	Std CV	Std CV Equivalent R^2	Std RMSE (Validation Set)	Std RMSE Equivalent R^2 (Validation Set)
Max Principal Stress (All Inputs)	0.4810	0.7687	0.4376	0.8085
Max Mid Plane Stress (All Inputs)	0.3193	0.8981	0.5562	0.6910
Max Principal Stress (Sleeve Thickness Only)	0.2402	0.9423	0.4324	0.8130
Max Mid Plane Stress (Sleeve Thickness Only)	0.2793	0.9220	0.2580	0.9334

Subsample Method 2

	Std CV	Std CV Equivalent R^2	Std RMSE (Validation Set)	Std RMSE Equivalent R^2 (Validation Set)
Max Principal Stress (All Inputs)	0.5244	0.7250	0.3272	0.8930
Max Mid Plane Stress (All Inputs)	0.2839	0.9194	0.3479	0.8790
Max Principal Stress (Sleeve Thickness Only)	0.3297	0.8913	0.1533	0.9765
Max Mid Plane Stress (Sleeve Thickness Only)	0.3282	0.8923	0.2120	0.9516





Set

- **Training**
- **Validation**

Questions?