ERSI 2021 Virtual Workshop

Date: 15-16 February, 2022
Location: Zoom

Agenda (All Times EST)

15 February:
13:00 – Committee Leads Discussion
15:00 – Adjourn

16 February:
13:00 – Opening Remarks and Overview (Spradlin)
13:05 – Residual Stress Measurement (Burba)
13:50 – Risk Analysis and Uncertainty Quantification (Hunt/Ocampo)
14:05 – Fatigue Crack Growth Analysis Methods + Validation Testing (Pilarczyk/Walker/Warner)
14:55 – Break
15:05 – Structures Bulletin Update (Spradlin)
15:35 – ERSI Path Forward (Spradlin/Leads)
15:50 – Open Discussion
17:00 – Adjourn

Working Group on Engineered Residual Stress Implementation

Residual Stress Measurement Committee Annual Summary

16 February 2022

(These charts are a team product)

Eric Burba, committee lead

micheal.burba.1@us.af.mil

Adrian DeWald, committee co-lead

atdewald@hill-engineering.com

Overview

Committee Logistics

- Typical Meeting Agenda
- Roster and Attendance
- Committee Mission and 2022 Goals

Update on Current Projects

- Texture and Anisotropy Sub-Team (Presenter: Dr. Mark Obstalecki, AFRL)
- 2inch Cx Residual Stress Determination for Process Simulation Validation (Presenter: Dr. Scott Carlson, Lockheed Martin)
- Contour Method Reproducibility Experiment A (CMRE-A) (Presenter: Dr. Mike Hill, UC Davis)
- Bulk RS Measurements in Cx Geometrically Large Holes (Presenter: Dr. Mike Hill)

Summary and Future Opportunities

Committee Logistics

Monthly Committee Meetings

- Meeting held on the first Wednesday of the month at 1400 Eastern
- Currently hosting meetings using ESRI's Zoom account
- Please contract Burba or DeWald if you would like to attend

Typical Meetings Agenda

Other ERSI Committee Updates

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

Measurement Committee Projects & Updates

- Texture and Anisotropy Sub-Team (Obstalecki)
- Large Cx Hole Bulk Stress (Hill)
- Multi-Point Fracture Mechanics, AFRL (Burba)
- A-10 Best Practices Document (Pineault)
- Contour Method Reproducibility Experiment A (CMRE-A) (Hill)
- 2x2 Working Group (Carlson)

New Business

Around the Room

Committee Roster and Attendance

✓	Jeferson	Araújo de Oliveira	StressMap - Director	44 (0) 1908 653 452	Jeferson.Oliveira@stressmap.co.uk
✓	David	Backman	National Research Council Canada / Government of Canada	(613) 993-4817	david.backman@nrc-cnrc.gc.ca
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	John	Bourchard	Professor of Materials Engineering Open University - Director of StressMap	44(0)7884 261484	john.bouchard@open.ac.uk
	Michael	Brauss	Proto Manufacturing Inc.	(734) 946-0974	mbrauss@protoxrd.com
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✓	Scott	Carlson	Lockheed Martin Aero (F-35 Service Life Analysis Group)	(801) 695-7139	SCarlson01@gmail.com
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	David	Denman	Fulcrum Engineering, LLC. (President & Chief Engineer)	(817) 917-6202	david@fulcrumengineers.com
✓	Adrian	DeWald	Hill Engineering, LLC	(916) 635-5706	atdewald@hill-engineering.com
	Daniele	Fanteria	Dipartimento di Ingegneria Civile e Industriale	(+)39.050.2217266	daniele.fanteria@unipi.it
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✓	Juan	Ocampo	St. Mary's University		jocampo@stmarytx.edu
	Sanjoo	Paddea	StresMap Ltd. - Director	44 (0) 7590498409	sanjooram.paddea@stress-map.com
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✓	James	Pineault	Proto Manufacturing Inc.	(313) 965-2900	xrdlab@protoxrd.com
	Mike	Reedy	U.S. Navy (NAVAIR - Compression Systems Engineer)	(301) 757-0486	michael.w.reedy1@navy.mil
	Steven	Reif	AFLCMC/EZFS	937-656-9927	steven.reif@us.af.mil
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✓	Mike	Steinzig	Los Alamos National Labs - Weapons Engineering Q17	(505) 667-5772	steinzig@lanl.gov
	Kevin	Walker	QinetiQ	+61457002775	kfwalker@qinetiq.com.au

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

What this Committee brings to ERSI

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

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

- Repeatability of residual stress measurement data (in lab variability)
- Reproducibility of residual stress measurement data (lab-to-lab variability)
- Inter-method residual stress comparisons (e.g. ND to x-ray to contour)
- Measurement model comparisons (e.g. for CX holes)
- UQ/Statistical methods relative to residual stress data (connect to inter-method as well as model-measurement)

Measurement Committee's 2022 Goals

- Support the drafting of the Air Force Structures Bulletin, "Analytical Methods, Validation Testing, and Process Compliance Record Requirements for Explicit Utilization of Residual Stresses at Cold Expanded Fastener Holes in the Damage Tolerance Analysis of Metallic Structure"

- Review and provide feedback on the residual stress measurement section of the A-10 Best Practices document.

- Assess/Quantify/Define effects of texture and anisotropy on residual stress measurement, document, and seek means to improve.

- Develop and document exemplar datasets (leverage prior work and drive new work). Experimental residual stress datasets that have been implemented and published (use of 2x2 Cx hole dataset)

Texture and Anisotropy Sub-Team

Team:

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

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

Mission Statement & Background

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

- Focused on RS hole drilling
- Utilizing Ring and Plug samples
  - Assembled with interference fit
  - Assume isotropic elasticity
  - Equal biaxial stress spatially in plug

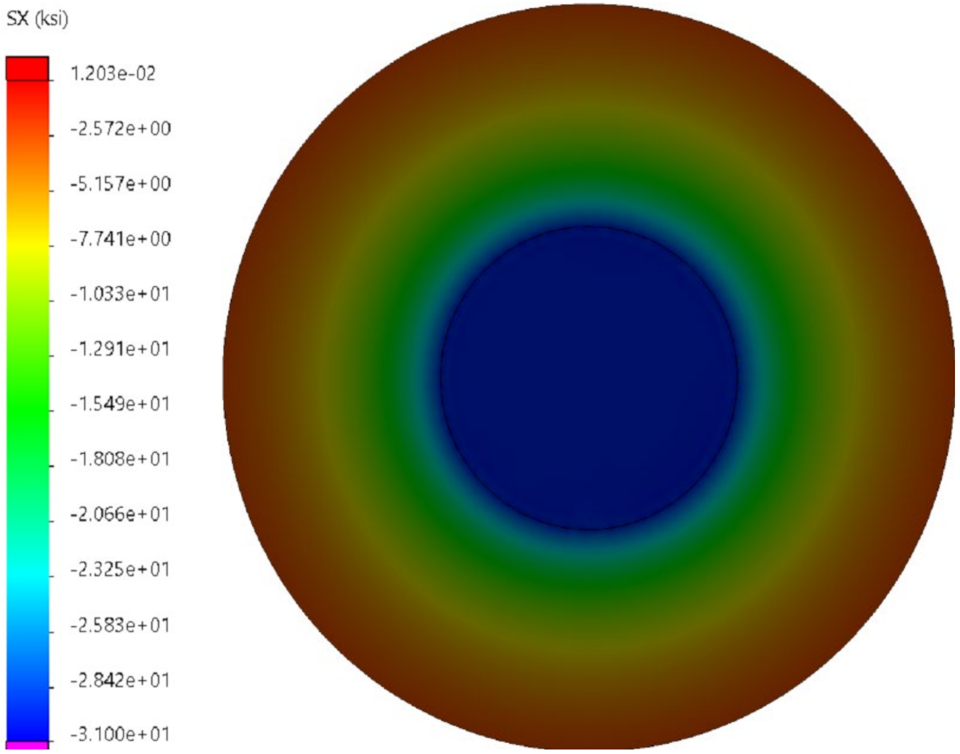


Figure 1: Radial stress of isotropic elastic material properties for stainless steel

Stainless Steel Ring and Plug Measurements

Figure 2: SSCAP ring/plug sample

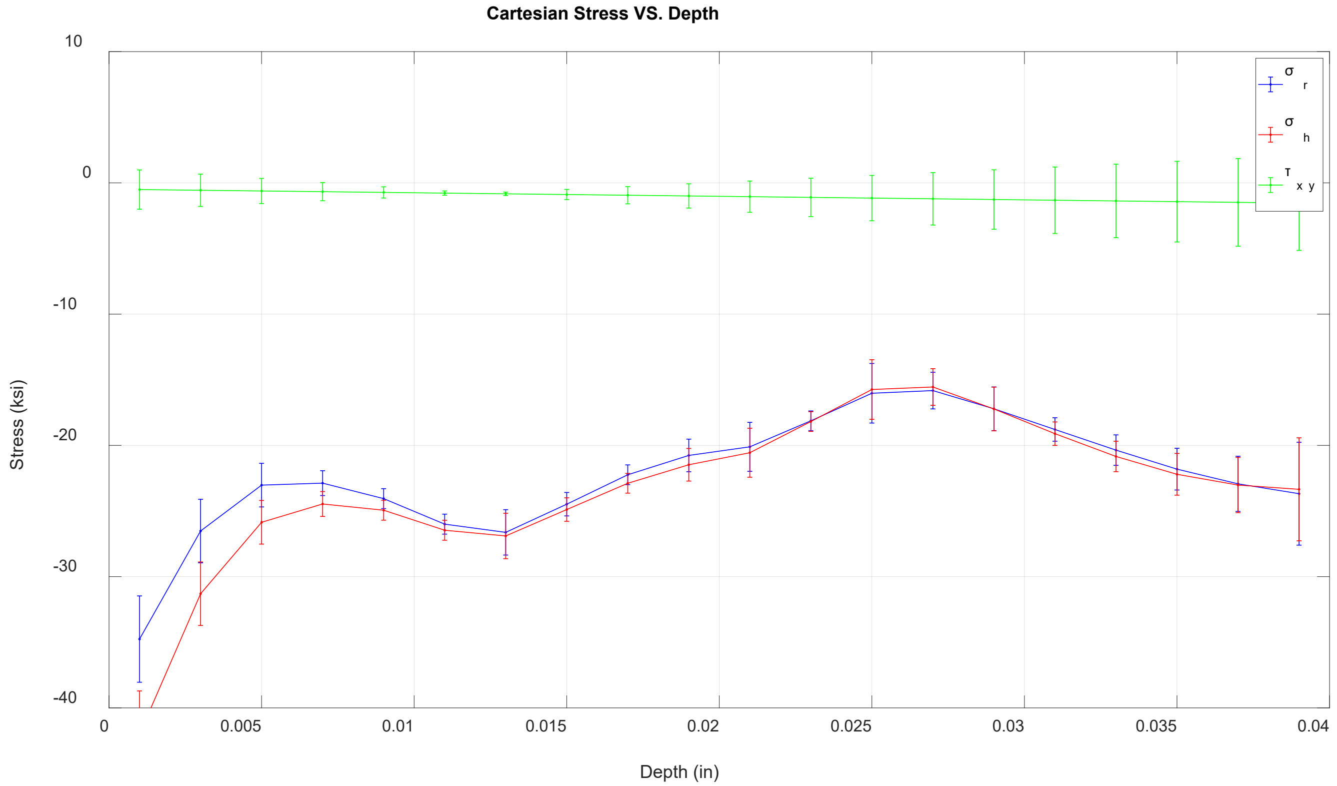


Figure 3: Stress VS. Depth graph of standard hole, circled in Figure 4

Stainless Steel Ring and Plug Measurements (Cont.)

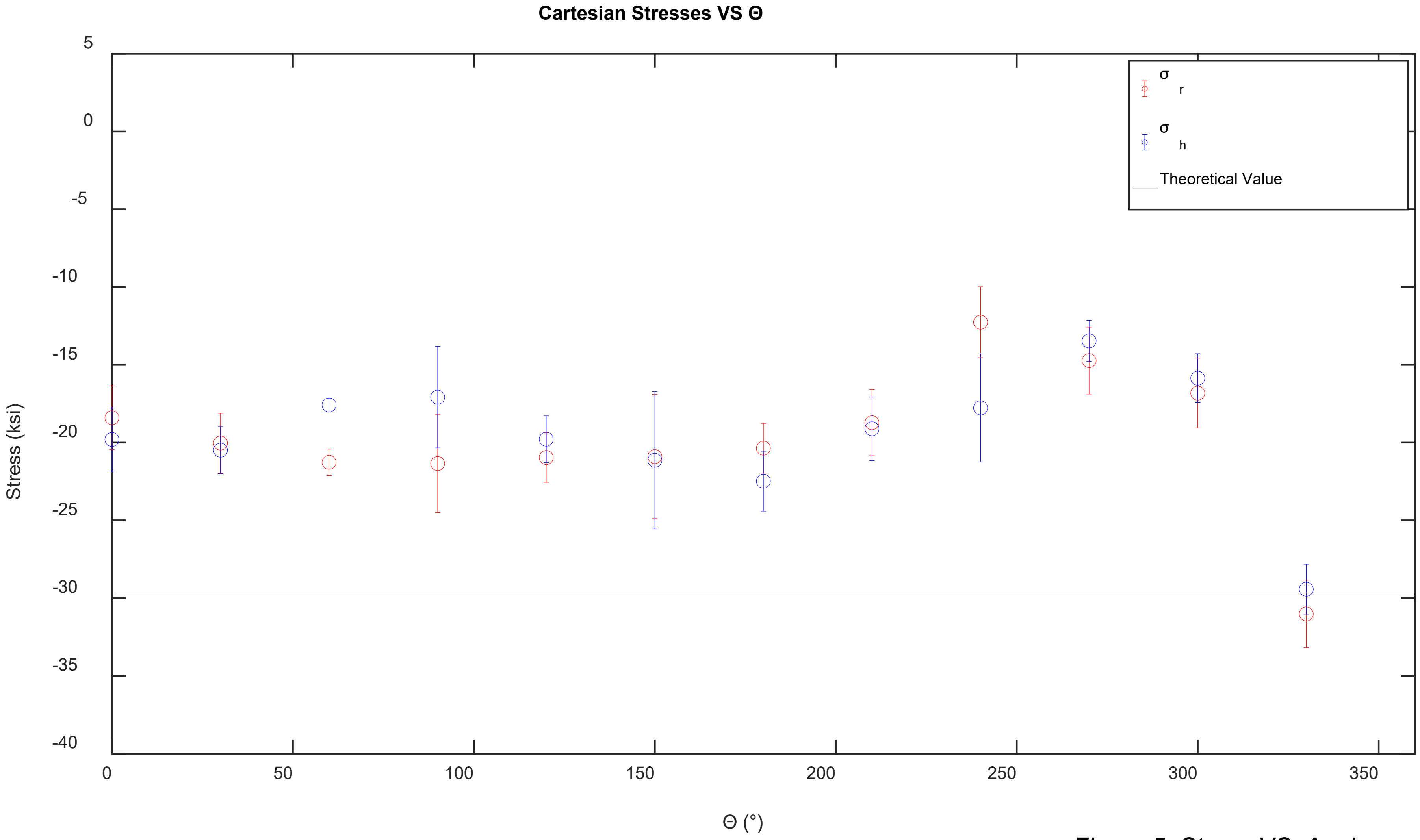
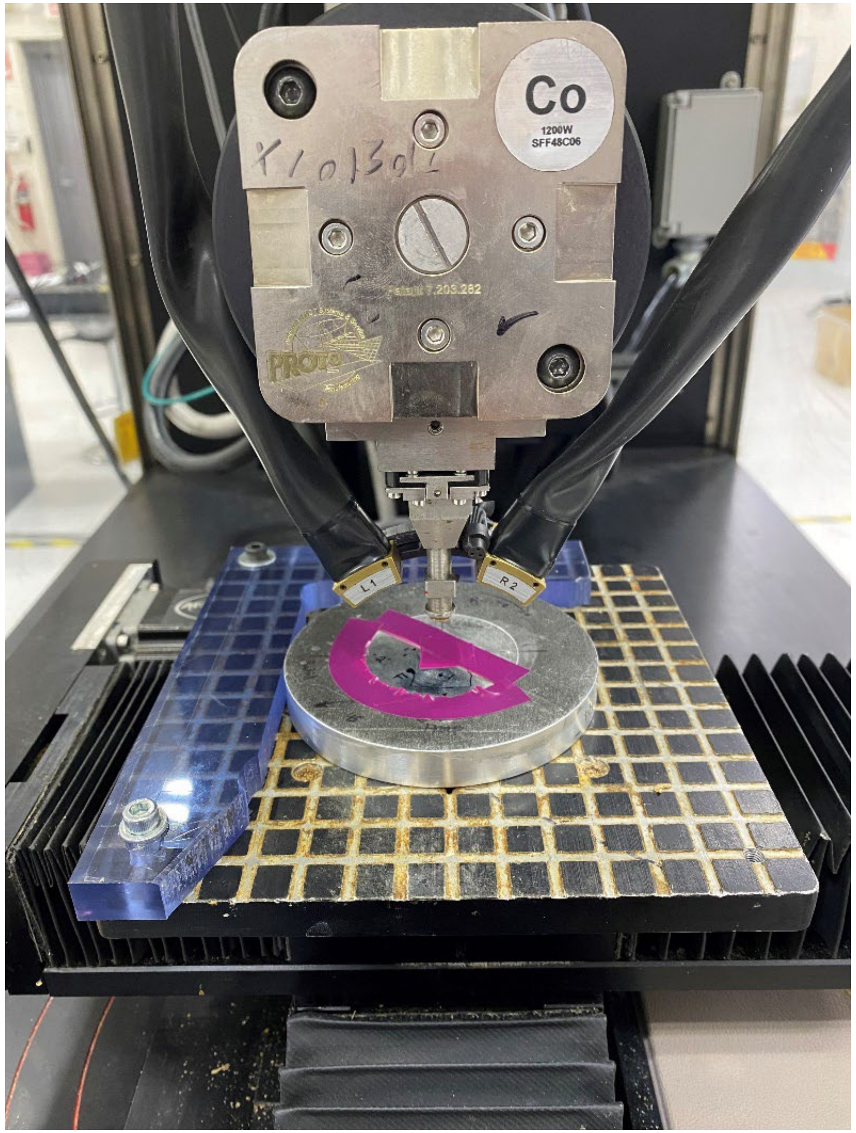
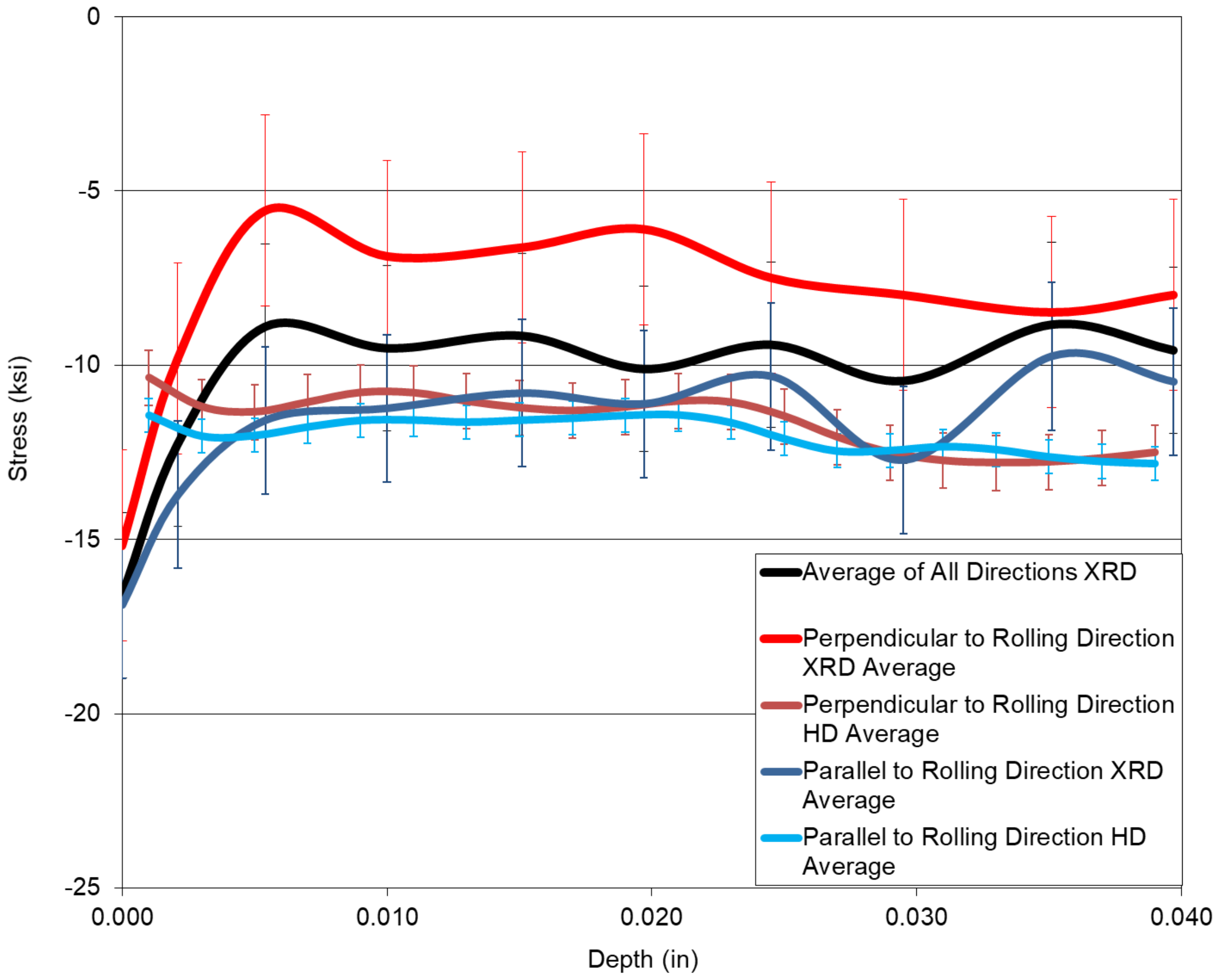


Figure 5: Stress VS. Angle around azimuth

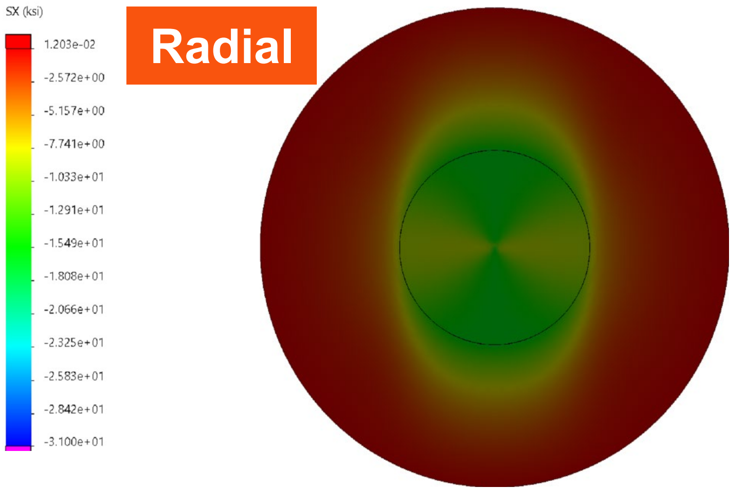
HD / XRD Round Robin (Aluminum)

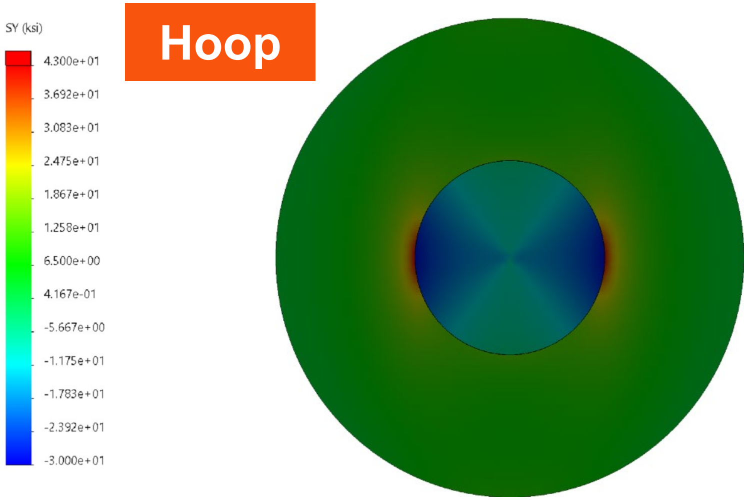




Analytical solution : -13 ksi

Gearing Toward Elastic Anisotropy

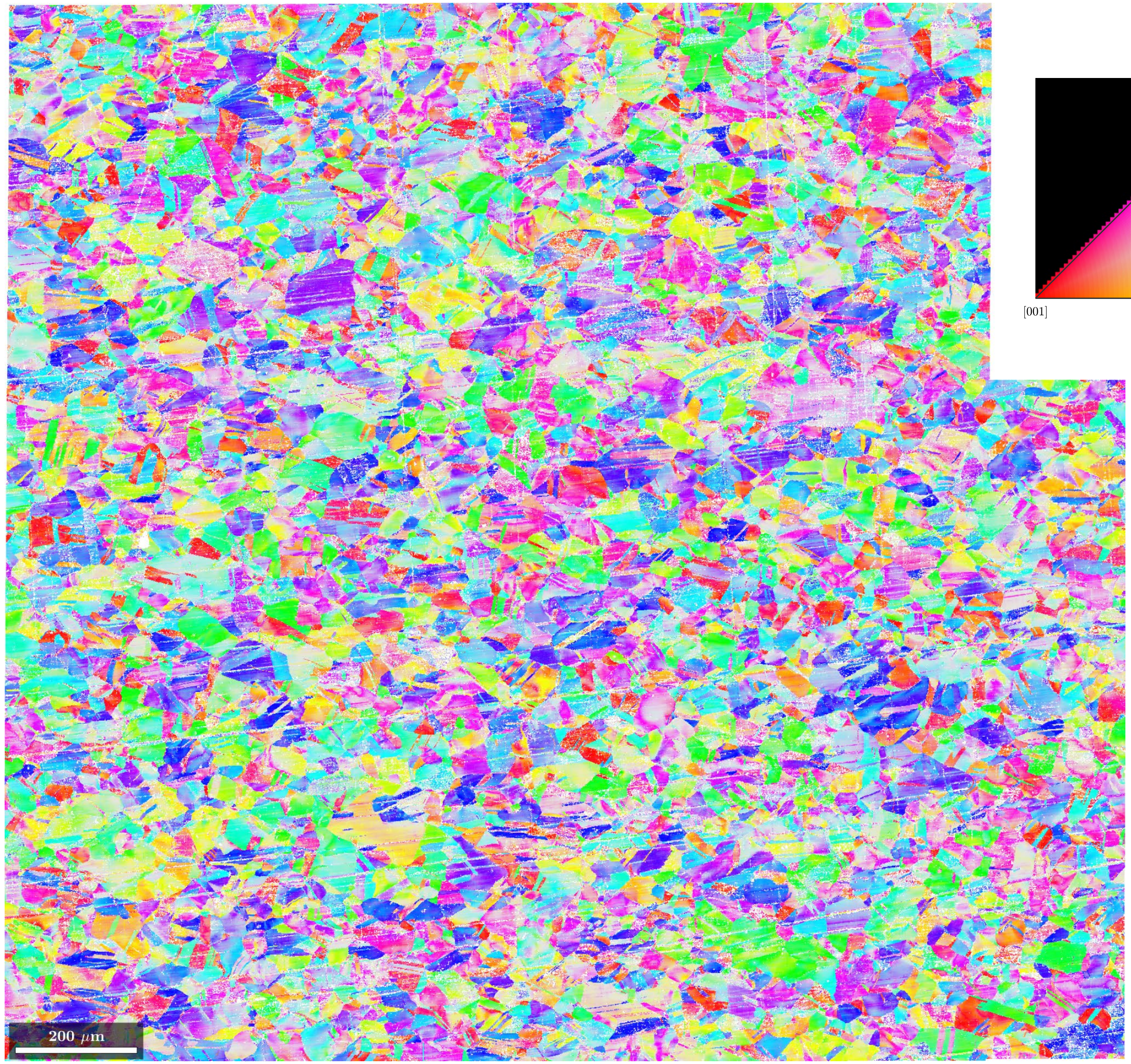


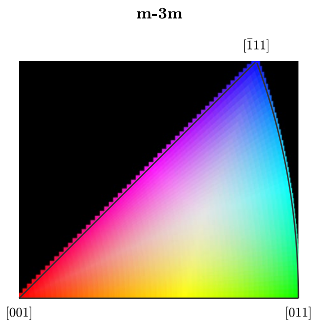


		Ring			
		Brass (260)	Stainless Steel (304)	Aluminum (6061)	Nickel (625)
Plug	Brass (260)				
	Stainless Steel (304)				
	Aluminum (6061)				
	Nickel (625)				

EBSD Texture Analysis

- C260 Brass
- Texture index of T = 1.3198
- Indexed using FCC Copper parameters
- White horizontal lines are due to polishing error
- RD into page





Ongoing Efforts

- Design samples using rolled brass to maximize spatial stress variation within plug
- ‘Sharpen’ brass texture by rolling
- Quantify anisotropic elastic constants from EBSD
  - Make EBSD measurements of different rolled thickness samples
  - Same single crystal elastic constants
  - Using MTEX calculate differences in aggregate response based on texture change
- Quantify anisotropic elastic constants from RUS
- Build framework to simulate incremental hole drilling measurement in elastically anisotropic materials

2inch Cx Residual Stress Determination for Process Simulation Validation

2inch Cx Project Overview

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

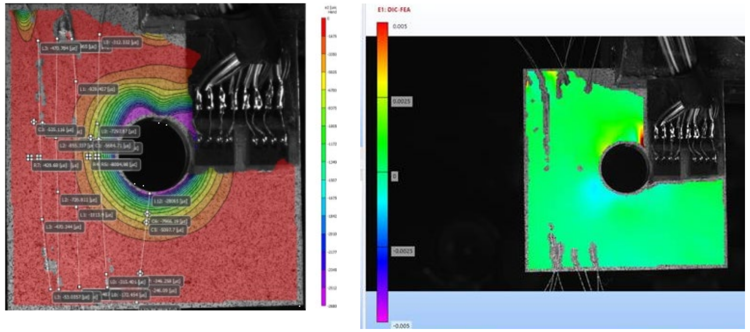
- Coupons Cold Expanded to the Max & Min of the Applied Expansion Range per the FTI Spec
  - 3.2% and 4.2%
  - High precision starting hole size
- One Set of Each Condition was Final Reamed for Future Use as a “Standard”
- During the Cx Process Surface Strain Measurements were Taken in ”Real-Time”
 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

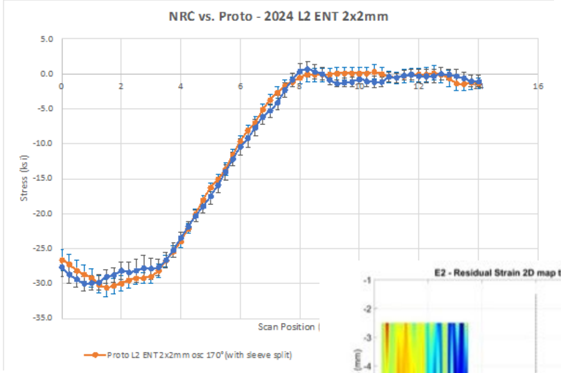
History of Program

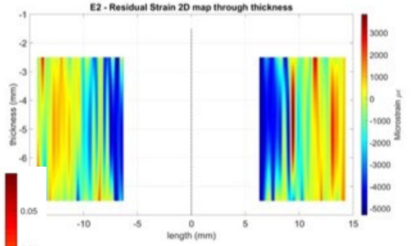
- **<u>No Central Funding Source for all Work</u>**
  - All Work provided at cost to the process/data owning organization
- 2016 NRC, FTI and SwRI Developed a FEA Round Robin Exercise
  - Goal was to compare state-of-the-art FEA process simulation methods and results
  - Compare results to contour method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

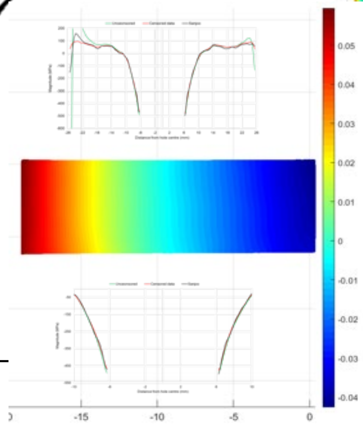
Work Completed - Update

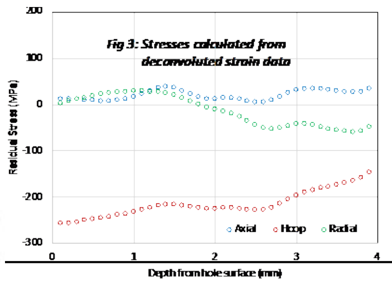
- Surface Strain Measurements During Cx Process ✓
  - Journal paper in draft form for release (focused on 2024-Low Cx level)
  - Utilizing MatchID for FEA-to-DIC comparison
- Surface XRD Inter-Laboratory Comparison and Method Development ✓
  - Journal paper in draft for final review (All configurations presented)
- Through Thickness Measurements
  - Argonne National Lab's Synchrotron (All coupons processed) ✓
  - CHESS Synchrotron (7075 coupons processed – need data) ✓
  - JPARC and Oakridge National Lab's Neutron Diffraction (All coupons will be processed)
  - Stress-Space - Contour Method (All coupons will be processed)











Future Work

- Complete Surface Strain Paper Comparison
  - Focused on FEA simulations, using multiple material models, to DIC/MatchID data
- Complete Data Processing of Neutron Diffraction Experiments
  - 2024 ”Low” and “High” have been completed the experiments – need to process data
  - 7075 “Low” and “High” are at Oakridge NL and need test plan defined and executed
- Complete Contour Method on Remaining 3 Coupons
- Develop Journal Papers on Through-Thickness Comparisons
  - Neutron vs. Contour
- Develop Method for Coupling Residual Stress Methods for Near-Surface and Away-from-Surface Stress Fields
  - Potential to use Neutron or XRD data near the bore of the hole and Contour data away from the hole
- Provide RS Field Data to Analysis Committee for Predictions of Test Conditions

Working Group on
Engineered Residual
Stress Implementation

ERSI RS Measurement

CMRE-A
and
Large Hole Bulk Stress

Mechanical and Aerospace Engineering
University of California, Davis

Contour Method Reproducibility Experiment A (CMRE-A)

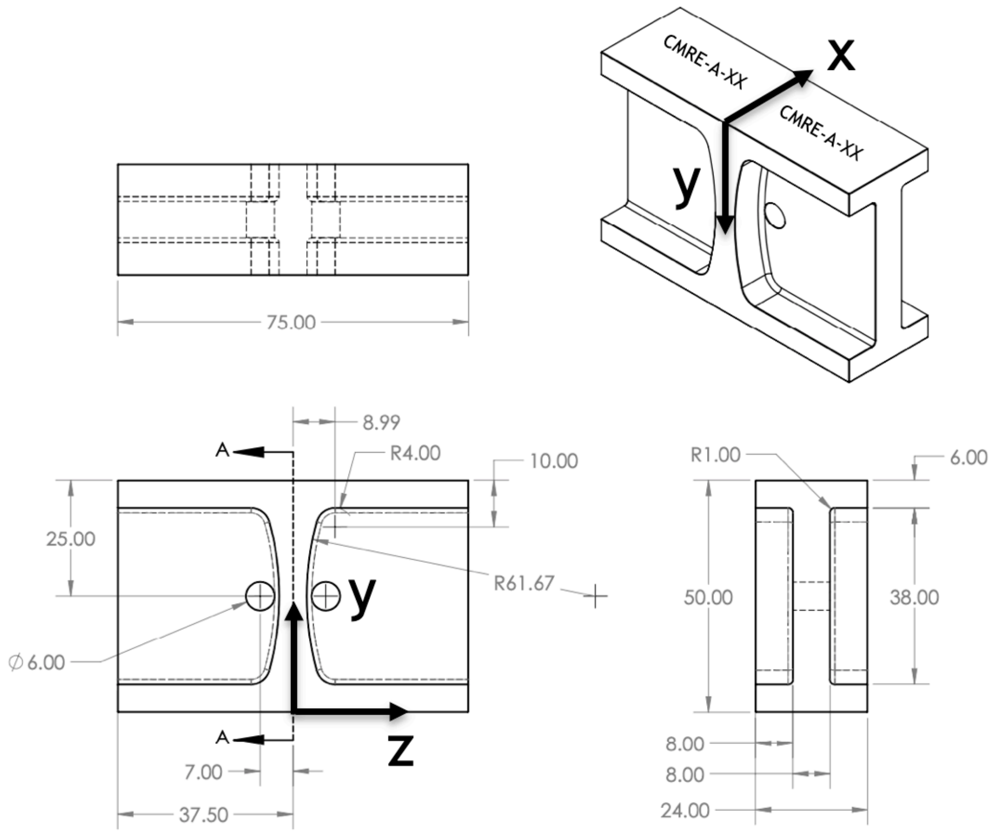
Summary for ERSI

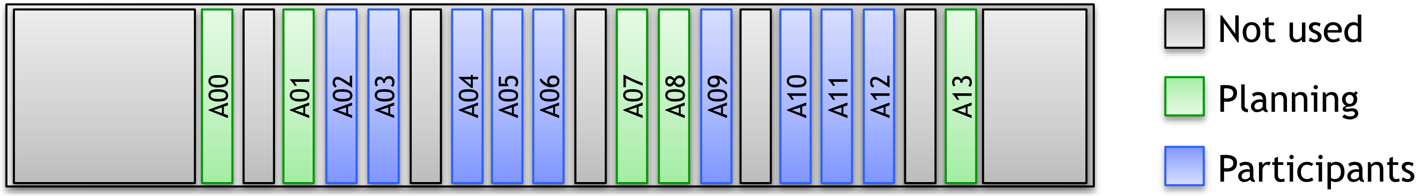
Initial version: February 15, 2022

Christopher D'Elia, Research student (crdelia@ucdavis.edu)
Professor Michael R Hill (mrhill@ucdavis.edu)

CMRE-A Sample

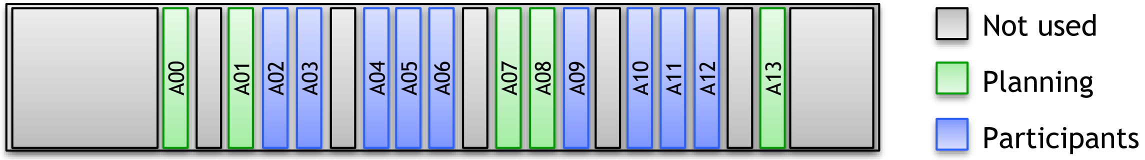
- Interest in bulk stress fields, neglecting machining or other near-surface stresses
- Several blanks cut from a single residual stress bearing bar
  - 7050-T74 high-strength aluminum alloy
  - Residual stress from quench/age of T74
- Mill identical samples 50 x 75 x 24 mm
  - Plane of interest A-A, 50 x 24 mm
  - Representative of heavy structural elements
- Fabricated 14 samples A00 to A13



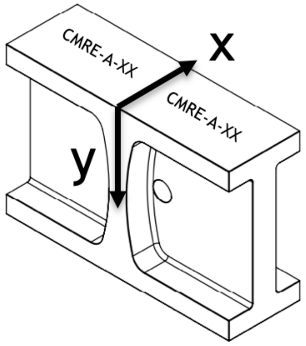


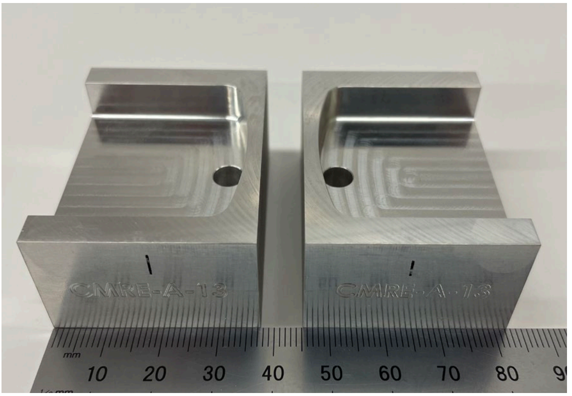
CMRE-A Measurements

- **Planning Measurements:**
  - 3 contour measurements to assess uniformity of material condition and measurement repeatability (UC Davis) (Samples A01, A07, A13)
  - Neutron diffraction measurement at HFIR (Oak Ridge National Lab) (Sample A08)
  - Hole-drilling at surfaces (UC Davis) (Sample A00)
- **Participants Measurements:**
  - International group of 8 participants from industry and academia provide contour measurement results on Plane A-A

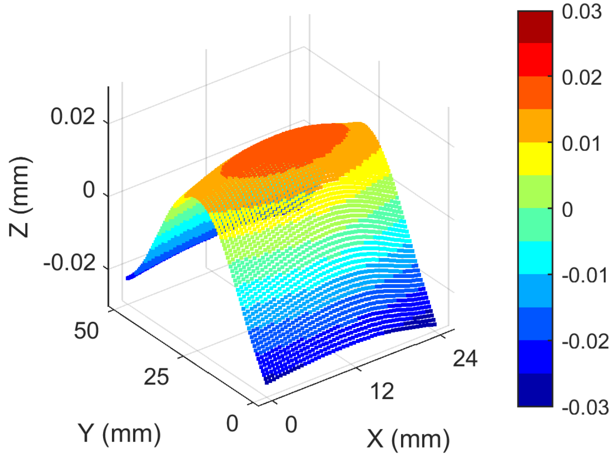


1) Cut the part (wire EDM)

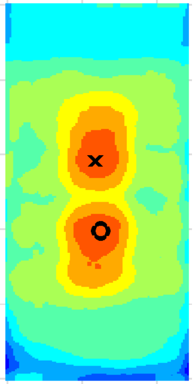




2) Measure the cut surface form

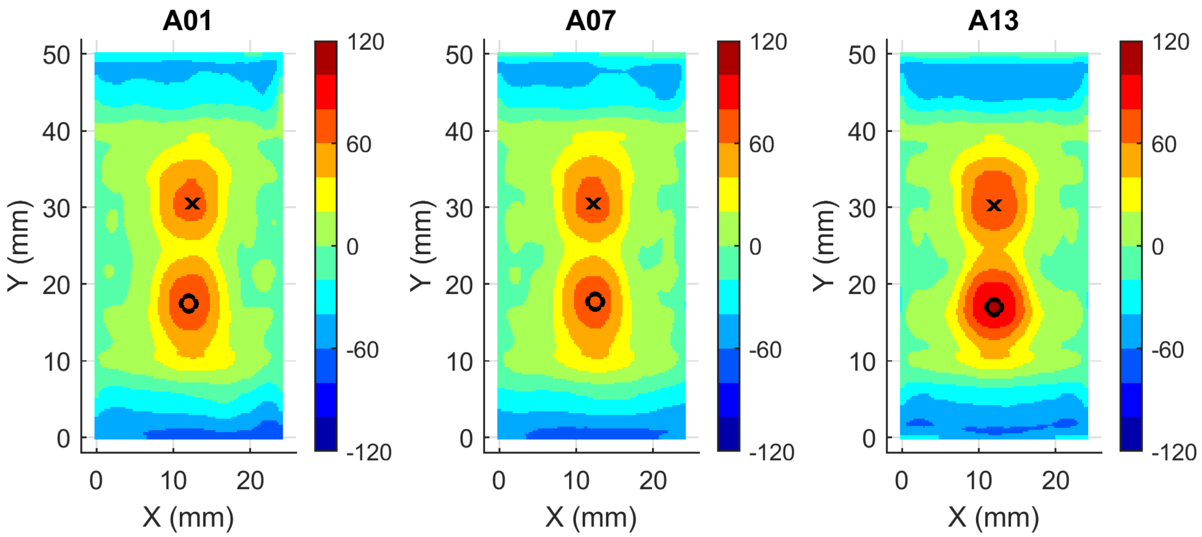


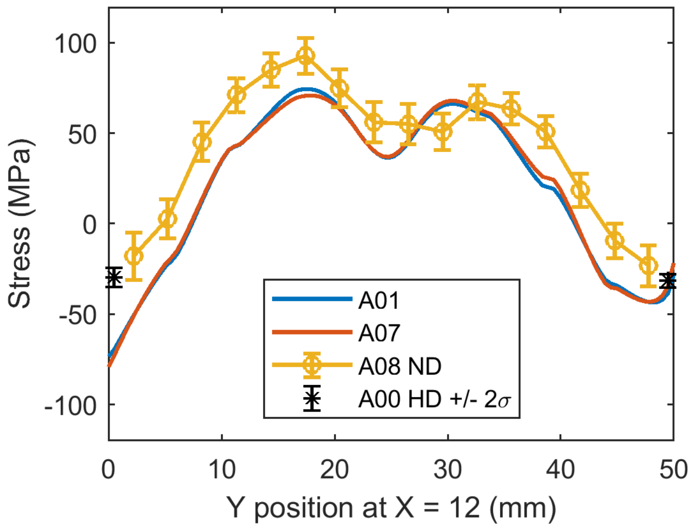
3) Compute RS (FEA)



CMRE-A Planning Measurements

- **Contour results:**
  - A01 and A07 are nearly identical
  - Magnitude higher for A13
    - Likely due to proximity to end of bar (see Olson 2015)
    - Distant from participant samples
  - Spatial distribution of stress is similar along length of bar
- **Neutron diffraction results:**
  - Similar spatial form, offset of ~ 25 MPa (within expectation)
- **Hole-drilling results:**
  - Near surface stress symmetric





Olson, M.D., Hill, M.R. A New Mechanical Method for Biaxial Residual Stress Mapping. *Exp Mech* 55, 1139-1150 (2015). https://doi.org/10.1007/s11340-015-0013-5

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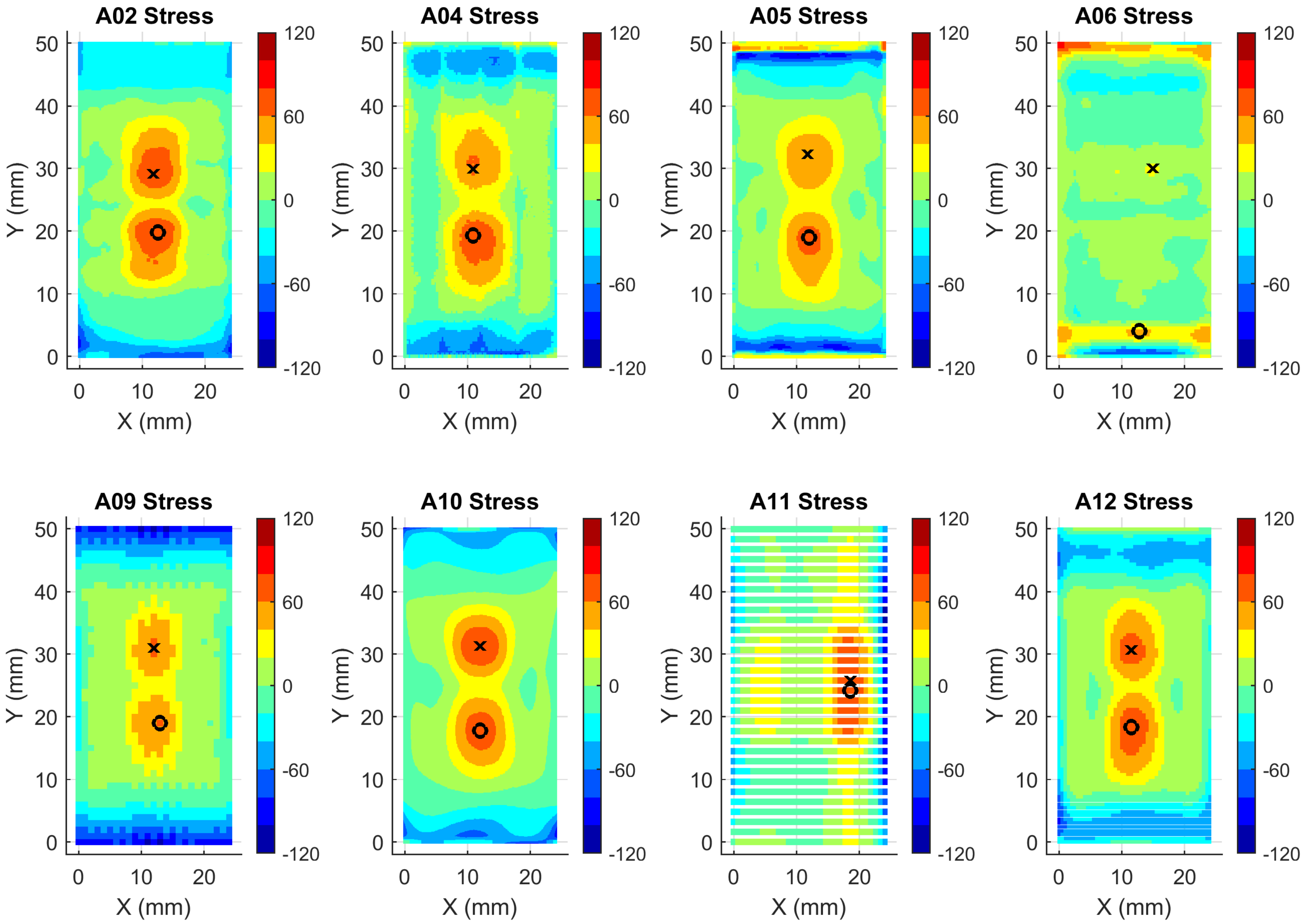
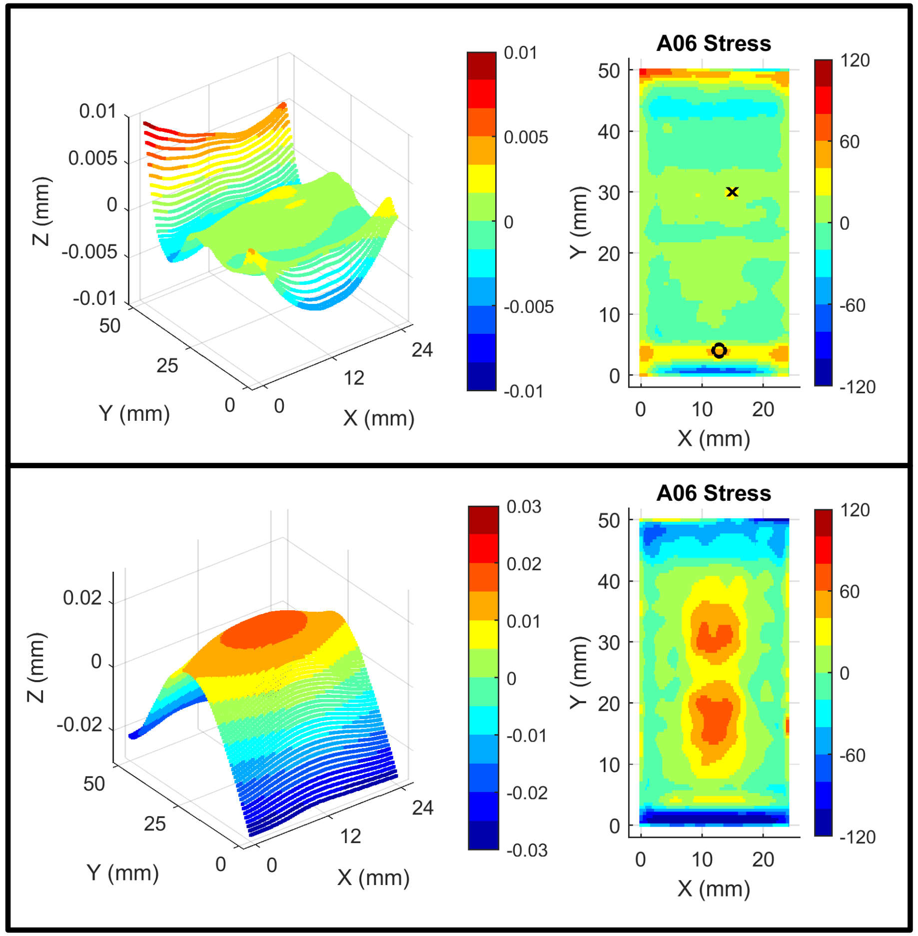
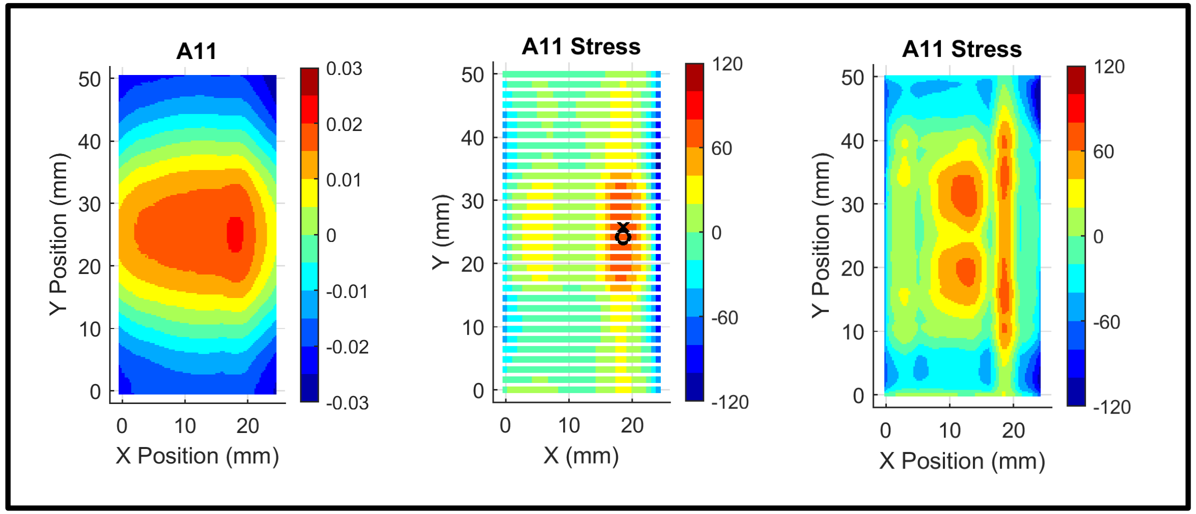
CMRE-A Results: Participant Reported Stress



CMRE-A Results: Outliers

- CMRE-A-06
  - Surface measurement problem
  - New surface form measurements provided results consistent with others
- CMRE-A-11
  - Wire EDM cutting problem
    - Cut surface of stress-free material would be non-flat (called a “cutting artifact”)
  - Analysis problem
    - Overly simplistic geometry





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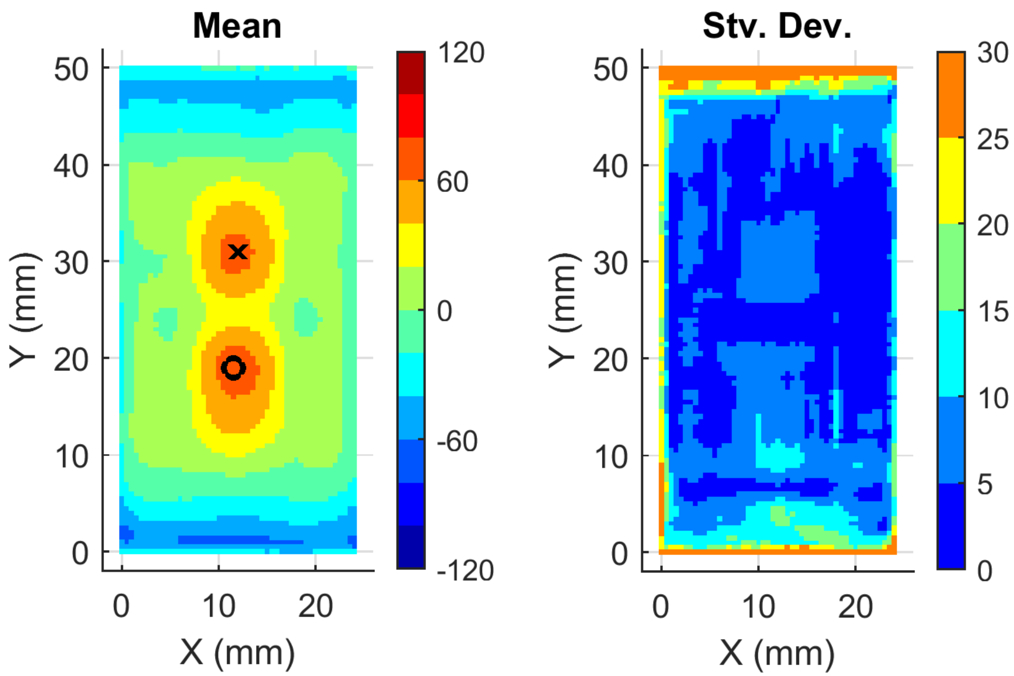
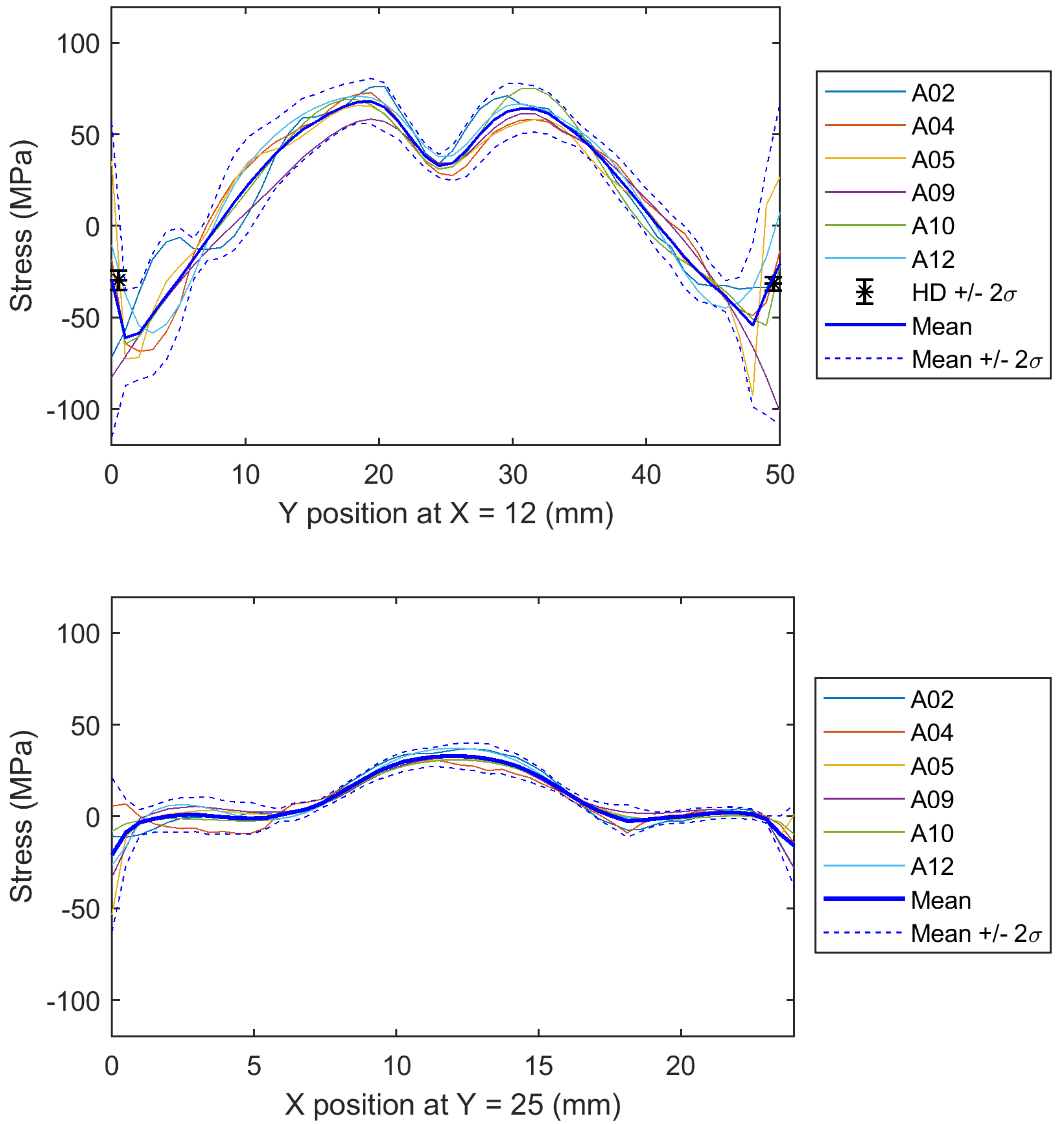
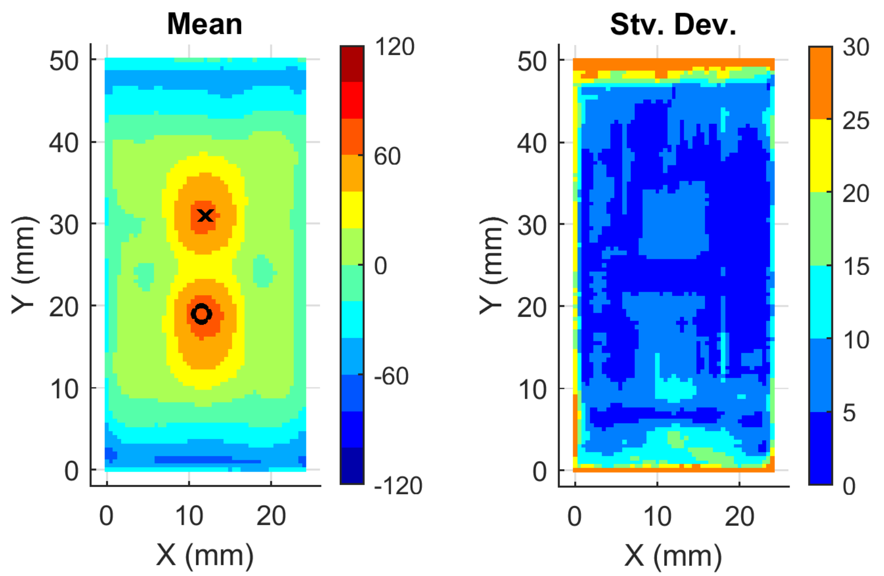
CMRE-A Results: Non-outlying

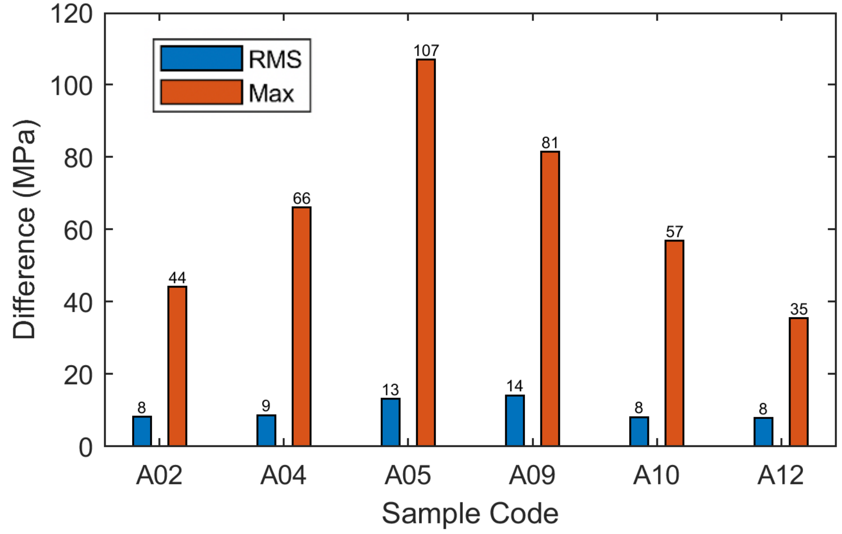




CMRE-A Results: Reproducibility (excluding outliers A06, A11)

- **Observed interlaboratory reproducibility**
  - 8.1 MPa average for all locations
  - 6.1 MPa on interior
  - 17.6 MPa near boundary (within 1 mm)
- **Observed reproducibility similar to intralaboratory repeatability reported earlier (Olson, et al, 2018)**
  - 9.0 MPa on interior
  - 18 MPa near boundary
- **Differences from group mean vary among participants**
  - RMS differences range 7.8 to 14.1 MPa
  - Maximum differences range 35.5 to 107 MPa





Olson, MD, DeWald, AT, & Hill, MR. Repeatability of contour method residual stress measurements for a range of materials, processes, and geometries. *Mater Perform Charact*, 7(4), 20170044-20170044, 2018. http://dx.doi.org/10.1520/MPC20170044

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CMRE-A Study Results Submitted for Publication in Experimental Mechanics

- Submitted Feb 2022

Interlaboratory Reproducibility of Contour Method Data in a High Strength Aluminum Alloy

C.R. D'Elia[1]*, P. Carlone[2], J. W. Dyer[3], J.B. Lévesque[4], J. Araújo de Oliveira[5], M.B. Prime[3], M.J. Roy[6], T.J. Spradlin[7], R. Stilwell[8], F. Tucci[2], A.N. Vasileiou[6], B.T. Watanable[9], M.R. Hill[1]

[1]University of California, Davis, CA 95616
[2]University of Salerno, Fisciano (SA) Italy
[3]Los Alamos National Laboratory, Los Alamos, NM 87545
[4]Hydro-Québec Research Institute, Varennes (Québec), Canada, J3X 1S1
[5]StressMap – The Open University, Milton Keynes – MK7 6AA – UK
[6]University of Manchester, Manchester, UK M1 3BU
[7]United States Air Force, Air Force Research Laboratory, Wright-Patterson, AFB, OH 45433
[8]Boeing Co, Seattle, WA 98108
[9]Hill Engineering, LLC, Rancho Cordova, CA 95670

Submitted February 2022 to Experimental Mechanics for Special Issue on Advanced in Residual Stress Technology in Honor of Drew Nelson

ABSTRACT

Background: The contour method for residual stress measurement has seen significant development, but an experimental reproducibility study has not been published. Objective: A double-blind reproducibly study is reported, having scope beginning with EDM cutting and ending with residual stress calculation. Methods: A reinforced I-beam sample geometry is identified for its unique residual stress profile when extracted from residual stress bearing quenched aluminum bar (7050-T74). Contour measurements are prescribed on a midplane of symmetry with dimensions 24 mm by 50 mm. Fourteen identically prepared samples are fabricated from a single long bar with well characterized and uniform residual stress. Five

ERSI

Working Group on
Engineered Residual
Stress Implementation

Bulk RS Measurements in Cx Geometrically Large Holes 7075-T651 and 7050-T7451

Residual stress measurements supported by process finite element modeling

Team

Organized under ERSI-RSM

Contributors:

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

ERSI

Working Group on
Engineered Residual
Stress Implementation

Background and Objectives

Background:

- Existing prior data for large (D = 1 inch) Cx holes in 7075-T651
  - Residual stress measurements (contour)
  - Residual stress outputs from nonlinear process model
- Disagreement between measurement results and model outputs

Objectives:

- Fabricate coupons for measurements in D = 1 inch Cx holes
  - Samples cut from 7050-T7451 2” thick plate (AFRL)
  - 100% processed and 50% processed (FTI)
- Develop process model outputs for coupon conditions (Hill Engineering)
- Assess bulk RS in coupons
  - Neutron Diffraction (ND) at SMARTS (LANL, UCD)
  - Synchrotron X-ray Diffraction (EDXRD) (CHESS, AFRL, UCD)
  - Contour (Hill Engineering)
- Report findings in a joint journal publication (e.g., Experimental Mechanics)

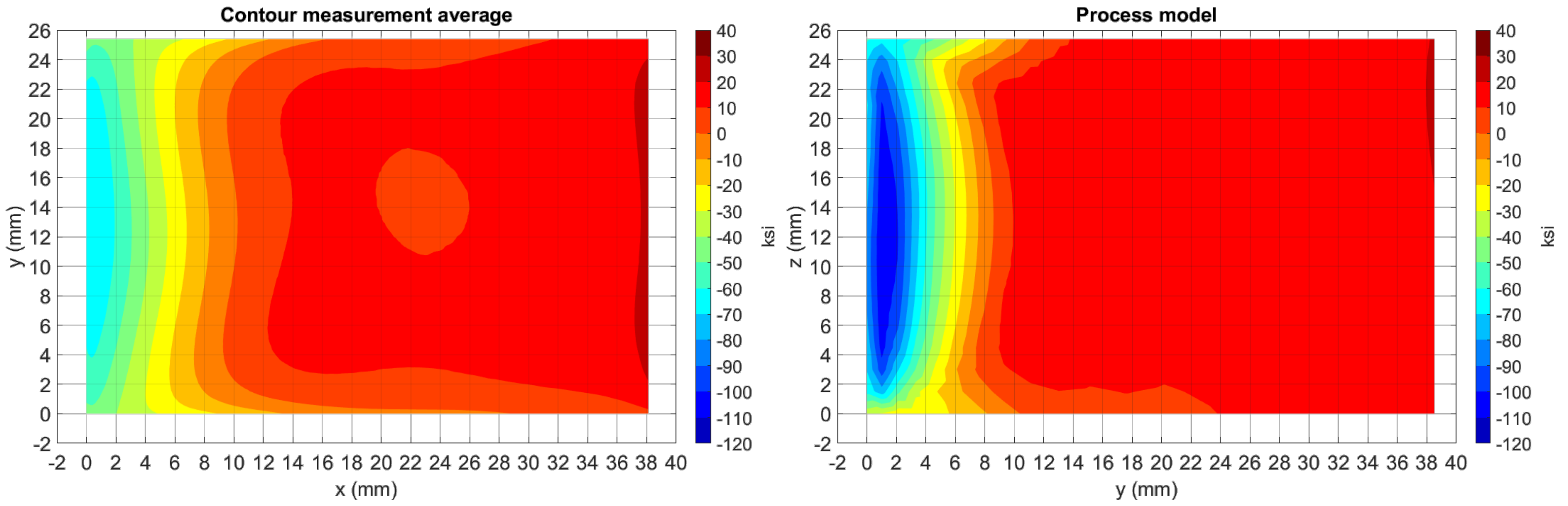
Today: Describe data gathered to date

Prior work: Measurement and model comparisons

Contour maps of the hoop residual stress below

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

7075-T651



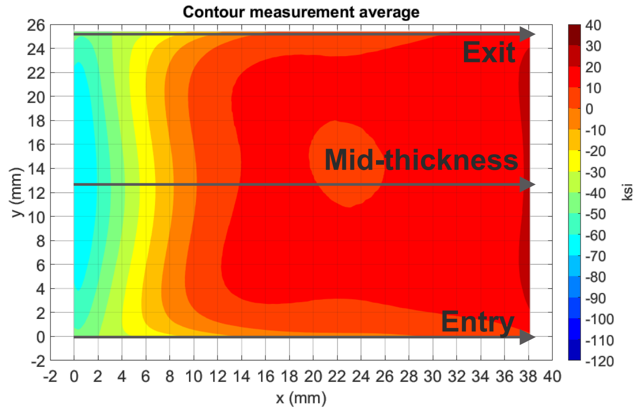
Prior work: Measurement and model comparisons

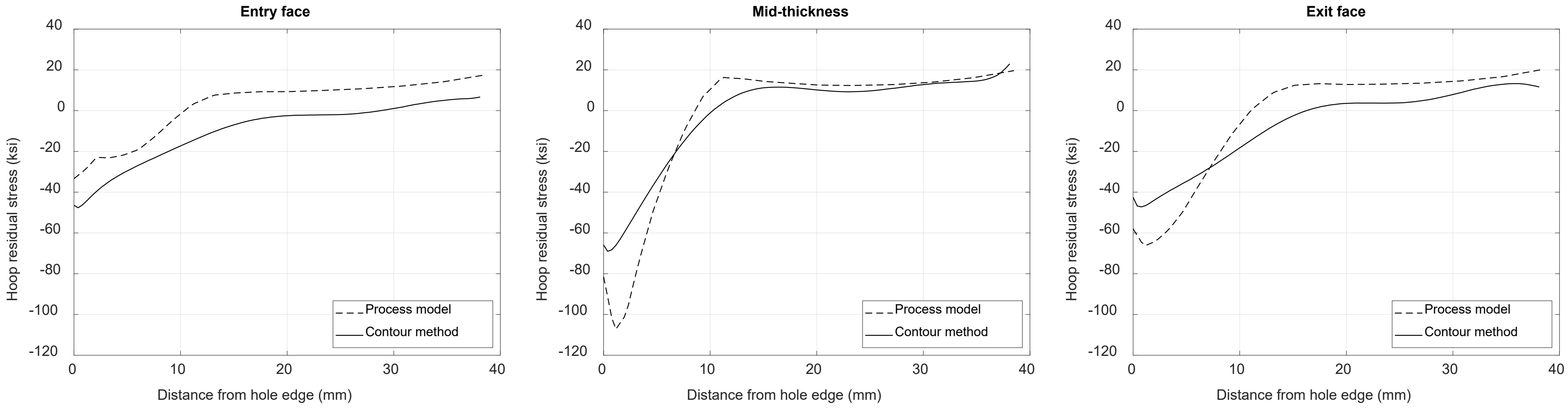
Comparisons below along entry surface, mid-thickness, and exit surface

Model results show

- Lower compressive residual stress on entry surface than measurement
- Higher magnitudes of compressive residual stress near the hole and on mid-thickness and exit surface than measurement

7075-T651





Samples for experiments

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

Material is AA7050-T7451 plate, 2 inch thick

Sample geometry (inches)

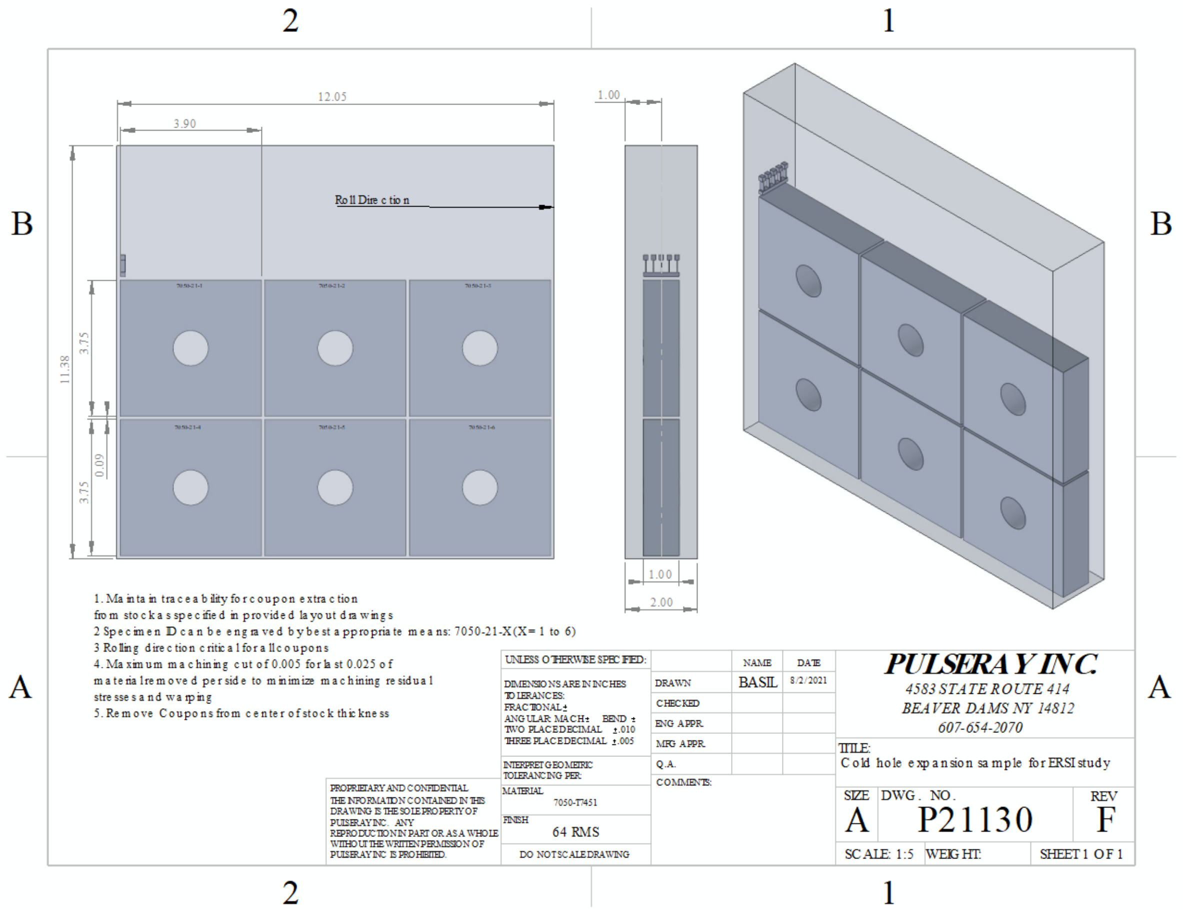
- Plates, L = 3.90 (along L), W = 3.75 (along LT), and T = 1.0 (along ST)
  - 1.0 dimension at plate mid-thickness to reduce texture
- Centered hole, D = 1.00

Fabricated 6 samples (AFRL)

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

Processing (FTI)

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

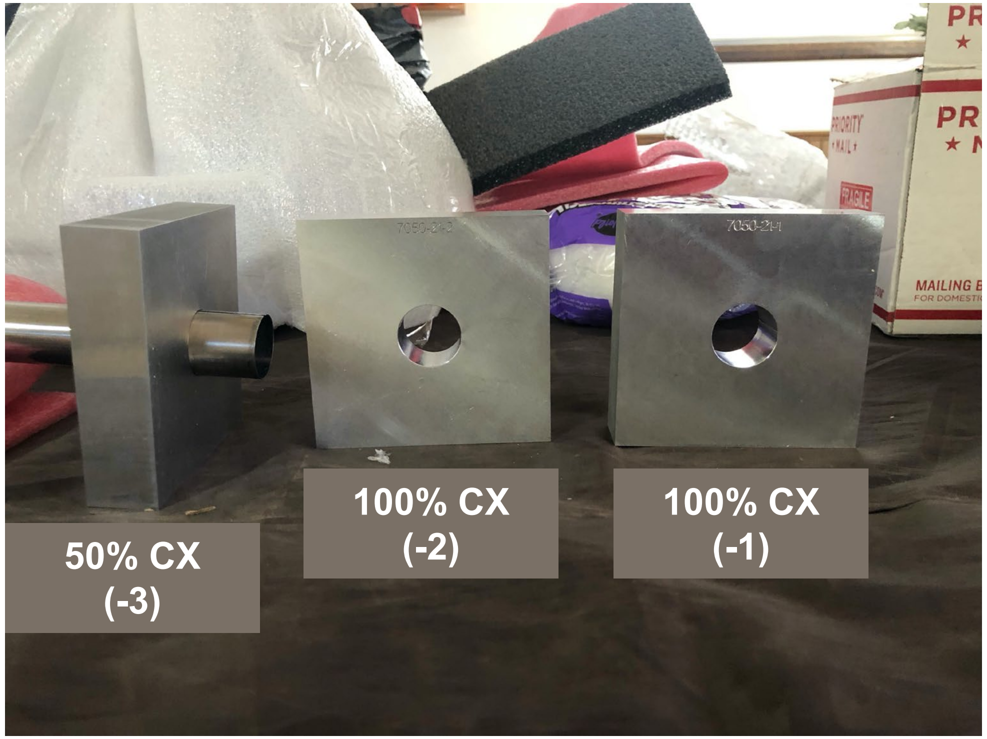


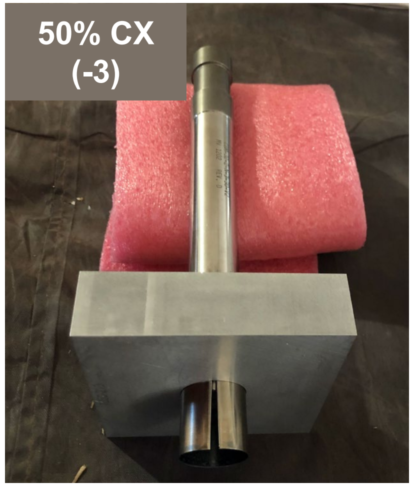
Processed samples at LANL

7050-21-1 – 100% CX (ND complete)

7050-21-2 – 100% CX (spare now, use for contour)

7050-21-3 – 50% CX (ND complete)





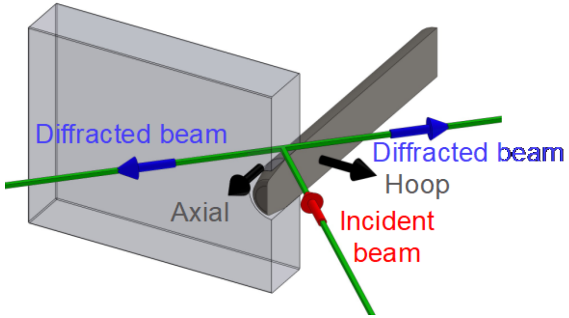
ND Setup and measurement locations (concept)

Note: ND measurements are complete

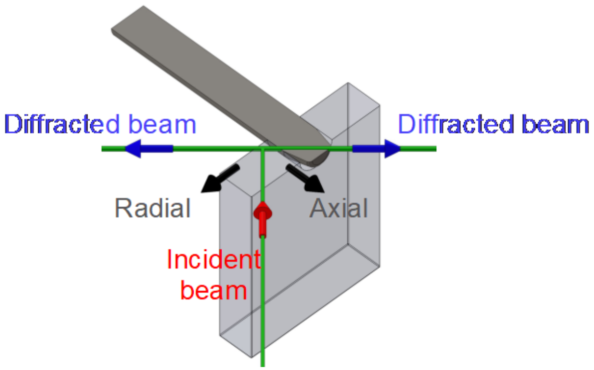
2 mm cubic gage volumes

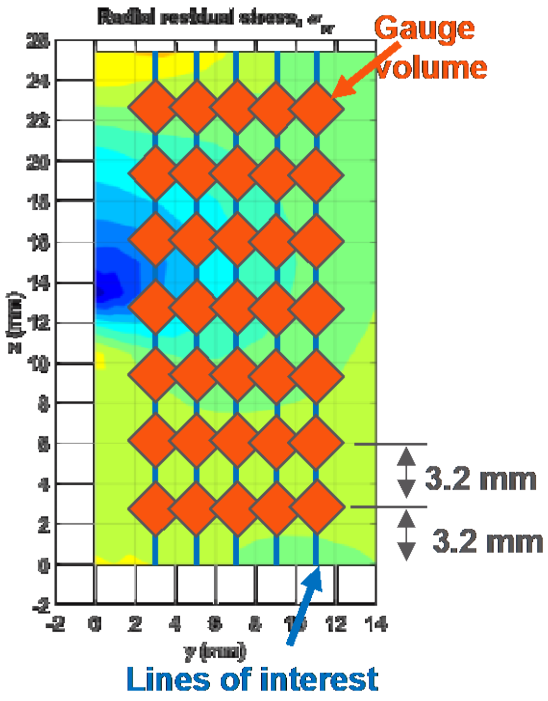
Background contours:
Stress for 7075-T651 (50%)

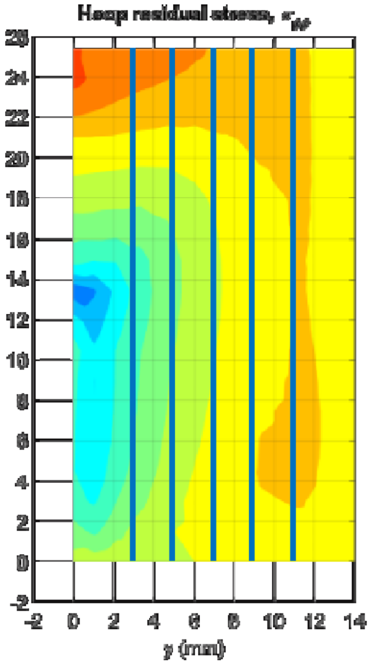
Horizontal orientation

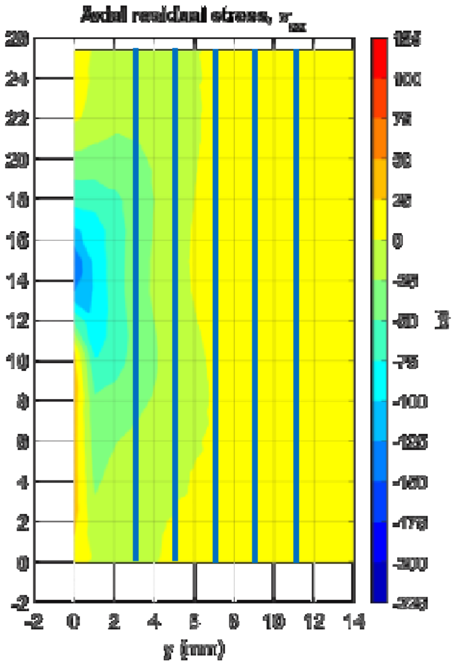


Vertical orientation









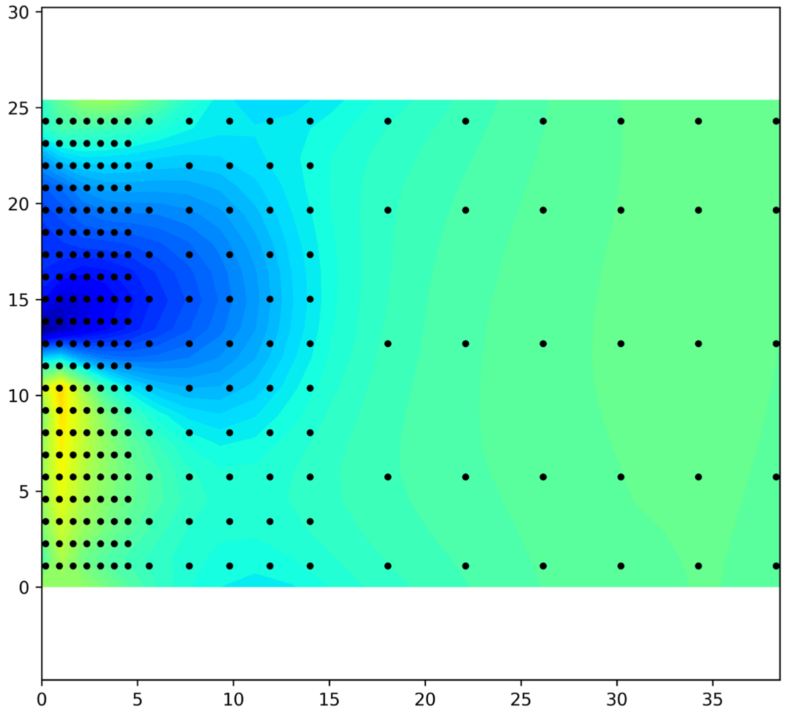
EDXRD measurement locations (concept)

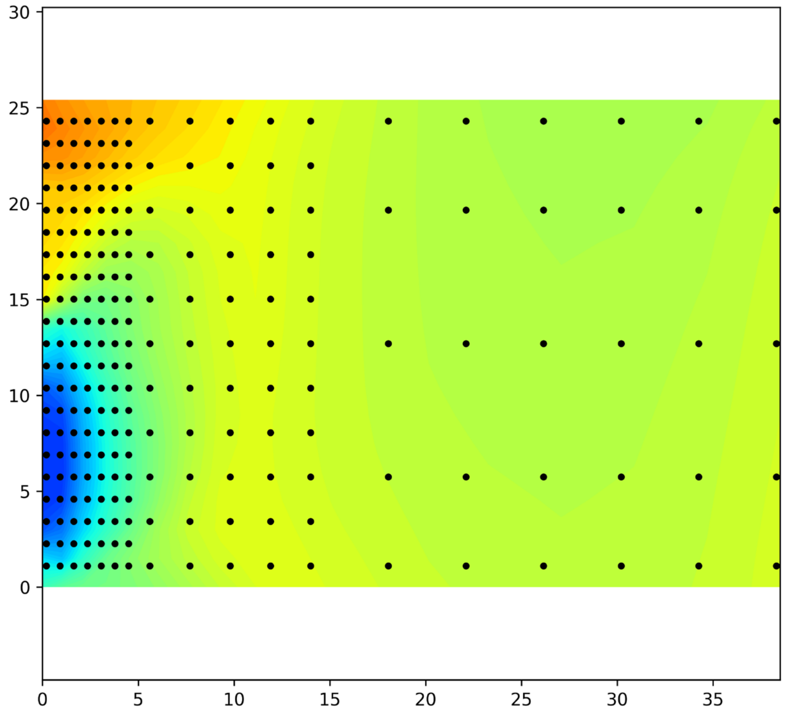
Note: EDXRD measurements are to begin Feb 16, 2022

Compared to ND, EDXRD allows for:

- More locations (faster per point)
- Closer spacing (smaller gage volume)

Background contours:
Elastic strain for 7050-T7451 (50%)

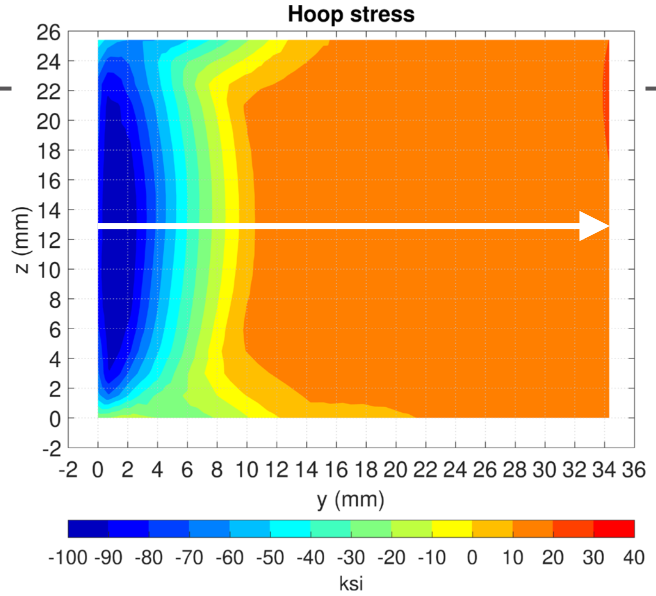


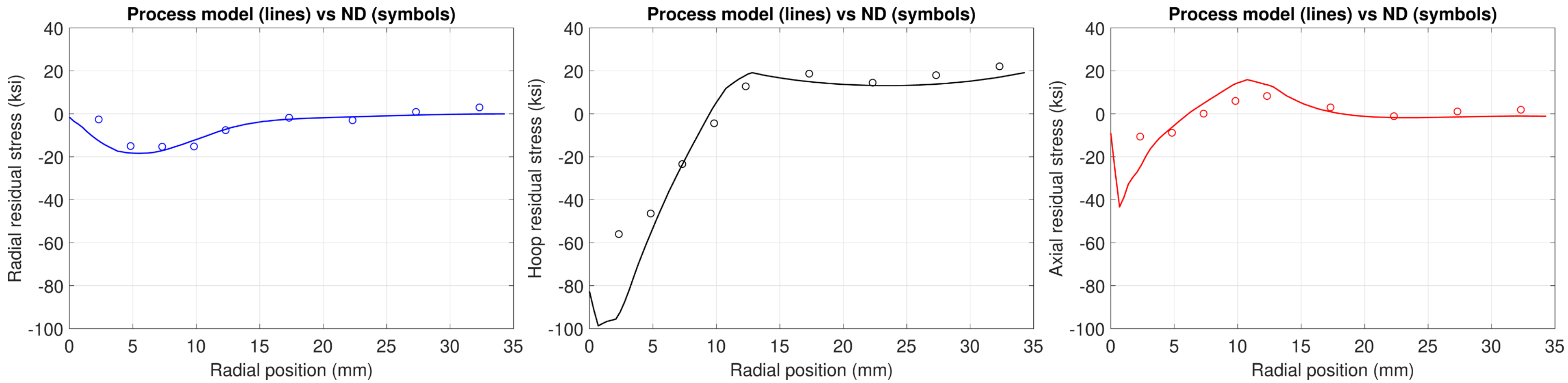


Results: Model and ND (100%)

7050-T7451

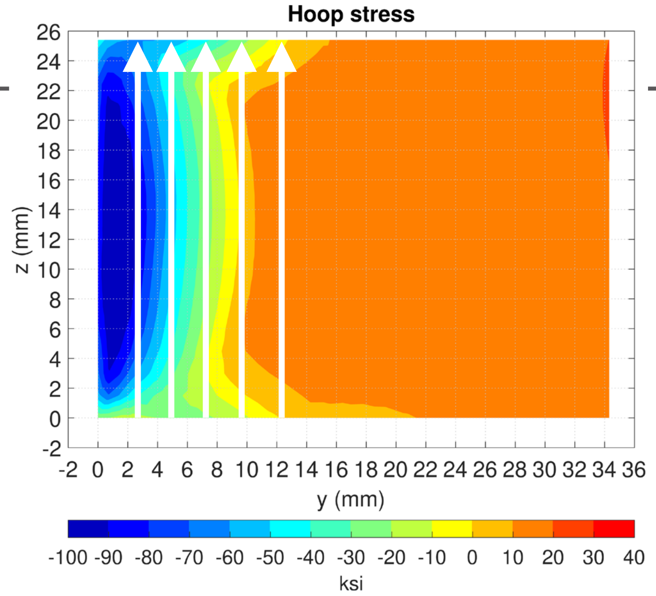
- Line plots comparing model output and neutron diffraction (ND) measurements below
- At the mid-thickness vs position from the hole bore
- Radial, hoop, and axial residual stress results shown





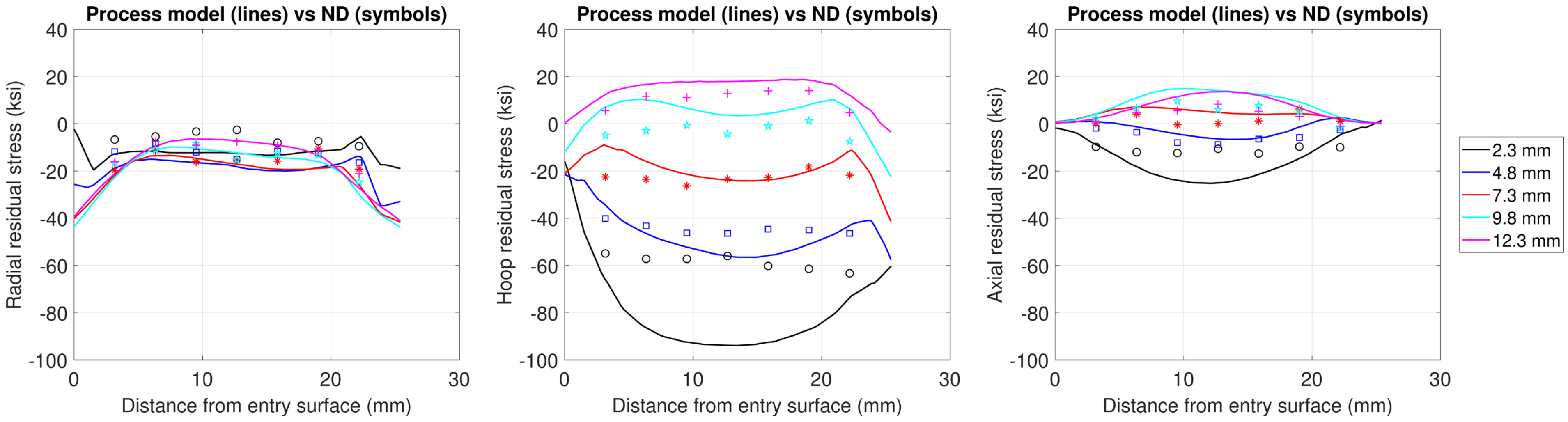
Results: Model and ND (100%)

7050-T7451



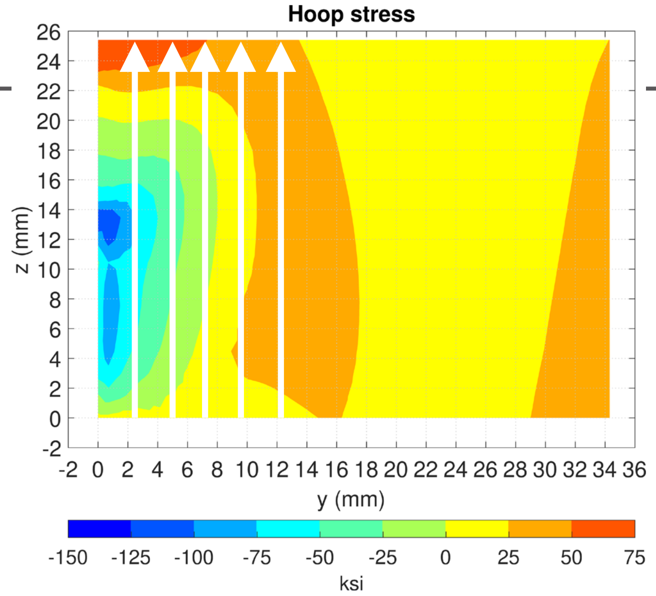
Line plots comparing model and neutron diffraction (ND) measurements below

- Through the thickness from the cx entry surface
- Radial, hoop, and axial residual stress results shown



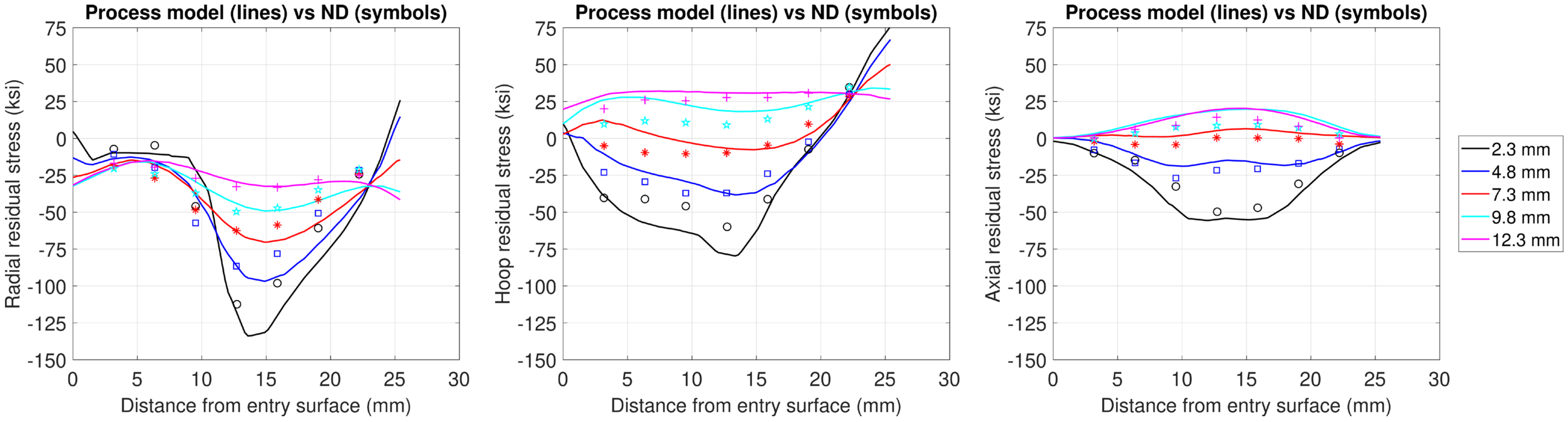
Results: Model and ND (50%)

7050-T7451



Line plots comparing model and ND measurements below

- Through the thickness from the cx entry surface
- Radial, hoop, and axial residual stress results shown



To be continued

EDXRD measurements this week (Feb 16-23, 2022)

Contour measurements to follow (Spring 2022)

Publication to be completed (Summer 2022)

Summary and Future Opportunities

Committee logistics

Active work

Opportunities in store

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

ERSI

ERSI RISK AND UQ SUBCOMMITTEE ACTIVITIES

Virtual ERSI Workshop

February 2022

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?

Committee Members

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

Statistics, UQ, and V&V References

- ASTM E739-10, “Standard Practice for Statistical Analysis of Linear or Linearized Stress-Life or Strain-Life Fatigue Data,” American Society of Testing and Materials, 2015.
- ASTM E2586-19, “Standard Practice for Calculating and Using Basic Statistics,” American Society of Testing and Materials, 2020 Revision.
- Efron, Hastie, *Computer Age Statistical Inference,* 2017 – Free PDF
- ASME V&V 10 – Standard for Verification and Validation in Computational Solid Mechanics

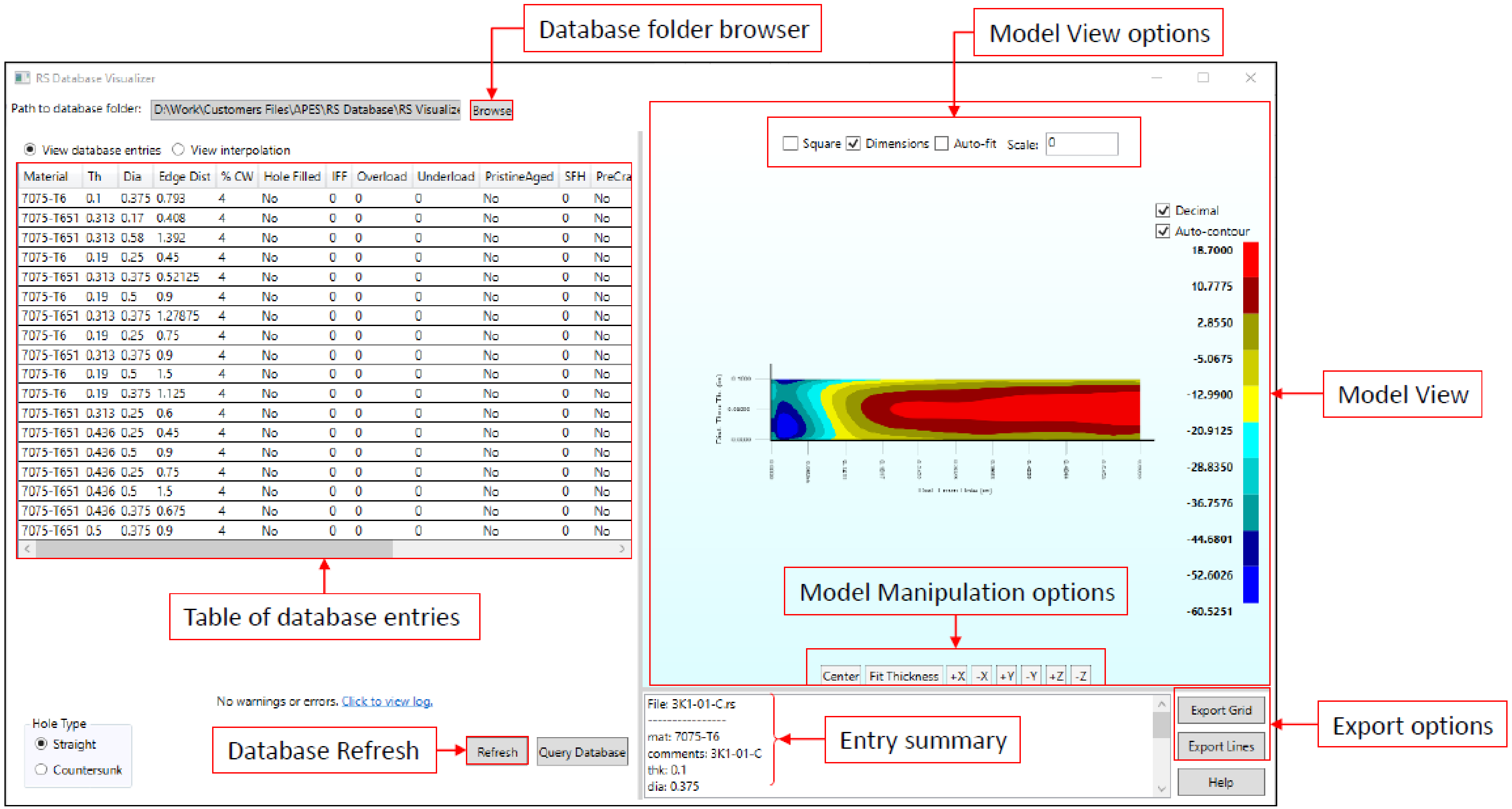
New Residual Stress Database

APES, Inc.

Residual Stress Database

- Old capabilities retained: visualization, library, search db, interpolations of multiple files.
- New capabilities
  - Filtering of over 15 new parameters (old (5): material, CX%, D, t, e/D. new (24): over/underload, pre-cycles, filled holes, pristine/aged, CX countersink process, etc.)
  - AFGROW .sd3 (Residual stress data) output (Export Lines)
  - Handles replicates

Residual Stress Database-Library & Visualization

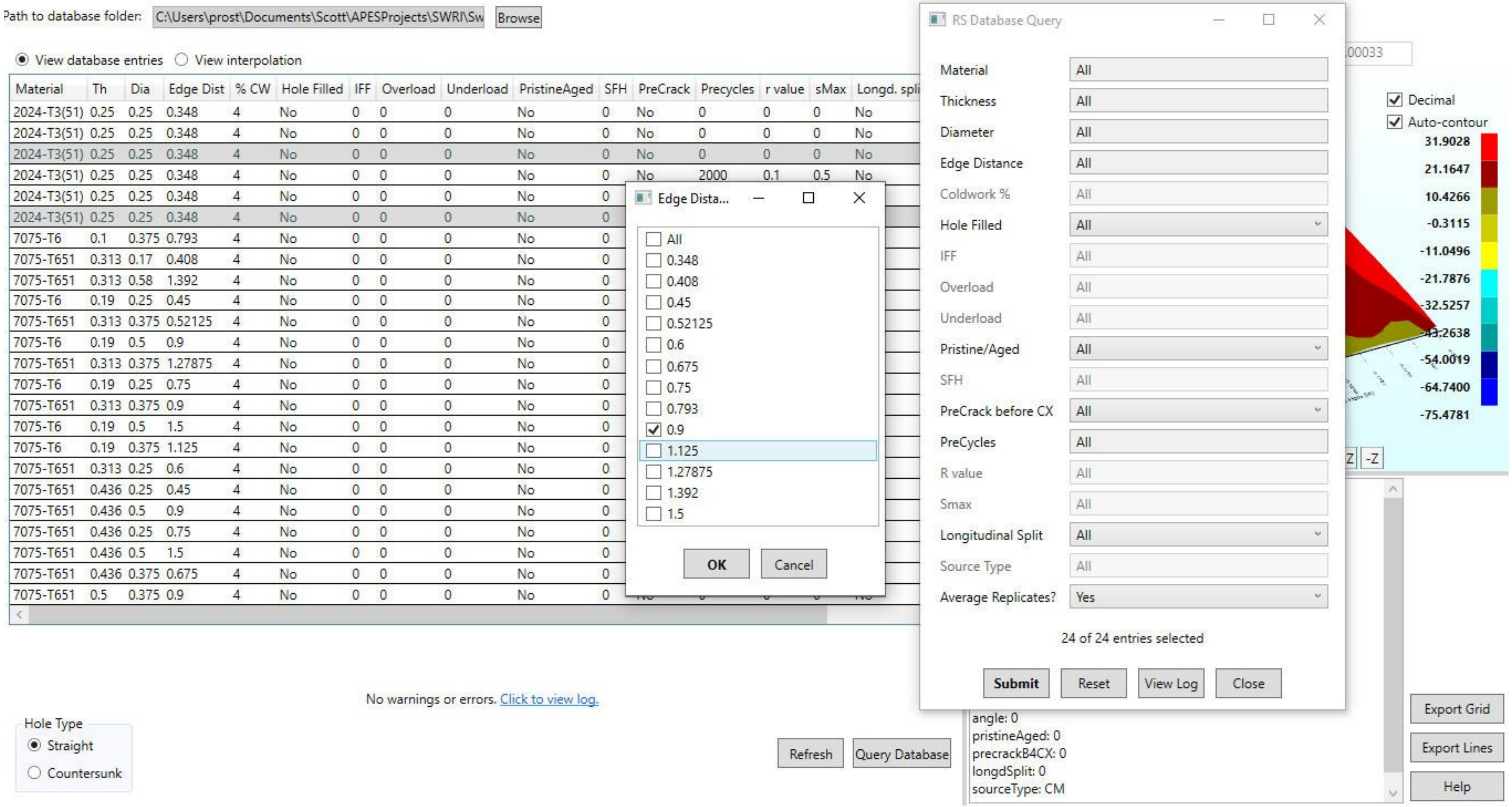


Over 15 unique parameters added

Entry Fields

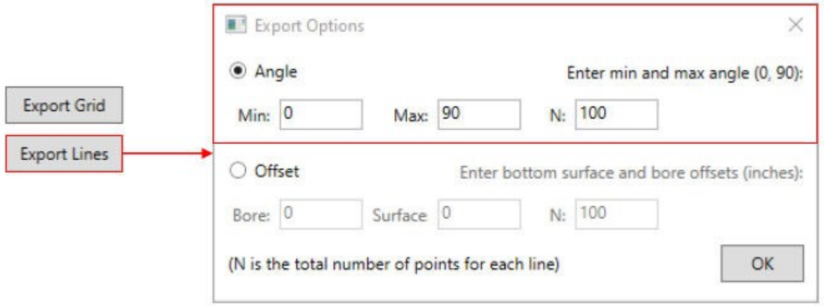
ID#	Parameter	Description	Type	Dependencies
1	mat	Material name	String	Required
2	comments	Coupon information or other	String	Required
3	thk	Thickness	Double	Required
4	Dia	Diameter	Double	Required
5	ed	Edge Distance	Double	Required
6	pctCX	Percentage Cold Work	Double	Required
7	cskProc1	Countersink process	String	10,11
8	angle	Countersink angle	Double	Required
9	depth	Countersink depth	Double	Required if 10 is not = 0, 7
10	precycles	Number of pre-cycles	Integer	20 must be Yes, 11,12
11	rvalue	R value	Double	20 must be Yes, 10,12
12	smax	Pre-cycle load	Double	20 must be Yes, 10,11
13	replicates	Replicate number out of a set	Integer.Integer	Required
14	holeFilled	Boolean	Boolean	Required
15	iff	Interference Fit during pre-cycle	Double	14 must be Yes
16	overload	Overload as percentage of Yield	Double	14 must be Yes
17	underload	Underload as a percentage of yield	Double	14 must be Yes
18	sfh	Spectrum Flight Hours	Integer	19 must be Yes
19	pristineAged	When cold work is performed on a pristine or aged material	Boolean	Required
20	precrackB4CX	Existing pre-crack on coupon	Boolean	Required
21	longdSplit	For specimens where longitudinal cut was made to compute RS	Boolean	Required
22	sourceType	FEA (Finite Element Analysis), CM (Contour Method), EC (Eddy Current), ND (Neutron Diffraction), etc.	String	Required

Filtering capability added



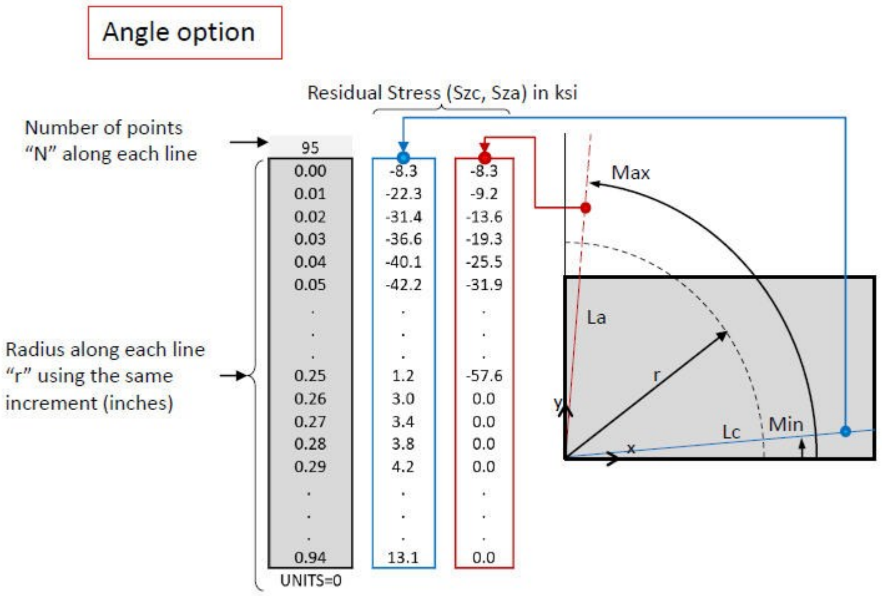
Export to AFGROW readable residual stress file

Export Lines option



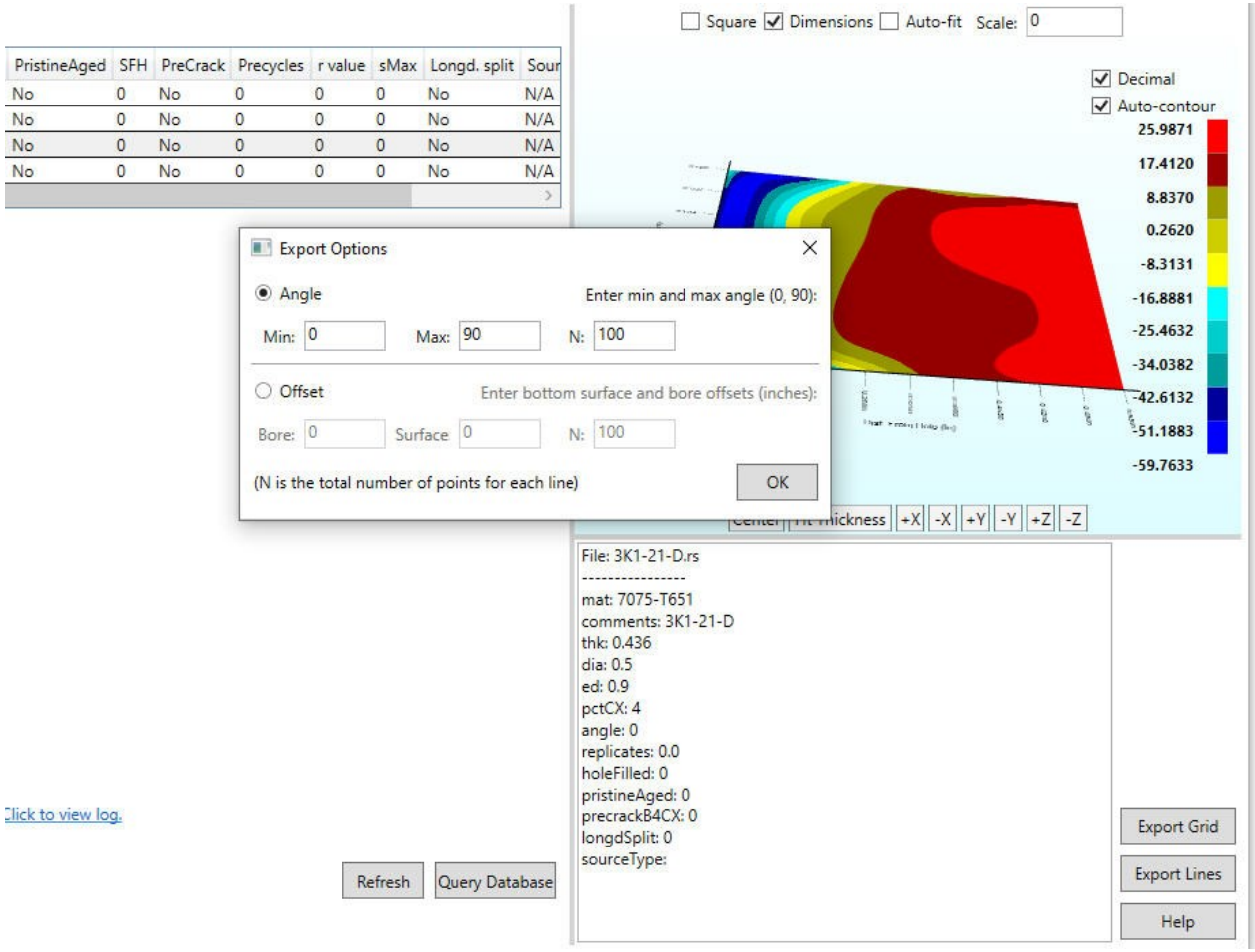
The Export Lines option can be used to output a file with interpolated residual stress in (x,y,Sz) columns in an ASCII file format with extension *.sd3:

N (integer)
r1 (double) Szc1 (double) Sza1 (double)
r2 (double) Szc2 (double) Sza2 (double)
...
rN (double) SzcN (double) SzaN (double)
UNIT=0 (string)



Increment = max(La,Lc)/(N-1)

Export along angles or offset distances



Available, Free!

- Original database had 47 RS profiles
- 2021 update includes 323 RS profiles
  - User can add profiles
- For access, contact Scott Prost-Domasky: prost@apesolutions.com

ERSI

Sensitivity Study on Cold Expanded Fastener Hole Damage Tolerance Life

A Collaborative ERSI Effort

Presented at the AFGROW Workshop 2021

Acknowledgements

- **Fatigue Technology Inc.**
  - Keith Hitchman
  - Sam Zimmerman
- **USAF**
  - Jake Warner
- **Hill Engineering**
  - Dallen Andrew
  - Josh Hodges
- **SwRI**
  - Matt Kirby

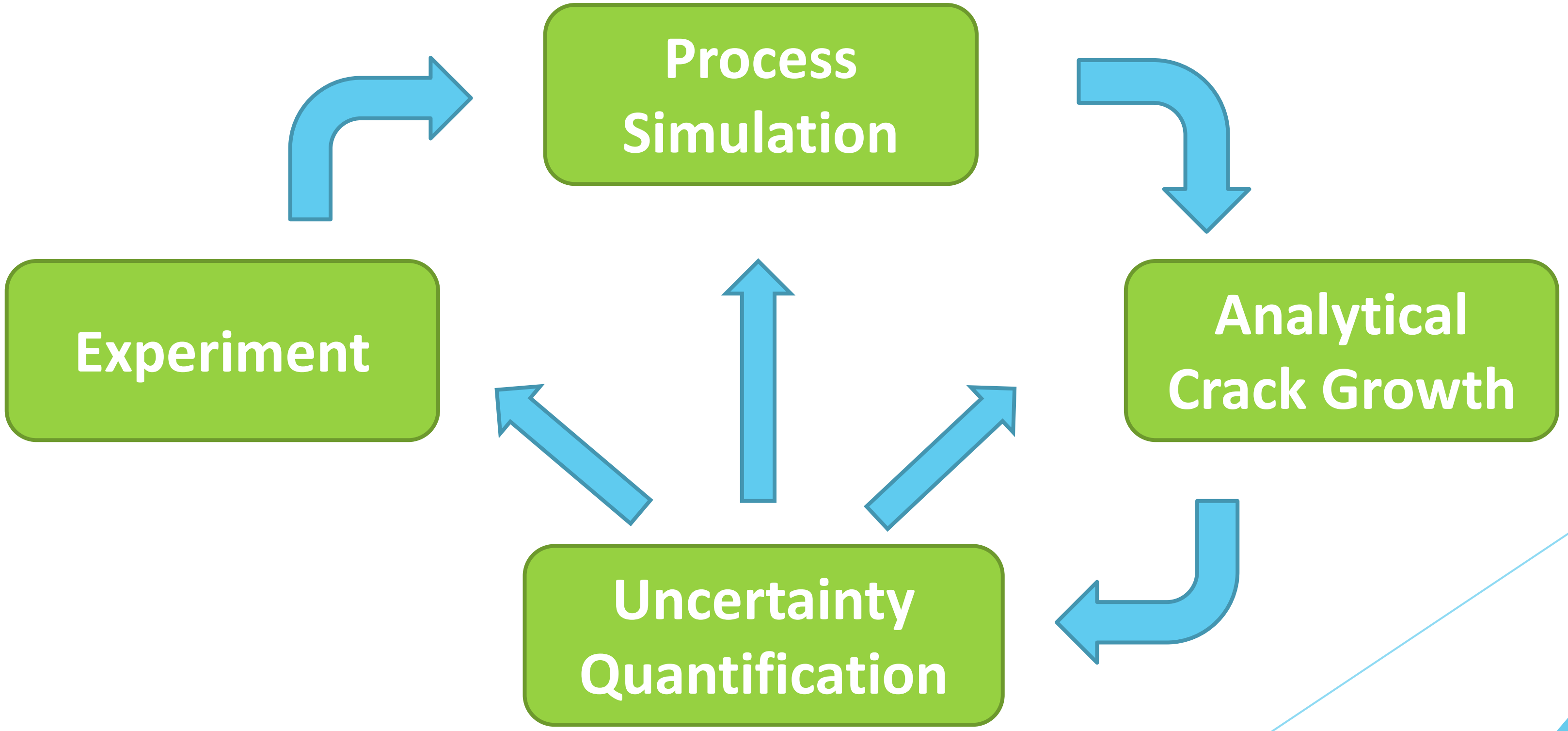
ERSI

What is Sensitivity Analysis?

- Sensitivity methods are analyses complementary to risk and uncertainty quantification that can help determine the impact of an input variable
- Sensitivity methods can have a tangible impact on analysis and testing
  - Save time
  - Save money
  - Spend time and money on characterizing the most important inputs

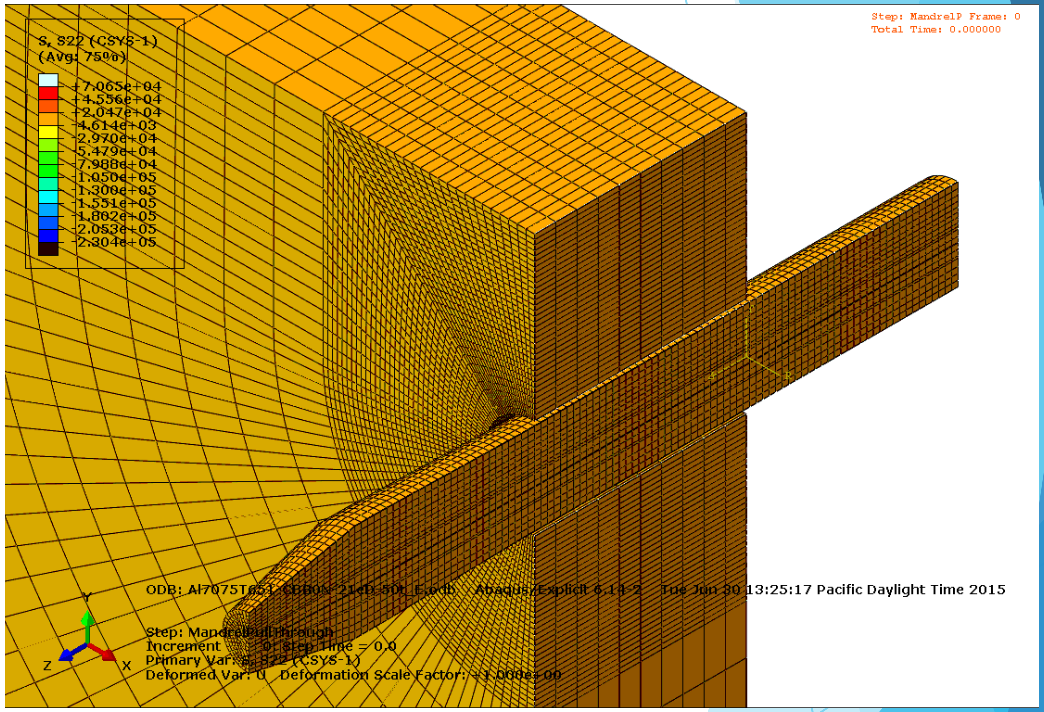
Data Flow

- Data flow through ERSI committees
  - Data gleaned from UQ/SA can inform all stages of the process



Specimen Geometry

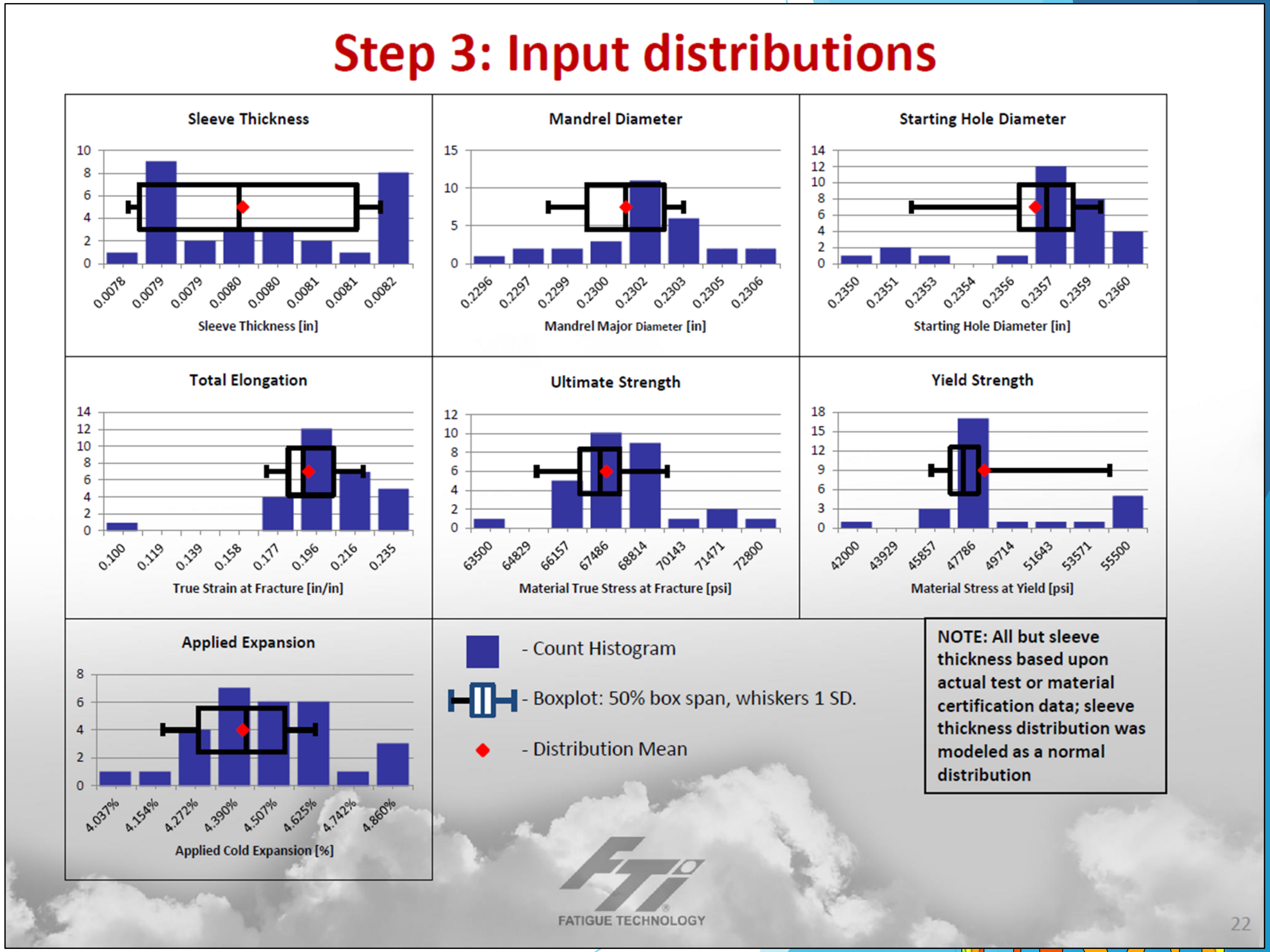
- FTI has an ABAQUS model of their cold expansion process
- Two load steps: mandrel pull-through and reaming
- 0.5” aluminum plate thickness



From 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.

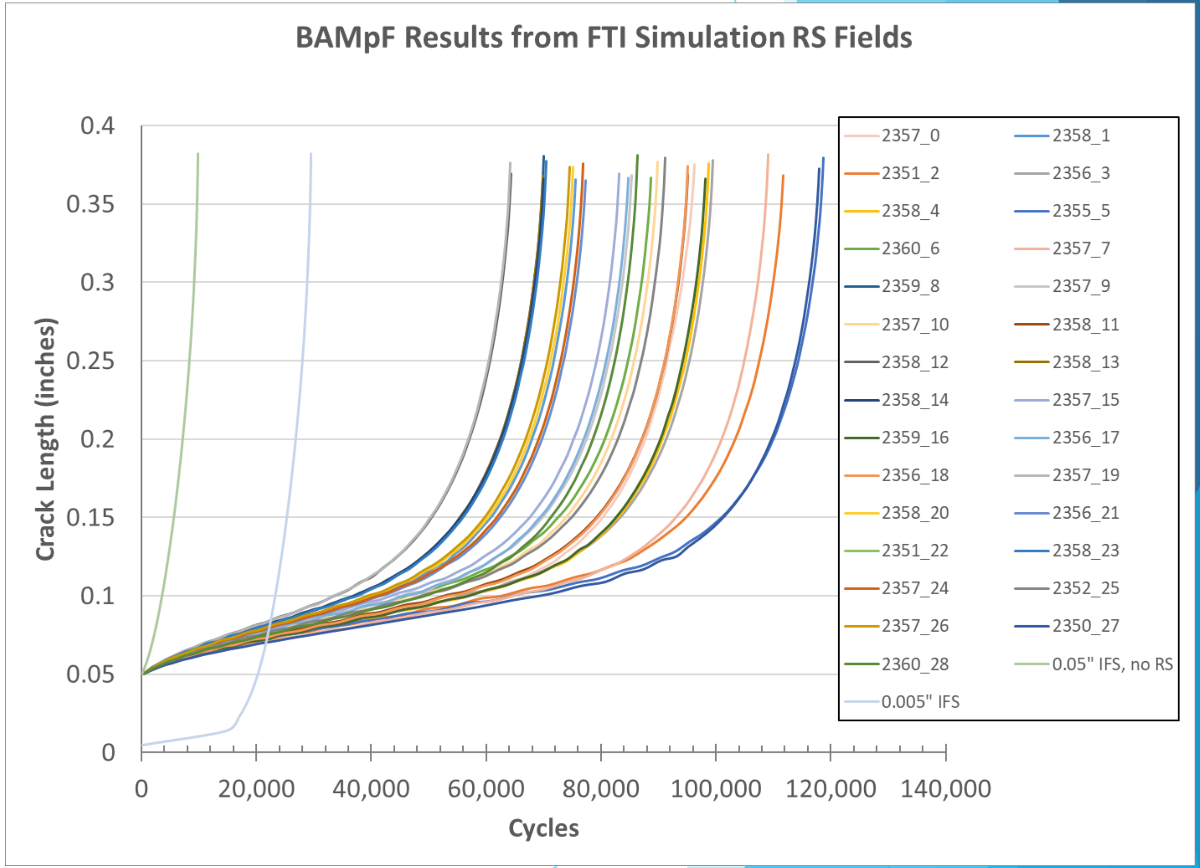
FTI Simulation Study

- FTI ran 29 samples of their cold expansion simulation ABAQUS model
- Results were provided to UQ and Analytical Methods Comms.
- Note that samples (except for sleeve thickness) were based on actual measurements, not from a distribution or DOE



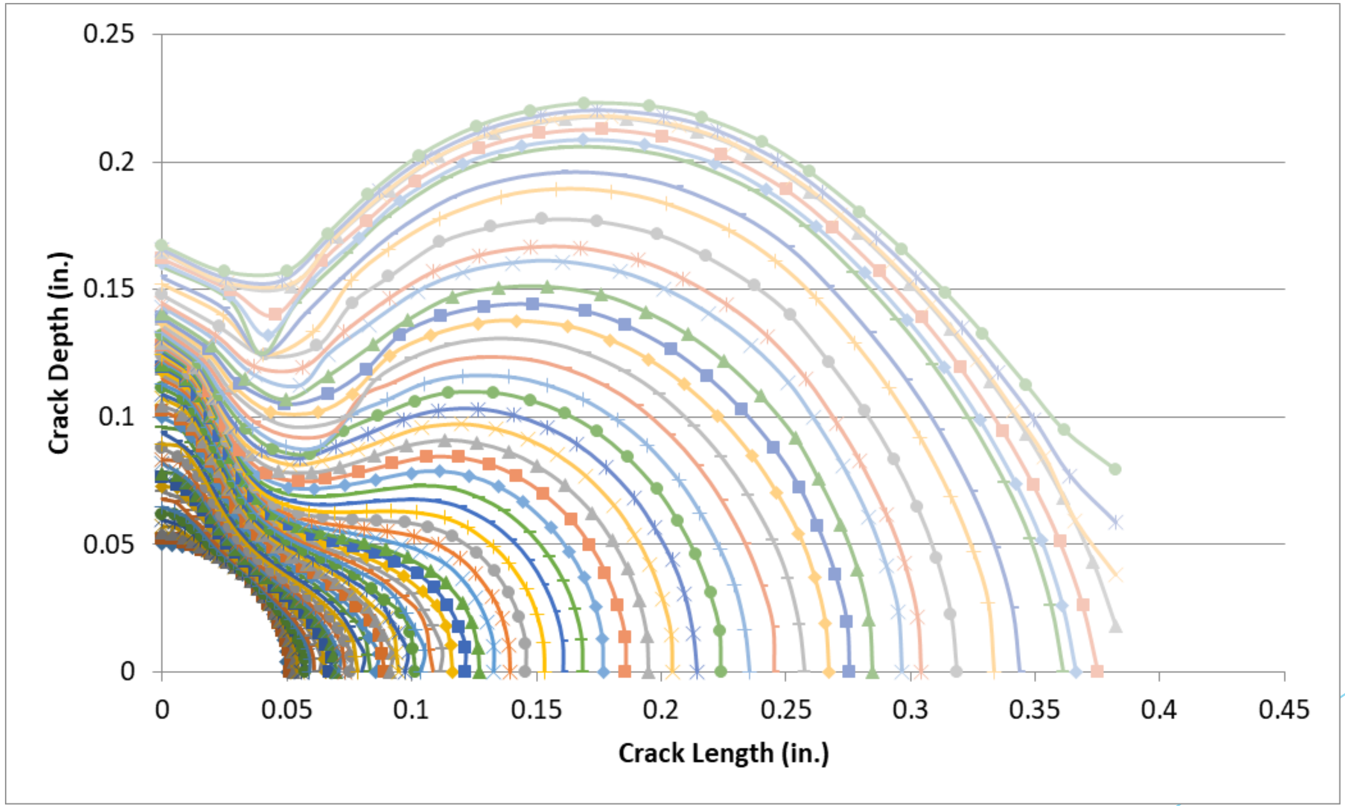
BAMpF Crack Growth Simulation

- Analytical Methods Committee used the resulting residual stress fields to grow a crack from an IFS of 0.05 in.
- Also ran cases with no RS from 0.05 and 0.005
- Note that most life benefit due to a compressive stress field happens below crack sizes of 0.05 inches
- However, since the initial flaw size of a DTA is associated with NDI capability, the initial flaw size remains the same despite the beneficial stress field



BAMpF Simulation

- Typical crack front with residual stress included



Correlation Matrix

	Starting D	Elongation	Mandrel Diameter	Sleeve Thickness	Applied Expansion	Ultimate Strength	Yield Strength	Life
Starting D	1.00	-0.02	0.02	-0.11	-0.61	0.15	0.09	-0.56
Elongation	-0.02	1.00	0.15	0.14	0.17	0.60	0.74	0.14
Mandrel Diameter	0.02	0.15	1.00	0.03	0.52	-0.22	-0.10	0.34
Sleeve Thickness	-0.11	0.14	0.03	1.00	0.67	-0.11	0.00	0.79
Applied Expansion	-0.61	0.17	0.52	0.67	1.00	-0.26	-0.10	0.95
Ultimate Strength	0.15	0.60	-0.22	-0.11	-0.26	1.00	0.80	-0.22
Yield Strength	0.09	0.74	-0.10	0.00	-0.10	0.80	1.00	-0.09
Life	-0.56	0.14	0.34	0.79	0.95	-0.22	-0.09	1.00

Applied Expansion (I_a) is given by the following formula:

$$I_a = \frac{(D + 2t - SHD)}{SHD} \times 100\%$$

Where:

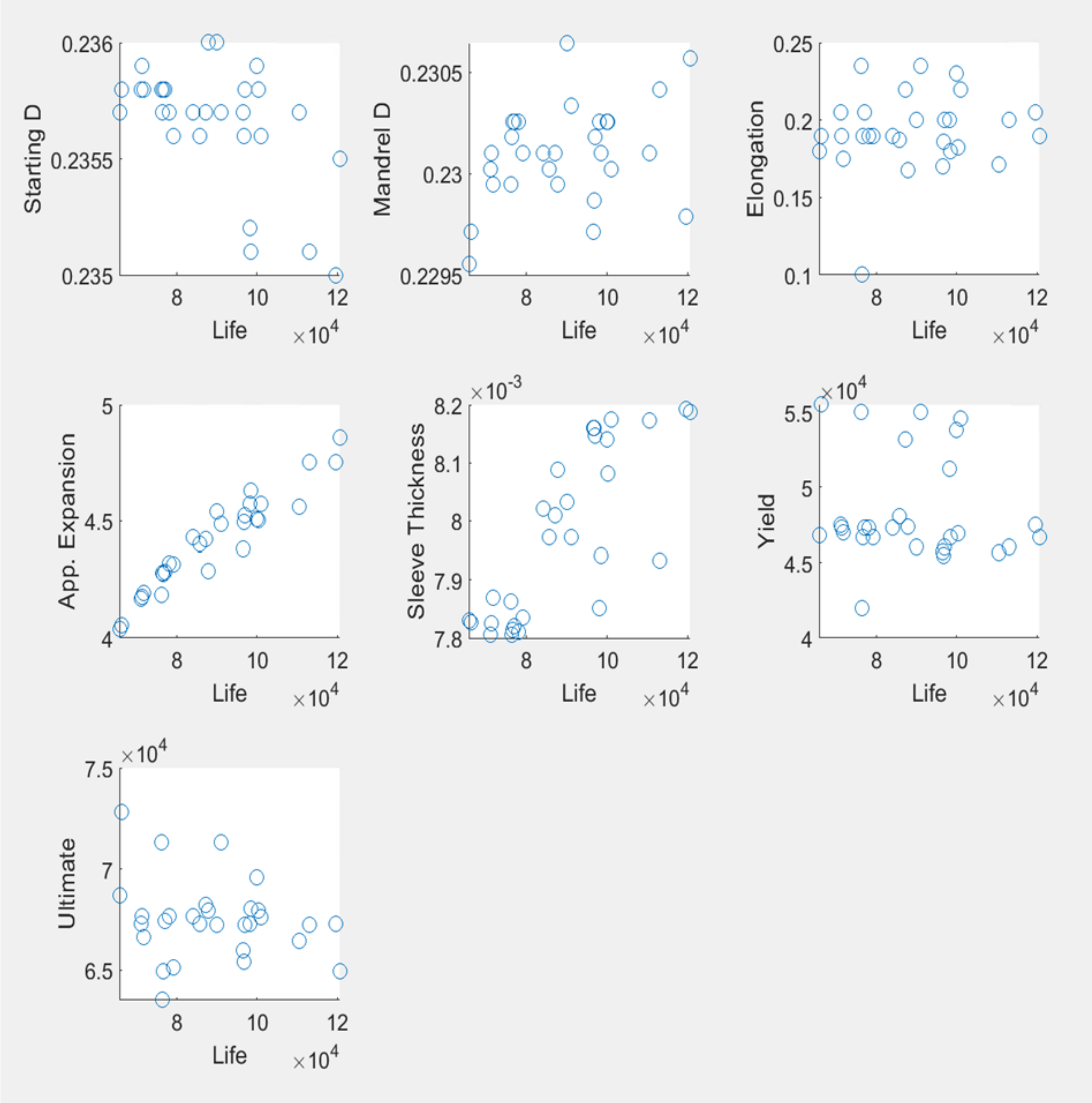
D = *Major Mandrel Diameter*
t = *Sleeve Thickness*
SHD = *Starting Hole Diameter*

Reality Check

- Life is strongly correlated to applied expansion
- Yield is positively correlated to Ultimate
- Applied expansion is inversely correlated to starting hole diameter

Scatter Plots

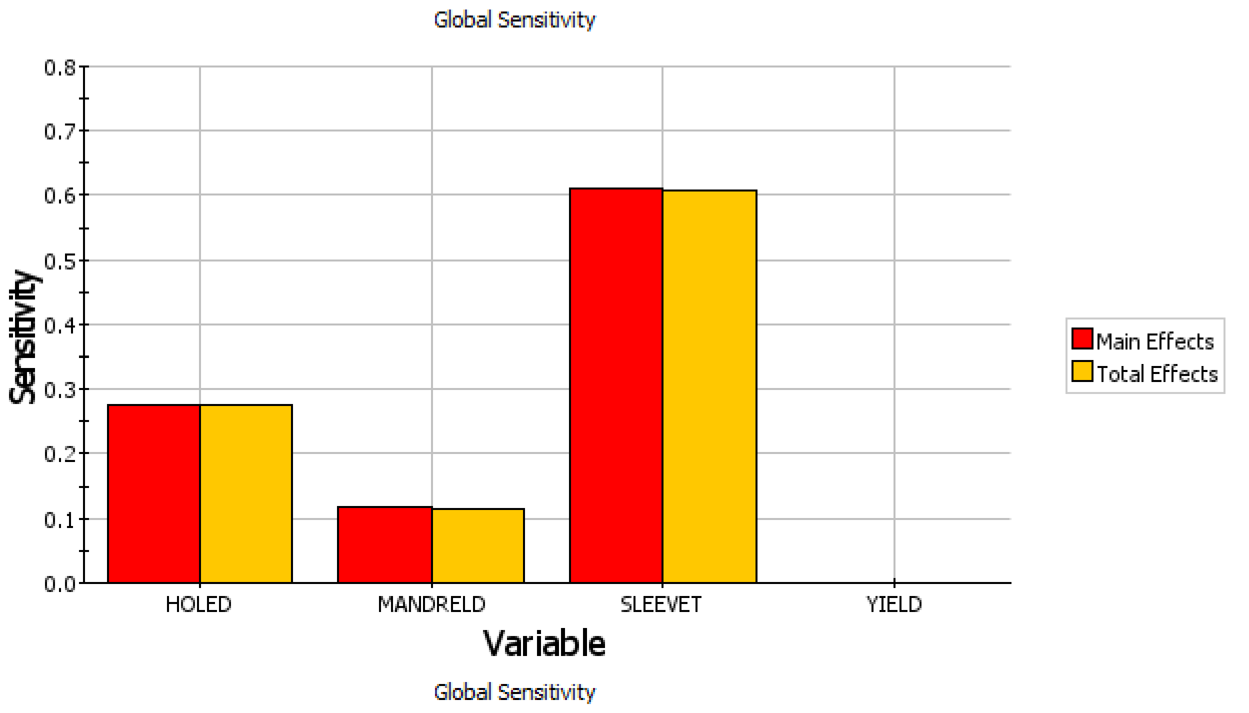
- All variables vs. Life
- High correlation between Applied expansion and Life
- Low correlation between Yield/Ultimate and Life
  - Sensitivity studies of RS fields found high correlation between material properties and outputs of interest
  - Emphasizes importance of defining the intended use of models



ERSI

Global Sensitivities

- Calculated sensitivities on the linear reduced model using NESSUS
  - Note that main and total effects are the same due to linear model
- Sleeve thickness dominates, however,
  - small sensitivities could be due to unstructured sampling



Recommended Future Studies

- Rerun FTI models using a structured sampling method, such as Latin Hypercube
- Do more detailed studies between RS fields and Life to determine a proper metric for RS fields
- Compare results of BAMpF vs. regular AFGROW 2-pt models

Activities for Upcoming Year

- Perform risk calculations for crack growth simulations in the presence of residual stresses.
- Sensitivity and parametric study
- Provide support to other subcommittees as needed.

Analytical Methods & Testing Committee: Overview Presentation

Engineered Residual Stress Implementation (ERSI) Workshop

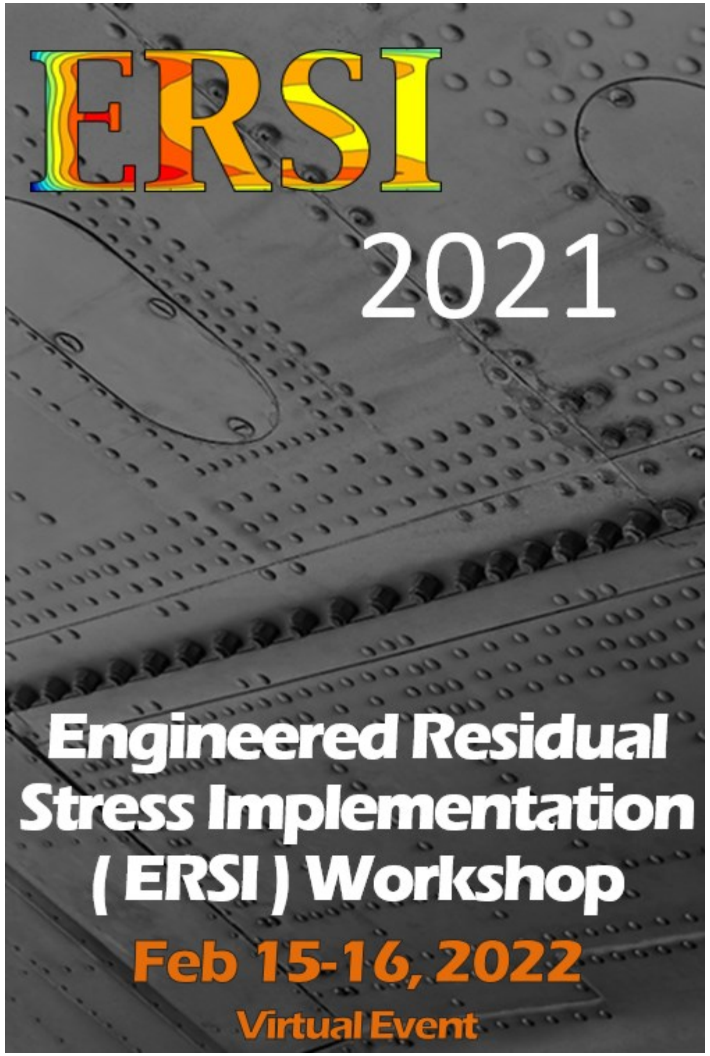
February 16, 2022

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

Kevin Walker, committee co-lead
kfwalker@qinetiq.com.au
kwalker999@hotmail.com

Agenda

- Mission Statement and Goals
- 2021 Achievements
  - Round Robins
    - Interference Fit Fastener Round Robin
    - Stress Intensity Factor Round Robin
    - Overload Challenge
  - Relevant Programs
    - Multi-Point MAI Program
    - Taper-Lok Analysis Methodology & Testing
  - Analysis Methods
    - Two vs. Multi-Point Analysis Comparisons
  - Testing
    - Kt-Free Coupons
- 2022 Focus Areas



ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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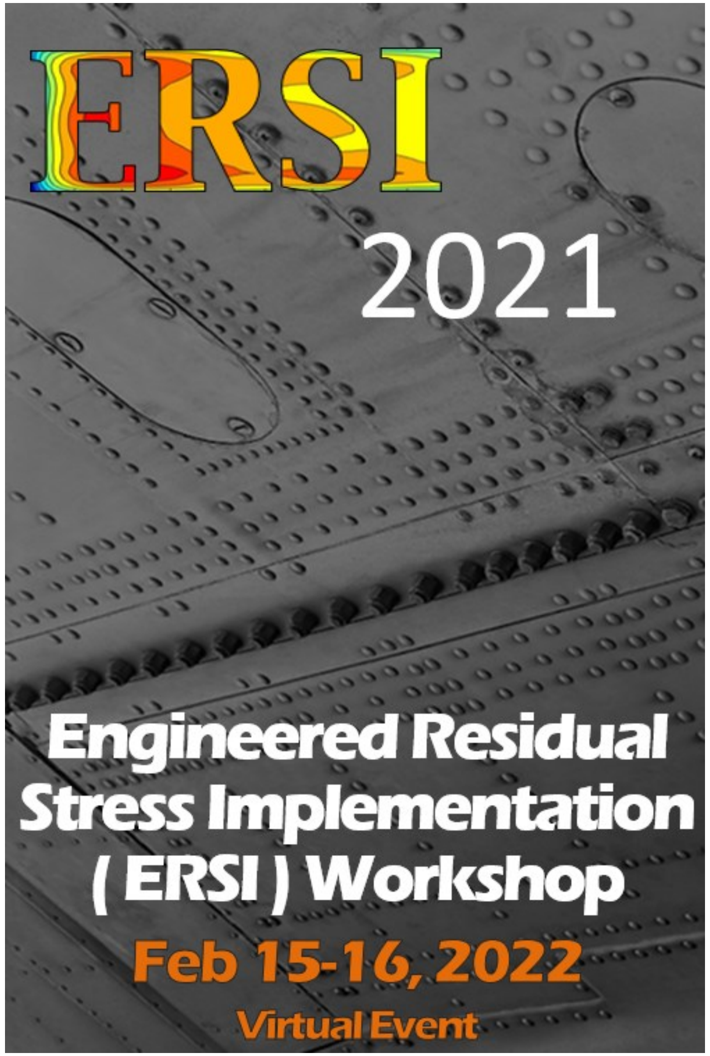


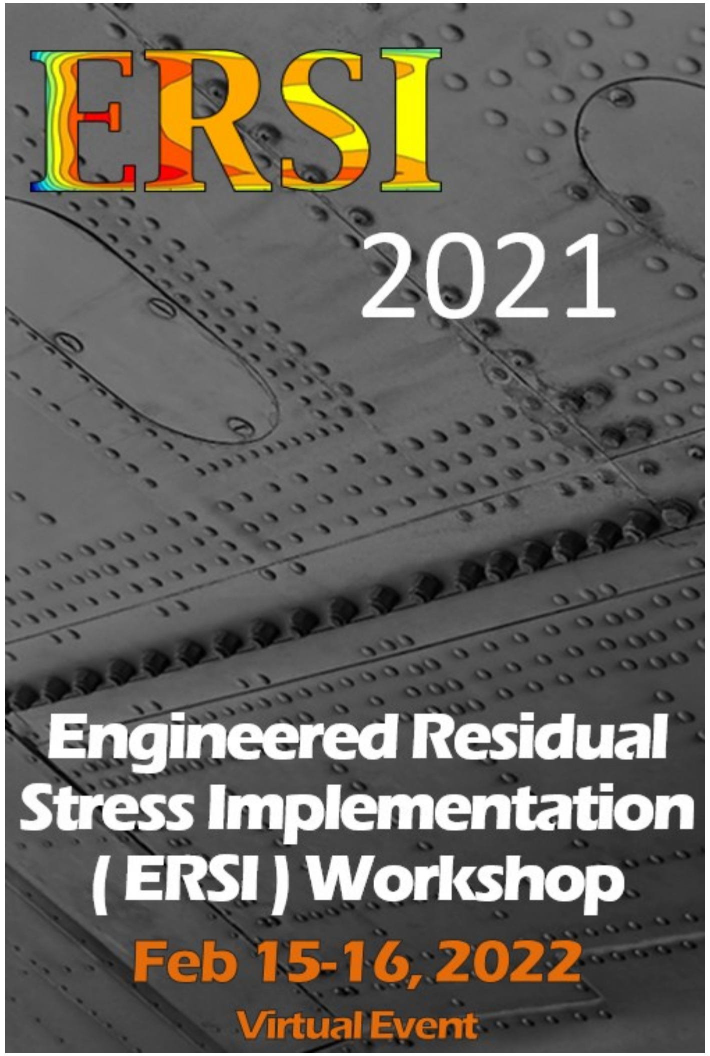
FCG Analysis & Test Committee Vision

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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

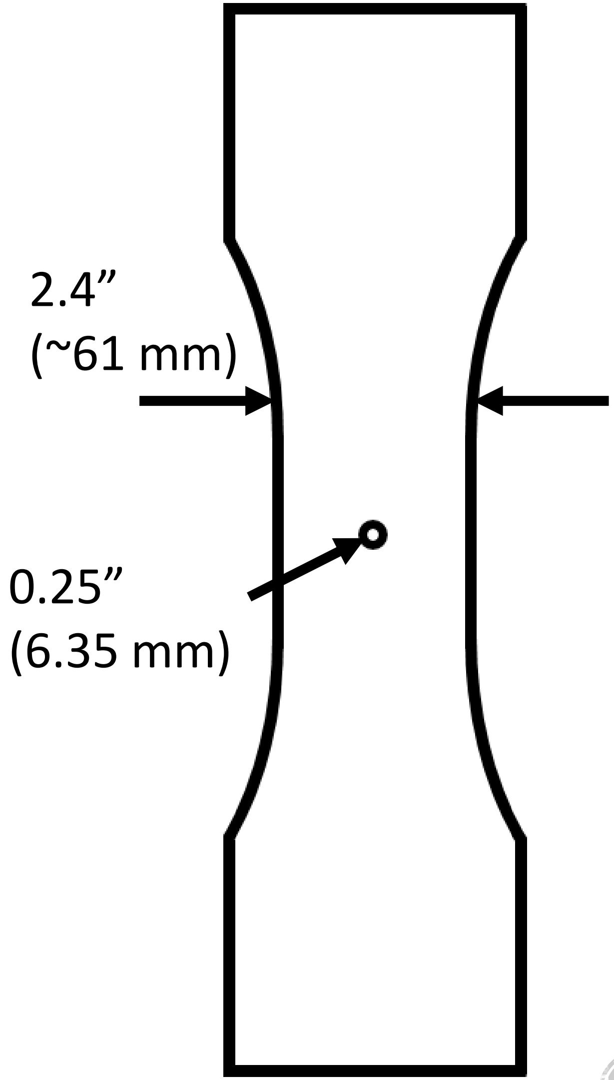
Agenda

- Mission Statement and Goals
- 2021 Achievements
  - Round Robins
    - Interference Fit Fastener Round Robin
    - Stress Intensity Factor Round Robin
    - Overload Challenge
  - Relevant Programs
    - Multi-Point MAI Program
    - Taper-Lok Analysis Methodology & Testing
  - Analysis Methods
    - Two vs. Multi-Point Analysis Comparisons
  - Testing
    - Kt-Free Coupons
- 2022 Focus Areas

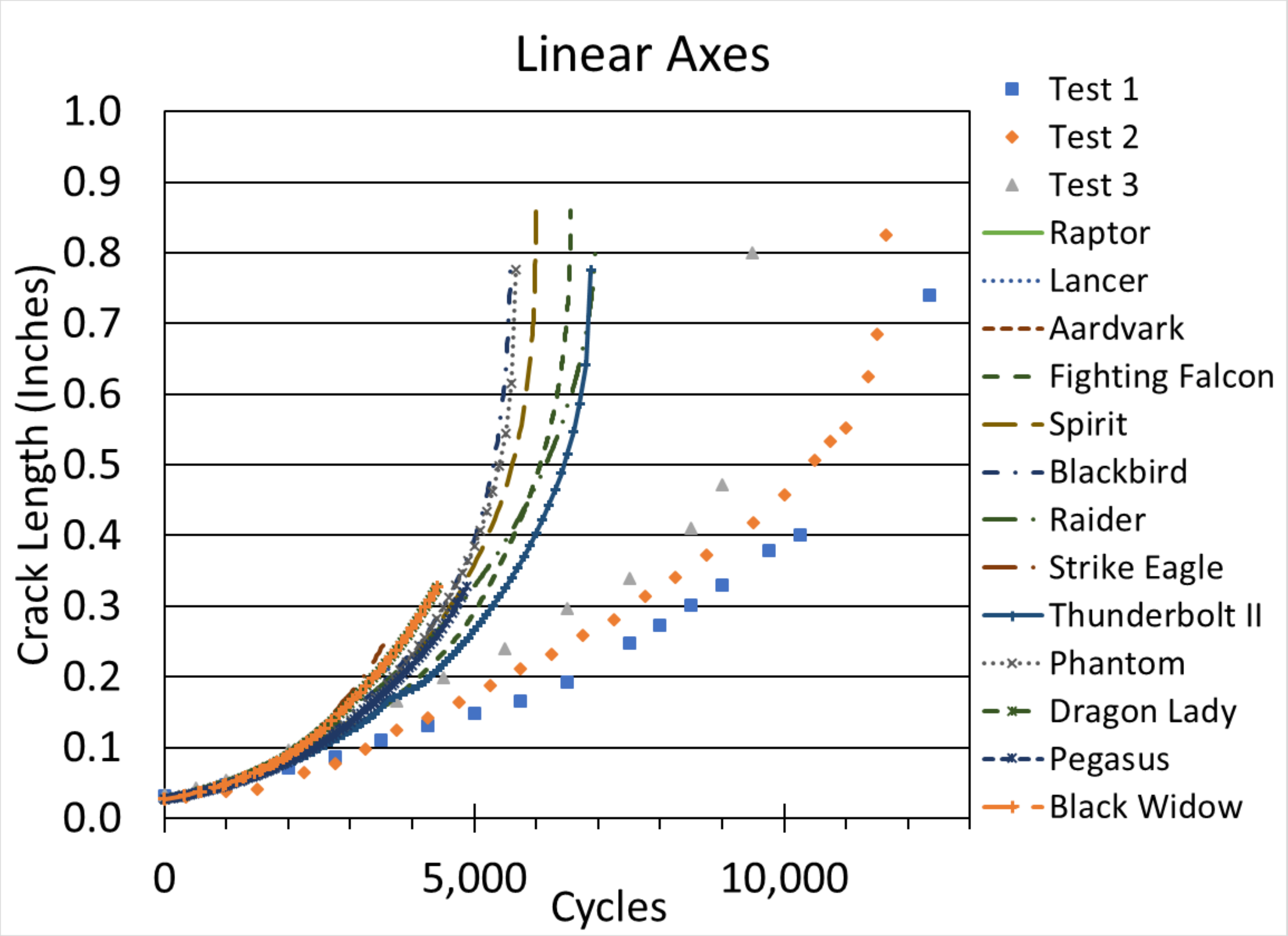


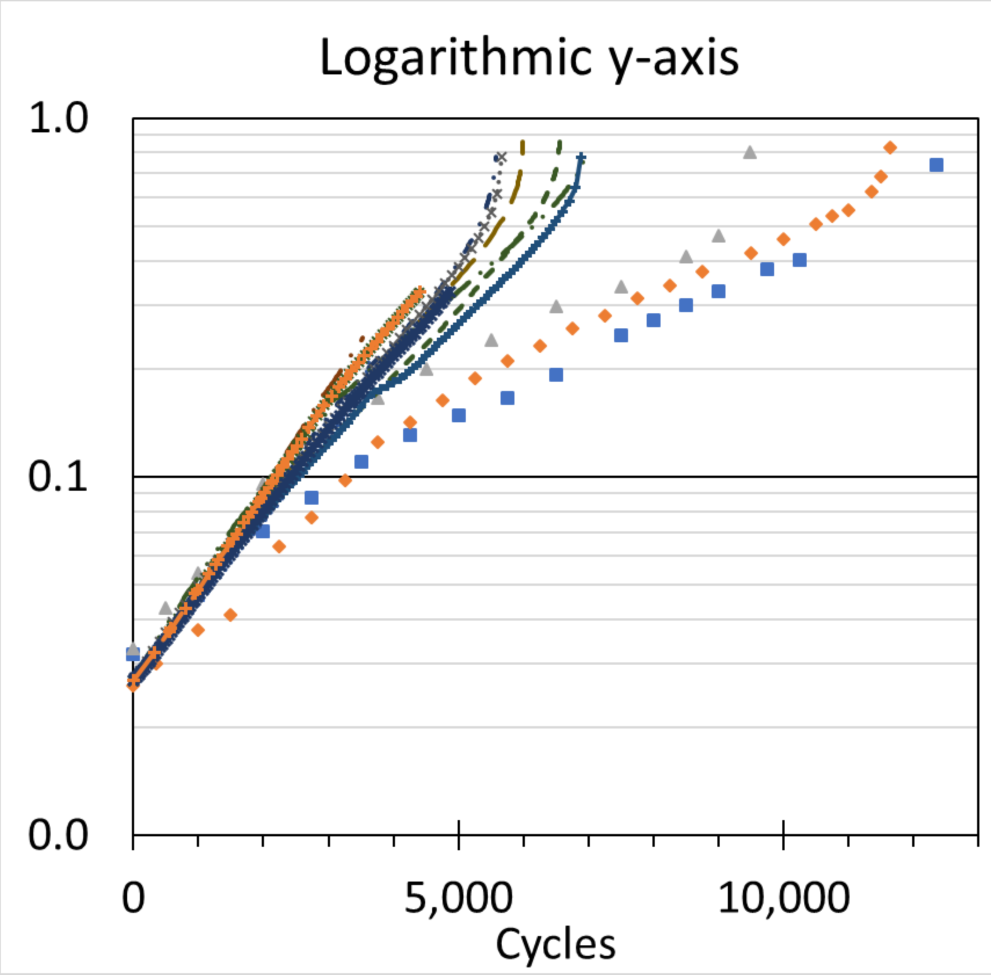
Interference Fastener Round Robin

- <u>Loading & Geometry</u>
  - Constant amplitude, R = 0.1, 27.9 ksi (192.4 Mpa)
  - 7075-T651, 0.25" (6.35 mm) thick
  - 0.027" (~0.69 mm) precrack
  - Hi-Lok (steel) fastener, target 0.4% interference
  - Two (2) conditions tested
    - Open hole
    - 0.4% interference Hi-Lok (not torqued)
  - Three (3) conditions predicted
    - Open hole
    - 0.4% interference
    - 0.6% interference

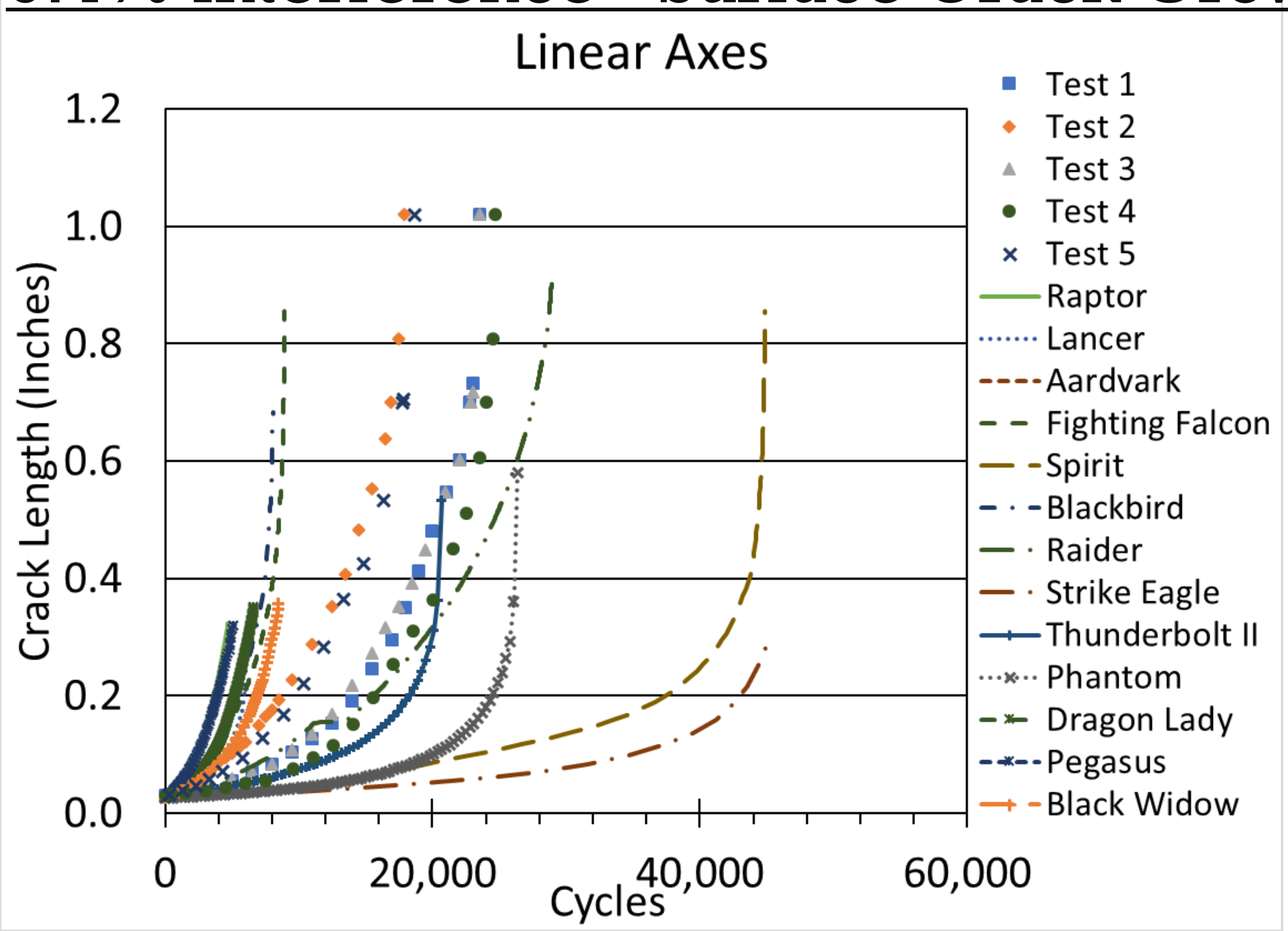


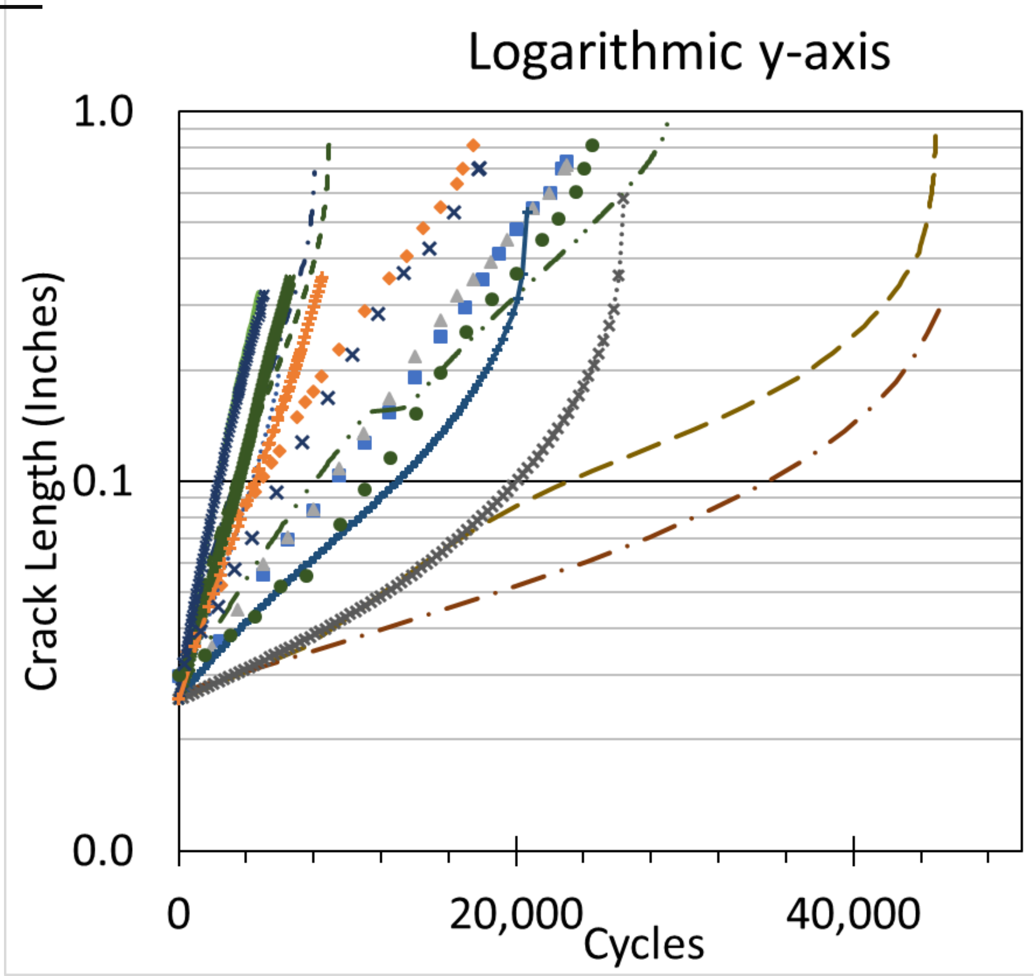
- Open Hole Results Surface Crack





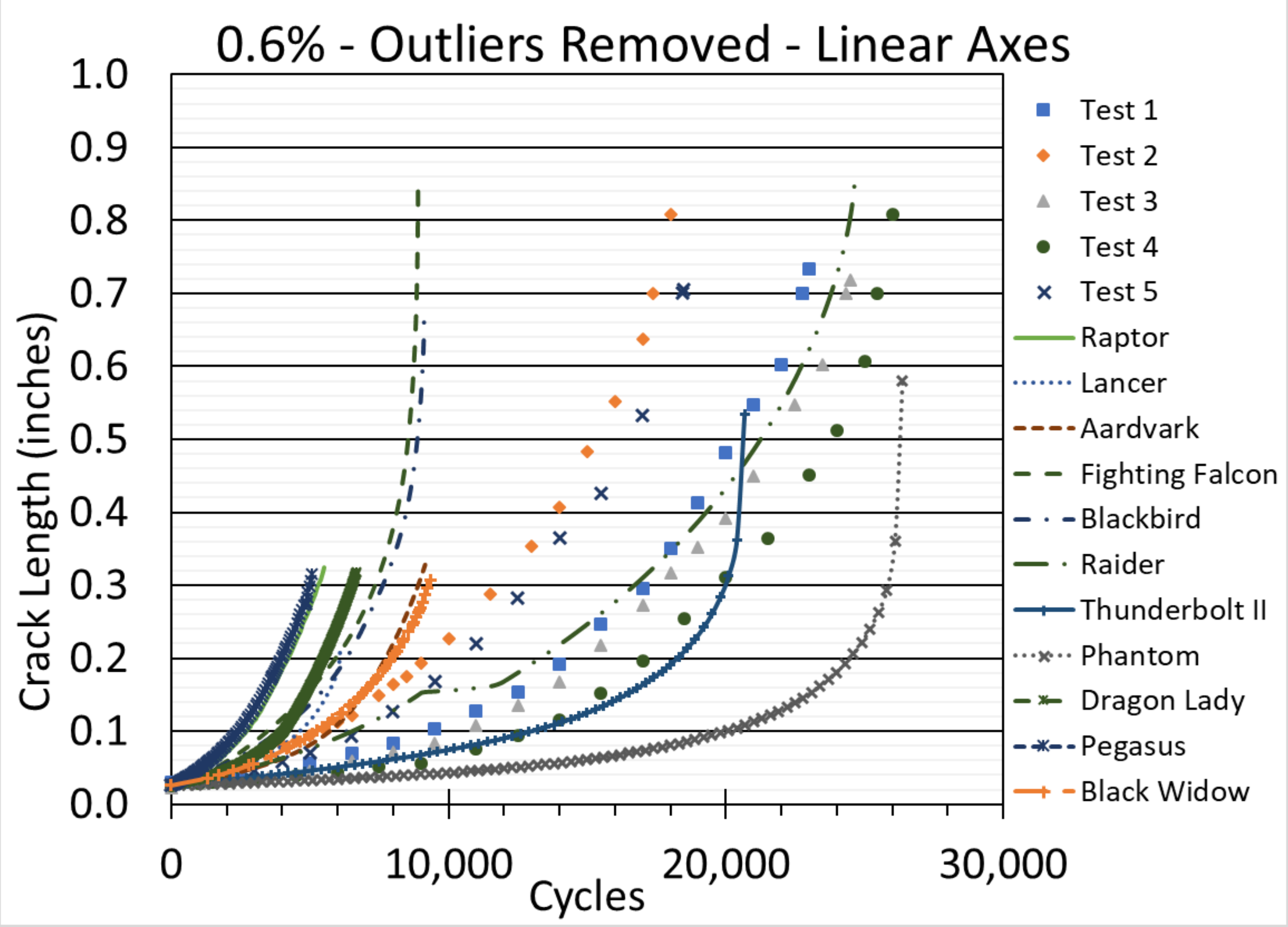
- 0.4% Interference - Surface Crack Growth

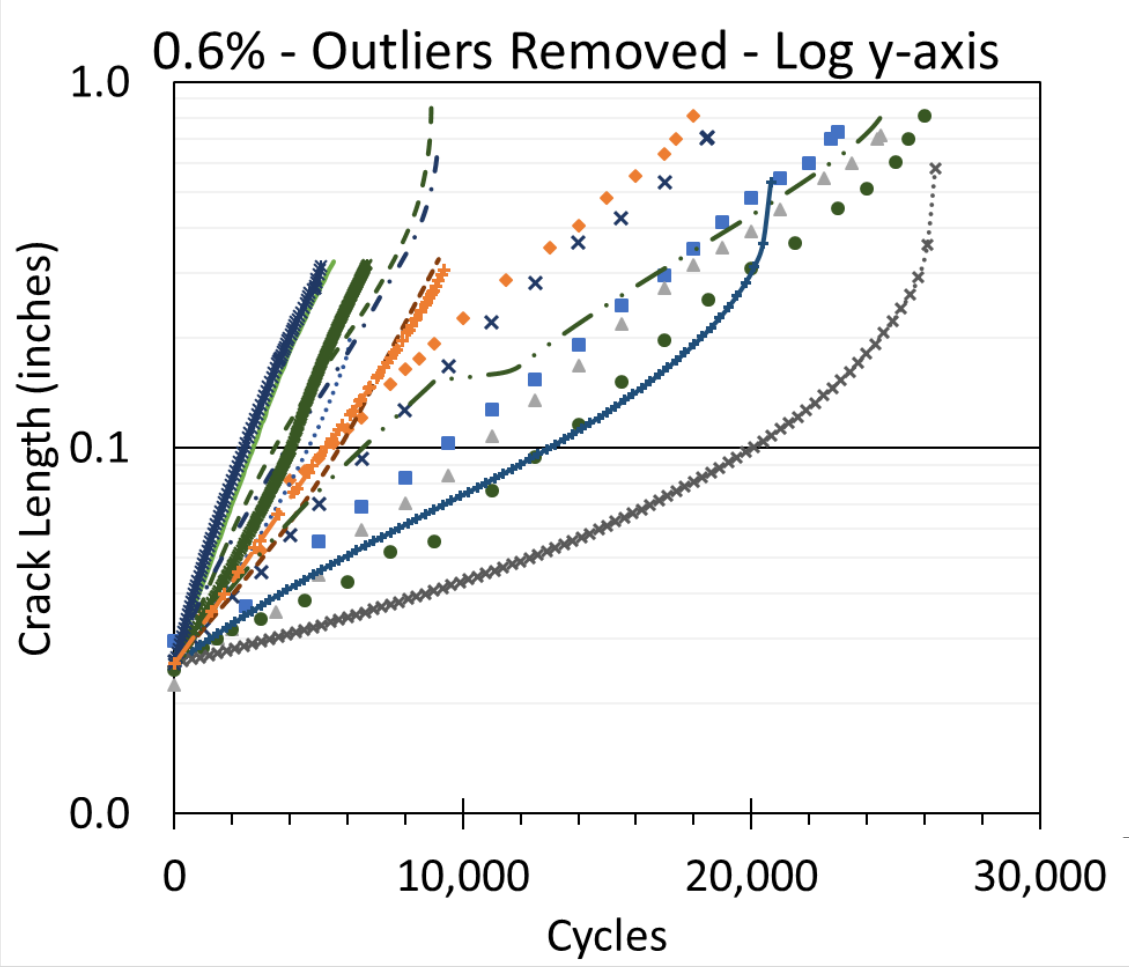




Interference Fastener Round Robin

▪ 0.6% Interference - Surface Crack Growth





Interference Fastener Round Robin

- Discussion
  - Is good correlation of interference fit cases a function of under predicting the open hole case? i.e. Is the analytical benefit too large and correlation appears good only because the open hole model under predicted?
  - How applicable is the surface correction offered for the open hole case?
  - Would a 27.9 ksi max stress cause plasticity effects that potentially violate the bounds of LEFM for the open hole case?
  - Would it be valuable to add a neat fit fastener condition to this set?

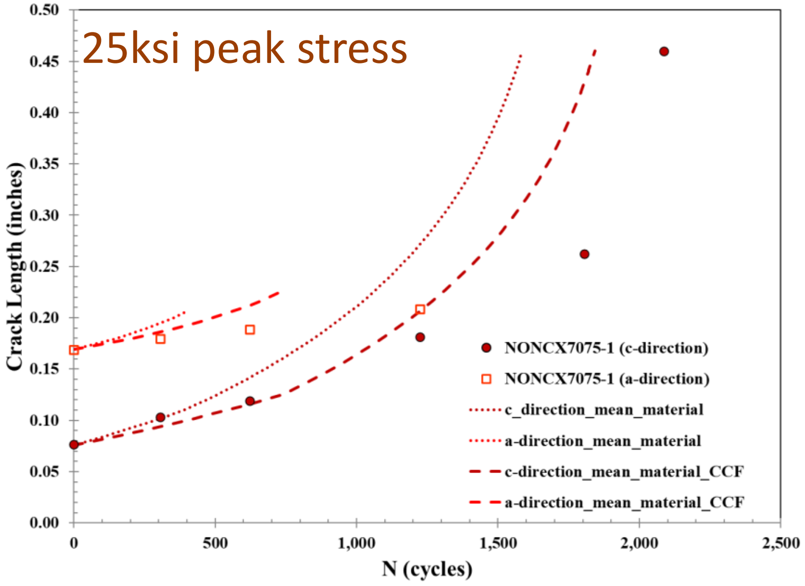
No, really.
Let's talk

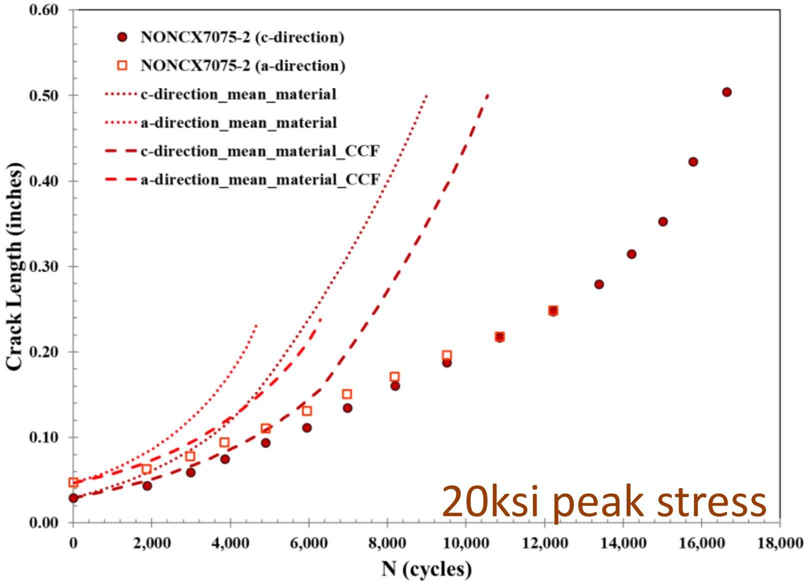
Interference Fastener Round Robin

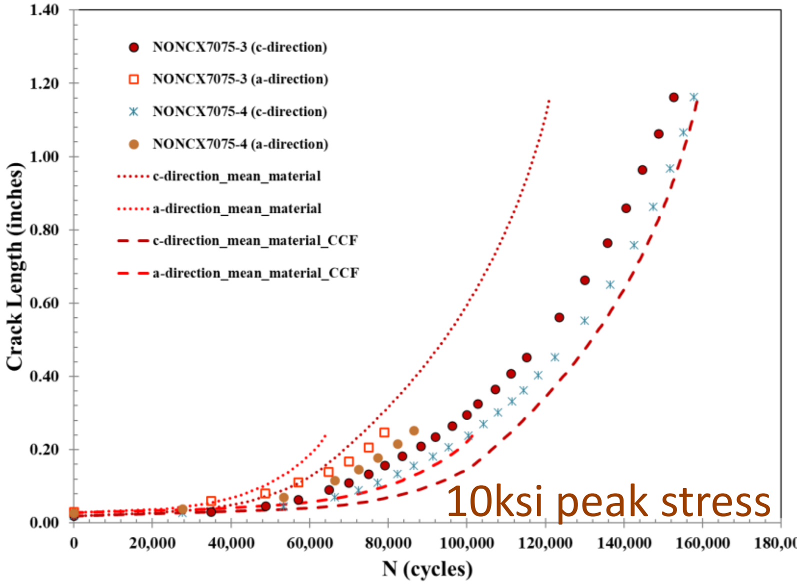
- Initial Conclusions
  - Tight grouping of open hole predictions, although all under predicted test data
  - Surface correction shows promise for open hole condition
  - Effective stress approach used by Raider submission closely matched life and crack growth curve shape
  - Raider approach with provided lookup file and using AFGROW matched one group of tests well with the 0.4% prediction and another set with the 0.6% prediction

Interference Fastener Round Robin

- <u>Follow-Up Investigations</u>
  - Utilized updated crack growth rate data, AFGROW Advanced Model [w Crack Closure Factor (CCF)] and BAMpF with surface correction predictions were completed for another test data set (Pilarczyk Master's Thesis)
  - New "mean" fit to crack growth rate data is still conservative relative to tests
  - AFGROW Advanced Model predictions with CCF improved predicted life
  - BAMpF with surface correction improved predicted life and crack growth shape







▪ Follow-Up Investigations

Provided data

Specimen Design

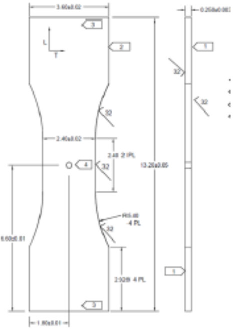
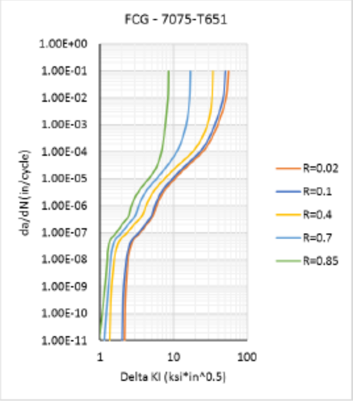


Table 1. Round-robin analysis conditions

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

Different 3D models were created based on different nominal dimensions

Fatigue Crack Growth Data



Fatigue Crack Growth Rate measurement data: Look-up Table

Experiment: Loading Conditions

R = 0.1
Max Loading = 27.9 ksi gauge section (no hole)
Interference fit values = {0%, 0.4%, 0.6%}

Material Model

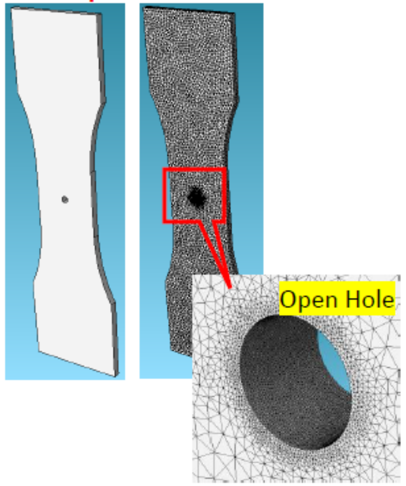
Property	Value
Material	7075-T651 plate
Modulus (ksi)	10400
Poisson	0.33

Same loading conditions and material properties used in the model

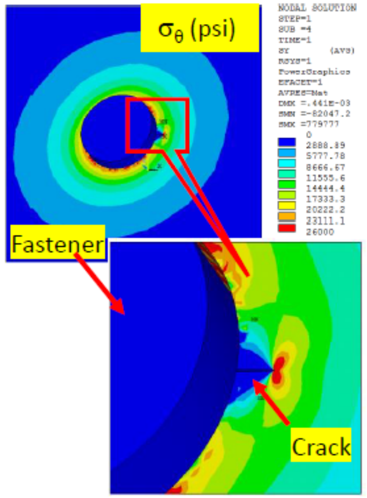
3D FEA Model

Units: psi, inch

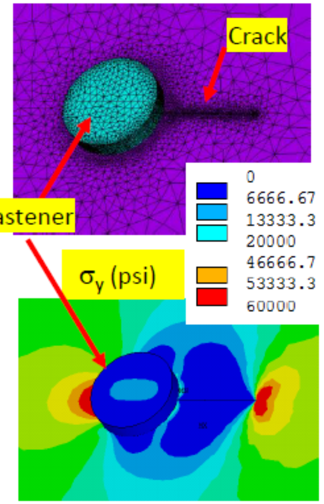
Benchmark #1 Open Hole



Benchmark #2 0.4%



Benchmark #3 0.6%



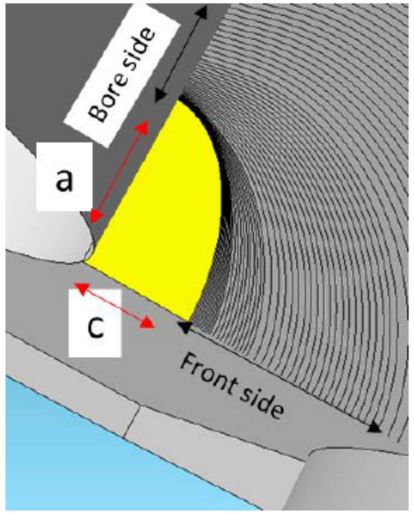
Analysis process:

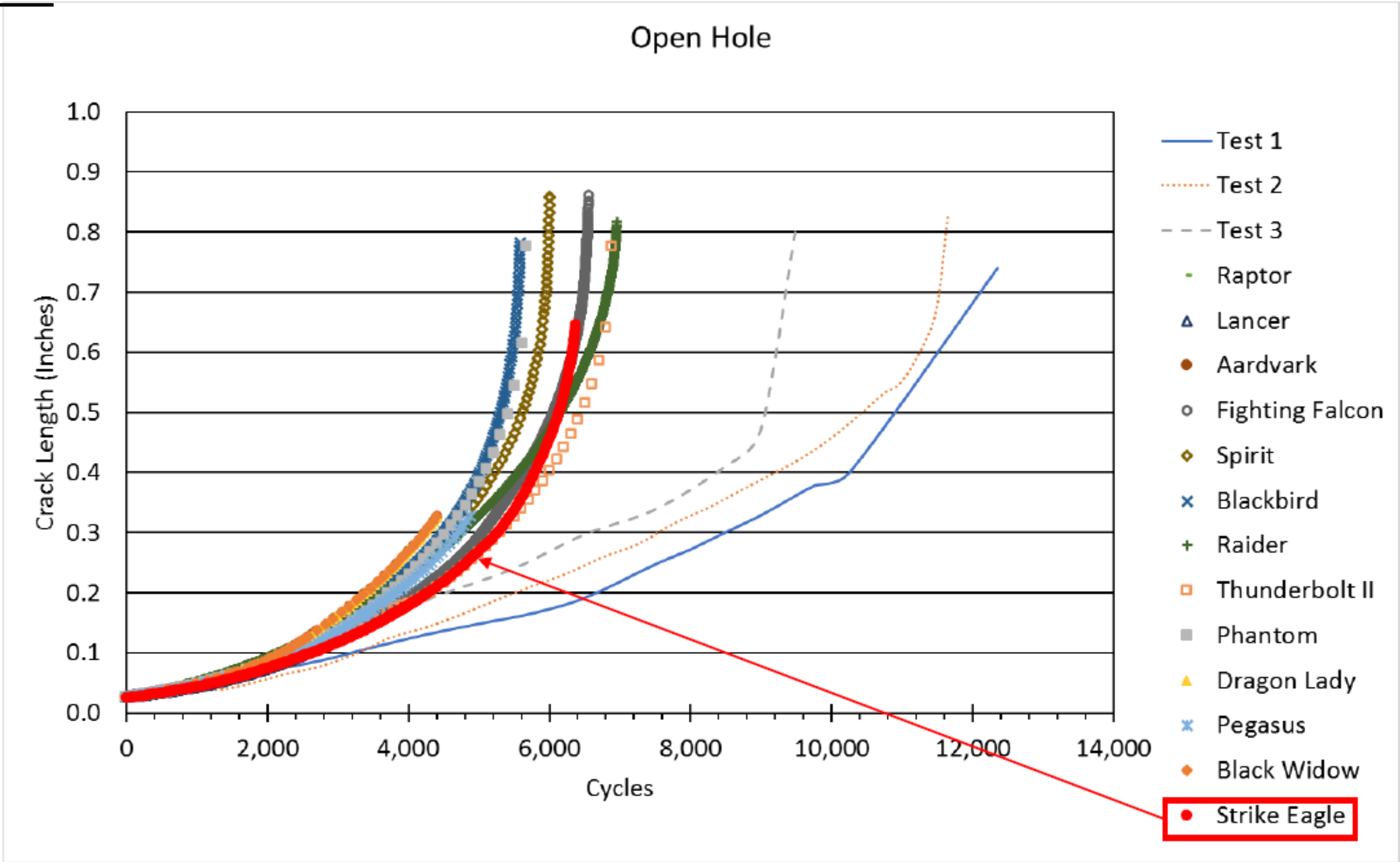
- Similar modeling process is followed for the three cases.
- Explicit crack incrementation; each crack increment has a representative 3D model; the same model setup is used for each simulated crack front.
- Two load steps for the open hole (max load, min load); three load step solution for the interference fit cases (fastener-specimen contact, max load, min load).
- Stress intensity factors computed based on displacement correlation technique. LEFM framework assumed valid.
- da/dN vs. DK table used for integration.
- The same model setup is used for each simulated crack front
- Three KI verification cases presented in the Nov. Tcon and one verification for interference fit stress field

Interference Fit Fastener Prediction Challenge
3D FEA Approach, Adrian Loghin, Simmetrix Inc.

Interference Fastener Round Robin

- <u>Follow-Up Investigations</u>



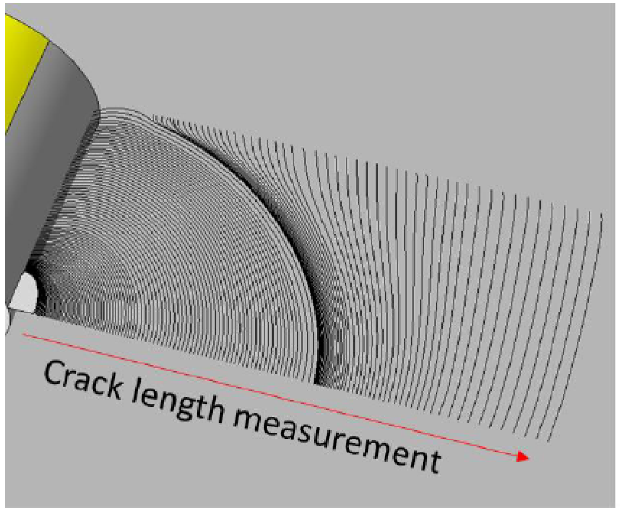


Interference Fit Fastener Prediction Challenge
3D FEA Approach, Adrian Loghin, Simmetrix Inc.

My model prediction (red dots) is similar to the other predictions. A large gap between test data and all predictions still needs to be addressed.

Interference Fastener Round Robin

▪ Follow-Up Investigations



All experiments performed at 0.4% IFF

Table 1. Round-robin analysis conditions

Condition	Specimen Type	Hole Diameter (in)	Fastener Diameter (in)	Surface Precrack Length (in)	Bore Precrack Length (in)	Loading	Max Stress (ksi)
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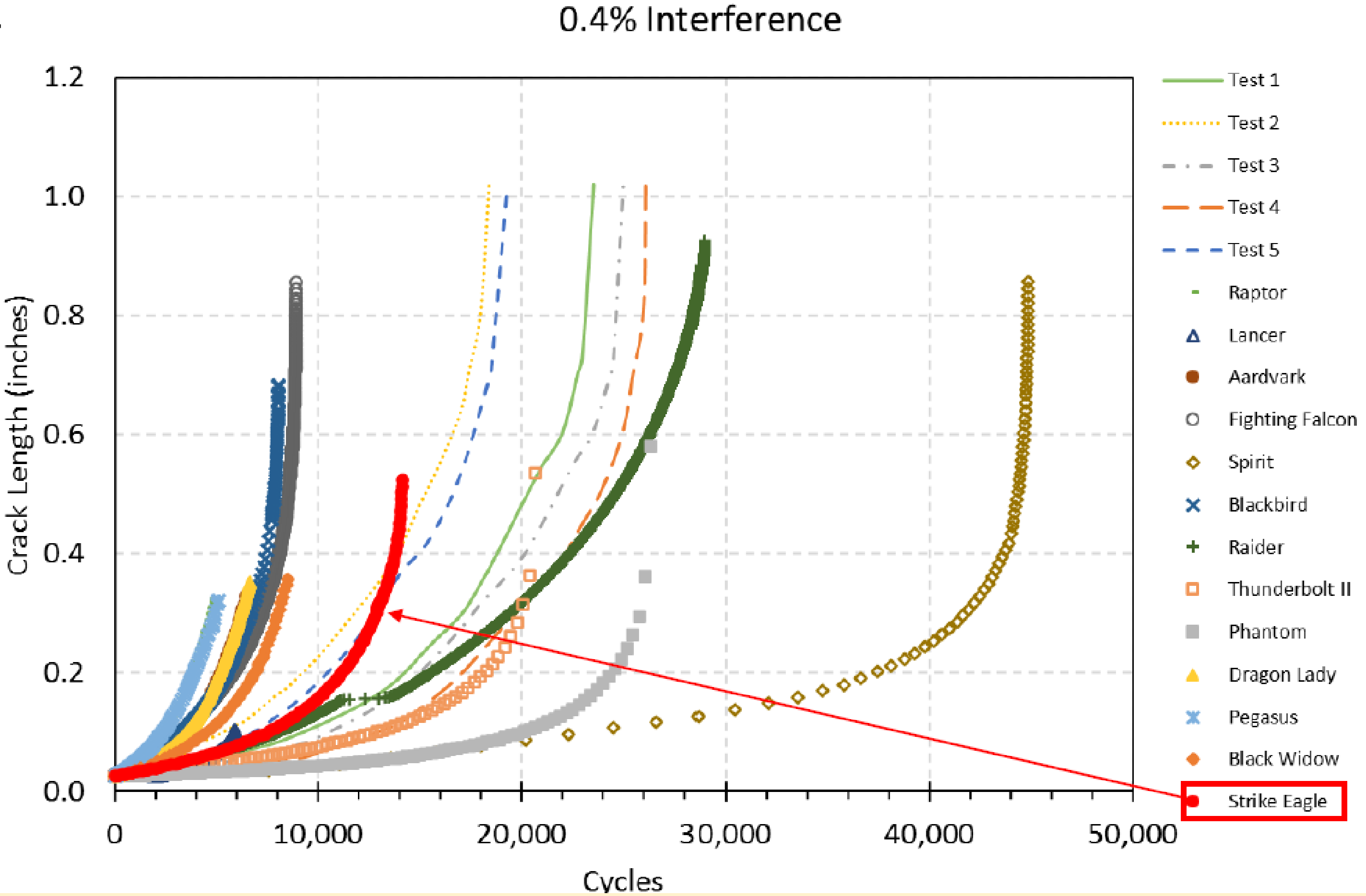
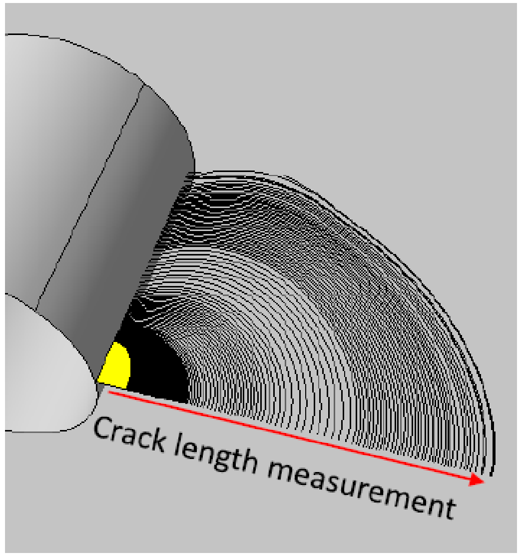


My model prediction (red dots) seems to capture better test data than the other models. One of the reasons could be that the influence of initial IFF is captured explicitly for each crack front increment.

Interference Fastener Round Robin

Follow-Up Investigations



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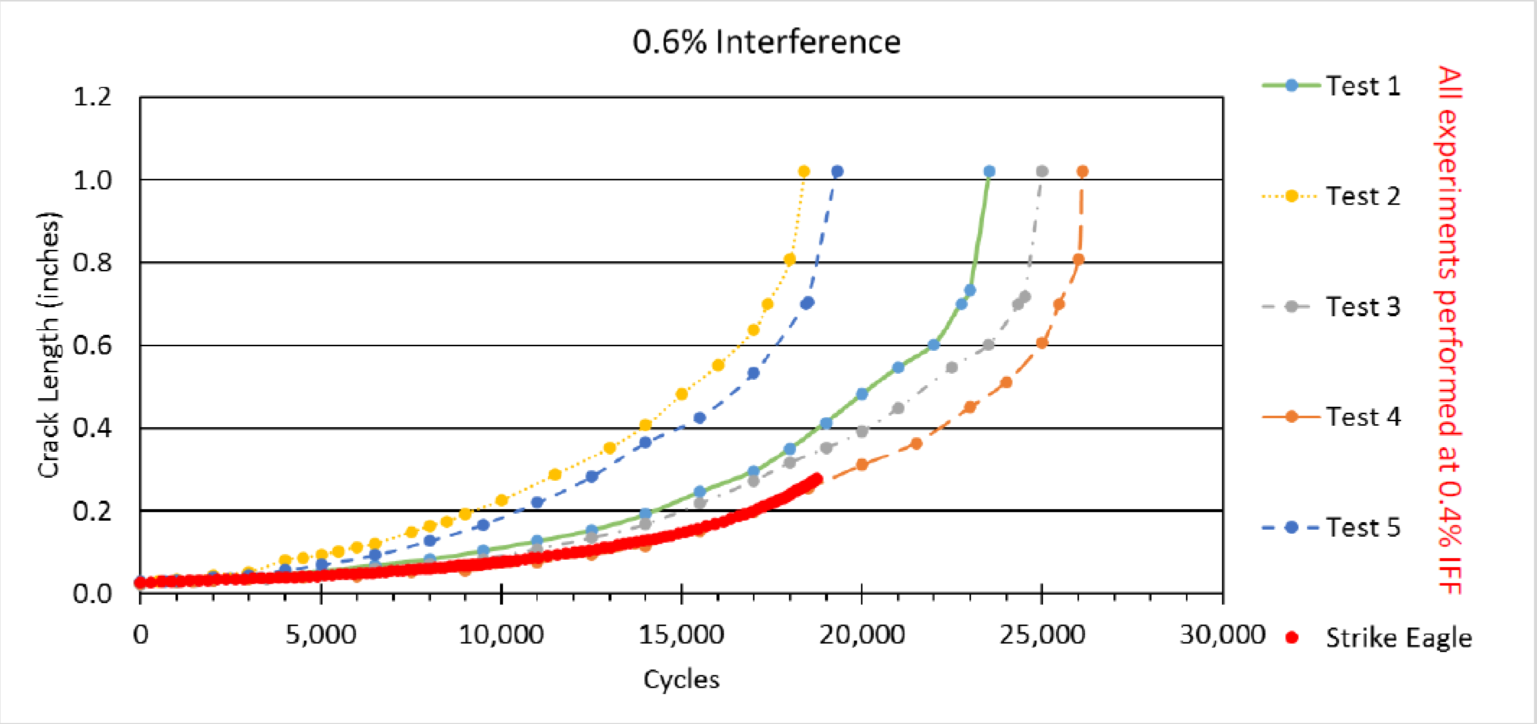


My model prediction for 0.6% IFF follows very closely Test 4 measurement (performed at 0.4% IFF).

Currently I am evaluating sensitivity of prediction relative to interference fit variability along the bore, specimen misalignment in the grip.

Interference Fastener Round Robin

- Future Work
  - Test a 0.6% or other slightly higher interference to understand life impacts
    - Is there an interference level at which greater interference is no longer beneficial?
    - Raider approach predicts shorter life for 0.6% interference than 0.4%
  - Understand applicability of surface correction proposed for open hole
  - Repeat similar effort with a neat fit fastener
  - Develop inspection tools capable of determining interference level of installed fasteners

Stress Intensity Factor Round Robin

- Overview
  - An initial FCG Analysis Methods round robin was completed to quantify the epistemic uncertainties in the prediction of crack growth life, given a fixed set of input data, for baseline and cold expanded (Cx) fastener holes [1,2]
  - During this initial round robin, the prediction sensitivity to the analysis inputs was highlighted with one specific case identifying the influence of error in the Mode I Stress Intensity Factor (K_I) for applied remote loading
    - For several cases, error resulted in no crack growth (ΔK_I lower than $\Delta K_{I,threshold}$)
  - As a result of these findings and subsequent discussions amongst the fatigue crack growth community, a follow-on collaborative round robin was established to investigate differences in stress intensity factors readily available in commercially available software like AFGROW and NASGRO

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Stress Intensity Factor Round Robin

- Special thanks to all the participants!!!!
  - Dr. Börje Andersson
    - BARE Research
  - Joseph W. Cardinal
    - Staff Engineer, Structural Engineering Department, Southwest Research Institute
  - Jim Harter
    - Senior Consultant, LexTech Inc.
  - Dr. Adrian Loghin
    - Senior Application Engineer, Simmetrix Inc.
  - Dr. Sebastian Nervi
    - Product Manager, Engineering Software Research and Development (ESRD) Inc
  - Dr. Jim Newman
    - Emeritus Professor, Department of Aerospace, Mississippi State University
  - Dr. Per Nordlund
    - MSC Software Corporation
  - Dr. Kevin Walker
    - QinetiQ Australia

Stress Intensity Factor Round Robin

- Objectives
  - Primary objective of the Stress Intensity Factor (SIF) round robin:

Evaluate differences between available SIF solutions for a single corner crack at a fastener hole with remote uniform tension loading

  - Evaluations included the root SIF solution and any corrections used to account for any additional corrections applied to the solution
    - Single vs multiple cracks, finite width, and hole offset
  - Solutions compared to explicit Finite Element Analysis (FEA) results of each case
  - Findings intended to drive improvements to solutions available to the fracture mechanics community

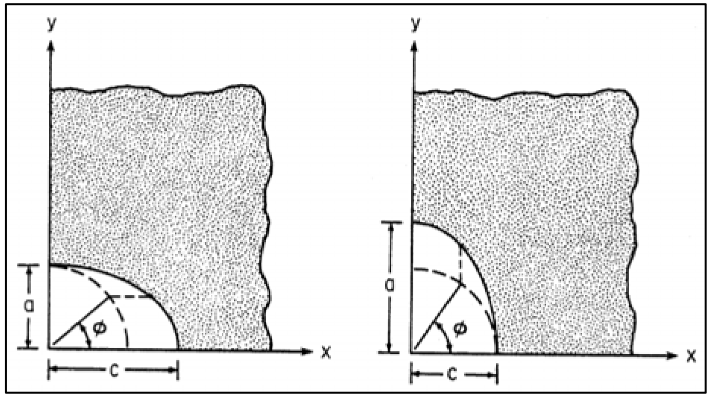
Stress Intensity Factor Round Robin

- Overview
  - Seven different cases of corner cracks at a hole were developed and SIF solutions along the crack front were requested from participants
  - A building block approach was utilized, with Case 1 representing the root SIF solution available
    - Without any corrections for single cracks, finite width, or hole offset, with a crack geometry aspect ratio (a/c) of 1.0
  - Each case added an additional level of complexity with corrections to the root solution as well as variations in the crack aspect ratio

Case #	Configuration
1	Infinite Plate, Double Crack
2	Infinite Plate, Single Crack
3	Finite Plate, Single Crack
4	Finite Plate, Single Crack, Offset Hole
5	Narrow Plate, Single Crack
6	Infinite Plate, Single Crack, a/c=1.5
7	Infinite Plate, Single Crack, a/c=0.5

Stress Intensity Factor Round Robin

- **Analysis Inputs**
  - Participants reported Mode I SIF versus the parametric angle
    - Minimum of 30 SIF extraction points along the crack front
  - For finite plate configurations (Cases 3-5), L = 3W
  - All cases considered a/c = 1 except:
    - Case 6, which considered a/c = 1.5
    - Case 7, which considered a/c = 0.5



Case #	Surface Crack Length (c) (inches)	Bore Crack Length (a) (inch)	a/c	Crack Configuration	Width (inch)	Thickness (inch)	a/t	Hole Diameter (inch)	W/D	r/t	r/W	Offset (inch)	Loading	Reference Stress (ksi)	Notes
1	0.050	0.050	1.00	Double Symmetric Corner Cracks	100.00	0.25	0.20	0.50	200.00	1.00	0.00	50.00	Tension	10.00	Infinite Plate, Double Crack
2	0.050	0.050	1.00	Single Corner Crack	100.00	0.25	0.20	0.50	200.00	1.00	0.00	50.00	Tension	10.00	Infinite Plate, Single Crack
3	0.050	0.050	1.00	Single Corner Crack	4.00	0.25	0.20	0.50	8.00	1.00	0.06	2.00	Tension	10.00	Finite Plate, Single Crack
4	0.050	0.050	1.00	Single Corner Crack	4.00	0.25	0.20	0.50	8.00	1.00	0.06	0.60	Tension	10.00	Finite Plate, Single Crack, Offset Hole
5	0.050	0.050	1.00	Single Corner Crack	1.20	0.25	0.20	0.50	2.40	1.00	0.21	0.60	Tension	10.00	Narrow Plate, Single Crack
6	0.050	0.075	1.50	Single Corner Crack	100.00	0.25	0.30	0.50	200.00	1.00	0.00	50.00	Tension	10.00	Infinite Plate, Single Crack, a/c=1.5
7	0.100	0.050	0.50	Single Corner Crack	100.00	0.25	0.20	0.50	200.00	1.00	0.00	50.00	Tension	10.00	Infinite Plate, Single Crack, a/c=0.5

- Submissions Summary
  - Nine submissions were received from eight participants, with solutions utilized by
    - AFGROW
    - NASGRO
    - Newman/Raju
    - Fawaz/Andersson
    - Explicit FEA
  - FEA approaches utilized various tools and methods which provides an additional opportunity to evaluate the different FEA approaches and their impact on the accuracy of the SIF
  - Seven reference solutions which have relative errors in K_I on the order of 0.03% or less were provided by Andersson (Submission 6), and were utilized as the reference solutions for each case evaluated

Submissions Summary

Submission #	Title	SIF solution source	Single Corner Crack Correction (Cases 2, 3, 4, 5, 6, 7)	Finite Width Correction (Cases 3, 4, 5)	Offset Hole Correction (Cases 4, 5)
1	Fawaz-Andersson Solutions, AFGROW	Fawaz-Andersson [3] (as implemented in AFGROW Advanced Model)	n/a	Newman correction [5]	Harter correction [6]
2	Newman-Raju Fit to Fawaz-Andersson	Updated equations by Newman [7] based on fit to Fawaz-Andersson solutions [4]	Shah-Newman Correction (2020) [8]	Tada, Paris and Irwin correction [9]	• center hole (conservative option) • Kt match approach
3	Newman-Raju (1986)	1986 Newman-Raju solution [9]	Shah correction	Newman correction [5]	Kt match approach
4	NASGRO (CC04 & CC02): Newman-Raju	1986 Newman-Raju solution [9] (as implemented in NASGRO CC04)	Shah correction (as implemented in NASGRO CC02)	NASGRO CC02 [12]	NASGRO CC02 [12]
5	NASGRO (CC16): Fawaz-Andersson	Fawaz-Andersson solutions [3] (as implemented in NASGRO CC16)	n/a	Modified version [13] of the Newman correction [5]	Harter correction [6] (as implemented in NASGRO CC16)
6	Andersson: FEA (2021)	Explicitly modeled each condition utilizing the STRIPE FE-software for the hp-version of the finite element method			
7	SimModeler Crack: FEA (2021)	Utilized SimModeler Crack to create 3D FEMs and compute Mode I SIFs via displacement correlation technique			
8	StressCheck: FEA (2021)	Utilized StressCheck to create 3D FEMs and compute Mode I SIFs			
9	MSC Marc: FEA (2021)	Utilized MSC Marc to create 3D FEMs and compute Mode I SIFs			

Case #	Configuration
1	Infinite Plate, Double Crack
2	Infinite Plate, Single Crack
3	Finite Plate, Single Crack
4	Finite Plate, Single Crack, Offset Hole
5	Narrow Plate, Single Crack
6	Infinite Plate, Single Crack, a/c=1.5
7	Infinite Plate, Single Crack, a/c=0.5

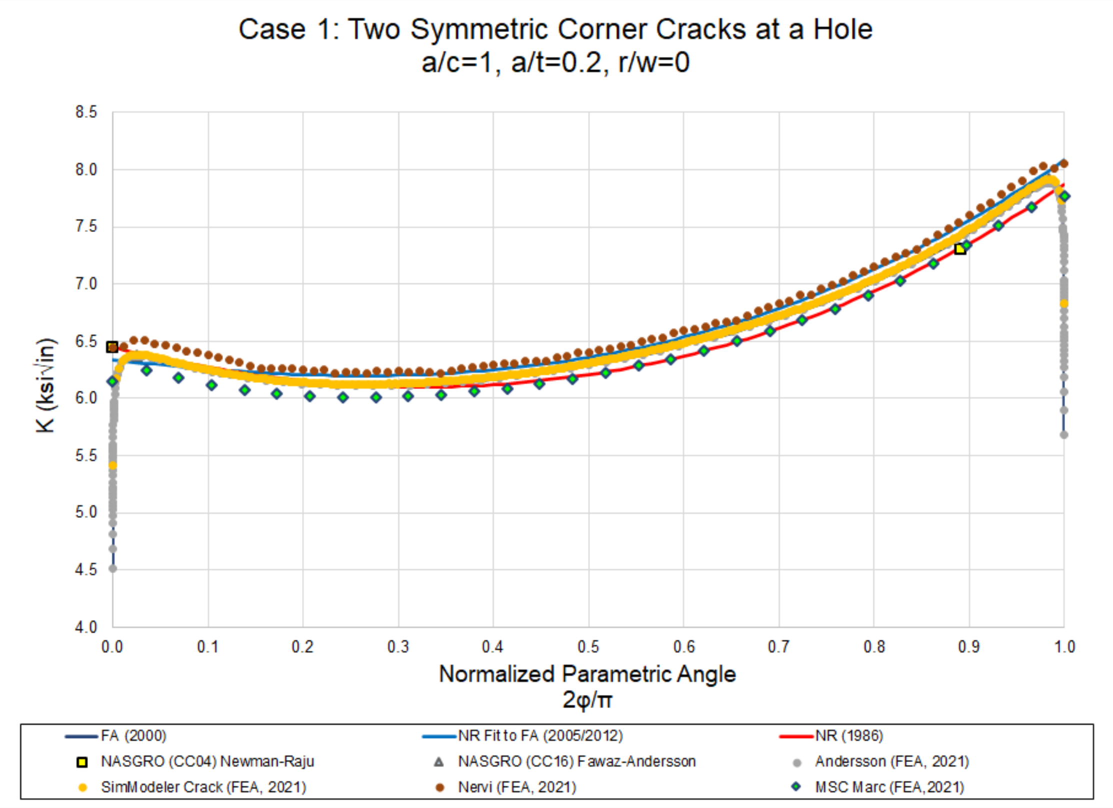
Stress Intensity Factor Round Robin

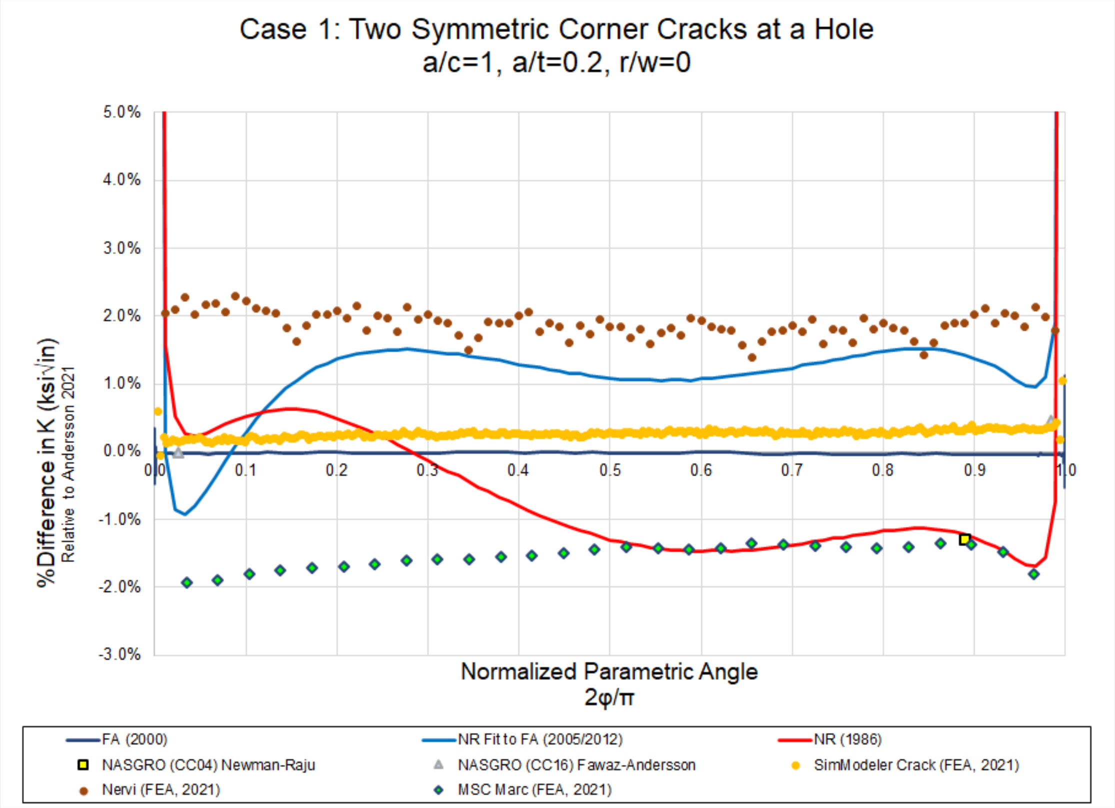
- Summary of Results
  - The following slides summarize comparisons for the seven cases evaluated
    - For these comparisons, the Mode I SIF is plotted along the crack front as a function of normalized parametric angle
    - Percent difference relative to Submission 6 from Andersson is also presented

Stress Intensity Factor Round Robin

- Case #1: Two Symmetric Corner Cracks at a Hole, Infinite Plate
  - Initial starting point to evaluate the root SIF solutions
    - For this case, single crack, finite width, and hole offset corrections are not utilized
  - Results within ±2% of Andersson submission, except near surface points

Case #	1
Configuration	Infinite Plate, Double Crack
Crack Configuration	Double Symmetric Corner Cracks
Surface Crack Length (c)	0.050
Bore Crack Length (a)	0.050
Width	100.00
Thickness	0.25
Hole Diameter	0.50
Hole Offset	50.00
a/c	1.00
a/t	0.20
W/D	200.00
r/t	1.00
r/W	0.00

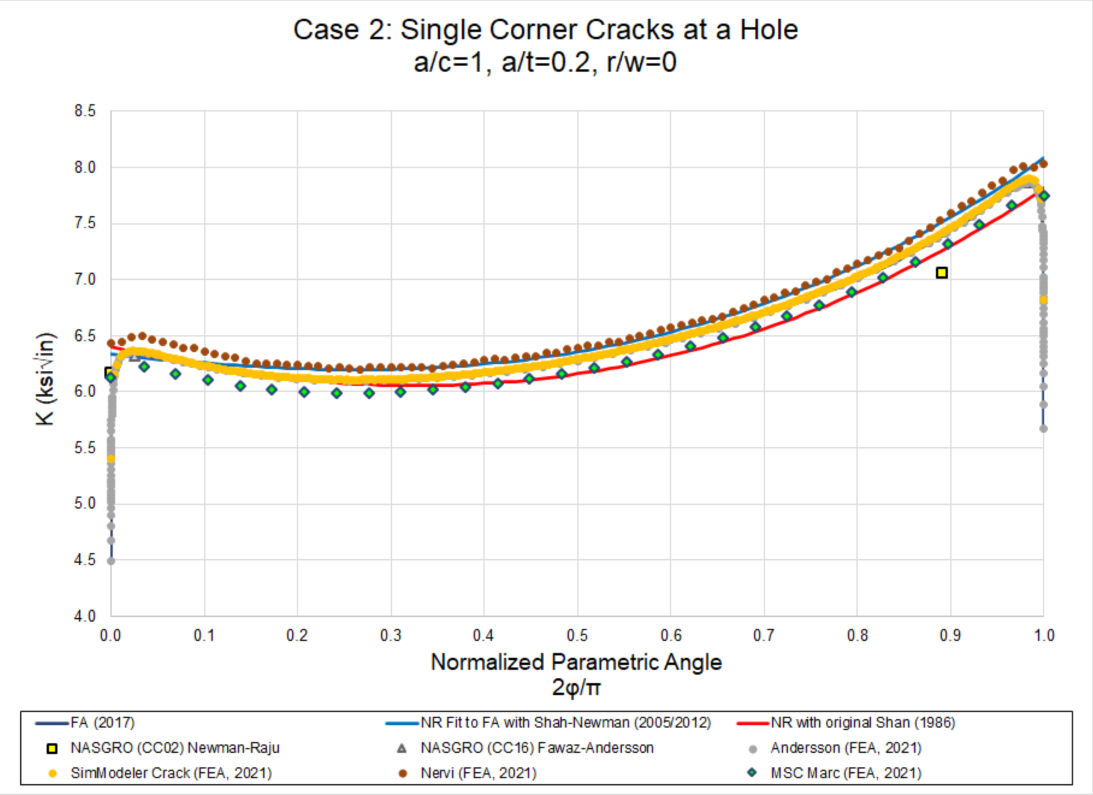


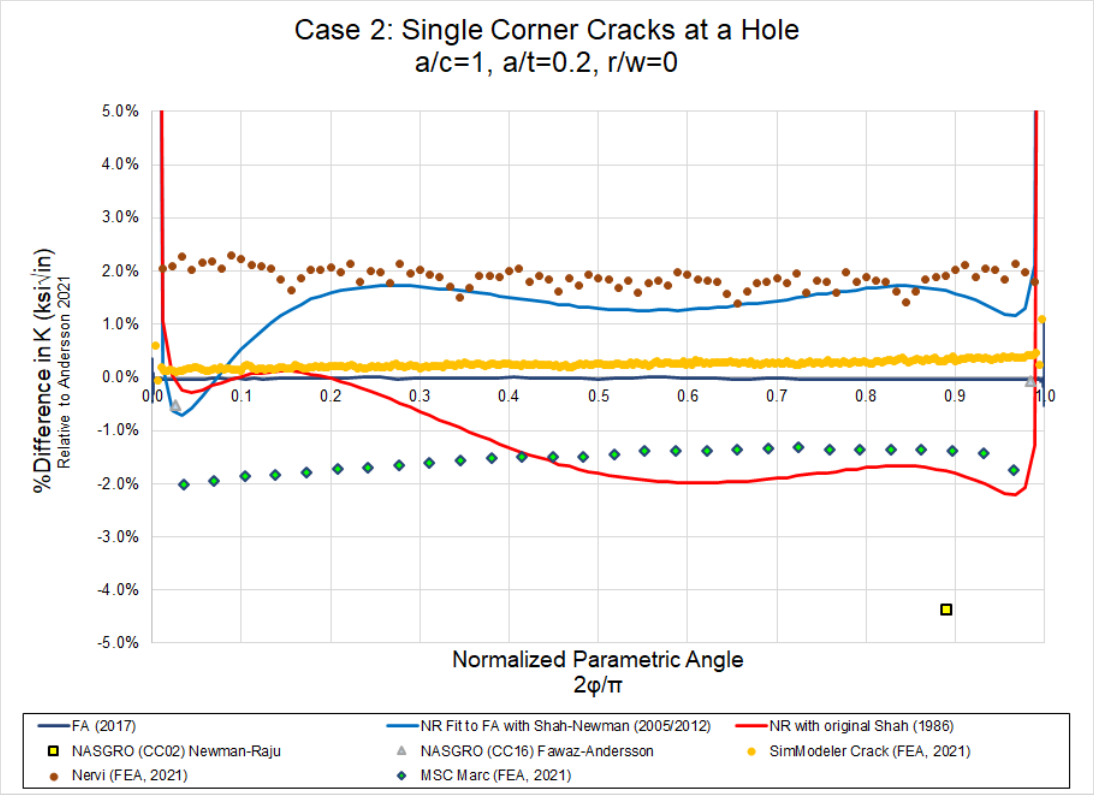


Stress Intensity Factor Round Robin

- Case #2: Single Corner Crack at a Hole, Infinite Plate
  - Continuation from Case #1, incorporating effects of a single corner crack
    - Submissions 2-4 utilize Shah or Shah/Newman corrections to adjust from double corner crack to single crack
    - Submissions 1 & 5 utilized single crack modeling in development of root SIF solution
  - Results generally within ±2% of Andersson submission, except near surface points
    - Submission 4 (NASGRO CC02) differences exceeded 4% for point representative of hole bore

Case #	2
Configuration	Infinite Plate, Single Crack
Crack Configuration	Single Corner Crack
Surface Crack Length (c)	0.050
Bore Crack Length (a)	0.050
Width	100.00
Thickness	0.25
Hole Diameter	0.50
Hole Offset	50.00
a/c	1.00
a/t	0.20
W/D	200.00
r/t	1.00
r/W	0.00





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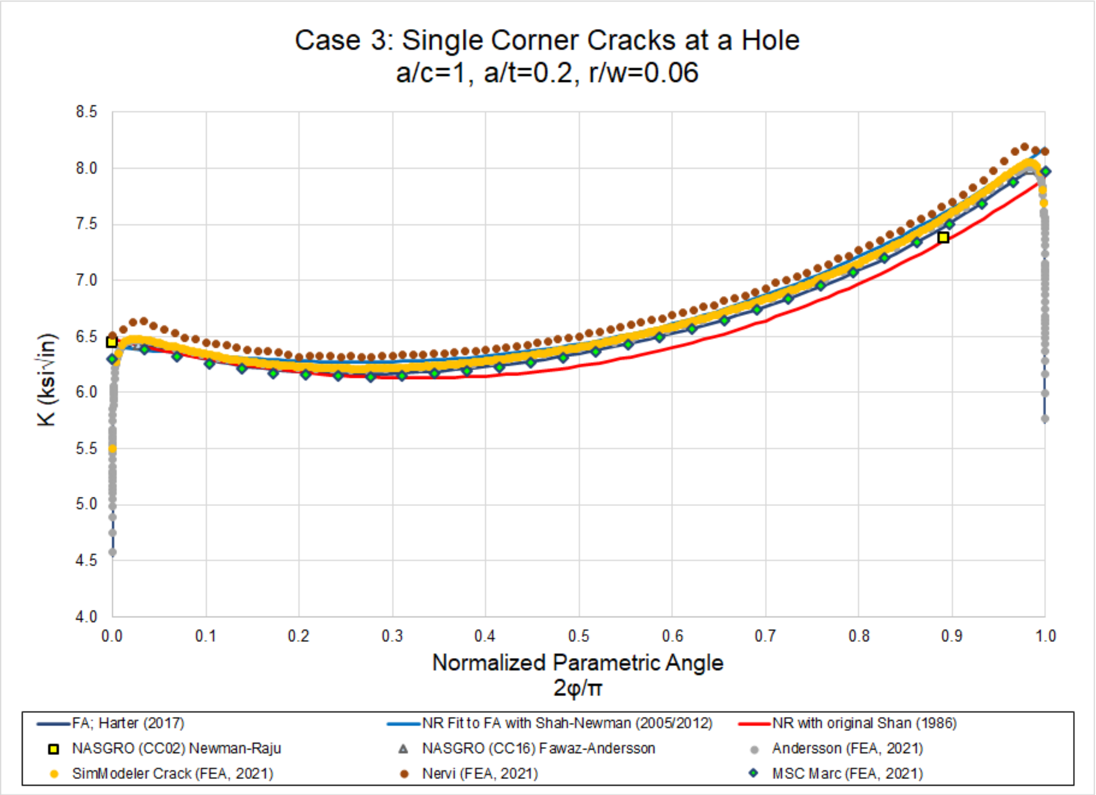
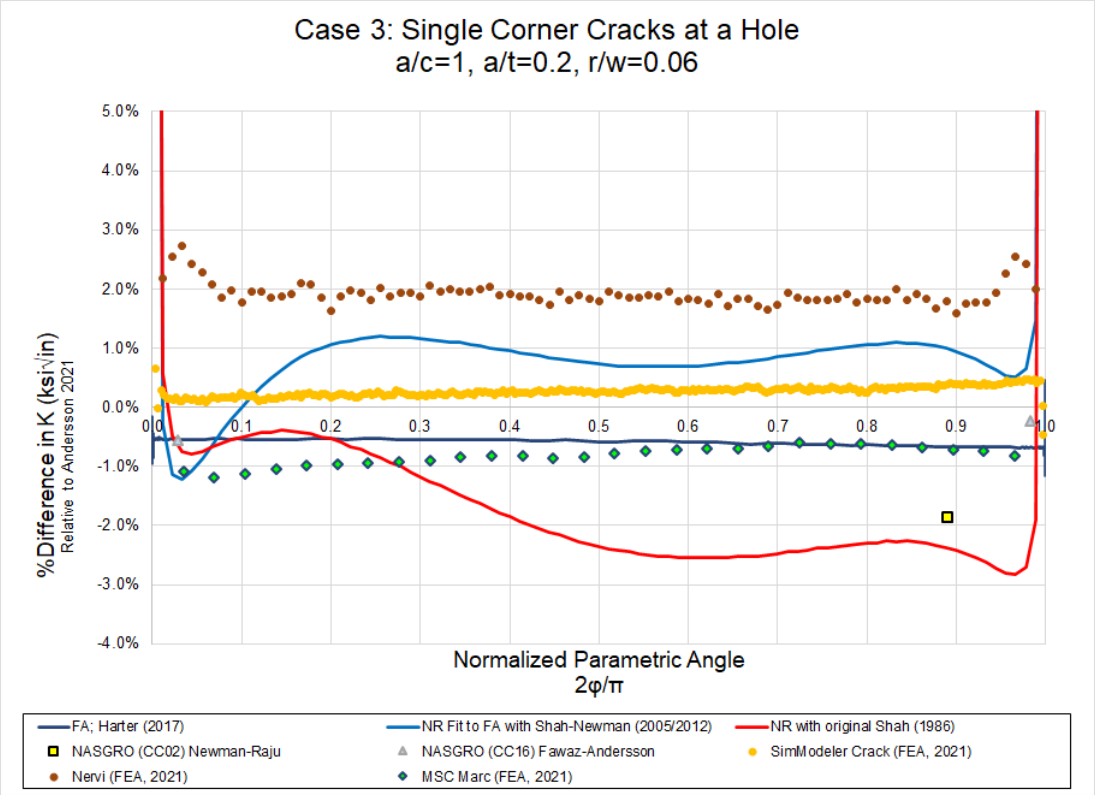
Stress Intensity Factor Round Robin

- Case #3: Single Corner Crack at a Hole, Finite Plate
  - Continuation from Cases 1-2, incorporating finite width effects
    - Submissions 1-3 utilized the Newman finite width correction. Submission 4 used the correction from [12] and Submission 5 used the correction from [13]
  - Results generally within ±2% of Andersson submission, except near surface points
    - Submission 3 (Newman-Raju 1986) differences exceeded 2% over a range of 0.4-1.0 normalized parametric angle, representative of crack front near the hole bore

Case #	3
Configuration	Finite Plate, Single Crack
Crack Configuration	Single Corner Crack
Surface Crack Length (c)	0.050
Bore Crack Length (a)	0.050
Width	4.00
Thickness	0.25
Hole Diameter	0.50
Hole Offset	2.00
a/c	1.00
a/t	0.20
W/D	8.00
r/t	1.00
r/W	0.06

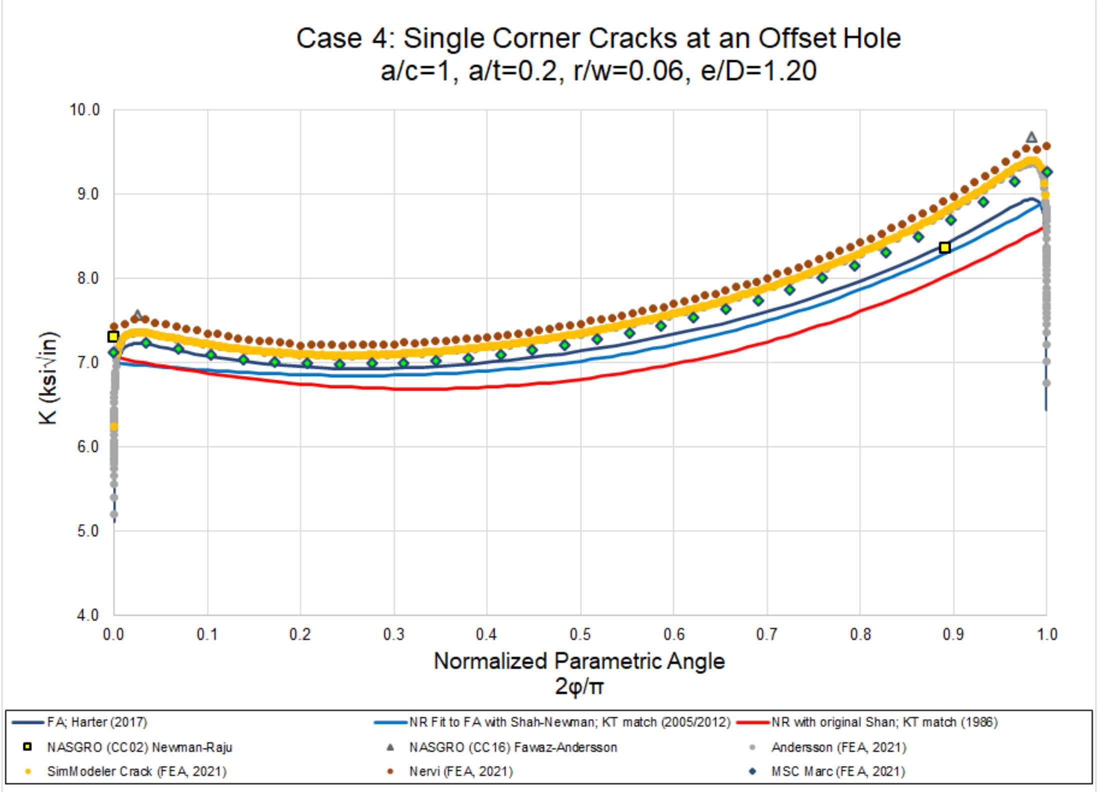


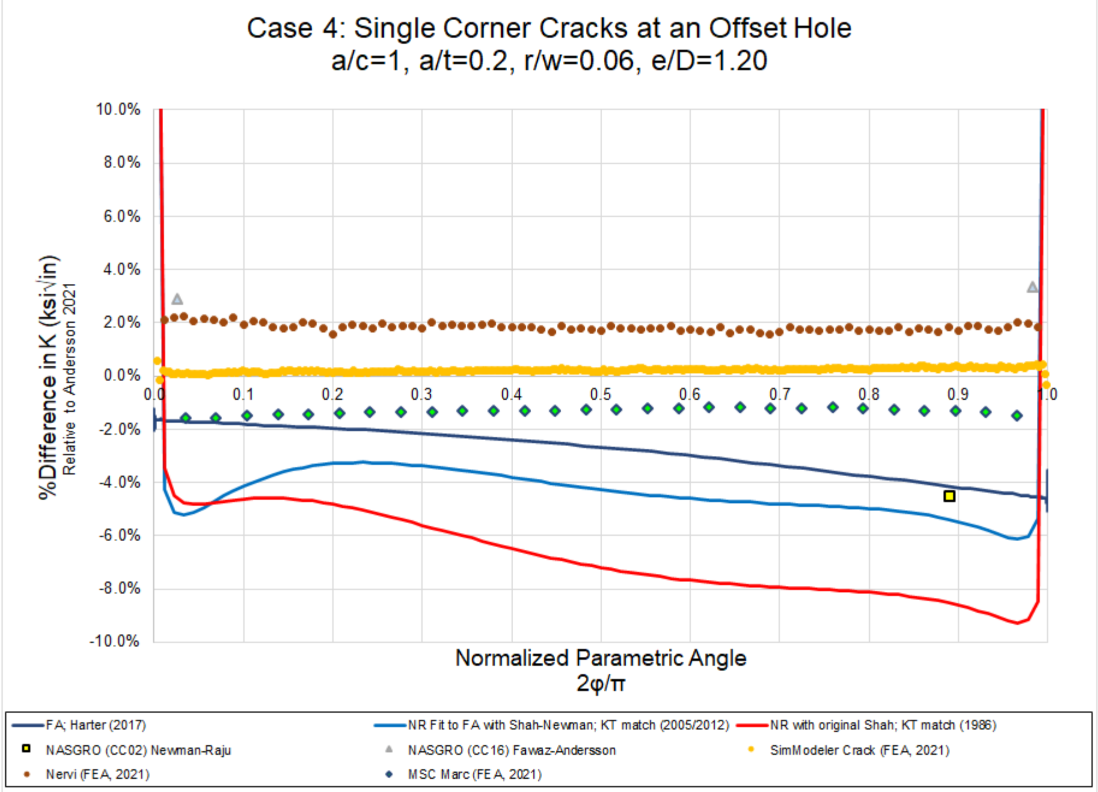


Stress Intensity Factor Round Robin

- Case #4: Single Corner Cracks at a Hole, Finite Plate, Offset Hole
  - Continuation from Cases 1-3, incorporating hole offset effects
    - Submission 1 utilized the Harter offset correction
    - Submission 2-3 investigated two approaches to characterize the short offset, however, the Kt match approach was utilized for comparison
    - Submission 4 used the correction from [12] and Submission 5 used the correction from [13]
  - Significant differences (nearly 10% relative to Andersson submission) observed for Submissions 1-4

Case #	4
Configuration	Finite Plate, Single Crack, Offset Hole
Crack Configuration	Single Corner Crack
Surface Crack Length (c)	0.050
Bore Crack Length (a)	0.050
Width	4.00
Thickness	0.25
Hole Diameter	0.50
Hole Offset	0.60
a/c	1.00
a/t	0.20
W/D	8.00
r/t	1.00
r/W	0.06

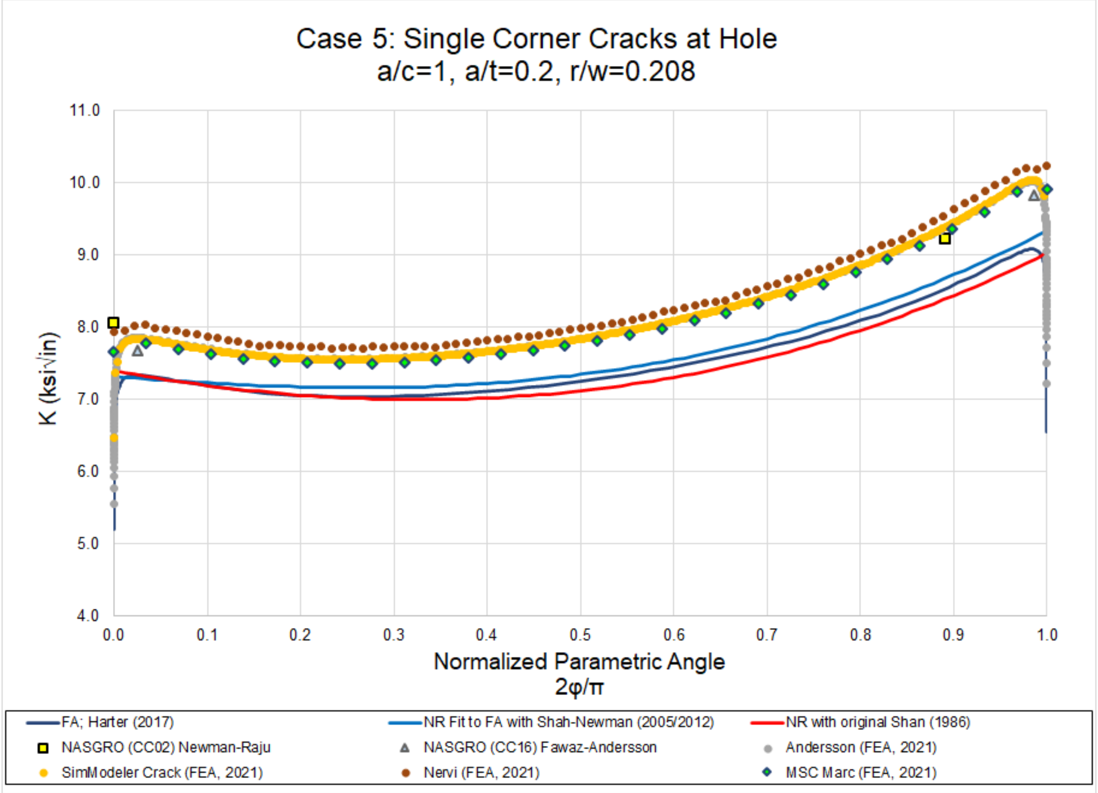


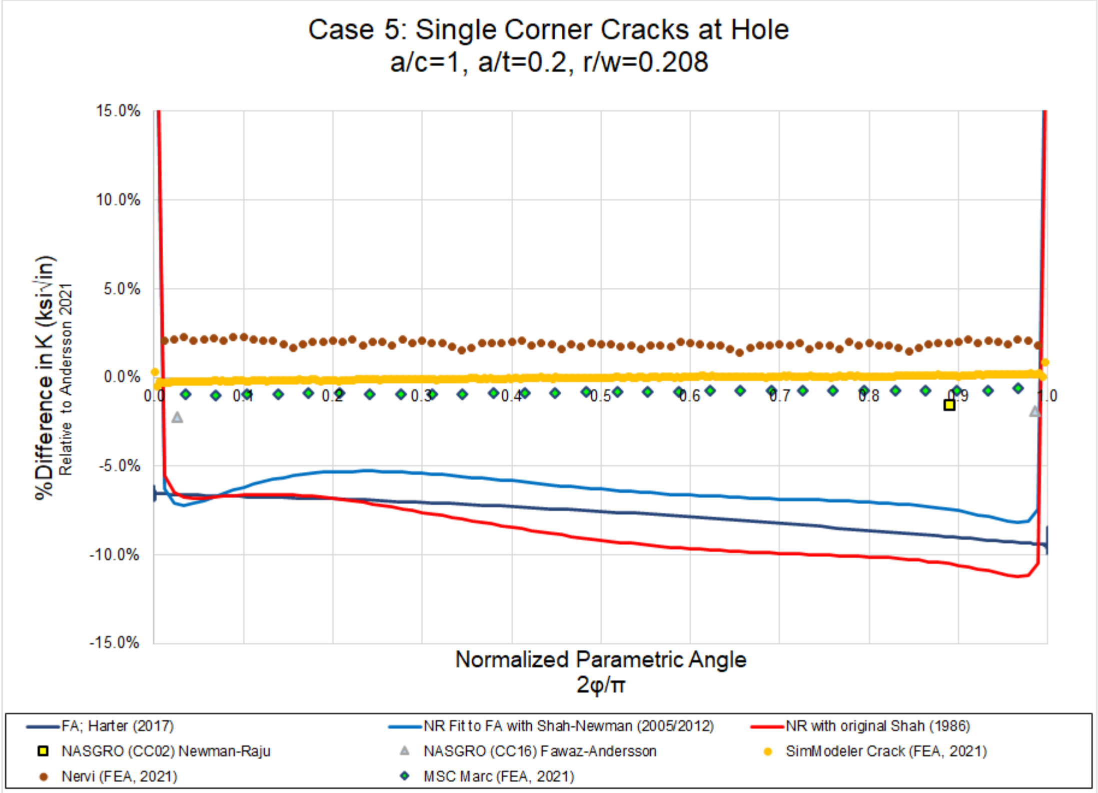


Stress Intensity Factor Round Robin

- Case #5: Single Corner Crack at a Hole, Narrow Plate
  - Continuation from previous cases, but for relatively "narrow" width
    - Submissions 1-3 utilized the Newman finite width correction
    - Submission 4 used the correction from [12] and Submission 5 used the correction from [13]
  - Significant differences (5-12% relative to Andersson submission) observed for Submissions 1-3, which utilized Newman finite width correction

Case #	5
Configuration	Narrow Plate, Single Crack
Crack Configuration	Single Corner Crack
Surface Crack Length (c)	0.050
Bore Crack Length (a)	0.050
Width	1.20
Thickness	0.25
Hole Diameter	0.50
Hole Offset	0.60
a/c	1.00
a/t	0.20
W/D	2.40
r/t	1.00
r/W	0.21

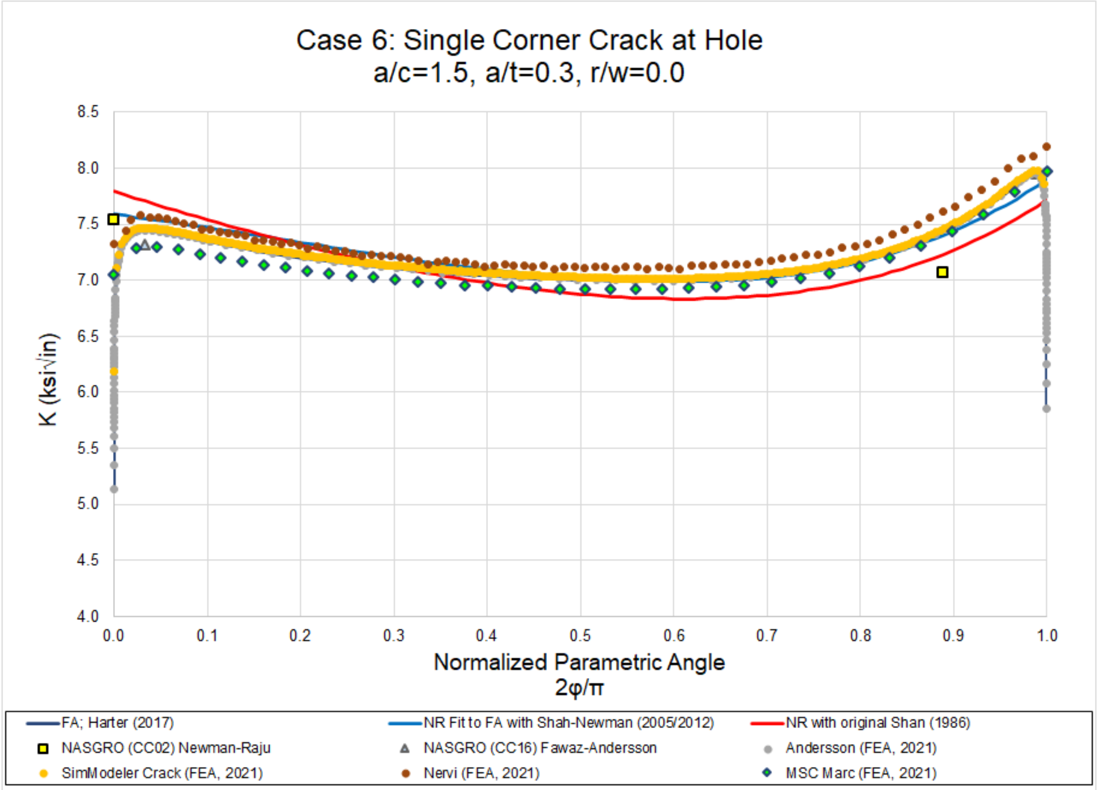


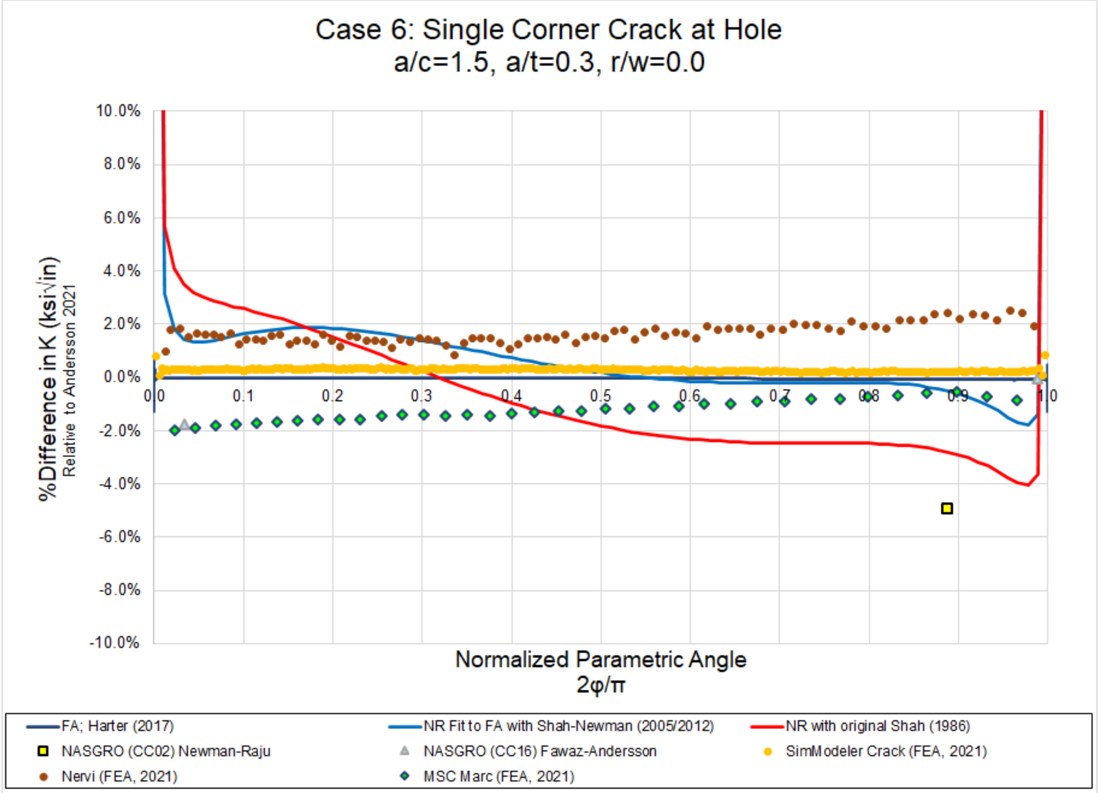


Stress Intensity Factor Round Robin

- Case #6: Single Corner Crack at a Hole, Infinite Plate, a/c=1.5
  - Replicate of Case #2 but with a crack aspect ratio of a/c=1.5
  - Results generally within ±2% of Andersson submission, except near surface points
    - Submission 3 (Newman-Raju 1986) showed differences of ±4% across crack front
    - Submission 4 (NASGRO CC02) showed differences over 4% for point representative of hole bore

Case #	6
Configuration	Infinite Plate, Single Crack, a/c=1.5
Crack Configuration	Single Corner Crack
Surface Crack Length (c)	0.050
Bore Crack Length (a)	0.075
Width	100.00
Thickness	0.25
Hole Diameter	0.50
Hole Offset	50.00
a/c	1.50
a/t	0.30
W/D	200.00
r/t	1.00
r/W	0.00





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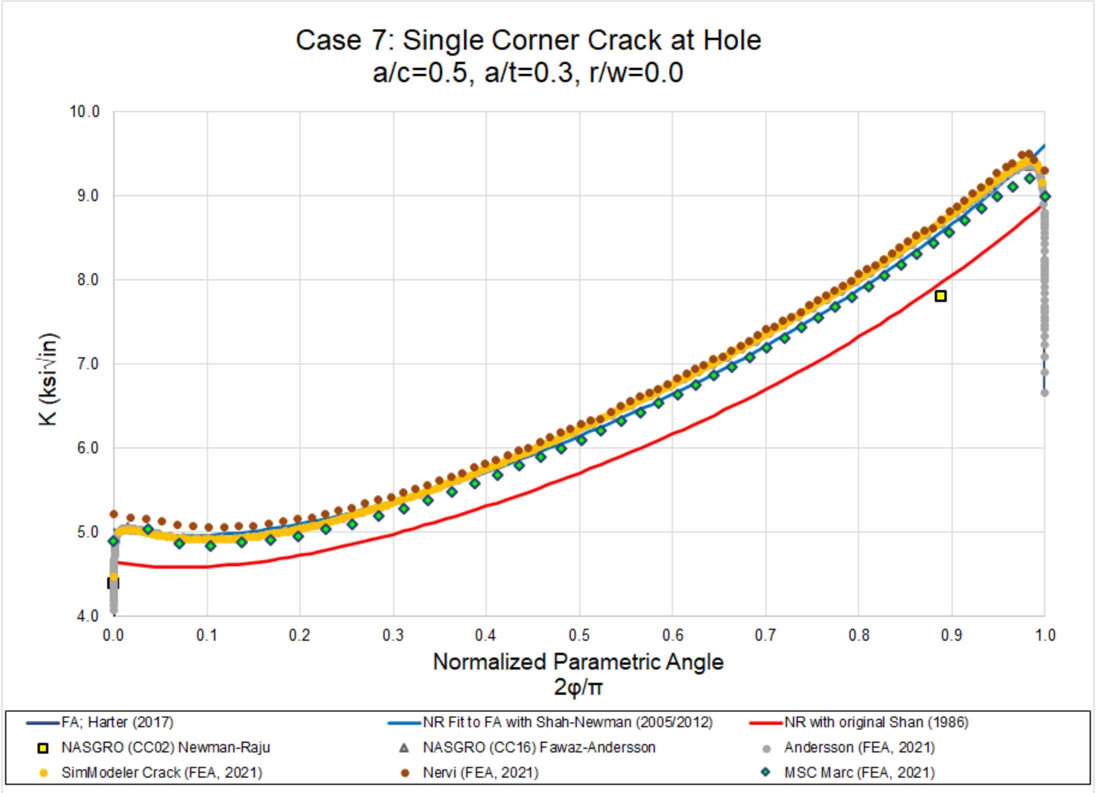
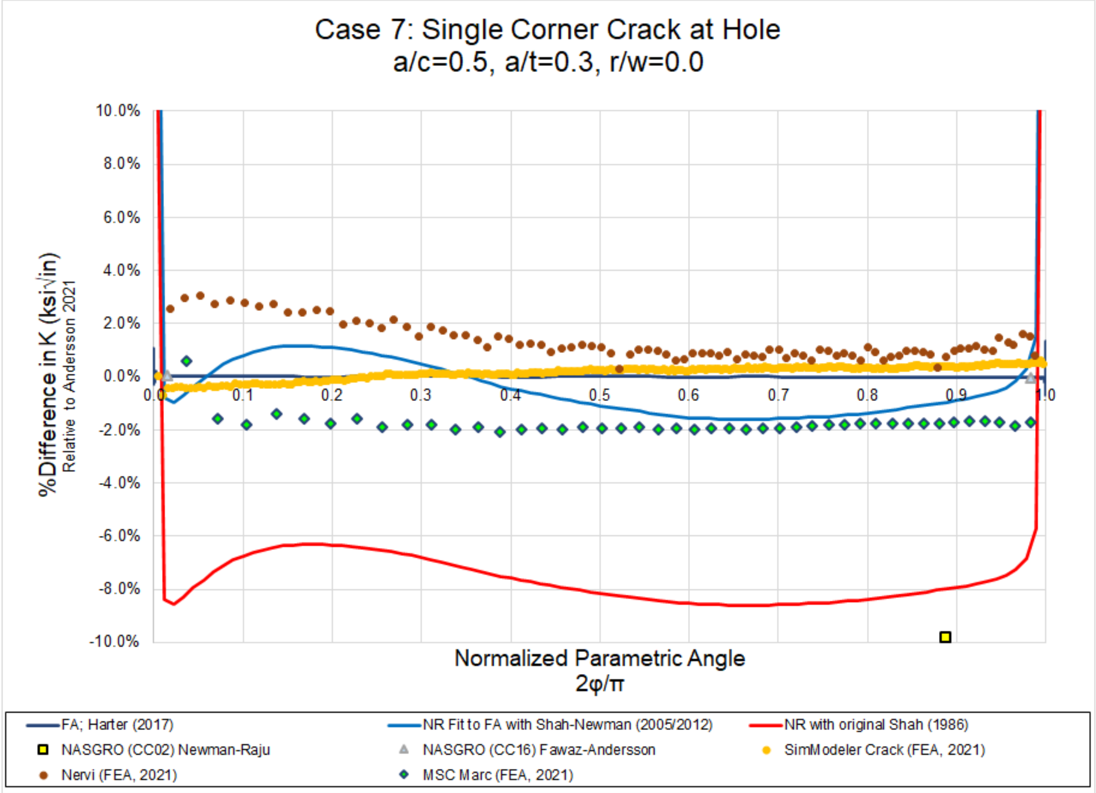
Stress Intensity Factor Round Robin

- Case #7: Single Corner Crack at a Hole, Infinite Plate, a/c=0.5
  - Replicate of Case #2 but with a crack aspect ratio of a/c=0.5
  - Results generally within ±2% of Andersson submission, except near surface points
    - Submission 3 (Newman-Raju 1986) showed differences averaging ~8% across the crack front
    - Submission 4 (NASGRO CC02) showed differences of 10% for point representative of hole bore

Case #	7
Configuration	Infinite Plate, Single Crack, a/c=0.5
Crack Configuration	Single Corner Crack
Surface Crack Length (c)	0.100
Bore Crack Length (a)	0.050
Width	100.00
Thickness	0.25
Hole Diameter	0.50
Hole Offset	50.00
a/c	0.50
a/t	0.20
W/D	200.00
r/t	1.00
r/W	0.00

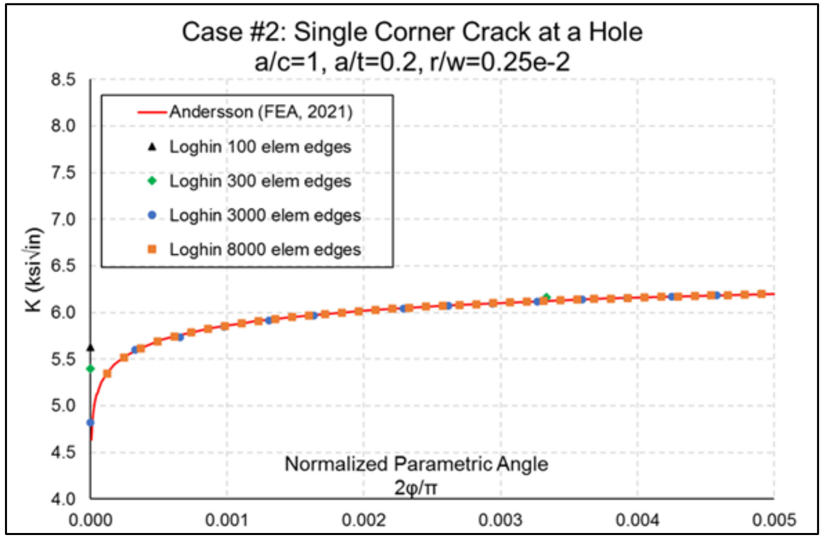


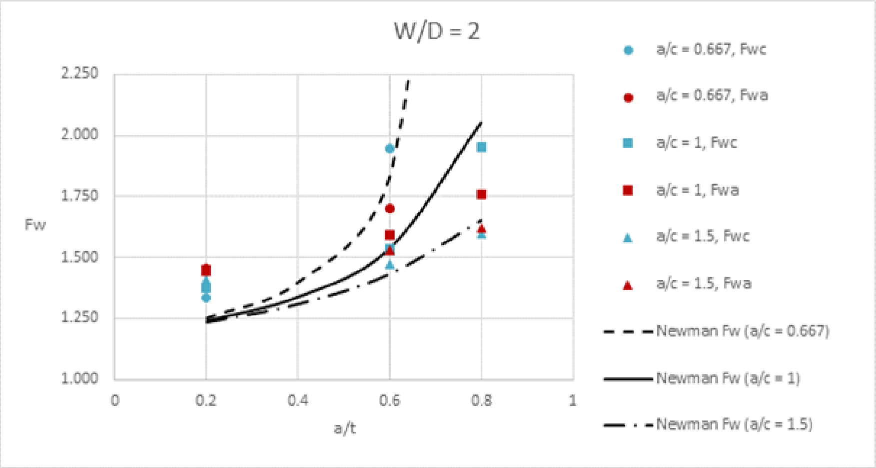


Stress Intensity Factor Round Robin

- Overall Summary and Conclusions
  - Successful SIF comparisons completed utilizing a wide array of available solutions and toolsets, with submissions provided by (8) different participants
  - Overall, results were within 2% of the reference case, however, deviations were observed for narrow width and varying aspect ratio cases exceeding 10% in some cases
  - Issues with commonly utilized finite width corrections were discovered
  - A robust dataset was developed that can be utilized as a reference set for follow-on studies
  - Comparisons between varying FEM approaches have highlighted the opportunity to identify modeling best practices and provide guidance to the community

- Follow-on Investigations
  - Case #2 Convergence Study: Two studies were carried out in parallel
  - Finite Width Correction
  - Submission 8 (StressCheck FEA) updated meshing strategy & associated results





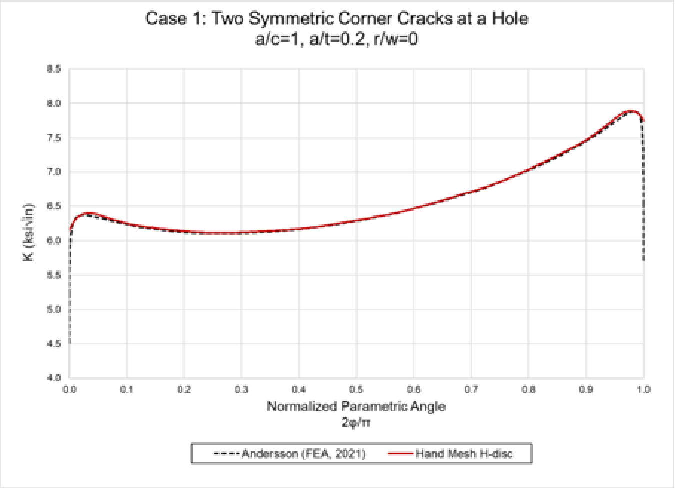


Figure 20 – Comparison of SIF extraction along the crack front with Andersson's reference solution for case 1.

Stress Intensity Factor Round Robin

- Next Steps
  - Finalizing summary report documenting round robin approach, results, conclusions, and follow-on investigations
  - New finite width corrections in work to support the community
  - Collaboration to identify FEA best practices and lessons learned
  - Consider publication of papers/presentations to share results with community

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Stress Intensity Factor Round Robin

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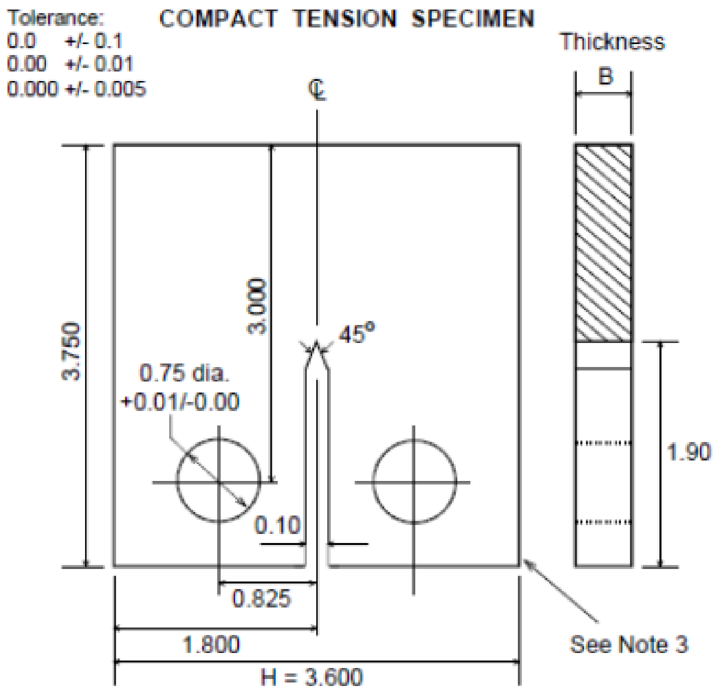
Overload Challenge

- Description
  - Compact tension specimen manufactured from 7075-T6
  - 3 inches wide, 0.125 inches thick
  - Initial notch length 1.15 inches
  - Constant amplitude loading
    - Pmax = 100 lb, Pmin = 10 lb
  - Single factor 2 (200 lb) spike overload applied when the crack length reached 1.4 inches, and then again at 1.6 inches
  - Participants in the challenge were invited to perform a blind prediction analysis, using whatever tool and method they preferred
  - Two submissions were received:
    - Submission 1: Jake Warner, USAF. Using AFGROW and the Generalised Willenborg retardation model
    - Submission 2: Luciano (Lucky) Smith, SWRI. Using NASGRO and the Generalised Willenborg retardation model



Notes:
(1) All dimensions are in inches.
(2) All surfaces perpendicular and parallel (as applicable) to within +/- 0.002 W, TIR
(3) Machine outer dimensions and holes before cutting notch.
(4) Measure and record height (H) of specimen before and after machining of notch (residual stress check).
(5) Notch may be machined or electrical-discharge machined but 45-degree V-notch root radius shall not exceed 0.003 in.

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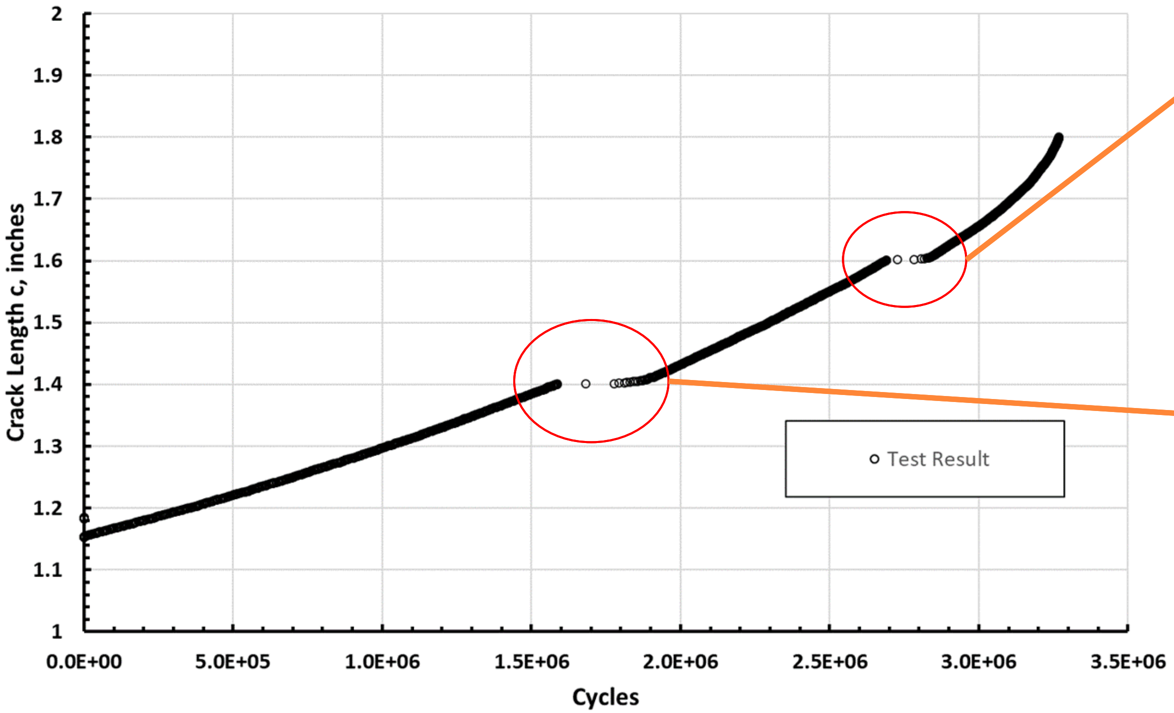
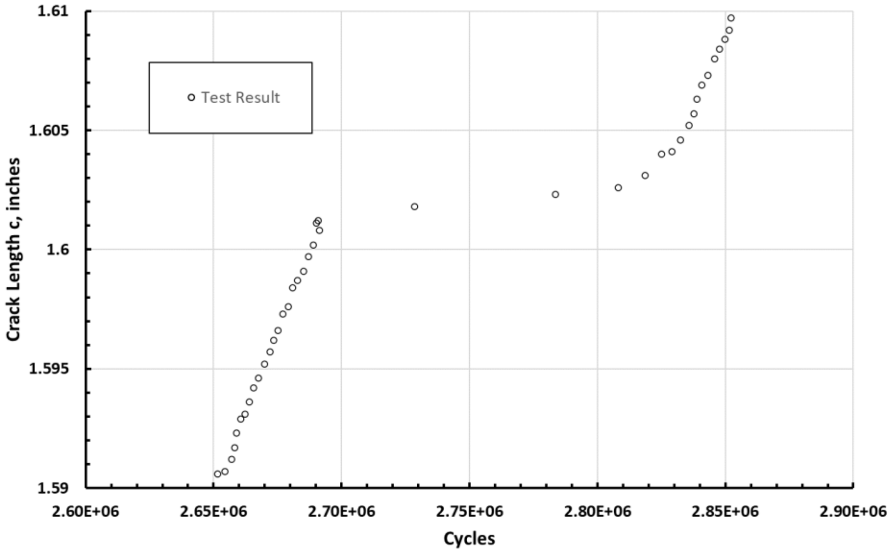
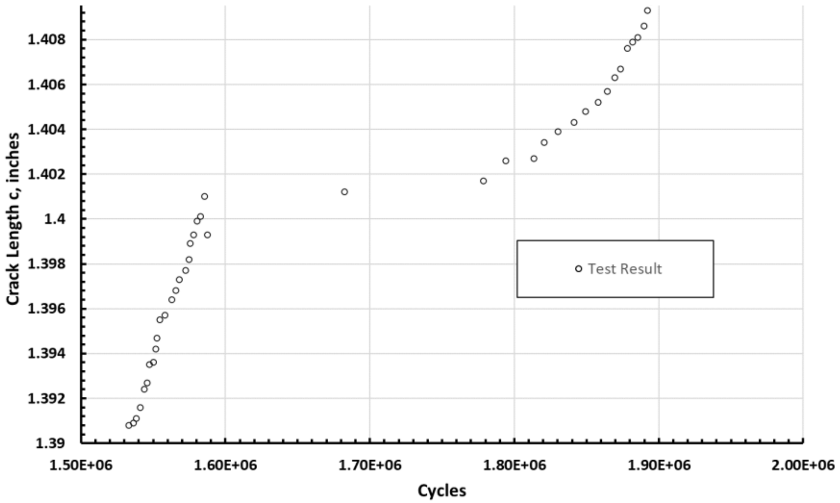
Overload Challenge

- Test Results
  - Total life to reach 1.8 inches – 3,269,818 cycles
    - Delay at OL1 about 220,000 cycles
    - Delay at OL2 about 120,000 cycles







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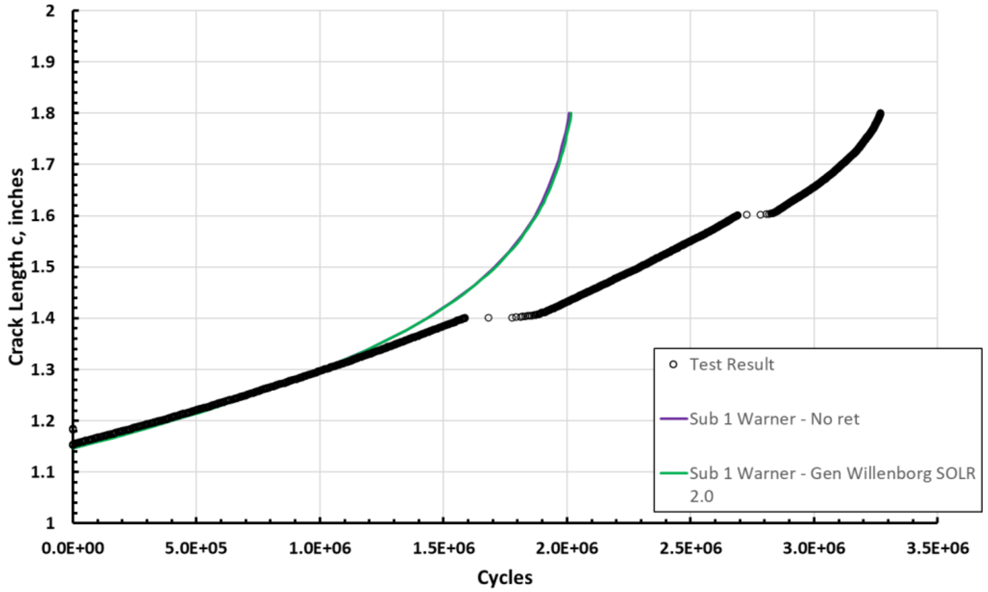
Overload Challenge

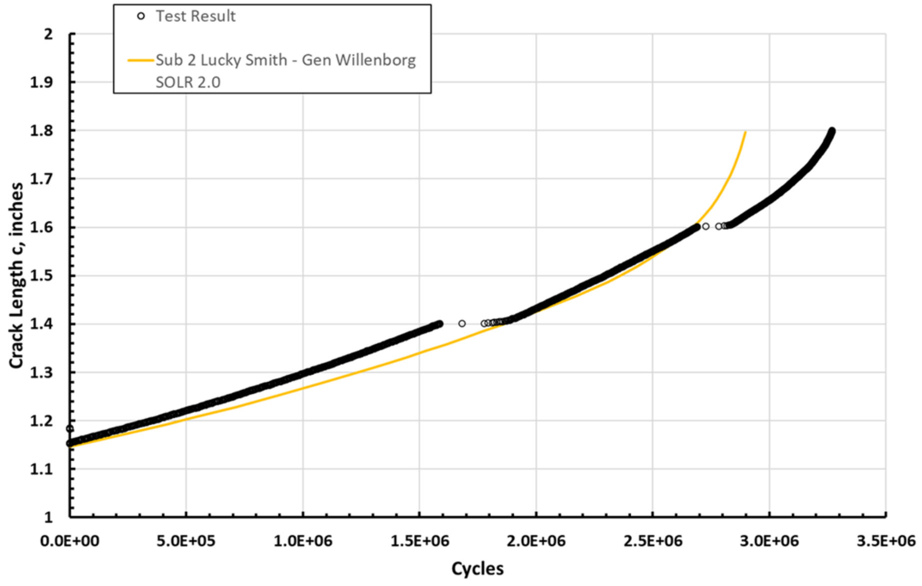
Submission 1: AFGROW

- Baseline prediction (no retardation/load interaction)
- Prediction with retardation:
  - Generalised Willenborg model SOLR=2.0
  - 2.0 was the lowest possible value without causing crack arrest



Submission 2: NASGRO

- Generalised Willenborg retardation SOLR=2.005
- 2.005 was the lowest possible value without crack arrest
- First overload added about 2,000 cycles. Second overload added about 5,000 cycles, i.e. very similar to Jake Warner's results



Overload Challenge

- Post-Test Analyses
  - FASTRAN Version 5.76 –Pseudo blind and Calibrated
  - AFGROW with different retardation models, including Hsu, Closure, Wheeler
  - Comparisons in the plastic zone region

Overload Challenge

- <u>FASTRAN analyses, Pseudo-blind</u>
  - ASIP 2012 rate data from: Walker, K.F., and Newman, J.C., Jr., *Development and validation of improved experimental techniques and modelling for fatigue crack growth under constant amplitude and spectrum loading*, in *USAF ASIP Conference*. 2012: San Antonio Texas USA.
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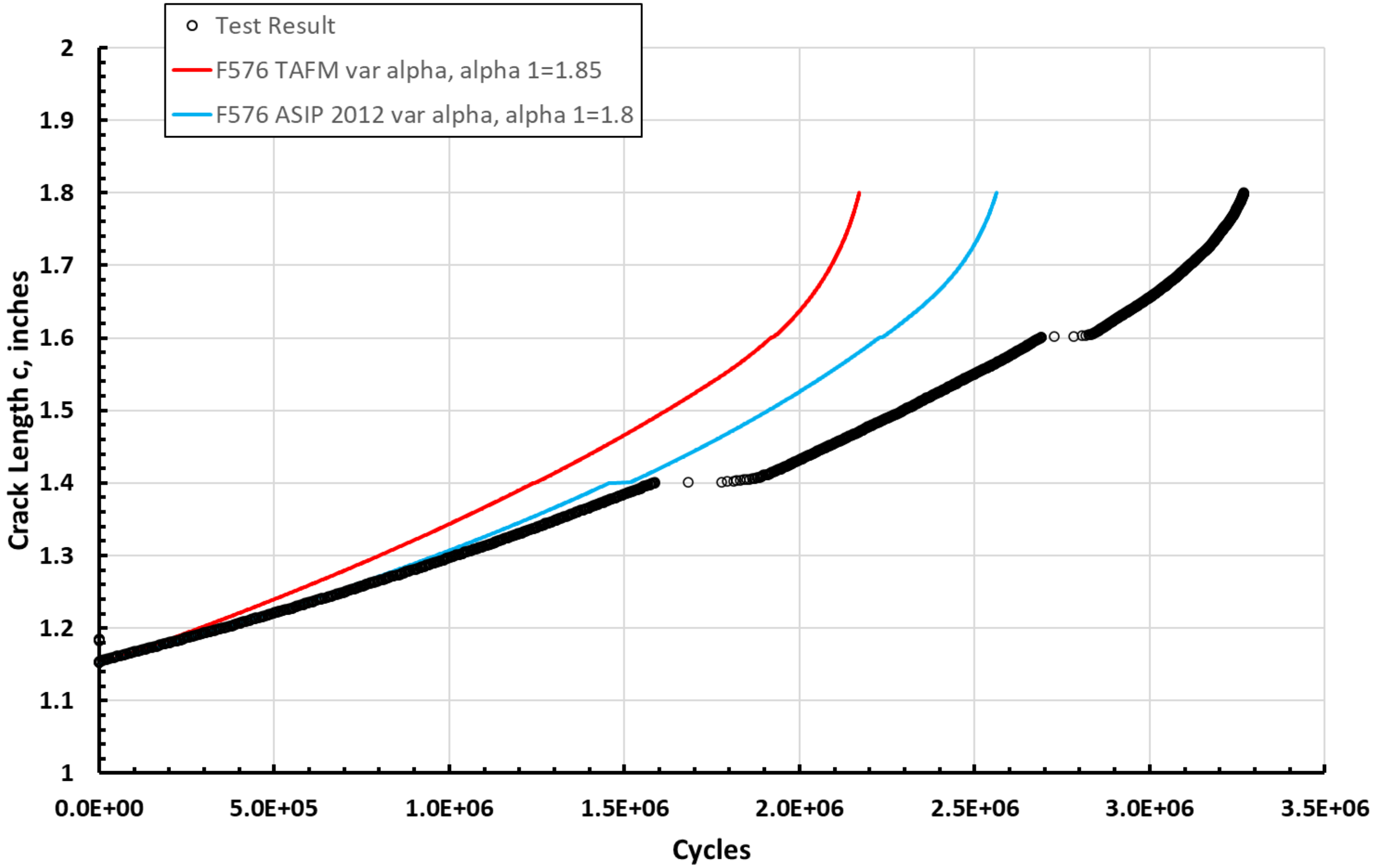
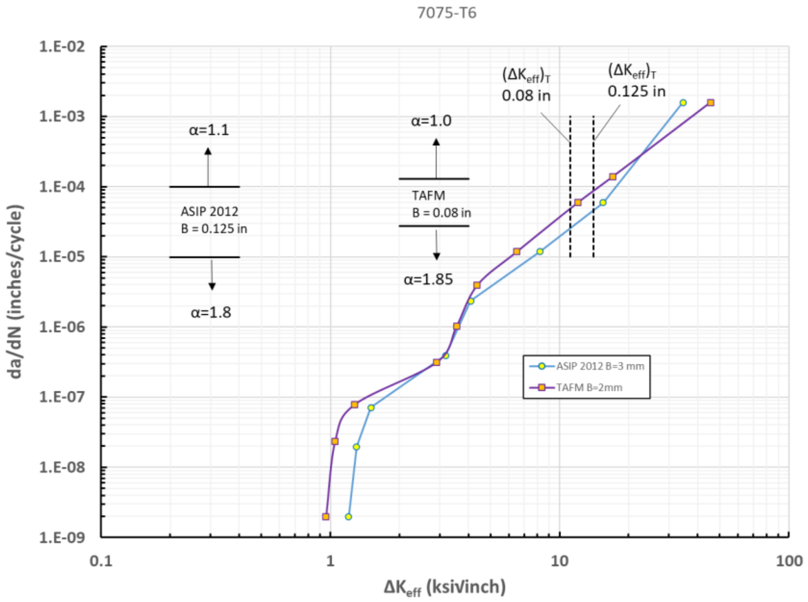
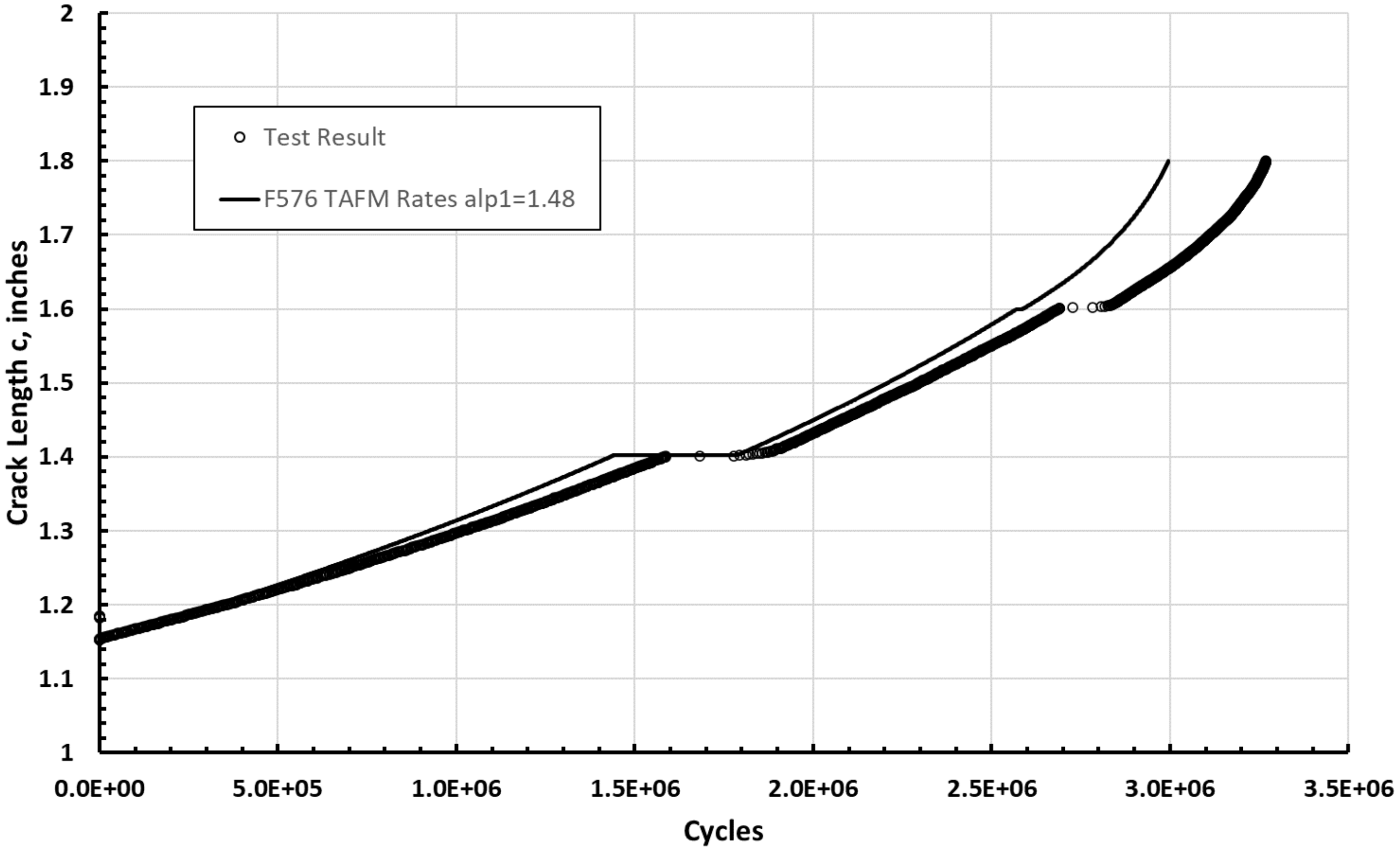




ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Overload Challenge

- <u>FASTRAN Calibrated</u>
  - $\alpha 1 = 1.48$ Lower than expected/used for regular spectrum loading cases. Should be around 1.8

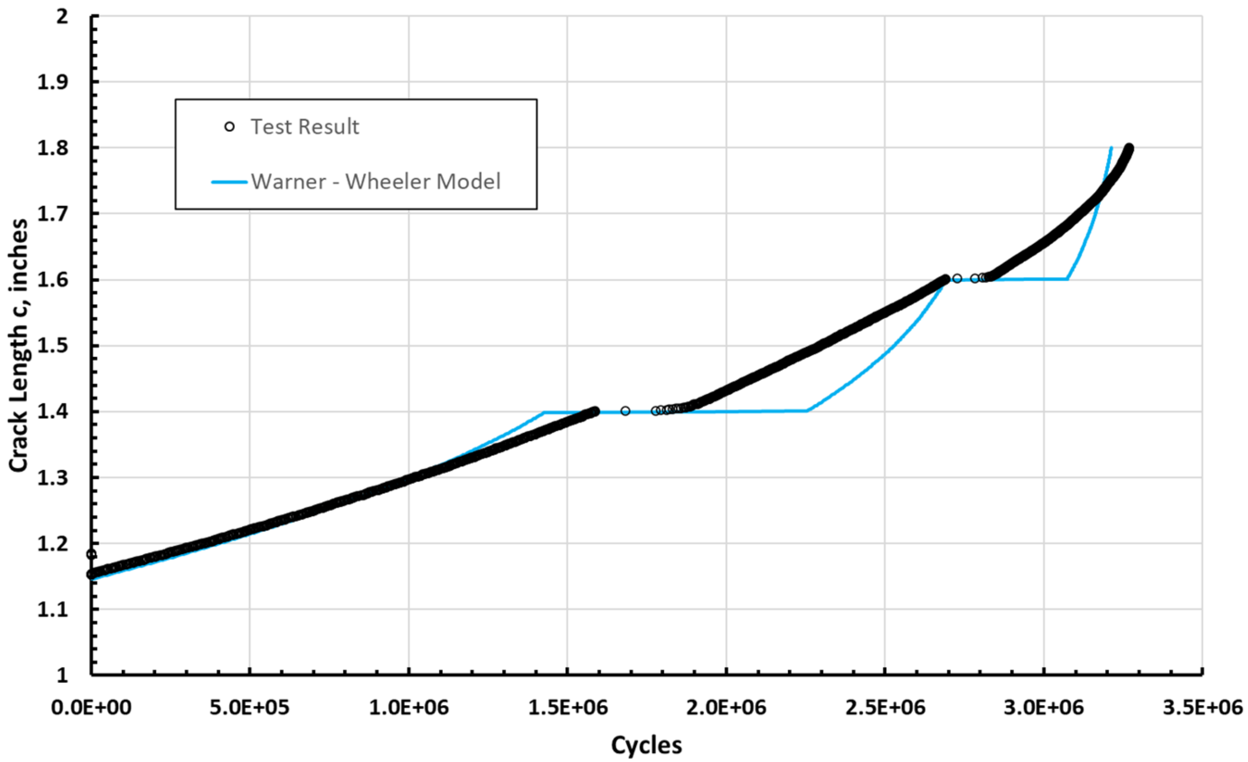


Overload Challenge

- AFGROW - Other retardation models
  - Hsu and Closure models showed similar behaviour to the Willenborg model, i.e. either little or no effect with variations in the parameters, or full crack arrest

Overload Challenge

- AFGROW with "calibrated" Wheeler model
  - Used trial and error to identify the "optimum" value of the Wheeler exponent "m".
  - Found that m=5.47 produced the best result



Overload Challenge

- Conclusions – Spike Overload
  - Despite what you might think, a simple spike overload scenario is difficult to predict/analyse
  - The overload effects seem to act over a length scale comparable with the plastic zone size, although they do persist well beyond that to a lesser extent
  - Retardation models focus attention on the plastic zone which appears justified and appropriate
  - The Willenborg, Hsu and Closure models as implemented in AFGROW (and NASGRO in the case of Willenborg) seemed unable to predict or correlate well to this case, blind or non-blind
  - The Wheeler model was able to qualitatively approximate the behaviour seen on the test with an empirically adjusted value of the exponent m. But some aspects including the rate after overloads did not match well.
  - The FASTRAN approach approximated the behaviour reasonably well, but only when the value of the constraint factor α was empirically adjusted to a low value (1.48 in this case, where 1.8-1.85 would be expected). The second overload effect was considerably under-estimated
  - Understanding and improving our ability to model spike overload cases is considered fundamental to the prediction for spectrum loading

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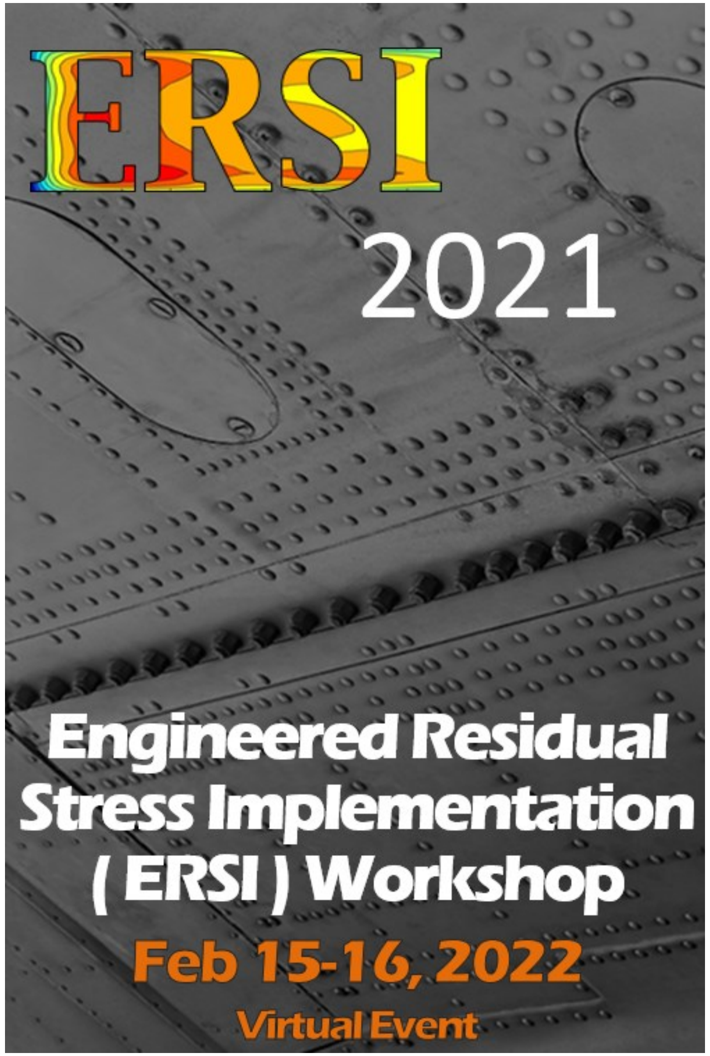
Overload Challenge

- Suggestions for further work
  - Continue research into spike overload cases and see if any existing models/software/approaches can better correlate to the case presented here, and others like it from the literature
  - Conduct further spike overload tests for the C(T) geometry, but also importantly for the M(T) geometry
  - Continue research into the constraint effects as modelled in FASTRAN to see if there is an effect which is not properly understood and modelled
  - Compressive constraint factor (β) in FASTRAN is typically set at 1.0. But that may not be always appropriate. Further investigation required.

Agenda

- Mission Statement and Goals
- 2021 Achievements
  - Round Robins
    - Interference Fit Fastener Round Robin
    - Stress Intensity Factor Round Robin
    - Overload Challenge
  - Relevant Programs
    - Multi-Point MAI Program
    - Taper-Lok Analysis Methodology & Testing
  - Analysis Methods
    - Two vs. Multi-Point Analysis Comparisons
  - Testing
    - Kt-Free Coupons
- 2022 Focus Areas



Multi-Point MAI Program

- Verification, Validation, & Demonstration of Multi-Point Fracture Mechanics Codes
  - NG-11 is a new program associated with the Metals Affordability Initiative and is being performed cooperatively with a team of government and industry participants

Air Force Research Laboratory
ATI ADVANCED TECHNOLOGY INTERNATIONAL
NORTHROP GRUMMAN
HILL ENGINEERING
Fracture Analysis Consultants, Inc

  - Objective
    - Validate and assess capability of three (3) multi-point fracture mechanics MPFM codes as applied to the linear elastic fracture mechanics (LEFM) analysis of Cx holes

BEASY
FRANC3D
BAMpF

Multi-Point MAI Program

- ## Test/Analysis Conditions

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

Technical POCs:
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Dr. TJ Spradlin (USAF AFRL), thomas.spradlin.1@us.af.mil

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Taper-Lok Analysis & Testing

- **Primary Objective:**
  - Develop a robust analytical approach to predict Damage Tolerance (DT) life at Taper-Lok fastener holes

Physics Based Analytical Methodology → Blind Predictions

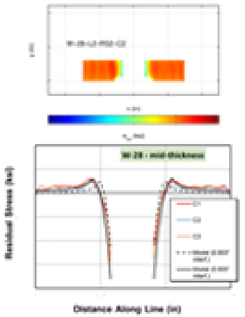
Validation Testing & Evaluations → Blind Predictions

Blind Predictions → Refined Analytical Approach Defined Best Practices → Updated B-1 DTAs

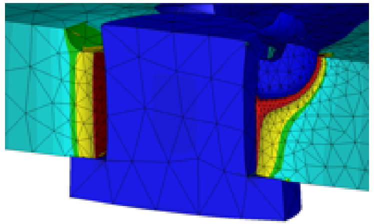
Multi-Point Analysis

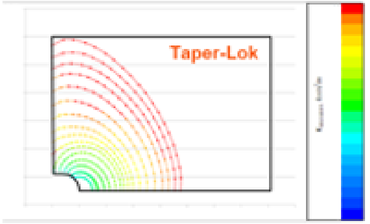
BAMpF (Broad Application for Multipoint Fatigue)

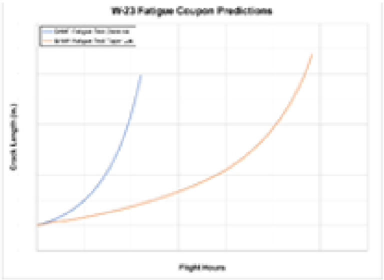
Residual Interference and Stress



Explicit Modeling of Geometry

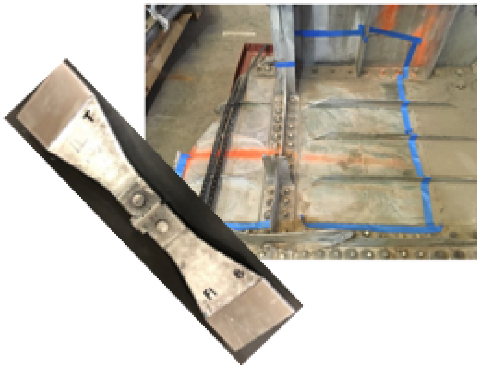






Representative Coupons

Excised Components

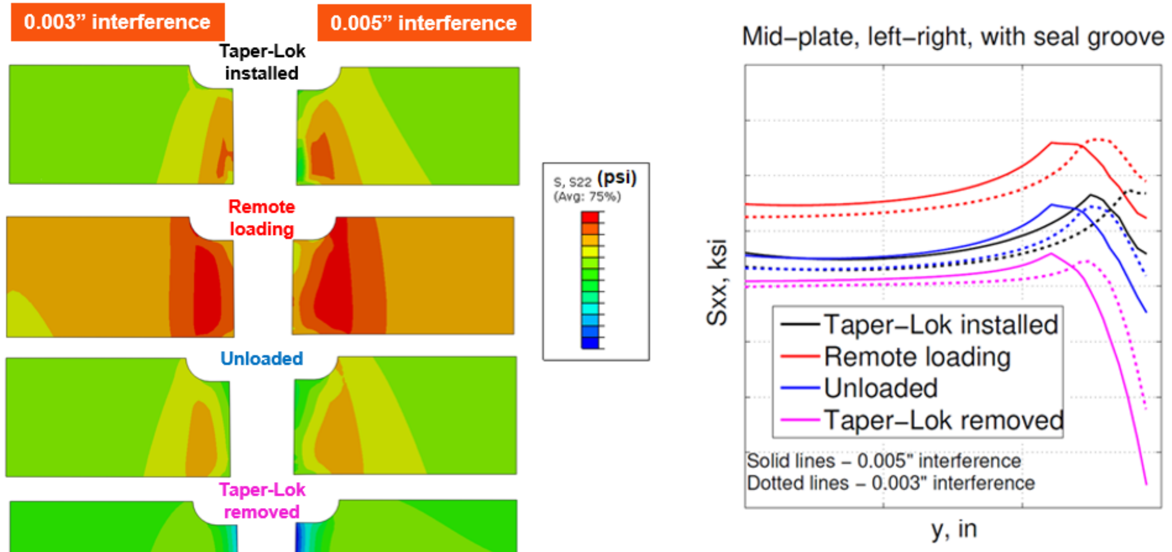


Presented at the 2021 Aircraft Structural Integrity Program (ASIP) Conference Austin, TX, Nov 29–Dec 02,2021; Reference Boeing RROI# 170258-BDS

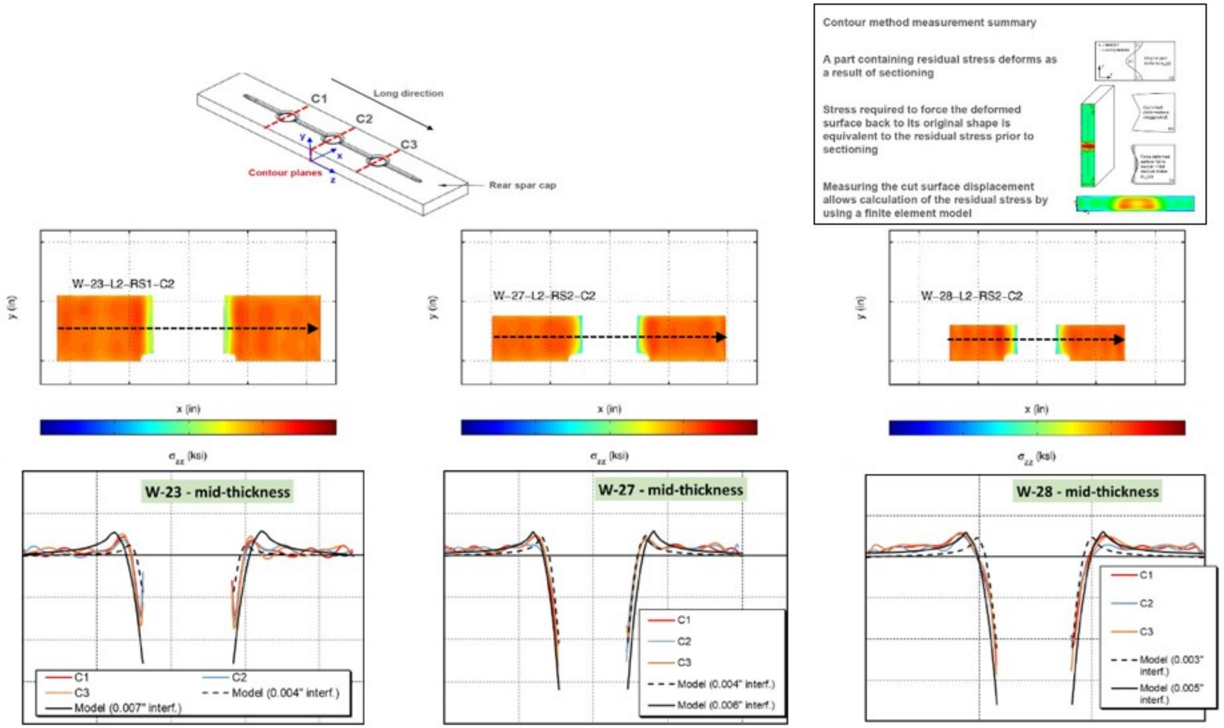
Taper-Lok Analysis & Testing

▪ Modeling and Measurements:

Process Model Results



Residual Stress Measurements



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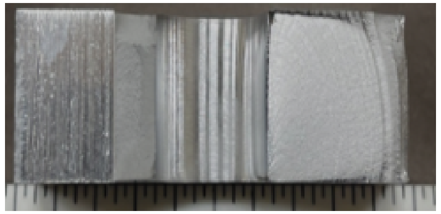
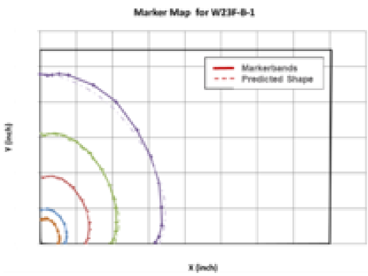
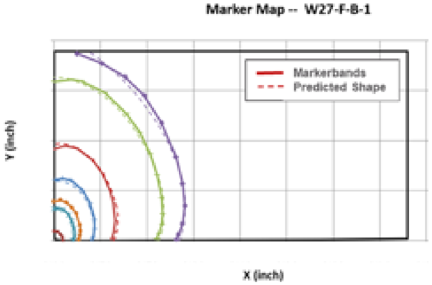
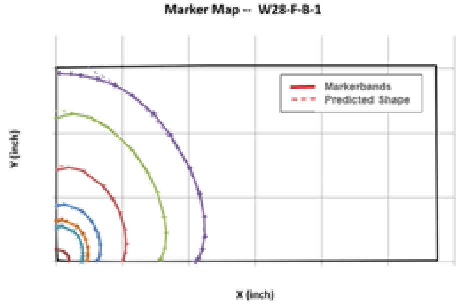
Baseline Comparisons:

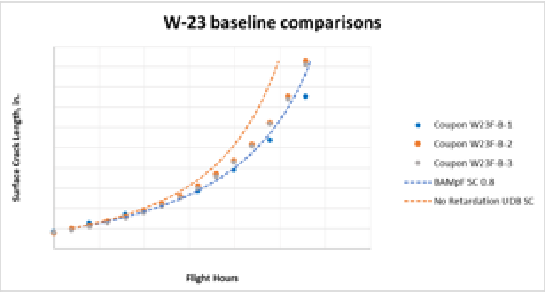
- Blind predictions* compared to test results
- Flaw size based on initial MB shape
  - Coupon W23-F-B-1 (0.0415in x 0.0582in)
  - Coupon W27-F-B-1 (0.0535in x 0.0783in)
  - Coupon W28-F-B-1 (0.046in x 0.063in)

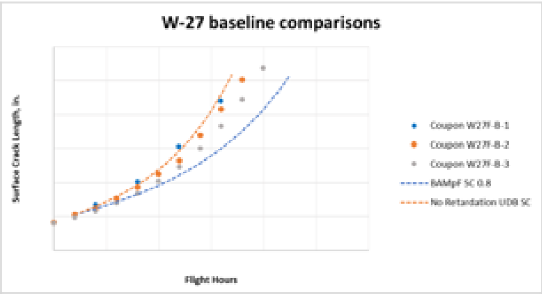


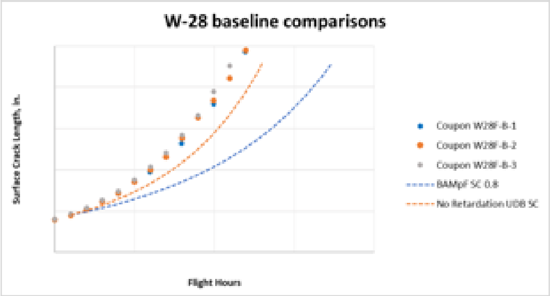












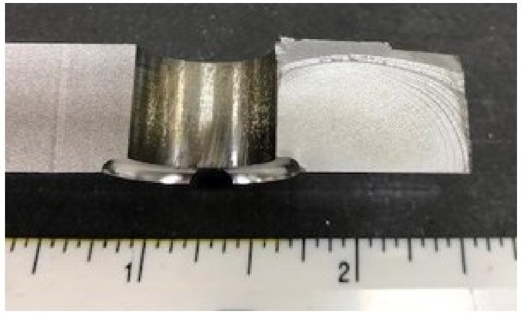
*BAMpF predictions utilized surface correction based on REF[1] AFGROW Presentation "The crack wants what it wants"

Presented at the 2021 Aircraft Structural Integrity Program (ASIP) Conference Austin, TX, Nov 29–Dec 02,2021; Reference Boeing RROI# 170258-BDS

Taper-Lok Analysis & Testing

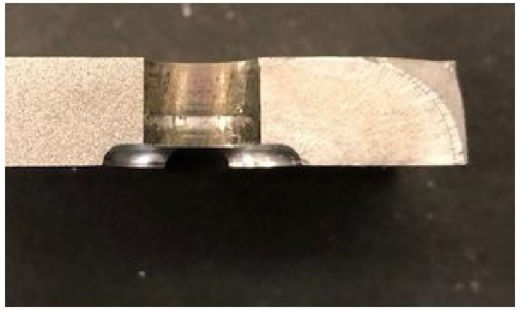
- Taper-Lok Comparisons:

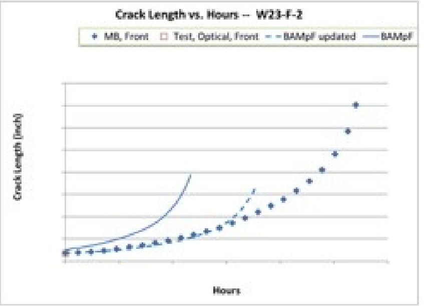
W23F-2

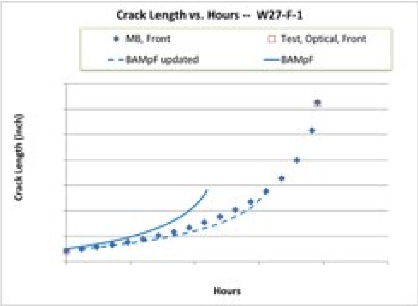


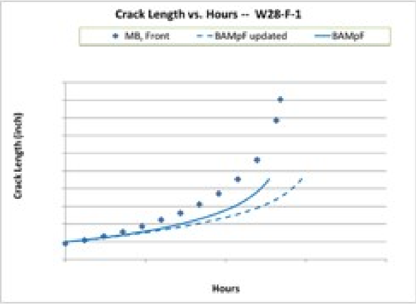
W27F-1

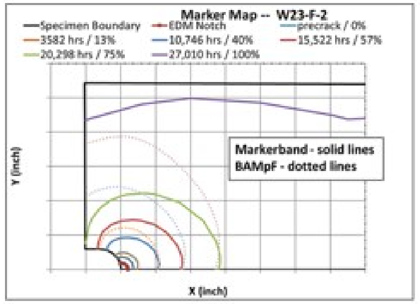
W28F-1

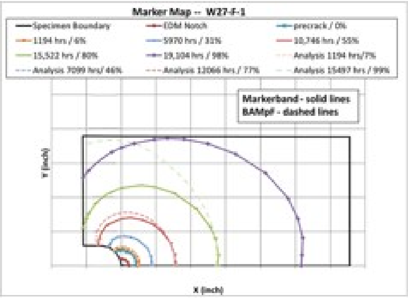


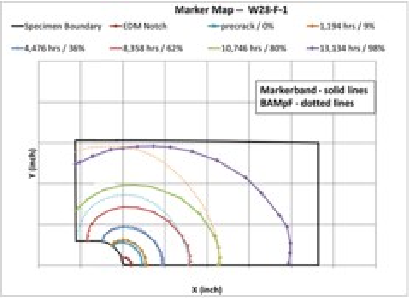












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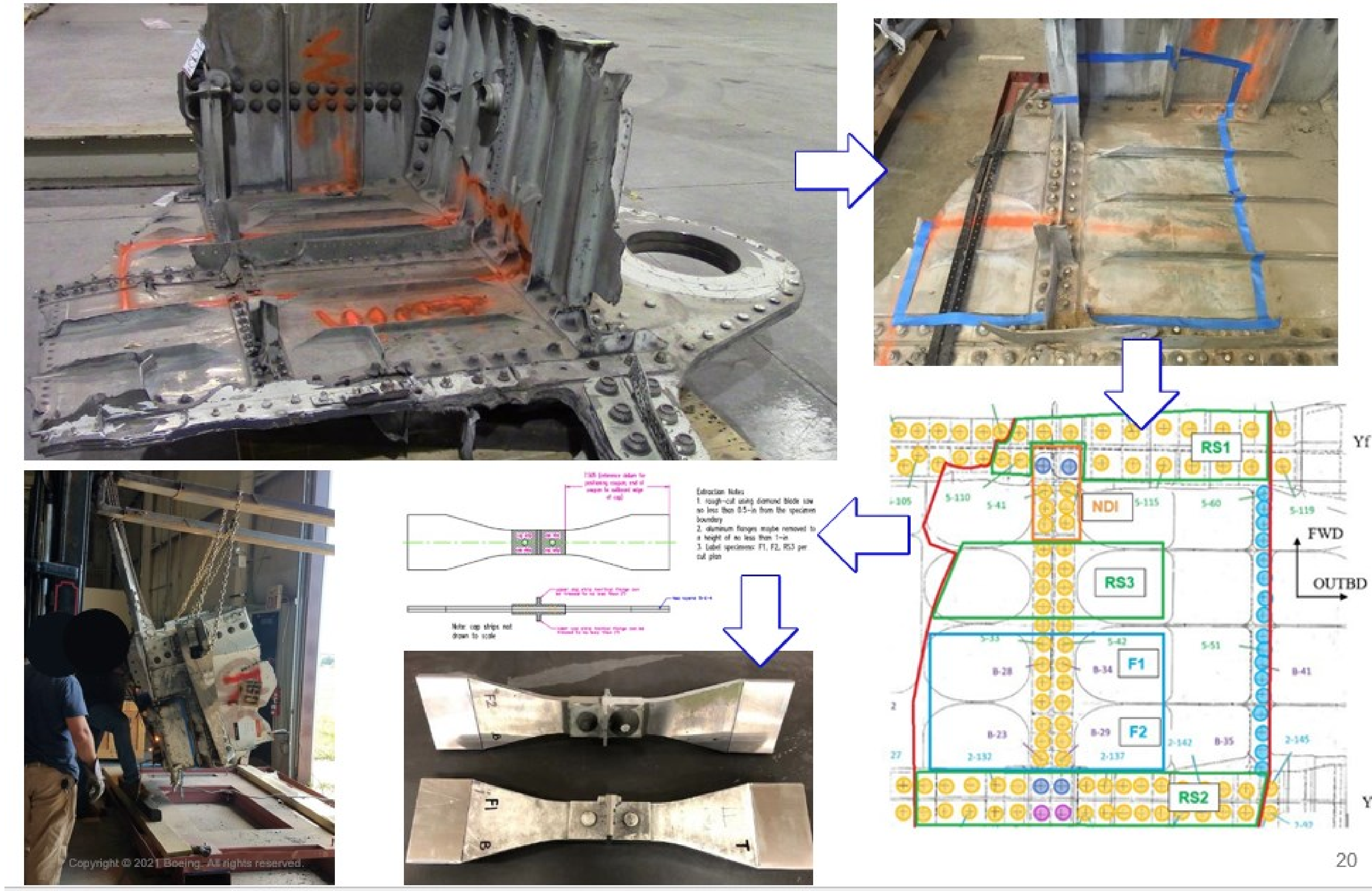
Taper-Lok Analysis & Testing

- <u>Component Coupons – Extracted B-1 Structure:</u>



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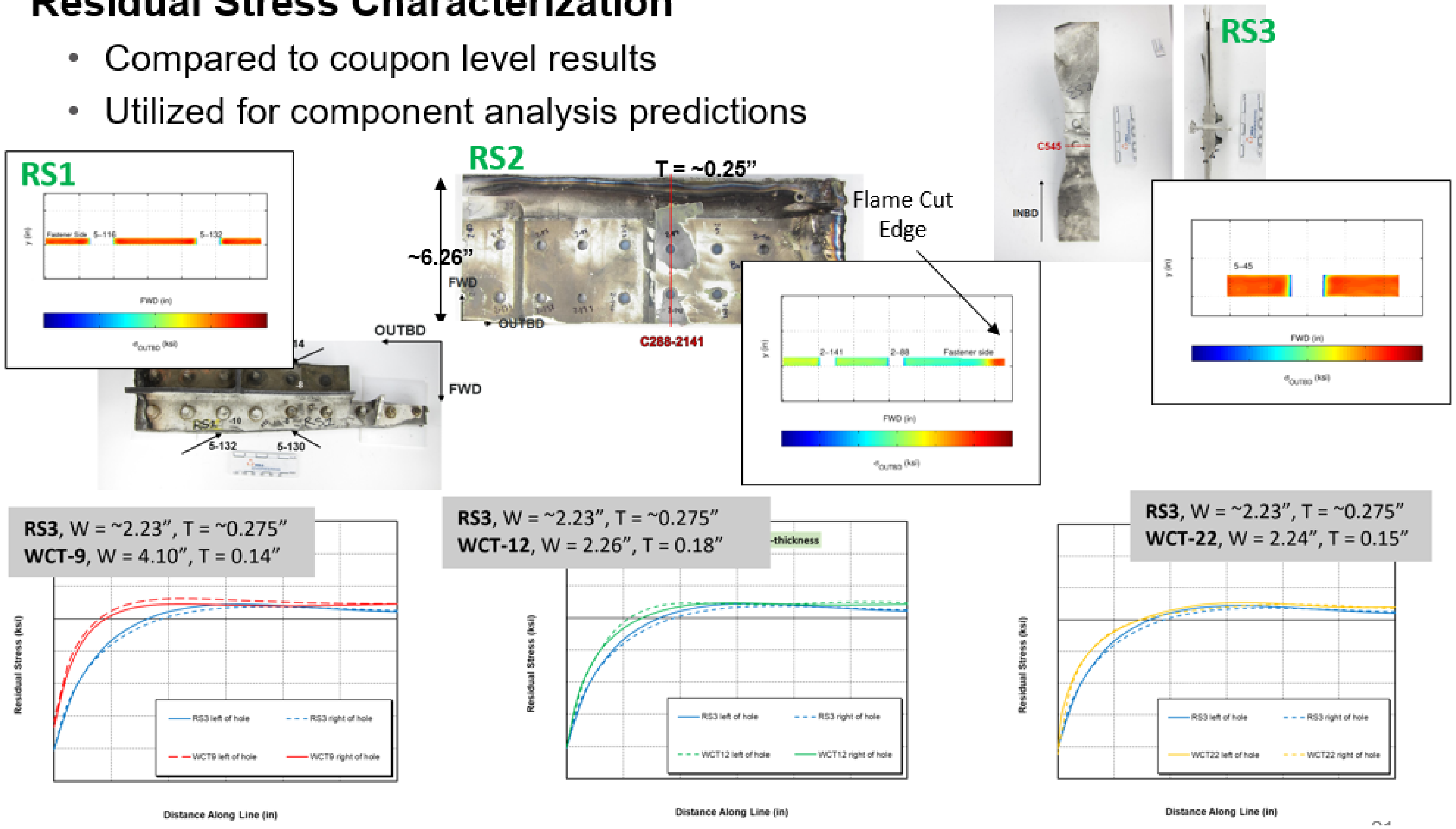
Component Coupons – Extracted B-1 Structure:

Multiple Extracted Sections of Wing Carry-Through Utilized for Residual Stress Characterization

- Compared to coupon level results
- Utilized for component analysis predictions



Taper-Lok Analysis & Testing

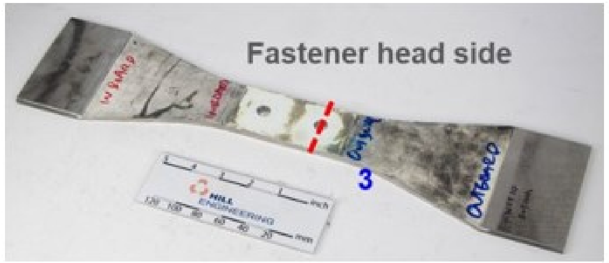
Component Coupons:

Component Coupon F2 Failed Near Grip at ~144k Flight Hours

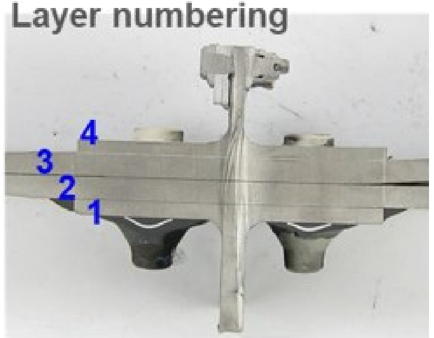
- Far exceeded life prediction with no RS benefit
- No induced notch

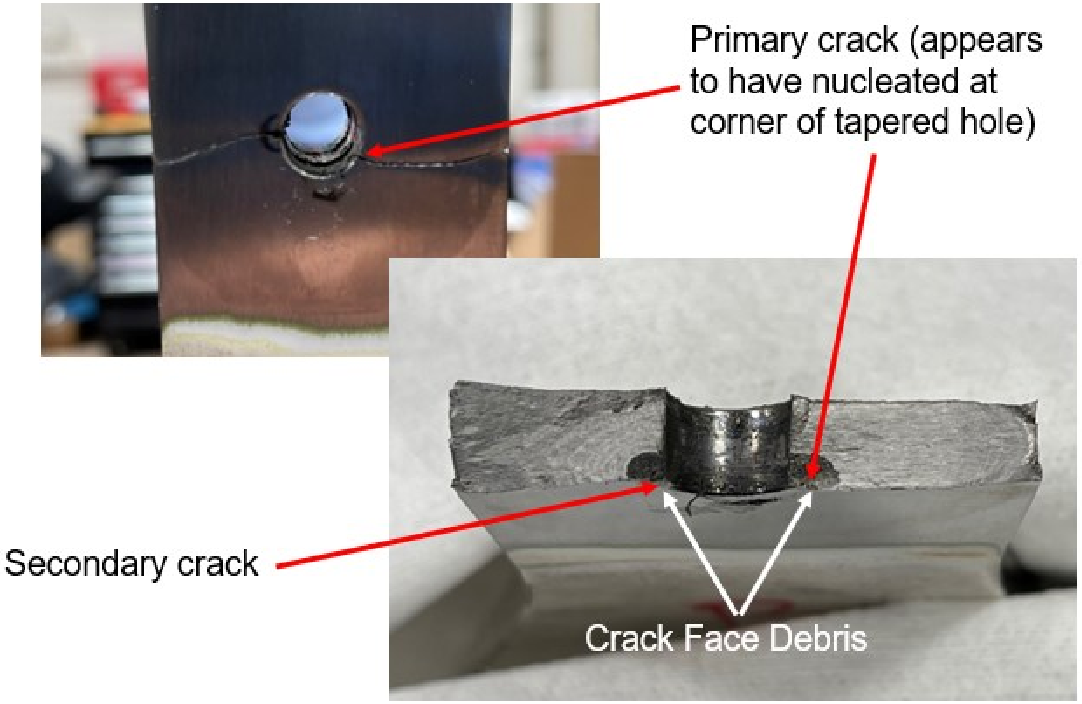
Component Coupon F1 Successfully Failed at Taper-Lok at ~ 352k Flight Hours

- Embedded EDM DT flaw at Taper-Lok hole to maximize potential of failure at gage section



Layer numbering





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Taper-Lok Analysis & Testing

- Conclusions:
  - Analytical Process
    - Robust analytical process established to characterize behavior at Taper-Lok fastener holes
    - Key data (residual stress and interference) characterized to support analyses
    - Consistent residual stress and interference results between coupons and extracted components
  - Testing
    - Efficient truncation and markerband approach established to support testing
      - Significant reduction in cycles
      - Marker bands easy to find for measured crack curve correlation
    - Baseline coupons correlated well with predictions
    - Taper-Lok coupons achieved failure at desired location
      - Challenging with RS benefit coupons
    - Coupon results were very repeatable
    - Component coupon showed long life and verified RS
      - Successful failure at Taper-Lok after 352k hours
  - Taper-Lok fasteners create significant life benefits from ERS

ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Agenda

- Mission Statement and Goals
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    - Overload Challenge
  - Relevant Programs
    - Multi-Point MAI Program
    - Taper-Lok Analysis Methodology & Testing
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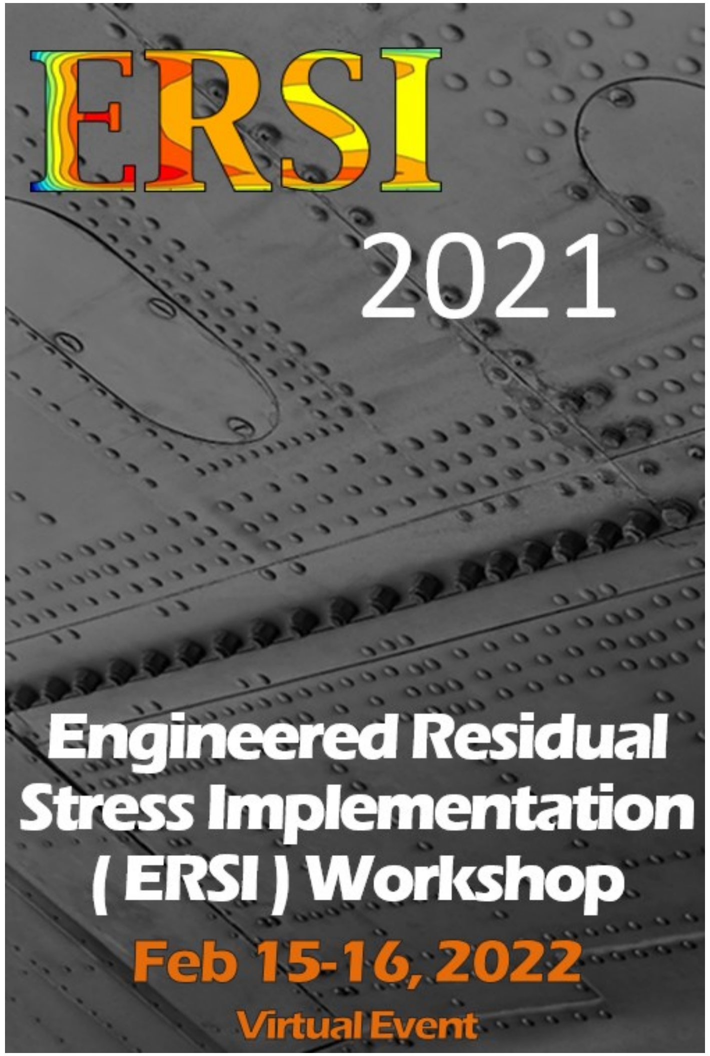
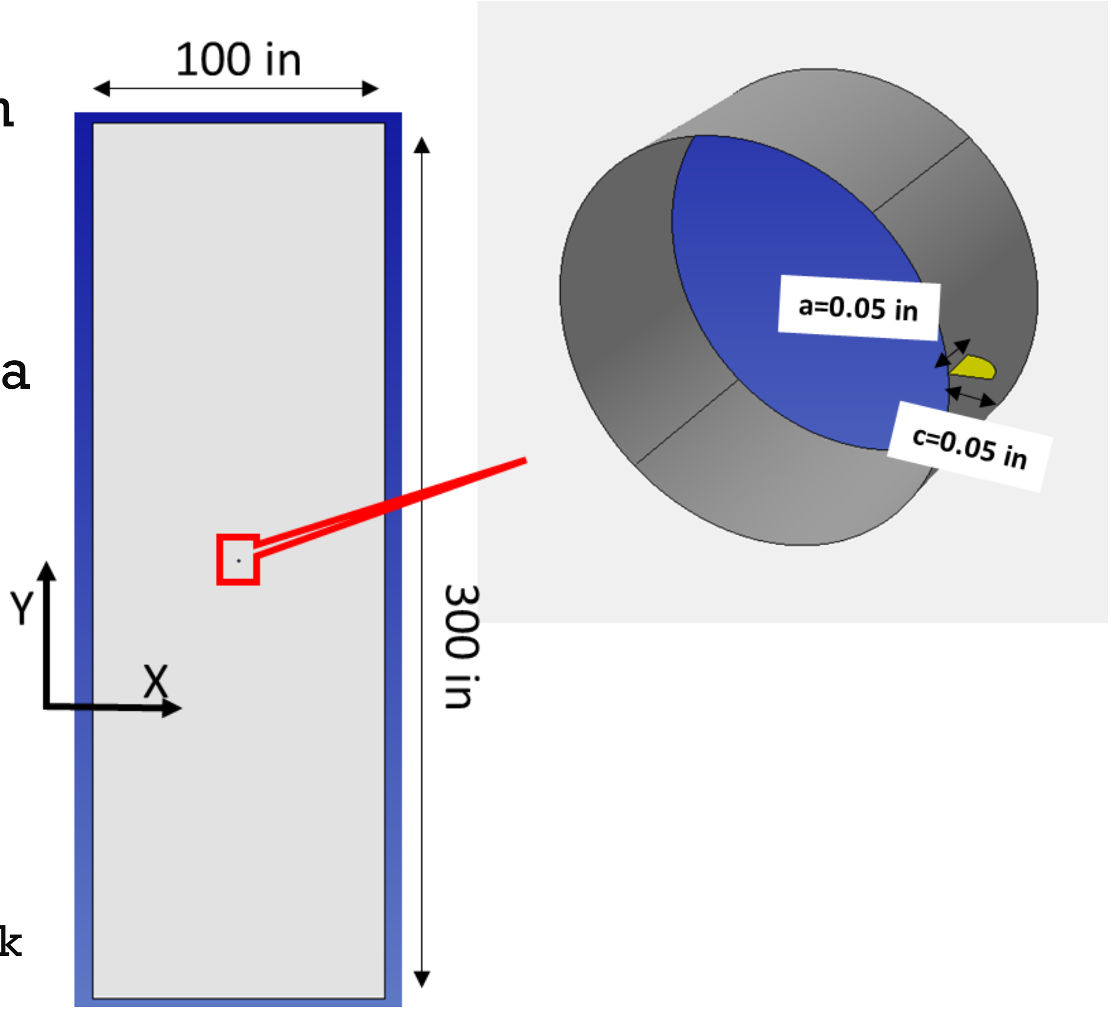
    - Two vs. Multi-Point Analysis Comparisons
  - Testing
    - Kt-Free Coupons
- 2022 Focus Areas



Two vs. Multi-Point Comparisons

- Benchmark Problem
  - Assess the fatigue crack growth solution difference due to an elliptical crack assumption between 2-point (DKIa, DKIc) reduced order models, multi-point (DKI values along given cross-sectional paths) reduced order modeling and, explicit 3D finite element modeling
  - Model definition: corner crack at a bolt hole in a panel under far field uniform tensile, axial loading ("condition 2" from Mode I stress intensity factor benchmarking).
    - Thickness = 0.25 inch, hole diameter = 0.5 inch
    - Material Properties: E = 10.4e6 psi, n = 0.3
    - Uniform tensile far field loading
    - Loading cycle: min(sy)=0 to max (sy)= 10 ksi, R =0
    - Initial crack size: c = a =0.05 inch
    - C = 1e-8, n = 3.2, US customary units (ksi, ksi*sqrt(in), inch/cycle), AA 2024-T62
    - B. Farahmand: "Fatigue and Fracture Mechanics of High Risk Parts"

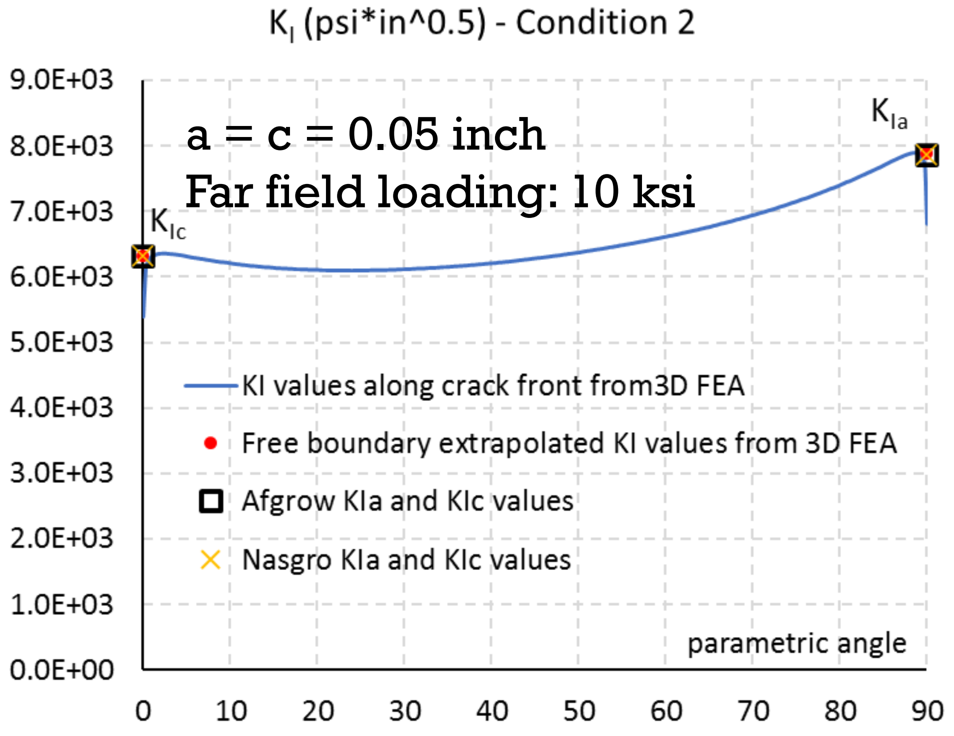


ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Two vs. Multi-Point Comparisons

- Procedure for Solution Comparison
  - A 2-point (DKIa, DKIc) crack growth modeling procedure is emulated in the explicit 3D FEA simulation
    - The free boundary KI gradient is removed from the KI solution along each crack front
    - The KI values are extrapolated to the free boundary
    - Advancement along the free boundary (Da, Dc) is estimated (Paris relationship)
    - An elliptical crack front increment is defined based on free boundary increments. Each crack front increment in the automatic 3D FEA simulation is elliptical.
  - The 2-point reduced order modeling solutions are then compared against multi-point and explicit 3D FEA where no shape constrained is assumed (default option)
  - Tools for solution comparison: NASGRO, AFGROW, BAMpF and, 3D FEA (SimModeler Crack capabilities).
  - No closure effects should be considered in ALL the predictions and verification of KI values is needed to make sure the solution difference is mostly attributable to the shape constraint

KIa and KIc verification agreement is reached



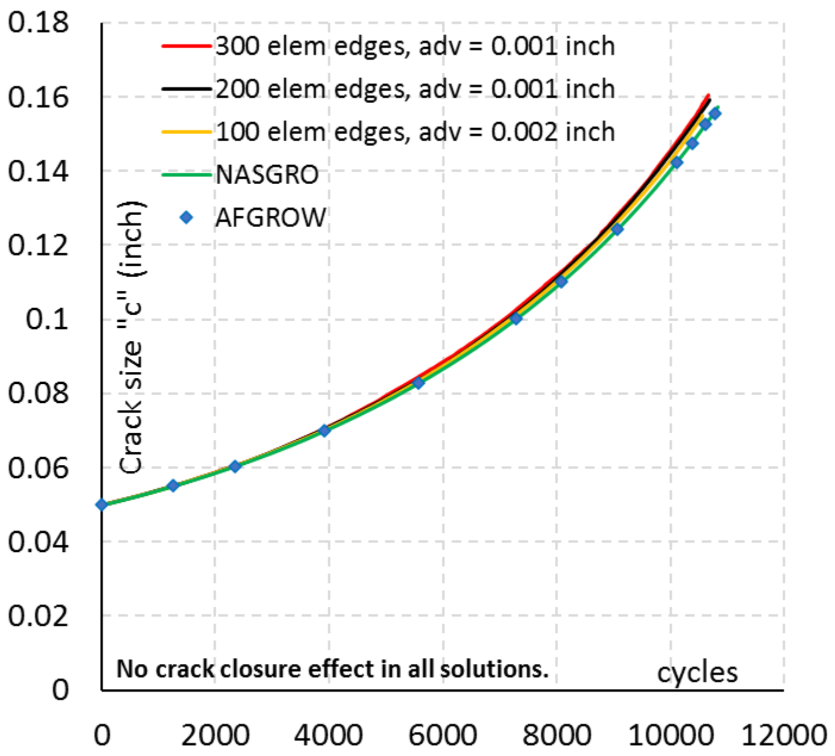
	Extrapolated	Afgrow	Nasgro
KIc (psi*in^0.5)	6.31E+03	6.32E+03	6.33E+03
KIa (psi*in^0.5)	7.89E+03	7.86E+03	7.86E+03

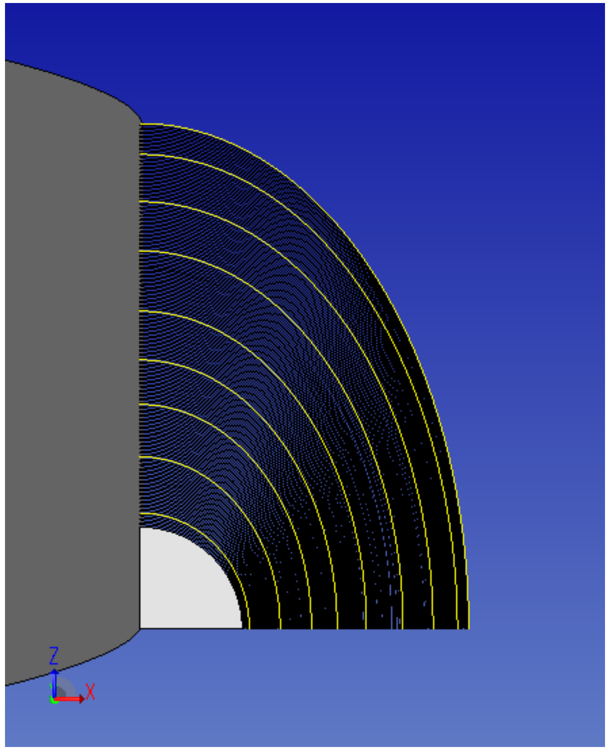
- The extrapolated values are from the 3D FEA solution after the free boundary gradient is removed
- KIc values match within 0.4%, KIa values match within 0.2%
- Nasgro's CC16 model (solution from Shak Ismonov) and Afgrow's advanced model (solution from Jim Harter) were used

Adrian Loghin, Simmetrix

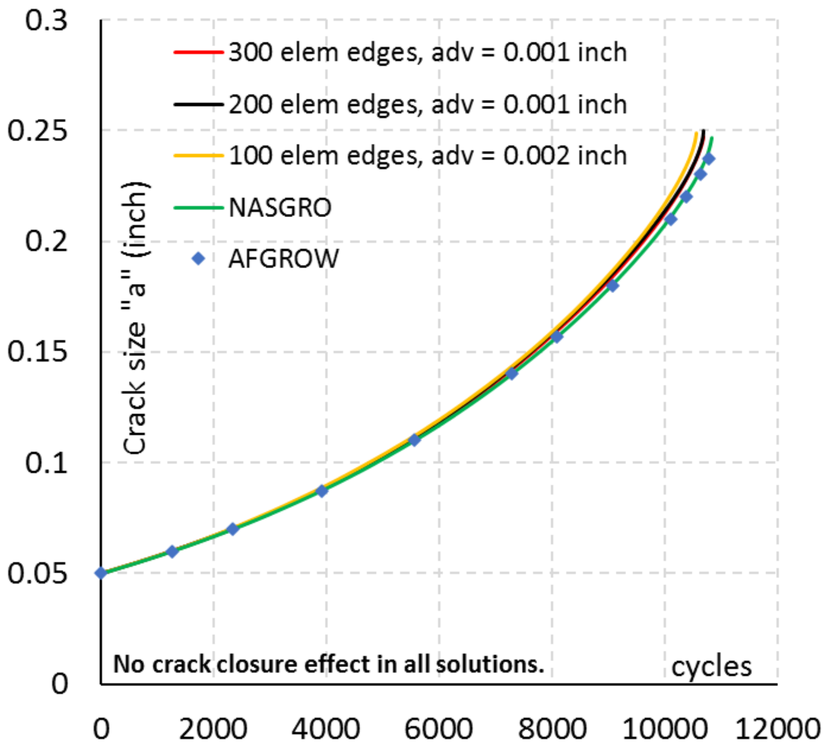
Two vs. Multi-Point Comparisons

- Solution Comparison for Elliptical Crack Front Increments
  - Quick convergence study shows that the 3D FEA explicit crack growth using elliptical crack front increments matches similar solutions using Afgrow and NASGRO models
  - The low mismatch between the reduced order model and the 3D FEA counterpart must come from slight KI numerical differences



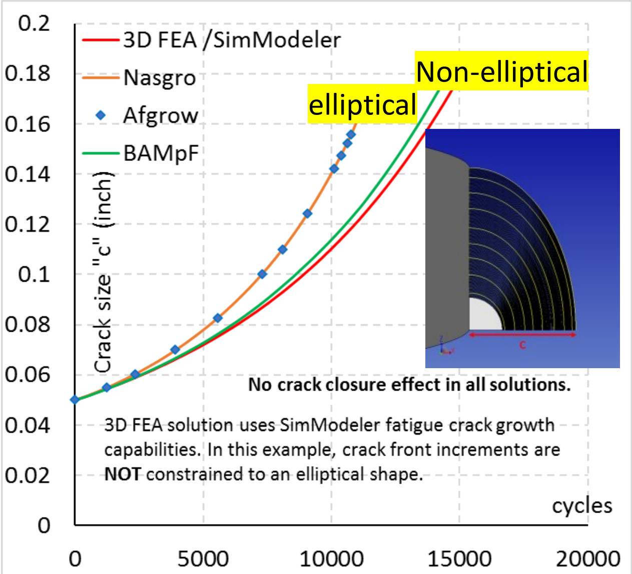


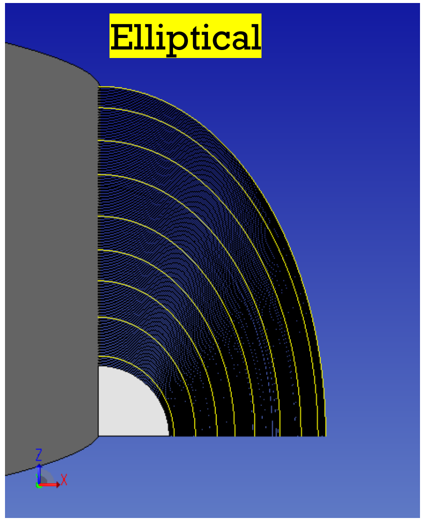
Adrian Loghin, Simmetrix

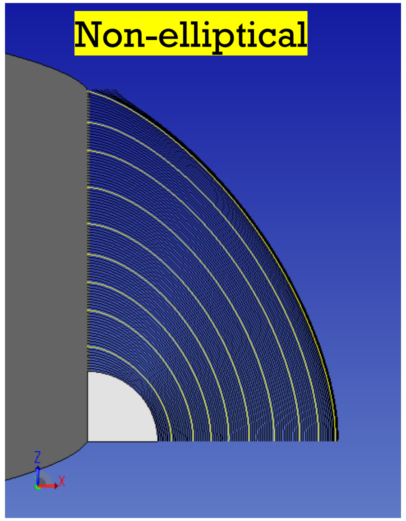


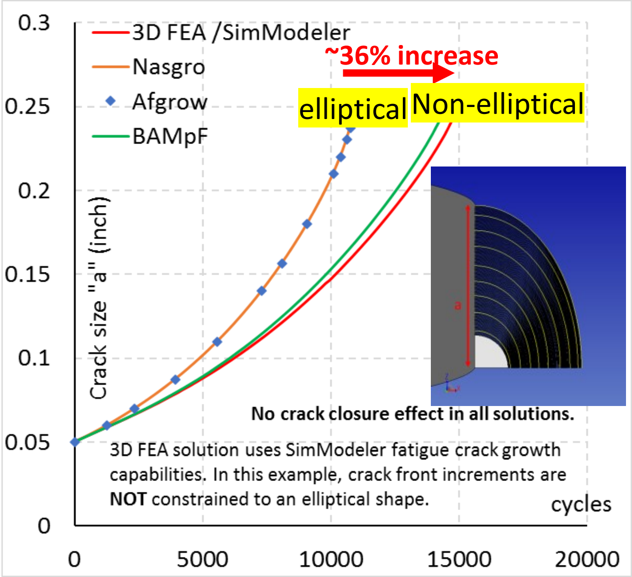
Two vs. Multi-Point Comparisons

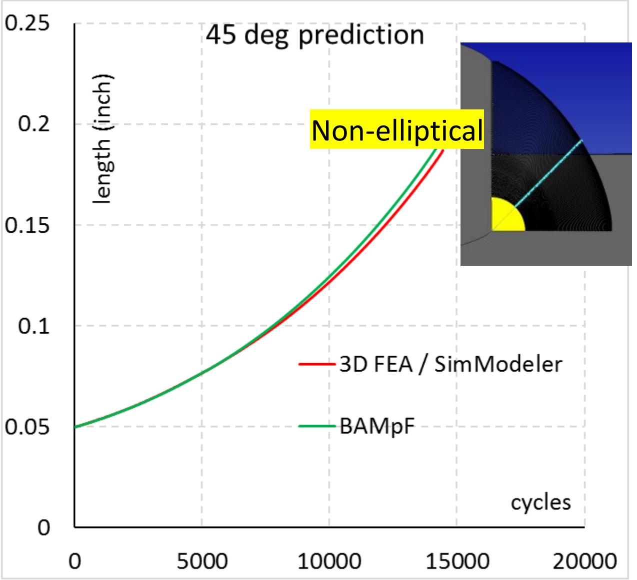
- Elliptical vs. No Shape Constraint
  - Using the 3D FEA verified solution for an elliptical crack front constraint, a comparison against the no-shape constraint (default option) solution can be performed
  - For this benchmark problem, if the crack front increments are not constrained to be elliptical, it is observed an increase in the predicted cycles with ~36%.
  - For the no shape constraint solutions, there is a good agreement between BAMpF and SimModeler











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Two vs. Multi-Point Comparisons

- Conclusions
  - A 36% remaining useful live solution difference between the two models (enforcing elliptical crack growth and allowing the increment to take a shape controlled by the local geometry and far field loading) is assessed
  - Effective crack area was collected from both 3D fatigue crack growth simulations, with elliptical shape constraint and with no constrained imposed to the crack front shape
  - Modeling verification was reached between the 2-point reduced order modeling and 3D FEA using same the modeling assumptions
  - Modeling verification was reached between BAMpF and SimModeler solutions where crack front increments are not constrained to be elliptical
  - This 36% difference for a corner crack at a hole model might have a direct impact in solutions submitted in the round robin challenges (interference fit, Afgrow/central hole specimens)

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    - Taper-Lok Analysis Methodology & Testing
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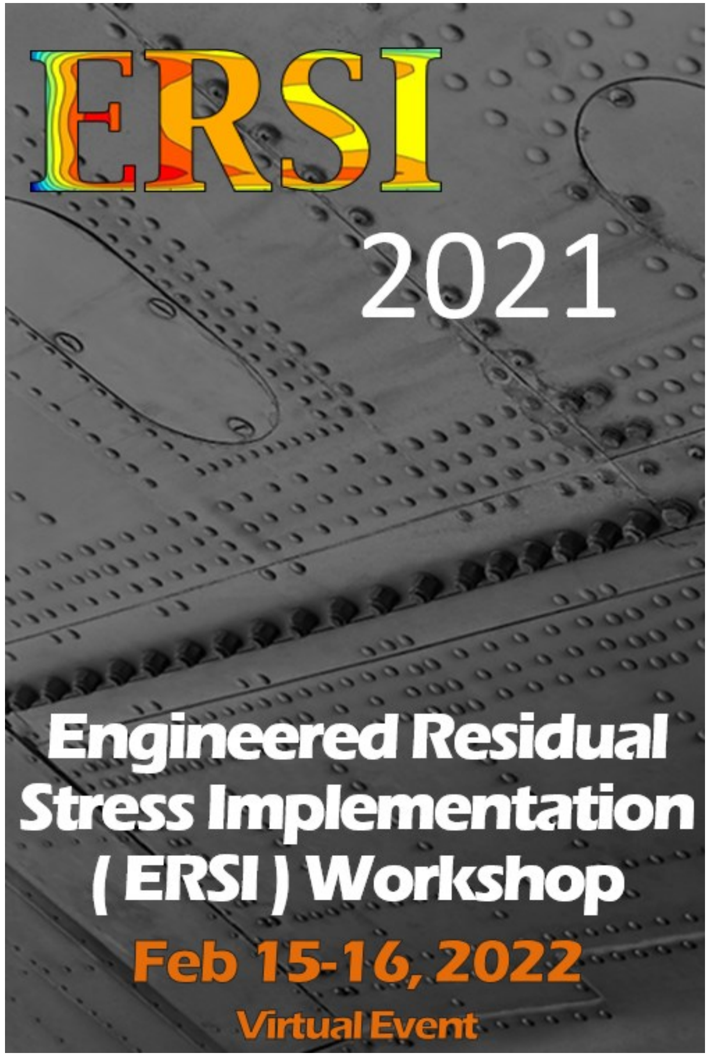
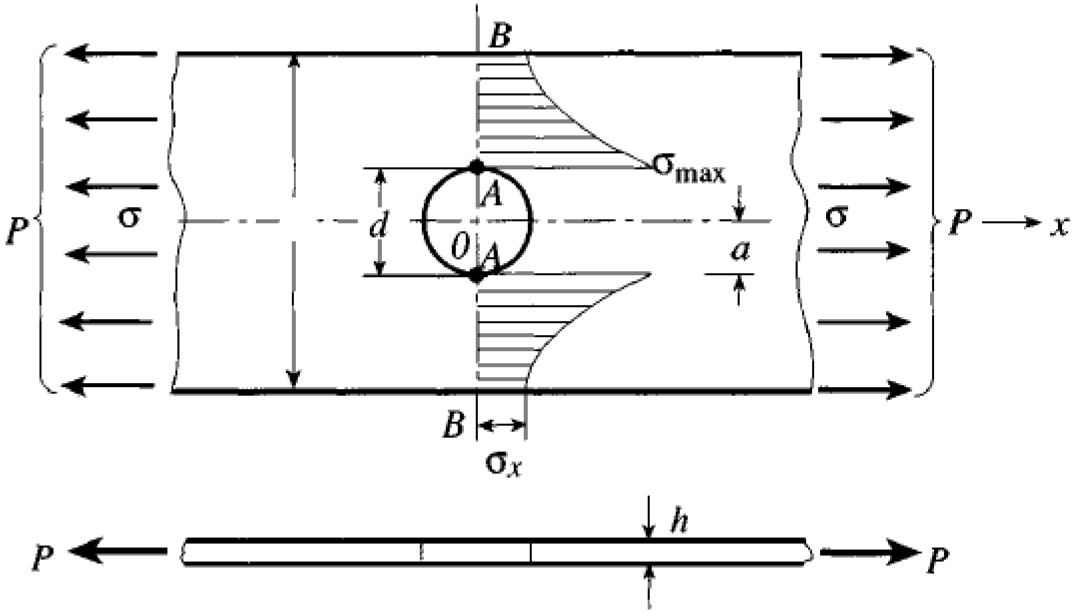
    - Kt-Free Coupons
- 2022 Focus Areas



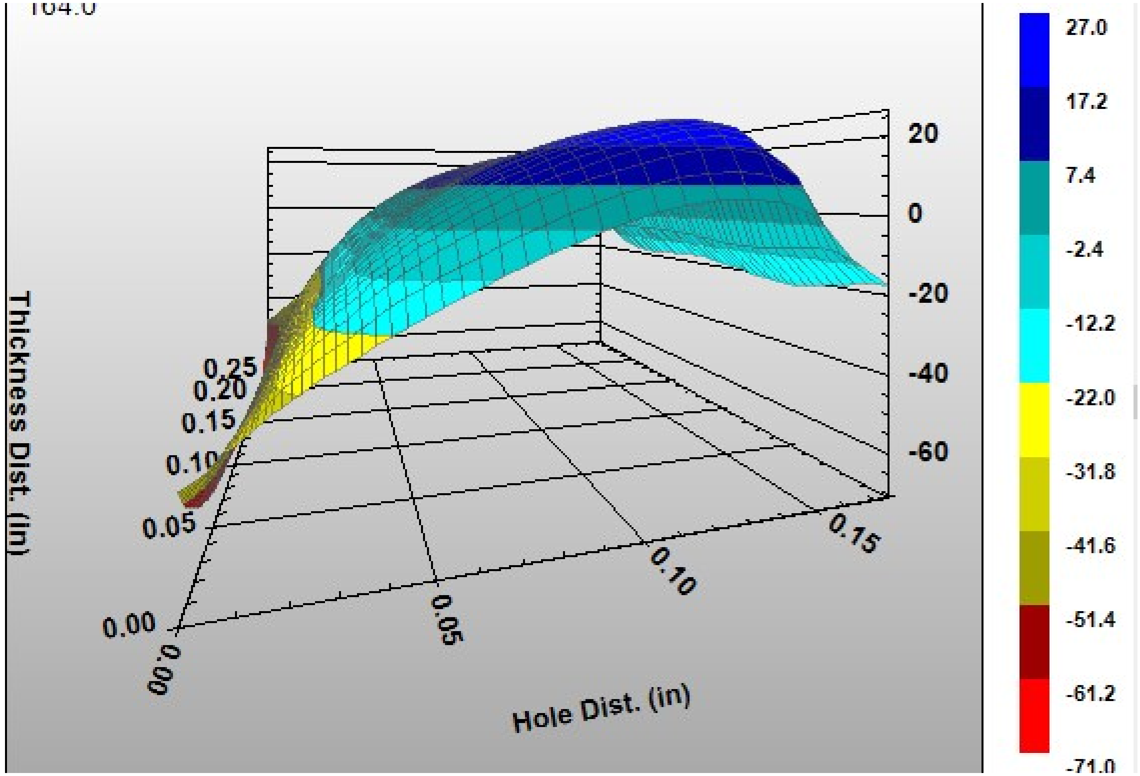
Kt Free Coupons

- **The Problem**
  - Residual Stress (RS) analysis has compounding steep stress gradients
    - Kt from the hole
    - Cold Expansion RS field



(a)

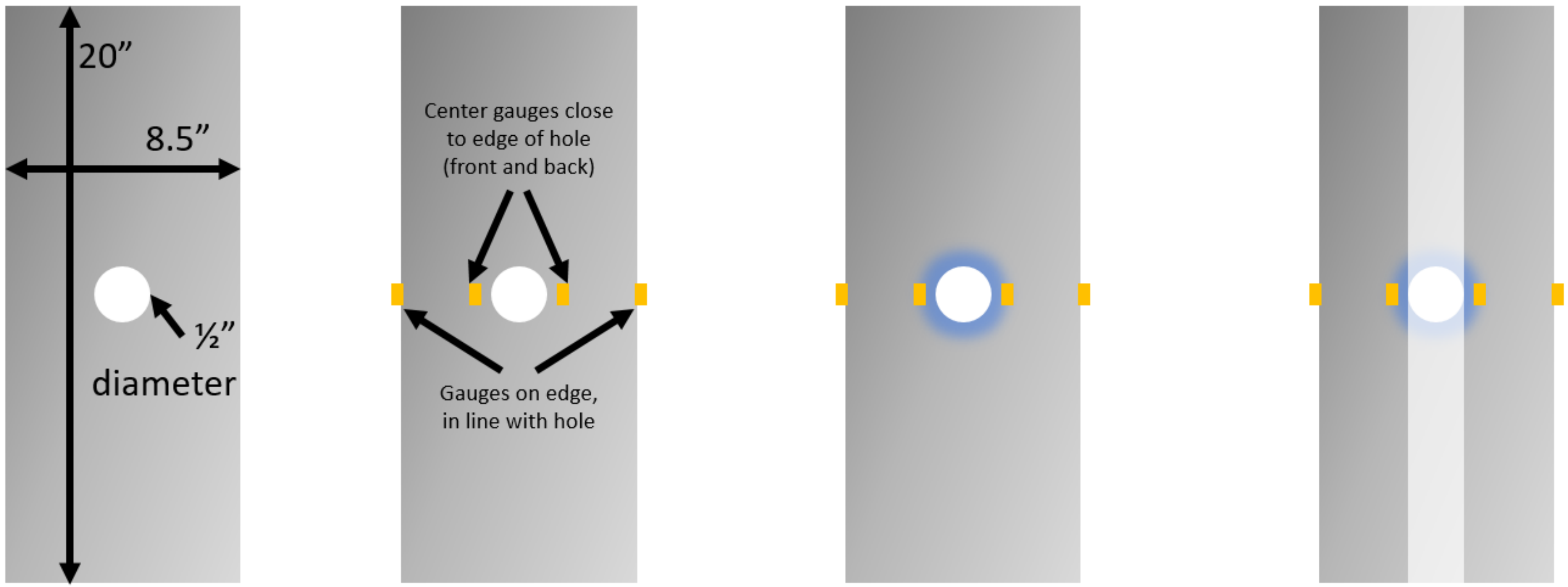
Peterson's Stress Concentration Factors, 2nd Edition



Coupon Development

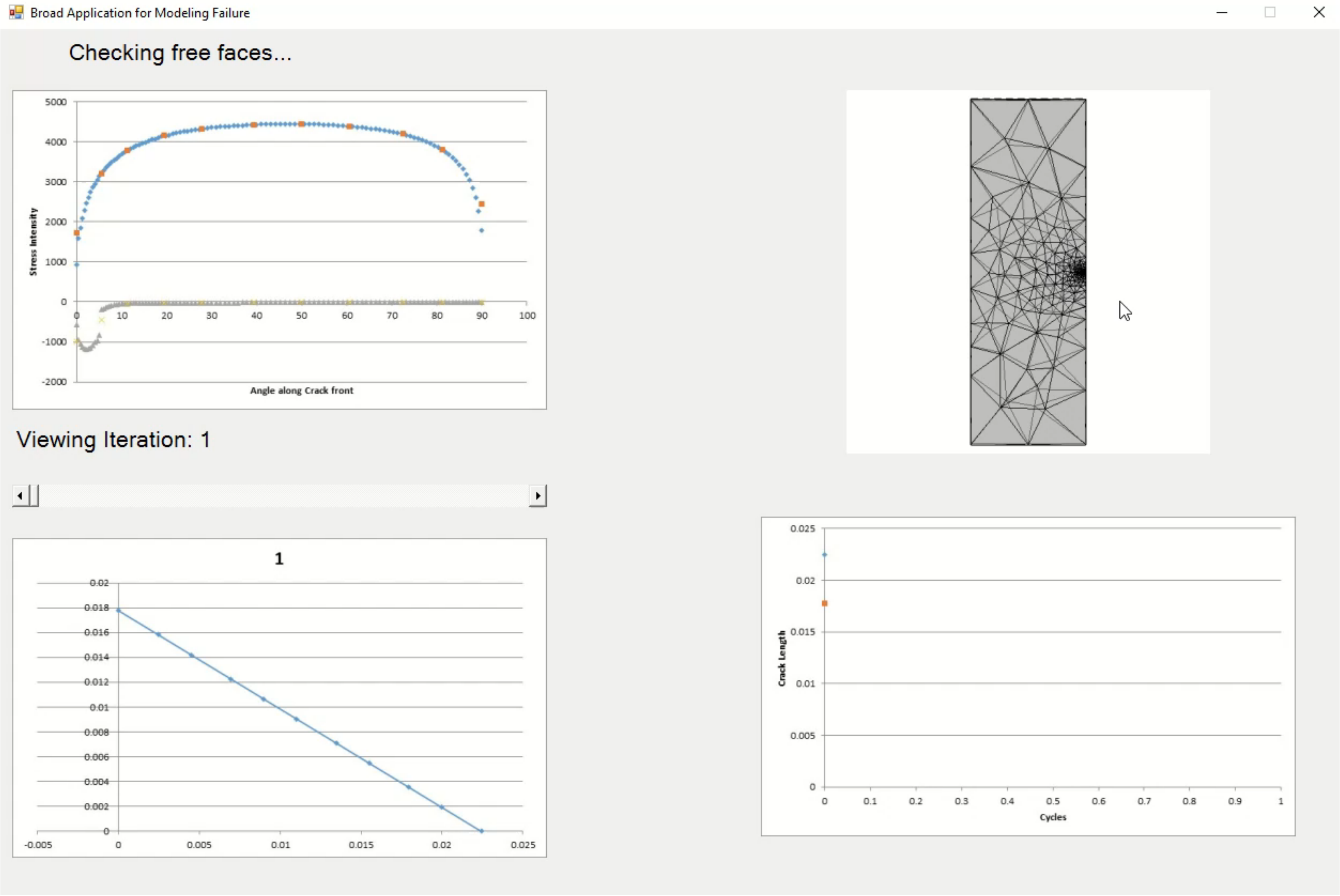
- Objective: Eliminate the effect of the hole K_t while preserving the RS field created by Cx

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



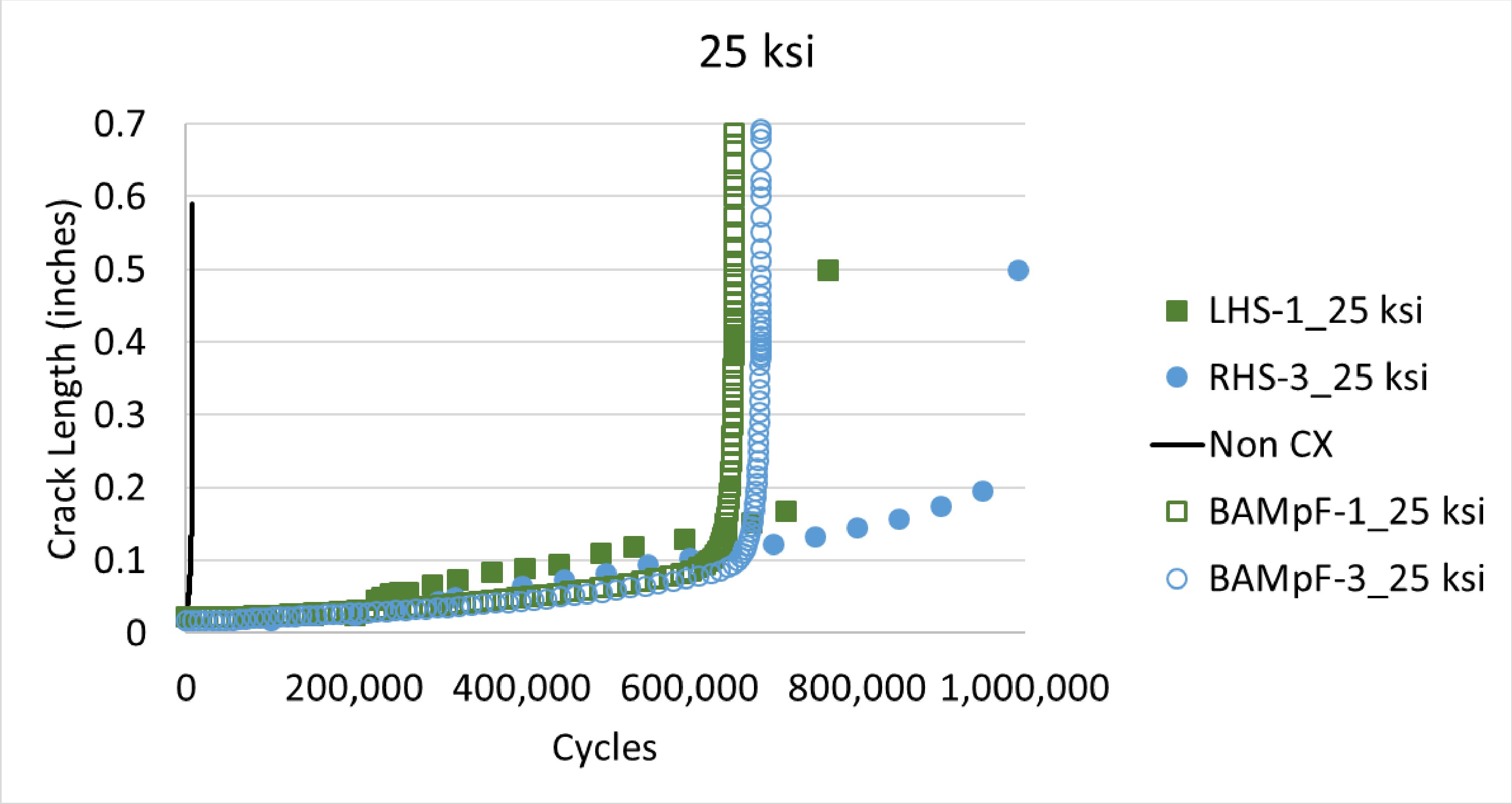
Kt Free Coupons

- Video of tensile at bore to avoid crack arrest



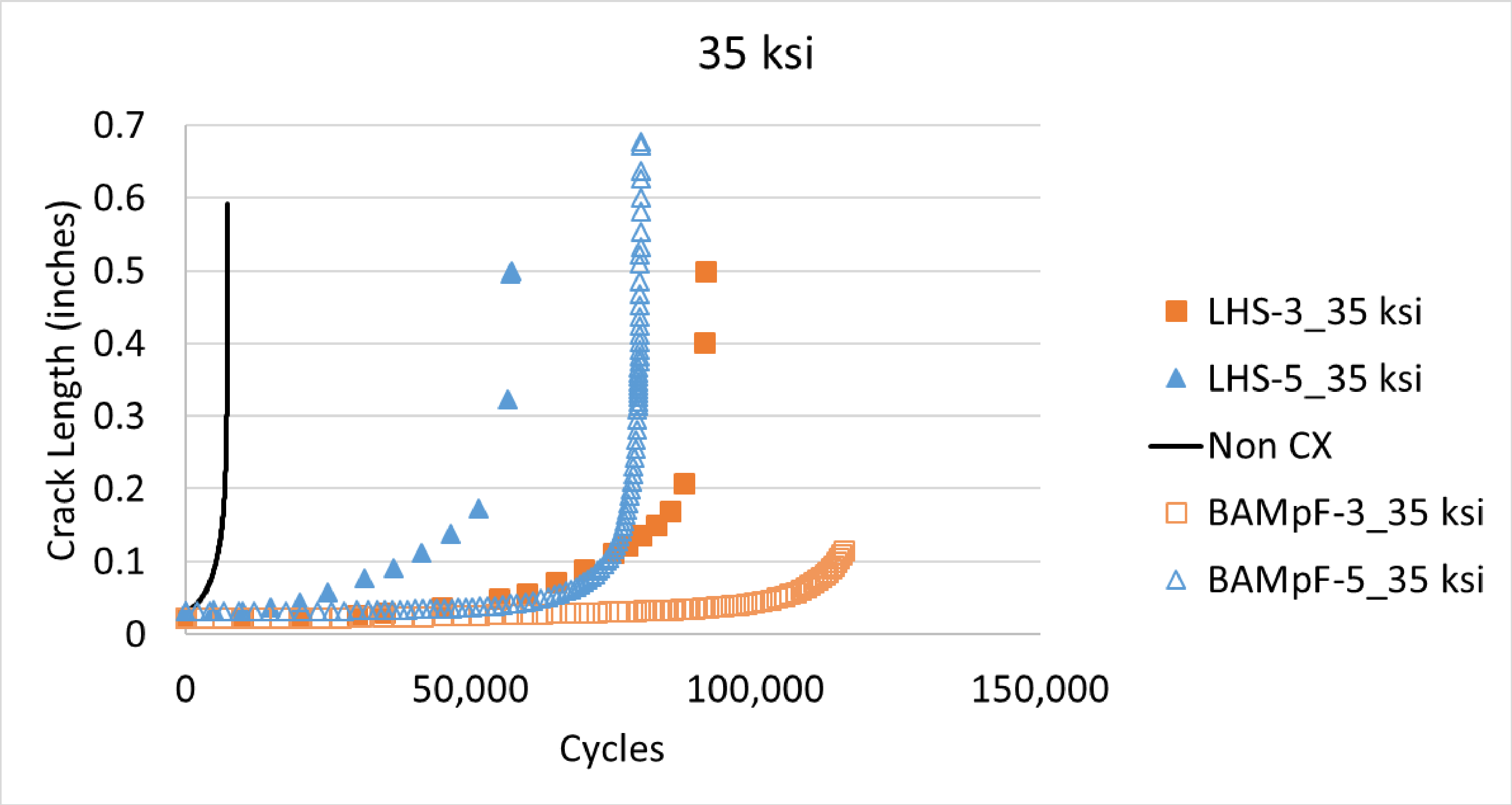
Kt Free Coupons

- <u>25ksi Results</u>
  - With minimal RS until 0.02" into the part, BAMpF results correlate very well



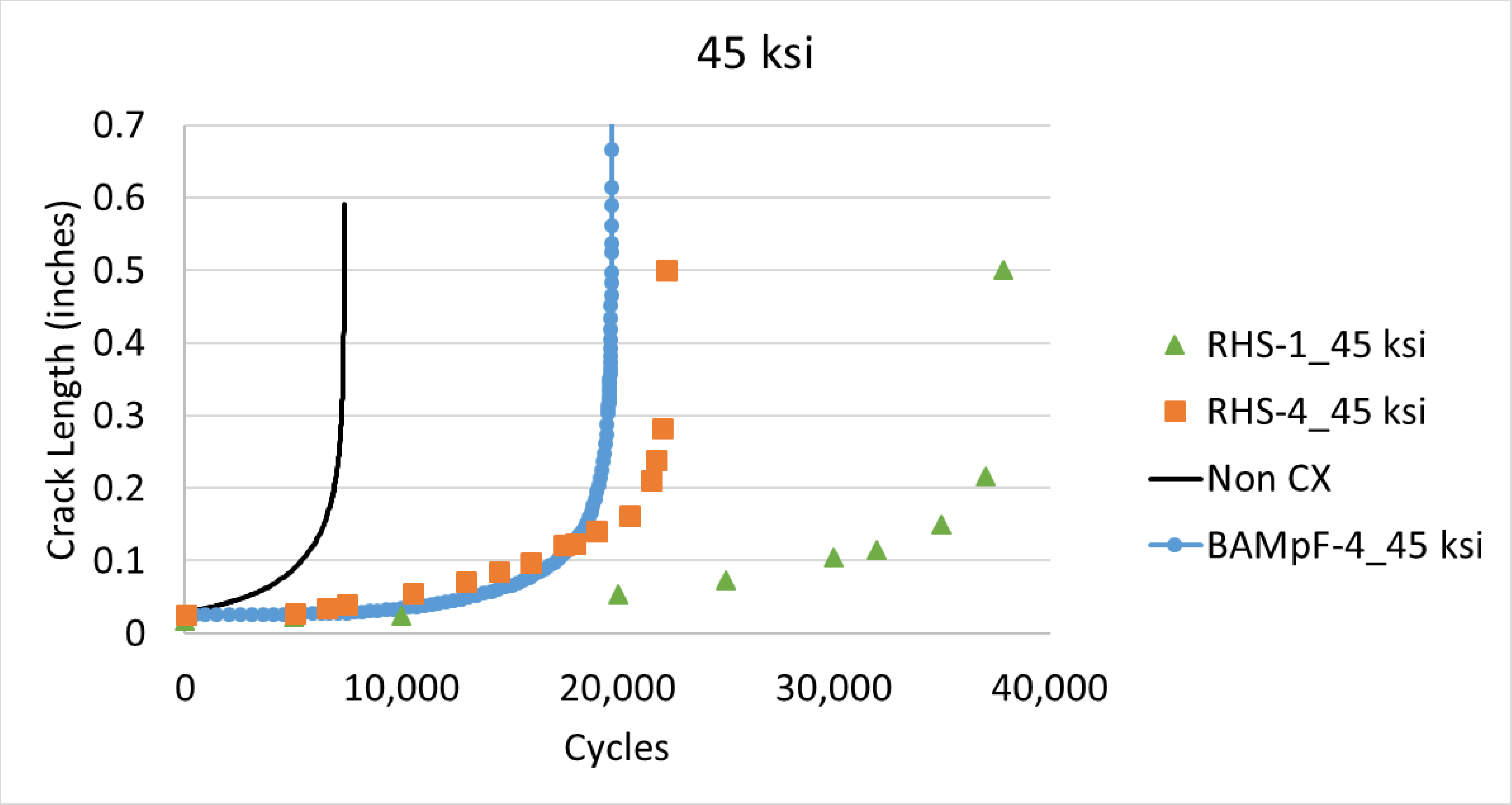
Kt Free Coupons

- 35ksi Results
  - Minimal RS for first 0.02" over predicts



Kt Free Coupons

- <u>45ksi Results</u>
  - Model correlates well for .02" minimal RS approach

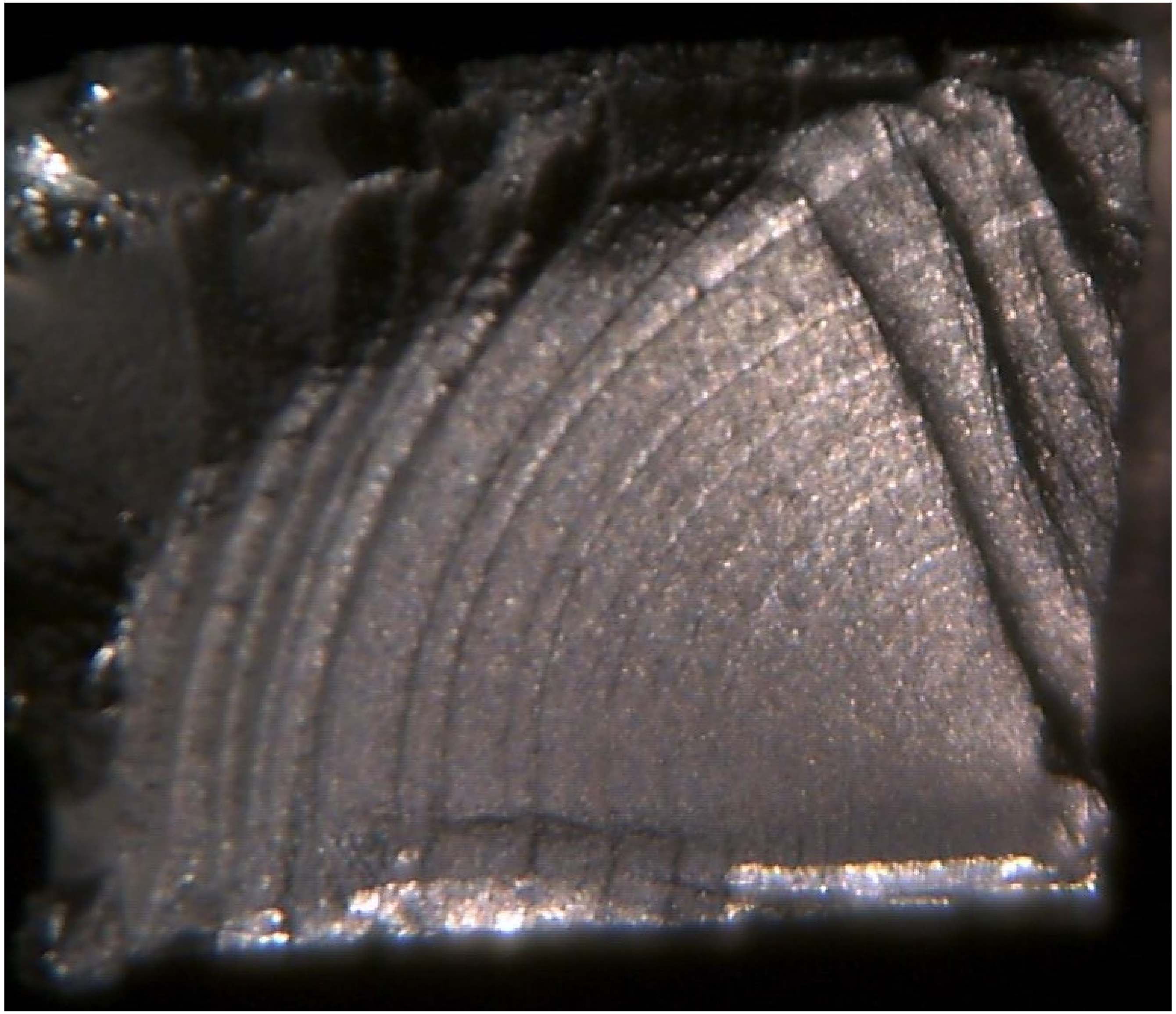


Kt Free Coupons

- Conclusions/Questions
  - Tests ran shorter than initially predicted
  - For analysis to correlate with prediction RS field needed to be changed
  - Why did blind predictions not correlate well?
  - How does thru thickness growth rate of Kt free tests compare to standard CX hole tests?
  - How does surface growth compare to standard CX hole tests?
  - How does aspect ratio compare to cracks from a standard CX hole?
  - Can strain data from machining operations inform better predictions?

Kt Free Coupons

- Questions?



ERSI
ENGINEERED RESIDUAL
STRESS IMPLEMENTATION

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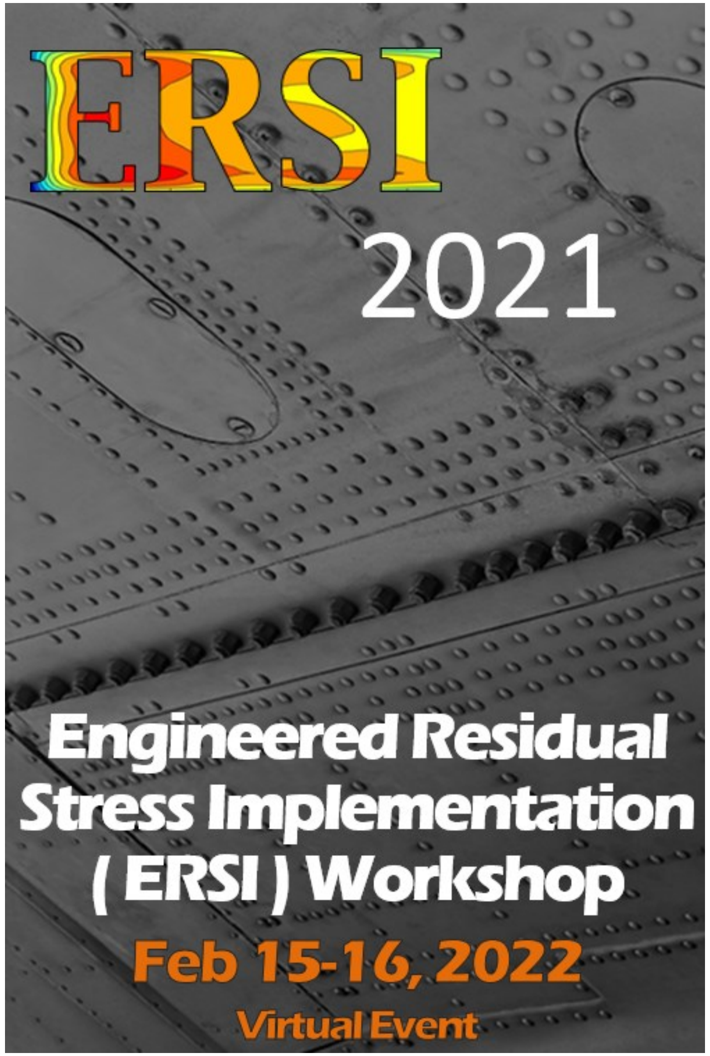

2022 Focus Areas

- Spectrum Loading and Retardation
  - Investigate the appropriate methods to characterize crack retardation due to spectrum loading for conditions with residual stress
  - Gather and/or develop test data to support validation of methods
  - Document best practices and lessons learned
- Interference Fasteners and Residual Stress
  - Investigate the relationship between interference fit fasteners and residual stresses from Cx and/or Taper-Lok
  - Identify appropriate methods to incorporate interference fit fastener benefit for conditions with residual stress
  - Document best practices and lessons learned
- Durability Testing and Fatigue Life Benefits
  - Review existing test data and develop summary to document Cx life impacts on early crack nucleation and growth
  - Identify any testing needs to further refine understanding

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Conclusions/Summary

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

Historical

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

→

Emerging

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

Questions?