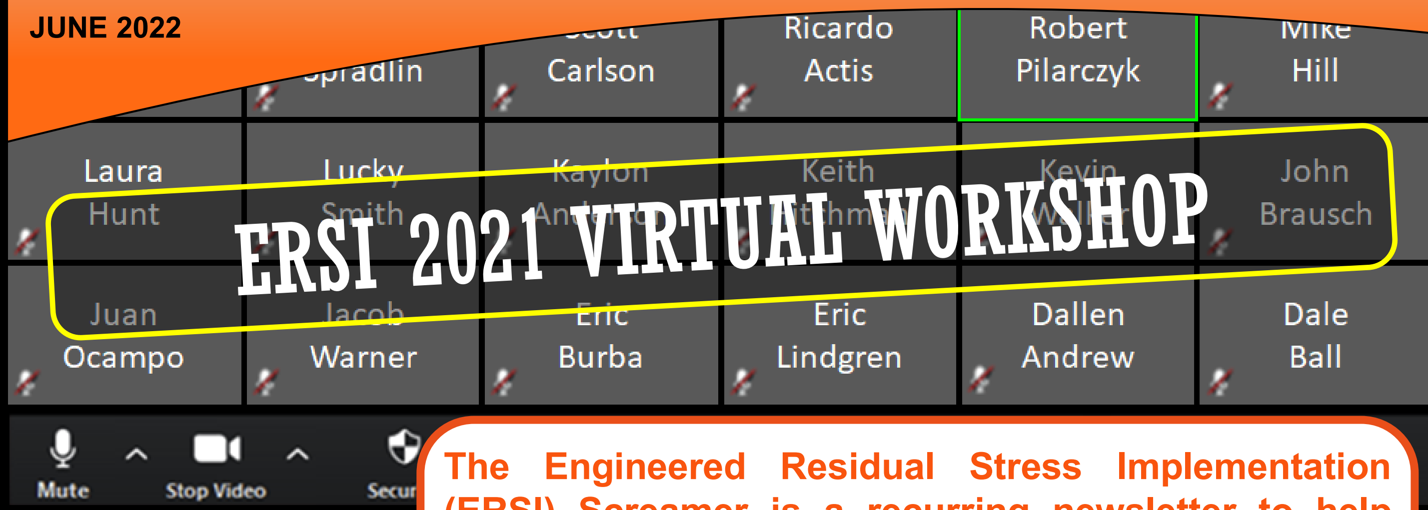
VOLUME 4
ISSUE 1

ERSI SCREAMER

JUNE 2022



This Issue:

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

Purpose of ERSI

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

Organization

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

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

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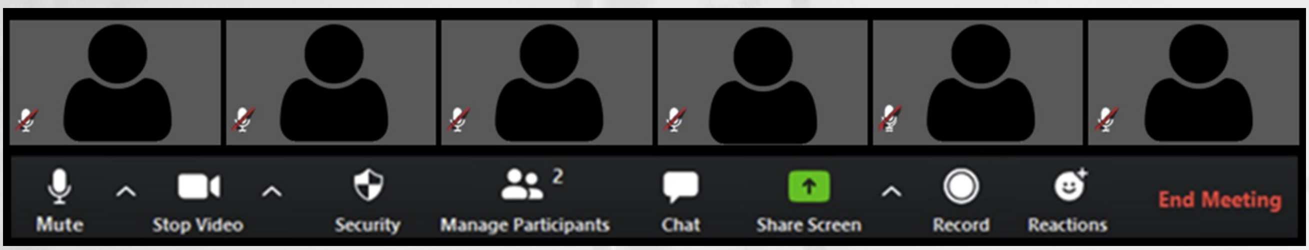
ERSI

ERSI as of December 2021

Countries Involved: **5**
DoD Organizations: **3 (+ FAA)**
USAF ASIP Managers: **10**
National Laboratory: **2**
Universities: **6**
OEMs: **3**
Industry Partners: **22**
ERSI Total: 154

6th Annual ERSI Workshop

The 2021 ERSI Workshop was held virtually on 15-16 February 2022 due to the COVID-19 pandemic. Virtual attendees included representatives of all three major airframe OEMs, both the USAF and USN, ASIP engineers from A-10, B-1, B-52, C-5, F-15, F-16, F-22, F-35, KC-135, and T-38, with much representation from industry partners and academia.



This issue of the Screamer provides an overview of the 2021 ERSI virtual workshop, which was formally held in 2022 and included virtual participants across the spectrum of ERSI members. The structure of the workshop was similar to the previous year with the online format. The first day was strictly for the committee leads to have a focused discussion of ERSI objectives. The second and final day included summaries from the committee leads and an open town hall discussion for the entire working group.

The different sessions provided a well-rounded summary of ERSI related activities and highlighted the accomplishments over the past year, which included recent publications resulting from ERSI collaboration as well as the status of the (then) draft USAF Structures Bulletin on the inclusion of engineered residual stresses in fatigue crack growth analysis methods (the bulletin has since been published and sections are included herein for reference). A high level summary of the open discussions from the workshop is also included.

6th Annual ERSI Workshop

Discussion Topic: Communications Committee

A communications committee was discussed that would coordinate the website, Screamer, ASIP manager's collaboration, etc. A draft ERSI Communications Committee charge was put together for participants to review and provide recommendations:

- Responsible to help ERSI communicate effectively with internal & external stakeholders
- Includes one representative from each of the other ERSI standing committees
- Includes the following officers: Chair, Vice Chair, Webmaster, Screamer master
- Facilitates and leads production of ERSI website and ERSI Screamer
- Facilitates and leads planning of ERSI Workshop (annual) and ERSI ASIP Manger Update (twice a year, ASIP and AA&S)
- Facilitates internal ERSI communications
- Reviews and approves all outward facing communications and publications

Discussion Topic: ERSI Governance

An ERSI charter was discussed that would define organizational structure, purpose/goals, near and long-term objectives, and committee lead rotation. A reminder of the original vision, mission, and key objectives of ERSI are included below.

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

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

ERSI Key Objectives

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

We welcome further expertise, participation, and input to the ERSI Working Group. Any individuals or entities interested in participating in ERSI please contact:
Dr. TJ Spradlin at thomas.spradlin.1@us.af.mil.

Publication of USAF Structures Bulletin EZ-SB-17-001 Rev. A

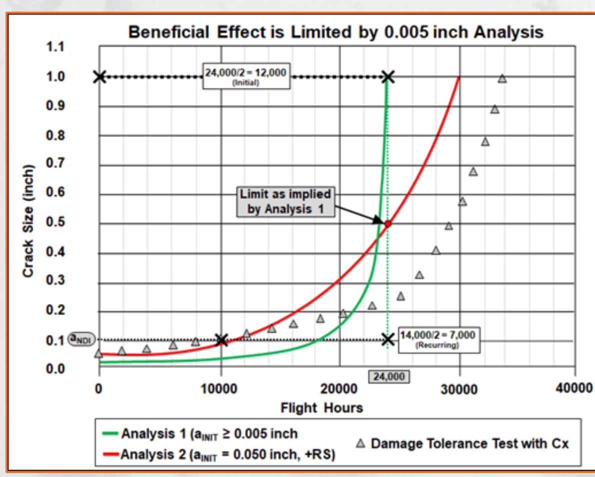
Requirements to Establish the Beneficial Effects of Cold Expanded Holes in Development of Damage Tolerance Initial and Recurring Inspection Intervals

- ***Note:*** *Sections of the published Structures Bulletin are included here for reference only.*

- **Scope:**
  - This Structures Bulletin (SB) establishes a tiered approach to account for the beneficial effects of cold expanded holes during the sustainment phase. Included are the testing and analysis requirements, durability and damage tolerance testing acceptance criteria, and descriptions of benefit determination for setting initial and recurring inspection intervals.

- **Benefit Levels:**
  - Variations in the amount of benefit needed for the range of aircraft structure applications, their associated complexity, and the cost to substantiate each, has prompted the need to establish different benefit levels as follows:
    - Level I: Initial inspection interval benefit with no recurring inspection interval benefit.
    - Level II. Level I initial inspection interval benefit and limited recurring inspection interval benefit through explicit incorporation of the non-verified residual stress field in the crack growth analysis.

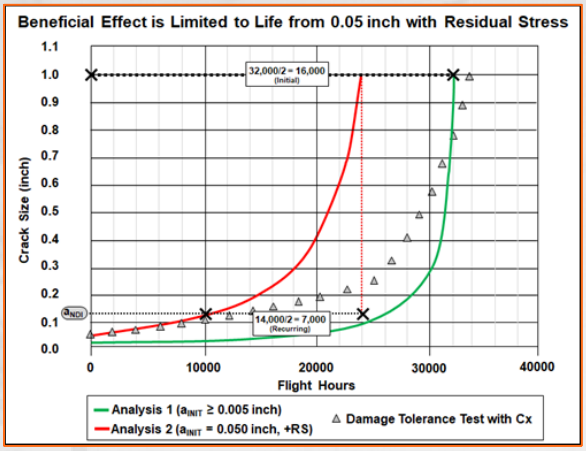
- **Level II Example Scenario A: Analysis 1 life is less than or equal to the test demonstrated damage tolerance life and less than Analysis 2.**
  - Initial Interval: Here Analysis 1, which satisfies an aINIT = 0.005 inch assumption, has a total life less than Analysis 2, which uses an aINIT = 0.05 inch prediction and includes residual stresses. Analysis 1 life shall be used for determining the initial inspection interval of 12,000 flight hours (24,000/2) for this example.
  - Recurring Interval: Assuming an appropriate NDI technique is used and the aNDI = 0.1 inch, the life from Analysis 1 (24,000 flight hours) and the flight hours at aNDI = 0.1 inch from Analysis 2 (10,000 flight hours) shall be used for determining the recurring inspection interval of 7,000 flight hours ((24,000-10,000) / 2) for this example. **Note that this method increases the recurring inspection interval from Level I by 4,000 flight hours for this example.**



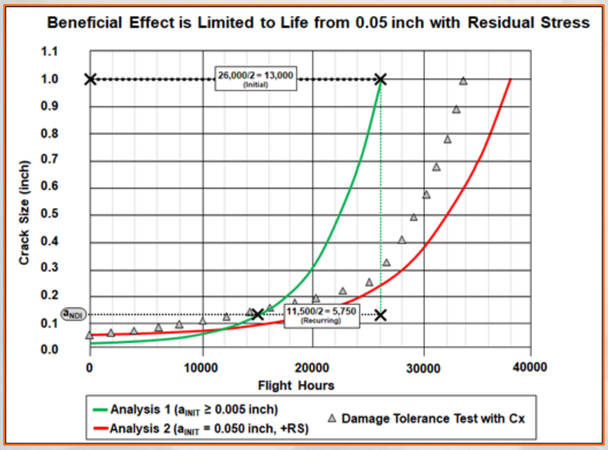
Publication of USAF Structures Bulletin EZ-SB-17-001 Rev. A

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

- **Level II Example Scenario B: Analysis 1 is less than or equal to test demonstrated damage tolerance life but greater than Analysis 2**
  - Initial Interval: If the Analysis 2 prediction (aINIT = 0.05 inch crack with residual stress), has a shorter life than the Analysis 1 prediction (aINIT = 0.005 inch assumption), the initial inspection interval can still be based on the Analysis 1 prediction and results in an initial inspection interval of 16,000 flight hours (32,000/2) for this example.
  - Recurring Interval: Assuming an appropriate NDI technique is used and an aNDI = 0.125 inch, the recurring inspection interval is calculated based on the damage tolerance life from aNDI to the critical crack size, resulting in a recurring interval of 7,000 flight hours ((24,000-10,000) / 2) for this example. **Note that this method increases the recurring inspection interval from Level I by 4,000 flight hours for this example.**



- **Level II Example Scenario C: Analysis 2 predicted lives are greater than test demonstrated damage tolerance life**



  - Initial Interval: For this scenario, the initial inspection interval shall be based on the Analysis 1 prediction and results in an initial inspection interval of 13,000 flight hours (26,000/2) for this example.
  - Recurring Interval: Assuming an appropriate NDI technique is used and an aNDI = 0.125 inch, the recurring inspection interval is limited to the Analysis 1 damage tolerance life from aNDI to the critical crack size, resulting in a recurring interval of 5,750 flight hours (11,500/2) for this example. No credit can be taken for Analysis 2 because it overpredicts the test data, but could potentially be refined to better agree with the test demonstrated life.

Preparers would like to acknowledge the significant contributions from all members of the ERSI Working Group.

Structures Bulletin
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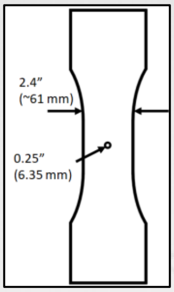
Fatigue Crack Growth Analysis Methods & Validation Testing (1 of 8)

Mission Statement

- Establish analytical & testing guidelines to support implementation of ERS

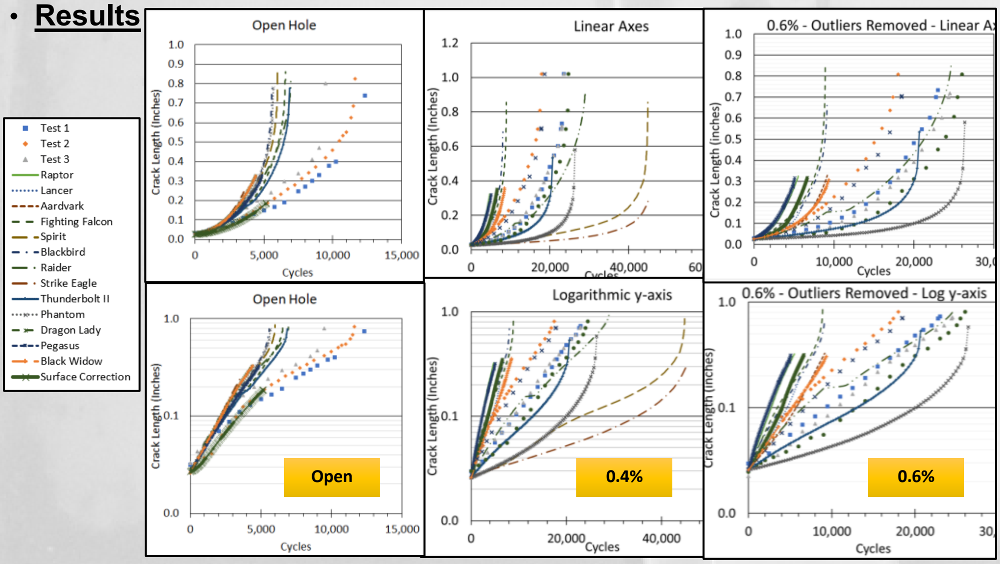
Key Objectives

- Develop & document best practices for integration of ERS in 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



2021 Achievements: Interference Fit Fastener Round Robin

- **Loading & Geometry**
  - Constant amplitude, R = 0.1, 27.9 ksi
  - 7075-T651, 0.25" thick, 0.027" precrack
  - Two conditions tested: Open hole, 0.4% interference Hi-Lok
  - Three conditions predicted: Open hole, 0.4% interference, 0.6% interference
- **Results**



Discussion

- Is good correlation of interference fit cases a function of under predicting the open hole case?
- How applicable is the surface correction offered for the open hole case?
- Would 27.9 ksi stress cause plasticity that violate bounds of LEFM for open hole case?

- **Initial Conclusions**
  - Tight grouping of open hole predictions, although all under predicted test data
  - Surface correction shows promise for open hole condition
  - Stress approach used by Raider closely matched life and crack growth curve shape

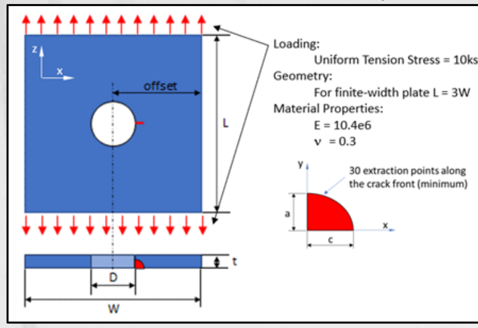
- **Future Work**
  - Test a 0.6% or other slightly higher interference to understand life impacts
  - Is there an interference level at which greater interference is no longer beneficial?
  - Raider approach predicts shorter life for 0.6% interference than 0.4%
  - Understand applicability of surface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

Fatigue Crack Growth Analysis Methods & Validation Testing (2 of 8)

2021 Achievements: Stress Intensity Factor Round Robin

- **Objectives**
  - Evaluate differences between available Stress Intensity Factor (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, hole offset, aspect ratio)
  - Findings intended to improvement solutions available to fracture mechanics community

- **Overview & Analysis Inputs**
  - 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
  - Each case added an additional level of complexity with corrections to the root solution



Case	Surface Crack Length (c) (inch)	Bore Crack Length (a) (inch)	Corner Crack Configuration	Width (inch)	Thickness (inch)	Hole Diameter (inch)	Hole Offset (inch)	Configuration
1	0.050	0.050	Double Symmetric	100.00	0.25	0.50	50.00	Infinite Plate, Double Crack
2	0.050	0.050	Single	100.00	0.25	0.50	50.00	Infinite Plate, Single Crack
3	0.050	0.050	Single	4.00	0.25	0.50	2.00	Finite Plate, Single Crack
4	0.050	0.050	Single	4.00	0.25	0.50	0.60	Finite Plate, Single Crack, Offset Hole
5	0.050	0.050	Single	1.20	0.25	0.50	0.60	Narrow Plate, Single Crack
6	0.050	0.075	Single	100.00	0.25	0.50	50.00	Infinite Plate, Single Crack, $a/c = 1.5$
7	0.100	0.050	Single	100.00	0.25	0.50	50.00	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 Finite Element Analysis (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
  - Reference solutions with relative errors in KI of ~0.03% or less provided by Andersson (Submission 6), and were utilized as the reference solutions for each case evaluated

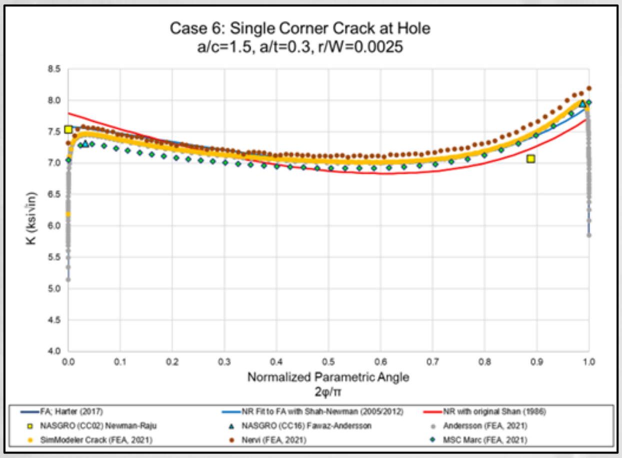
Submission #	Title	SIF solution source	Single Corner Crack Correction (Cases 2, 3, 4, 5, 6, 7)	Finite Width Correction (Cases 3, 4, 5)	Offset Hole Correction (Cases 4, 5)
1	Fawaz-Andersson Solutions, AFGROW	Fawaz-Andersson [3] (as implemented in AFGROW Advanced Model)	n/a	Newman correction [7]	Harter correction [5]
2	Newman-Raju Fit to Fawaz-Andersson	Updated equations by Newman [6] based on fit to Fawaz-Andersson solutions [4]	Shah-Newman Correction (2020)	Newman correction [7]	• center hole (conservative option) • Kt match approach
3	Newman-Raju (1986)	1986 Newman-Raju solution [7]	Shah correction	Newman correction [7]	Kt match approach
4	NASGRO (CC04 & CC02): Newman-Raju	1986 Newman-Raju solution [7] (as implemented in NASGRO CC04)	Shah correction (as implemented in NASGRO CC02)	NASGRO CC02 [9]	NASGRO CC02 [9]
4	NASGRO (CC16): Fawaz-Andersson	Fawaz-Andersson solutions [3] (as implemented in NASGRO CC16)	n/a	Modified version [10] of the Newman correction [7]	Harter correction [5] (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	Marc: FEA (2021)	Utilized Marc to create 3D FEMs and compute Mode I SIFs			

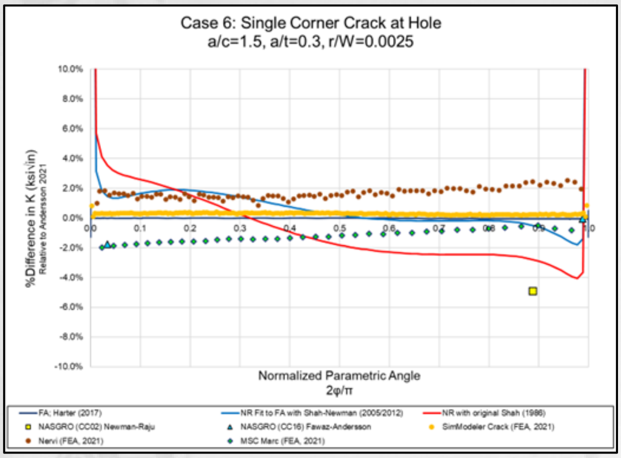
Fatigue Crack Growth Analysis Methods & Validation Testing (3 of 8)

2021 Achievements: Stress Intensity Factor Round Robin (cont'd)

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

- **Summary of Results**
  - 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





- **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

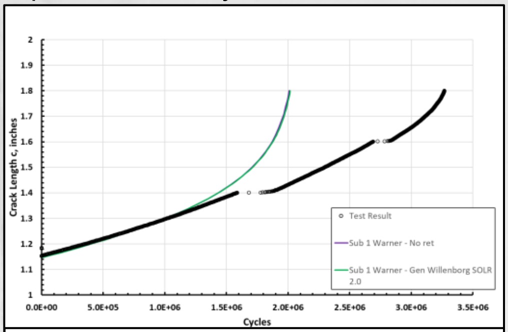
- **Next Steps**
  - Finalizing summary report documenting round robin approach, results, conclusions, and follow-on investigations
  - New finite width corrections in work to support the community

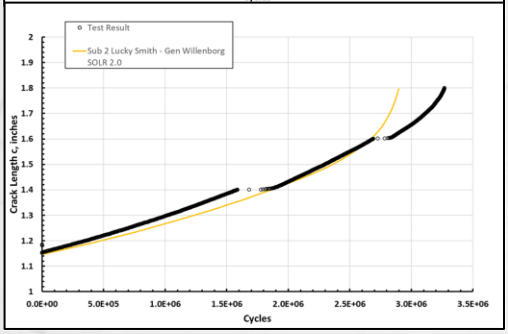
Special thanks to all the participants!!!!
- Dr. Börje Andersson, BARE Research
- Joseph W. Cardinal, SwRI
- Jim Harter, LexTech Inc.
- Dr. Adrian Loghin, Simmetrix Inc.
- Dr. Sebastian Nervi, ESRD Inc
- Dr. Jim Newman, Mississippi State University
- Dr. Per Nordlund, MSC Software Corporation
- Dr. Kevin Walker, QinetiQ Australia

Fatigue Crack Growth Analysis Methods & Validation Testing (4 of 8)

2021 Achievements: Overload Challenge Round Robin

- **Description**
  - C(T) manufactured from 7075-T6, 3” wide, 0.125” thick, notch length 1.15”
  - Constant amplitude loading, Pmax = 100 lbf, Pmin = 10 lbf
  - Single factor 200 lbf spike overload (OL) applied at c = 1.4” and again at c = 1.6”
  - Participants in the challenge were invited to perform a blind prediction analysis

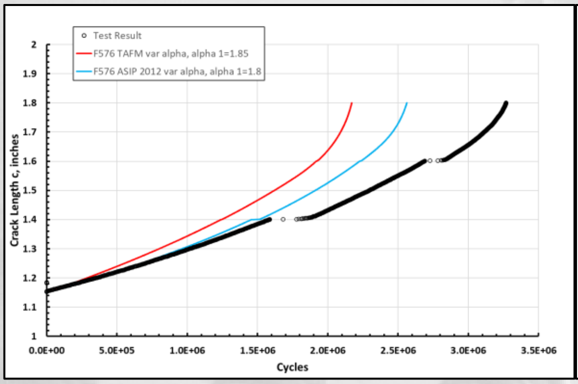


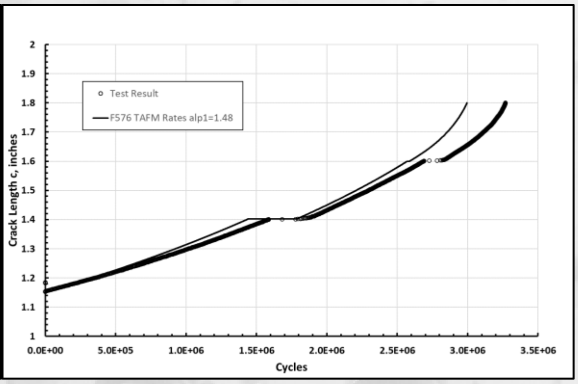


- **Test Results**
  - Total life to reach 1.8” = 3,269,818 cycles
  - Delay at OL1 about 220,000 cycles
  - Delay at OL2 about 120,000 cycles

- **Submissions**
  - Submission 1: AFGROW (J. Warner, USAF)
  - Submission 2: NASGRO (L. Smith, SwRI)
  - Generalized Willenborg retardation SOLR=2.0
    - Lowest value without causing crack arrest
  - First overload added ~2,000 cycles, second overload added about ~5,000 cycles

- **Post-Test Analyses**
  - FASTRAN Version 5.76 – pseudo blind and calibrated
  - AFGROW with different retardation models
    - Including Hsu, Closure, Wheeler





- **Conclusions – Spike Overload**
  - Despite what you might think, a simple spike overload scenario is difficult to predict/analyze
  - 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
  - Understanding and improving our ability to model spike overload cases is considered fundamental to the prediction for spectrum loading

Fatigue Crack Growth Analysis Methods & Validation Testing (5 of 8)

2021 Achievements: Multi-point MAI Program

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

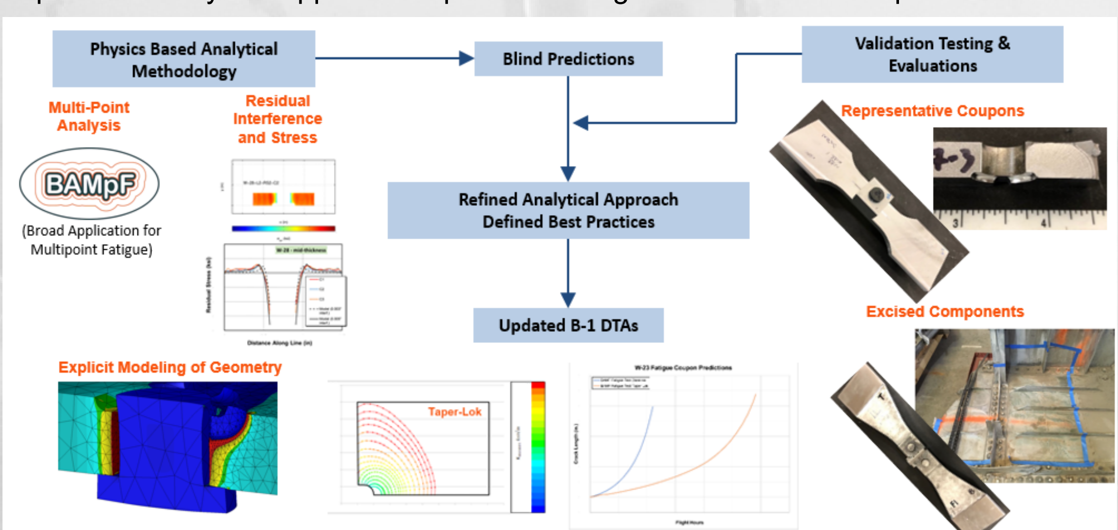
Air Force Research Laboratory | ATI ADVANCED TECHNOLOGY INTERNATIONAL | NORTHROP GRUMMAN | HILL ENGINEERING | Fracture Analysis Consultants, Inc | FRANC3D | BAMpF | BEASY

- **Objective**
  - Validate and assess capability of three (3) multi-point fracture mechanics (MPFM) codes as applied to the analysis of Cx holes: BAMpF, BEASY, and FRANC3D

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

2021 Achievements: Taper-Lok Analysis Methodology & Testing

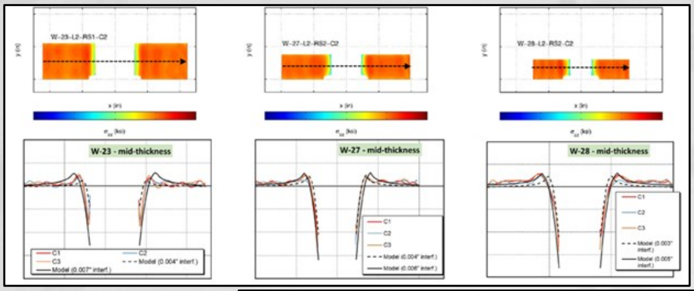
- **Objective**
  - Develop robust analytical approach to predict damage tolerance life at Taper-Lok fastener holes

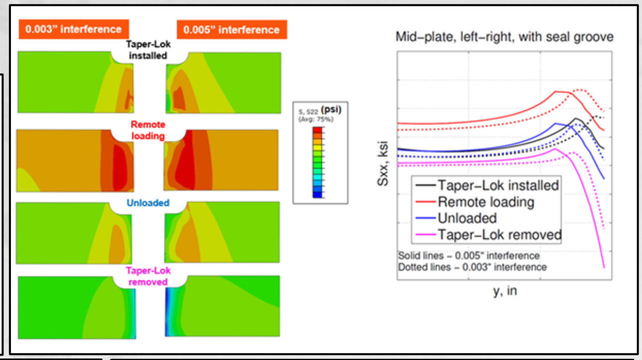


Fatigue Crack Growth Analysis Methods & Validation Testing (6 of 8)

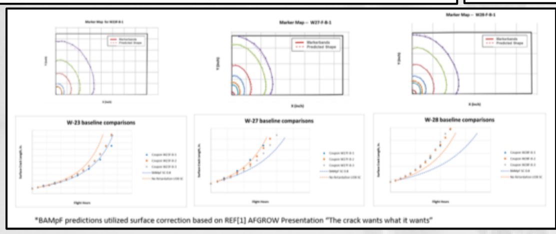
2021 Achievements: Taper-Lok Analysis Methodology & Testing (cont'd)

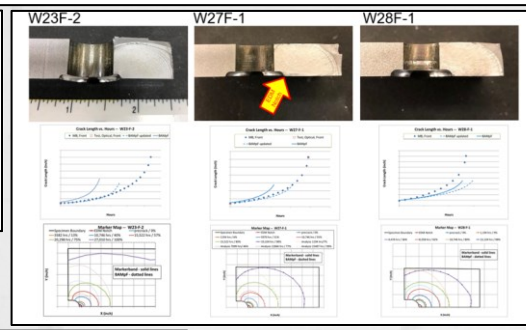
- **Modeling and Measurements**
  - Process Model Results, RS Measurements



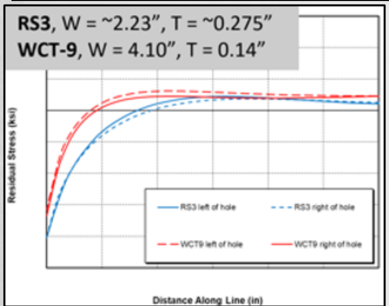


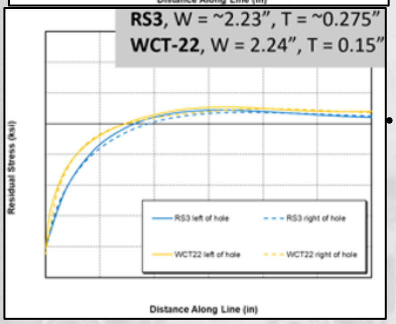
- **Comparisons**
  - Baseline
  - Taper-Lok

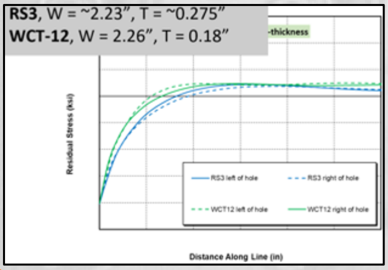




- **Component Coupons – Extracted B-1 Structure**

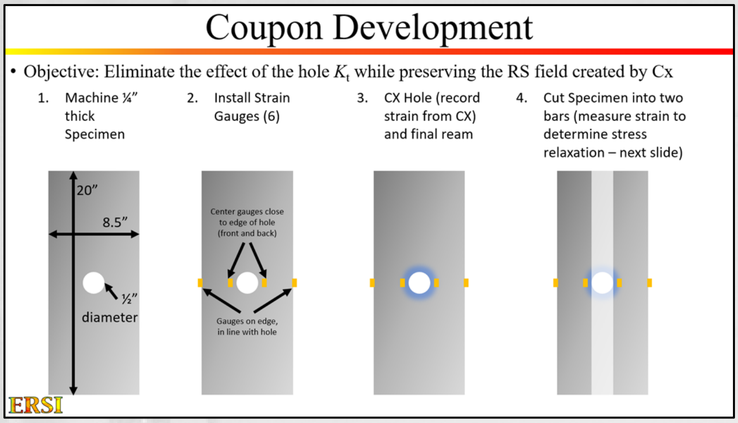






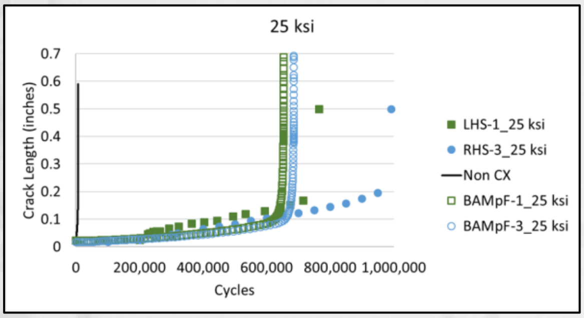
- **Conclusions**
  - Analytical Process
    - Robust analytical process established to characterize behavior at Taper-Lok fastener holes
    - Key data (RS and interference) characterized to support analyses
    - Consistent RS and interference results between coupons and extracted components
  - Testing
    - Efficient truncation and marker band approach established to support testing
    - Taper-Lok coupons achieved failure at desired location
    - 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

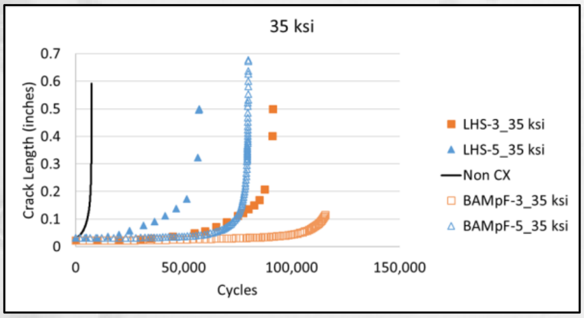
Fatigue Crack Growth Analysis Methods & Validation Testing (7 of 8)

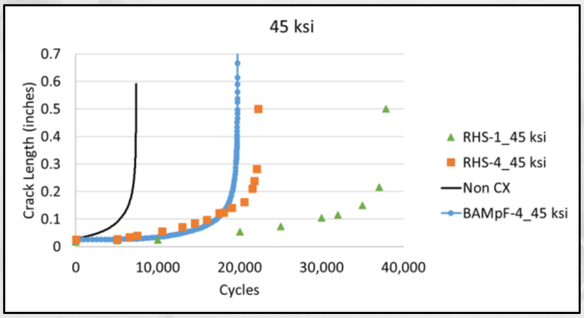


2021 Achievements: Kt-free Coupon Testing

- **Description**
  - RS analysis has compounding steep stress gradients
    - Kt from the hole, Cx RS field
- **Results**
  - 25ksi Results
    - With minimal RS until 0.02” into the part, BAMpF results correlate very well
  - 35ksi Results
    - Minimal RS for first 0.02” over predicts
  - 45ksi Results
    - Model correlates well for .02” minimal RS approach
- **Conclusions/Questions**
  - Tests ran shorter than initially predicted
  - For analysis to correlate with prediction, the 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?*







Fatigue Crack Growth Analysis Methods & Validation Testing (8 of 8)

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

Summary

- **Incrementally, we are making progress within the committee – many thanks to those individuals that have contributed!!**
- **We must continue to push forward with a focus on refining our analytical capability and addressing technical gaps**

Historical

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

Emerging

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

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Residual Stress Measurement (1 of 5)

What this Committee brings to ERSI

- 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. neutron diffraction to x-ray to contour)
  - Measurement model comparisons (e.g. for Cx holes)
  - Uncertainty quantification & statistical methods relative to residual stress data (connect to inter-method as well as model-measurement)

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)

Residual Stress Measurement (2 of 5)

Texture and Anisotropy Sub-Team

- **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

- **Ongoing efforts**
  - Design samples using rolled brass to maximize spatial stress variation within plug
  - 'Sharpen' brass texture by rolling
  - Quantify anisotropic elastic constants from Electron Backscatter Diffraction (EBSD)
    - Make EBSD measurements of different rolled thickness samples
    - Same single crystal elastic constants
    - Calculate differences in aggregate response based on texture change
  - Quantify anisotropic elastic constants
  - Build framework to simulate incremental hole drilling measurement in elastically anisotropic materials

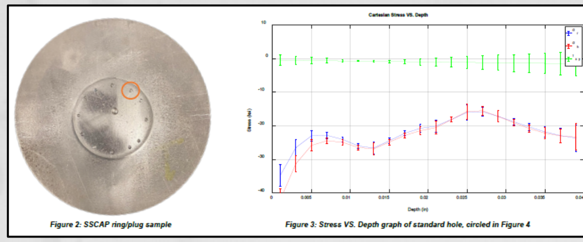
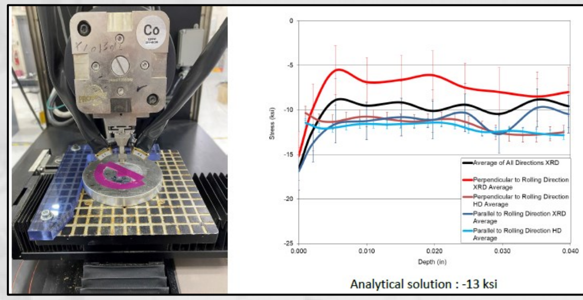
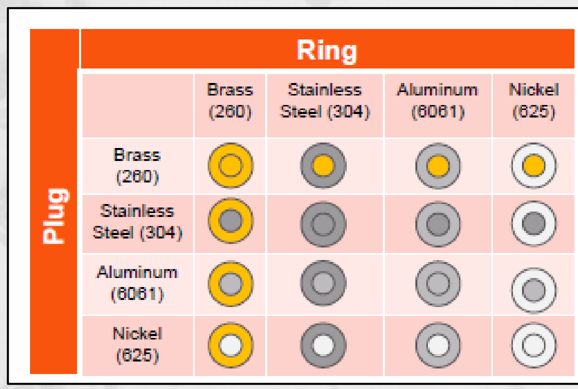
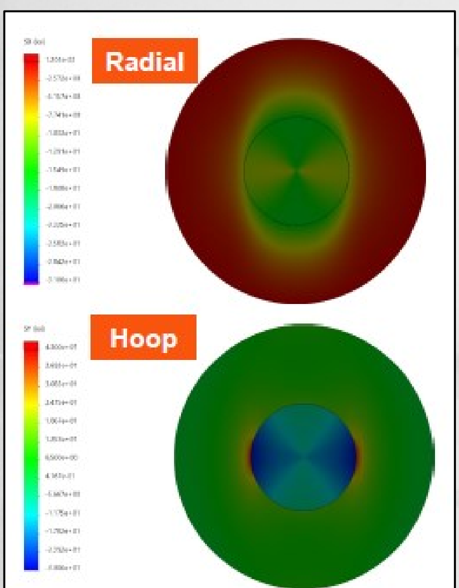


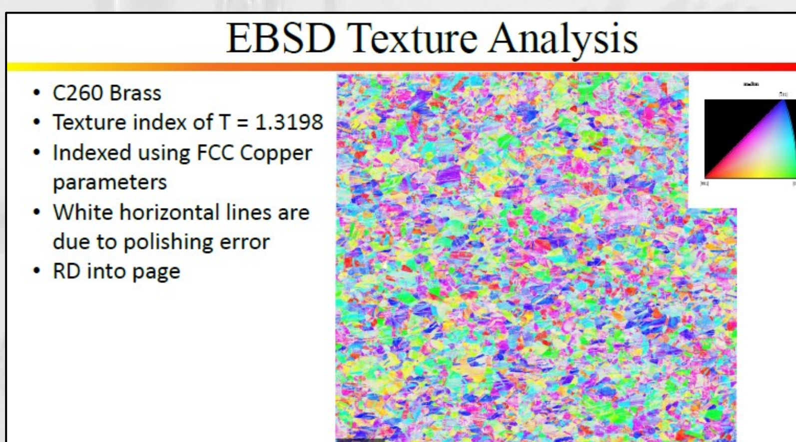
Figure 2: SSCAP ring/plug sample

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





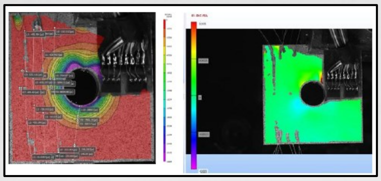




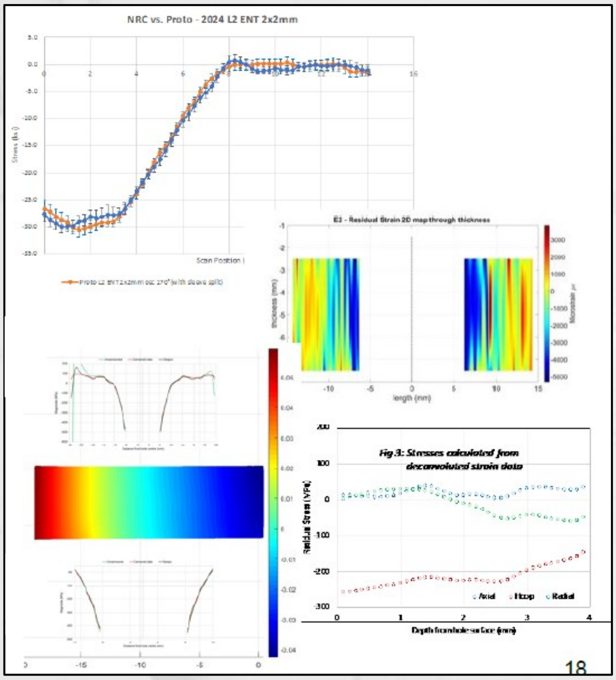
Residual Stress Measurement (3 of 5)

2inch Cx Residual Stress Determination for Process Simulation Validation

- **Overview**
  - 2024-T351 & 7075-T651 aluminum, 0.25” thick, 0.50” diameter hole, 2” wide
  - Cx to max & min of applied expansion range per the FTI Spec: 3.2% and 4.2%
  - During the Cx process surface strain measurements were taken in ”real-time”
    - Strain gauges installed (FTI)
    - LUNA fiber optics (Clarkson University)
    - Digital Image Correlation (SwRI)



- **History**
  - 2016 Developed FEA Round Robin
  - 2017 Performed Cx on 8 Aluminum coupons
  - 2017 Argonne National Lab (NL) performed Energy-dispersive X-ray diffraction (EDXRD)
  - 2018 Through Transmission Neutron Diffraction performed at Coventry in UK
  - 2018 7075 Cx Coupon Processed at the CHESS EDXRD Facility
  - 2019 Proto and NRC Performed an Inter-laboratory Round Robin using Surface XRD
  - 2020 Neutron Diffraction was Performed on the 2024 Cx coupons at Joint Physics Analysis Center (JPAC)
  - 2021 2024-Low Cx Coupon Contour Cut at Stress-Space in UK
  - 2021 7075 Cx Coupons Provided to Oakridge NL for Neutron Diffraction



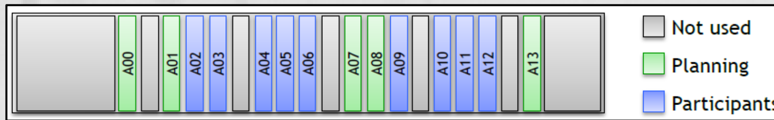
- **Future Work**
  - Complete Surface Strain Paper Comparison
    - Focused on FEA simulations, using multiple material models, to DIC/MatchID data
  - Complete Data Processing of Neutron Diffraction Experiments
    - 2024 ”Low” and “High” have been completed the experiments – need to process data
    - 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 RS Methods for Near-Surface and non-Surface Stress Fields
    - Potential to use Neutron or XRD near bore of hole and Contour away from hole
  - Provide RS Field Data to ERSI Analysis Committee for Predictions of Test Conditions

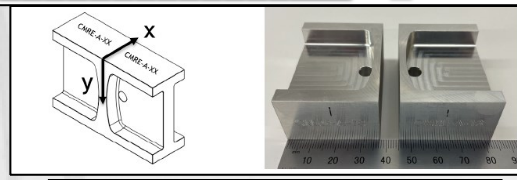
No central funding source - all work provided at cost to the process/data owning organization!

Residual Stress Measurement (4 of 5)

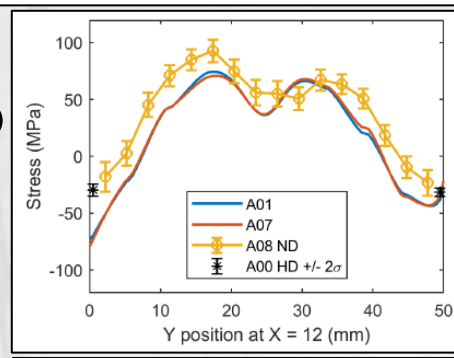
Contour Method Reproducibility Experiment A (CMRE-A)

- **Background:**
  - 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 (RS from quench/age of -T74)
  - Mill identical samples 50x75x24 mm
  - Fabricated 14 samples: A00 to A13

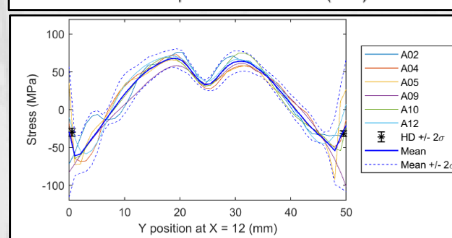


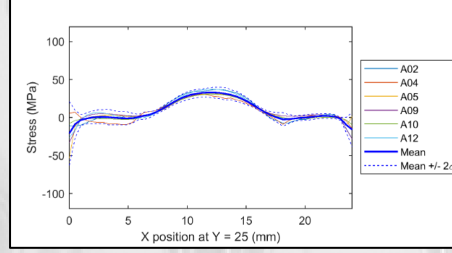


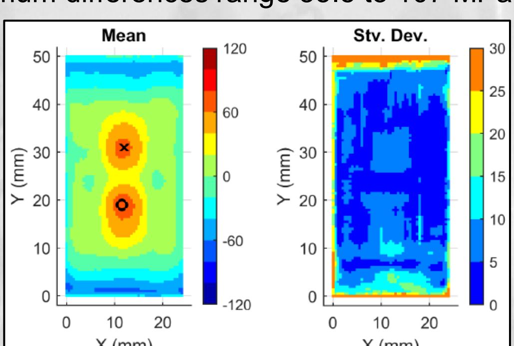
- **Planning Measurements:**
  - Contour results (UC Davis) (A01, A07, A13)
    - A01 and A07 are nearly identical
    - Magnitude higher for A13
      - Likely due to proximity to end of bar
      - Distant from participant samples
    - Spatial distribution of stress is similar along length of bar
  - Neutron diffraction results (Oak Ridge NL) (A08)
    - Similar spatial form, offset of ~ 25MPa (within expectation)
  - Hole-drilling results (UC Davis) (A00)
    - Near surface stress symmetric

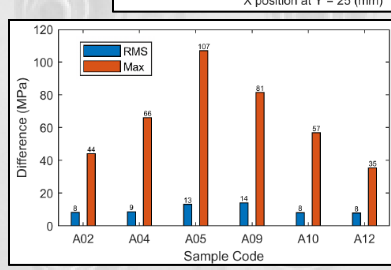


- **Participants Measurements:**
  - International group of 8 participants from industry and academia provide contour measurement results
  - Observed interlaboratory reproducibility
    - 8.1 MPa average for all locations
    - 6.1 MPa on interior
    - 17.6 MPa near boundary (within 1 mm)
  - Observed reproducibility similar to intralaboratory repeatability in 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







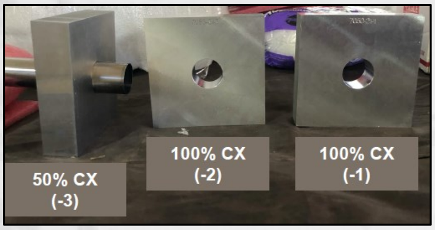


Residual Stress Measurement (5 of 5)

Bulk RS Measurements in Cx Geometrically Large Holes

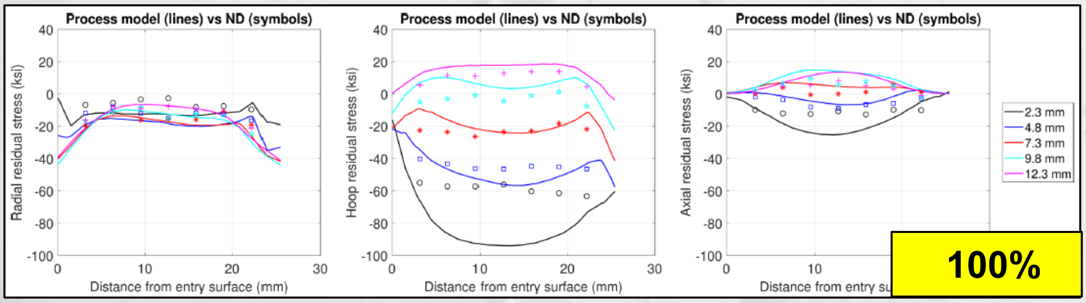
- **Background:**
  - Existing prior data for large (D = 1inch) Cx holes in 7075-T651
    - RS measurements (contour), RS outputs from nonlinear process model
  - Disagreement between measurement results and model outputs

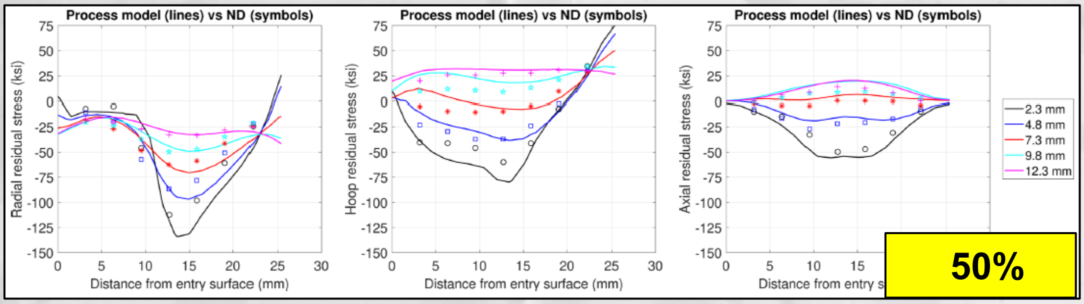
- **Objectives:**
  - Fabricate coupons for measurements in D = 1inch Cx holes
    - Samples cut from 7050-T7451 2” thick plate (AFRL)
    - 100% processed and 50% processed (FTI)
  - Develop process model outputs for coupon conditions (Hill Engineering)
  - Assess bulk RS in coupons
    - Neutron Diffraction (ND) at SMARTS (LANL, UCD)
    - Synchrotron X-ray Diffraction (EDXRD) (CHESS, AFRL, UCD)
    - Contour (Hill Engineering)



- **Samples for experiments**
  - Fabricated 6 samples (AFRL)
  - Processing (FTI), Cx to 3.43% to 3.45%

- **Results: Model and ND (50%, 100%)**
  - Line plots comparing model output and neutron diffraction (ND) measurements below
  - Radial, hoop, and axial residual stress results shown





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NDI, NDE, Data Management, and Quality Assurance (1 of 4)

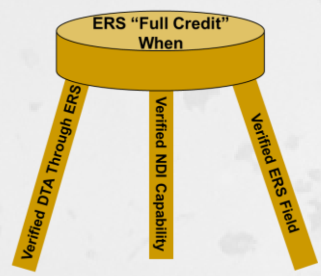
Tools and Methodologies to Sew the Digital Thread: Definitions

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

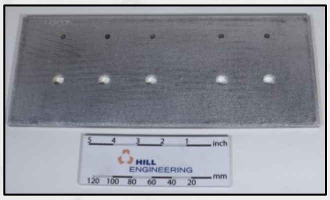
- **What does a digital thread look like?**
  - It depends…
  - Different scenarios require different levels of need for data capture
  - Customized Data Fidelity Level (DFL) should be developed for different levels of need
    - DFL 1: One-off type repairs
    - DFL 2: Depot-level repairs
    - DFL 3: Major modification programs

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

- **Specifically for cold expansion (Cx) of fastener holes, the digital thread data must answer some critical ASIP questions to qualify for full credit:**
  - Was Cx accomplished at the correct location?
  - Was Cx accomplished (go/no-go)?
  - Is the ERS validation traceable?
  - Has NDI/NDE been accomplished at each Cx hole?
  - What are the analysis requirements for full credit?

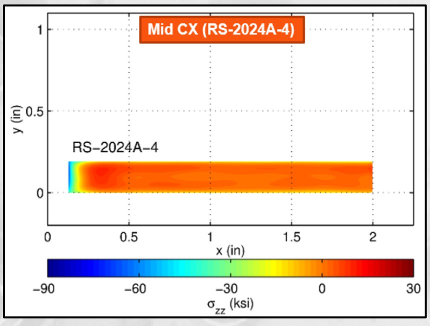


Tools & Methods: Nondestructive Evaluation for Quality Assurance and Surveillance of Cx Fastener Holes



- **Program objectives**
  - Develop NDE techniques for quantifying the RS state at Cx holes
  - Evaluate and rank NDE techniques for quantifying RS state at Cx holes
  - Investigate key confounding factors and their influence on NDE response
  - Applied expansion, diameter, thickness, material, edge margin, coatings, etc.
  - Optimize, demonstrate, and verify NDE techniques for Cx hole evaluation

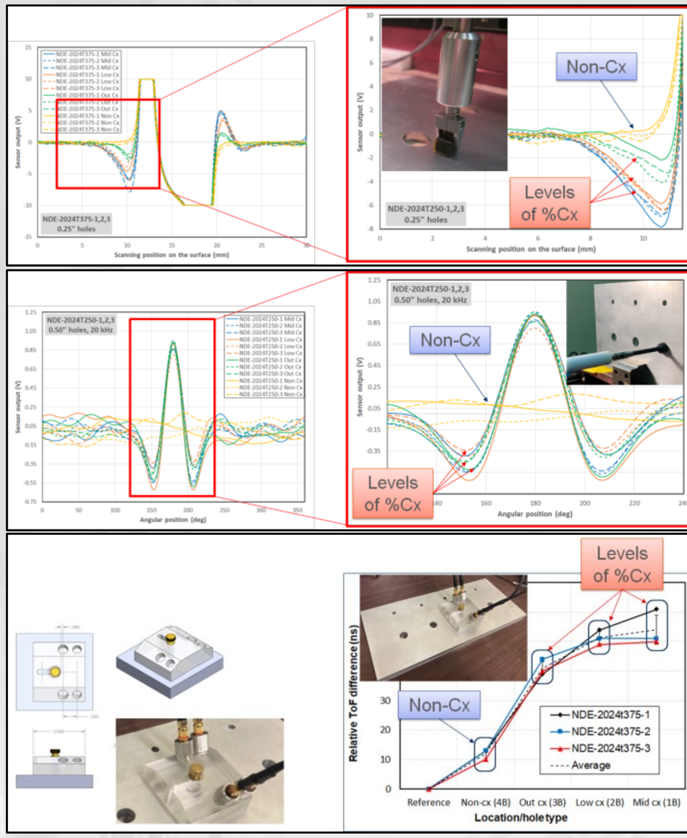
- **Key points**
  - Verify RS is present at the hole post-Cx (go/no-go)
  - Necessary for “full-credit” for RS benefit from Cx



NDI, NDE, Data Management, and Quality Assurance (2 of 4)

Tools & Methods: Nondestructive Evaluation for Quality Assurance and Surveillance of Cx Fastener Holes (cont'd)

- **Current NDE tools**
  - Eddy current surface probe
    - Measures gradient of conductivity at the surface
    - Clear distinction between Cx and non-Cx holes in all cases
  - Eddy current low frequency in-hole probe
    - Measures gradient of conductivity caused by the split-sleeve ridge
    - Clear distinction between Cx and non-Cx holes in most cases
  - Ultrasonic probe
    - Ultrasonic critically refracted longitudinal (LCR) wave probe in pitch-catch configuration
    - Clear distinction between Cx and non-Cx holes in most cases



- **These NDE tools help answer critical ASIP questions to qualify for full credit:**
  - Was Cx accomplished (go/no-go)?
  - Is the ERS validation traceable?
  - Was NDI/NDE accomplished at each Cx hole?

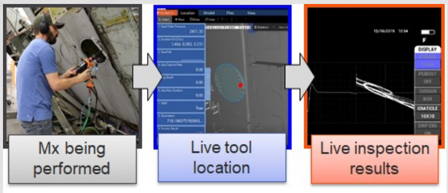
- **For these NDE tools, the digital thread might look like:**
  - DFL 1: One-off type repairs
  - DFL 2: Depot-level repairs
  - DFL 3: Major modification programs

Category	Source	Data Description
NDE	UT/ET Probe	Cx Applied % Expansion
		UT/ET response data
		Go/No-Go indication (Cx or nonCx)

NDI, NDE, Data Management, and Quality Assurance (3 of 4)

Tools & Methods: The Integrated Maintenance System (IMx+)

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



- **Stated Need:**

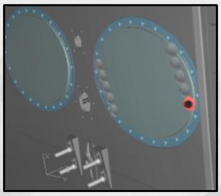
> **"Current challenges include an automated method for digital procedural compliance, importing digital NDI equipment outputs & interfacing with legacy maintenance processing systems. In terms of capturing maintenance data, an automated integrated system doesn't exist."**
> *-Lt. Col Gary Steffes, 76 CMXG/CR, ASIP Conference 2020*

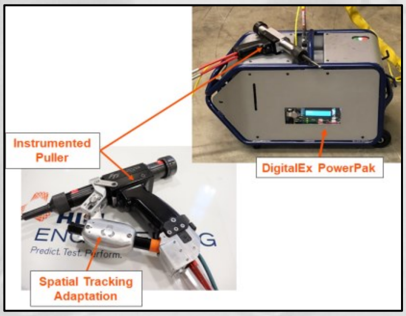
- **Introduction to the IMx+ system**
  - **An advanced maintenance technology integrating smart shop tools with automated data collection and spatial position tracking to improve aircraft quality assurance**

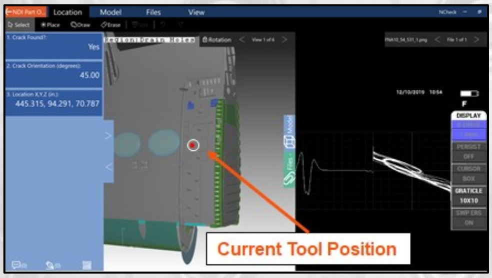
- Focused on maintenance operations using these integrated components:
  - Integration Module
  - Spatial Position Tracking
    - Live display of tool location
    - With add-on LED lights for integrated feedback to maintainer
  - DigitalEx Instrumented Cx Puller
  - NDI tools: NORTEC 600D + SpitFire
  - User Interface and Digital Thread
    - NCheck: User interface for maintainers
    - NLign: User interface for engineering

FATIGUE TECHNOLOGY

NLIGN ANALYTICS



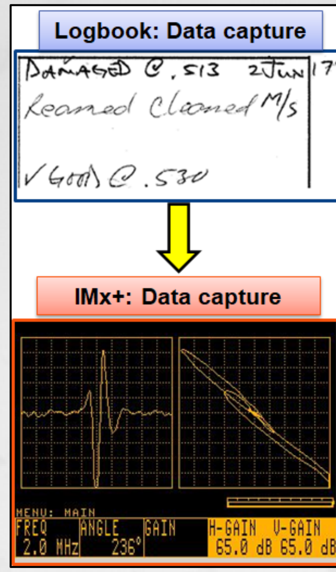




NDI, NDE, Data Management, and Quality Assurance (4 of 4)

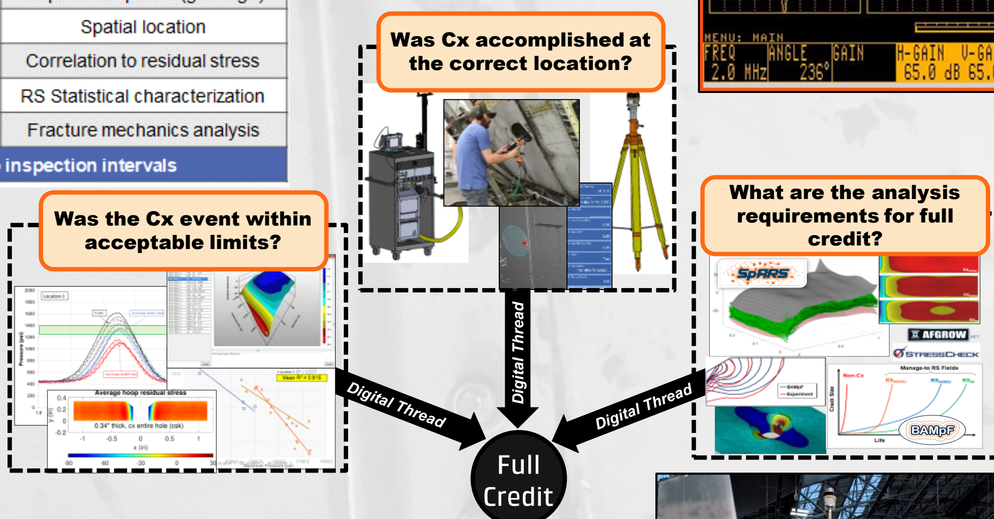
Tools & Methods: The Integrated Maintenance System (IMx+) (cont'd)

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



- **A-10: Why do we want IMx+?**
  - Meets MIL-STD-1530D requirements
  - Automates data entry and upload (faster and easier for inspector)
  - Improves value by saving inspection data, not just pass/fail
  - Includes Mx location in aircraft coordinates
  - Identifies correct location of Mx

Tool/Source	Data
DigitalEx Puller	Cx pressure profile (go/no go)
iGPS system	Spatial location
RS measurement data	Correlation to residual stress
SpARS	RS Statistical characterization
BAMpF	Fracture mechanics analysis
►► Develop inspection intervals	



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

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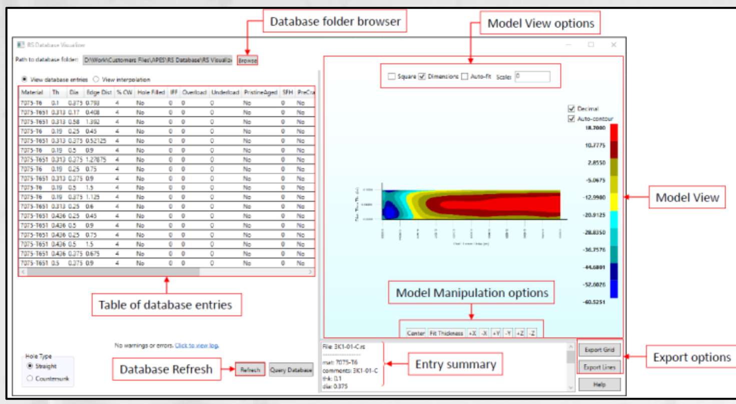
Risk Analysis and Uncertainty Quantification (1 of 2)

Committee Overview

Investigate and implement UQ methods that enhance the overall understanding of how residual stress affects life prediction analyses using:

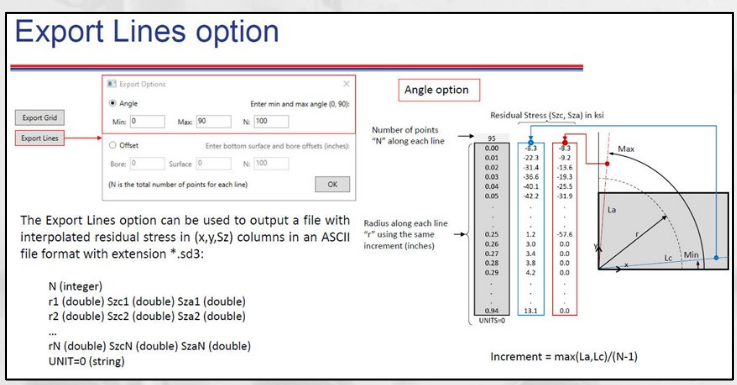
- **Uncertainty Quantification**
  - How do we understand and describe the uncertainty and variability in the relevant parameters?
- **Sensitivity Analysis**
  - What are the most significant variables in the ERS process?
  - How can we maximize/minimize the benefits/damages of these variables?

New Residual Stress Database



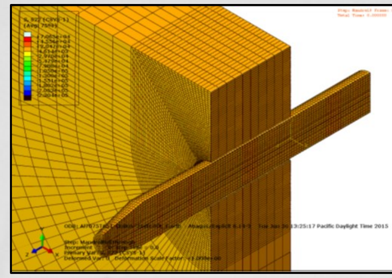
- **Existing capabilities retained**
  - Visualization, library, search database, interpolations of multiple files
  - User can add profiles
  - Filtering of 5 parameters
    - Material, CX%, D, t, e/D
- **New capabilities**
  - Filtering of over 15 new parameters
    - Over/underload, pre-cycles, filled holes, pristine/aged, CX countersink process, etc.
  - AFGROW .sd3 (Residual stress data) output
  - Export lines, along angles or at offset distances
  - Handles data replicates

Parameter	*Description*
mat	Material name
comments	Coupon information or other
thk	Thickness
Dia	Diameter
ed	Edge Distance
pctCX	Percentage Cold Work
cskProc1	Countersink process
angle	Countersink angle
depth	Countersink depth
precycles	Number of pre-cycles
rvalue	R value
smax	Pre-cycle load
replicates	Replicate number out of a set
holeFilled	Boolean
iff	Interference Fit during pre-cycle
overload	Overload as percentage of Yield
underload	Underload as a percentage of yield
sfh	Spectrum Flight Hours
pristineAged	When cold work is performed on a pristine or aged material
precrackB4CX	Existing pre-crack on coupon
longdSplit	For specimens where longitudinal cut was made to compute RS
sourceType	FEA (Finite Element Analysis), CM (Contour Method), EC (Eddy Current), ND (Neutron Diffraction), etc.



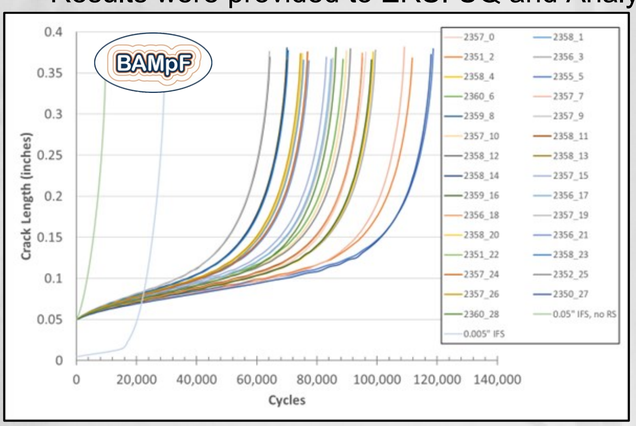
- **Available, Free!**
  - Original database had 47 RS profiles
  - 2021 update includes 323 RS profiles
  - For access, contact Scott Prost-Domasky: prost@apesolutions.com

Risk Analysis and Uncertainty Quantification (2 of 2)



Sensitivity Study on Cold Expanded Fastener Hole Damage Tolerance Life

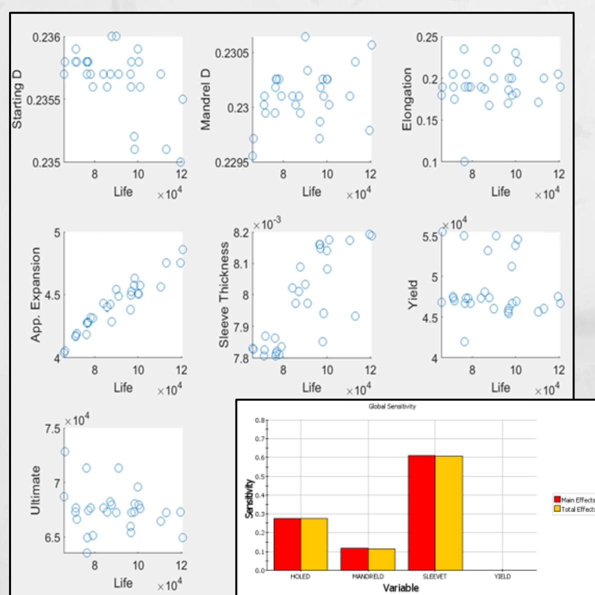
- **FTI Simulation Study**
  - FTI previously ran 29 samples of their cold expansion simulation ABAQUS model (~2016)
    - Two load steps: mandrel pull-through and reaming, 0.5" aluminum plate thickness
    - Variables included starting hole D, mandrel D, sleeve thickness, Cx applied expansion, material elongation, yield strength, and ultimate strength
    - Note: Samples (except for sleeve thickness) were based on actual measurements, not from a distribution or design of experiments
  - Results were provided to ERSI UQ and Analytical Methods Committees



- **BAMpF Crack Growth Simulation**
  - Analytical Methods Committee used the resulting RS fields to perform BAMpF analyses:
    - Fatigue crack growth life from an IFS of 0.05 in
    - Also ran cases with no RS from 0.05 and 0.005

	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

- **Correlation**
  - Life is strongly correlated to applied expansion
  - Yield is positively correlated to Ultimate
  - Applied expansion is inversely correlated to starting hole diameter
  - Low correlation between Yield/Ultimate and Life
  - Sensitivity studies of RS fields found correlation between material properties and outputs of interest
  - Emphasizes defining the intended use of models



- **Global Sensitivities**
  - Calculated sensitivities on the linear reduced model using NESSUS
  - Main & total effects are same due to linear model
  - Sleeve thickness dominates, but small sensitivities could be due to unstructured sampling

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Announcements

Upcoming ERSI related events:

- AA&S Conference, Aug. 29 – Sept. 1, 2022, Ponte Vedra, FL
- ASTM E08 Committee Week, Oct. 31 – Nov. 3, 2022, New Orleans, LA
- ASIP Conference, Nov. 28 – Dec. 1, 2022, Phoenix, AZ

ERSI committee participation

- We encourage you to continue to discuss ERSI-related topics with colleagues, at conferences, and in other technical interchanges. If you find there are others who would like to participate, please refer them to the applicable committee chair(s).

ERSI website

- If you have an account, go to https://member-ersi.swri.org and login. If you need an account, please send an email to Lucky Smith at luciano.smith@swri.org and an account will be created for you. Please include your name, organization, and contact information.