Engineered Residual Stress Implementation (ERSI) Working Group

Residual Stress Summit 2017

Oct 23-26, 2017

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Acknowledgements

- Thanks to all ERSI coordinators, integrators, subcommittee chairs, and ERSI working group participants
  - Tremendous progress since initial workshop

<ins>All presentation content derived from ERSI Workshop 2017</ins>

Overview

- ERSI Mission and Vision
- Organizational Structure
  - Participating members
- Subcommittees
  - Purpose
  - Current Projects & Outcomes
  - Identified Gaps
  - Future Initiatives
- Summary

Purpose

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

Vision

Within 3-7 years develop a framework for fleet-wide implementation of a holistic, physics-based approach for taking analytical advantage of deep residual stresses, induced through the Cold Expansion process, into the calculations of initial and recurring inspection intervals for fatigue and fracture critical aerospace components. Utilizing this foundation, also address other deep residual stress inducing processes, like Laser Shock Peening and Low Plasticity Burnishing.

Who We Are

DEPARTMENT OF THE NAVY · UNITED STATES MARINE CORPS

NAVAL AIR SYSTEMS COMMAND

BOEING

Coventry University

THE UNIVERSITY OF UTAH

LOCKHEED MARTIN

AIR FORCE MATERIEL COMMAND

FEDERAL AVIATION ADMINISTRATION

FTI FATIGUE TECHNOLOGY

L3 communications

CLARKSON UNIVERSITY · FOUNDED 1896 TO HONOR THOMAS S. CLARKSON

AIR FORCE RESEARCH LABORATORY

AIR FORCE LCMC

HILL ENGINEERING

Predict. Test. Perform.

APES, INC.

analytical processes / engineered solutions

THE UNIVERSITY OF CALIFORNIA · UCDAVIS · DAVIS

AFGROW.NET

SwRI

NORTHROP GRUMMAN

NRC·CNRC

AEROSPACE SYSTEMS DIRECTORATE

ARCONIC

StMU

Australian Government

Department of Defence

Science and Technology

STRESSCHECK

TRI AUSTIN

Constellium

Working Group Structure

Total Individuals within the Working Group - 78

- Countries Involved - 4
- DoD Organizations - 3 + FAA
- National Laboratory - 1
- Universities - 5
- OEMs - 3
- Industry Partners - 16
- Weapon Systems - 8

Integrators

Dr. Mark Thomsen - A-10 ASIP Manager; Dr. Dale Ball - Lockheed Martin Aero; Dr. TJ Spradlin - USAF/AFRL

Integrator Subcommittee

Organizational Group

Mr. Robert Pilarczyk – Hill Engineering, LLC.; Mr. Dallen Andrew and Mr. Scott Carlson - SwRI

Verification and Validation Testing

Dr. Tom Mills – APES, Inc.

Fatigue Crack Growth Analytical Methods

Mr. Robert Pilarczyk – Hill Engineering, LLC.

Residual Stress Process Simulation

Mr. Keith Hitchman – FTI – A PPC Company

Data Management and Quality Assurance

Dr. Carl Magnuson - TRI Austin

Effects of Residual Stress on Non-Destructive Inspection (NDI) Methods

Mr. John Brausch - USAF/AFRL

Residual Stress Measurements

Dr. Mike Hill - Hill Engineering, LLC.

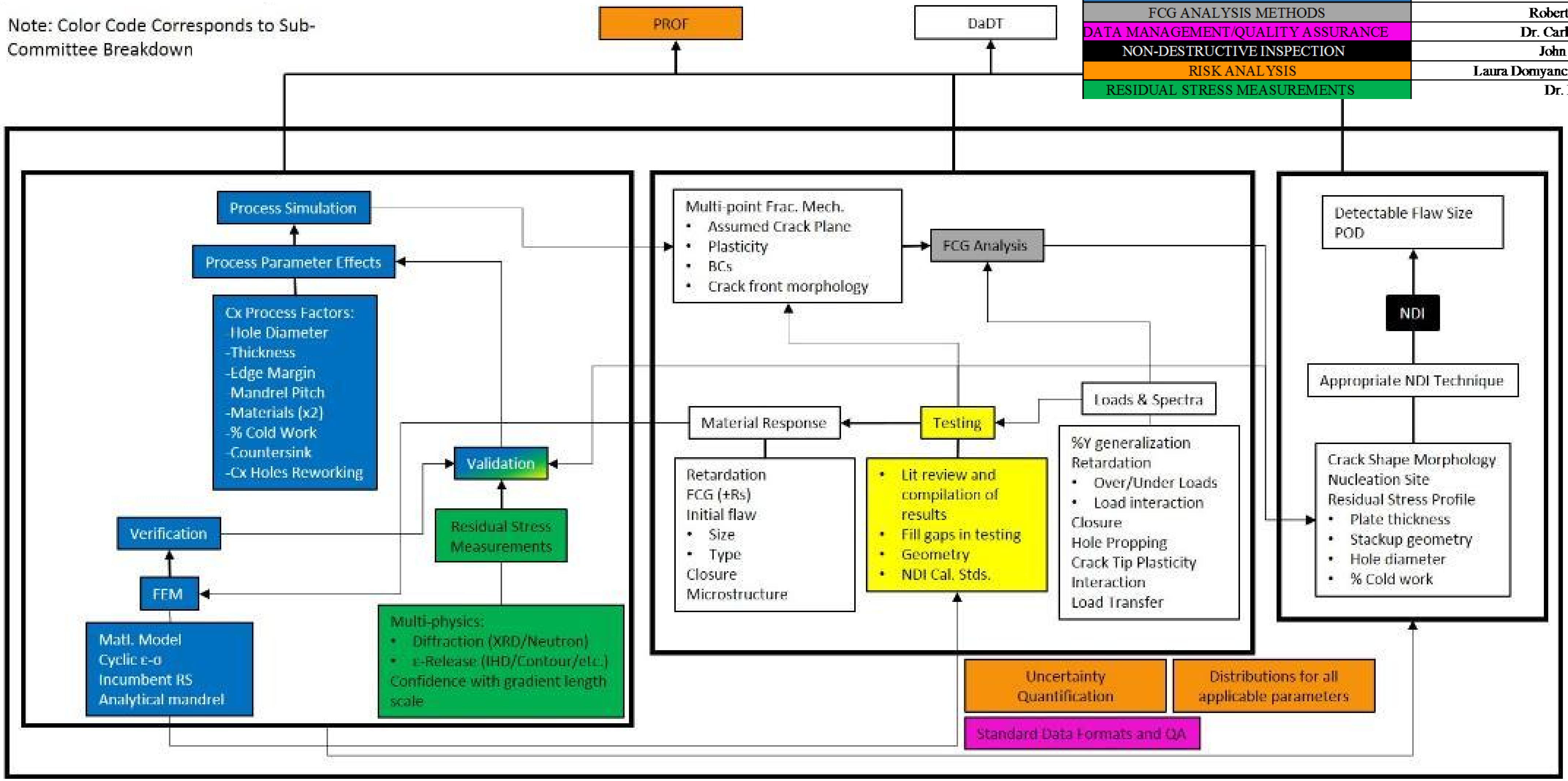
Risk Analysis

Mr. Lucky Smith & Ms. Laura Domyancic - SwRI

Technical Dependencies - Currently

Subcommittee	Chair
INTEGRATOR	Dr. Mark Thomsen, Dr. TJ Spradlin, Dr. Dale Ball
VALIDATION TESTING	Dr. Tom Mills
RESIDUAL STRESS PROCESS SIMULATION	Keith Hitchman
FCG ANALYSIS METHODS	Robert Pilarczyk
DATA MANAGEMENT/QUALITY ASSURANCE	Dr. Carl Magnuson
NON-DESTRUCTIVE INSPECTION	John Brausch
RISK ANALYSIS	Laura Domyancic & Lucky Smith
RESIDUAL STRESS MEASUREMENTS	Dr. Mike Hill

Note: Color Code Corresponds to Sub-Committee Breakdown



Technical Dependencies - Proposed

Subcommittee	Chair
INTEGRATOR	Dr. Mark Thomsen, Dr. TJ Spradlin, Dr. Dale Ball
VALIDATION TESTING	Dr. Tom Mills
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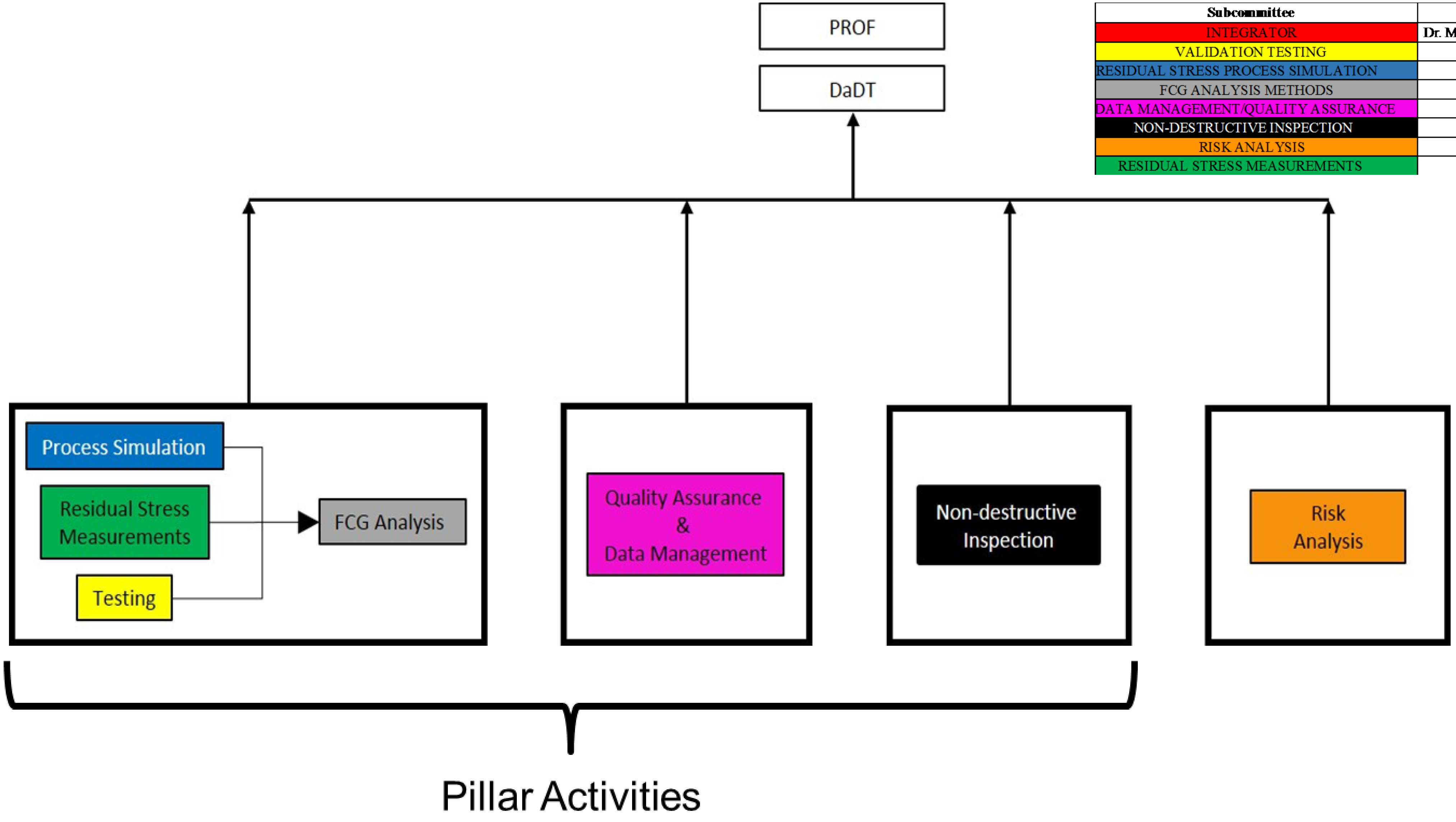


Subcommittee Overviews

Fatigue Crack Growth Analytical Methods

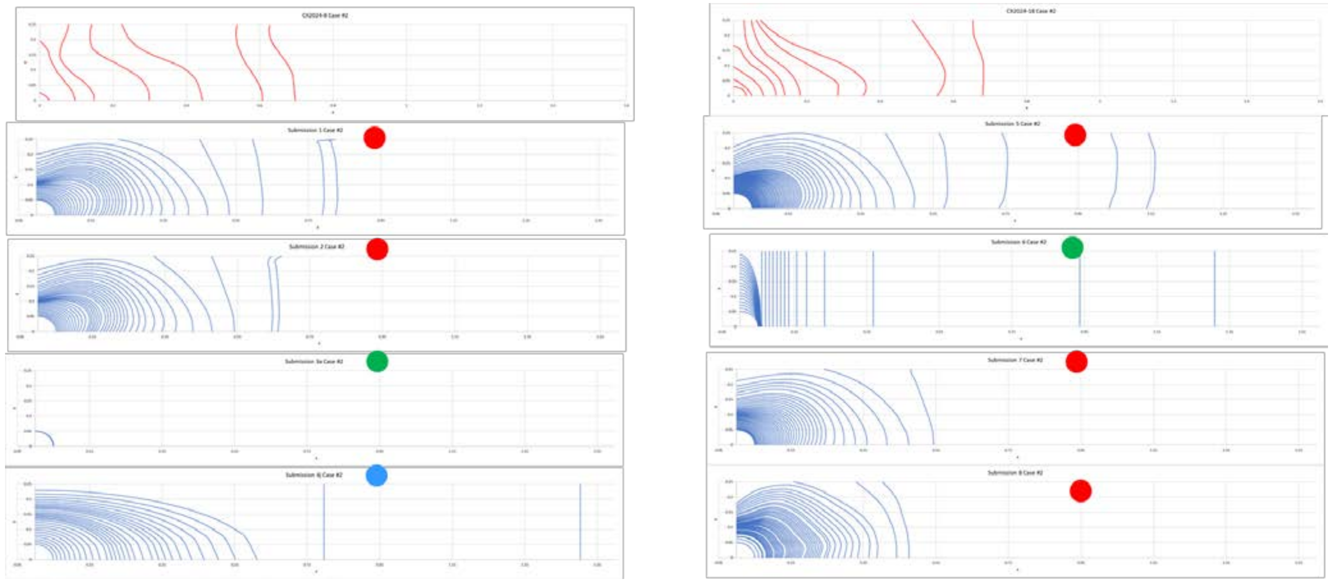
- **<u>Purpose</u>** – *Develop and document best practices for the integration of deep engineered residual stresses into the fatigue crack growth prediction methods used with the Damage Tolerance paradigm*

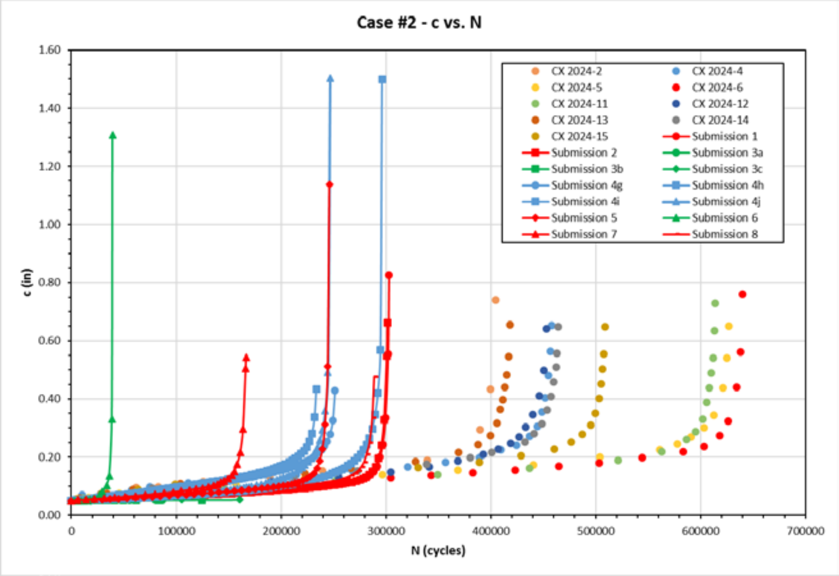
- **<u>Recent Initiatives</u>**
  - Round Robin for Cx Holes
  - Best Practices Document
  - Multi-Crack Effects
  - Engineering Implementation of RS
  - Near Surface RS
  - Overloads/Underloads/Load-X

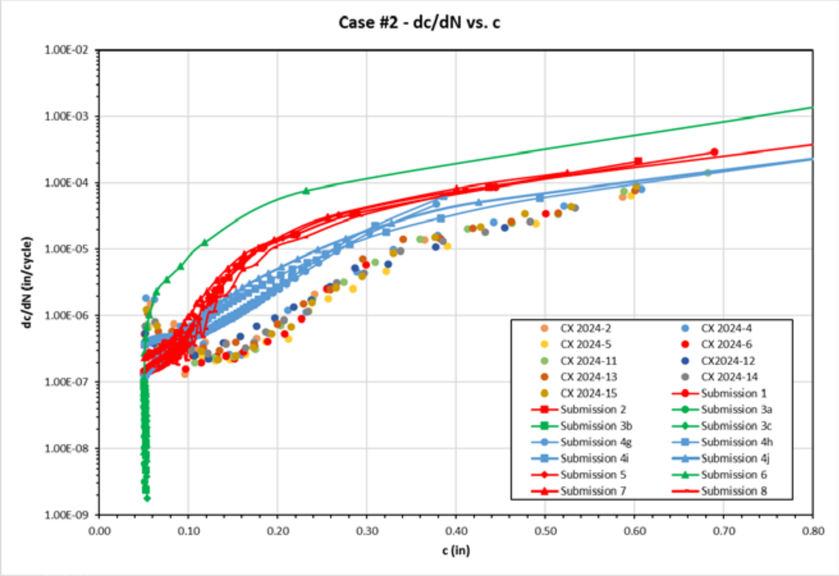
- **<u>Outcomes</u>**
  - Successful collaboration for round robin – lessons learned / best practices / journal article
  - Draft Best Practices Document – community collaboration
  - Non-dimensional behavior of residual stress

Fatigue Crack Growth Analytical Methods

- **Round Robin**
  - Focused on systematic uncertainties
  - (4) different conditions
  - (8) different analysts

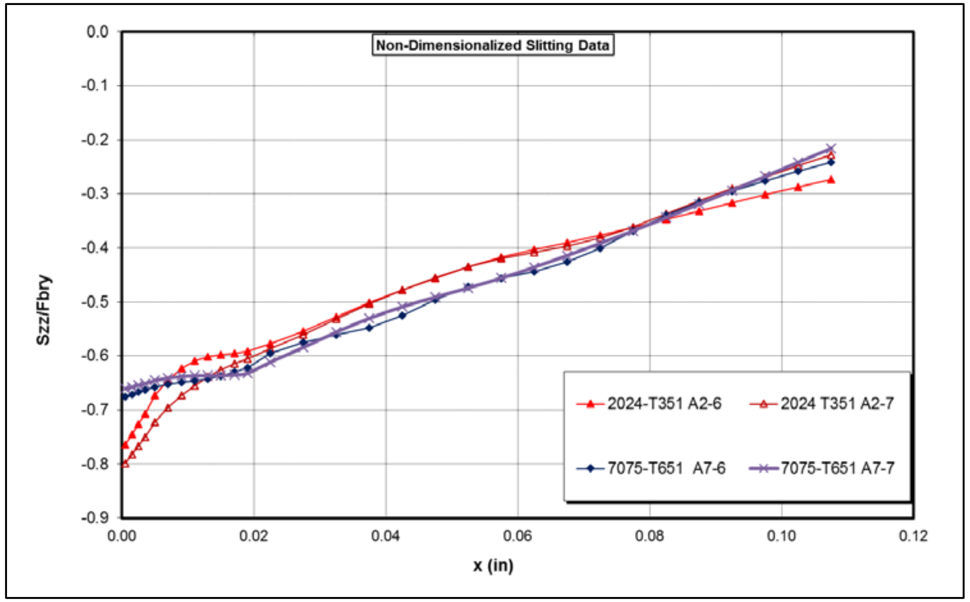






Fatigue Crack Growth Analytical Methods

- **Identified Gaps**
  - Remote / partial crack closure
  - Near surface residual stress understanding
  - Countersunk holes
  - Load transfer impacts
  - Crack growth rate data (Negative R)



- **Future Initiatives**
  - Follow-on Round Robin
  - Crack closure
  - Near surface residual stress
  - Engineering implementation of RS (Manage-to-RS?)

Validation and Verification Testing

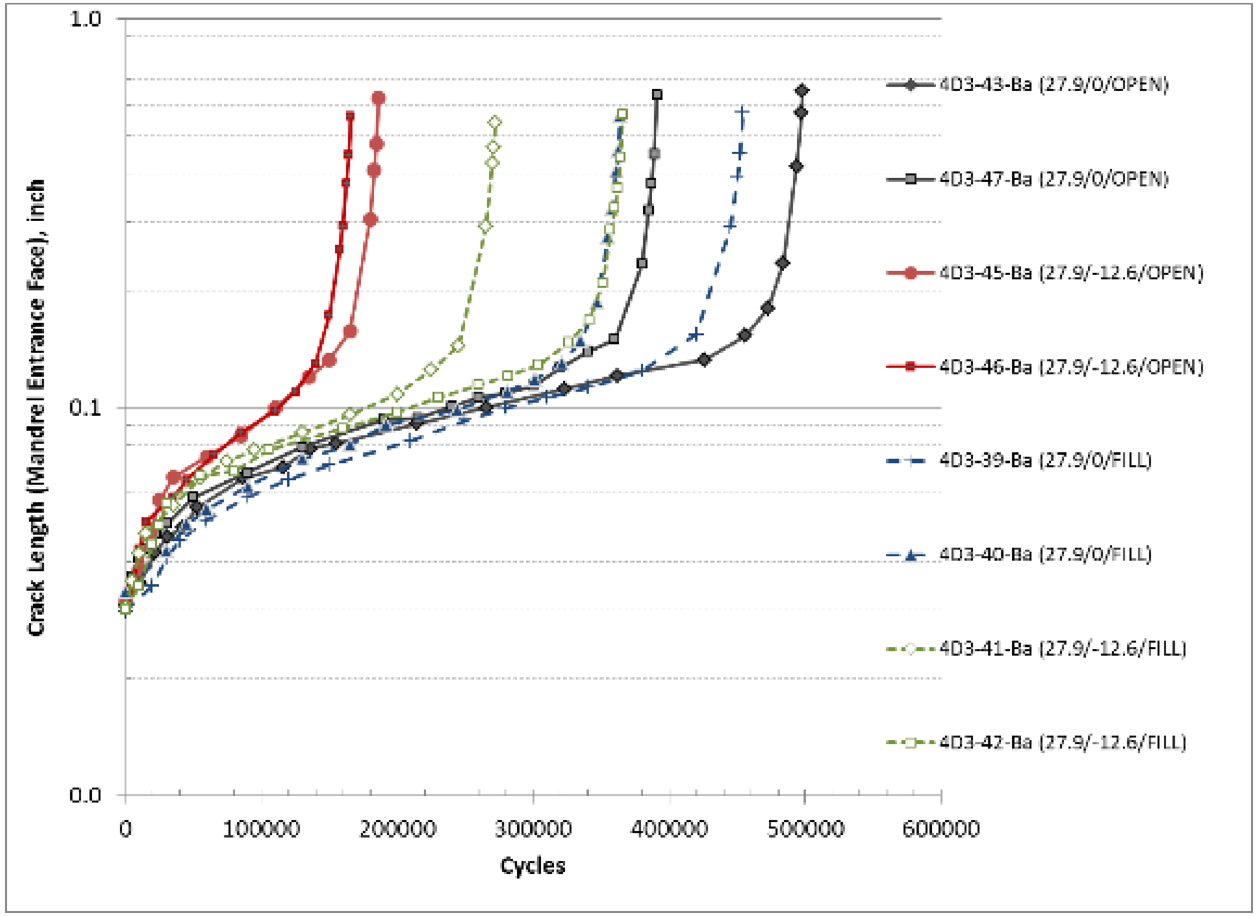
- **Purpose** – *Provide material characterization data through standardized and experimental testing which can be utilized for the V&V of mathematical models used to represent the physics of material and component response*

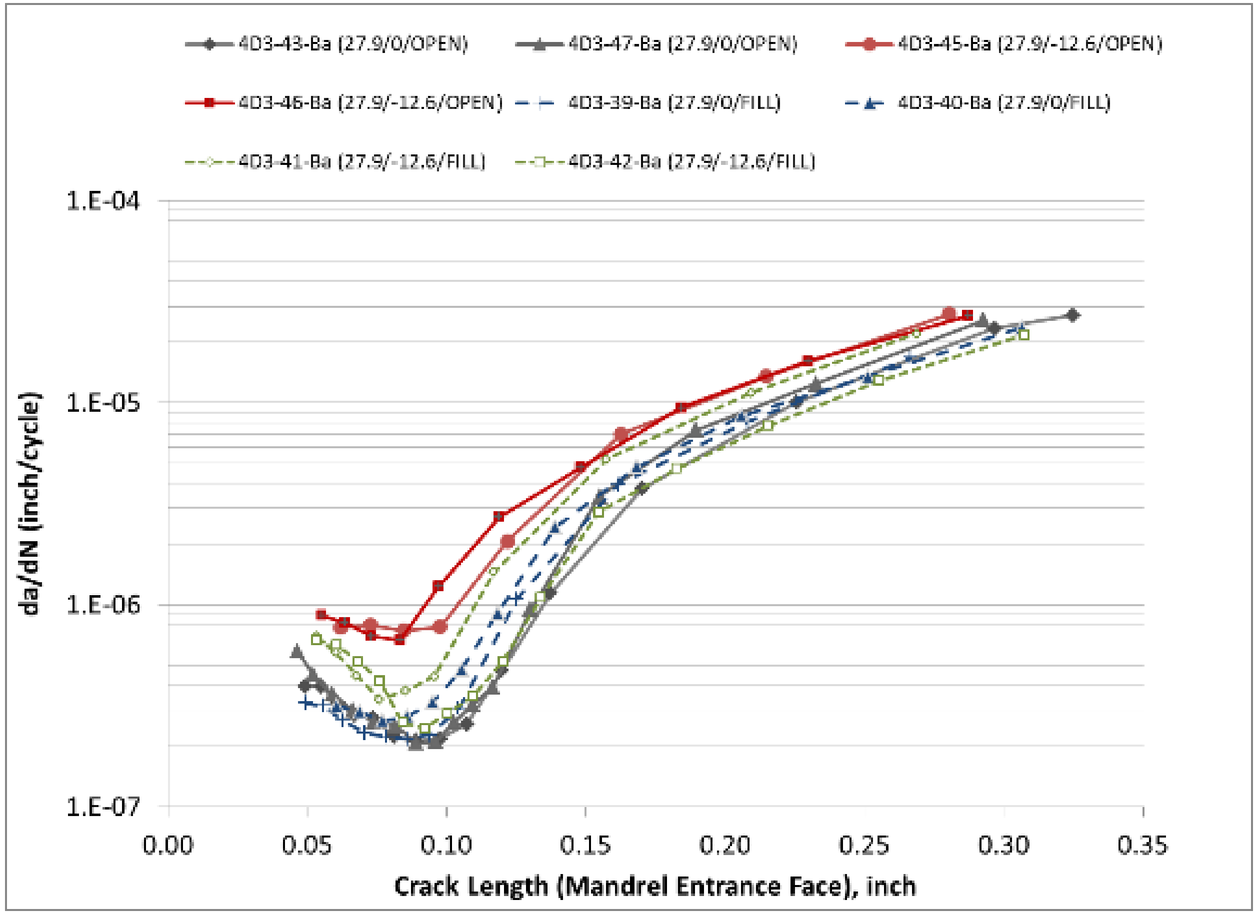
- **Recent Initiatives**
  - Effects of peak compression and tension
  - Applied Stress Ratio (R) impacts
  - Focused regions of crack growth testing
  - Development of crack growth rates for corner cracks

- **Outcomes**
  - Development and publishing of test data
  - Presentations at ASTM, ASIP or other professional conferences

Validation and Verification Testing

- **Underloads**





Validation and Verification Testing

- **<u>Identified Gaps</u>**
  - Available fatigue test data to compliment residual stress measurement conditions
  - Negative-R test data

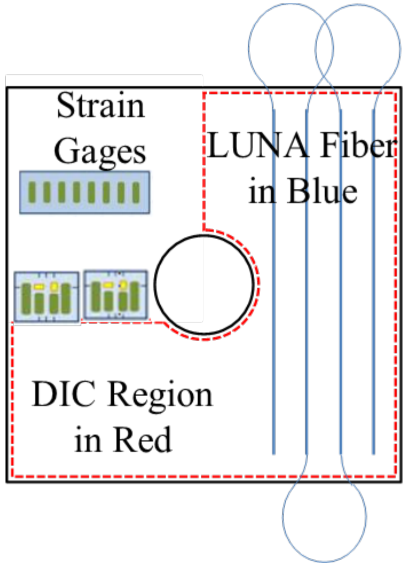
- **<u>Future Initiatives</u>**
  - Test data to support 2nd Round Robin
  - Sensitivity analysis for negative R data
  - Part-through crack da/dN vs. ΔK data
  - Evaluate available data pools to support analysis group for evaluations

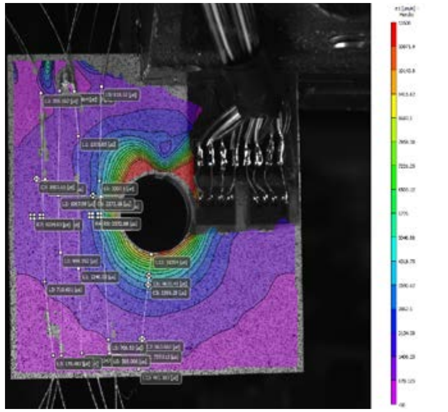
Residual Stress Process Simulation

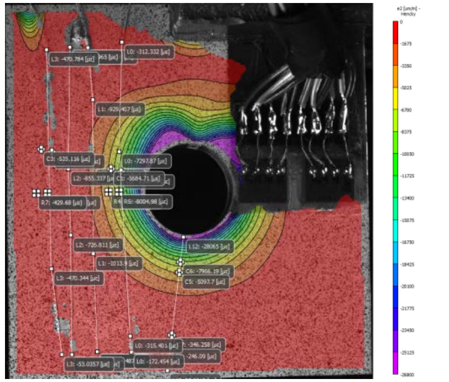
- **<u>Purpose</u>** – *Develop methods and standards for the determination and validation of residual stresses via FEA simulation*
- **<u>Recent Initiatives</u>**
  - Assessing different material hardening models
  - Benchmarking of current state-of-the-art, adjusting model parameters as compared to measurement
  - Determination of model validation requirements, macro to micro scale
- **<u>Outcomes</u>**
  - Best practices document for process simulation
  - Best practices regarding material hardening model
  - FEA validation requirements document

Residual Stress Process Simulation

- **Validation Program**
  - Perform experiments to capture surface and through-thickness strains for FEA process simulation validation
  - Measurement techniques
    - Surface strain
      - Digital Image Correlation (DIC)
      - Fiber optics
      - Strain gages
    - Through-thickness measurement techniques
      - High energy X-ray Diffraction (XRD)
      - Neutron Diffraction
      - Contour Measurements



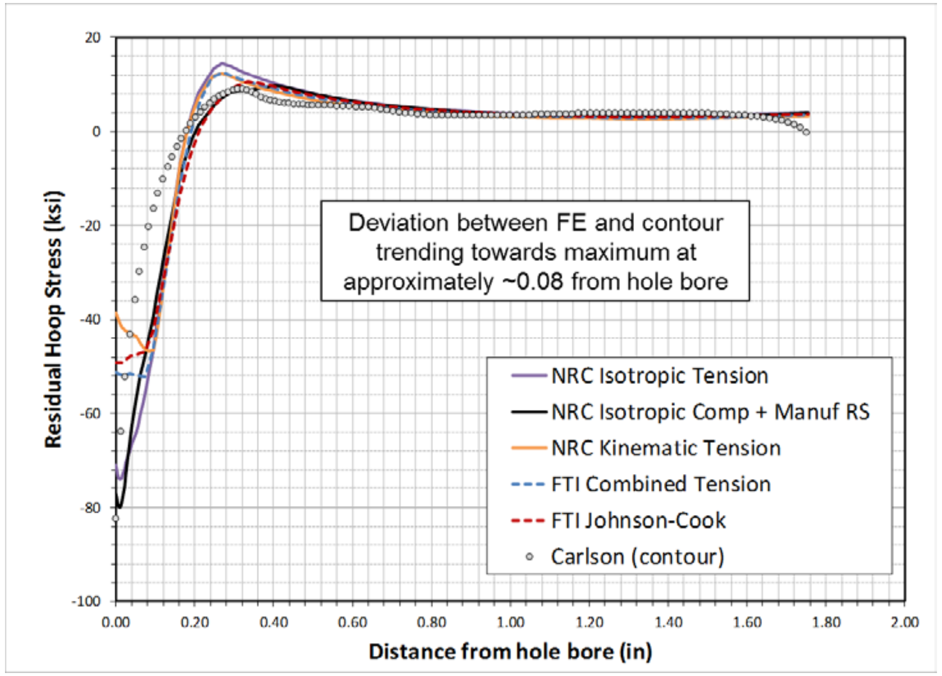




Residual Stress Process Simulation

- **Identified Gaps**
  - Appropriate material hardening models/data for Cx holes
  - Defined verification and validation requirements

- **Future Initiatives**
  - Development of material hardening models
  - Defined verification and validation requirements

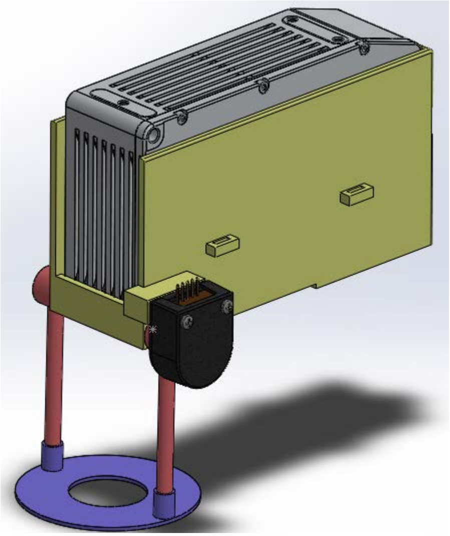


Data Management & Quality Assurance

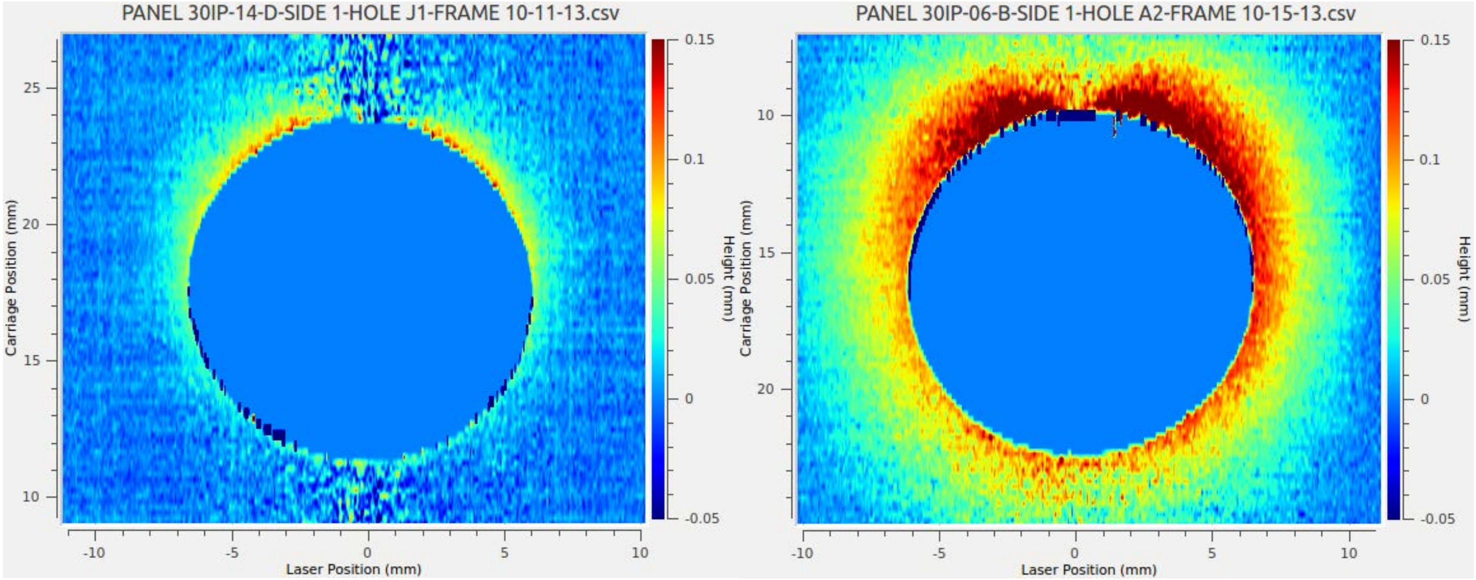
- **Purpose** – *Develop requirements and standardized formats for the acquisition, storage, and analysis of data which enables confidence in the quality of the process to introduce engineered residual stress.*
- **Recent Initiatives**
  - Development of additional quality assurance tools
  - Documentation requirements
- **Outcomes**
  - Productionized FastenerCam™ tool in development

Data Management & Quality Assurance

- **FastenerCam™ Development**



1.24% Cx **4.00% Cx**



0.494" Diameter Straight Shank Holes

Data Management & Quality Assurance

- **Identified Gaps**
  - Identification of data fidelity requirements
  - Auditable and quantitative measurement of Cx process
  - Defined acceptance levels of variability and uncertainty
  - Data storage location, capacity, etc.
- **Future Initiatives**
  - Protocols to capture Cx data and store appropriately
  - AFSC involvement / buy-in – capturing data

Effect of RS on NDI Methods

- **Purpose** – *Quantify the impacts of deep engineered residual stresses on NDI detection capability and reliability*

- **Recent Initiatives**

  - Quantify shear-wave ultrasonic detection capability impact for fatigue cracks at Cx holes
    - Quantification of "Dead Zone" within the RS field via the Cx process
    - Develop standard POD correction factors
  - Quantify effects of engineered RS on crack closure and NDI of open surfaces
    - Effects of LSP on detectability of fatigue cracks in aluminum fittings

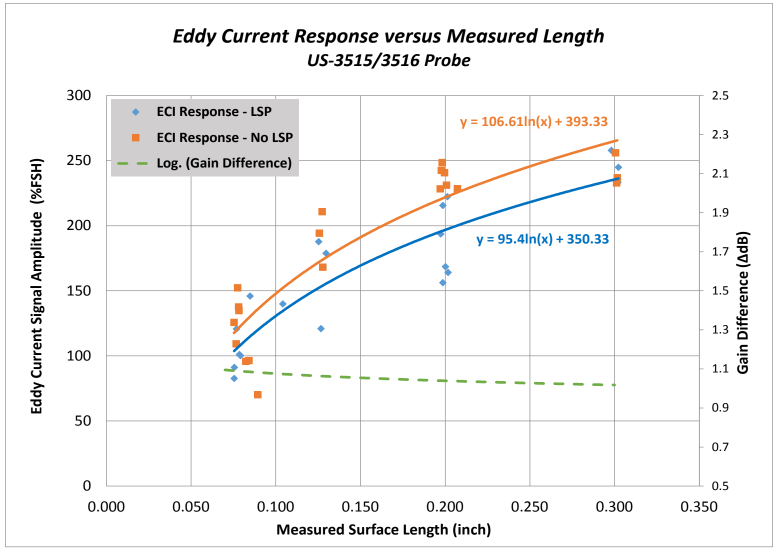
- **Outcomes**

  - Update to NDI Structures Bulletin – EN-SB-008-012
  - Combined NDI techniques for RS situations
  - Best practices

Effect of RS on NDI Methods

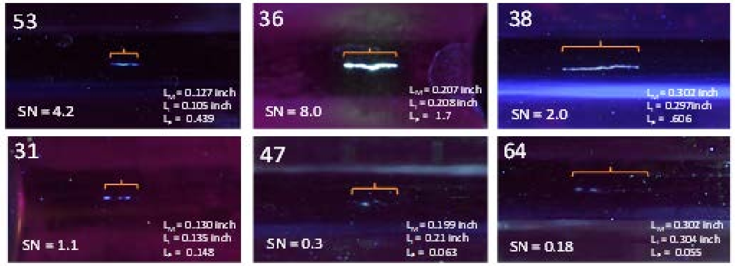
- **LSP Effects on NDI**

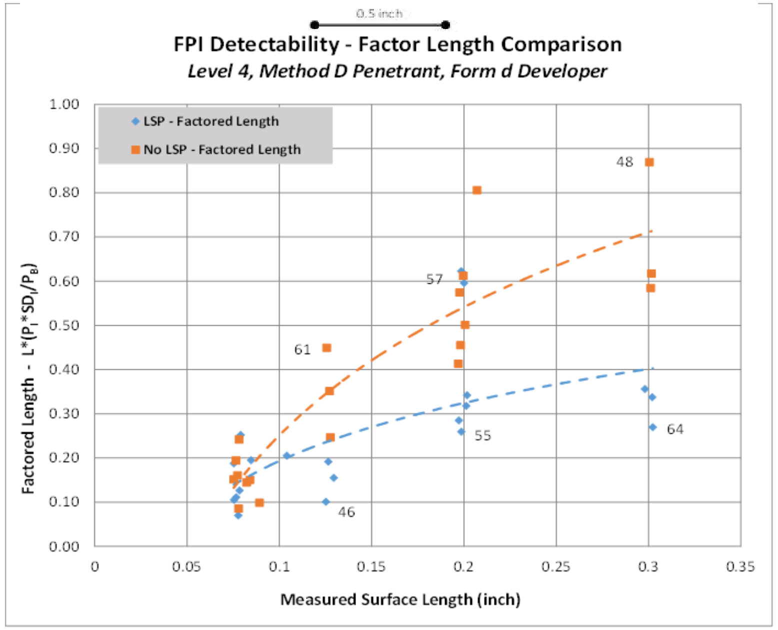
Surface Eddy Current



Minimal Impact

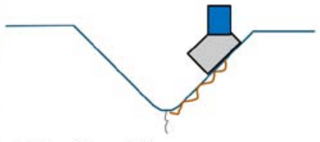
Fluorescent Penetrant





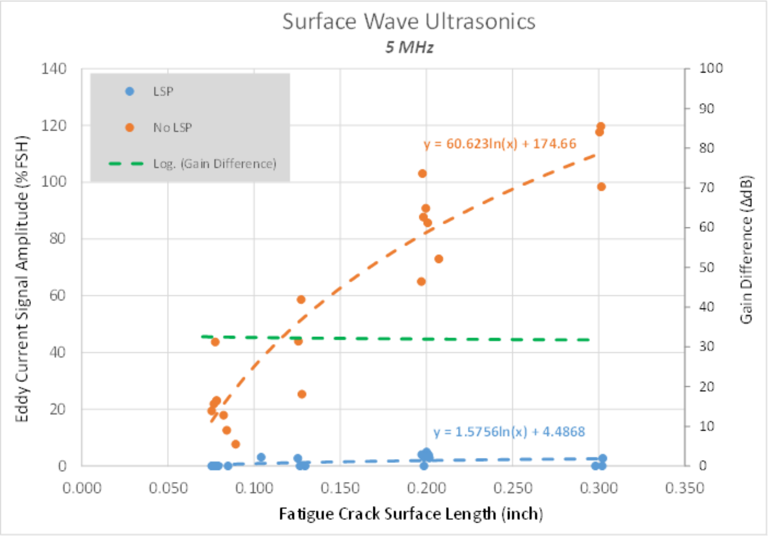
Significant Impact

Surface Wave Ultrasonics



Surface Wave Unit
90º shear wedge
10 MHz, 0.25 inch diameter transducer

Calibration
80%FSH from 0.02 x 0.01 inch notch
in a 7075-T7 reference plate



Significant Impact

Effect of RS on NDI Methods

- **Identified Gaps**
  - UT “dead zone” at Cx holes
  - Fastener installation impacts on UT fatigue crack detectability

- **Future Initiatives**
  - Develop UT probability of detection corrections factors
  - Map UT “dead zone” for Cx holes
  - Best practices document
  - Investigate fastener installation impacts on UT detectability
  - Updates to NDI Structures Bulletin

Residual Stress Measurement

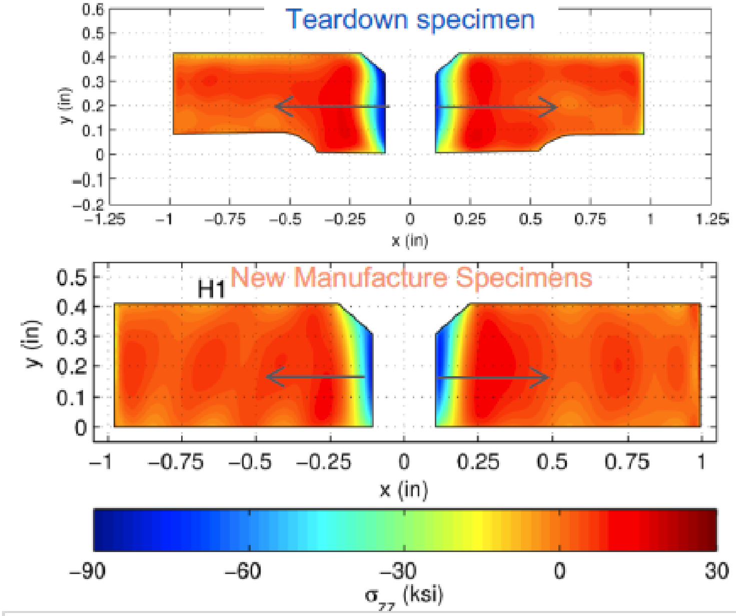
- **Purpose** – *The development and validation of residual stress measurement methods as a means of defining a stress state which can be integrated into life calculations*

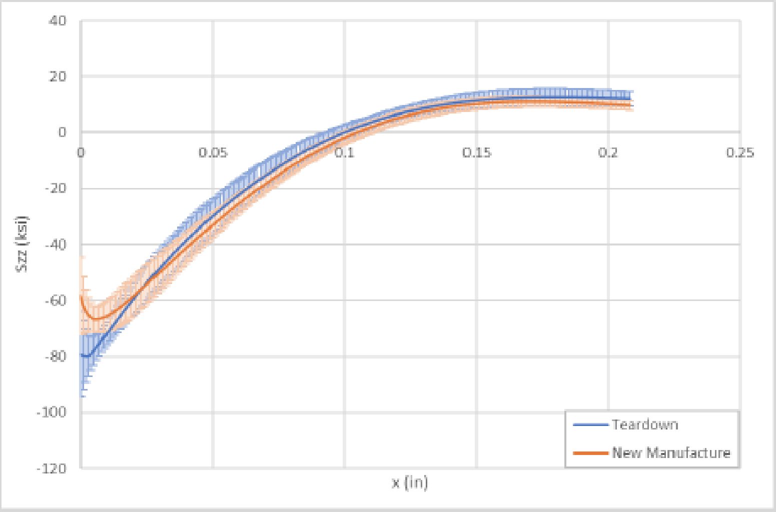
- **Recent Initiatives**
  - Legacy vs. new manufacture residual stress
  - Residual stresses at cracked Cx holes
  - Near surface residual stress
  - Contour method inter-laboratory uncertainty quantification

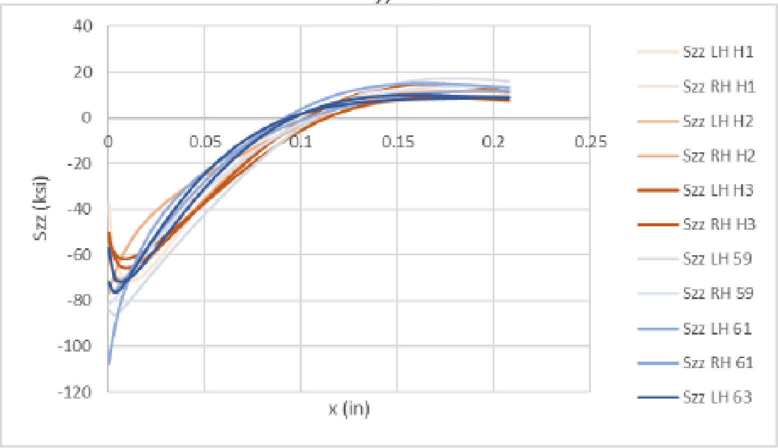
- **Outcomes**
  - Legacy vs. new manufacture comparisons in work
  - Quantifying impacts of cracks on residual stress
  - Micro-slotting procedure
  - Cross-method residual stress validation efforts

Residual Stress Measurement

- **Legacy vs. New Cx Comparisons**







Sample ID	Midthickness 0.125*rad	Midthickness 0.25*rad	Midthickness 0.5*rad	Midthickness 0.75*rad	Depth at crossover (midthickness)	Point Value of Entrance	Avg RS in 0.05" Radius Entrance	Standard Deviation of Avg RS in 0.05" Radius CSK Entrance	Point Value CSK Knee	Avg RS in 0.05" Radius CSK knee	Standard Deviation of Avg RS in 0.05" Radius CSK Knee
L-59	-75.54	-62.37	-38.23	-17.06	0.11	-41.55	-42.52	12.53	-64.33	-67.77	8.86
R-59	-64.36	-50.39	-28.75	-12.05	0.11	-64.08	-30.42	14.86	-71.14	-54.33	12.20
L-61	-62.45	-48.14	-24.19	-5.89	0.09	-28.52	-34.95	9.23	-63.39	-59.91	10.61
R-61	-60.65	-41.99	-20.82	-7.91	0.10	-39.61	-33.14	13.49	-76.55	-60.63	14.44
L-63	-66.68	-53.25	-26.83	-7.67	0.10	-14.52	-37.40	8.14	-62.45	-61.08	10.12
R-63	-63.46	-46.85	-20.96	-5.06	0.09	-35.68	-34.90	11.51	-69.72	-56.33	13.47
L-H1	-65.31	-50.67	-26.36	-8.31	0.10	-20.19	-35.79	8.86	-62.90	-58.60	10.04
R-H1	-70.67	-60.17	-31.85	-9.90	0.10	-39.71	-33.49	9.47	-41.25	-62.40	8.67
L-H2	-50.49	-38.61	-23.31	-11.22	0.11	-34.93	-28.68	9.45	-69.66	-51.47	10.46
R-H2	-67.34	-55.92	-32.30	-13.30	0.11	-22.62	-35.97	9.23	-53.31	-66.29	8.02
L-H3	-60.45	-53.04	-34.46	-16.40	0.11	-40.85	-36.05	8.28	-57.51	-56.82	5.93
R-H3	-64.40	-55.64	-33.52	-13.27	0.10	-23.61	-32.05	6.60	-50.19	-65.40	8.68
Mean	**-65.52**	**-50.50**	**-26.63**	**-9.27**	**0.10**	**-37.33**	**-35.56**	**11.63**	**-67.93**	**-60.01**	**11.62**
Stdev	**4.84**	**6.32**	**5.93**	**4.12**	**0.01**	**14.94**	**3.76**	**2.33**	**5.03**	**4.23**	**1.94**
Mean	**-63.11**	**-52.34**	**-30.30**	**-12.07**	**0.11**	**-30.32**	**-33.67**	**8.65**	**-55.80**	**-60.17**	**8.63**
Stdev	**6.43**	**6.79**	**4.05**	**2.62**	**0.01**	**8.44**	**2.68**	**1.00**	**9.08**	**5.15**	**1.47**
Residuals (Td-NM)	**-2.41**	**1.84**	**3.67**	**2.79**	**-0.01**	**-7.01**	**-1.88**	**2.98**	**-12.13**	**0.16**	**2.98**

Residual Stress Measurement

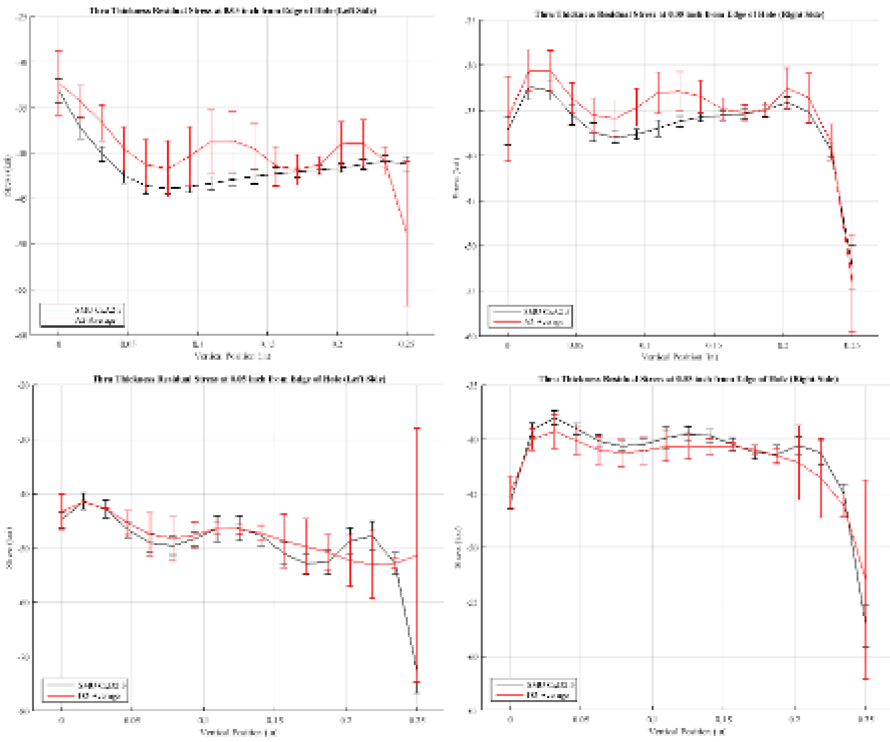
- **Identified Gaps**
  - Near-bore residual stress understanding
  - Mapping results from simple coupon to complex structure
  - What's necessary for quality assurance?
- **Future Initiatives**
  - Near-bore follow-up measurements
    - Geometrically "large" coupon program
    - Combination of methods
    - Standard work
  - Validation test coupons (Cx – ream – cycle)
  - Pooled statistics on RS at Cx holes – Involve UQ group

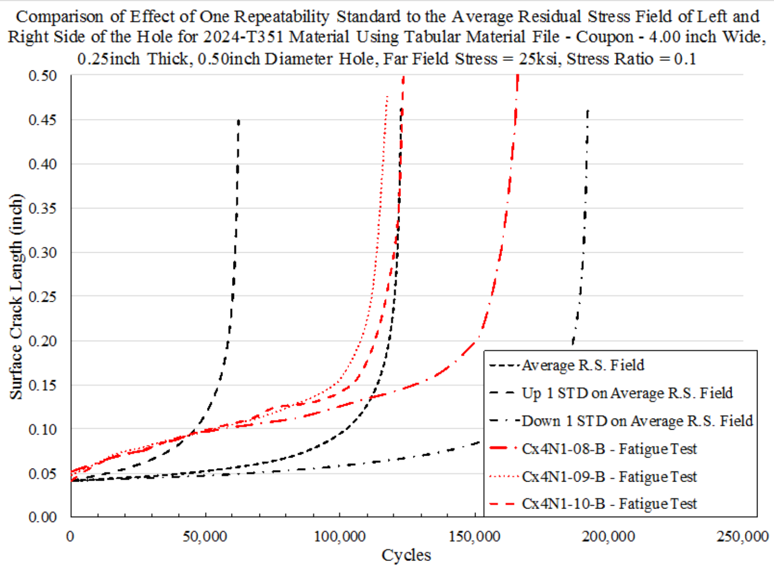
Risk Analysis

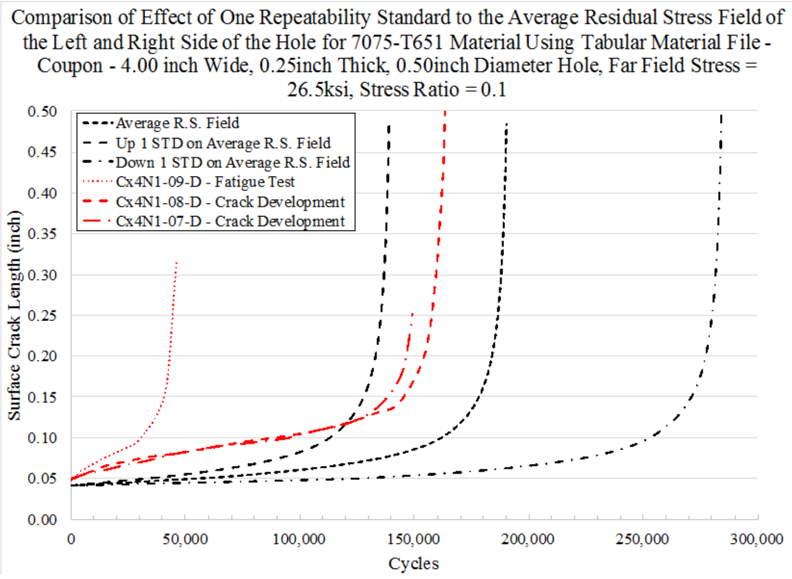
- **Purpose** – *Support deterministic damage tolerance analysis development through quantifying the uncertainty in critical variables, and develop of a methodology for incorporating residual stress fields into probabilistic damage tolerance assessments.*
- **Recent Initiatives & Outcomes**
  - Incorporation of residual stresses into DARWIN and SMART/DT analyses
  - Uncertainty quantification of contour method measurements
- **Outcomes**
  - Predictive processes of residual stress from material processing
  - Fitting of residual stress response surface
  - Initial sensitivity studies for determination of critical parameters

Risk Analysis

- **<u>Uncertainty quantification of contour method measurements</u>**
  - Quantifying the uncertainty in single measurements and in repeat measurements for two materials
  - Investigating the impact of repeatability uncertainty on analysis and comparing to test







Risk Analysis

- **Identified Gaps**
  - How can we use the UQ work performed to date for problems with other materials, geometries, etc.?
  - Which of the many available surrogate/response surface modeling methods would be most applicable to this problem?
  - Which inputs are the most important for understanding the impact of residual stresses?
- **Future Initiatives**
  - Determine how to extend contour method UQ work to all potential scenarios
  - Determine best surrogate modeling methods for residual stress surfaces
  - Calculate deterministic and probabilistic sensitivity for the inputs to determine which parameters are critical

Summary

- Diverse group spanning many disciplines and industries collectively coming together to:
  - Define roadmap for implementation of engineered residual stresses
  - Highlight the gaps in the state-of-the-art
  - Documenting lessons learned and best practices
  - Define the most effective way to document requirements and guidelines

- If you’re interested in participating let us know!!!

Questions?

ERSI