THE ENGINEERED RESIDUAL STRESS IMPLEMENTATION (ERSI) WORKING GROUP

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Abstract: The Engineered Residual Stress Implementation (ERSI) working group was formed in 2016 with a mission to "develop a holistic paradigm for the implementation of engineered residual stresses into lifing of fatigue and fracture critical components". ERSI emerged from within the United States Air Force (USAF) aircraft structural integrity community as a forum for individuals and organizations to collaborate constructively, transition technology and data to the public sphere, and consult on policy/best practices concerning the incorporation of residual stresses with other entities such as the FAA, DoD, ASTM, SAE, etc. ERSI members represent a broad diversity of interests and backgrounds, both domestic and international, from military, academia, and industry.

The primary focus of ERSI so far has been the transition of a classic engineered residual stress technology, cold expansion of holes, into life extension for USAF weapon systems. Although hole cold expansion is known to provide significant structural fatigue life extension, the full potential improvement has not been included in certified airworthiness limits. With extensive support from ERSI, the USAF recently issued a Structures Bulletin which allows aircraft structural integrity managers to utilize cold expansion benefits for initial and recurring inspection intervals, a significant achievement for both platform availability and fleet-wide cost savings.

This achievement is a holistic product from the three primary focus areas, or committees, within ERSI that represent different technical disciplines of aircraft structural integrity: 1) analysis and test, 2) residual stress characterization, and 3) nondestructive inspection/evaluation, quality assurance, data management.

These three committees work together to identify and address technical gaps, define the requirements and guidelines for implementation, and collaboratively develop and accomplish new round robin activities that advance the state-of-the-art. This paper describes recent work performed by the ERSI working group across these three committees.

Keywords: residual stress, cold expansion

INTRODUCTION

The overarching vision of ERSI is to help 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 (Cx) process, into the calculations of initial and recurring inspection intervals for fatigue and fracture critical aerospace components. ERSI has a mission statement to develop a holistic paradigm for the implementation of engineered residual stresses into lifing of fatigue and fracture critical components through the following key objectives:

- Define a common vision for the accounting of engineered residual stress at Cx 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

Since its inception in 2016, ERSI has grown to over 120 participants from different countries, Department of Defense organizations, national labs, universities, original equipment manufacturers (OEMs), industry partners, and USAF Aircraft Structural Integrity Program (ASIP) managers.

ERSI COMMITTEE: ANALYSIS AND TEST

The mission of the analysis and test committee is to establish analytical & testing guidelines to support implementation of engineered residual stress, with key objectives of:

- Develop and document best practices for integration of engineered residual stress 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

The following sections discuss recent achievements of the analysis and test committee.

2021 Achievements: Interference Fit Fastener Round Robin

In 2021, the ERSI analysis and test committee performed a round robin activity for analysis of interference fit fasteners. The loading and geometry information are listed below.

- Constant amplitude, R = 0.1, max stress = 192.3 MPa (27.9 ksi)
- 7075-T651 aluminium alloy, 6.35 mm thick (0.25 inch)
- Two conditions tested: Open hole, 0.4% interference
- Three conditions predicted: Open hole, 0.4% interference, 0.6% interference

The results from the various contributors are given in Figure 1. Overall, these results showed tight grouping of the open hole predictions, although all analysts under-predicted the test data. The surface correction approach shows promise for the open hole condition. The stress approach used by Raider closely matched life and crack growth curve shape. More evaluations and testing are planned by ERSI to further look at these cases and other interference fit cases in the future.

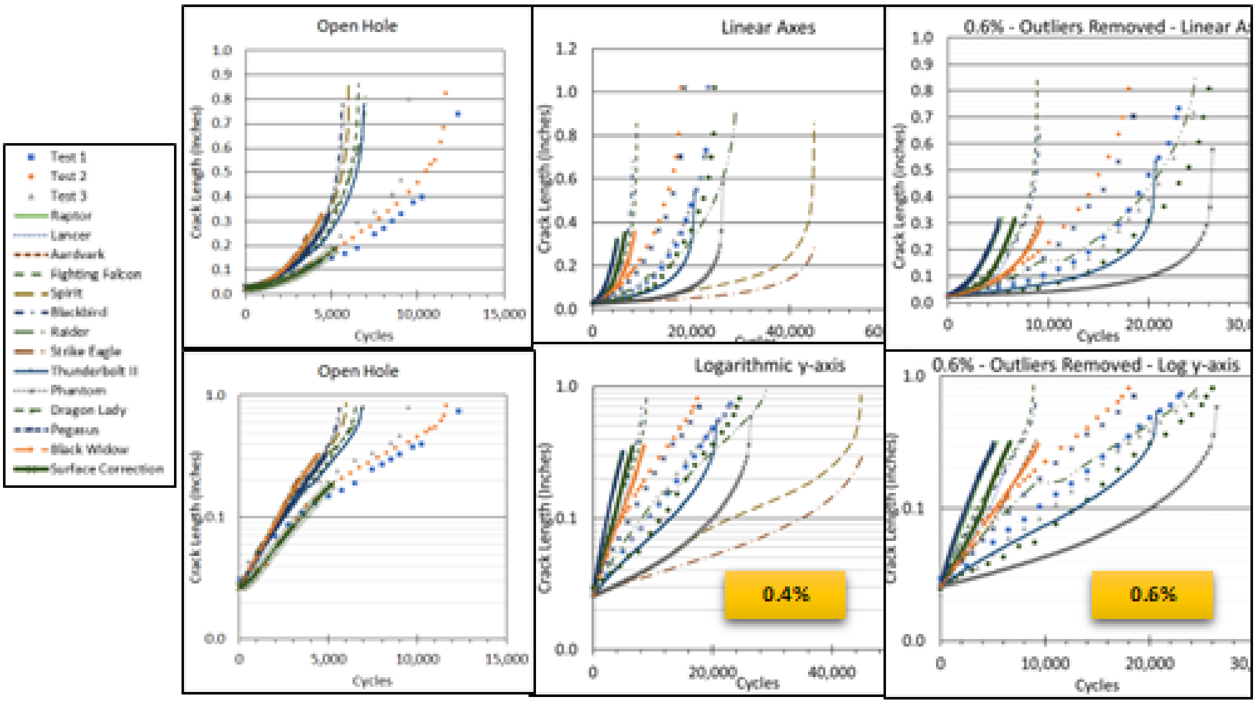


Figure 1: Interference fit round robin results [1].

<u>2021 Achievements: Stress Intensity Factor Round Robin</u>

In 2021, the ERSI analysis and test committee completed a round robin activity for the comparison of stress intensity factors. The primary objective of the Stress Intensity Factor (SIF) round robin was to evaluate differences between available SIF solutions for a single corner crack at a fastener hole with remote uniform tension loading. The evaluations included not only the root SIF solution but any corrections to account for single vs multiple cracks, finite width, and hole offset. These solutions were compared to explicit Finite Element Analysis (FEA) results of each case. Any findings were intended to drive improvements to solutions available to the fracture mechanics community.

Seven different cases of corner cracks at a hole were developed and SIF solutions along the crack front were requested from participants (see configuration details in Figure 2. A building block approach was utilized (see Table 1) with Case 1 representing the root SIF solution, and each case added an additional level of complexity with corrections to the root solution.

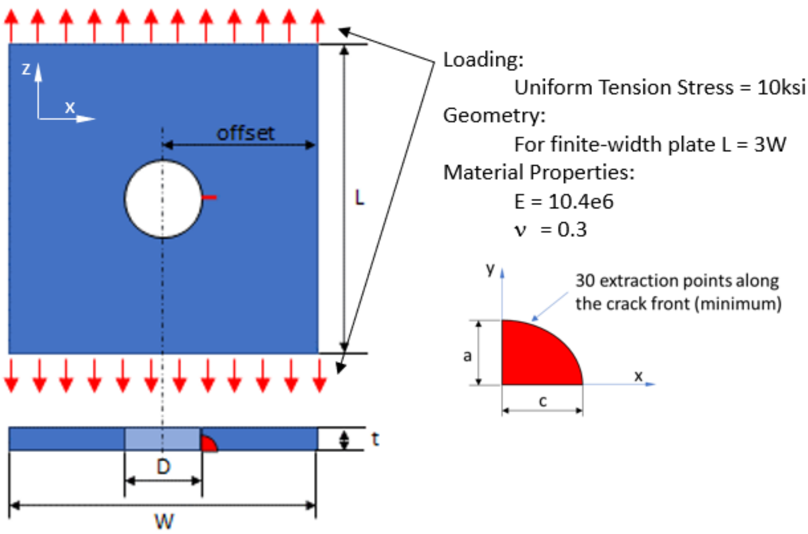


Figure 2: Round robin corner crack at a hole configuration [2].

Table 1: SIF round robin matrix of cases [2].

Case	Surface Crack Length (c) (inch)	Bore Crack Length (a) (inch)	Corner Crack Configuration	Width (inch)	Thickness (inch)	Hole Diameter (inch)	Hole Offset (inch)
1	0.050	0.050	Double Symmetric	100.00	0.25	0.50	50.00
2	0.050	0.050	Single	100.00	0.25	0.50	50.00
3	0.050	0.050	Single	4.00	0.25	0.50	2.00
4	0.050	0.050	Single	4.00	0.25	0.50	0.60
5	0.050	0.050	Single	1.20	0.25	0.50	0.60
6	0.050	0.075	Single	100.00	0.25	0.50	50.00
7	0.100	0.050	Single	100.00	0.25	0.50	50.00

Nine submissions were received from eight participants which included solutions utilized by AFGROW and NASGRO, solutions from Newman/Raju and Fawaz/Andersson, and explicit FEA of each case (see Table 2). FEA approaches utilized various tools and methods which provides an additional opportunity to evaluate the different approaches and their impact on the accuracy of the SIF. Seven reference solutions (correlating with the seven cases) with relative errors in KI on the order of 0.03% or less were provided by Andersson (Submission 6) under USAF contract and were utilized as the reference solutions for all cases.

Table 2: Summary of SIF submissions [2].

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 (as implemented in AFGROW Advanced Model)	n/a	Newman correction	Harter correction
2	Newman-Raju Fit to Fawaz-Andersson	Updated equations by Newman based on fit to Fawaz-Andersson solutions	Shah-Newman Correction (2020)	Newman correction	• center hole (conservative option) • Kt match approach
3	Newman-Raju (1986)	1986 Newman-Raju solution	Shah correction	Newman correction	Kt match approach
4	NASGRO (CC04 & CC02): Newman-Raju	1986 Newman-Raju solution (as implemented in NASGRO CC04)	Shah correction (as implemented in NASGRO CC02)	NASGRO CC02	NASGRO CC02
4	NASGRO (CC16): Fawaz-Andersson	Fawaz-Andersson solutions (as implemented in NASGRO CC16)	n/a	Modified version of the Newman correction	Harter correction (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 software based on the hp-version of the finite element method, to create 3D models and compute Mode I SIFs using the Contour Integral Method (CIM).			
9	Marc: FEA (2021)	Utilized Marc to create 3D FEMs and compute Mode I SIFs			

Table 3 lists the input parameters for Case 6 only, which are the only results included in this paper. The Mode I SIF is plotted along the crack front as a function of normalized parametric angle in Figure 3, while the percent difference relative to Submission 6 from Andersson is presented in Figure 4.

Table 3: Case 6 input parameters [2].

Case	6
Configuration	Infinite Plate, Single Crack, a/c=1.5
Crack Configuration	Single Corner Crack
Surface Crack Length (*c*) (inch)	0.050
Bore Crack Length (*a*) (inch)	0.750
Width (inch)	100.00
Thickness (inch)	0.25
Hole Diameter (inch)	0.50
Hole Offset (inch)	50.00
a/c	1.50
a/t	0.30
W/D	200.00
r/t	1.00
r/W	0.0025

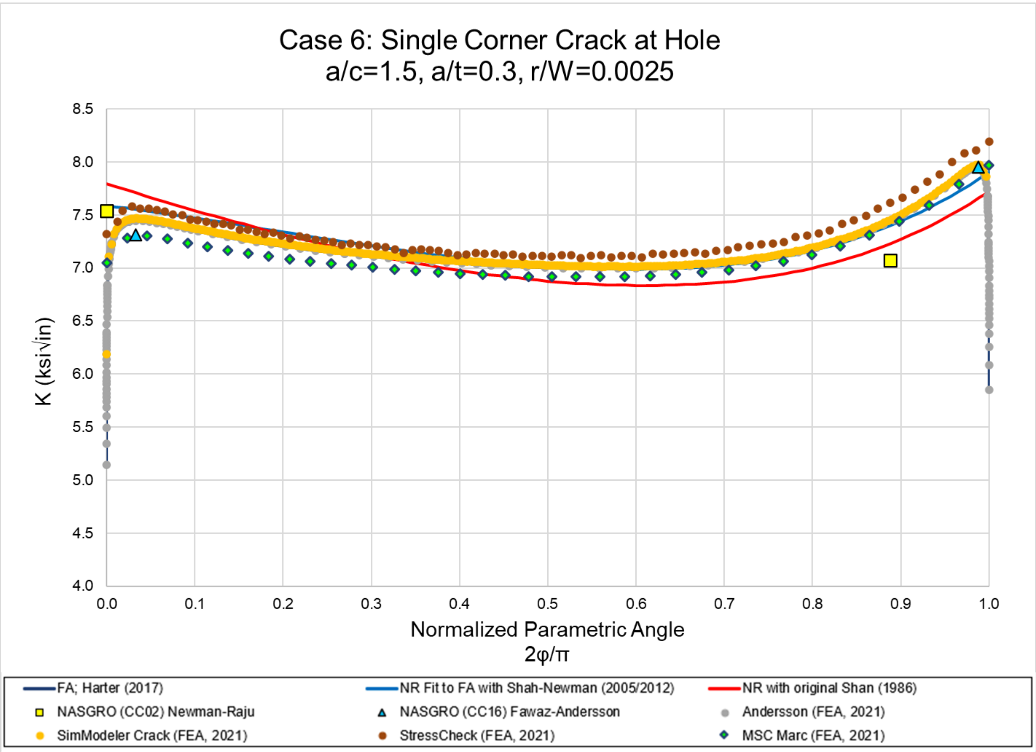


Figure 3: Stress intensity vs. normalized parametric angle (Case 6) [2].

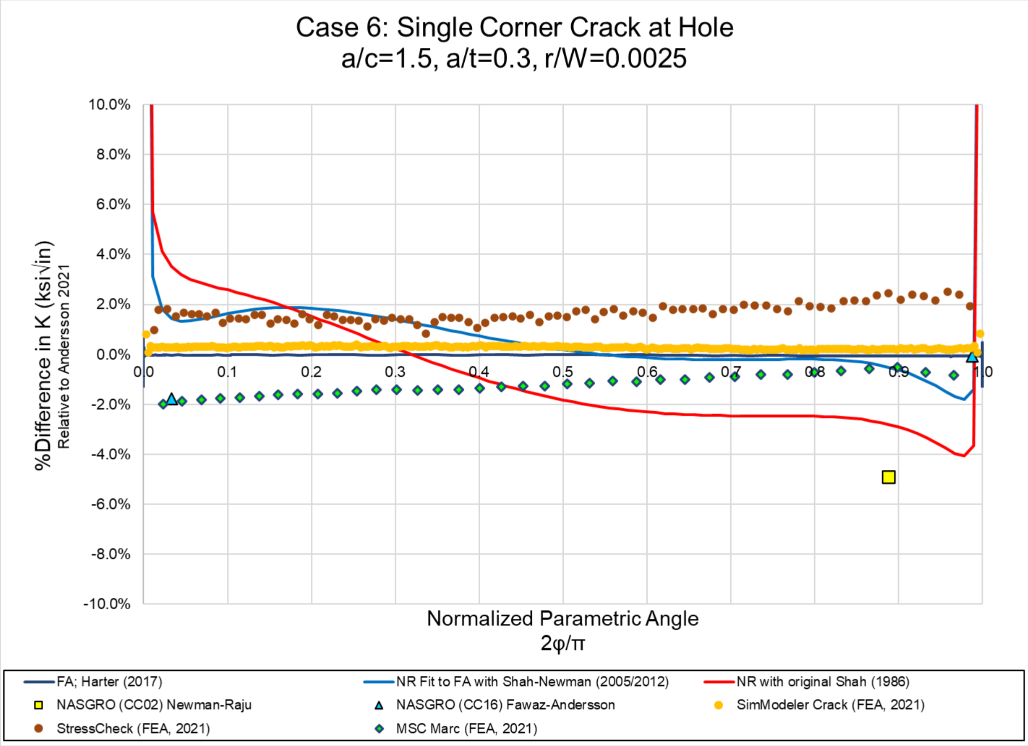


Figure 4: Percent difference in stress intensity vs. normalized parametric angle (Case 6) [2].

The overall summary and conclusions include:

- Successful SIF comparisons completed utilizing a wide array of available solutions and toolsets, with submissions provided by eight 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
- Significant discrepancies were discovered with commonly utilized finite width corrections, with differences/error up to 10%
- Follow-on actions are in work to resolve discrepancies uncovered by the round robin effort
- A robust dataset was developed that can be utilized as a reference set for follow-on studies
- Comparisons between varying FEA approaches have highlighted the opportunity to identify modelling best practices and provide guidance to the community

A full report of the results of this round robin is available and can be shared upon request to the author.

ERSI COMMITTEE: RESIDUAL STRESS CHARACTERIZATION

The mission of the residual stress characterization committee is to help ERSI stakeholders (e.g., end users and aircraft programs) design and implement fit-to-purpose residual stress measurement and simulation efforts. The committee has an established group of residual stress measurement and simulation 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)

The following sections discuss recent achievements of the residual stress characterization committee.

2inch Cx Residual Stress Determination for Process Simulation Validation

In 2017 a research program was started that would allow for cross-validation of residual stress measurement methods and for the validation of finite element simulations of the Cx process. Two aluminum alloys were selected, 2024-T351 and 7075-T651. The level of applied expansion was varied from approximately 3.16% to 4.16%. An image of two of these coupons is shown in Figure 5. Multiple strain measurement methods were used during the Cx process, including Digital Image Correlation (DIC), a fiber optic system, and strain gages. Images of the initial data capture is shown in Figure 6.

In addition to the strain measurements that were performed during the Cx process, many additional measurements have been performed over the last several years (see Figure 7 for notional results from several of the different methods). A high-level summary of what measurements have been performed is listed below:

- 2017 Performed Cx
- 2017 Argonne National Lab 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 Surface XRD
- 2020 Neutron Diffraction was Performed 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

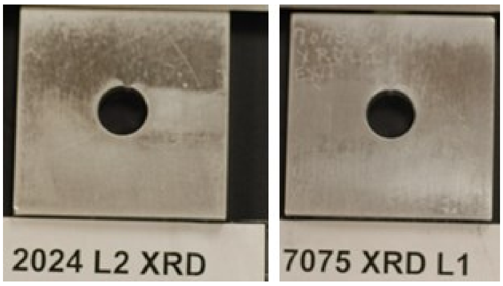


Figure 5: Photos of two of the coupons [3].

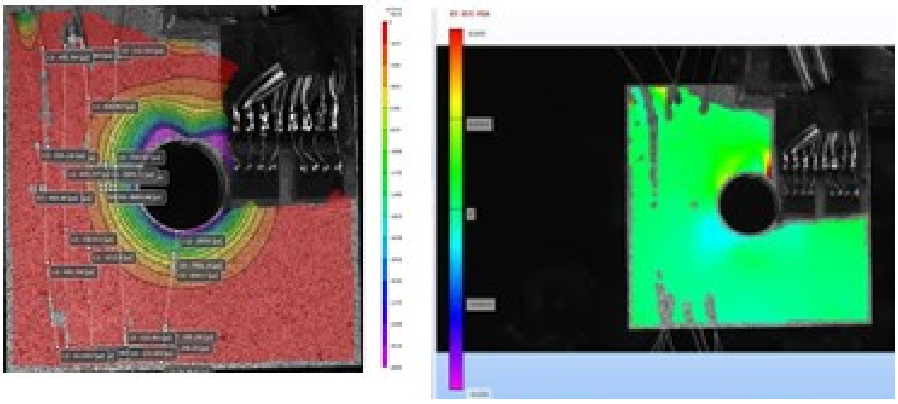


Figure 6: Initial strain results from Cx processing [3].

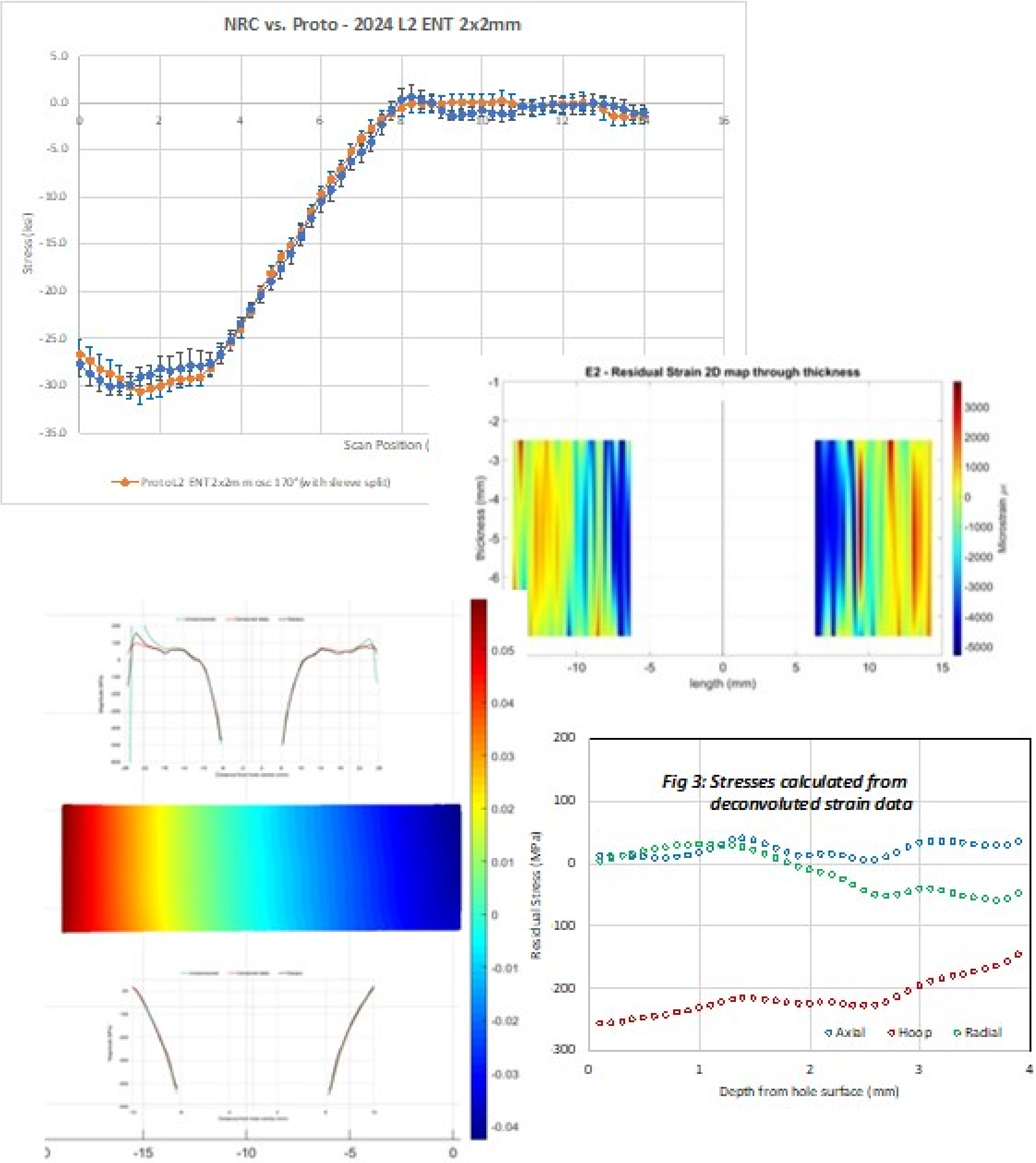


Figure 7: Residual stress/strain results from multiple methods [3].

In addition to the listed work that has already been accomplished, additional work remains to be done with these coupons in the future, including the writing of multiple journal papers to discuss various aspects of the results. It is noted that as part of being an ERSI round robin, there has been no central funding source, and all work provided was done at cost to the process/data owning organization. Additional information and data can be provided upon request to the author.

Contour Method Reproducibility Experiment

One area of research that has received some focused attention is the uncertainty quantification of the methods by which residual stresses within a body are determined. One method that has demonstrated excellent spatial resolution and that can be easily integrated into a fatigue crack growth analysis is the contour method. An area that has not been published on is the interlaboratory variability that is associated with the contour method. In an effort to begin this quantification effort, a group of international contour method practitioners was formed.

The scope of the effort was in regard to bulk stress fields, neglecting machining or other near-surface stresses. Several coupon blanks cut from a single residual stress bearing bar of 7050-T74 high-strength aluminum alloy, where the residual stress was generated during the quench/age process. 14 samples were fabricated, numbered A00 to A13 (see Figure 8), of identical geometry of 50x75x24 mm.

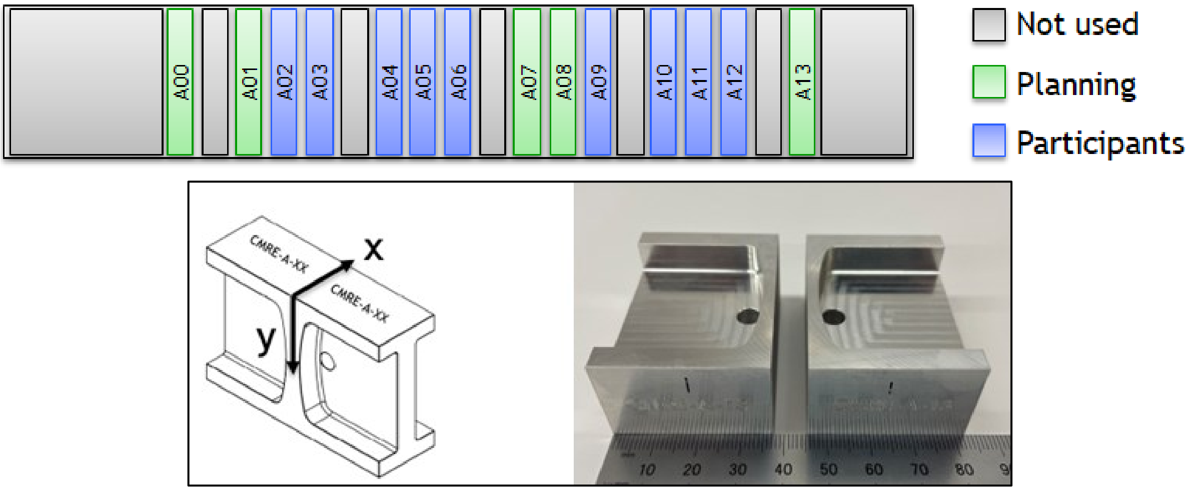


Figure 8: Contour method sample details [4].

Several coupons were used for planning measurements to help guide the remainder of the program and what would be given to the round robin participants (see green samples in Figure 8). The initial contour results were performed by UC Davis on samples A01, A07, A13. The A01 and A07 results were nearly identical, with a higher magnitude for A13, likely due to proximity to end of bar (and was distant from participant samples). It was also observed that the spatial distribution of stress was similar along length of bar. Neutron diffraction results were also performed at the Oak Ridge National Laboratory facility on sample A08, where similar spatial form was observed with an offset of ~ 25MPa (within expectation). Lastly, hole-drilling results were performed by UC Davis using sample A00, where it was observed that the near surface stresses were very symmetric. Results are shown in Figure 9.

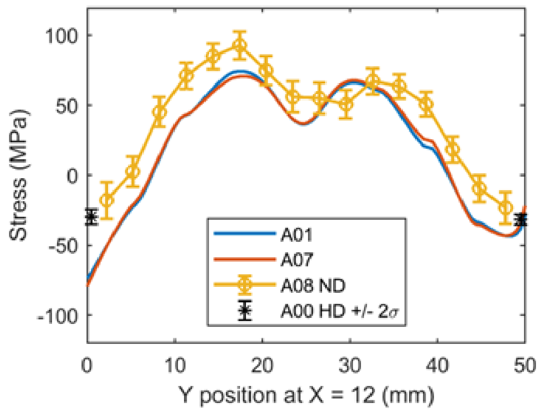


Figure 9: Planning measurement results [4].

An international group of eight participants from industry and academia were then asked to provide contour measurement results from the eight samples in blue in Figure 8. The observed interlaboratory reproducibility was reported as 8.1 MPa average for all locations, 6.1 MPa on interior, and 17.6 MPa near boundary (within 1 mm). Results are shown in Figure 10. The differences from the group mean varied among the participants (see Figure 11) with RMS differences range 7.8-14.1 MPa and maximum differences range 35.5-107 MPa.

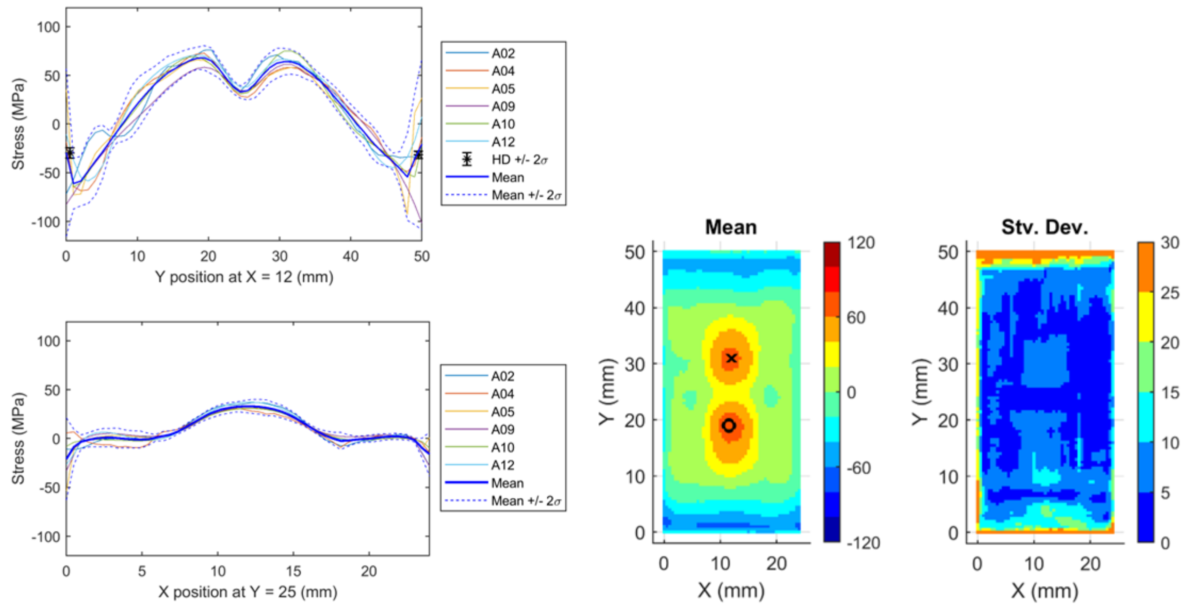


Figure 10: Participant results [4].

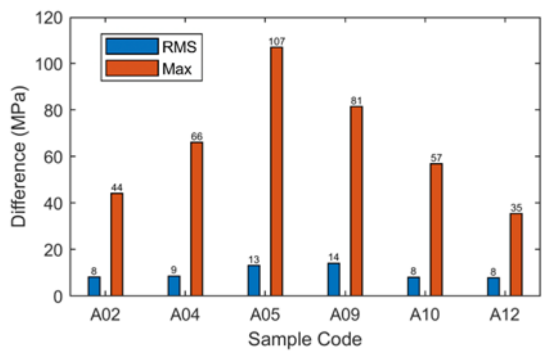


Figure 11: Participant result differences [4].

ERSI COMMITTEE: NDI, NDE, QUALITY ASSURANCE AND DATA MANAGEMENT

Validated quality assurance (QA) and nondestructive evaluation (NDE) methods continue to be a key focus on the path to "full credit" for engineered residual stresses. A valid QA/NDE method is necessary to verify the engineered residual stresses are attained as intended, both when the residual stress is first imparted into the structure and during sustainment of that structure. There are several programs under way which will help to establish a valid NDE method. One program that is under way is described in the following section. The last section discusses the development and update of a residual stress database and the associated data management related challenges in dealing with all the data associated with Cx holes and residual stresses.

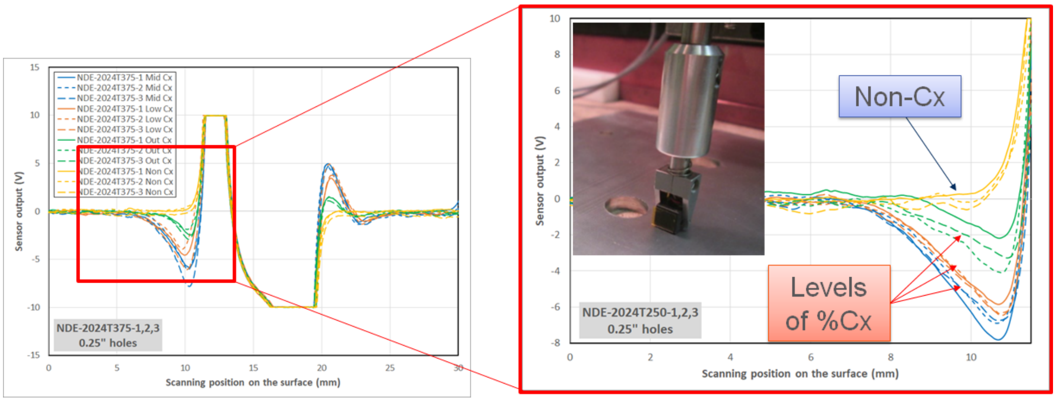
Nondestructive Evaluation for Quality Assurance and Surveillance of Cx Fastener Holes

The program objectives for this effort included:

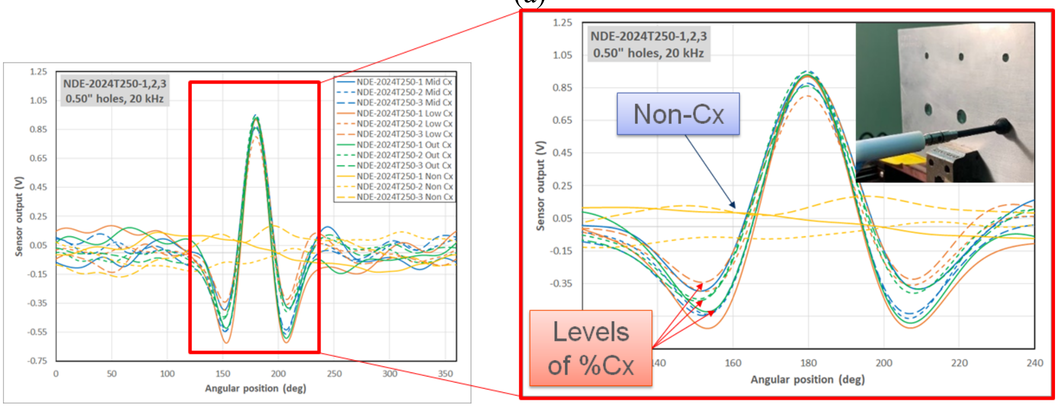
- Develop NDE techniques for quantifying the residual stress state at Cx holes
- Evaluate and rank NDE techniques for quantifying residual stress state at Cx holes
- Investigate key confounding factors and their influence on NDE response
- Applied expansion, diameter, thickness, material, edge margin,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

The key objective was to be able to verify residual stress is present at the hole post-Cx (i.e., go/no-go), which is necessary to be able to obtain "full-credit" for residual stress benefit from Cx. The NDE technology used in the program included (see Figure 12):

- 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



(a)



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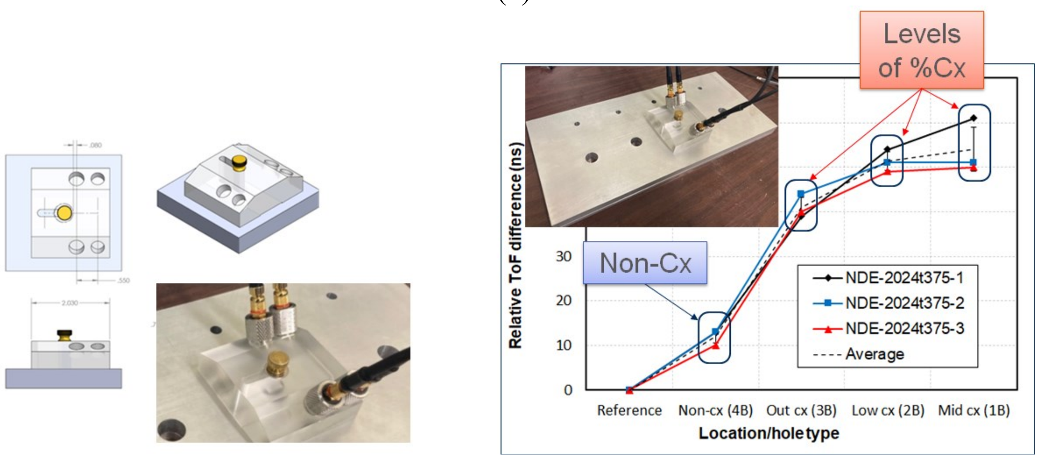

(c)

Figure 12: NDE technologies [5].

Extensive development and testing of NDE technology prototypes for detection of compressive residual stress at Cx holes was performed throughout the program. Testing was performed under a variety of conditions and confounding factors. The probes were able to successfully differentiate between non-Cx and Cx holes. Several were capable of accurately detecting Cx in the presence of confounding factors including, shot peening, paint, and low edge margin. These NDE technologies appear to be a promising technique for NDE of residual stress near Cx holes. Future work is already being planned to further pursue this topic.

<u>Residual Stress Database</u>

The residual stress database is a publicly available dataset of residual stresses from the contour method, which consists of a folder with a collection of files each representing a residual stress database entry. The database includes visualization, library, searching, and interpolations of multiple files, with the capability of allowing the user to add profiles (see screenshot of the user interface in Figure 13).

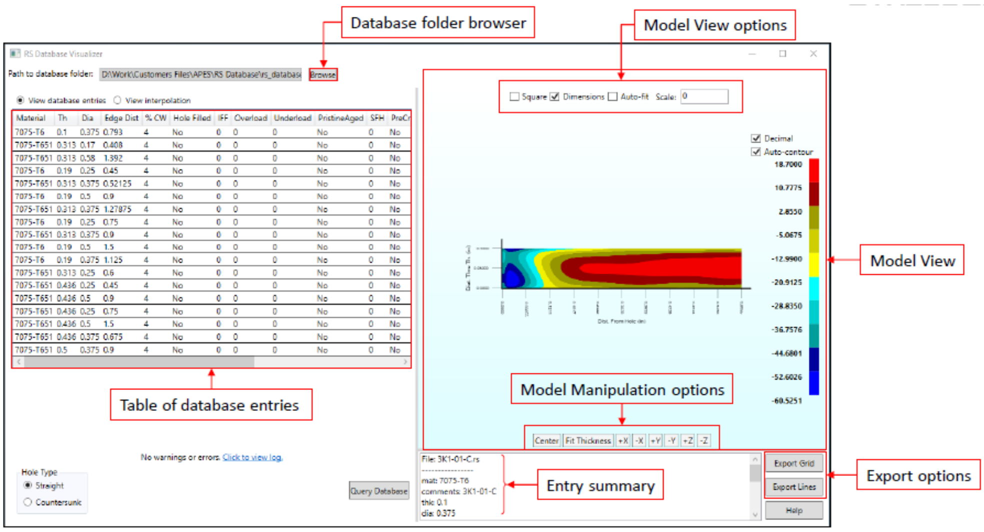

Figure 13: Screenshot of residual stress database interface [6].

The original residual stress database was organized in the ~2015 timeframe and included filtering of only five parameters: material, applied expansion, hole diameter, thickness, and edge margin. The newly updated database includes new capabilities, including:

- Filtering of over 15 new parameters (see Figure 14)
- Over/underload, pre-cycles, filled holes, pristine/aged, Cx countersink process, etc.
- Custom residual stress data output
- Export lines, along angles or at offset distances
- Handling of 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.

Figure 14: List of parameters within the updated residual stress database [6].

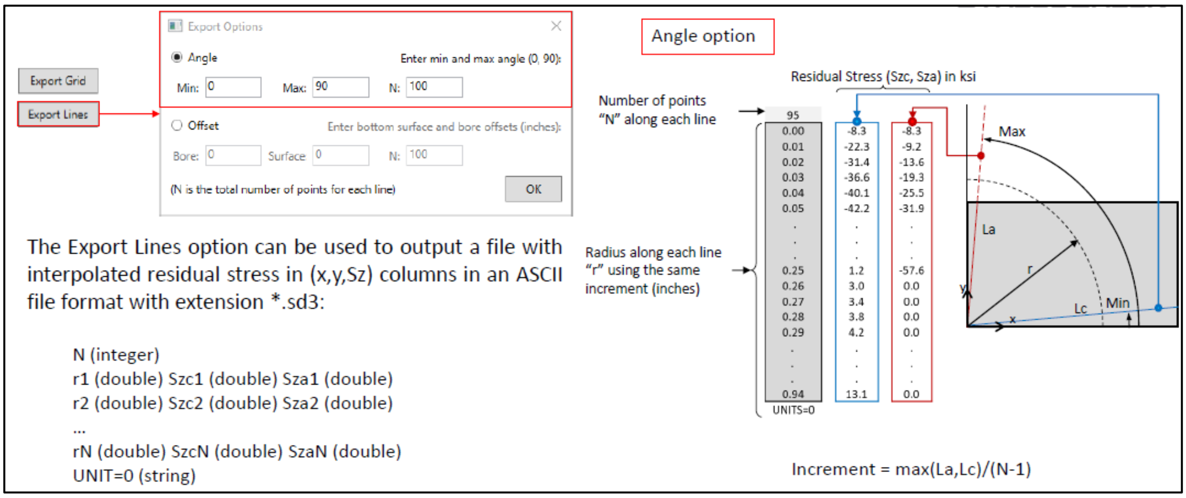

Figure 15: Screenshot 'export lines' option within the updated residual stress database [6].

The residual stress database is available to anyone and is completely free. While the original database had 47 total residual stress profiles, the updated version includes 323 total residual stress profiles. For access, contact the author.

SUMMARY

To summarize the value of the ERSI working group and its members, Dr. James Castle (The Boeing Company) wrote the following:

> "Engineered residual stresses provide a significant opportunity to extend the life of existing DoD platforms. With the increased number of assets grounded for maintenance, the ability to develop engineered residual stress techniques to extend airframes and lengthen intervals between inspections is essential technology. However, it has been demonstrated repeatedly that the ability to properly analyze, apply, and measure engineered residual stresses requires advanced knowledge to ensure

appropriate application. Typically this has been accomplished through an extensive test and analysis program on each individual case with significant cost. This working group provides the opportunity to share the best practices the community has experienced in individual case by case insertions enabling tools and processes to be developed for the general cases that benefits all stakeholders especially the DoD which will benefit in improved platform availability at less investment per insertion."

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