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ERSI SCREAMER

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this issue

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The Who, What, and Why of ERSI

For those who are new to the Engineered Residual Stress Implementation (ERSI) working group, the ERSI Screamer is a recurring newsletter designed to facilitate communication across subcommittees. A brief description of the who, what, and why of ERSI is included here.

Sponsoring Organization: This working group is sponsored by the A-10 Aircraft Structural Integrity Program (ASIP) under the direction and guidance of Mr. Chuck Babish.

Purpose:
1. To 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. To highlight gaps in the state-of-the-art and define how those gaps will be filled.
3. Then to define the most effective way to document requirements and guidelines for fleet-wide implementation.

Vision: Within 3-7 years have developed a framework for fleetwide 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. Then move from there to other deep residual stress inducing processes, like Laser Shock Peening and Low Plasticity Burnishing.

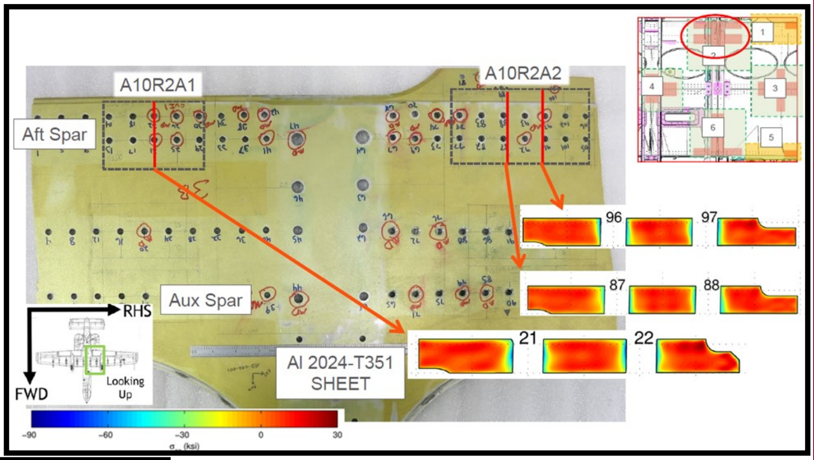
Organization: The Working Group is broken up into 8 subcommittees with a chairperson for each committee, as shown below.

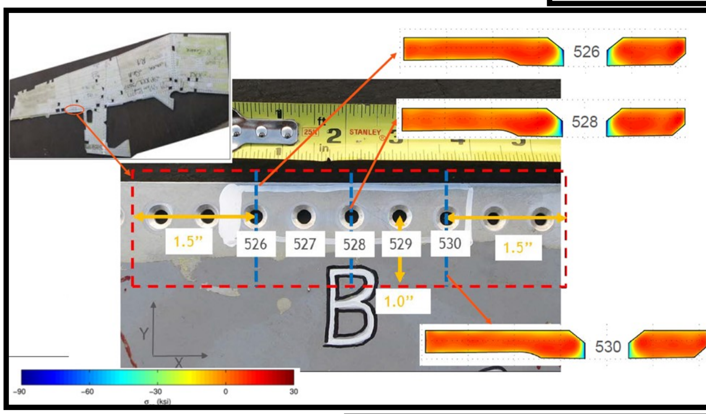
Subcommittee	Chair(s)
INTEGRATOR	Dr. Mark Thomsen, Dr. TJ Spradlin, Dr. Dale Ball
VALIDATION TESTING	Dr. Tom Mills
RESIDUAL STRESS PROCESS SIMULATION	Keith Hitchman
FCG ANALYSIS METHODS	Robert Pilarczyk
DATA MANAGEMENT/QUALITY ASSURANCE	Dr. Carl Magnuson
NON-DESTRUCTIVE INSPECTION	John Brausch
RISK ANALYSIS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

ERSI Participation at the 2018 AA&S Conference

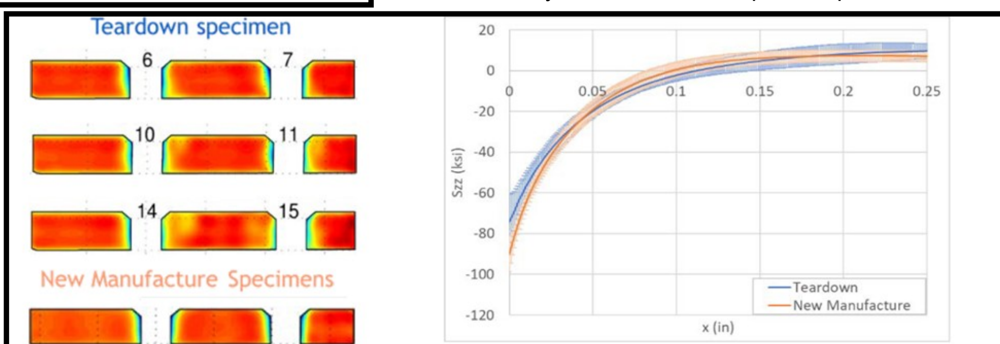
This year's AA&S conference included a presentation by Robert Pilarczyk entitled 'Residual Stress Evaluation in Legacy Aircraft Cold Expanded Fastener Holes"

The initial state and in-service stability of residual stress at Cx holes is a key factor associated with the path to full engineered residual stress credit. Questions often arise, such as: "Was the hole Cx'd?", "Was the hole Cx'd properly?", and "Is the residual stress stable over time?". Also, some factors can degrade residual stress throughout the in-service life of the structure. These perceived risks (sometime actual risk) are a major roadblock to full engineered residual stress credit. To address these risk factors, a program was developed to investigate the cracking and residual stress at Cx holes from post-service fleet assets and understand if there is a degradation over time as a result of loading or environment. In concert with this teardown and measurement effort, newly manufactured coupons were developed, replicating the legacy asset configurations, to compare and contrast residual stresses between the two populations and estimate the original (pre-service) residual stress.





The program scope included the teardown of A-10 and T-38 wing structure where Cx is used prolifically throughout the lower wing critical locations. A detailed disassembly, teardown, and measurement program was developed and executed. Ultimately, the scope included 300+ residual stress measurements utilizing the contour method. Examples of the resulting residual stress fringe plots of the teardown assets are shown in the figures above and to the left. Additionally, a multi-level comparison plan was developed, focused on an incremental approach to interpret, compare, and contrast the 300+ residual stress measurements. The level I analysis comparison, which focused on an initial look at the data to understand differences between the teardown and new manufacture populations, has been completed. An example of these comparisons is shown in the image to the right. Additional details are contained in the recent AA&S presentation in the link below.



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

http://meetingdata.utcdayton.com/agenda/airworthiness/2018/proceedings/presentations/P14878.pdf

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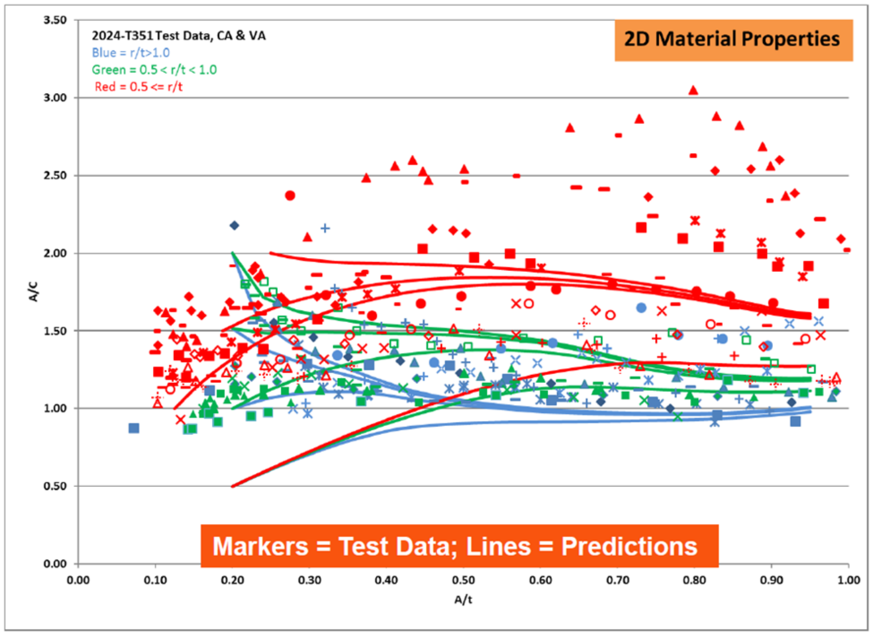
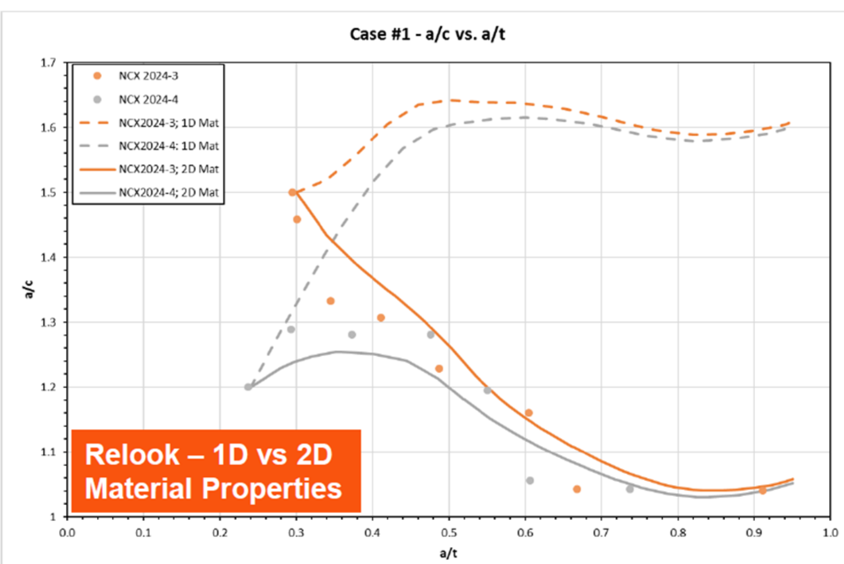
Subcommittee Spot — Fatigue Crack Growth Analysis

Round Robin for Residual Stress (Year 2)

Collectively as a team, the FCG Analysis Subcommittee has decided to continue focusing on the Year 1 round robin cases and investigate analysis methods and key modeling factors (post-diction). The overall goal is to understand the influence of methods and key inputs to improve prediction vs. test correlation and ultimately provide best practice guidance for analytical methods with Cx. As a team, we developed a list of action items and we're currently working through each item to understand the implications to the predictions.



Teaming with Lextech, the ERSI FCG Analysis Subcommittee investigated the crack shape differences between predictions and test, to include the 2017 AFGROW and ERSI Round Robin datasets, both of which demonstrated a lack of correlation. In these investigations, FCGR data in the a- and c-directions was inversely calculated based on the population of baseline coupons. Utilizing this data, tabulated FCGR data was developed for both crack directions and the baseline predictions were re-accomplished (Note, we realize this is somewhat of a self-licking ice cream cone). Minimal life prediction differences were observed for the multi-directional rate data; however, the crack shape predictions were significantly improved. Similar results were observed for the AFGROW (7075-T651) and ERSI (2024-T351) Round Robin dataset. To further the investigation, the multi-directional rate data developed from the ERSI coupons was utilized to update a previous aspect ratio investigation presented at the 2015 AFGROW Workshop—see figure above. This updated approach to characterize FCGR data resulted in better correlation to test data, demonstrated similar trends of aspect ratio as a function of differing hole radii to thickness (r/t) and through thickness percentage (a/t). This differentiation was not previously observed in the predictions utilizing 1-D FCGR data—see left figure. Note that these comparisons have only been completed for non-Cx predictions. Additional investigations are underway to define how to incorporate multi-directional material properties into multi-point fracture mechanics analyses. Also, it's unclear at this point what else may be "cooked into" the inversely calculated rate data. Additional investigations are necessary to understand the applicability of multi-directional rate data.



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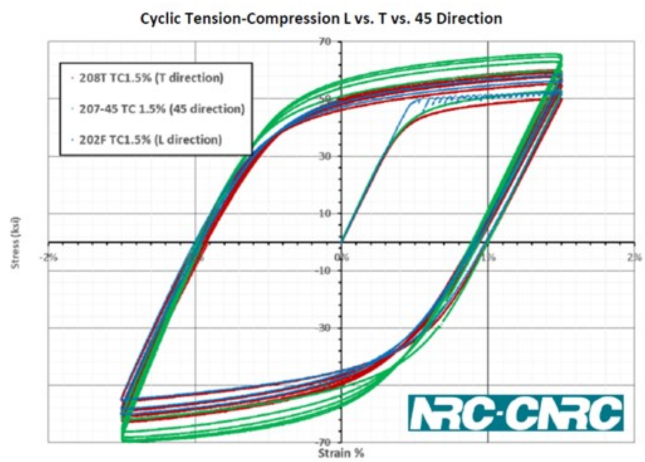
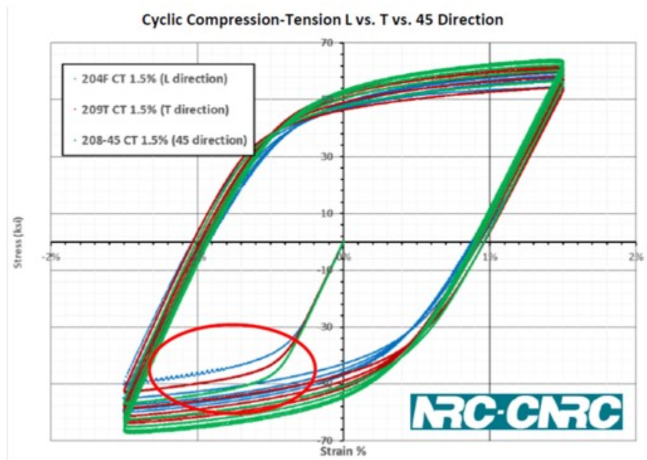
Residual Stress Process Simulation

Subcommittee Spot

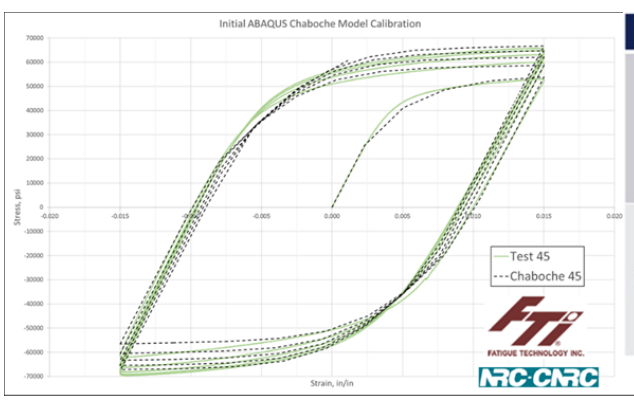
The team at NRC has been hard at work, and has completed cyclic testing on L, LT and 45° specimens of 2024-T351. At the May 2018 sub-committee meeting, Dr. Guillaume Renaud of NRC distributed the raw data and provided a nice summary presentation of the testing to the group. Completed tests include monotonic tension and compression, and cyclic tension-first and compression-first E606-style tests (see below for draft results).

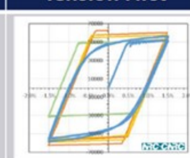
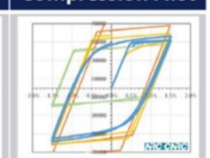
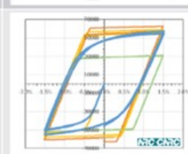
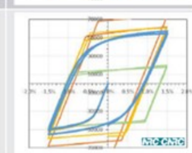




NRC has recommended performing a limited number of additional compressive tests in LT and 45° directions, and has evaluated the feasibility of obtaining true E9 compressive specimens out of the existing plate. E9 specimens in L and T direction should be possible and work planning on E9 specimens has been discussed (machining to take place at FTI).

Primary focus moves to material model calibration within the process calibration software. Besides the more simplistic linear isotropic and kinematic models available in the software, NRC is working on a Barlat model, and FTI is focusing on a Chaboche model (see below for draft results).



Curve	Tension First	Compression First
L Tension		
L Compression		

Test
Isotropic
Kinematic
Combined (50%)

NRC·CNRC

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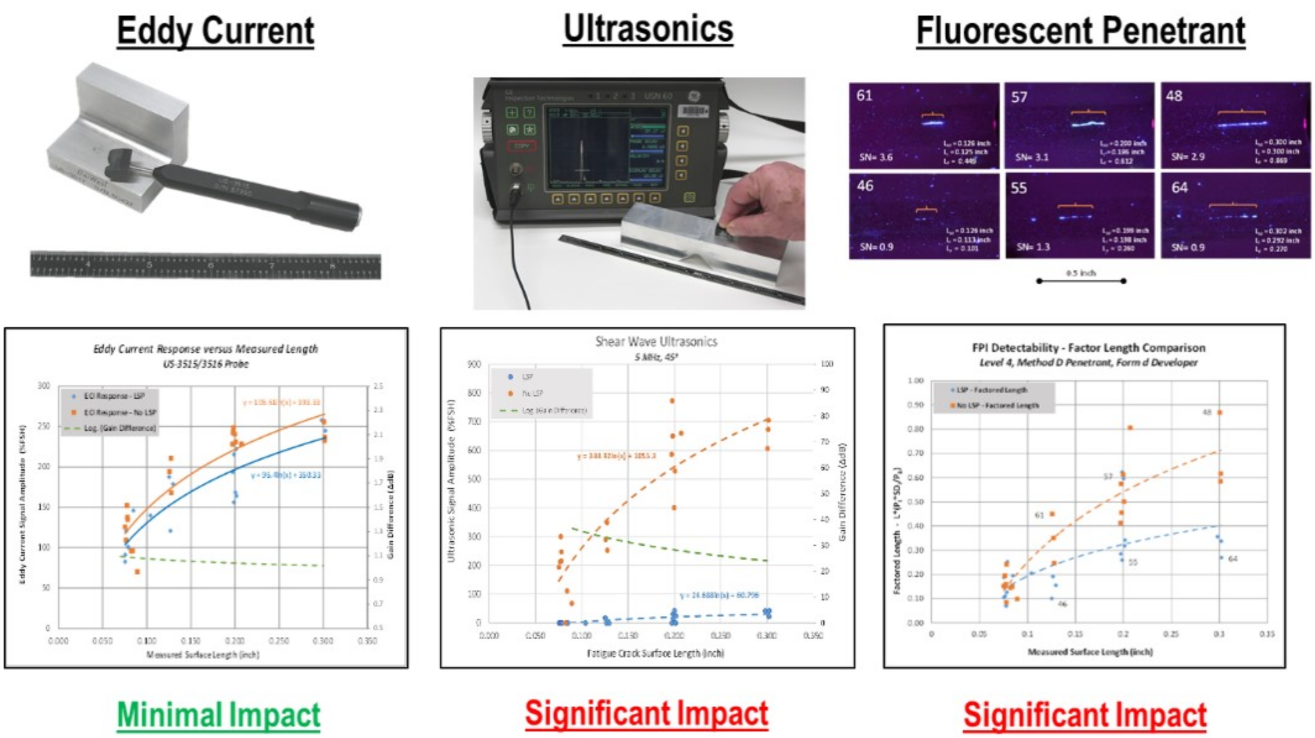
Subcommittee Spot

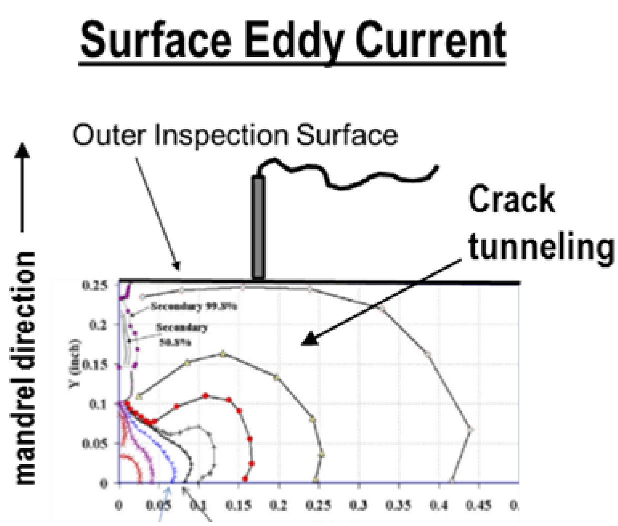
Nondestructive Inspection

Since the inception of the ERSI working group in 2016, the NDI Subcommittee has been evaluating existing literature and executing a series of experiments to quantify the impact of residual stress treatments on detectability of fatigue cracks using conventional inspection methods. Significant contributions by Texas Research Institute, Hill Engineering, APES Engineering, the A-10 Program and the Air Force Research Laboratory have led to initial quantitative understanding of these impacts.

One series of experiments explored effects of laser shock peening on detectability of fatigue cracks in 7050-T6 alloy. The results revealed a small reduction in surface eddy current inspection detection sensitivity but a significant reduction in fatigue crack detectability when applying shear-wave ultrasonic and fluorescent penetrant inspection methods—see figure below.



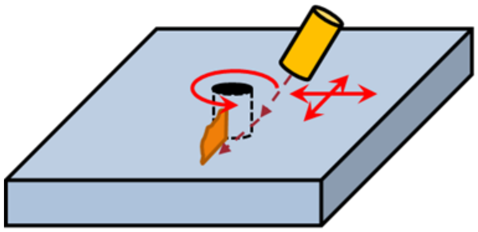
A second series of experiments quantified the impact of 4% cold expansion of fastener holes in 2024-T3 aluminum. These results revealed a significant impact to surface eddy current inspection for inspection at the mandrel exit surface due to crack tunneling—see figure at right. No debit was observed for rotary bolt hole inspection.

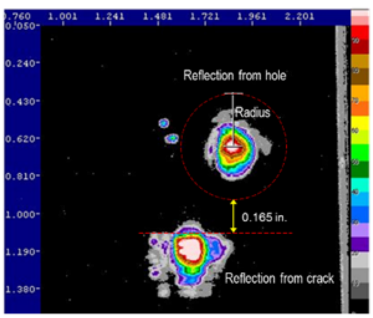


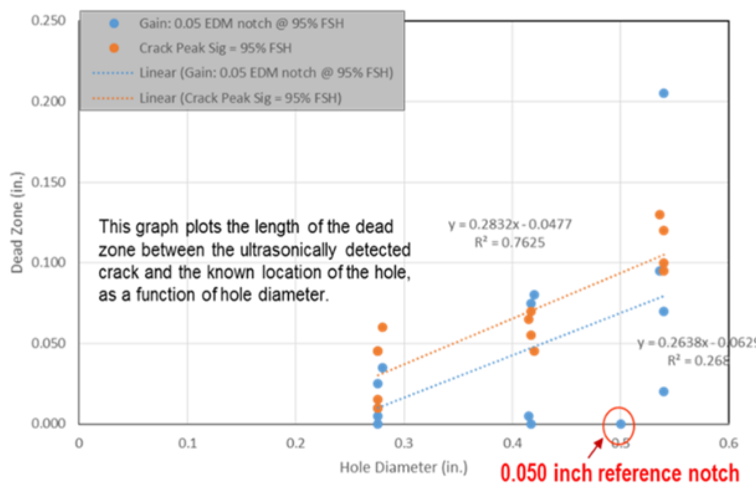
Nondestructive Inspection (cont'd)

Subcommittee Spot

Further experiments revealed that cold expansion results in an ultrasonic dead zone proportional to the hole diameter—see figure below. This dead zone is driven by crack closure in the presence of compressive residual stresses at the hole circumference. These findings have led to establishing basic capability correction factors when estimating detection capability for ultrasonic inspection of holes with 4% cold expansion.







In recent developments, the NDI Subcommittee has documented this newly gained knowledge in EN-SB-008-012, *In-Service Inspection Crack Size Assumptions for Metallic Structures, Rev D* published March 2018.

Near term efforts will focus on exploring the interaction of installed Taper-Lok fasteners on ultrasonic inspection as well as quantifying cold expanded hole ultrasonic dead zone in the presence of fastener filled holes.

The NDI Subcommittee is actively seeking opportunities for collaboration in this research areas particularly with planned or ongoing programs generating specimens representing these configurations.

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Subcommittee Spot

Validation Testing

APES, Inc. and ESRD, both of St. Louis, MO, have working projects funded by the USAF to explore hypotheses of crack closure and/or residual stress redistribution to explain unusual fatigue crack growth behavior prevalent at cold-worked fastener holes and to seek sources of modeling error.

Figure 1 shows data from a typical crack growth experiment at a low applied R (0.02) where growth rate is plotted as a function of the optically measured crack length along the mandrel entrance face. Length is measured from the bore of the hole. Here we see a characteristic “dip” in the crack growth rate data around 0.1 inch. Simulations of these same conditions do not capture this behavior at all, which illustrates that something is missing from the simulations. In Figure 2, the overall residual stress field has been tuned (read, reduced) to match the end point of the test (total life), but the fact remains that overall shape of the crack growth simulation relative to test data leaves much to be desired.

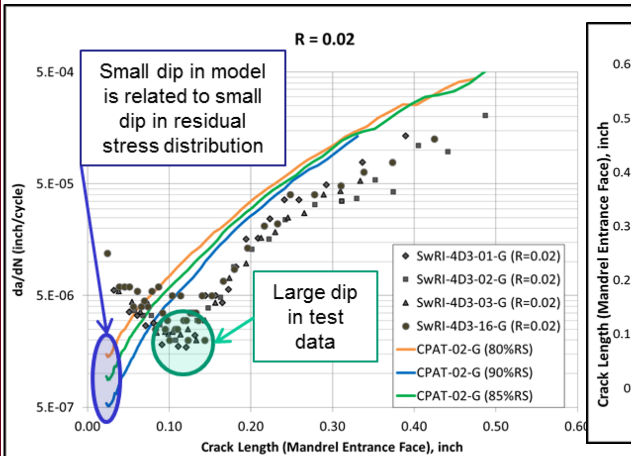

Figure 1. Crack growth rate vs. crack length, simulation vs. experiments, for test data with an applied R of 0.02

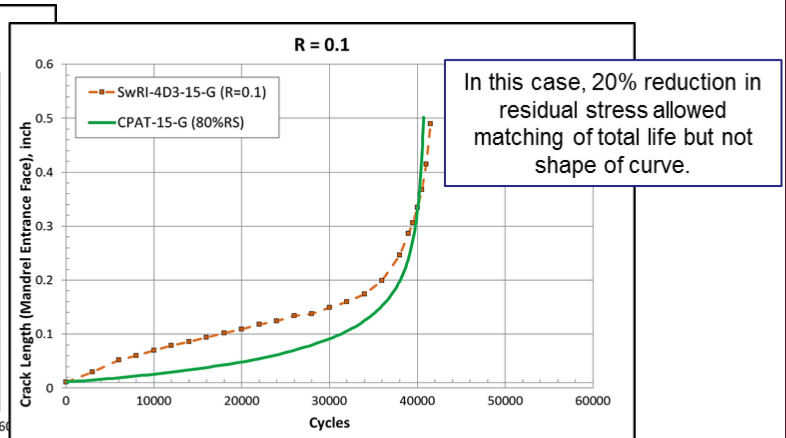

Figure 2. Crack length vs. cycles, simulation vs. experiment, for an experiment with an applied R of 0.1

However, it is interesting to note that in cases of high applied R (0.8, for instance), the same type of dip is not present in the test data (Figure 3), and the thus the models do a reasonable job matching experimental behavior (Figure 4).

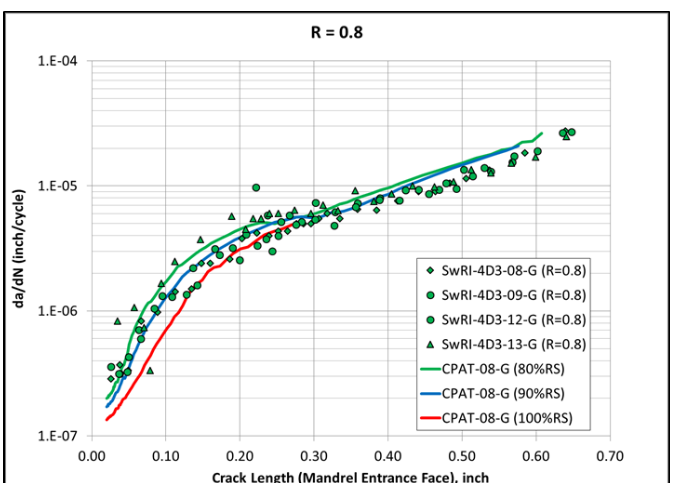

Figure 3. Crack growth rate vs. crack length, simulation vs. experiments, for test data with an applied R of 0.8

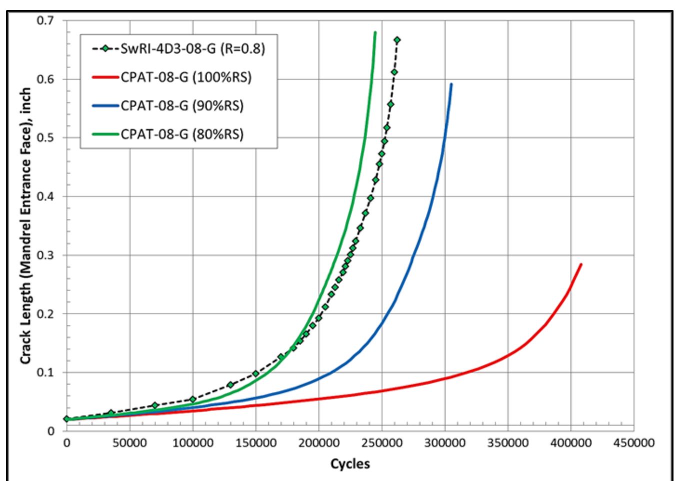

Figure 4. Crack length vs. cycles, simulation vs. experiment, for an experiment with an applied R of 0.8

Validation Testing (cont'd)

Subcommittee Spot

Attempts to isolate causal factors for the dip in the test data showed that the dip disappears in these cases when R applied exceeds 0.4 (Figure 5). This also happens to correlate to the point where R total (R_{tot}) become positive. R_{tot} is defined by:

$$\frac{(Kmin)app + Kres}{(Kmax)app + Kres}$$

Figure 6 shows 2D maps of R_{tot} indicating that at low applied R (such as R = 0.02) the majority of the crack face within 0.2 inch of the hole bore will be in contact at minimum load. At R applied = 0.8, most of the crack is open at minimum applied load.

Efforts are under way to determine how to best model these scenarios, as it is readily apparent that regions of negative R_{tot} correlate well with crack growth behavior showing "dips" that elude current models. It is possible that contact of crack faces is causing some sort of redistribution of stress, and this has been shown in the literature [Lopez, 2015] for through cracks. However, it remains to be seen how this may apply to small, part-through crack scenarios. Stay tuned!

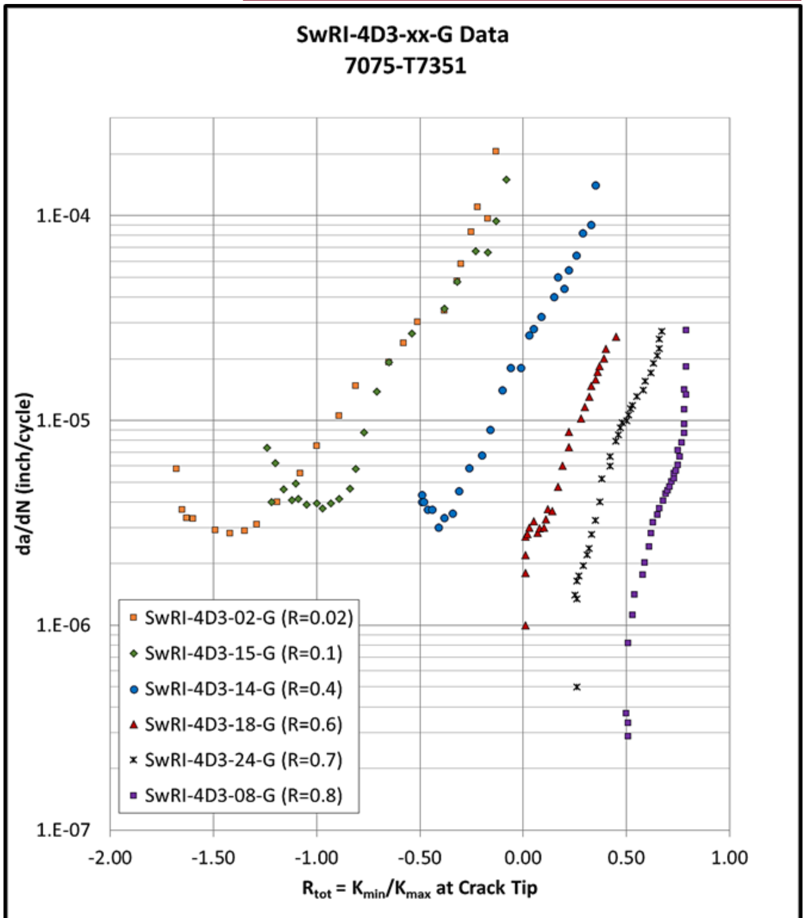

Figure 5. Crack growth rate (different applied R) as a function

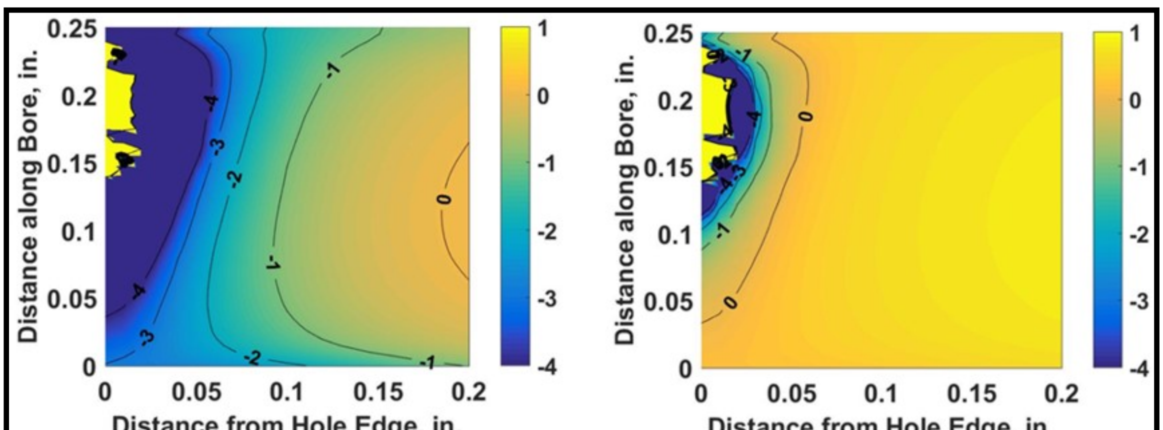

Figure 6. 2D contour map of Rtot (as defined by stress) for two different R applied cases, 0.02 (left) and 0.8 (right)

REF: Lopez, C.J.G., "Modeling of Residual Stress Fields and their Effects on Fatigue Crack Growth," dissertation, Carelton Univeristy, 2015.

POC: Tom Mills (APES); tmills@apesolutions.com@apesolutions.com

We Need You!

We would like to have input from these subcommittees for the following edition of the ERSI Screamer:

- INTEGRATOR
- DATA MANAGEMENT/ QUALITY ASSURANCE
- RISK ANALYSIS
- RESIDUAL STRESS MEASUREMENTS

Announcements

- **Upcoming ERSI-related Events:**
  - **ERSI Workshop, Sept. 13-14, 2018**
  - **European Conference on Residual Stress, Sept. 11-14, 2018**
  - **ASTM E08 Committee Week, Nov. 5-8, 2018**
- **Recent ERSI-related Events:**
  - **ASTM Sub-Committee E08.04 on Structural Applications Kick-off for New Task Group E08.04.06 on Residual Stress in Structural Design and Sustainment – San Diego, May 23-26, 2018**
    - 20+ attendees from a range of backgrounds: Aerospace, Auto, Earth Moving
    - Goal is to develop a Best Practices document to cover broadly the application of engineered residual stresses within the structural integrity community, with subjects covering:
      - Residual stress determination
      - Integration of residual stress into analysis methods
      - Quality assurance (NDE)
      - Process simulation
      - Validation methodologies
    - Members of the Task Group will have regular (monthly) telecoms and it is recommended that ERSI individuals participate
  - **ASM Workshop – Spartanburg, SC – June 5-7, 2018**
    - Feedback from Workshop is in work
- **ERSI email address has been created!**
  - If you ever have questions, suggestions, complaints, etc., please let us know by sending an email to ERSI@swri.org
- **New ERSI website has been setup!**
  - If you have an account, go to https://member-ersi.swri.org/ and login. If you need an account, please send an email to ERSI@swri.org and an account will be created for you. Please include your name, organization, and contact info.

Who is ERSI?

- Analytical Processes/Engineering Solutions (AP/ES), Inc.
- Defence Science and Technology Group
- Clarkson University
- Dipartimento di Ingegneria Civile e Industriale
- Engineering Software Research and Development (ESRD)
- Federal Aviation Administration (FAA)
- Fatigue Technology Inc. (FTI)
- Fulcrum Engineering
- Hill Engineering
- Jones Engineering
- L3 Communications
- LexTech
- Lockheed Martin Aero
- Mercer Engineering Research Center (MERC)
- National Research Council Canada
- Northrop Grumman Aerospace Systems
- Southwest Research Institute (SwRI)
- St. Mary's University
- Steve Swift Consulting
- Texas Research International (TRI) - Austin, Inc.
- The Boeing Company
- United States Air Force
- United States Marine Corps
- United States Navy