2023 ERSI Workshop: Welcome!

19 April 2023

Dallen Andrew

Agenda

- ERSI Purpose
- ERSI Organization
- Who is who
- EZ-SB-17-001 update
- RS Best Practices Document
- ‘Lincoln Wheel’ Roadmap
- USAF Academy Testing
- ERSI Communications
- Questions

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

Agenda

- **ERSI Purpose**
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ERSI purpose

ERSI
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

- Where & why did we start ERSI?
- Where does ERSI add value? (next slides)
  - Round robin activities
  - Opportunity for collaboration
  - Dissemination of Cx-related information/data to raise awareness & interest
- Where do we want to go now?
- What is the primary goal/target?

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 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

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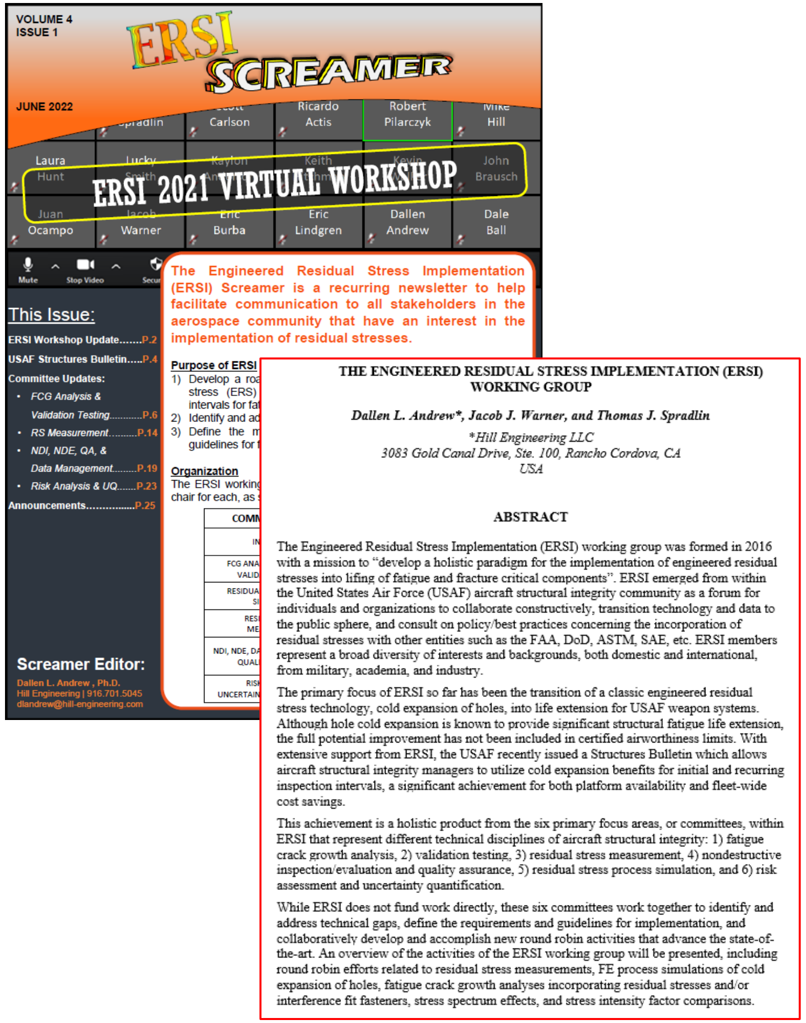
ERSI purpose: Where does ERSI add value?

- **Fatigue crack growth analysis methods / Validation testing**
  - 2016: FCG analysis of Cx holes
  - 2020: Interference fit fasteners
  - 2021: SIF Comparison
  - 2021: Overload challenge
  - 2022: Interference fit fasteners round 2
- **Residual stress process simulation**
  - 2017: 2x2 material modeling data
  - 2019: 2x2 process simulation analysis
- **Residual stress measurement**
  - 2017: 2x2 Cx Coupons
  - 2017: Contour method inter-laboratory reproducibility uncertainty
  - 2021: Texture and anisotropy sub-team
  - 2021: Bulk RS measurements in Cx geometrically large holes
  - 2022: Contour method reproducibility experiment A (CMRE-A)
- **NDI / NDE / Data management / Quality assurance**
  - xx: Cx hole blind study [POC: Dallen Andrew, Hill Engineering]
- **Risk analysis / Uncertainty quantification**
  - x



THE ENGINEERED RESIDUAL STRESS IMPLEMENTATION (ERSI) WORKING GROUP

Dallen L. Andrew, Jacob J. Warner, and Thomas J. Spradlin*

**Hill Engineering LLC*
3083 Gold Canal Drive, Ste. 100, Rancho Cordova, CA
USA

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 six primary focus areas, or committees, within ERSI that represent different technical disciplines of aircraft structural integrity: 1) fatigue crack growth analysis, 2) validation testing, 3) residual stress measurement, 4) nondestructive inspection/evaluation and quality assurance, 5) residual stress process simulation, and 6) risk assessment and uncertainty quantification.

While ERSI does not fund work directly, these six 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. An overview of the activities of the ERSI working group will be presented, including round robin efforts related to residual stress measurements, FE process simulations of cold expansion of holes, fatigue crack growth analyses incorporating residual stresses and/or interference fit fasteners, stress spectrum effects, and stress intensity factor comparisons.

ERSI purpose: Where does ERSI add value?

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- James B. Castle, D.Sc., Boeing Research & Technology
  - 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.

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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- Questions

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Organization: Committees (current)

- **Integrator**
  - TJ Spradlin
  - Dale Ball
- **Fatigue crack growth analysis methods / Validation testing**
  - Kevin Walker
  - Robert Pilarczyk
- **Residual stress process simulation**
  - Keith Hitchman
- **Residual stress measurement**
  - Eric Burba
  - Adrian DeWald
- **NDI/NDE / Data management / Quality assurance**
  - Eric Lindgren
  - John Brausch
  - Kaylon Anderson
- **Risk analysis / Uncertainty quantification**
  - Laura Hunt
  - Juan Ocampo

"We need to rethink how we collaborate so that the data generators have more talk with the data analyzers."

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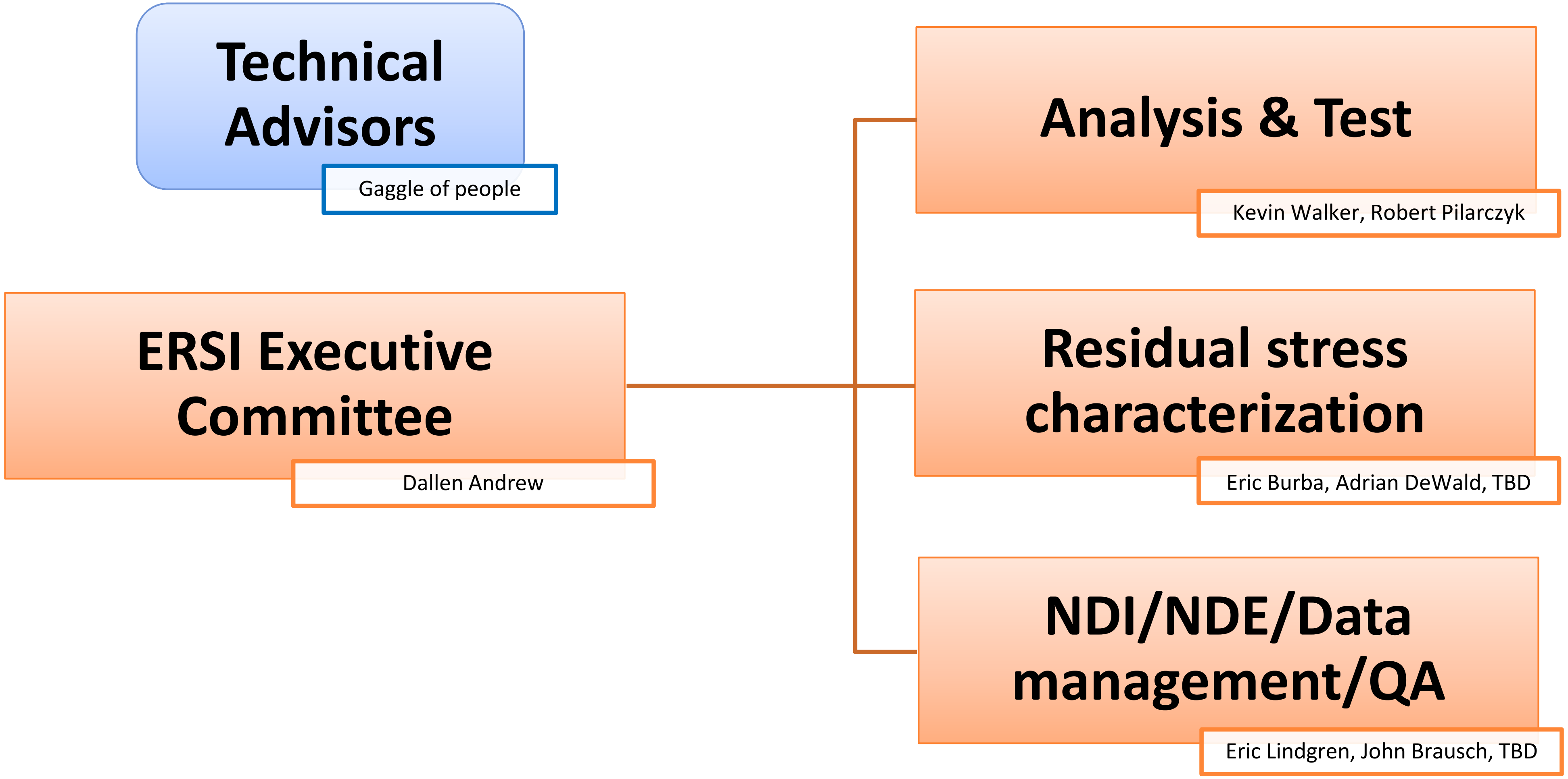
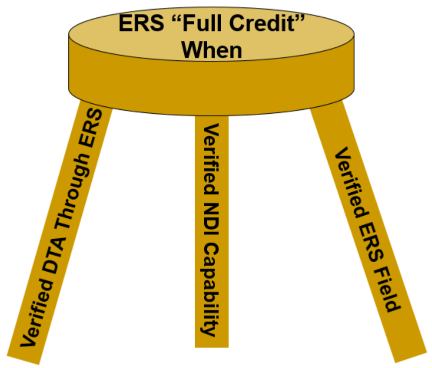
Organization: Committees (updated)





ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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Who am I?

- Original Bio
  - Dallen started his career off working with the A-10 team under Dr. Mark Thomsen where he learned how to be personable. His love of ridiculous belt buckles grew strong and pulled him to Texas where he worked for Southwest Research Institute for 5 years where he spent his free time finding ways to break the USAF cybersecurity policies. To be closer to family his wife and 4 children moved back to Utah accepting a job with Hill Engineering where he has spent the last 4 years using his impeccable helping skills to help.

- Work
  - USAF A-10 ASIP, Hill AFB, Utah (2009-2014)
  - SwRI, San Antonio, Texas (2014-2019)
  - Hill Engineering, Utah (2019-current)
- School
  - BS, Utah State University (2009)
  - MS, University of Utah (2011)
  - PhD, University of Texas at San Antonio (2020)

ERSI
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Who are you?

- (30-60 seconds)
- Name
- Company
- What do you do
- Why are you here

Ricardo	Actis	ESRD
Dallen	Andrew	Hill Engineering
Ana	Barrientos	Northrop Grumman
Daniel	Bavaro	USAF
Michael	Brauss	Proto
Dave	Breuer	Curtiss Wright
Eric	Burba	USAF
Joe	Cardinal	SwRI
Scott	Carlson	Lockheed Martin
Aditya	Chattopadhyay	Boeing
George	Crosthwaite	USAF
Adrian	DeWald	Hill Engineering
AJ	Flusche	Boeing
Jim	Greer	USAF
Tyler	Gruters	USAF
Jim	Harrison	Proto
Jason	Hawks	Boeing
Mike	Hill	Hill Engineering
Keith	Hitchman	FTI
Haydn	Kirkpatrick	Boeing
Eric	Lindgren	USAF
Adrian	Loghin	Simmetrix
Dean	Madden	FTI
Craig	McClung	SwRI
Robert	McGinty	MERC
Matt	McSwiggen	Lockheed Martin
Adam	Morgan	Northrop Grumman
Doyle	Motes	TRI-Austin
Mark	Obstalecki	USAF
Moises	Ocasio-Latorre	Boeing
Robert	Pilarczyk	Hill Engineering
James	Pineault	Proto
Scott	Prost-Domasky	APES
Evan	Ryker	TRI-Austin
Sandeep	Shah	Boeing
Greg	Shoales	USAF
Lucky	Smith	SwRI
TJ	Spradlin	USAF
Michael	Stivers	Lockheed Martin
Mike	Steinzig	Los Alamos National Lab
Hiram	Vega	Boeing
Jesse	Vickers	Sabreliner
Josh	Ward	UDRI
Jacob	Warner	USAF
Kevin	Gibbons	Sabreliner
Jude	Restis	PartWorks

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Structures Bulletin

AFLCMC/EZ
Bldg. 28, 2145 Monahan Way
WPAFB OH 45433-7101
Phone: 937-255-5312

Number: EZ-SB-17-001, Revision A

Date: December 2021

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

References:

1. JSSG-2006, "Joint Service Specification Guide Aircraft Structures," 30 Oct 1998
2. MIL-A-83444, "Airplane Damage Tolerance Requirements", 2 Jul 1974
3. AFI 20-106, "Management of Aviation Critical Safety Items", Department of the Navy, Air Force, Army, Defense Logistics Agency, and Defense Contract Management Agency, 27 January 2020
4. MIL-STD-1530D, "Aircraft Structural Integrity Program (ASIP)", Department of Defense Standard Practice, 31 Aug 2016
5. EN-SB-08-012 Rev. D, "In-Service Inspection Flaw Assumptions for Metallic Structures", Apr 2018
6. EZ-SB-14-003, "Durability Test Programs to Validate Aircraft Structure Service Life Capability for Repairs, Modifications, and Materials & Processes Changes", 9 Apr 2014
7. Barter, S.A., et al., "Marker Loads for Quantitative Fractography of Fatigue Cracks in Aerospace Alloys", 25th ICAF Symposium, May 2009
8. EZ-SB-13-002, "Correlating Durability Analysis to Unanticipated Fatigue Cracks in Metallic Structure", 26 Feb 2013
9. ASTM E 647, "Standard Test Method for Measurement of Fatigue Crack Growth Rates", AD1070087

EZ-SB-17-001 Rev. A, Page 1 of 13

- Example Case

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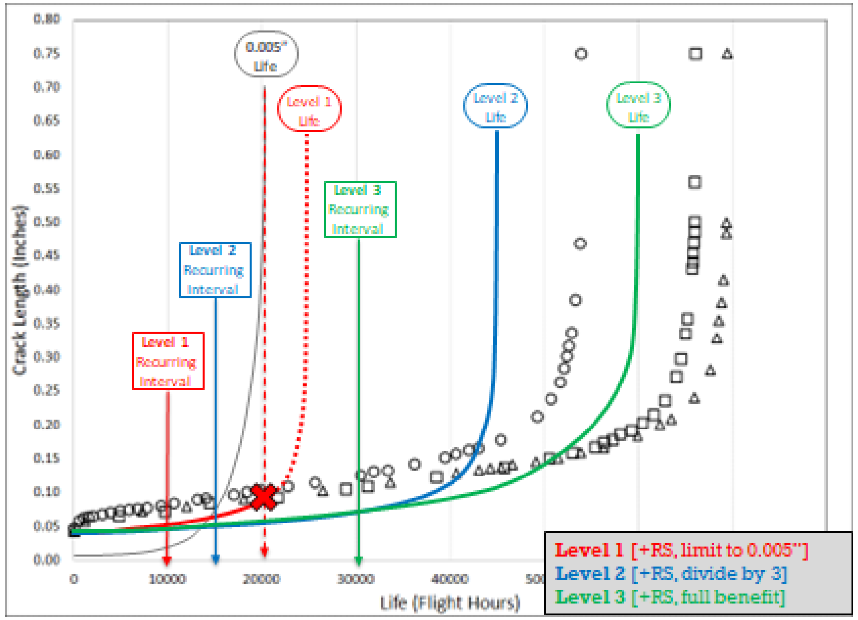
FCG BENEFIT FOR CX HOLES: EXAMPLE CASE

- Cx hole coupon test results[4]
  - e/D=2.0
  - Spectrum loading, σ_{max}=33 ksi
  - Average test life ~60,000 flight hours
- **Level 1**
  - 10,000 hour recurring interval
  - ½ life of 0.005" prediction
- **Level 2**
  - Up to 15,000 hour recurring interval
  - Predicted life divided by 3
- **Level 3**
  - Up to 30,000 hour recurring interval
  - Predicted life divided by 2



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ENGINEERED RESIDUAL STRESS IMPLEMENTATION

EZ-SB-17-001 update

- Revision A
  - Includes Level 1 benefit (explicit RS, limit to 0.005" life)
- Revision B in-work
  - Targeting Level 2 benefit

ENGINEERED RESIDUAL STRESS IMPLEMENTATION

FCG BENEFIT FOR CX HOLES: TIER SUMMARY

+RS = Explicit incorporation of residual stress field in FCG analyses

- Level 0 *[current state]*
  - Current use of 0.005" for initial inspection, no benefit for recurring inspections
- Level 1 *[+RS, limit to 0.005"]*
  - Include RS explicitly in analysis with traditional initial crack size of 0.05"
  - Same test and validation requirements as Level 0
  - Limit life benefit to match 0.005" approach (permits benefit for recurring inspections)
- Level 2 *[+RS, divide by 3]*
  - Include RS explicitly in analysis with traditional initial crack size of 0.05"
  - Prediction validated by at least 5 FCG test replicates
  - RS field validated by direct determination or validated FEA
  - Definitive verification Cx was performed within specification limits
  - Benefit limited to dividing by 3
- Level 3 *[+RS, full benefit]*
  - Include RS explicitly in analysis with traditional initial crack size of 0.05"
  - Prediction validated by at least 5 FCG test replicates
  - RS field validated by direct determination or validated FEA
  - Definitive verification Cx was performed within specification limits
  - Load interaction effects permitted

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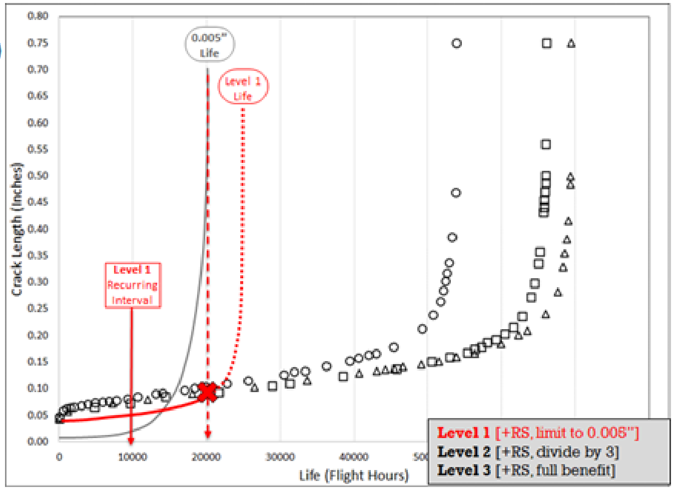
ENGINEERED RESIDUAL STRESS IMPLEMENTATION

FCG BENEFIT FOR CX HOLES: LEVEL 1 REQUIREMENTS

- RS explicitly included in DTA using standard assumed crack size (0.05")
- Recurring & initial inspections limited to 0.005" life divided by 2
- User may define RS field and implementation approach
- Test requirements per EZ-17-SB-001[6] (or other acceptable justification)
- Recurring inspection benefit with no significant increased risk



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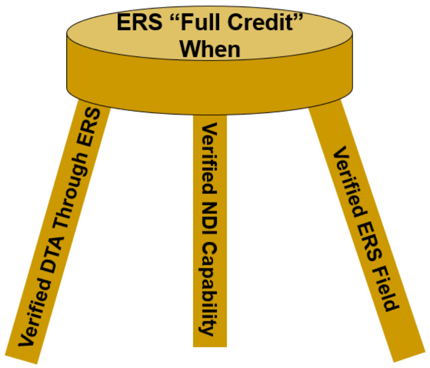
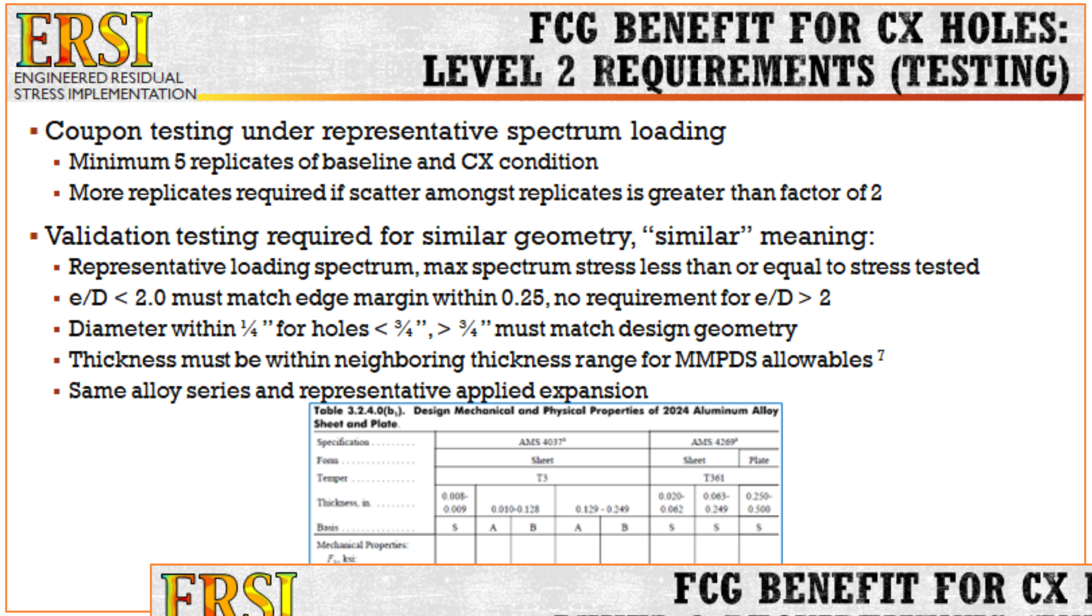
EZ-SB-17-001 update

- Revision B in-work
  - Targeting Level 2 benefit
  - Major challenges
    - Defining/prescribing the MPFM analysis process & associated details
    - Defining/prescribing requirements for RS field
  - Other challenges
    - Verifying Cx was done & was in-spec
    - Include benefit for interference fit fasteners





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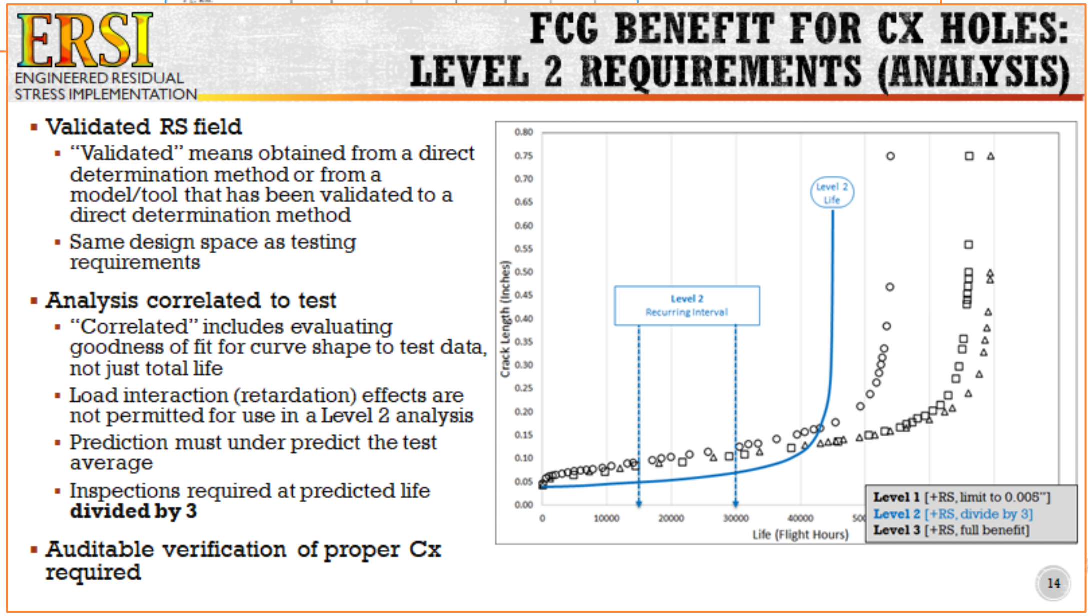
FCG BENEFIT FOR CX HOLES: LEVEL 2 REQUIREMENTS (TESTING)

- Coupon testing under representative spectrum loading
  - Minimum 5 replicates of baseline and CX condition
  - More replicates required if scatter amongst replicates is greater than factor of 2
- Validation testing required for similar geometry, "similar" meaning:
  - Representative loading spectrum, max spectrum stress less than or equal to stress tested
  - e/D < 2.0 must match edge margin within 0.25, no requirement for e/D > 2
  - Diameter within ¼" for holes < ¾", > ¾" must match design geometry
  - Thickness must be within neighboring thickness range for MMPDS allowables[7]
  - Same alloy series and representative applied expansion

Table 3.2.4.0(b1). Design Mechanical and Physical Properties of 2024 Aluminum Alloy Sheet and Plate.

Specification	AMS 4037[a]					AMS 4269[a]		
Form	Sheet					Sheet		Plate
Temper	T3					T361		
Thickness, in.	0.008-0.009	0.010-0.128		0.129 - 0.249		0.020-0.062	0.063-0.249	0.250-0.500
Basis	S	A	B	A	B	S	S	S
Mechanical Properties: F_{tu}, ksi:								



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FCG BENEFIT FOR CX HOLES: LEVEL 2 REQUIREMENTS (ANALYSIS)

- Validated RS field
  - "Validated" means obtained from a direct determination method or from a model/tool that has been validated to a direct determination method
  - Same design space as testing requirements
- Analysis correlated to test
  - "Correlated" includes evaluating goodness of fit for curve shape to test data, not just total life
  - Load interaction (retardation) effects are not permitted for use in a Level 2 analysis
  - Prediction must under predict the test average
  - Inspections required at predicted life **divided by 3**
- Auditable verification of proper Cx required

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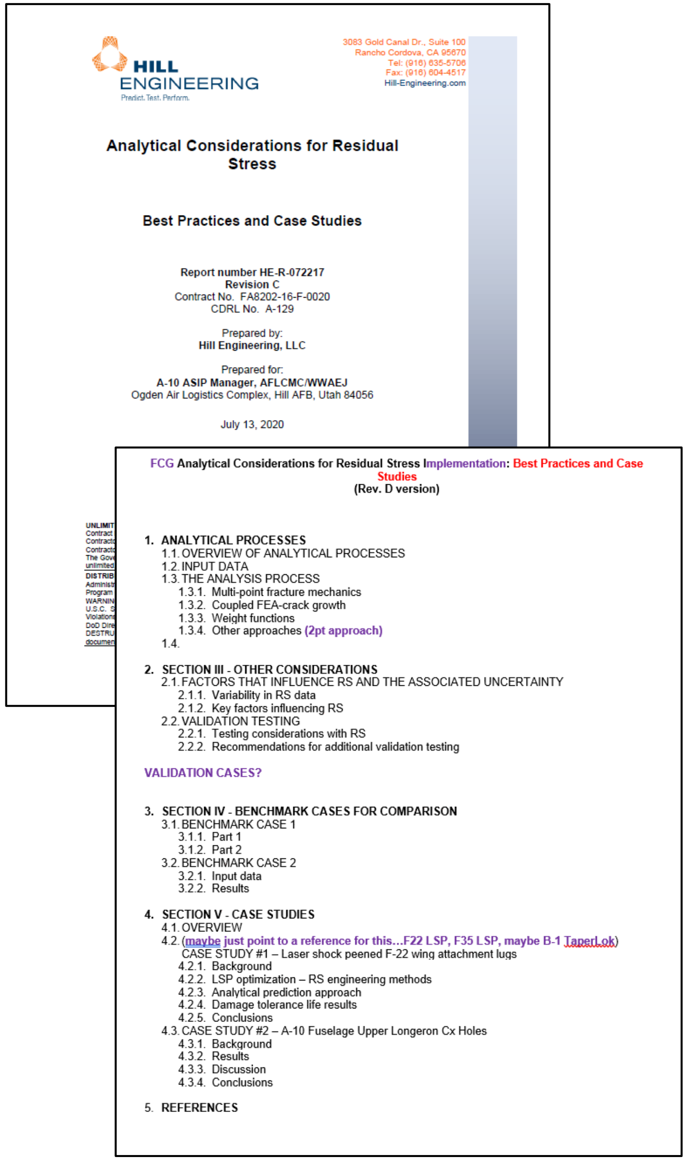
RS Best Practices Document

- 2 reasons people are asking for this
  - How do we do it (analysis steps; best practices; guide)
  - How has it been done in the past (case studies; lessons learned)
- If XYZ comes to you and wants to use RS, what are the step by steps we go through to help them
  - So you want to do RS in your analysis, how do you do it? (we hand them this document);
    - 1: get RS field from source you believe
    - 2: applying RS to FEA model
    - 3: doing MPFM
- Maybe add section on other sources for RS process models, instrumented puller, SpARS, Ball closed-form, marks math model, etc. ("sources of RS")
- RS inducing processes as appendix
- Maybe ref DT design handbook for 'how to do DTA'



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Analytical Considerations for Residual Stress

Best Practices and Case Studies

Report number HE-R-072217
Revision C
Contract No. FA8202-16-F-0020
CDRL No. A-129

Prepared by:
Hill Engineering, LLC

Prepared for:
A-10 ASIP Manager, AFLCMC/WWAEJ
Ogden Air Logistics Complex, Hill AFB, Utah 84056

July 13, 2020

FCG Analytical Considerations for Residual Stress Implementation: Best Practices and Case Studies
(Rev. D version)

1. ANALYTICAL PROCESSES
   1.1. OVERVIEW OF ANALYTICAL PROCESSES
   1.2. INPUT DATA
   1.3. THE ANALYSIS PROCESS
      1.3.1. Multi-point fracture mechanics
      1.3.2. Coupled FEA-crack growth
      1.3.3. Weight functions
      1.3.4. Other approaches (2pt approach)
   1.4.
2. SECTION III - OTHER CONSIDERATIONS
   2.1. FACTORS THAT INFLUENCE RS AND THE ASSOCIATED UNCERTAINTY
      2.1.1. Variability in RS data
      2.1.2. Key factors influencing RS
   2.2. VALIDATION TESTING
      2.2.1. Testing considerations with RS
      2.2.2. Recommendations for additional validation testing

VALIDATION CASES?

3. SECTION IV - BENCHMARK CASES FOR COMPARISON
   3.1. BENCHMARK CASE 1
      3.1.1. Part 1
      3.1.2. Part 2
   3.2. BENCHMARK CASE 2
      3.2.1. Input data
      3.2.2. Results
4. SECTION V - CASE STUDIES
   4.1. OVERVIEW
   4.2. (maybe just point to a reference for this…F22 LSP, F35 LSP, maybe B-1 TaperLok)
   CASE STUDY #1 – Laser shock peened F-22 wing attachment lugs
      4.2.1. Background
      4.2.2. LSP optimization – RS engineering methods
      4.2.3. Analytical prediction approach
      4.2.4. Damage tolerance life results
      4.2.5. Conclusions
   4.3. CASE STUDY #2 – A-10 Fuselage Upper Longeron Cx Holes
      4.3.1. Background
      4.3.2. Results
      4.3.3. Discussion
      4.3.4. Conclusions
5. REFERENCES

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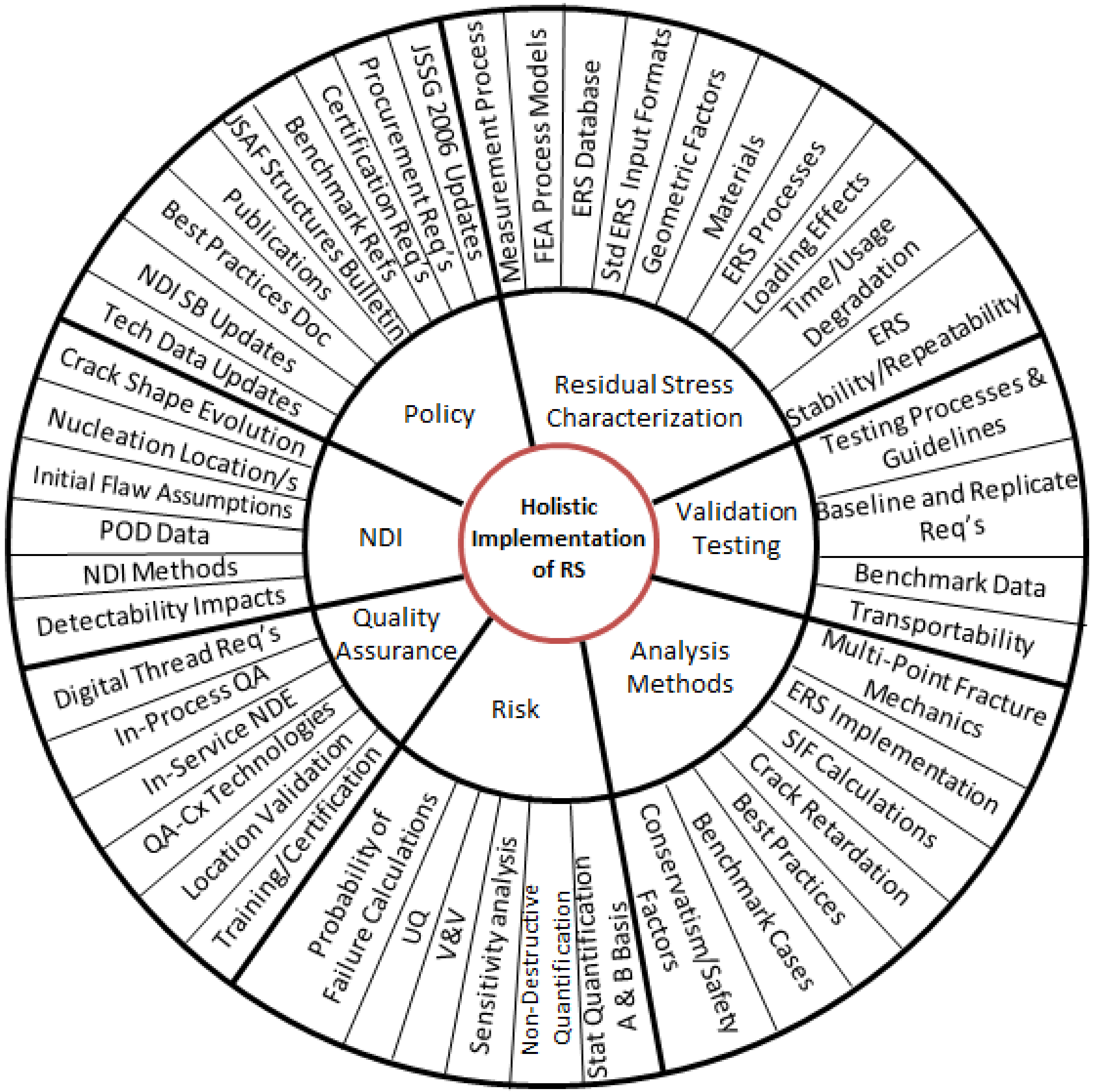
'Lincoln Wheel' Roadmap



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UNITED STATES
AIR FORCE
ACADEMY

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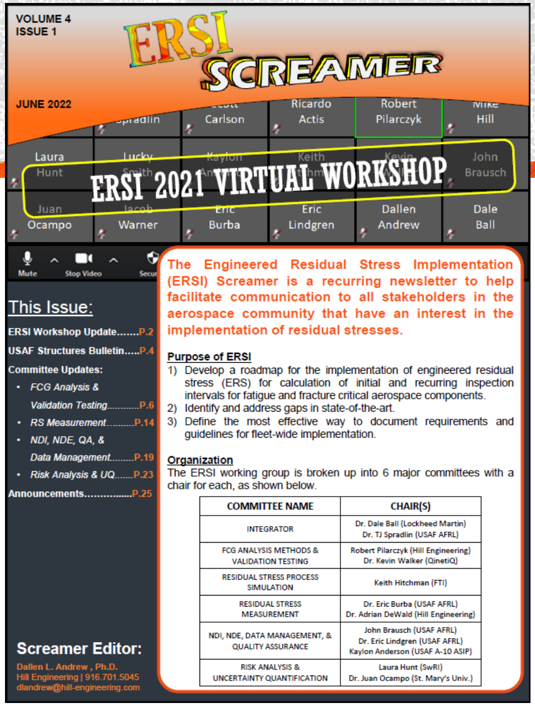


VOLUME 4
ISSUE 1

ERSI SCREAMER

JUNE 2022

ERSI 2021 VIRTUAL WORKSHOP

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

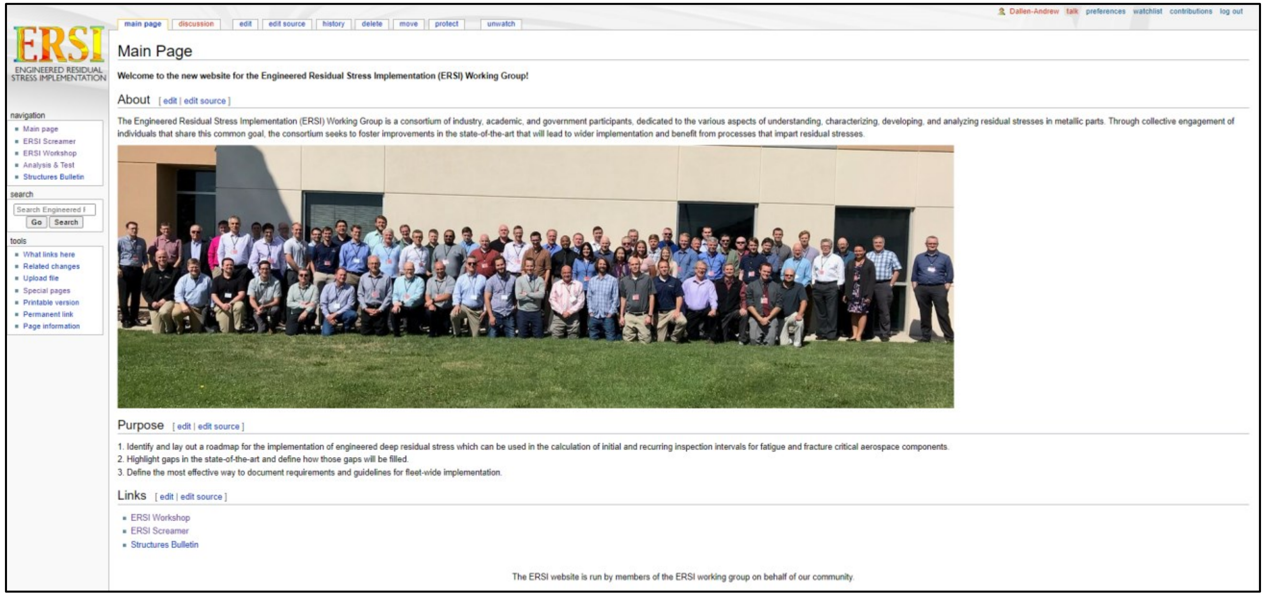
1) Develop a roadmap for the implementation of engineered residual stress (ERS) for calculation of initial and recurring inspection intervals for fatigue and fracture critical aerospace components.
2) Identify and address gaps in state-of-the-art.
3) Define the most effective way to document requirements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

Screamer Editor:
Dallen L. Andrew , Ph.D.
Hill Engineering | 916.701.5045
dlandrew@hill-engineering.com



ENGINEERED RESIDUAL STRESS IMPLEMENTATION

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Main Page

Welcome to the new website for the Engineered Residual Stress Implementation (ERSI) Working Group!

About [edit | edit source]

The Engineered Residual Stress Implementation (ERSI) Working Group is a consortium of industry, academic, and government participants, dedicated to the various aspects of understanding, characterizing, developing, and analyzing residual stresses in metallic parts. Through collective engagement of individuals that share this common goal, the consortium seeks to foster improvements in the state-of-the-art that will lead to wider implementation and benefit from processes that impart residual stresses.

Purpose [edit | edit source]

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.

Links [edit | edit source]

- ERSI Workshop
- ERSI Screamer
- Structures Bulletin

The ERSI website is run by members of the ERSI working group on behalf of our community.

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Dallen Andrew

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