Topical National Review: Fatigue Life Extension Method and Repair

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Eric Lindgren (USAF), Micheal Gorelik (FAA) and Takao Okada (JAXA)

June 10, 2025

Topical National Review: Fatigue Life Extension Method and Repair Solution

- Contents
  - Topics in ICAF2023 Presentations
  - Topics in ICAF2025 National Reviews
  - Activities for Fatigue life extension method and repair solution in Japan
  - Activities for Fatigue life extension method and repair solution in USA

Fatigue Life Extension Method and Repair Solution

- Topics in ICAF2023 presentation
  - 2 Sessions, 9 Presentations (USA, UK, China, Finland, Germany)

15:30 Session 3: Fatigue life enhancement methods and repair solutions I
Chair: Ben Main

15:30 (20 mins) **The A-10 Warthog damage tolerance and residual stresses in transition**
Jacob Warner, Dallen Andrew

15:50 (20 mins) **Enhanced technology repair for corrosion and fatigue damage in hybrid aerostructure**
Matthew Kokaly, Jude Restis

16:10 (20 mins) **Evaluation of cold spray for aircraft repair**
Sarah Galyon Dorman, Justin Rausch, Moriah Ausherman, Gregory Shoales

16:30 (20 mins) **Retardation of fatigue cracks in welded structures through laser shock peening**
Nikolai Kashaev, Sören Keller, Uceu Fuad Hasan Suhuddin, Volker Ventzke, Benjamin Klusemann

10:50 Session 12: Fatigue life enhancement and repair solutions II
Chair: Takao Okada

10:50 (20 mins) **Bonded prestressed method for fatigue crack repair**
Wandong Wang

11:10 (20 mins) **Tools and methods for landing gear fatigue analysis with surface treatment effects**
Rob Plaskitt, Michelle Hill, Andrew Halfpenny, Ben Griffiths, Andrew Clark, Ben Madsen

11:30 (20 mins) **Assessment of chromate free alternatives as paint primers**
Jay Patel

11:50 (20 mins) **Optical simulation of scratch repair in F/A-18 transparences**
Matti Okkonen, Aki Mäyrä, Aslak Siljander, Mika Siitonen

12:10 (20 mins) **Using digital twins to accelerate qualification and certification of fatigue critical components**
Gary Whelan, Jiadong Gong, Greg Olson

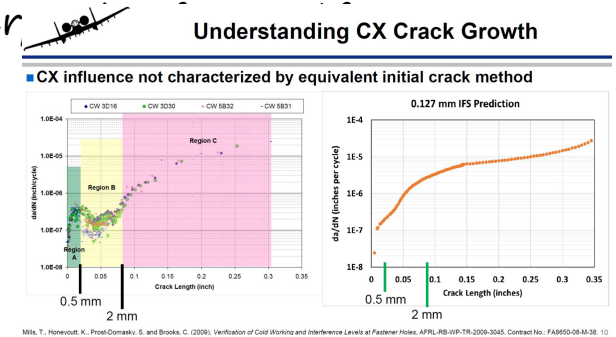
- Residual stress, (Cold spray, Cold work, Laser shock peening, Surface treatment …)
- Repair
- Digital Twin

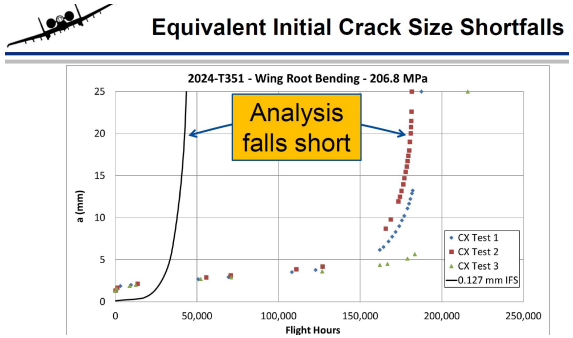
Fatigue Life Extension Method and Repair Solution

- Residual stress:
  - Structures Bulletin (SB), EZ-SB-17-001, Revision A "Requirements to Establish the Beneficial Effects of Cold Expanded Holes in Development of Damage Tolerance Initial and Recurring Inspection Intervals."
  - 2023 ICAF presentation by Warner et.al, highlights an example of implementation
  - If nondestructive inspection (NDI) for quality assurance in development is successful (Lindgren ASIP 2023), SB will be updated
- Cold Spray for Aircraft Repair:
  - Continued interest is using cold spray to repair aircraft components
  - One limitation for implementation: NDI method to integrity of cold spray repair
  - Publication of MIL HDBK 542, "Cold Spray Nondestructive Testing Methods for Quality Assurance" describes the challenges of using available NDI methods when applied to cold spray repairs.
  - Cold spray currently used for geometric restoration for the USAF
  - Research projects exploring how to address limitations of NDI techniques.
- Digital Twins / Digital Engineering:
  - Excellent summary in 2023 ICAF paper by Mr. Charles Babish: "Digital Engineering for Improved Aircraft Structural Integrity Program Execution."
  - Digital Twins include digital models and digital representations which can enhance ASIP execution
  - Paper includes references to Digital Thread: material properties, structural element, and usage can be integrated into the digital twin for enhanced ASIP execution

Fatigue Life Extension Method and Repair Solution

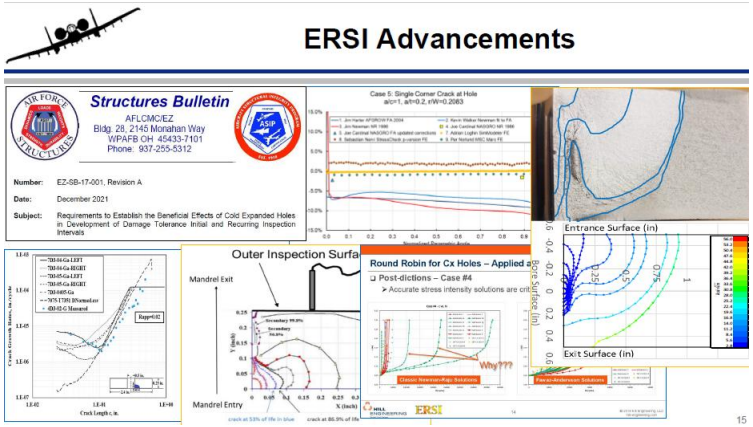
- Topics in ICAF2023 presentation
  - The A-10 warthog: damage tolerance and residual stress in transition, J. Warner et. al., (USAF, USA)
    - In residual stress, the reduced initial flaw size approach significantly under predicts the damage tolerant life benefits, while in extreme cases it can over



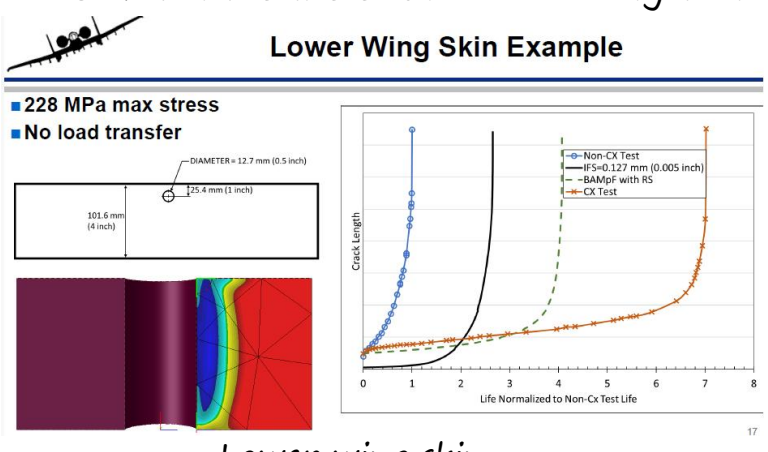


    - Following research activities have been conducted.
      - Evaluation of crack growth rates at cold expanded hole, including multiple loading and cracking scenario, overload/underload effect, load transfer influence, retardation model use, crack interaction model and etc.
      - Development of Broad Application for Multi-point Fatigue (BAMpF), in order to capture unique crack front morphology at cold expanded hole due to residual stress.

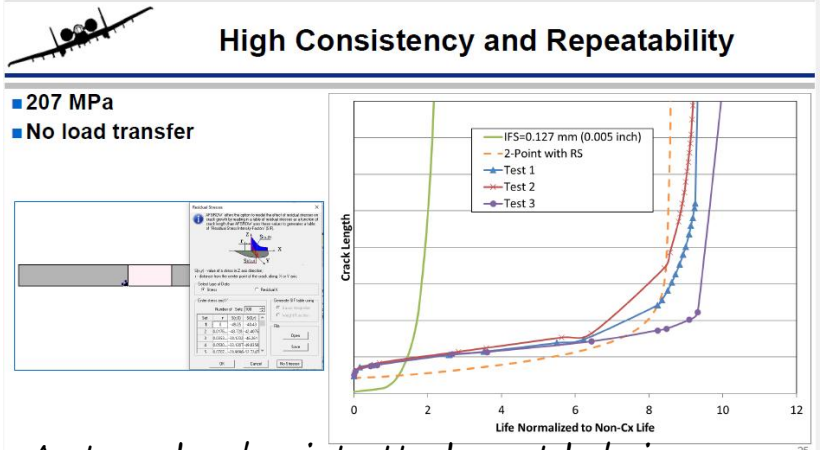
Fatigue Life Extension Method and Repair Solution



- Several results show that analytical accuracy is improved by proposed procedure.



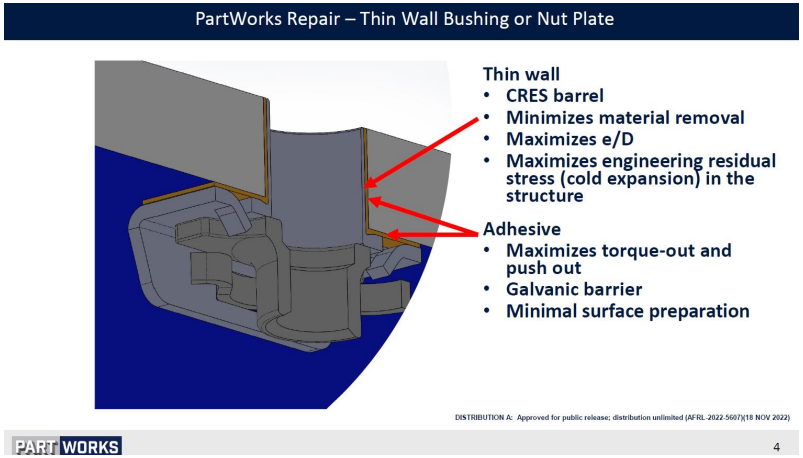
Lower wing skin example

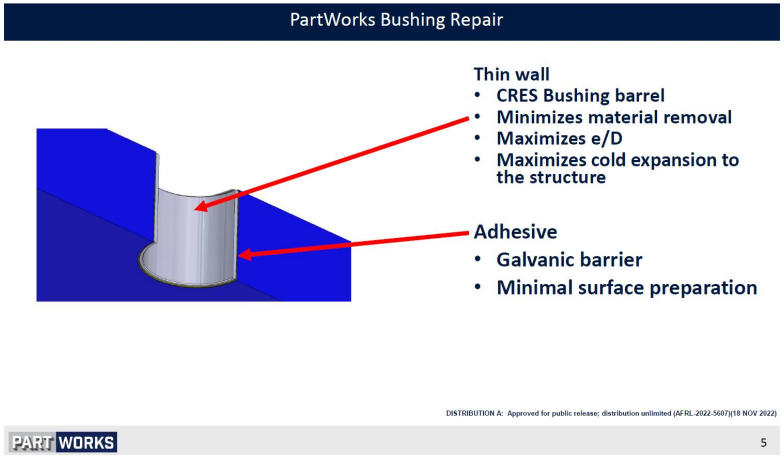


A stores hard point attachment hole in a spar can

Fatigue Life Extension Method and Repair Solution

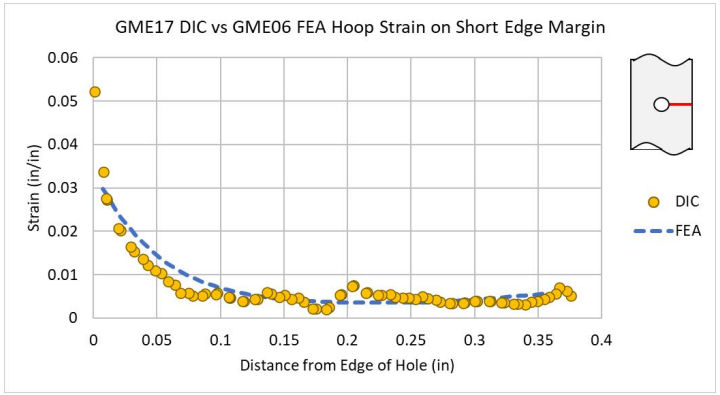
- Topics in ICAF2023 presentation
  - Enhanced technology repair for corrosion and fatigue damage in hybrid aerostructure, Jude Restis (PART WORKS, USA)
    - Typical repair to fastener hole
      - Ream hole to remove all corrosion
      - Perform analysis
      - Install oversize fastener or bushing
    - Proposed procedure

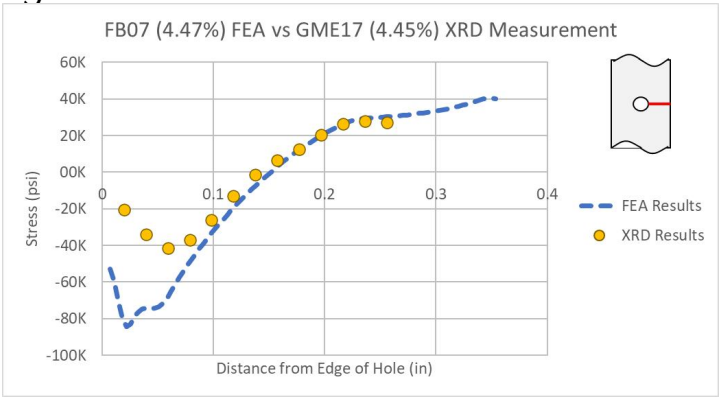




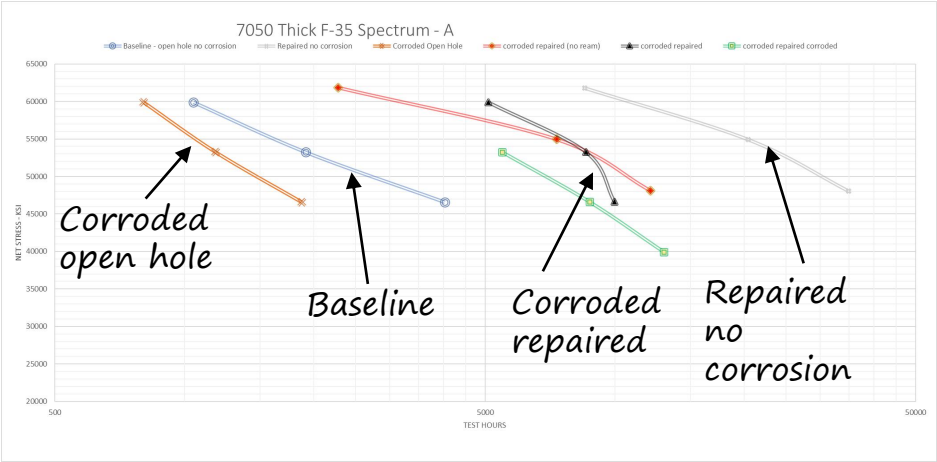
Fatigue Life Extension Method and Repair Solution

- Correlation between FEA, DIC and X-ray diffraction





- Corrosion protocol development
- Fatigue testing



Fatigue Life Extension Method and Repair Solution

- Topics in ICAF2023 presentation
  - Evaluation of cold spray for aircraft repair, Sarah Galyon Dorman (SAFE Inc., USA)

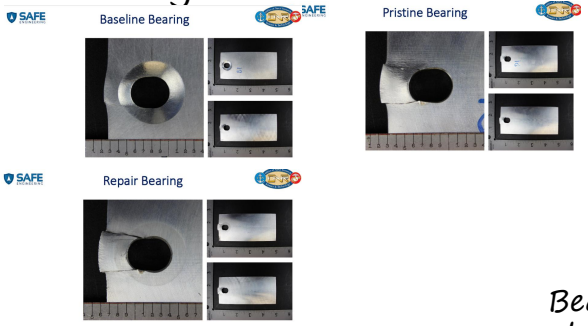
SAFE ENGINEERING

Program Goals and Objectives

- Show that cold spray can be used to improve fatigue life in repaired aluminum alloy 7050-T7451
- Demonstrate a cold spray repair can be used for structural repair of 7xxx series aluminum alloys
- Develop samples for use in validating structural repair using cold spray

- Following tests are conducted to evaluate for repair performance
  - Tensile, Compression, Three point bend, Bearing, Fatigue

Bearing



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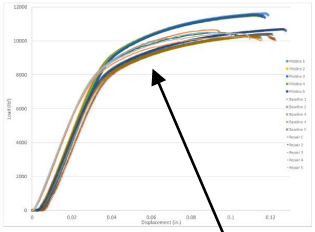
Bearing Property Summary



No disbondment for any repaired sample

Specimen	Pmax (lbf.)	t (in.)	d (in.)	Fbru (ksi.)
P-1	11620	0.241	0.379	127.2
P-2	11512	0.241	0.377	126.7
P-3	11542	0.242	0.378	126.7
P-4	11515	0.241	0.378	126.4
P-5	11547	0.241	0.379	126.4
Average	11547			126.6

Specimen	Pmax (lbf.)	t (in.)	d (in.)	Fbru (ksi.)
B-1	10306	0.245	0.376	111.9
B-2	10386	0.242	0.377	113.8
B-3	10421	0.244	0.377	113.3
B-4	10279	0.243	0.376	112.5
B-5	10702	0.245	0.376	116.2
Average	10418.8			113.5

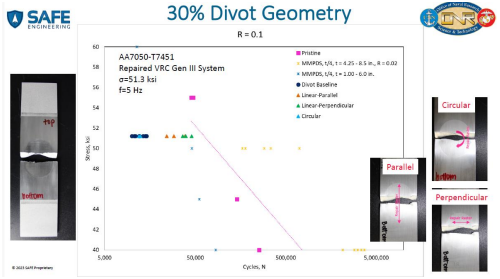
Specimen	Pmax (lbf.)	t (in.)	d (in.)	Fbru (ksi.)
R-1	10660	0.242	0.379	116.2
R-2	10502	0.242	0.38	114.2
R-3	10516	0.244	0.38	113.4
R-4	10248	0.243	0.379	111.3
R-5	10459	0.2445	0.38	112.6
Average	10477			113.5

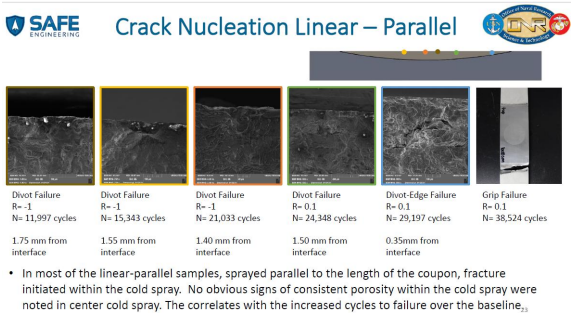
Bearing stress is dominated by the yield strength making the baseline and repair data almost the same due to the earlier yield properties of cold spray.

Bearing stress between baseline and repair data are almost the same due to earlier yield properties of cold spray.

Fatigue Life Extension Method and Repair Solution

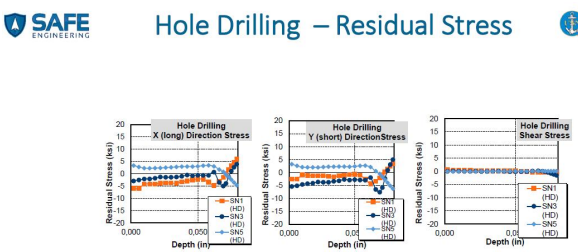
Fatigue



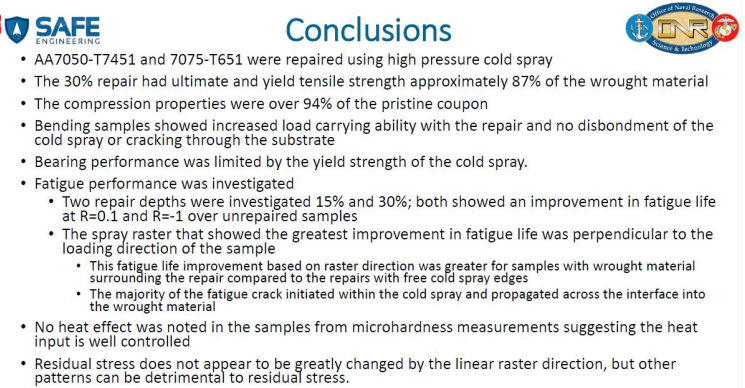


The majority of the fatigue crack initiated within the cold spray and propagated across the interface into the wrought material.

Residual stress



Residual stress does not appear to be greatly changed by the linear raster direction, but other patterns can be detrimental to residual stress.



Additional test would be required for implementation.

Fatigue Life Extension Method and Repair Solution

- Topics in ICAF2025 National reviews
  - Australia
    - A Fractographic Study of FCG from a Cold-expanded Fastener Hole at an Engineering 'Crack Initiation' Scale
  - Canada
    - Airframe Digital Twin Technology Development and Demonstration
    - Development of a Rotorcraft Structural Component Digital Twin
    - Development of Stress Intensity Factor Solutions for a Radial Crack at a Hole Filled with Neat Fit and Interference Fit Fastener
  - Finland
    - EDA PATCHBOND II project
  - Germany
    - Application of Laser Shock Peeing as a Manufacturing and Repair Process to Improve the Fatigue Performance of Refill Friction Stir Spot Welded AA2024 Joints
    - Correlation of fatigue damage with polymer and microstructural parameters in thermoplastic tapes and epoxy resin with non-crimp fabric

Fatigue Life Extension Method and Repair Solution

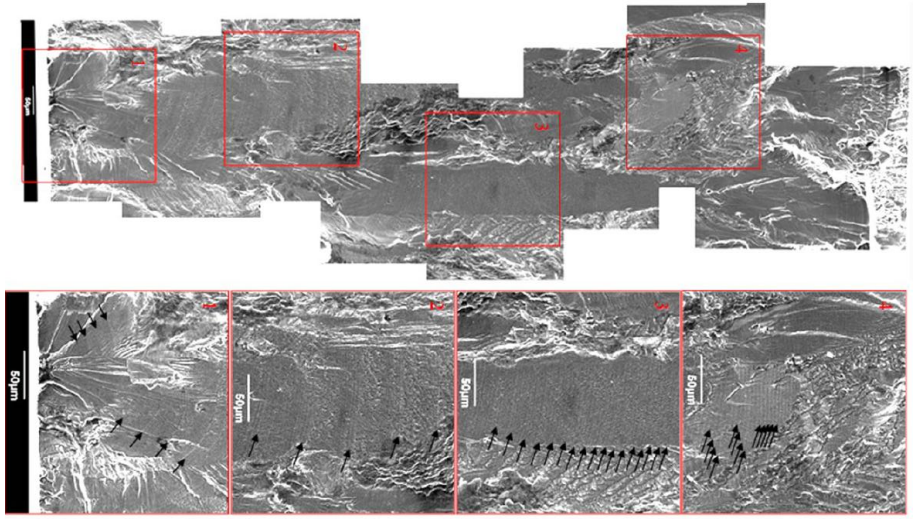
- Topics in ICAF2025 National reviews
  - Italy
    - Interference Fit Fasteners with Cold working: improvement on Fatigue life evaluation
    - Fatigue assessment of LSP treated joints: the «Pressure Floor» specimen
  - Japan
    - Ply Curving Termination for Improving Fatigue Characteristics of Composite Ply Drop-Off
    - Effect of Interface Microstructure on Interlaminar Fracture Toughness in Dissimilar Joints of Thermoplastic CFRP and Aluminum Alloys
    - Experimental study of intrinsically conductive resin as a functional repair for CFRP laminates against simulated lightning strike
  - The Netherland
    - Cold Spray Research

Fatigue Life Extension Method and Repair Solution

- Topics in ICAF2025 National reviews
  - Sweden
    - Testing of repairment method EPOCAST for incorrectly drilled bolt holes in CFRP joints
    - Surface postprocessing to improve fatigue strength of AM titanium
    - Testing of cold spray for repair of aircraft components
  - Swiss
    - Piano Hinge Optimized Repair Development (RUAG AG)
    - TEF Hinge Lug Repair Coupon Test

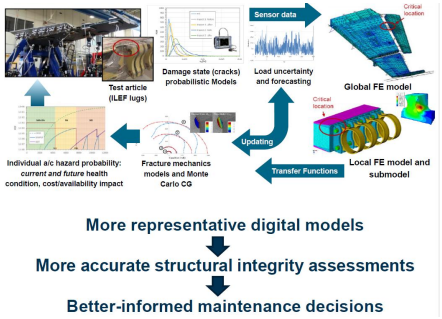
Fatigue Life Extension Method and Repair Solution

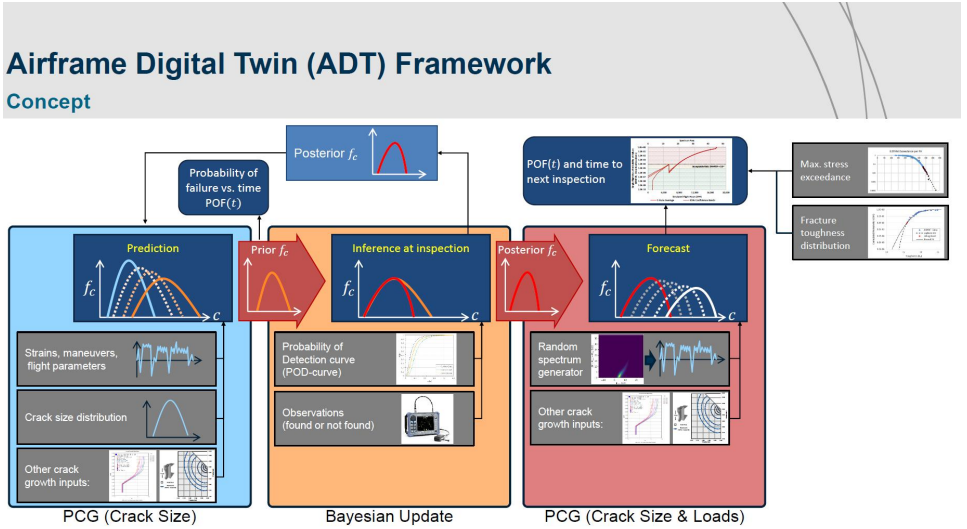
- Topics in ICAF2025 National reviews
  - A Fractographic Study of FCG from a Cold-expanded Fastener Hole at an Engineering 'Crack Initiation' scale – B. Main (DSTG, Australia) et. al.
    - QF technology is used to measure FCG from naturally occurring discontinuities.
    - FCG in cold-expanded specimens (about 0.2mm away from crack origin) was markedly slowed to the point at which failure ultimately arose from cracks away from, or growing into, the fastener hole.



Fatigue Life Extension Method and Repair Solution

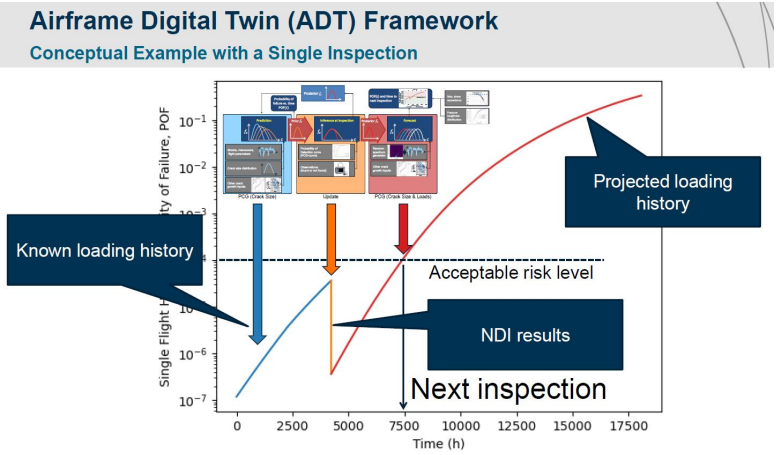
- Topics in ICAF2025 National reviews
  - Airframe digital twin technology development and demonstration, Yan Bombardier et. al. (NRC, Can
    - The framework integrates cutting-edge structural analyses including high-fidelity finite element simulations, probabilistic modelling techniques including advanced probabilistic crack growth modelling and quantitative risk assessments.
    - Two new modeling aspects are included. a) the calculation of hazard rate (HR) and cumulative probability of failure (CPOF) using conditional probability of failure equations, and b) the effect of local load





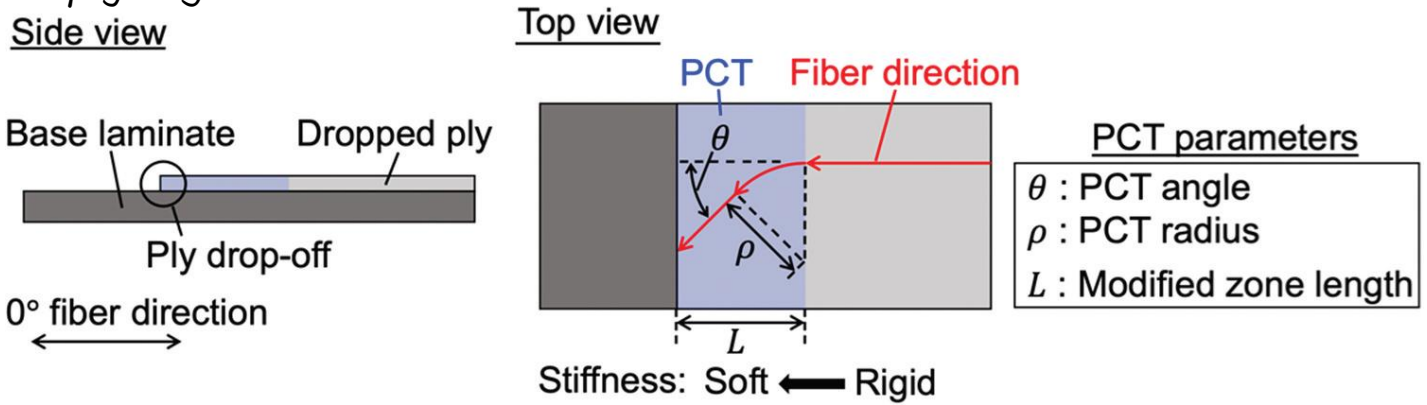
Fatigue Life Extension Method and Repair Solution

- Followings are demonstrated:
  - a) The load tracking factor could be reduced from 1.50 to 1.36, resulting in +10% life extension,
  - b) The time to the first inspection could be increased by up to 47% from the point of acceptable limit (PAL) calculated using the CF-188 Lifing Policy, for a scenario of 1% of the cracks nucleated from surface scratches and 99% of the cracks nucleated from the equivalent pre-crack size (EPS)at time zero, and
  - c) The repeated inspection interval could be increased by up to 230%, compared to the inspection interval for safety by inspection (SBI) calculated using the CF-188 conventional lifing method, for a scenario of 1% of the cracks nucleated from surface scratches and 99% of the cracks nucleated from the equivalent pre-crack size (EPS) at time zero.

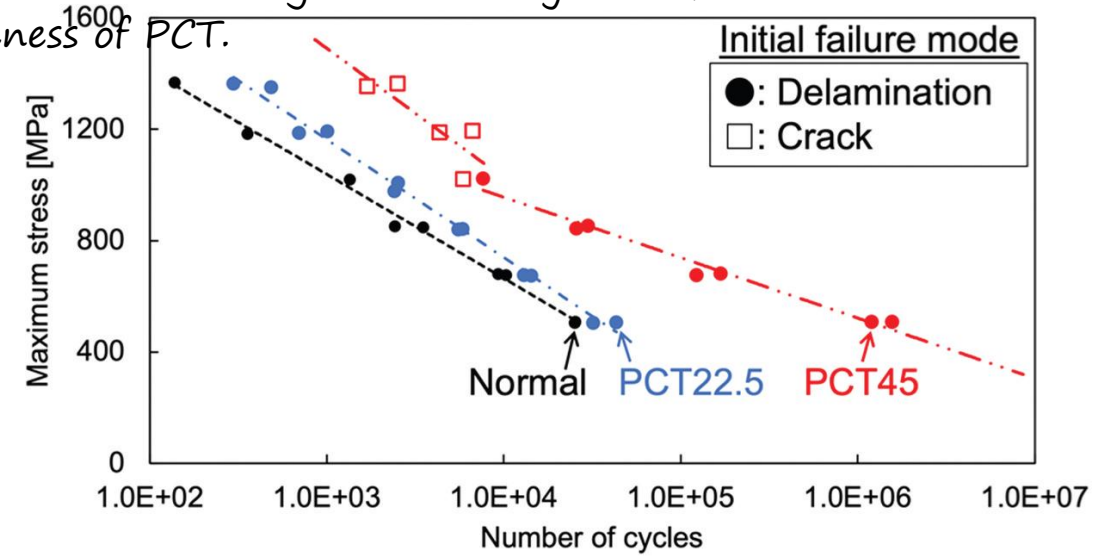


Fatigue Life Extension Method and Repair Solution

- Activities for Fatigue life extension method and repair solution in Japan
  - Ply Curving Termination for Improving Fatigue Characteristics of Composite Ply Drop-Off, S. Minakuchi (The U. of Tokyo)
    - Ply curving termination (PCT) locally changes the fiber direction at the edge of the dropped ply, to suppress delamination from the ply edge.



- Under fatigue loading, two types of initial damage, delamination and crack are observed, depending on the angle of PCT.
- Large PCT angles are effective in improving the fatigue properties of tapered laminates and that controlling the location of initial damage is necessary to maximize the effectiveness of PCT.



- *Activities for Fatigue life extension method and repair solution in USA*
  - *Metallic material: Engineered residual stress implementation (ESRI)*
    - ESRI working group (industry, academic and government participants) has been working since 2016 and seeks to foster improvements in the state-of-the-art that will lead to wider implementation and benefit from processes that impart residual stresses.
    - *Followings three committees, 'Analysis & Test', 'Residual Stress Characterization' and 'Nondestructive Inspection/Evaluation, Quality Assurance, Data Management', have been working since 2023, after re-arrangement of the former eight committees.*
  - Polymer matrix composite: Material system testing for aerospace industry qualification supported by FAA and DoD. Computational and experimental methods for predicting and testing fatigue damage growth in composites under variable amplitude fatigue loading at Joint advanced materials and structures center of excellence (JAMS)

AFRL

NONDESTRUCTIVE EVALUATION FOR ENGINEERED RESIDUAL STRESS VERIFICATION

ERIC LINDGREN, NONDESTRUCTIVE EVALUATION TECHNOLOGY LEAD
MATERIALS AND MANUFACTURING DIRECTORATE, 30 NOVEMBER 2023

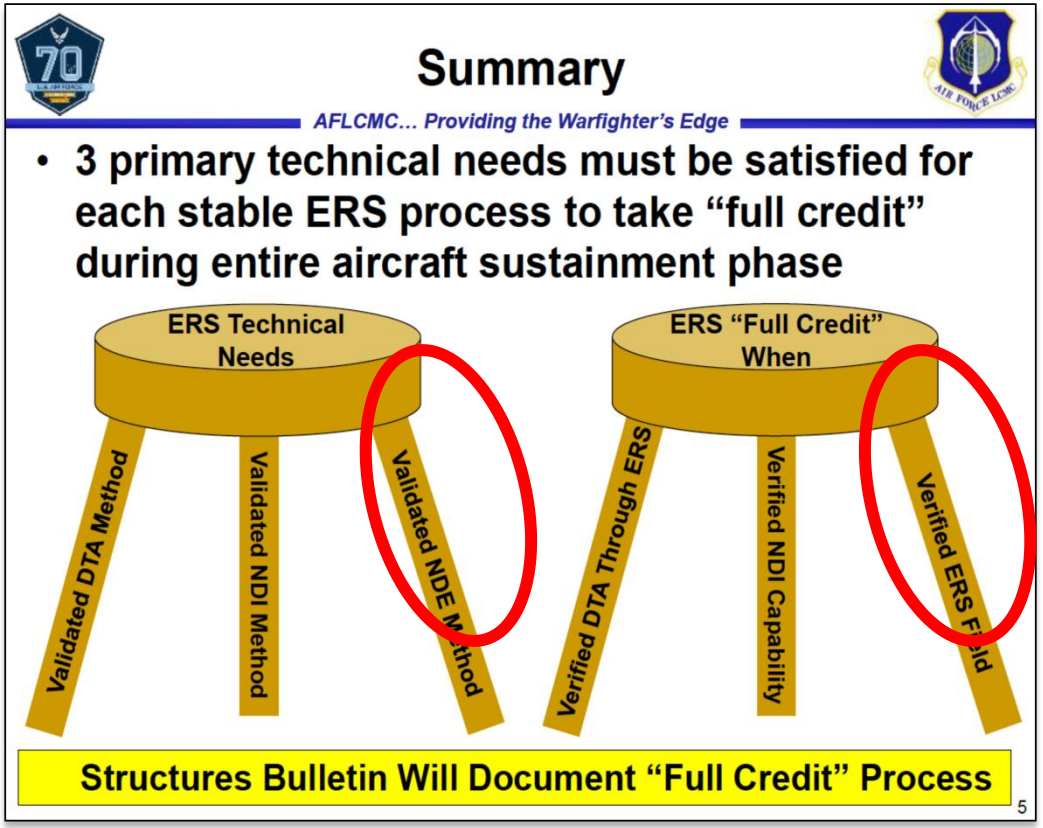
Motivation / Impact

Motivation

- QA of Cx process to ensure residual stresses are present
- Verification residual stresses remain present during life

Impact

- Enhanced life management
- Extended inspection intervals



Briefing chart from Charles Babish, available at: http://www.meetingdata.utcdayton.com/agenda/asip/2017/proceedings/presentations/P13677.pdf

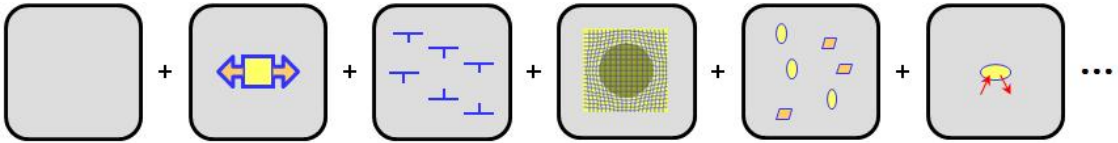
Program Goals

Representative Depot Maintenance

Representative Manufacturing

- Develop NDE techniques for quantifying the residual stress state at Cx holes
- Investigate key confounding factors and their influence on NDE response
- Optimize NDE techniques for evaluation of Cx holes
- Demonstrate the NDE techniques for evaluation of Cx holes
- Verify the NDE techniques for evaluation of Cx holes

Challenges for NDE of Residual Stress in Metals



*Temperature controlled environment

- Lots of factors affect measurement in addition to residual stress
  - Microstructural complications simplified with aluminum alloys
  - Macro-scale considerations: temperature and geometry
  - USAF considerations: manufacturing (e.g. fit-up stresses), maintenance, modification, repair, use
- Deconvolve or control as much as possible
- Maximize sensitivity analysis

Testing (Lots of Testing!)

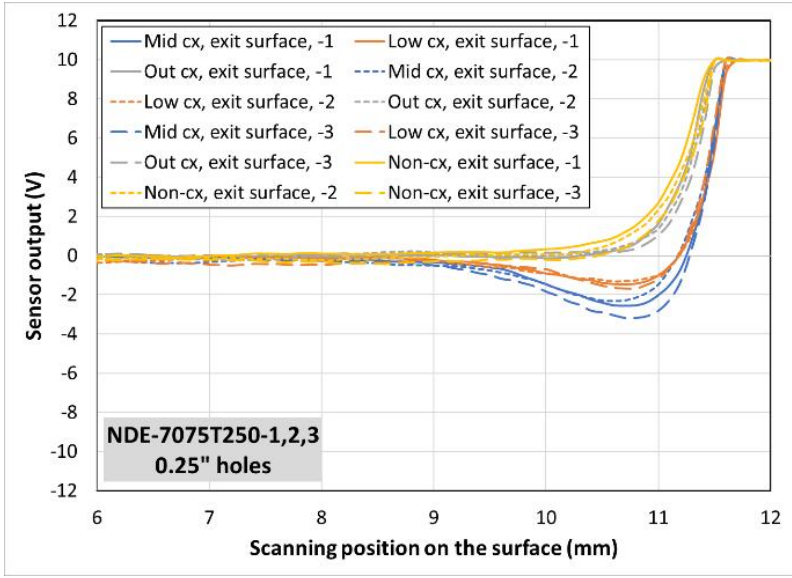
Testing matrices included:

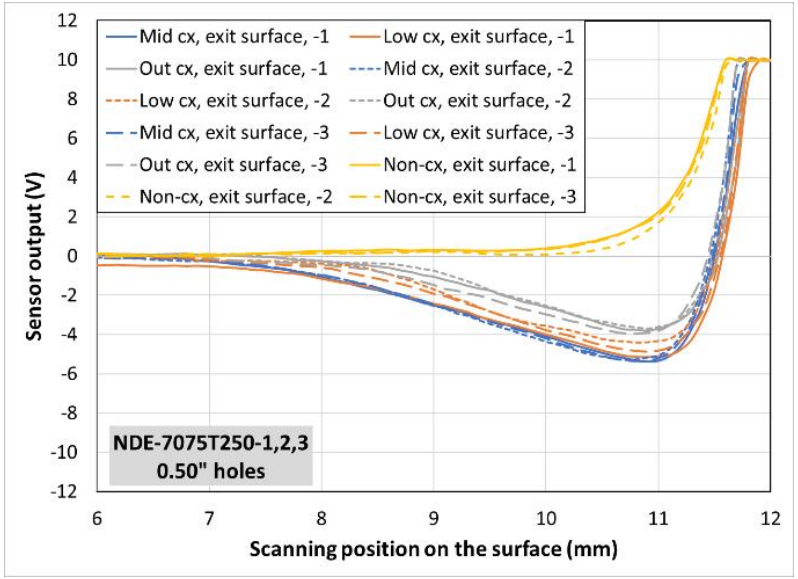
- Levels of cold work
- Hole diameters
- Confounding factors
- Variability
- Coupons
- Extracted components
- In-Depot demonstration

Representative test matrix parameters

Applied expansion	**Mid spec**
	Low spec
	Out of Spec, Low
	Out of Spec, Extreme 1
	Out of Spec, Extreme 2
	Out of Spec, Extreme 3
	None
Material type	2024-T351
	7075-T651
Material thickness	0.250 inch
	0.3125 inch
	0.375 inch
	0.500 inch
Nominal hole diameter	0.250 inch
	0.500 inch
Loading state	Non-cycled
	Cycled
Paint/coating	With paint/coating
	Without paint/coating

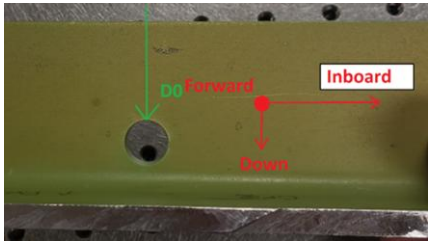
Representative Result: Eddy Current Surface Probe

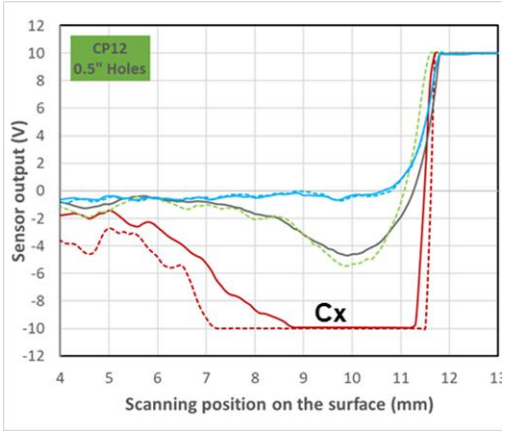


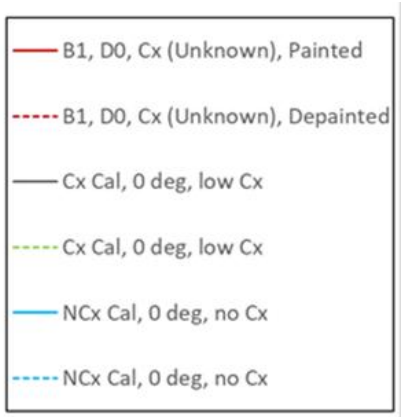


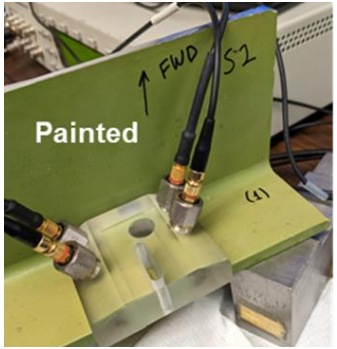
- **Left: 7075 coupons with 0.250 inch thickness, 0.25 inch holes**
- **Right: 7075 coupons with 0.250 inch thickness, 0.50 inch holes**

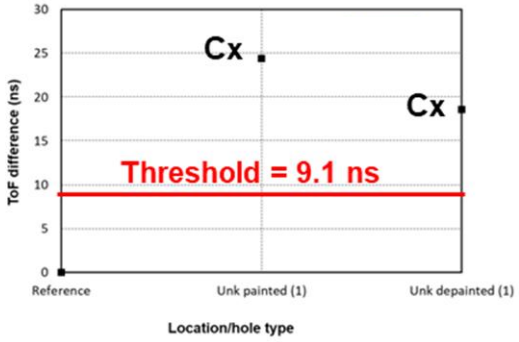
Testing in Representative Environment











Eddy current uses current USAF equipment, ultrasound requires specialized equipment

Summary

Current 6.2 funded effort realized objectives
- Leveraged NDE experience assessing residual stress

Two potential approaches identified
- Surface scanning eddy current with differential coil
- **Longitudinal critically refracted (LCR) ultrasound probe**

Lots of testing to support identified approaches
- Confounding factors, e.g. surface and sub-surface
- Reproducibility: repeated measures on similar conditions
- Variability: hole diameter, magnitude of cold work, and material

Solutions look favorable, but more development required:
- Probe optimization
- Volcano effect
- Validation

} **Follow-on program**

ICAF
International Committee on Aeronautical Fatigue and Structural Integrity

Thank you for your kind attention!

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