ERSI

ENGINEERED RESIDUAL STRESS IMPLEMENTATION WORKSHOP 2016

Date: September 15, 2016
Location: Weber State University Downtown Campus,
2314 Washington Blvd, Ogden, UT 84401

Agenda:

07:15-07:30	Arrive and Breakfast
07:30-08:00	**Introductions, Projected Timeline, and Purpose** - *Scott Carlson, SwRI*
08:00-08:30	**The Lockheed Martin OEM Perspective to ERSI** - *Dr. Dale Ball, Lockheed Martin*
08:30-09:00	**The Boeing Company OEM Perspective to ERSI** - *Dr. Jeff Bunch, The Boeing Company*
09:00-09:30	**Analysis Methods: State-of-the-Art** - *Robert Pilarczyk, Hill Engineering*
09:30-10:00	Discussion: Future needs for analysis methods
10:00-10:10	Break
10:10-10:40	**Quantification of Residual Stress Fields via FEA Compared to Measurement** - *Keith Hitchman, FTI*
10:40-11:10	Discussion: Future needs for modeling
11:10-11:40	**Testing: Verification and Validation of Analysis Methods** - *Dallen Andrew, SwRI*
11:40-12:10	Discussion: Future needs for testing
12:10-1:10	Lunch (Open)
1:10-1:40	**NDI: Impacts of Deep Residual Stresses** - *John Brausch, USAF AFRL*
1:40-1:55	Discussion: Future needs for NDI
1:55-2:25	**Quality Assurance & Data Capture** - *Dave Forsyth, TRI-Austin*
2:25-2:40	Discussion: Future needs for QA
2:40-3:10	**Risk & Uncertainty Quantification** - *Dr. Min Liao, NRC Canada*
3:10-3:40	Discussion: Future needs for Risk & UQ
3:40-3:50	Break
3:50-4:20	**An ASIP Perspective** - *Dr. Mark Thomsen, USAF A-10 ASIP*
4:20-5:15	**ERSI General Discussion Topics** Funding ERSI Org Structure Inter-Organization Collaboration Efforts Plans for Next Year
5:15-5:30	**Closing Remarks**

Welcome to the 1st Engineered Residual Stress Implementation Workshop

Weber State University – Downtown Ogden Campus
Ogden, Utah
September 15, 2015

Sponsored by United States Air Force – A-10 Aircraft Structural Integrity Program (ASIP) Office

Opening Remarks

- Thank you!
- Restrooms
- Coffee Shop Downstairs –Discount
- Internet Password - downtownabby
- Fire Exit
- Agenda, Proposed Format for Discussion
  - Dialogue is necessary
  - Presenter’s will provide specific instructions
- Goal Oriented

Purpose of ERSI Workshop

1. To identify and **lay out a road map 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 stat-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 of ERSI Workshop

Within 2-5 years have developed a framework for fleet-wide implementation of a more holistic, physics-based approach for taking analytical advantage of the deep residual stresses 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.

Engineered residual stress implementation workshop 2016
Ogden UT

Engineered Residual Stress in Military Aircraft Structure

15 September, 2016

Dale L. Ball

LOCKHEED MARTIN
Aeronautics Company

Engineered Residual Stress in Military Aircraft Structure

- **STRUCTURES POLICY**
  - *Shot Peening*
  - *Laser Peening*
  - *Hole Cold-working*
- **Cold-Worked Hole R&D**
  - *Residual Stress Analysis*
  - *Fatigue Crack Initiation Analysis*
  - *Fatigue Crack Growth Analysis*
- **Conclusions**

GENERAL POLICY

- Compressive engineered residual stresses in metallic materials are known to be beneficial:
  – *Increase time for fatigue crack initiation*
  – *Decrease fatigue crack growth rate*

- General structures policy is:
  – *Don’t take credit for beneficial residual stresses during design, with exceptions as approved by the procuring agency*
  – *For approved exceptions, don’t take full credit*
    - Typically allow one half of test demonstrated Life Improvement Factor (LIF/2)
    - This helps mitigate impact of issues discovered later
  – *Take full advantage of beneficial residual stresses during sustainment.*

STRUCTURES POLICY: SHOT PEENING

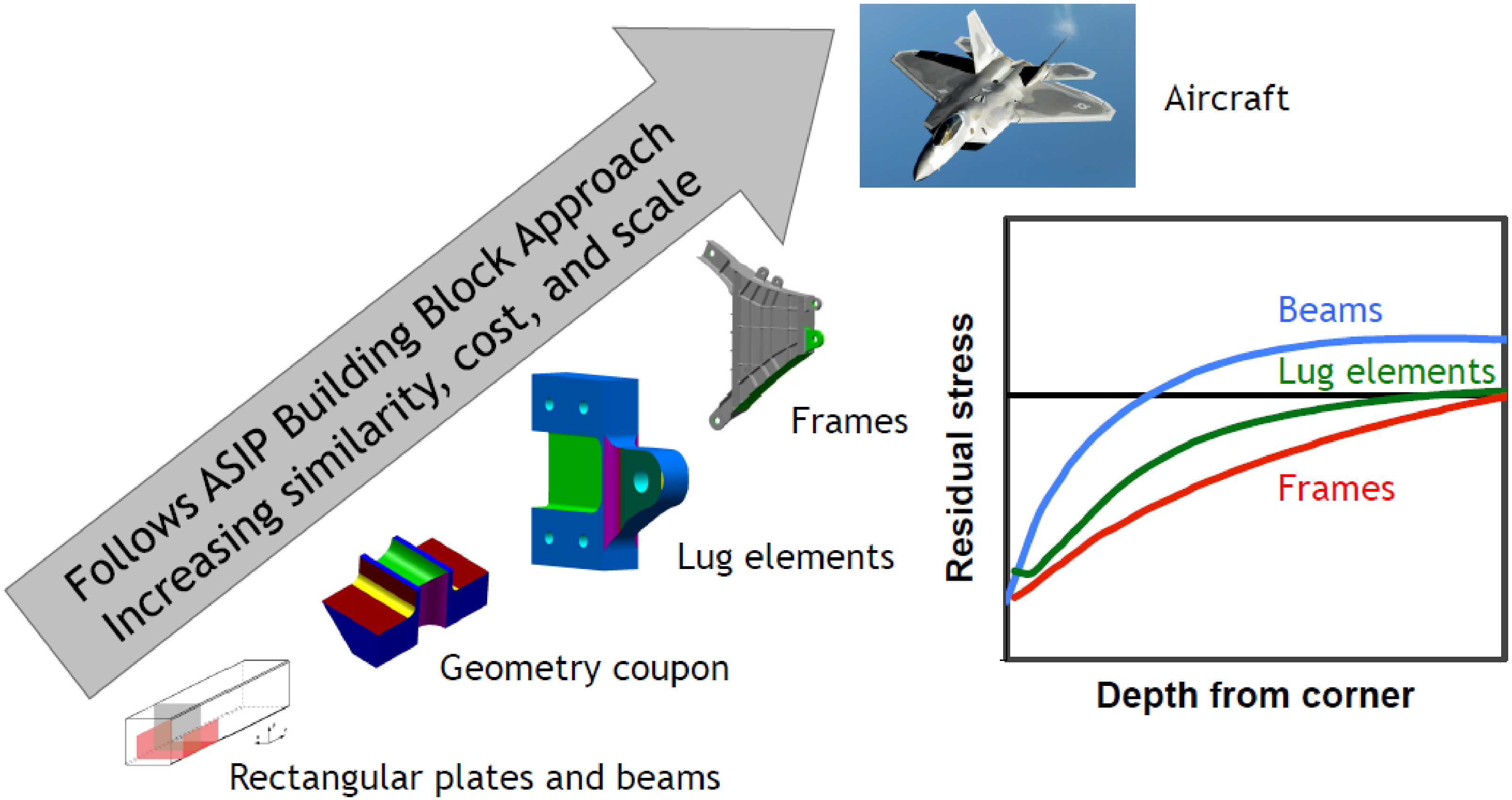
- Shot peening (SP) often applied to mitigate adverse effects of other manufacturing processes:
  - *Welding*
  - *Grinding*
  - *Plating*
  - *Anodizing*
  - *etc.*
- Standard practice is to apply SP at manufacture
  - *No credit (for beneficial residual stresses) is taken in design or sustainment analyses*

STRUCTURES POLICY: LASER PEENING

- Laser peening (LP) has been (or is being) developed and applied on two major LM airframes
- F-22 wing attach lugs
  - *Significant investment in process development, building block test program and methods development*
  - *Mod of in-service aircraft*
  - *Full credit taken for test demonstrated life extension*
- F-35 bulkheads and spars
  - *VERY significant investment in process development, building block test program and methods development*
  - *Mod of in-service aircraft*
  - *Full credit taken for test demonstrated life extension*

STRUCTURES POLICY: LASER PEENING

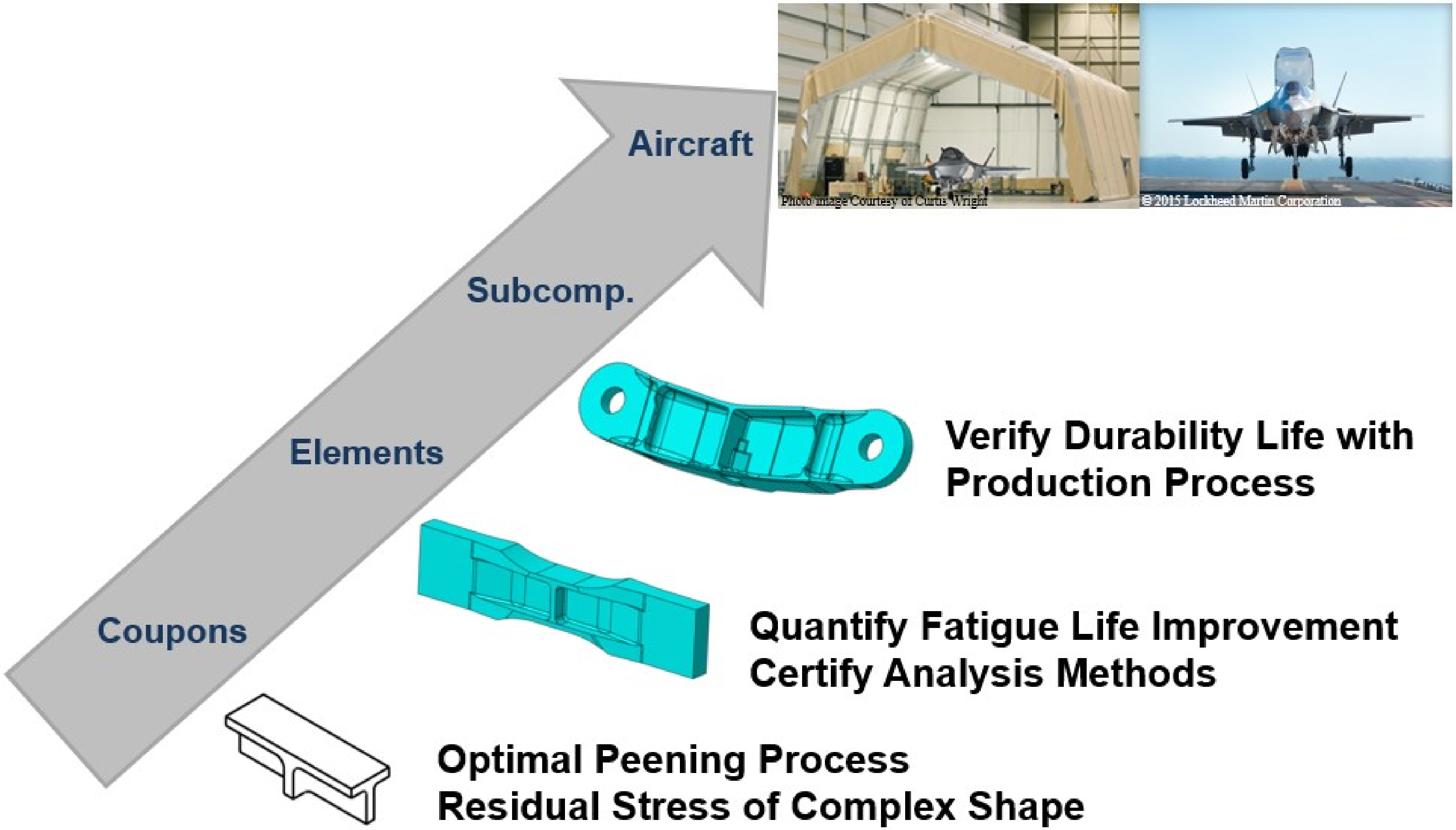
- F-22 wing attach lugs



Ref: M.Hill, et.al., USAF ASIP 2012

STRUCTURES POLICY: LASER PEENING

- F-35 bulkheads and spars
  - **Building Block Approach Reduces Risk during Qualification**



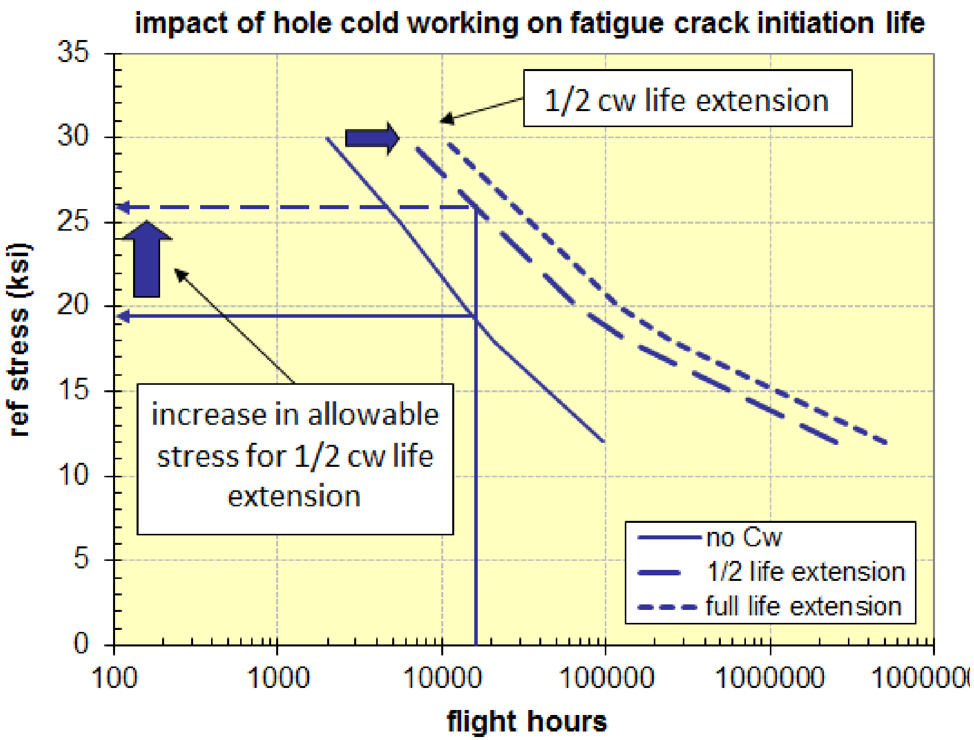
Ref: P.Caruso, 5th Intl.Conf. on Laser Peening, May 2015

STRUCTURES POLICY: HOLE COLD-WORKING

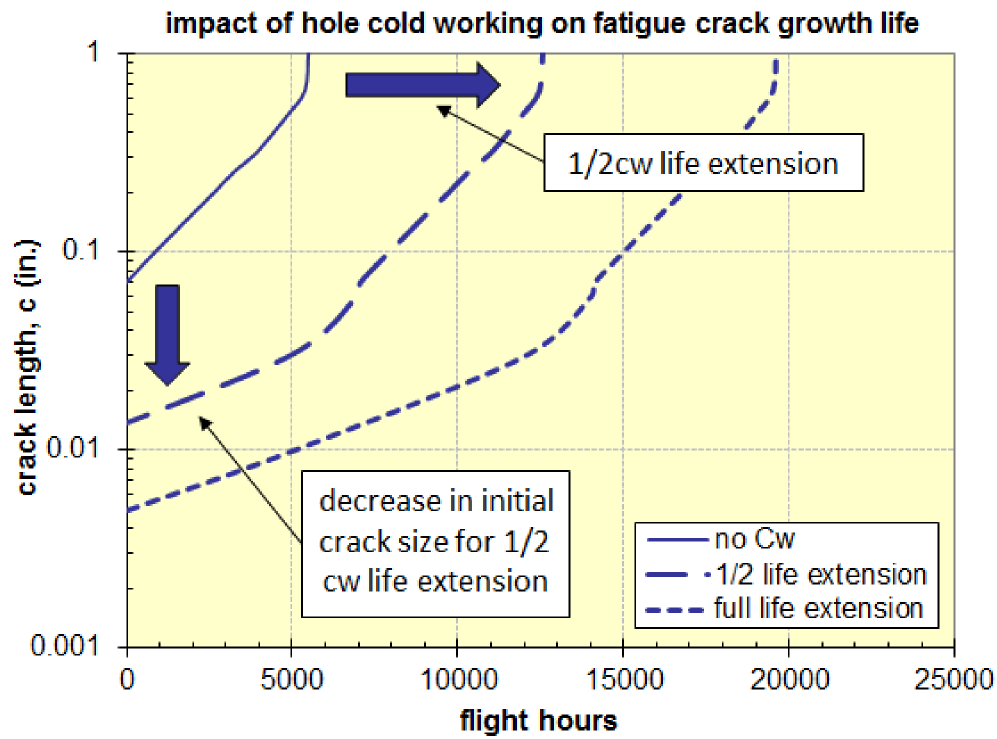
- Hole Cold-working (CW) is applied extensively on all LM airframes
- General policy is the same as stated above:
  - *No credit during design (with exceptions as approved by the procuring agency)*
  - *Half credit for approved exceptions during design*
  - *Full credit during sustainment*
- However, each program has its own policy (especially true for legacy programs)

STRUCTURES POLICY: HOLE COLD-WORKING

- ½ cold work life extension for design exceptions



fatigue crack initiation analysis



fatigue crack growth analysis

STRUCTURES POLICY: HOLE COLD-WORKING

- C-130 program:
  - *Cold-working is being used:*
    - Half credit taken for DT flaw (ci reduced from 0.05 to 0.03 inch)
    - No credit taken for continuing damage flaw (ci=0.005).

- C-5 program:
  - *Cold-working is being used for RERP and selected mod programs*
    - No credit is being taken for sustainment DaDT analyses.
  - *C-5 program currently coordinating with AFLCMC, experimental program to define appropriate LIF*

STRUCTURES POLICY: HOLE COLD-WORKING

- F-16 program:
  - *Cold-working is being used extensively for sustainment*
    - No FCI analysis
    - No credit taken for FCG-based durability analysis: ci=0.005 inch
    - Full credit taken for FCG-based damage tolerance analysis: ci reduced from 0.05 to 0.005 inch (typically corresponds to 3x to 5x extension in life)
    - No credit taken for continuing damage flaw: ci=0.005 inch
    - No credit allowed for compression dominated spectra
  - *Has been very successful for both mitigation of design deficiency and for life extension beyond initial design life*
  - *Selected investigations of explicit use of cold-work-induced residual stress fields have been performed*

STRUCTURES POLICY: HOLE COLD-WORKING

- F-22 program:
  - *For approved exceptions during design, half credit was taken*
    - For FCI analysis of durability critical parts, life improvement incorporated via a local stress reduction factor for selected critical holes – C_{LI}=0.87 stress reduction factor corresponds to approximately 15% increase in design allowable stress
    - For FCG analysis of durability critical parts, no credit taken, ci=0.005 inch
    - For FCG analysis of fracture critical parts, half credit taken, ci=0.03 inch
    - No credit if Kt*DLS<1.2*Fcy
  - *Cold-working is being used for sustainment*
    - Full credit taken for DT flaw (ci reduced from 0.05 to 0.005 inch)
    - No credit taken for continuing damage flaw (ci=0.005).
    - No credit if Kt*DLS<1.2*Fcy

STRUCTURES POLICY: HOLE COLD-WORKING

- F-35 program:
  - *For approved exceptions during design, half credit being taken to mitigate impact of issues discovered during FSDT*
    - For FCI analysis, reduction factor applied
    - For FCG analysis of durability critical parts, no credit taken, ci=0.005 inch
    - For FCG analysis of fracture critical parts, half credit taken, ci=0.03 inch

Coldworked hole stress reduction factors for FCIA[1]	
Material	**Stress Reduction Factor**
2124 and 7050 Aluminum	0.87
Ti 6Al-4V beta Annealed and Ti 6-2222	0.85
All other materials	0.90

[1] Applicable when $\sigma_{max} * K_t \leq 1.2 * F_{cy}$

Coldworked hole initial flaw size assumptions for FCGA	
Material	**Ci, ai**
Ti 6Al-4V HIPped casting	0.03
All other materials	0.015

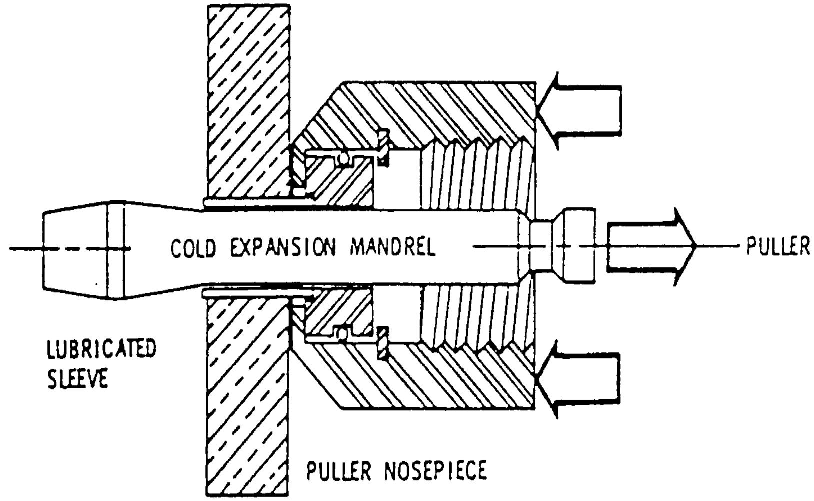
Engineered Residual Stress in Military Aircraft Structure

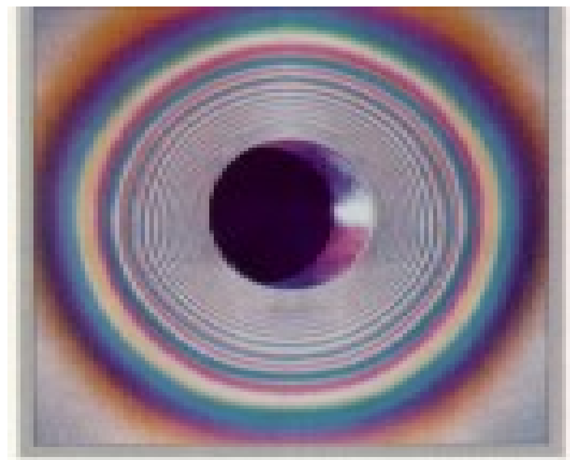
- **STRUCTURES POLICY**
  - ***Shot Peening***
  - ***Laser Peening***
  - ***Hole Cold-working***
- **COLD-WORKED HOLE R&D**
  - ***Residual Stress Analysis***
  - ***Fatigue Crack Initiation Analysis***
  - ***Fatigue Crack Growth Analysis***
- **Conclusions**

CW HOLE R&D: RESIDUAL STRESS ANALYSIS

COLD WORK PROCESS:

- Radially expand hole by drawing oversized mandrel though
- Radial expansion causes permanent plastic deformation
- Beneficial compressive residual stress field formed around hole upon unloading (removal of mandrel), **provided have sufficient surrounding elastic material**

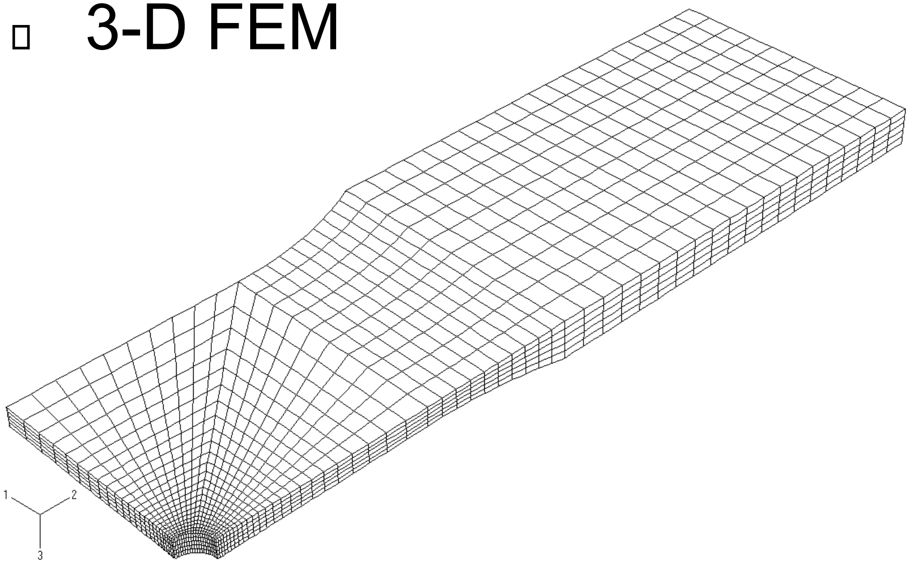




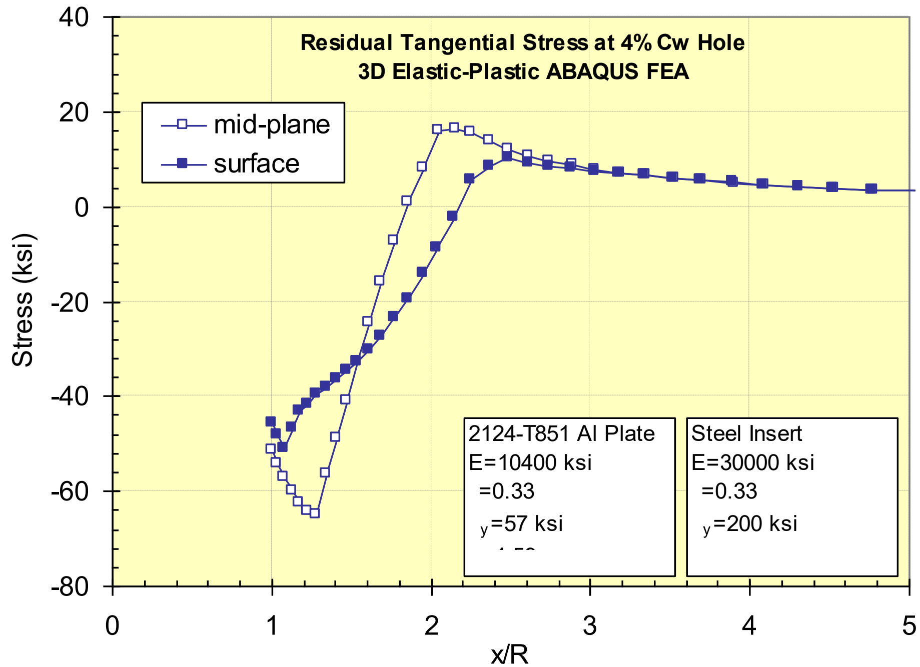
CW HOLE R&D: RESIDUAL STRESS ANALYSIS

STRESS ANALYSIS OF UNCRACKED HOLE - FEA (ABAQUS):

- Elastic-plastic analysis, kinematic hardening, bi-linear s-e curve
- Cold work process modeled as radial displacement (2-D) and release at hole perimeter
- 3-D FEM



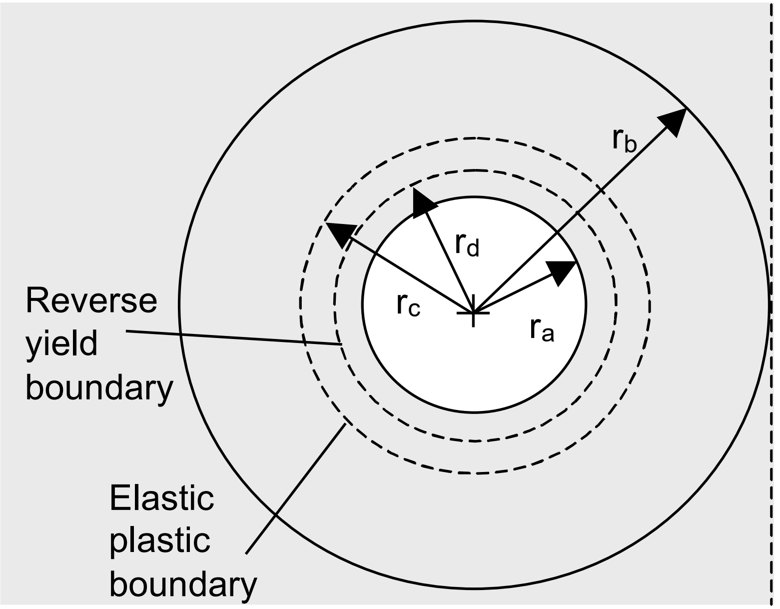
ABAQUS V6.3-2 3D FEA model of dogbone specimen (xy, xz, & yz symmetry



CW HOLE R&D: RESIDUAL STRESS ANALYSIS

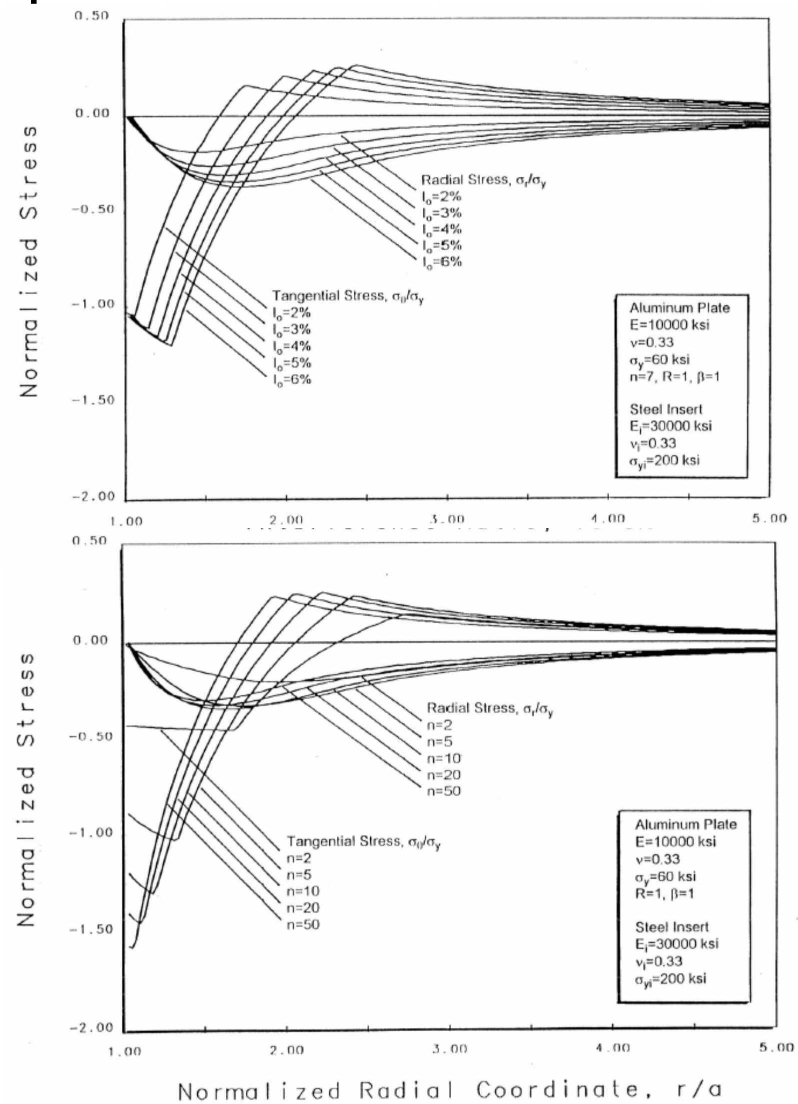
STRESS ANALYSIS OF UNCRACKED HOLES - CLOSED FORM SOLUTIONS:

- Assume axisymmetric thick walled cylinder (for eccentric holes, assume edge distance defines outer radius)
- 2D analysis (applied displacements are radial only)
- J_2 plasticity with kinematic hardening
- Plane stress solution due to G. Wanlin
- Plane strain solution due to G.S. Wang



CW HOLE R&D: RESIDUAL STRESS ANALYSIS

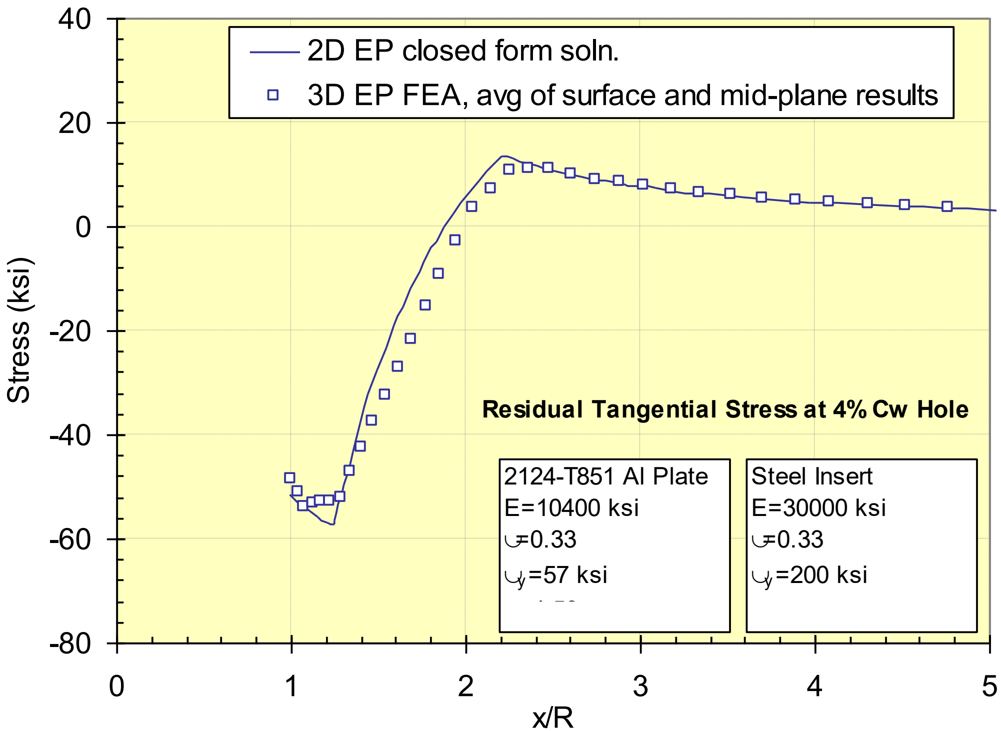
- Closed form solutions allow rapid, parametric evaluations of residual stress dependence on:
  - *Level of cold expansion*
  - *Mandrel and plate elastic constants*
  - *Plate material yield strength*
  - *Plate material strain hardening characteristics and cyclic plasticity behavior (isotropic, kinematic, mixed hardening)*
  - *Hole size and edge distance*
  - *Stress state (plane stress vs. plane strain)*



CW HOLE R&D: RESIDUAL STRESS ANALYSIS

STRESS ANALYSIS OF UNCRACKED HOLES:

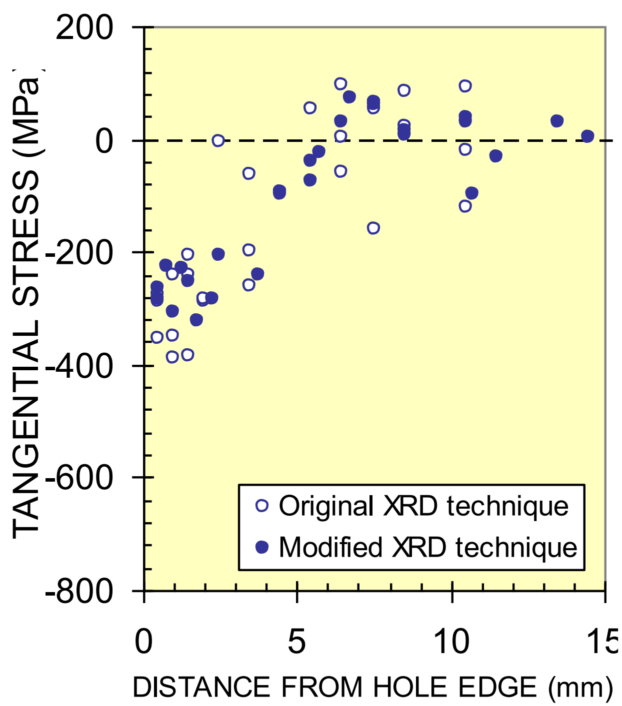
- Closed form solution for initial, cold work induced residual stress field compares favorably with FEA results



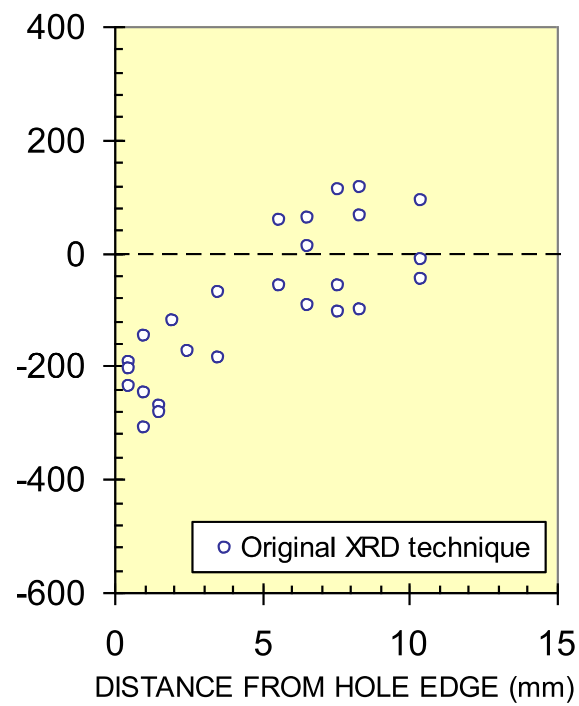
CW HOLE R&D: RESIDUAL STRESS ANALYSIS

EXPERIMENTAL VALIDATION

- X-Ray diffraction not suitable for quantitative analysis for most Al alloys under Cw conditions
  - Large grain size, texturing introduced large scatter in calculated residual stresses
  - Results do provide qualitative information regarding residual stress profiles



centered hole
e/D=5

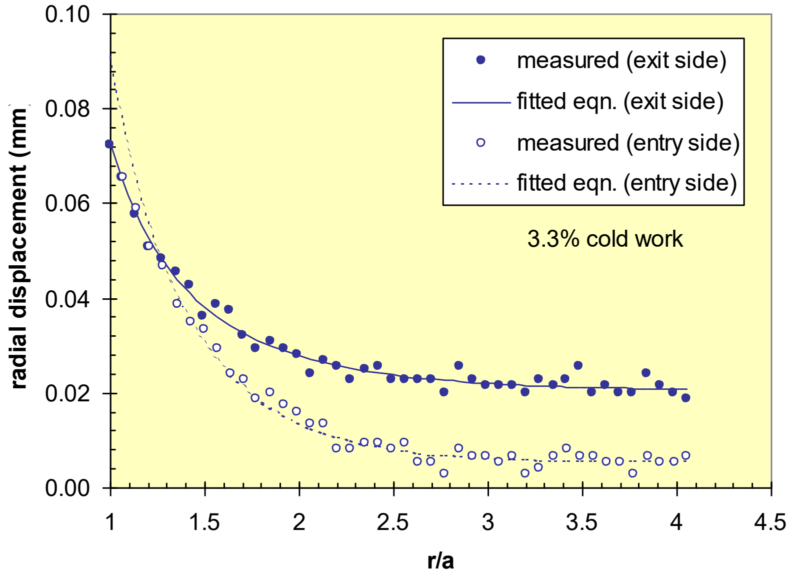


eccentric hole
e/D=2

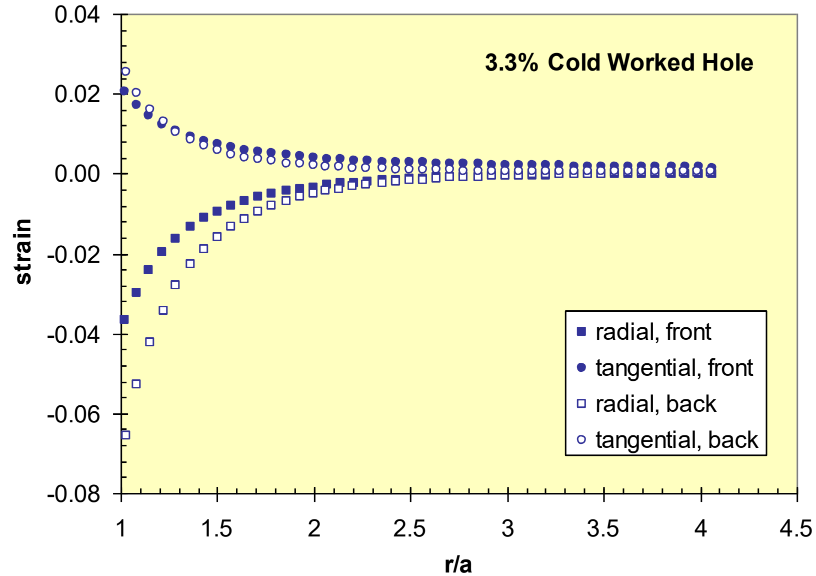
CW HOLE R&D: RESIDUAL STRESS ANALYSIS

EXPERIMENTAL VALIDATION (cont'd)

- Surface Displacement Mapping:
  - Rectangular grid painted on surface prior to Cw, positions of nodes (grid line intersections) measured before and after cold work
  - Strains calculated from displacements
  - Able to discriminate between entry and exit side residual strain profiles



Measured Residual Displacement Profiles



Calculated Residual Strain Profiles

CW HOLE R&D: RESIDUAL STRESS ANALYSIS

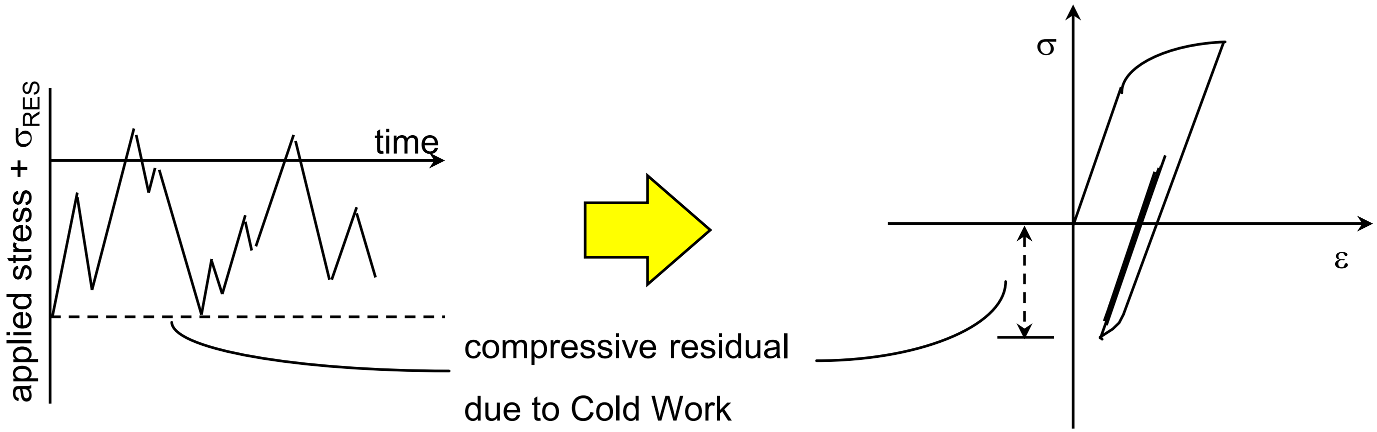
EVOLUTION OF RESIDUAL STRESS AND STRAIN FIELDS DURING FATIGUE LOADING:

- Initial, cold-work-induced residual stress and strain fields can be modified by tensile and compressive overloads experienced during subsequent fatigue loading.
- Tensile overload tends to reinforce compressive residual, beneficial impact on fatigue life
- Compressive overload can cause reverse yielding, reduction or elimination of compressive residual stress. This causes reduction in fatigue life benefit.

CW HOLE R&D: RESIDUAL STRESS ANALYSIS

STRESS ANALYSIS OF UNCRACKED HOLES – NOTCH PLASTICITY:

- Residual stress field evolution under tension dominated loading



Applied stress history

(R_{avg}>0)

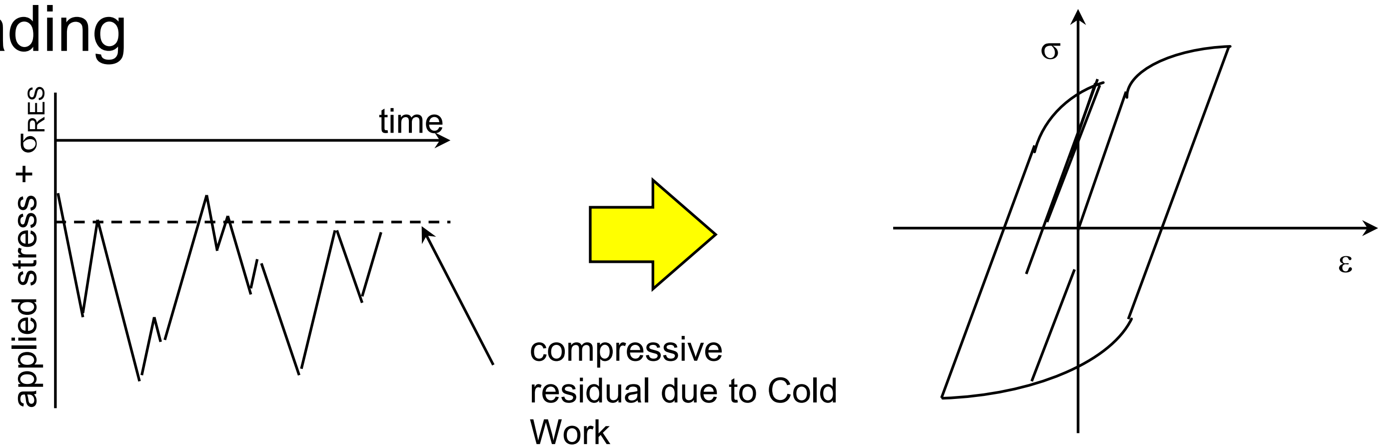
Response stresses and strains:

- Due to compressive residual, response cycles have lower mean than applied cycles
- Absence of compressive applied stresses minimizes chance of reverse yielding

CW HOLE R&D: RESIDUAL STRESS ANALYSIS

STRESS ANALYSIS OF UNCRACKED HOLES – NOTCH PLASTICITY (cont'd):

- Residual stress field evolution under compression dominated loading



Applied stress history

(R_{avg}<0)

Response stresses and strains:

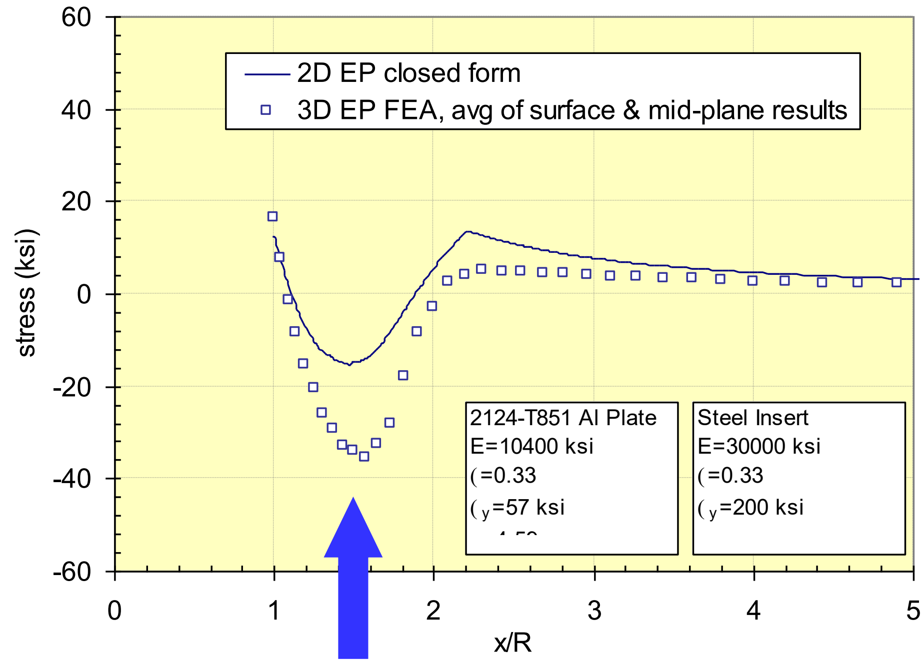
- Compressive underloads cause reverse yielding and eventual loss of compressive residual stress field

Engineered Residual Stress in Military Aircraft Structure

CW HOLE R&D: RESIDUAL STRESS ANALYSIS

RS FIELD EVOLUTION:

- Cyclic, elastic-plastic response in vicinity of cold worked hole estimated using both FEA and notch plasticity algorithm with cold work induced residual stresses and strains as initial condition



After removal of compression overload, much of Cw induced residual stress has been lost

CW HOLE R&D: FCI ANALYSIS

FATIGE CRACK INITIATION ANALYSIS WITH COLD WORK INDUCED RESIDUAL STRESS FIELDS:

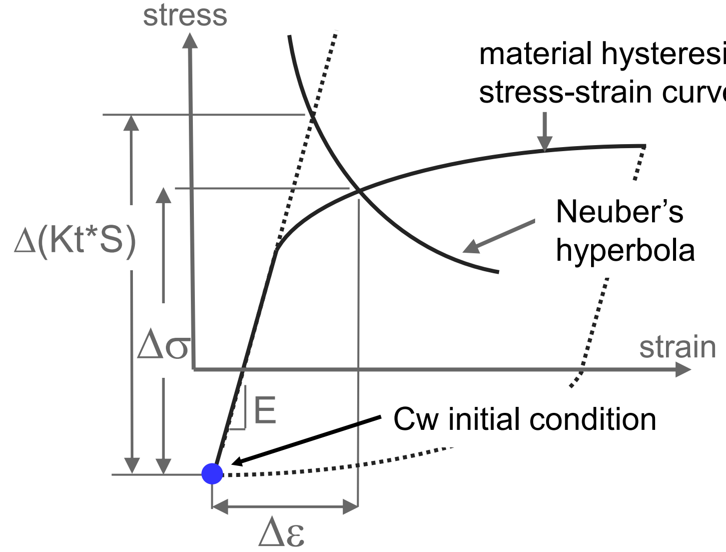
- Adaptation of industry standard stress-strain hysteresis loop tracking (LOOPIN)
- Calculate local stress-strain history
   - *Determine stress and strain at hole edge due to Cw*
   - *Hysteresis loop tracking starting from Cw initial condition*
- Calculate incremental damage
   - *Mean stress reduction at analysis point produces increase in crack initiation life*
- Sum damage, compute life

Engineered Residual Stress in Military Aircraft Structure

CW HOLE R&D: FCI ANALYSIS

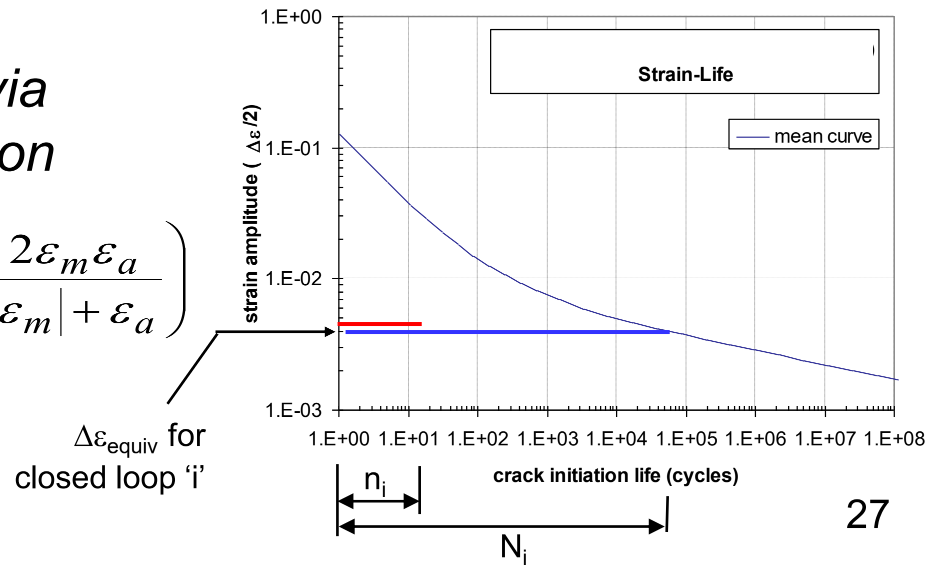
- Local stress-strain history
  - *Initial condition found from stress analysis of Cw process*
  - *Neuber's rule used for subsequent, cyclic stress-strain analysis*

$$\Delta\sigma\Delta\varepsilon = \frac{\left(SSF_{max}S_{max} - SSF_{min}S_{min}\right)^2}{E}$$



- Damage calculation
  - *Effect of mean stress introduced via equivalent strain amplitude equation*

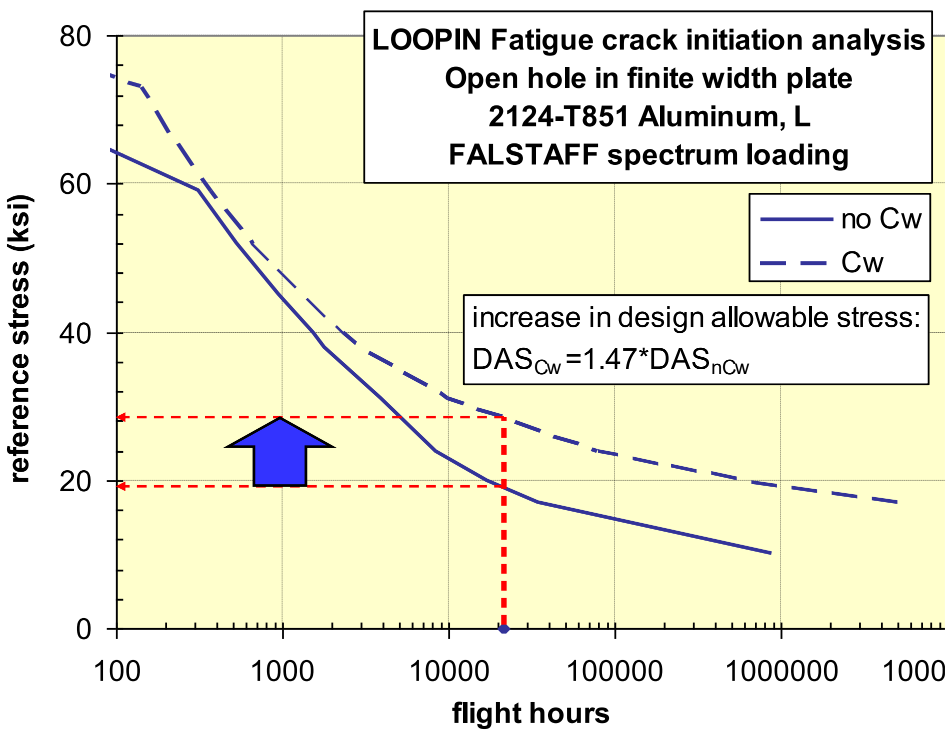
$$\left(\frac{\Delta\varepsilon}{2}\right)_{equiv,R=-1} = \left(\frac{\Delta\varepsilon}{2}\right) + A\left(\frac{2\sigma_m\sigma_a}{|\sigma_m| + \sigma_a}\right)\frac{1}{E} + B\left(\frac{2\varepsilon_m\varepsilon_a}{|\varepsilon_m| + \varepsilon_a}\right)$$

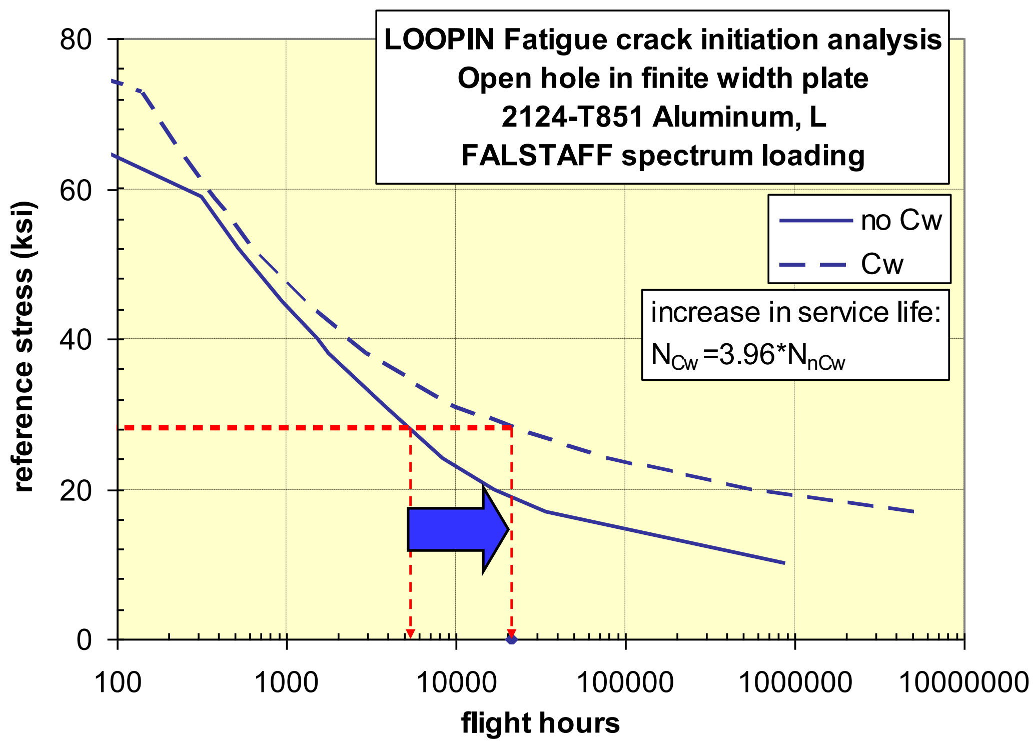


CW HOLE R&D: FCI ANALYSIS

FCI ANALYSIS ALLOWS CALCULATION OF Cw EFFECT:

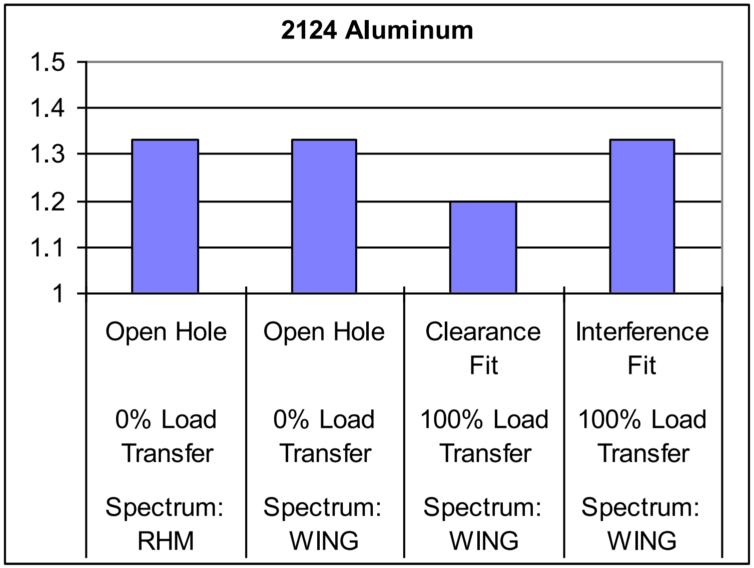
- For tension dominated loading, approx 50% increase in DAS (depending on nominal stress)
- For tension dominated loading, approx 4x increase in life

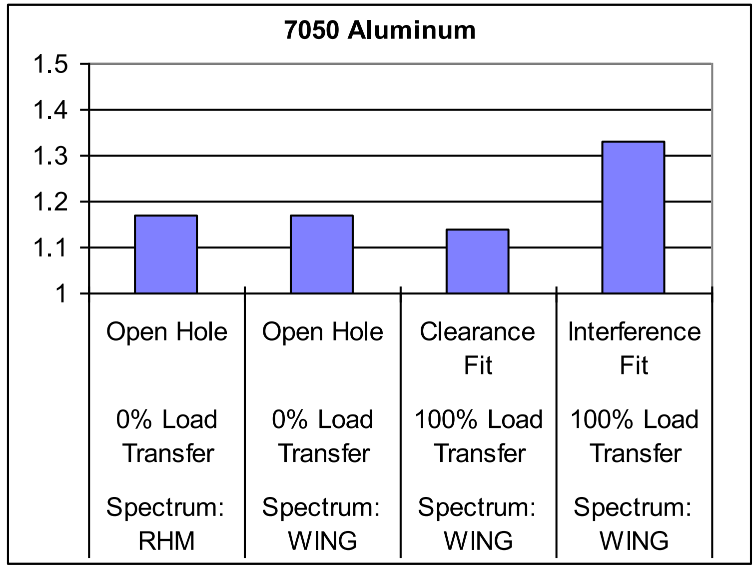




CW HOLE R&D: FCI ANALYSIS

- Test demonstrated life improvement factors for various geometry and spectrum types
  - Minimum 15% improvement in allowable stress obtainable with cold work





CW HOLE R&D: FCG ANALYSIS

FATIGE CRACK GROWTH ANALYSIS WITH COLD WORK INDUCED RESIDUAL STRESS FIELDS :

- Standard LEFM approach
- Calculate stress intensity factors (SIF)
  - *Green's function approach*
  - *Compute applied SIF and residual SIF and sum*
  - *Adjust for load interaction, closure*
- Calculate fatigue crack growth rate
- Increment crack size
- Repeat until K>Kc or c>cmax

CW HOLE R&D: FCG ANALYSIS

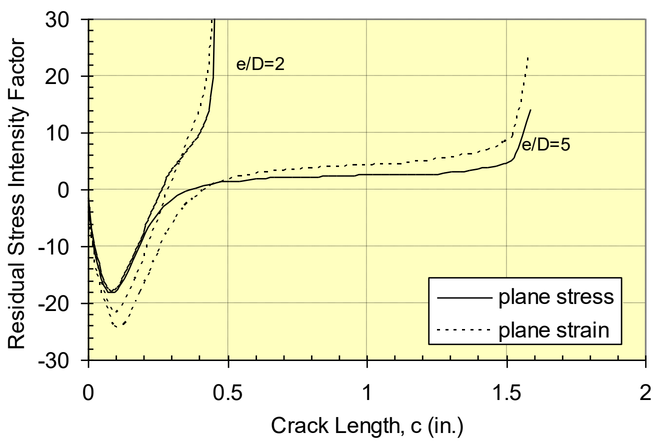
CALCULATION OF SIF – GREEN'S FUNCTION APPROACH:

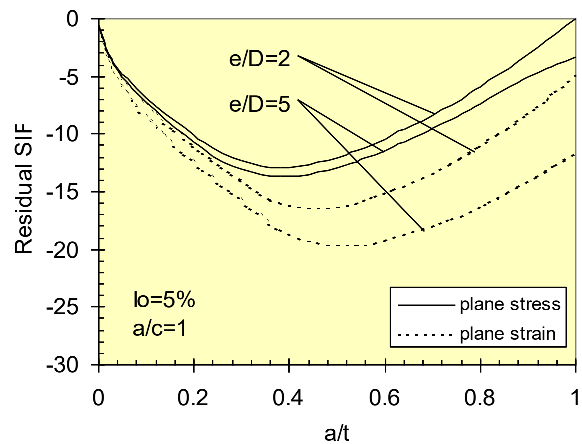
- For 1-D (thu thickness) crack at hole

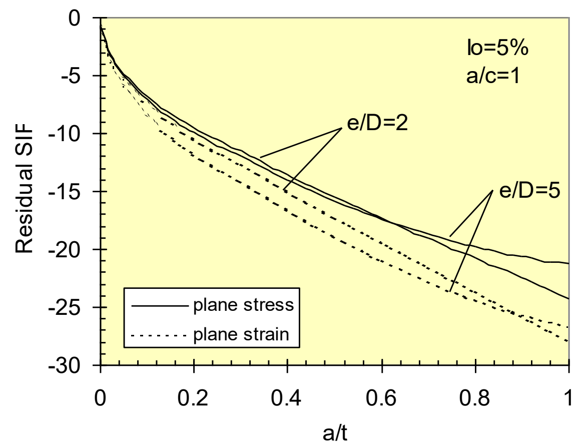
$$K_I = \int_c \sigma_y(x) G(x,c) t dx$$

- For 2-D (corner) crack at hole

$$K_I = \frac{1}{(\pi c)^{3/2}} \int_0^{\pi/2} \int_0^{r_f} \sigma(r,\theta) G(R,b,t,a,c) r_L dr_L d\theta_L$$



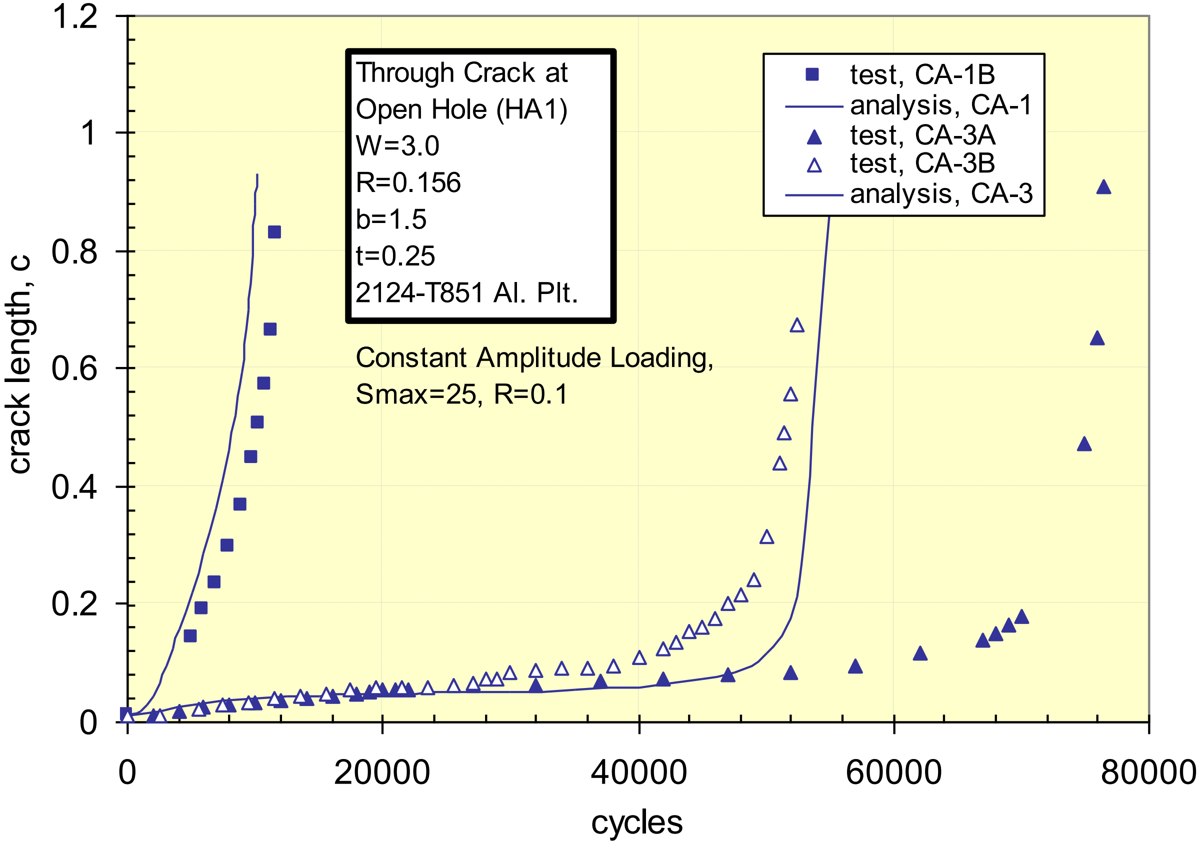




CW HOLE R&D: FCG ANALYSIS

COMPARISON WITH EXPERIMENT:

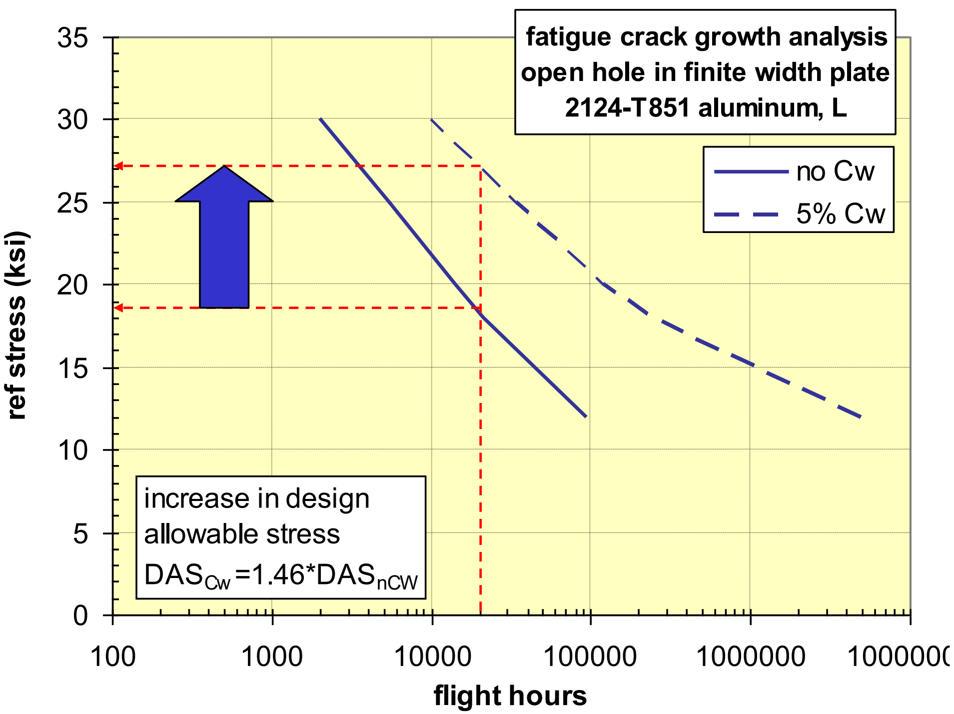
- R=0.1 CA loading after 4% cold expansion – 5x to 7x increase in life

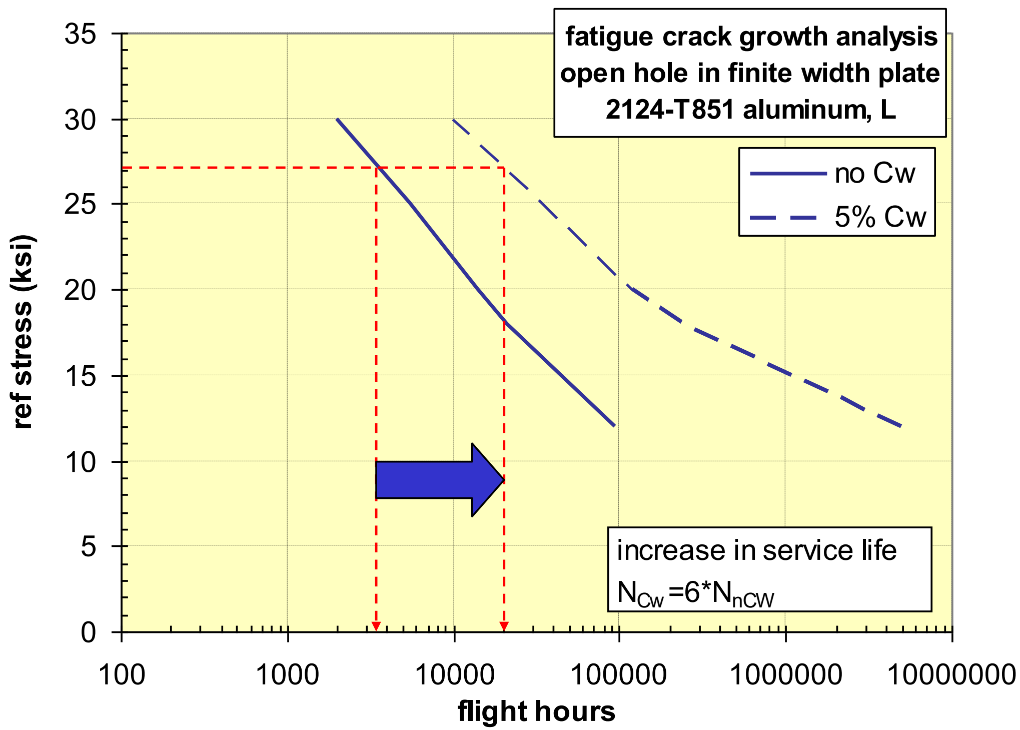


CW HOLE R&D: FCG ANALYSIS

FCG ANALYSIS ALLOWS CALCULATION OF Cw EFFECT:

- For tension dominated loading, approx 50% increase in DAS (depending on nominal stress)
- For tension dominated loading, approx 6x increase in life



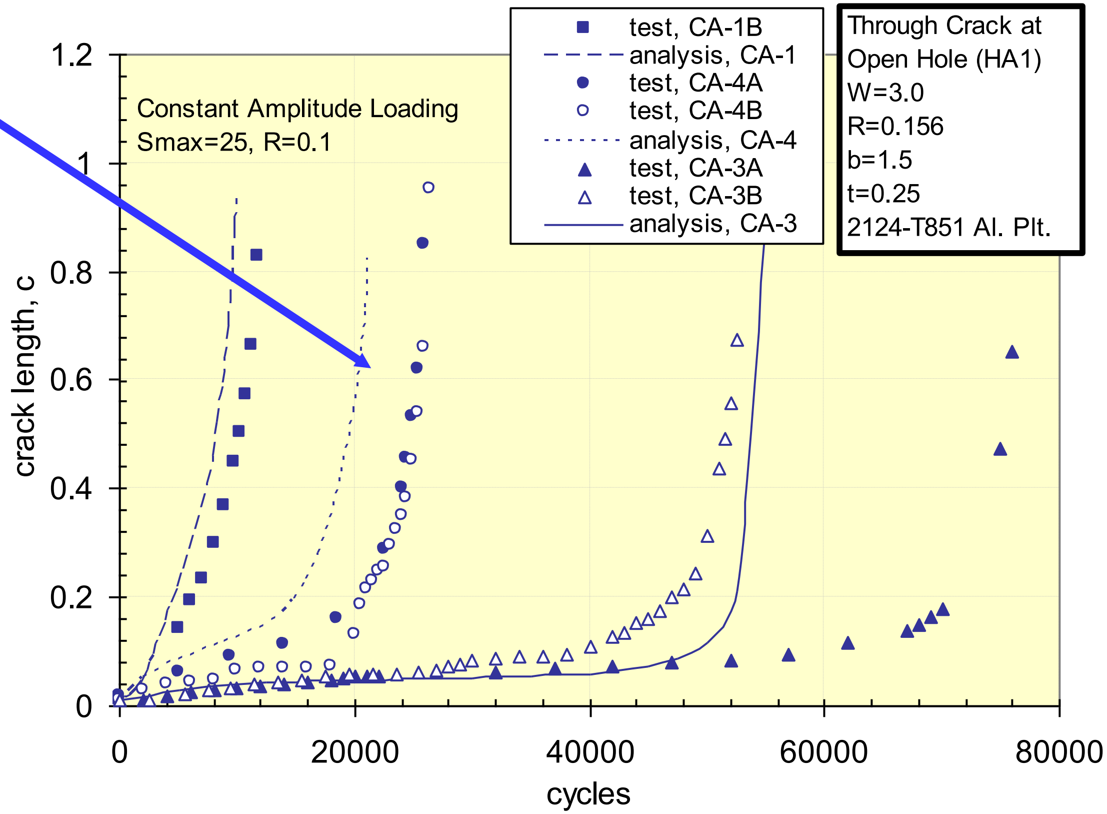


CW HOLE R&D: FCG ANALYSIS

ELASTIC-PLASTIC FCG REQUIRED TO SIMULATE LOSS OF CW RS FIELD DUE TO COMPRESSION OVERLOAD:

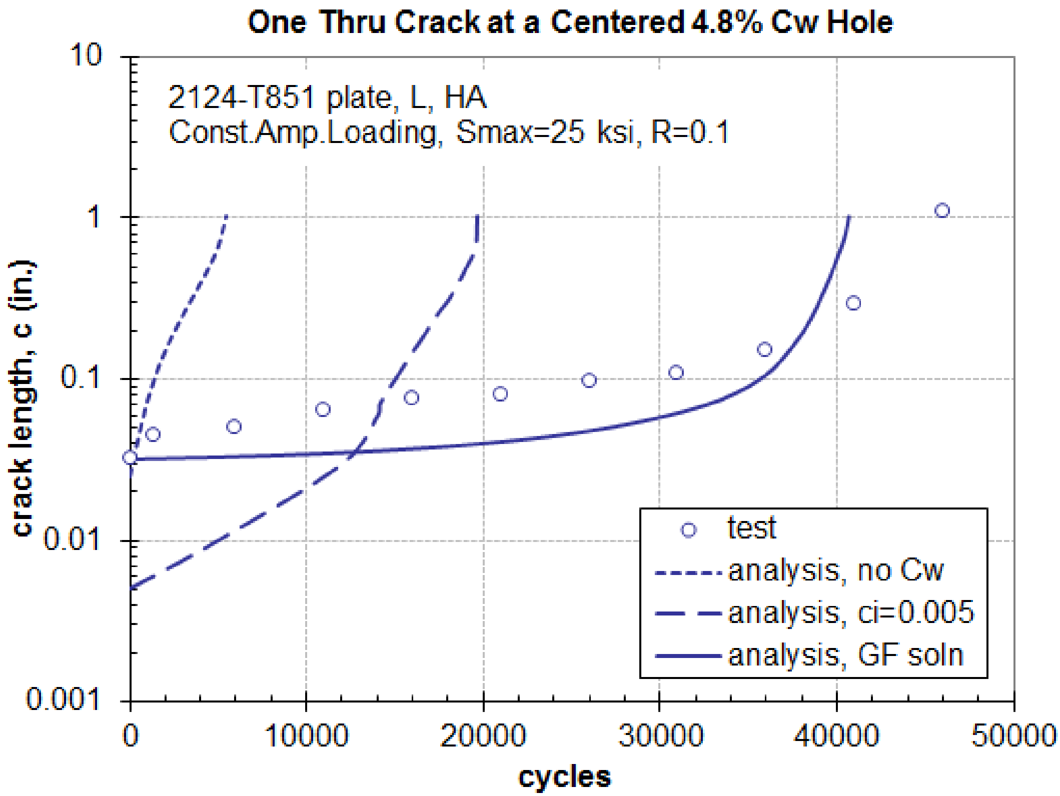
- 4% cold expansion, -25 ksi overload, R=0.1 CA loading – life improvement factor reduced from about 5 to 7 down to about 2

LOSS OF COMPRESSIVE RESIDUAL RESULTS IN REDUCED AMOUNT OF LIFE EXTENSION



CW HOLE R&D: FCG ANALYSIS

- Strong motivation for explicit inclusion of cold work induced residual stress field in FCG analysis
  - *EIFS approach does not address underlying mechanics of the problem*
  - *EIFS approach can be conservative (compared to test) in some cases*
  - *EIFS approach does not produce correct crack growth curve shape, which can be significant for IAT / maintenance planning*



Engineered Residual Stress in Military Aircraft Structure

- **STRUCTURES POLICY**
  - ***Shot Peening***
  - ***Laser Peening***
  - ***Hole Cold-working***
- **Cold-worked hole r&d**
  - ***Residual Stress Analysis***
  - ***Fatigue Crack Initiation Analysis***
  - ***Fatigue Crack Growth Analysis***
- **CONCLUSIONS**

CONCLUSIONS

- Very heavy reliance on engineered residual stresses for mitigation of life short-falls, and for service life extensions on almost all products
- Restrictions are imposed for large compression loads, short eoD etc.
- Extensive testing required to determine / validate design factors / life extension available
- Current standard analysis procedures (for cold worked holes) are based on reduction factors (FCI) or EIFS (FCG) – these methods do not address mechanics of Cw process and may not allow full utilization of Cw benefit

CONCLUSIONS

- Methods that do address appropriate mechanics are available and may improve use / optimization of Cw in design and service life extension
  - *Closed form solutions for residual stress / strain fields due to cold expansion, explicit dependence on most material, geometric and Cw process parameters*
  - *Notch plasticity algorithm gives estimated response stress distribution on critical plane*
  - *Green's function approach gives SIF based on response stress distribution*
  - *Model captures effects of both initial Cw induced residual stresses and subsequent modification of residual profiles due to notch plasticity*
  - *Effects of crack closure must be studied further, current treatment is inadequate*

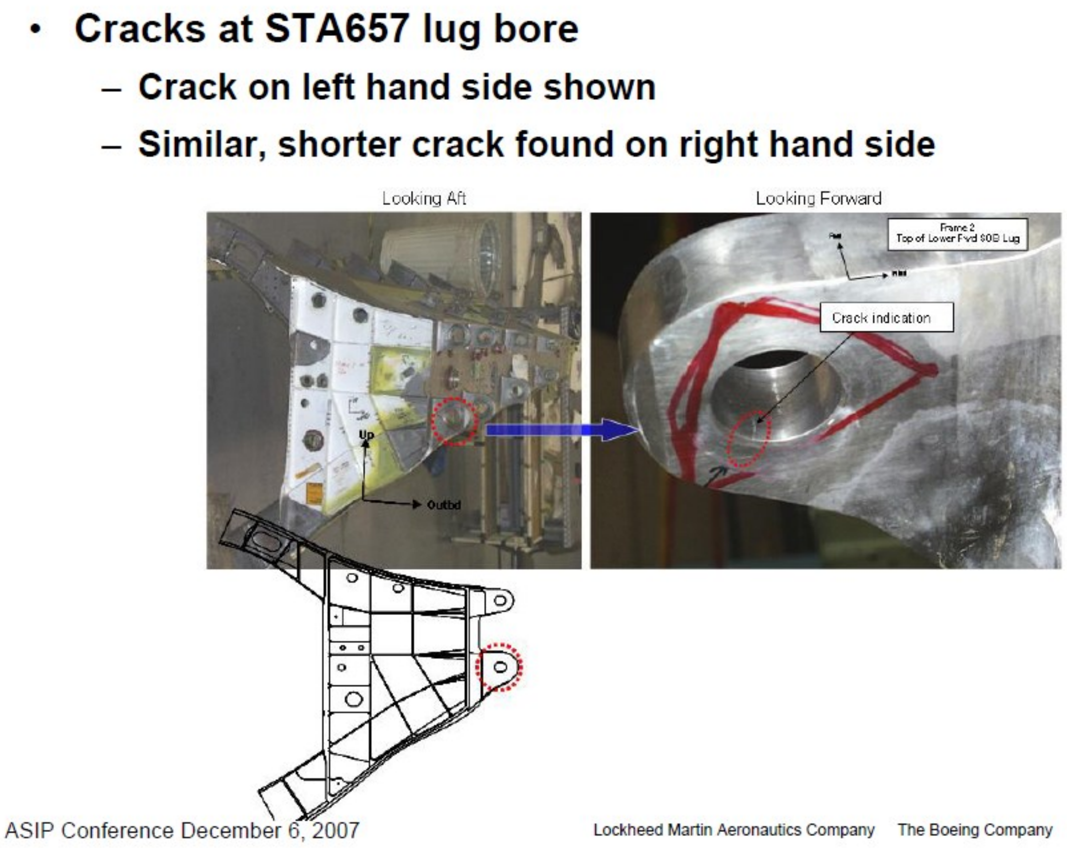
Using Engineered Residual Stresses to Eliminate Damage Tolerance Inspections

Jeffrey Bunch
The Boeing Company

Bibliography

- Test Demonstrated Damage Tolerance of F-22 Wing-Attach Lugs with ForceMate™ Bushings, 2007 ASIP Conference
- Application of Surface Residual Stresses for Durability and Damage Tolerance Improvements in F-22 Wing Attachment Lugs, 2009 ASIP Conference
- Full Scale Component Tests to Validate the Effects of Laser Shock Peening, 2011 ASIP Conference
- Adaptation of LSP Capability for Use on F-22 Raptor Primary Structure at an Aircraft Modification Depot, 2nd International Conference on Laser Peening, 2010

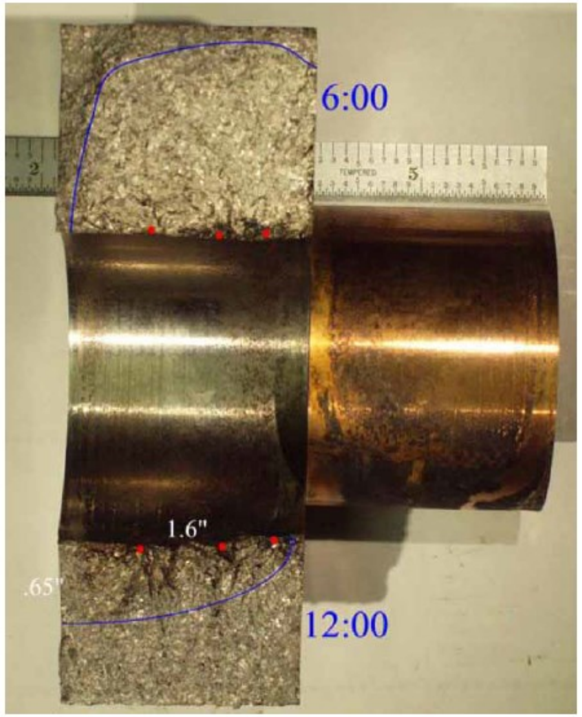
Wing attach lug bore



- Full scale fatigue test result . . .
  - Significant cracks at wing attach lug
  - Lugs on both left and right hand sides cracked

Crack initiation due to fretting

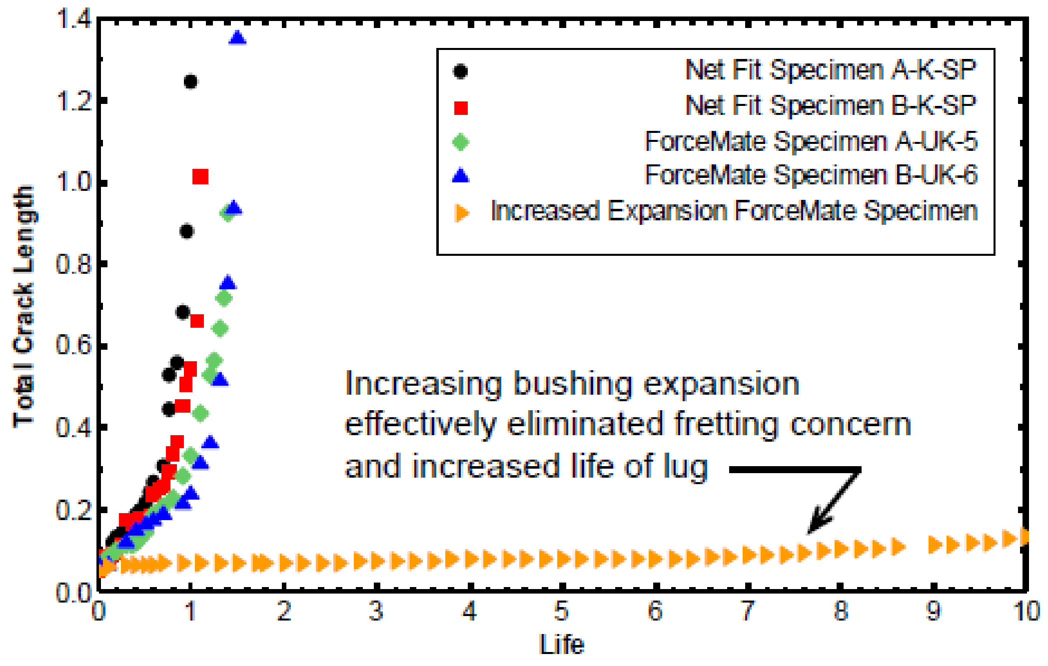
- Crack initiated along bore
  - Multiple initiation sites on both sides of bore
  - Pre-crack at EDM notch did not contribute to failure
- Evidence of fretting and galling observed on bushing and lug bore



- Component tests replicated cracking observed on FSFT
  - Identified fretting as cause of cracking
  - Insufficient cold work
  - Modified application to increase cold work

Inspections Eliminated with Design Change to Bushing

- **To increase damage tolerance capability and mitigate crack initiation due to fretting**
  - **Bushing expansion level increased**



ASIP Conference December 6, 2007 Lockheed Martin Aeronautics Company The Boeing Company

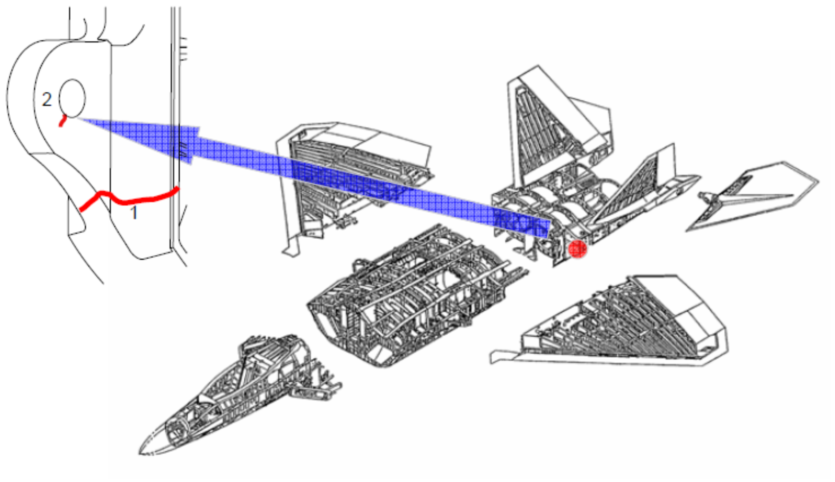
- Increasing level of cold work increased damage tolerance life
- Eliminated multiple inspections
- Eliminated cost of wing removals for inspection access
- Lesson learned: Don't assume residual stress benefit is automatic
  - i.e. Understand the parameters that impact residual stress levels

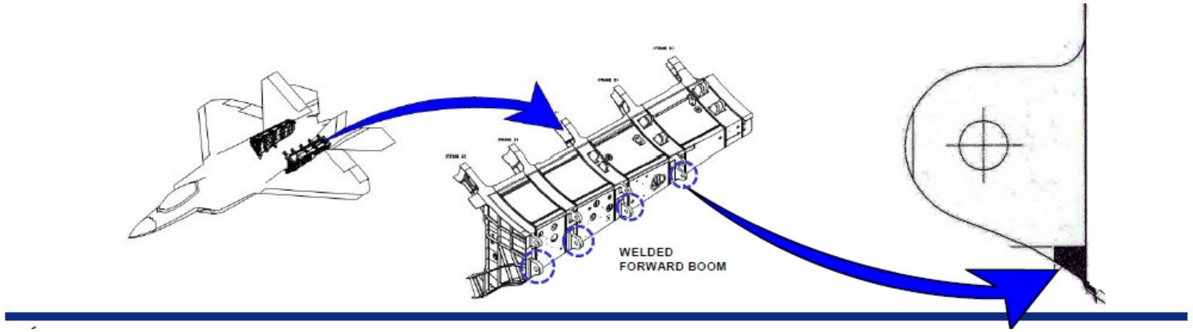
Surface residual stresses at fillet radii

Crack "1" discovered and repaired at 1.2 lifetimes

Crack "2" dicovered during teardown after 2.5 lifetimes

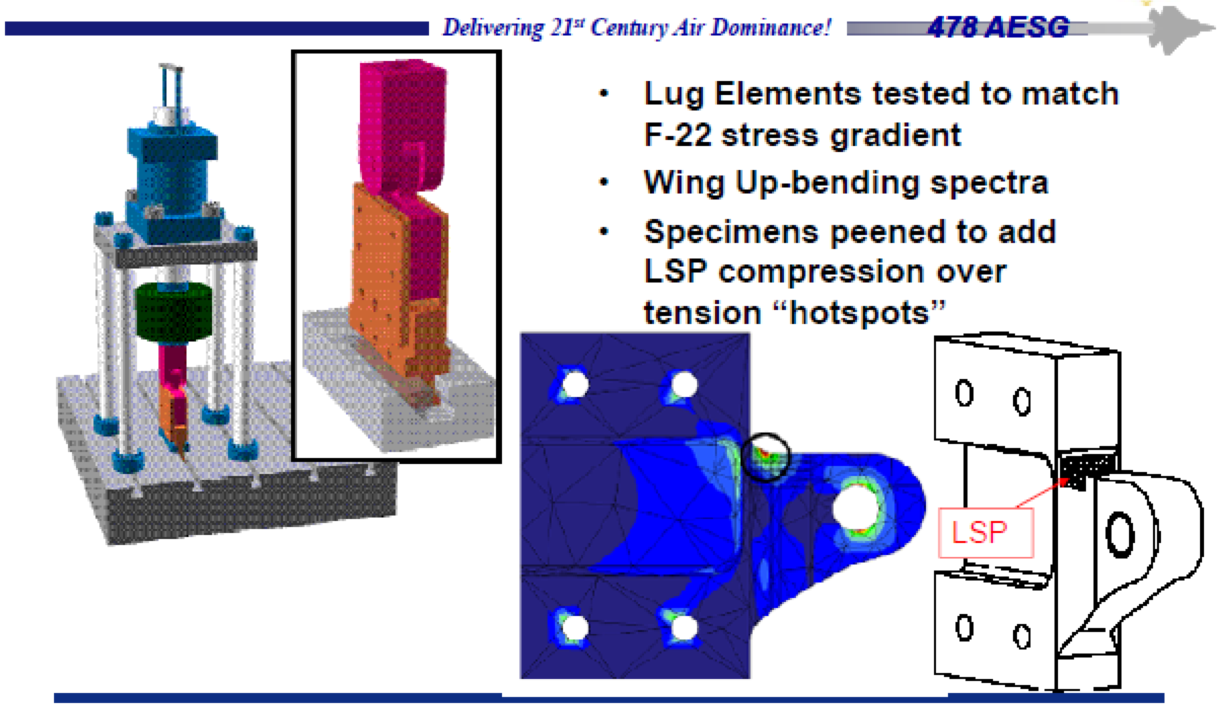
Similar cracking on left and right hand sides





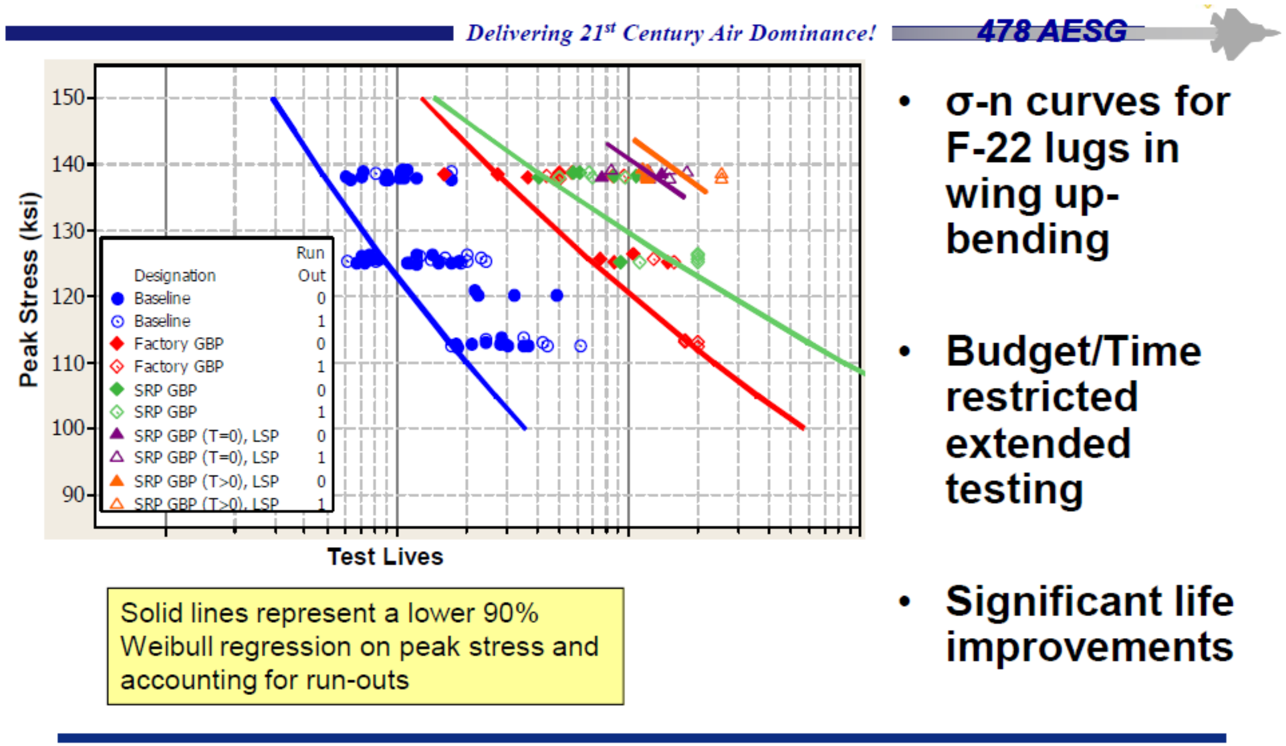
- In addition to crack at lug bore
- Cracks observed on lower fillet radii at multiple wing stations
- Limited repair options if cracks found
  - Needed pre-emptive intervention to prevent cracks

Building block test verification



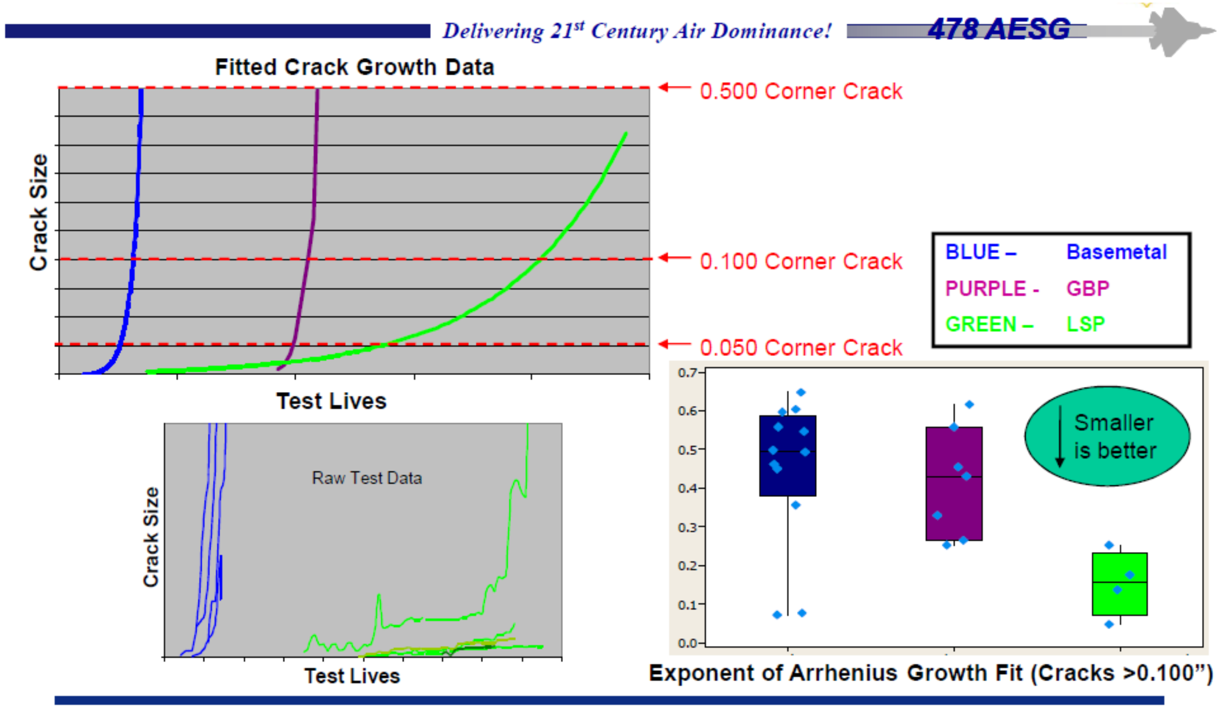
- Component test program developed to investigate fatigue life improvement
- Multiple configurations
  - Baseline (no peening)
  - Glass bead peen (GBP)
  - Laser shock peen (LSP)
  - GBP + LSP

Impressive Crack Initiation Benefit of Peening



- Crack initiation improvement impressive
- But not sufficiently better than GBP to justify cost

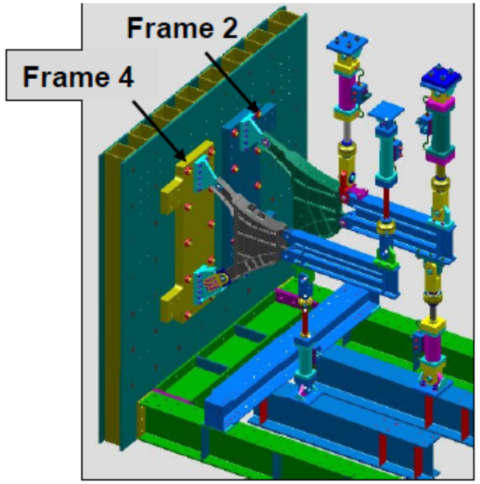
Potential crack growth benefit more impressive



- Crack Growth results on the other hand . . .
  - . . . Indicated LSP could significantly reduce inspection intervals
  - . . . If validated on full scale components

Significant Test Program to Validate Benefit

- **Test Objectives**
  - **Validate test setup to match Full Scale Fatigue Test**
  - **Establish baseline life**
  - **Obtain crack growth fatigue data**
  - **Validate benefit of LSP over GBP**
    - **Durability**
    - **Crack growth**



Fatigue Test Setup

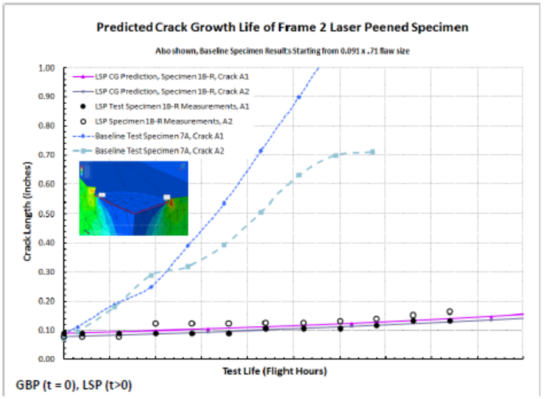
CONFIGURATION *	BASELINE	GBP	LSP over GBP
Frame 2 Durability	x 2	X	X
Frame 2 Crack Growth	X		X
Frame 4 Durability	x 2		X
Frame 4 Crack Growth	x 3		x 2

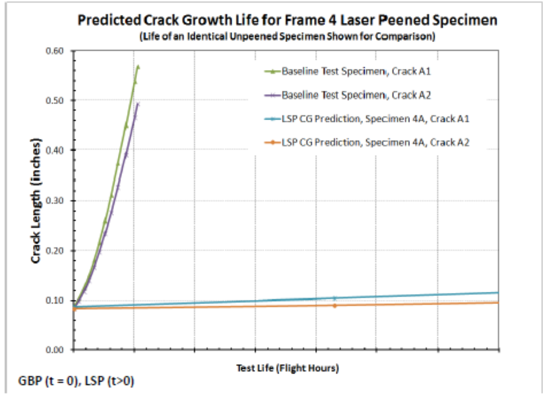
** Test articles produced from Ti-6Al-4V F-22 Production Die Forgings*

- Multiple full scale components including pre-cracked damage tolerance tests

Results:
Damage Tolerance Benefit Predicted and Validated

- **LSP over GBP applied to full scale frames at same flight hour requirements as structures retrofit aircraft**
- **Frames pre-cracked prior to LSP in order to gather CG data**
- **Test Results:**
  - **LSP successfully retards cracks in thick titanium structure**
  - **Validates subcomponent findings [2]**



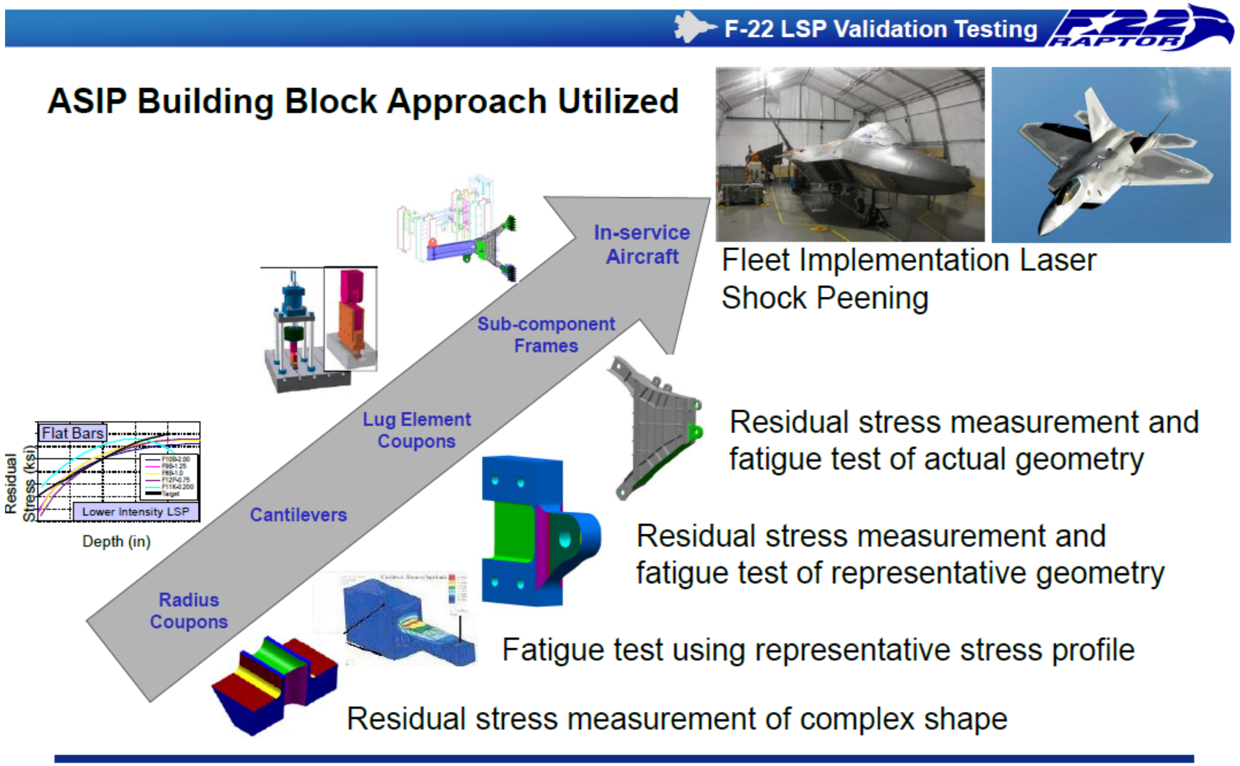


BOEING

[2] Reference R. Bair, et. al., "Application of Surface Residual Stresses for Durability and Damage Tolerance Improvements in Wing Attachment Lugs", 2009 ASIP Conference, Jacksonville, FL.

- Significant inspection relief achieved by implementation of LSP
- Residual stress profile predicted and modeled
- Damage tolerance predictions validated by test

Goal Achieved



- Results achieved
  - Eliminated expensive and intrusive inspections
  - Improved flight safety
  - Reduced cost of ownership
- Methodology
  - Multi-year test program
  - 2000 lbs of titanium converted to test specimens
- How can engineered residual stresses find wider application at lower cost?

Design guides discourage use of engineered residual Stresses

- Design guides drive toward goal of weight efficient design without considering residual stress benefits
- From JSSG 2006: To maximize safety of flight and to minimize the impact of potential manufacturing errors, it should be a goal to achieve compliance with the damage tolerance requirements of this specification without considering the beneficial effects of specific joint design and assembly procedures such as interference fasteners, cold expanded holes, or joint clamp-up. In general, this goal should be considered as a policy but exceptions can be considered on an individual basis. The limits of the beneficial effects to be used in design should be no greater than the benefit derived by assuming a .005 inch radius corner flaw at one side of an as-manufactured, non-expanded hole containing a neat fit fastener in a non-clamped-up joint. A situation that might be considered an exception would be one involving a localized area of the structure involving a small number of fasteners. In any exception, the burden of proof of compliance by analysis, inspection, and test is the responsibility of the contractor.
- Language of design guides drives discussion for sustainment even though requirements are different.

Modifications to guidelines needed to reflect sustainment realities and to promote a culture of accepting the benefit of residual stresses
Culture of acceptance backed by test and experience

Engineered Residual Stress for Damage Tolerance Benefit

- Path to broader acceptance
  - Standardization of processes
    - Process specifications should result in definable benefit
    - Benefit obtained from residual stress must be independent of vendor
    - Variables affecting level of benefit should be predictable
  - Broader acceptance of prediction and measurement methods
    - Challenge of education→ and building user base

Analysis Methods: Residual Stress Implementation

Engineered Residual Stress Implementation Workshop 2016
September 15, 2016

Robert Pilarczyk
Principal Engineer, Hill Engineering, LLC
rtpilarczyk@hill-engineering.com
Phone: 801-391-2682

Michael R. Hill, Ph.D.
Founder and CEO, Hill Engineering, LLC
mrhill@hill-engineering.com
Phone: 530-304-7296

HILL ENGINEERING
Predict. Test. Perform.

ERSI

Acknowledgements

- A-10 & T-38 Aircraft Structural Integrity Teams
- Air Force Research Lab
- Analytical Processes/Engineering Solutions (AP/ES), Inc.
- Southwest Research Institute (SwRI)

Historical

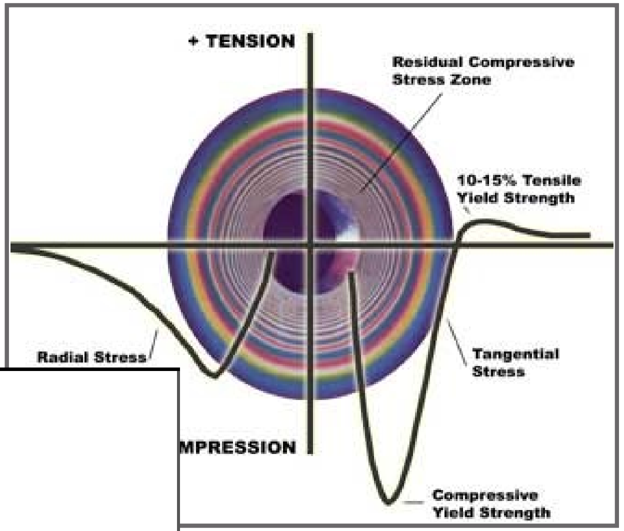
Residual Stress is considered a problem or used as a *band-aid* to address design deficiencies

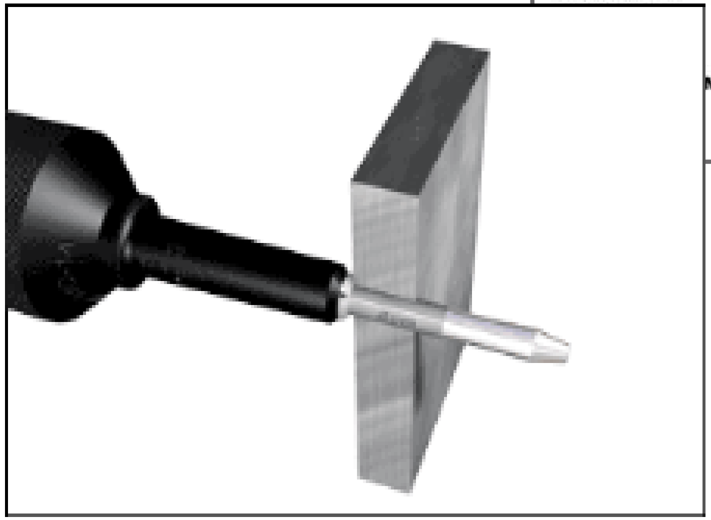
Emerging

Residual Stress Engineering is a *conventional technology* that assures performance

Overview/Outline

- The talk is about analysis methods for residual stress effects on fatigue crack growth:
  - Classic USAF approach
  - Past struggles
  - Recommended framework
  - Recent keys to success
  - Focus areas moving forward

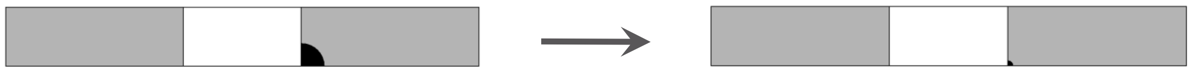


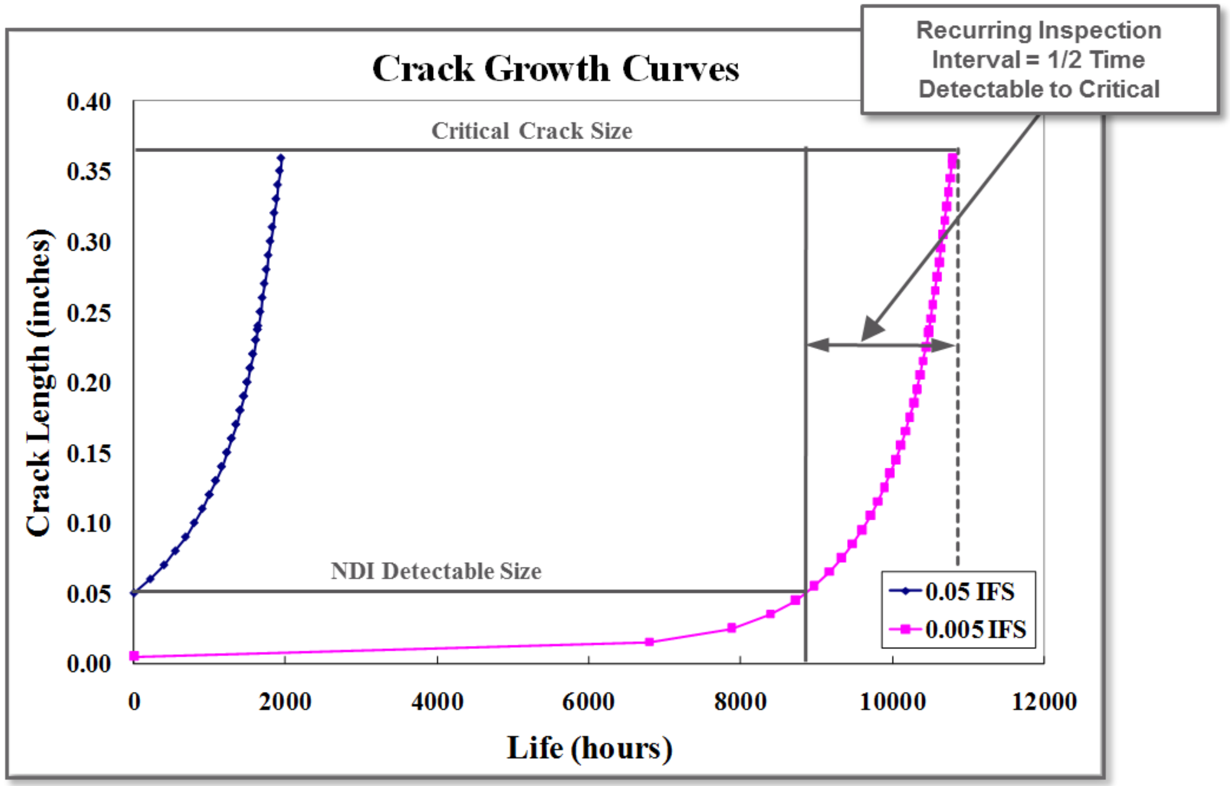


Fatigue Technology, Inc.

Classical USAF Approach

- Reduce Initial Flaw Size in Damage Tolerance Analysis
  - Based upon guidance from JSSG-2006
- Limitations of this approach
  - NOT PHYSICS BASED
  - One size fits all…
  - Doesn't account for:
    - Residual Stress (RS) field
    - Changes/Interaction between RS field and geometric notches
    - Crack shape evolution
  - Limited benefit in sustainment scenarios
    - Recurring inspection intervals based on NDI Detectable Flaw Size





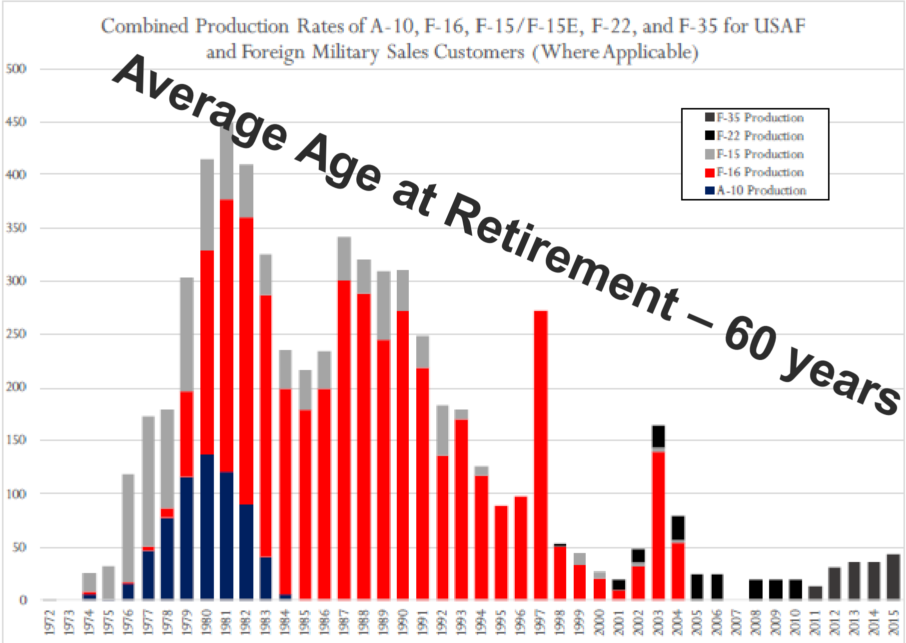
Classical USAF Approach

- Life Enhancement Processes:
  - To maximize safety of flight and to minimize the impact of potential manufacturing errors, it should be a goal to achieve compliance with the damage tolerance requirements of this specification without considering the beneficial effects of specific joint design and assembly procedures such as interference fasteners, cold expanded holes, or joint clamp-up. In general, this goal should be considered as a policy but exceptions can be considered on an individual basis. The limits of the beneficial effects to be used in design should be no greater than the benefit derived by assuming a .005 inch radius corner flaw at one side of an as-manufactured, non-expanded hole containing a neat fit fastener in a non-clamped-up joint. A situation that might be considered an exception would be one involving a localized area of the structure involving a small number of fasteners. In any exception, the burden of proof of compliance by analysis, inspection, and test is the responsibility of the contractor (us).

Classical USAF Approach

- ❑ **WHY MUST WE MOVE BEYOND THE CLASSICAL APPROACH???**
- ❑ **DoD annual depot maintenance budget - any guesses??**

➢ USAF Active Duty	$2,498,700,000
➢ Army Active Duty	$1,001,200,000
➢ Navy Active Duty	$8,191,200,000
➢ Marine Corps Active Duty	$229,100,000
➢ USAF Reserve	$407,900,000
➢ Army Reserve	$58,800,000
➢ Navy Reserve	$101,700,000
➢ Marine Corps Reserve	$18,400,000
	$12,507,000,000



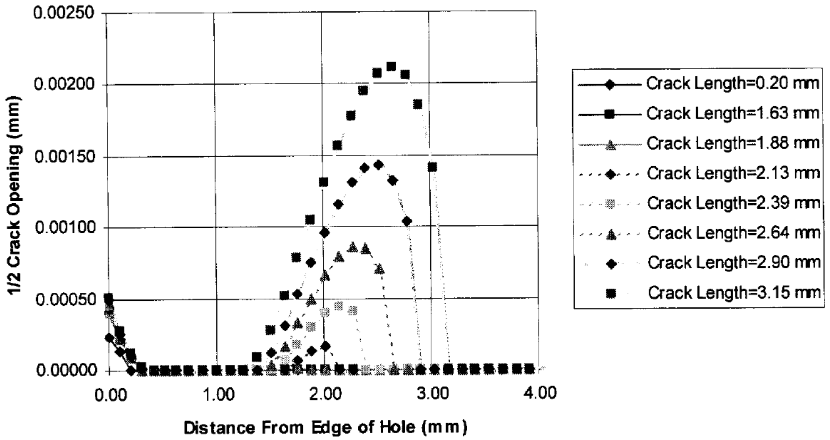
Carlson, Gen Bruce (Ret.); Thomsen, M; Pilarczyk, R; Carlson, S; Developing the State-of-the-Art Aerospace Workforce within the State of Utah – Ensuring Integrity of the Aging Aerospace Fleet; (2016).

We Have 12.5 Billion Reasons to Sharpen Our Pencils…

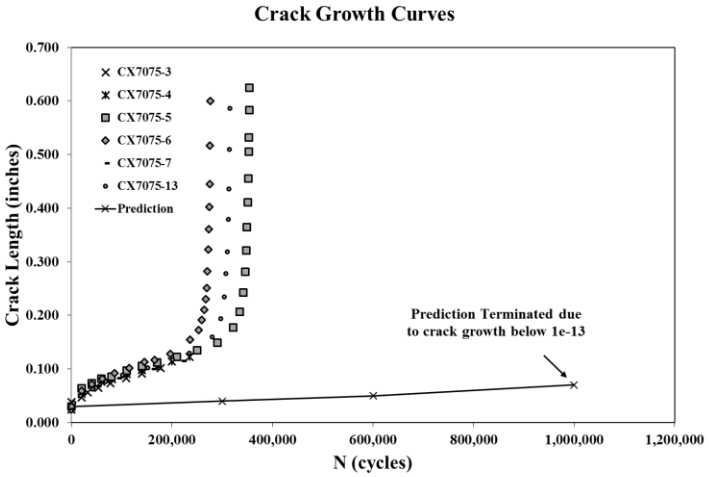
Understanding & Incorporating Engineered Residual Stresses are Key to Safely Minimize Sustainment Costs and Extend the Lifetimes of Our Aging Fleets

Past Struggles

- ❑ **Predictions often not consistent with expectations**
  - ➢ Terminate for zero growth
  - ➢ Predictions far exceed test lives
- ❑ **Why?**
  - ➢ Incorrect residual stress inputs/assumptions
  - ➢ No data capturing full 2-D residual stress on crack plane
  - ➢ 2-D stress intensity methodology
    - Crack cannot "ooze"
    - Assumed elliptical crack fronts

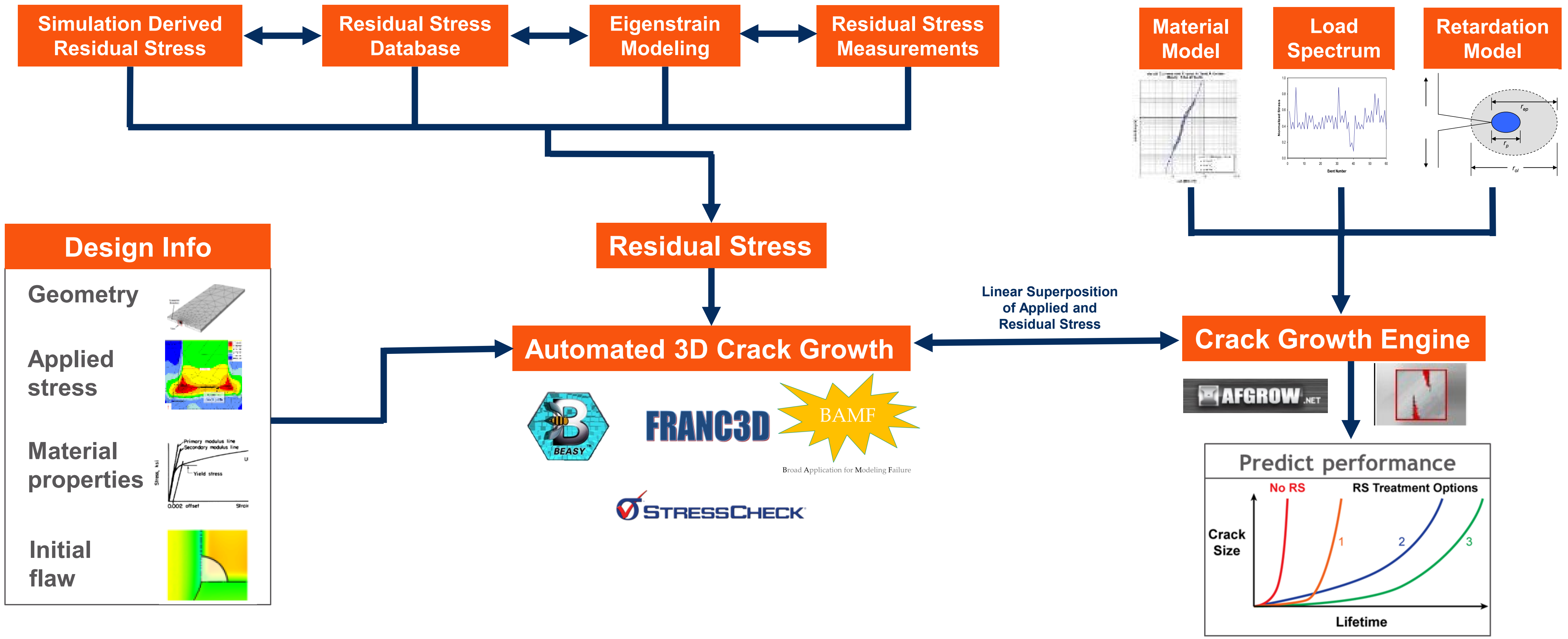


Kokaly, M.T.; Ransom, J.S.; Restis, J.H.; Reid, L.F.; (2002) Prediction fatigue crack growth in the residual stress field of a cold worked hole. Journal of Testing and Evaluation. 20, 1-15.



Recommended Approach

Analysis Approach

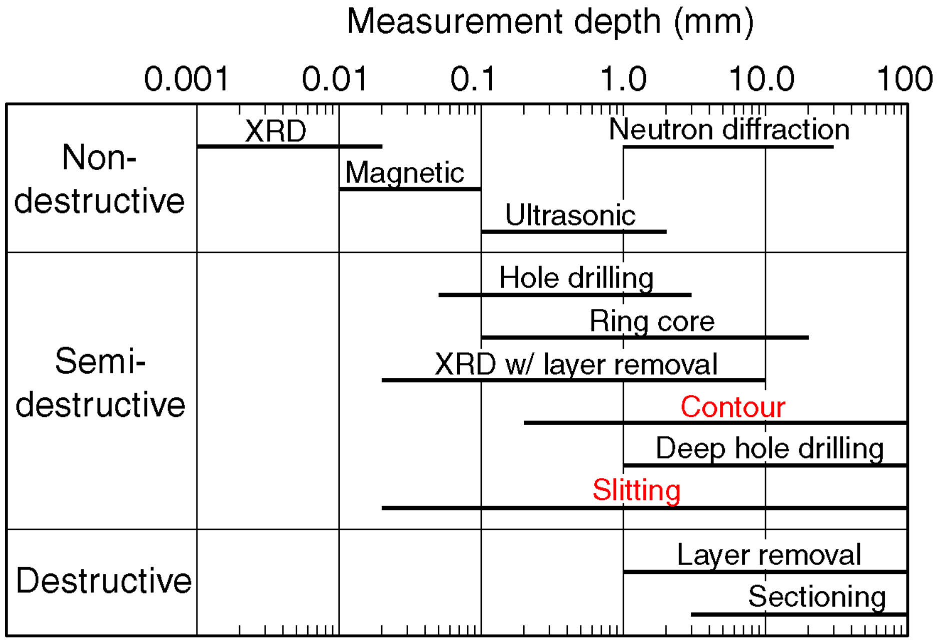


Recent Keys to Success

Direct Incorporation of Residual Stresses

- ❑ Residual Stress Measurement is Challenging
  - ➢ No direct measurement of residual stress
    - Typically measure strain then calculate residual stress
- ❑ Variety of accepted RS measurement methods
  - ➢ Each method has advantages and disadvantages
  - ➢ Select method based on needs of application:
    - Stress field to be measured:
      - Depth of RS
      - Stress gradients, spatial variations
      - Number of RS components
    - Body containing the stress
      - Geometry, size
      - Material property variations
      - Hazards
    - Required accuracy, uncertainty
    - Other factors to consider:
      - Destructiveness
      - Required equipment
      - Measurement time
      - Cost
      - Portability
      - Required expertise
      - Material handling

Three classes of technique:
- Diffraction (E beams)
- Mechanical (cut, deform)
- Other (physics-based)

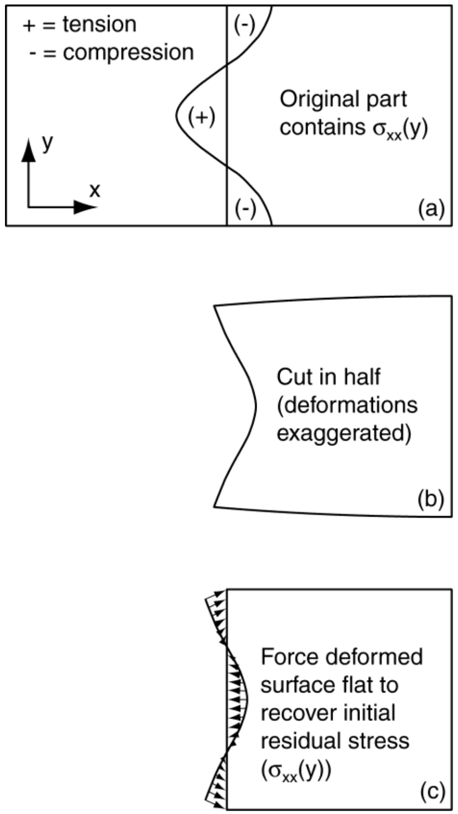


After: Prime, www.lanl.gov/residual/compare.shtml

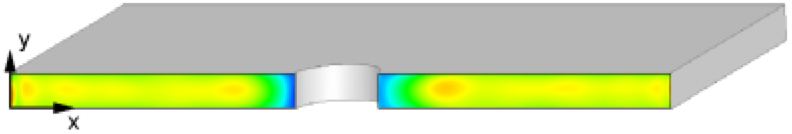
Direct Incorporation of Residual Stresses

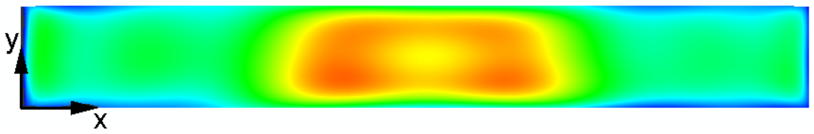
- Contour Method
  - generates a 2D map of residual stress normal to a plane
- Contour method steps (illustrated for 2D body)
  - Part contains unknown RS (a)
  - Cut part in two: stress release ⇒ deformation (b)
  - Measure deformation of cut surfaces
  - Apply reverse of average deformation to finite element model of body (c)
  - Map of RS normal to surface determined
  - Same procedure holds for 3D

M. B. Prime, "Cross-Sectional Mapping of Residual Stresses by Measuring the Surface Contour After a Cut," JEMT, 123, 2001.



Cut → measure → FEM → 2D residual stress map

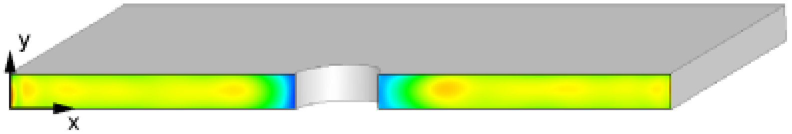


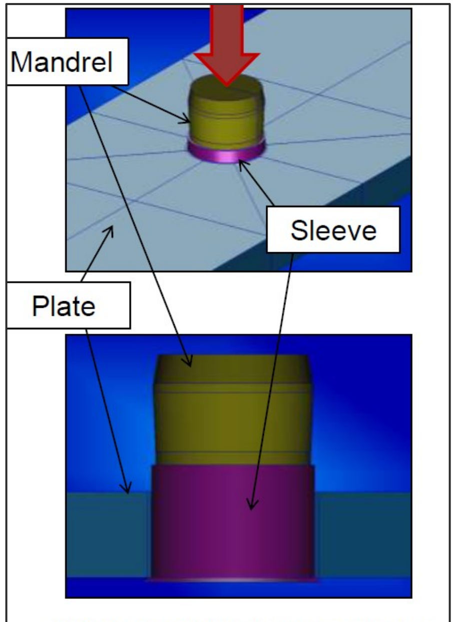


HILL ENGINEERING
Predict. Test. Perform.
ERSI

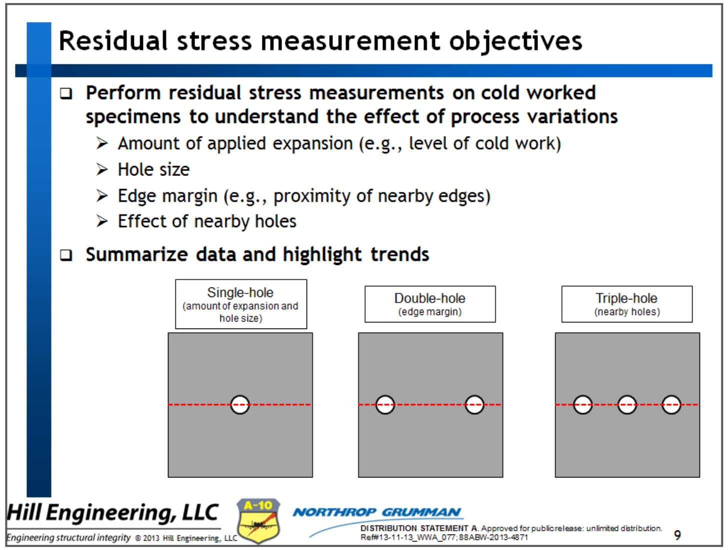
Improved Quality of Residual Stress Inputs

- The accuracy of residual stress inputs used in analysis have improved due to:
  - Advances in residual stress measurement methods
    - E.g., Contour Method
  - Improved cold expansion simulations
    - NRC and FTI current efforts
  - Focused research programs
    - Designed to quantify and document residual stress fields for various conditions
      - Thickness
      - Hole size
      - Edge margin
      - Material
      - Etc.



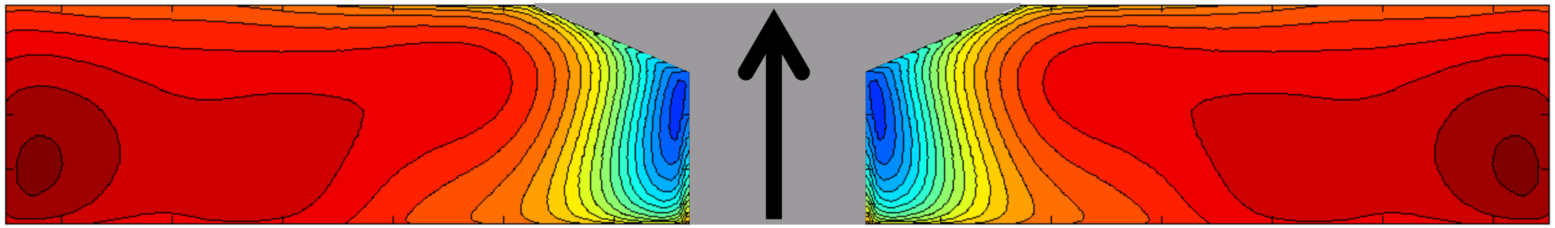


*%Cx defined by geometry parameters



Improved Residual Stress Measurement Capability

- Contour method allows us to resolve fine residual stress details
  - E.g., 2D variations in residual stress due to direction of mandrel travel
  - The details are important for accurate analysis

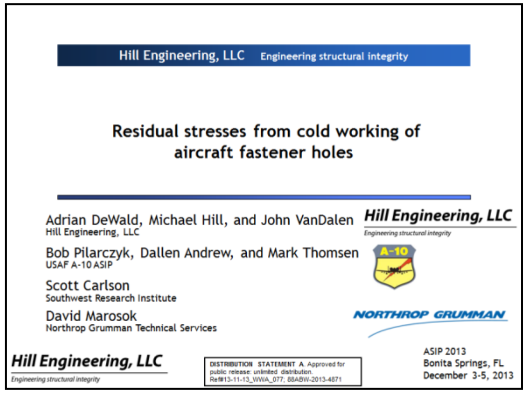


Mandrel pull direction

- With contour method technology, we can better assess data trends
  - Examples shown on following slides

Influence of Key Variables on Residual Stress

- ❑ **Roughly 5 years of support through USAF**
  - ➢ (A-10, T-38, SBIR Phase 3)
- ❑ **Contour measurements on hundreds of CX holes**
  - ➢ Range of material
  - ➢ Range of hole size
  - ➢ Range of interference
  - ➢ Range of edge margin
  - ➢ Effects of service (teardown)
  - ➢ Repeated measurements (statistical bounds)


Hill Engineering, LLC Engineering structural integrity

Residual stresses from cold working of aircraft fastener holes

Adrian DeWald, Michael Hill, and John VanDalen
Hill Engineering, LLC

Bob Pilarczyk, Dallen Andrew, and Mark Thomsen
USAF A-10 ASIP

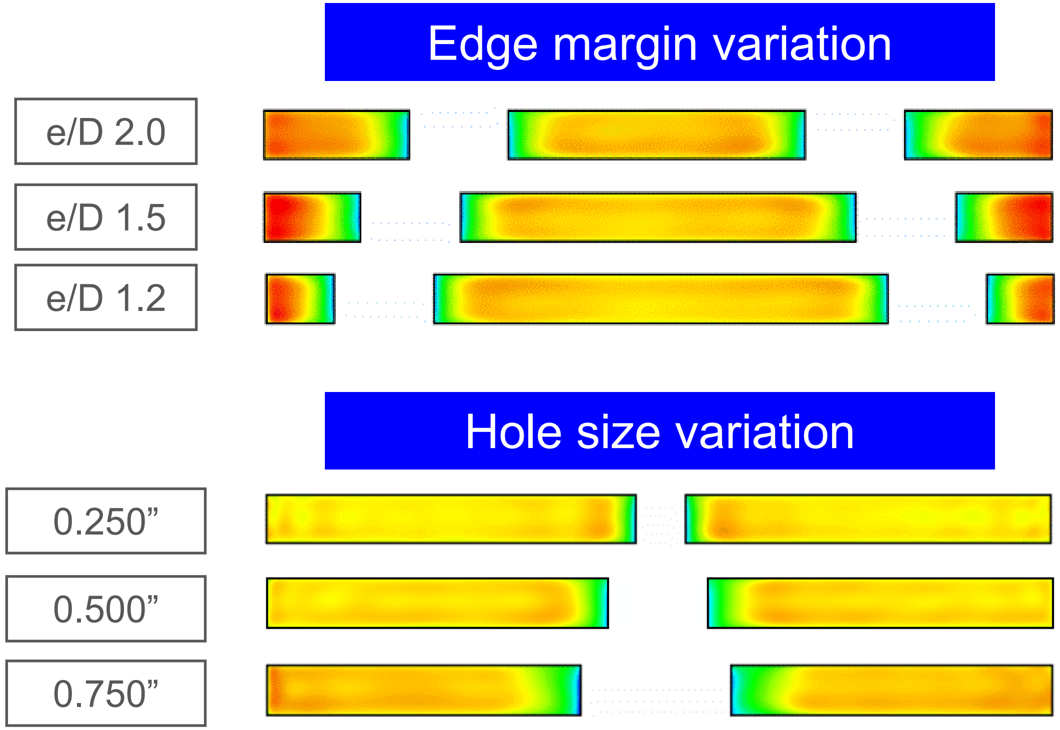
Scott Carlson
Southwest Research Institute

David Marosok
Northrop Grumman Technical Services

Hill Engineering, LLC
Engineering structural integrity

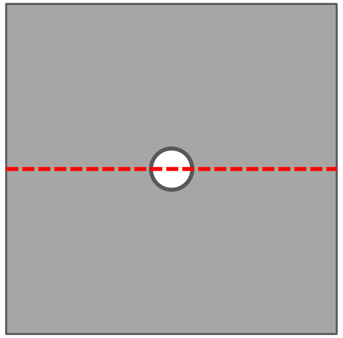
DISTRIBUTION STATEMENT A. Approved for public release: unlimited distribution. Ref#13-11-13_WWA_077; 88ABW-2013-4871

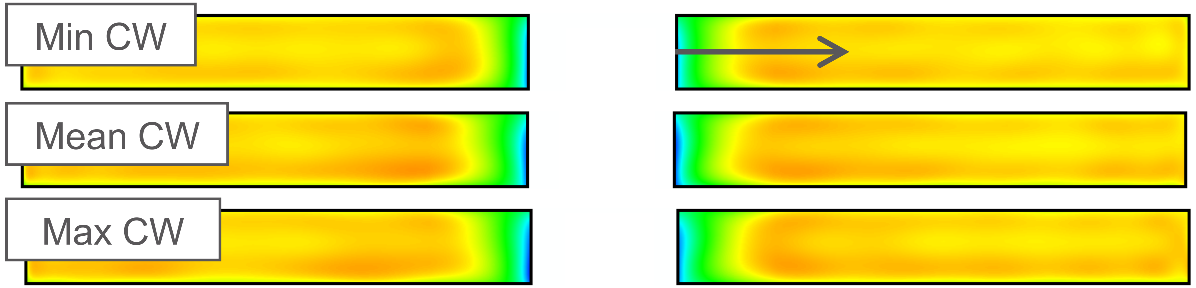
ASIP 2013
Bonita Springs, FL
December 3-5, 2013



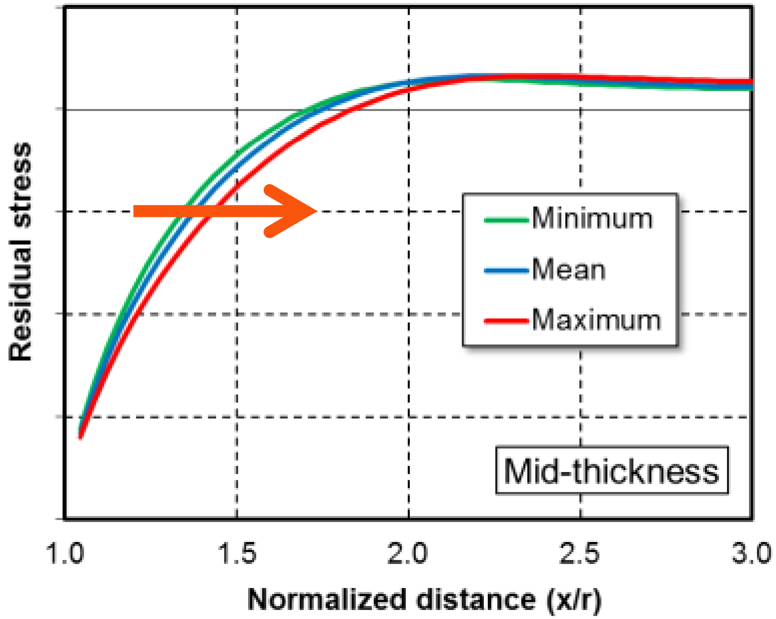
Influence of Key Variable on Residual Stress

- Effect of amount of applied expansion
  - Contour plots of measured residual stress





- Data provide residual stress variation allowed by process specification
  - Scatter from:
    - Measurement uncertainty/error
    - Process variability
  - Averaging over population improves interpretation and understanding of trends
    - Peak compressive magnitude is similar
    - Larger applied expansion increases compressive region



Improved Analysis Tools

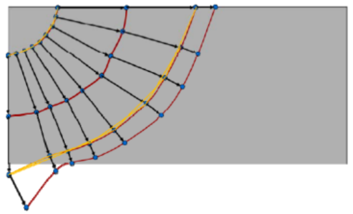
- The ability to execute advanced fatigue crack growth simulations has improved due to:
  - Advances in computational analysis technology
  - Advances in software tools
    - Analysis at multiple points on the crack front
    - Arbitrary crack shape progression
    - Improved compatibility with residual stresses
    - Ease of use

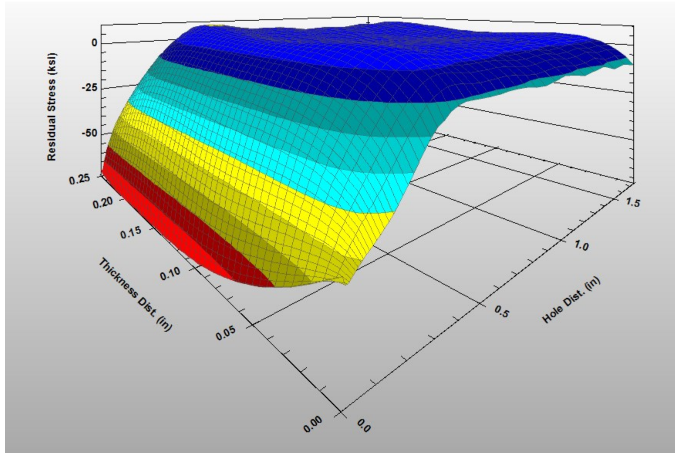
FRANC3D

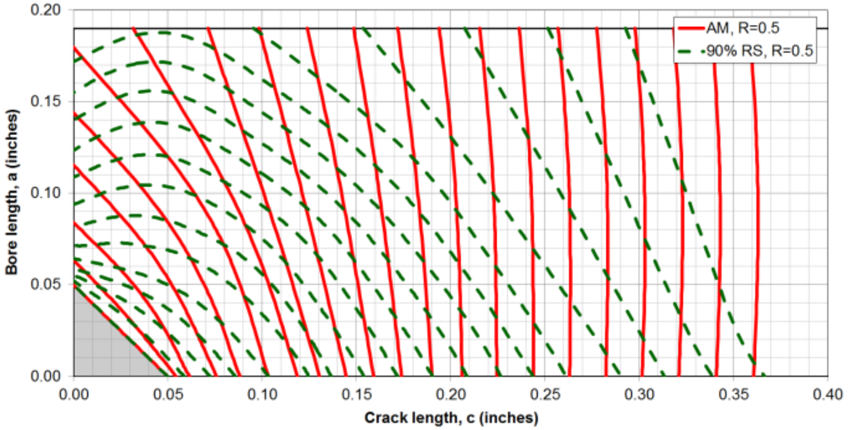
BEASY

BAMF

Broad Application for Modeling Failure





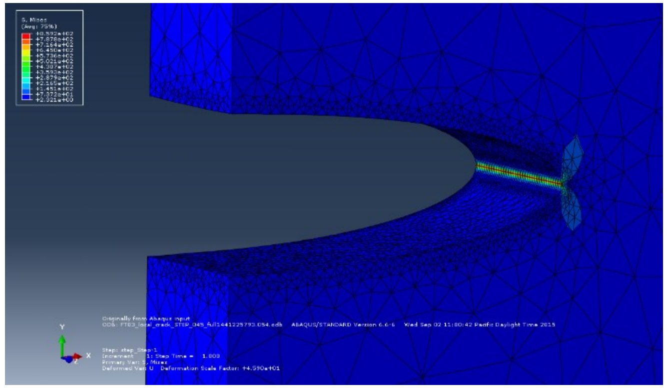


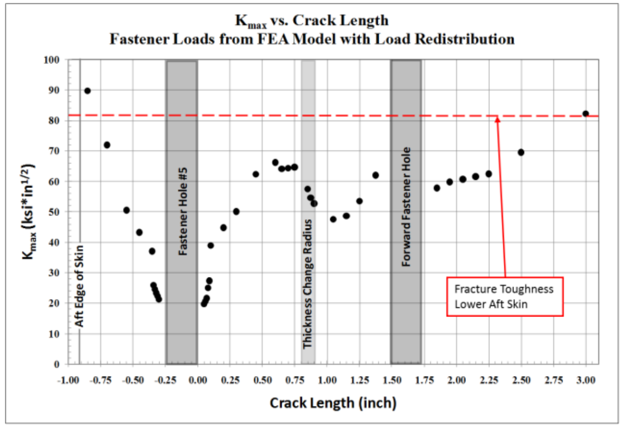
HILL ENGINEERING
Predict. Test. Perform.

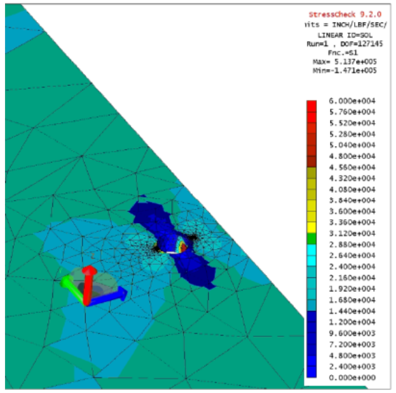
ERSI

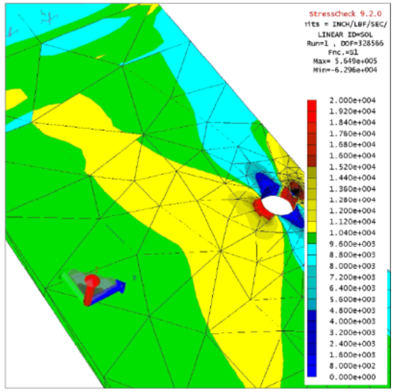
Finite Element Based Stress Intensity Capability

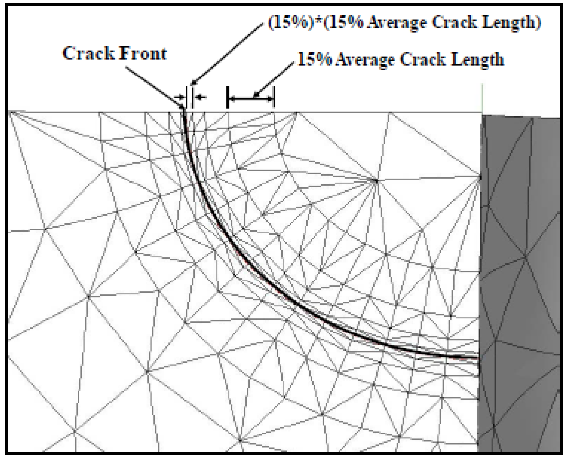
- Increased capability of FE codes to represent cracks and extract stress intensities
- Becoming more common practice for "complicated" situations
- Standardized guidelines developed
- J-integral for crack face pressures

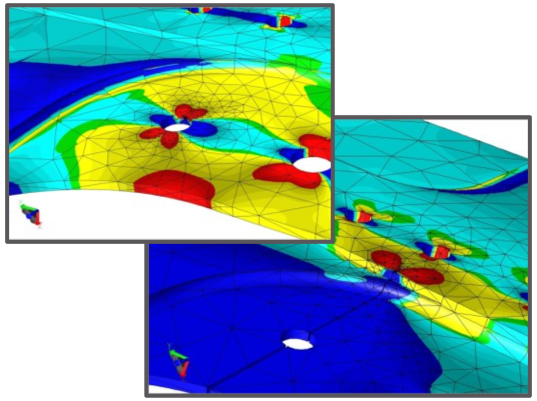










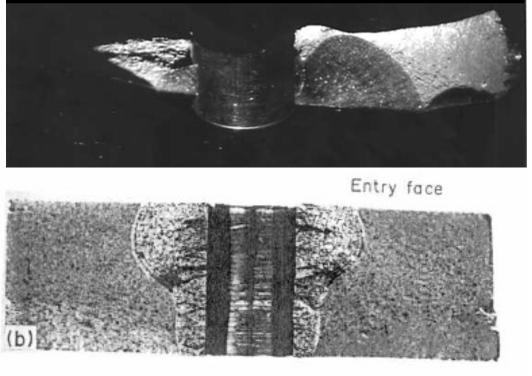


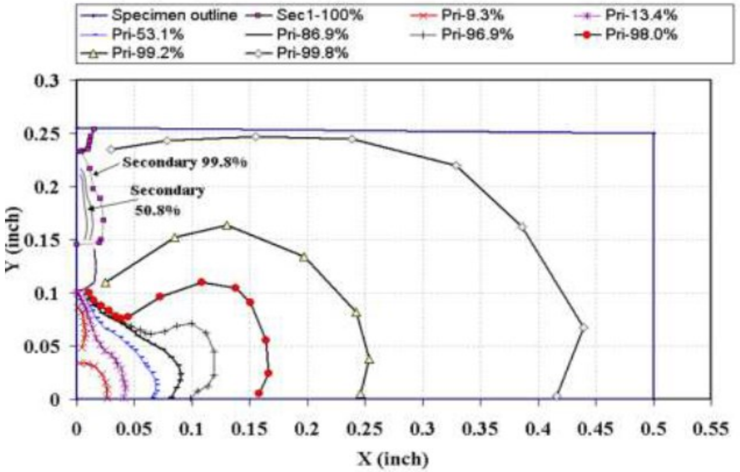
Pilarczyk, R.; Carlson, S.; Stowe, G.; (2009) Is ASIP Still Alive, The A-10 Lower Wing Skin Cracking Issue.; ASIP Conference 2009.

Multi-Point Crack Shape Evolution

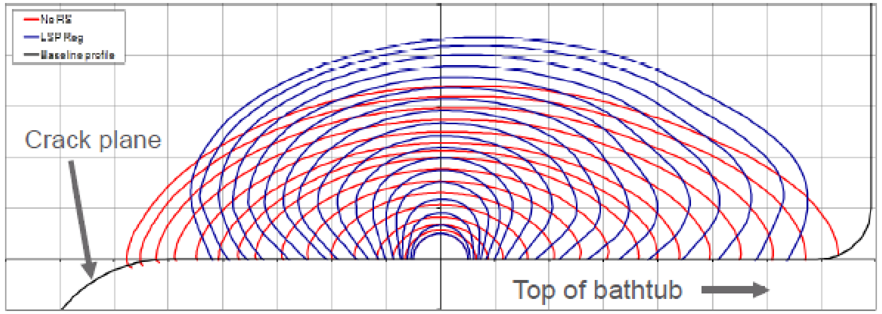
- Crack growth through complicated geometry, loading, etc.
- Move away from utilizing two discrete points (typically) along crack front to characterize overall behavior
- For cold worked holes critical to allow crack to “ooze” through path of least resistance

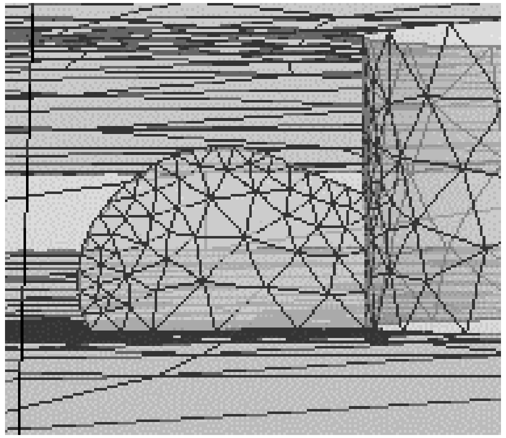
Photo from: Clark and Johnson, IJF 25(2), 2003
7050T7451, 0.25” plate, 4% CX

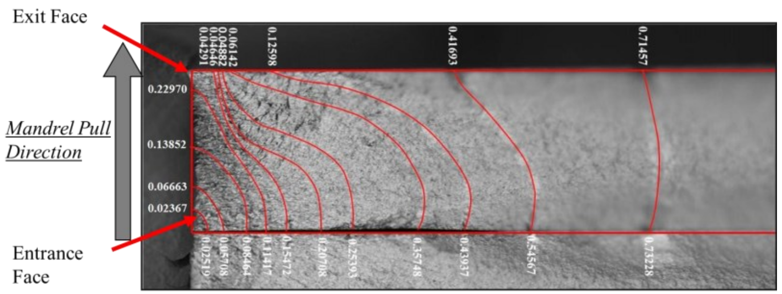




Mills, T.; Prost-Domasky, S.; Pilarczyk, R.; Hodges, J.; (2014) Important Factors for Modeling Fatigue Performance at Cold Worked Holes.; AA&S Conference 2014.





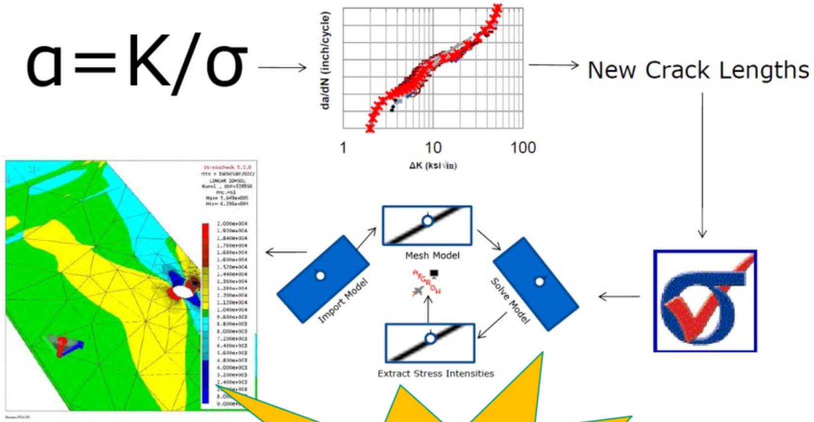


HILL ENGINEERING
Predict. Test. Perform.

ERSI

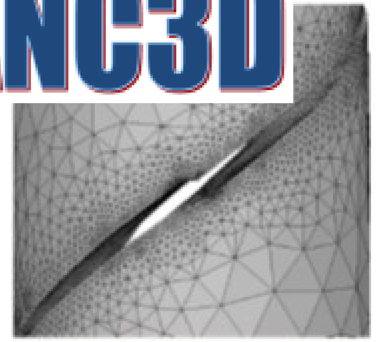
Coupled Crack Growth and FEA Stress Intensity Calcs

- Critical to support natural crack shape evolution
- Multiple analysis tools available
  - Broad Application for Modeling Failure (BAMF)
  - BEASY
  - FRANC3D
  - Automated Crack Growth Program (ACGP)
  - Etc…
- Analyst must understand nuances of each
  - Boundary vs. Finite Element Codes
  - Meshing along crack front
  - Stress Intensity and/or crack front smoothing
  - Crack growth engines



BEASY

FRANC3D

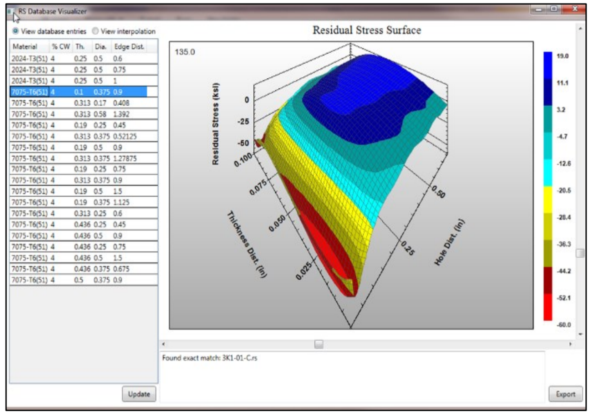


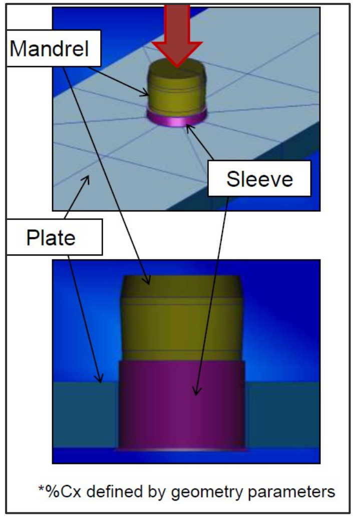
BAMF

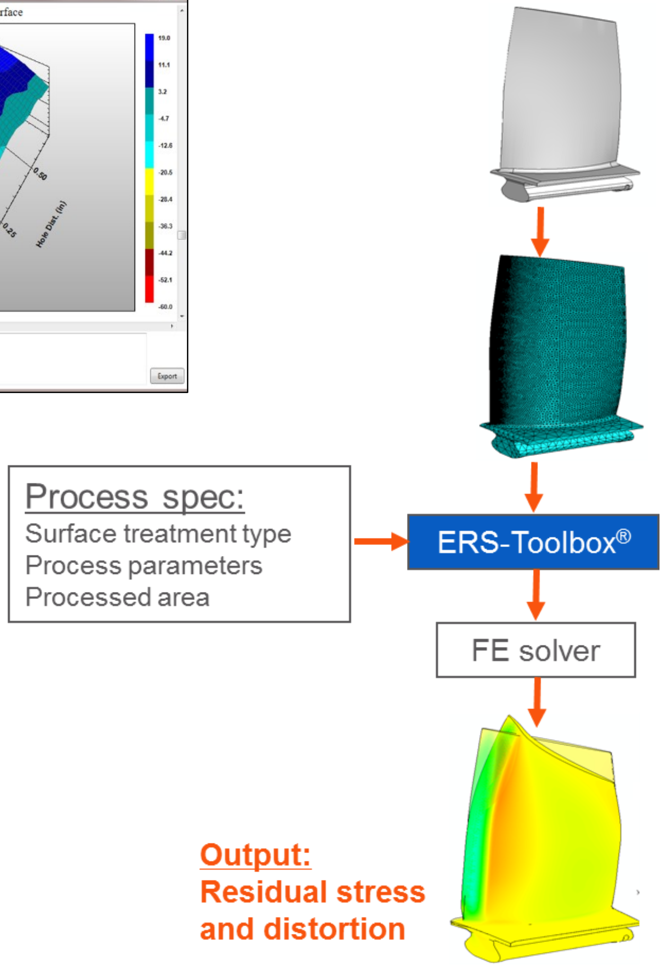
Broad Application for Modeling Failure

Methods to Incorporate Residual Stresses

- ❑ **Multiple methods available to define residual stress input**
  - ➢ ERS-Toolbox®
  - ➢ Measurement Data
    - • Residual Stress Database
  - ➢ Process Modeling
    - • FEA Derived Full Field Residual Stress
      - • Recent efforts by:
        - • NRC Canada
        - • Fatigue Technologies, Inc.
- ❑ **Full field residual stress vs. 2D stress (crack face pressure)**
  - ➢ Pros/cons



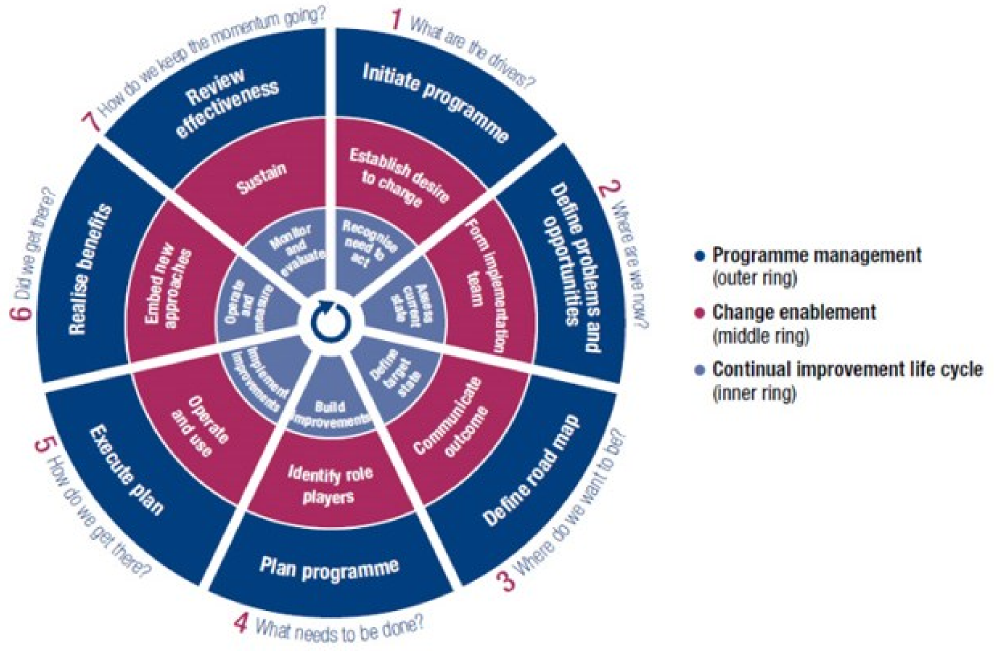




Focus Areas Moving Forward

Develop Implementation Plan

- ❑ What are we trying to change
- ❑ Who has the authority to change it
- ❑ What information is required to justify the changes
- ❑ What is the timeline for the change to occur
- ❑ What resources are required
- ❑ Who is the lead person / organization
- ❑ How will we track progress



Source: ISACA, COBIT 5, USA, 2012

We Must Establish an Overarching Implementation Plan

Establish Standards

- Establishing standards and ground rules are paramount for implementation success
  - Define Certification Requirements:
    - Acceptable analysis methods
    - Conservatism/safety factors
    - Testing/measurement requirements
    - Inspection considerations
    - Quantification of detrimental tensile residual stresses
    - Quantification of risk
- Documented as:
  - USAF Structures Bulletin
  - JSSG 2006 incorporation

AIR FORCE
LOADS DYNAMICS WEIGHTS ASIP EST. 1958 STRENGTH DURABILITY
STRUCTURES

Structures Bulletin

ASC/EN
Bldg 28, 2145 Monahan Way
WPAFB, OH 45433-7101
Phone 937-656-9956

DEPARTMENT OF DEFENSE

JOINT SERVICE SPECIFICATION GUIDE

DEPARTMENT OF DEFENSE · UNITED STATES OF AMERICA

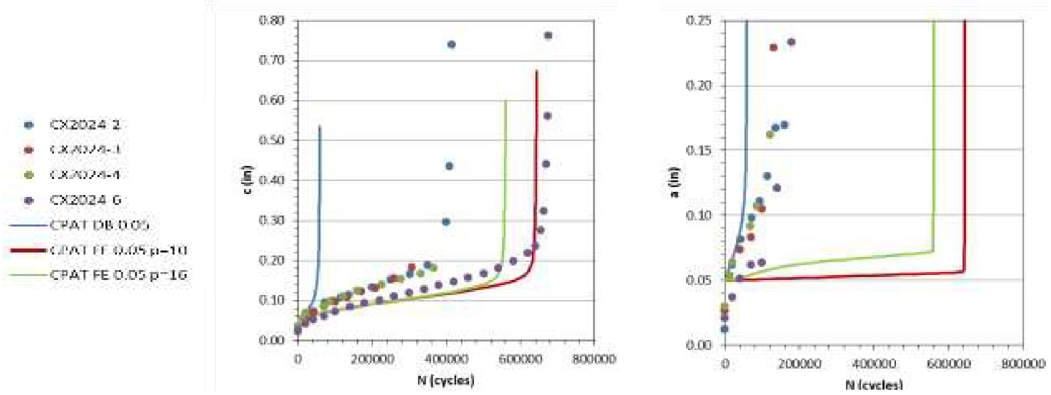
AIRCRAFT STRUCTURES

Life Enhancement Processes:

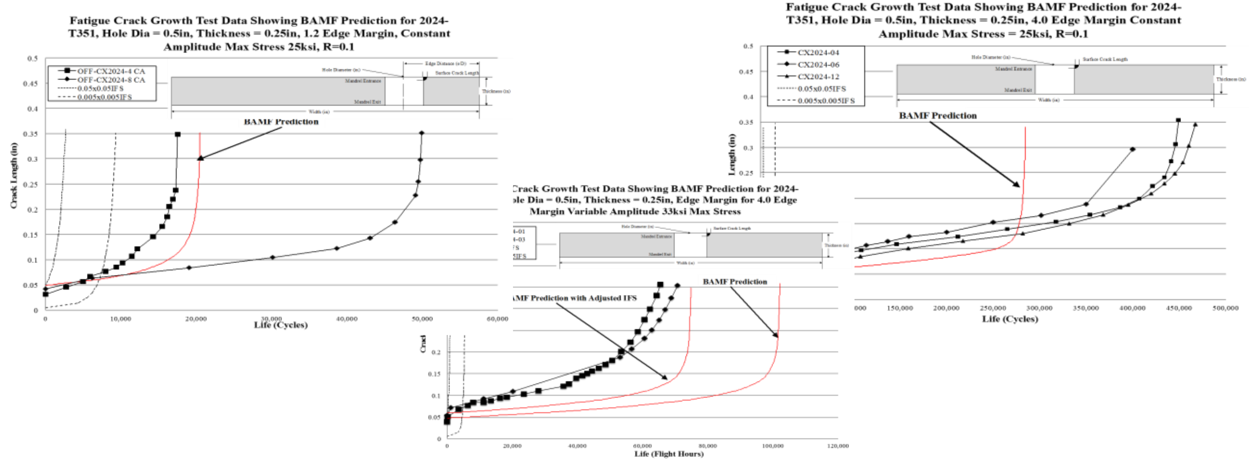
To maximize safety of flight and to minimize the impact of potential manufacturing errors, it should be a goal to achieve compliance with the damage tolerance requirements of this specification without considering the beneficial effects of specific joint design and assembly procedures such as interference fasteners, cold expanded holes, or joint clamp-up. In general, this goal should be considered as a policy but exceptions can be considered on an individual basis. The limits of the beneficial effects to be used in design should be no greater than the benefit derived by assuming a .005 inch radius corner flaw at one side of an as-manufactured, non-expanded hole containing a neat fit fastener in a non-clamped-up joint. A situation that might be considered an exception would be one involving a localized area of the structure involving a small number of fasteners. In any exception, the burden of proof of compliance by analysis, inspection, and test is the responsibility of the contractor (us).

Exercise, Exercise, Exercise

- ❑ **Exercise tools to understand where they breakdown**
  - ➢ Dissect results to identify limitations
    - What are the root causes for poor predictions
- ❑ **Benchmark w/ different tools, same framework and approach**
  - ➢ Identify 3-5 benchmark datasets
  - ➢ Utilize different residual stress inputs
    - ERS-Toolbox®, Residual Stress Database, Simulation derived residual stress
  - ➢ Utilize different analysis tools
  - ➢ Compare results



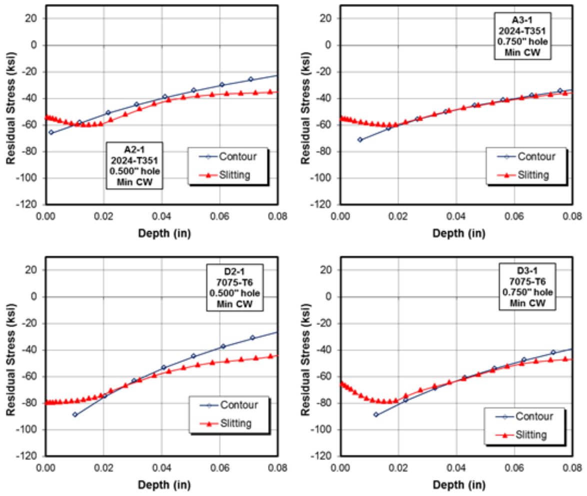
Renaud, G.; Liao, M.; Li, G.; Bombardier, Y.; (2016) Validation of Hole Cold Expansion Modeling and Simulation. AA&S Conference 2016.

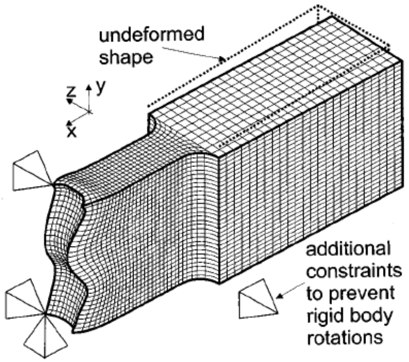


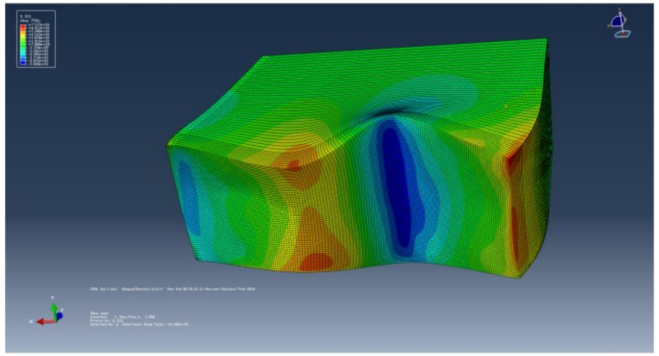
Hodges, J.; (2014) Integration of Incremental Crack Front Evolution into the Structural Integrity Process: Examples, Experimental Comparisons, and Lessons Learned. ASIP Conference 2014.

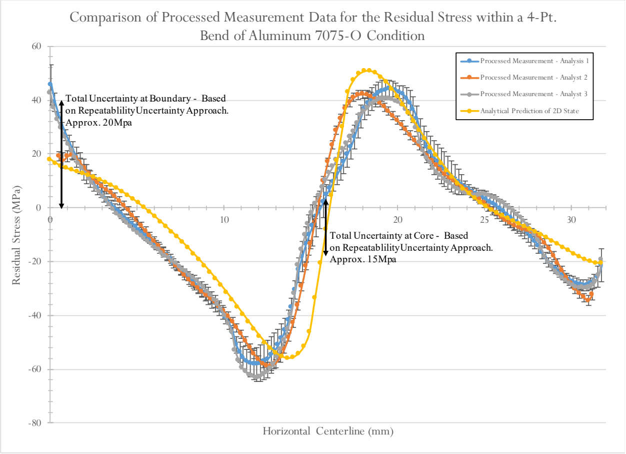
Confidence in Residual Stress Input Data

- ❑ **Measurement**
  - ➢ Uncertainty Quantification
  - ➢ Contour Method - international inter-laboratory round robin
- ❑ **Simulation**
  - ➢ Overcoming historical stigma
- ❑ **We must utilize both measurement & simulation**
  - ➢ Leverage strengths of each method to refine our residual stress understanding
  - ➢ Benchmark comparisons are key to success



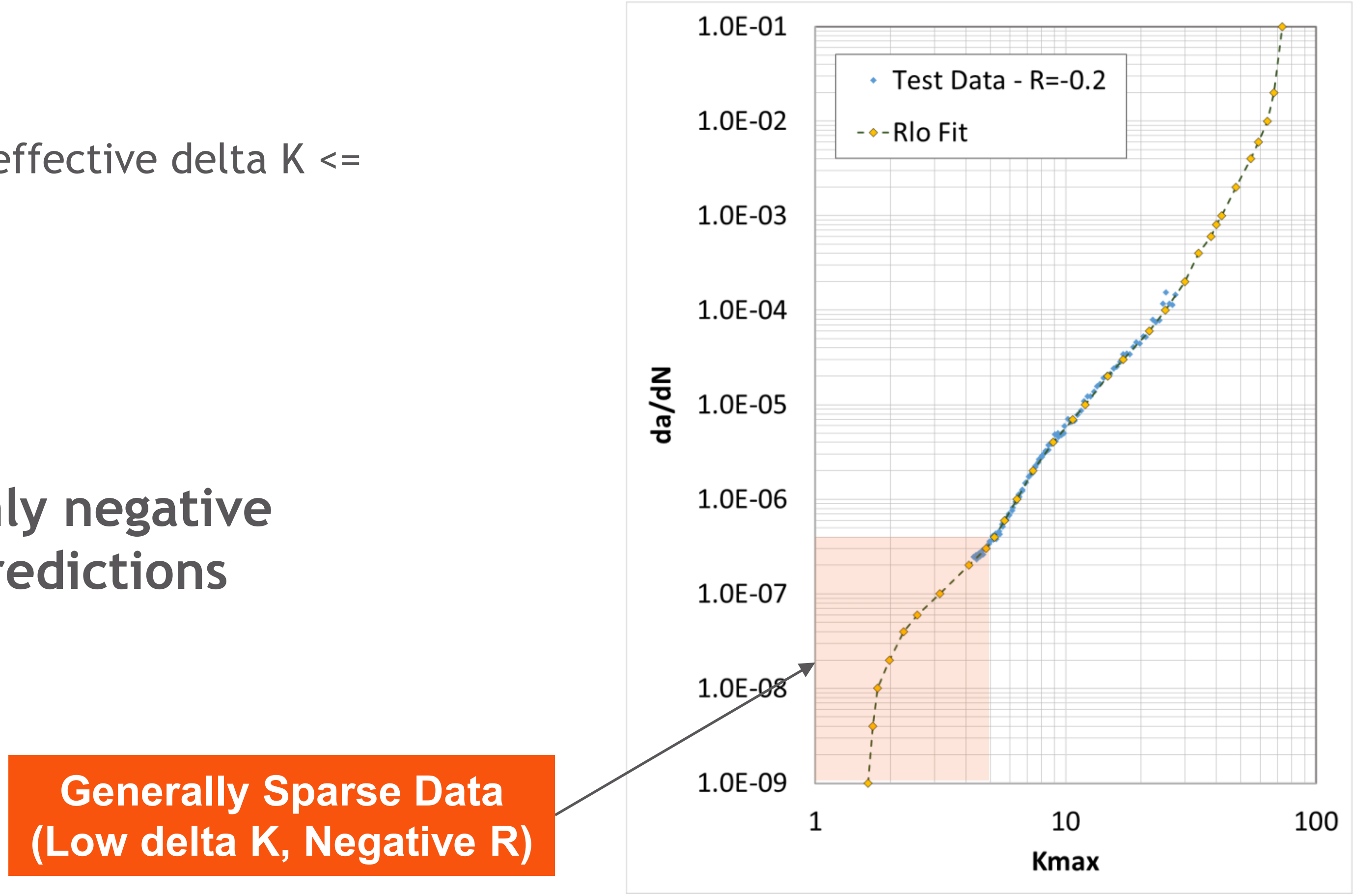






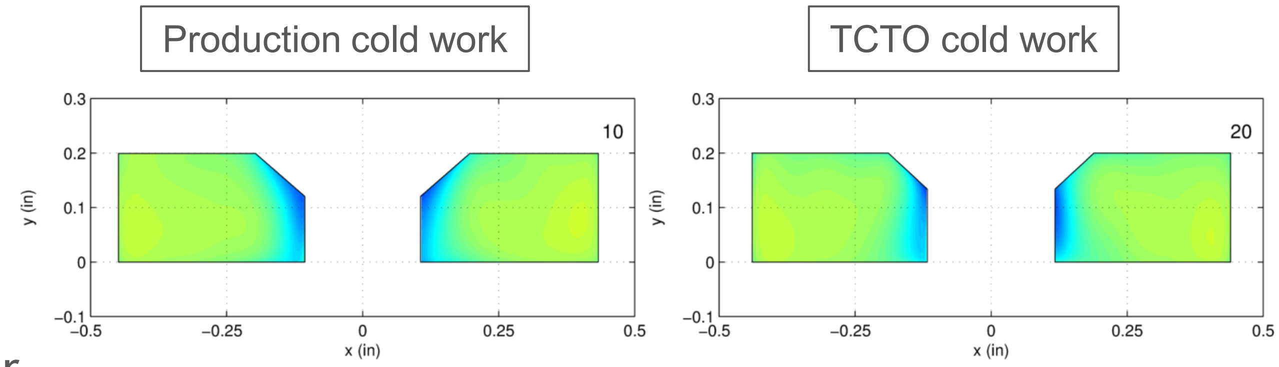
Improve Material Models

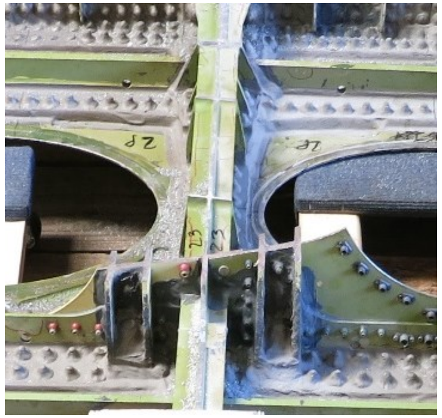
- Incorporating residual stresses drives analyses into atypical regimes
  - "Low" delta K
    - Can be significant for predictions when effective delta K <= 5 ksi-sqrt(in)
  - Highly negative stress ratios
    - Revisit Rlo with residual stresses
- Crack closure affects are Important
- Additional test data at low R and highly negative stress ratios is critical for accurate predictions

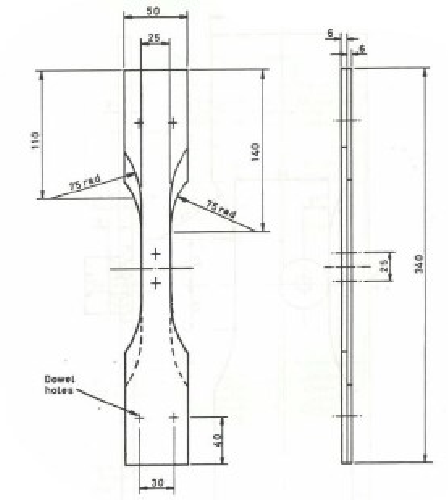


Understand Factors Affecting Residual Stress

- ❑ **Overloads/Underloads**
  - ➢ Understand and define limits
- ❑ **Unique spectrum effects**
- ❑ **Crack tip plasticity interaction**
- ❑ **Countersunk holes**
  - ➢ Variation in Csk method can significantly effect residual stress
- ❑ **Operational usage - 40+ year old structure**
  - ➢ Time and/or Cycle Based Stress Relaxation
- ❑ **Local stresses from fastener loads**
  - ➢ Do localized fastener loads alter residual stress
  - ➢ Filled vs. open holes
- ❑ **<u>Key questions to answer:</u>**
  - ➢ How do we address these factors?
    - Test, analysis, etc.?
  - ➢ How do we incorporate the findings?





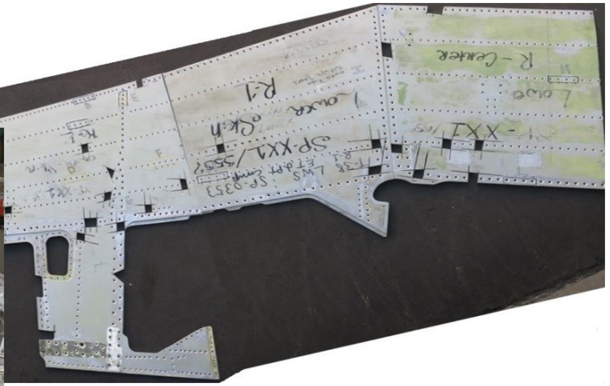


HILL ENGINEERING Predict. Test. Perform.
ERSI

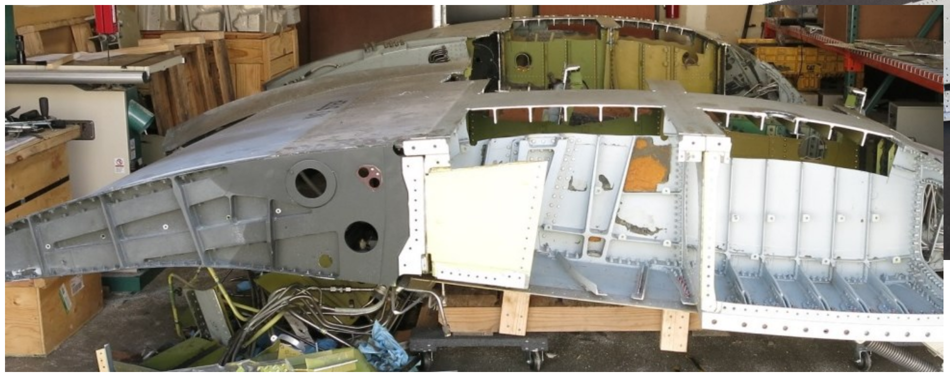
Translation to Real-World Applications

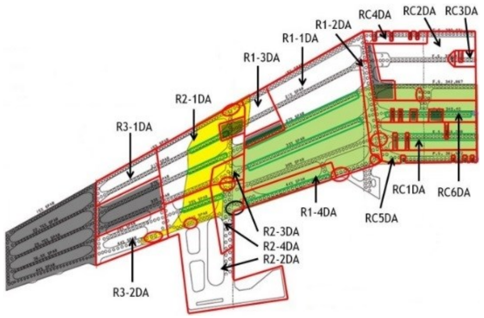
- Teardown measurement campaign
  - Two aircraft models
  - Assess lower wing skins
- Includes effects from:
  - Stack up (e.g., skin, strap, spar)
  - Prior service
  - Time of installation
    - OEM processes, versus
    - Depot rework
- Measurements at dozens of holes
  - Average process outcome
  - Variability
  - Lower bound
- How do we address any differences we see?

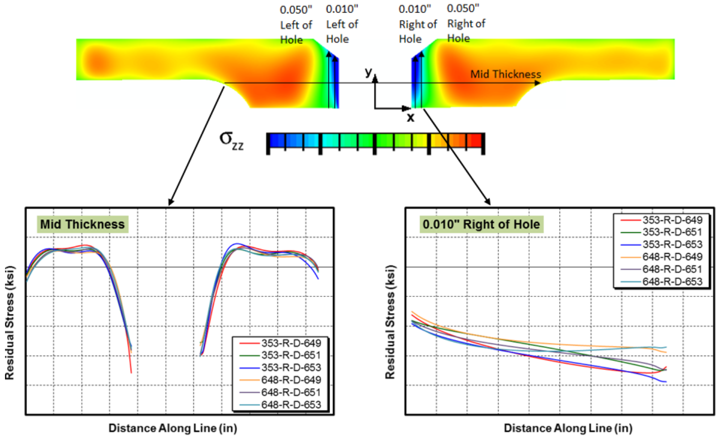
T-38



A-10





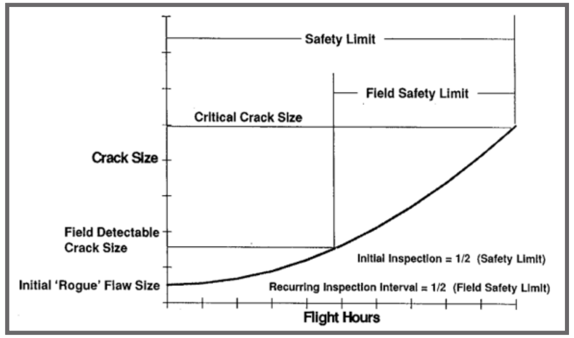


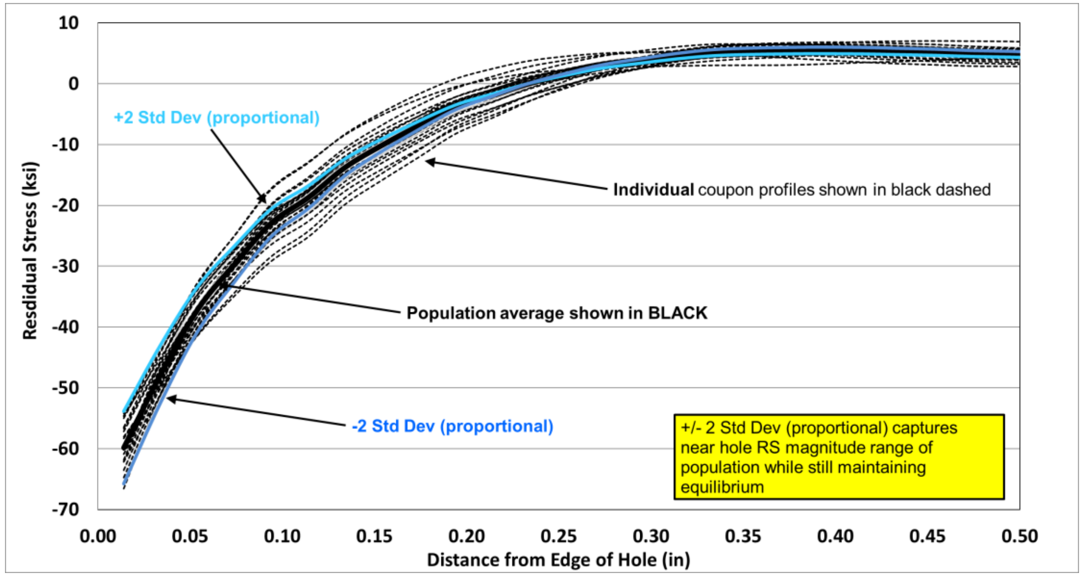
HILL ENGINEERING
Predict. Test. Perform.

ERSI

How to Handle Conservatism/Safety Factors

- ❑ **Incorporation of conservatism/safety factors are critical for:**
  - ➢ Consistency between analysis groups
  - ➢ Clear understanding of final prediction
  - ➢ Associated risk with final prediction
- ❑ **Where do safety factors belong?**
  - ➢ Crack growth rate data "threshold"
  - ➢ Initial/recurring inspection requirements
  - ➢ Residual stress
  - ➢ Nuances of analysis approach
  - ➢ Others to account for:
    - Residual stress relaxation
    - Just to make you feel good… 🙂
- ❑ **How do we handle assessment of risk?**





HILL ENGINEERING Predict. Test. Perform. ERSI

Questions?

Quantification of Residual Stress Fields via FEA Compared to Measurement

Engineered Residual Stress Implementation Workshop 2016
Ogden, Utah, USA
September 15, 2016

Keith Hitchman - FTI

FATIGUE TECHNOLOGY

OUTLINE

- Introduction
- Finite Element Analysis Methodologies
  - Analysis at FTI and a Case Study
  - Cold Expansion Analysis Best Practices
- FEA Benchmarking Introduction and Status
  - The Test Case
  - The Preliminary Results
- Conclusions and Future Work
- References

A little bit about FTI

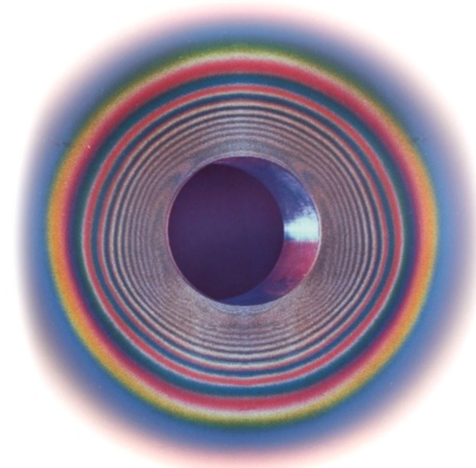
- FTI is a wholly-owned subsidiary of Precision Castparts Corp. (PCC).
- Recognized as industry experts on RS field technology relative to fastened joints and holes.
- FTI utilizes finite element analysis (FEA) together with static and dynamic testing to validate solutions prior to implementation.
- FTI repeatedly lowers manufacturing and MRO installation costs and aircraft weight while enhancing structural performance.

FTI is committed to internal and collaborative research programs that enable continual improvements to the fidelity and accessibility of RS data for customer use

ERSI FTI FATIGUE TECHNOLOGY

DM#740763

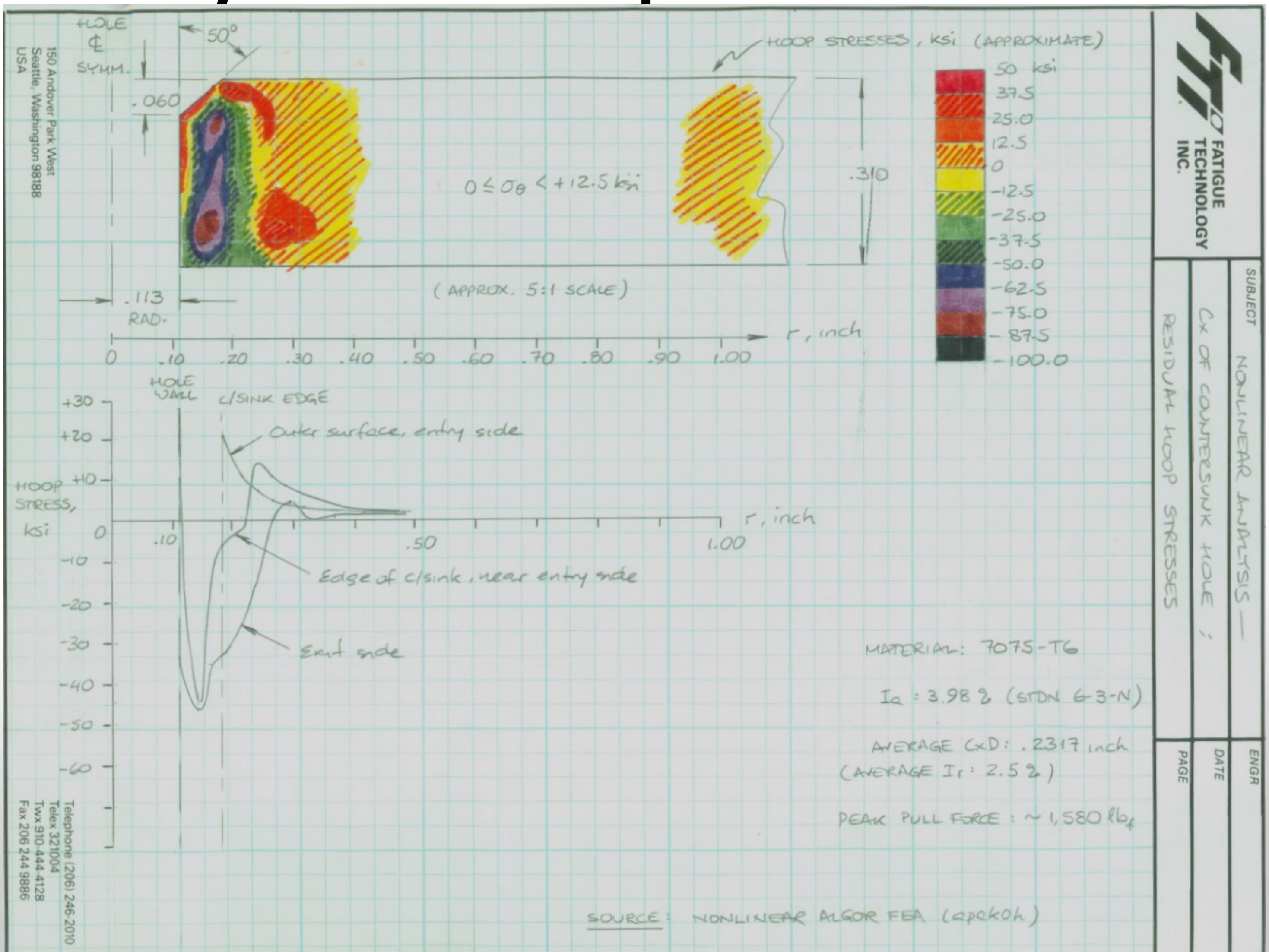
A little bit about FTI's Split Sleeve Cold Expansion



- Generates large, controllable zone of residual stress surrounding the hole.
- Effective in nearly all aerospace materials.
- Typical applied expansion levels:
  - 3% to 5% for aluminum
  - 4% to 6% for Titanium and high strength steels
- Applicable in new production and rework for holes up to 6.0 inch in diameter.

- Numerous derivative products:
  - ForceMate
  - ForceTec
  - GromEx
  - RailTec
  - StopCrackEX
  - ForceLoc
  - TukLoc

Analysis of Cold Expansion circa 1991

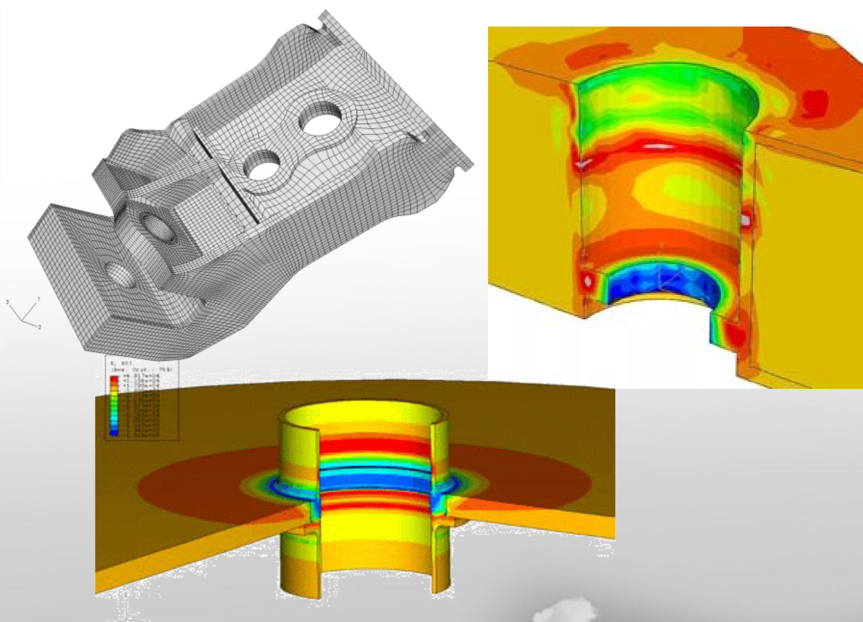


ERSI FATIGUE TECHNOLOGY

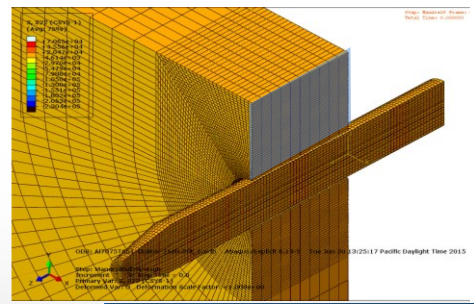
DM#740763

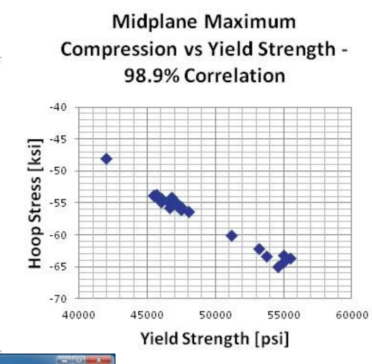
Analysis of Cold Expansion circa 2016

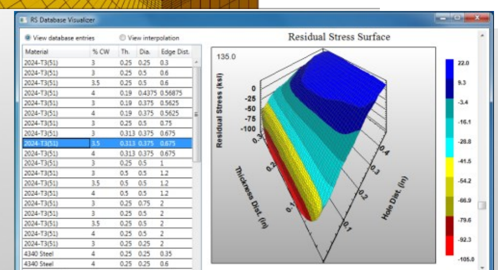
- Complex analyses:
  - Multiple FTI process steps
  - Refined correlation
  - All FTI processes



- Script driven 3D analysis:
  - Parametric studies
  - RS database population





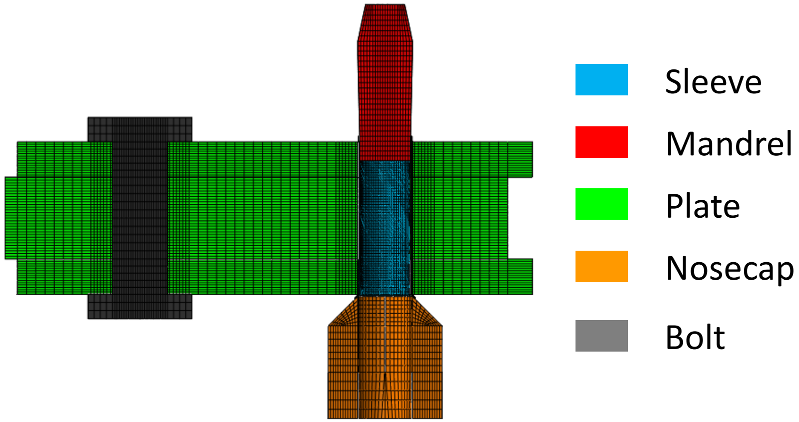


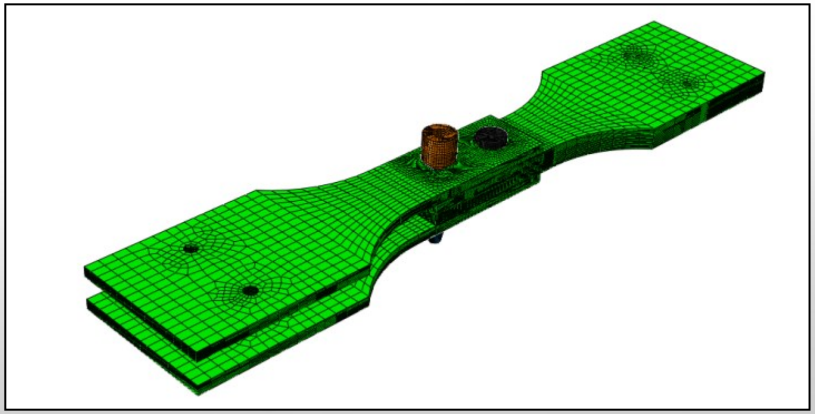
APES, ESRD

ERSI FATIGUE TECHNOLOGY

Complex Cx Analysis Case Study

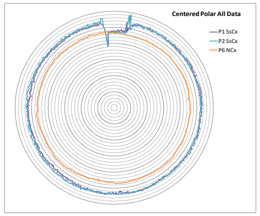
- High Load Transfer Specimen:
  - 7000 series aluminum (MMPDS)
  - Multiple Steps
    - Cx (two holes, full specimen stack)
    - Ream
    - Fastener Clamp
    - Fastener Interference
    - Remote Load.
  - Not modeled: surface preparations
- Goals:
  - Understand specimen performance
  - Evaluate RS interactions
  - Evaluate RS differences that may affect fatigue life.

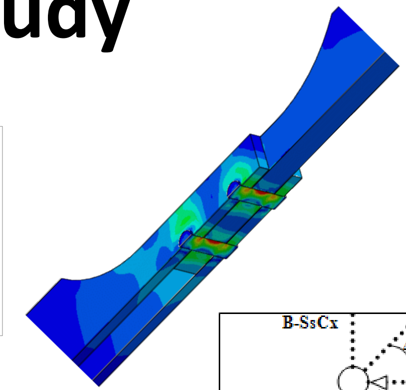


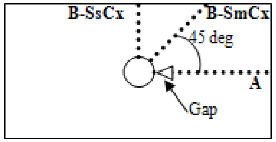


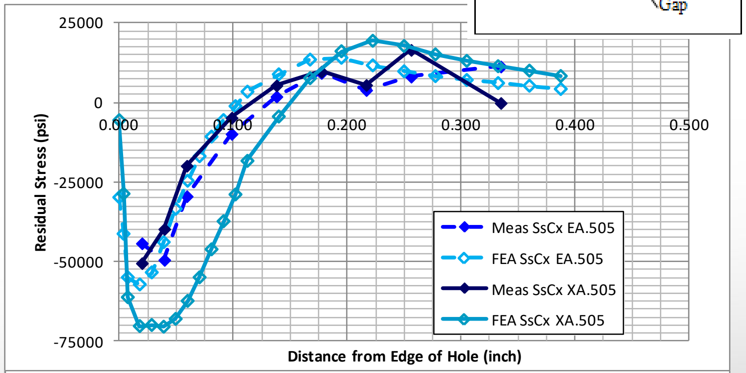
Complex Cx Analysis Case Study

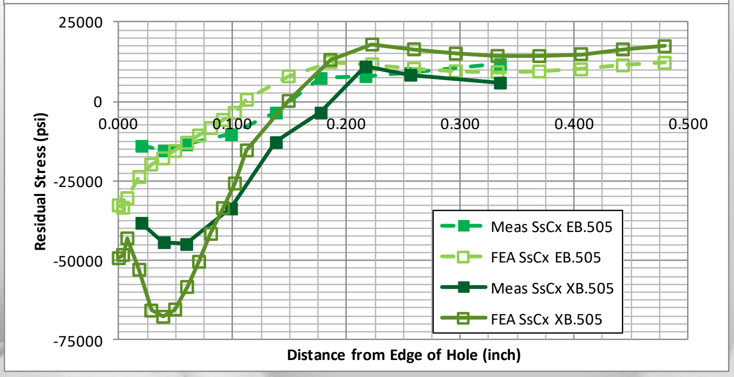
- Results:
  - RS states useful in predicting fatigue performance in bare specimens.
  - Repeated localized yielding may not be accurately represented by the assumed material model (combined hardening, half-cycle tensile data).
  - Fatigue performance impacted by the non-modeled surface preparation the highest remote loads ($S_{gross} \sim 0.3\ S_{yield}$).







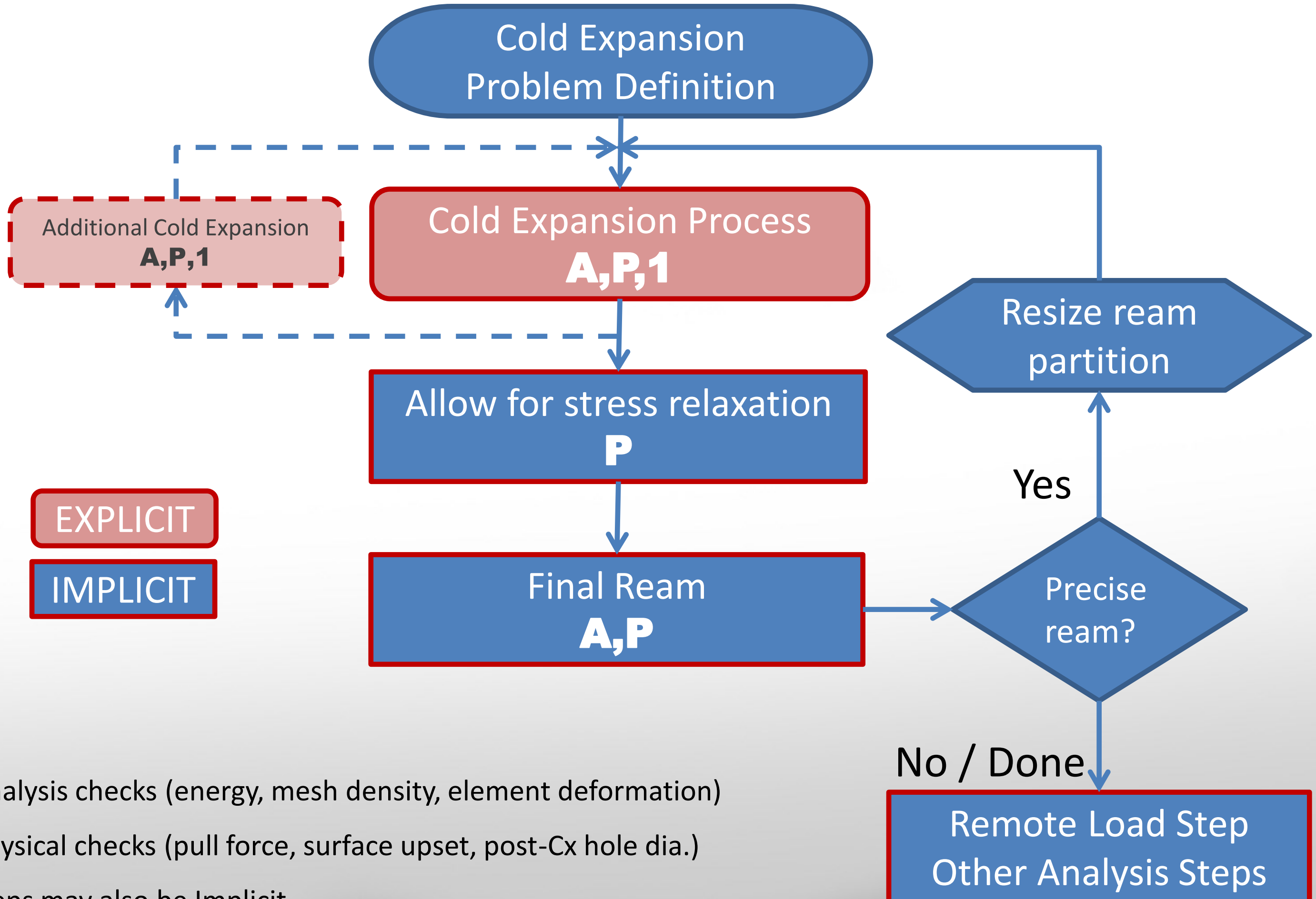




ERSI

FTI FATIGUE TECHNOLOGY

Typical Cold Expansion FE Workflow



A: analysis checks (energy, mesh density, element deformation)

P: physical checks (pull force, surface upset, post-Cx hole dia.)

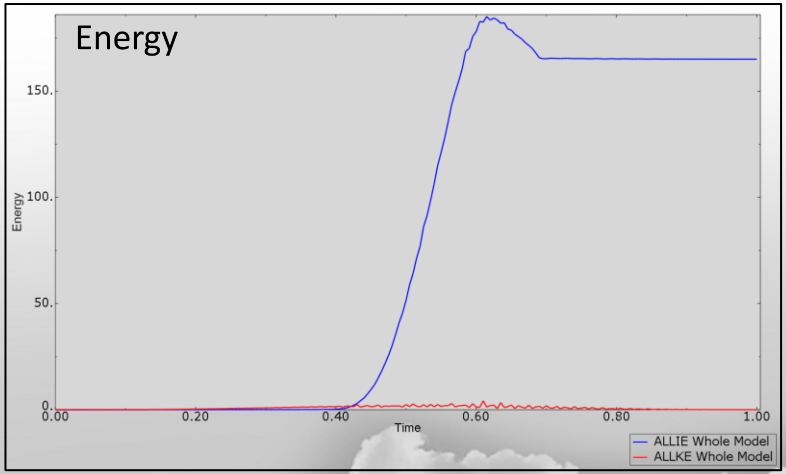
1: Steps may also be Implicit

Some Basic Analysis Setup Tips

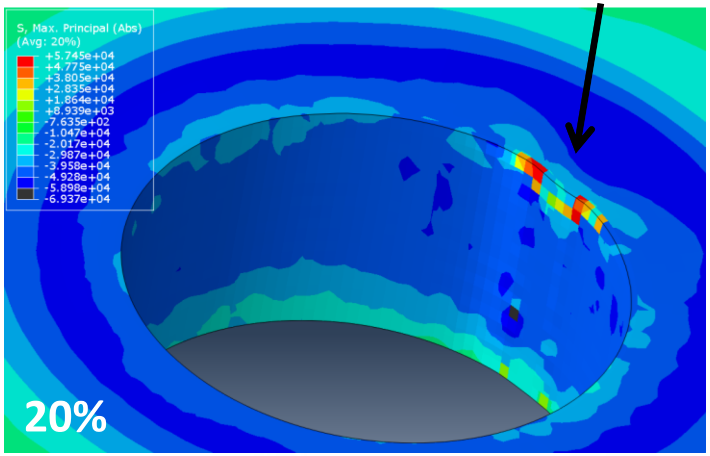
- Geometry
  - Pay particular attention to tooling geometry, as residual stresses can be affected by tooling geometry.
  - Consider subsequent analysis steps when considering how to represent model changes (ream, c'bore, c'sink); additional analysis runs may be required.
- Constraints
  - Appropriate model fixity may require additional parts to be modeled (nosecap).
  - Avoid mismatches in contact pair mesh density, regardless of what the manual tells you.
- Material Behavior
  - Consider specifics of material constitutive model:
    - May impact element selection.
    - Desired endpoint (failure during expansion, or just RS).
  - Avoid rigid bodies for tooling; use of plasticity for tools can be useful.

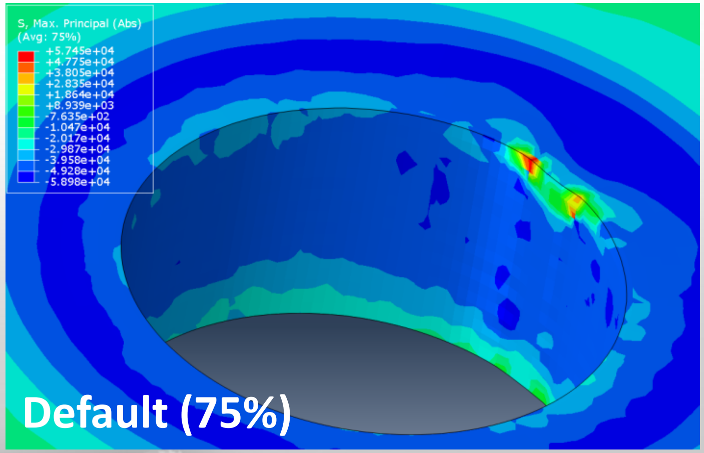
Quality Assurance

- Analysis Checks
  - Mesh refinement (via averaging checks, for example).
  - Contact penetration checks (penetration a possible factor in local mesh deformation).
  - KE checks to confirm quasi-static assumption remains valid (explicit).
  - Stabilization checks to confirm minimal influence (if used).
  - Closed form solutions (Lame, Grandt/Potter).



Sleeve Ridge



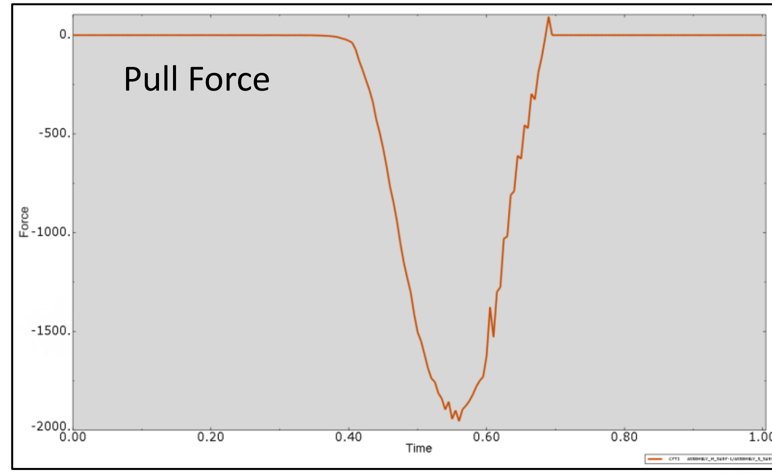


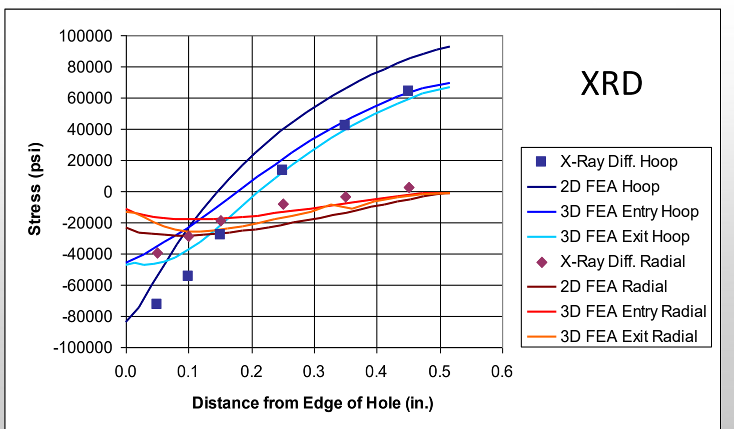
ERSI FTI FATIGUE TECHNOLOGY

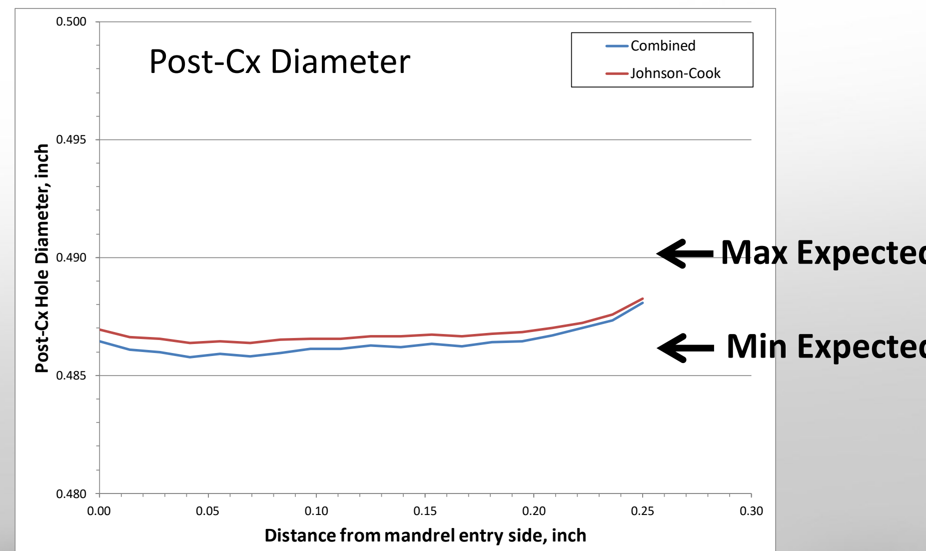
DM#740763

Quality Control

- Physical Checks
  - In-process measures:
    - Pull force
    - Deflection/deformation
    - Instrumented (strain gauges, DIC).
  - Post-process measures:
    - Hole diameters
    - Retention forces
    - Deflection/deformation
    - Instrumented (strain, XRD, etc.).







ERSI FTI FATIGUE TECHNOLOGY

FEA Benchmarking Exercise

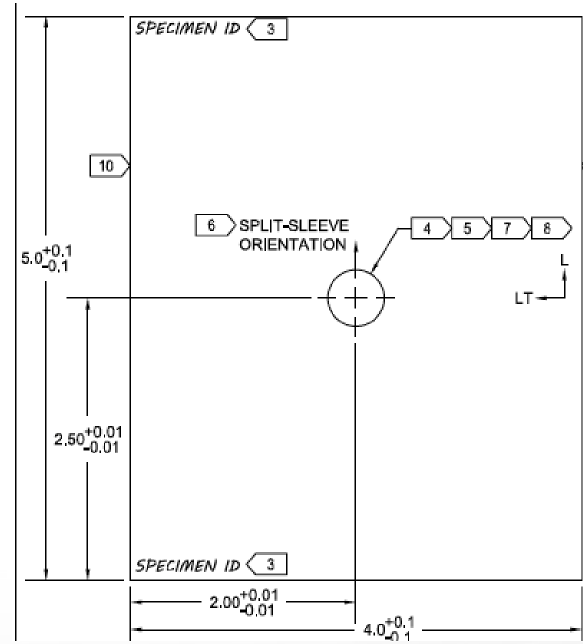
Goal: To increase confidence in FE modeling of RS.

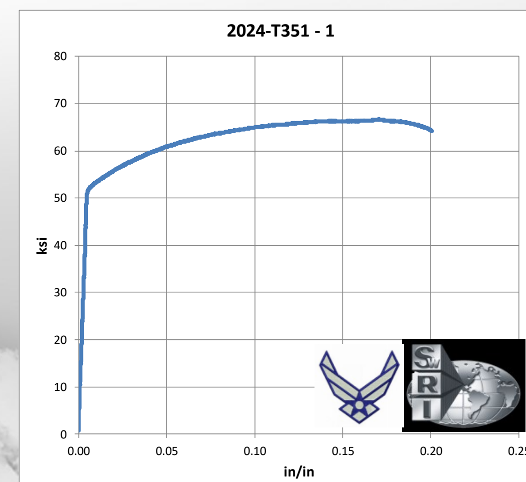
- Phase I
  - Compare RS distribution between NRC and FTI 3D analysis on selected Cx hole, using same geometry inputs.
  - Compare analytical RS with experimental measurements from SwRI and APES.
- Phase II (optional)
  - Compare crack growth and life predictions from the FE models and from experiments.

FATIGUE TECHNOLOGY

FEA Benchmarking Exercise

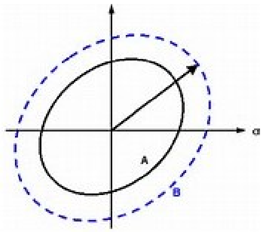
- 16-0-N tooling, low applied expansion
  - Mandrel just below bottom of tolerance: ∅0.4683”
  - Starting hole at top of tolerance: ∅0.4770”
  - Final hole: ∅0.5000”
- Previously tested plate geometry
  - Width: 4.00”
  - Thickness: 0.25”
  - e/D: 8
  - K_{tg} = 3.04, K_{tn} = 2.66
- Material properties from USAF uniaxial tensile tests; see next slide
  - 2024-T351 (current results)
  - 7075-T651 (for later)

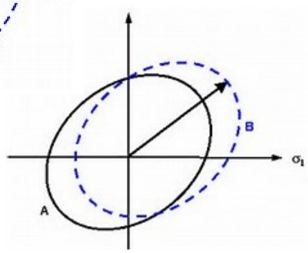


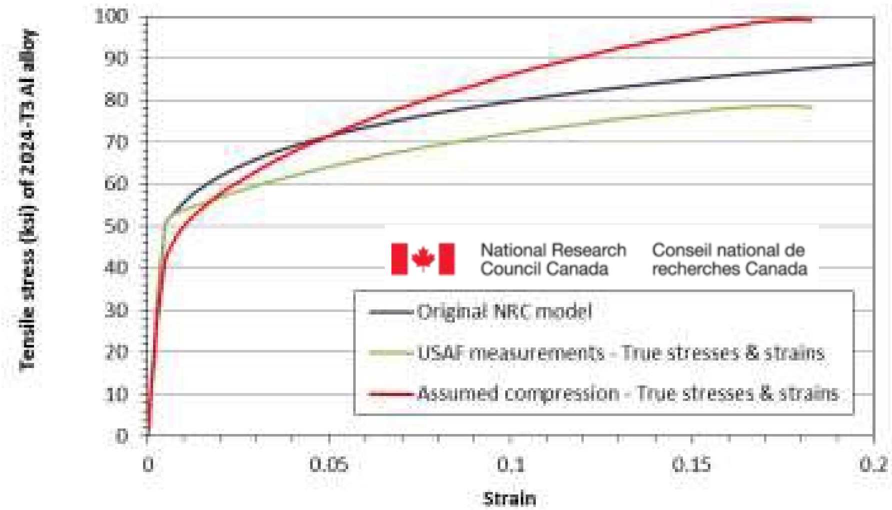


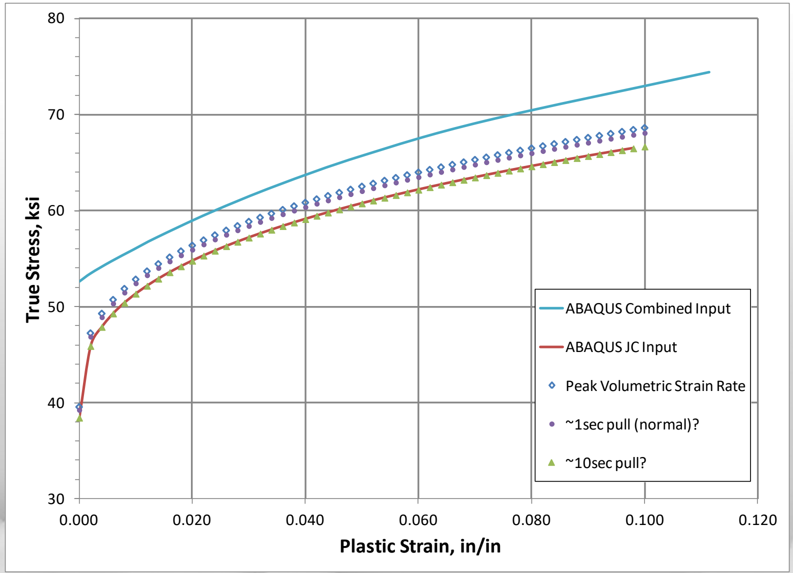
FEA Benchmarking – Material Models

- Isotropic
- Kinematic
- Combined
- Johnson-Cook
- Others not used in benchmark:
  - Drucker-Prager: may be appropriate for ultra-LCF metal response (P. Allen dissertation, 2002)
  - Hill
  - Barlat









FATIGUE TECHNOLOGY

DM#740763

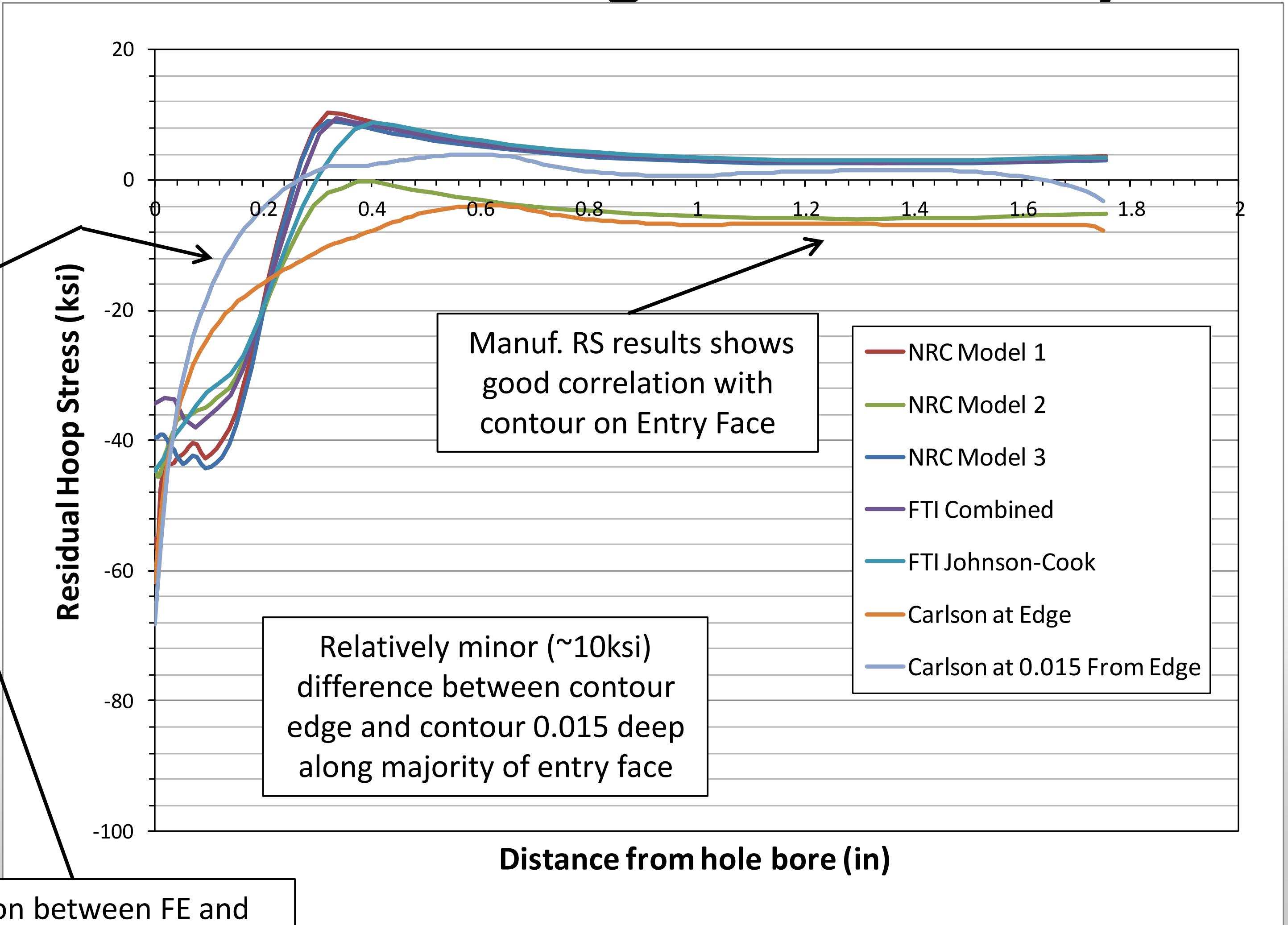
FEA Benchmarking Exercise Analyses

	Model ID	Material Curve	Material Model (hardening law)	Plate Manuf. Residual Stress?	Precise (re-sized) Ream?
NRC	1	Tension based	Isotropic	No	No
	2	Compression based (approximate)	Isotropic	Yes	No
	3	Tension based	Kinematic	No	No
FTI	Combined	Tension based	Combined	No	No
	Johnson-Cook	Tension based	Johnson-Cook	No	No

ERSI

FATIGUE TECHNOLOGY

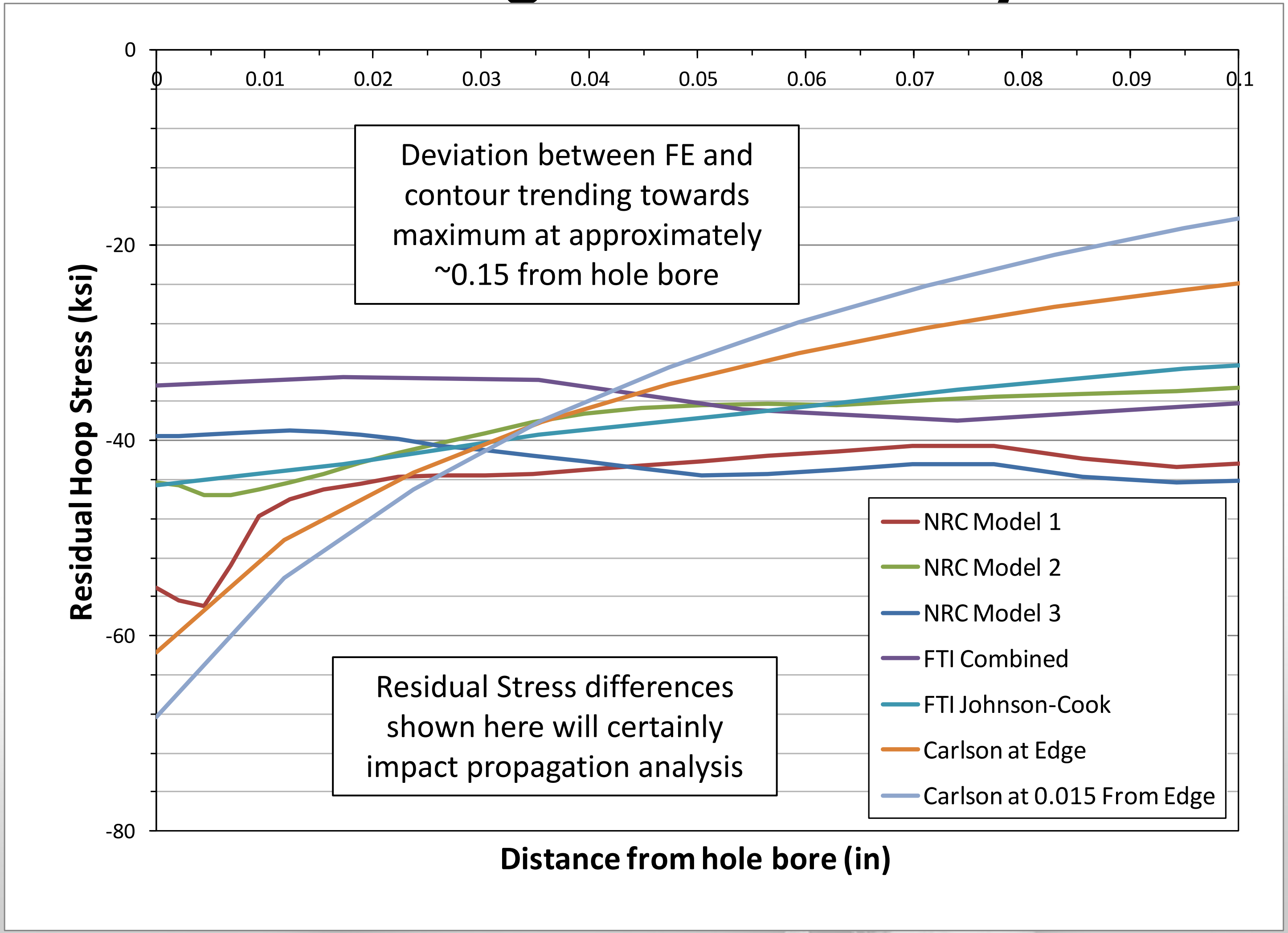
FEA Benchmarking Results – Entry Face



Deviation between FE and contour trending towards maximum at approximately ~0.15 from hole bore

ERSI FTI FATIGUE TECHNOLOGY

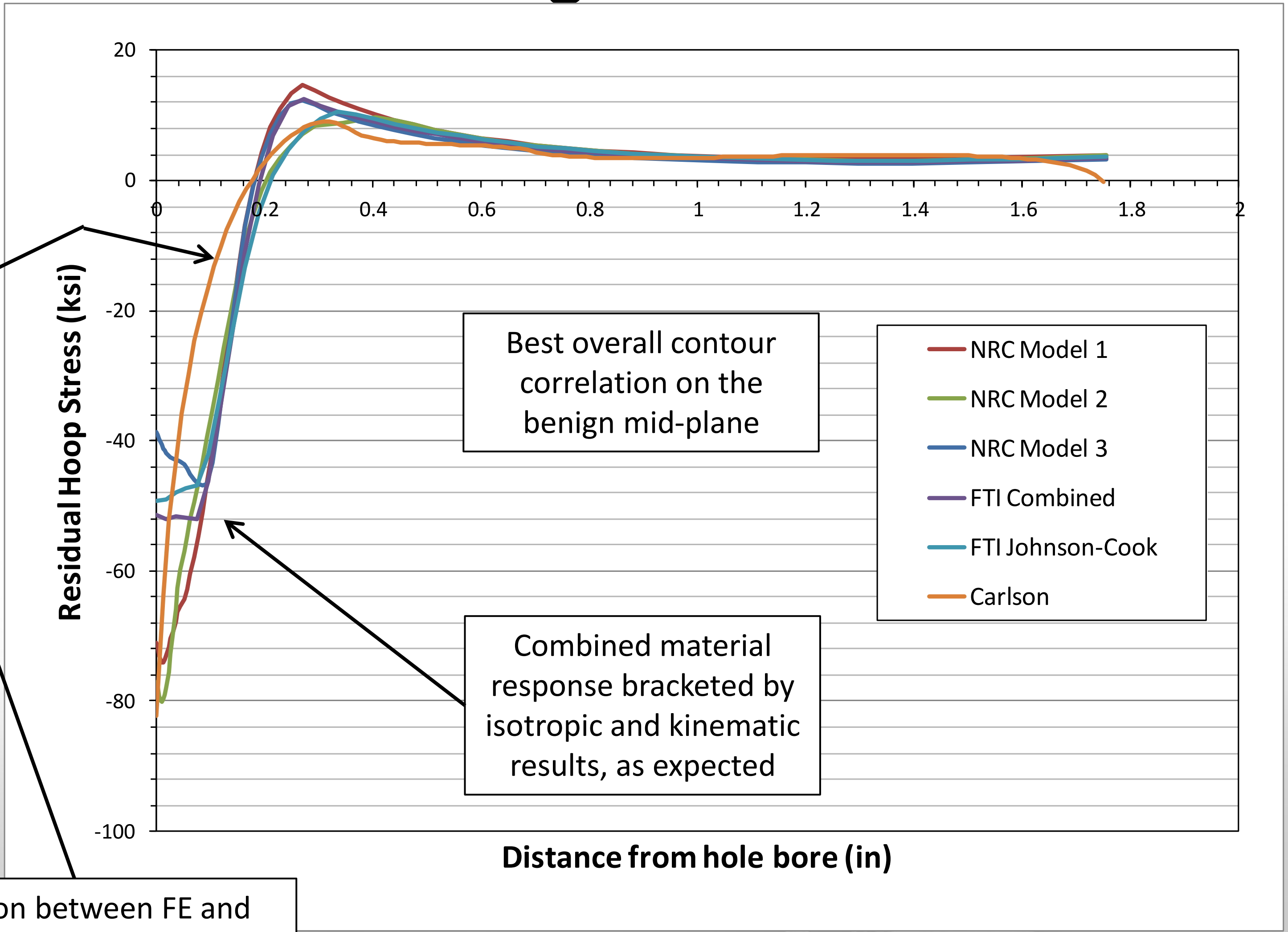
FEA Benchmarking Results – Entry Face Detail



ERSI FTI FATIGUE TECHNOLOGY

DM#740763

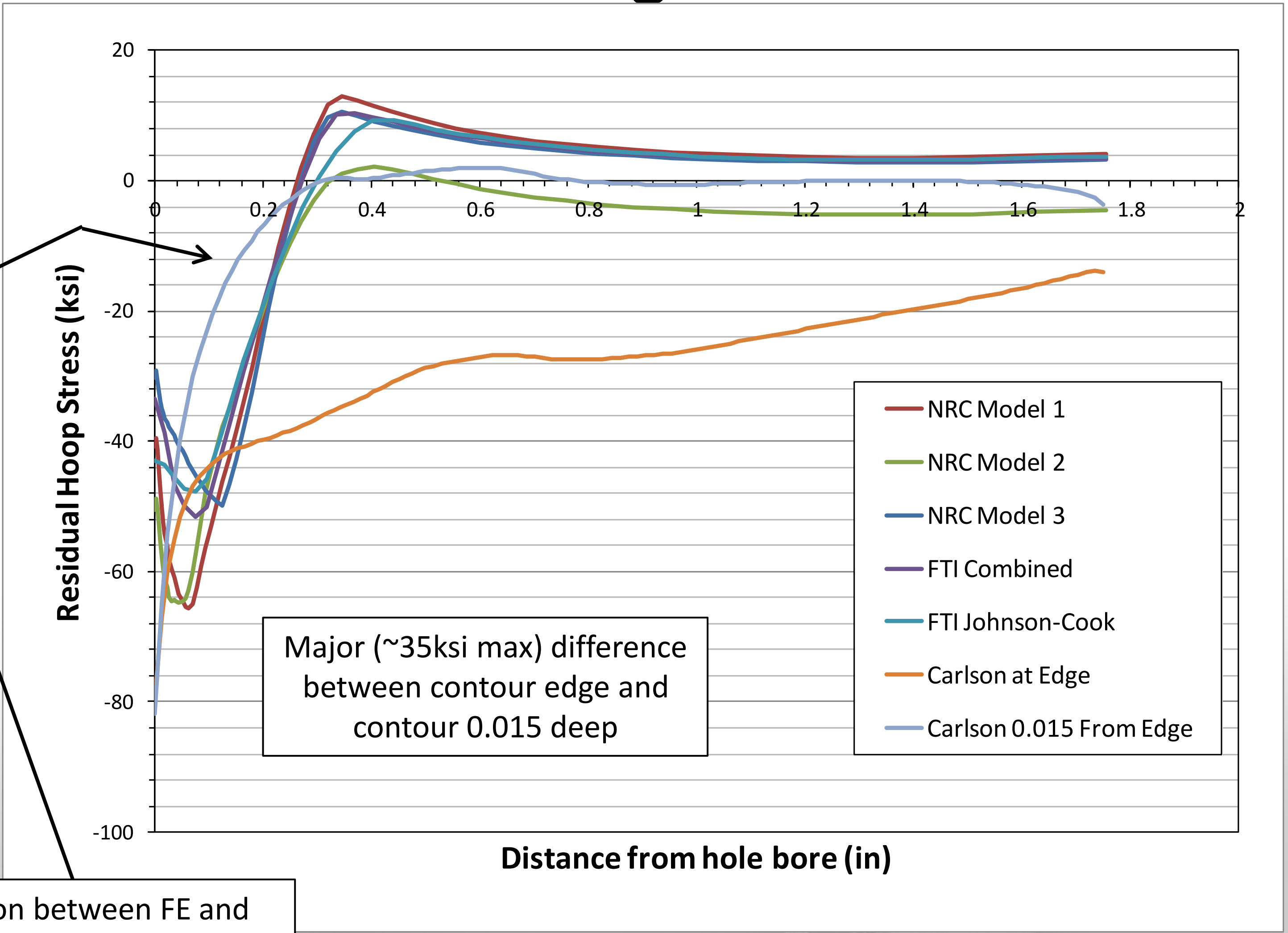
FEA Benchmarking Results – Mid-thickness



Deviation between FE and contour trending towards maximum at approximately ~0.15 from hole bore

ERSI FATIGUE TECHNOLOGY

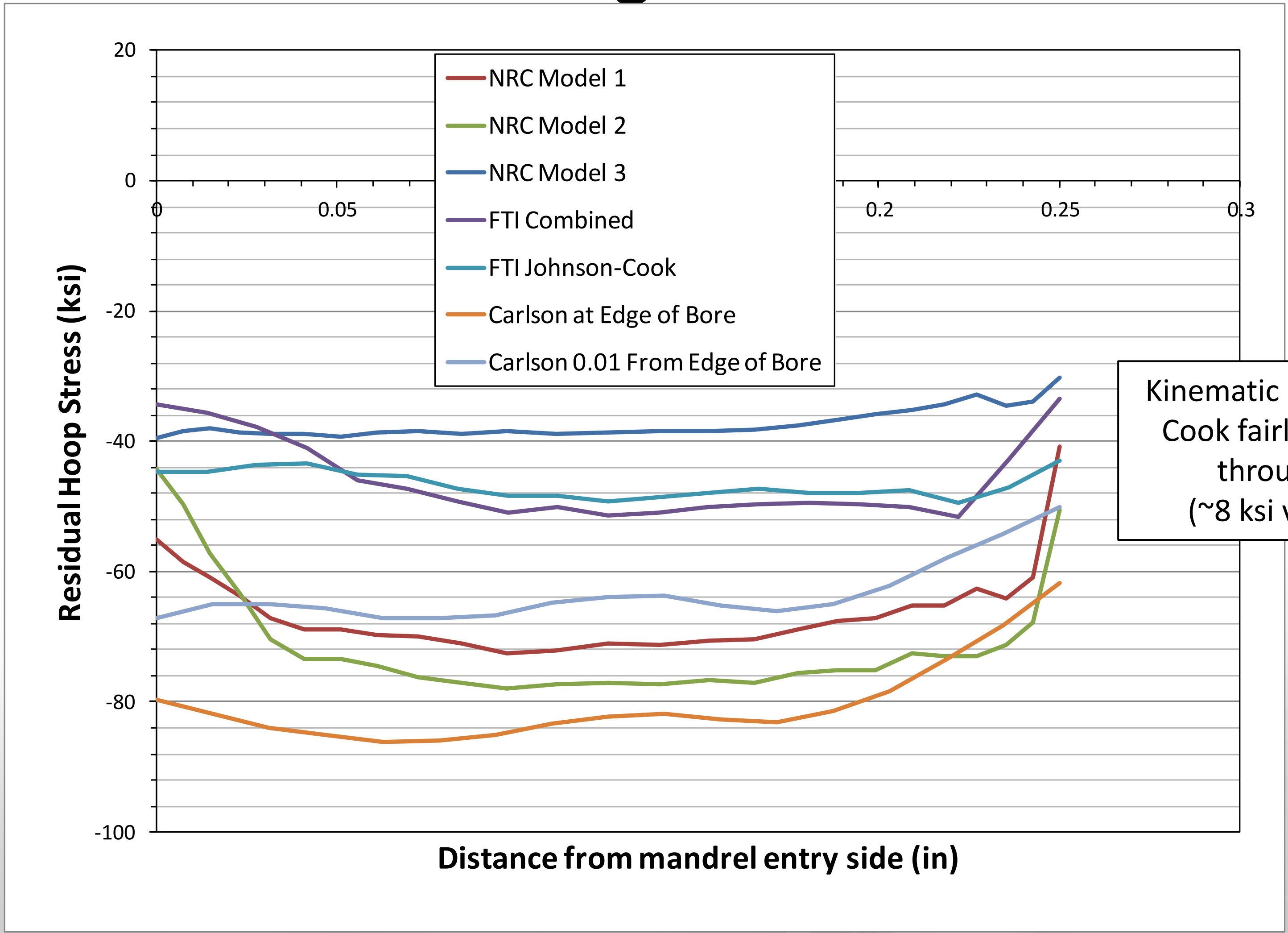
FEA Benchmarking Results – Exit Face



Deviation between FE and contour trending towards maximum at approximately ~0.15 from hole bore

ERSI FTI FATIGUE TECHNOLOGY

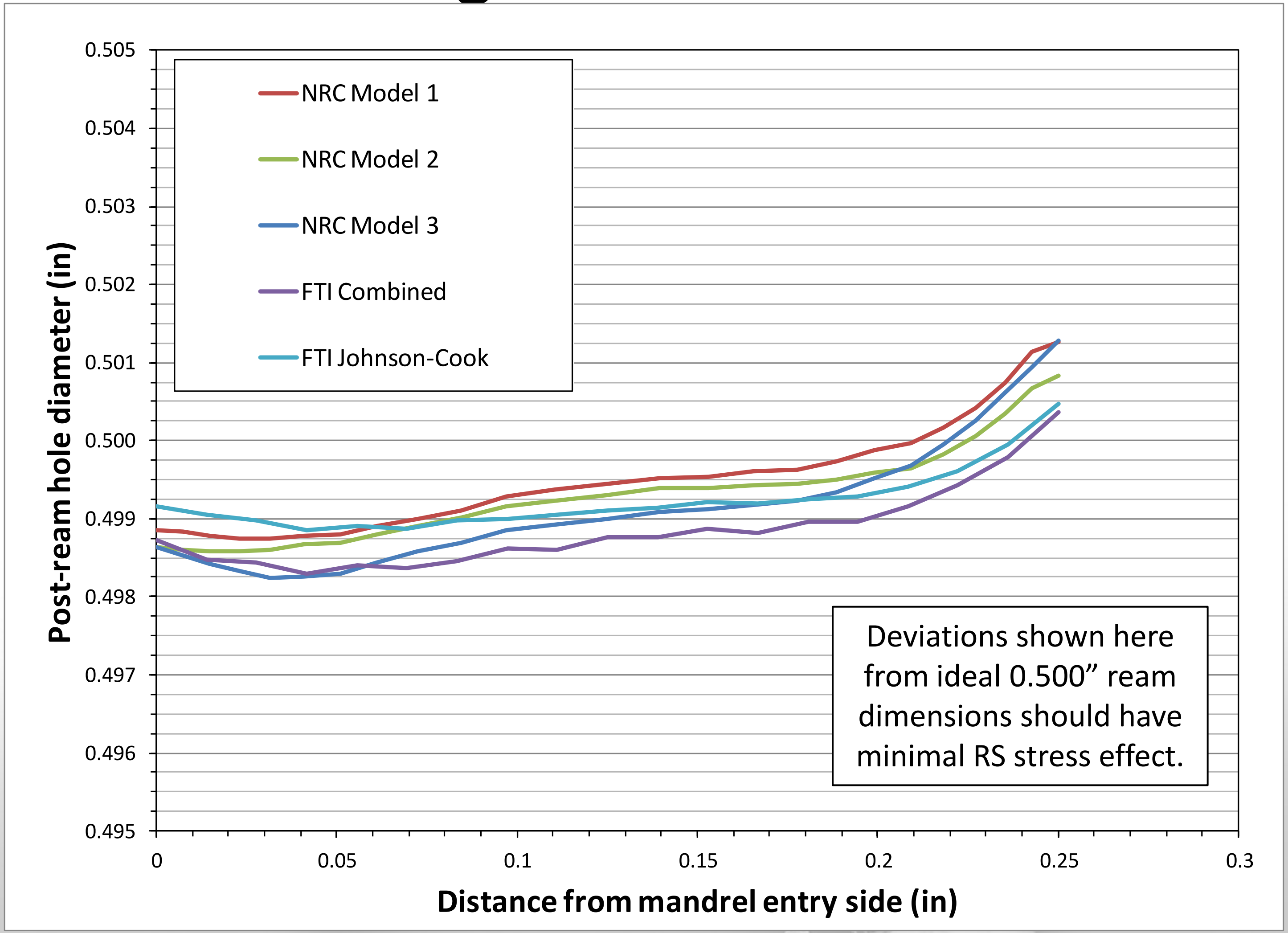
FEA Benchmarking Results – Hole Bore



Kinematic and Johnson-Cook fairly consistent through bore (~8 ksi variability)

ERSI FTI FATIGUE TECHNOLOGY

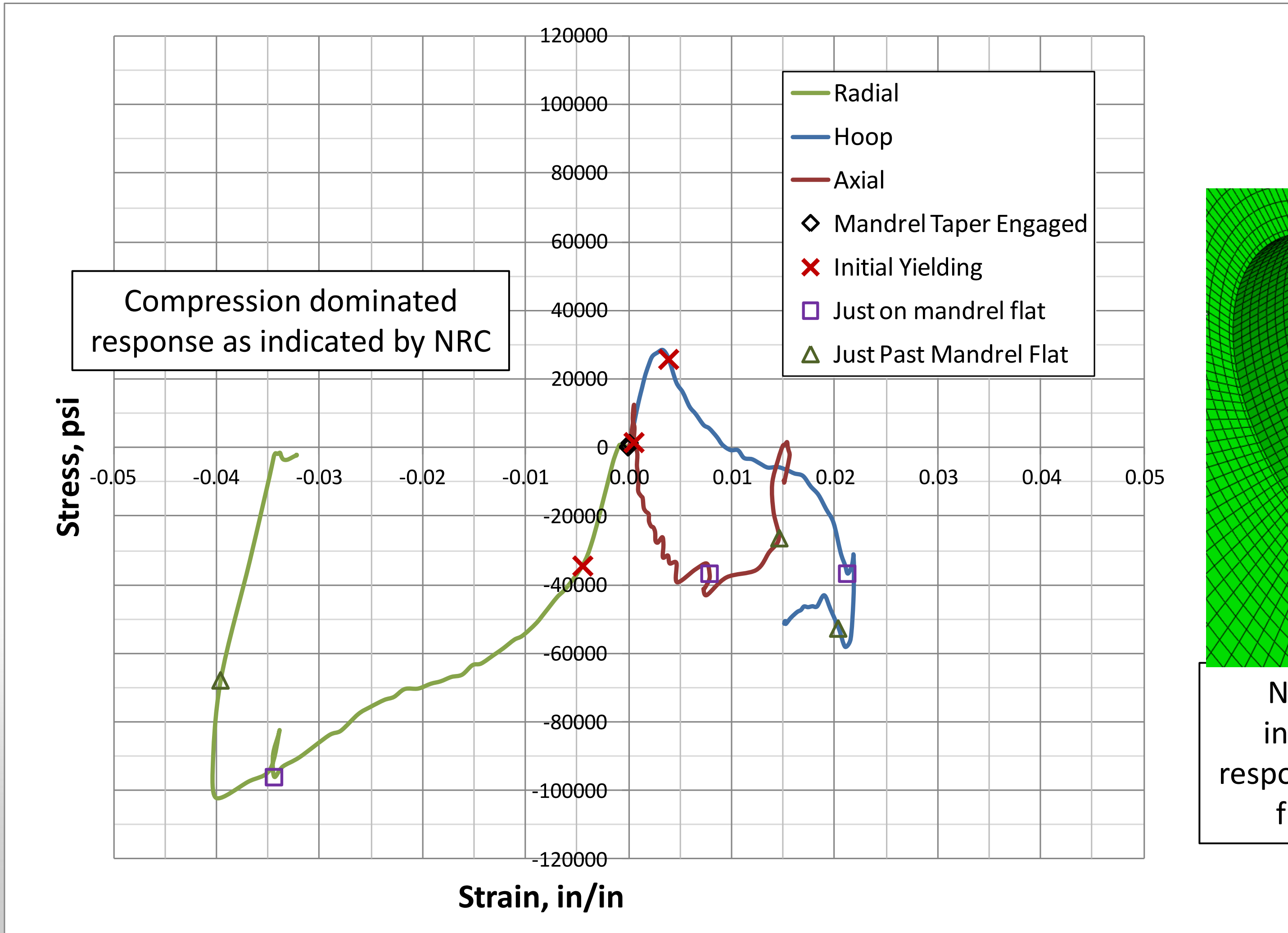
FEA Benchmarking Results – Post-ream Hole Dia.

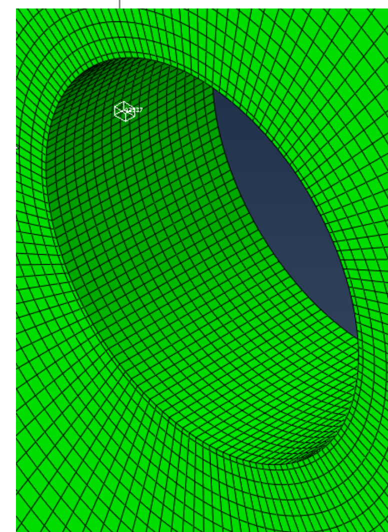


ERSI FTi FATIGUE TECHNOLOGY

DM#740763

FEA Benchmarking – Stress/Strain Response





NOTE: Shown is integration point response two elements from hole bore

FEA Benchmarking – Conclusions

- Each group used their best practice, resulting in some differences:
  - Mesh Density/Solver/Convergence criteria.
  - Constraints (nosecap vs sleeve).
  - Deformable tooling.
  - Manufacturing RS.
  - Material models for plastic response.
- Correlation between NRC and FTI models seem to be generally comparable when considering the differences above, especially material model differences.
- Correlation with contour method mixed:
  - Isotropic models showed best correlation with contour along bore.
  - All models show less than ideal correlation with contour in compressive region, overall.
  - Maximum deviation between contour and FE occurs ~0.15” from hole bore.

FEA Benchmarking – Next Steps

- Identify and obtain better material data (USAF/SwRI to test):
  - Test to ASTM E606 (LCF), not ASTM E8 (tensile)
  - Obtain at least one full hysteresis loop w/representative total strain range
  - Tensile-compressive or compressive-tensile?
  - Appropriate strain rate?
- Unify model construction practices.
- Re-run and compare with contour (and other test data, as available) in greater detail.
- Begin drafting a cold expansion FE modeling "standard".
- Phase II….

ERSI FTI FATIGUE TECHNOLOGY

FTI would like to thank Scott Carlson, SwRI, and the USAF for the opportunity to participate in ERSI, and FTI looks forward to future collaborations with NRC, SwRI, APES and others enabling the full benefits of cold expansion residual stresses to be realized by our customers.

Keith Hitchman
Project Engineer, Analyst
khitchman@fatiguetech.com
Phone: +1-206-701-7232
Mobile: +1-509-948-8240

ERSI

FATIGUE TECHNOLOGY

Testing Goals to Support

Engineered Residual Stress Integration into ASIP

1st Annual ERSI Workshop

15 Sept 2016

Thomas Mills, Ph.D. * • Dallen Andrew **

*** Analytical Processes / Engineered Solutions, Inc.**
**** Southwest Research Institute**

Contents

- Accomplishments
  - Understanding fatigue at CX holes
  - Modeling advancements
- What is missing?
- Need open discussion on:
  - What factors are important to model?
  - What testing would identify factors?
  - What testing would validate models?

Lots of Folks doing Lots of Stuff

- Decades of research into life improvement from CX processes at fatigue-loaded holes
  - The deepest bodies of work are proprietary
- Since 2006: USAF-supported efforts….
  - Isolating major sources of variation in fatigue performance
    - Edge margin
    - Interference level
    - Maximum remotely applied stress
    - Typical goal was to understand CX performance relative to current USAF ASIP guidance, "0.005"
  - Understanding Failure Progression
    - Crack formation locations
    - Crack propagation behavior
    - Evolution of shapes
    - Variations resulting from constant amplitude vs. spectrum load
  - Public Domain

http://www.a-listinternational.com/motivation-monday-how-to-be-a-great-team-player/

we think

Simulating What We See

- Primary technical advancements of the last decade
  - High-density residual stress data (Contour Method)
  - Integrated multi-point crack growth
    - Allows crack front to take natural shape
    - Not forced to be semi-elliptical
    - USAF focused on integrating StressCheck / AFGROW using

BAMF !!

  - Computation of stress intensity for crack in residual stress fields
    - A-10 & T-38 ASIP utilize StressCheck
    - J-integral and Contour Integral Method for Loaded Cracks (CIM-LC) **
    - CIM-LC only requires one component of RS tensor, which is important when using Contour Method data, as it supplies one component.

*******Actis et al., ASIP 2013, Bonita Springs, FL*

The Future of CX Experimental Programs

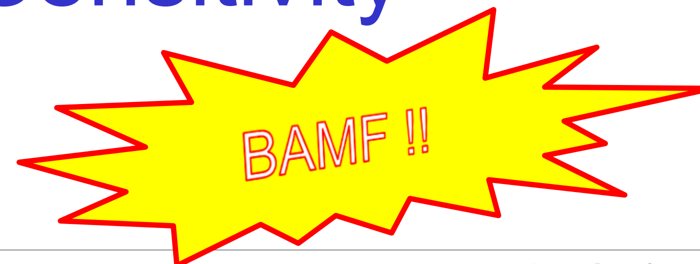
- Experimental work….
  - Illustrates important factors to model
  - Provides data so we can validate models
- One advantage of having completed extensive fatigue tests in CX holes:
  - Creates many questions that we can go answer.
- Topic Areas
  - Many currently identified
  - Need input from working group

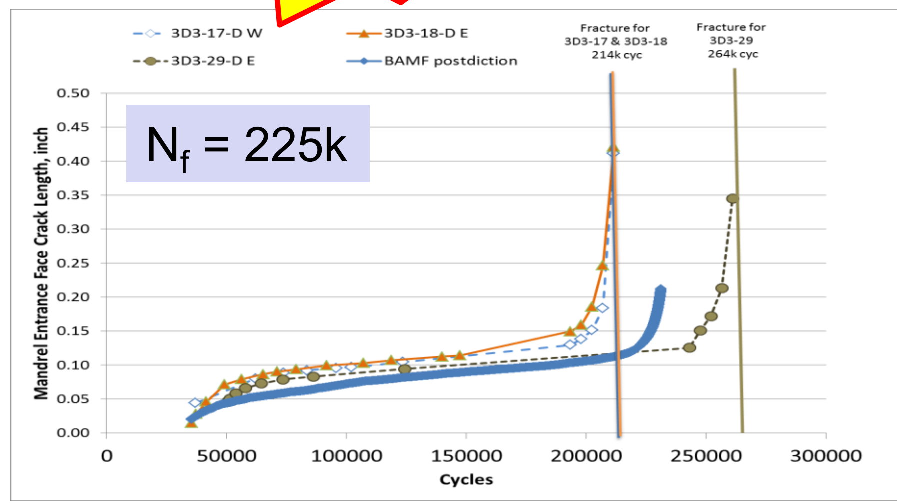
Experiments to Support Modeling Needs

- Material Behavior
- Residual Stress Redistribution
- Countersunk holes (95% of USAF efforts in straight-bore holes)
- Other CX Processes
- Other Engineered RS Processes

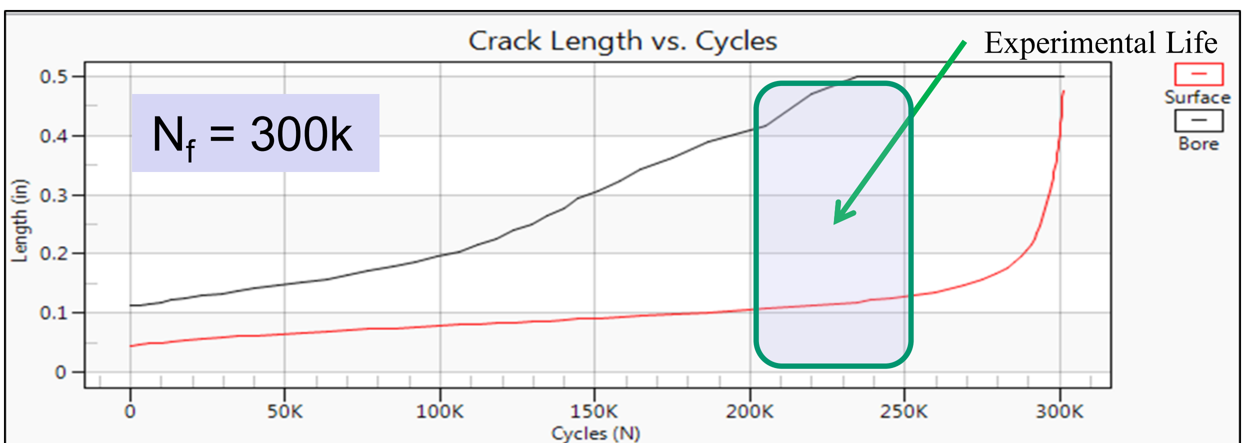
Material Model Sensitivity

- da/dN vs. ΔK relationships have major impact on predicted life
- In this example, BAMF using material model 1 (MM1) computed a life that is 75% of that of CPT and MM2



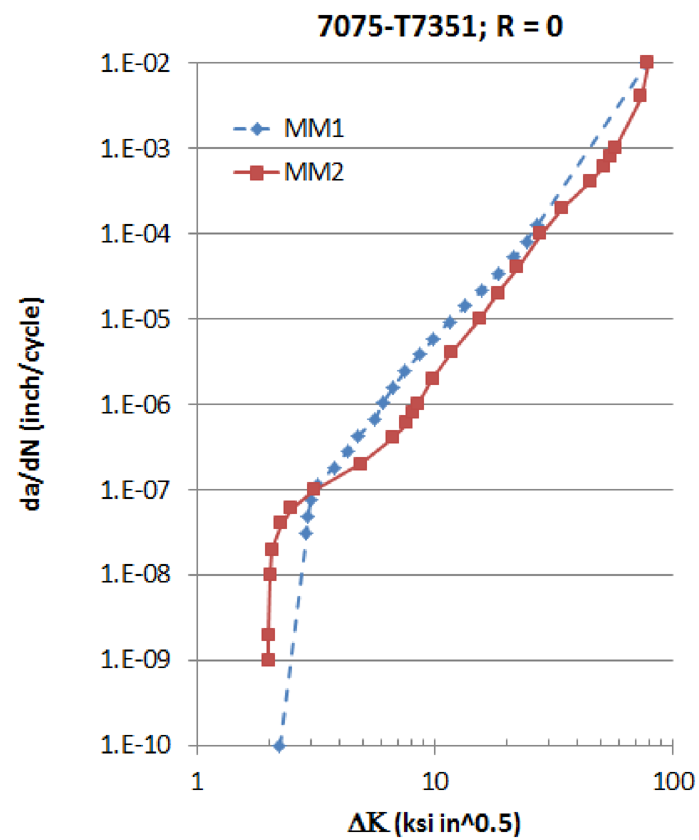


CPT



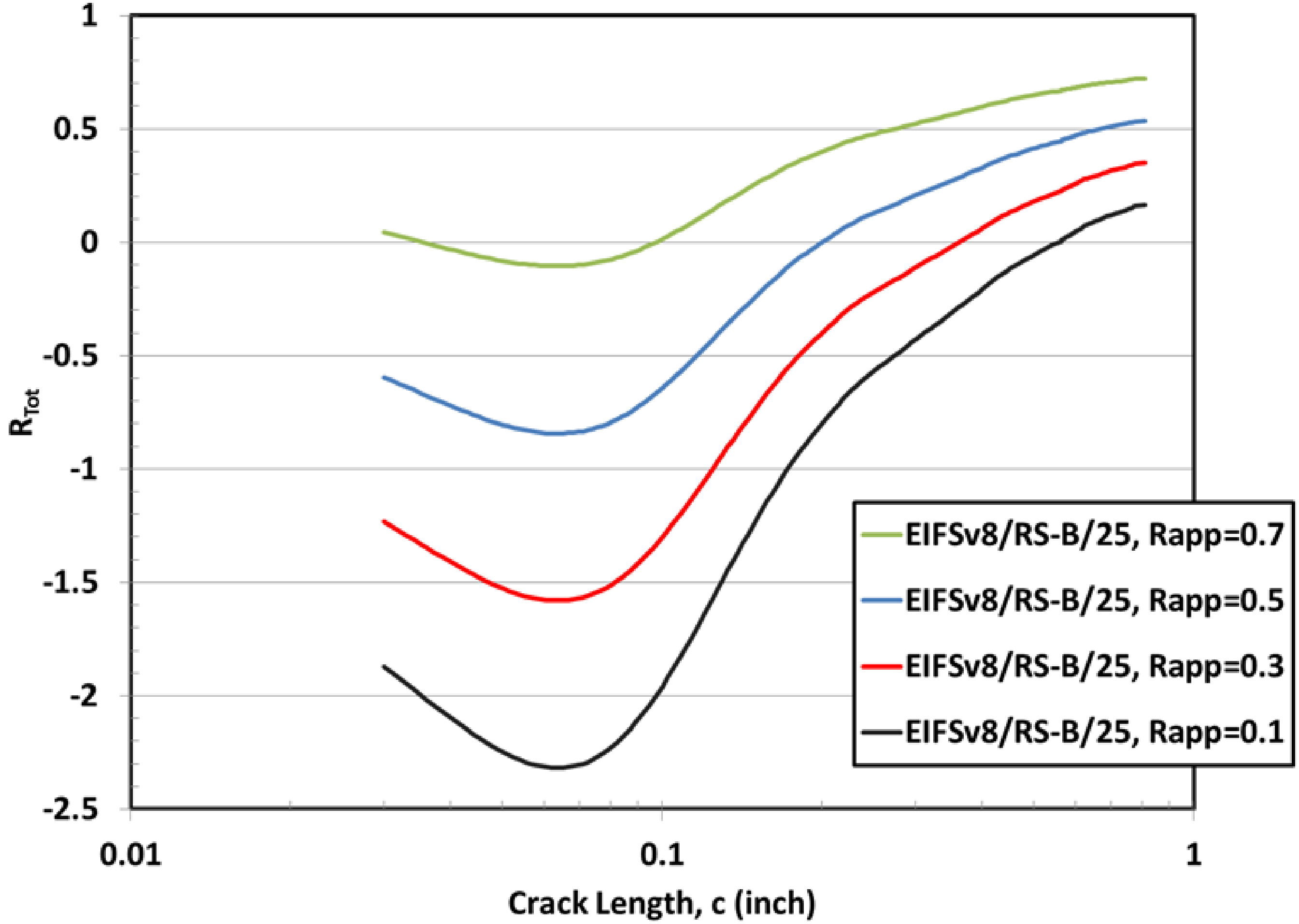
Thorough da/dN v. ΔK Curves

- History of long crack data with severe "threshold" behavior
- High R data
  - Not as critical to RS applications because K_{res} typically pushes R_{tot} negative)
- Weak on Negative R data
  - K_{res} pushes R_{tot} deeply negative
  - Not a typical consideration in tension-dominated DT control points

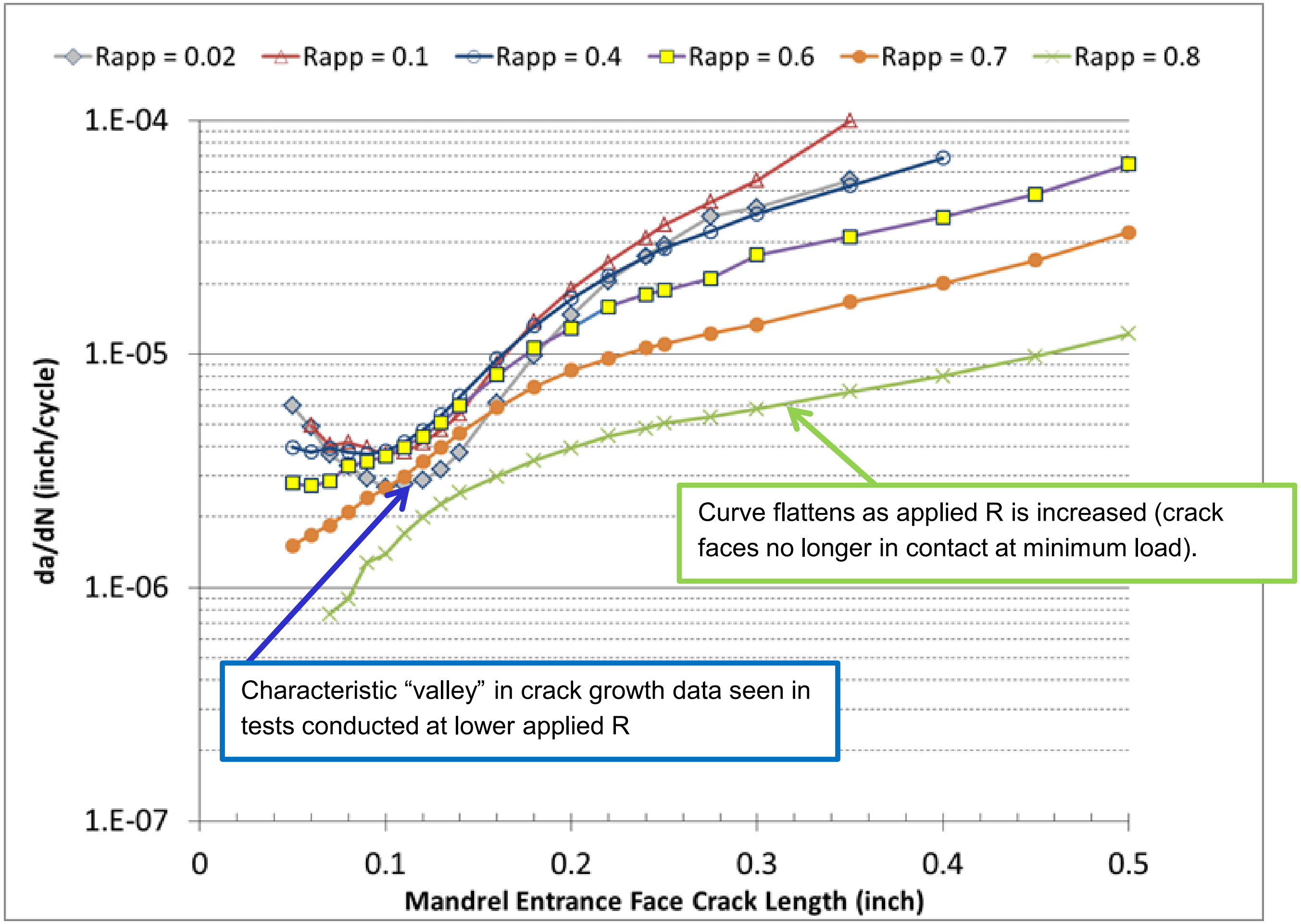


Relationship of Crack Size and Total R

- Example using 3.8% CX interference and 25 ksi remotely applied stress (varying applied R, R_{app}).



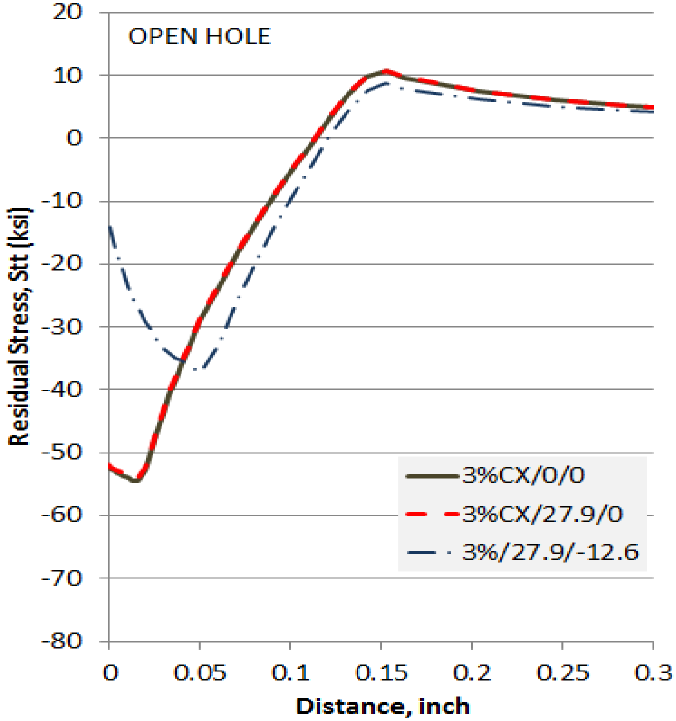
Evidence of Closure Processes?



Other Material Behavior Considerations

- Modeling of CX process
  - RS distribution sensitive to "hardening parameter"
  - Kinematic vs. isotropic
- Closure
  - Characteristic "hook" in da/dN vs. 'a' data disappears at high applied R (Rapp > 0.7)
- Retardation
  - Commonly used in DTA
  - Proper application for RS cases?

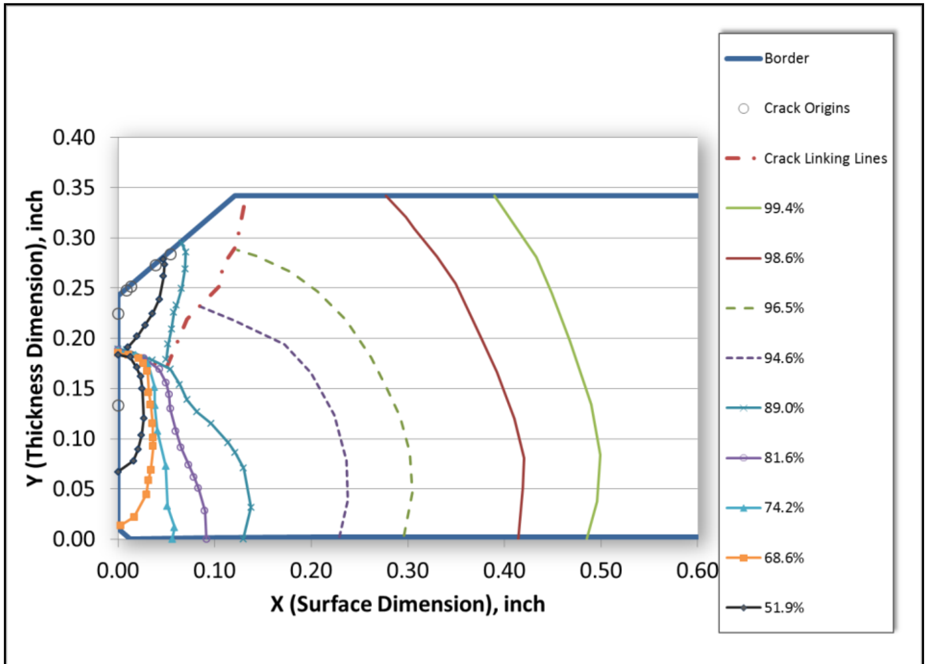
Residual Stress Redistribution and Interactions



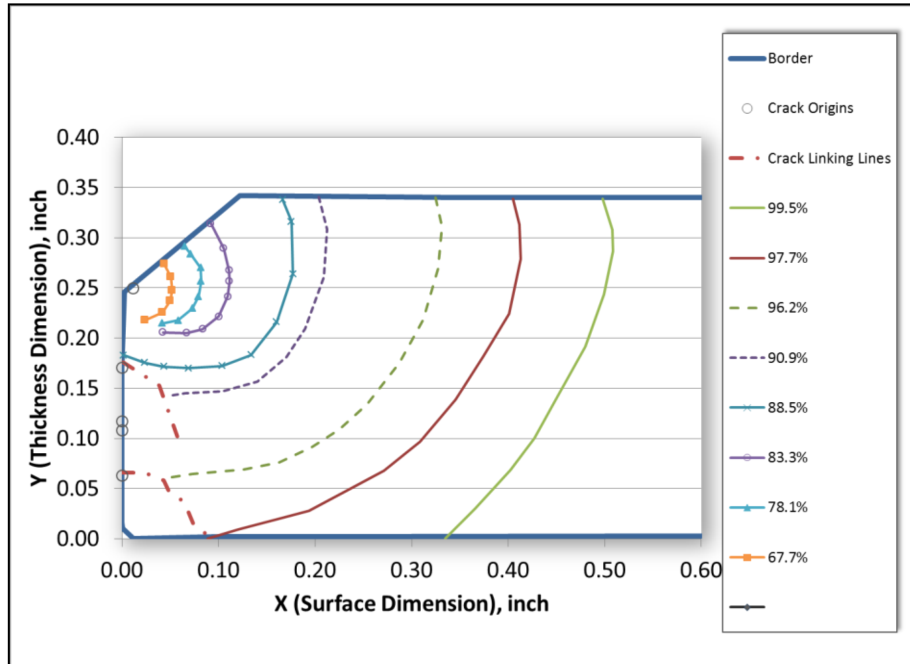
- Load spectra
  - Peak tension and compression effects
  - How do stresses redistribute?
    - Open hole
    - Filled hole
    - Load transfer
- Stress interaction
  - CX holes and interference pins
  - RS distributions and nearby geometric effects (moving failure)
  - Re-working a CX hole
- *At least one* dissertation here just for straight-bore holes.
  - Somebody can get another dissertation for countersunk holes

Speaking of Countersunk Holes….

- Fatigue origins (and life) are sensitive to CX method.



- CX straight bore hole, then machine countersink
- Modeling redistribution of RS when material is removed?



- CX existing countersunk hole using FTI's CsCX

Left: crack growth inhibited at countersink knee despite higher Kt.

Other RS Methods

- Current efforts have mostly focused on split sleeve CX of fastener holes
- Laser Peening
  - Hill Engineering has done some work in this area
- Other CX processes (split mandrel)?
- Other surface RS methods?
  - Many of these would not be friendly to damage tolerance analyses
  - Stress not deep enough

"Legacy" CX Holes

- Building a robust toolbox based on "new build" scenarios and data.
- What if holes were CX'd in days of yore?
- Some effort underway to look at RS of legacy CX holes
  - Teardown wings from T-38 & A-10
- Fatigue response to be examined as well

As we prepare to open discussion….

- USAF current contracted efforts are examining the following:
  - RS redistribution from external loads and pin loads (limited capacity)
  - Material model deficiencies (da/dN vs. ΔK)
  - Some work in countersunk holes
  - Some legacy CX considerations
- Goal here is get feedback on other important test data needed for validation or for exploring pitfalls
- Road to ASIP integration

Air Force Research Laboratory

Impact of Deep Residual Stress on NDI Methods

Engineering Residual Stress Implementation Workshop

15 September 2016

John Brausch
Materials Integrity Branch
Systems Support Division
Materials and Manufacturing Directorate

Integrity ★ Service ★ Excellence

Questions to Answer (v2)

A Century of Scientific Excellence

1. What role does Non-Destructive Inspection play within your role of managing airframe structure?

2. What guiding documents define the role of NDI within your organization?

3. Do you see the need to make any changes or updates to the NDI techniques used to find "damage" within a deep residual stress field and if so how would you propose making these changes or updates?

4. What roles do you see statistical quantification of NDI techniques playing in these potential changes?

5. What document do you see defining NDI capabilities within deep residual stress fields?

Questions to Answer (V1)

A Century of Scientific Excellence

- What is the current state-of-the-art of knowledge on the impact of deep residual stresses to various NDI methods?
- What requirements to you see the USAF putting out to better define the impacts of deep residual stresses on POD at coldworked (Cx) holes?
  - What additional testing/analysis must be performed to allow the fulfillment of these requirements?
- What type of document do you see being developed to provide users to know how deep residual stresses impact POD?
- What needs to happen from an NDI perspective for accounting for RS in USAF depot maintenance?
- How can the knowledge gained through the work on Cx holes be applied to other deep residual stress inducing processes like Laser Shock Peening or Low Plasticity Burnishing?

Agenda

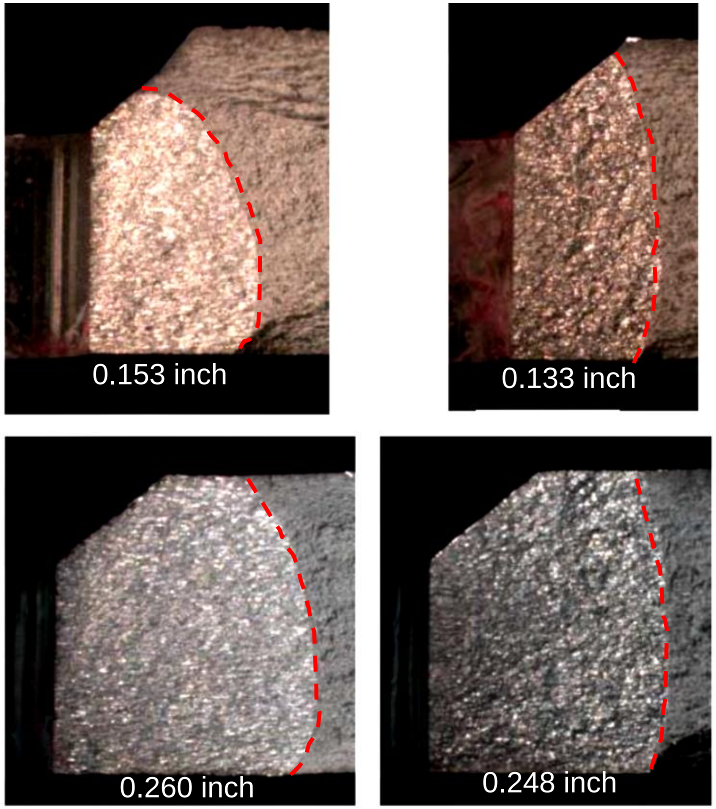
A Century of Scientific Excellence

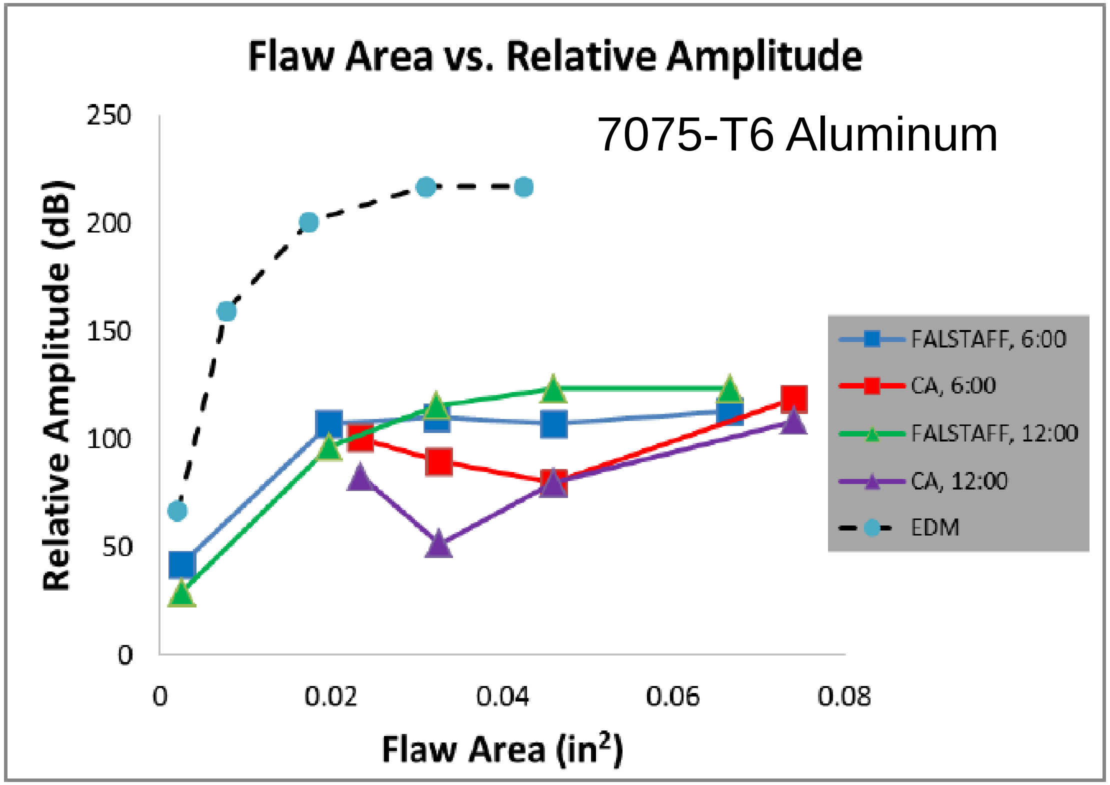
- Current Understanding
- Future Research Needs
- Guidance for Depot and Field Inspections
- Documenting Lessons Learned

EDM vs. Fatigue Cracks in Holes – No Load
Shear-Wave Ultrasonic Response

A Century of Scientific Excellence

FALSTAFF Constant Amplitude





Henry, T. "Correlating Ultrasonic Responses of Fatigue Cracks Propagated Under Different Load Spectra."

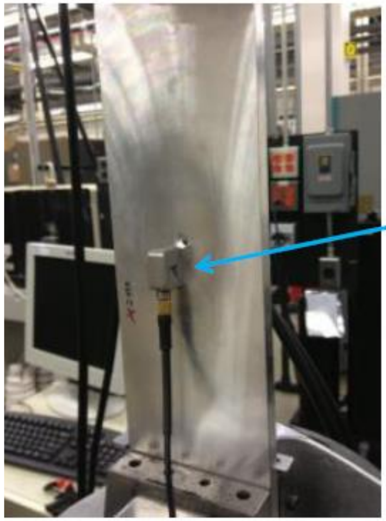
- UT response from EDM slots and fatigue cracks differ considerably.
  - 6dB difference between UT response from EDM and unloaded fatigue cracks
- UT response will vary depending on crack profile and fracture surface texture.

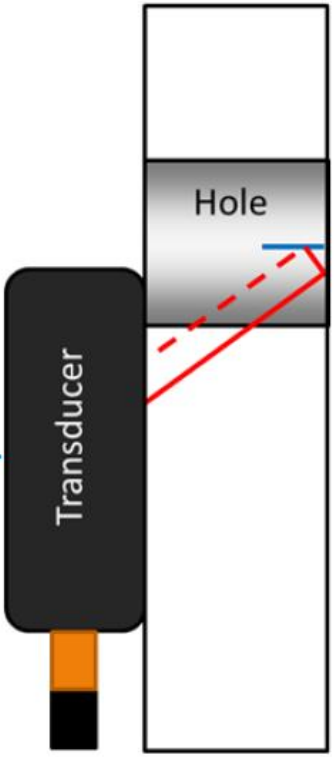
Return Energy a Function of Reflector Geometry Surface Texture, Crack Closure

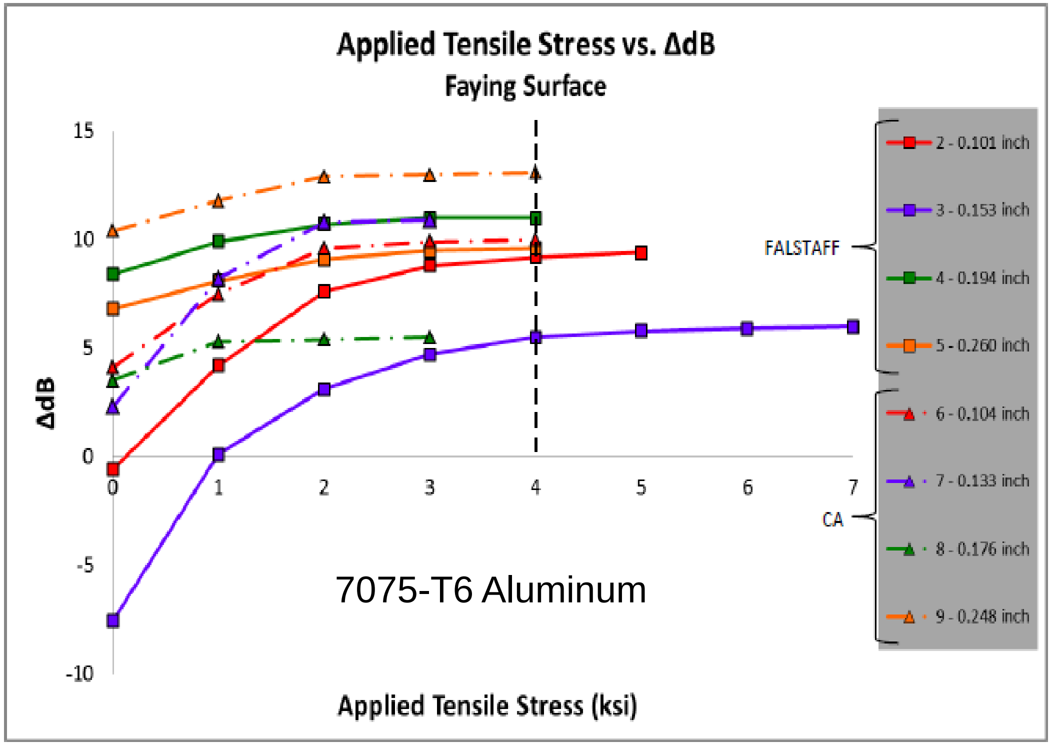
Fatigue Cracks in Holes, Applied Tensile Stress
Shear-Wave Ultrasonic Response

A Century of Scientific Excellence

Tensile stress required to fully open fatigue cracks in holes w/o Cx.







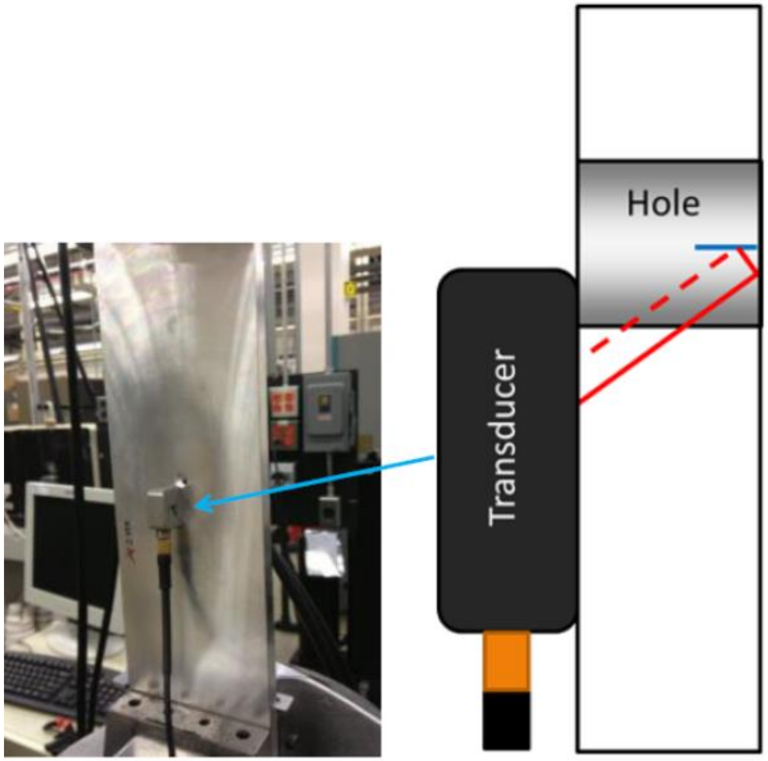
Henry, T. "Correlating Ultrasonic Responses of Fatigue Cracks Propagated Under Different Load Spectra."

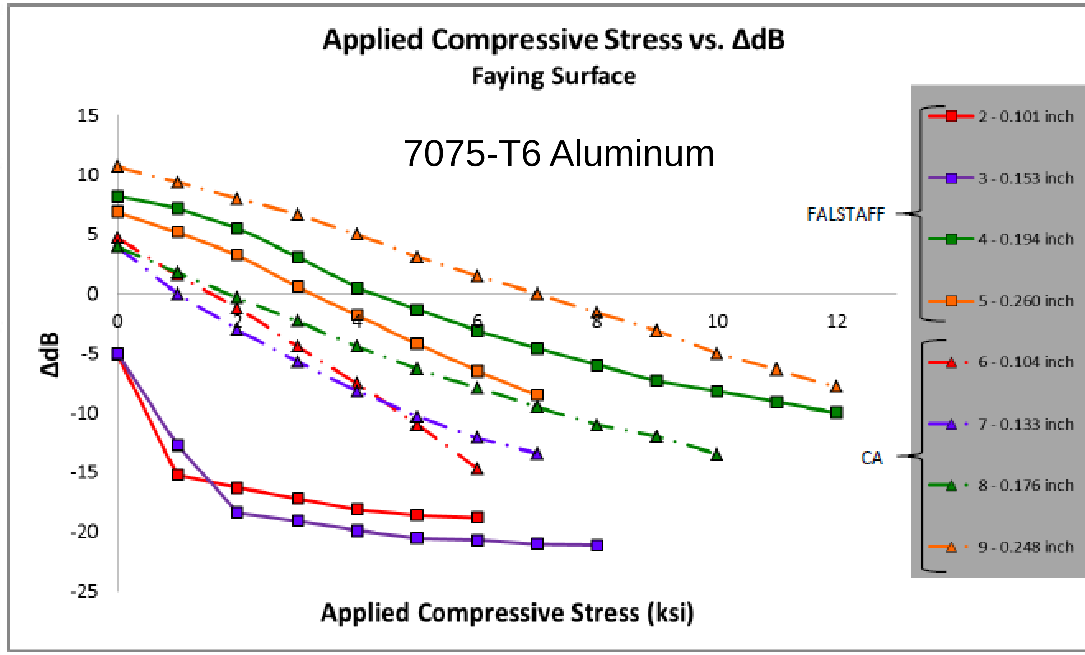
~ 4 ksi tensile stress sufficient to open crack for maximum UT detectability.

Fatigue Cracks in Holes, Applied Compressive Stress
Shear-Wave Ultrasonic Response

A Century of Scientific Excellence

Ultrasonic response from fatigue cracks under applied compressive stress.



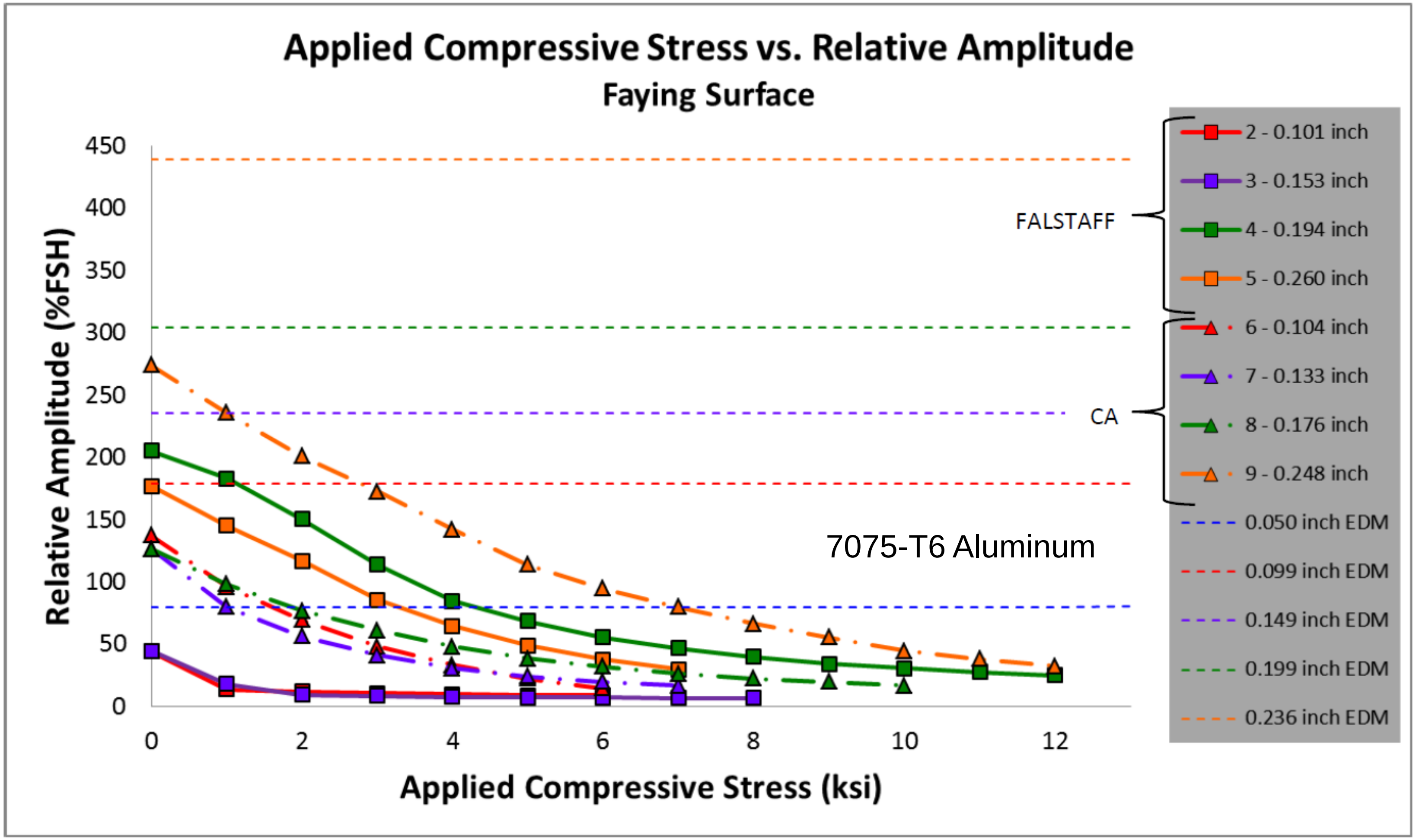


Henry, T. "Correlating Ultrasonic Responses of Fatigue Cracks Propagated Under Different Load Spectra."

~6dB (50%) signal reduction per 4 ksi applied compressive stress.

Fatigue Cracks in Holes, Applied Compressive Stress
Shear-Wave Ultrasonic Response

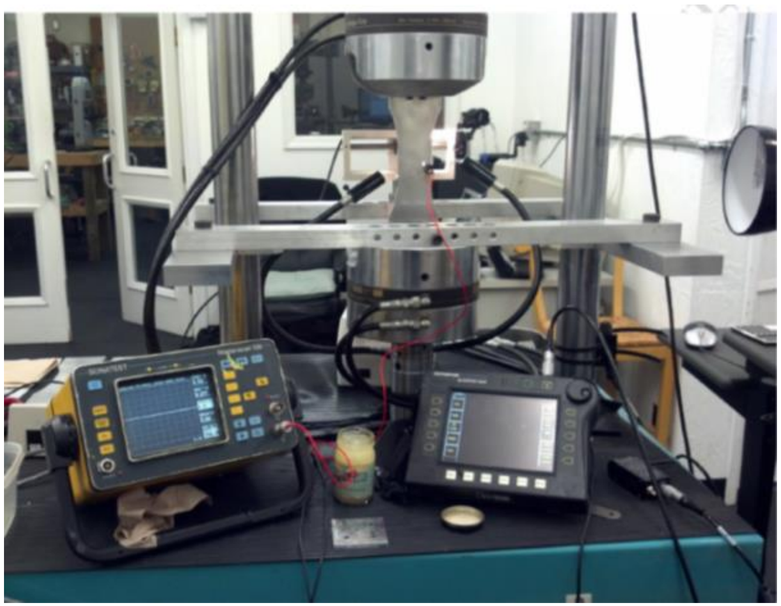
A Century of Scientific Excellence

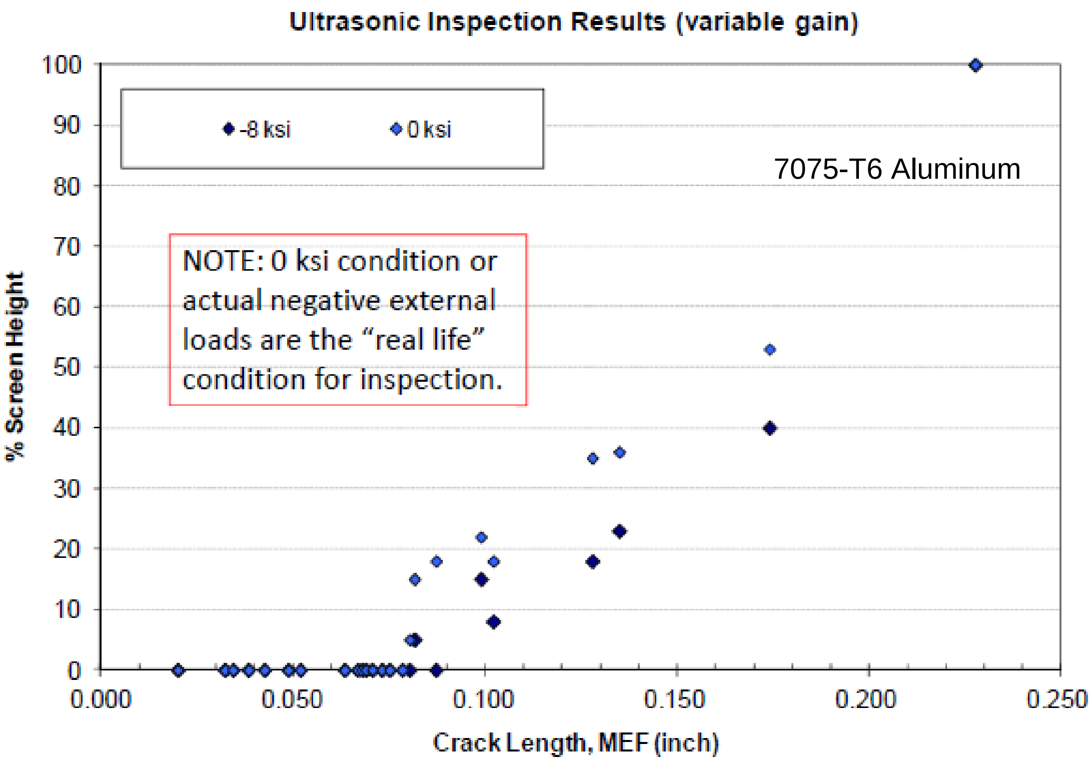


Henry, T. "Correlating Ultrasonic Responses of Fatigue Cracks Propagated Under Different Load Spectra."

Fatigue Cracks Grown in Cx Holes, Applied Stress
Shear-Wave Ultrasonic Response

A Century of Scientific Excellence



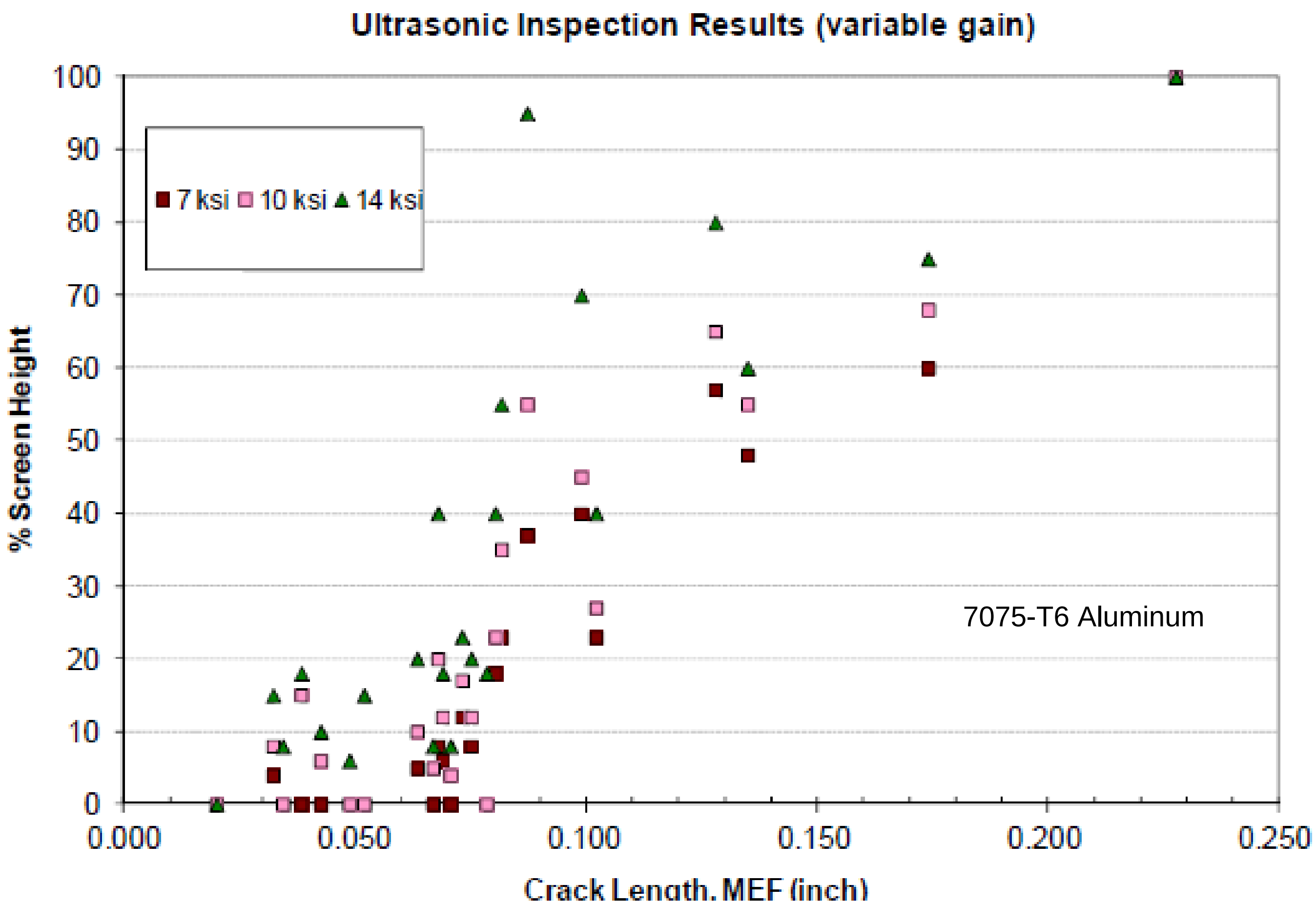


Forsythe, D., Mills, T. "Results of Study of Applied Stress and CX Process on Detectability of Fatigue Cracks"

- Crack must extend beyond compressive zone to be detectable by UT.
- Compressive stress zone extends >0.075 inch beyond edge of hole for this scenario.

Fatigue Cracks Grown in Cx Holes, Applied Stress
Shear-Wave Ultrasonic Response

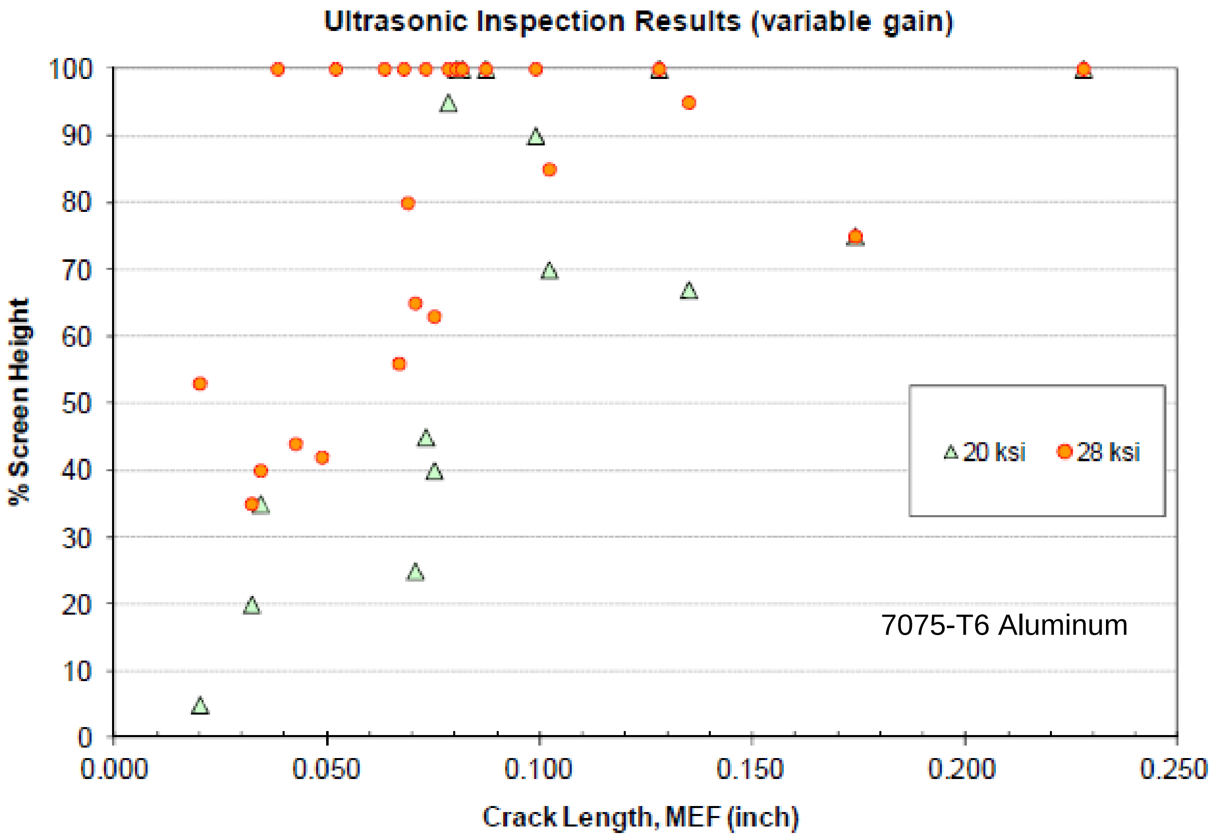
A Century of Scientific Excellence



Forsythe, D., Mills, T. "Results of Study of Applied Stress and CX Process on Detectability of Fatigue Cracks"

Fatigue Cracks Grown in Cx Holes, Applied Stress
Shear-Wave Ultrasonic Response

A Century of Scientific Excellence



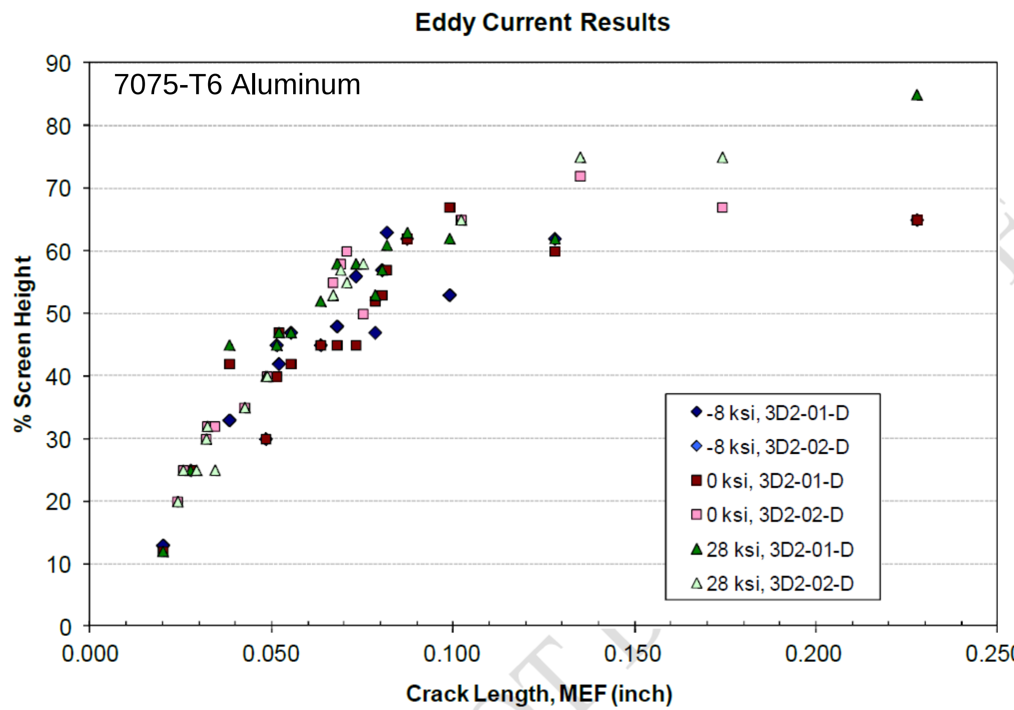
Forsythe, D., Mills, T. "Results of Study of Applied Stress and CX Process on Detectability of Fatigue Cracks"

Significant applied tensile stress required to fully open fatigue crack in CX holes

Fatigue Cracks Grown in Cx Holes, Applied Stress
Bolt Hole Eddy Current Response

A Century of Scientific Excellence

Rotary bolt hole eddy current response from fatigue cracks under compressive stress.



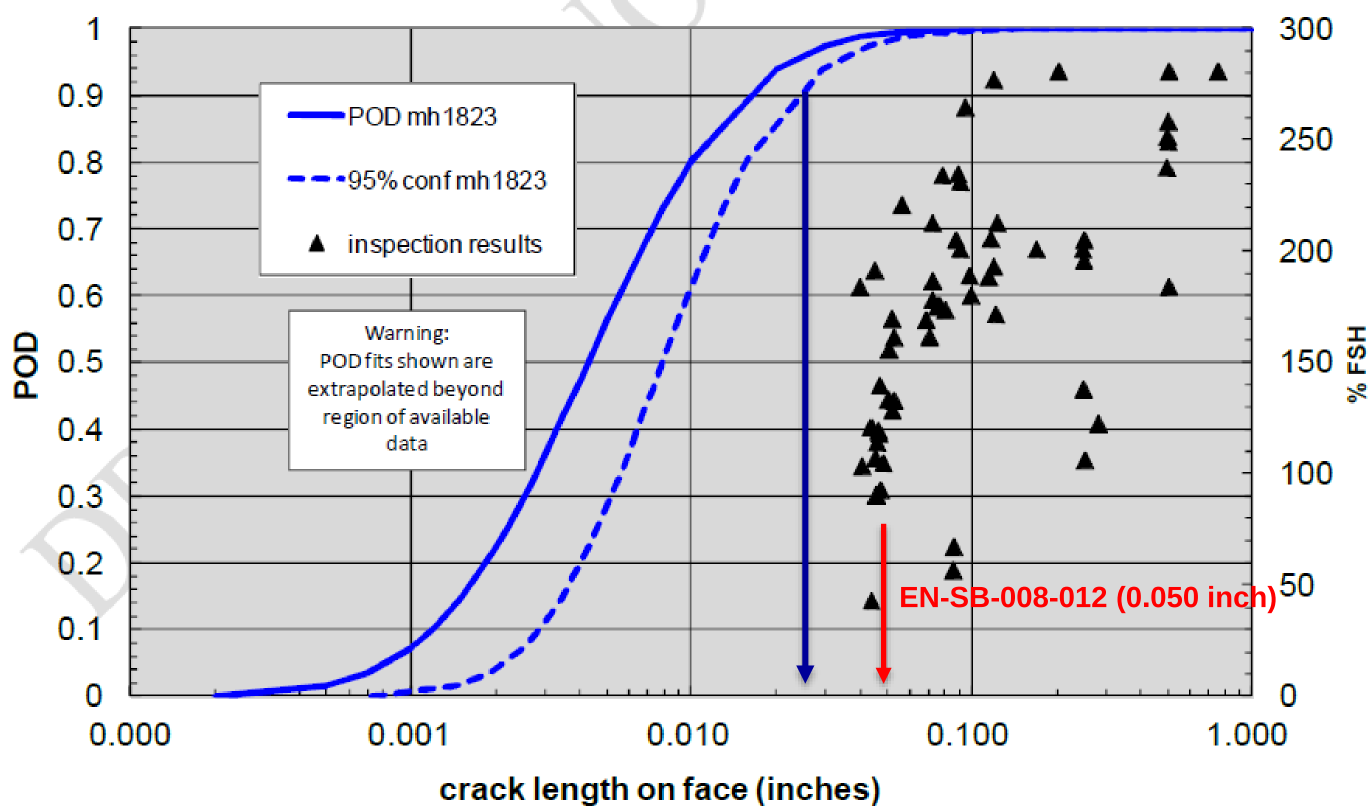
Forsythe, D., Mills, T. "Capability of Inspections for the Detection and Sizing of Cracks in Cold Worked Holes"

Applied compressive stress has no significant effect on rotary bolt-hole eddy current response.

Fatigue Cracks Grown in Cx Holes

Bolt Hole Eddy Current POD

A Century of Scientific Excellence



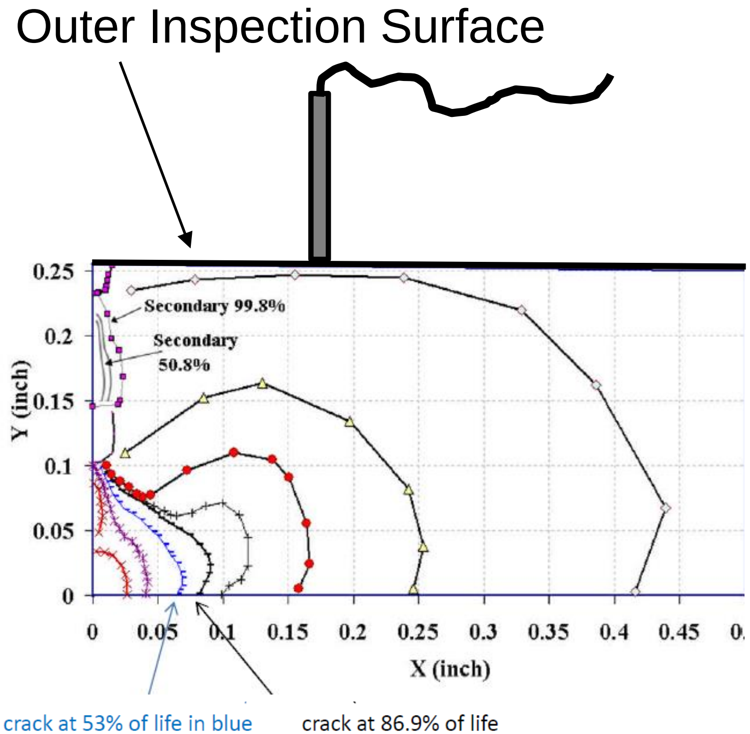
Forsythe, D., Mills, T. "Capability of Inspections for the Detection and Sizing of Cracks in Cold Worked Holes"

- Existing EN-SB-008-012 guidance is valid for BHEC in CX holes.

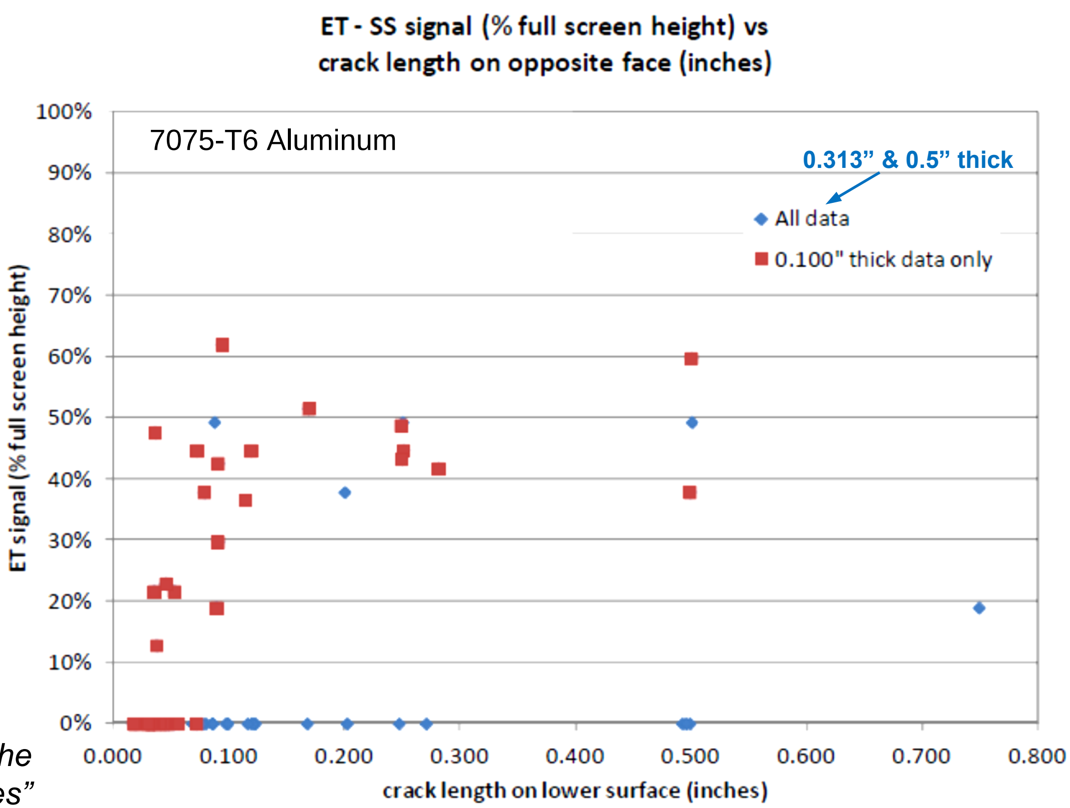
Fatigue Cracks Grown in Cx Holes

Surface Eddy Current Response

A Century of Scientific Excellence



Forsythe, D., Mills, T. "Capability of Inspections for the Detection and Sizing of Cracks in Cold Worked Holes"



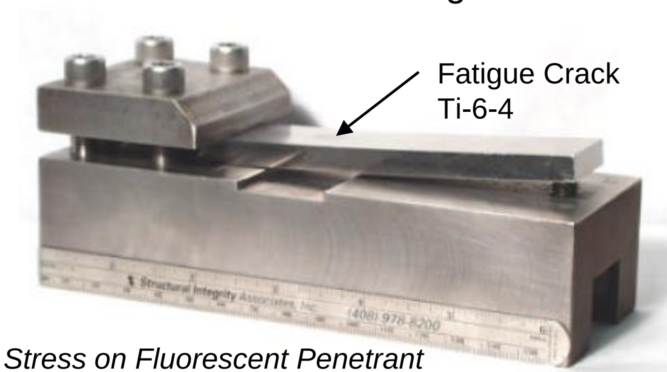
- Cracks in CX holes initiate at mandrel entry surface, typically faying surface.
- Cracks must grow to inspection surface to be detectable.
- Fatigue cracks in CX tend to "tunnel" under inspection surface.
- ***ECSS from mandrel exit surface not effective for plate thicknesses >0.100 inch!!***

Fatigue Cracks Under Applied Compressive Stress
Fluorescent Penetrant Response

A Century of Scientific Excellence

<u>Result</u>:
Significant measurable reduction in penetrant indication size with application of compressive stress.

Cantilever Bending Fixture



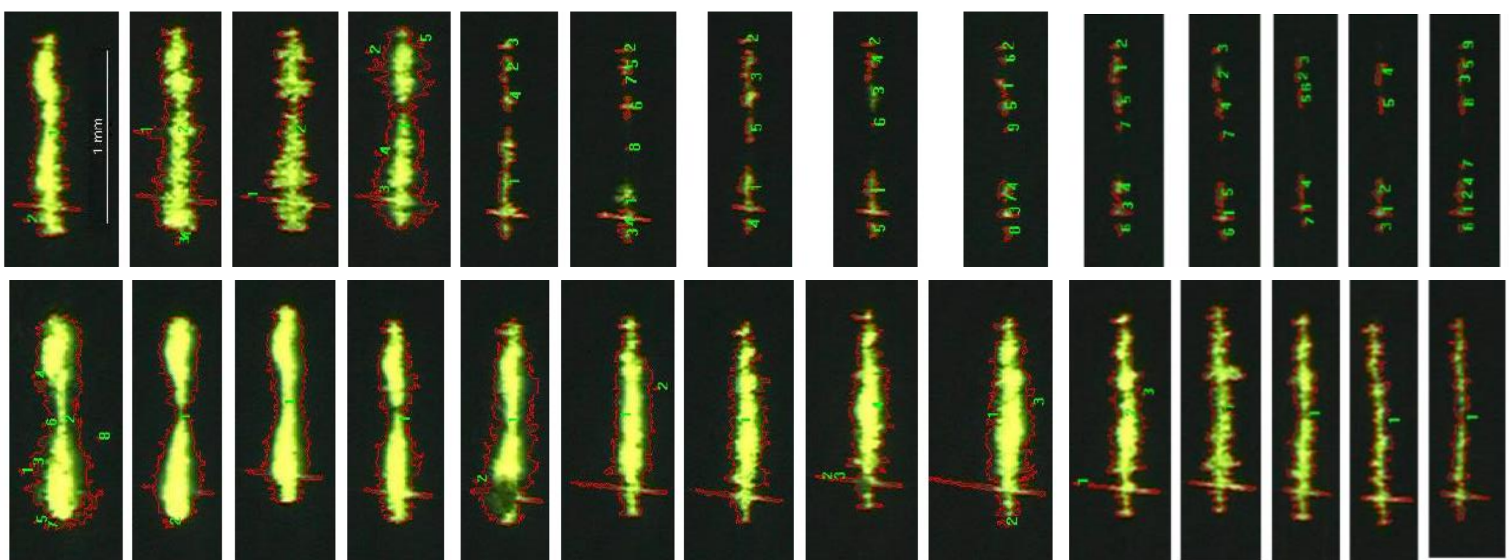
Brausch, J., Tracy, N., Effects of Compressive Stress on Fluorescent Penetrant Indications of Fatigue Cracks in Titanium, AFRL-ML-WP-TR-2001-4139

Measured residual surface stress (X-Ray Diff)

	Longitudinal Residual Stress (ksi)	
Specimen Number	Before Annealing	After Annealing
17	-50.9 ± 4.5	4.2 ± 1.3 0.3 ± 2.1
63	-40.6 ± 2.3	-5.8 ± 1.8 -3.8 ± 1.2
41	-38.3 ± 4.5	0.9 ± 1.9 -0.1 ± 1.5
44	-35.7 ± 3.3	-4.1 ± 1.5 1.7 ± 1.5
53	-60.3 ± 3.6	-2.8 ± 1.6 -3.1 ± 1.4

Applied Stress (ksi) 0 3.5 8.5 13.5 18.5 23.5 28.5 33.5 38.5 43.5 48.5 53.5 58.5 63.5

Specimen #44

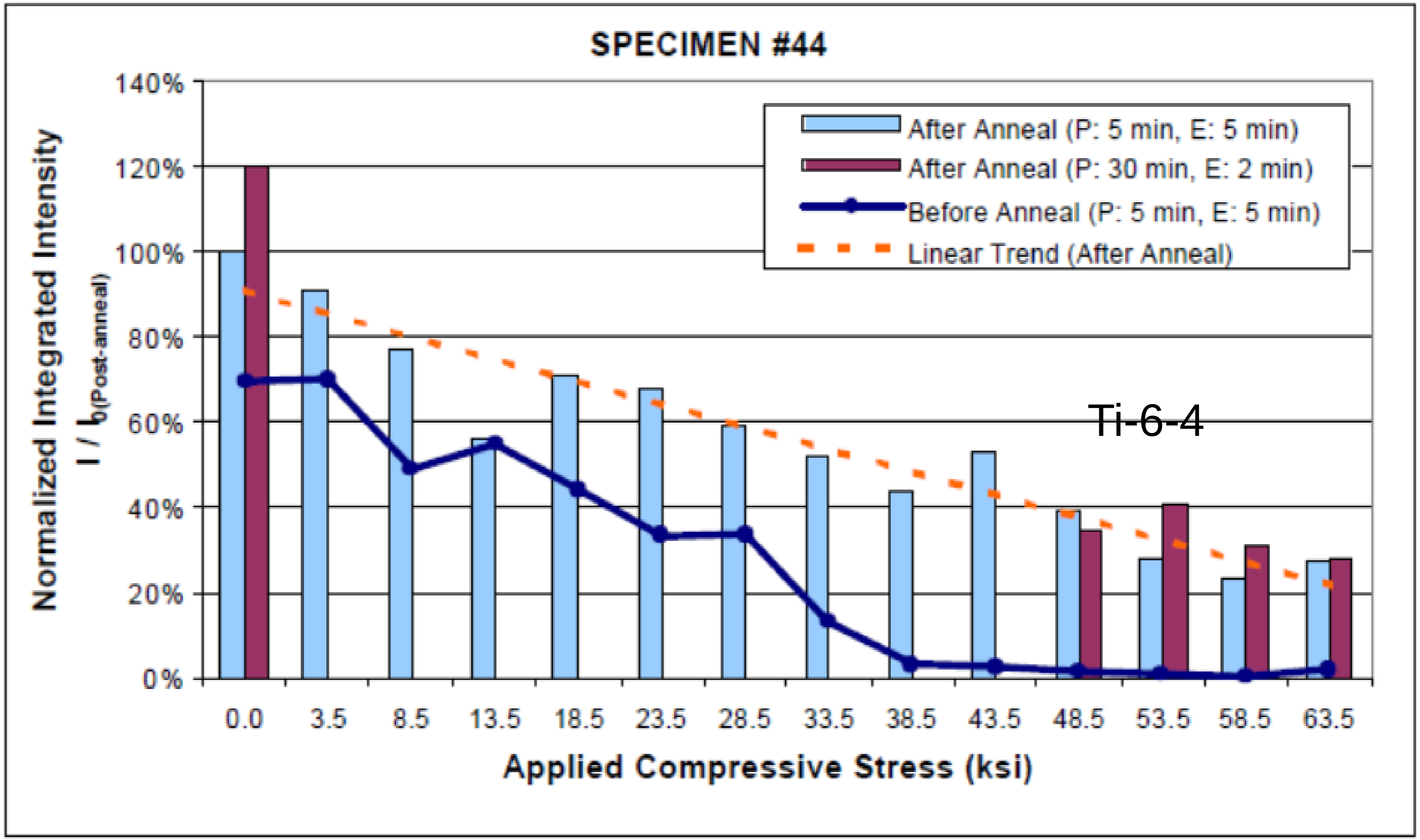


Post Stress Relief

Fatigue Cracks Under Applied Compressive Stress
Fluorescent Penetrant Response

A Century of Scientific Excellence

- Combined effect of residual and applied stress is significant.
- Increased penetrant dwell times generally improved performance.

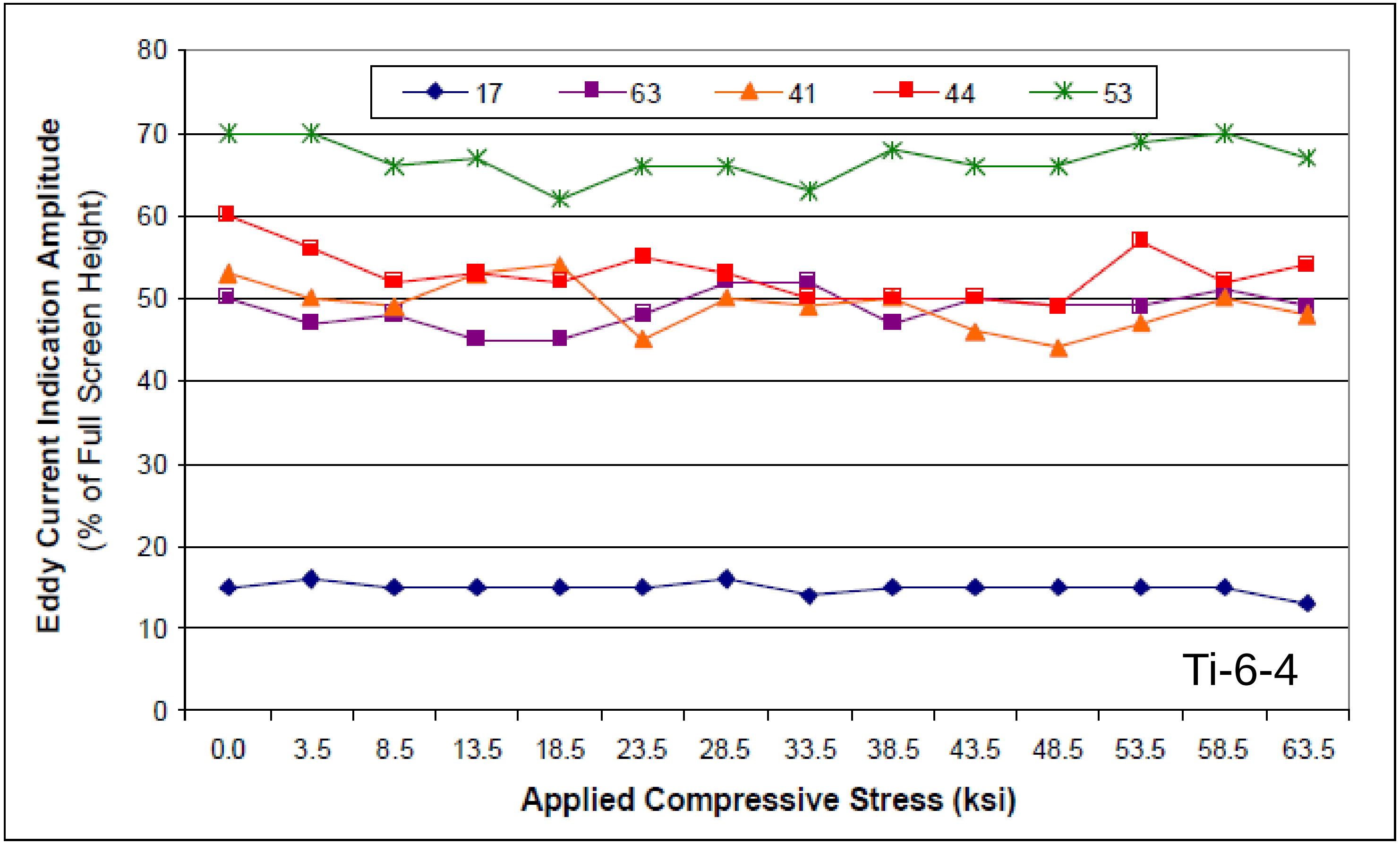


Brausch, J., Tracy, N., Effects of Compressive Stress on Fluorescent Penetrant Indications of Fatigue Cracks in Titanium, AFRL-ML-WP-TR-2001-4139

Fatigue Cracks Under Applied Compressive Stress
Eddy Current Response

A Century of Scientific Excellence

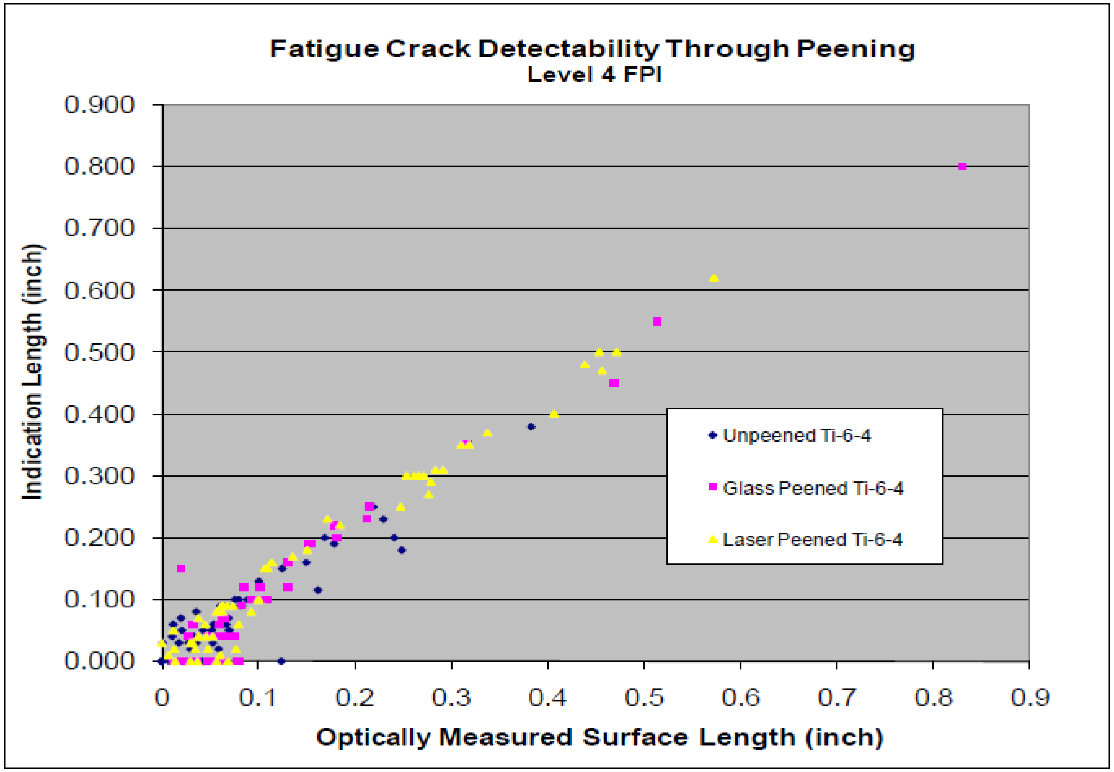
- No significant change in eddy current response up to 63.5 ksi.

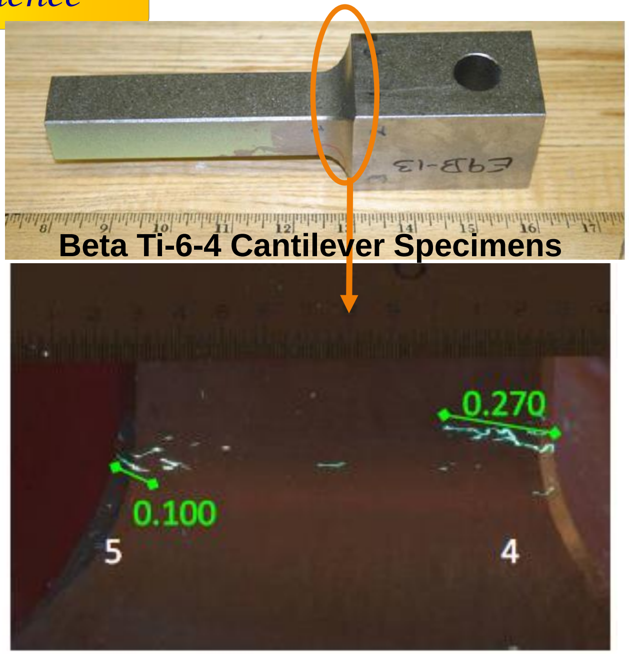


Brausch, J., Tracy, N., Effects of Compressive Stress on Fluorescent Penetrant Indications of Fatigue Cracks in Titanium, AFRL-ML-WP-TR-2001-4139

Fatigue Cracks Grown Through Deep Residual Stress
Fluorescent Penetrant Response

A Century of Scientific Excellence





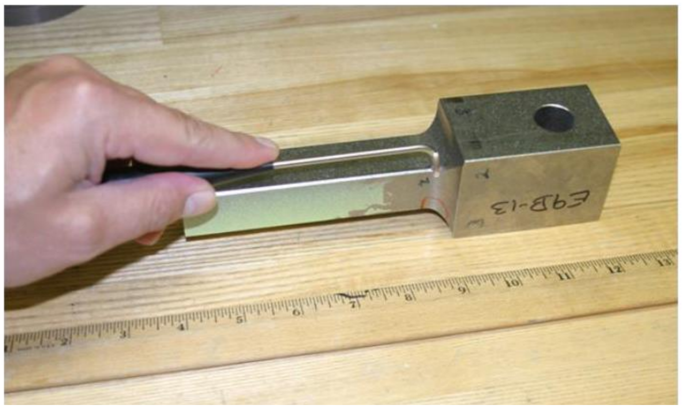
Penetrant:	Sherwin RC-77
Solvent Remover:	Isopropyl Alcohol
Developer:	Magnaflux ZP-4B
Penetrant Dwell Time:	60 minutes
Developer Dwell Time:	15 minutes

- FPI indication lengths compared well to optically measured fatigue crack surface lengths for:
  - Unpeened Ti-6-4
  - Glass Peened Ti-6-4 (MIL-STD-13165, BAC 5730)
  - Laser Peened Ti-6-4 (AMS 2546)
- Indications were clearly discernible **but exhibited less bleed-out on peened surface**.

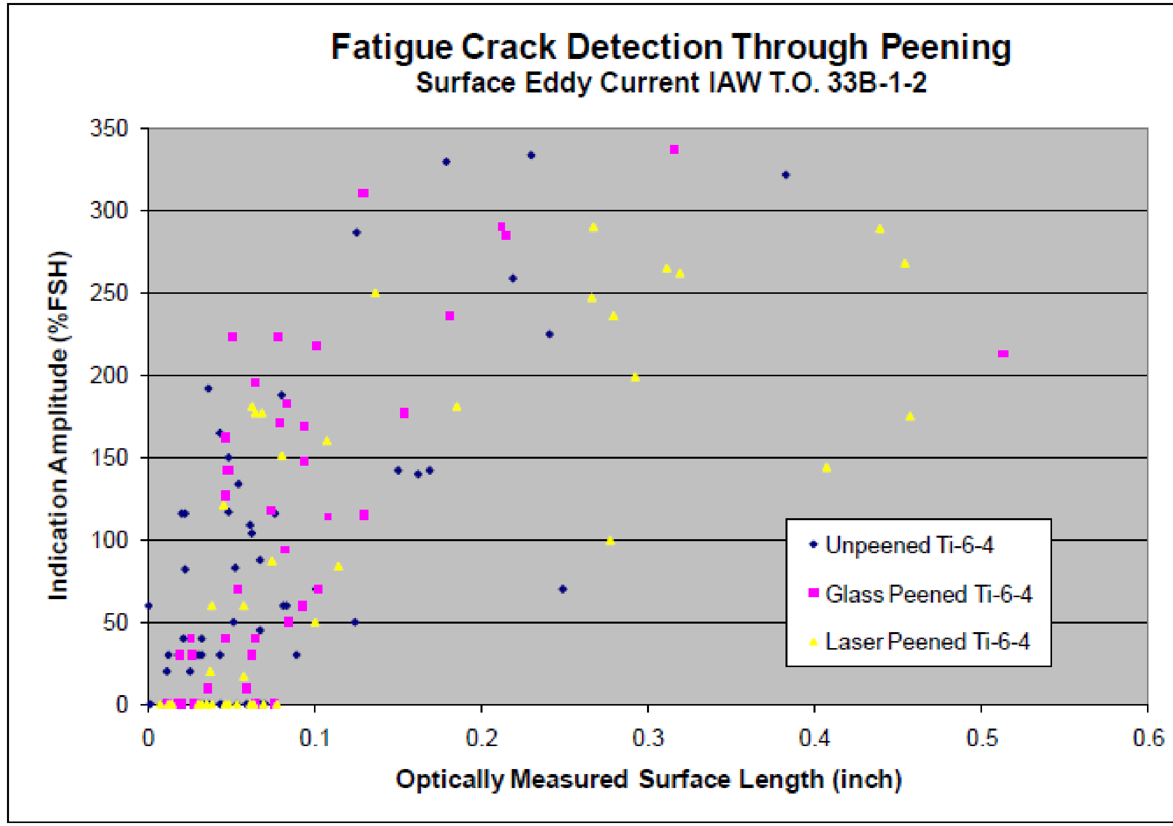
Fatigue Cracks Grown Through Deep Residual Stress
Surface Eddy Current Response

A Century of Scientific Excellence

Beta Ti-6-4 Cantilever Specimens



Eddy Current Inspection
IAW T.O. 33B-1-2, WP 402



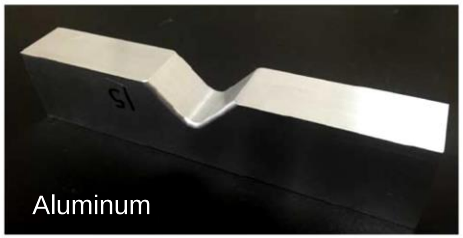
- Surface eddy current response exhibits typical scatter induced by human variance.
- Fatigue cracks within unpeened, glass-peened and laser-peened Beta Ti-6-4 exhibited comparable SECI detectability.

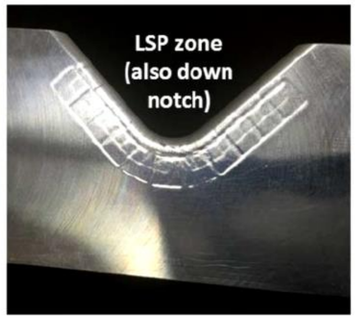
Laser Peening Study

Preliminary Surface Eddy Current Results

A Century of Scientific Excellence

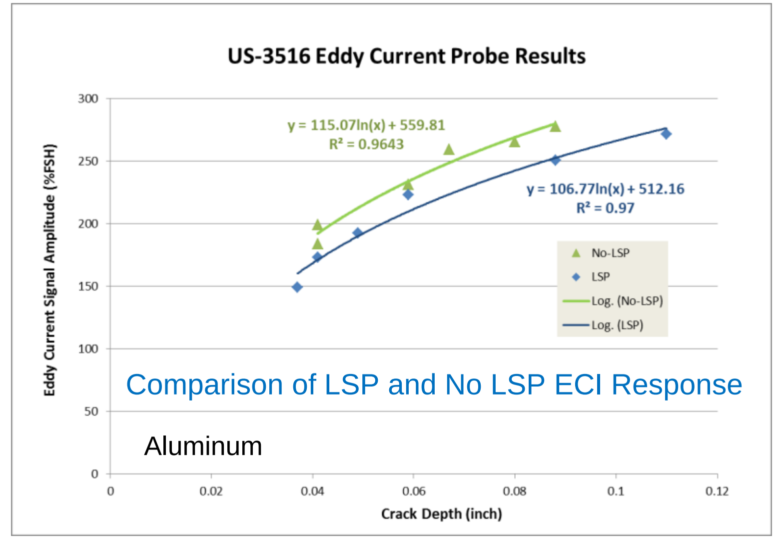
Typical bend bar blank with chamfered notch

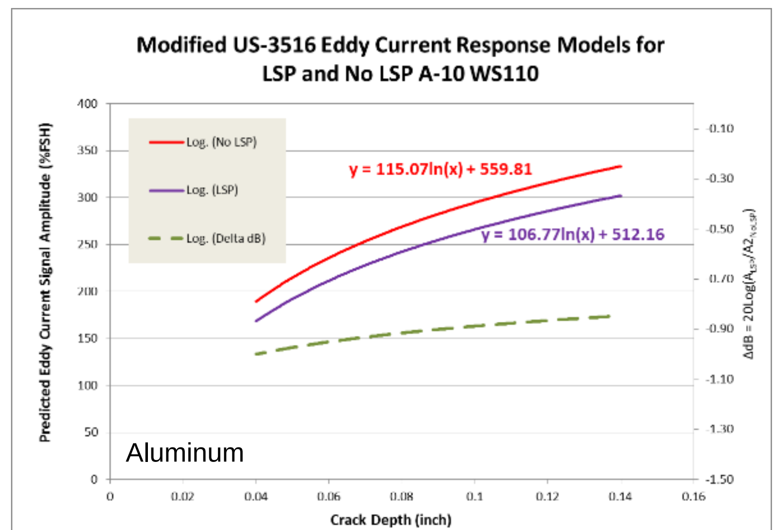




Courtesy of Hill Engineering, LLC

J. *Brausch, W. Fong, Briefing Charts to Hill Engineering, March 2016.*

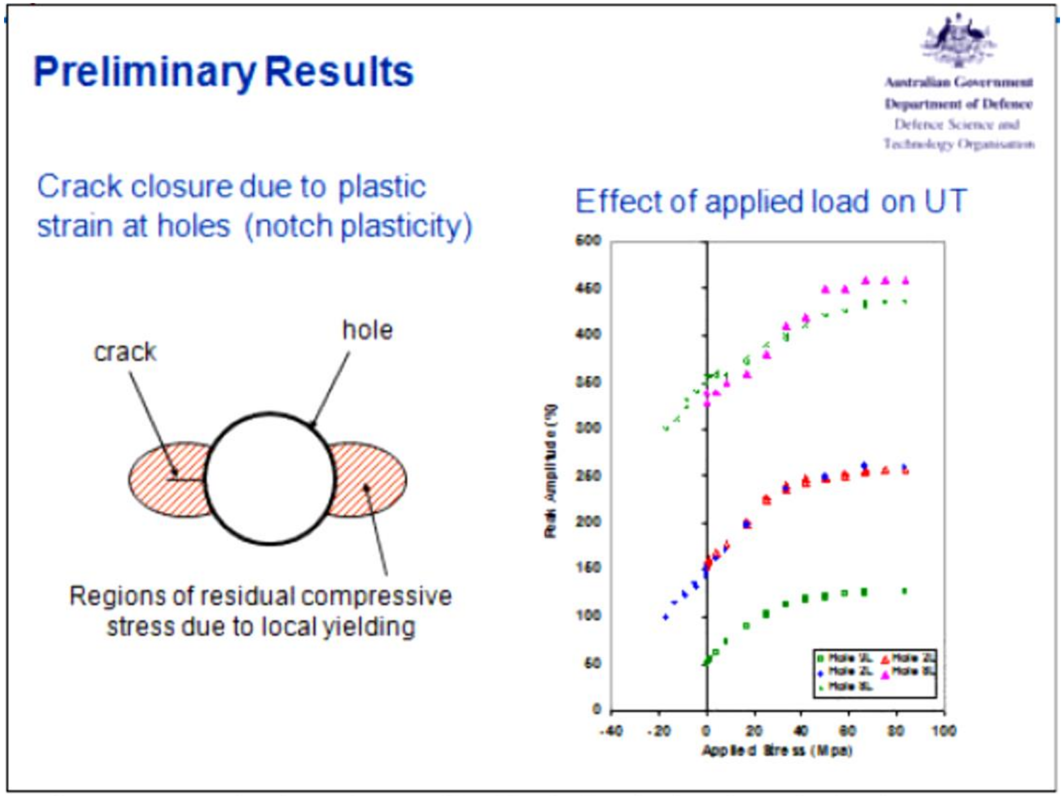




- Separation between ECI response from LSP and No-LSP results suggests two populations yielding two ECI response models
- Less than 1 dB deviance between the LSP and No LSP models.
- **<1dB shift is well within typical calibration tolerance and typical POD assumptions.**
- Possible sources of shift: crack morphology, crack closure, crack profile, local conductivity change resulting from cold work.
- <u>Phase II work underway</u>: includes ECI and FPI characterization of cracks grown in peened and unpeened surfaces.

Other Works

A Century of Scientific Excellence



Harding, C. A., Hugo, G. R., & Bowles, S. J. (2006, March). Model-Assisted POD for Ultrasonic Detection of Cracks at Fastener Holes. Presented at RPQNDE 2005. In *AIP Conference Proceedings* (Vol. 820, p. 1862).

Harding, C. A, Hugo, G.R., & Bowles, S.J. (2006 March), "Model-Assisted POD for Ultrasonic Detection of Cracks at Fastener Holes", Presented at RPQNDE 2005. In AIP Conference Proceedings (Vol 820, p1862)

L.J. Nelson, K. Brown, A Young, L.D. Jones and R.A. Smith "Ultrasonic Detectability of Potentially Closed Cracks from Cold-Worked Holes Under Loaded Conditions", Presented at NDT 2007, 46th Annual British Conference on NDT, 2007.

Summary of Current Knowledge

A Century of Scientific Excellence

- Ultrasonic response from EDM and unloaded fatigue cracks differ by ~ 6dB for aluminum.
- Applied compressive stress reduces ultrasonic signal amplitude by -6dB for every 4ksi for aluminum.
- **Applied compressive stresses** do not significantly affect BHEC or SECI on aluminum or titanium.
- Applied compressive stress affects fluorescent penetrant detection capability.
- CX of holes does not measurably affect BHEC on aluminum or titanium.
- CX of holes significantly affects SECI at the mandrel exit surface due to crack “tunneling”.

Summary of Current Knowledge

A Century of Scientific Excellence

- CX of holes **reduces** ultrasonic detectability of fatigue cracks
  - A function of hole diameter, plate thickness
  - Detectability begins beyond the compressive field.
- Deep residual stress surface treatments **do not** significantly affect SECI detectability in aluminum or titanium.
- Deep residual stress surface treatments **may affect** fluorescent penetrant detection capability - further study required.

Future Research Needs

A Century of Scientific Excellence

I. Quantify shear-wave ultrasonic detection capability for fatigue cracks propagating from CX holes.

- POD study for typical CX and no-CX countersink hole scenario
  - Semi-automated and manual scanning
- Develop model (using POD inputs) to address component geometry, plate thickness, hole diameter, % hole expansion, hole fill
- Conduct empirical sensitivity studies to calibrate model.

II. Study effects of deep residual stress on crack closure and fluorescent penetrant inspection on open surfaces.

- Ti-6-4 Beta peening study suggests compressive stress surrounding crack may be relieved, enabling penetrant to enter crack.
- Laser Peening study (Hill Engineering) should provide additional learning for Aluminum.

Guidance for Depot and Field Inspection

A Century of Scientific Excellence

Holes without CX (Aluminum):
- Perform BHEC whenever possible.
- SECI effective for surface breaking cracks
- For ultrasonics, apply 4ksi tensile stress by jacking or other means to open cracks for optimum UT detectability.
- Add >6dB gain above calibration to account for:
  - Crack closure of unloaded cracks.
  - Difference between fatigue crack and EDM notch UT response.
  - Coupling variance.
- If applied compressive stress (i.e. ground loads) can be estimated and jacking is not practical:
  - Add 6dB gain per 4ksi of compressive stress.

Holes with CX:
- Perform BHEC whenever possible
- SECI may be ineffective for small crack detection from mandrel exit surface
- Consider ultrasonic inspection if fasteners cannot be removed. Further study needed to quantify ultrasonic detection capability.
  - Assume detection capability begins beyond CX zone.
- Low frequency eddy current inspection may be considered as an alternative if large crack sizes can be tolerated.

Guidance for Depot and Field Inspection

A Century of Scientific Excellence

Surfaces with Deep Residual Stress Treatments:

- Perform both surface eddy current and fluorescent penetrant inspections
- Extend fluorescent penetrant dwell times to 60 minutes minimum.
- Ensure surface treatments do not result in crack tunneling.

Documenting Lessons Learned

A Century of Scientific Excellence

- Incorporate current and updated knowledge into T.O. 33B-1-1.
- Develop and incorporate shear-wave ultrasonic inspection procedures in T.O. 33B-1-2 for manual inspection around fastener holes.
- Modify existing NDI field and depot procedures to implement best NDI practices for CX and deep residual stress treatments.
  - ***Engineering must identify structures where CX or peening has been applied. Not typically identified.***
- Incorporate POD guidance into EN-SB-08-012
  - Surface eddy current limitations from mandrel exit surface for CX holes.
  - Shear-wave ultrasonic detection capability guidelines.
  - Establish validated models for POD estimation based on plate thickness, hole diameter, % hole expansion. Reference models is the SB.

References

A Century of Scientific Excellence

Henry, T. “Correlating Ultrasonic Responses of Fatigue Cracks Propagated Under Different Load Spectra.” Honors Thesis, Department of Chemical and Materials Engineering, University of Dayton, April 2013

Forsythe, D., Mills, T., “Capability of Inspections for the Detection and Sizing of Cracks in Cold Worked Holes”, Report: Task 9, Contract # FA9453-12-C-0218.

Brausch, J., Tracy, N., “Effects of Compressive Stress on Fluorescent Penetrant Indications of Fatigue Cracks in Titanium”, AFRL-ML-WP-TR-2001-4139, March 2001.

Harding, C. A, Hugo, G.R., & Bowles, S.J. “Model-Assisted POD for Ultrasonic Detection of Cracks at Fastener Holes”, Presented at RPQNDE 2005. In AIP Conference Proceedings (Vol 820, p1862), March 2006.

L.J. Nelson, L.J., Brown, K, Young, A., Jones, L.D., Smith, R.A., “Ultrasonic Detectability of Potentially Closed Cracks from Cold-Worked Holes Under Loaded Conditions”, Presented at NDT 2007, 46th Annual British Conference on NDT, 2007.

Questions

A Century of Scientific Excellence

Quality Assurance & Data Capture

David Forsyth (discussion facilitator)

ENGINEERED RESIDUAL STRESS IMPLEMENTATION WORKSHOP 2016

Date: September 15, 2016

Location: Weber State University Downtown Campus,

2314 Washington Blvd, Ogden, UT 84401

TRI/Austin, Inc.

Outline

- The Role of Capturing Quality Assurance Data for Deep Residual Stress Inducing Processes and How to Manage that Data for Future Use.

- Outline
  1. What is the current state-of-the-art for capturing the proper application of the Cx process at fastener holes?
  2. What are the technological gaps that still need to be overcome?
  3. What type of governing document do you see the requirements for this type of quality assurance tool being placed for USAF usage?
     a. TO, Workspec, Planning documents????
  4. How can the data produced via this method be stored?
  5. Why is the capture and storage of this information so important for the implementation of residual stresses into the sustainment paradigm?

Outline

1. What is the current state-of-the-art for capturing the proper application of the Cx process at fastener holes?
2. What are the technological gaps that still need to be overcome?
3. What type of governing document do you see the requirements for this type of quality assurance tool being placed for USAF usage?
   a. TO, Workspec, Planning documents????
4. How can the data produced via this method be stored?
5. Why is the capture and storage of this information so important for the implementation of residual stresses into the sustainment paradigm?

TRI/Austin, Inc.

1. Current State of the Art

- Measurement of hole diameter during the process.
  - Post-ream?

- Performed by the technician using manual gauge.

- If within spec, no record is required and process moves to the next step.

1. Current State of the Art

- Measurement of hole diameter during the process.
  - Post-ream?
- Performed by the technician using manual gauge.
- If within spec, no record is required and process moves to the next step.

Typical of -6, -36 processes in the depot. If everything is "good", no record exists.

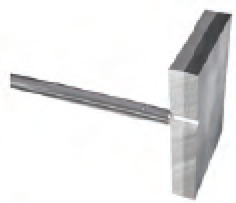
TRI/Austin, Inc.

FTI process overview

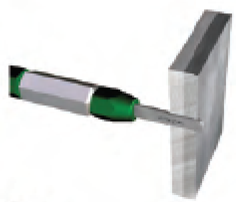
STEPS FOR PROPER COLD EXPANSION:

1) If necessary, drill the starting hole to size it for the starting reamer

2) Ream to correct starting hole size



3) Verify the starting hole dimensions with the stepped blade on the combination gauge



4) Check the expansion portion of mandrel is within tolerance

5) Slide a split sleeve onto the mandrel

6) Insert the mandrel and sleeve into the hole

instructions may require specific orientation of sleeve split

7) Activate the puller unit to retract the mandrel and expand the hole

8) Retract the mandrel fully through the sleeve and into the nosecap

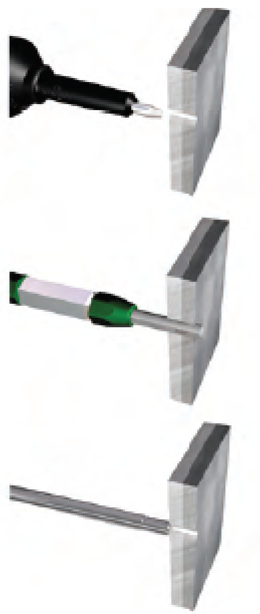
release trigger to return mandrel

FTI process overview

9) Remove the split sleeve from the cold expanded hole and discard

10) Verify the expanded hole size with the pin end on the combination gauge

11) If necessary, size hole for required fastener



- Multiple QA steps built into this process.

2. Always observe these process quality steps:

- Use the combination gauge to verify hole size before and after cold working.
  - Use the stepped blade end of the gauge to check starting holes
  - Use the pin "go/no-go" end of the guage to verify that the hole has been properly cold expanded
- Use the mandrel check fixture to ensure that the major diameter of the mandrel is not worn beyond acceptable limits. A worn mandrel will result in insufficient cold expansion and life enhancement.

Outline

1. What is the current state-of-the-art for capturing the proper application of the Cx process at fastener holes?
2. What are the technological gaps that still need to be overcome?
3. What type of governing document do you see the requirements for this type of quality assurance tool being placed for USAF usage?
   a. TO, Workspec, Planning documents????
4. How can the data produced via this method be stored?
5. Why is the capture and storage of this information so important for the implementation of residual stresses into the sustainment paradigm?

TRI/Austin, Inc.

2. Technology Gaps

- Depends on your requirements.

- IF you need auditable, quantitative measurement to show:
  a. CX process was performed to spec
  b. residual stress amount was at least per spec.
  c. residual stress is X

2, 5

1. What is the current state-of-the-art for capturing the proper application of the Cx process at fastener holes?
2. What are the technological gaps that still need to be overcome?
3. What type of governing document do you see the requirements for this type of quality assurance tool being placed for USAF usage?
   a. TO, Workspec, Planning documents????
4. How can the data produced via this method be stored?
5. Why is the capture and storage of this information so important for the implementation of residual stresses into the sustainment paradigm?

TRI/Austin, Inc.

2, 5

- What is the variability and uncertainty (not the same thing) that you can accept
  - in your processes of prediction
  - in your manufacture/depot process
- This drives the answer.
- Typical CX hole expansions are in 3% to 5% range. How precise do you need to know for your particular application?
  - Validate your measurement capability w.r.t. your requirements.

TRI/Austin, Inc.

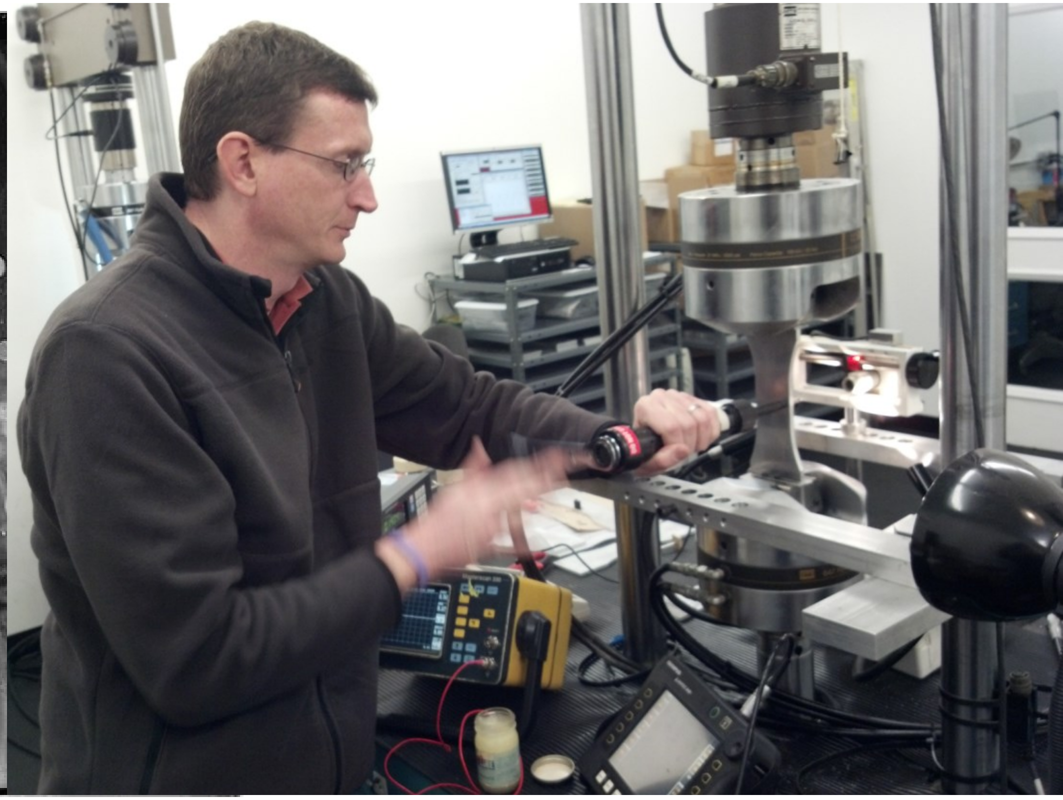
2. Technology Gaps

- Depends on your requirements.

- IF you need auditable, quantitative measurement to show:
  a. CX process was performed to spec
  b. residual stress amount was at least per spec.
  c. residual stress is X

2. a. Process performed to spec

- Could take a photo!



2 b. residual stress amount was at least per spec.

- Basically a threshold. Easier than a precise measurement.
- Measure hole diameter before and after?
  - What is required precision, tooling to do this?
- Measure CX
  - Deformation due to process
  - Surface residual stresses due to process

TRI/Austin, Inc.

2 b. residual stress amount was at least per spec.

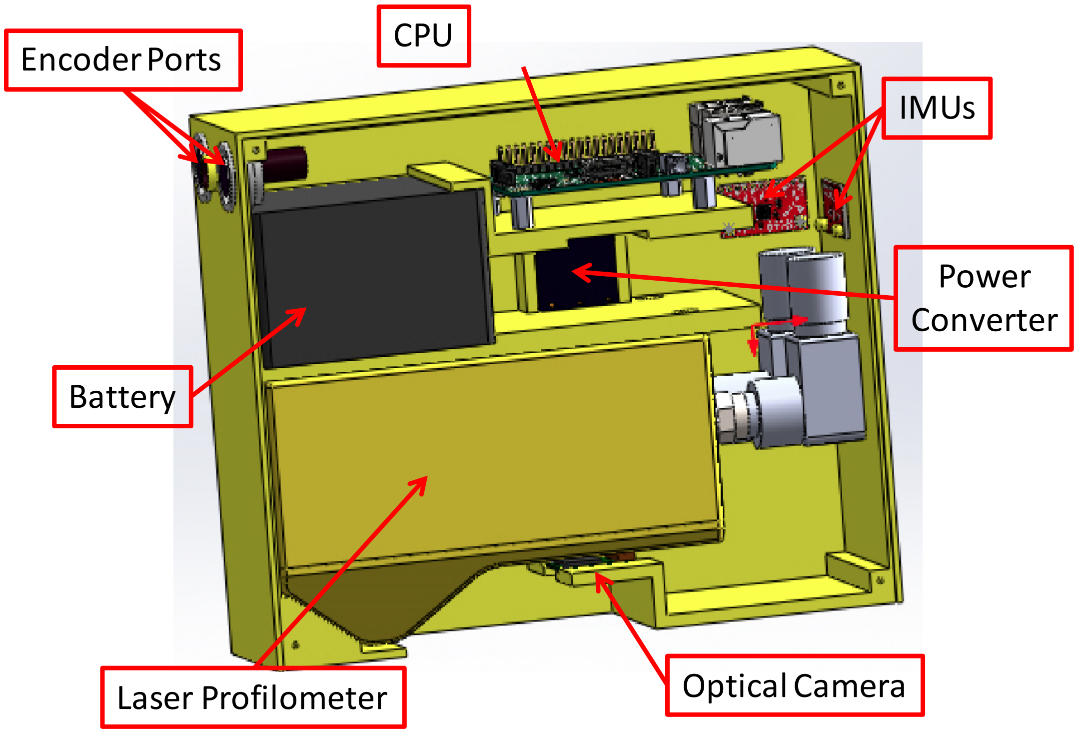
- Some examples of hole diameters and changes due to CX.

	MAX	MID	MIN	OUT
Hole Diameter	Hole 1 CX %	Hole 2 CX %	Hole 3 CX %	Hole 4 CX %
0.168”	4.75	3.98	2.80	1.40
0.246”	4.41	3.27	2.63	1.17
0.374”	3.99	3.42	3.00	1.20
0.494”	4.00	3.44	2.99	1.24
0.574”	3.63	3.20	2.93	1.07

TRI/Austin, Inc.

Measuring plastic deformation caused by CX process

- TRI/Austin's FastenerCam™ mark I and mark II design



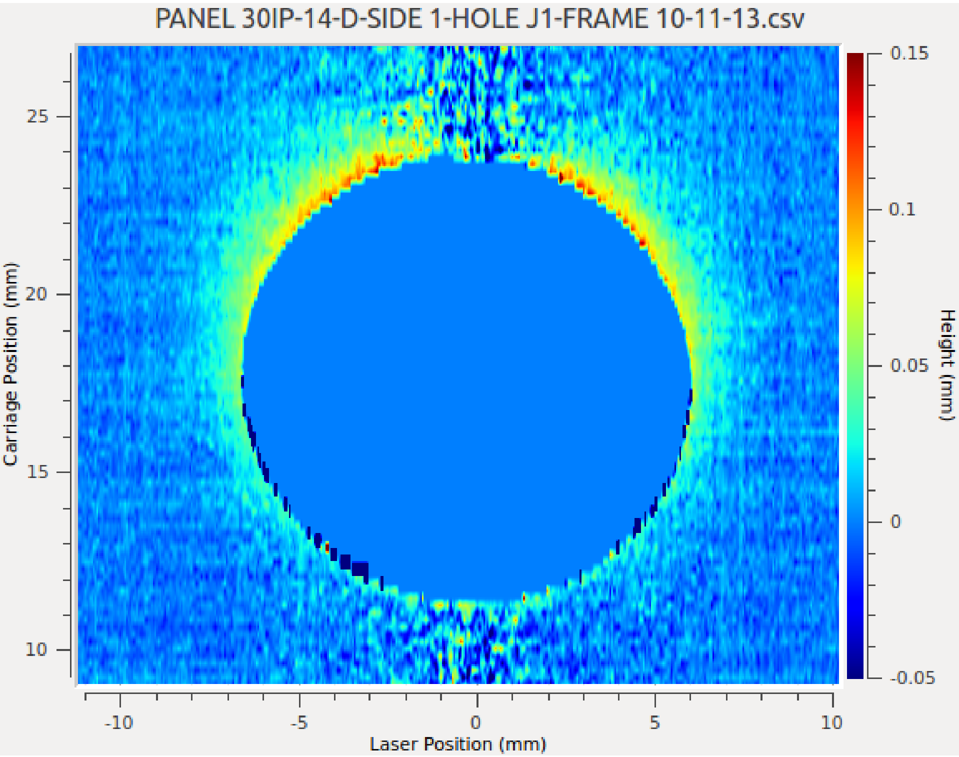
Measuring plastic deformation caused by CX process

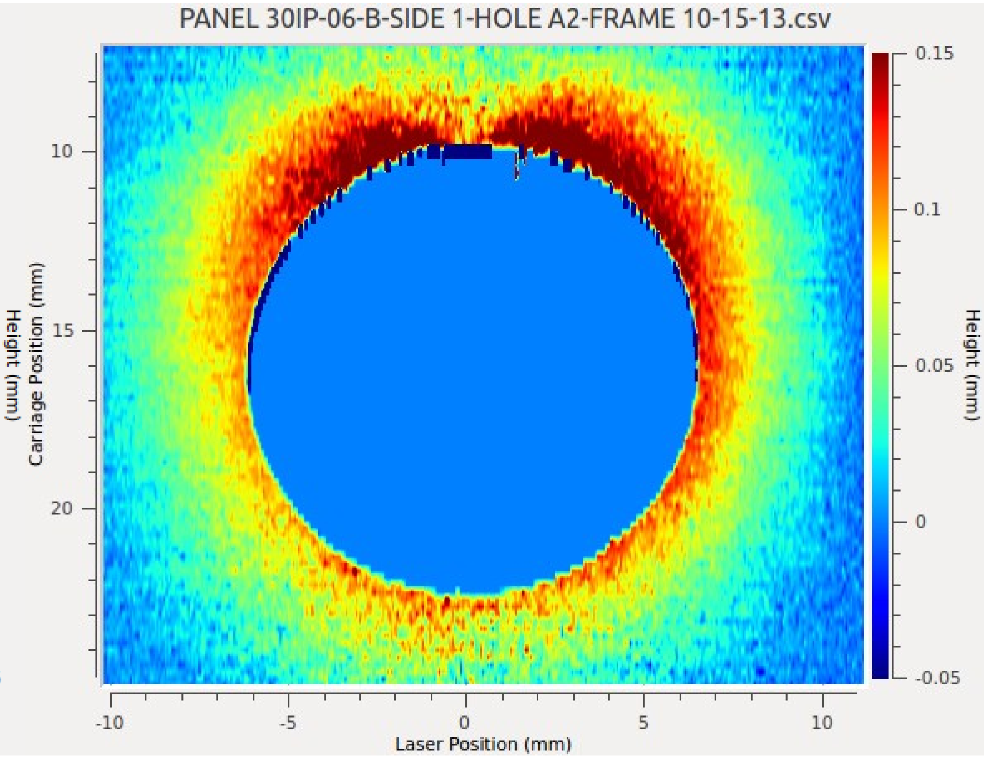
- TRI/Austin's FastenerCam™

0.494" Diameter Straight Shank Holes

1.24% CX

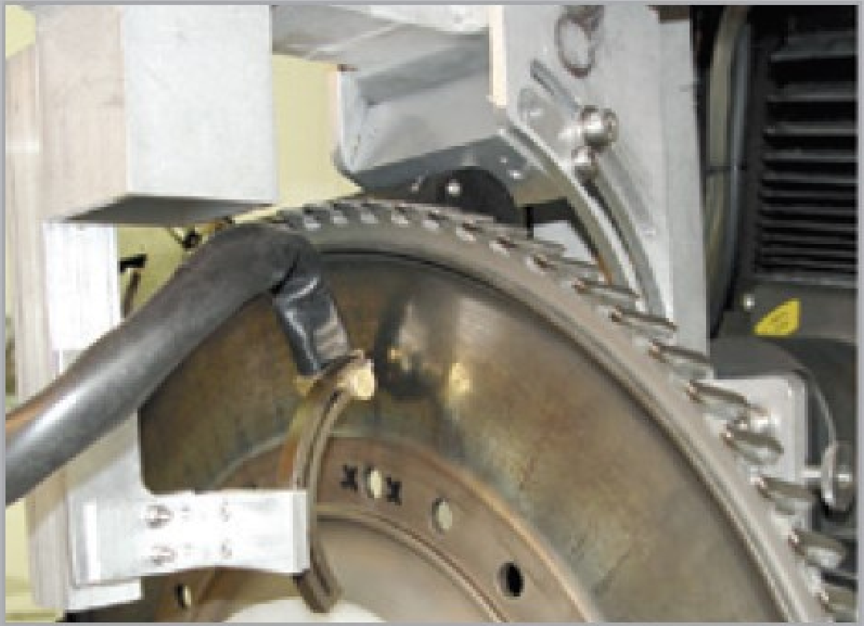
4.00% CX





Measuring residual stresses caused by CX process*

- A system by Proto



Measuring Residual Stress
Inside a Bolthole

Measuring residual stresses caused by CX process*

Residual Stress Analysis Near a Cold Expanded Hole in a Textured Alclad Sheet Using X-ray Diffraction

by J.C.P. Pina, A.M. Dias, P.F.P. de Matos, P.M.G.P. Moreira and P.M.S.T. de Castro

Vol. 45, No. 1, February 2005

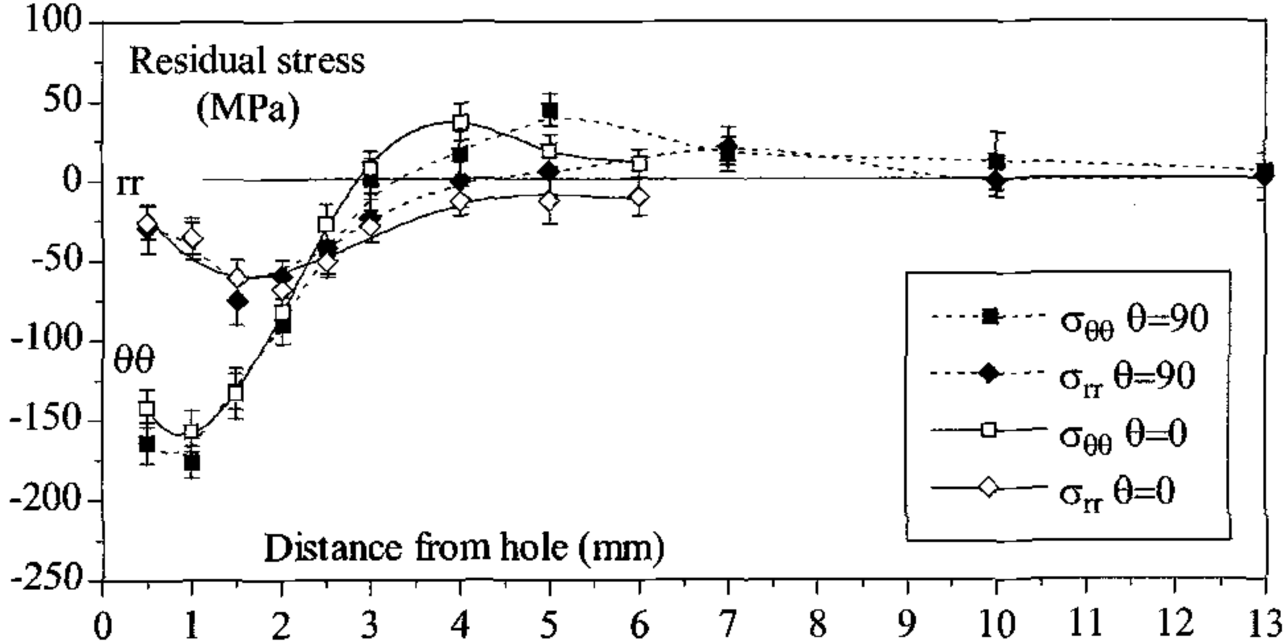


Fig. 6—Residual stresses determined on the entrance face of the aluminum sheet for θ = 90° and θ = 0°

TRI/Austin, Inc.

2. c. residual stress is X

- You have some model to convert the measured parameter to your residual stress.
  - Hole diameter, plastic deformation, surface residual stresses
- You really want to know stress tensor at all locations.
  - Modeling, experimental work described by previous speakers provides a means to infer this from simpler measurements

So are we there yet?

- That's up to you to decide.
  - Does the system of measurement provide sufficient performance and variability to enable prediction of structural performance?
  - Is it affordable, practical for use?

- I don't think we have solid answers for either the
  - structural performance prediction requirements
  - measurement system capabilities

TRI/Austin, Inc.

Outline

1. What is the current state-of-the-art for capturing the proper application of the Cx process at fastener holes?
2. What are the technological gaps that still need to be overcome?
3. What type of governing document do you see the requirements for this type of quality assurance tool being placed for USAF usage?
   a. TO, Workspec, Planning documents????
4. How can the data produced via this method be stored?
5. Why is the capture and storage of this information so important for the implementation of residual stresses into the sustainment paradigm?

3. Governing Docs

What type of governing document do you see the requirements for this type of quality assurance tool being placed for USAF usage?

a. TO, Workspec, Planning documents????

- This belongs to the owner. Discuss to your hearts' content, but you don't get to decide unless you are the owner.

TRI/Austin, Inc.

Outline

1. What is the current state-of-the-art for capturing the proper application of the Cx process at fastener holes?
2. What are the technological gaps that still need to be overcome?
3. What type of governing document do you see the requirements for this type of quality assurance tool being placed for USAF usage?
   a. TO, Workspec, Planning documents????
4. How can the data produced via this method be stored?
5. Why is the capture and storage of this information so important for the implementation of residual stresses into the sustainment paradigm?

TRI/Austin, Inc.

4. Data Storage

- This is a problem of the owner. Argue amongst yourselves. Manufacturing, depot, field all have their issues.

- Any of the processes described for QA provide digital data. You need to provide a receptacle for said data.

4. Data Storage

TRI/Austin, Inc.

Outline

1. What is the current state-of-the-art for capturing the proper application of the Cx process at fastener holes?
2. What are the technological gaps that still need to be overcome?
3. What type of governing document do you see the requirements for this type of quality assurance tool being placed for USAF usage?
    a. TO, Workspec, Planning documents????
4. How can the data produced via this method be stored?
5. Why is the capture and storage of this information so important for the implementation of residual stresses into the sustainment paradigm?

5. Why?

- CX doesn't get credit it deserves sometimes.
- CX sometimes gets extra/wrong credit.
- If you are going to make lifing/risk decisions, you need to ensure CX has been done to your specifications.

TRI/Austin, Inc.

FINAL DISCUSSIONS

1. What is the current state-of-the-art for capturing the proper application of the Cx process at fastener holes?
2. What are the technological gaps that still need to be overcome?
3. What type of governing document do you see the requirements for this type of quality assurance tool being placed for USAF usage?
   a. TO, Workspec, Planning documents????
4. How can the data produced via this method be stored?
5. Why is the capture and storage of this information so important for the implementation of residual stresses into the sustainment paradigm?

TRI/Austin, Inc.

NRC·CNRC

Risk & Uncertainty Quantification

-- for implementing engineering residual stress into damage tolerance analysis

M. Liao, G. Renaud

September 2016

ERSI

Engineered Residual Stress Implementation (ERSI) Workshop, September 15th, 2016

Contents

- **Brief Review of Some Current Practices Considering ERS**
  - Some fleet survey
- **UQ for ERS**
  - ASME V&V
- **Risk Analysis Considering ERS**
  - Safe-Life based
  - DaDTA based
- **Discussion**
  - TTCP Roadmap

Brief Review of Some Current Practices Considering ERS

- RCAF CF-18 Improvement Process Guideline (2010)
  - Coupon tests and literatures based guidelines, eng. judgments
- ASIWG/P-3 CW Coupon Tests (2014)
  - Coupon test based LIF, reduced from lab tests
- RCAF CP-140/IMP (2014, 2015)
  - Coupon tests and modeling needs, FCG from 0.005” under review
- RCAF/LM CC-130J (2010)
  - Initial & continuing crack size assumptions, analytical benefit
- USAF/SwRI/APES, CW and RS Database (2014, 2015)
  - RS measuring and database; NDI for Quality Assurance; Using RS in crack growth analysis to calculate a LIF
- NRC/DTAES Validation and Transfer of CW Modeling Technology (2015-2016)
  - RS modeling and database; Using RS in crack growth analysis to calculate a LIF, test validation

M. Liao, G. Renaud, G. Li, and Y. Bombardier, Update on NRC Hole Cold Expansion Modeling and Validation, HOLSIP2016

Brief Review of Some Current Practices Considering ERS -- summary

- ERS induced LIF (life improvement factor) varies with lifing policy (Safe-Life vs. Damage Tolerance, CI vs.CG)
- Taking ERS benefits by coupon test based LIF -- based on extensive lab tests, limited to specific conditions (material, e/D, spectra, a/c…), along with engineering judgement
- Taking ERS benefits by reducing initial crack size in DTA (ex. 0.005" current USAF approach)
- Using ERS in FCGR – some methods
  - Effective K approach, K=Kapp+Krs
    - RS model by Rich-Impellizzeri, Ball, Chang…
    - RS database (USAF)
  - Beta correction based on test (Boeing, FTI)
  - QF based da/dN (EU ADMIRE project)…

M. Liao, G. Renaud, G. Li, and Y. Bombardier, Update on NRC Hole Cold Expansion Modeling and Validation, HOLSIP2016

Uncertainty Qualification (UQ) in ASME V&V 10-2006

ASME V&V 10-2006: Verification and Validation Computation Solid Mechanics

Uncertainty Qualification (UQ): *"the process of characterizing all uncertainties in the model or experiment and of quantifying their effect on the simulation or experimental outcomes".*

- *Characterize "inputs"*
- *Quantify "outputs"*

Validation Metrics: to compare the simulation outcomes with the experimental outcomes, ex. relative error

Accuracy Adequacy: ex. partially accuracy met (10% vs. 15%), confidence level (90% vs. 95%)

Validation Documentation: document the process, conclude if the model/experiment are successfully validated for the intended use

Uncertainty Qualification (UQ) in ASME V&V 10-2006

ASME V&V 10-2006: Verification and Validation Computation Solid Mechanics

UQ in Experiment: to *quantify* the effects of measurement error, design tolerances, construction uncertainty, and other uncertainties on the experimental outcomes.

Two types of errors in experiment:

1) **Random error** (precision, inherent/irreducible, ex. dimensional tolerances on test parts or measurement locations, variability of material properties, and mechanical equipment variances due to friction...)
2) **Systematic error** (bias, maybe difficult to estimate, ex. transducer calibration error, data acquisition error, data reduction error, and test technique error)

Uncertainty Qualification (UQ) in ASME V&V 10-2006

ASME V&V 10-2006: Verification and Validation Computation Solid Mechanics

UQ for Simulation: the process of characterizing all uncertainties in the model, and of quantifying their effect on both simulation and experimental outcomes

Two types of uncertainties for UQ in Model:

1) **Irreducible/Inherent/Aleatory** (ex. geometry/material property/load/environment/assembly...)
   - Characterizing methods: component-level tests + prior experience/engineering judgment
   - Quantifying methods: statistical distribution, probabilistic methods (Monte Carlo/sensitivity study/FORM/SORM…)
2) **Reducible/Epistemic** (ex. lack of data, prior knowledge)
   - Statistical uncertainty – limited samples/data/info.
   - Model uncertainty – model form, assumptions, errors.

UQ for Engineering Residual Stress (ERS)

- UQ for FEM on ERS
  - Characterize inputs ?
  - Quantify outputs ?
- UQ for experimental measurement on ERS
  - Characterize inputs ?
  - Quantify outputs ?
- Validation Metrics: mean vs. mean, variance vs variance, distribution vs distribution?
- Accuracy Adequacy: acceptable errors? confidence level?

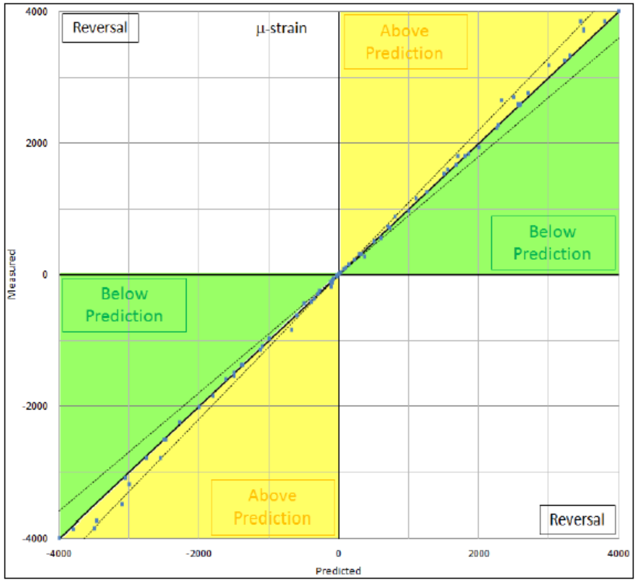


Figure 1 – Sample Correlation Plot with Error Bands

Example: USAF EN-SB-11-001, Guidance on Correlating Finite Element Models to Measurements from Structural Ground Tests. ***How about "Guidance on Correlating FEM to ERS Measurements" ?***

Risk Analysis Considering ERS -- Safe-Life based

1) Fatigue origin/nucleation mechanisms due to surface finish and ERS (ex. sub-surface cracking, fretting..)

2) Stress-Life Analysis: S-N curve shift

3) Strain-Life Analysis (ε-N curve), ex. affecting mean stress/strain,

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma'_f - \sigma_m}{E}\left(2N_f\right)^b + \varepsilon'_f\left(2N_f\right)^c$$

4) Risk analysis based on Lognormal or Weibull analysis – *how will ERS affect fatigue life scatter factor (or stdev for Lognormal, shape factor for Weibull)?*

-- CF-18 example (next slide)

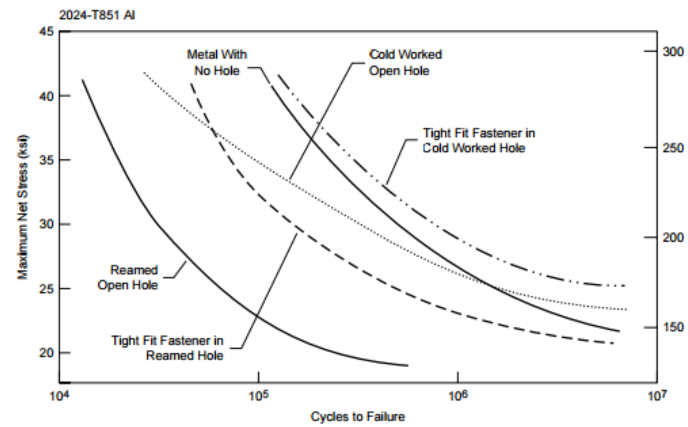


Fig. 14.27 Fatigue life improvement with cold working. Source: Ref 13

ASM Chapter 14

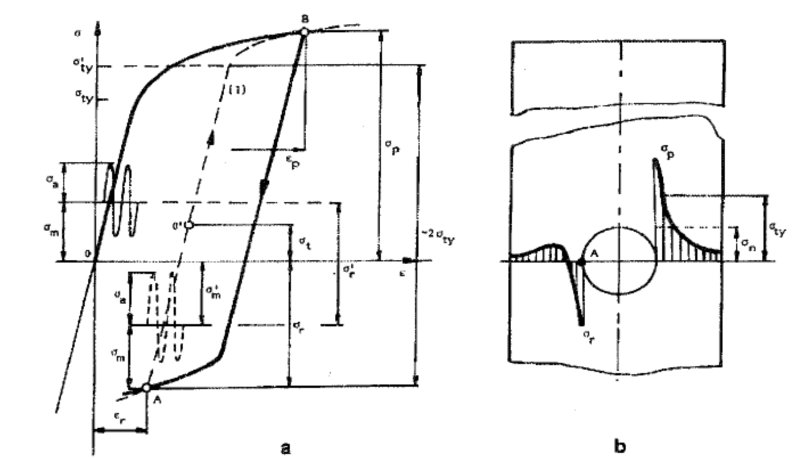


Fig. 1 Loading and unloading of the material volume inside the hole: (a) stress–strain curve and cyclic loading parameters; (b) stresses during loading (expansion) at the peak stress level σ_p and unloading reaching σ_r in the hole root

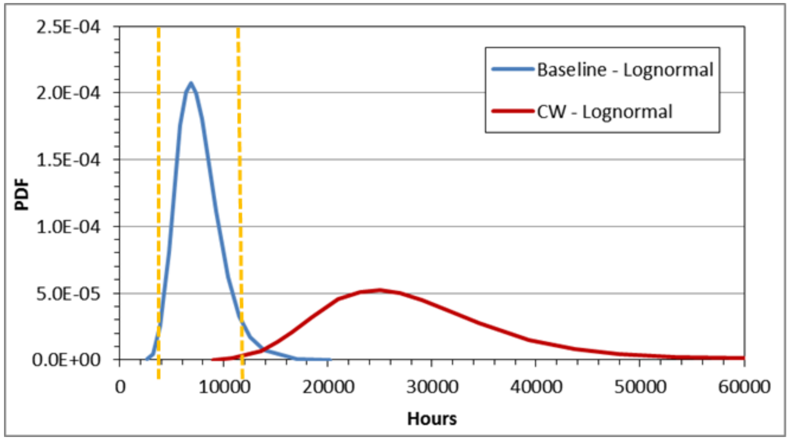
Int. J. Fatigue, 15. No. 2 (1993), pp 93-100

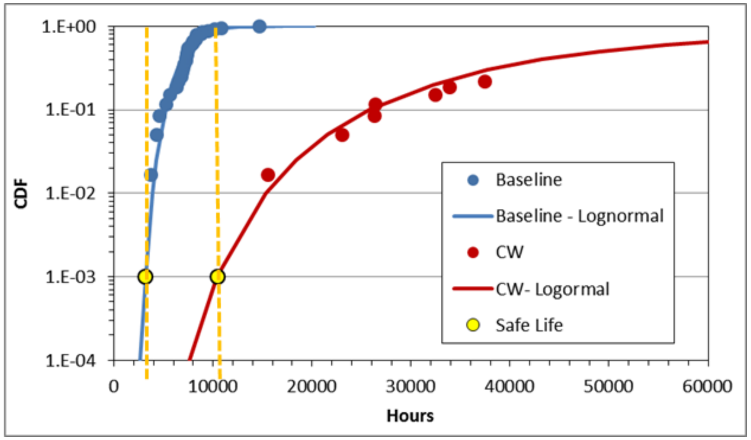
NRC·CNRC

Risk Analysis Considering ERS -- Safe-Life based

- **CF-18 LIF calculation for "CI" (crack to 0.01" depth)**
  - LIF is calculated based on the ratio of the life at a CPOF of 1/1000 between the baseline and improved holes. The 1/1000 life is obtained by dividing the log-average life by a scatter factor
  - The scatter factor utilized for the current test data is derived from the same equation currently used in the CF-18 lifing policy,
    - Lognormal, μ–unknown, σ–known, Bullen Case (III) $SF = 10^{Z\sigma\sqrt{\frac{n+1}{n}}}$
    - In case σ–unknown (new process), Bullen Case (I) $SF = 10^{T\sigma\sqrt{\frac{n+1}{n}}}$

      Should this case be included in the lifing policy?





NRC·CNRC

Risk Analysis Considering ERS – DaDTA based

Current ASIP DaDTA and Risk Analysis for a cold-worked hole,

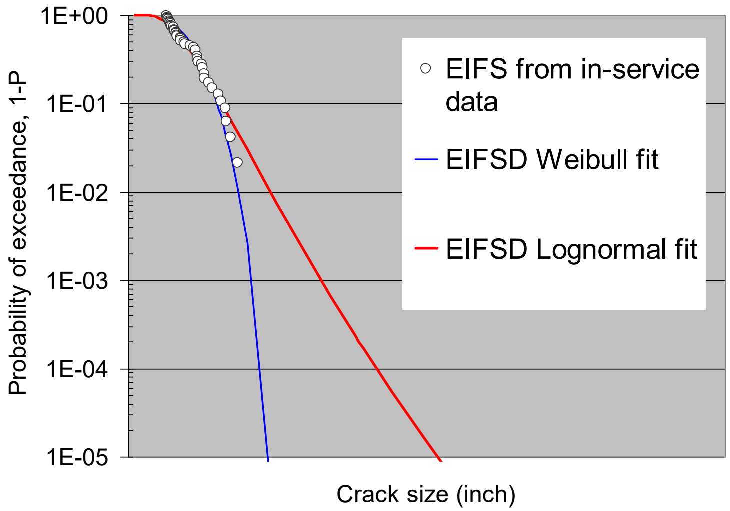
1) DaDTA
   - Durability Analysis (ex. a0=0.01”→0.005”)
   - Damage Tolerance Analysis (ex. a0=0.05”→ 0.03”, no continue damage)
     - Determine initial inspection interval by DTA
     - Determine repeat inspection intervals with a_{NDI}
2) Risk Analysis using,
   - In-service damage based EIFSD
   - Durability analysis a-t curve (even lower, ex. a0=0.002”)
   - POD for Taper-Lok, High-Tigue hole, cold-worked hole
   - Calculate SFPOF to determine service life limit (with MSD/WFD)

No direct/physical ERS consideration? Worst case scenario? Conservative or not ?

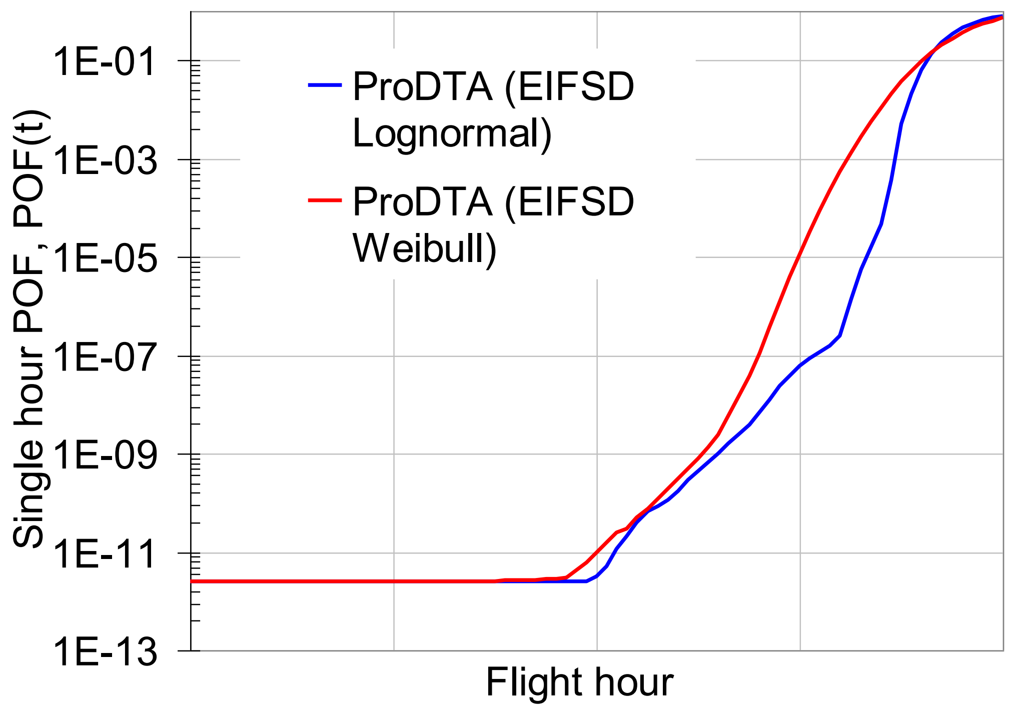
Risk Analysis Considering ERS – DaDTA based (working table)

RA Inputs	ERS Impact	Significance / Confidence	How to quantify uncertainty and variability
Initial crack size distribution (ICSD/IDS/EIFSD): related to material, geometry, manufacturing, usage/load, plus analytical method for EIFSD	Nucleation mechanism (sub-surface cracking, fretting etc.), EIFSD changed if DaDTA method changed too	High / ?	Discussion -- below
Crack growth a-t curve: material/geometry/loads fracture mechanics (LEFM) modeling	Short crack growth, near threshold growth, high quality data. New a-t with ERS	High / ?	Discussion -- below
Maximum stress distribution: stress exceedance, loads/usage	Nominally no effect	None / None	Discussion ?
Fracture toughness (Kc) distribution or residual strength: material, geometry/thickness, analytical method	Bulk ERS may affect Kc or σ_{RS} (integral panel with ERS), self-equilibrating RS effect? conservative assumption?	Low-Med / High?	Discussion ?
POD data: over 20 factors including human factor	Lower POD, higher a90/95	High / ?	Discussion
Repaired crack size distribution: repair & modification (drilling/grind-out/cold-work/peening/bonding…)	Different RCSD (CW) from ICSD (non-CW), EIFSD also depending on DaDTA method/curve. New a-t curve, new POD	High / ?	combine EIFSD and POD discussion

Significance of ICSD (EIFSD/IDS) on PoF



Probability of exceedance (1-CDF) for ICSD



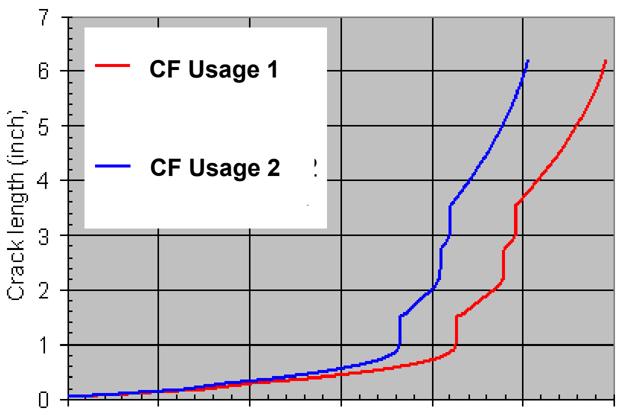
Single hour PoF(t), using different ICSD curves

- ICSD tail fits showed that a Lognormal distribution resulted in higher PoF results than a Weibull distribution.

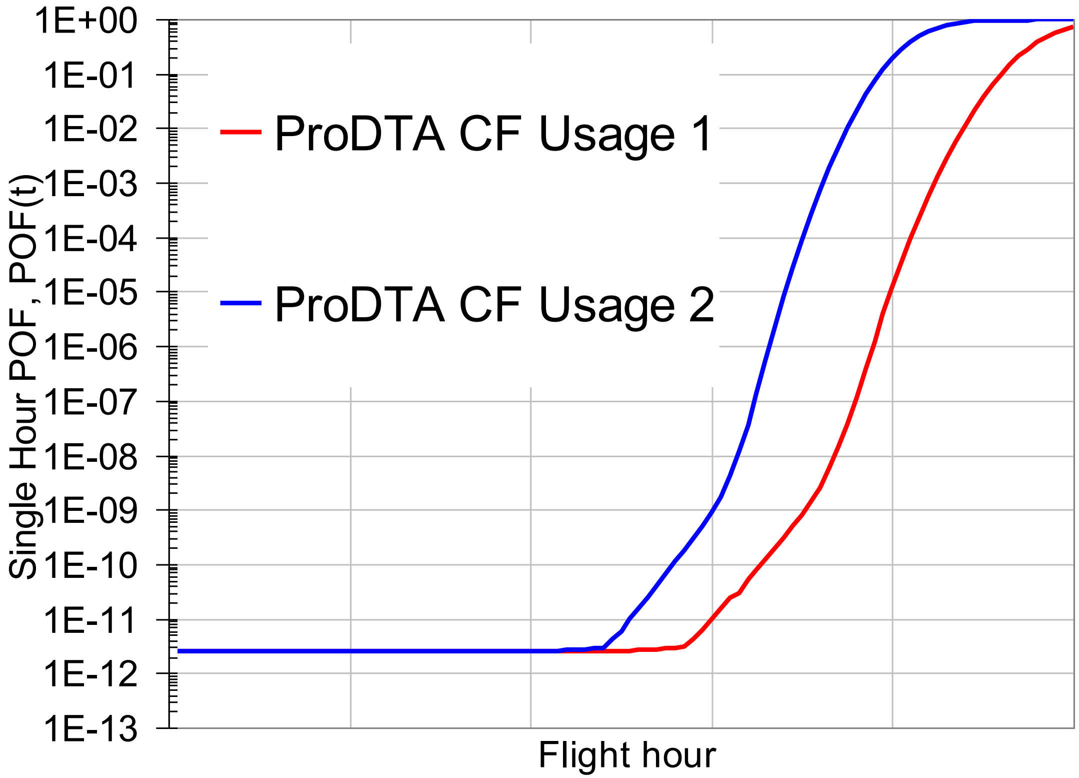
Risk Analysis Considering ERS – DaDTA based (ICSD)

RA Inputs	ERS Impact	Significance / Confidence	How to quantify uncertainty and variability
Initial crack size distribution (ICSD/IDS/EIFSD): related to material, geometry, manufacturing, usage/load, plus analytical method for EIFSD	Nucleation mechanism (sub-surface, fretting etc.), EIFSD changed if DaDTA method changed	High / ?	• In-service damage based EIFSD, including ERS effect already? • New ICSD/EIFSD from new a-t curve • Statistical analysis/Lognormal/Weibull/censored/non-censored data

Significance of crack growth (a-t curve) on PoF



Crack growth (a-t) curve

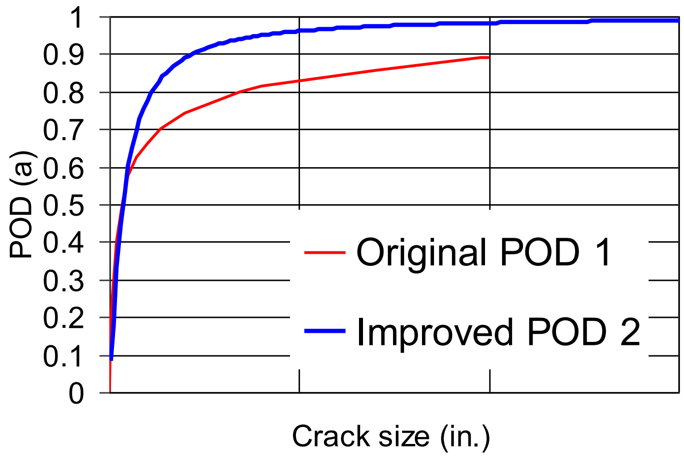


Single hour POF(a), using different crack growth curves

Risk Analysis Considering ERS – DaDTA based (CG)

RA Inputs	ERS Impact	Significance / Confidence	How to quantify uncertainty and variability
Crack growth a-t curve: material/geometry /loads fracture mechanics (LEFM) modeling	Short crack growth, near threshold growth, high quality data. New a-t with ERS	High / ?	• Using a0=0.005” a-t curve, upper bound? • Using ERS based a-t curve, upper bound/1Stdev? • Using ERS distribution to determine a-t distribution by Monte Carlo simulation, i.e., ***one more random variable ERS?*** • Using QF based FCGR?

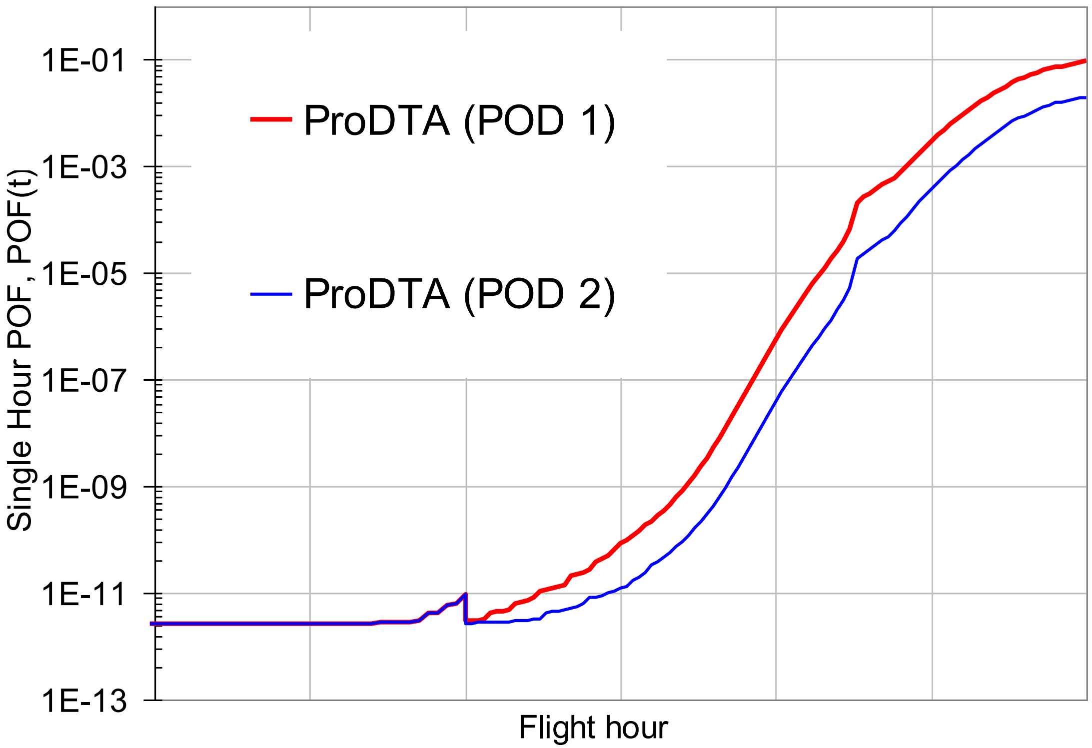
Significance of POD (a) on PoF



Bolt hole EC POD (a)

Red – original POD(a) 1

Blue – improved POD(a) 2, std dev reduced by 50%



Single hour POF(a), using different BHEC POD(a) curves

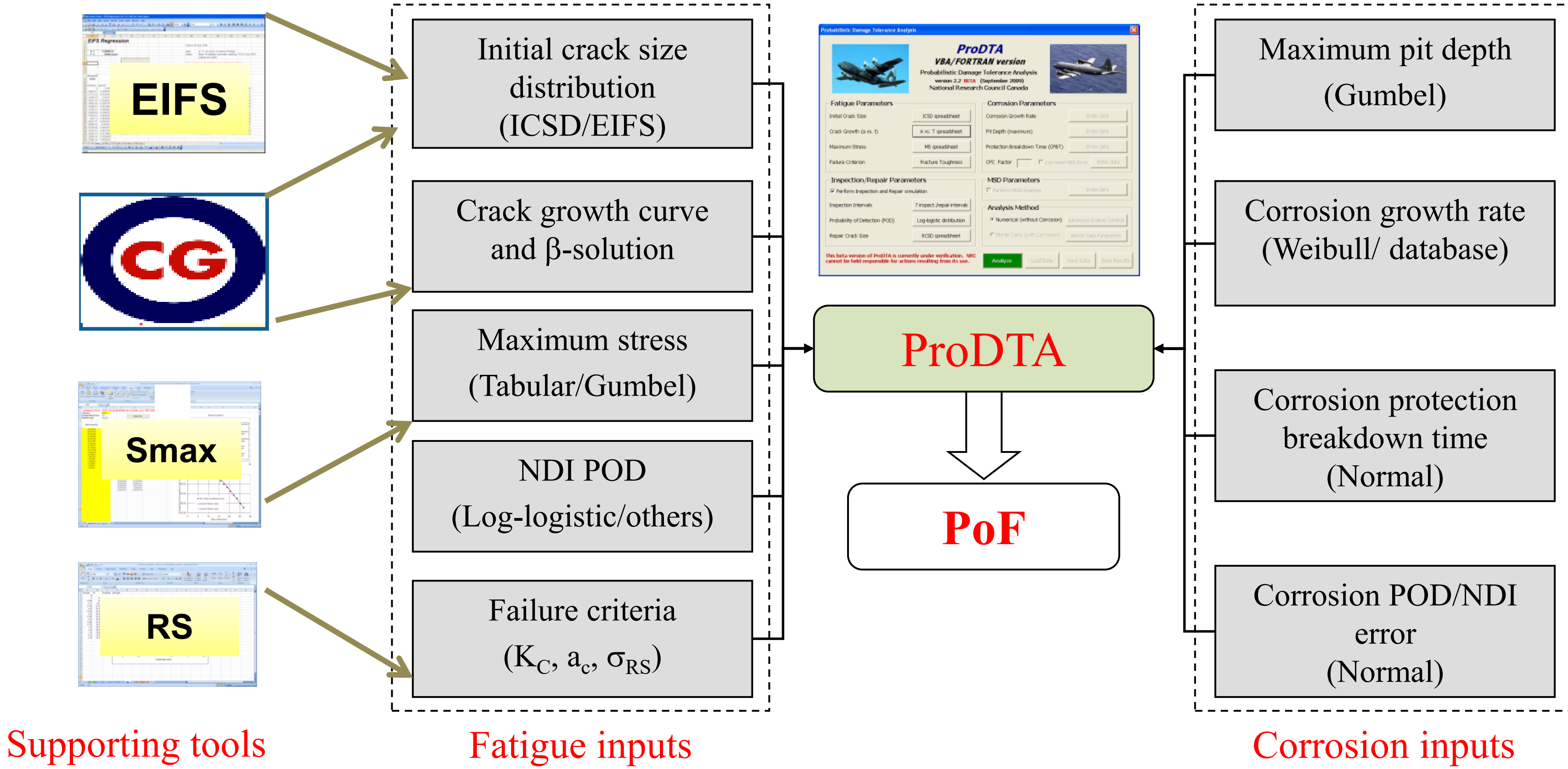
Also POD can affect in-service damage based EIFSD when censored scenarios are considered

Risk Analysis Considering ERS – DaDTA based (POD)

RA Inputs	ERS Impact	Significance / Confidence	How to quantify uncertainty and variability
POD data: over 20 factors including human factor	Lower POD, higher a90/95	High / ?	• Full POD study? • Model-assisted POD study?

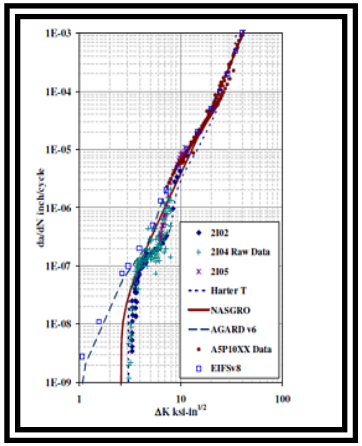
NRC·CNRC

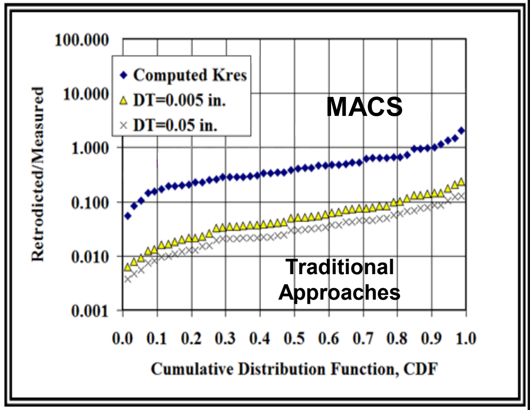
Needs on Risk Analysis Tool
-- Flexibility, Accessibility, for example

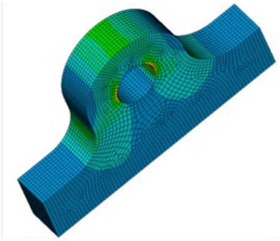


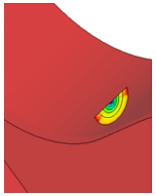
- NRC tools use either Lincoln, Berens, or Freudenthal SFPOF calculations
- NRC tools have gone through some verification and validation
- NRC tools do both probabilistic integration and Monte Carlo simulation

TTCP Activity









AER TP 4 Work Unit: **CP 4A.2 (Closing)**

Improved Fatigue Models for Engineered Residual Stresses

Problem Statement: Improved fatigue models are needed by airworthiness authorities to allow certification of structure containing engineered residual stresses, with a lesser requirement on costly physical testing.

Outcomes: Improved fatigue models and methodologies to support certification of structures with reduced amount of testing needed, e.g. AU AP-3C, C-130 fleets.

Exploitation Route: Improved life prediction models will be assessed experimentally.

S&T Challenges: Computational simulation of fatigue crack growth and non linear residual stress fields.

Outputs: Preliminary fatigue models and modelling techniques, documented in reports.

Measures of Success: Experimental validation of improved life prediction models.

Timeline: (2013 – 2015)

2013
- CP initiated as a follow on from CP4A.8
- Refinement of Stress Models

2014
- Development of model enhancement
- Comparison of new models to test data
- Refinement models

2015
- Incorporation of new models into existing tools
- Certification aspects pushed forward to SA4A.12

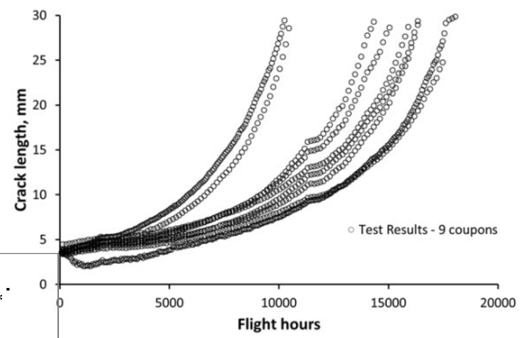
Milestones:

- Re-design cold rolling tool using FEA that resulted in a 40% life improvement.
- First-ever method to link desired fatigue response to Laser Shot Peening parameters.
- Simulation technique reduces computational time by factor of 10.
- Submodeling technique developed for large scale problems
- Tests carried out to remove residual effect on crack growth

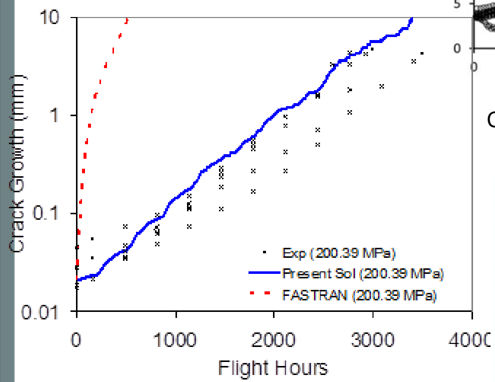
CP 4A.2 Achievements/Outcomes

- Improved life prediction models that reliably account for the effects of residual stresses are the critical first step toward achieving certification of ERS-enhanced structure with reduced reliance on physical testing*.
- Under this CP, various fatigue models were augmented to include residual stresses, with varying levels of experimental support. The planned benchmarking of these models for certification and acceptance was pushed to SA 4A.12 to allow for more in-depth development.
- Enhancements accomplished under this CP include:
  - Re-design of an cold rolling tool using finite element analysis that improves fatigue life by 40%
  - Preliminary development of a two-level damage tolerance assessment method (initial screening followed by detailed analysis)
  - Development of closed-form equations for estimating the laser peening parameters required to achieve a specified fatigue response
  - Development of analysis method for removing residual stress effects from fatigue crack growth data
  - Enhanced computational techniques for accelerating laser peening simulation time by a factor of 10
- Reports/papers done by New Zealand, Australia on 3D FEM on hole cold expansion, and weight function to calculate stress intensity factors of fastener hole with residual stress

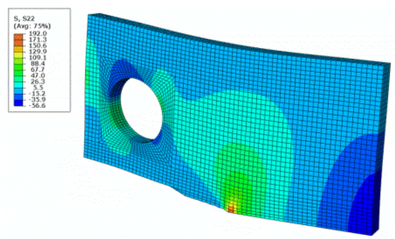
** ERS: Engineered residual stress, such as resulting from laser peening, burnishing, cold- working, etc.*



Crack growth variability under representative spectrum loading



Fatigue crack growth predictions (open hole subject to spectrum loading



AER TP 4 Work Unit: **SA 4A.12 (Extension Requested)**

Roadmap Towards Maintenance Credit for Engineered Residual Stresses (ERS)

Problem Statement: To increase service lives and reduce maintenance requirements, military fleet managers would like to exploit ERS. Current regulations to extend fleet lives based on ERS favor extensive physical testing. Operators have a need for analytical tools to reduce the testing burden.

Outcomes: Stakeholders will have a clear path identifying the R&D activities required to support routine acceptance and certification of ERS-enhanced aircraft structures with minimal physical testing

Exploitation Route: Technology development plans will be assessed by regulators; CP results will be provided to OEMs and aircraft structural integrity managers.

S&T Challenges: Coordinate all relevant activities being carried out in the TTCP nations to establish barriers to routinely incorporating lifing credit for beneficial residual stresses in metallic airframe components. Creation and acceptance of a combined technology development roadmap

Outputs: A detailed technological roadmap which can be used as a basis for developing an R&D programme leading to the certification of life extension based on ERS.

Measures of Success: Acceptance of the roadmap by regulators, operators, OEM's and maintainers. Development of a R&D strategy to optimise the physical testing and analysis requirements for certifying residual stress effects

SA Timeline:

Task	July-15	Apr-16	Oct-16
Collect requirements for incorporating lifing credit			
Develop combined roadmap & proposed path forward			
Obtain national buy-in and concurrence for roadmap			
Report Deliverable			

Milestones:

- Develop combined roadmap & proposed path forward
- Obtain national buy-in and concurrence for roadmap
- Report Deliverable

TTCP TP4 Panel Discussion on SA 4A.12

- SA 4A.12 is aiming for a technical roadmap for various ERS techniques (cold expansion, shot peening, laser peening, low plasticity burnishing), and for wide range of aircraft fleet application
- SA 4A.12 is being extended for incorporating with the USAF sponsored ERSI workshop on roadmap development
  - NRC participation
  - DSTG participation
  - AFRL/USAF participation
  - US Army (Nate Bordick) request: laser peening and tool path optimization to achieve desired residual stresses. One concern is residual stress relaxation, “will the same residual stresses that are present on day 1 still be there on day 10,000. If not, how do you analytically predict relaxation and still take advantage of any benefits in certification / maintenance”

Summary

- **Brief Review of Some Practices Considering ERS**
  - LIF varies with lifing policy (CI vs CG), based on extensive lab tests, strictly limited to specific conditions (material, e/D, spectra, a/c…), no analytical LIF adopted yet.
- **UQ for ERS Modeling and Experimental Measuring**
  - ASME UQ Process
  - UQ for ERS: a new EN-SB similar to EN-SB-11-001 (FEM and Test)?
- **Risk Analysis Considering ERS**
  - Safe-Life based risk analysis
  - DaDTA based risk analysis
    - ICSD – impact of ERS
    - Master a-t curve – impact of ERS
    - POD/NDI – impact of ERS
- **Discussion**
    - TTCP Roadmap on ERS

The effort was supported funded by the Department of National Defence (DND), Department of Directorate of Technical Airworthiness and Engineering Support (DTAES)

Thank you

Dr. Min Liao
Group Leader – Structural Integrity
Tel: 613-990-9812
min.liao@nrc-cnrc.gc.ca
www.nrc-cnrc.gc.ca

Air Force Life Cycle Management Center

Residual Stress Workshop: An ASIP Manager Perspective

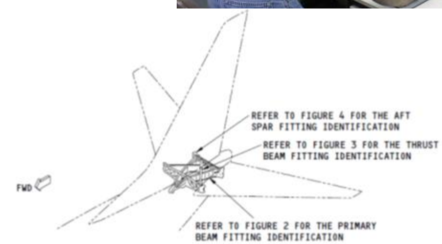
15 September 2016

Mark L Thomsen, Ph.D.
A-10 ASIP Manager
DSN: 586-7141
Mark.Thomsen@us.af.mil

Overview

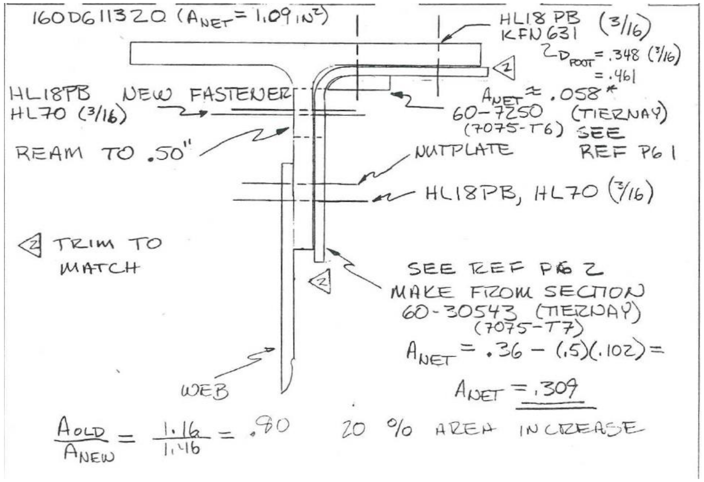
- Pre-History
- Recent Investments
- Completed Efforts
- In-Work
- Vision

Pre-History (1994-2005)

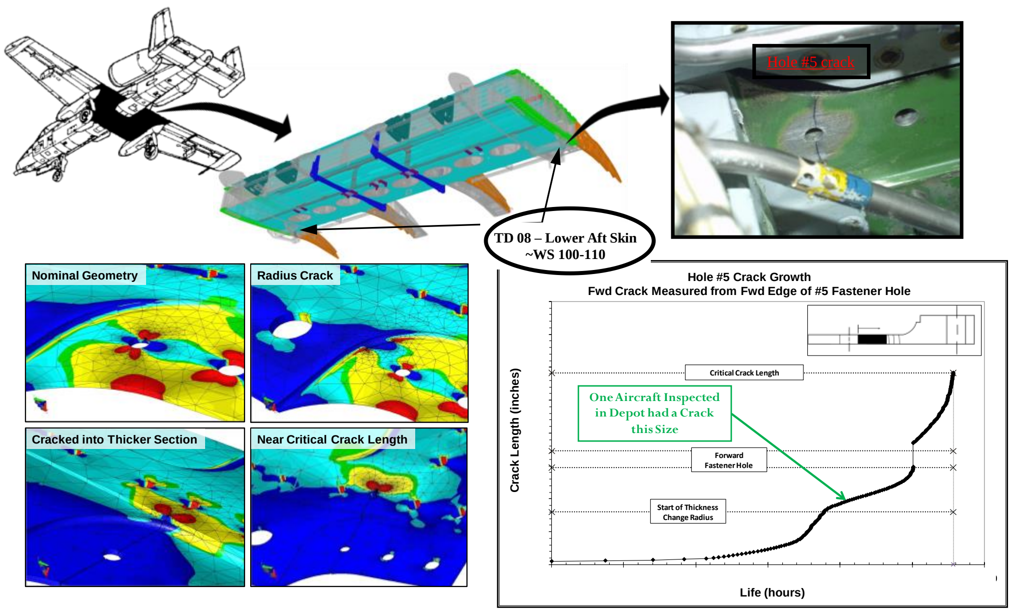


- **Work with FTI® on cold expansion**
  - **737 lap splice fleet improvement**
    - **Point design solution**
  - **737 Texas-Star bushing migration**
    - **Improve retention**
- **Analytical Prediction of Residual Stress State and Influence on Fracture Mechanics Modeling**
  - **Simple relationship between residual stress and F_{ty}**
  - **Crack growth sensitivity through β - correction**
- **Palace Acquire (PAQ) Program**
  - **Provides Program Office an applied research avenue**
  - **Modernize fracture mechanics methods in general**

Perspective



Example Repair (202 Disposition)
(A-10 Structures 2002)



Fleet Cracking (TCTO Support)
(A-10 Analysis Group 2008)

Analytical Basis

Finite Element Analysis (Bootleg)

OGDEN AIR LOGISTICS CENTER

- Axi-symmetric 3-dimensional
  - Non-linear ABAQUS (Material)
  - W = 4”
  - T=0.25”
  - D = 0.5”
    - Nodal spacing near bore about 0.003” varies to 0.015” away from hole
- Hoop stress
  - May need to alter method to include radial and thickness stress components (Von Mises? Other?)
  - May need to consider the impact of toughness and F_{ty} in combination along with material hardening (?)

For Official Use Only

BE AMERICA’S BEST

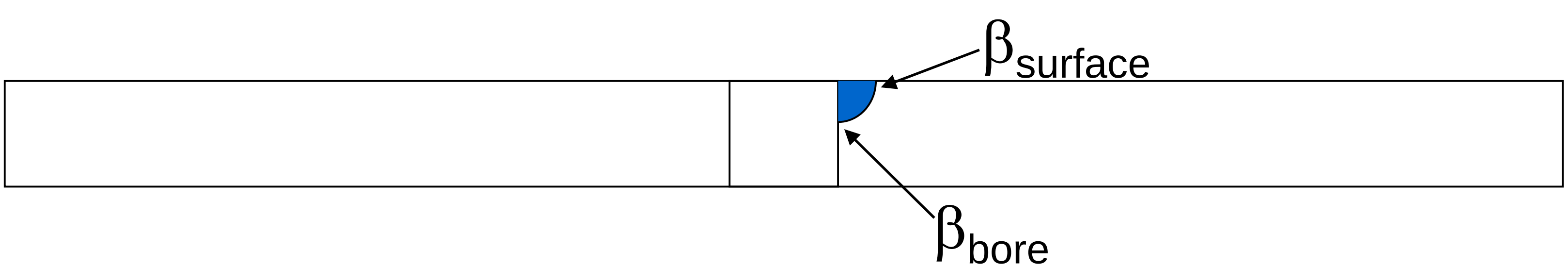
$$K = \sigma\sqrt{\pi a}\,\beta_{Detail}\,\beta_{Cx}$$

where

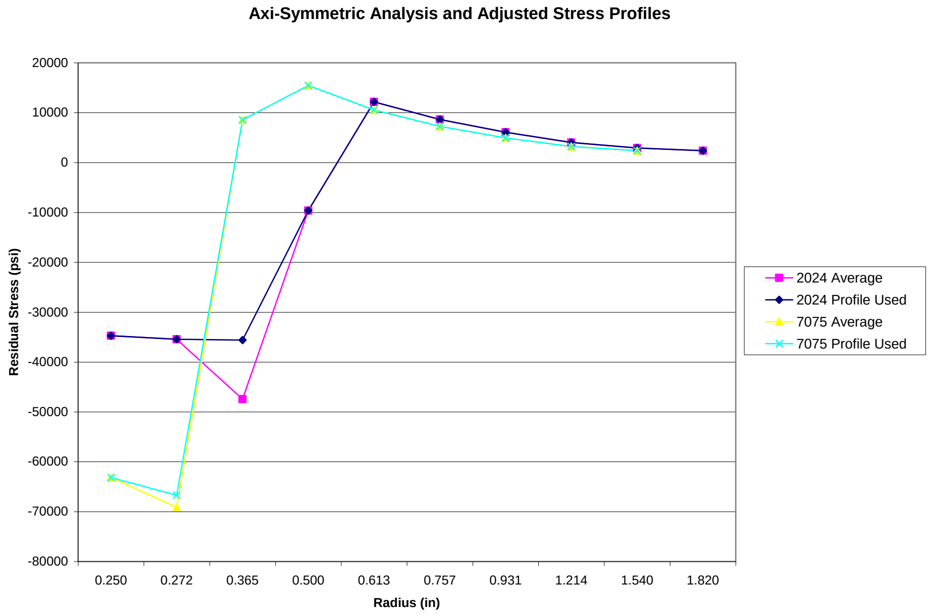
$$\beta_{Cx} = \frac{F_{ty} + \sigma_{Cx}}{F_{ty}}$$

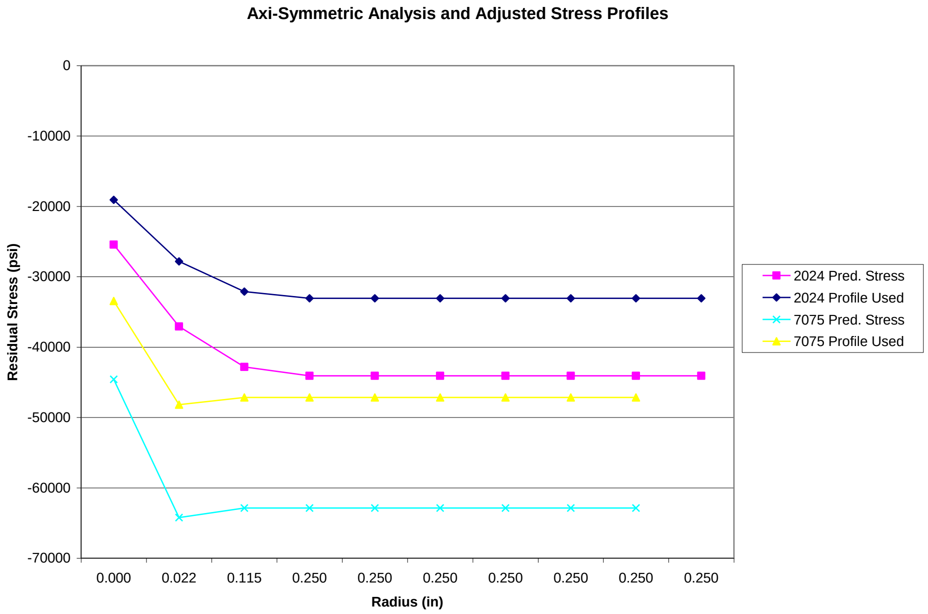
$$\sigma_{Cx} = F(Cx)$$

Comparative Model



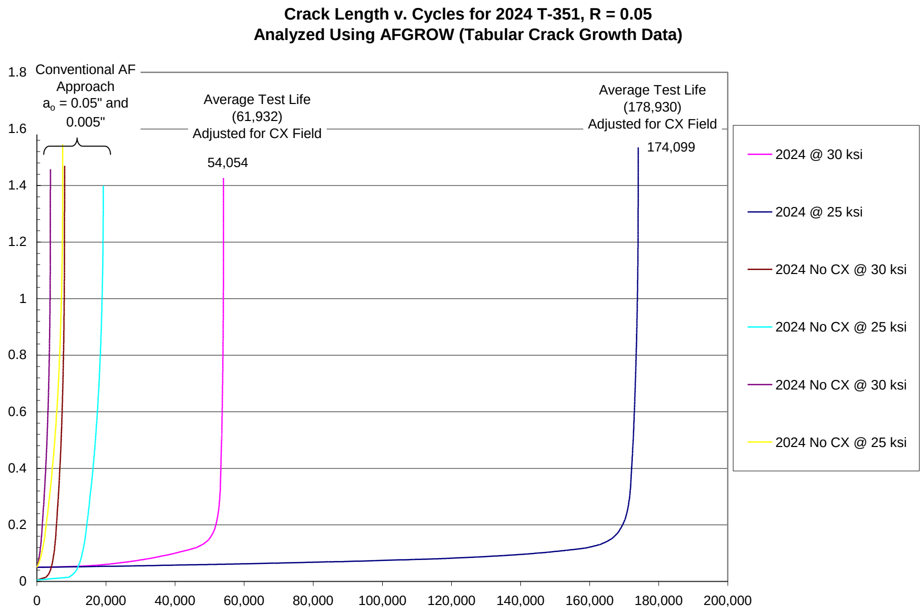
Adjustment

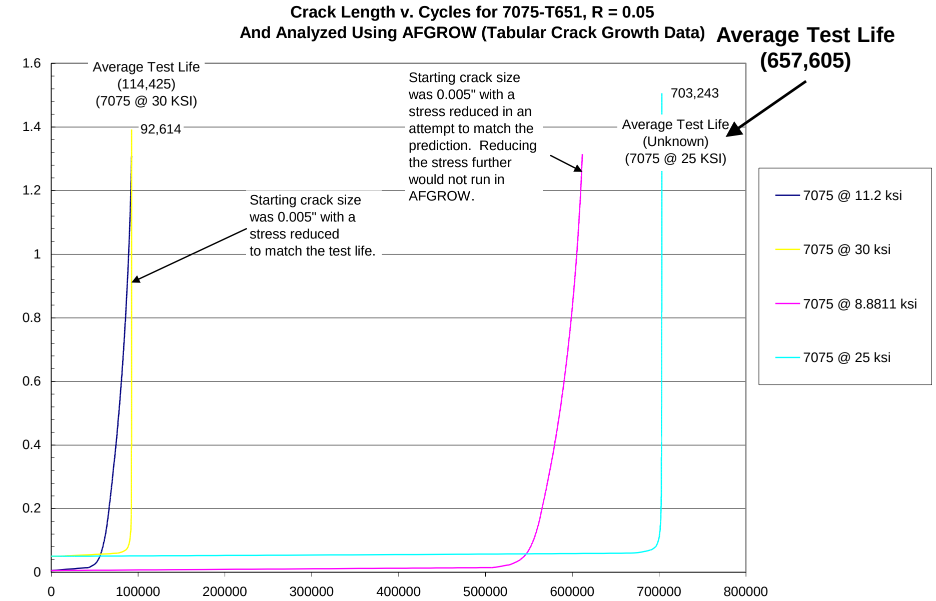

Axi-Symmetric Analysis and Adjusted Stress Profiles
20000
10000
0
-10000
-20000
-30000
-40000
-50000
-60000
-70000
-80000
Residual Stress (psi)
0.250
0.272
0.365
0.500
0.613
0.757
0.931
1.214
1.540
1.820
Radius (in)
2024 Average
2024 Profile Used
7075 Average
7075 Profile Used


Axi-Symmetric Analysis and Adjusted Stress Profiles
0
-10000
-20000
-30000
-40000
-50000
-60000
-70000
Residual Stress (psi)
0.000
0.022
0.115
0.250
0.250
0.250
0.250
0.250
0.250
0.250
Radius (in)
2024 Pred. Stress
2024 Profile Used
7075 Pred. Stress
7075 Profile Used

Test Comparison

- Testing was performed by the Academy to compare cold expansion in stack-ups
  - NO Precrack





U.S. AIR FORCE

Work Looking Into Residual Stresses

A-10 ASIP
MS thesis
Experimentally derived beta corrections to predict FCG at Cx holes

A-10 ASIP
MS thesis
Experimentally derived beta corrections to predict FCG at Cx holes

A-10 ASIP
MS thesis
Cx effects on cracked fastener holes

A-10 ASIP
MS thesis
Cx of short e/D holes with preexisting cracks

A-10 ASIP
Mod III
Crack Growth Analyses in Residual Stress Fields

T-38 ASIP
TO 34
Residual Stress Measurement

A-10 ASIP
Mod V
Residual Stress Measurement

T-38 ASIP
TO 52
RS and fatigue of countersunk Cx holes

A-10 ASIP
Mod V+
UQ of Contour Method

2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017

APES
SBIR Phase I

APES
SBIR Phase II

APES
SBIR Phase II Add

APES
Rapid Innovation Fund Program

APES
SBIR Phase III
Deep Residual Stress Method Demo Program

Hill Eng.
SBIR Phase III
ERS Toolbox for Cx holes

TRI Austin
SBIR Phase II ??
FastenerCam

GRAND TOTAL:
~$8M

Completed Programs

Mod III: 38 total RS coupons
- Straight shank holes
- 2024-T351
  - Center hole, varying D
  - Center hole, varying %Cx
  - Offset hole, varying e/D
  - Multi hole, varying D
- 7075-T651
  - Center hole, varying D

APES Phase I, II, II-add SBIRs
- Life Prediction
- Residual Stress Relaxation
- Understanding Failure
- 2024-T351 & 7075-T651
  - 10 RS Coupons
  - 70+ Fatigue Tests
  - Straight shank holes

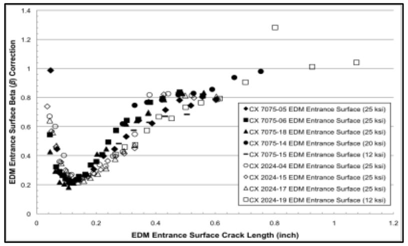
T-38 TO 34: 15 total RS coupons
- 3 Straight hole coupons
- 12 Csk hole coupons
- 7075-T7351
- Vary Cx process
  - Cx then Csk
  - Cx csk hole with CsCx
  - Cx csk hole w/o CsCx
- 3 hole (3 coupons)
  - Identify effect of pitch

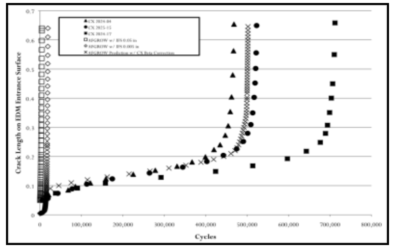
A-10 Mod V: 12 total RS coupons
- Straight shank holes
- Center hole
- Varying process:
  - No ream
  - Standard Ream
  - Double Cx

APES Rapid Innovation Fund
- Three Technology Areas
  - Life Prediction
  - FastenerCam (800+ holes)
  - NDT (118 coupons)
- 7 Materials
- Various Spectra
- Many geometric variables
- Large amounts of data
  - 200+ fatigue tests
  - 70 RS Coupons

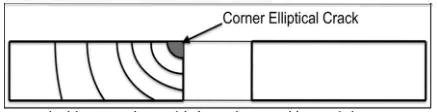
A-10 Masters Thesis Work
- Life Prediction
- Two materials
- Various load spectra
- Various peak stress levels
- Center hole & Low e/D
- 70+ Fatigue Tests

Application-Based Research Efforts



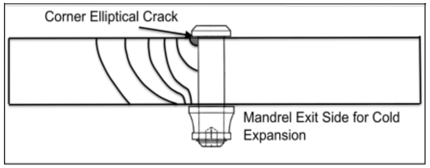


Impact of Cold Expansion (CX) on Crack Growth



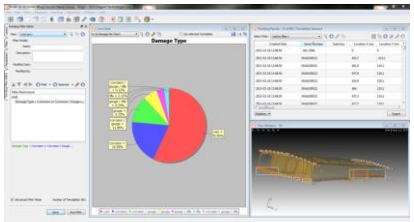
Standard fatigue crack growth behavior for non cold expanded specimens.

Image of experimental fatigue crack growth.



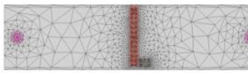
Unique fatigue crack growth behavior for cold expanded specimens.

Impact of Cold Expansion (CX) on NDI

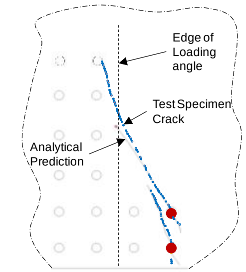


Rapid Innovation Fund MX Data Visualization

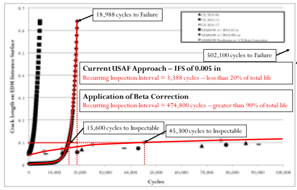
Test



Analysis



Validation

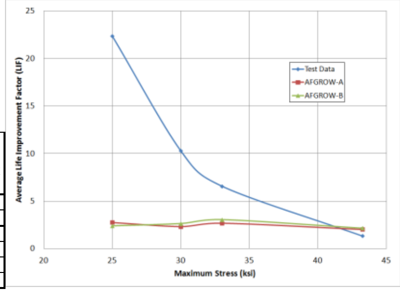


Analysis v. Test

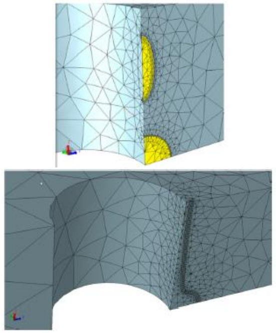
Spar Web Analysis

- LIF decreases with increasing stress

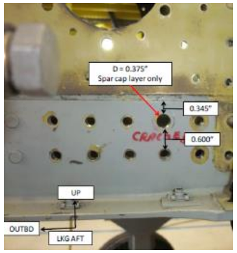
Loading	Max Stress (ksi)	Non-CX Life (cycles)	PC-CX Life (cycles)	LIF NCX to PC-CX
Constant Amplitude	20	47443	4296067	90.6
	25	7443	452585	60.8
Spectrum	25	31521	704450	22.3
	30	N/A	194950	10.3
	33	12201	80220	6.6
	43	4658	6201	1.3



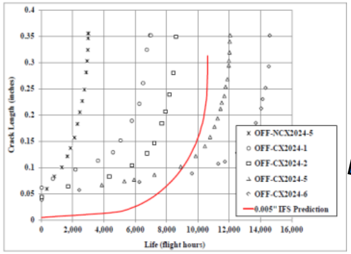
Influence of Spectrum Peak Stress on Benefits of CX



Rapid Innovation Fund CX-Residual Stress Characterization

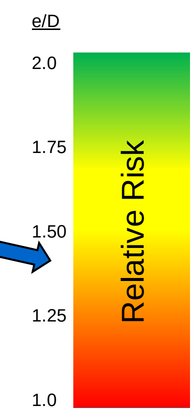


Rework Requirement



Test

CX Edge Margin Sensitivity



Result

Currently In Work

T-38 TO 52
- Fatigue Life Prediction in Cx Csk Holes
  - Three Cx methods
- 30 Fatigue Tests
- 26 Residual Stress

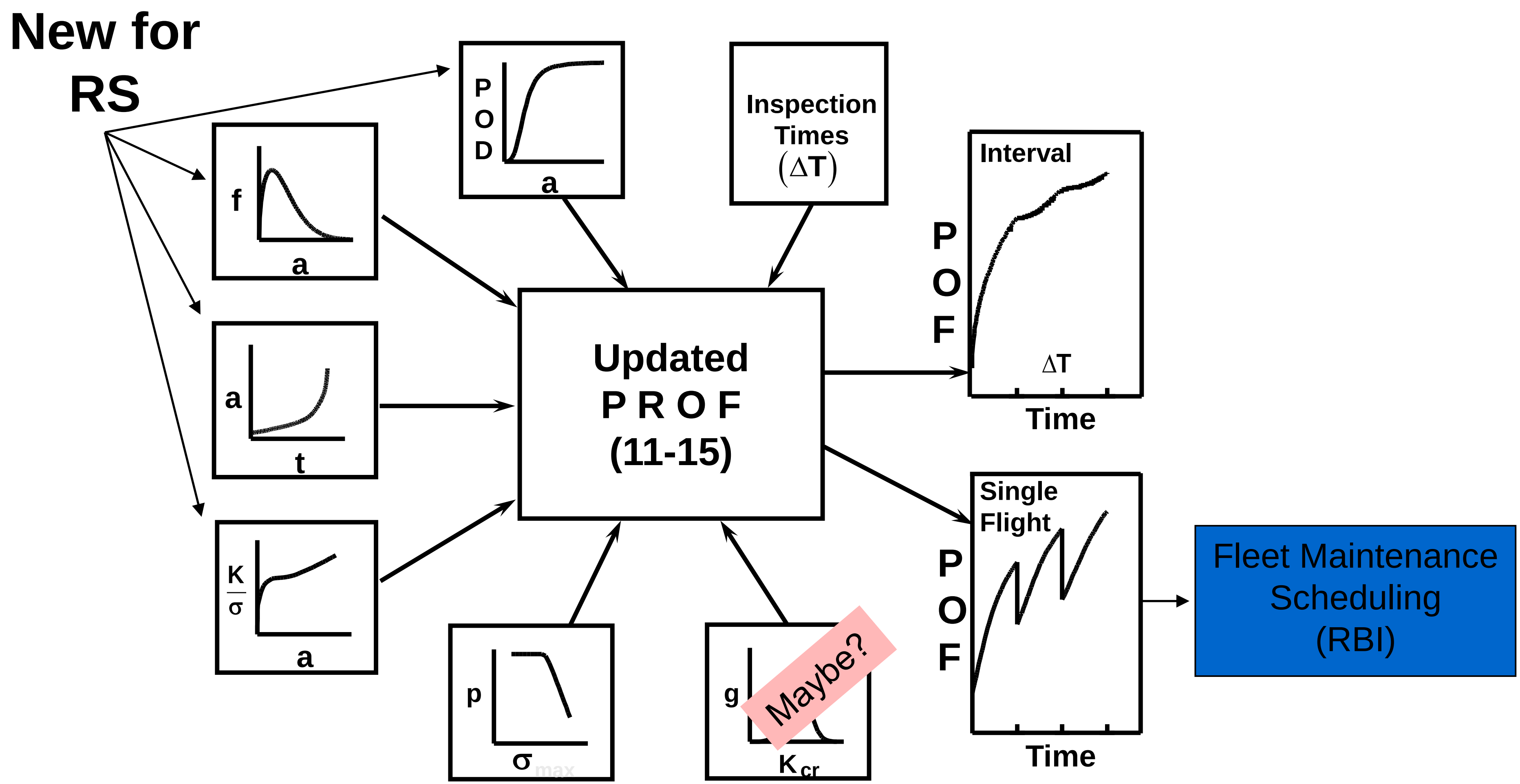
Phase III SBIR -- APES
- Stress Redistribution Due to Crack Propagation
- Material Models & Response
- Filled Hole
- Loaded Hole
- 80 Fatigue Tests
- 40 RS Distributions

A-10 Mod V+: UQ Effort
- Primarily an Analysis Task
- Quantify Uncertainty Qssociated with Contour Method
  - Inter-Laboratory round robin

Phase III SBIR --Hill Engineering
- Legacy Cx Compared with New Production
- 110 RS Coupons
  - 80 off aircraft
  - 30 new material
- 34 Fatigue Coupons

Phase II SBIR –TRI Austin
- FastenerCam Evolution
  - Countersunk holes
  - Non-Contact
- Not on Contract yet….Dave???

Risk Comments



Or something altogether new?

Overall Vision

- Improve Understanding of Deep Residual Stress Quantification Uncertainty
  - Influence of current measurement processes on residual stress quantification (Best Practices)
  - Influence of aging on residual stress treatments
  - Sensitivity of crack propagation predictions through statistical characterization (Quasi-Allowable)
- Evolve Crack Propagation Data Collection Processes to Complement Analytical Capabilities
- Further Develop Non-Destructive Inspection Methods to Validate and Correlate Treatments to Benefits
- Implement through Comprehensive Qualification