Analysis Methods: Residual Stress Implementation

Engineered Residual Stress Implementation Workshop 2016
September 15, 2016

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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

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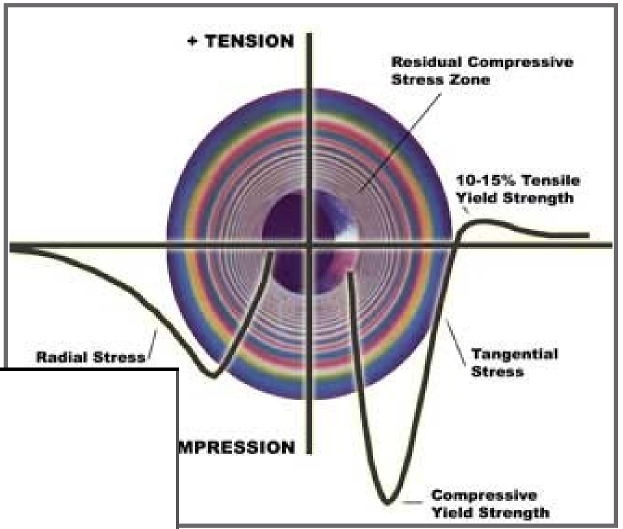
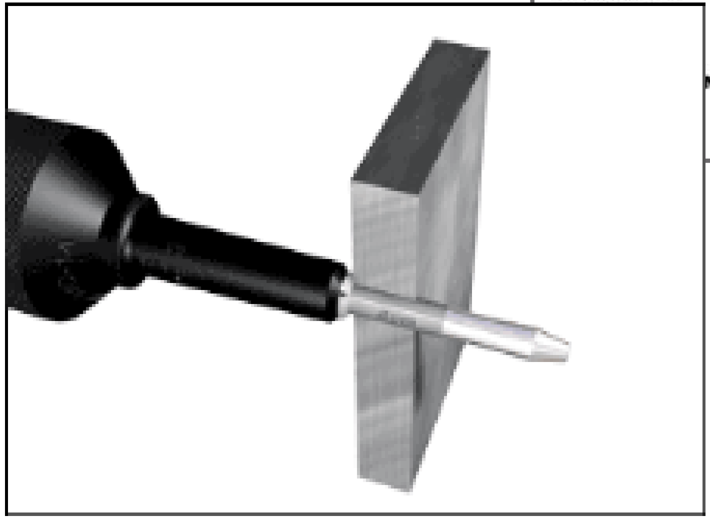
Overview/Outline

- 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

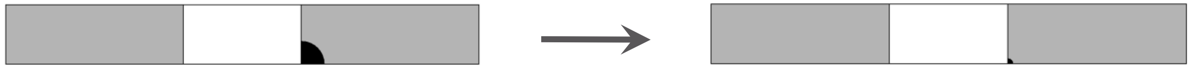


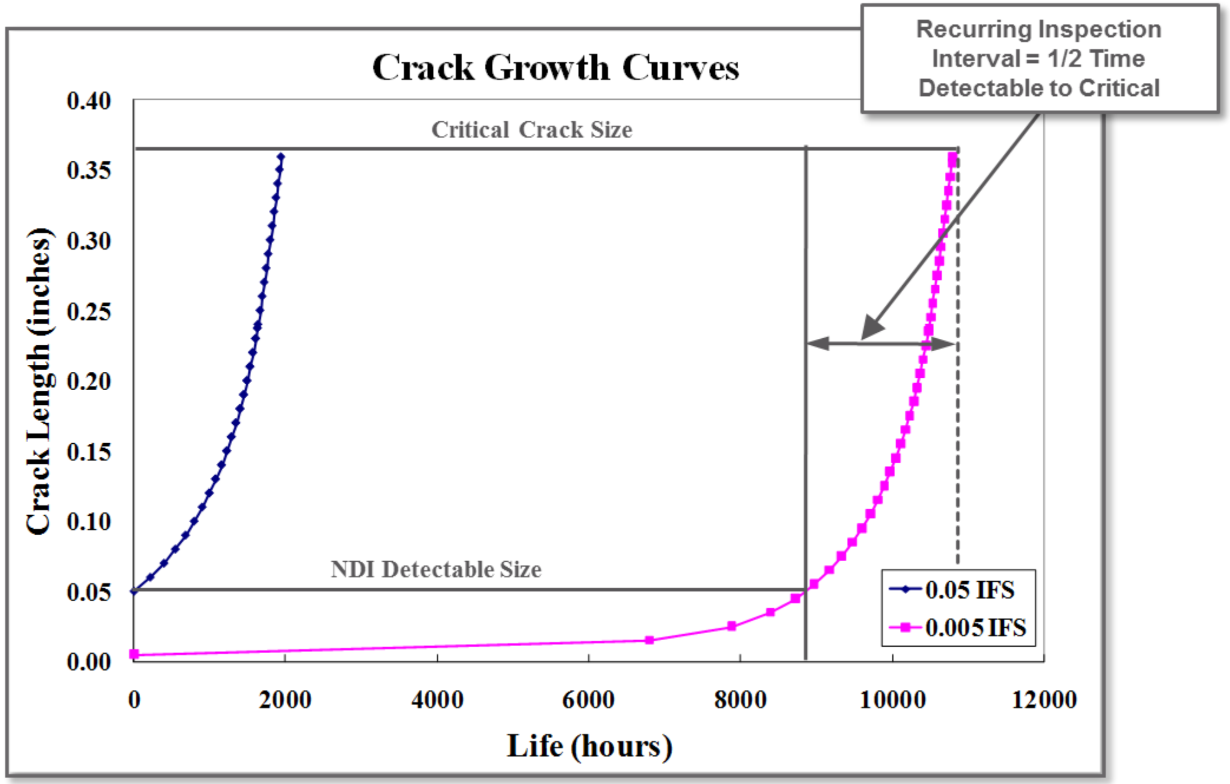


Fatigue Technology, Inc.

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





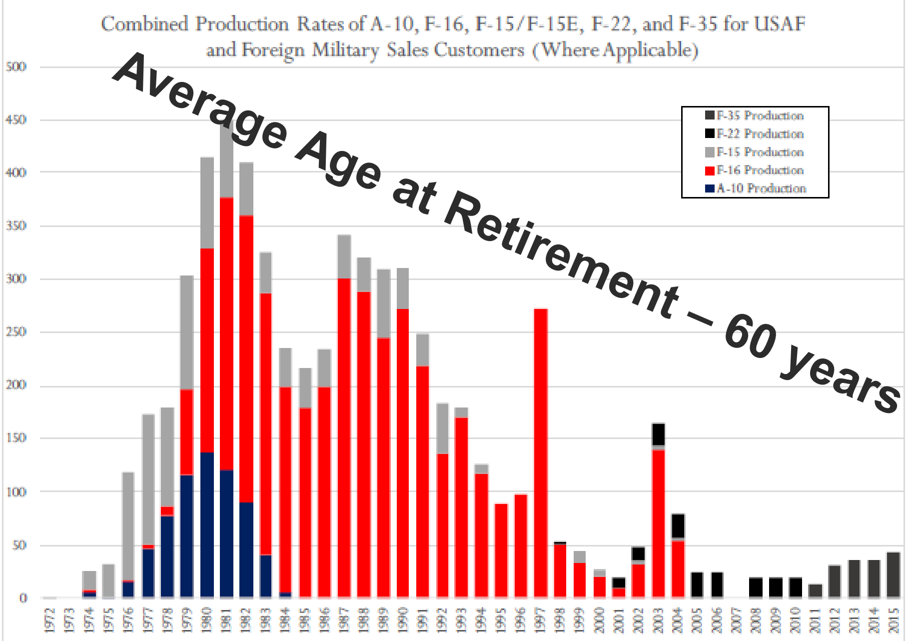
Classical USAF Approach

- 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).

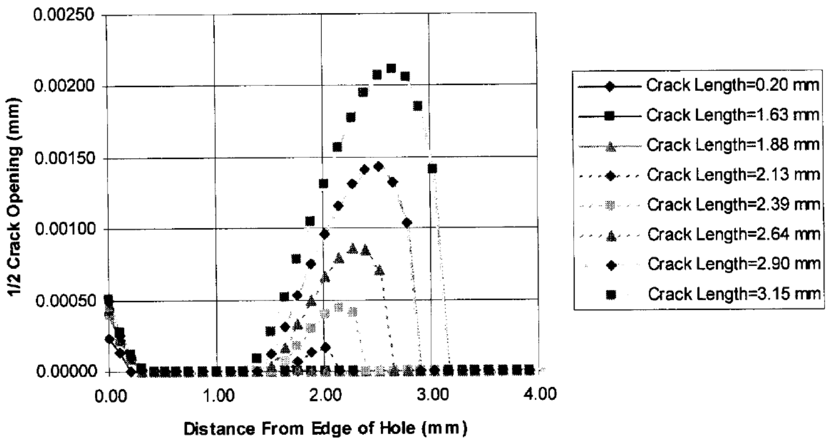
We Have 12.5 Billion Reasons to Sharpen Our Pencils…

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

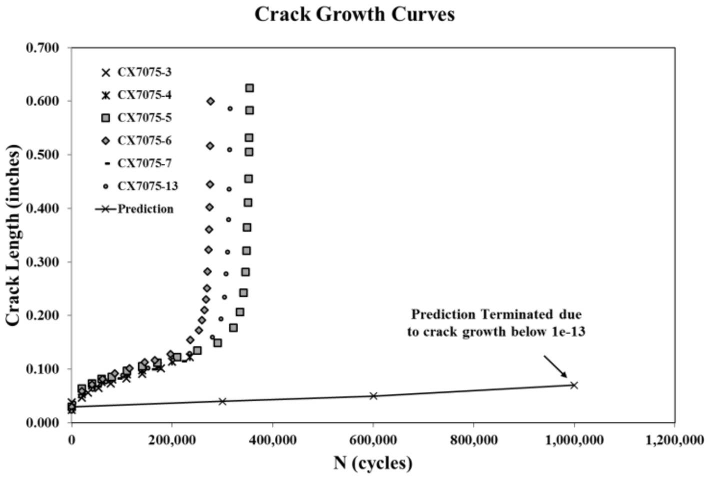
Ref: Operation and Maintenance Overview, Fiscal Year 2015; Office of the Under Secretary of Defense (COMPTROLLER)/Chief Financial Officer

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

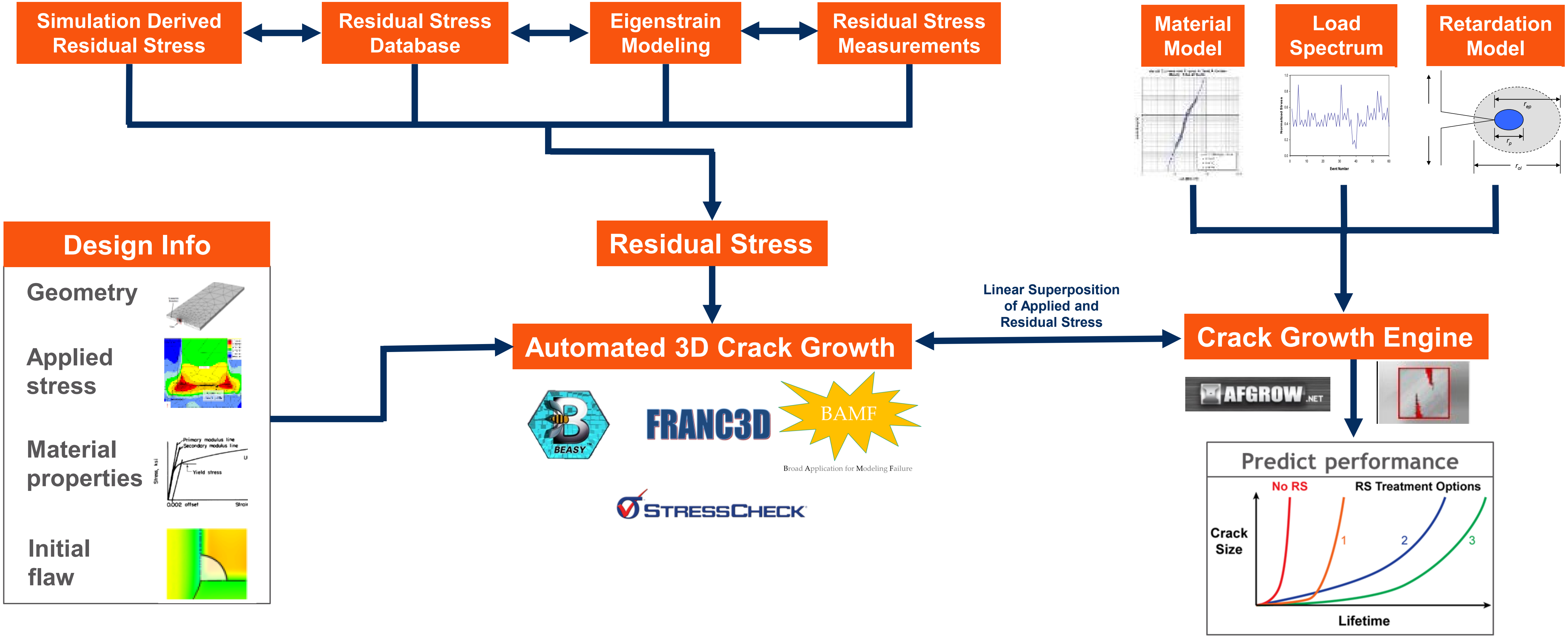


Kokaly, M.T.; Ransom, J.S.; Restis, J.H.; Reid, L.F.; (2002) Prediction fatigue crack growth in the residual stress field of a cold worked hole. Journal of Testing and Evaluation. 20, 1-15.



Recommended Approach

Analysis Approach

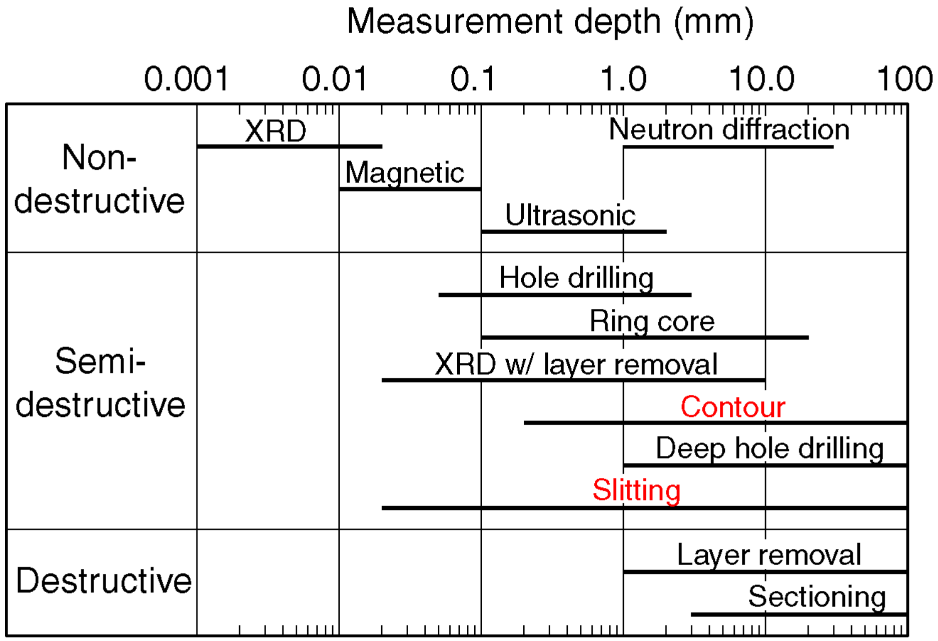


Recent Keys to Success

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)

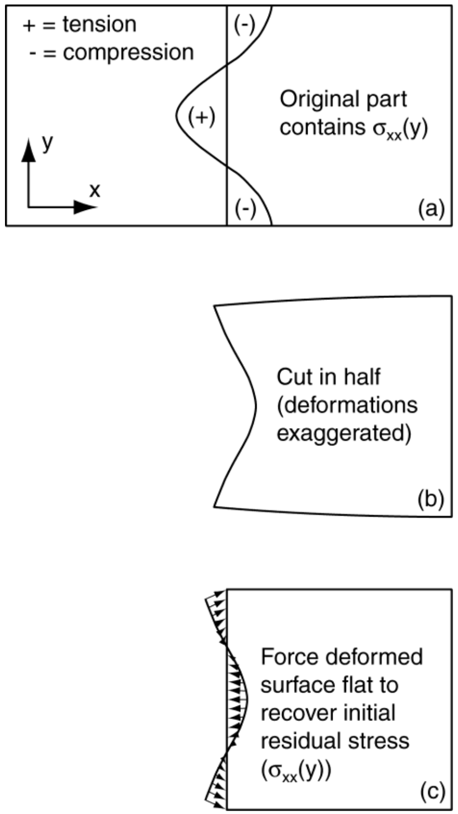


After: Prime, www.lanl.gov/residual/compare.shtml

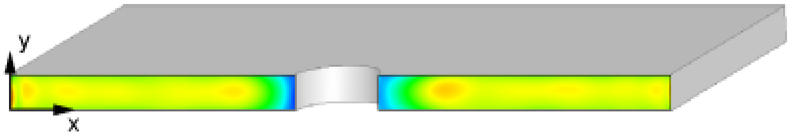
Direct Incorporation of Residual Stresses

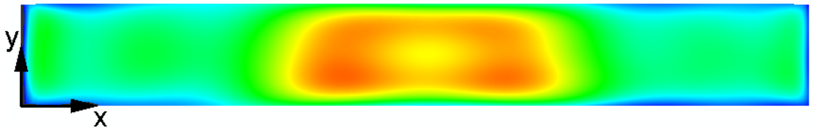
- Contour Method
  - generates a 2D map of residual stress normal to a plane
- Contour method steps (illustrated for 2D body)
  - Part contains unknown RS (a)
  - Cut part in two: stress release ⇒ deformation (b)
  - Measure deformation of cut surfaces
  - Apply reverse of average deformation to finite 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.



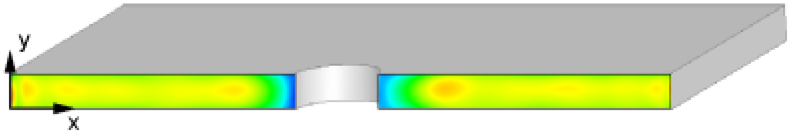
Cut → measure → FEM → 2D residual stress map



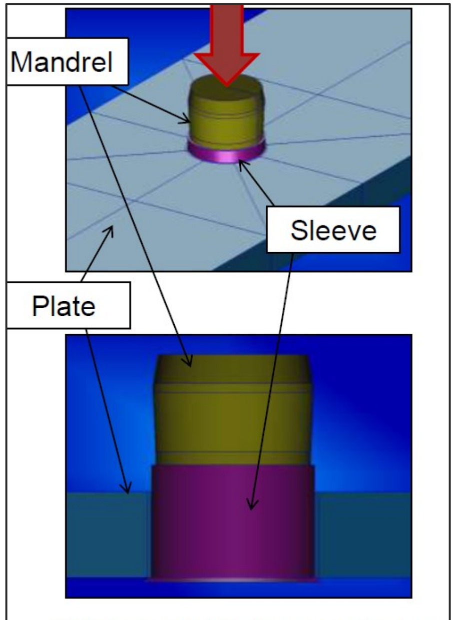


Improved Quality of Residual Stress Inputs

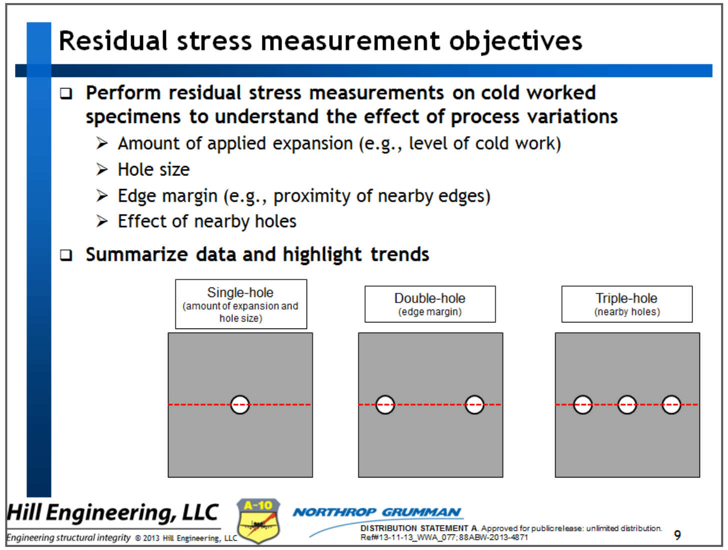
- The accuracy of residual stress inputs used in analysis have improved due to:
  - Advances in residual stress measurement methods
    - E.g., Contour Method



  - 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.

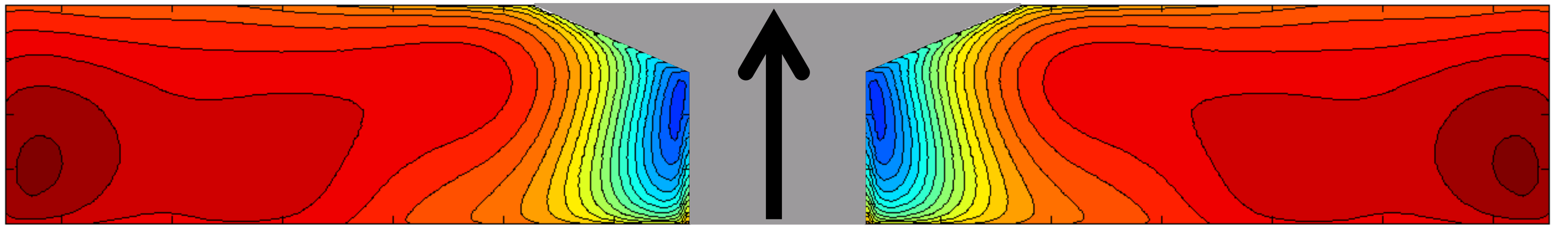


*%Cx defined by geometry parameters



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

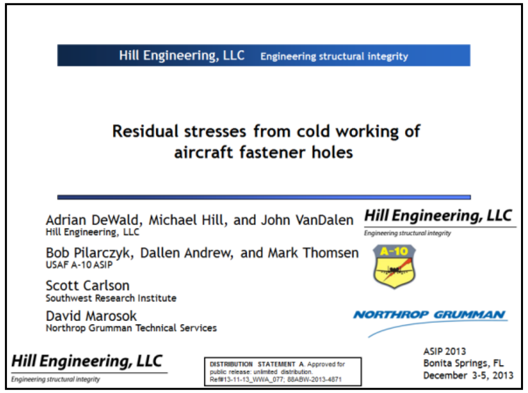


Mandrel pull direction

- 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

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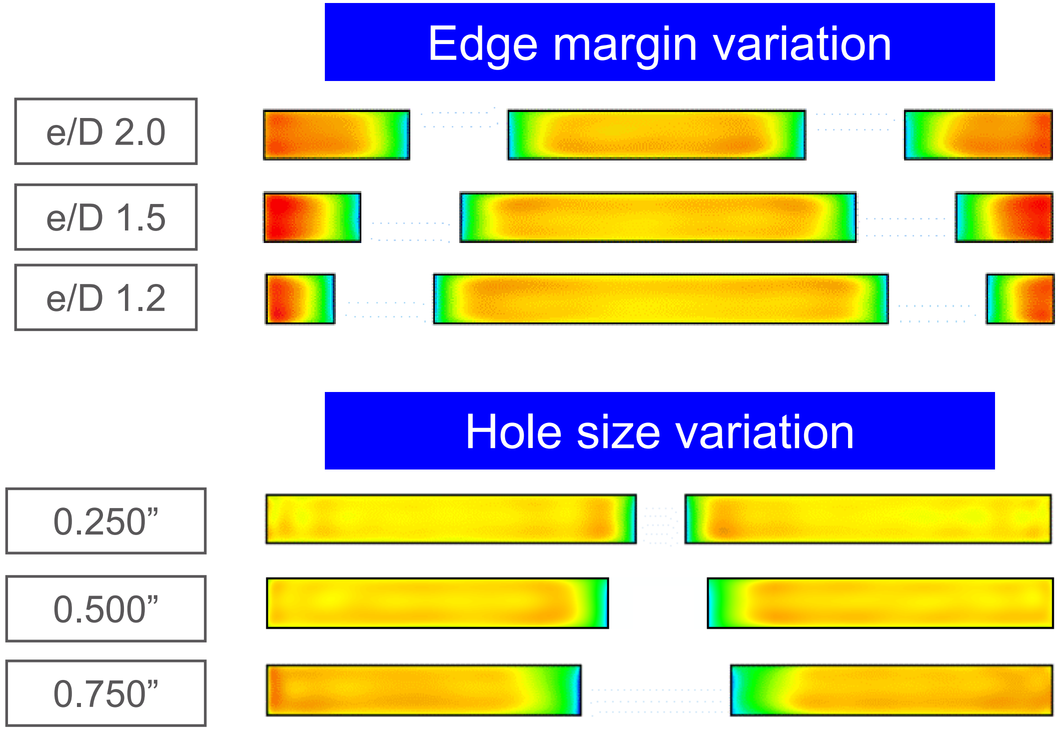
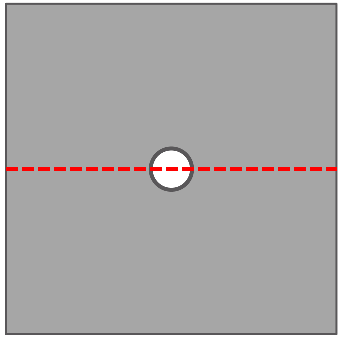
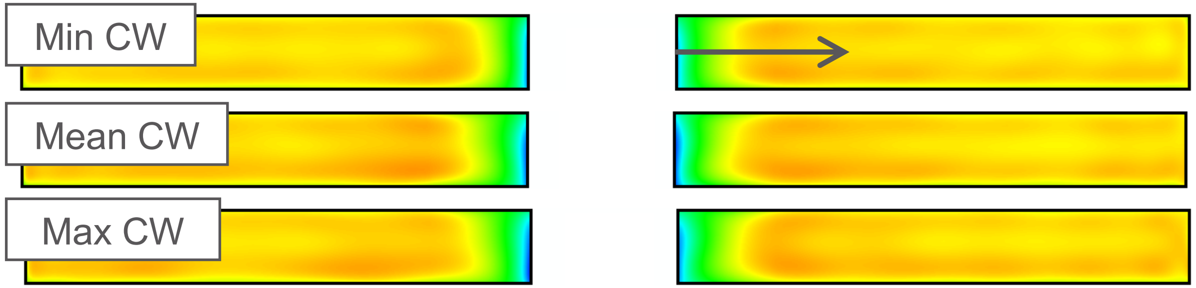
ASIP 2013
Bonita Springs, FL
December 3-5, 2013



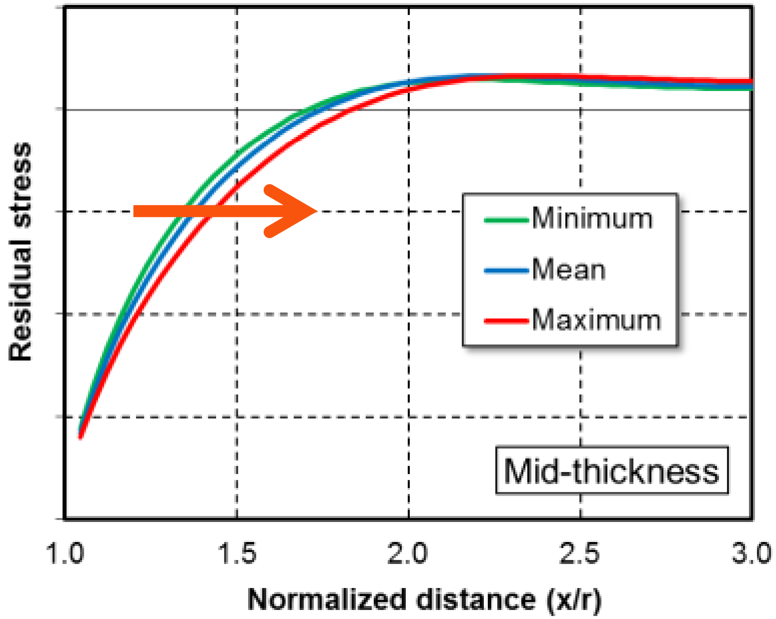
Influence of Key Variable on Residual Stress

- 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

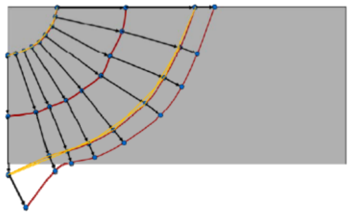
- The ability to execute advanced fatigue crack growth simulations has improved due to:
  - Advances in computational analysis technology
  - Advances in software tools
    - Analysis at multiple points on the crack front
    - Arbitrary crack shape progression
    - Improved compatibility with residual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

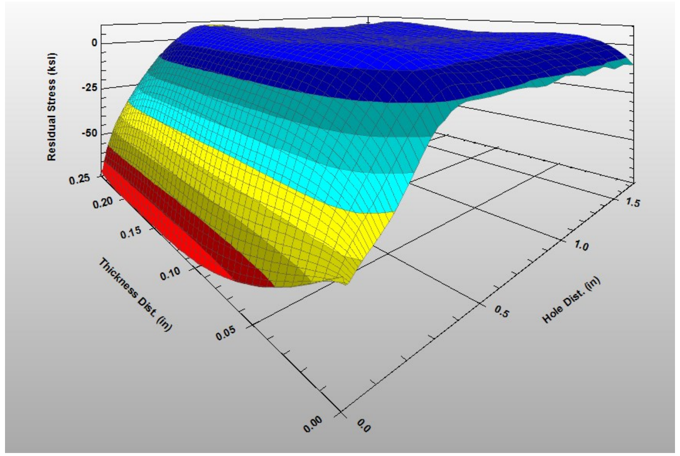
FRANC3D

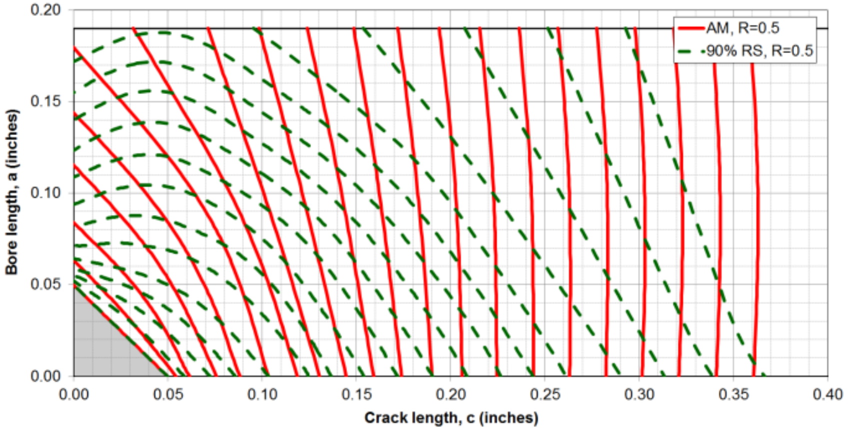
BEASY

BAMF

Broad Application for Modeling Failure

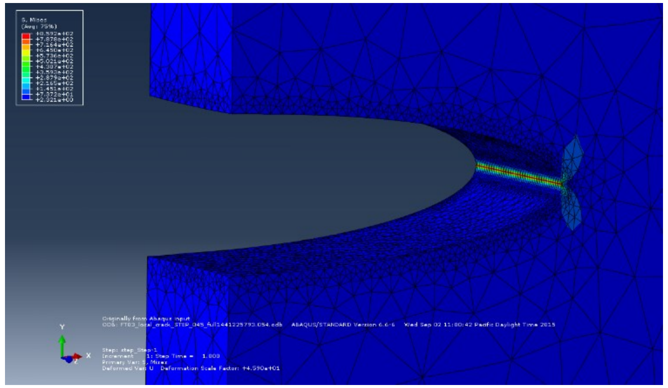


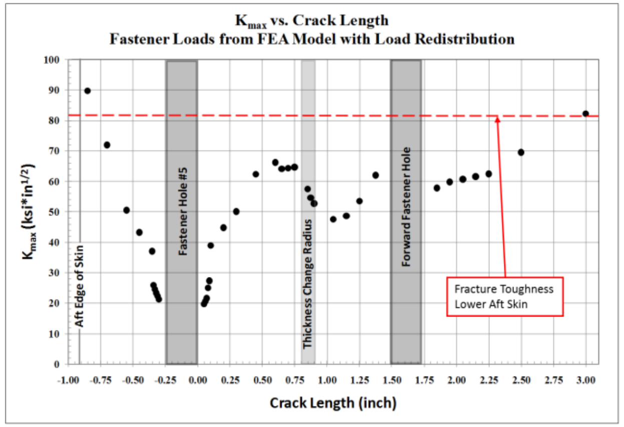


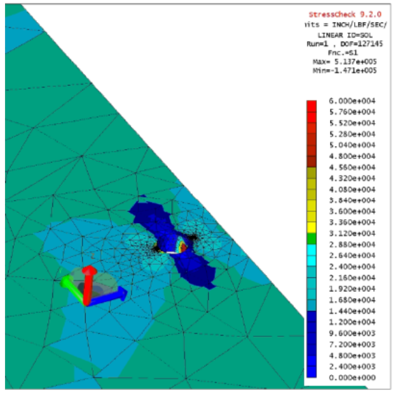


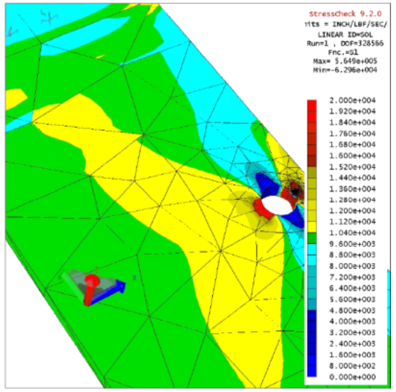
Finite Element Based Stress Intensity Capability

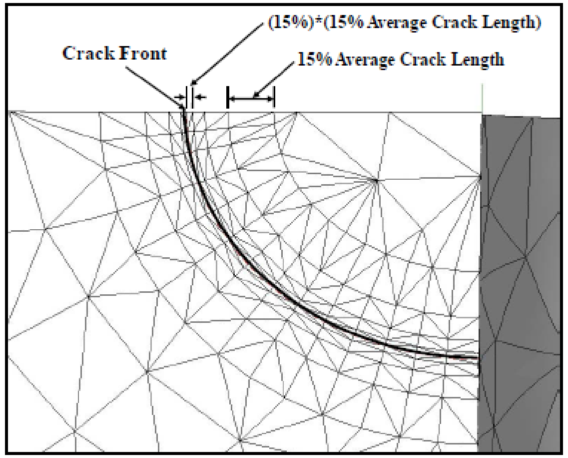
- Increased capability of FE codes to represent cracks and extract stress intensities
- Becoming more common practice for “complicated” situations
- Standardized guidelines developed
- J-integral for crack face pressures

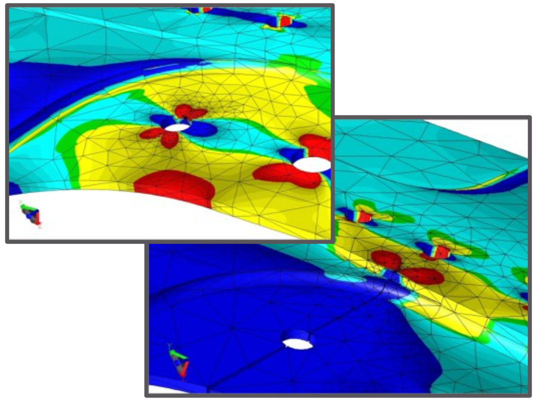








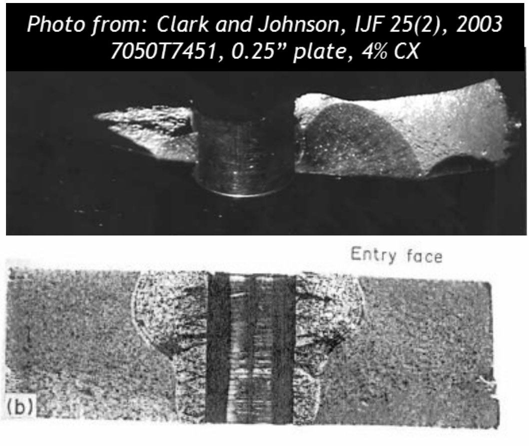


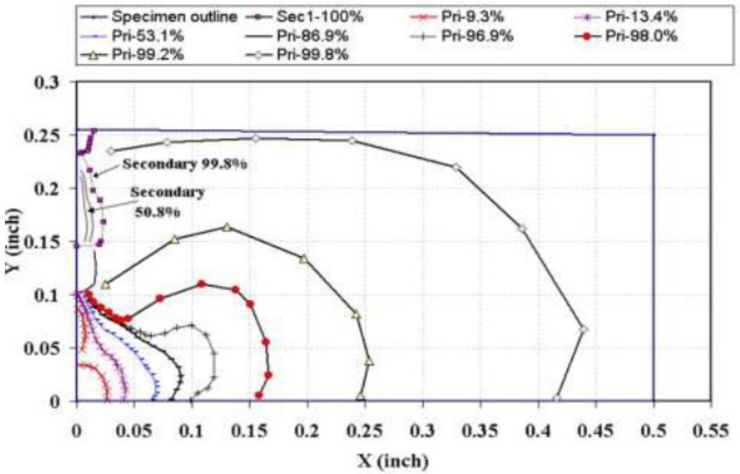


Pilarczyk, R.; Carlson, S.; Stowe, G.; (2009) Is ASIP Still Alive, The A-10 Lower Wing Skin Cracking Issue.; ASIP Conference 2009.

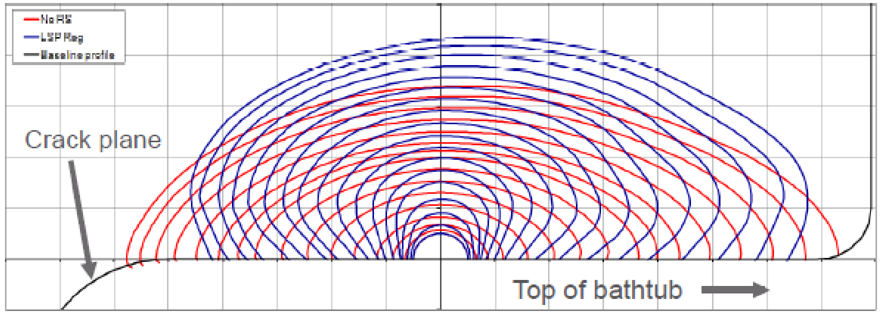
Multi-Point Crack Shape Evolution

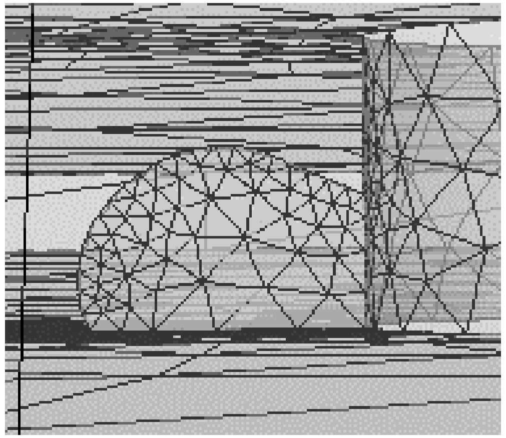
- Crack growth through complicated geometry, loading, etc.
- Move away from utilizing two discrete points (typically) along crack front to characterize overall behavior
- For cold worked holes critical to allow crack to “ooze” through path of least resistance

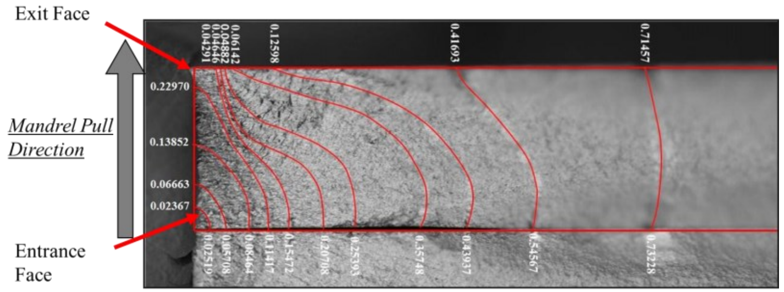




Mills, T.; Prost-Domasky, S.; Pilarczyk, R.; Hodges, J.; (2014) Important Factors for Modeling Fatigue Performance at Cold Worked Holes.; AA&S Conference 2014.

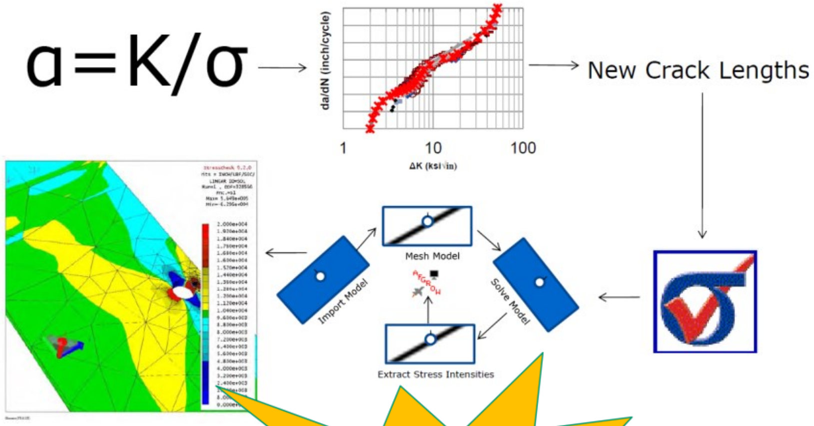






Coupled Crack Growth and FEA Stress Intensity Calcs

- 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



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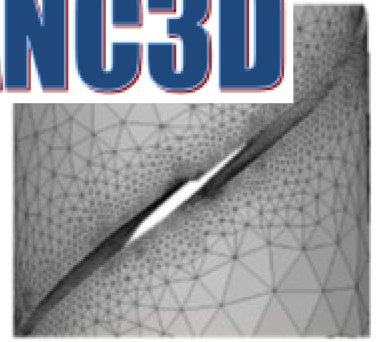

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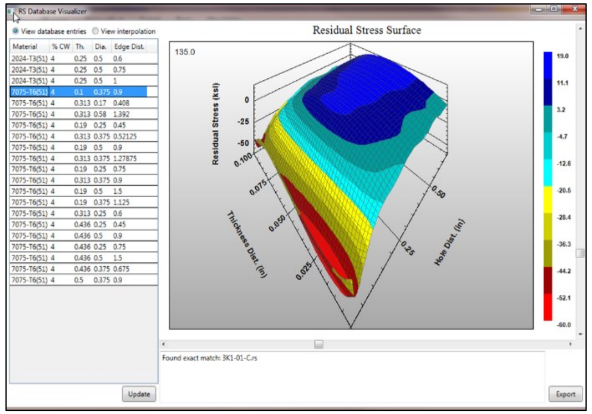
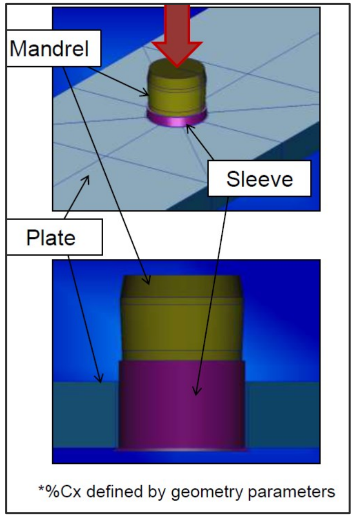
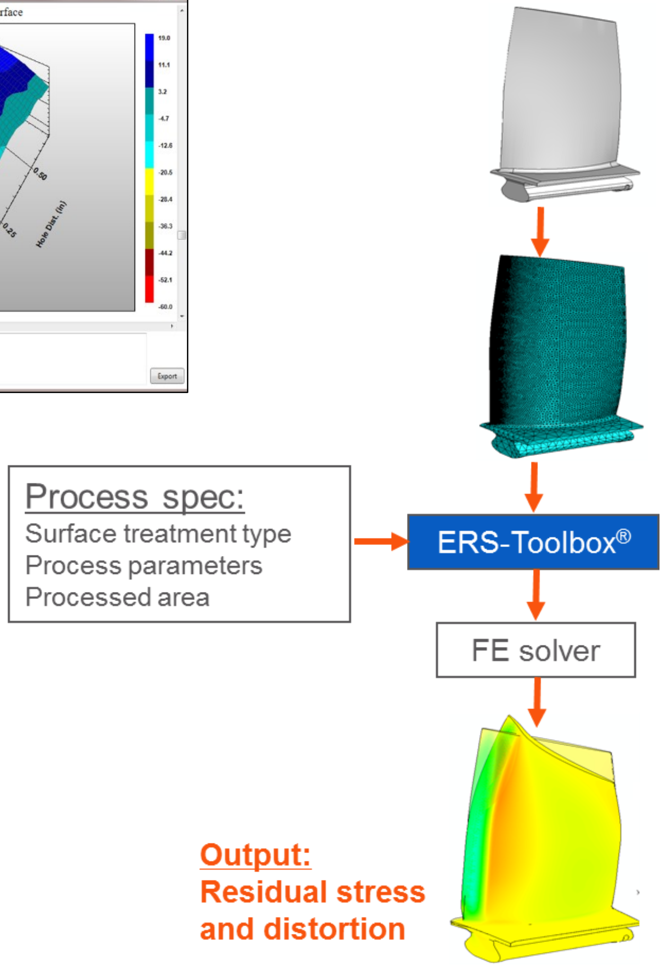
Methods to Incorporate Residual Stresses

- ❑ **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



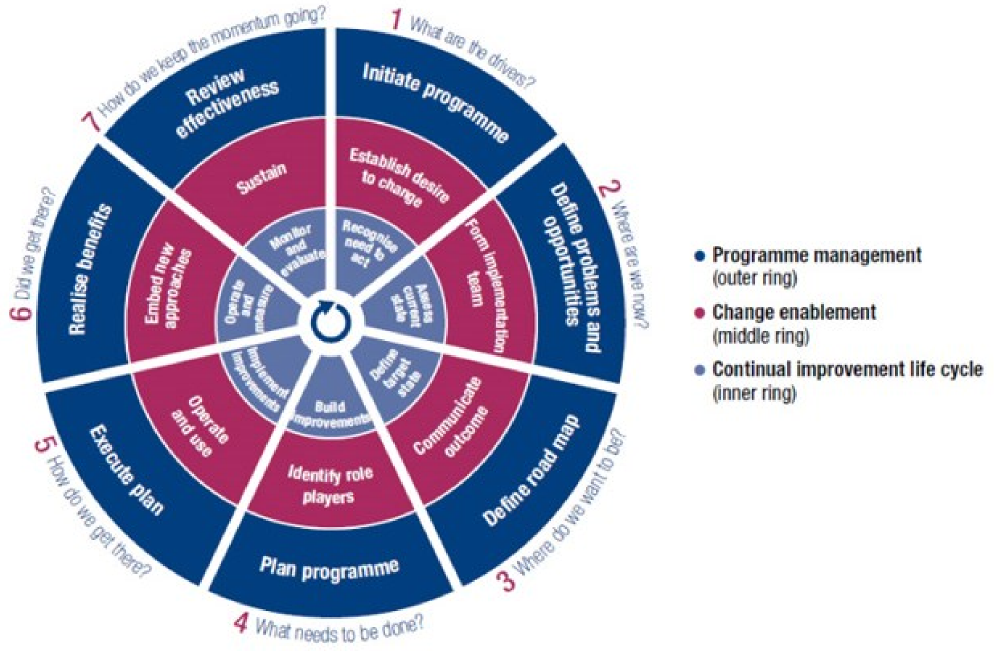




Focus Areas Moving Forward

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 STRUCTURES

Structures Bulletin

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Phone 937-656-9956

DEPARTMENT OF DEFENSE

JOINT SERVICE SPECIFICATION GUIDE

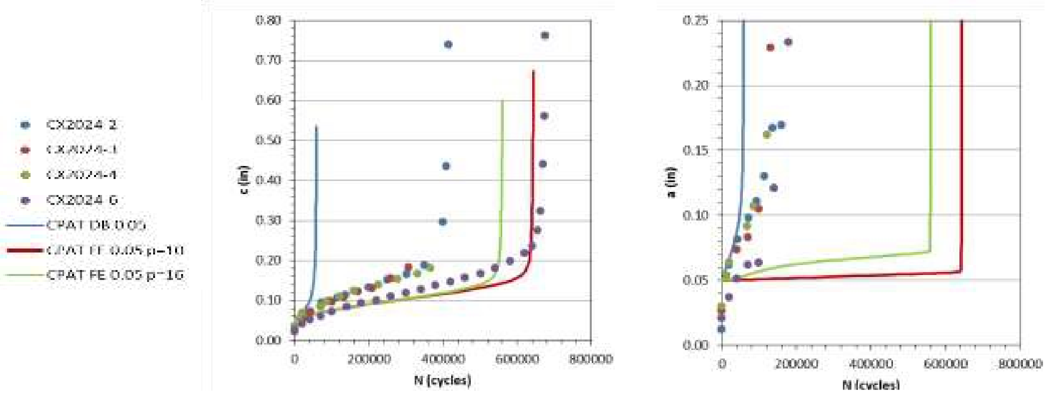
AIRCRAFT STRUCTURES

Life Enhancement Processes:

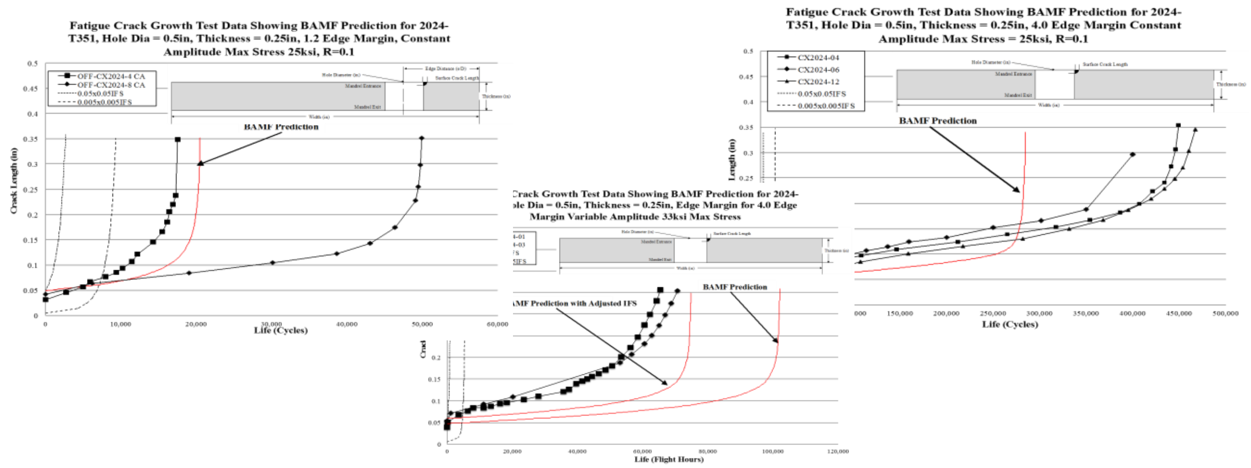
To maximize safety of flight and to minimize the impact of potential manufacturing errors, it should be a goal to achieve compliance with the damage tolerance requirements of this specification without considering the beneficial effects of specific joint design and assembly procedures such as interference 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.

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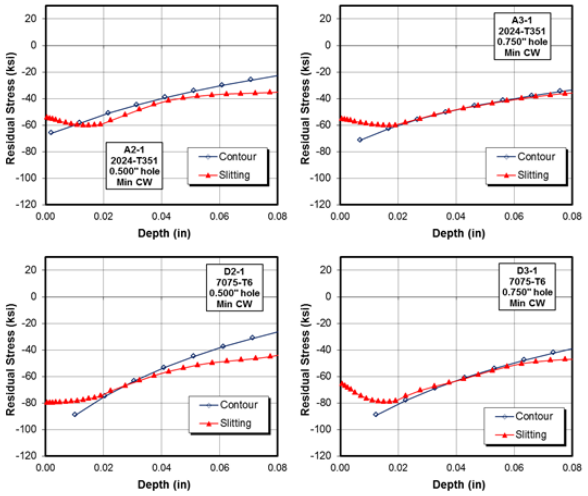
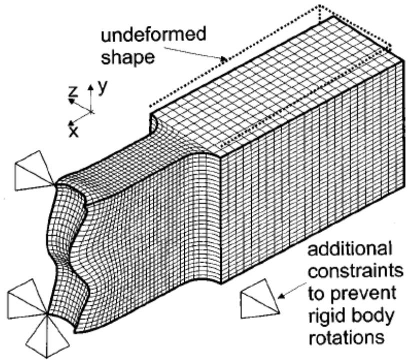
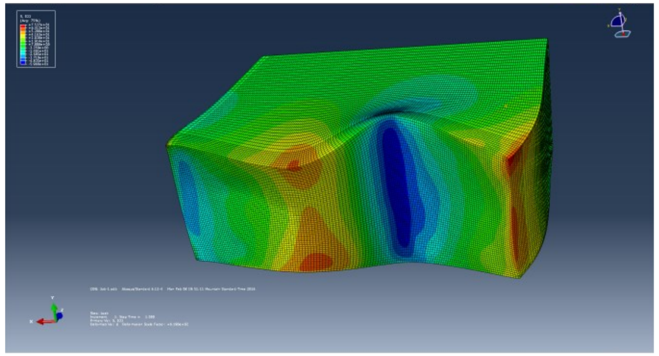
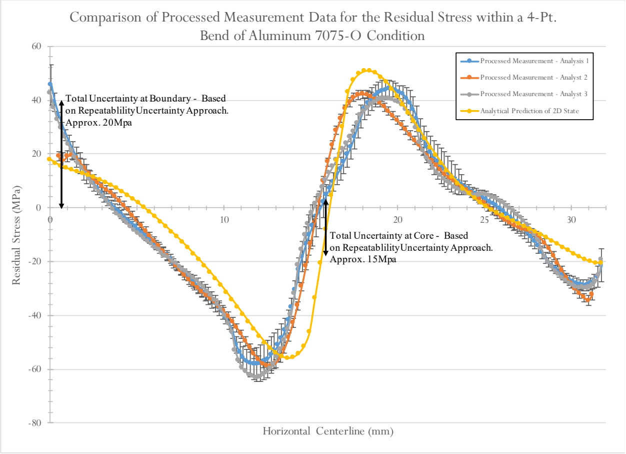
Confidence in Residual Stress Input Data

- **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





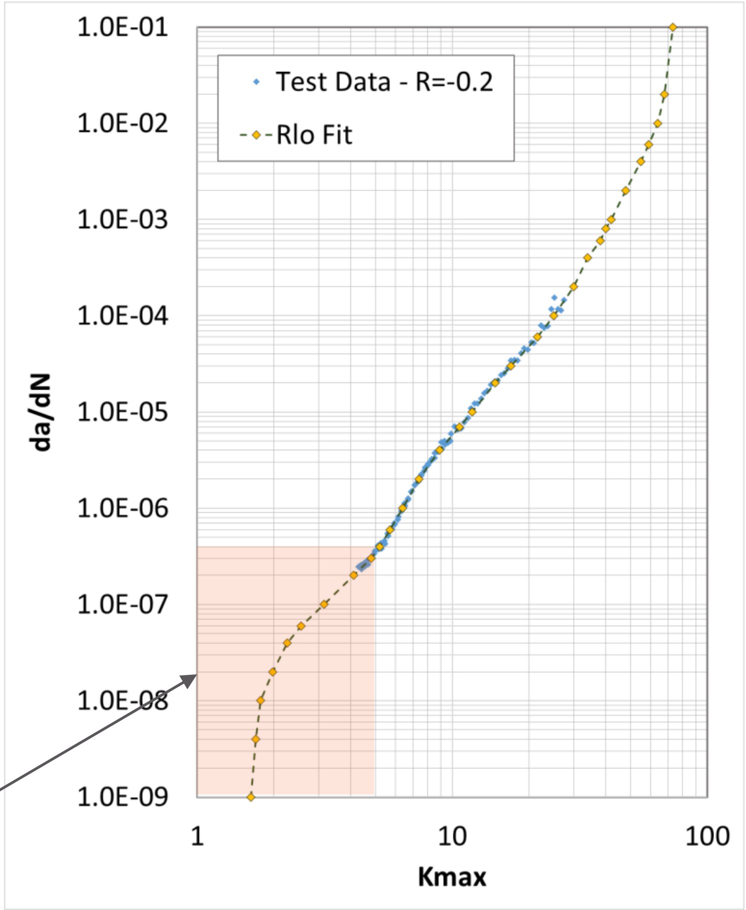




Improve Material Models

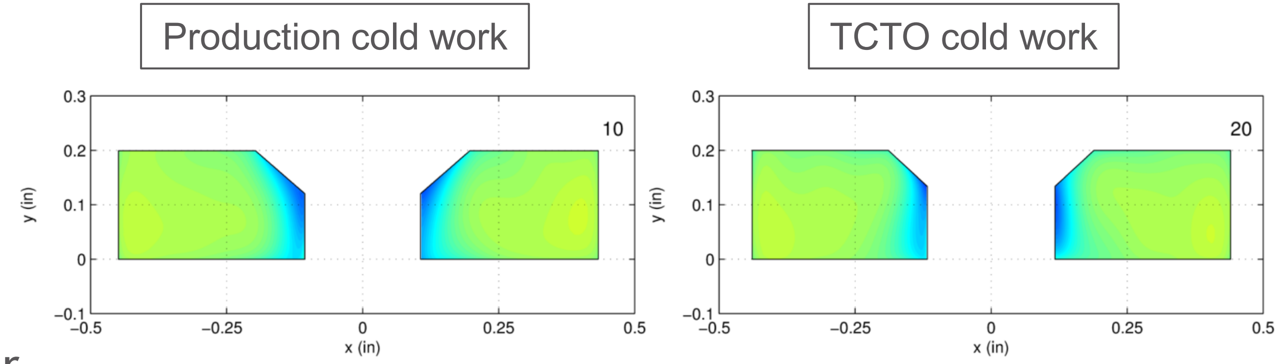
- Incorporating residual stresses drives analyses into atypical regimes
  - "Low" delta K
    - Can be significant for predictions when effective delta K <= 5 ksi-sqrt(in)
  - Highly negative stress ratios
    - Revisit Rlo with residual stresses
- Crack closure affects are Important
- Additional test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

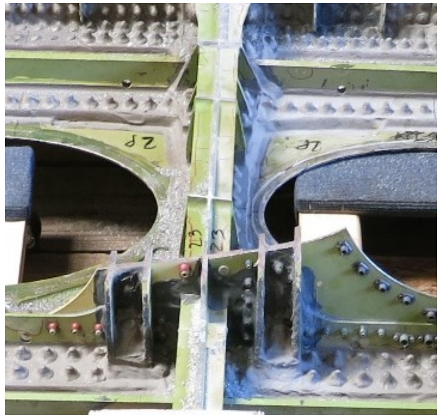
Generally Sparse Data (Low delta K, Negative R)

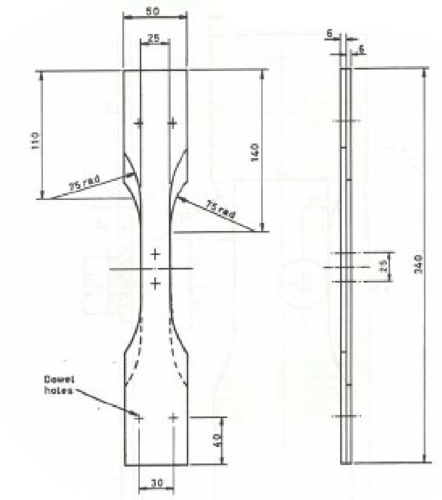


Understand Factors Affecting Residual Stress

- **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?







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?

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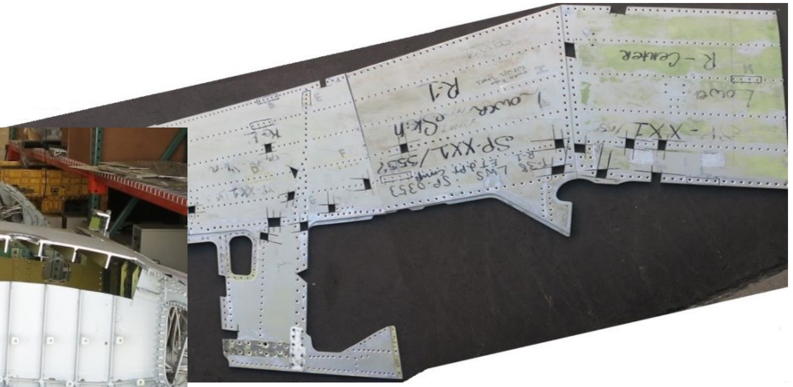

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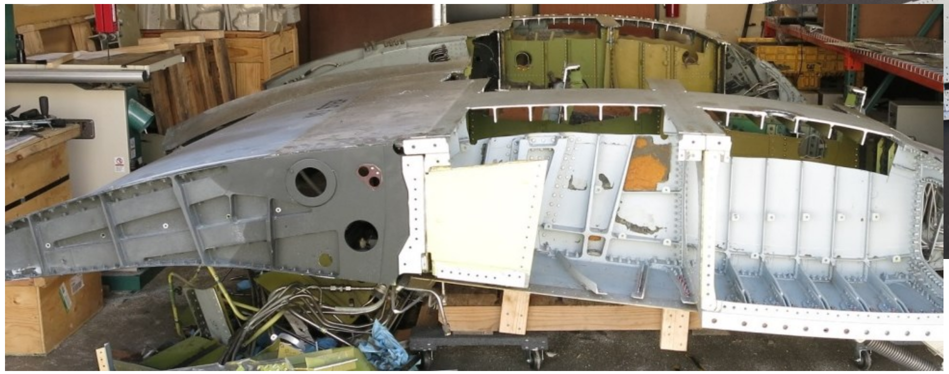
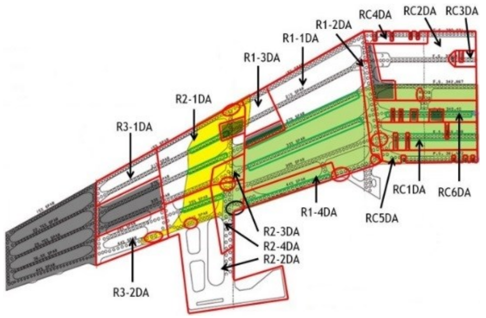
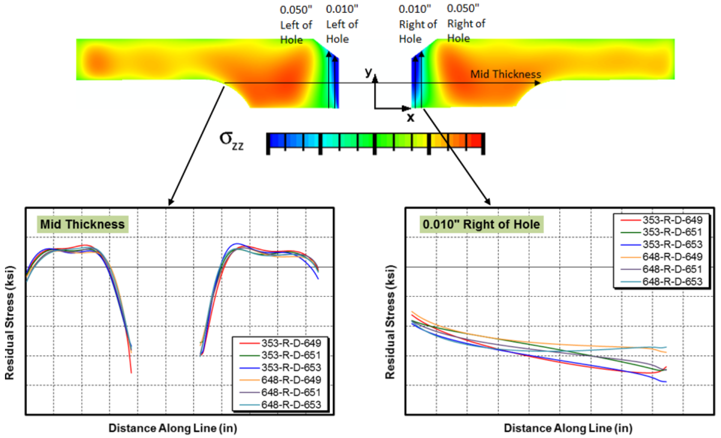
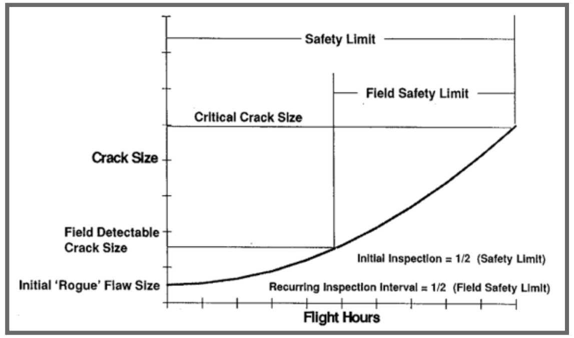


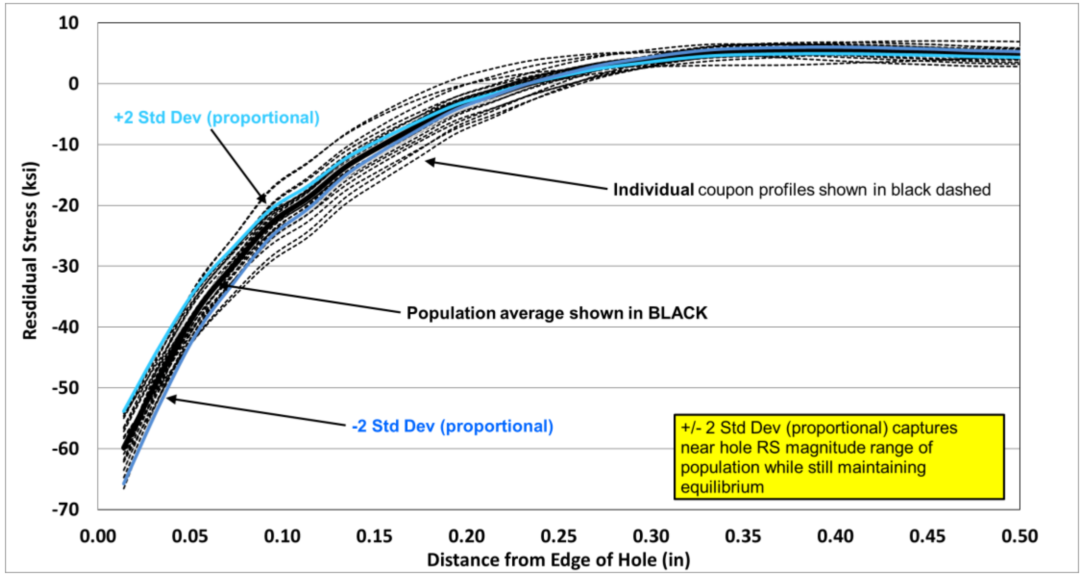




How to Handle Conservatism/Safety Factors

- 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?





Questions?