Analytical Methods & Testing Subcommittees: Overview of Recent Efforts

Engineered Residual Stress Implementation Workshop 2018
September 13, 2017

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Predict. Test. Perform.

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Acknowledgements

- A-10 & T-38 Aircraft Structural Integrity Teams
- Air Force Research Lab
- Analysis Methods & Testing Subcommittee Participants
- ERSI Working Group

Historical

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

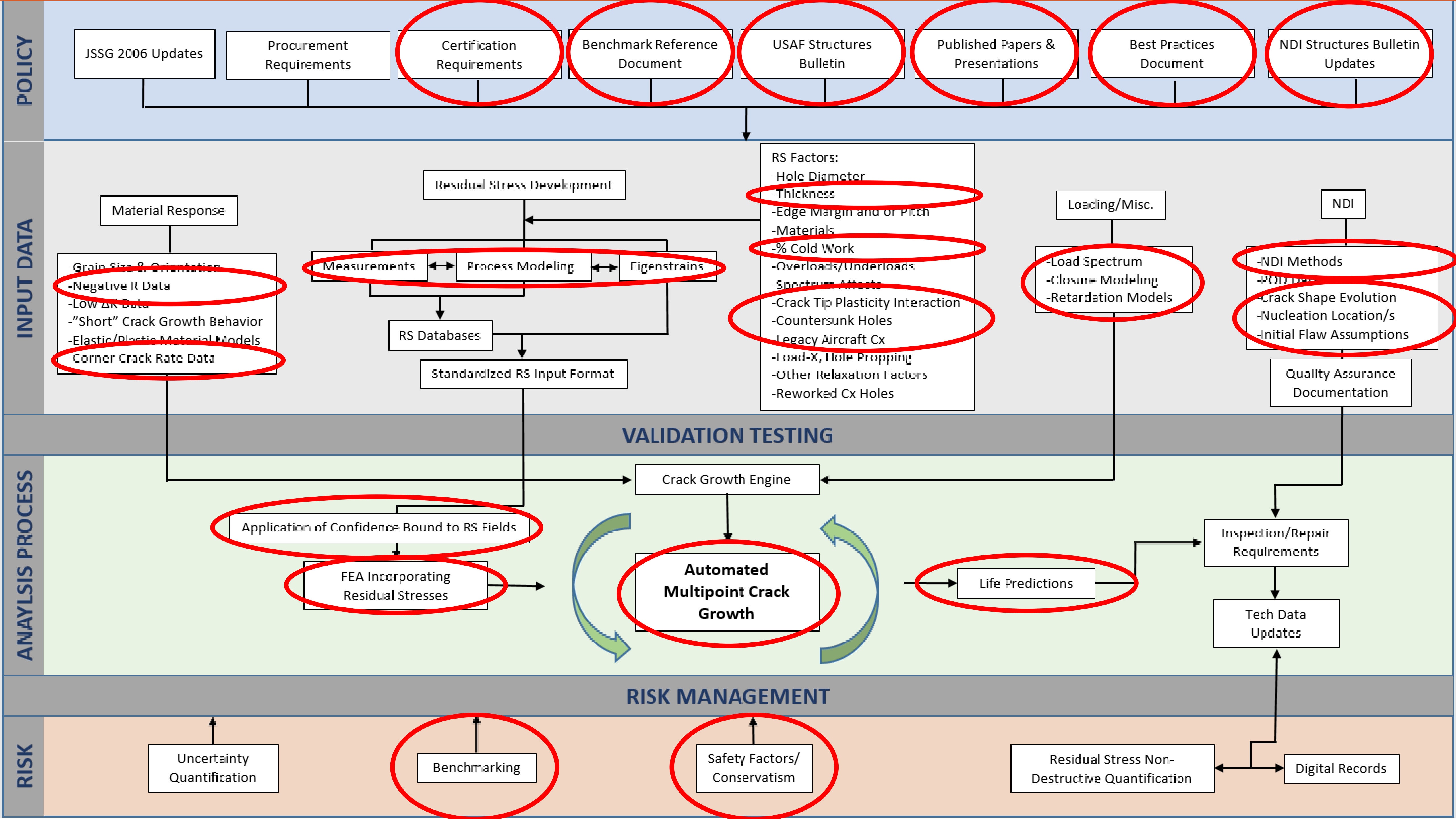
→

Emerging

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

Agenda

- Round Robin for Cx Holes
- Best Practices Document
- Draft Structures Bulletin
- Engineering Implementation of Residual Stress
- Crack Closure Effects
- Negative-R Test Data



POLICY
JSSG 2006 Updates
Procurement Requirements
Certification Requirements
Benchmark Reference Document
USAF Structures Bulletin
Published Papers & Presentations
Best Practices Document
NDI Structures Bulletin Updates
INPUT DATA
Material Response
-Grain Size & Orientation
-Negative R Data
-Low ΔK Data
-"Short" Crack Growth Behavior
-Elastic/Plastic Material Models
-Corner Crack Rate Data
Residual Stress Development
Measurements
Process Modeling
Eigenstrains
RS Databases
Standardized RS Input Format
RS Factors:
-Hole Diameter
-Thickness
-Edge Margin and or Pitch
-Materials
-% Cold Work
-Overloads/Underloads
-Spectrum Affects
-Crack Tip Plasticity Interaction
-Countersunk Holes
-Legacy Aircraft Cx
-Load-X, Hole Propping
-Other Relaxation Factors
-Reworked Cx Holes
Loading/Misc.
-Load Spectrum
-Closure Modeling
-Retardation Models
NDI
-NDI Methods
-POD
-Crack Shape Evolution
-Nucleation Location/s
-Initial Flaw Assumptions
Quality Assurance Documentation
VALIDATION TESTING
ANAYLSIS PROCESS
Crack Growth Engine
Application of Confidence Bound to RS Fields
FEA Incorporating Residual Stresses
Automated Multipoint Crack Growth
Life Predictions
Inspection/Repair Requirements
Tech Data Updates
RISK MANAGEMENT
RISK
Uncertainty Quantification
Benchmarking
Safety Factors/ Conservatism
Residual Stress Non-Destructive Quantification
Digital Records

Round Robin for Cx Holes

- **Purpose (Initial)**
  - Identify the random and systematic uncertainties associated with DTAs that incorporate residual stresses produced by Cx of fastener holes
  - Many factors influencing the total uncertainty have been discussed and are currently under investigation by various members of the ERSI team
  - For the first round-robin exercise, the focus will be on systematic uncertainties, or the uncertainty associated with the system or process used by the analyst (also known as epistemic uncertainties or model-form uncertainties)
  - Specific input data was provided to each analyst participating in the exercise to minimize the random uncertainties associated with these types of analyses.
  - The analyst was free to use any means to incorporate the residual stress into the DTA, any software suite, etc., however, it was important that the analyst adhered closely to the guidance provided so that the variability in the predictions will be limited to the aspects left to analyst's discretion.
- **Main Focus – understand analyst-to-analyst prediction variability given fixed input data**

Round Robin for Cx Holes

- **Purpose (Actual)**
  - Identify the random and systematic uncertainties associated with DTAs that incorporate residual stresses produced by Cx of fastener holes
  - Many factors influencing the total uncertainty have been discussed and are currently under investigation by various members of the ERSI team
  - For the first round-robin exercise, the focus will be on systematic uncertainties, or the uncertainty associated with the system or process used by the analyst (also known as epistemic uncertainties or model-form uncertainties)
  - Specific input data was provided to each analyst participating in the exercise to minimize the random uncertainties associated with these types of analyses.
  - The analyst was free to use any means to incorporate the residual stress into the DTA, any software suite, etc., however, it was important that the analyst adhered closely to the guidance provided so that the variability in the predictions will be limited to the aspects left to analyst's discretion.
- **Main Focus – Investigate the consistency, strengths and weaknesses of each method to define best practices moving forward**

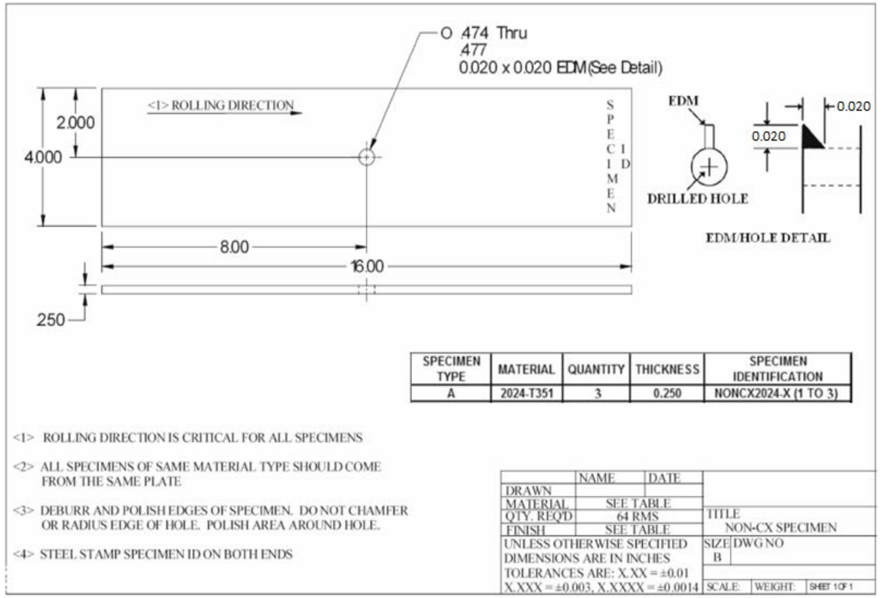
Round Robin for Cx Holes

❑ Conditions

Benchmark Condition #	Material	Specimen Type	Thickness (in)	Width (in)	Hole Diameter (in)	Hole Edge Margin	Loading	Max Stress (ksi)
1	2024-T351	Non-CX Baseline	0.25	4.00	0.50	4.0	CA (R=0.1)	10
2		CX						25
3		Non-CX Baseline				1.2		10
4		CX						25

❑ Input Data

- Geometry
- Initial flaw size, shape, location, and orientation
- Material properties
- Loading spectrum
- Constraints
- Residual stress (contour results)



Round Robin for Cx Holes

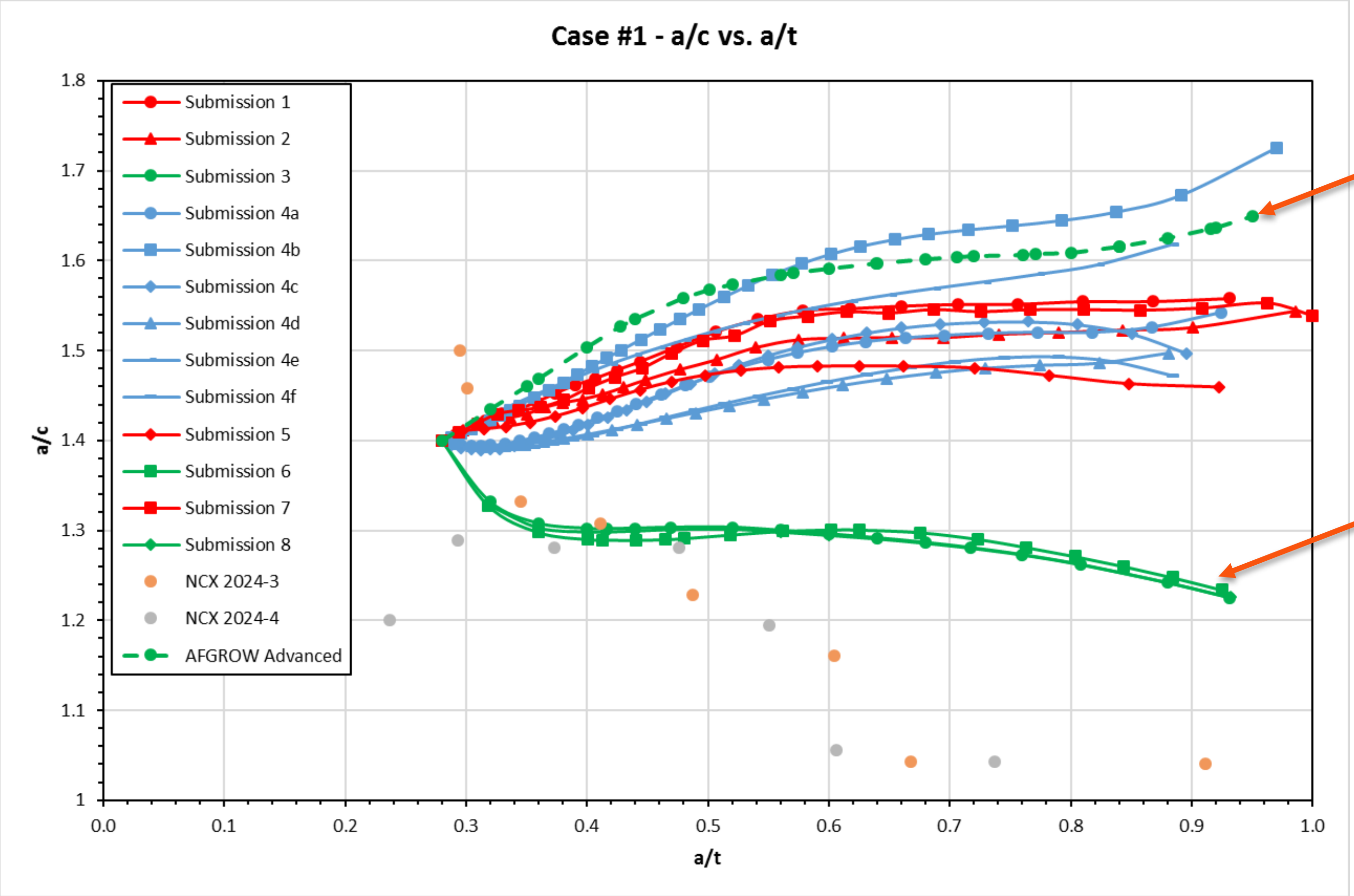
A Year of Answering the Why's???

Round Robin for Cx Holes – Action Items

Action Item	Title	Description	Focal/s	Current Status
1	Additional Fractography	Complete additional fractography of Cx test coupons to refine markerband definition and identify any secondary cracking	Mills	Complete
2	Baseline Stress Intensity Plots	Develop stress intensity plots for non-Cx conditions (case #1 and #3) for comparisons		
3	AFGROW vs. Other Crack Aspect Ratio	Investigate AFGROW aspect ratio differences for case #1	Harter/Pilarczyk	Complete
4	Crack Transition Points	Incorporate crack size and cycle through thickness transition points	Warner	Complete
5	"Low" Crack Growth Rate Data	Investigate crack growth rate data between 1E-7 - 1E-6. Better correlations to test were observed for Case #4, which had rates > 1E-6. Case #2 correlation wasn't as good, and much of the life was in the range of rates 1E-7 to 1E-6.	Harter/Pilarczyk	Complete
6	Bore vs. Surface Crack Growth Rates	Reverse calculate bore and surface crack growth rate data for baseline coupons. Is there an observed difference between the different material orientations and does it correlate with observed differences in the recent AFGROW round robin results.	Harter/Pilarczyk	Complete
7	Crack Growth Rate "Dip"	Investigate the common "dip" in the crack growth rate and identify possible contributing factors.	APES / ESRD	Active contract until Aug
8	Baseline Rate Data	Investigate baseline rate data and its contribution to baseline predictions. Update accordingly and investigate impact on predictions for residual stress cases.	Harter/Pilarczyk	Complete
9	Crack Aspect Ratio	Investigate contributing factors to crack aspect ratio discrepancies, collaborating with AFGROW round robin.	Harter/Pilarczyk	Complete
10a	Applied Negative R Baseline Testing	Complete fatigue testing with ASTM E(647) M(T) coupons as well as Case #1 geometry/material, but with an applied R roughly consistent with the R total for the residual stress cases (R=-1?)	Warner/Greer	INW
10b			APES	Active contract until Sep
11	Residual Stress Variability	Provide replicate measurement data, not just average, and statistically characterize and quantify impact on predictions	Carlson	INW
12	Part-thru and thru crack segregation	Segregate the test data and predictions for part-thru and thru cracks to see what additional insight we can gain	Warner	Complete
13	Verification of SIF calculations	Sanity check of SIF calculations		

Round Robin for Cx Holes – AFGROW Aspect Ratios

- Classic Newman-Raju solutions vs. Advanced Fawaz-Andersson



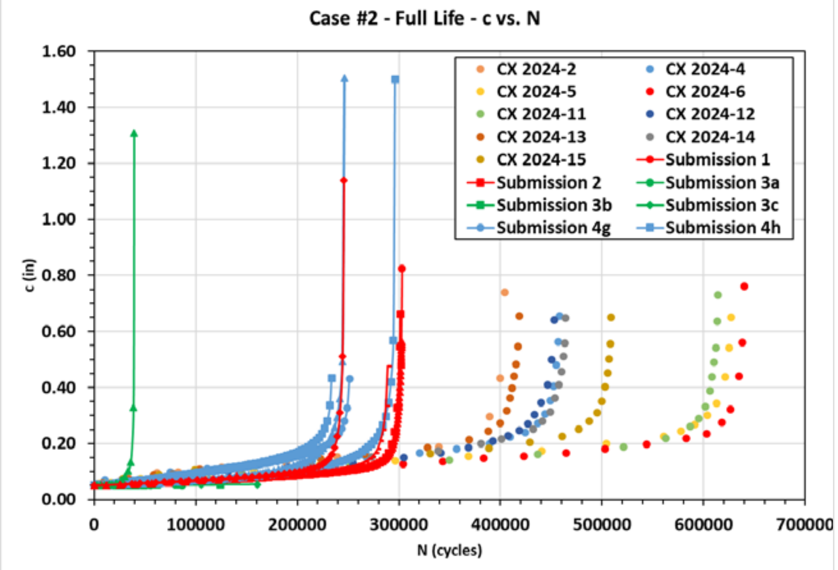
Fawaz-Andersson

Newman-Raju

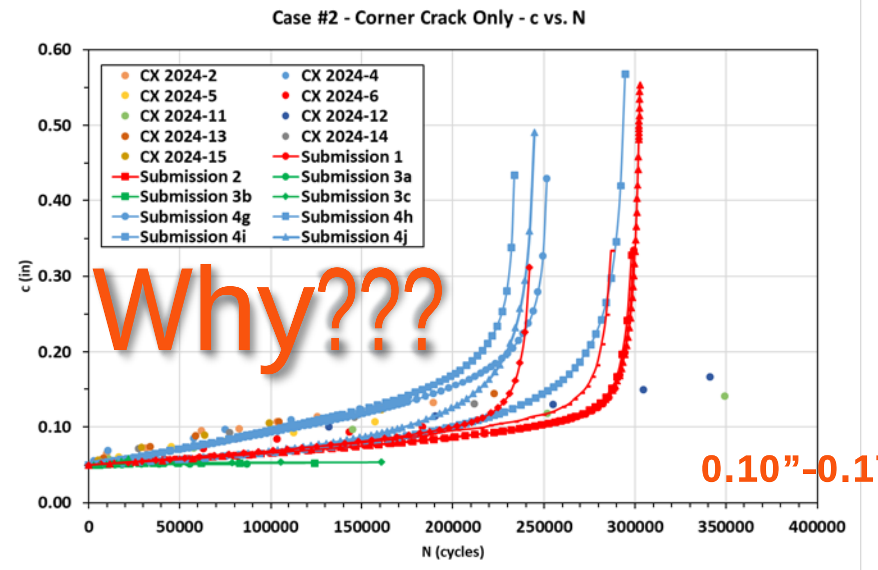
Why???

Round Robin for Cx Holes – Corner & Thru Crack Segregation

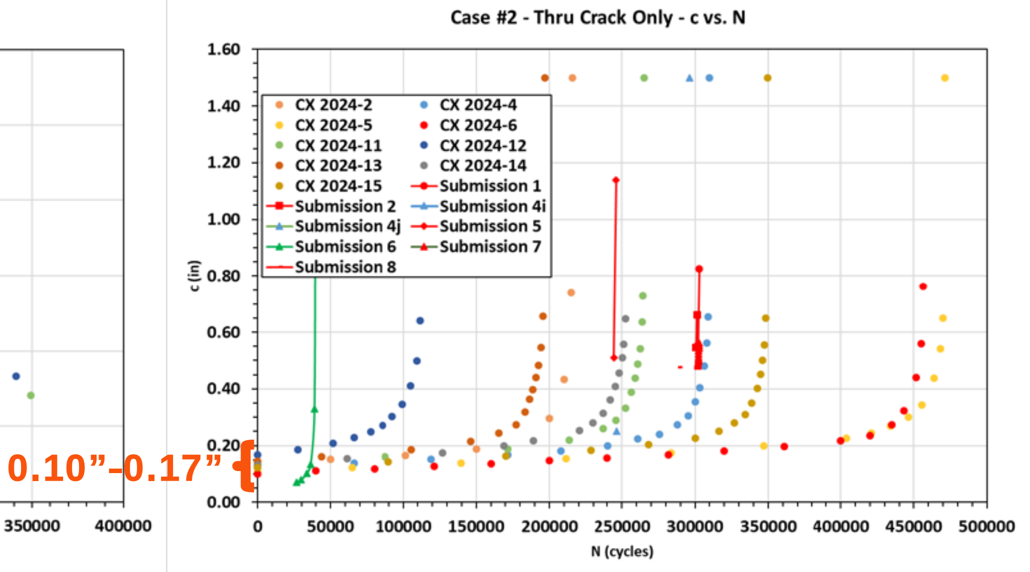
Full Life



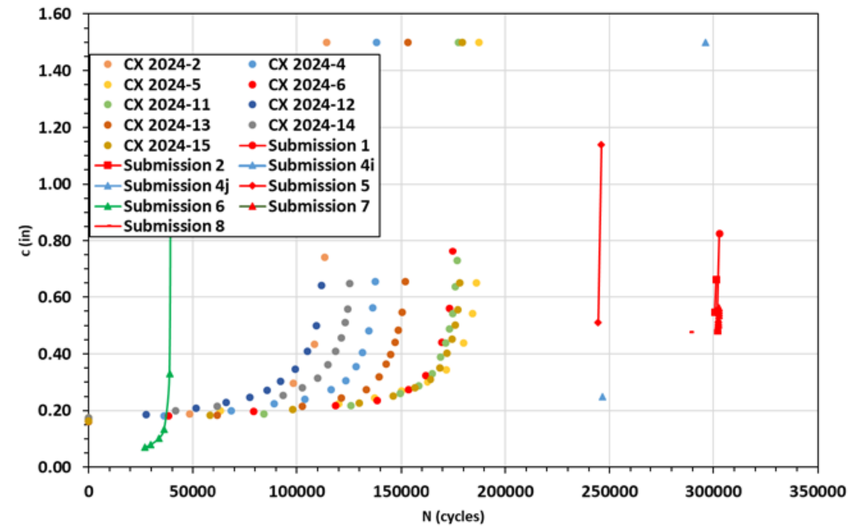
Corner Crack only



Thru Crack only

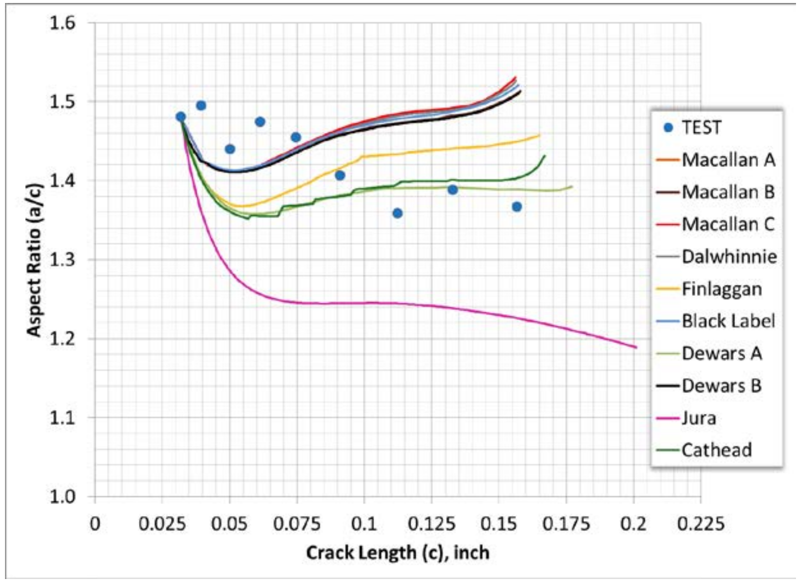


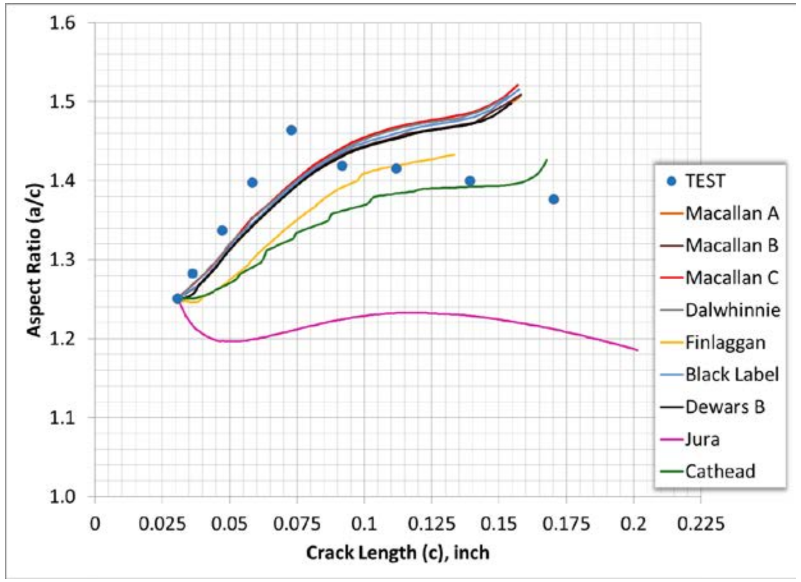
- Most analyses predict failure prior to test even becoming thru thickness crack
- Tests were thru thickness over a range of “c” lengths (0.1”-0.17”)
- If thru thickness test crack lengths are plotted from c=0.17” to failure, as shown in bottom right, the test time to failure is fairly consistent, although that is only about ¼ of the tests life

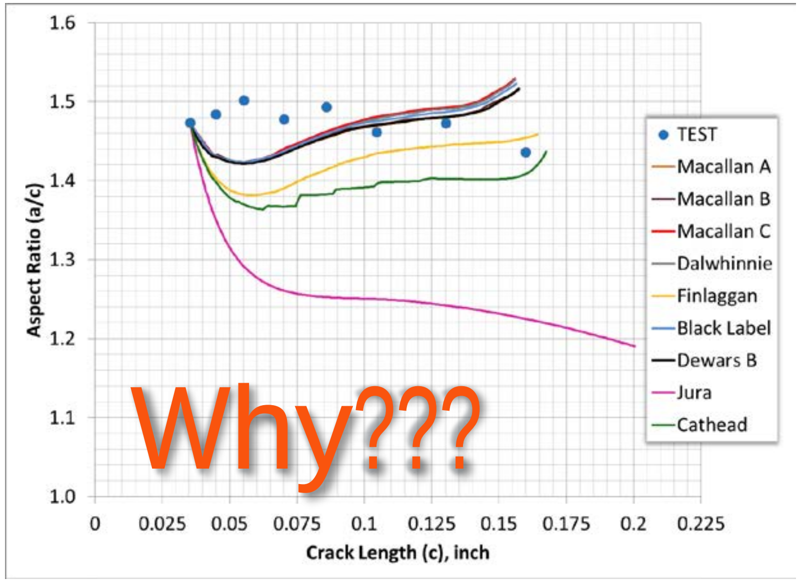


Round Robin for Cx Holes – Multi-Direction Material Properties

- **AFGROW Round Robin (2017)**
  - Determine the ability of users, given the same loading spectrum, material data, and a given Initial Flaw Size (IFS), to predict the evolution of the crack front shape and total life of a given geometry using the AFGROW framework as the life prediction tool



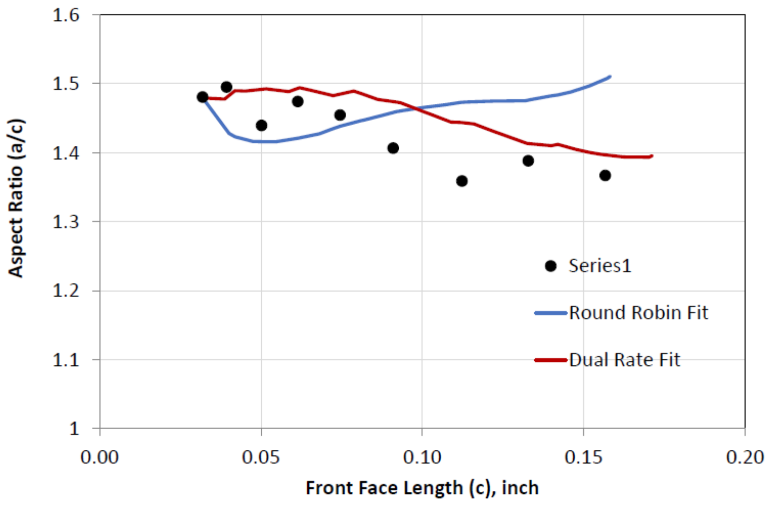


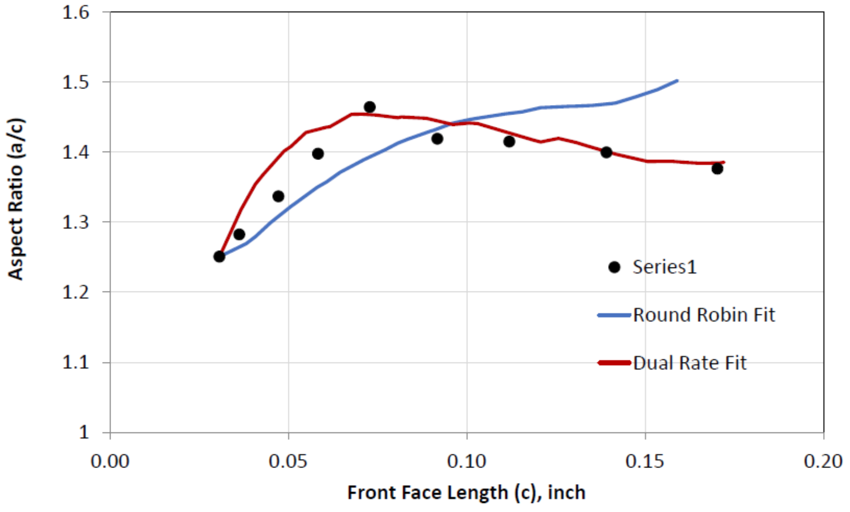


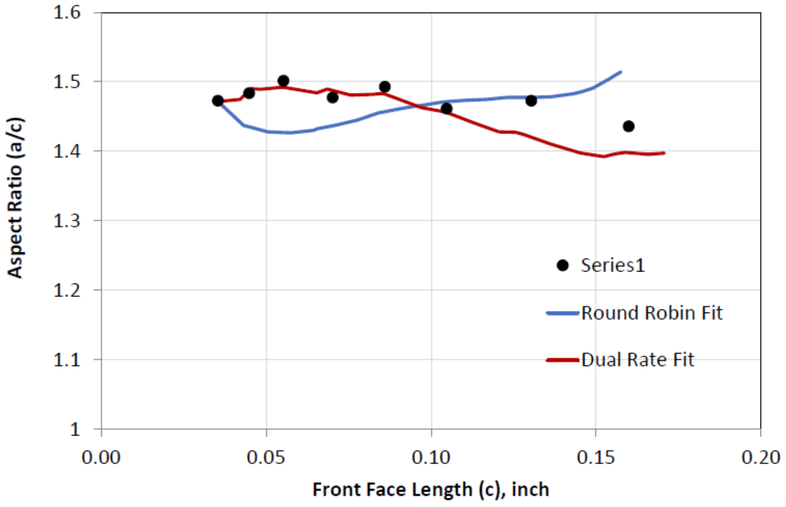
Ref: Harter, J., Case Study on Test/Prediction Correlation for Corner Cracks at Holes, Proceedings from the 2018 AA&S Conference, Jacksonville, FL.

Round Robin for Cx Holes – Multi-Direction Material Properties

- **AFGROW Round Robin (2017)**
  - Multi-directional rate data resulted in:
    - Minimal changes to life predictions
    - Better correlation to crack aspect ratio trends







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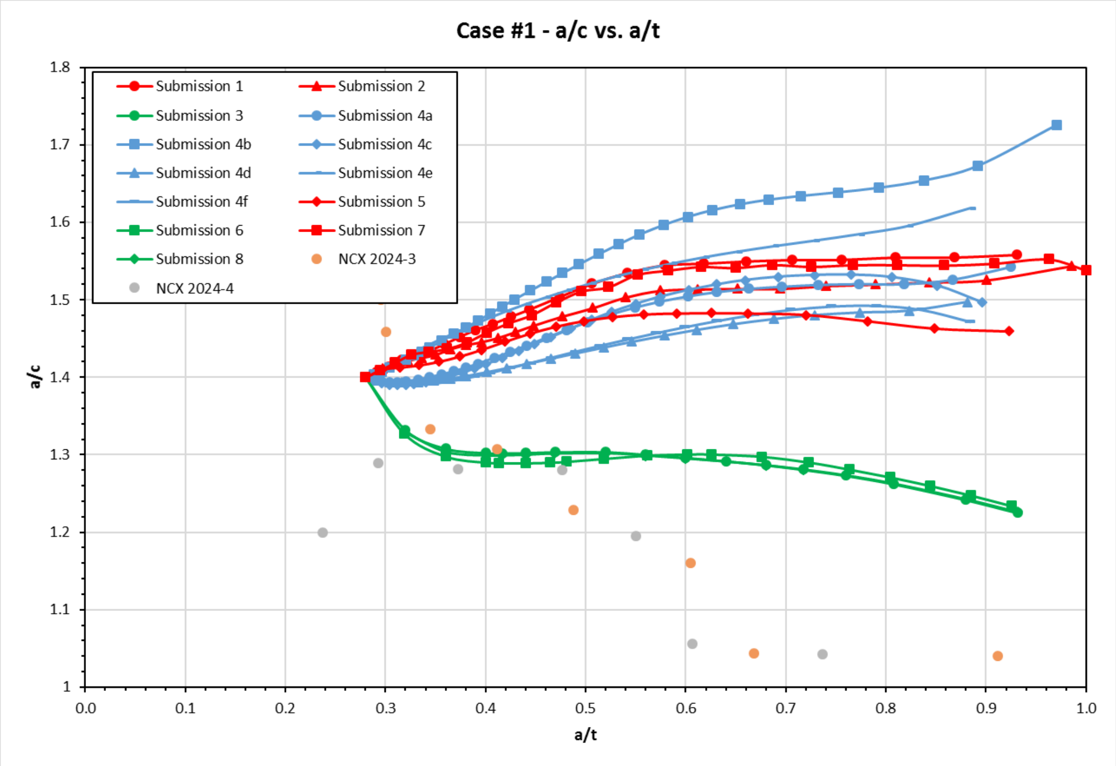
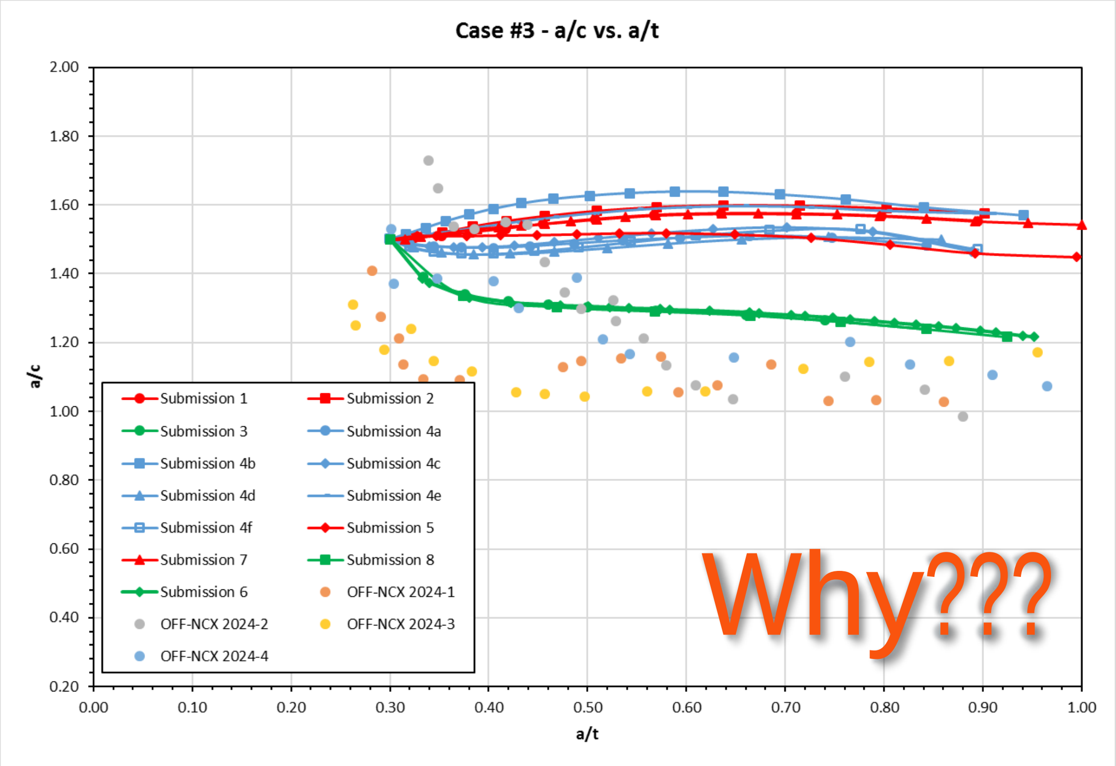
Round Robin for Cx Holes – Multi-Direction Material Properties

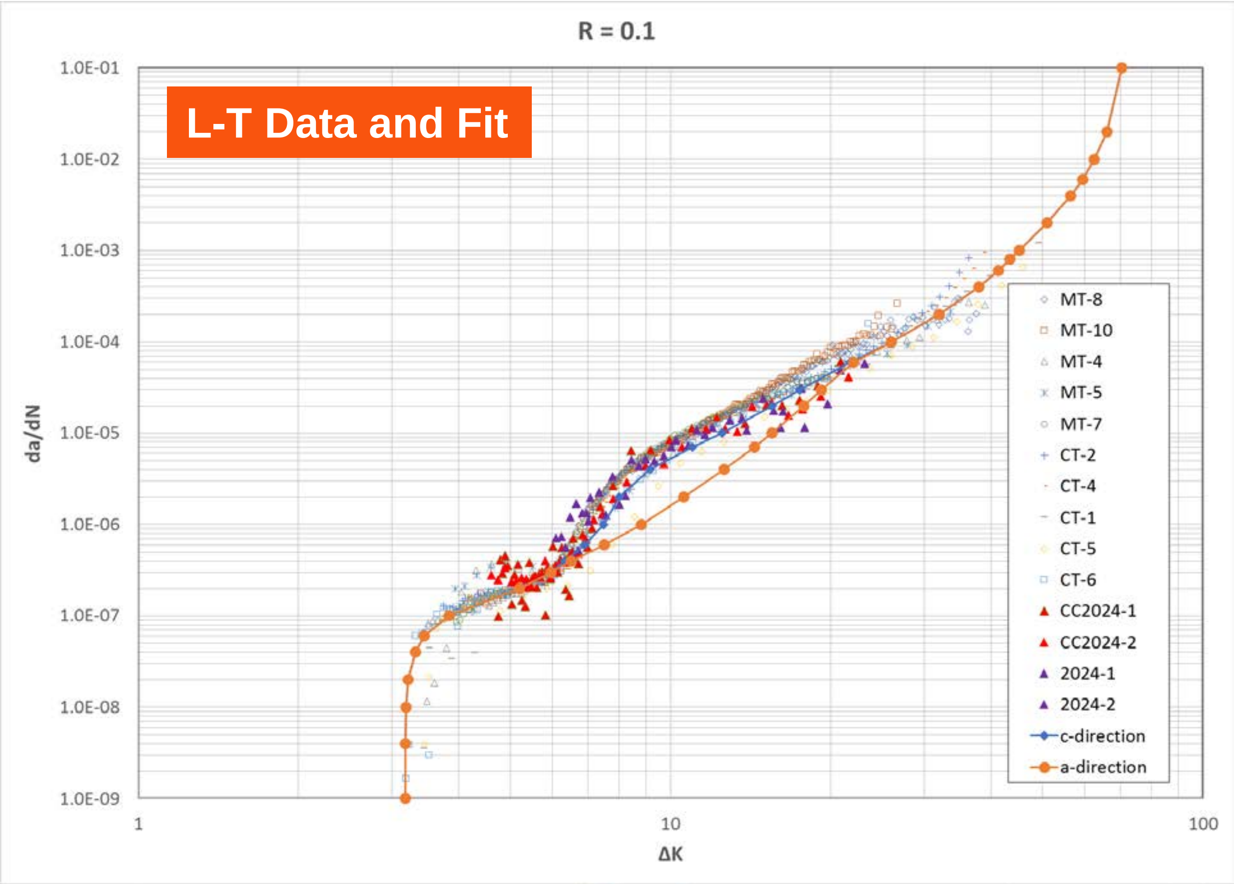
- Similar mismatch for ERSI Round Robin

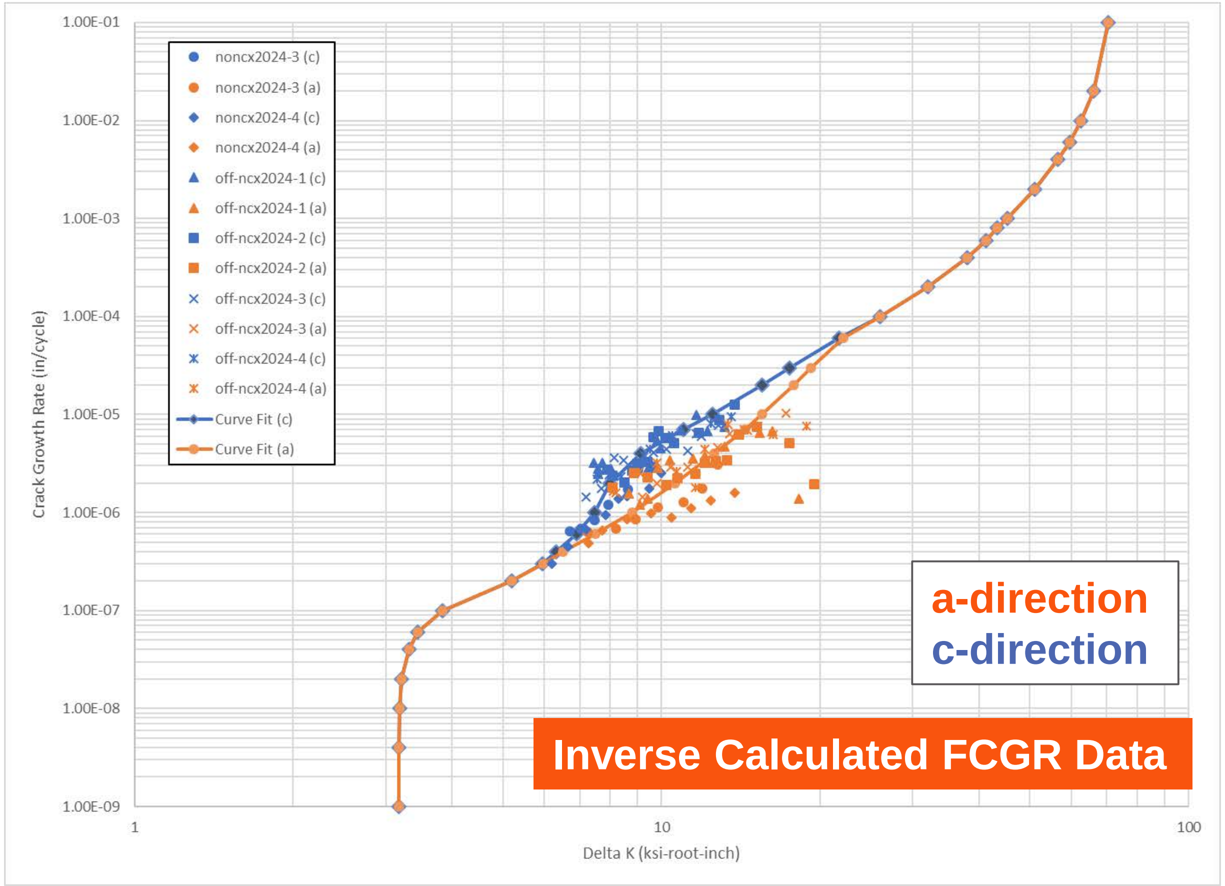




Round Robin for Cx Holes – Multi-Direction Material Properties

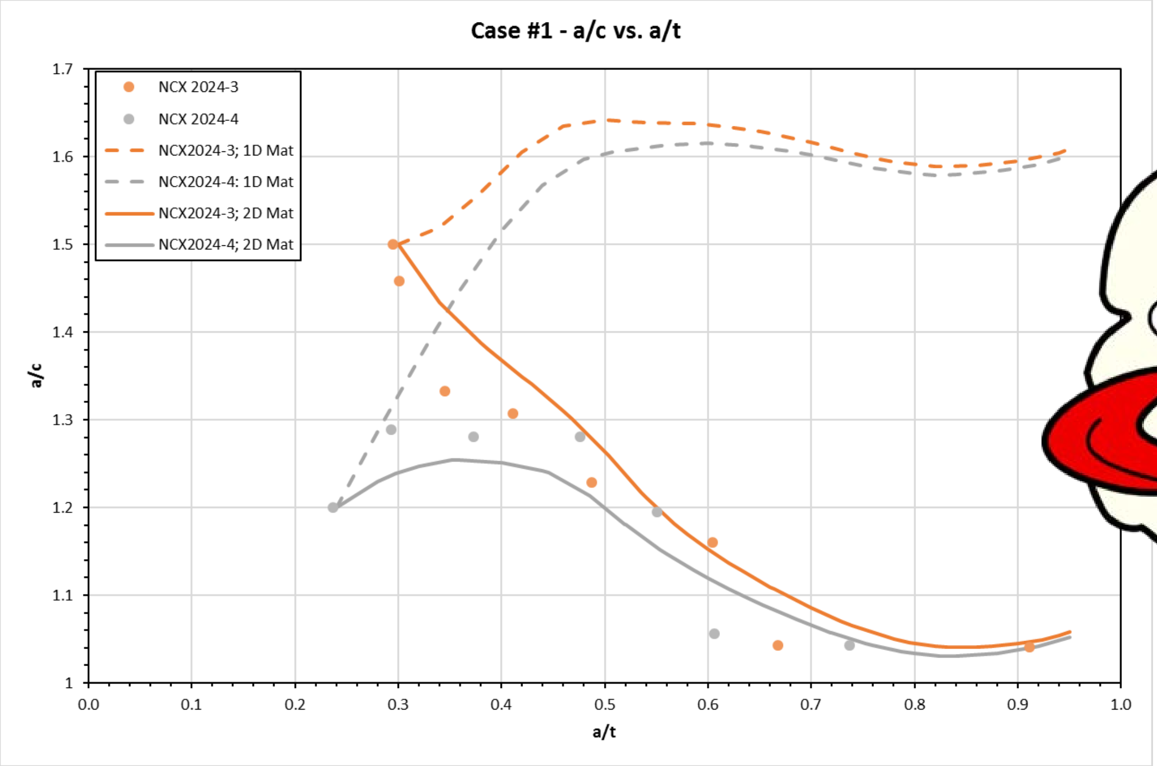
- Retrodiction of crack growth rate data in (a) and (c) direction

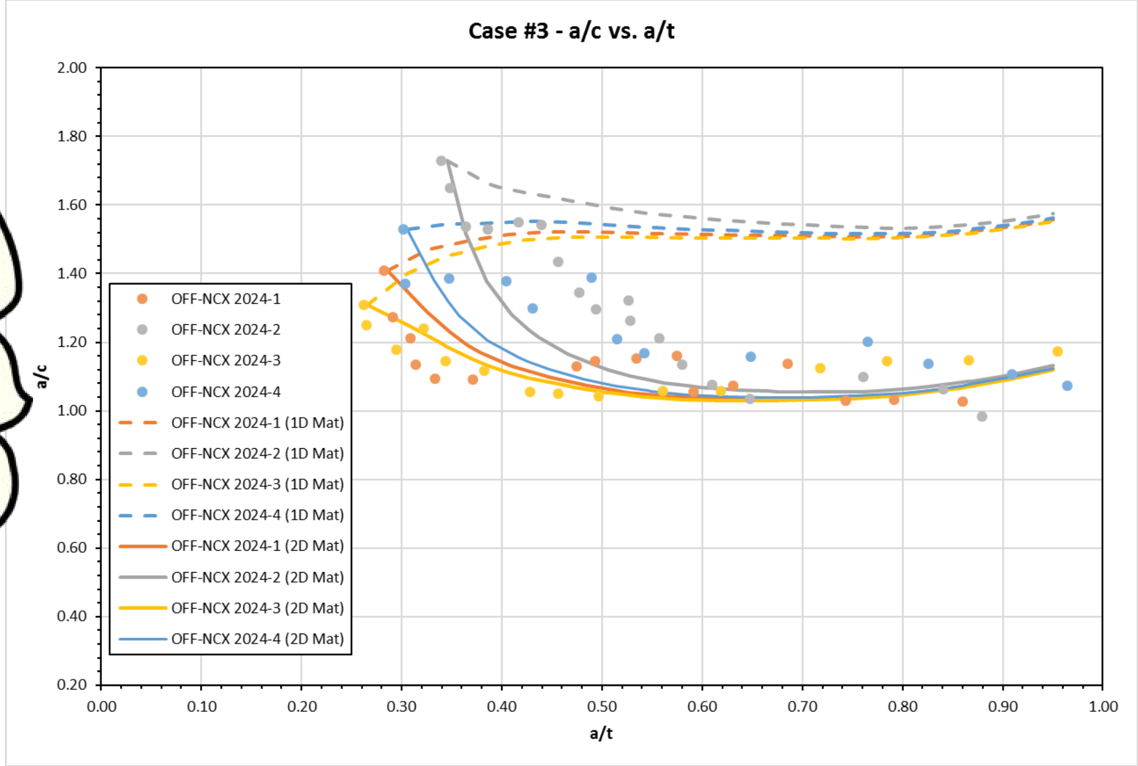




Round Robin for Cx Holes – Multi-Direction Material Properties

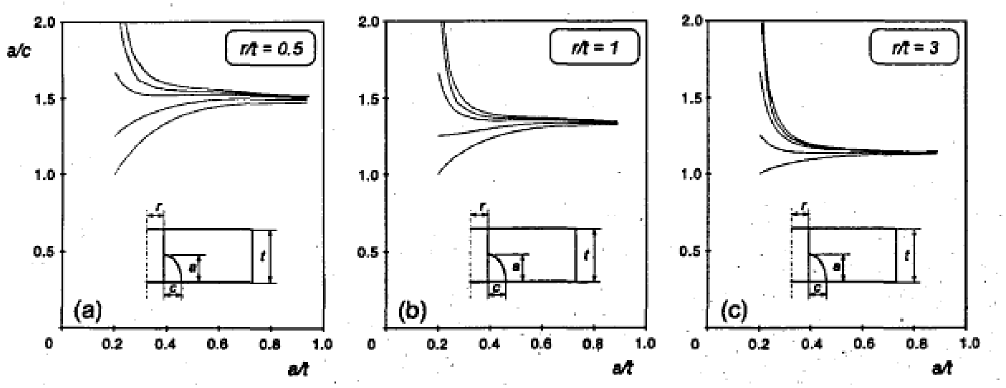
- Post-dictions with multi-directional material properties

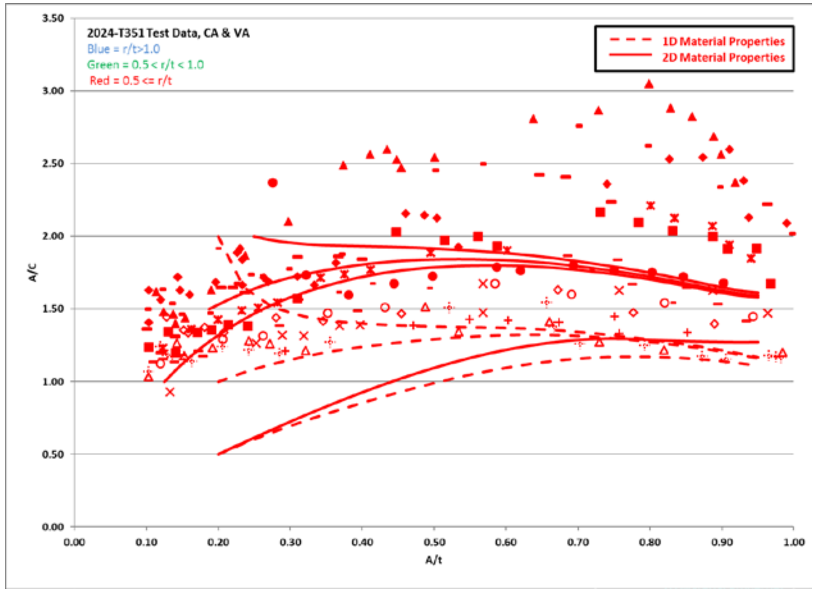


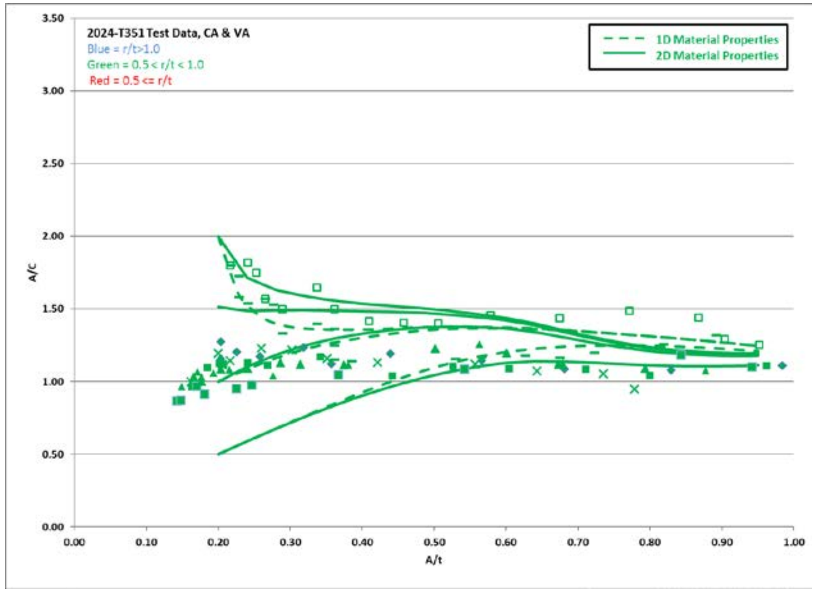


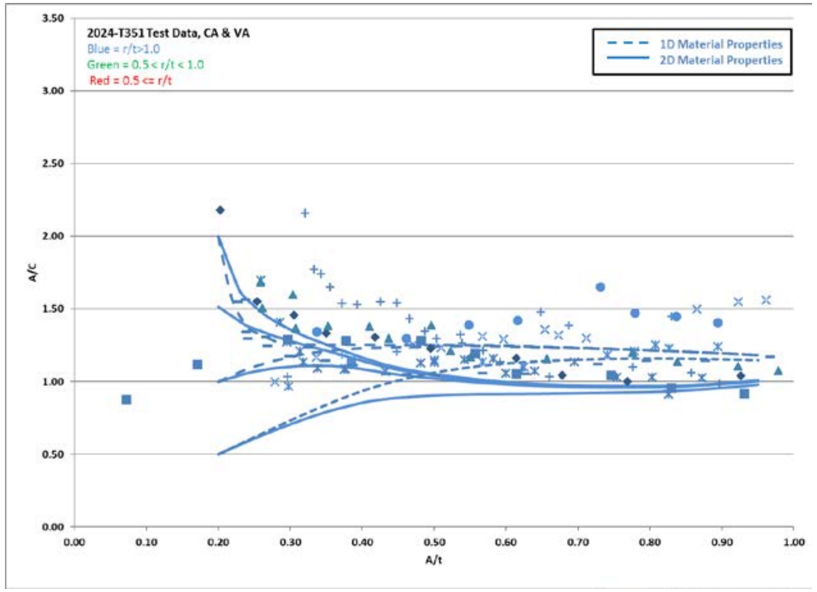
Round Robin for Cx Holes – Multi-Direction Material Properties

- **1D Material**
  - Minimal differentiation with r/t
- **2D Material Properties**
  - Distinct trend consistent with open literature and test data





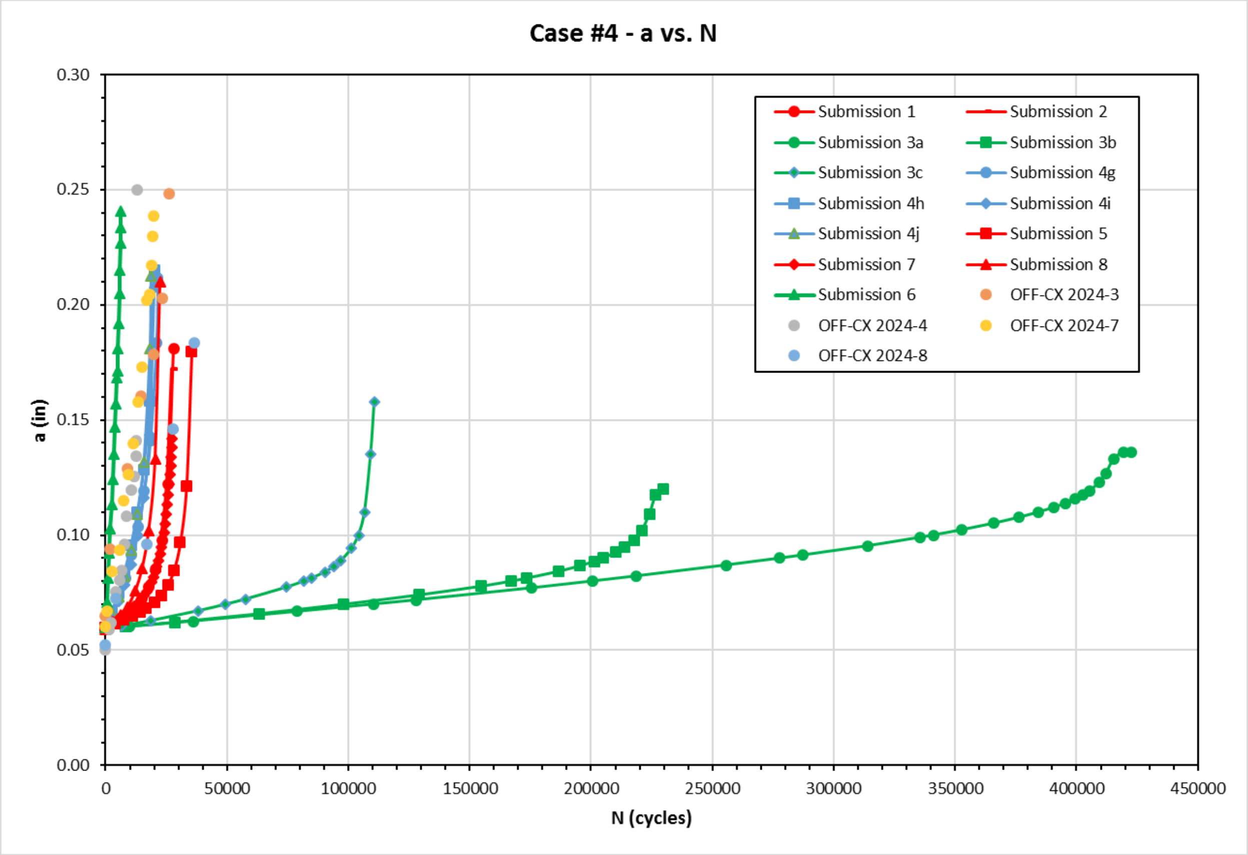


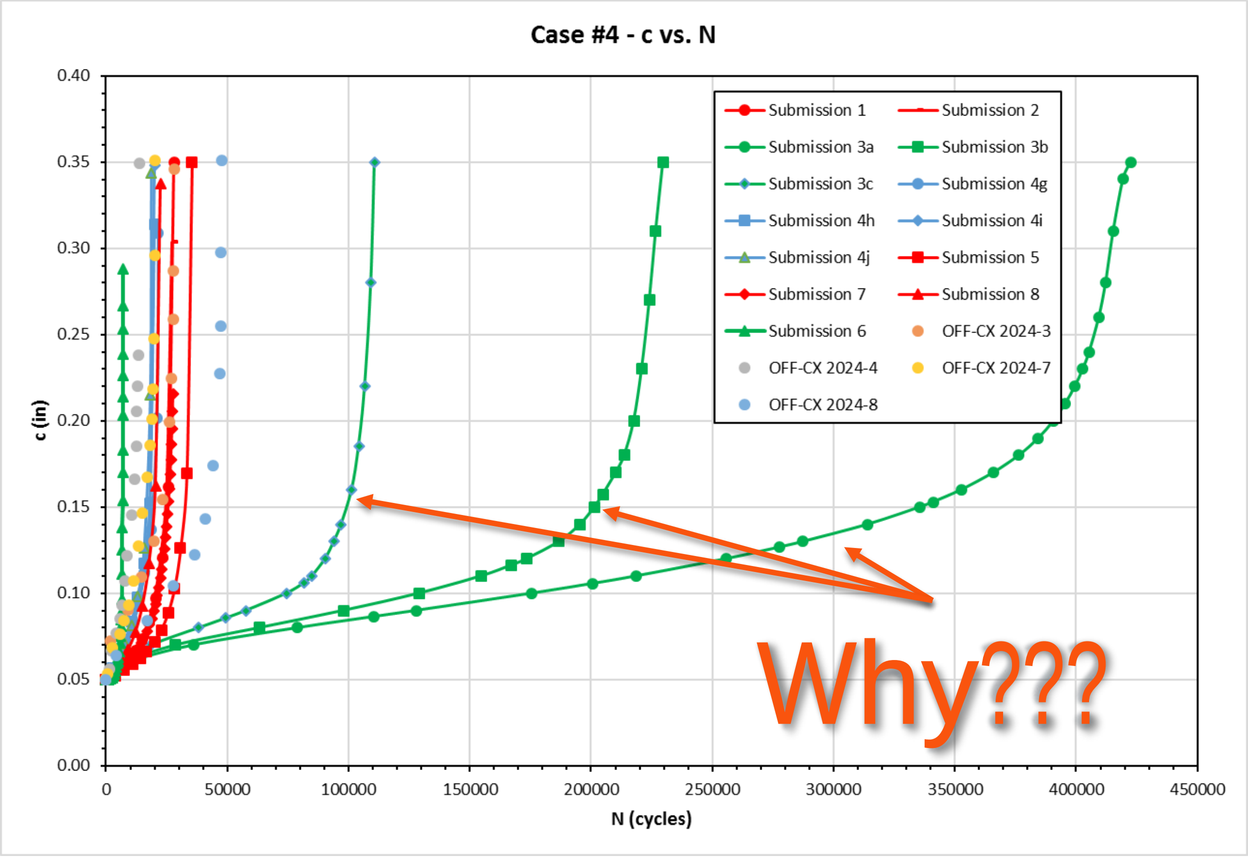


Round Robin for Cx Holes – Applied and Residual Stress Intensities

❑ Significant Overpredictions from AFGROW

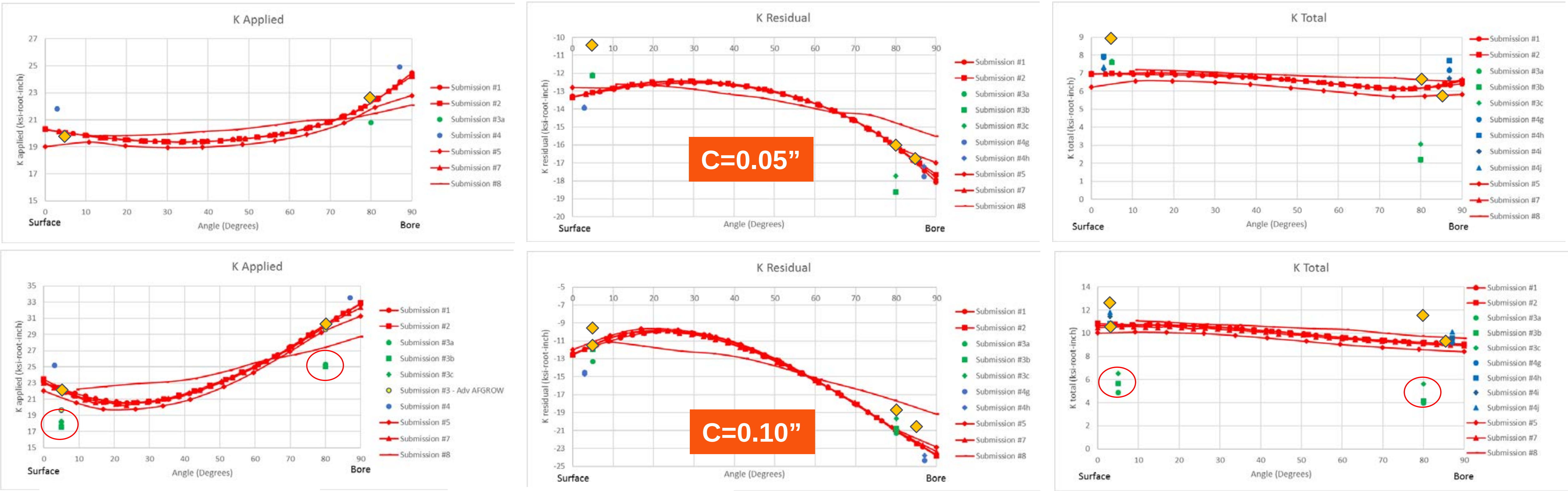
- ➢ Newman-Raju solutions w/ Gaussian Integration for residual stress





Round Robin for Cx Holes – Applied and Residual Stress Intensities

- Significant contribution from Newman-Raju solutions
- Incorporated ability to input RS with Fawaz-Andersson solutions



◆ Original Predictions ◆ Updated Predictions

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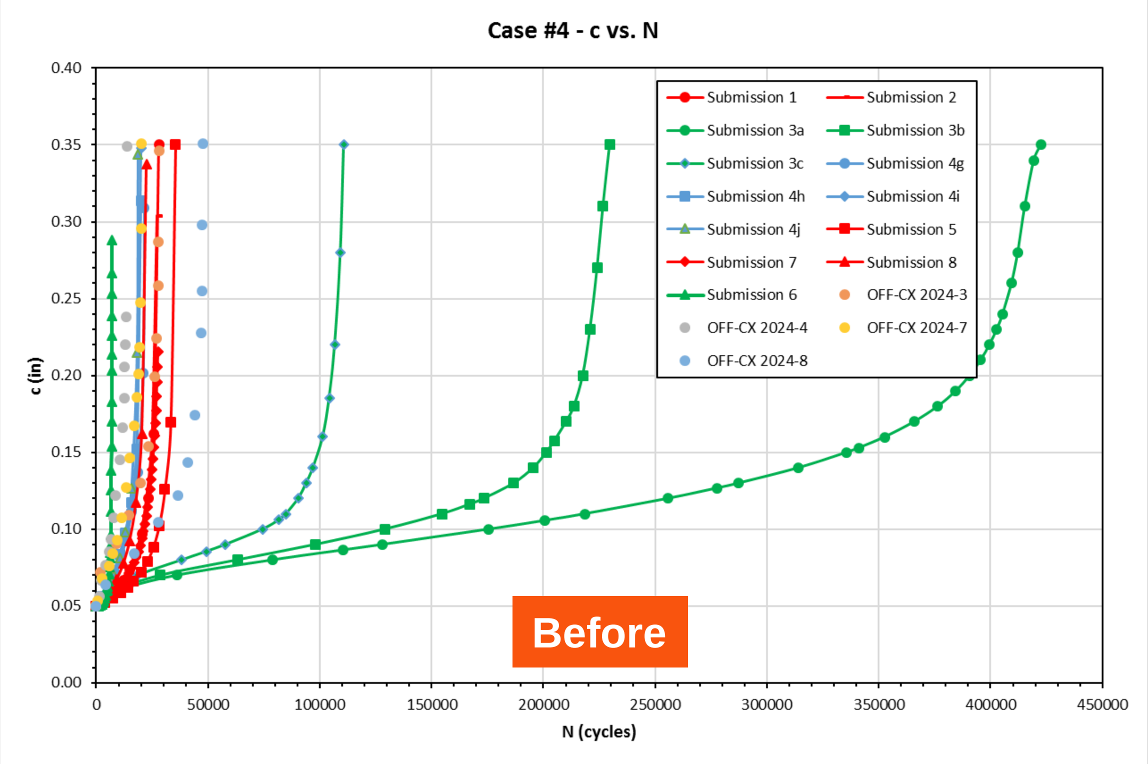
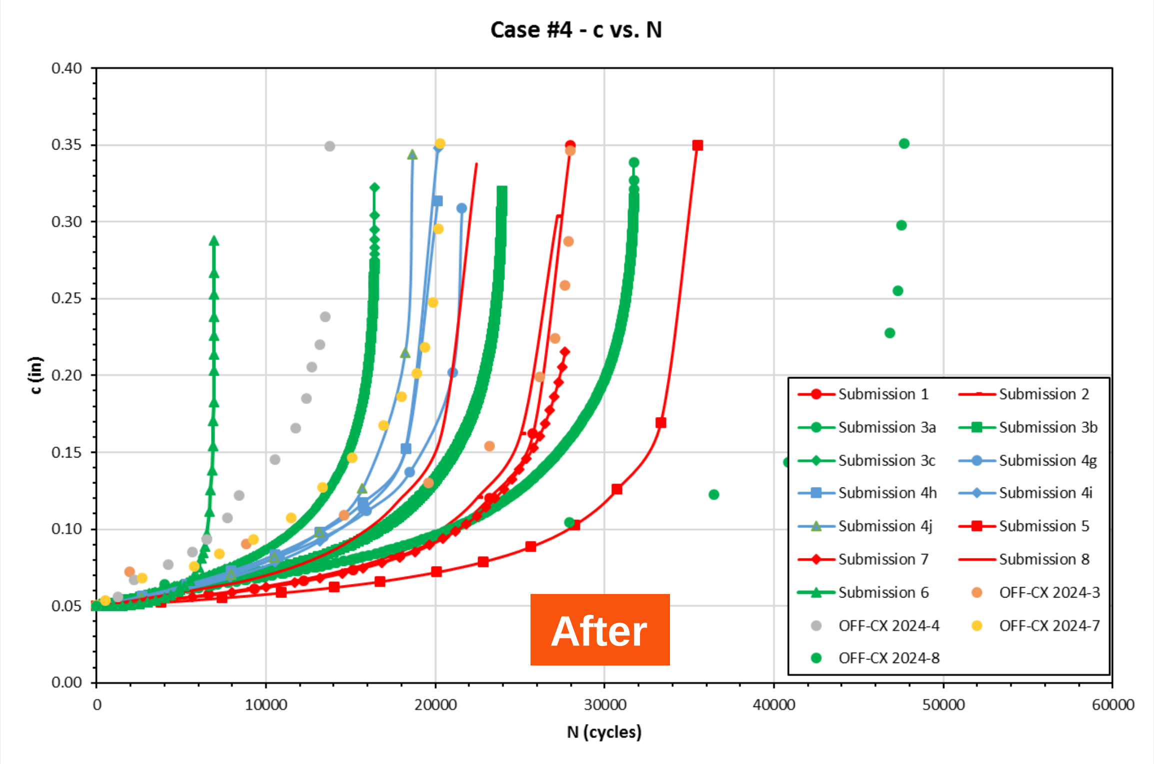
Round Robin for Cx Holes – Applied and Residual Stress Intensities

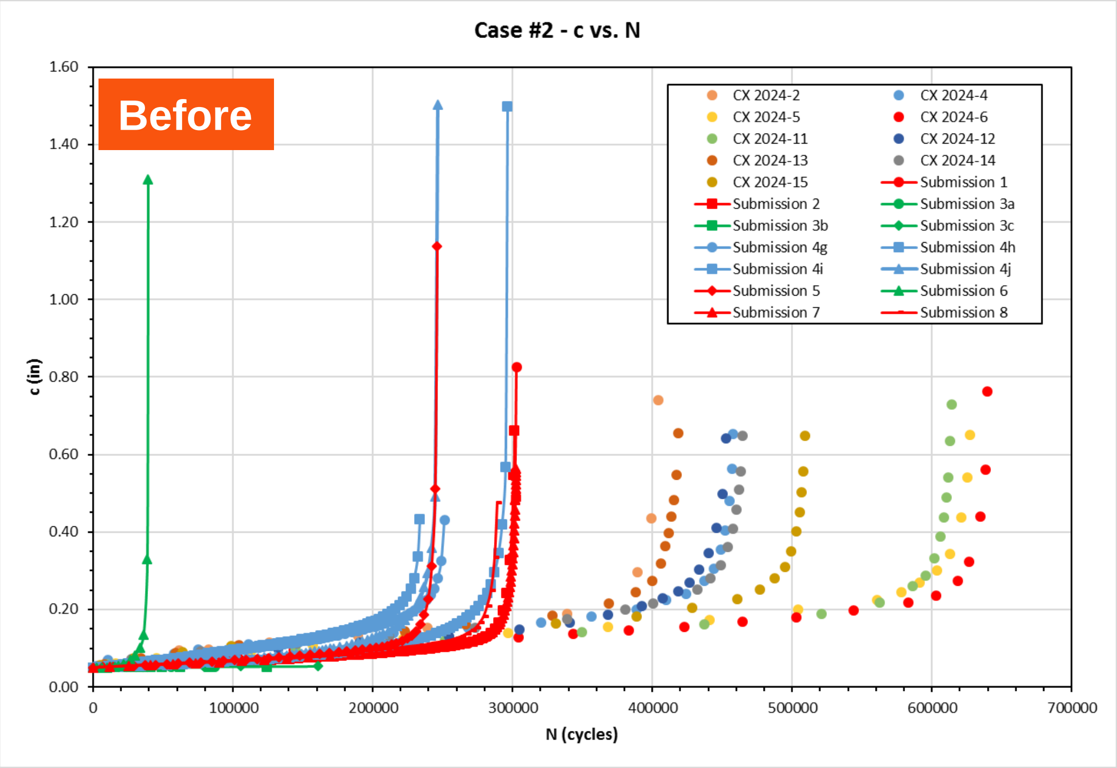
- Post-dictions – Case #4

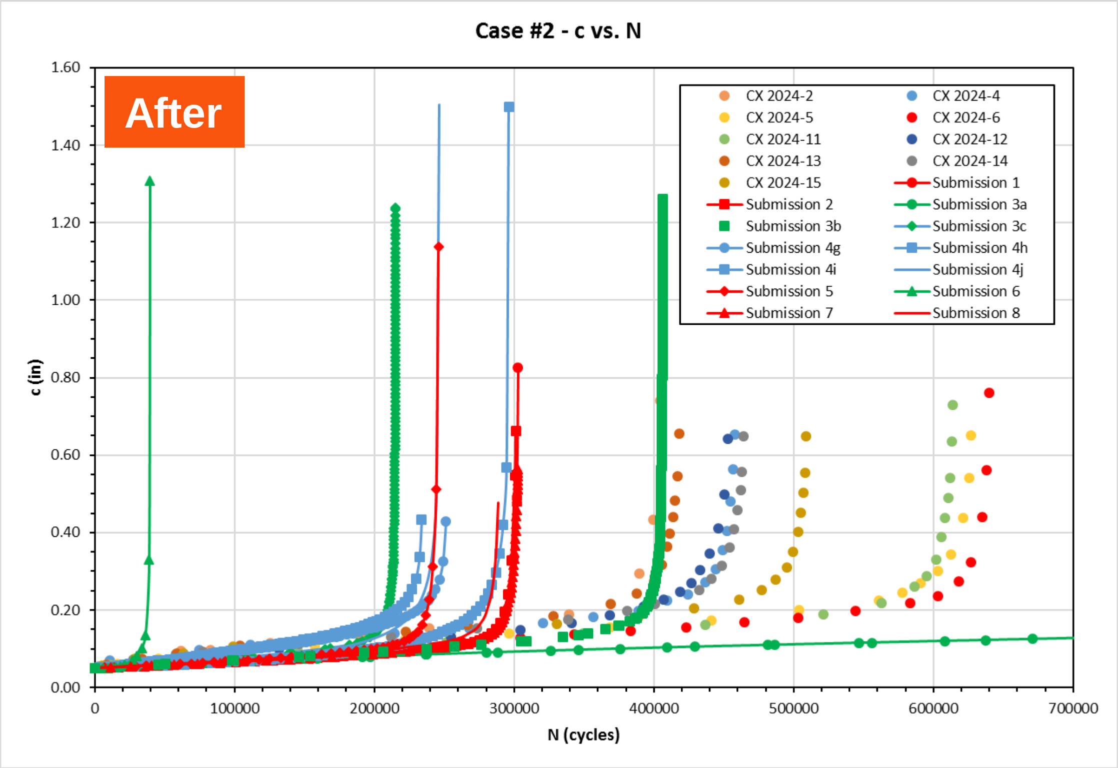




Round Robin for Cx Holes – Applied and Residual Stress Intensities

❑ Post-dictions – Case #2



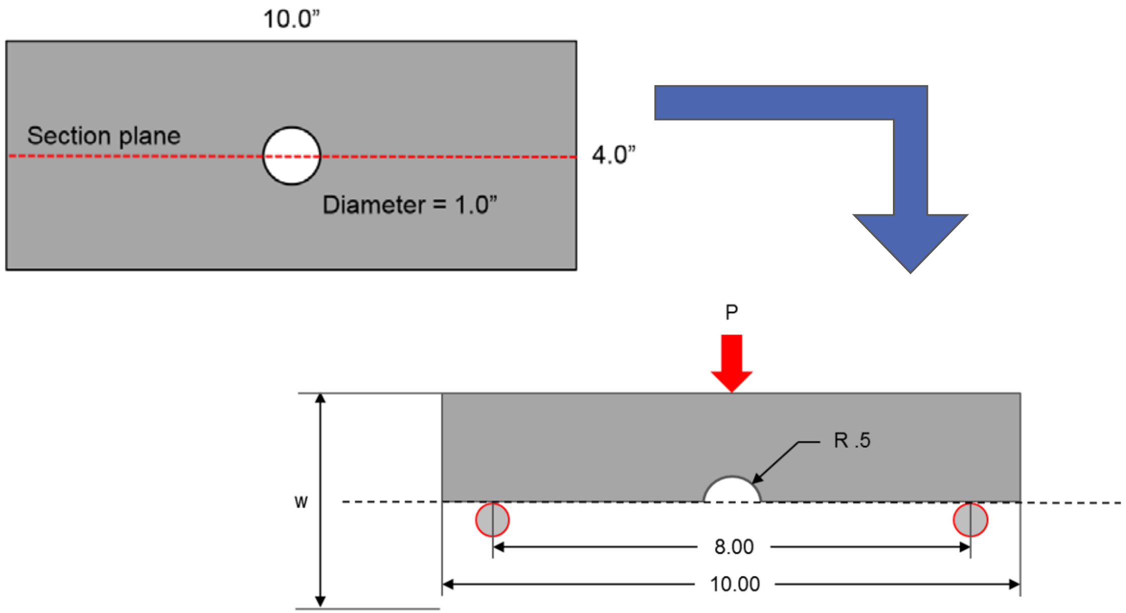


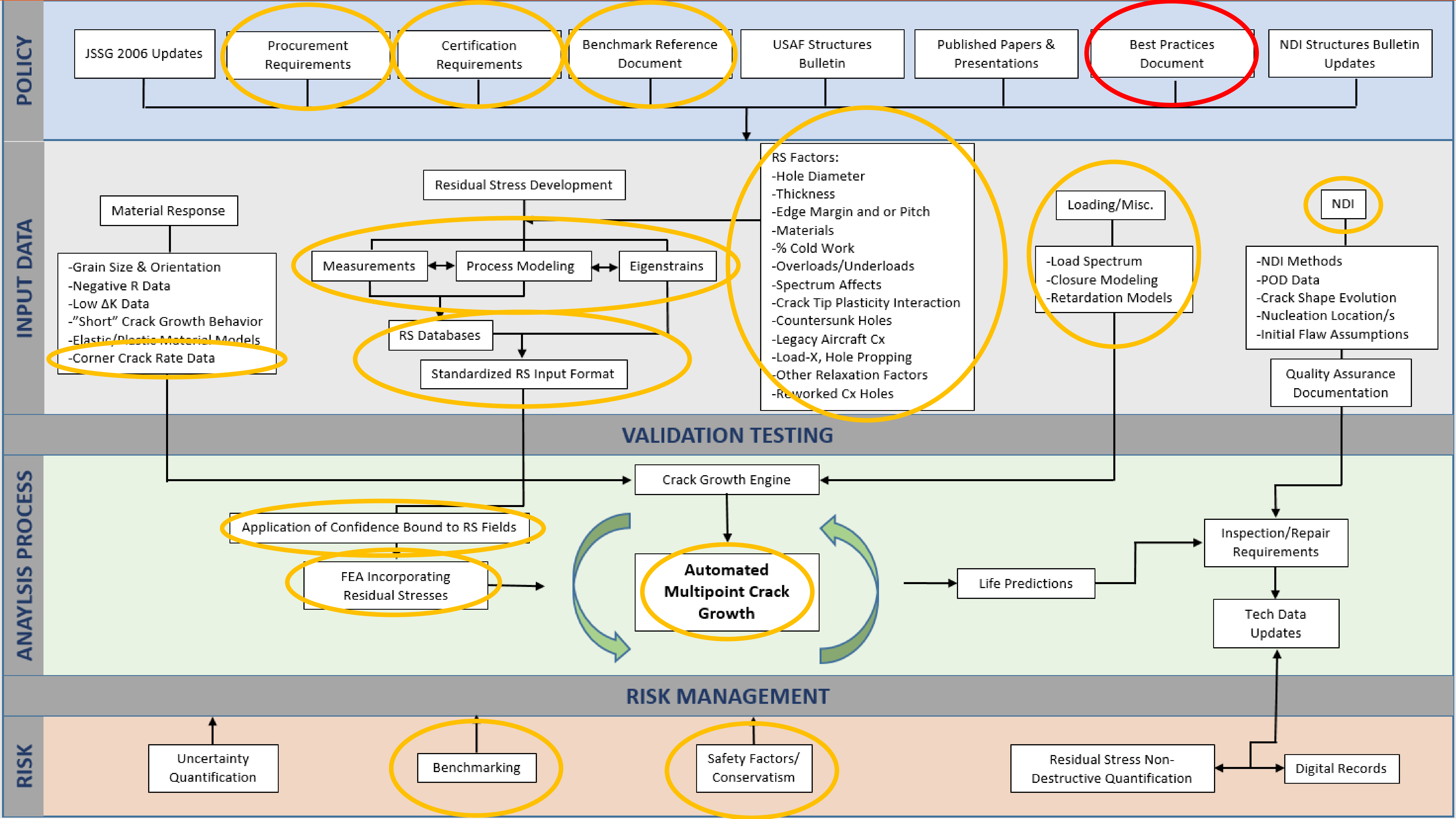
Round Robin for Cx Holes - Summary

- **The Year of Why's Has Been Fruitful**
- **Additional Action Items Need to Be Resolved**
- **Publish Journal Article**
  - White paper submitted to 19th International ASTM/ESIS Symposium on Fatigue and Fracture Mechanics (42nd National Symposium on Fatigue and Fracture Mechanics)
- **Follow-on Round Robin Efforts in Work**

Round Robin for Cx Holes – Round #2 Candidate

- **Geometrically “large” coupons**
  - Part of the difficulty with the CX hole problem is the significance of the RS and applied stress gradients near the hole. Both gradients are very steep, which creates issues for measurements and life correlations. In an effort to minimize the impact of the gradients and increase the understanding of the RS near the hole, geometrically “large” coupons were developed to accomplish RS measurements and fatigue testing
  - Multi-tier approach:
    - Residual stress characterization ✓
    - Fatigue testing
  - Coupon details:
    - Material: 2024-T351 Plate, 7075-T651 Plate
    - Thickness: 1.0 inch
    - Hole Diameter: 1.0 inch
    - Centered Hole, Baseline (no CX) and Mid CX

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Residual Stress Non-Destructive Quantification
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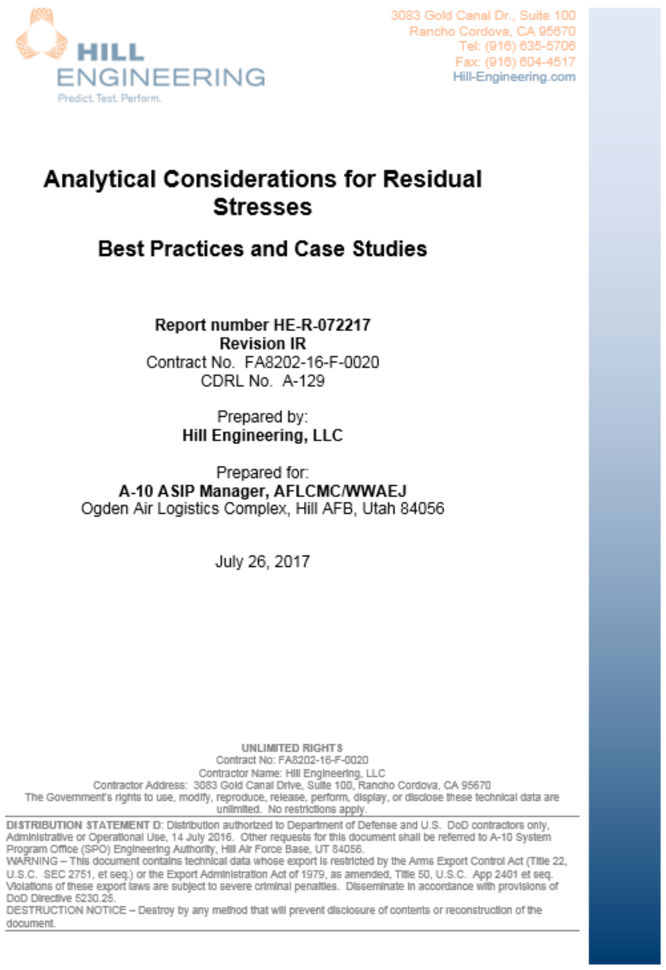
Best Practices Document

- **Purpose**
  - Share best practices, lessons learned, and analysis methods with community
  - Document benchmarks and case studies
  - Compliment other policy documents
- **Goal – Open Source Document**
- **Organizational Structure**
  - Organized similar to AGARD documents
    - Background information
    - Best practices and lessons learned
    - Benchmark problems
    - Case studies



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Analytical Considerations for Residual Stresses

Best Practices and Case Studies

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

Prepared by:
Hill Engineering, LLC

Prepared for:
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July 26, 2017

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Contractor Name: Hill Engineering, LLC
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Best Practices Document

❑ Chapter I - Introduction

- Introduction to fatigue, damage tolerance, and residual stress
- Residual stress inducing processes and associated key characteristics
- Residual stress measurement techniques and associated key characteristics
- Considerations for modeling approaches
- Current guiding policy
- Historical modeling approaches

Mechanical Methods – Key Characteristics

Mechanical Method	Typical Applications	Typical Depth of Residual Stress	Durability Benefit	Damage Tolerance Benefit
Shot Peening	Widespread – Surface of Parts	~ 0.002-0.008	Yes	Minimal
Surface Rolling	Rolled Threads, Gear Teeth, Fillets	~ 0.04”	Yes	Yes
Low Plasticity Burnishing	Fan Blades, Radii	~ 0.04”	Yes	Yes
CX Holes	Critical Fastener Holes	~ 1 radius	Yes	Yes
Laser Shock Peening	Critical Geometric Features	~ 0.04”	Yes	Yes
Forming		Surface to Full Field	Yes	Yes

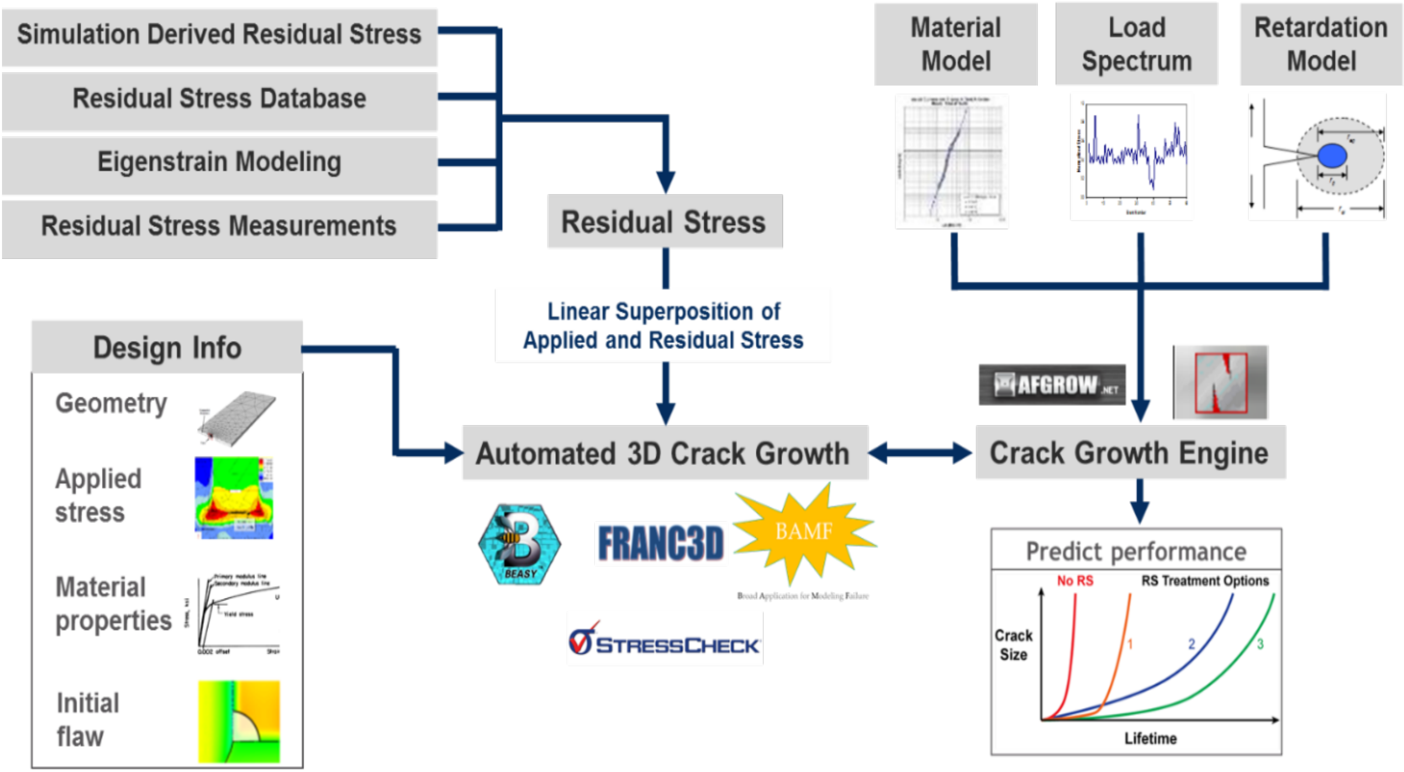
Strengths & Weaknesses of Various Residual Stress Measurement Techniques

Measurement Technique	Strengths	Weaknesses
XRD with layer removal	Portable equipment	Significantly affected by microstructure variations Less repeatable than other techniques
Neutron Diffraction	2D mapping of multiple components Bulk residual stress	Difficult to obtain (limited facilities) Significantly affected by microstructure variations
Hole Drilling	Portable equipment ASTM standard Near-surface measurement Multiple stress components	Less repeatable than other techniques
Ring Core	Portable equipment Near-surface measurement Multiple stress components	Large averaging volume
Contour	2D mapping of residual stress Bulk residual stress	Difficult to resolve sharp stress gradients
Slitting	Excellent measurement repeatability	Limited to extruded cross-sections

Best Practices Document

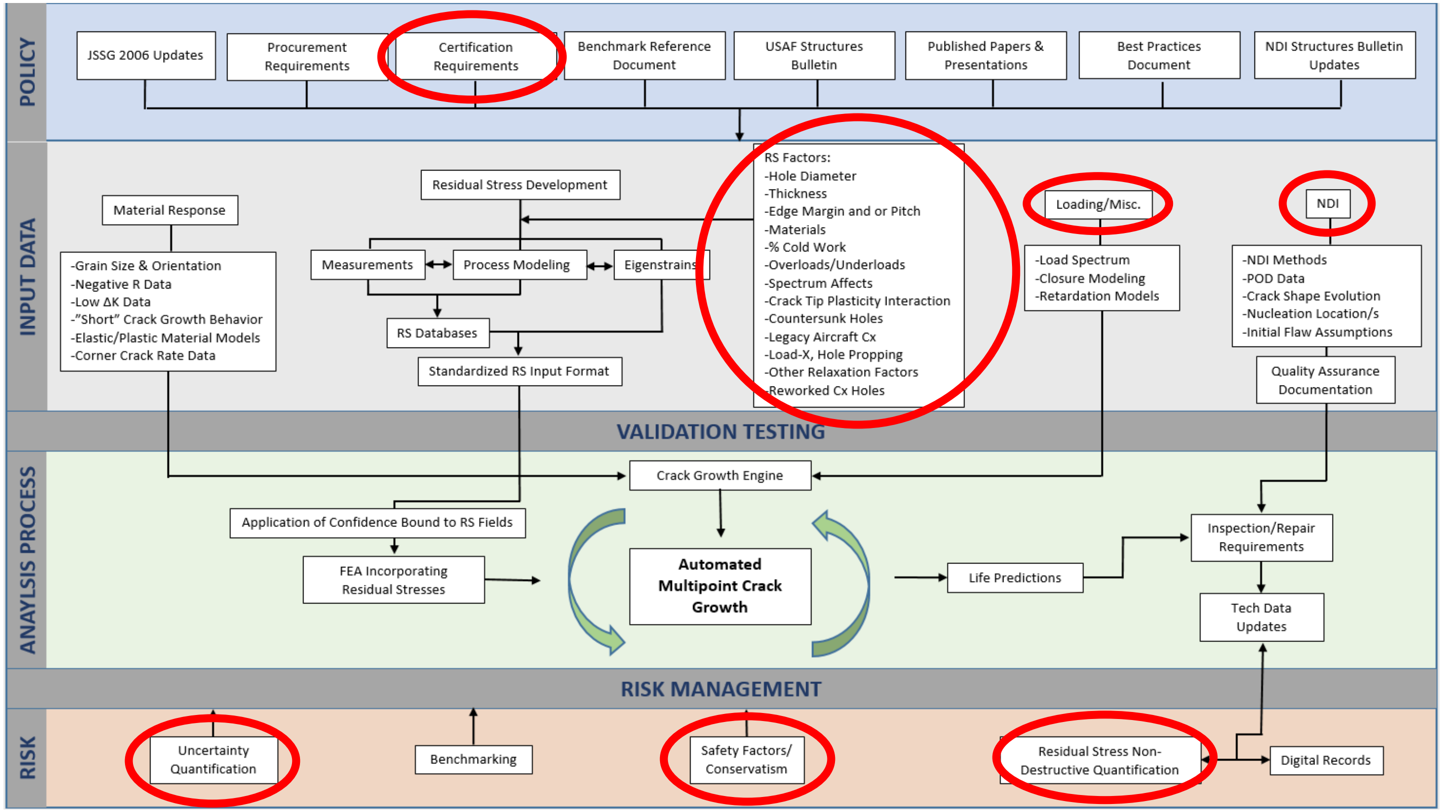
❑ Chapter II – Analytical Processes

- ➢ Overview of analytical processes
- ➢ Key input data
  - Design info
  - Material models
  - Loading spectrum & retardation
  - Residual stress
- ➢ Analysis processes
  - Multi-point fracture mechanics
  - Coupled FEA
  - Other analytical approaches
- ➢ Way forward & recommendations



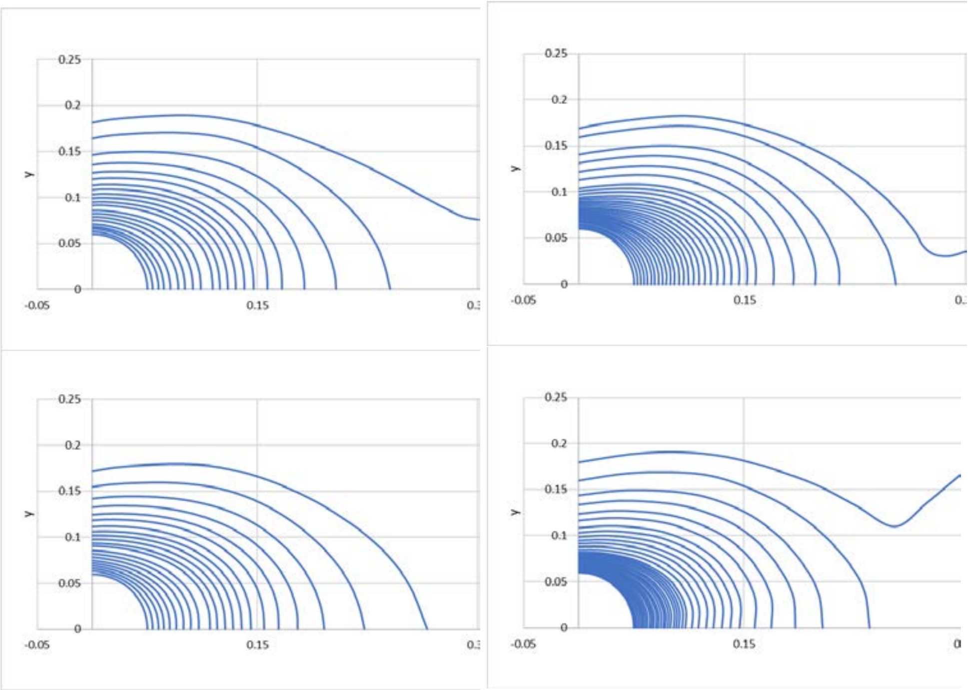
Best Practices Document

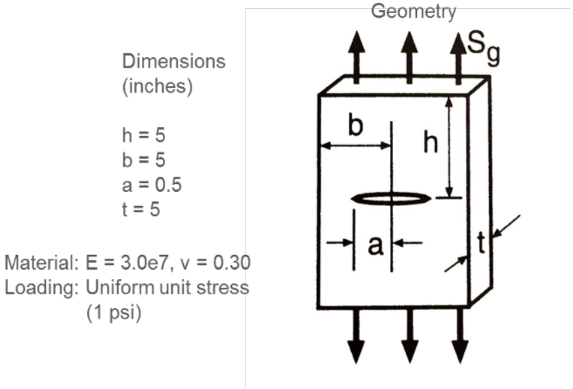
- Chapter III – Other Considerations
  - Factors influencing residual stress and the associated uncertainty
    - Key factors influencing residual stress
    - Variability in residual stress data
  - Validation testing
  - Non-destructive inspections
  - Quality assurance
  - Risk management
  - Certification considerations
  - Way forward & recommendations

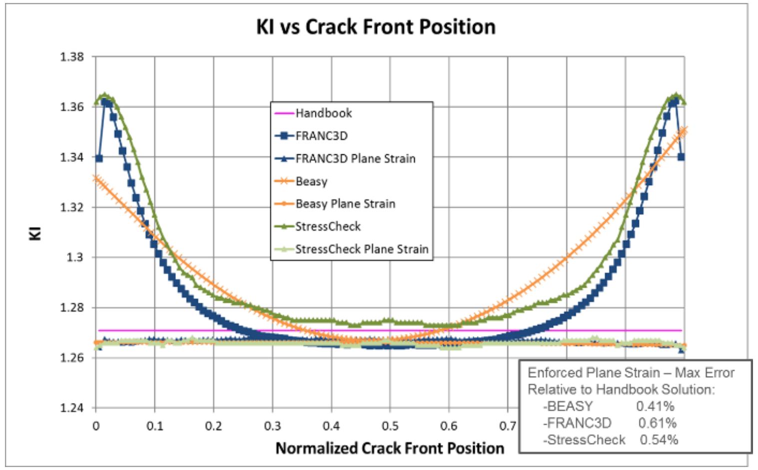


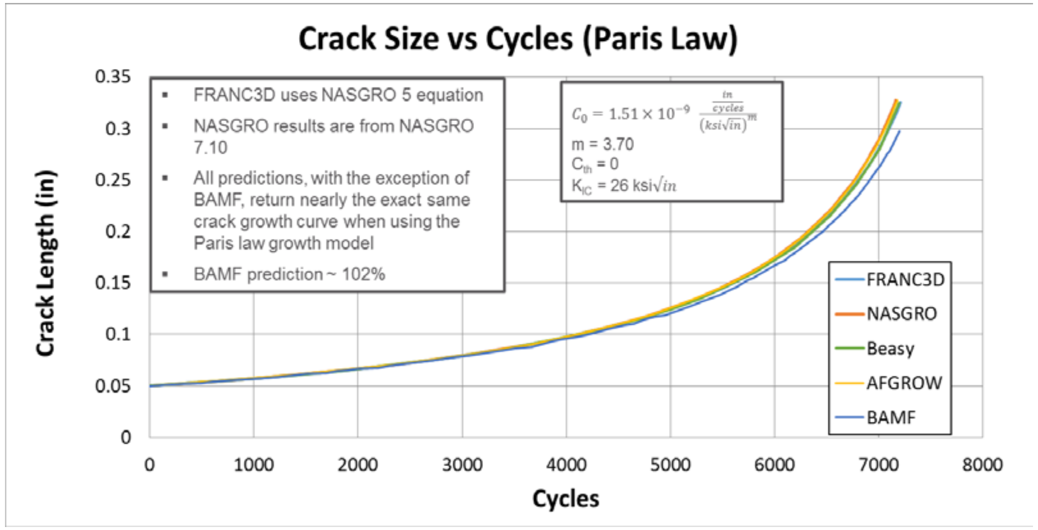
Best Practices Document

- **Chapter IV – Benchmark Cases**
  - Handbook solutions
  - ERSI round robin results



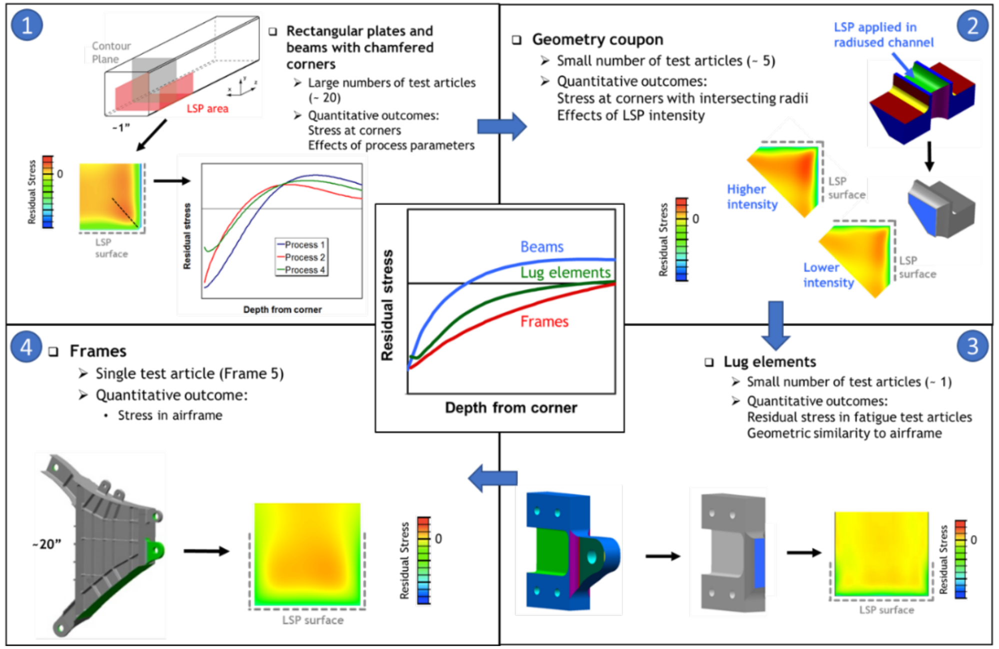


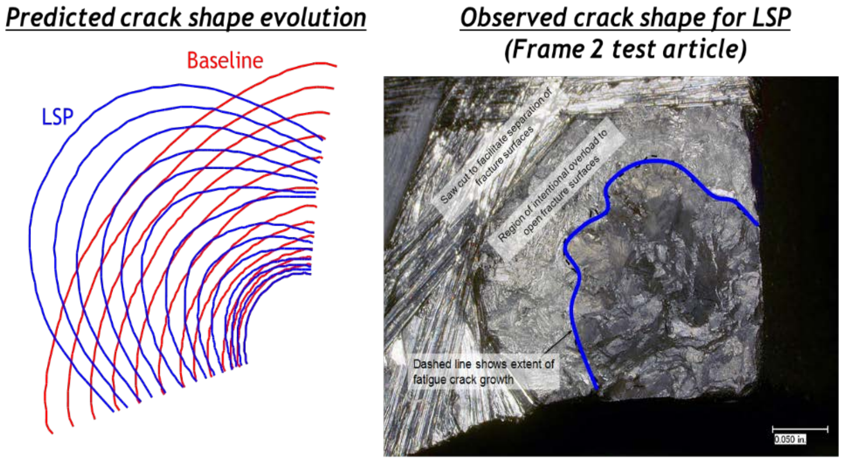


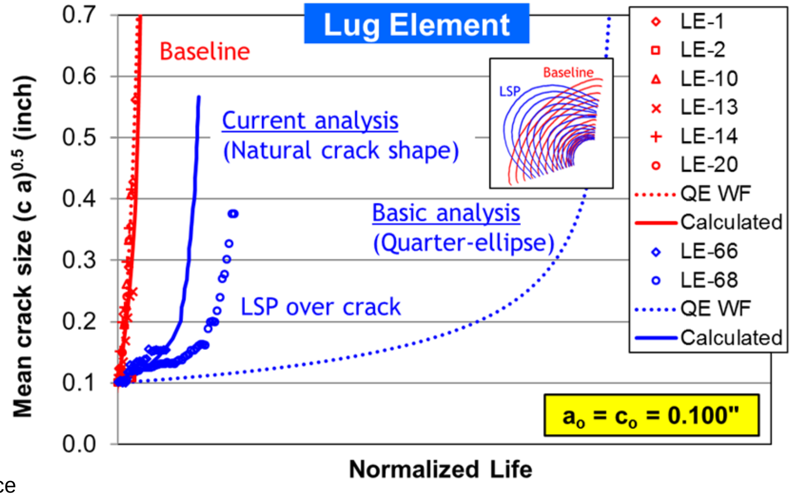


Best Practices Document

- **Chapter V – Case Studies**
  - Laser shock peening case study
  - Cx hole case study







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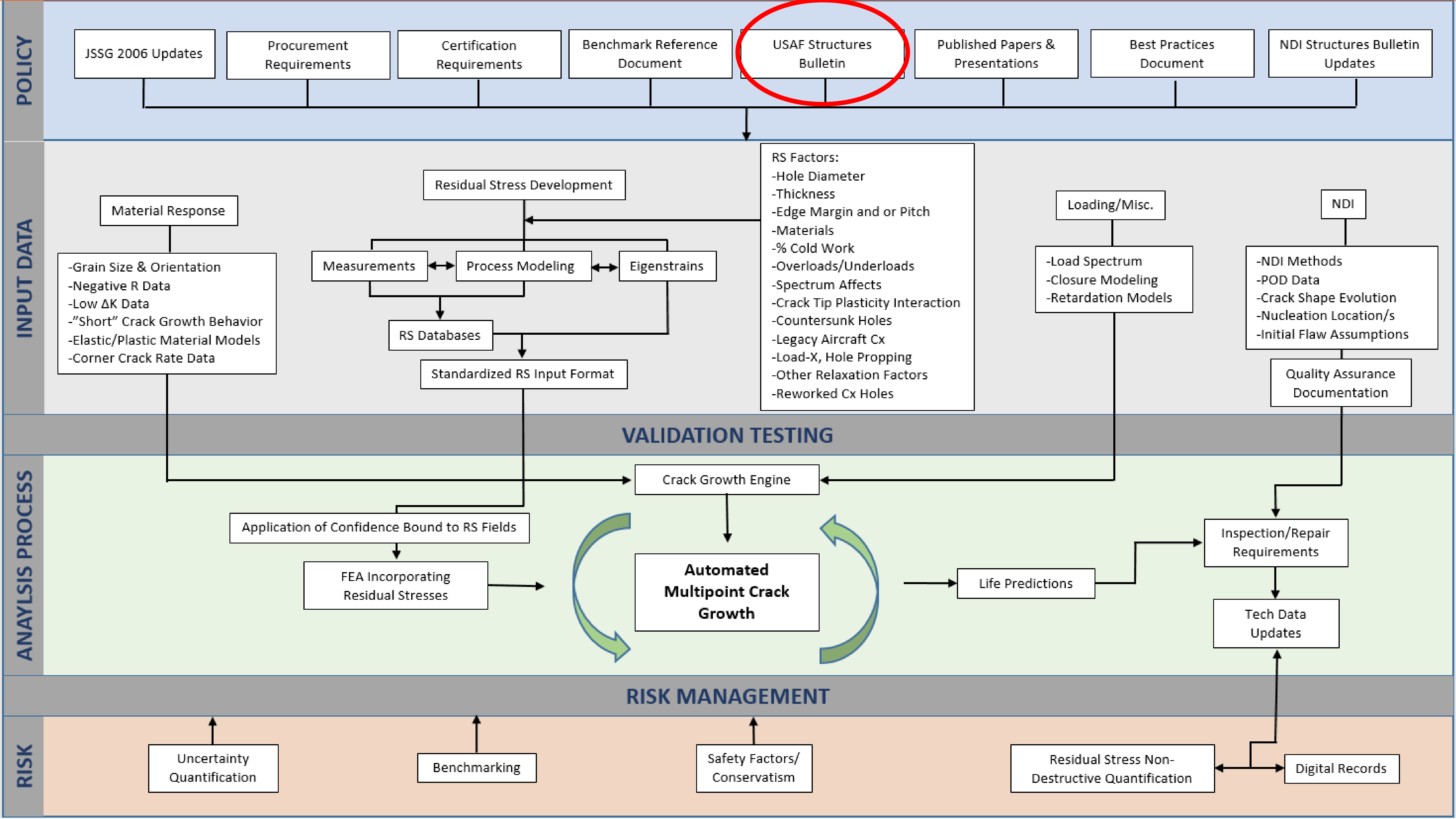
Hill, M., DeWald, A., VanDalen, J., Bunch, J., Flanagan, S., Langer, K. (2012), Design and analysis of engineered residual stress surface treatments for enhancement of aircraft structure, 2012 ASIP Conference

Best Practices Document

- **Current Status**
  - Publicly released version available (July 2018) ✓
- **Moving Forward**
  - Document only as good as the inputs provided by community
  - Need inputs related to:
    - Process modeling best practices
    - Other analysis methods
    - Factors that influence residual stress
    - Risk assessment considerations
    - Certification considerations
    - Procurement vs. sustainment considerations
    - Case studies

WE NEED YOU!!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Draft Structures Bulletin

- Analytical Methods, Quality Assurance, and Validation Testing Requirements for Explicit Utilization of Deep Residual Stresses to Establish the Beneficial Effects of Cold Expanded Fastener Holes for Damage Tolerance
- Initial Draft Developed
  - Jan-Aug 2018
- Current Status
  - USAF internal review

AIR FORCE STRUCTURES

Structures Bulletin

AFLCMC/EZ
Bldg. 28, 2145 Monohan Way
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Phone 937-255-5312

Number: EZ-SB-18-YYY

Date: Draft v0

Subject: Analytical Methods, Quality Assurance, and Validation Testing Requirements for Explicit Utilization of Deep Residual Stresses to Establish the Beneficial Effects of Cold Expanded Fastener Holes for Damage Tolerance

References:

1. JSSG-2006, "Joint Service Specification Guide Aircraft Structures", 30 October 1998
2. MIL-STD-1530D, "Aircraft Structural Integrity Program", 13 August 2016
3. EN-SB-17-001, "Testing and Evaluation Requirements for Utilization of an Equivalent Initial Damage Size Method to Establish the Beneficial Effects of Cold Expanded Holes for Development of the Damage Tolerance Initial Inspection Interval,", 24 April 2017
4. Northrop Grumman Corporation, "Analytical Considerations for Residual Stress, Best Practices and Case Studies, A-10 Thunderbolt Life-cycle Program Support (TLPS) ASIP Modernization VI, Crack Growth Analysis in Residual Stress Fields", HE-R-072217 Revision B, 27 June 2018
5. Mills, T.; Honeycutt, K.; Prost-Domasky, S.; Brooks, C., "Integrating Residual Stress Analysis of Critical Fastener Holes into USAF Depot Maintenance", A3G-2015-185420, 2 November 2014
6. Hill, M.; DeWald, A.; VanDalen, J.; Bunch, J.; Flanagan, S.; Langer, K., "Design and analysis of engineered residual stress surface treatments for enhancement of aircraft structure, 2012 ASIP Conference
7. EN-SB-08-012, "In-Service Inspection Crack Size Assumptions for Metallic Structures", April 2018
8. Brausch, J.; Stubbs, D.; Fong, W., "Impact of Deep Residual Stress on NDI Methods", Engineered Residual Stress Implementation Workshop, 21 September 2017

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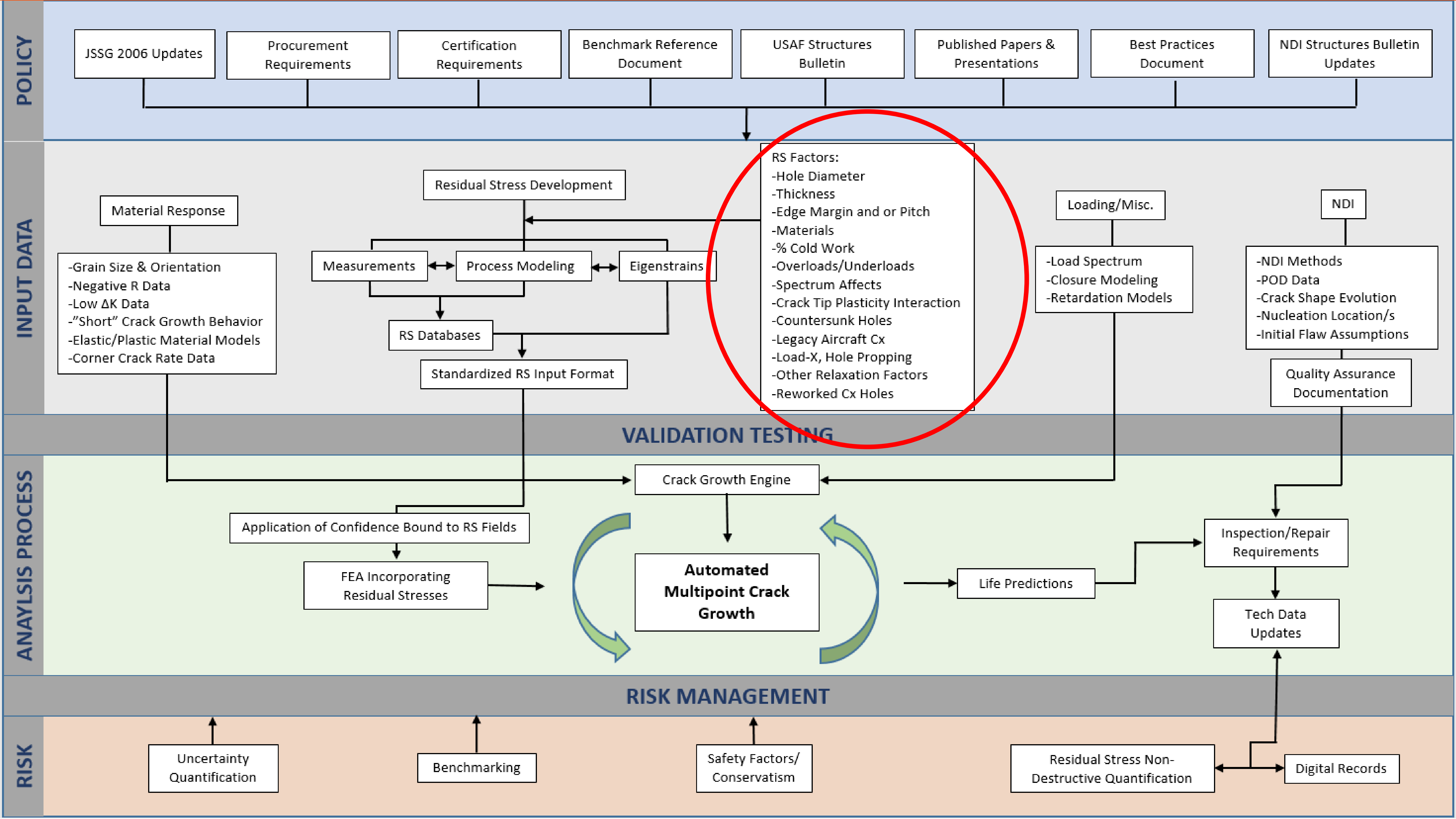
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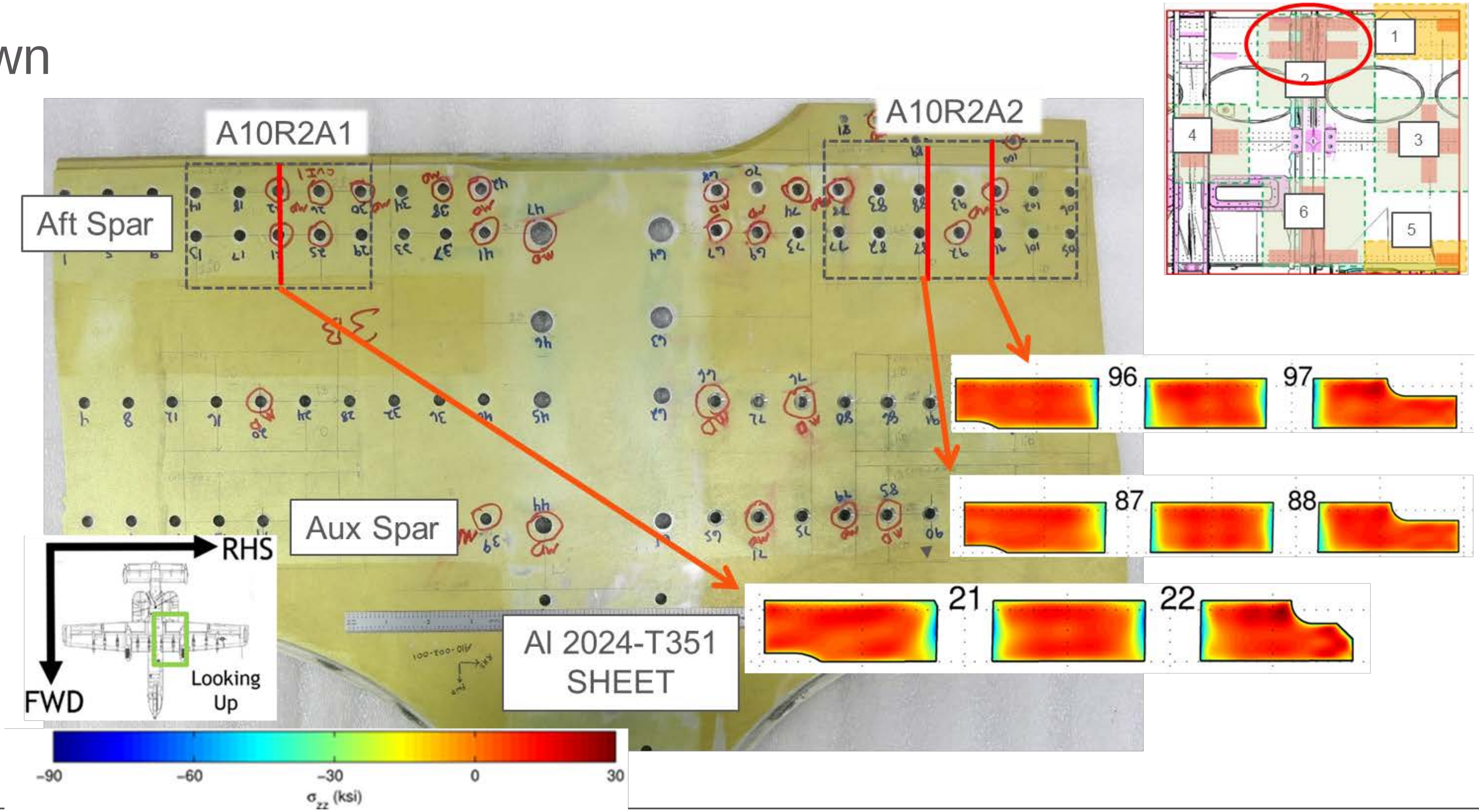
Engineering Implementation of Residual Stress

- **Post-Service vs. New Manufacture Coupon Residual Stresses**
  - Load history / environment effects
  - Initial stress shakedown

How Should We Account for in Analyses???



Engineering Implementation of Residual Stress

❑ Crack Tip Plasticity Interaction – 2024-T351

- ➢ Life predictions for average R.S. field – shows minimal effect on predicted fatigue life

Plot Number	Residual Stress from Fatigue Cracked Coupons	Distance Applied
1	Baseline Non-Cracked Residual Stress	0.00 - 0.04inch
2	Residual Stress for -01-02 (0.08inch) Crack Length	0.04 - 0.09inch
3	Residual Stress for -03-04 (0.10inch) Crack Length	0.09 - 0.1125inch
4	Residual Stress for -05-06 (0.125inc) Crack Length	0.1125 - 0.1875inch
5	Residual Stress for -07 (0.25inch) Crack Length	0.1875 - 0.375inch
6	Residual Stress for -08 (0.5inch) Crack Length	0.375 - 0.75inch

Plot Number	Residual Stress from Fatigue Cracked Coupons	Distance Applied
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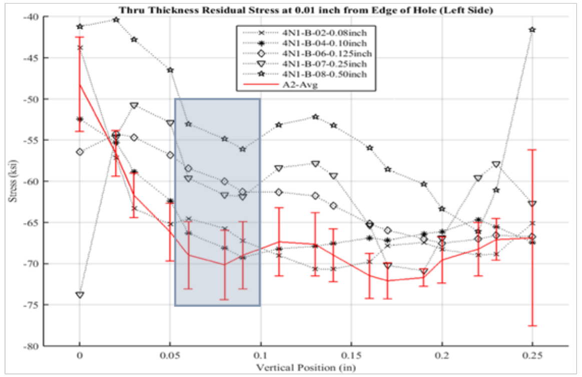

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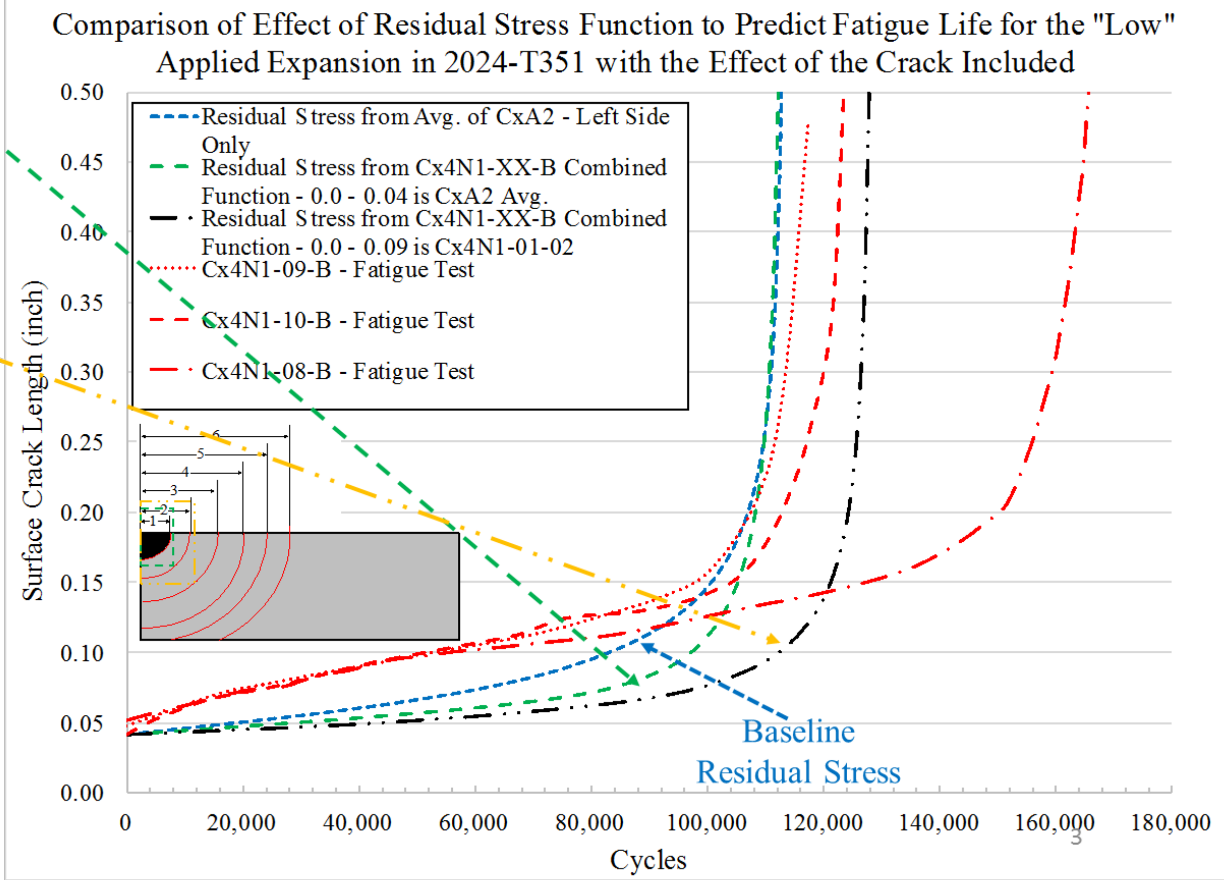

Engineering Implementation of Residual Stress

❑ Crack Tip Plasticity Interaction – 7075-T651

- ➢ Life predictions for average R.S. field – showing shift to the left, closer to average fatigue test results

Plot Number	Residual Stress from Fatigue Cracked Coupons	Distance Applied
1	Baseline Non-Cracked Residual Stress	0.00 - 0.04inch
2	Residual Stress for -01-02 (0.08inch) Crack Length	0.04 - 0.09inch
3	Residual Stress for -03-04 (0.10inch) Crack Length	0.09 - 0.1125inch
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5	Residual Stress for -07 (0.25inch) Crack Length	0.1875 - 0.375inch
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4	Residual Stress for -05-06 (0.125inc) Crack Length	0.1125 - 0.1875inch
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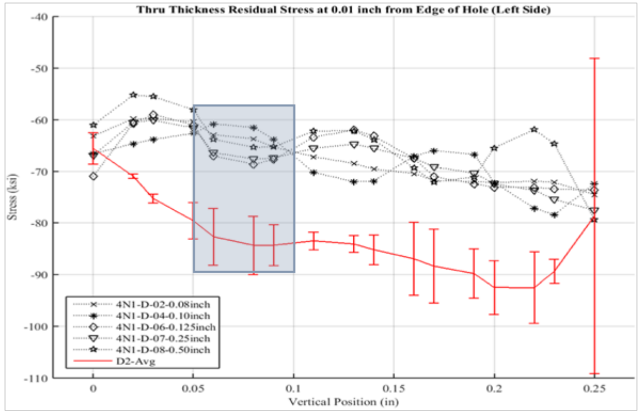
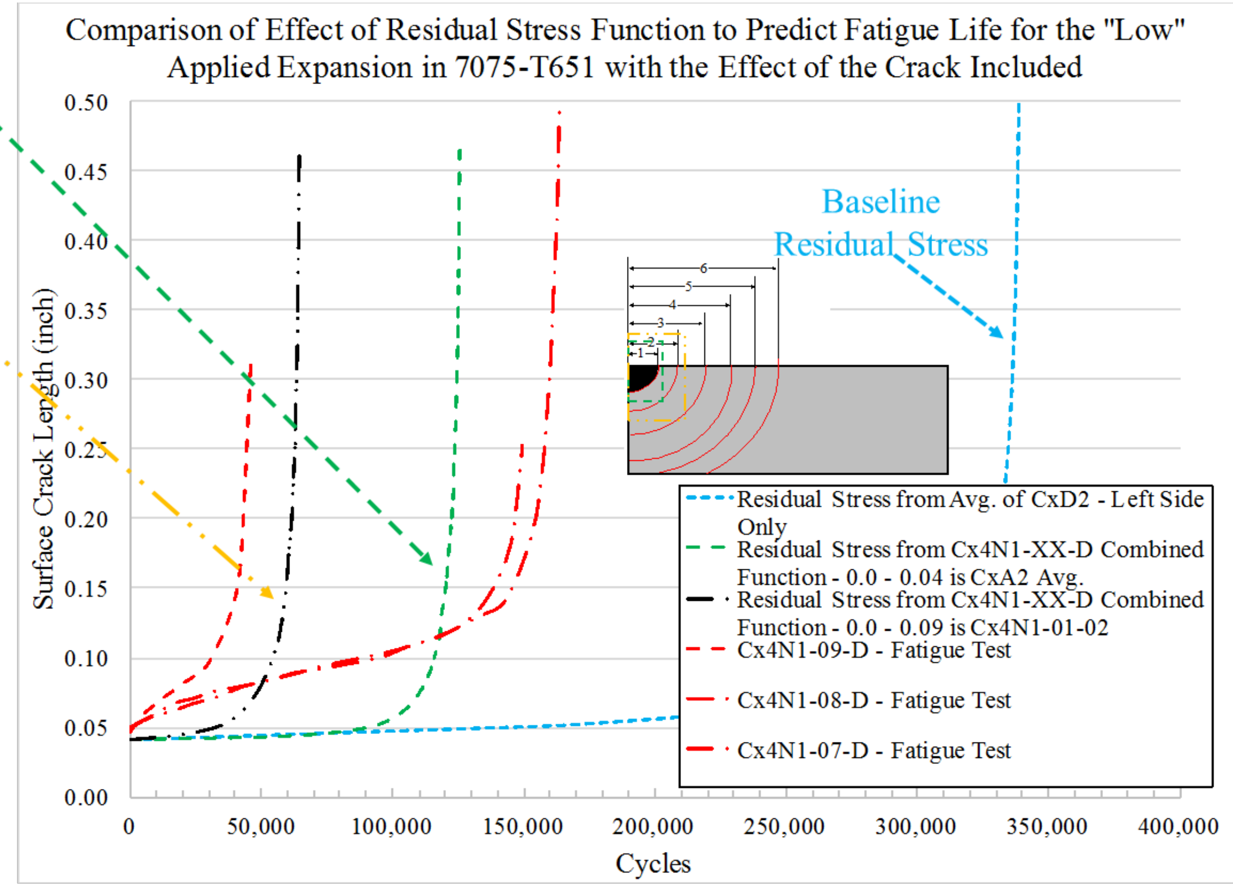
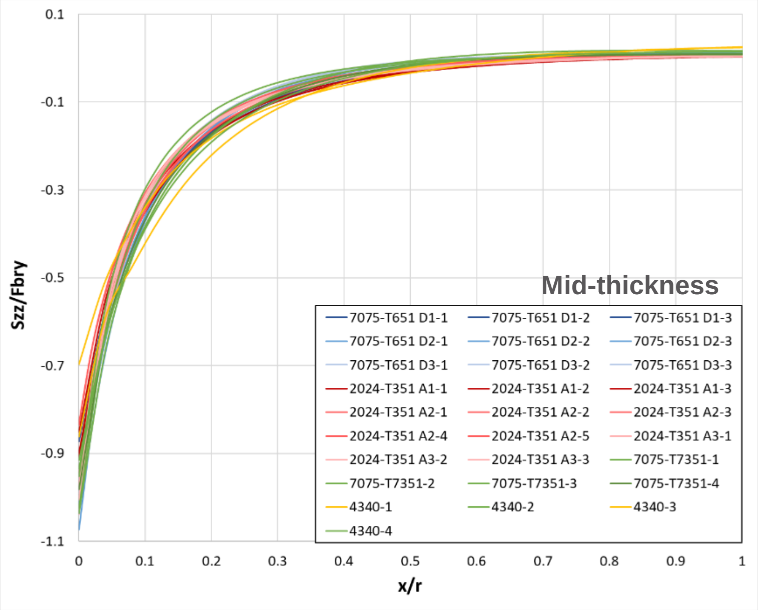


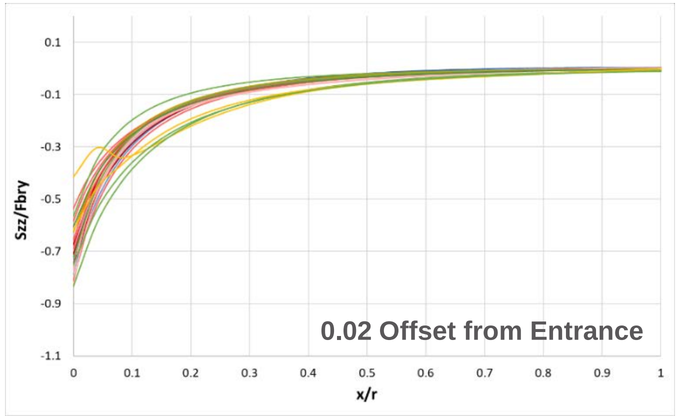


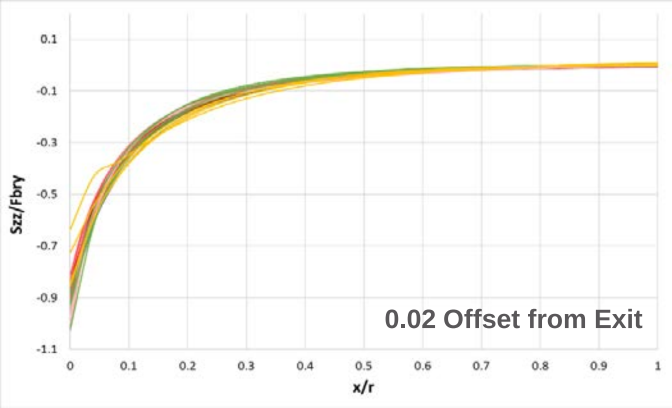
Engineering Implementation of Residual Stress

Non-Dimensional Residual Stress - The Hodge Podge

- Key factors
  - Material (Fbry)
  - Hole diameter
  - Applied expansion
  - Thickness







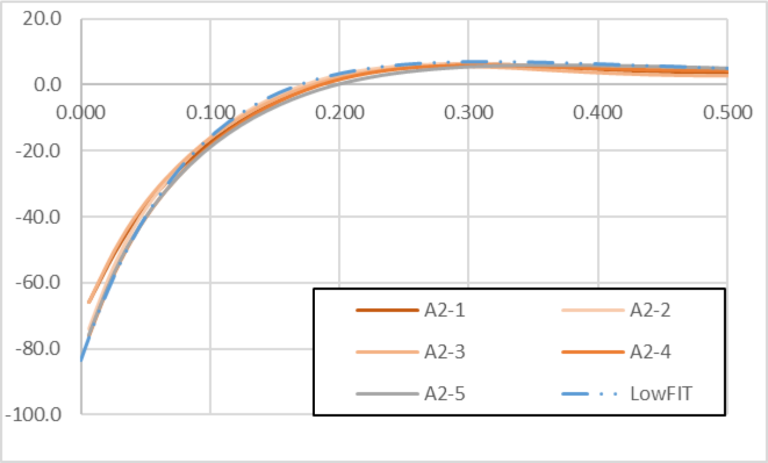
Engineering Implementation of Residual Stress

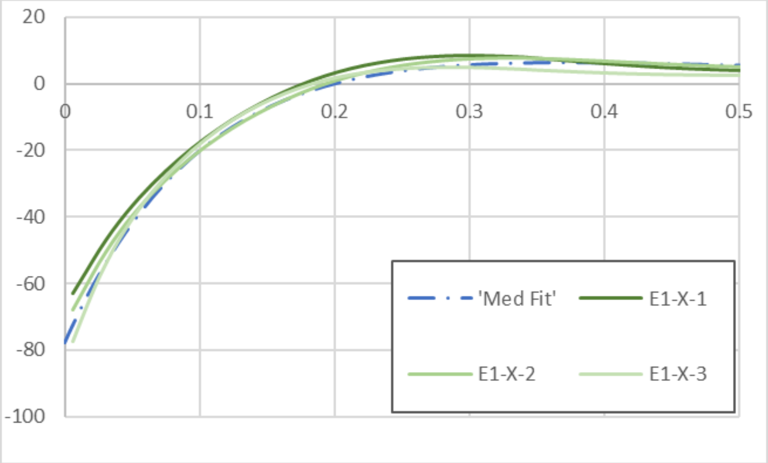
Non-Dimensional Residual Stress

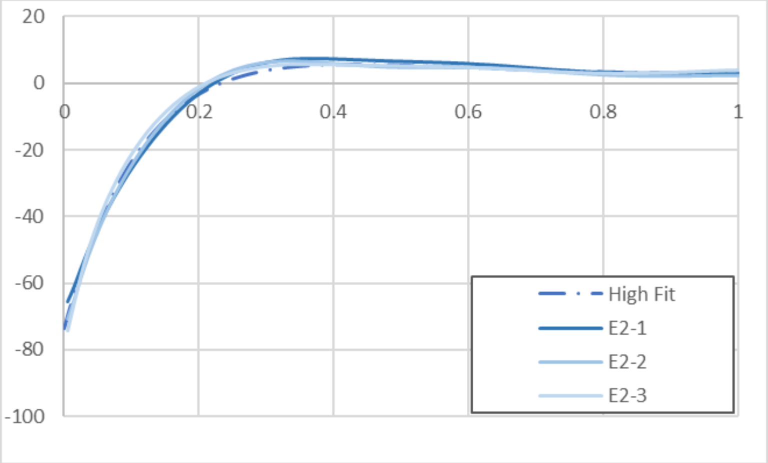
- Applied Expansion

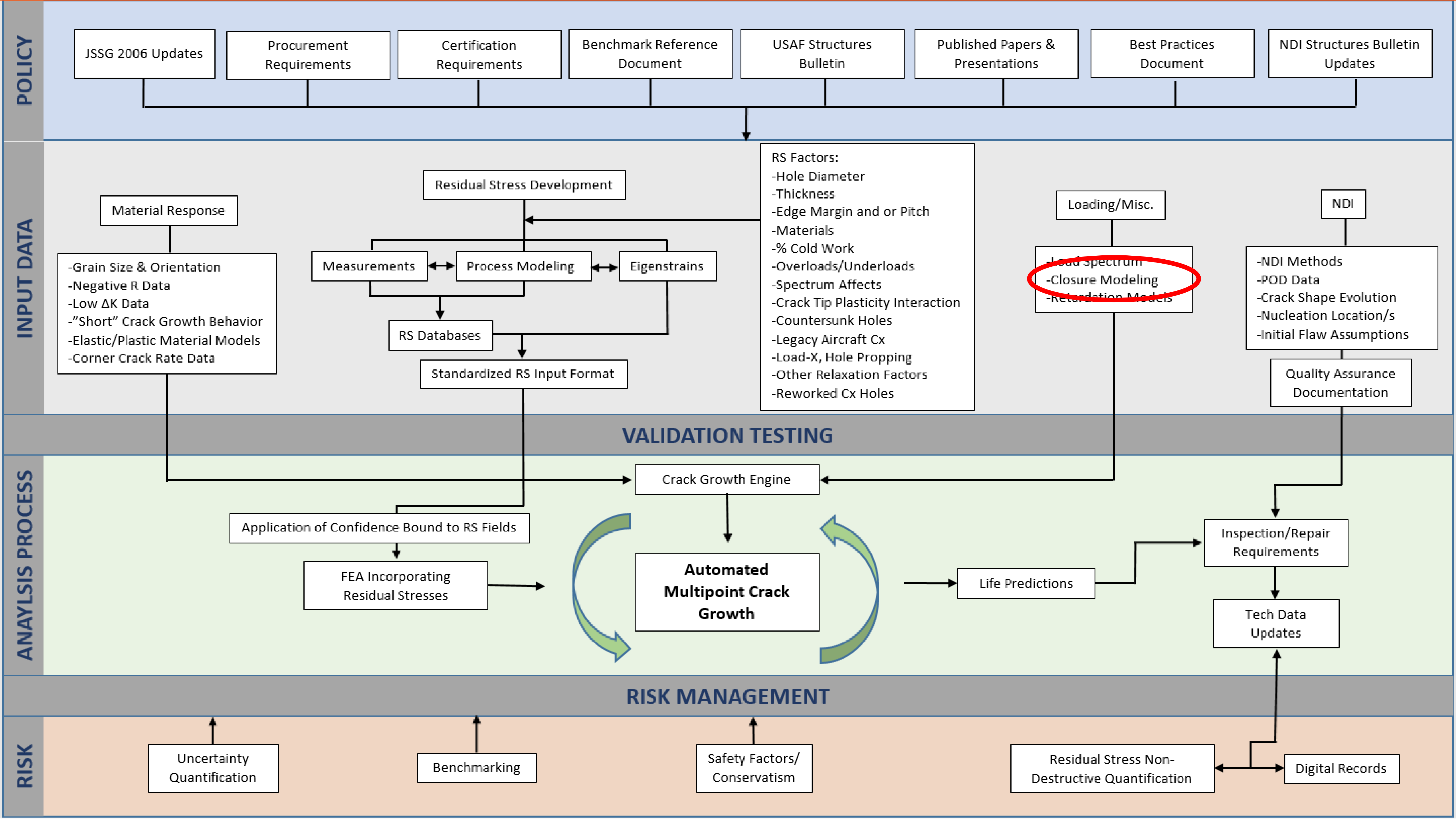
$$SzzMidthickness = e^{(\omega)x}[SzzMax + ((Vo) + (\omega)SzzMax)x] + SzzMin$$

% Applied Expansion	ω	Vo	Szz Max	Szz Min
3.18	-7.75	-231.4	-86.0	2.08
3.68	-7.20	-215.6	-80.1	2.37
4.16	-5.98	-160.6	-75.9	2.57





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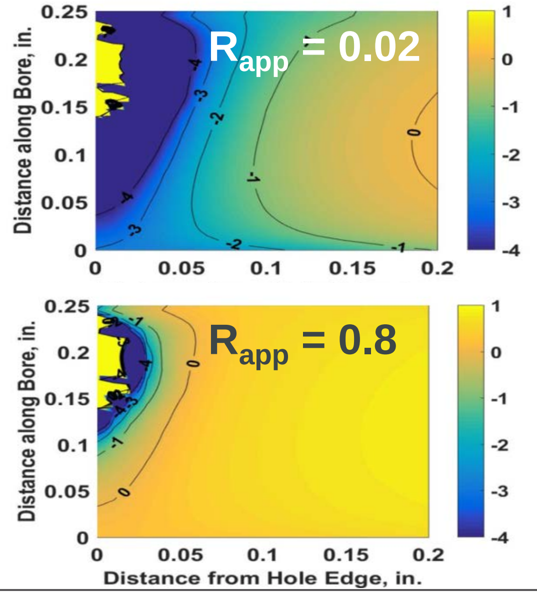
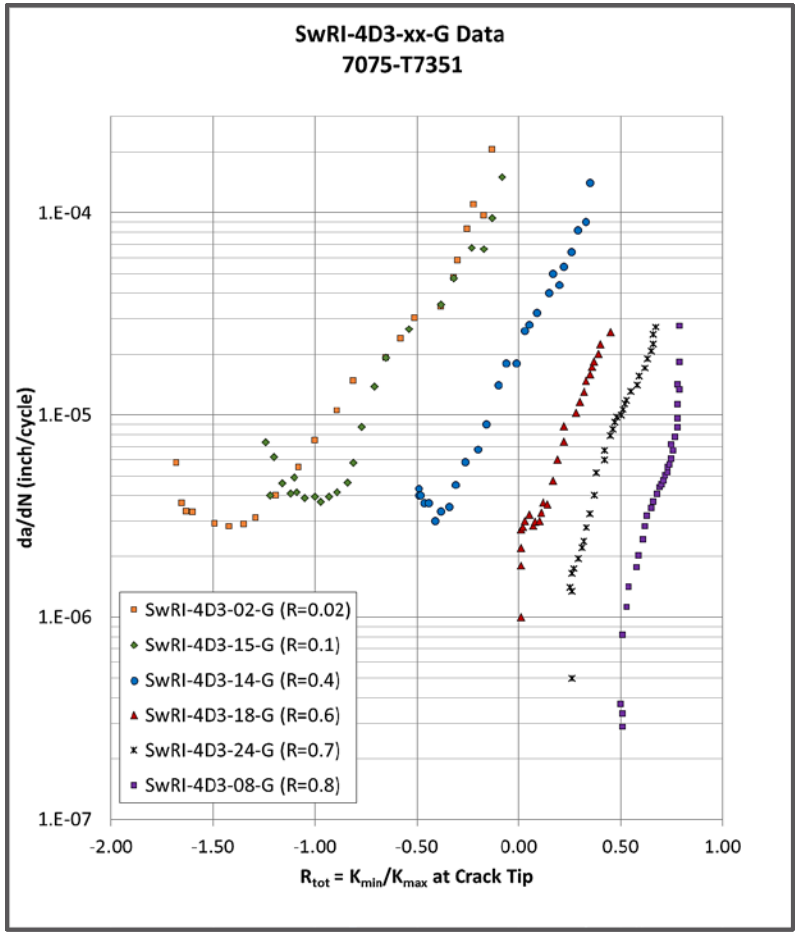
Crack Closure Effects

- Extensive evaluation of crack growth tests at CX holes and various applied R (APES & ESRD)
- Variation of experimentally derived da/dN growth rate as a function of $R_{tot} = K_{min}/K_{max}$ at the crack tip determined from simulation
  - The ‘dip’ in the da/dN curve occurs for cracks < 0.1 inch at negative R_{tot}
- For R_{tot} > 0, the ‘dip’ is not present
  - Corresponding to R_{app} = 0.6, 0.7, 0.8





AFRL Phase III SBIR: Deep Residual Stress Methods

Public Release Authority: 88ABW-2018-4366

Crack Closure Effects

- Modeling Closure

AFRL Phase III SBIR: Deep Residual Stress Methods

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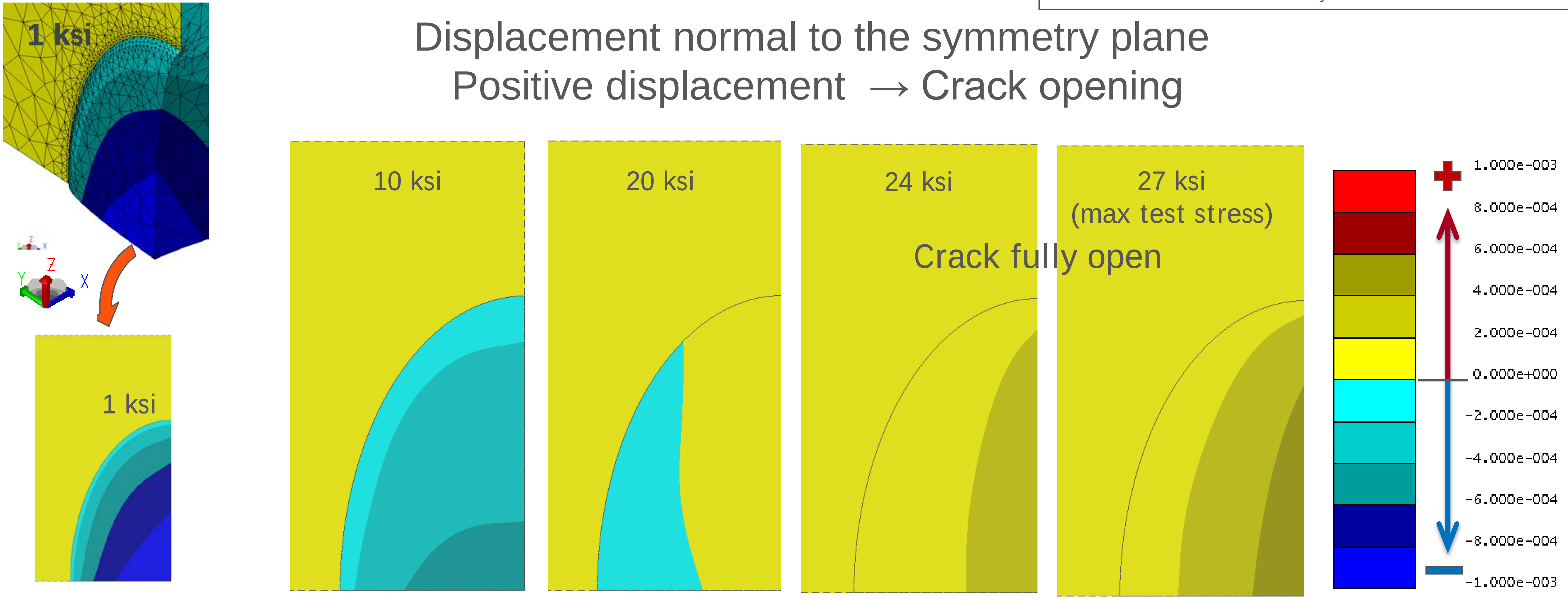
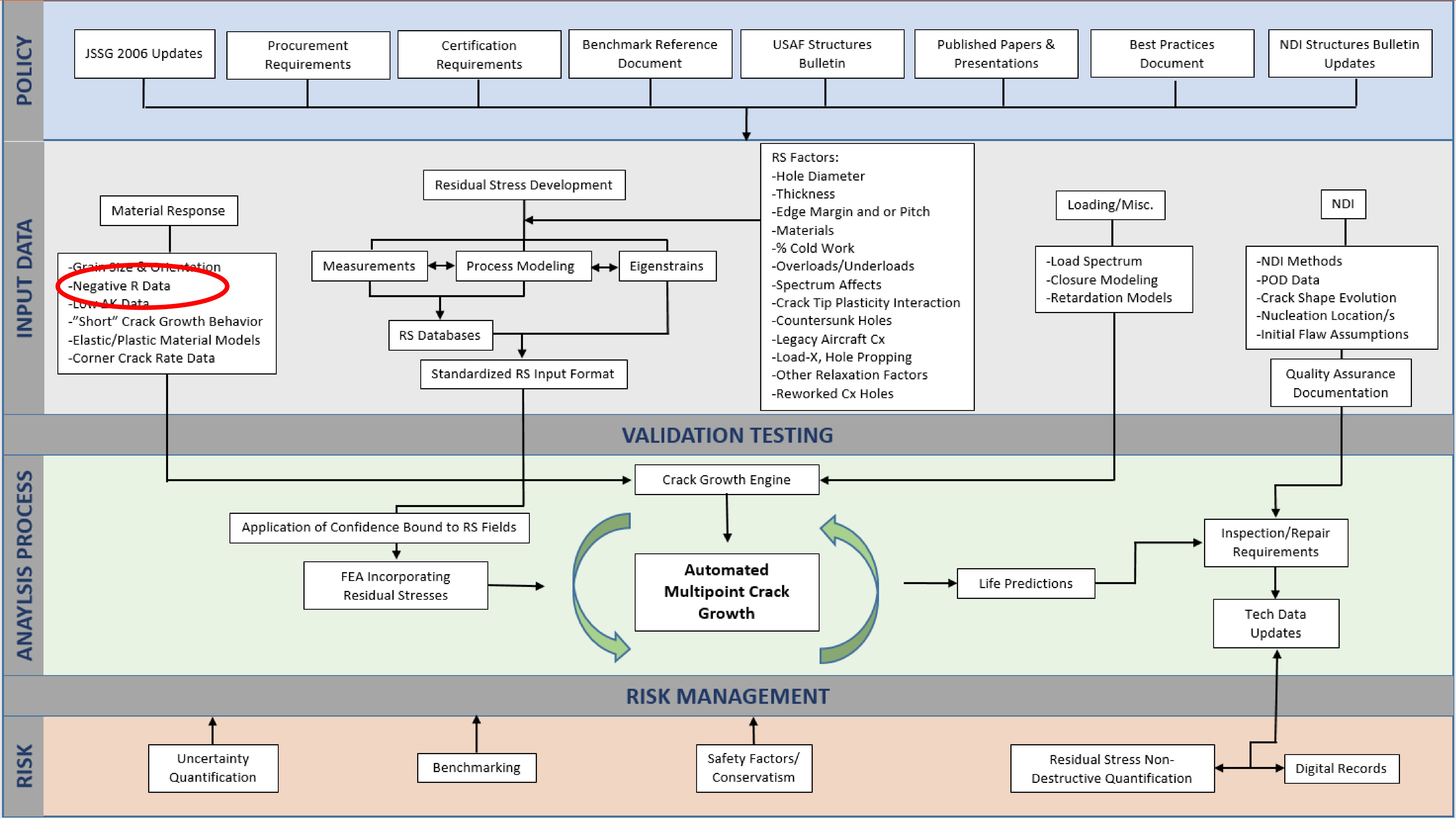
Displacement normal to the symmetry plane
Positive displacement → Crack opening





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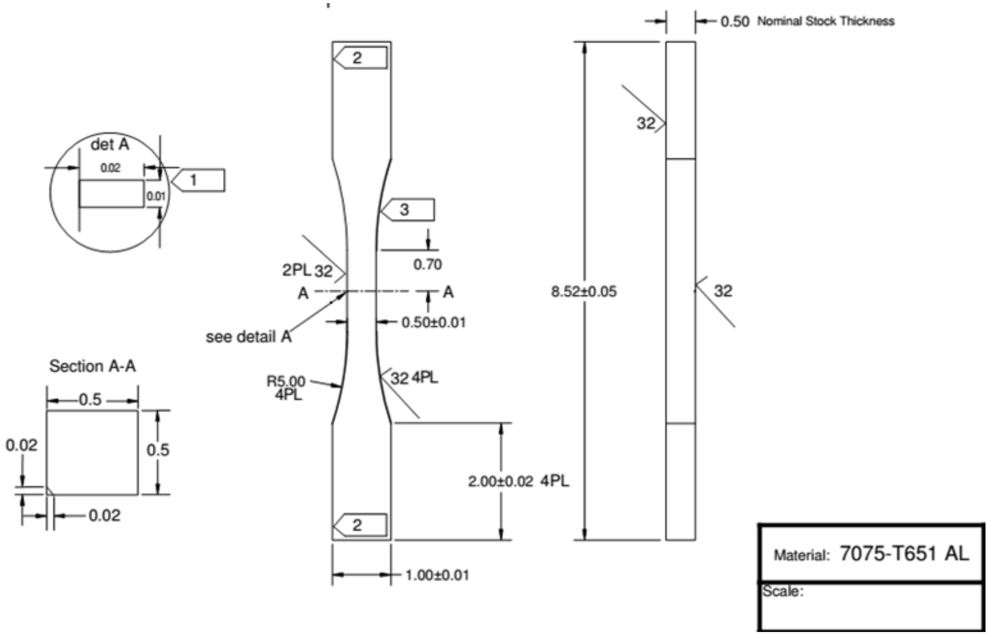
Negative R Testing

- Much of the crack growth from CX holes can occur in regions of negative R_{tot}
- GOAL: conduct limited negative-R crack growth testing to compare to AFRL historical data
  - center cracked M(T) panels (as AFRL tested)
  - part-through crack "dog-bones"
- 6 specimens of 2024-T351
  - R = -1
    - 1 x M(T) same as AFRL design
      - requires buckling guides
      - through-crack design
    - 2 x dogbones
      - non-standard geometry
      - no need for buckling guides
      - part-through crack design
  - Repeat for R = -4
- Repeat 6-specimen matrix for 7075-T651



Contract Vehicle--Engineering and Analysis Activities in Aging Structures: A-10 ASIP Engineering Support

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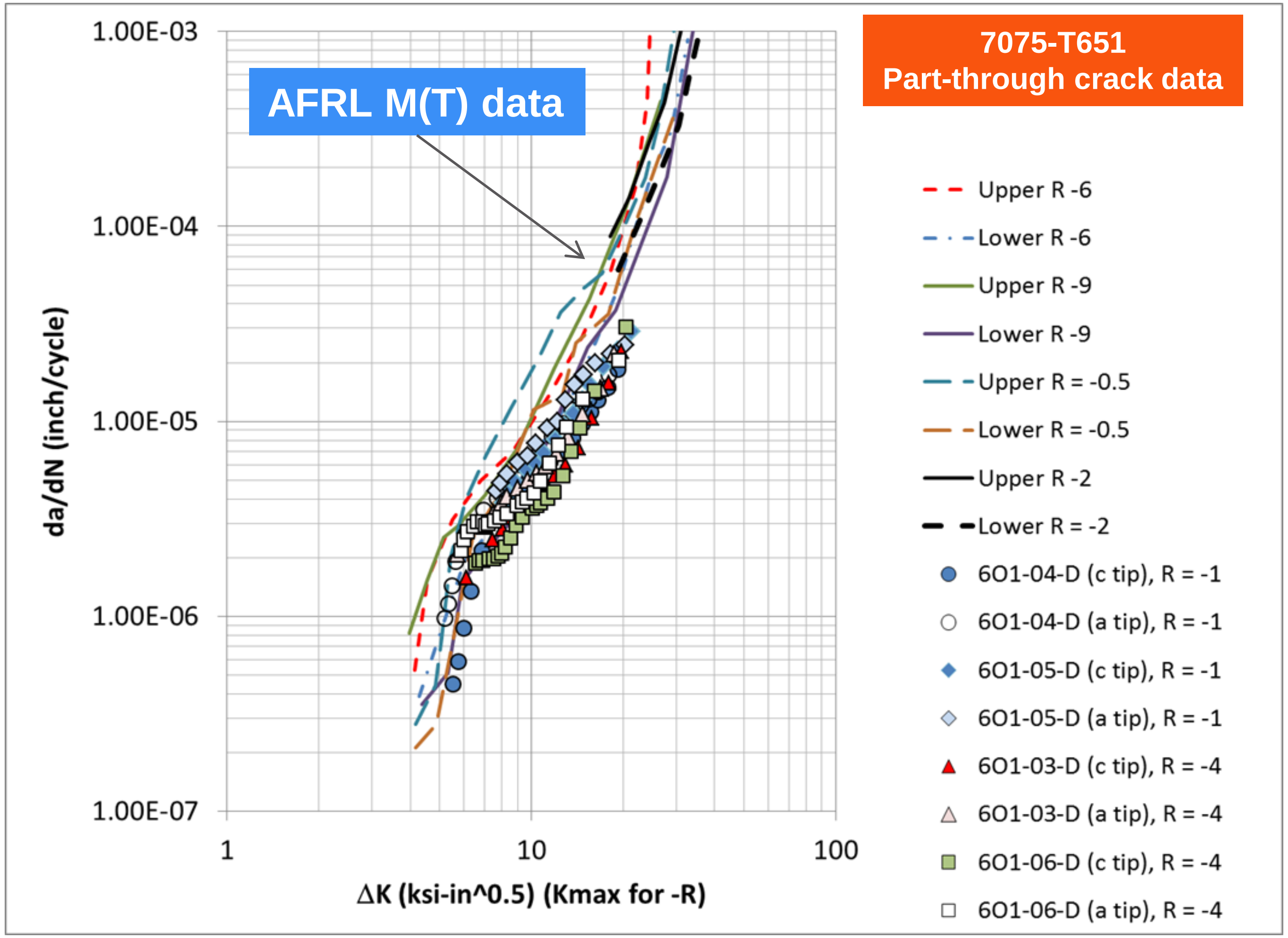
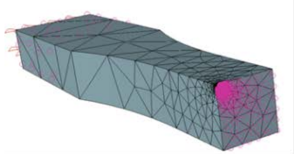
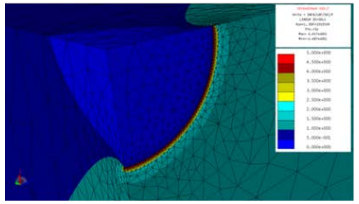
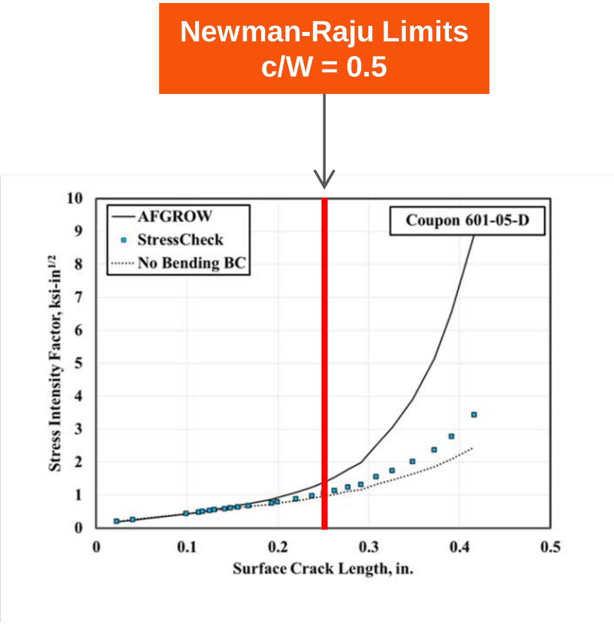
Negative R Testing









Contract Vehicle--Engineering and Analysis Activities in Aging Structures: A-10 ASIP Engineering Support

Public Release Authority: USAFA-DF-2018-322

Negative R Testing – Upcoming

- **Specimen Details: Center hole, corner crack, R=-1, σ_{Max} = 7.5 ksi**
  - Attempt detailed measurements in bore to get thru thickness rate data
  - 2024-T351 and 7075-T651
  - 3 specimens each
  - Testing by USAFA for A-10 ASIP; supported by SwRI & APES
- **2024 test specimens have been machined out of specimen remnants from the same material lot as the tests used in the round robin**
- **Augment growing Negative-R data sets for part-through cracks**
  - SwRI: R = -0.3 (presented data at ERSI last year)
  - APES: R = -1, R = -4
- **Variety of specimen geometries to compare with M(T) "long crack" data**

Conclusions/Summary

- **Significant Collaboration within Analysis Methods Subcommittee**
  - Thanks to those individuals that have provided inputs
- **First Cx Hole Residual Stress Round Robin Successful**
  - (8) submissions – thank you
- **Second Cx Hole Residual Stress Round Robin in Discussions**
- **Initial Best Practices Document Released**
  - Need inputs from community
- **Significant progress made on understanding crack closure implications to FCG modeling in residual stress fields**
- **Negative-R crack growth data continues to be developed for part-through crack geometries**

Questions?