Analytical Methods Subcommittee: Overview of Recent Efforts

Engineered Residual Stress Implementation Workshop 2017
September 21, 2017

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ERSI

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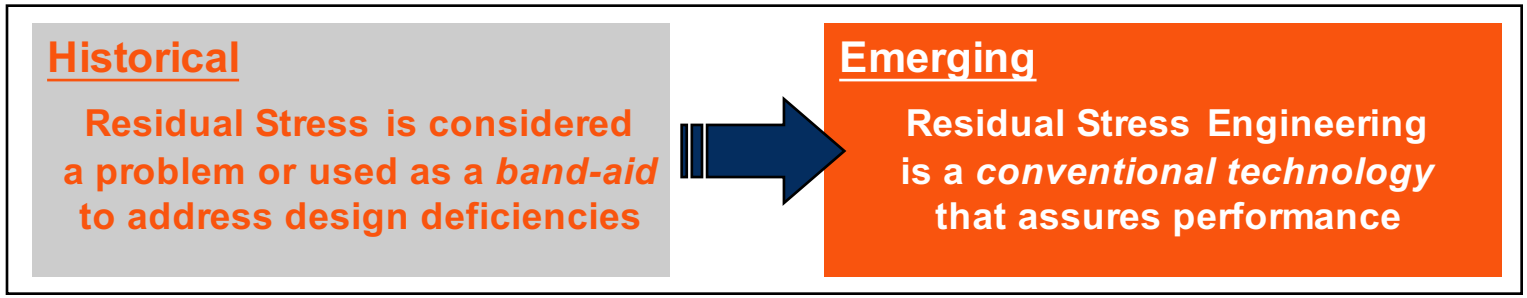
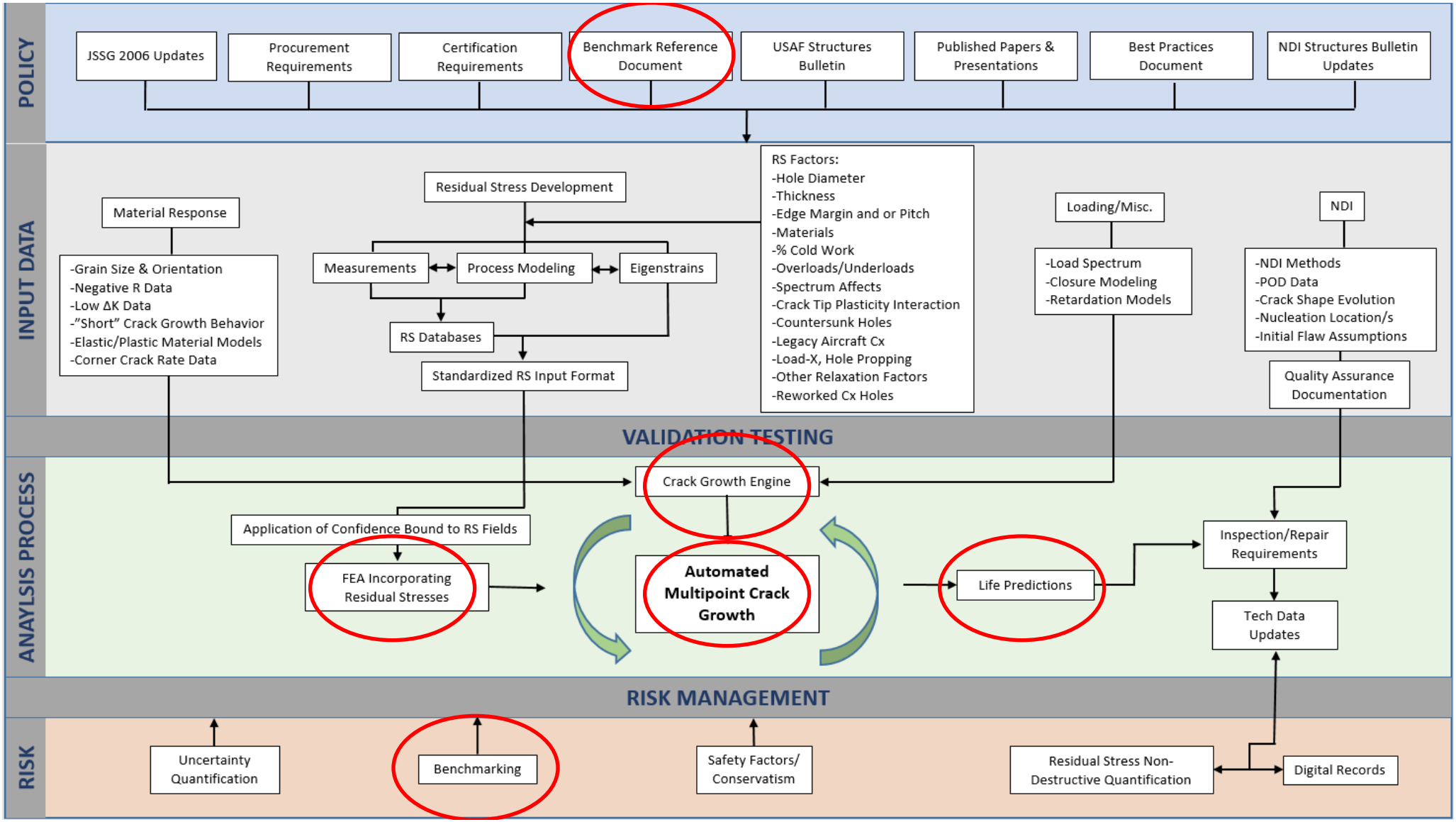
Acknowledgements

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



Agenda

- Round Robin for Cx Holes
- Best Practices Document
- Engineering Implementation of Residual Stress
- Near Surface Residual Stress
- Residual Stress Relaxation
- Overloads/Underloads/Load-X
- Multi-Crack Effects


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 Data
-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

- 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

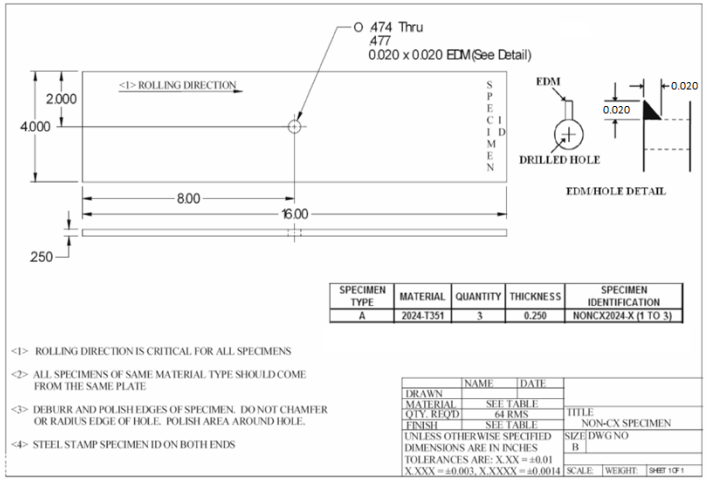
Round Robin for Cx Holes

❑ 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

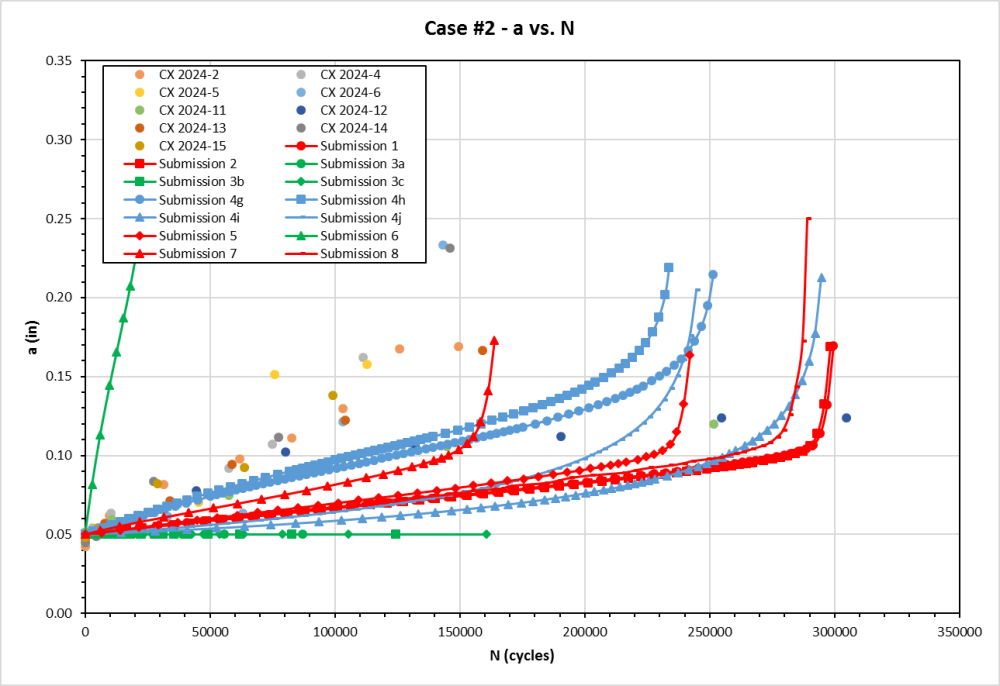
- How do we measure "success"?
- Recall, we are focused on the systematic, not random uncertainties
- The goal is to understand the consistency, strengths and weaknesses of different analysis methods to focus our efforts moving forward
- Analysis comparisons:
  - a vs. N, c vs. N
  - da/dN vs. a, dc/dN vs. c
  - a/c vs. a/t
  - Goodness of fit
  - Thru thickness transition
  - Critical crack length
  - Slope transition point

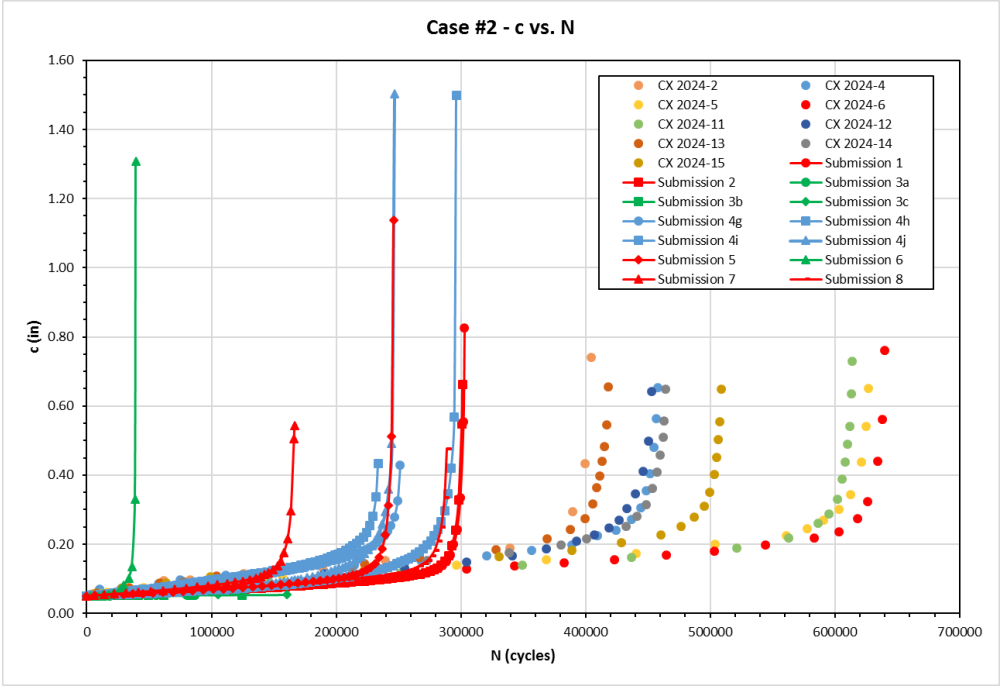
Legend:
- Coupled FEA-Crack Growth
- AFGROW Standard Solutions
- NASGRO Standard Solutions

Key modeling factors summary sheets available for each case

Round Robin for Cx Holes - Case #2

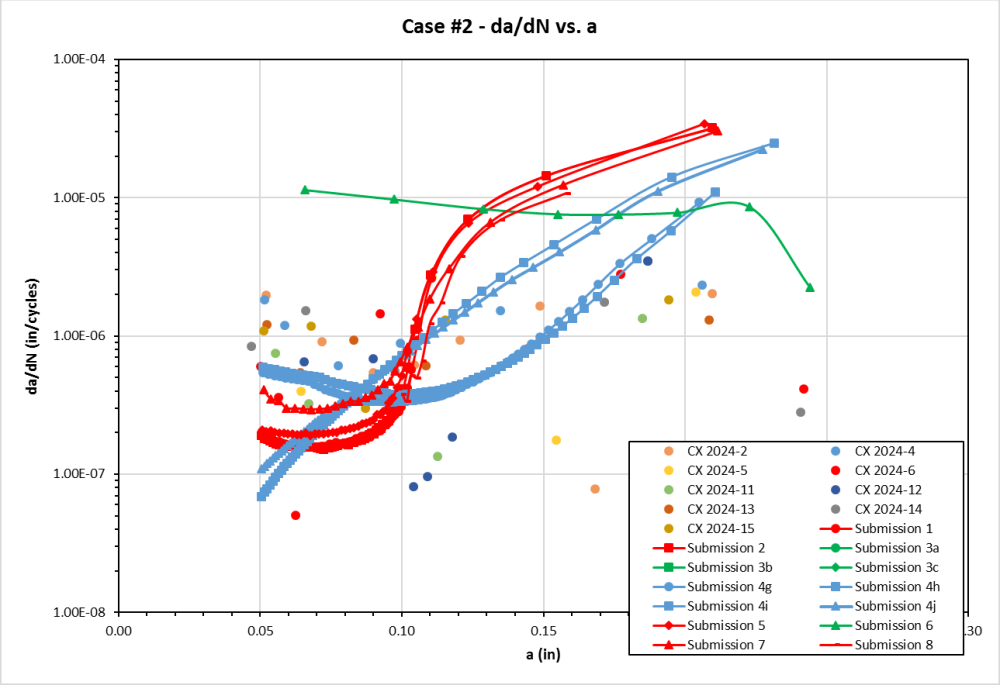
❑ Cx Centered Hole

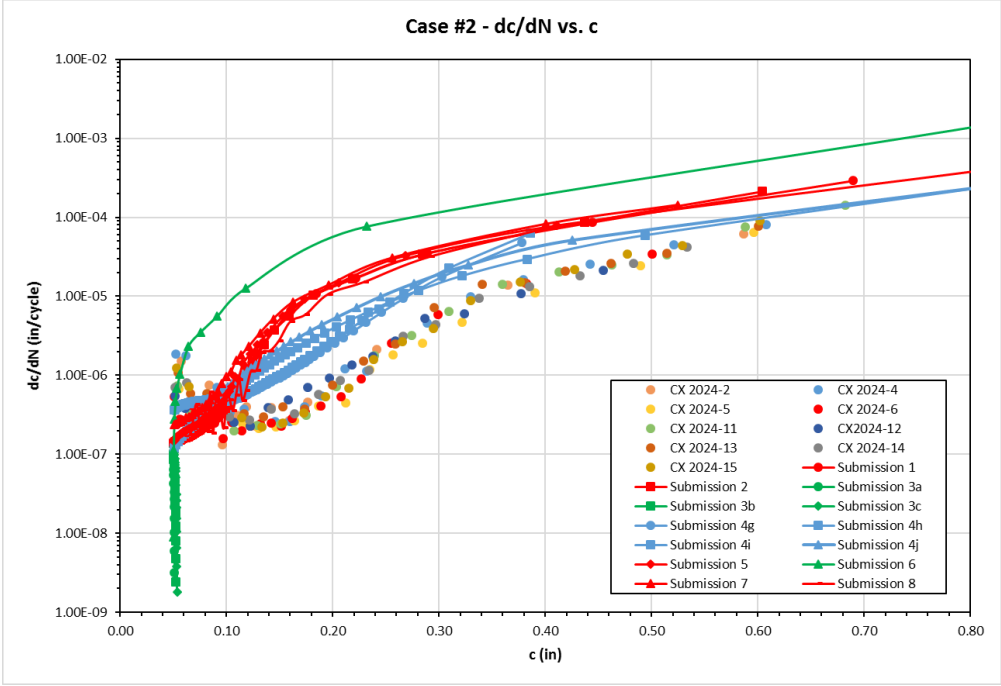




Round Robin for Cx Holes - Case #2

- Cx Centered Hole





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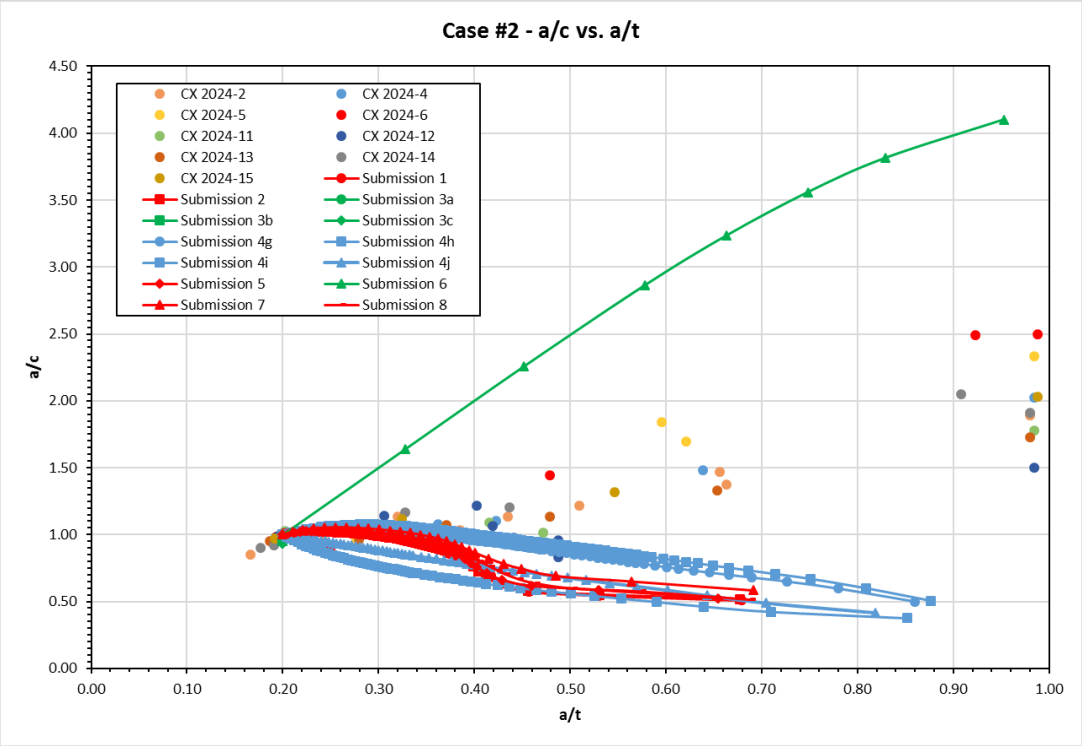

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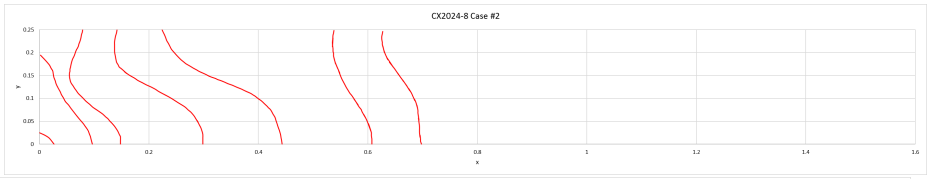

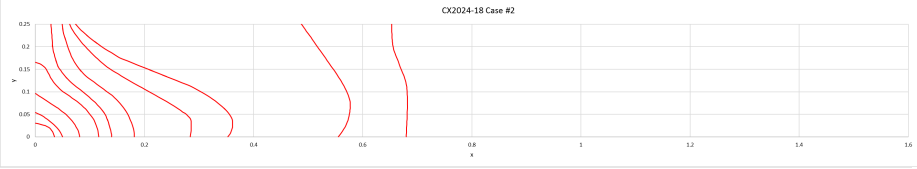

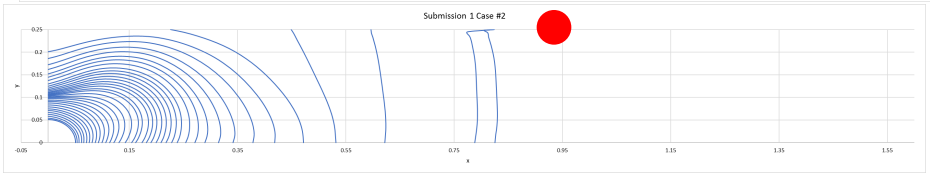

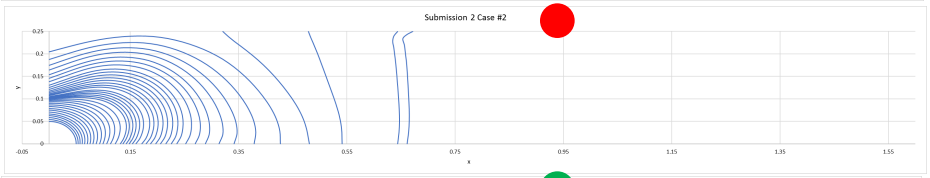

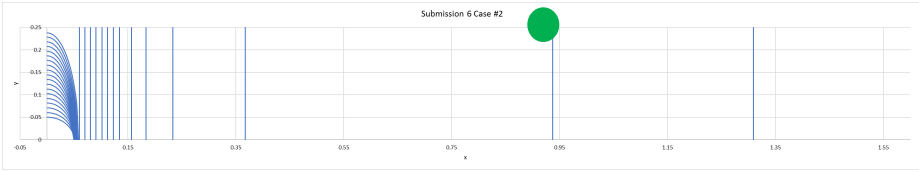

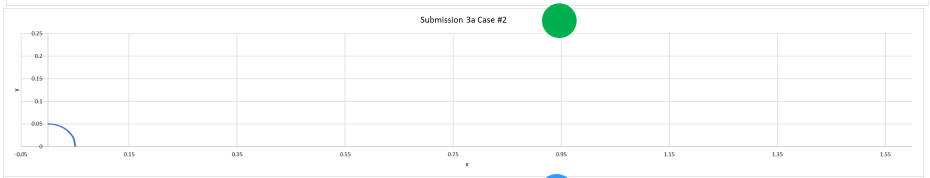

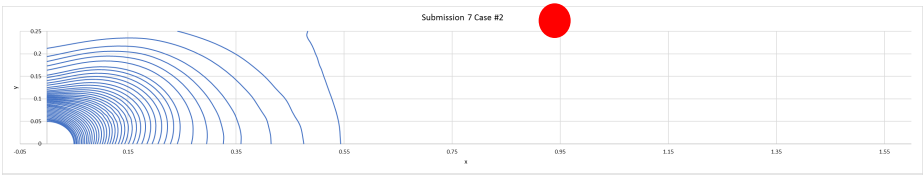

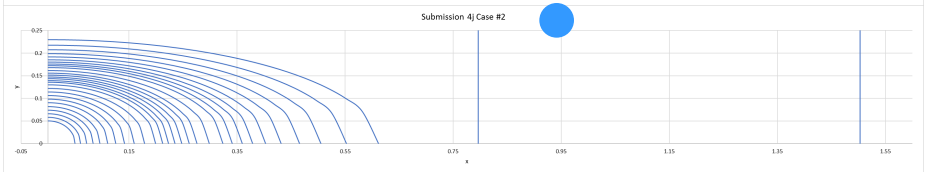

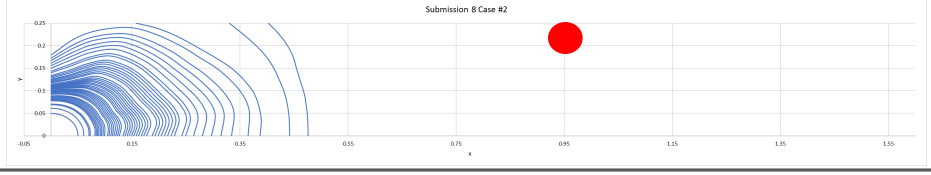

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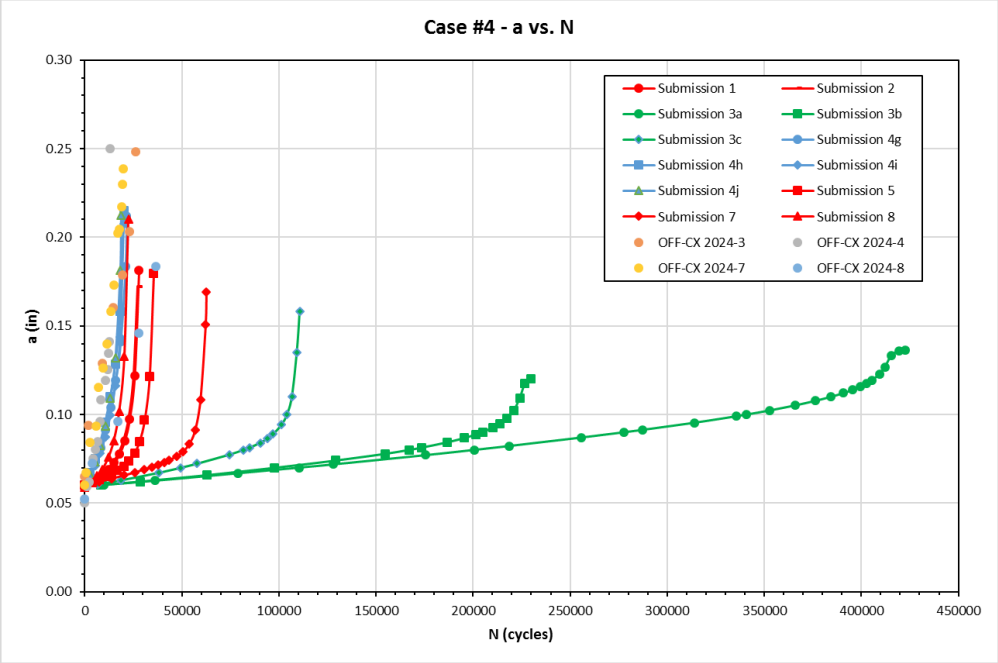
Round Robin for Cx Holes - Case #2

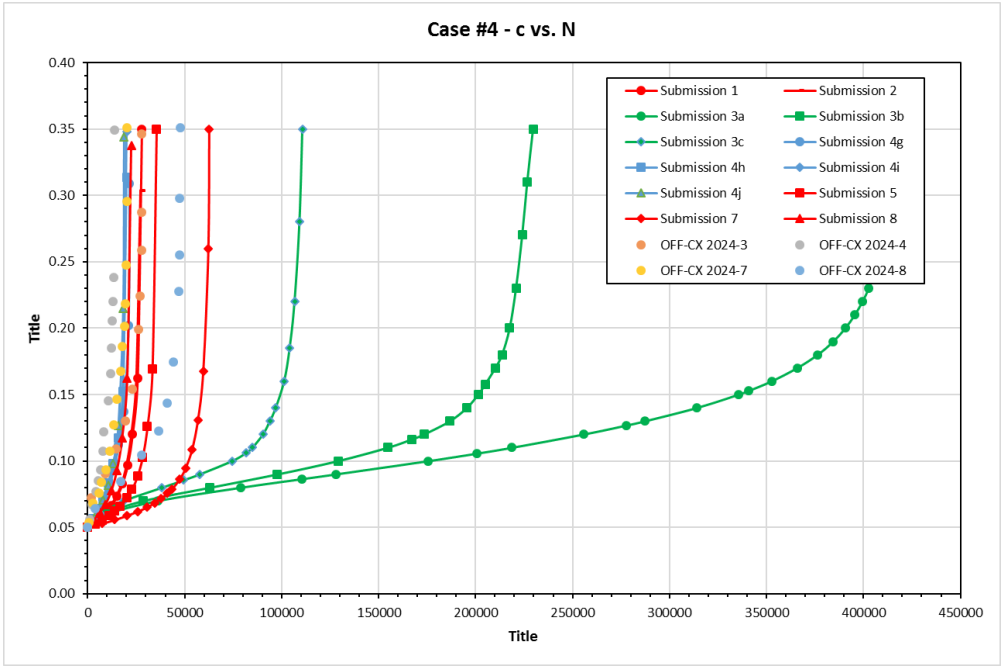
❑ Cx Centered Hole Summary

- ➢ Fatigue life
  - Gaussian integration – AFGROW – No growth for several cases
  - Consistency between similar analytical approaches
  - Under-predict test lives
- ➢ Growth rates
  - Initial – under-predict
  - >0.10” – over-predict
- ➢ Crack aspect ratio
  - Predictions ≠ test behavior

Round Robin for Cx Holes - Case #4

❑ Cx Offset Hole





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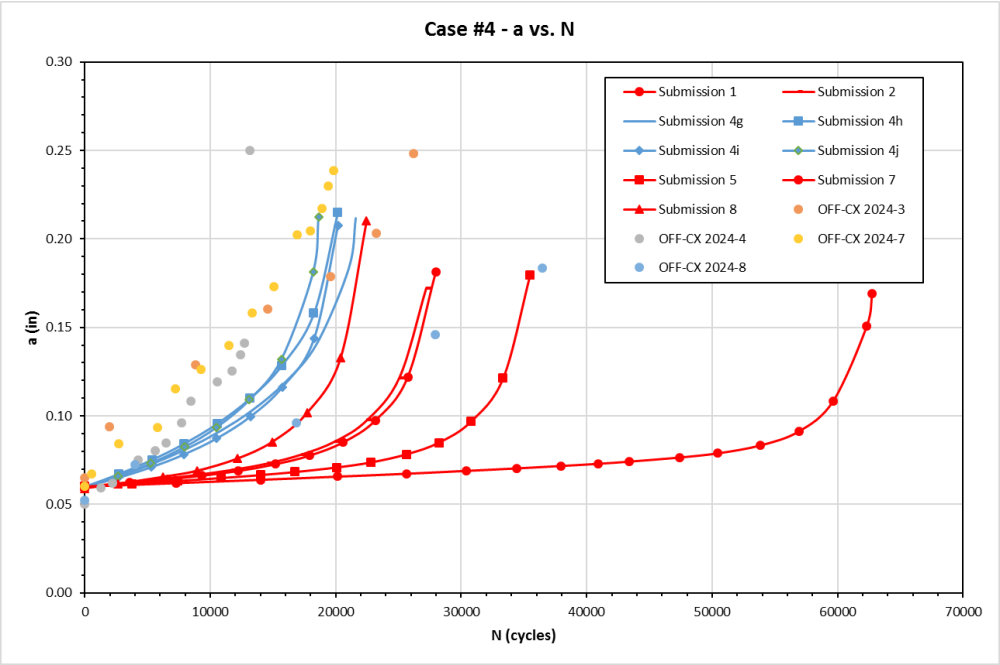

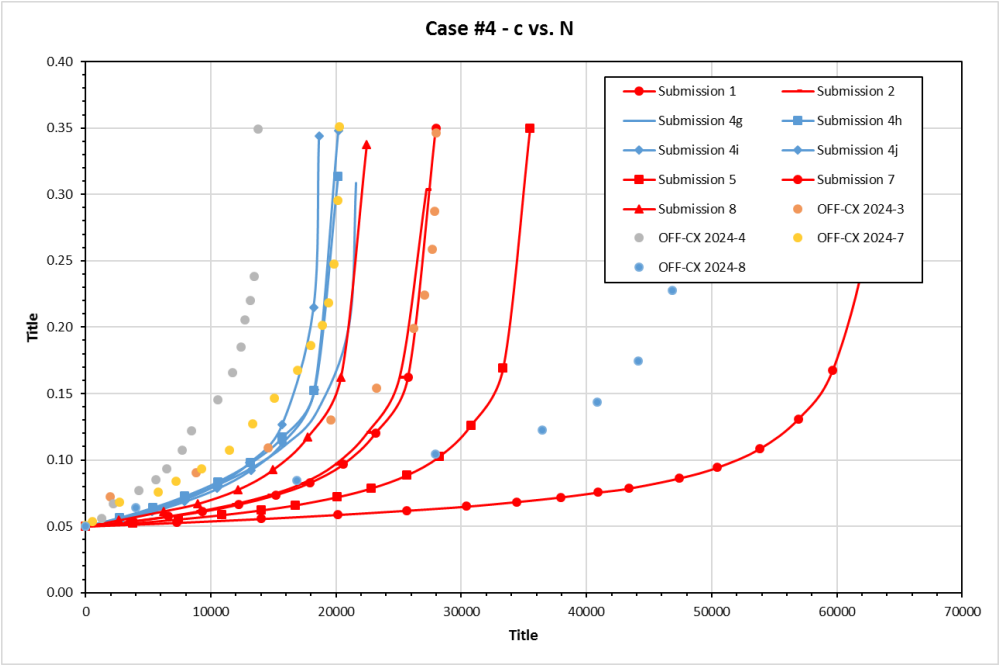

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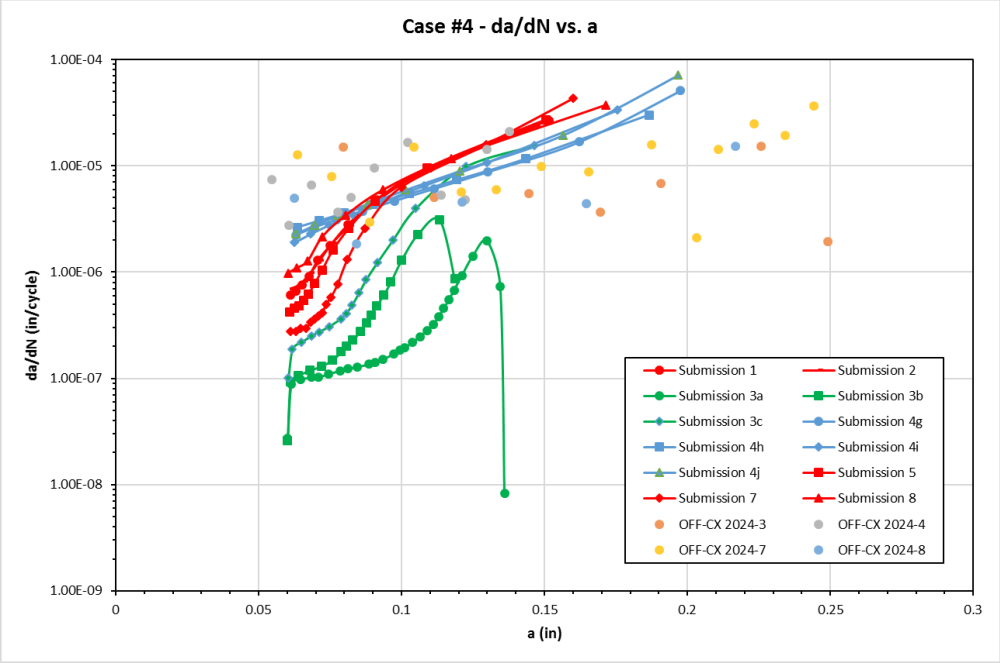
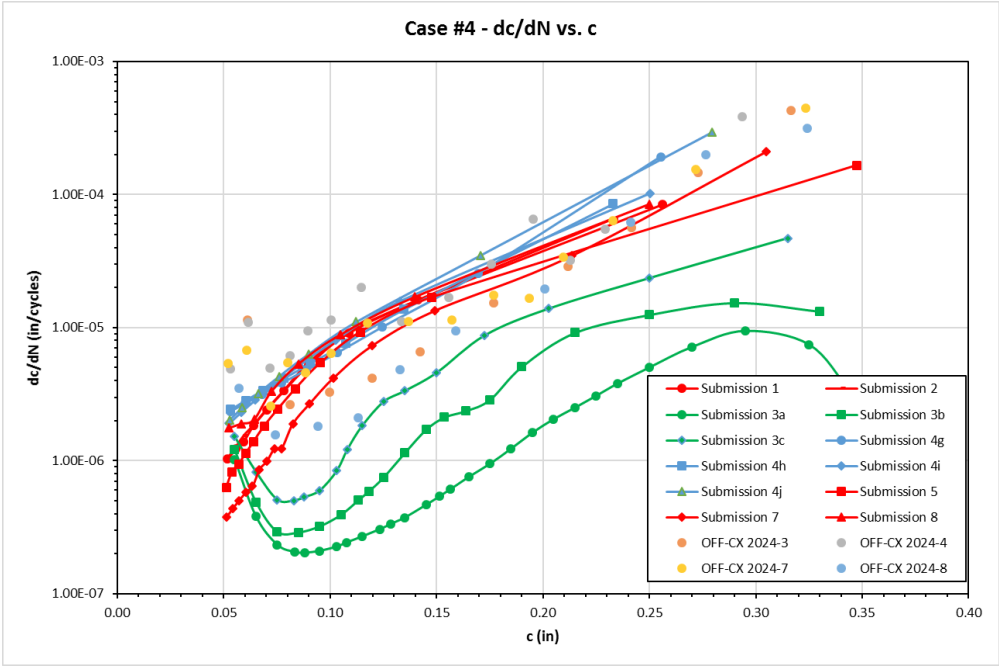
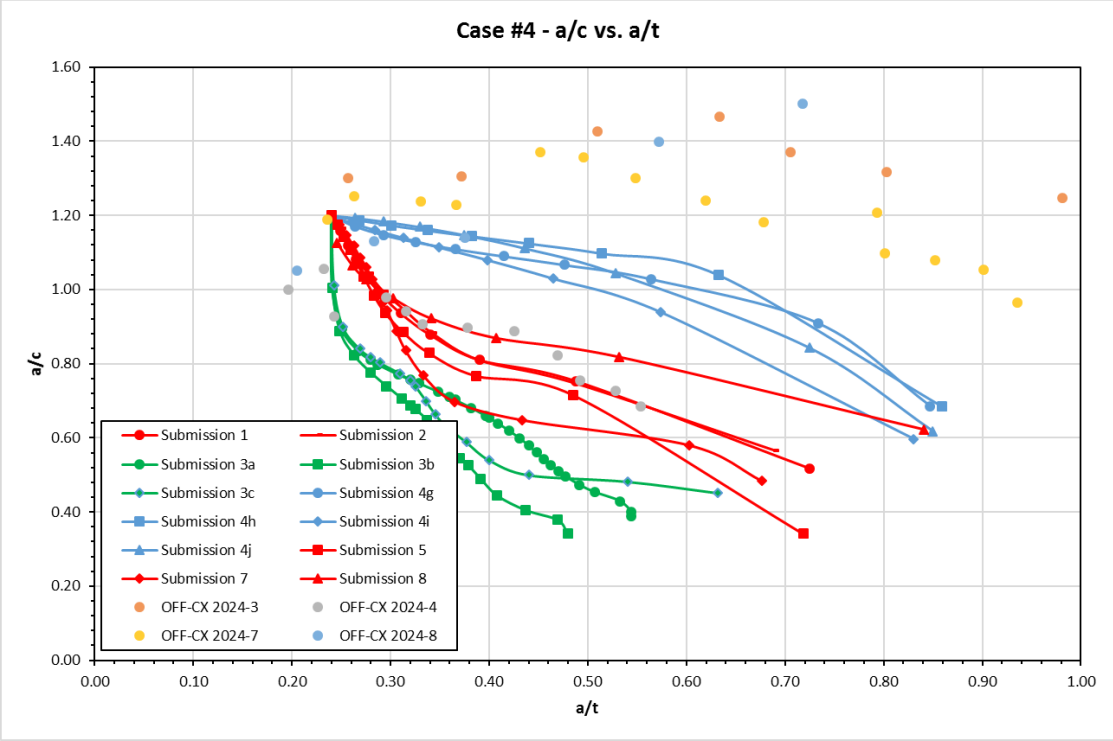




Round Robin for Cx Holes - Case #4

- Cx Offset Hole



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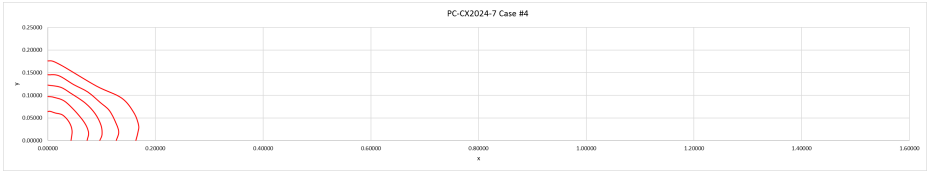
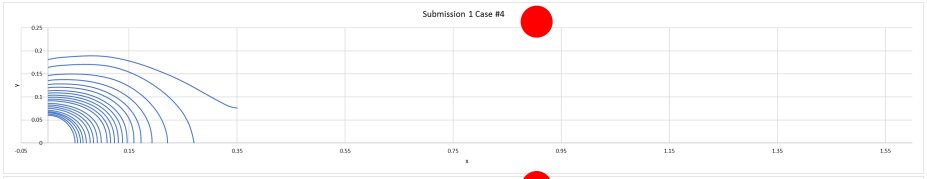
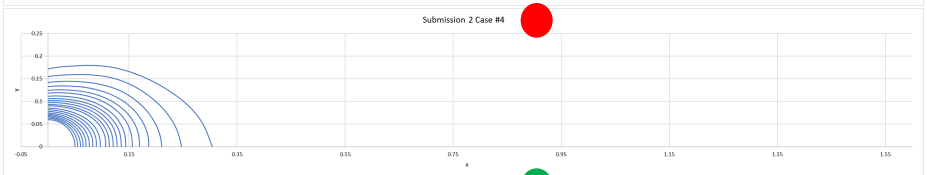
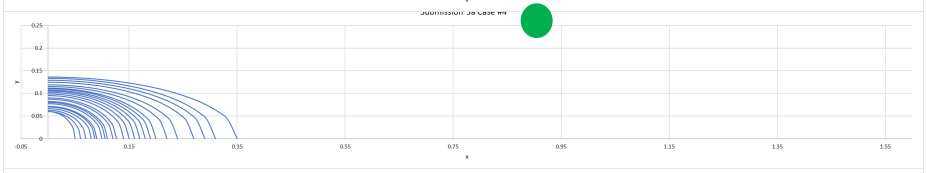
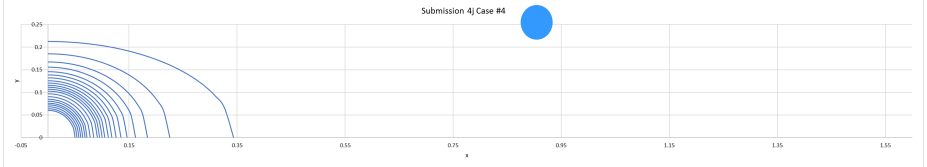
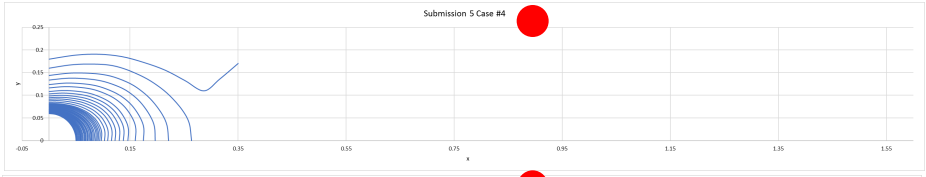


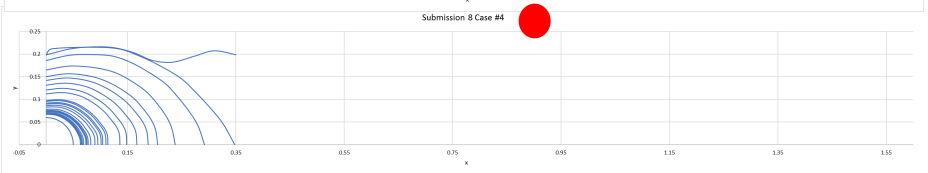










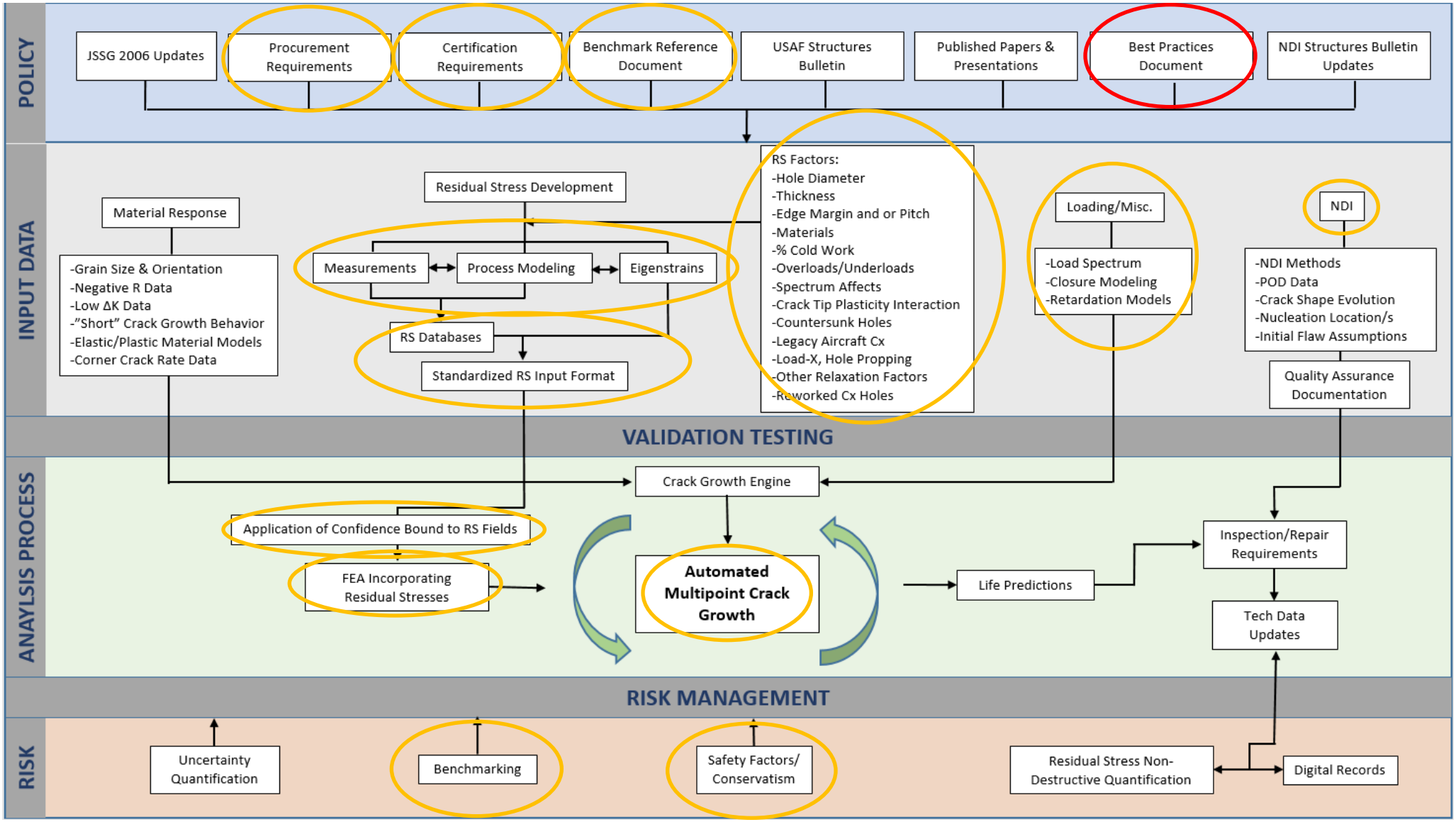


Round Robin for Cx Holes - Case #4

- **Cx Offset Hole Summary**
  - Fatigue life
    - Gaussian integration – AFGROW – significant over-prediction of life
    - Consistency between similar analytical approaches
    - Reasonable predictions
  - Growth rates
    - Initial – under-predict – coupled FEA-crack growth
  - Crack aspect ratio
    - Variation between test coupons

Round Robin for Cx Holes - Summary

- **Collectively Review Results in Analysis Methods Subcommittee**
  - Additional approaches to compare/contrast results
- **Identify:**
  - Analysis best practices
  - Focus areas for additional investigation
- **Publish Journal Article**
- **Identify Follow-On Round Robin Details**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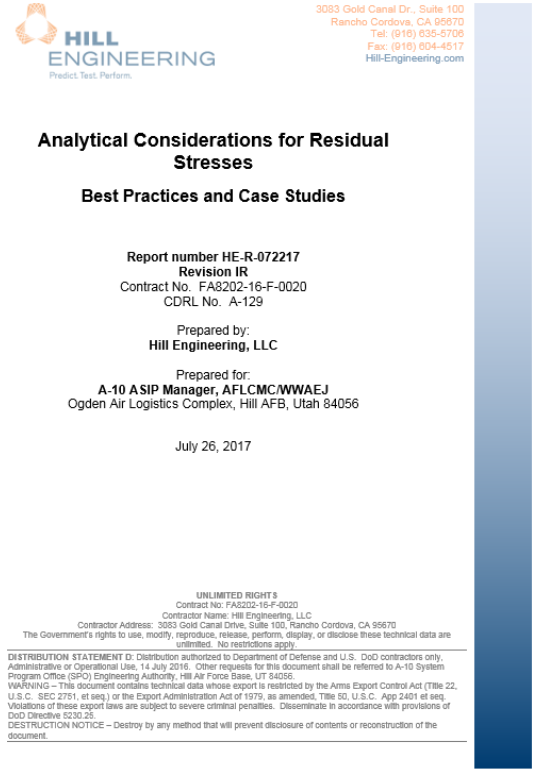
Best Practices Document

- **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:
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Prepared for:
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July 26, 2017

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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

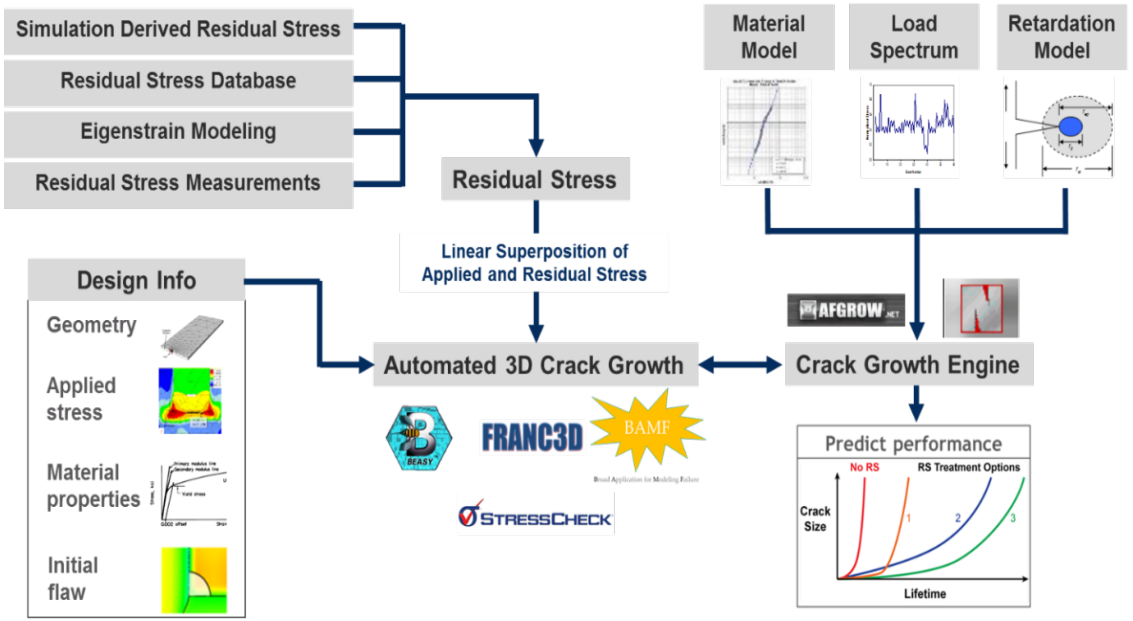
Strengths & Weaknesses of Various Residual Stress Measurement Techniques

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

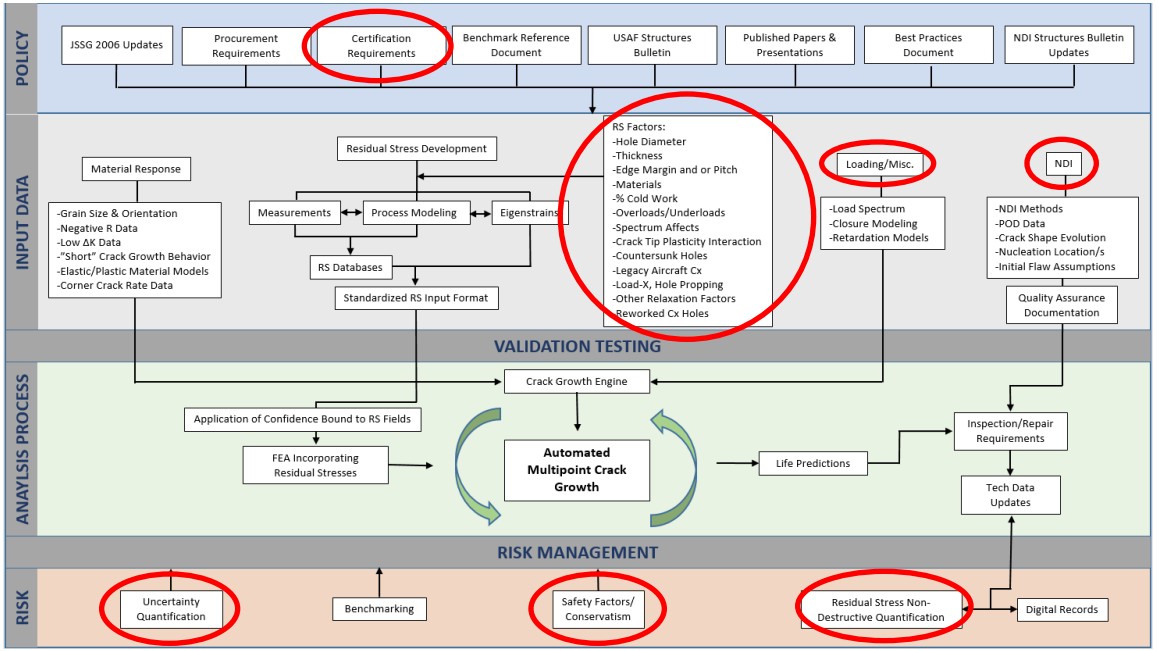
- ➢ Overview of analytical processes
- ➢ Key input data
  - Design info
  - Material models
  - Loading spectrum & retardation
  - Residual stress
- ➢ Analysis processes
  - Multi-point fracture mechanics
  - Coupled FEA
  - Other analytical approaches
- ➢ Way forward & recommendations



Best Practices Document

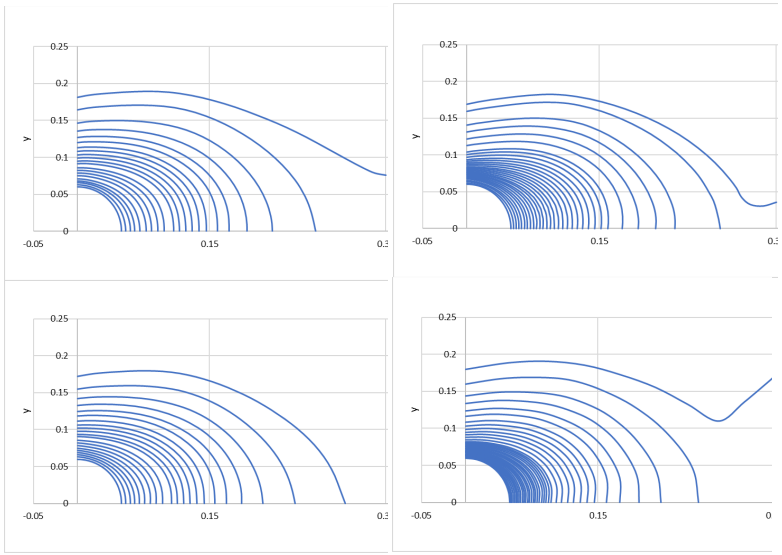
❑ Chapter III – Other Considerations

- ➢ 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

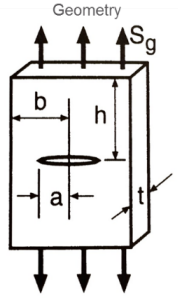
- **Chapter IV – Benchmark Cases**
  - Handbook solutions
  - ERSI round robin results

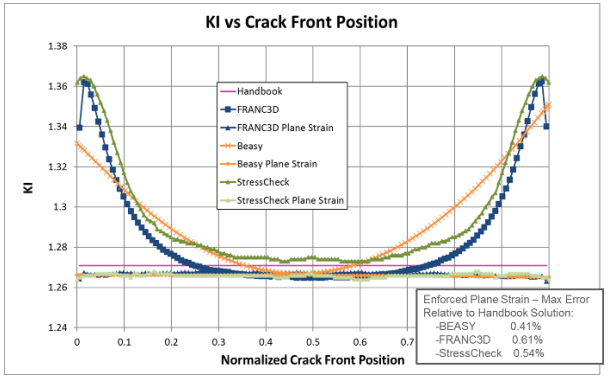


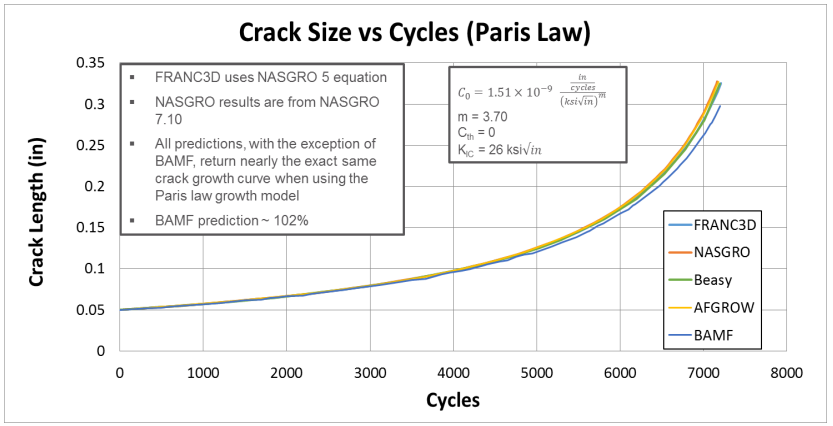
Dimensions (inches)

h = 5
b = 5
a = 0.5
t = 5

Material: E = 3.0e7, v = 0.30
Loading: Uniform unit stress (1 psi)

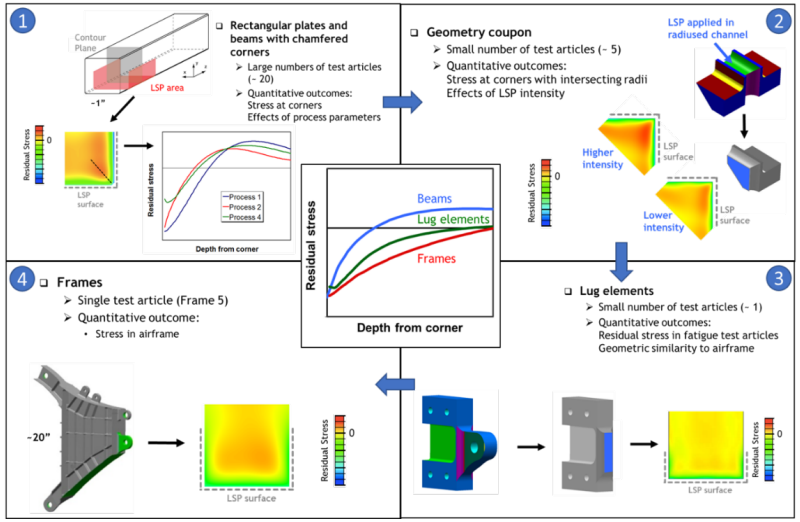




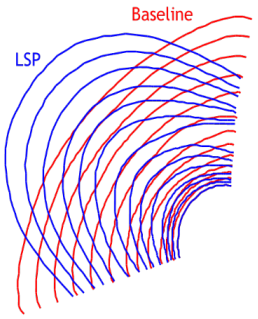


Best Practices Document

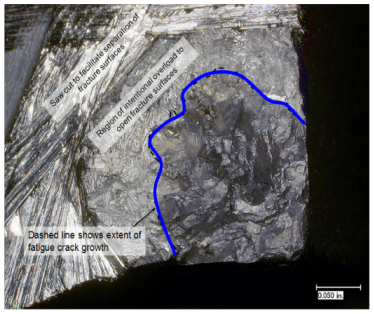
- **Chapter V – Case Studies**
  - Laser shock peening case study
  - Cx hole case study

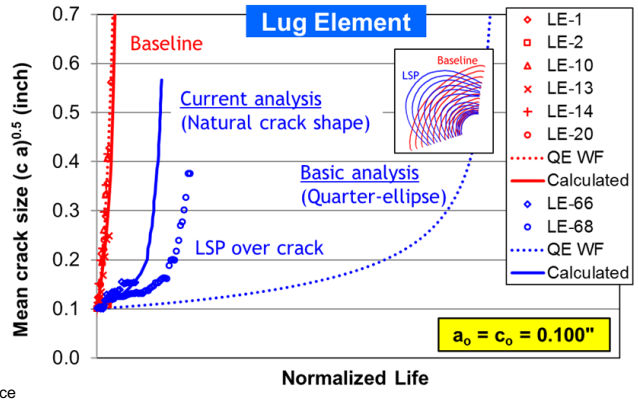


Predicted crack shape evolution



Observed crack shape for LSP (Frame 2 test article)





References:
Polin, L., Bunch, J., Caruso, P., McClure, J. (2011), F-22 Program Full Scale Component Tests to Validate the Effects of Laser Shock Peening, 2011 ASIP Conference
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

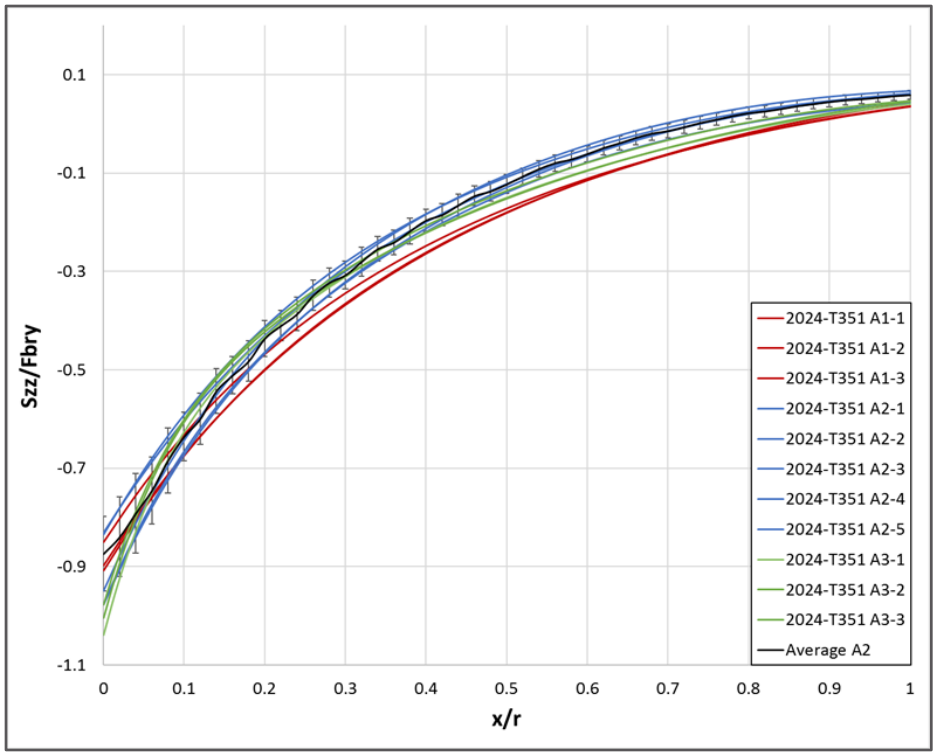
Best Practices Document

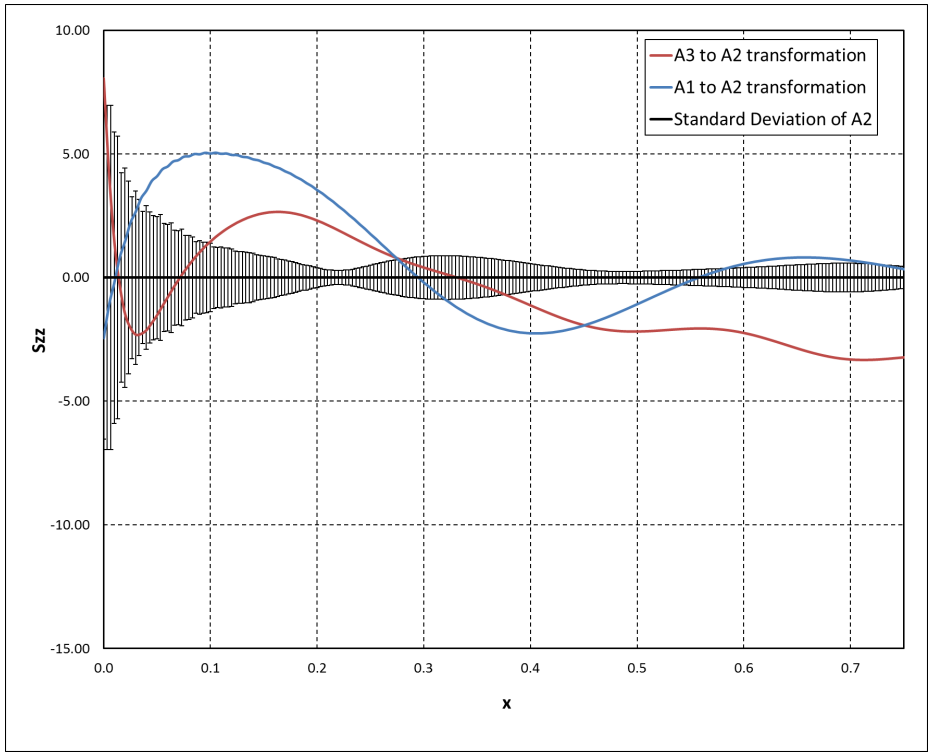
- **Current Status**
  - Initial draft delivered end of Sep. 2017
  - Review/feedback from USAF
- **Moving Forward**
  - Document only as good as the inputs provided by community
  - Need inputs related to:
    - Process modeling best practices
    - Other analysis methods
    - Factors that influence residual stress
    - Risk assessment considerations
    - Certification considerations
    - Procurement vs. sustainment considerations
    - Case studies

WE NEED YOU!!

Engineering Implementation of Residual Stress

- Non-Dimensional Residual Stress – Hole Diameter

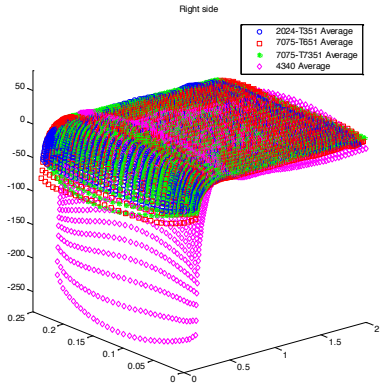




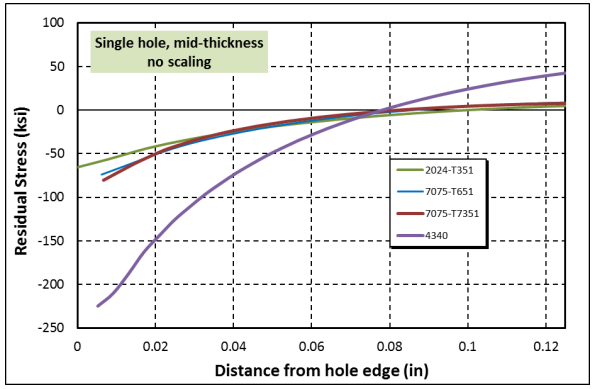
Engineering Implementation of Residual Stress

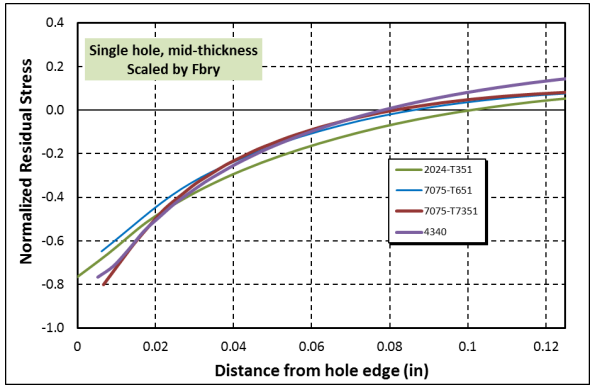
❑ Non-Dimensional Residual Stress – Material Properties

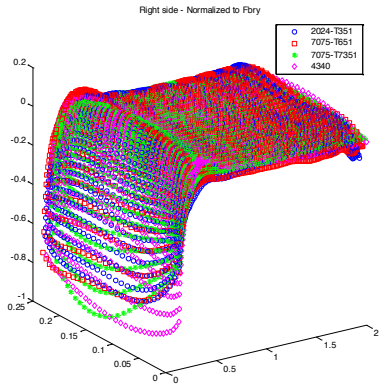
➢ Can we utilize basic material properties (F_{ty}, F_{su}, F_{bru}, F_{bry}, etc.) to understand residual stress variations across different material types?



From MMPDS-04	2024-T351	7075-T651		7075-T7351		4340	
Basis	A	A		A		S	
Ftu (L)	64	77	1.20	67	1.05	220	3.44
Fty (L)	48	69	1.44	55	1.15	185	3.85
Fcy (L)	39	67	1.72	54	1.38	193	4.95
Fsu (L)	38	43	1.13	38	1.00	132	3.47
Fbru (e/D=1.5) (L)	97	117	1.21	105	1.08	297	3.06
Fbru (e/D=2.0) (L)	119	145	1.22	134	1.13	385	3.24
Fbry (e/D=1.5) (L)	72	97	1.35	83	1.15	267	3.71
Fbry (e/D=2.0) (L)	86	114	1.33	100	1.16	294	3.42

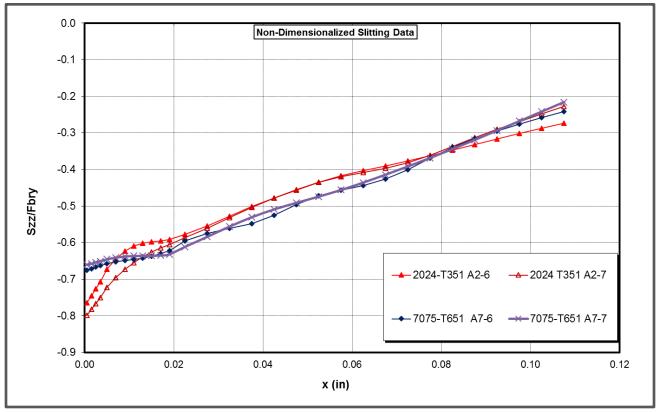


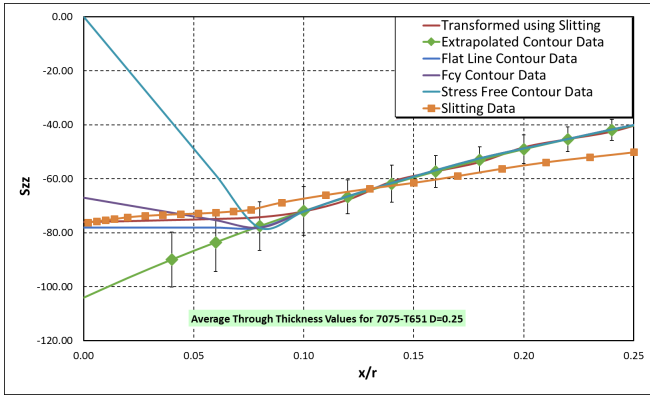




Refine Near Surface Residual Stress Understanding

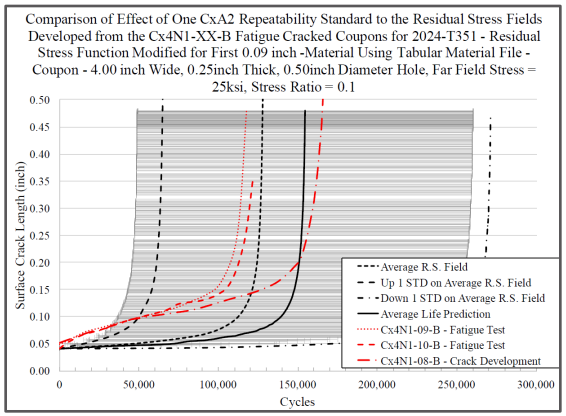
- Investigate compliment of different measurement techniques to understand near surface residual stress
  - All measurement techniques have strengths/weaknesses
  - Cx hole process modeling and measurement investigation
  - Geometrically “large” coupon program
- Investigate engineering approaches to near surface residual stress behavior
  - Impacts on:
    - Residual stress
    - Residual stress intensity, K_{res}
    - Damage tolerance life

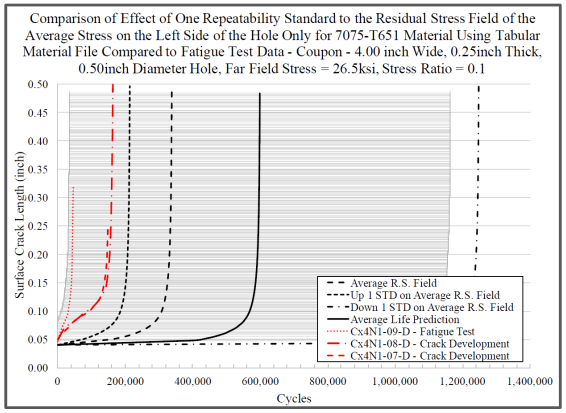




Residual Stress Relaxation

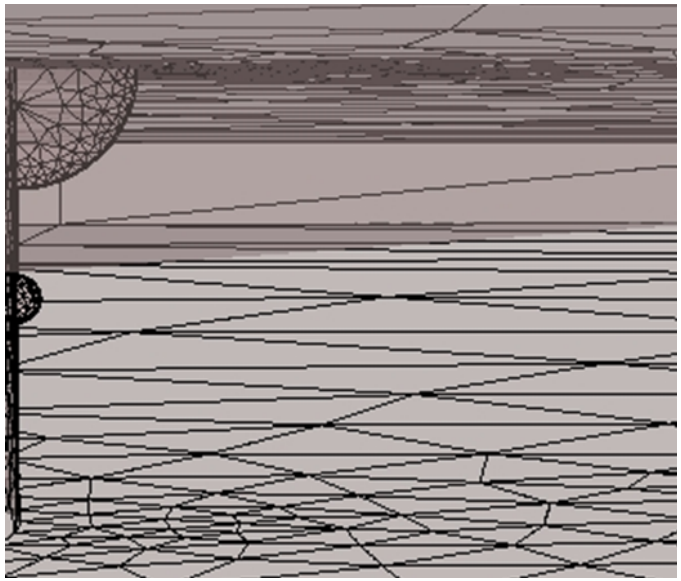
- Modeling Residual Stress Relaxation under Cyclic Loading (Jones)
  - Short presentation in breakout session
- Quantifying the Effect of a Fatigue Crack on the Residual Stress Field (Carlson)
- Effects of Tensile and Compressive Overloads (APES-AA&S)
  - Open and filled holes
- Effects of Load Transfer (APES-AA&S)
- Legacy vs. New Manufacture Residual Stress Comparisons
  - Review during measurement overview presentation





Other Focus Areas

- **Multi-Crack Effects (APES, HE)**
  - Compare growth of single crack with same primary crack (mandrel entrance corner) in presence of secondary bore crack.
  - Compare evolution of SIFs (primary crack) for single vs. multi-crack scenarios.
- **Crack Closure Effects (APES)**



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
  - Need to digest results to understand key findings
- **Best Practices Document Established**
  - Need inputs from community
- **Additional Programs Addressing Key Modeling Factors/Questions**

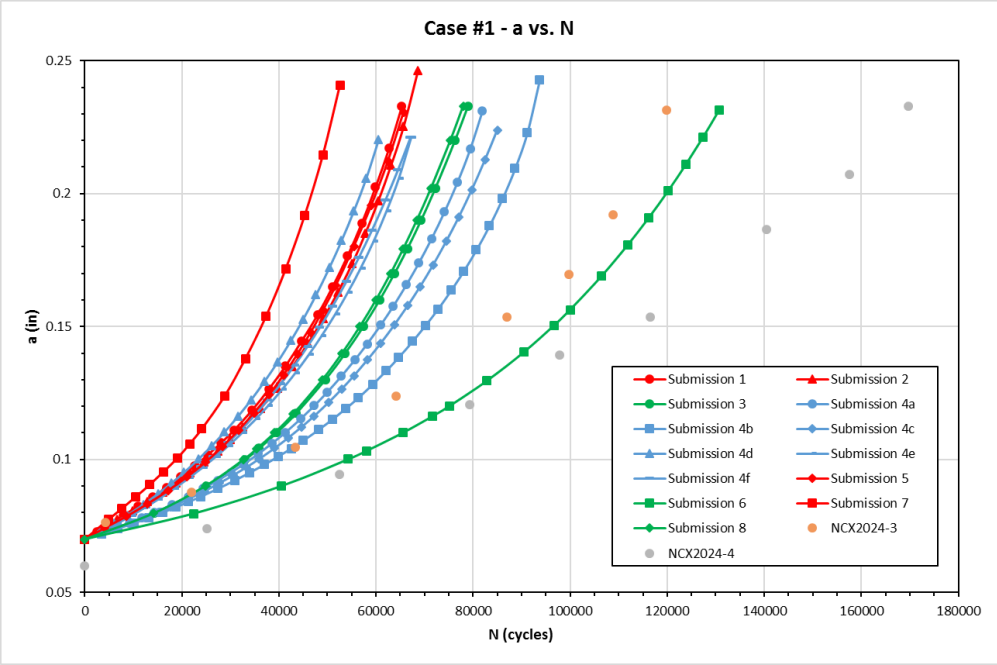
We are Positively Progressing Progressively – Cheers!!

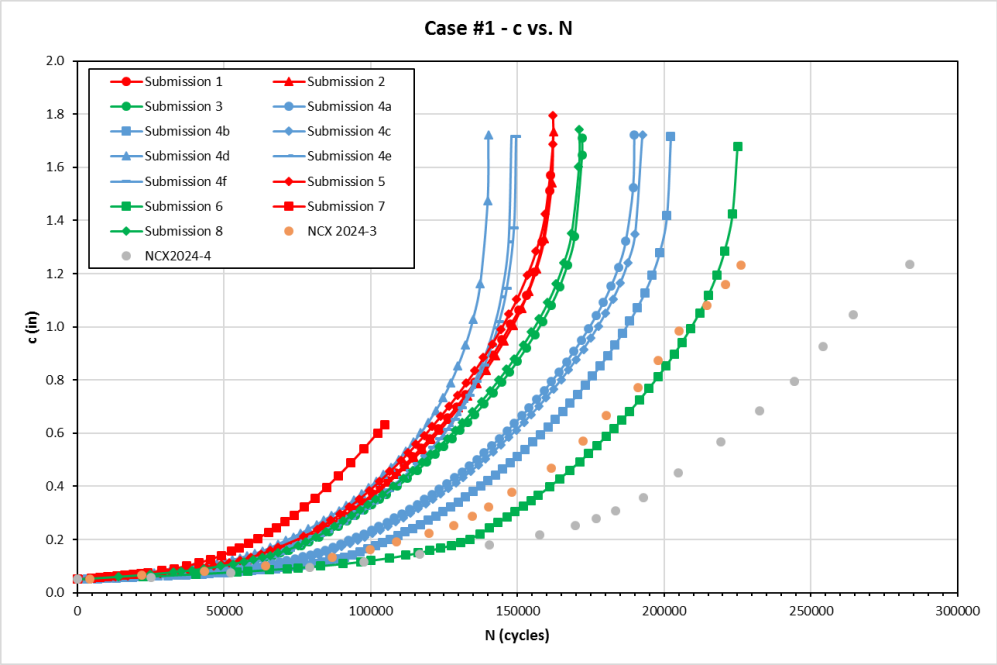
Questions?

Backup Slides

Round Robin for Cx Holes - Case #1

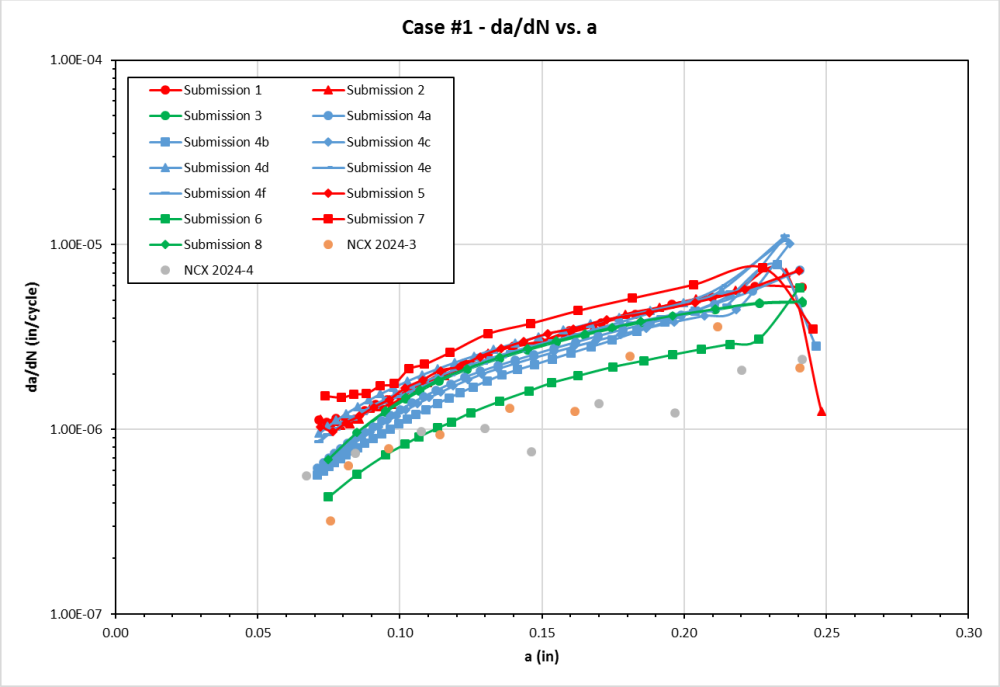
- Non-Cx Centered Hole

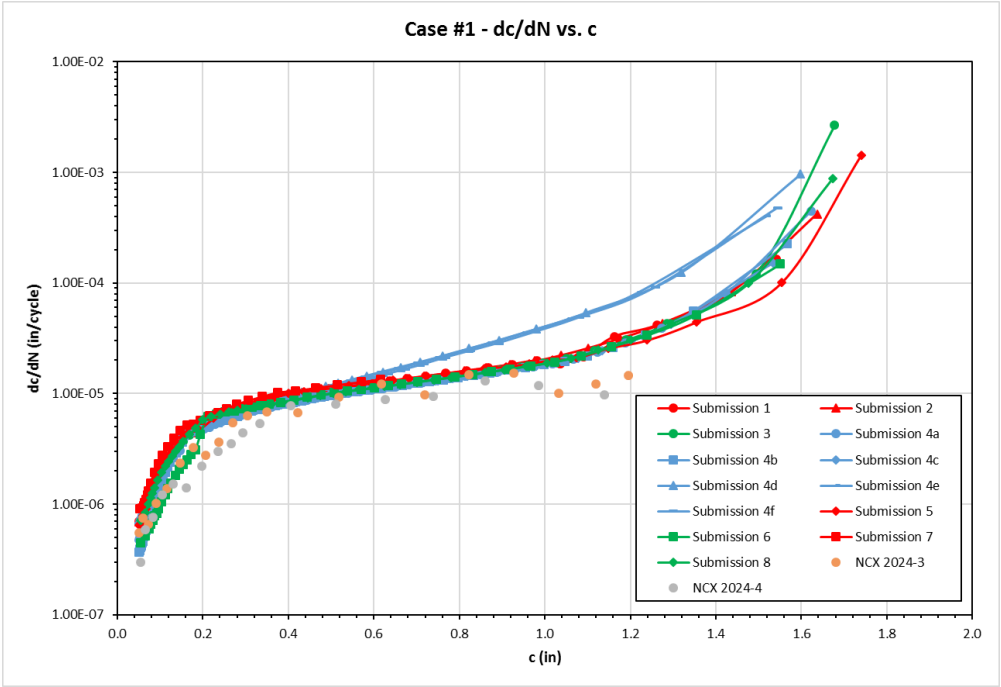




Round Robin for Cx Holes - Case #1

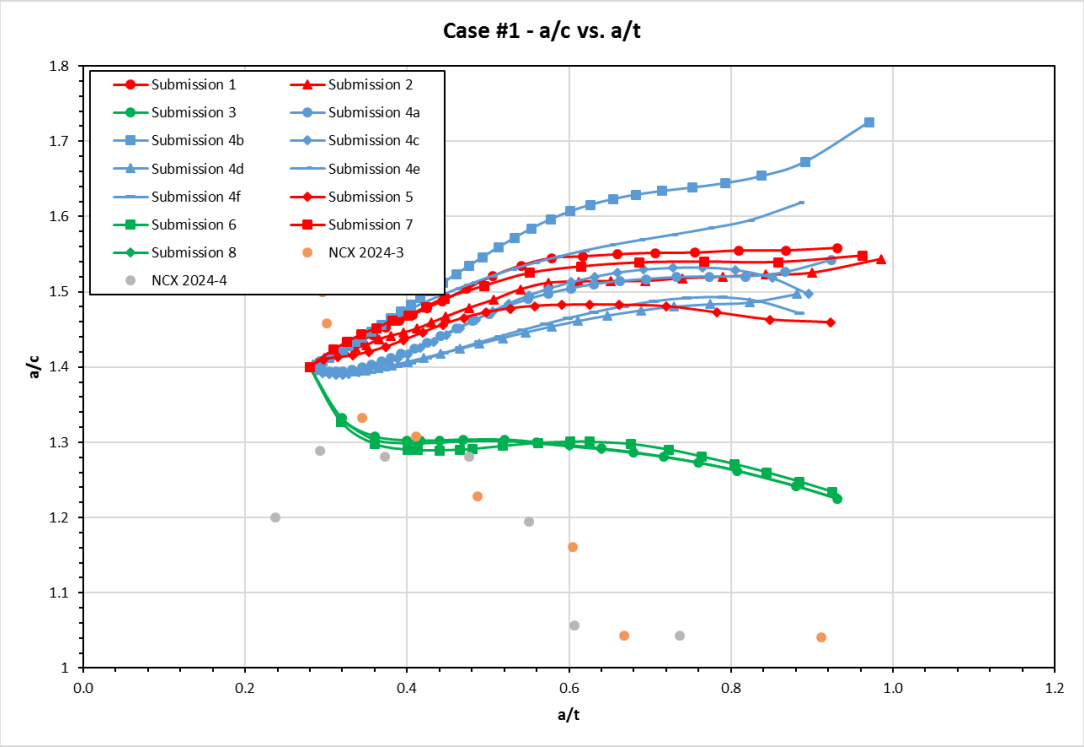
❑ Non-Cx Centered Hole



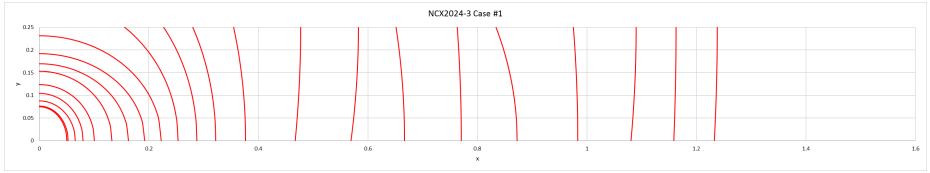


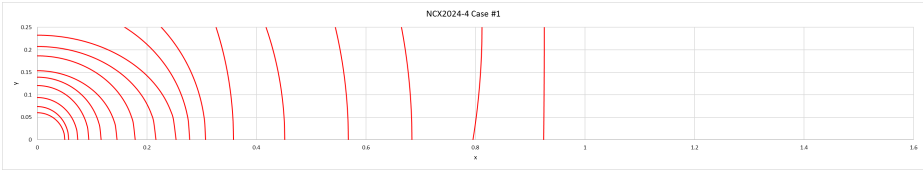
Round Robin for Cx Holes - Case #1

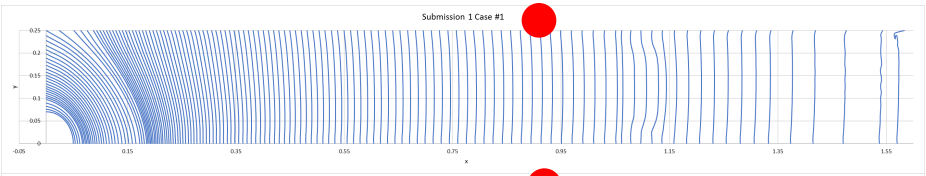
- Non-Cx Centered Hole

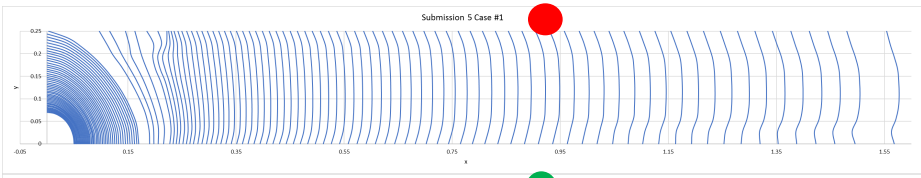


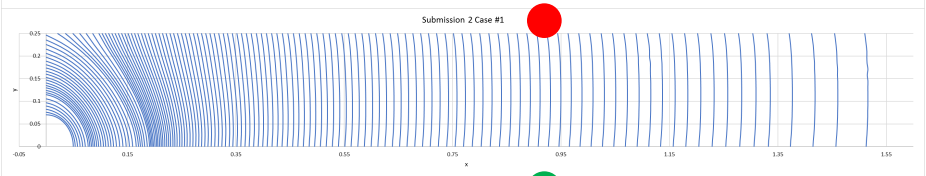
Round Robin for Cx Holes - Case #1

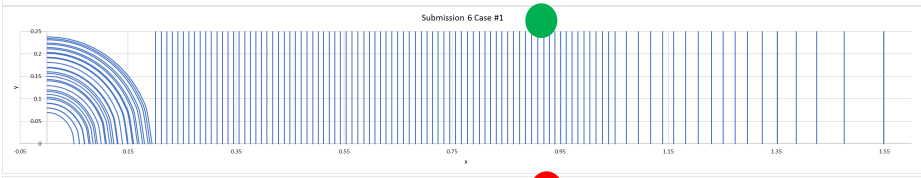


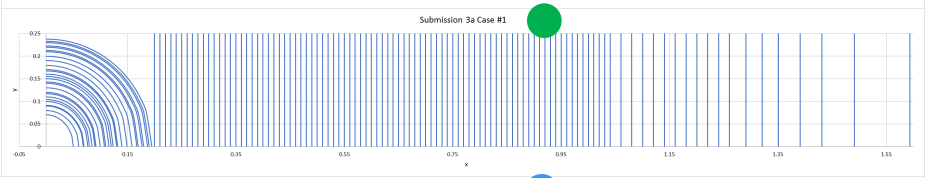


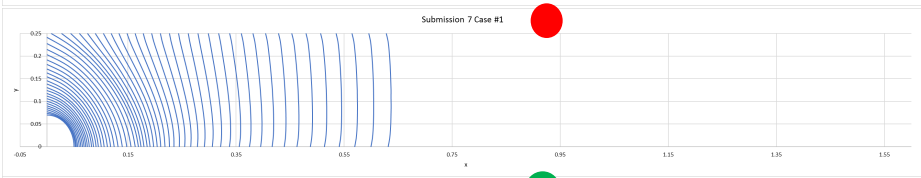


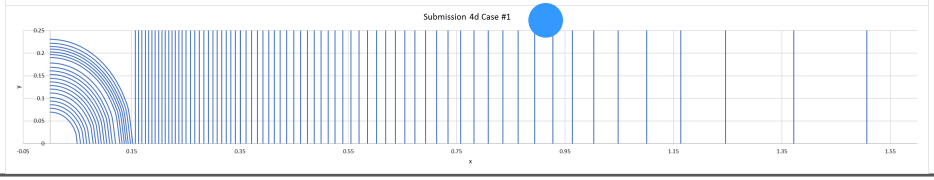


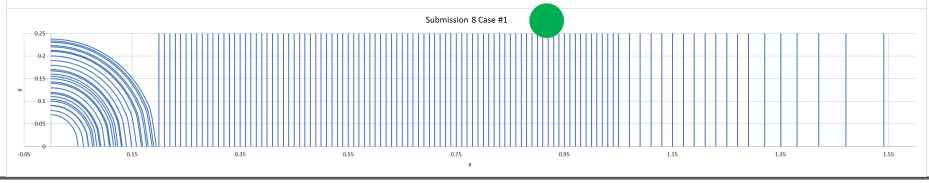












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Predict. Test. Perform.

ERSI

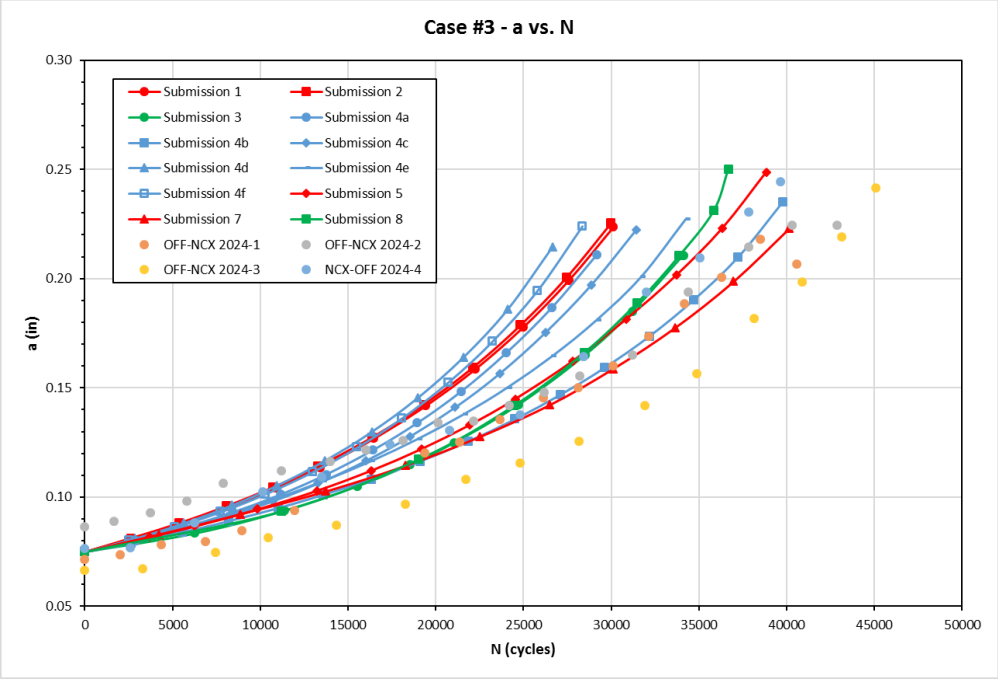
Round Robin for Cx Holes – Case #1

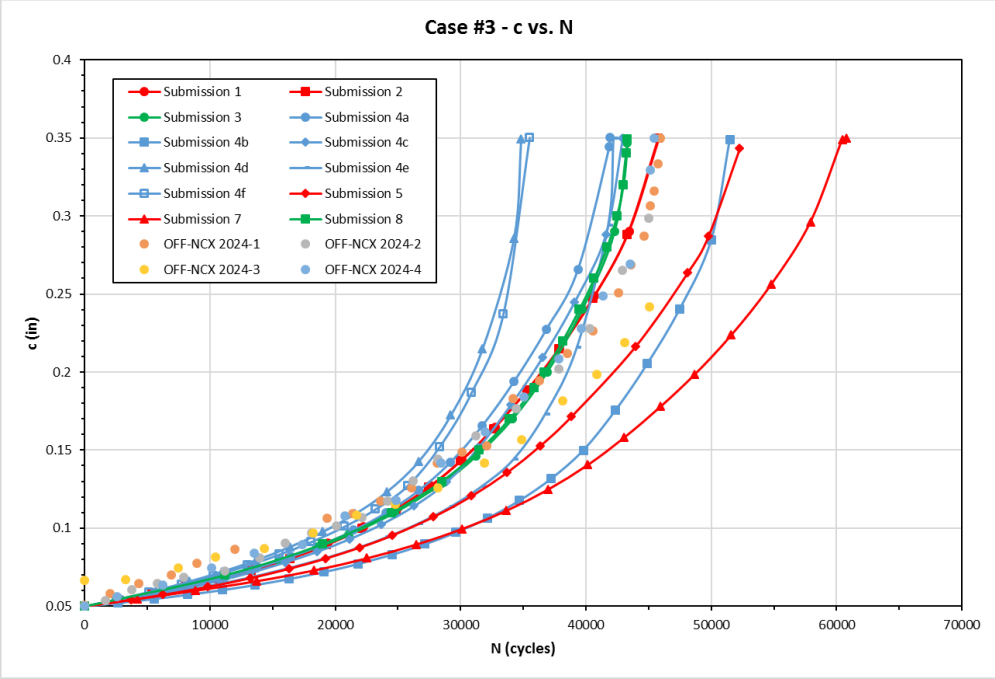
❑ Non-Cx Centered Hole Summary

- ➢ Fatigue life
  - Consistency between similar analytical approaches
  - Over-predict test lives
- ➢ Growth rates
  - Slight over-prediction, but similar slopes/trends
- ➢ Crack aspect ratio
  - AFGROW closest representation of crack aspect ratio
  - Continues to be a struggle

Round Robin for Cx Holes - Case #3

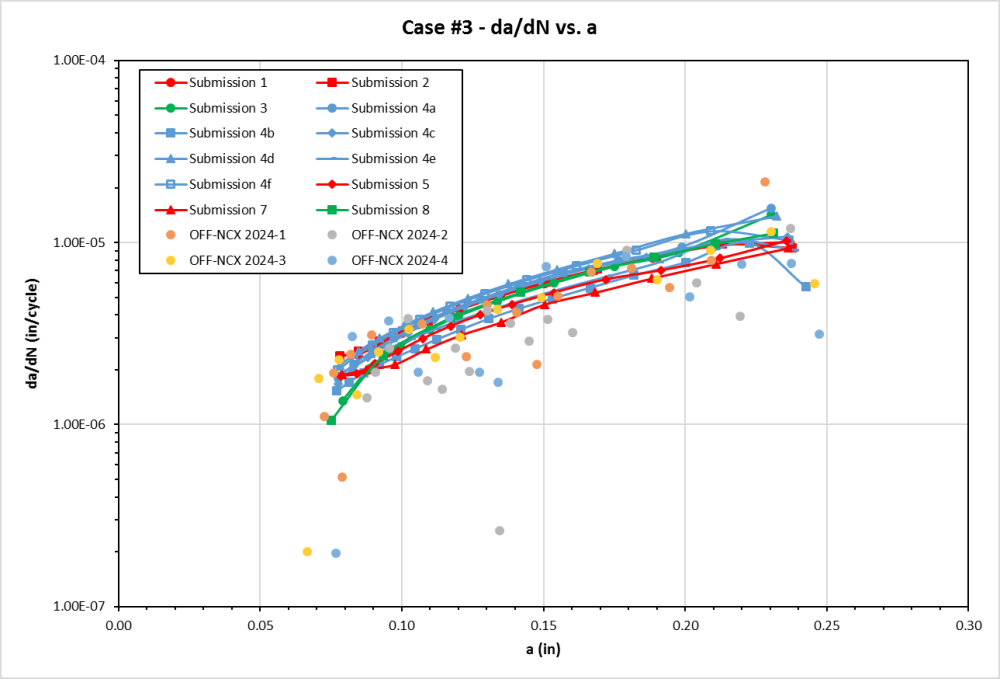
- Non-Cx Offset Hole

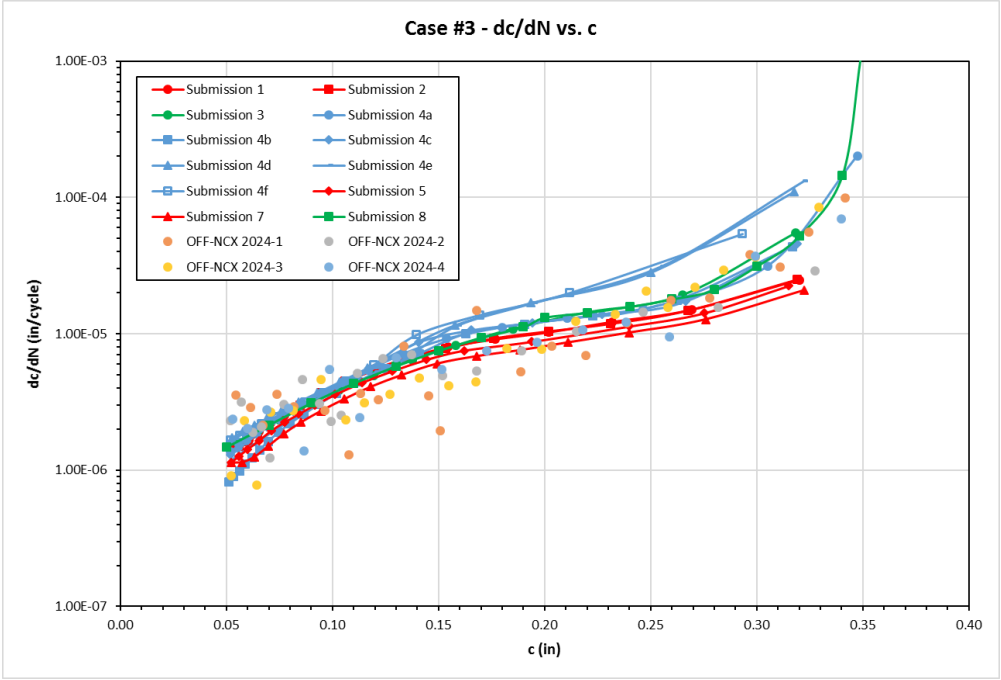




Round Robin for Cx Holes - Case #3

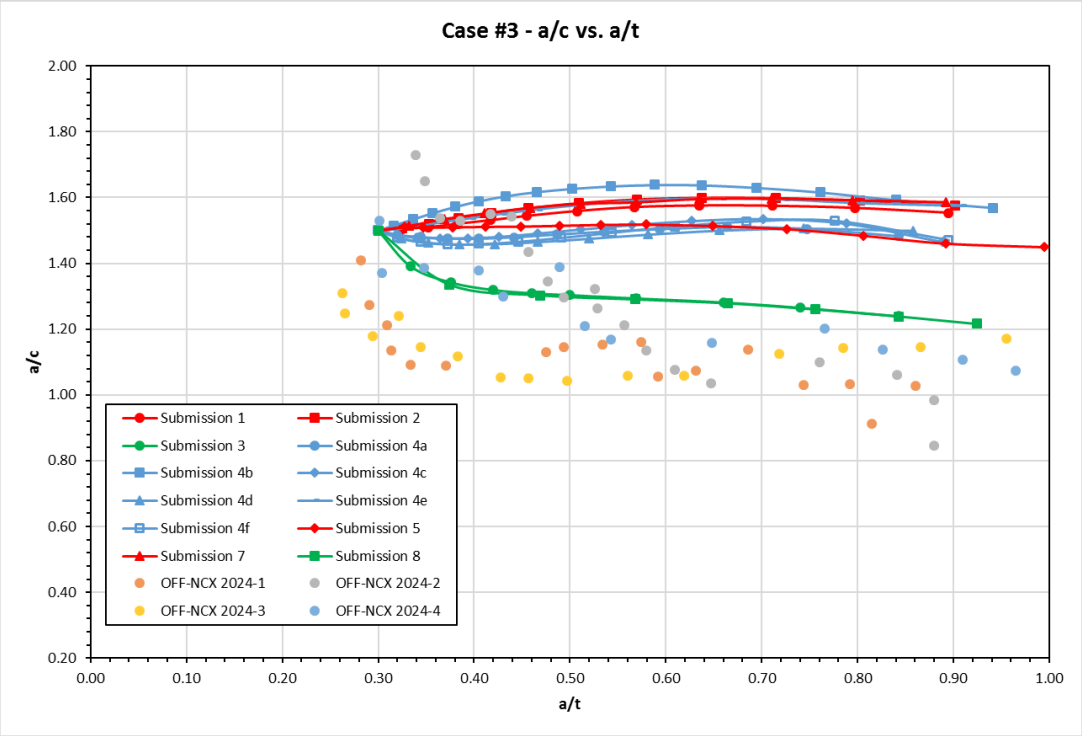
❑ Non-Cx Offset Hole



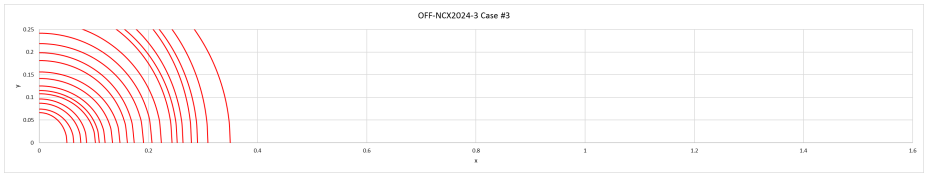


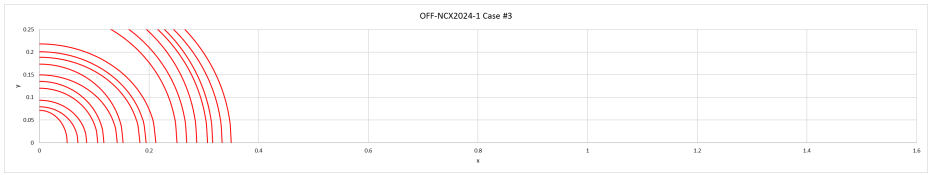
Round Robin for Cx Holes - Case #3

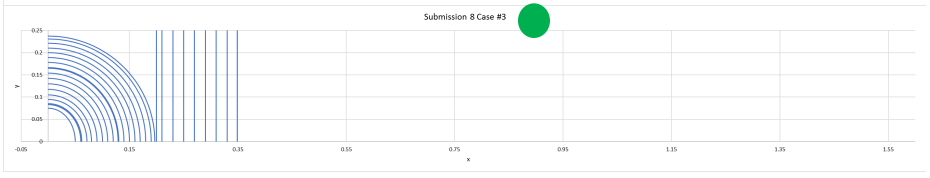
- Non-Cx Offset Hole

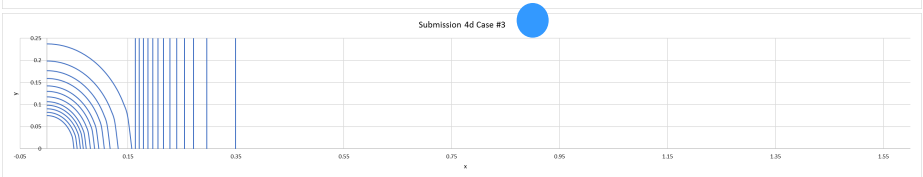


Round Robin for Cx Holes - Case #3









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Round Robin for Cx Holes - Case #3

- **Non-Cx Offset Hole Summary**
  - Fatigue life
    - Consistency between similar analytical approaches
    - Over-predict test lives
  - Growth rates
    - Similar slopes/trends
  - Crack aspect ratio
    - AFGROW closest representation of crack aspect ratio
    - Continues to be a struggle