Lifing Methods and Experimental Validation of Engineered Residual Stresses

2019 ASIP Conference, San Antonio, TX

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ERSI

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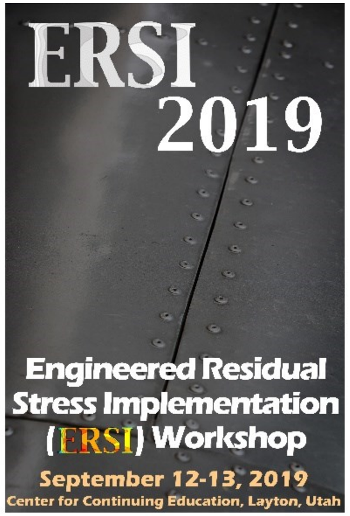
  - Dr. Scott Carlson
  - Mr. Jacob Warner
  - Dr. TJ Spradlin
- Round robin participants
- Thanks to the ERSI Working Group for all your hard work!!!



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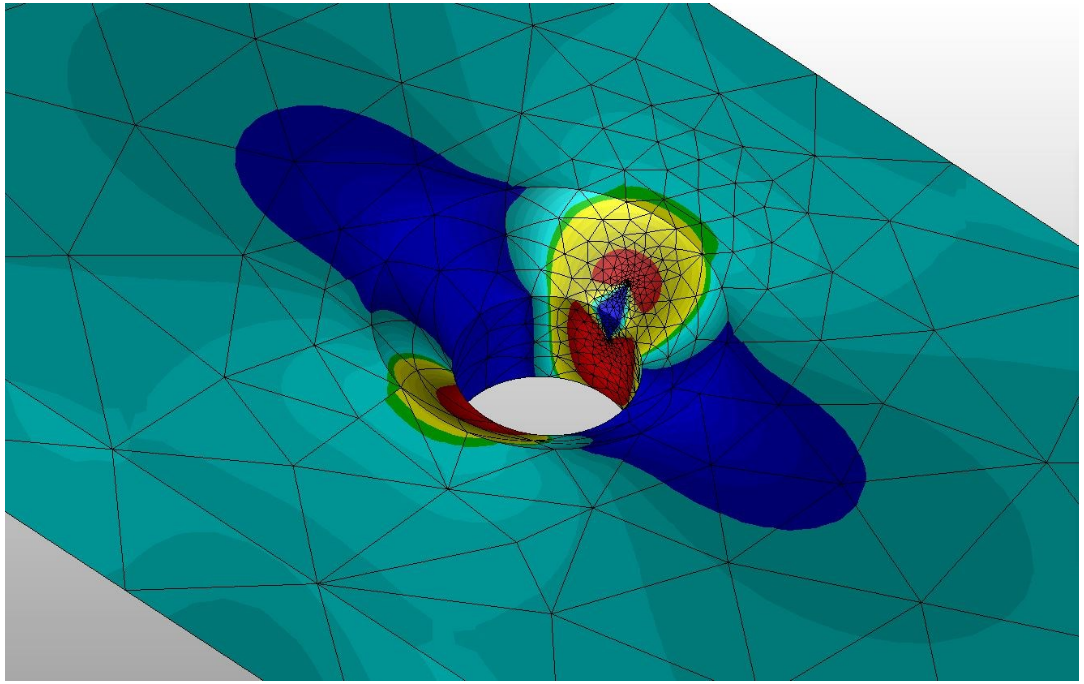
Overview/Outline

- ERSI overview & participants
- Recent initiatives
  - Round robin for Cx holes
  - Cyclic redistribution
  - Weapon system analyses
- Remaining gaps & key focus areas
- Conclusions



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Engineered Residual Stress Implementation (ERSI) Working Group

- **Mission statement:**
  - Develop a **holistic** paradigm for the **implementation** of engineered residual stresses into **lifing** of fatigue and fracture **critical components**
- **Key objectives:**
  - Define a common vision for the accounting of engineered residual stress at cold expanded fastener holes
  - Provide a forum for the community to collaborate on new developments, best practices, and lessons learned
  - Develop an implementation roadmap
  - Identify, define, and enable the resolution of gaps in the state-of-the-art

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ERSI Working Group

- **Wide breadth of participation**
  - Countries – 5
  - DoD Organizations – 3 + FAA
  - USAF ASIP Managers - 10
  - National Laboratories – 2
  - Universities – 6
  - OEMs – 3
  - Industry Partners – 23

ERSI Executive Committee
Dr. Dale Ball (Lockheed Martin)
Dr. TJ Spradlin (USAF AFRL)
Dr. Scott Carlson (Lockheed Martin)
Mr. Robert Pilarczyk (Hill Engineering)

Integrator Committee

Technical Advisors
Mr. Chuck Babish (USAF ASIP)
Dr. Michael Gorelik (FAA)

Validation Testing
Mr. Jacob Warner
(USAF A-10 ASIP)

Fatigue Crack Growth Analysis Methods
Mr. Robert Pilarczyk
(Hill Engineering)

Residual Stress Process Simulation
Mr. Keith Hitchman
(FTI)

Data Management & Quality Assurance
Mr. Kaylon Anderson
(USAF A-10 ASIP)

Non-Destructive Inspection (NDI)
Mr. John Brausch
(USAF AFRL)

Residual Stress Measurement
Dr. Mike Hill
(Hill Engineering)

Risk Analysis & Uncertainty Quantification
Ms. Laura Hunt
Mr. Lucky Smith
(SwRI)

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ERSI Working Group

- **Fatigue Crack Growth Analysis Methods Committee**
  - Purpose
    - Develop and document best practices for the integration of deep engineered residual stresses into the fatigue crack growth prediction methods used with the Damage Tolerance paradigm
  - Key initiatives
    - Round Robin for Cx Holes
    - Best Practices Document
    - Engineering Implementation of RS
    - Analysis Methods, Tools, and Ground Rules
    - Cyclic Redistribution of RS
    - Crack Closure
    - Material Behavior in RS Applications
    - Filled Hole Applications (Taper-Lok, other)
    - Weapon System Applications
    - Durability Analysis Benefits
    - Cx Hole Literature Survey
    - Structures Bulletin Development

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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Recent Initiatives

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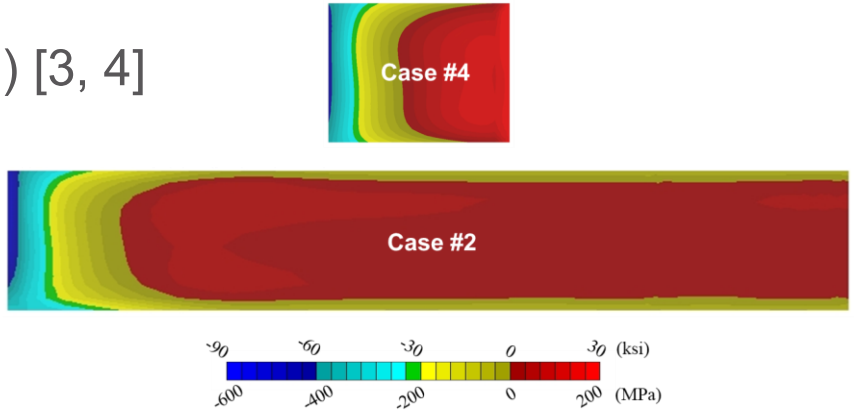
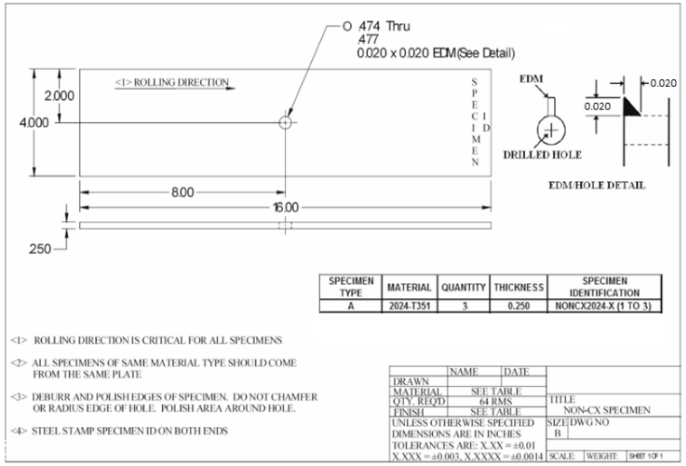
Round Robin for Cx Holes

- **Focus: Investigate the consistency, strengths and weaknesses of different analysis methods to define best practices moving forward**

- **Input data**
  - Geometry
  - Initial flaw size, shape, and location
  - Material properties
  - Loading spectrum
  - Constraints
  - Residual stress (contour results) [3, 4]
    - Average of replicates

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





- **Test data from:**
  - Carlson, Pilarczyk [1]
  - Andrew, Clark, Hoeppner [2]

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Round Robin for Cx Holes

- Many participants with varying analysis approaches

Submission #	Key Modeling Factors Cx Cases 2 & 4					
	Software		Crack Definition			
	Lifing Software	FE Software	Crack Front Shape	# of Crack Front Points	RS Incorporation Approach	Stress Intensity Calculation
1	CPAT	StressCheck	Multi-Point	30	Crack Face Pressure (B-Spline)	CIM-LC
2	CPAT	StressCheck	Multi-Point	20	Crack Face Pressure (Legendre Polynomial)	CIM-LC
3a	AFGROW	N/A	Elliptical	2	2-D Gaussian Integration (Free Surface)	Classic Newman/Raju
3b	AFGROW	N/A	Elliptical	2	2-D Gaussian Integration (5 degrees)	Classic Newman/Raju
3c	AFGROW	N/A	Elliptical	2	2-D Gaussian Integration (10 degrees)	Classic Newman/Raju
4g	NASGRO	N/A	Elliptical / Straight Thru	2	Bivariant WF	NASGRO CC10/TC13 Bivariant WF
4h	NASGRO	N/A	Elliptical / Straight Thru	2	Bivariant WF	NASGRO CC10/TC13 Bivariant WF
4i	NASGRO	N/A	Elliptical / Straight Thru	2	Univariant WF	NASGRO CC08/TC13 Univariant WF
4j	NASGRO	N/A	Elliptical / Straight Thru	2	Univariant WF	NASGRO CC08/TC13 Univariant WF
5	BAMF	StressCheck	Multi-Point	11	Polynomial Fit Crack Face Pressure	CIM-LC
6	AFGROW	N/A	Elliptical / Straight Thru	2	1-D Gaussian Integration (20% from free surface)	Classic Newman/Raju
7	CPAT	StressCheck	Multi-Point	15	Crack Face Pressure (Legendre Polynomial)	CIM-LC
8	BAMF	StressCheck	Multi-Point	10	Crack Face Pressure (Legendre Polynomial)	CIM-LC

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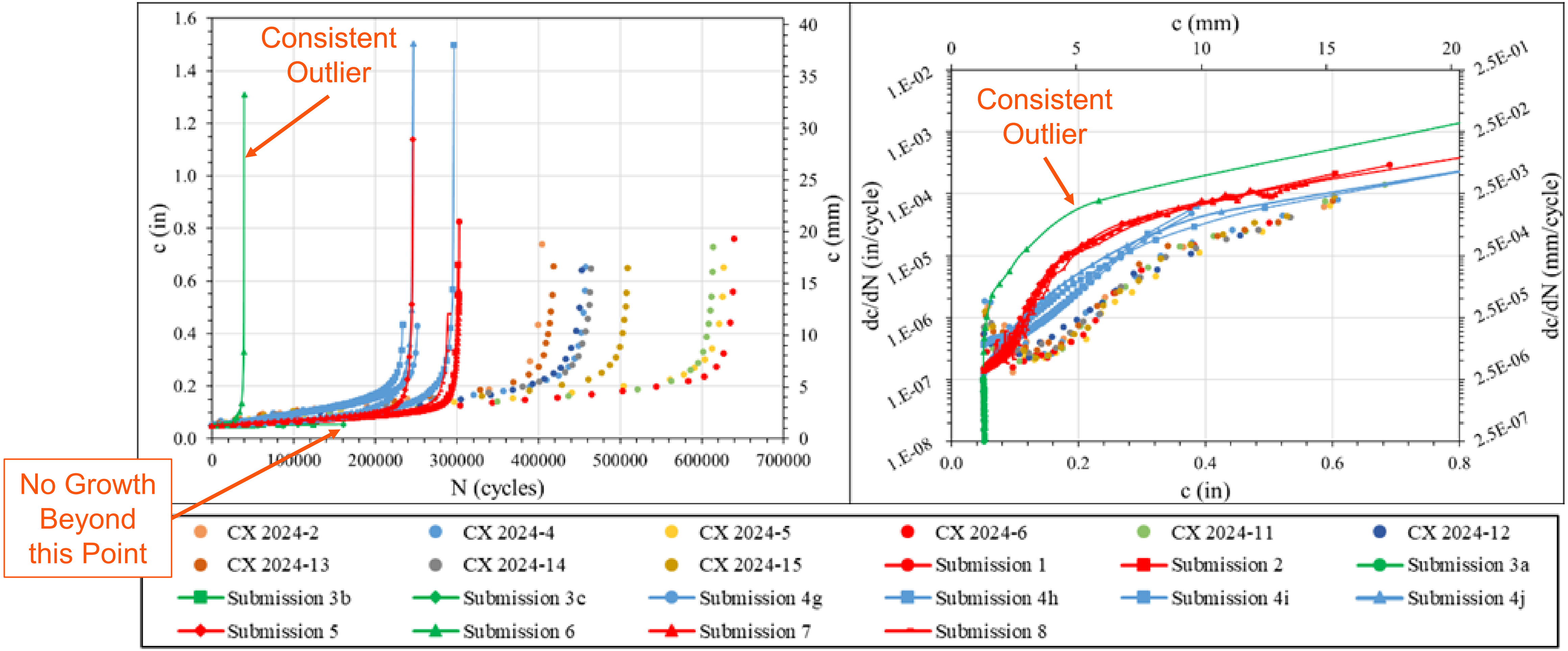
Round Robin for Cx Holes – Case #2

- Cx centered hole - results



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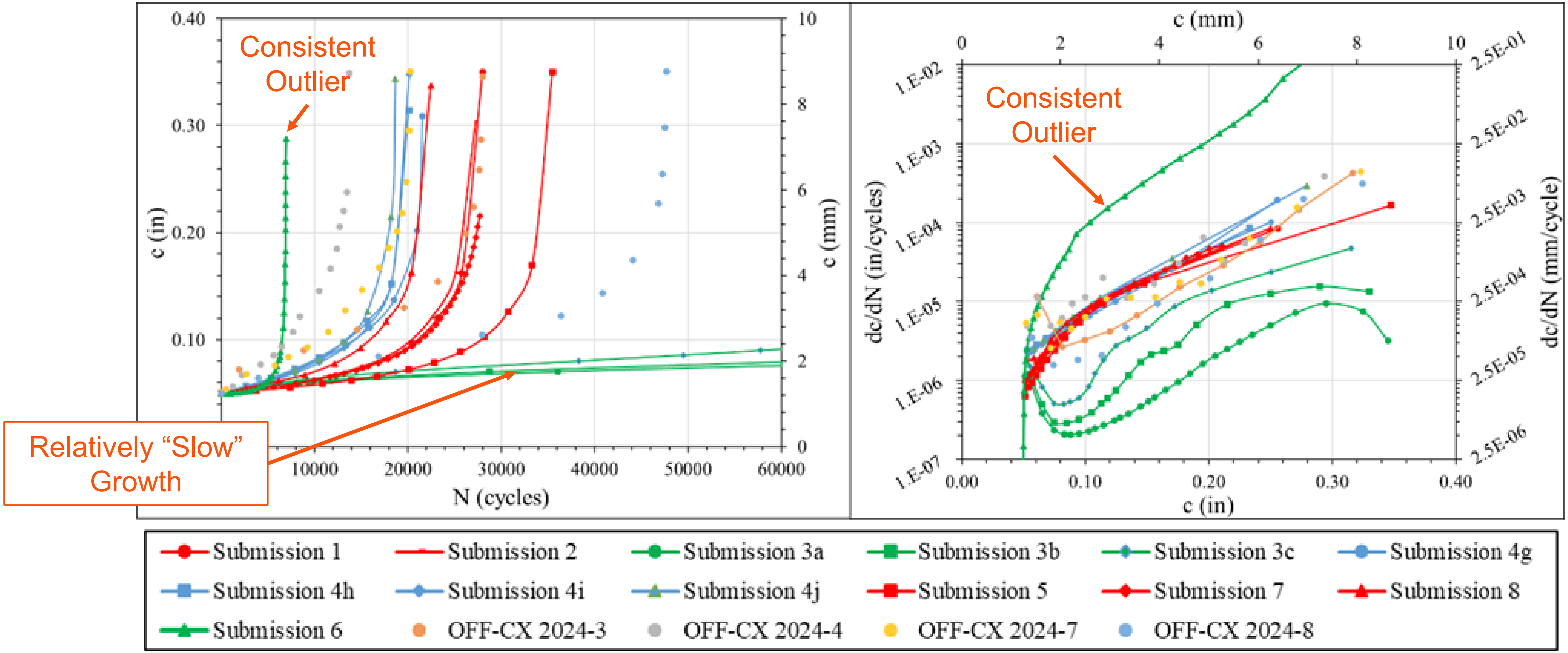
Round Robin for Cx Holes – Case #4

- ❑ Cx offset hole



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Round Robin for Cx Holes – Initial Observations

- **Cx hole summary (Cases #2 and #4)**
  - Fatigue life
    - Consistent life predictions for NASGRO and coupled FEA-FCR approaches
      - Case #2 - similar to Case #1, under-predicted experimental results (45-60%)
      - Case #4 – predictions within range of experimental results
    - AFGROW predictions utilizing Newman-Raju solutions with 1-D and 2-D Gaussian integration for residual stress were inconsistent with other predictions and experimental results
      - Significant over-prediction of observed experimental life Why???
  - Mismatch of crack aspect ratio Why???

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Round Robin for Cx Holes – Answering the Why's

- **Follow-on efforts**
  - Focused on investigating prediction differences, answering the "Why's", documenting lessons learned, and refining best practices
- **Key focus areas**
  - Stress intensity contributions from remote and residual stress
  - Residual stress variability
  - Crack aspect ratio
  - Negative R baseline test data
  - Dissecting crack growth rate data

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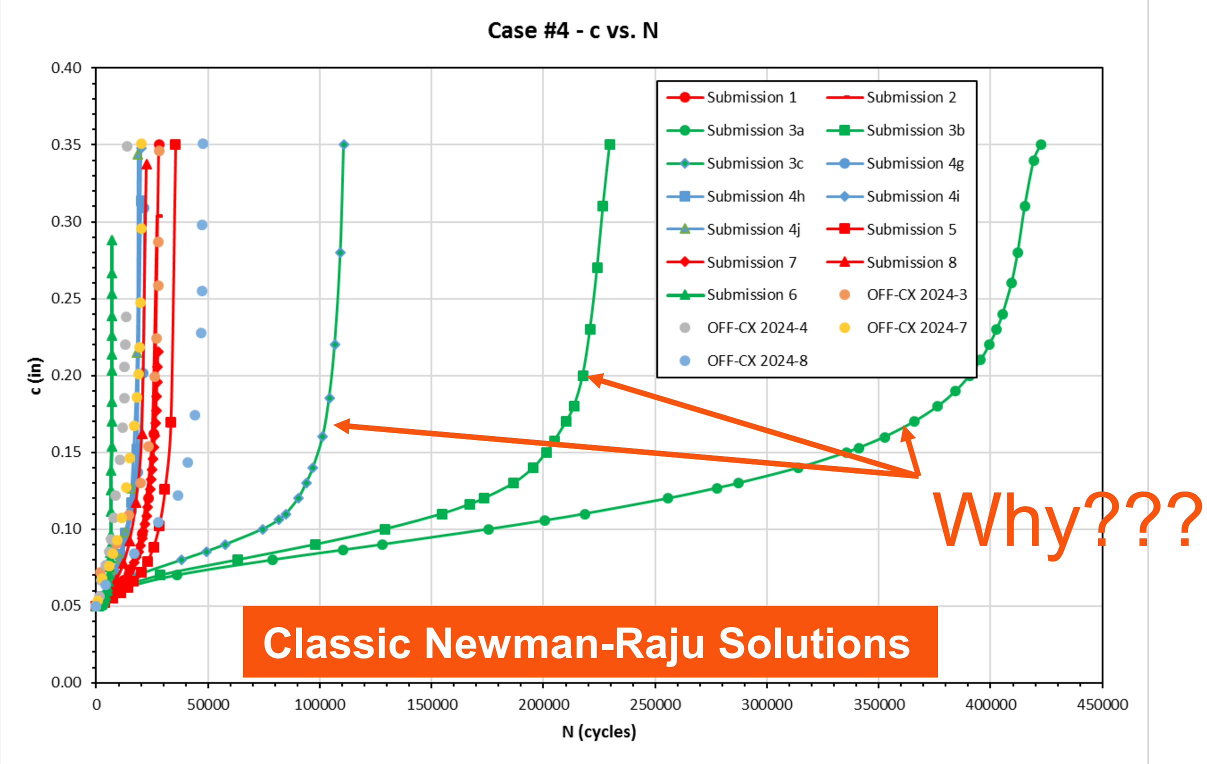
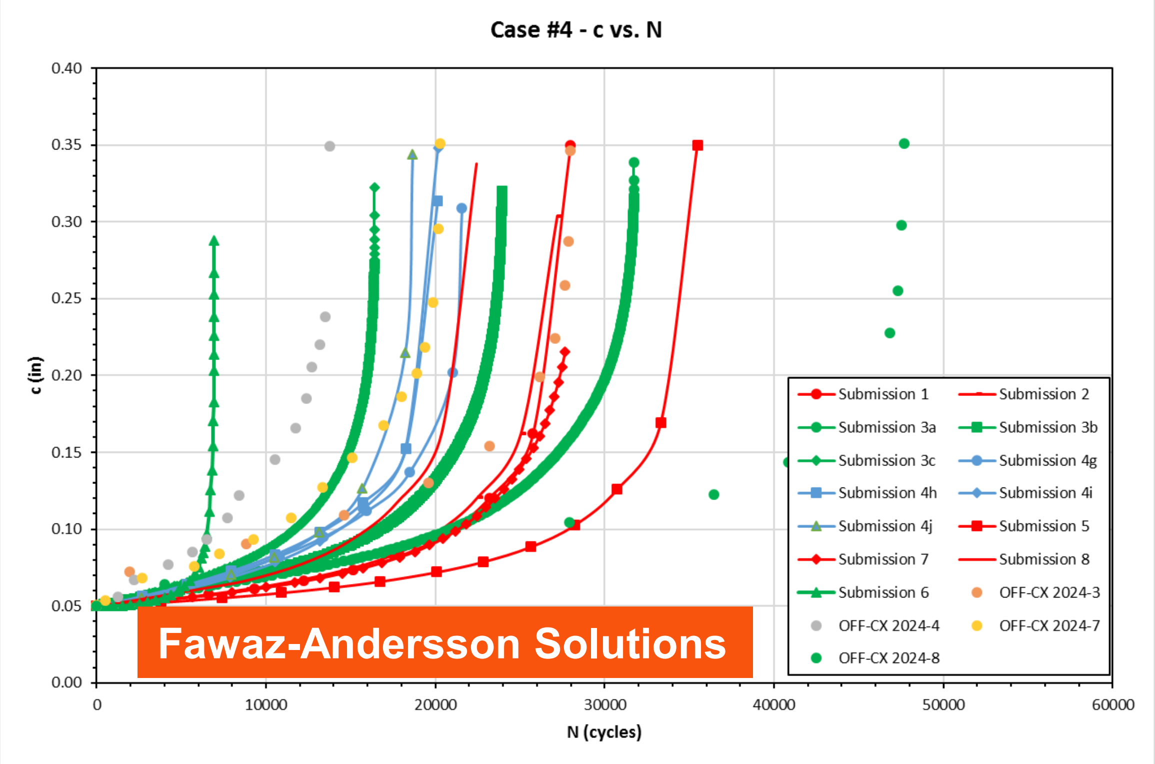
Round Robin for Cx Holes – Applied and Residual Stress Intensities

❑ Post-dictions – Case #4

- ➢ Accurate stress intensity solutions are critical





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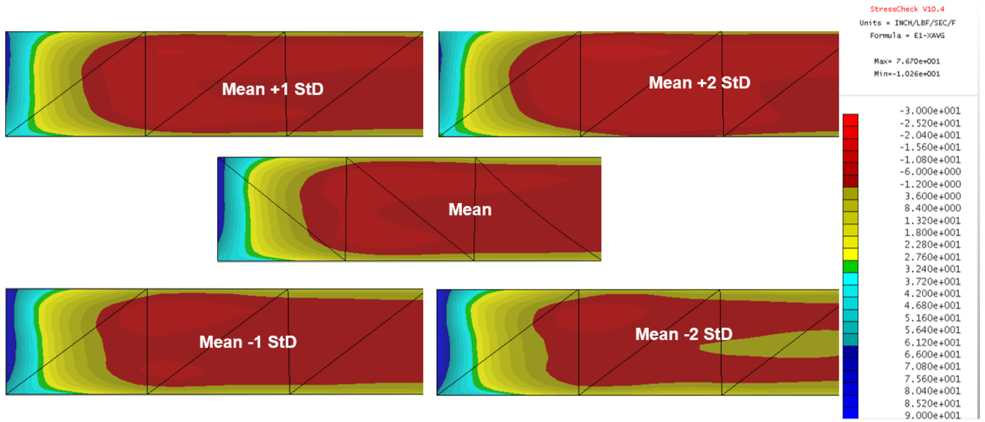
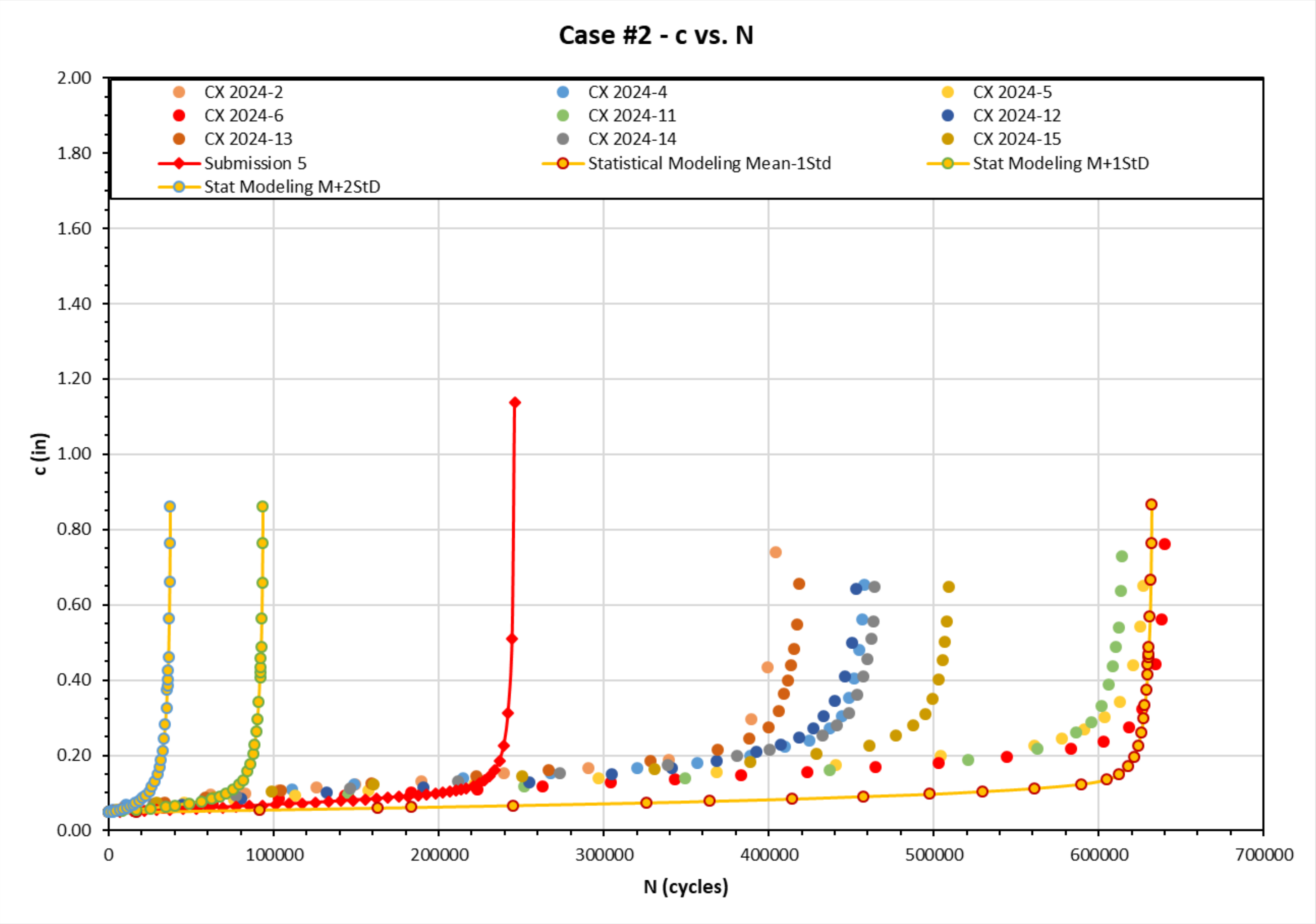
Round Robin for Cx Holes – Residual Stress Variability

- **Post-dictions – Case #2**
  - Mean
  - -1 StD
  - +1 StD
  - +2 StD





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Round Robin for Cx Holes – Summary

- Overall, the round robin effort was quite beneficial highlighting the differences in various approaches
- With the exception of submission #6, which tended to be an outlier, all cases were consistent between similar approaches
- Multi-directional material data enabled more accurate aspect ratio predictions
- Publications
  - Presented at 19th International ASTM/ESIS Symposium on Fatigue and Fracture Mechanics, May 2019
  - Publication in upcoming Special Issue on Fatigue and Fracture Mechanics for Materials Performance and Characterization

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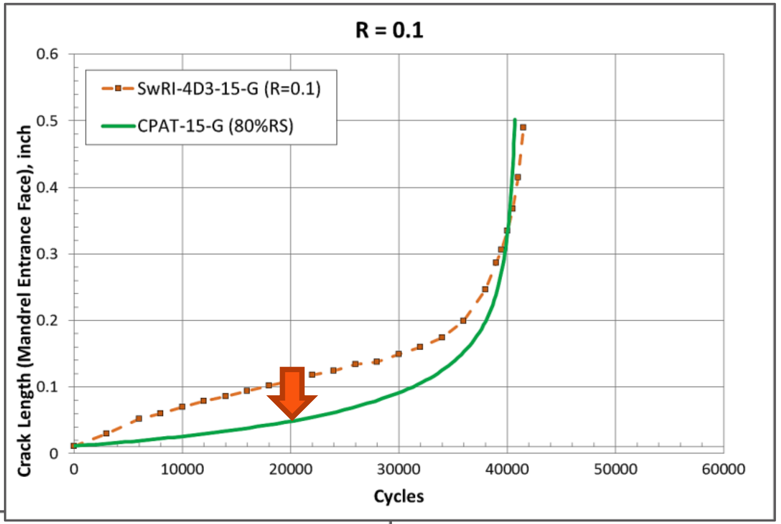
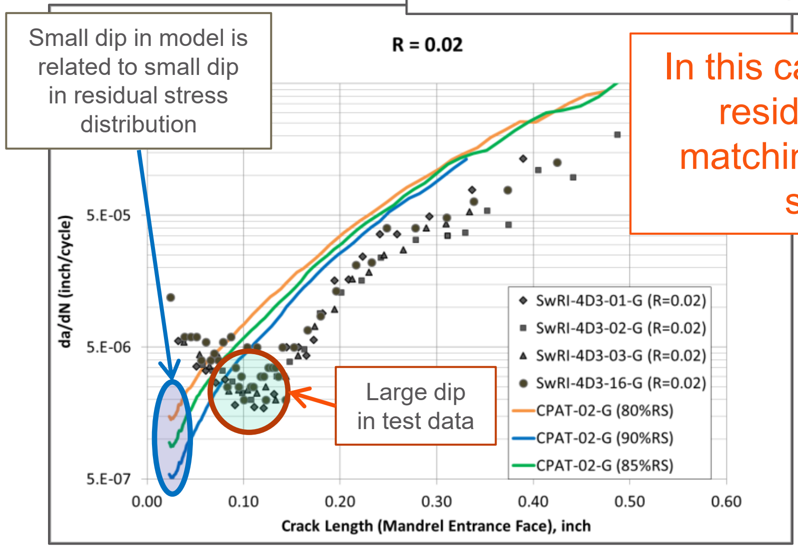
Crack Growth Curve Mismatch Investigation

- Most fatigue crack growth testing at CX holes has traditionally focused on lower stress ratios
- These data sets show a characteristic dip in crack growth rates
  - Crack propagation modeling efforts of the last several years do not capture this behavior
- Dip only occurs when $R_{tot} < 0$
  - Hypothesis of crack closure
- Dip leads to inaccuracy in modeling





In this case, 20% reduction in residual stress allowed matching of total life but not shape of curve

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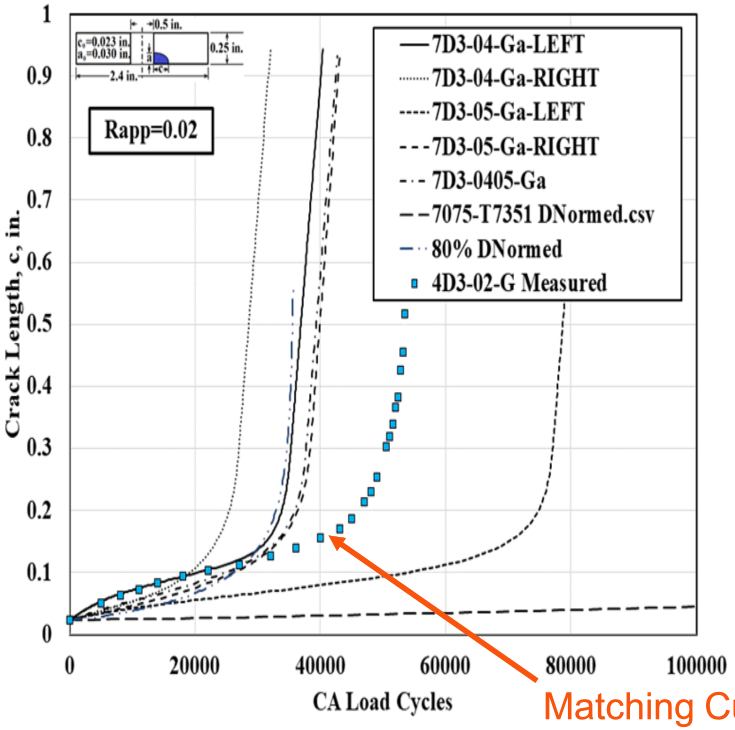
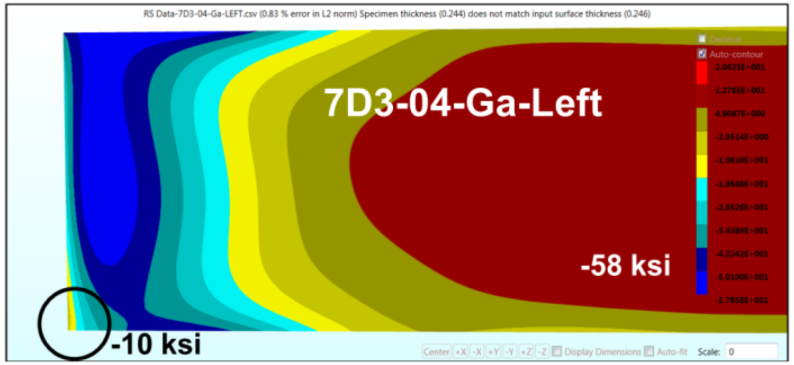
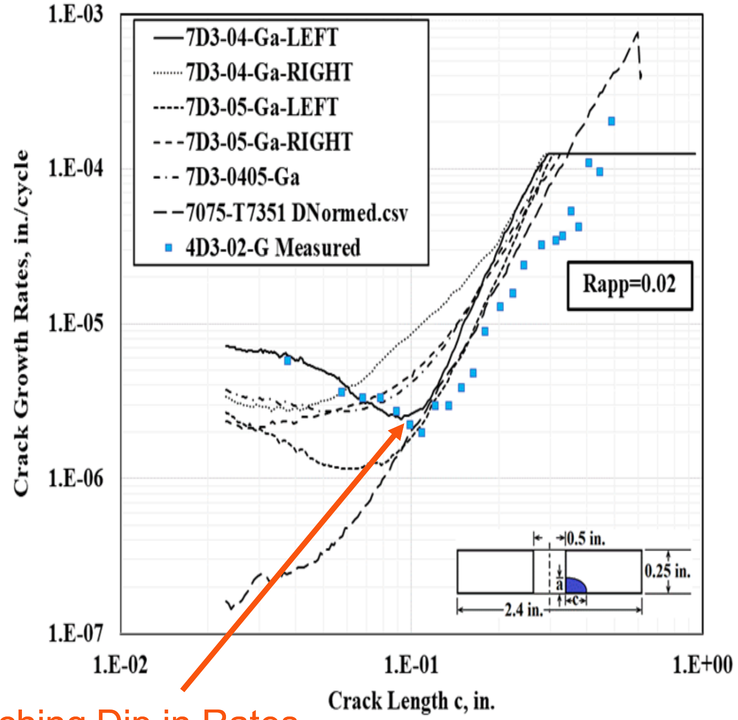
Crack Growth Curve Mismatch Investigation

- Open hole Cx specimens pre-cycled 2000 cycles at test stress
- Resulted in redistribution of stress
  - Less compressive at the surface, compression extends further from hole



Matching Curve Shape





Matching Dip in Rates

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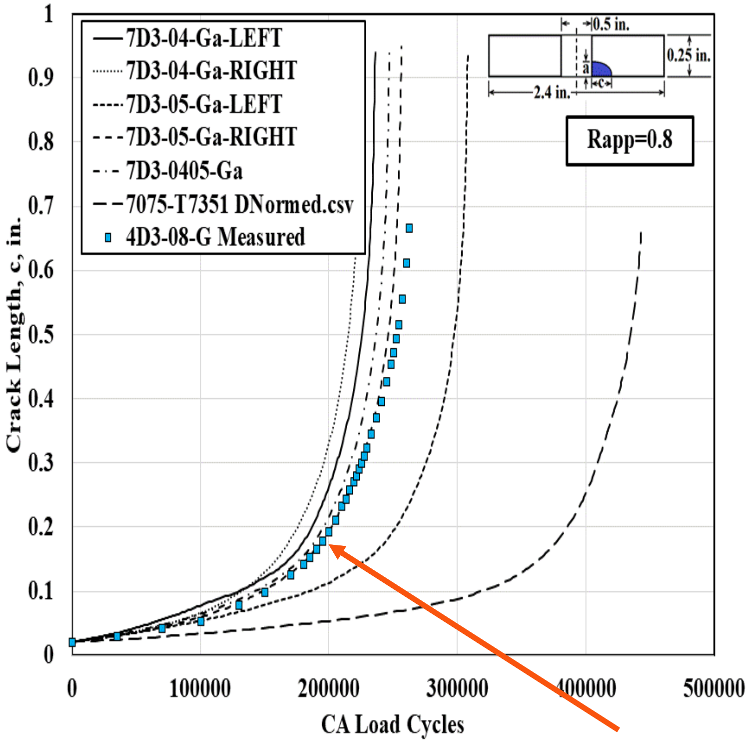
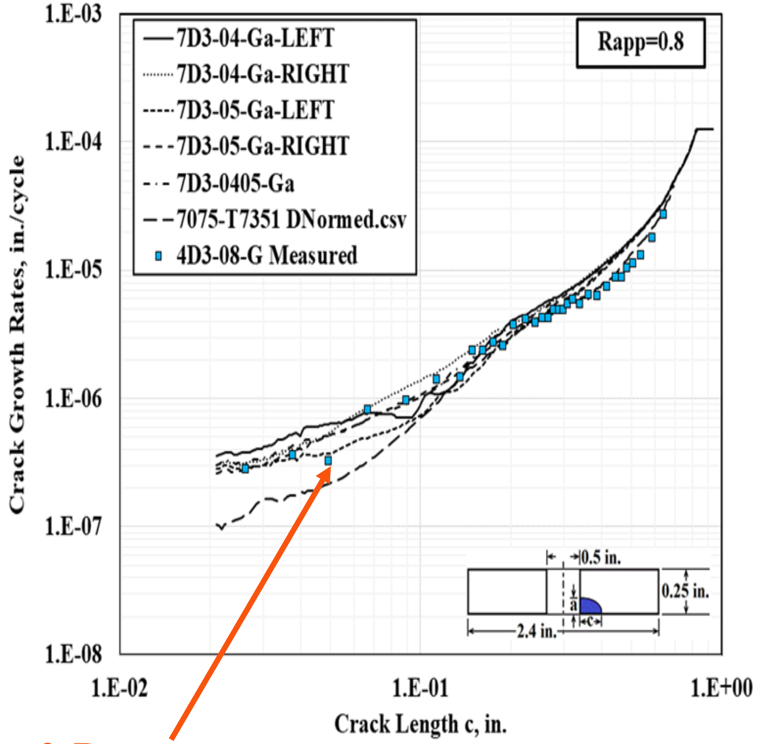
Redistributed Residual Stress Leads to Improved Modeling

- Same RS correlates well at R_{app} = 0.8 (R_{tot} > 0)
  - No dip in da/dN test data when R_{tot} > 0
  - New RS captures this behavior as well





Matching Curve Shape & Rates

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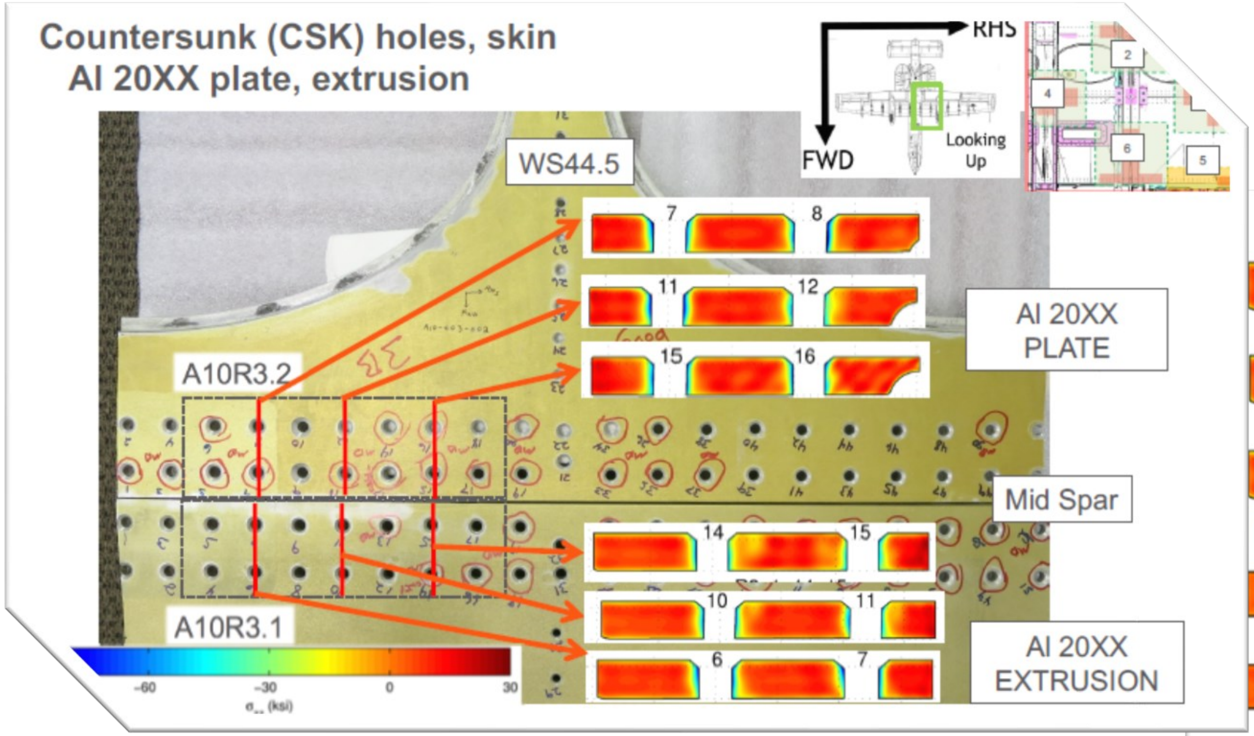
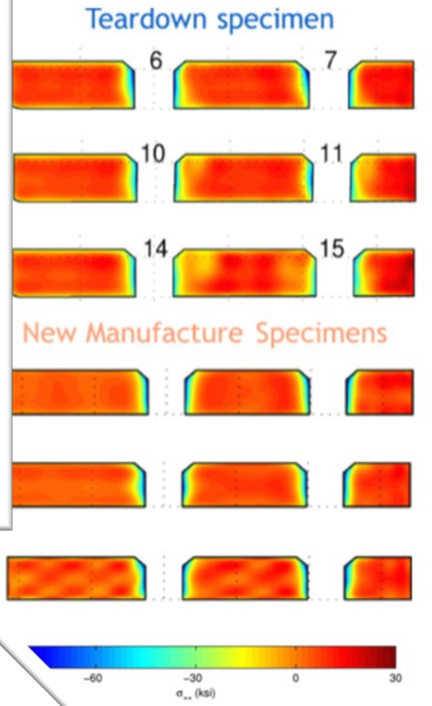
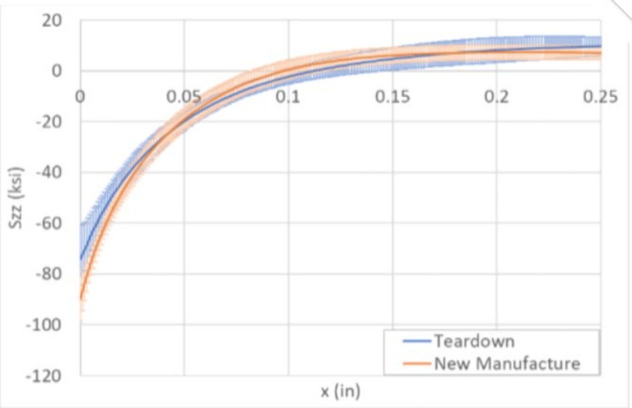
Residual Stress Redistribution

- Why is the behavior not evident in teardown assets?







Sample ID	Midthickness 0.125*rad (ksi)	Midthickness 0.25*rad (ksi)	Midthickness 0.5*rad (ksi)	Midthickness 0.75*rad (ksi)	Depth at crossover (midthickness) (in)	Point Value of Entrance (ksi)	Avg RS in 0.05" Radius Entrance (ksi)	Point Value CSK Knee (ksi)	Avg RS in 0.05" Radius CSK knee (ksi)
Mean	-47.15	-31.04	-12.29	-2.60	0.13	-51.30	-34.67	-77.92	-44.59
Stdev	5.17	4.10	2.71	2.99	0.04	21.61	6.68	16.67	10.37
Mean	-52.82	-32.95	-10.82	-0.19	0.10	-49.72	-31.57	-98.82	-55.33
Stdev	3.68	3.91	3.91	3.65	0.02	21.46	3.05	14.72	2.64
Residuals (Td-NM)	5.68	1.91	-1.46	-2.42	0.03	-1.58	-3.09	20.90	10.74
P Value	0.00	0.13	0.15	0.05	0.02	0.43	0.08	0.00	0.00
Significant	Yes	No	No	Yes	Yes	No	No	Yes	Yes

Filled Hole Effects?

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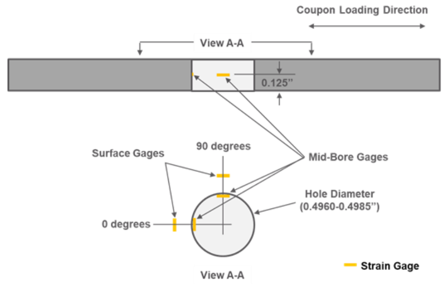
Residual Stress Redistribution

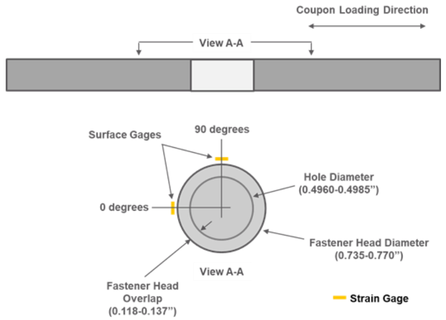
- **Next Steps**
  - Complete initial investigate for standard configurations
- **Approach**
  - Investigate differences between:
    - non-cycled coupons
    - open hole cycled coupons
    - filled hole cycled coupons
- **Pre-cycling**
  - Strain gage (1) coupon from each configuration to characterize changes during incremental increases in cycle stress levels
- **Residual Stress Measurement**
  - Complete contour method measurements of non- and pre-cycles coupons
  - Compare/contrast results

Condition	Material	Thickness (in)	Width (in)	Hole Edge Margin	Pre-Cx Ream Diameter (in)	Applied Expansion	Post-Cx Ream Diameter (in)	Replicates
Non-Cycled	2024-T351	0.25	4.00	Centered	0.4755+/-0.0005	Mid	0.4960-0.4985	3
Open Hole Cycled								3
Filled Hole Cycled								3
Non-Cycled	7075-T651							3
Open Hole Cycled								3
Filled Hole Cycled								3

Open Holes



Filled Holes



Condition	Loading	Strain Monitoring	Gauge Location	Max Stress (ksi)	Cycles	Replicates (each material)
Open Hole Cycled	CA R=0.1	Yes	Bore & Surface	10, 15, 20, 25, 30	2000/each	1
		No	N/A	30	2000	2
Filled Hole Cycled		Yes	Surface	10, 15, 20, 25, 30	2000/each	1
		No	N/A	30	2000	2

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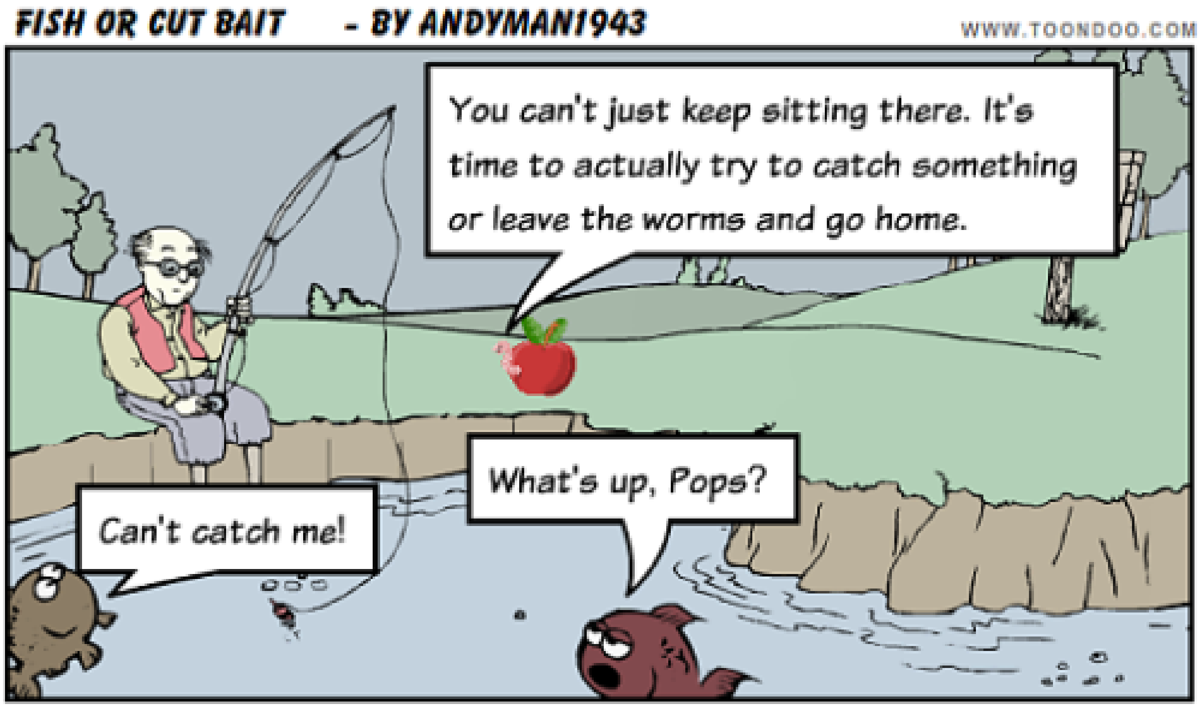
Weapon System Analyses

- **Objectives**
  - Utilizing state-of-the-art methods and inputs, update DTAs for select Control Points (CPs), explicitly incorporating residual stress
  - Compare/contrast with reduced flaw size predictions (partial credit)
  - Identify gaps and refine best practices
  - Define initial ground rules
- **Approach**
  - Select candidate locations
  - Review baseline input data/methods
  - Complete baseline analyses
  - Complete multi-point analyses w/ RS
  - Compare/contrast predictions
  - Provide conclusions and recommendations



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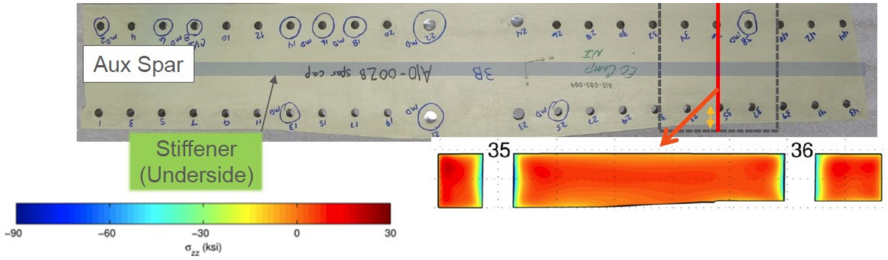
Weapon System Analyses

Inputs and results

- Oversized conditions
- Variations in residual stress
- Variation in stress spectrum



Location 1 residual stresses

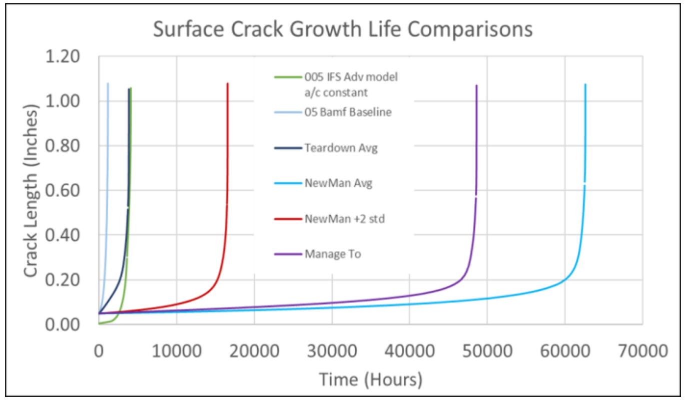
Analysis Details

Location	Description	Material	Thickness (in)	Hole Size (in)	Edge Margin (e/D)	Max Stress (ksi)
1	Lwr Fwd Skin, WS 23 (SLEP)	2024-T3511	0.300	0.625	2.256	31.2
2	Lwr Fwd Skin, WS 23 (Thick Skin)	2024-T3511	0.420	0.562	2.508	24.0
3	Lwr Wing Skin at Mid Spar, WS 23 (SLEP)	2024-T351	0.300	0.328	1.981	42.4

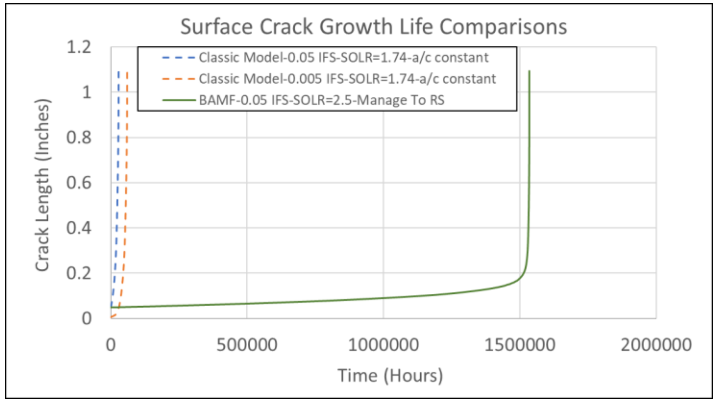
Residual Stresses

Location	New Manufacture Mean	Teardown mean	New Manufacture +2 Std	Teardown +2 Std	Manage To
1	x	x*	x		x
2		x			
3	x	x	x	x	

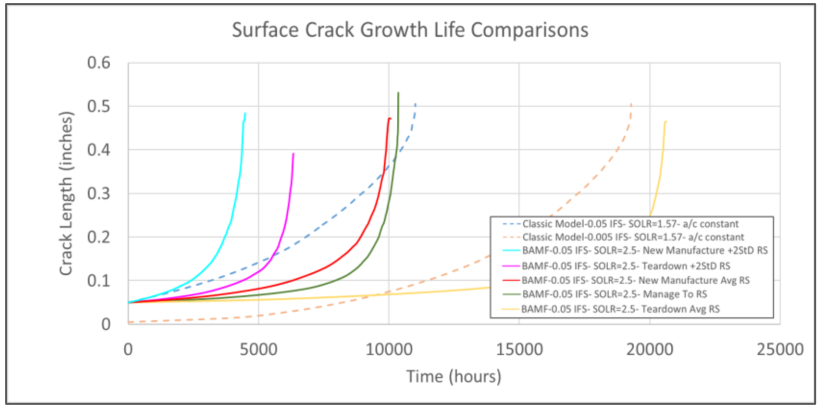
Location 1 Predictions



Location 2 Predictions



Location 3 Predictions



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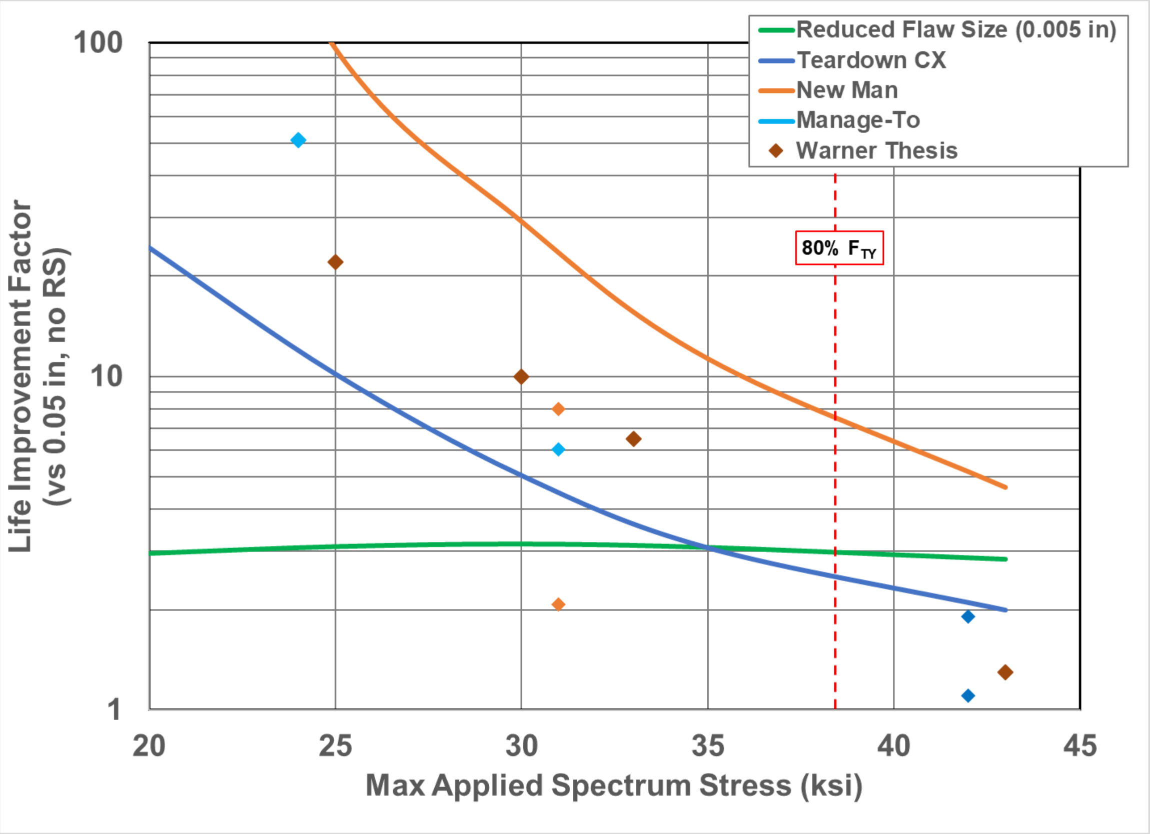
Weapon System Analyses

❑ Conclusions

- Peak spectrum stress has a key influence on the life improvement at Cx holes
- Traditional DTA methods utilizing a reduced flaw size may be unconservative in some situations
- Cx benefit is significantly reduced for locations with peak spectrum stresses greater than 85% of the yield strength. Experimental results demonstrate minimal benefit.
- The residual stress utilized for analyses is critical for the predictions and must be considered closely, considering the impacts of in-service degradation and statistical variation



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Remaining Gaps & Key Focus Areas

- Additional round robin efforts
  - Interference fit fastener RR about to be released
- Residual stress redistribution
- Material characterization
  - Increased breadth of materials
  - Multi-directional material properties
  - Negative R behavior
- Analysis input variability and uncertainty propagation
- Other applications
  - Taper-Lok installations
  - Interference fasteners and bushing
- Weapon system specific demonstrations
- Finalization of new structures bulletin

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Conclusions/Summary

- Incrementally, we are making progress within the Analysis Methods and Validation Testing committees
  - Thanks to those individuals that have contributed
- We must continue to push forward with a focus on refining our analytical capability and addressing technical gaps while ensuring accuracy, identifying uncertainties, and maintaining acceptable levels of risk

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Thanks for your attention

Any questions?

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