ENGINEERED RESIDUAL STRESS IMPLEMENTATION (ERSI) WORKSHOP 2018

Date: September 13 – 14, 2018
Location: Weber State University's Center for Continuing Education, 775 University Park Blvd., Clearfield, UT 84015

Thursday September 13 Agenda:

07:00-07:30 Arrive, Breakfast
07:30-07:45 Welcome
- *Dr. Scott Carlson, Mr. Robert (Bob) Pilarczyk, Mr. Dallen Andrew*

Presentations by Leads Covering Progress:
- 25 min Presentation with 15 mins for Discussion

07:45-08:00 **Integrator Review – Programmatic Overview and Roadmap**
- *Dr. T.J. Spradlin (USAF – AFRL)*

08:00-08:40 **Residual Stress Process Simulation**
- *Mr. Keith Hitchman (Fatigue Technologies Incorporated (FTI))*

08:40-09:10 **Quantification of Residual Stresses Through Measurement Techniques**
- *Dr. Adrian DeWald (Hill Engineering, LLC.)*

09:10-09:50 **Fatigue Crack Growth Methods with Inclusion of Residual Stresses**
- *Mr. Robert (Bob) Pilarczyk (Hill Engineering, LLC – Utah Branch.)*

09:50-10:00 BREAK

10:00-10:40 **Verification and Validation of Analytical Methods Through Test**
- *Dr. Tom Mills (Analytical Processes/Engineering Solutions, Inc. (AP/ES))*

10:40-11:20 **Effects of Engineered Residual Stresses on Non-Destructive Inspection**
- *Mr. John Brausch (USAF – AFRL)*

11:20-12:00 **Quality Assurance and Data Management for the Inclusion of Residual Stresses**
- *Dr. Carl Magnuson (Texas Research Institute/Austin, Inc.(TRI-Austin))*

12:00-13:20 LUNCH

13:20-14:00 **Uncertainty Quantification and Risk Analysis with the Inclusion of Residual Stresses**
- *Mr. Lucky Smith, Ms. Laura Domyancic (Southwest Research Institute (SwRI))*

14:00-15:00 **Open Discussion**
15:00-17:30 **Breakout Discussions (Block 1)**
- *Analytical Methods for Residual Stress Integration into Fatigue Predictions and Testing and Validation of Analytical Methods Combined*
- *Residual Stress Process Simulation*
- *Impact of Deep Residual Stress on Non-Destructive Inspection (NDI) Methods*

Friday September 14 Agenda:

07:00-07:30 Arrive, Breakfast

07:30-10:30 **Breakout Discussions (Block 2)**

- *Residual Stress Measurements*
- *Analytical Methods for Residual Stress Integration into Fatigue Predictions and Testing and Validation of Analytical Methods Combined*
- *Quality Assurance and Data Management*
- *Risk Analysis and Uncertainty Quantification*

10:30-13:00 **Open Discussion and Lunch (***Lunch to be provided by Hill Engineering – Utah Branch***)**

- *Review*
- *Future Planning*
- *Governance*
- *Funding*

1300 **We Bid You Adieu and Thank You!**

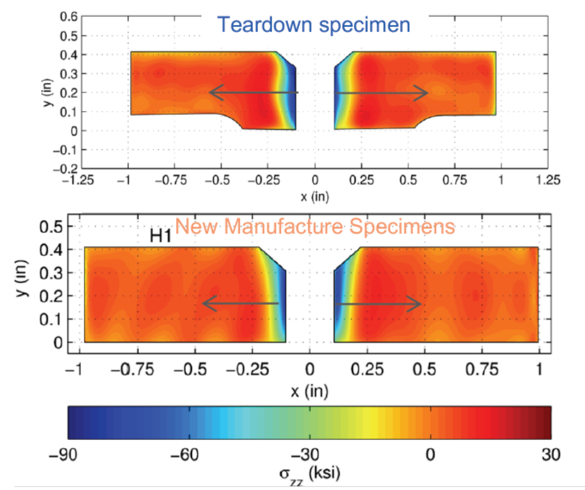
2018 Engineered Residual Stress Implementation (ERSI) Workshop

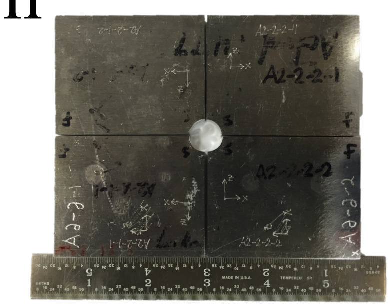
Held in Layton Utah

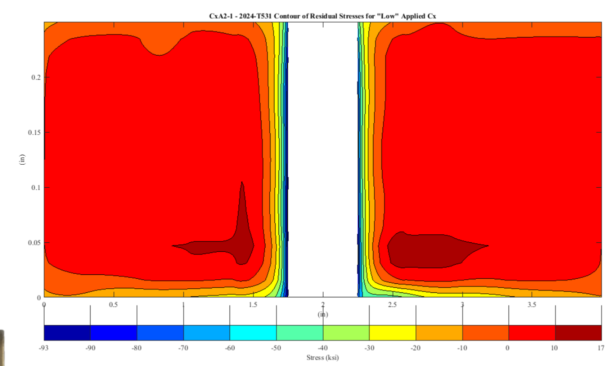
September 13 – 14, 2018

Welcome to the 2018 ERSI Workshop

- Thank you all for coming!
  - Food and Funding
- Restrooms and Break Area are Upstairs
- Internet is Provided for Free as a Guest
- Agenda and Proposed Discussion Format
- Purpose Focused Discussion
  - Closing the gaps
  - Developing the documents
- ERSI Website







Overview of Working Group Structure

Total Individuals within the Working Group - 78

- Countries Involved - 4
- DoD Organizations - 3 + FAA
- National Laboratory - 1
- Universities - 5
- OEMs - 3
- Industry Partners - 16
- Weapon Systems - 8

Integrators - Dr. Mark Thomsen - A-10 ASIP Manager, Dr. Dale Ball - Lockheed Martin Aero, Dr. TJ Spradlin - USAF/AFRL

Integrator Subcommittee

Organizational Group – Mr. Robert Pilarczyk – Hill Engineering, LLC., Mr. Dallen Andrew and Dr. Scott Carlson, LM-Aero

Verification and Validation Through Test – Dr. Tom Mills – APES, Inc.

Fatigue Crack Growth Analytical Methods – Mr. Robert Pilarczyk – Hill Engineering, LLC.

Residual Stress Process Simulation – Mr. Keith Hitchman – FTI – A PPC Company

Data Management and Quality Assurance – Dr. Carl Magnuson - TRI Austin

Effects of Residual Stress on Non-Destructive Inspection (NDI) Methods – Mr. John Brausch - USAF/AFRL

Residual Stress Measurements – Dr. Mike Hill - Hill Engineering, LLC.

Risk Analysis with the Inclusion of Engineered Residual Stresses – Mr. Lucky Smith & Ms. Laura Domyancic - SwRI

Purpose of ERSI Workshop

1. To identify and **lay out a road map for the implementation of engineered deep residual stress** which can be used in the calculation of initial and recurring inspection intervals for fatigue and fracture critical aerospace components.
2. To **highlight gaps in the stat-of-the-art** and define how those gaps will be filled.
3. Then to define the most **effective way to document requirements and guidelines** for fleet-wide implementation.

Vision of ERSI Working Group

Within 3-7 years have developed a framework for fleet-wide implementation of a more holistic, physics-based approach for taking analytical advantage of the deep residual stresses field, induced through the Cold Expansion process, into the calculations of initial and recurring inspection intervals for fatigue and fracture critical aerospace components. Then move from there to other deep residual stress inducing processes, like Laser Shock Peening , and Low Plasticity Burnishing.

Residual Stress Process Simulation Subcommittee Progress Report

Engineered Residual Stress Implementation Workshop 2018

Layton, Utah, USA

September 13, 2018

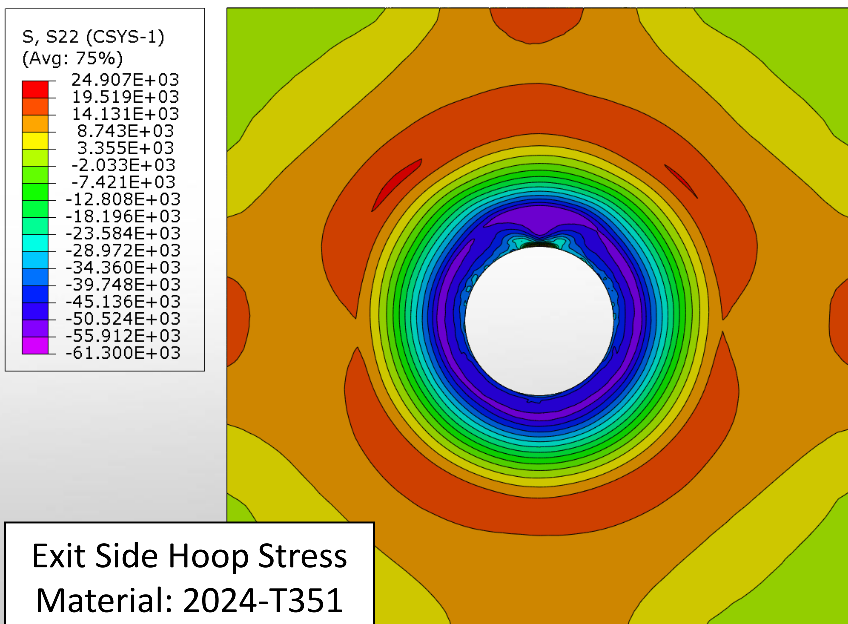
ERSI

FATIGUE TECHNOLOGY

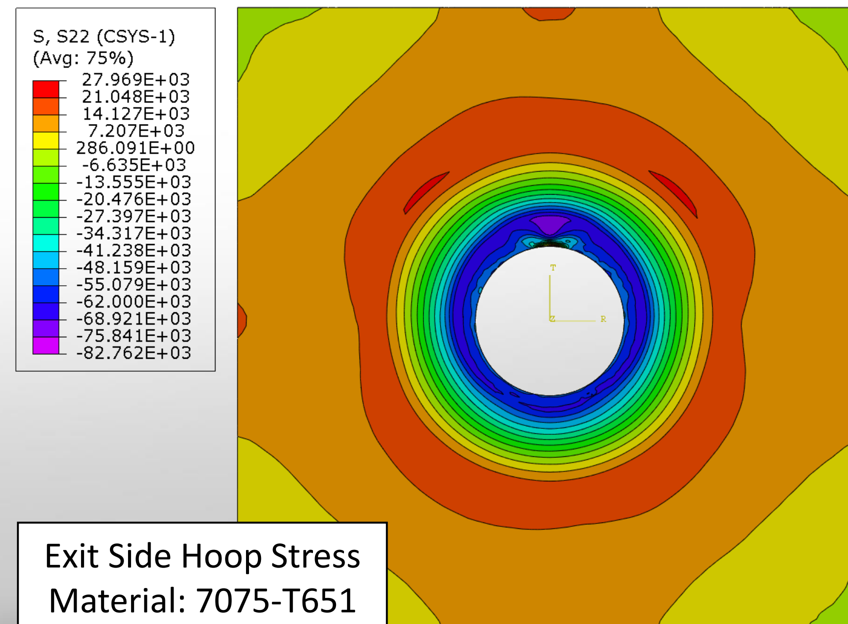
DM#808860

Outline

- Subcommittee Activity
- Material Testing and FEA Model Validation
- 2” x 2” Coupons: Further preliminary correlations



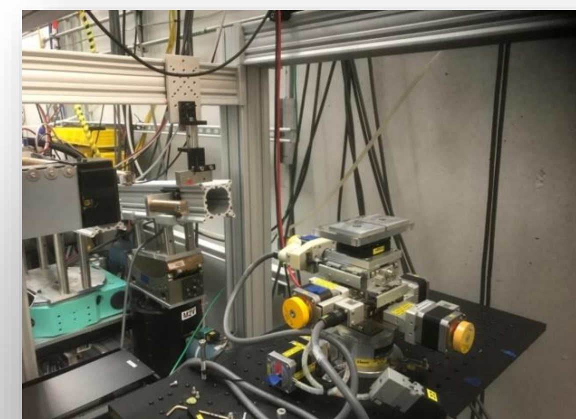
Exit Side Hoop Stress
Material: 2024-T351

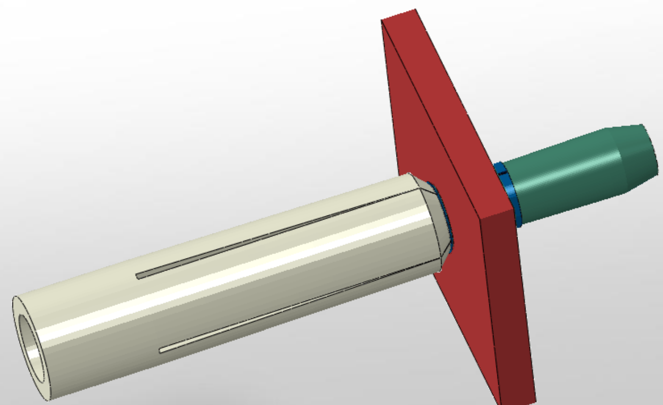


Exit Side Hoop Stress
Material: 7075-T651

Subcommittee Activity

- Three teleconferences
  - March - June
- Material model coupon fabrication and testing
- 2” x 2” Coupon Correlation Study
  - Measurements (i.e., XRD)
  - Presentations (i.e., ASTM)

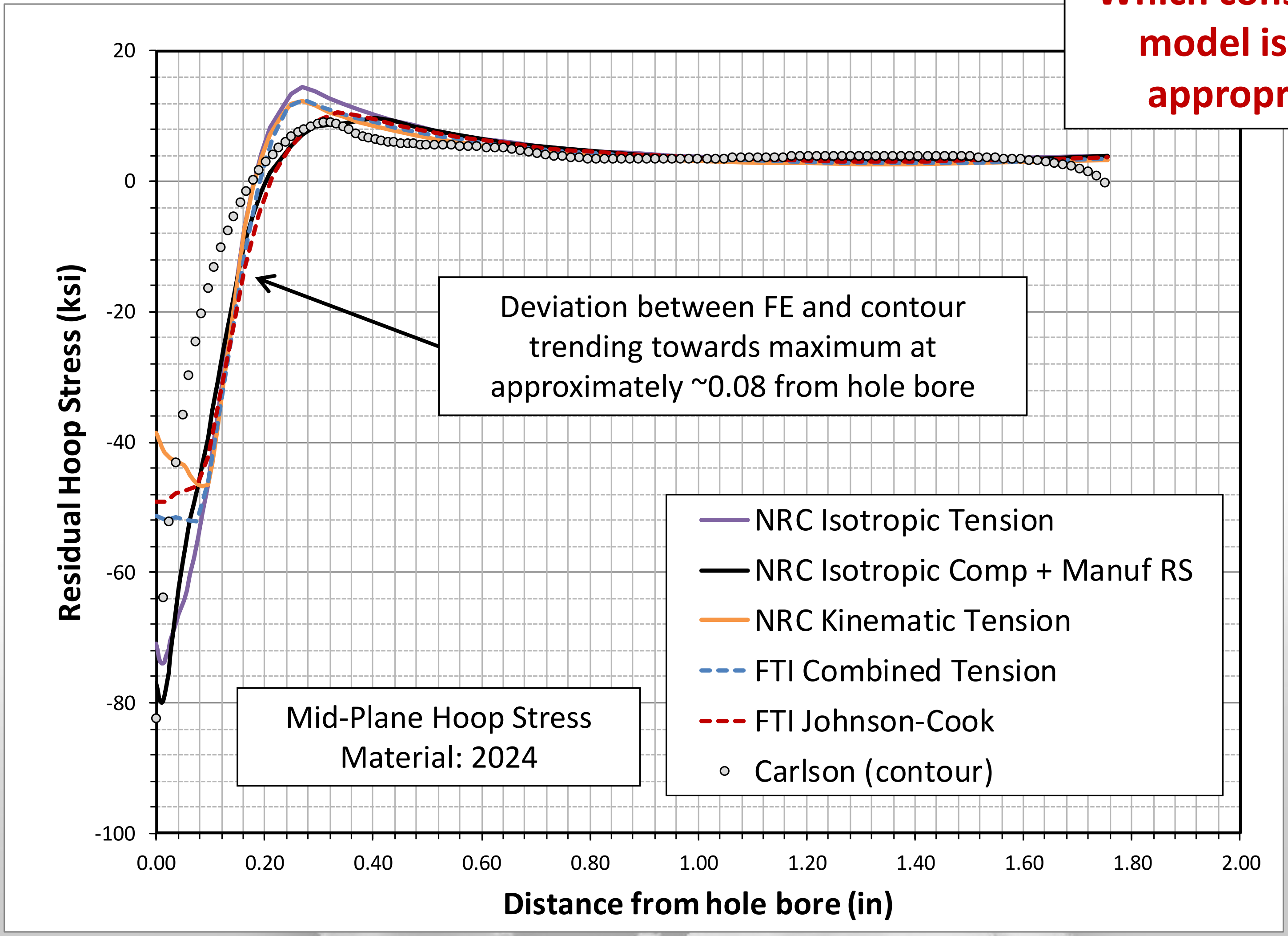




ERSI FTI FATIGUE TECHNOLOGY

Material Model Testing
Purpose of Program

Which constitutive model is most appropriate?



ERSI FATIGUE TECHNOLOGY

Material Model Testing

Purpose of Program

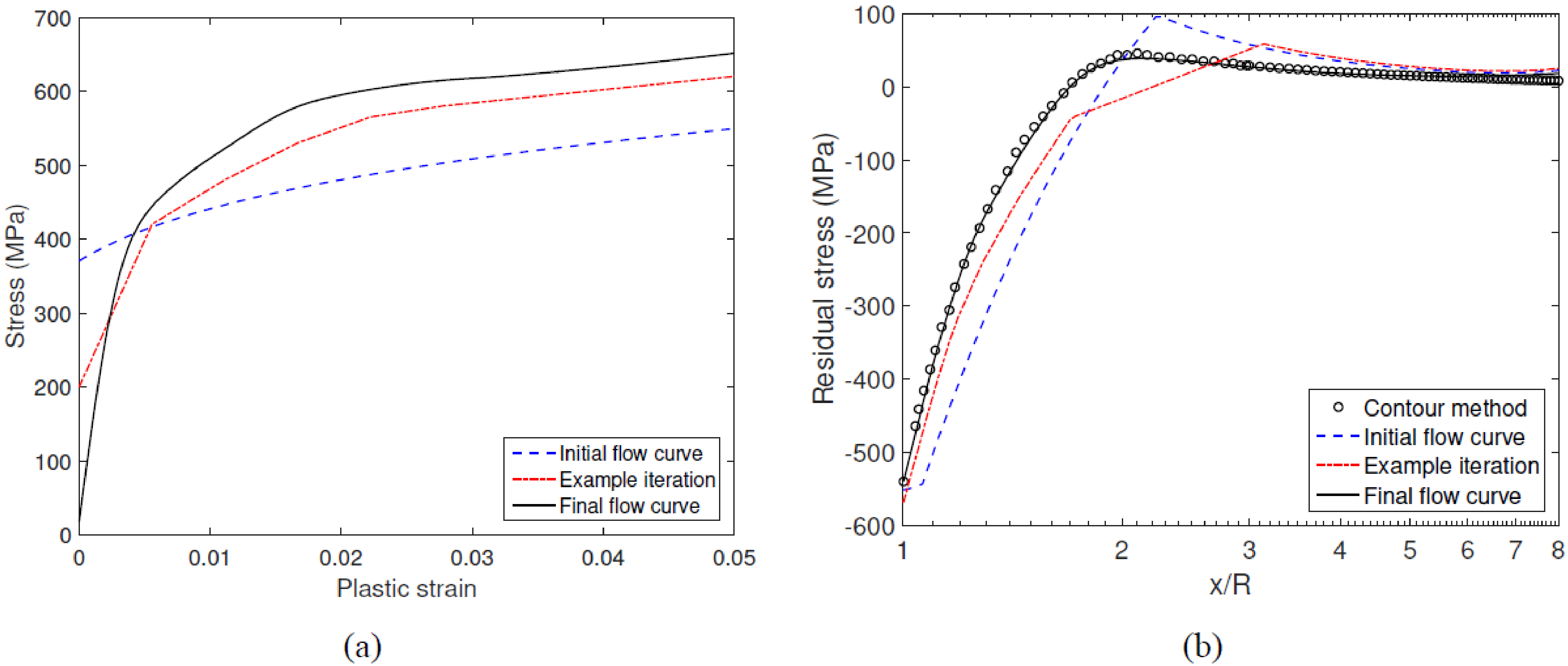


Figure 7 – (a) Flow curves tested, (b) resulting hoop residual stress ($\sigma_{\theta\theta}$); note log scale on x/R

Ribeiro, Renan L., and Michael R. Hill. "Residual Stress From Cold Expansion of Fastener Holes: Measurement, Eigenstrain, and Process Finite Element Modeling." Journal of Engineering Materials and Technology 139.4 (2017): 041012. https://doi.org/10.1115/1.4037021

ERSI FTI FATIGUE TECHNOLOGY

Material Model Testing
General Plan

- Based upon E606 LCF, up to ±4% in./in., reduced to ±1.5%
- Isolating current investigation to orthotropy
- Non-stabilized cyclic loading capturing reverse-yield behavior (2024 currently, 7075 to follow)
- **Testing was to be complete Fall 2017, actually completed late Spring 2018.**

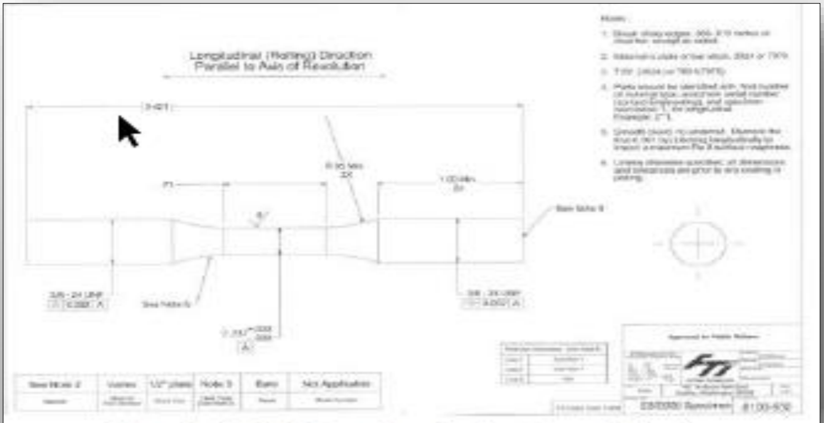


Figure 5: E8/E606 Specimen Design (Longitudinal).

FATIGUE TECHNOLOGY

Material Model Testing

Test Results

- FTI fabricated 10 each T, L and 45° specimens from plate provided (same lot as 2” x 2” coupons).
  - Issue: Poor transition on one side of specimen
  - Issue: specimen design (grip, gauge length) not conducive to high (~4% strains).
- NRC worked through issues to provide an excellent body of data.

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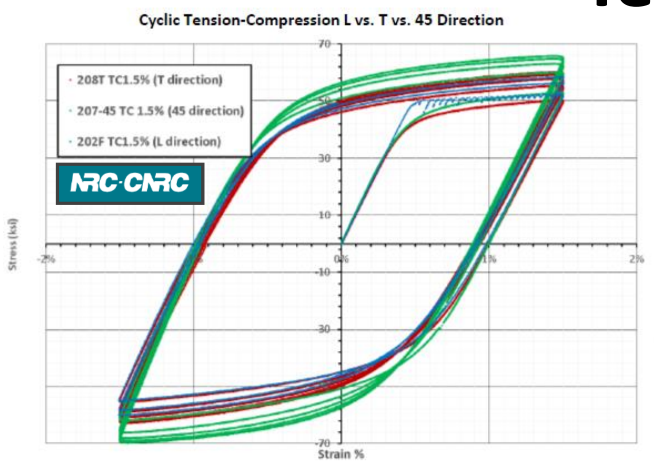
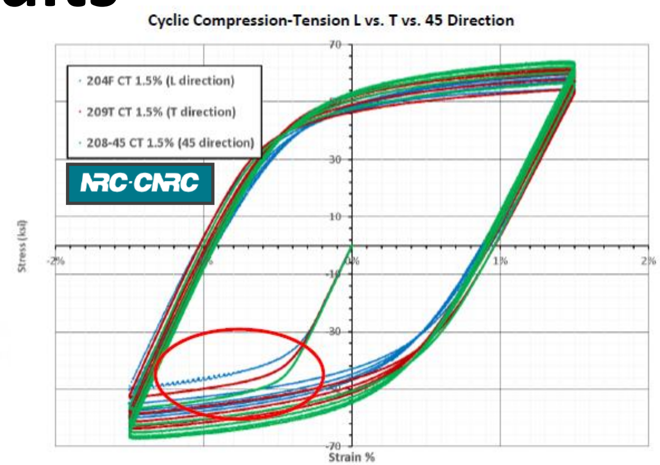
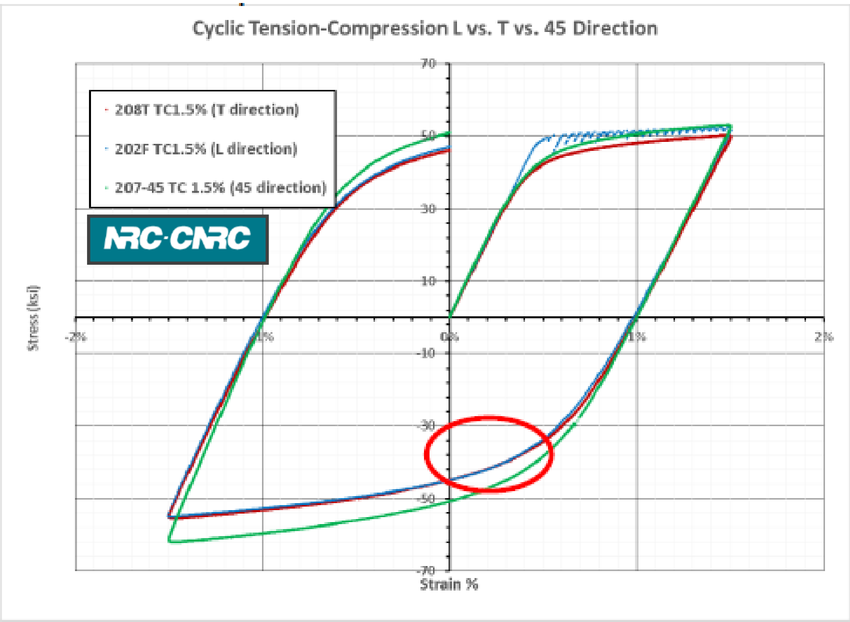
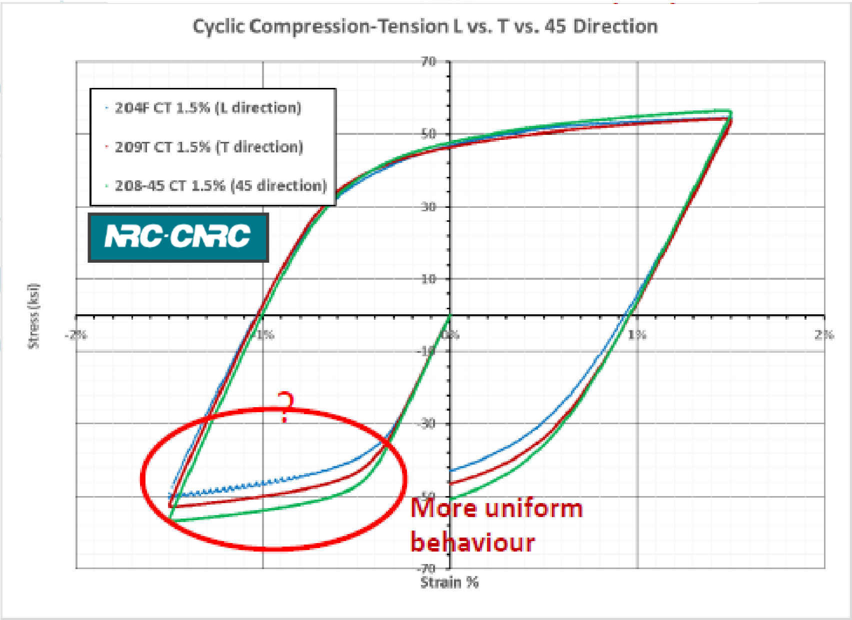
Material Model Testing

Test Results









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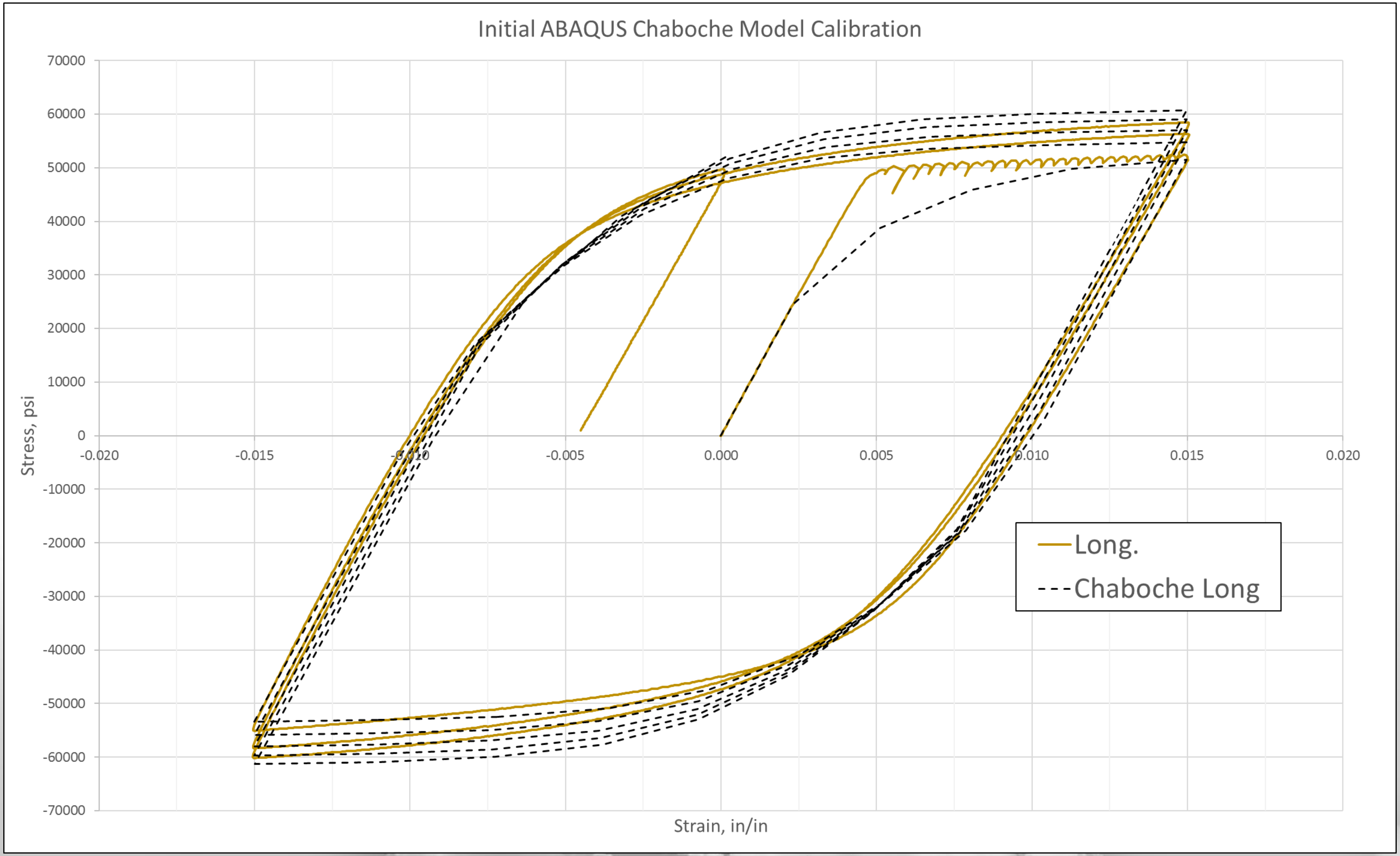
Material Model Testing

Preliminary Abaqus Model Calibration



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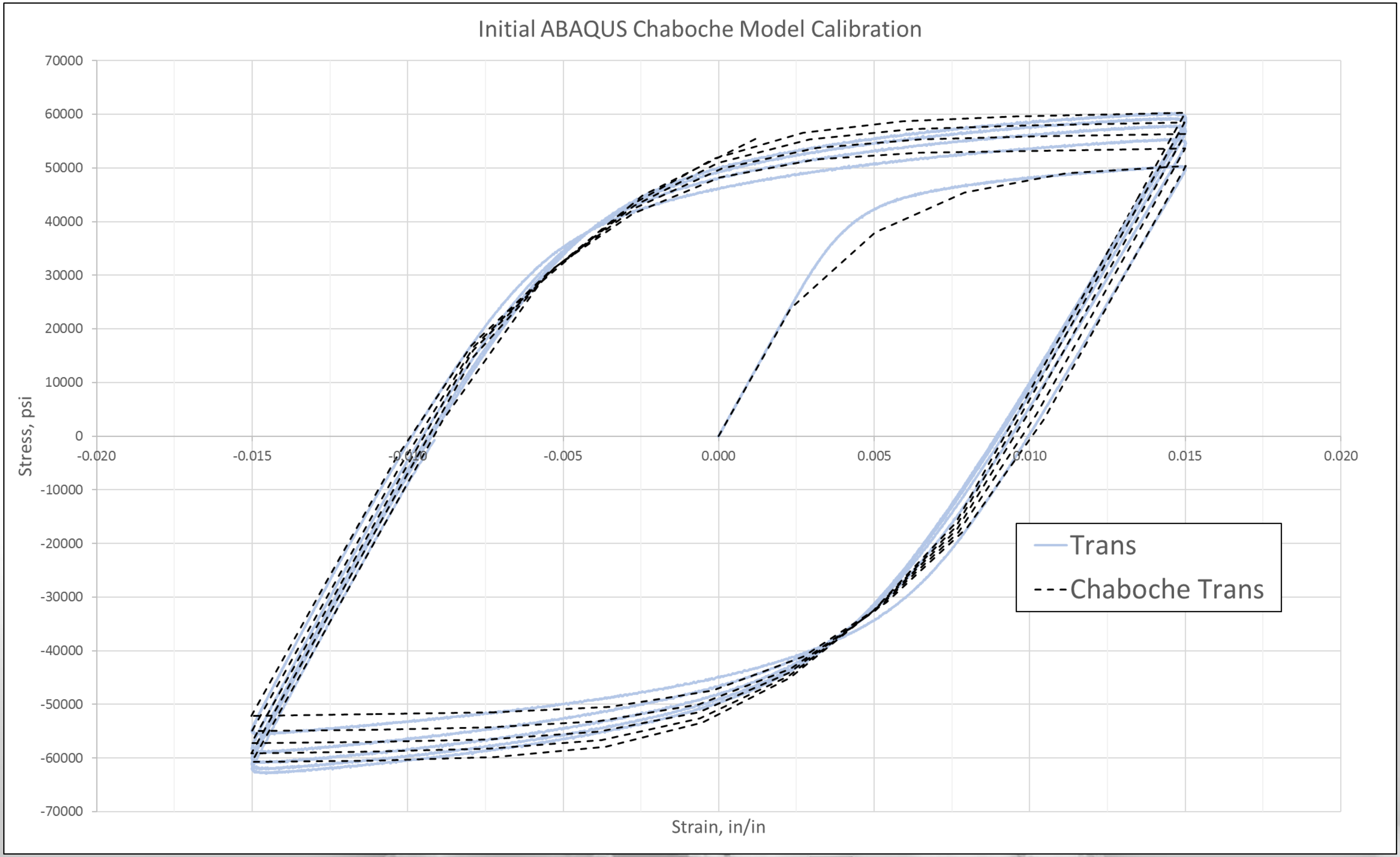
DM#808860

Material Model Testing

Preliminary Abaqus Model Calibration



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FATIGUE TECHNOLOGY

Material Model Testing

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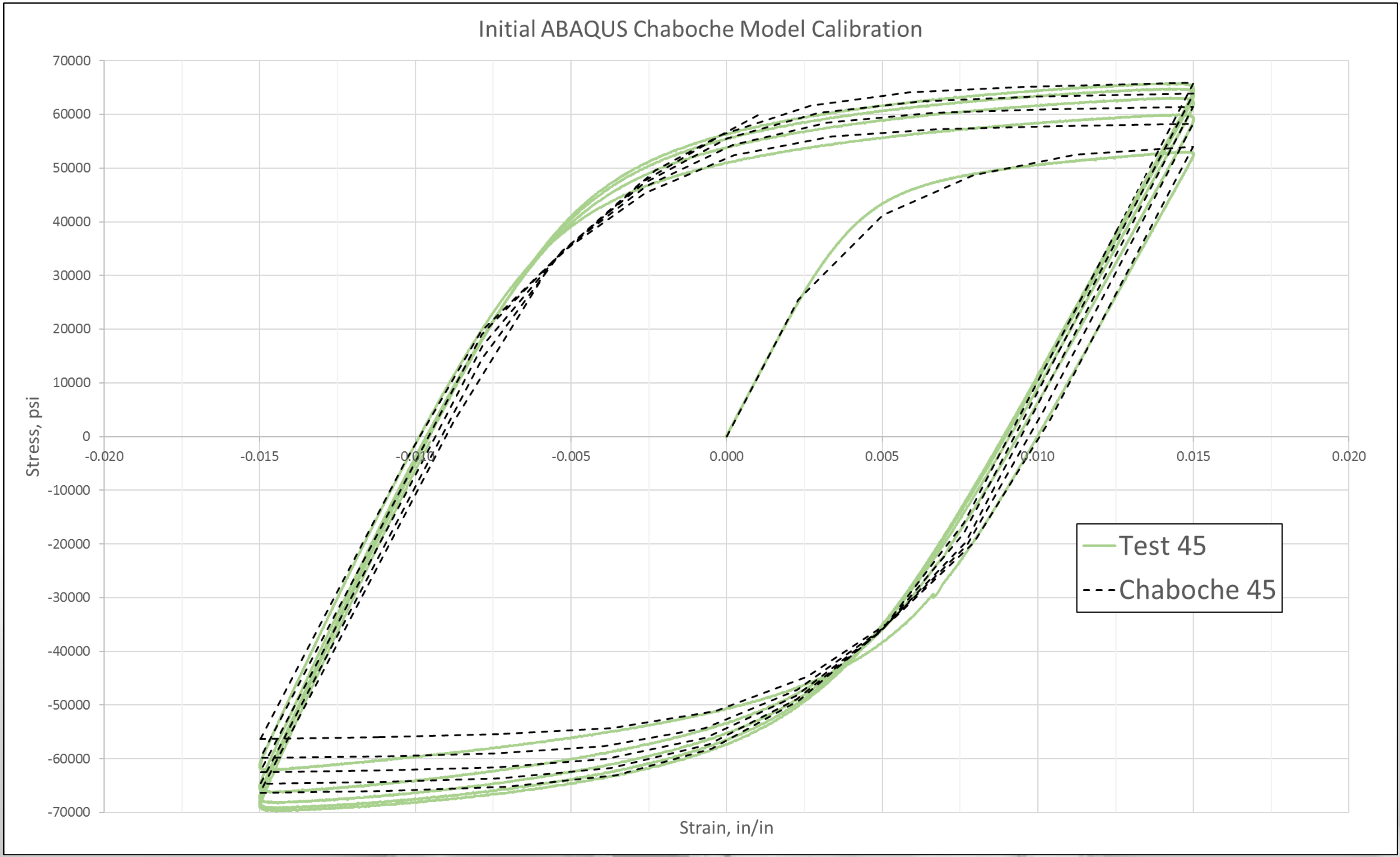

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Material Model Testing

Abaqus Model Calibration Results

Chaboche Parameter	Long.	Trans.	45°	Avg.	Clausen, et. al.*
σ_{ys}, psi	30281	28942	32786	30670	31894
C, psi	7.35e6	8.69e6	8.19e6	8.08e6	9.74e6
ϒ	346.88	412.96	399.09	386.31	412.0
Q, psi	21202	21042	20526	20923	23637
b	3.37	3.85	5.53	4.70	7.00
E, psi	10.56e6	10.36e6	11.10e6	10.67e6	10.62e6
ϵ	0.33	0.33	0.33	0.33	0.33

* public.lanl.gov/clausen/Clausen_et_al_PrePrint_SEM_2009.pdf

ERSI FTI FATIGUE TECHNOLOGY

RS Process Simulation Validation

Purpose of Program

- Perform Experiments to Capture Surface and Through-Thickness Strains for FEA Process Simulation Validation
  - Quantification of residual stresses through process simulation is a critical path for future ERSI realization
  - Perform Residual Stress Validation Through Comparison of Techniques
  - Limited open literature on cross-comparison of residual stress measurement methods for Cx holes
  - Potential to complement through-thickness techniques with surface techniques for a more accurate understanding of the complete residual stress field
  - Current work underway through Process Simulation Subcommittee, with the kind assistance of the *Organization and Execution Group*:

  - Dr. TJ Spradlin (AFRL)
  - Keith Hitchman (FTI)
  - Dr. Marcias Martinez (Clarkson U.)
  - Marcus Stanfield (SwRI)
  - Prof. Michael Fitzpatrick (Coventry U.)
  - Scott Carlson (SwRI)
  - Dr. Min Liao (NRC)
  - Dr. Guillaume Renaud (NRC)
  - Dr. Mike Hill (Hill Engineering)

ERSI FATIGUE TECHNOLOGY

RS Process Simulation Validation

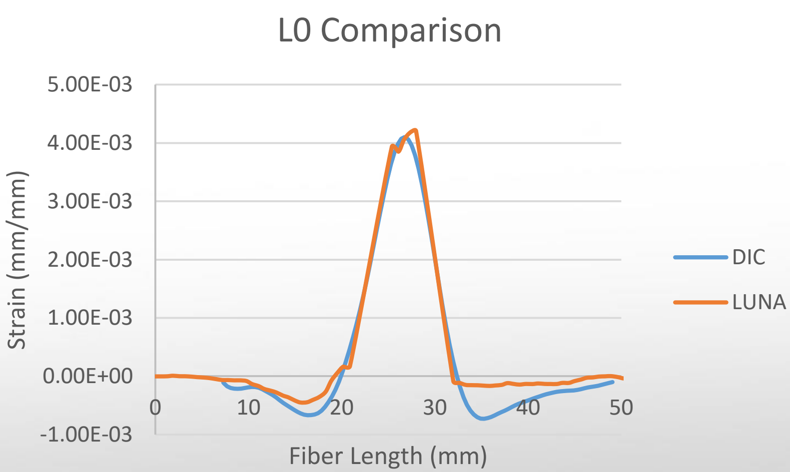
Test Plan (evolved)

- Material: 2024-T351 & 7075-T651
- Two Applied Expansion Levels: “Low” (3.16%), “High” (4.16%)
- Center Hole Diameter: 16-0-N Tool Set
  - 0.50inch final diameter
  - Hole not reamed
- Finite Element Analysis (various material models)
- Surface Measurement (Exit and Entrance Surfaces)
  - Digital Image Correlation (DIC)
  - Fiber Optics (LUNA)
  - Strain gages
  - X-ray Diffraction (XRD)
- Volume (Through-Thickness) Measurement Techniques
  - High Energy X-ray Diffraction (APS HE-XRD) - Argonne National Labs
  - High Energy X-ray Diffraction (CHESS) - Cornell
  - Neutron Diffraction - Coventry University (UK)
  - Contour Method - Hill Engineering, LLC

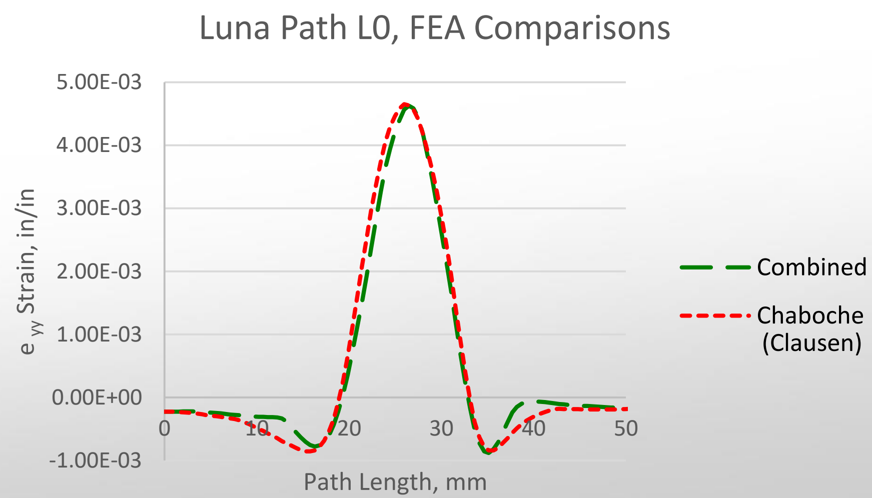
ERSI FATIGUE TECHNOLOGY

RS Process Simulation Validation
Surface Strain Measurements

- Tabular surface strain measurement data available for correlation:
  - Luna (M. Martinez, Clarkson University)
  - Strain Gage (M. Stanfield, SWRI)
- Working on revised FEA with NRC-based Chaboche
- Full correlation to follow.



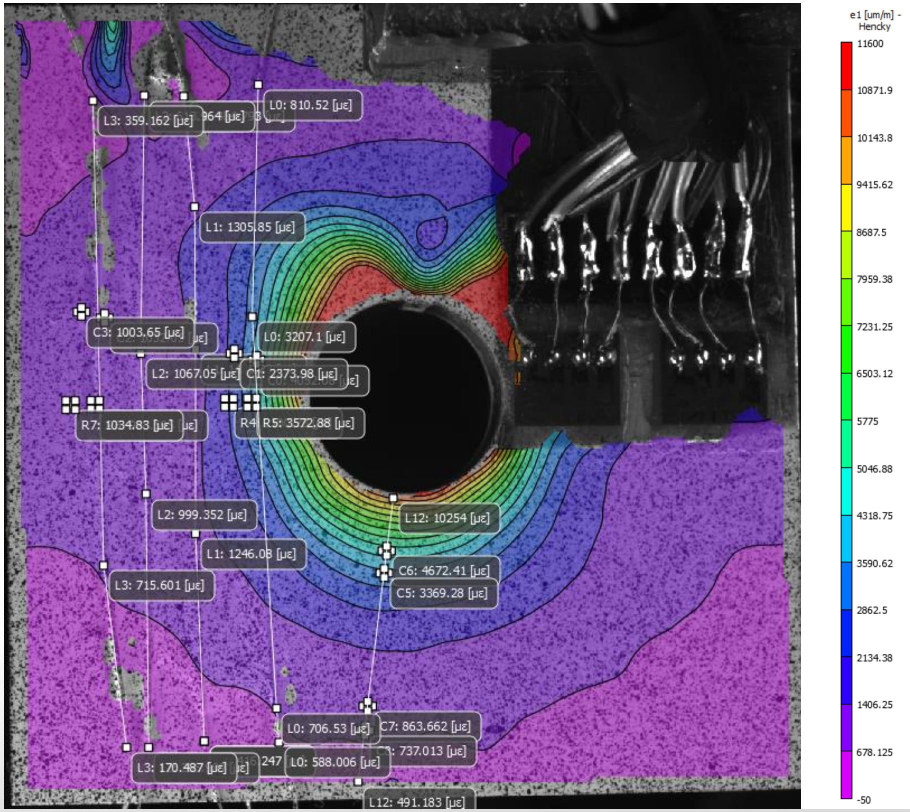
Luna/DIC e_{yy} strains



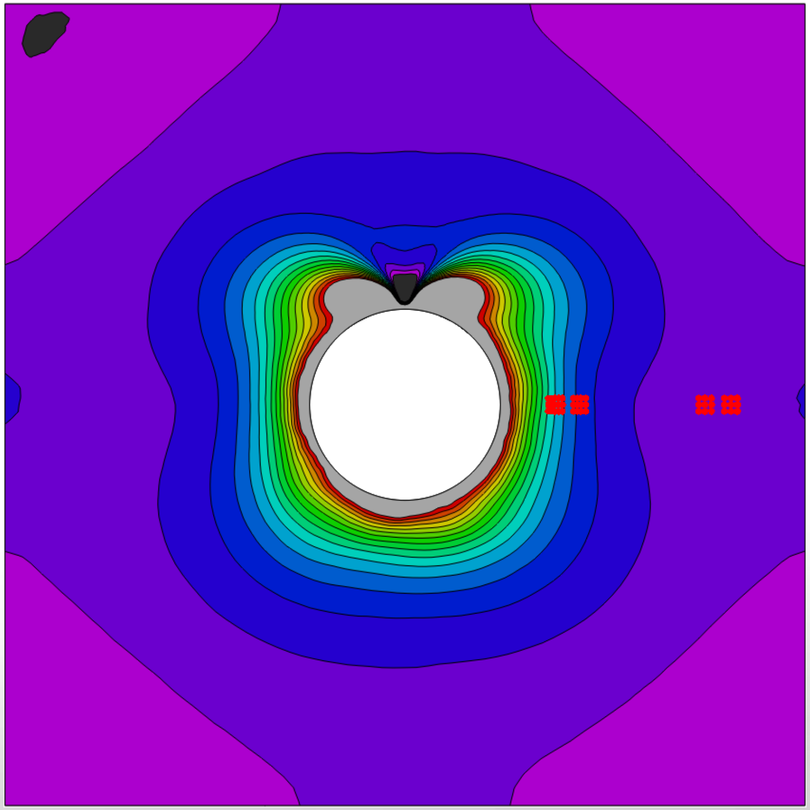
FEA e_{yy} strains

RS Process Simulation Validation

Surface Strains



DIC Hoop strains



FEA Hoop strains
Chaboche Hardening (Clausen)

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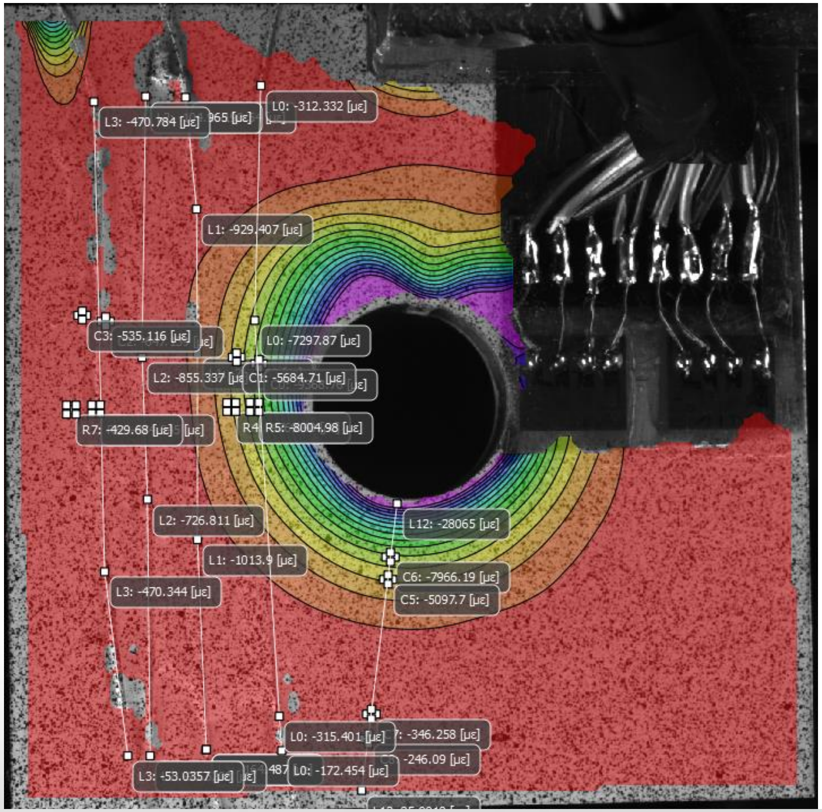
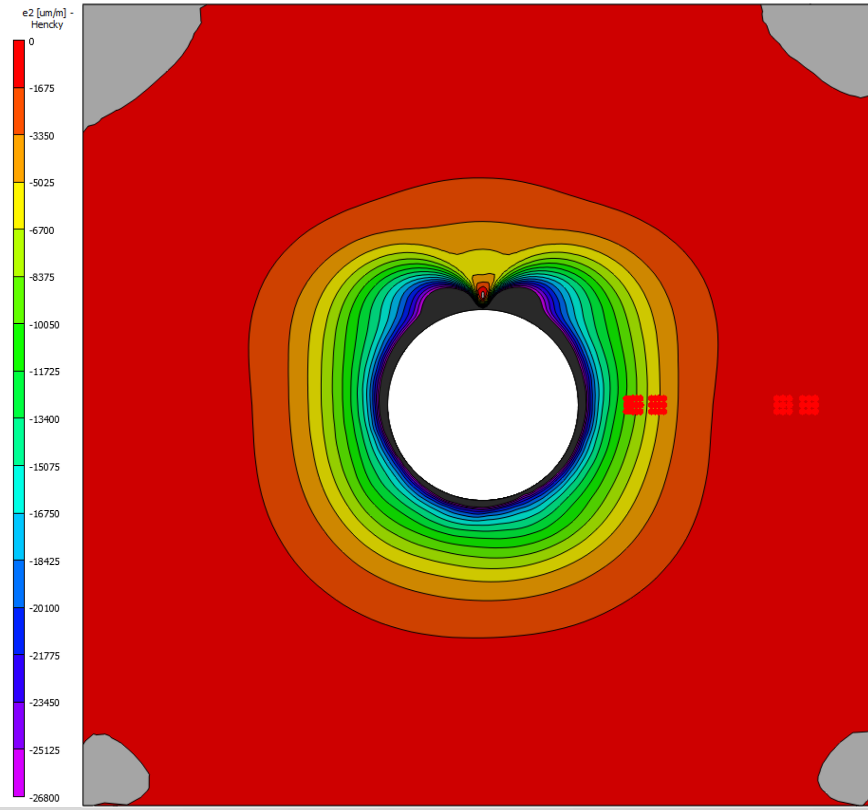
RS Process Simulation Validation

Surface Strains





DIC Radial strains

FEA Radial strains
Chaboche Hardening (Clausen)

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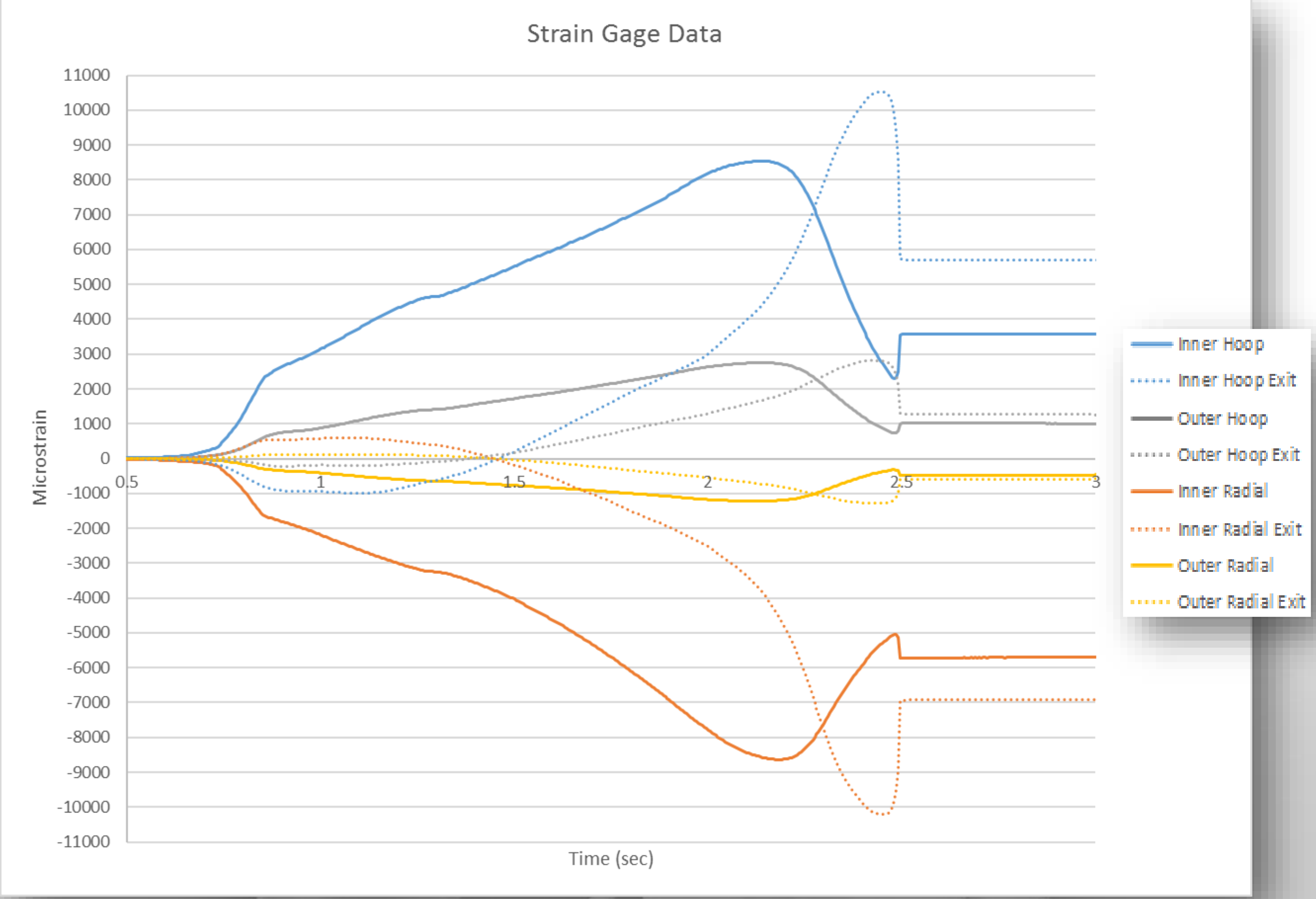
RS Process Simulation Validation

Surface Strains

Solid Lines – Entrance **Dotted Lines – Exit**



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RS Process Simulation Validation

Surface Strains

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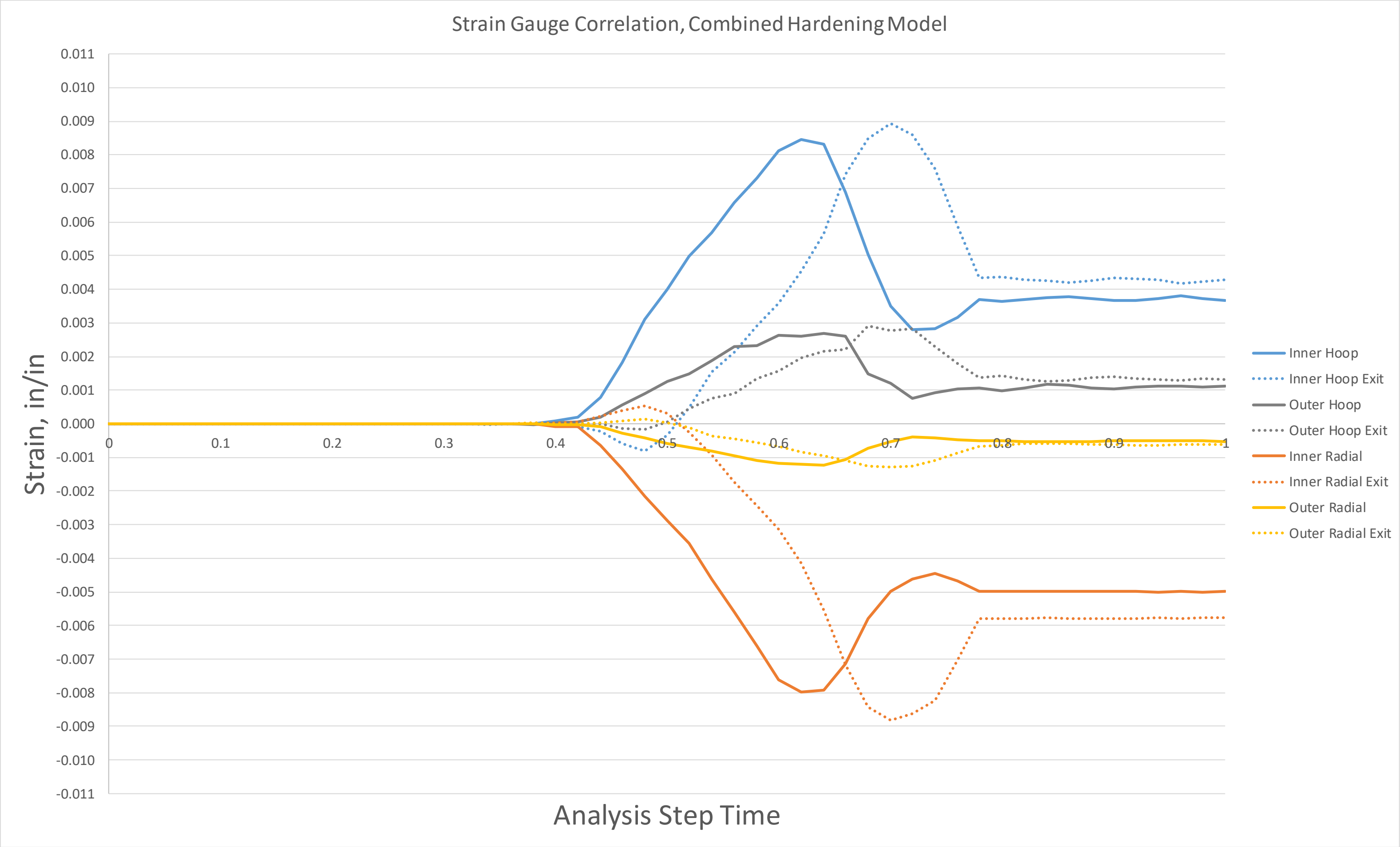

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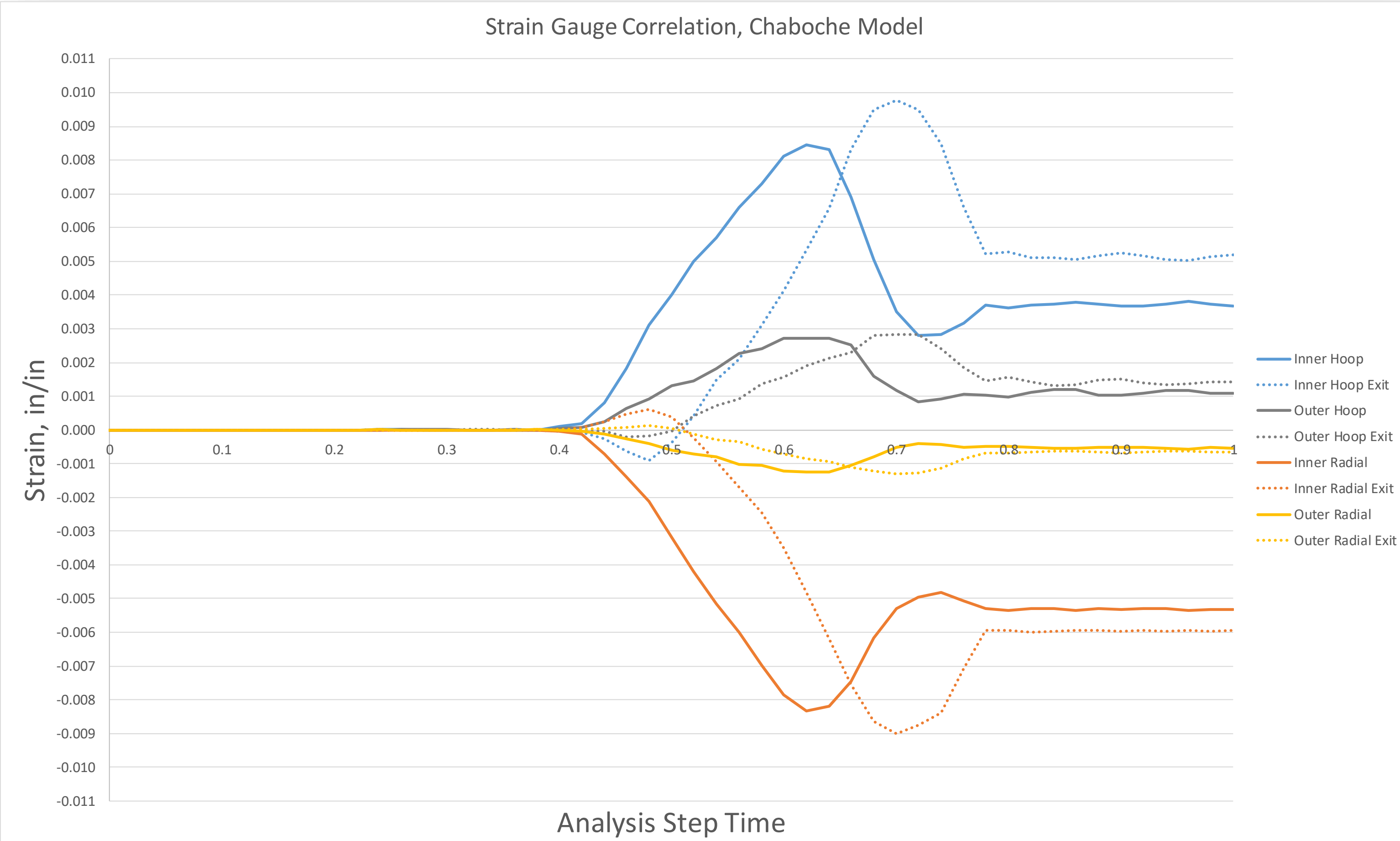
RS Process Simulation Validation

Surface Strains

Solid Lines – Entrance **Dotted Lines – Exit**



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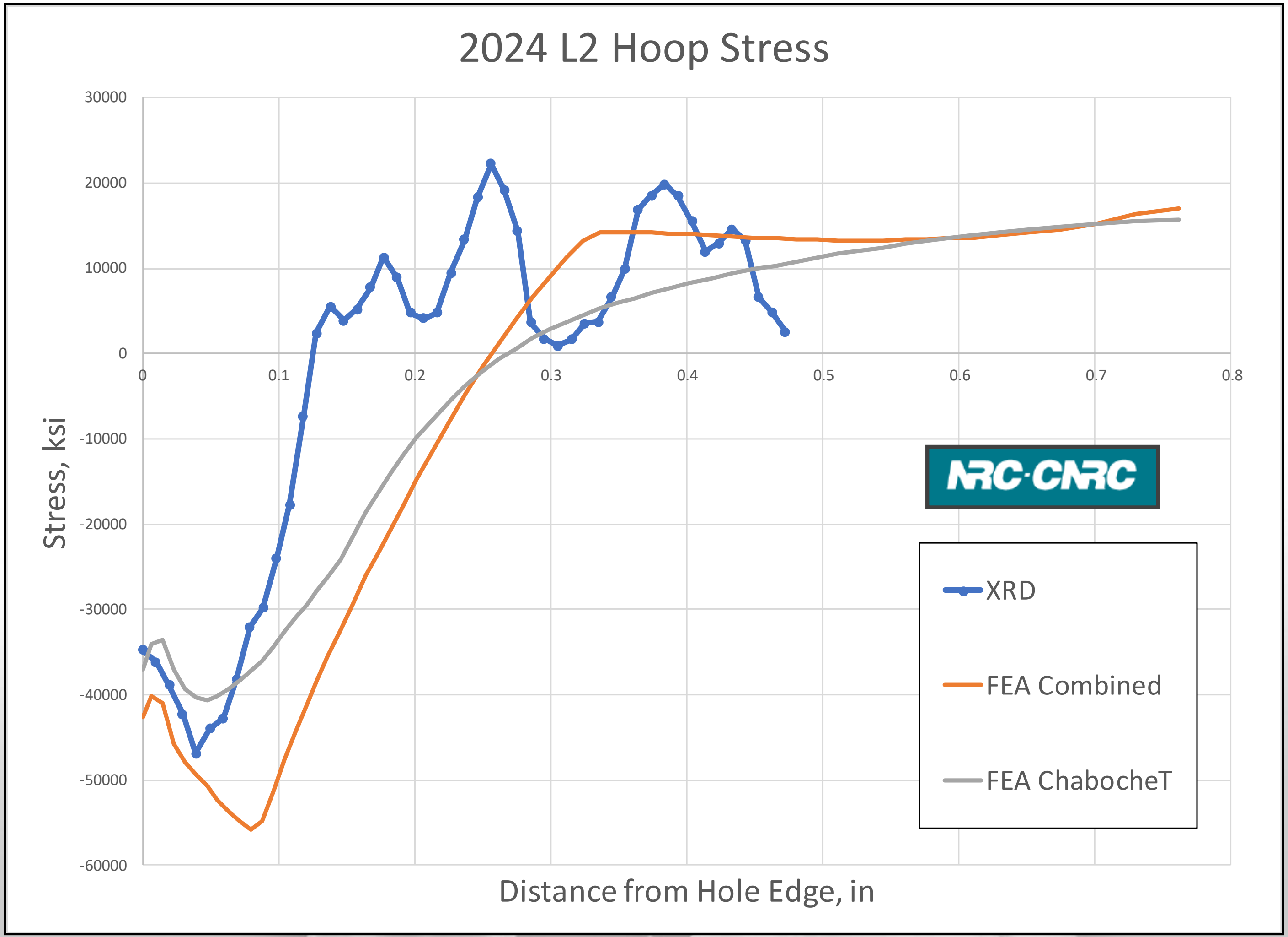
RS Process Simulation Validation

XRD Surface Stress



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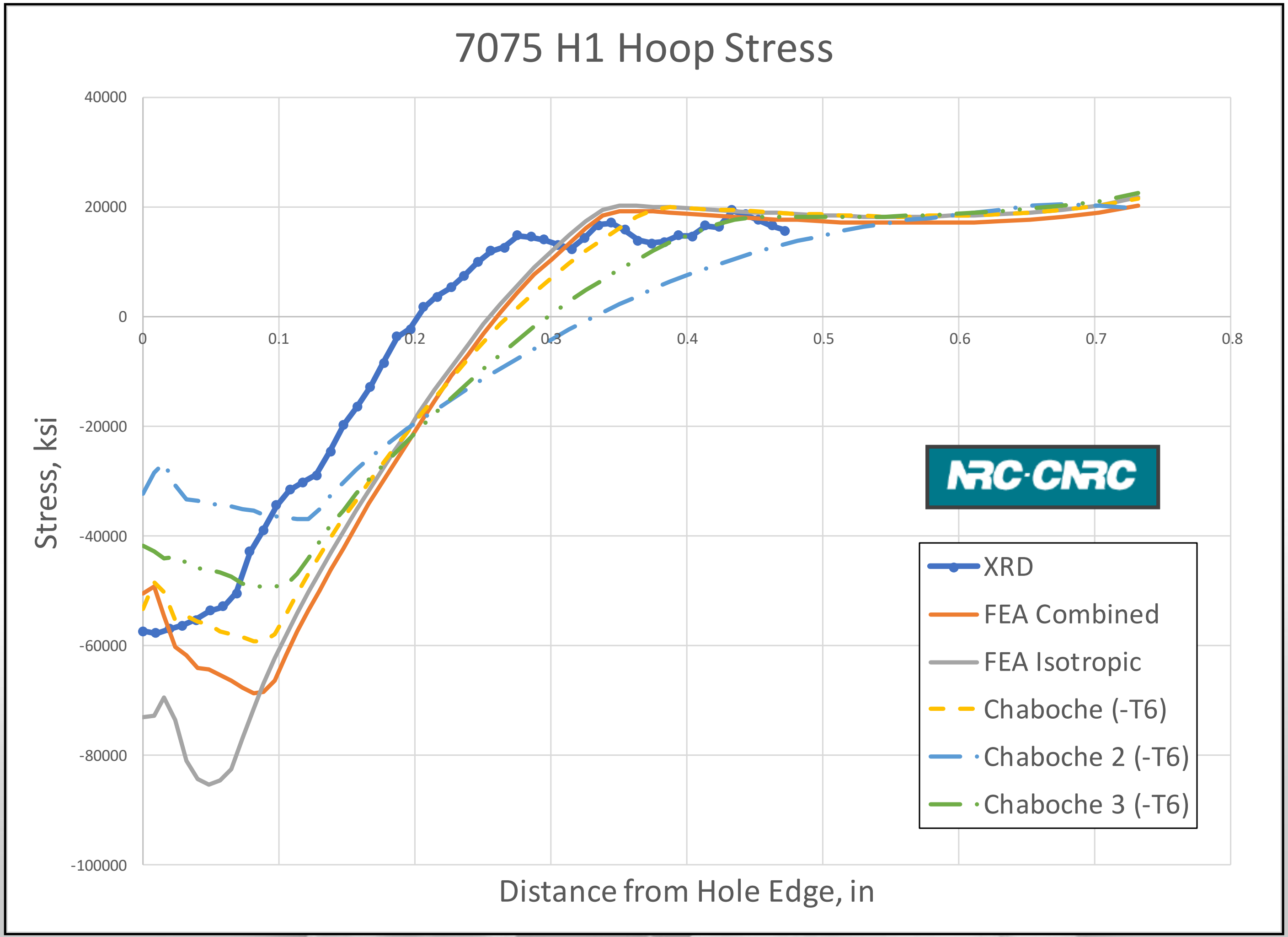
RS Process Simulation Validation

XRD Surface Stress



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RS Process Simulation Validation

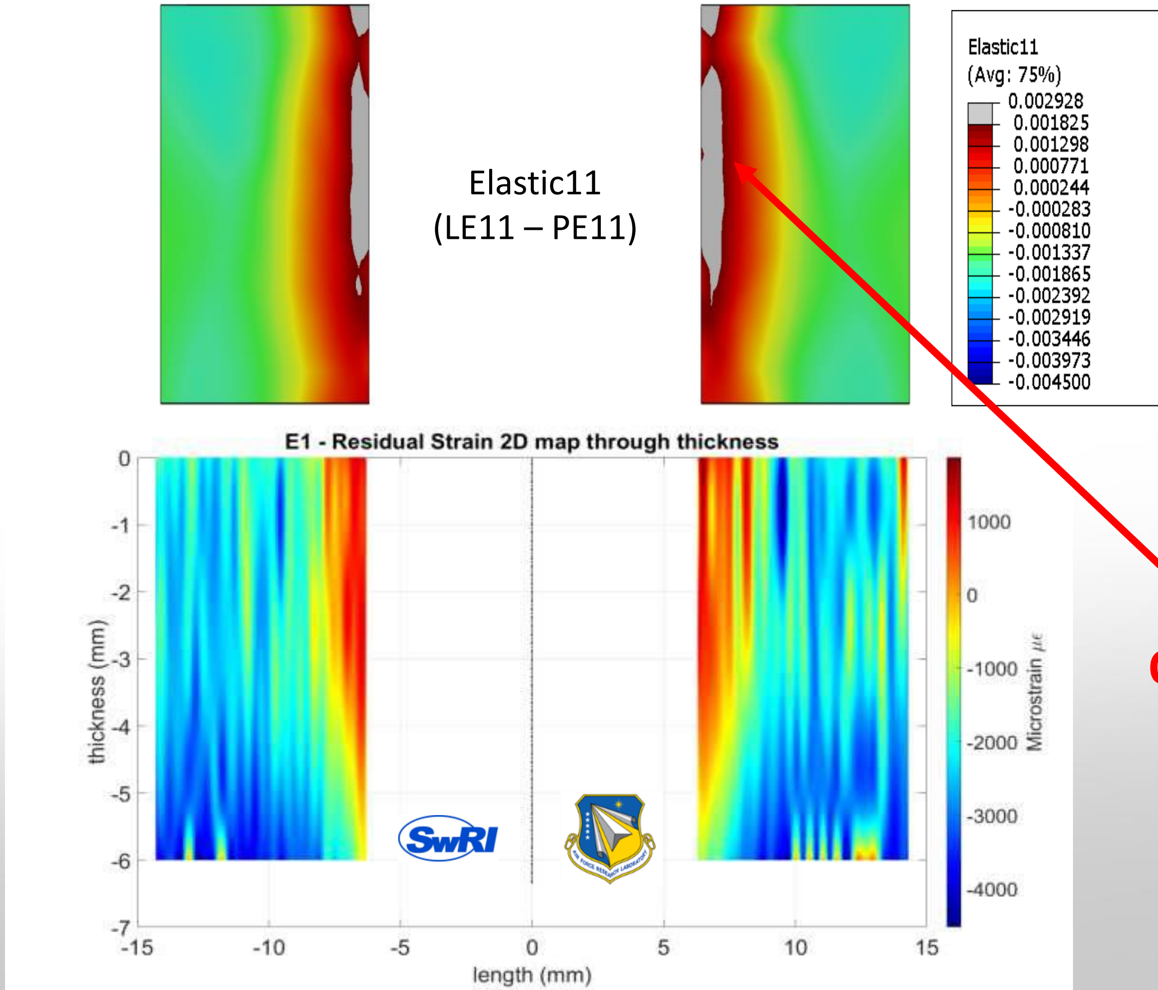
Volume Strain Measurements

- Raw data still being evaluated and reduced.
- All results and correlations shown are to be considered preliminary examples, and may likely change

RS Process Simulation Validation

APS Preliminary Radial Strain

AA7075-L1 {200}   7075-L1 Combined

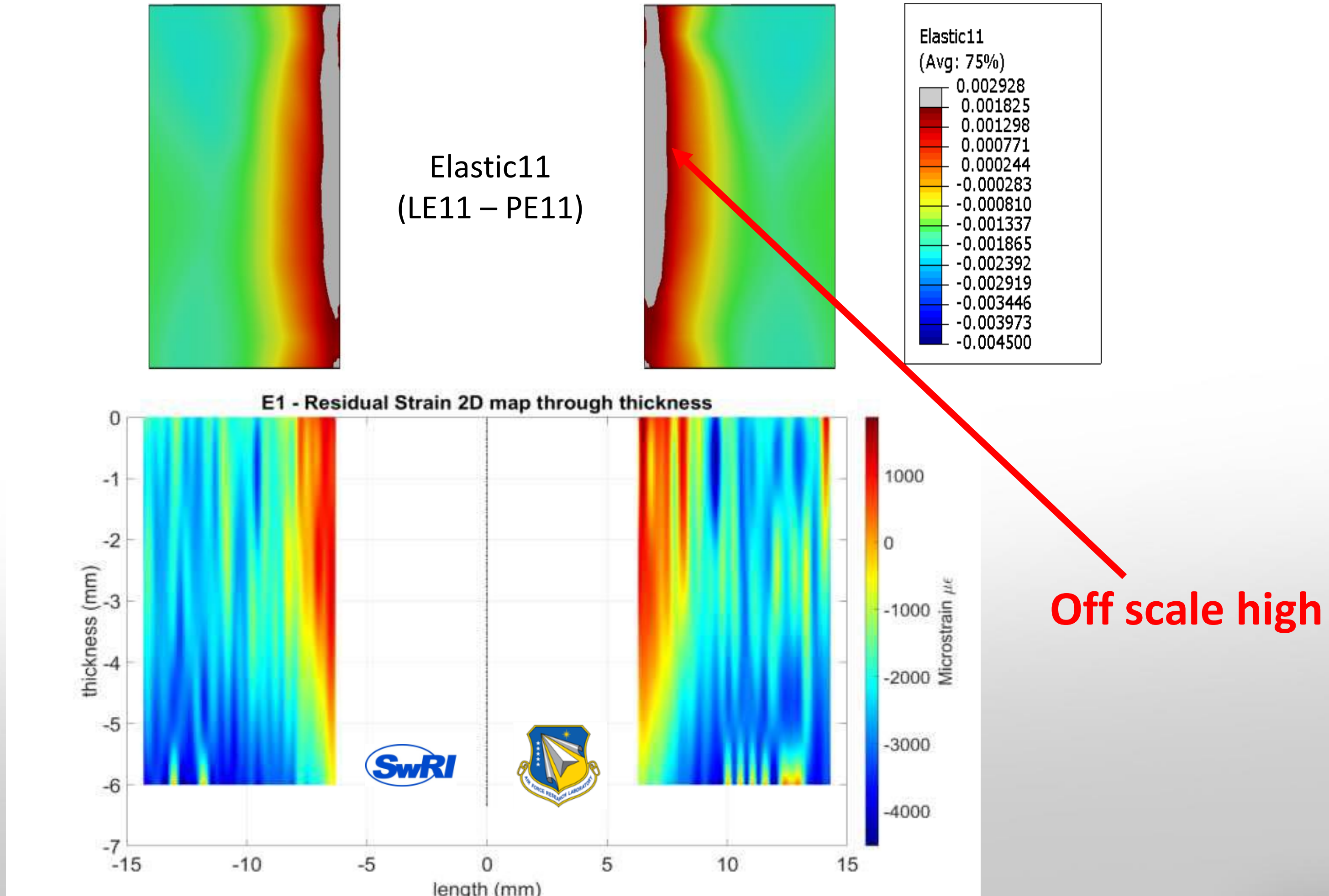


Off scale high

RS Process Simulation Validation

APS Preliminary Radial Strain

7075-L1 Isotropic



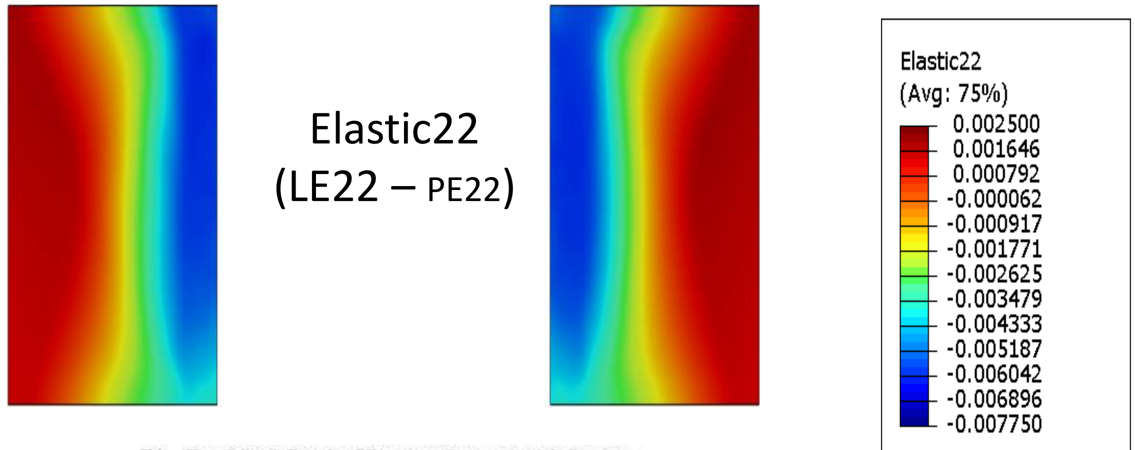
AA7075-L1 {200}

FATIGUE TECHNOLOGY

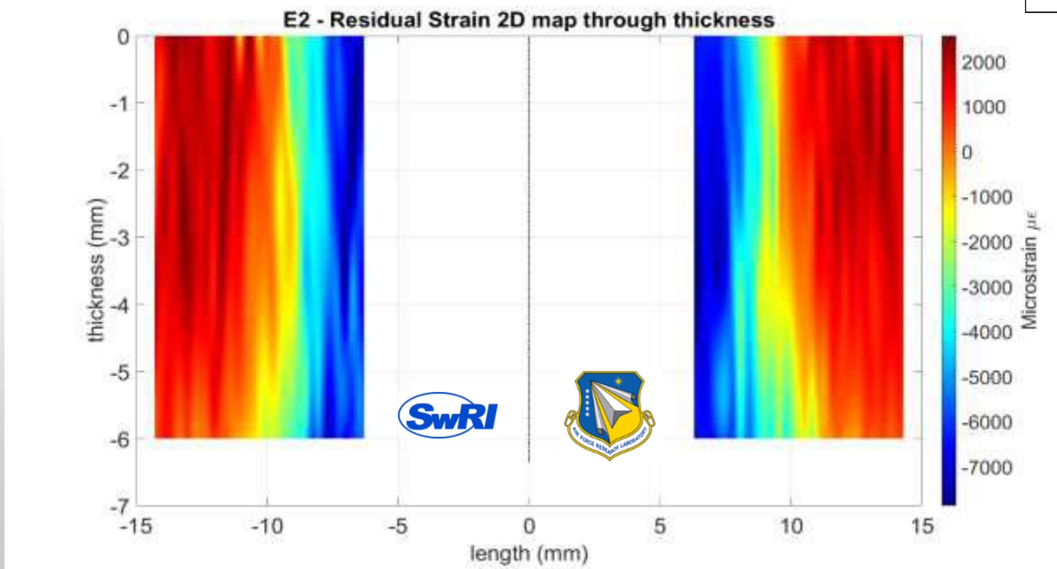
RS Process Simulation Validation

APS Preliminary Hoop Strain

7075-L1 Combined



AA7075-L1 {200}



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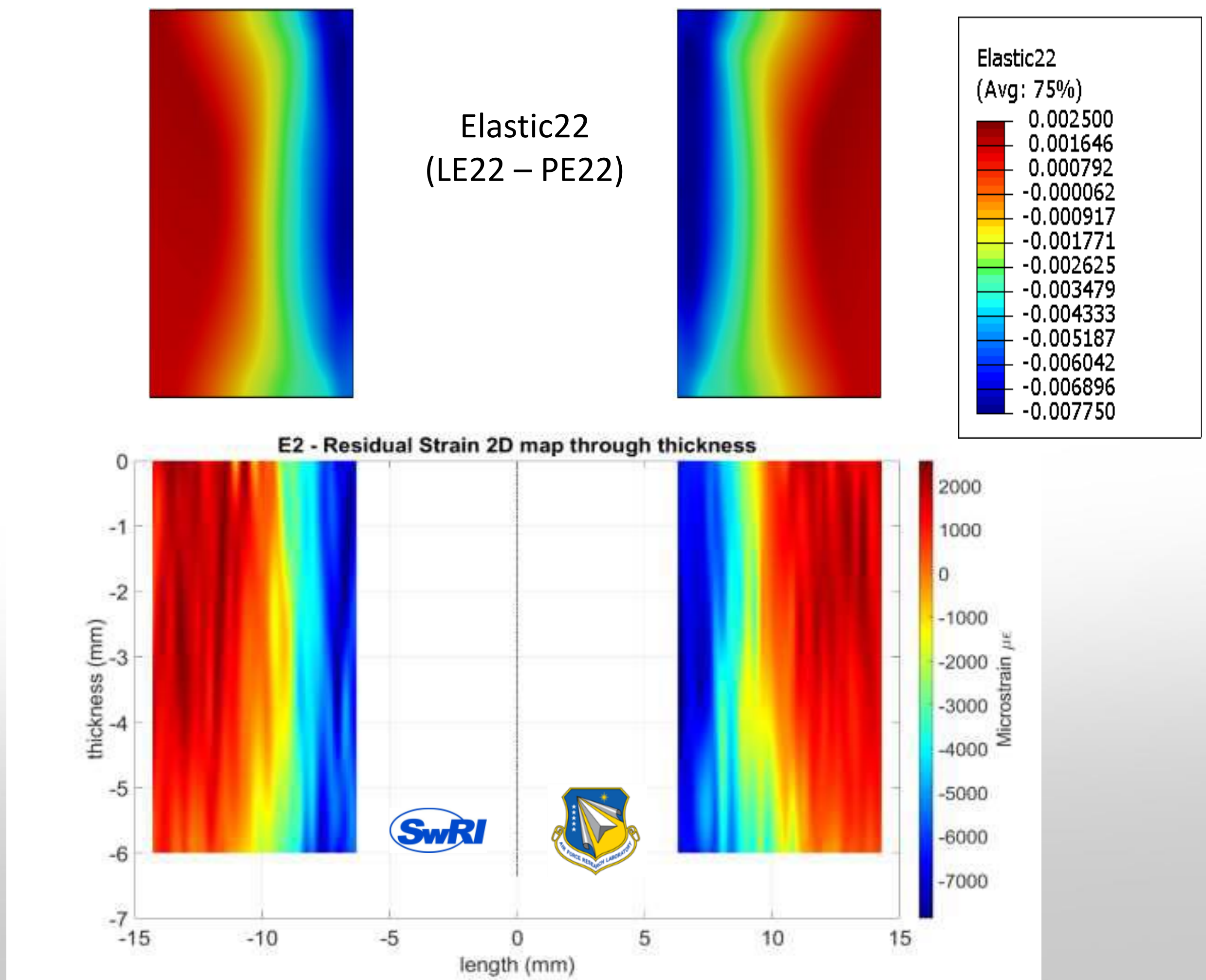
FATIGUE TECHNOLOGY

RS Process Simulation Validation

APS Preliminary Hoop Strain

7075-L1 Isotropic

AA7075-L1 {200}

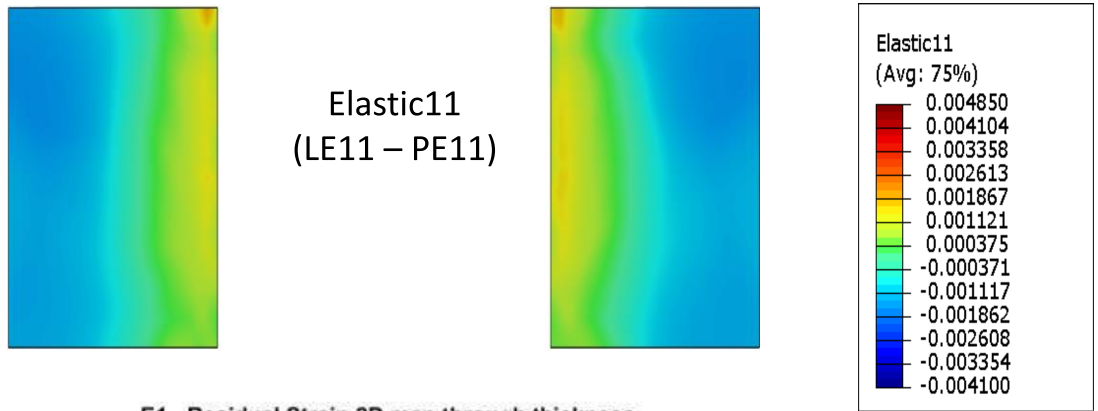


DM#808860

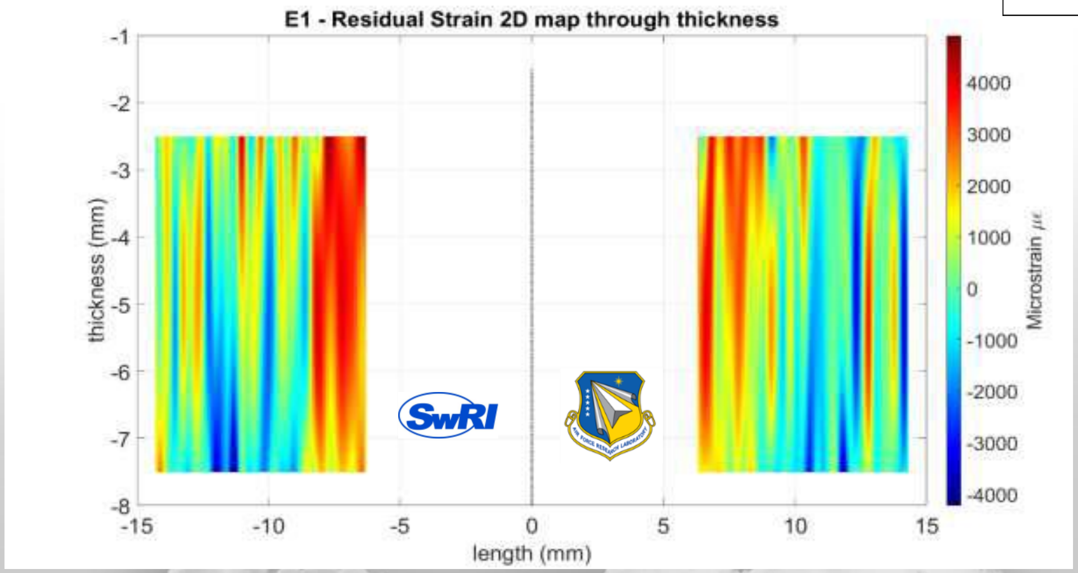
RS Process Simulation Validation

APS Preliminary Radial Strain

2024-L2 Combined



AA2024-L2 (i1) {311}



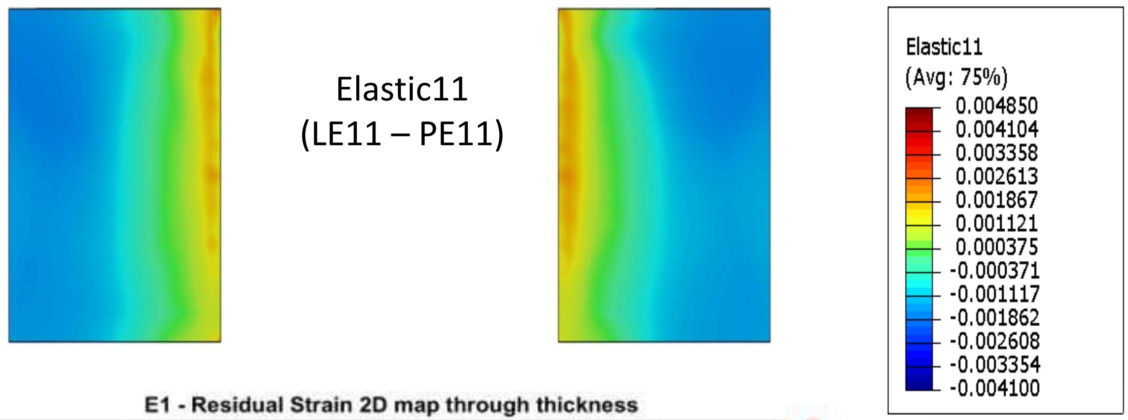
FATIGUE TECHNOLOGY

DM#808860

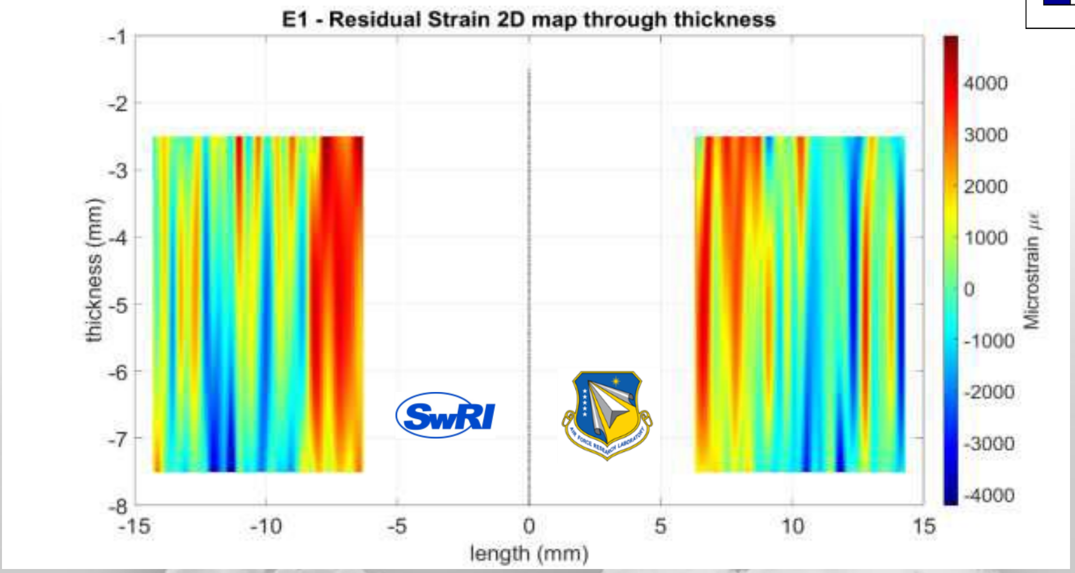
RS Process Simulation Validation

APS Preliminary Radial Strain

2024-L2 Isotropic



AA2024-L2 (i1) {311}



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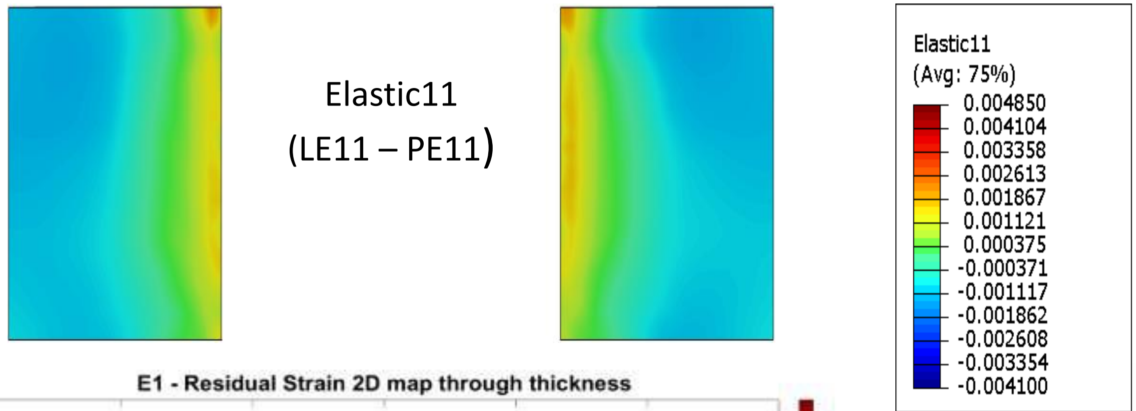
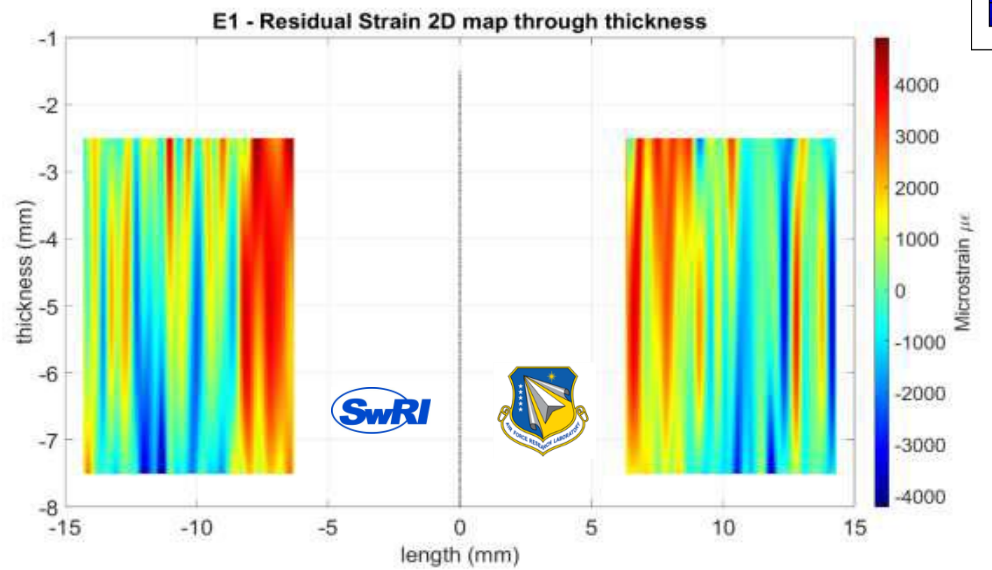
RS Process Simulation Validation

APS Preliminary Radial Strain

AA2024-L2 (i1) {311}   2024-L2 Chaboche



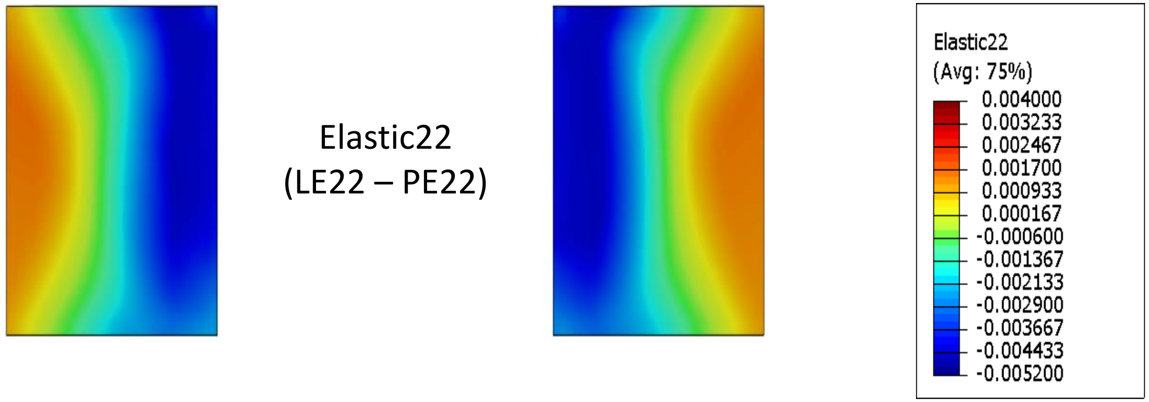


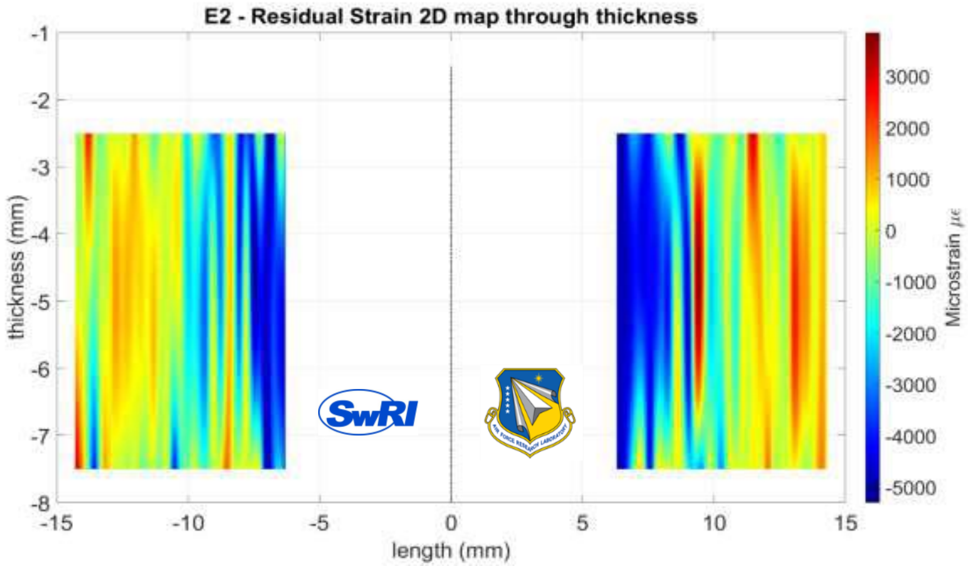
FATIGUE TECHNOLOGY

RS Process Simulation Validation

APS Preliminary Hoop Strain

AA2024-L2 (i1) {311}   2024-L2 Combined

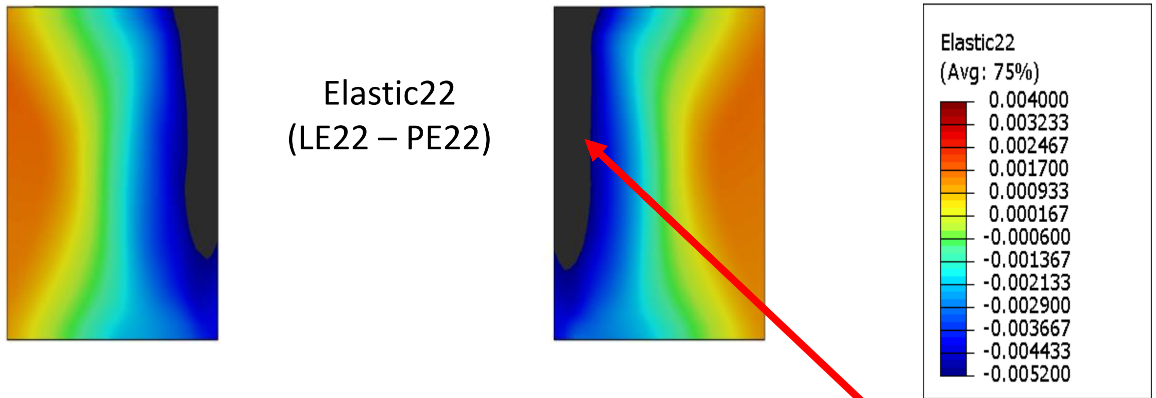




RS Process Simulation Validation

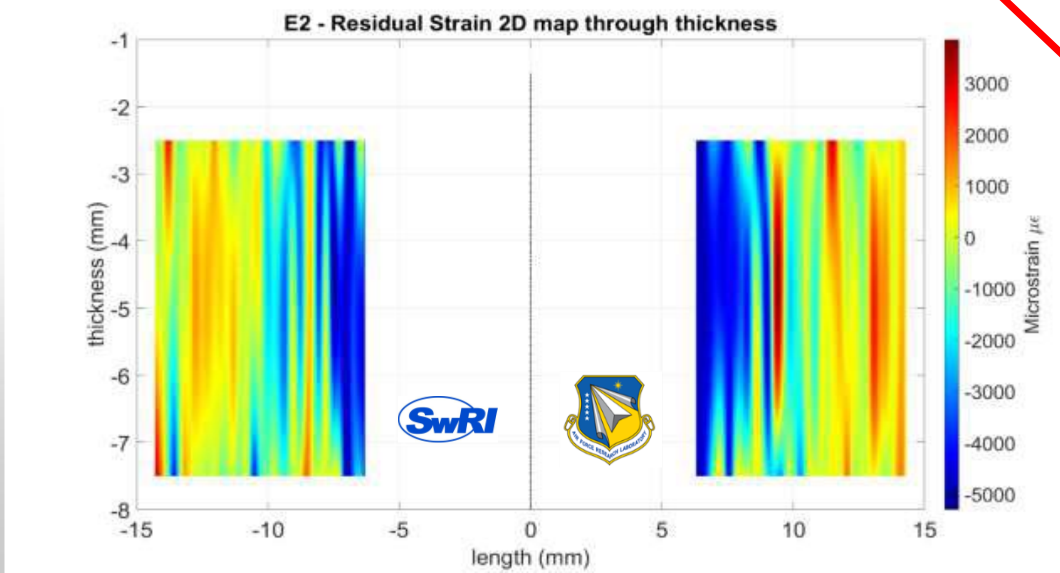
APS Preliminary Hoop Strain

2024-L2 Isotropic



Off scale low

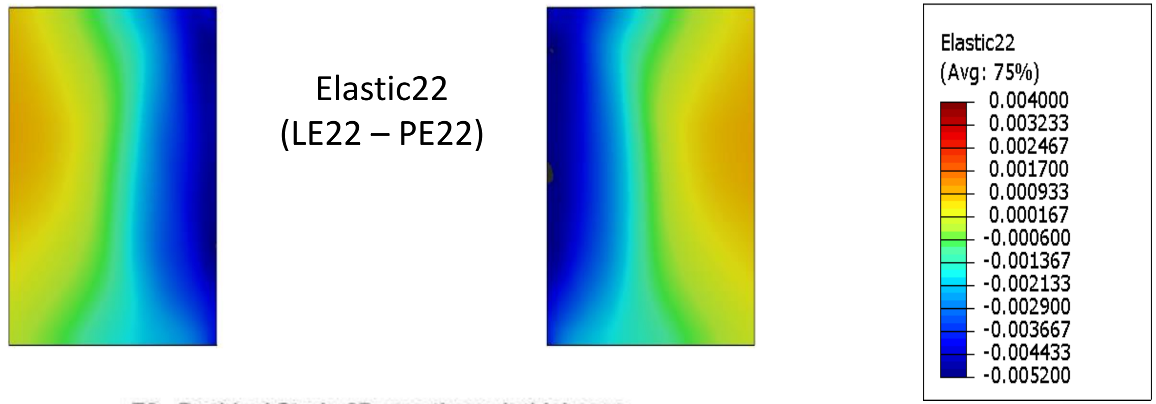
AA2024-L2 (i1) {311}



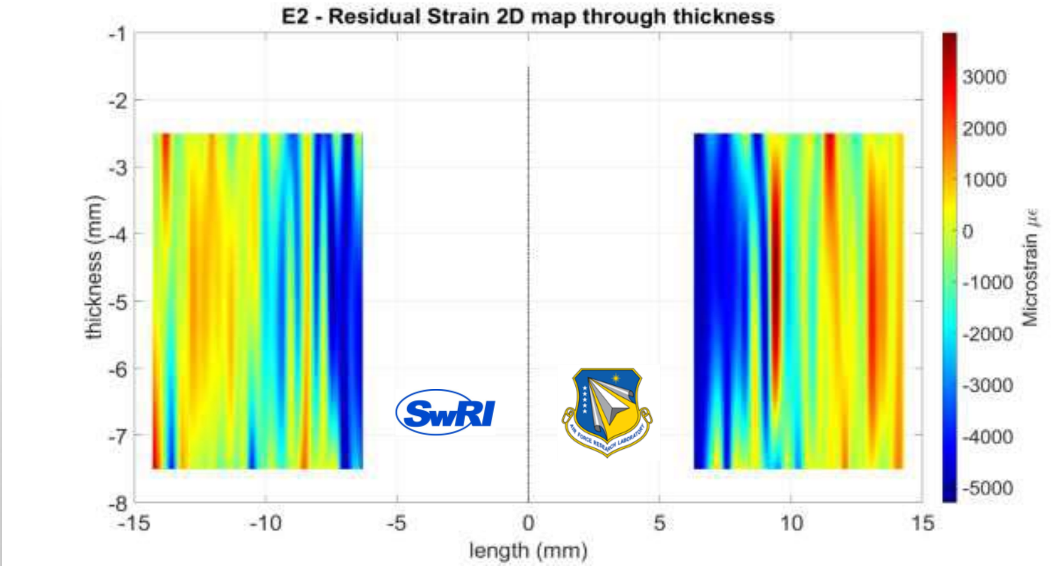
RS Process Simulation Validation

APS Preliminary Hoop Strain

2024-L2 Chaboche

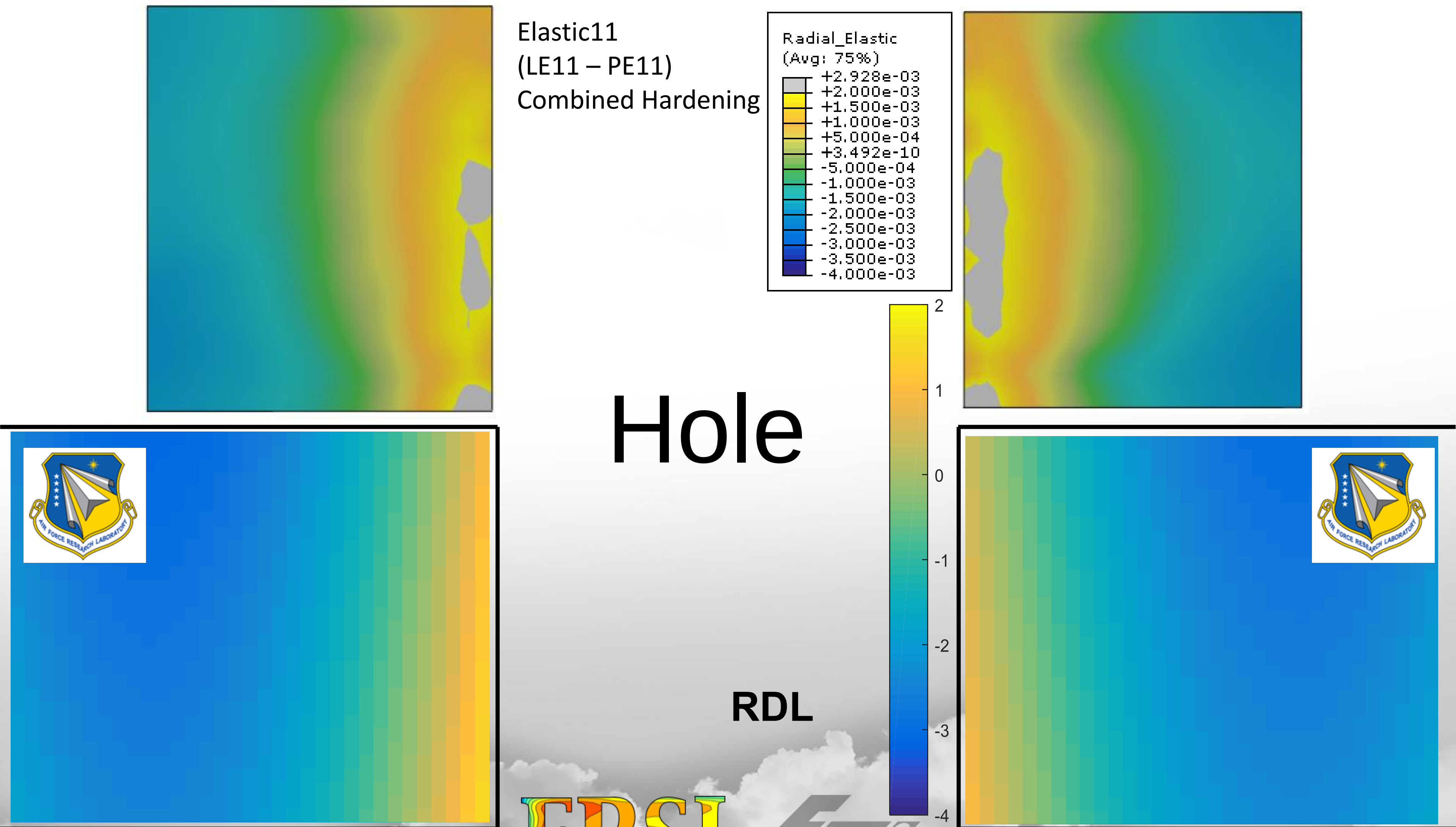


AA2024-L2 (i1) {311}



RS Process Simulation Validation

CHESS Preliminary Radial Strain



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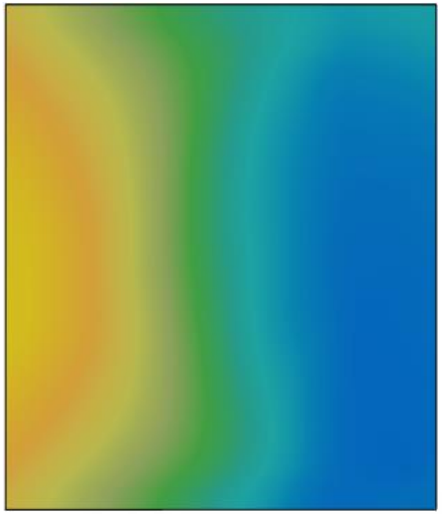
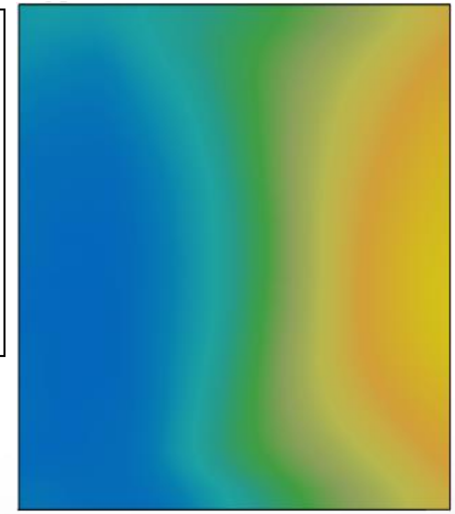
RS Process Simulation Validation

CHESS Preliminary Hoop Strain



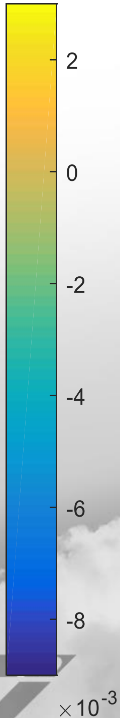
Elastic22
(LE22 – PE22)
Combined Hardening

Hoop_Elastic
(Avg: 75%)
+2.500e-03
+1.583e-03
+6.667e-04
-2.500e-04
-1.167e-03
-2.083e-03
-3.000e-03
-3.917e-03
-4.833e-03
-5.750e-03
-6.667e-03
-7.583e-03
-8.500e-03



Hole

RDL



FATIGUE TECHNOLOGY

DM#808860

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Residual Stress Process Simulation Sub Committee

Dr. Scott Prost-Domasky, Analytical Processes/Engineering Solutions (AP/ES), Inc.
Dr. Guillaume Renaud, National Research Council Canada
Dr. Ralph Bush, United States Air Force Academy
Marcus Stanfield, Southwest Research Institute
Dr. Min Liao, National Research Council Canada
Dr. Marcias Martinez, Clarkson University
Dr. Adrian DeWald, Hill Engineering, LLC
Dr. Keith Jones, Jones Engineering, LLC
Robert Pilarczyk, Hill Engineering, LLC
Dr. Mike Hill, Hill Engineering, LLC
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Olym ic Peninsula

Chair:
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Project Engineer, Analyst
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ERSI FTI FATIGUE TECHNOLOGY

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Predict. Test. Perform.

Measurements Su -grou date

To ics or Today

Contour method round ro in

Measurements o residual stress at legacy versus new C holes

Residual stress uality system

Large C hole e eriments

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Predict. Test. Perform.

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Measurements Su -grou date

Contour Method Round Robin

Contour Method Round Ro in

Organi ation: Scott Carlson, Marcus Stan ield, Mark Thomsen

- Efforts by 6 participating labs (mix of industry, government, academia)

Pur ose: Provide initial assessment o contour method inter-la oratory re eata ility

- Contour consists of cutting, measuring, data analysis, stress analysis
- Current focus on data analysis and stress analysis

A   roach

- Subject is an elastic-plastic bent beam (prior benchmark)
- Multi-phase program of blind analyses (participants don't interact)
  1. Pure calculation, using simulation derived stress field and surface data
  2. Controlled experiment
- For each phase:
  - Provide same data sets to all participants (surface profiles)
  - Request submission of estimated residual stress field
  - Assess submissions
  - Discuss results
  - Document findings

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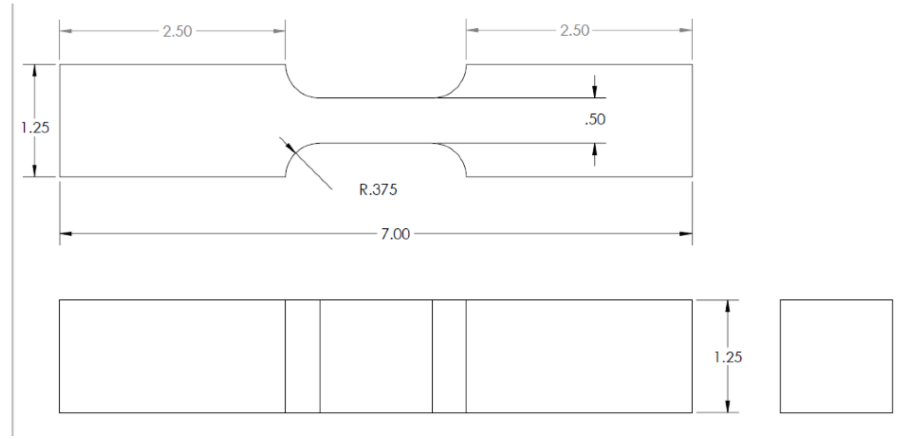
Contour Method Round Ro in

Phase descri tion

- Context is a simulation of an elastic-plastic bent beam
  - Classical residual stress experiment used for method validation
- Simulation performed by SwRI
  - Bend beam in four-point configuration
  - Cut beam (remove symmetry constraints)
  - Extract surface profile of deformed surface
  - Add noise
- Send to surface profiles to participants for blind analysis
- Collect and assess results returned
  - Compare submissions to simulation benchmark (known stress)



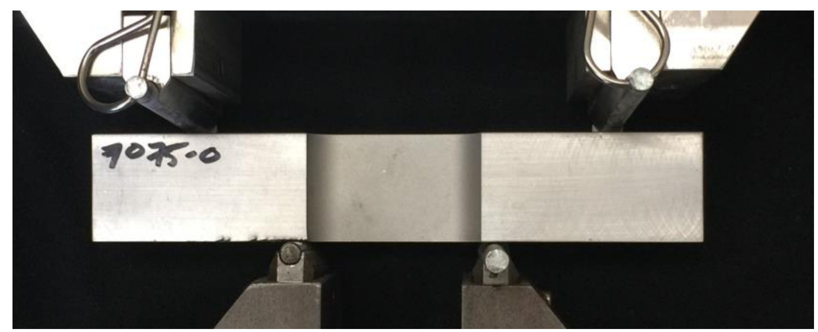
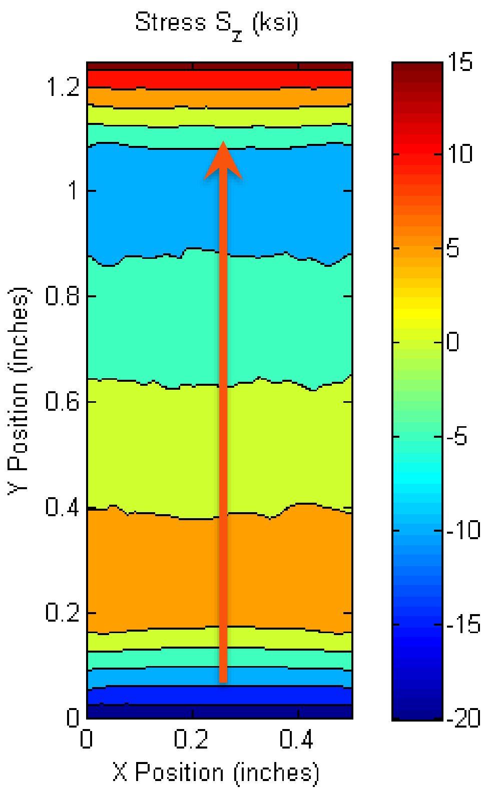


Photo of experimental set-up corresponding to simulation

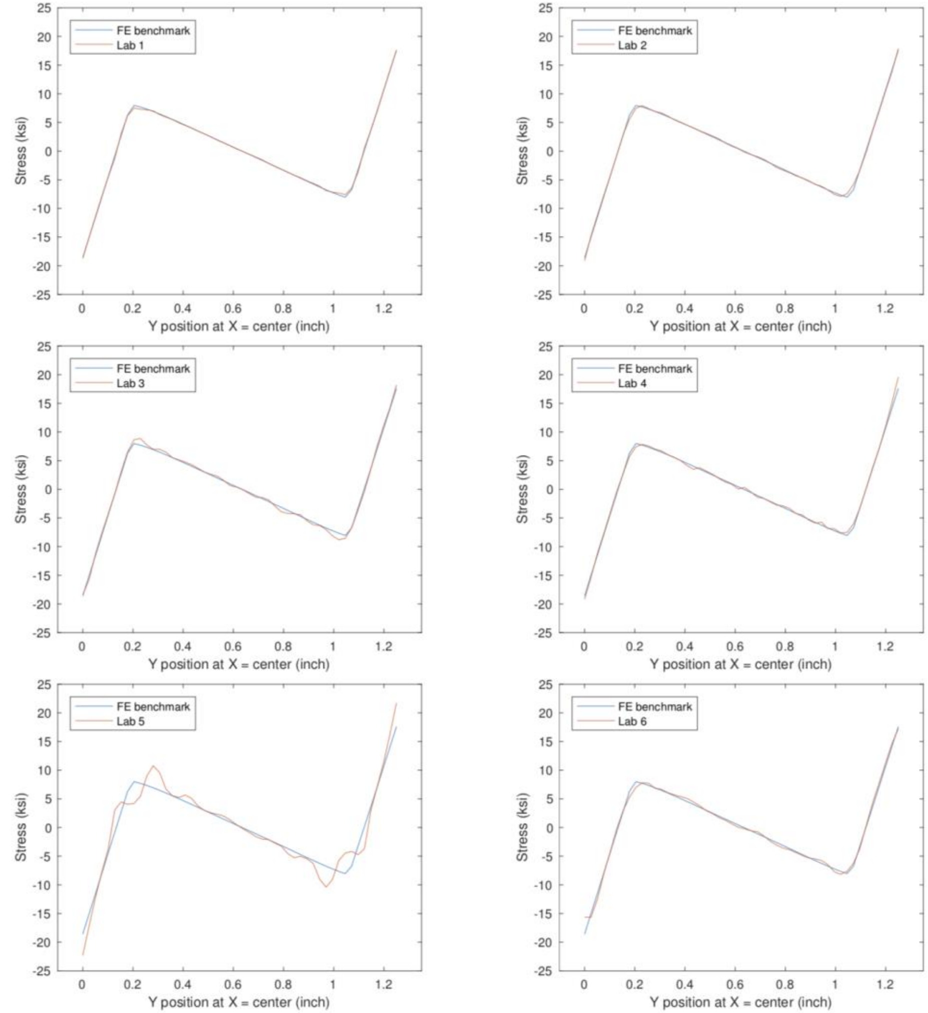
Contour Method Round Ro in

Phase results

Example submission



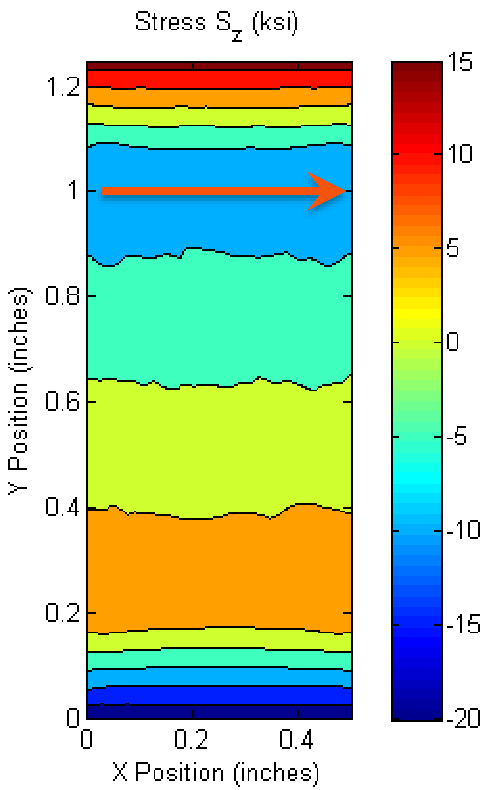
Line plots of each submission with FE benchmark



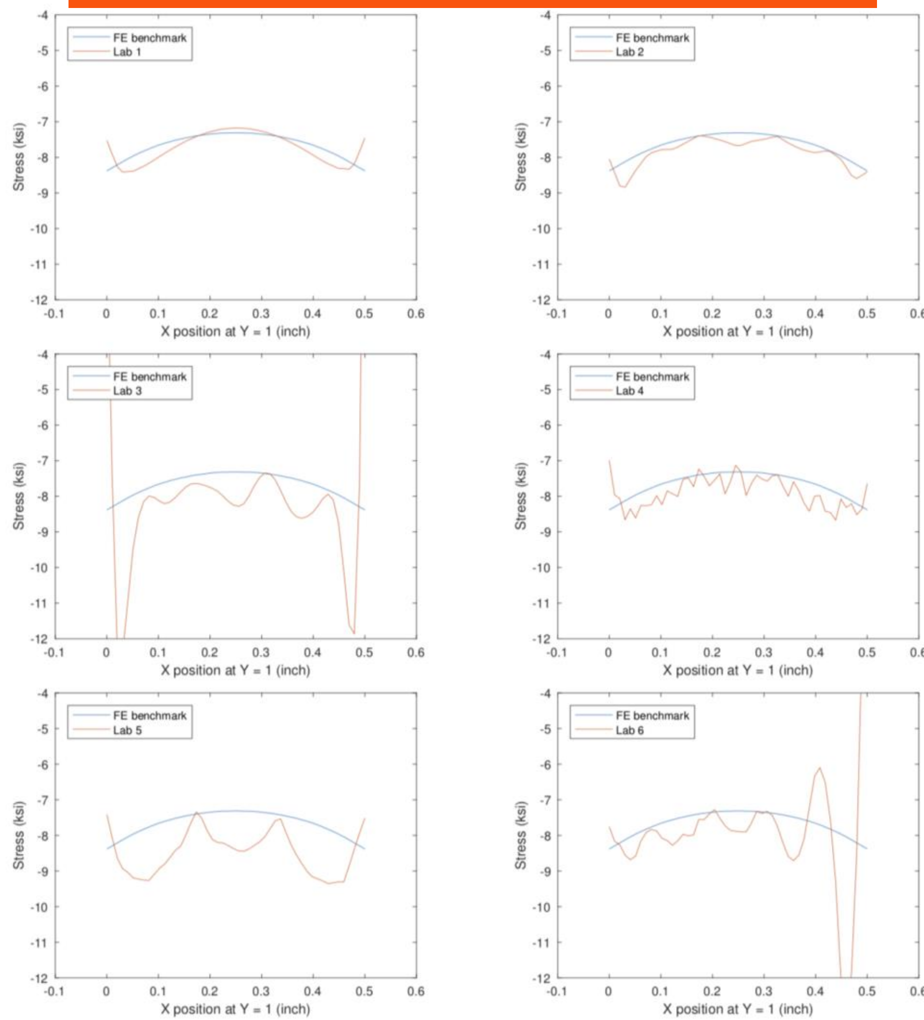
Contour Method Round Ro in

Phase results

Example submission



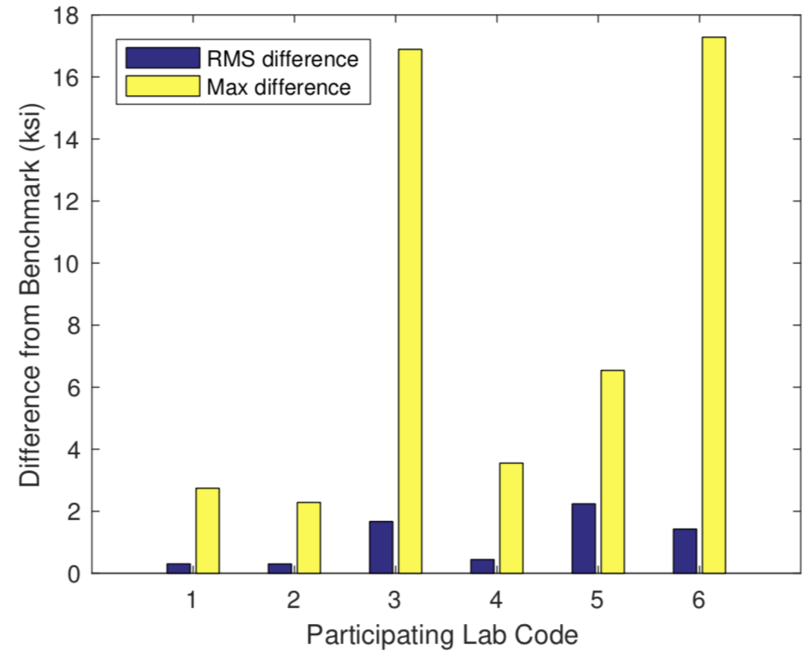
Line plots of each submission with FE benchmark



Contour Method Round Ro in

Phase results

- Given the same input data, participants return results very similar to the benchmark simulation stress field
  - RMS difference with benchmark better than 2 ksi
  - Some participant results had localized differences in stress
    - Consistent with those labs using approaches with less smoothing



Phase uses e erimental data

- Work nearly complete

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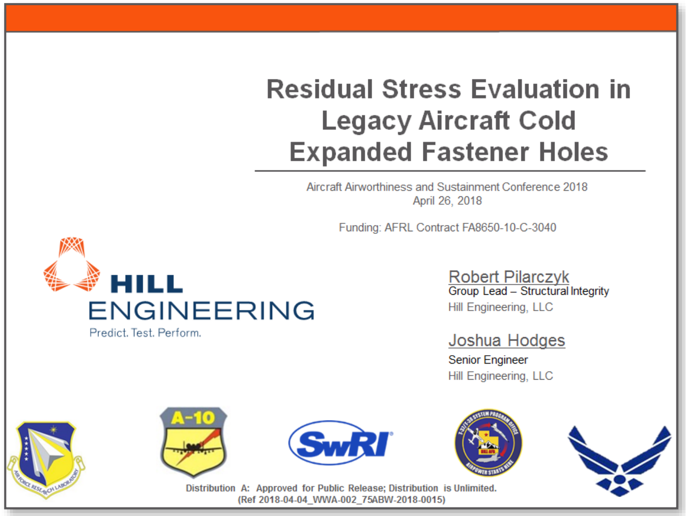
Measurements Su -grou date

Legacy vs New CX Residual Stress Evaluations

Note: this is an excerpt taken from here:



Residual Stress Evaluation in Legacy Aircraft Cold Expanded Fastener Holes

Aircraft Airworthiness and Sustainment Conference 2018
April 26, 2018

Funding: AFRL Contract FA8650-10-C-3040

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Robert Pilarczyk
Group Lead – Structural Integrity
Hill Engineering, LLC

Joshua Hodges
Senior Engineer
Hill Engineering, LLC

Co-Authors

Tremendous team su orting rogram:

- A-10 & T-38 Aircraft Structural Integrity Teams
  - Dr. Mark Thomsen
  - Dr. Mike Blinn
- Air Force Research Lab
  - Dr. Pam Kobryn
  - Scott Wacker
- Southwest Research Institute (SwRI)
  - Dallen Andrew
  - Dr. Scott Carlson
- Hill Engineering
  - Dr. Mike Hill
  - Dr. Adrian DeWald

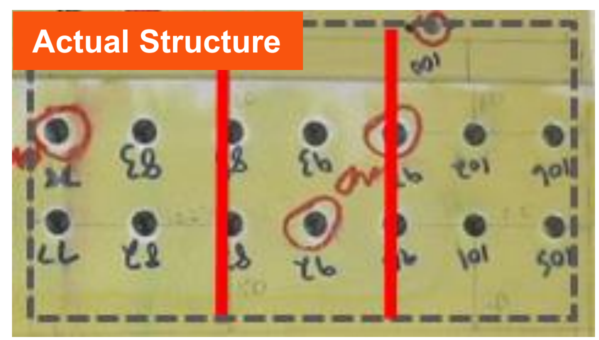
Program Overview A roach

Overview

- Investigate cracking and residual stress at Cx holes from retired fleet assets to understand if there is a degradation over time as a result of loading or environment

A roach

- Full A-10 wing teardown – disassembly, NDI, fractography, RS measurement
- Residual stress measurements of legacy assets (A-10/T-38)
- Residual stress measurements of newly manufactured specimens
  - Replicate legacy asset configurations
- Compare/contrast residual stresses between new manufacture and teardown coupons



History o Teardown Assets

A-   asset

- (1) Center Wing Assembly
- Location details:
  - Lower wing structure (skins/spars)
  - 2000 series aluminum
  - Production and depot rework Cx
- Usage details:
  - Predominantly tension loads – 40-85% FTY (peak)
  - Negligible compression ~ -5 ksi
- Service history:
  - Service life: 33 years
  - SLEP: 2004
  - Retirement: 2012
  - Average usage severity
  - Moderate EFH

T-   assets

- (3) Wing Assemblies
- Location details:
  - Lower wing skin
  - 7000 series aluminums
  - Production and TCTO Cx
- Usage details:
  - Predominantly tension loads - 35-70% FTY (peak)
  - Negligible compression ~ -10 ksi
- Service history:
  - Service life: 12-26 years
  - Retrofit Cx: 1999-2002
  - Retirement: 2006-2010
  - Mix of severe and moderate usage
  - Moderate – High EFH

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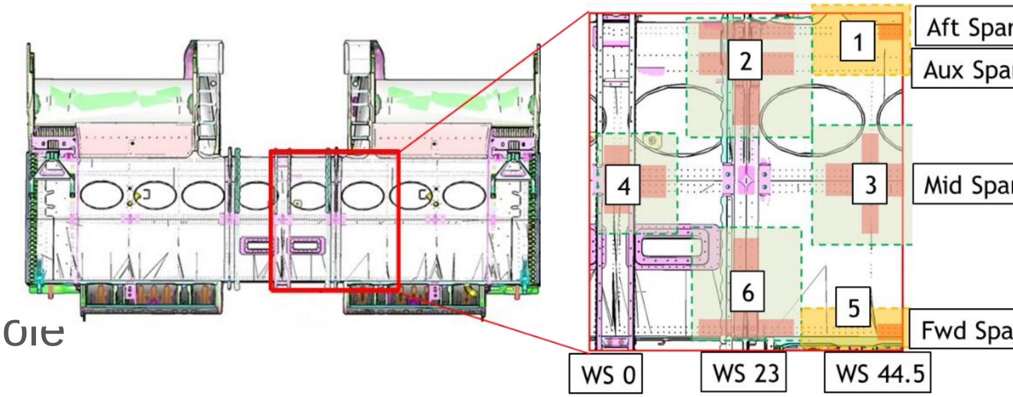
Disassem ly Teardown

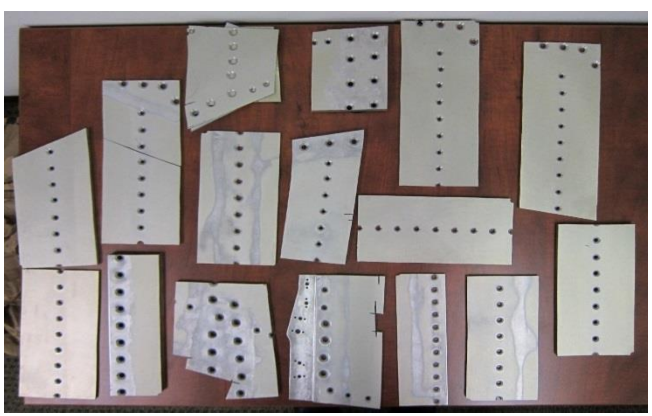
ull A- Center ing teardown

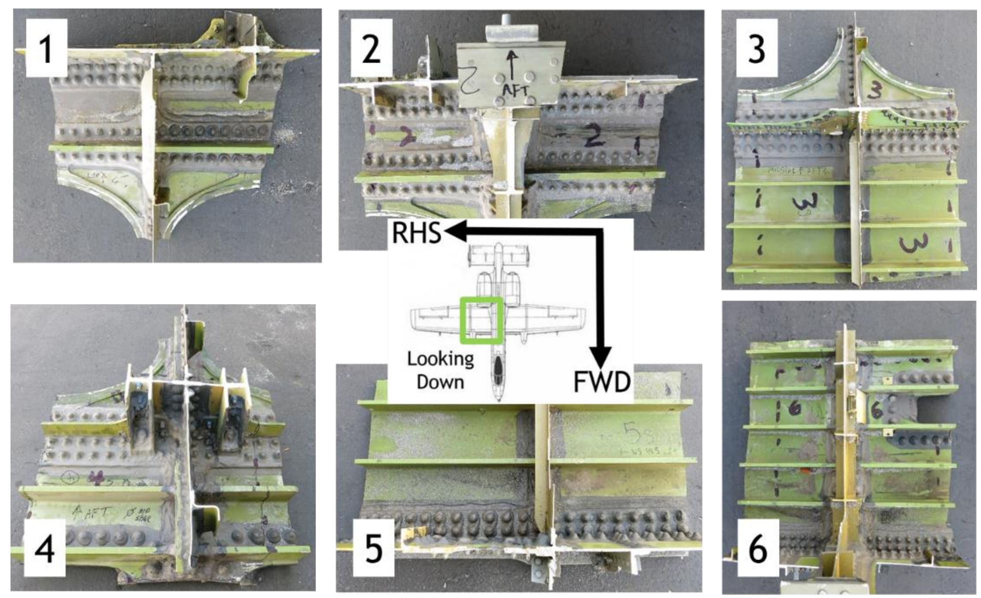
- Sectioning
- Fastener removal per USAFA PASTA
- Coating removal
- Non-destructive inspections
- Failure Analysis
  - Only (1) confirmed crack at Cx hole



T- ings reviously torn-down

- Excised coupons received for program





Residual Stress Measurement Plan – A-

A roach

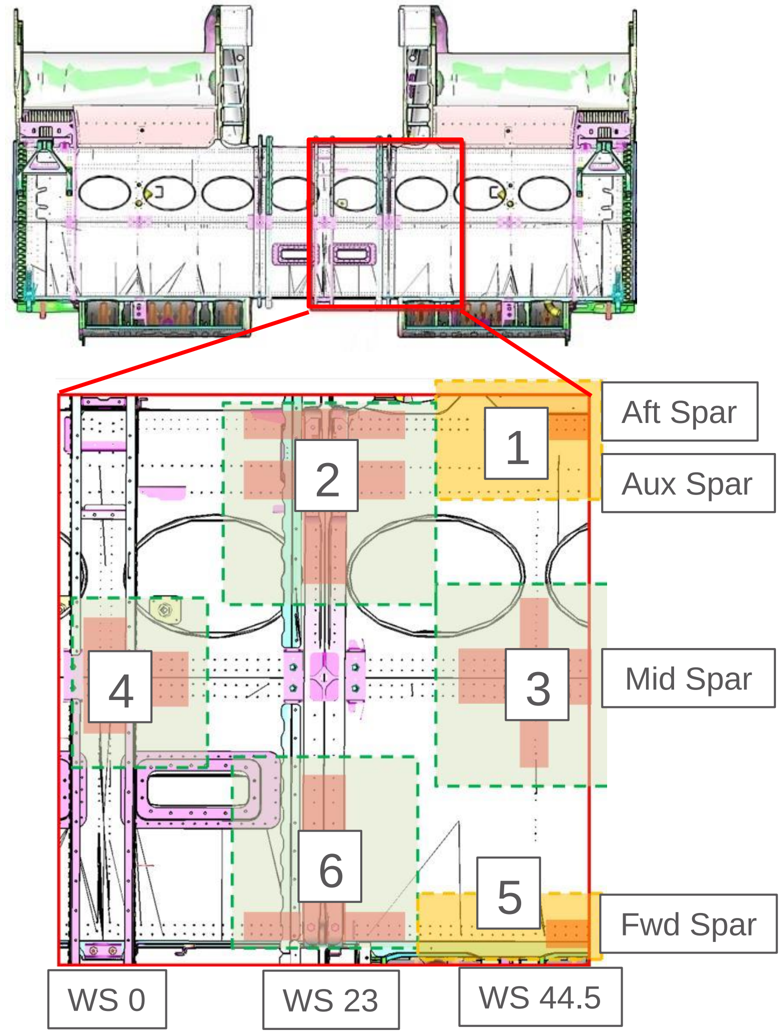
- Cover the scope of A-10 lower wing fatigue critical locations
- Lower skins and spars

Primary considerations:

- Range of peak stresses
- Production and rework Cx
- Varying thicknesses
- Varying hole sizes
- Production vs. rework holes

Sco e o Measurements

- 146 teardown holes
- 72 new manufacture holes



Residual Stress Measurement Plan – T-

A roach

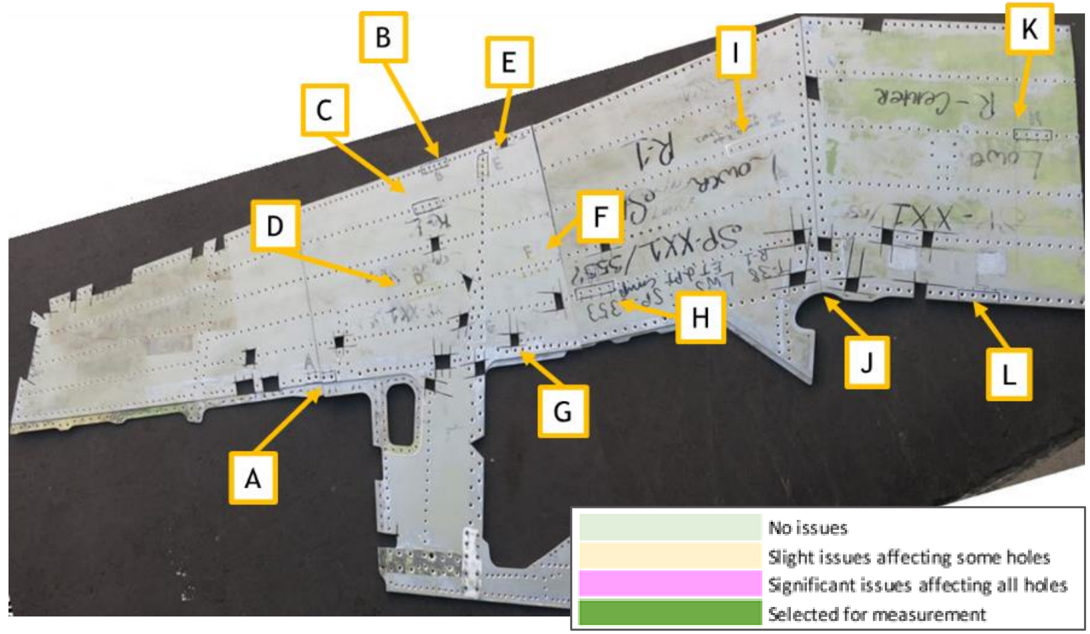
- Wing #SP900
  - Breadth of locations
- Wings #SP353 and #SP648
  - Variability between wings

T- rimary considerations:

- Fatigue critical locations
- Range of peak stresses
- Production & field Cx
- Varying thicknesses

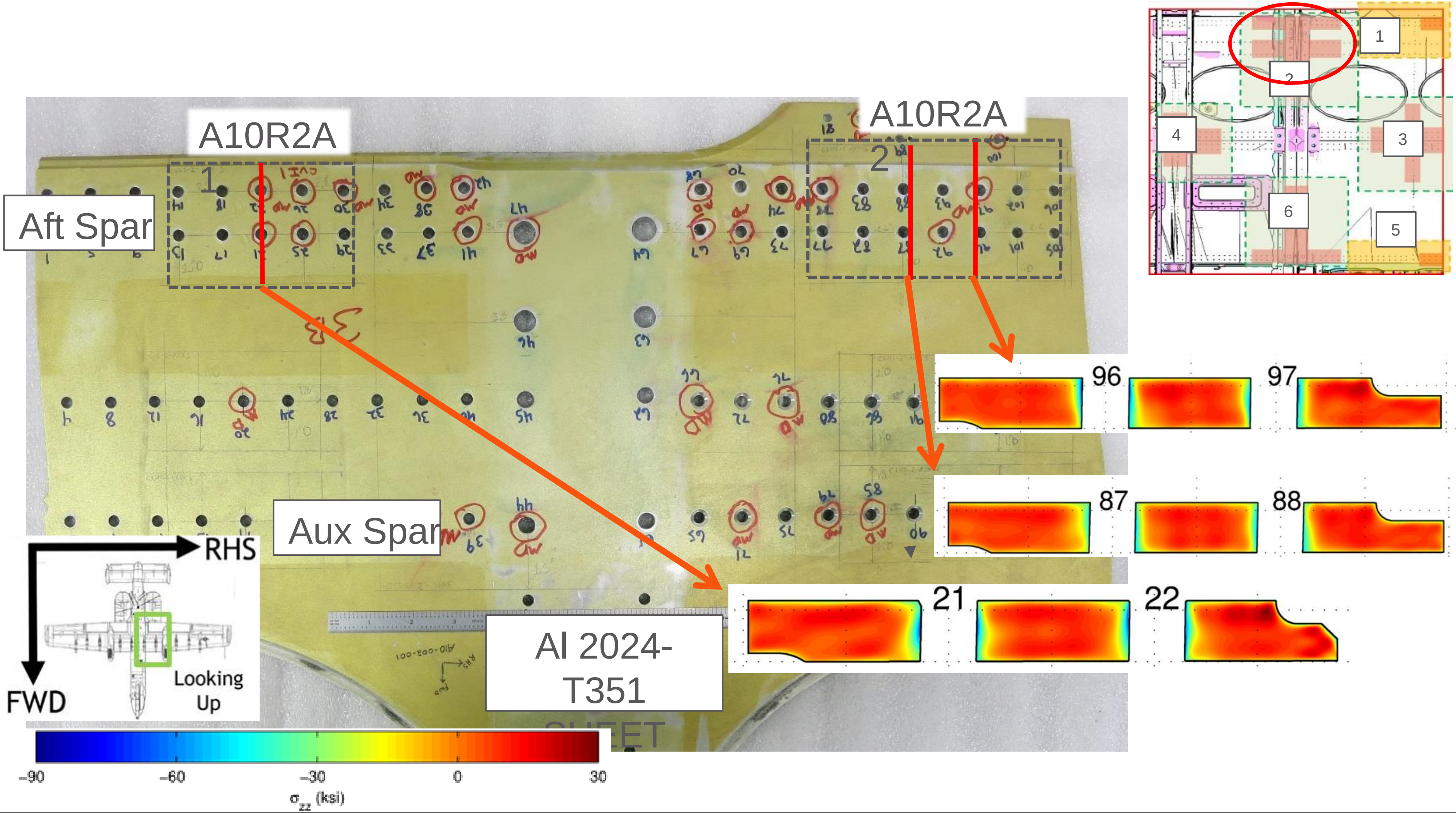
Sco e o Measurements

- 57 teardown holes
- 33 new manufacture holes

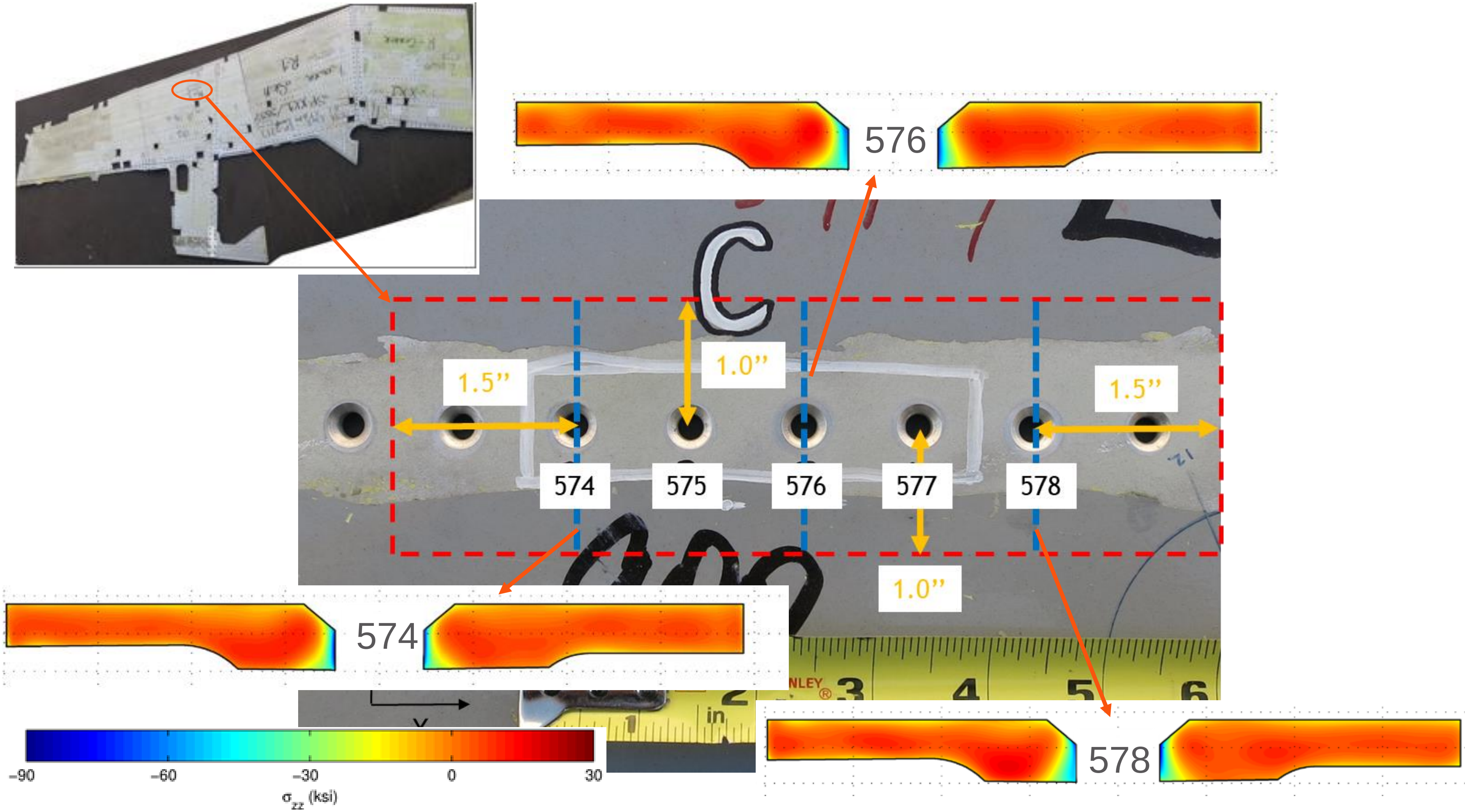


Location	SP 353 RHS	SP 648 LHS	SP 648 RHS	SP 900 LHS	SP 900 RHS
A	Cuts between holes	Hole oversized 0.31"	2 holes damaged	Hole removed	Good
B	Good	Good	Good	Good	Hole OS 0.26"
C	Damage to 3 holes	Removal near hole	Good	Good	Good
D	Good	Cut near hole (0.5")	Good	Good	Cut right of hole, 1.48"
E	Good	Hole dmg, OS 0.32"	Cut near hole, minor dam	Good	Cut below hole, 0.35"
F	Good	Cut left of hole, 1.45"	Cut right of hole (1.35")	Cuts 1.25", hole damage	Cut Left 1.52" Left
G	Cut near 3 of 6 holes	Cuts near 3 of 6 holes	Cuts near 2 of 6 holes	Good	Majority Removed
H	Good	Good	Good	Good	Good
I	Good	Good	Good	Good	Cut Between 296, 297
J	Compromised	Good	Good	#198, #210 dmg	Compromised
K	Good	Good	Good	Cut 1.16" below, above	Good
L	Cut 7/8" near hole	Good	Good	Good	Cut right of hole, 0.5"

Teardown Measurement Results – A-



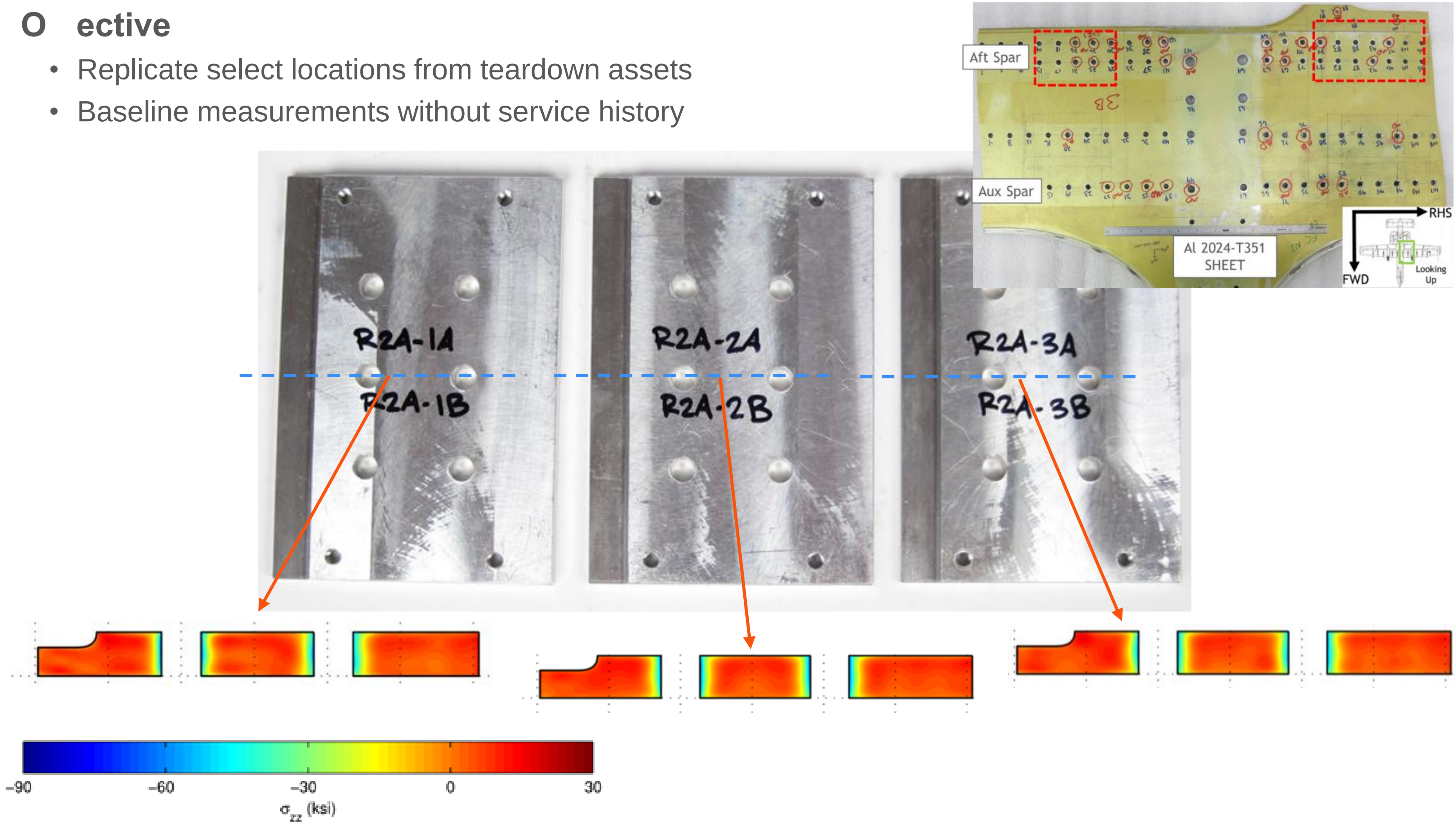
Teardown Measurement Results – T-



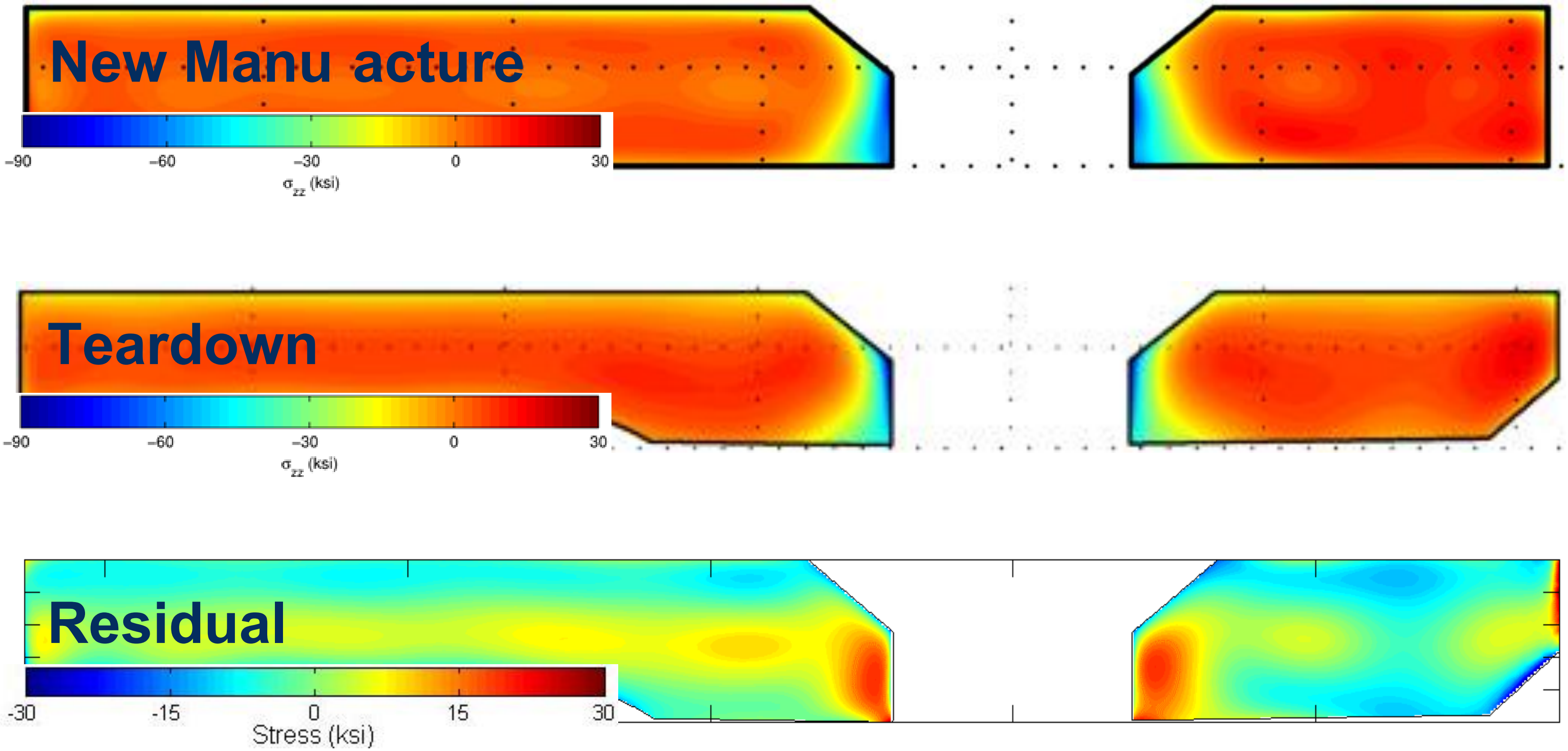
New Manu acture Measurement Results

O ective

- Replicate select locations from teardown assets
- Baseline measurements without service history

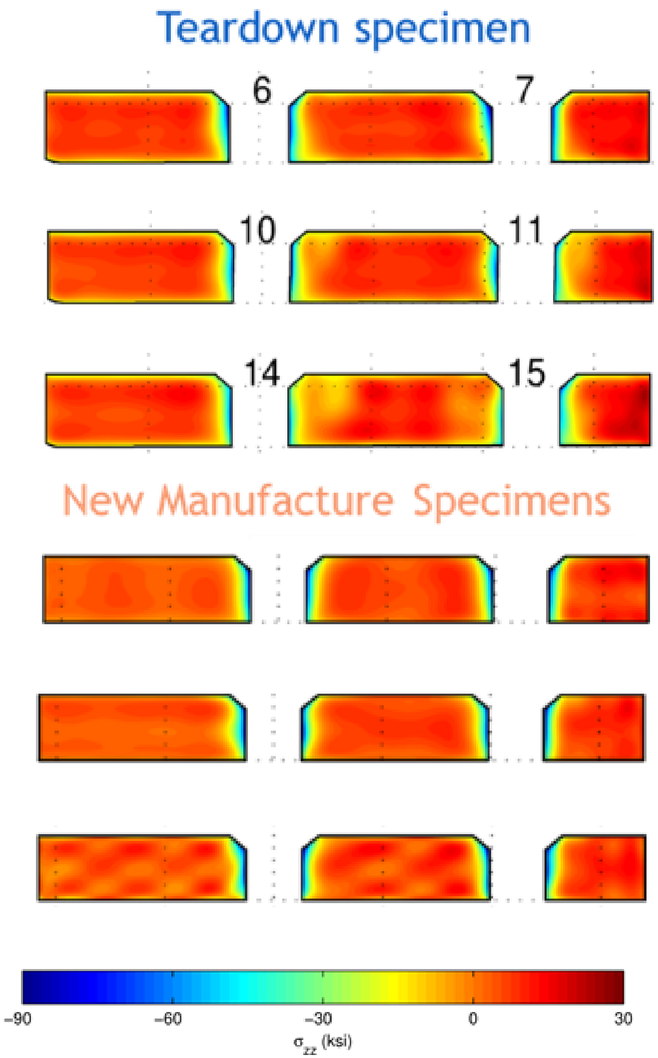


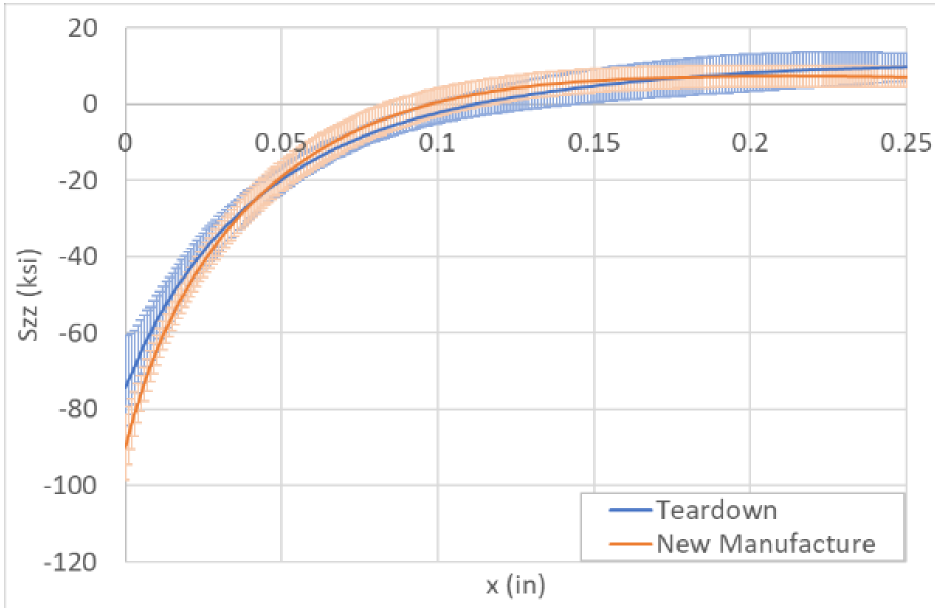
New vs. Teardown Com arisons



hat is considered signi icant

Level I Analysis - Com arison Results A- Section R . P





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

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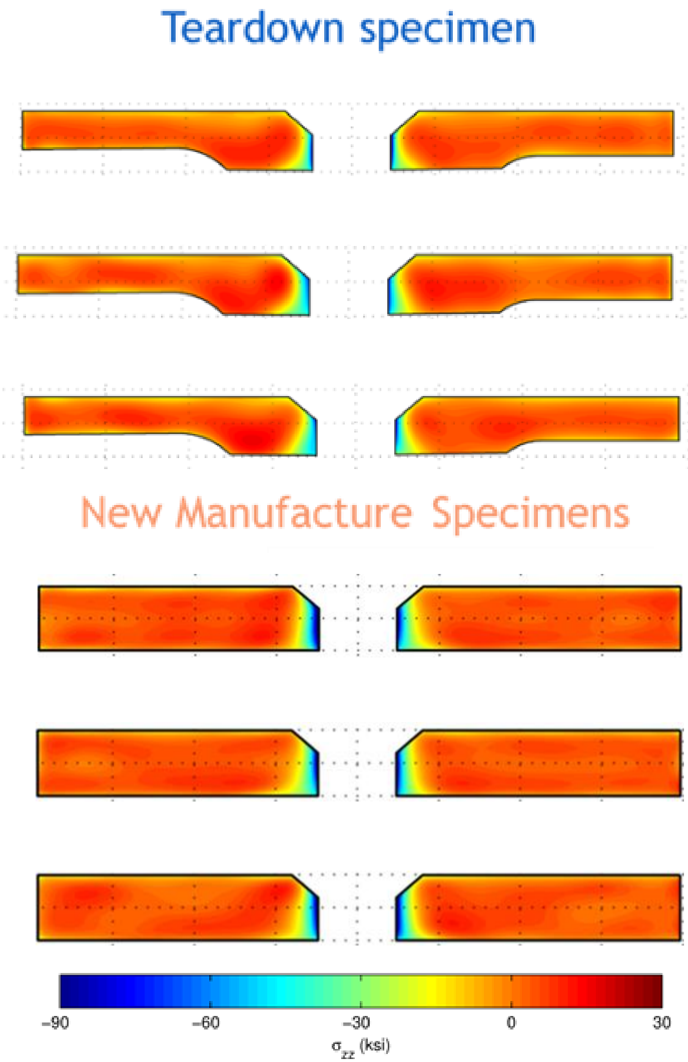
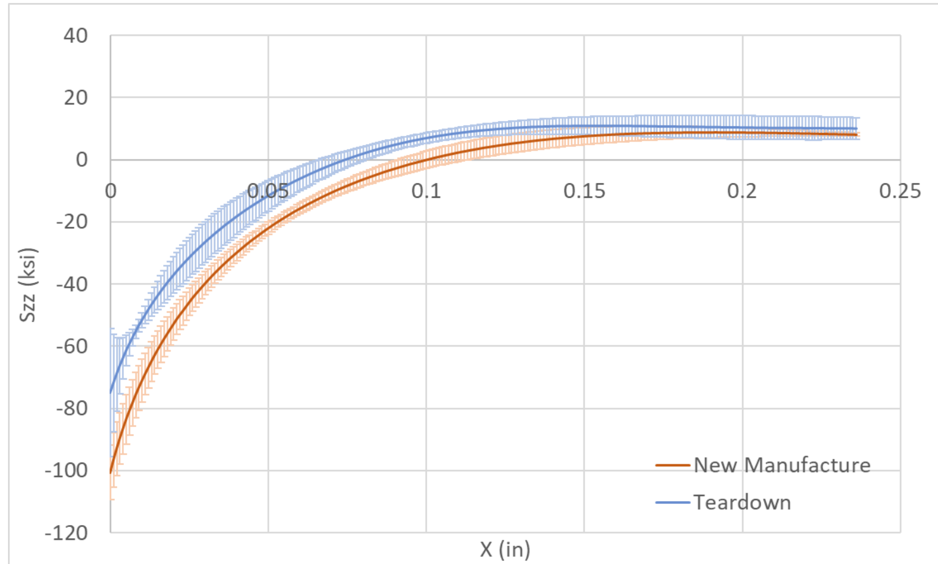
Level I Analysis - Com arison Results T- Section C





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	**-42.64**	**-26.04**	**-6.11**	**4.67**	**0.07**	**-41.00**	**-40.14**	**-76.26**	**-31.94**
Stdev	**4.81**	**6.48**	**3.85**	**1.83**	**0.01**	**18.30**	**2.85**	**11.50**	**3.94**
Mean	**-59.31**	**-38.63**	**-15.11**	**-2.53**	**0.10**	**-48.86**	**-49.02**	**-101.18**	**-49.57**
Stdev	**5.80**	**3.56**	**1.65**	**2.51**	**0.01**	**19.58**	**4.44**	**12.11**	**4.67**
Residuals (Td-NM)	16.67	12.59	9.01	7.20	-0.03	7.86	8.87	24.92	17.63
P Value	0.00	0.00	0.00	0.00	0.00	0.24	0.00	0.00	0.00
Significant	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes

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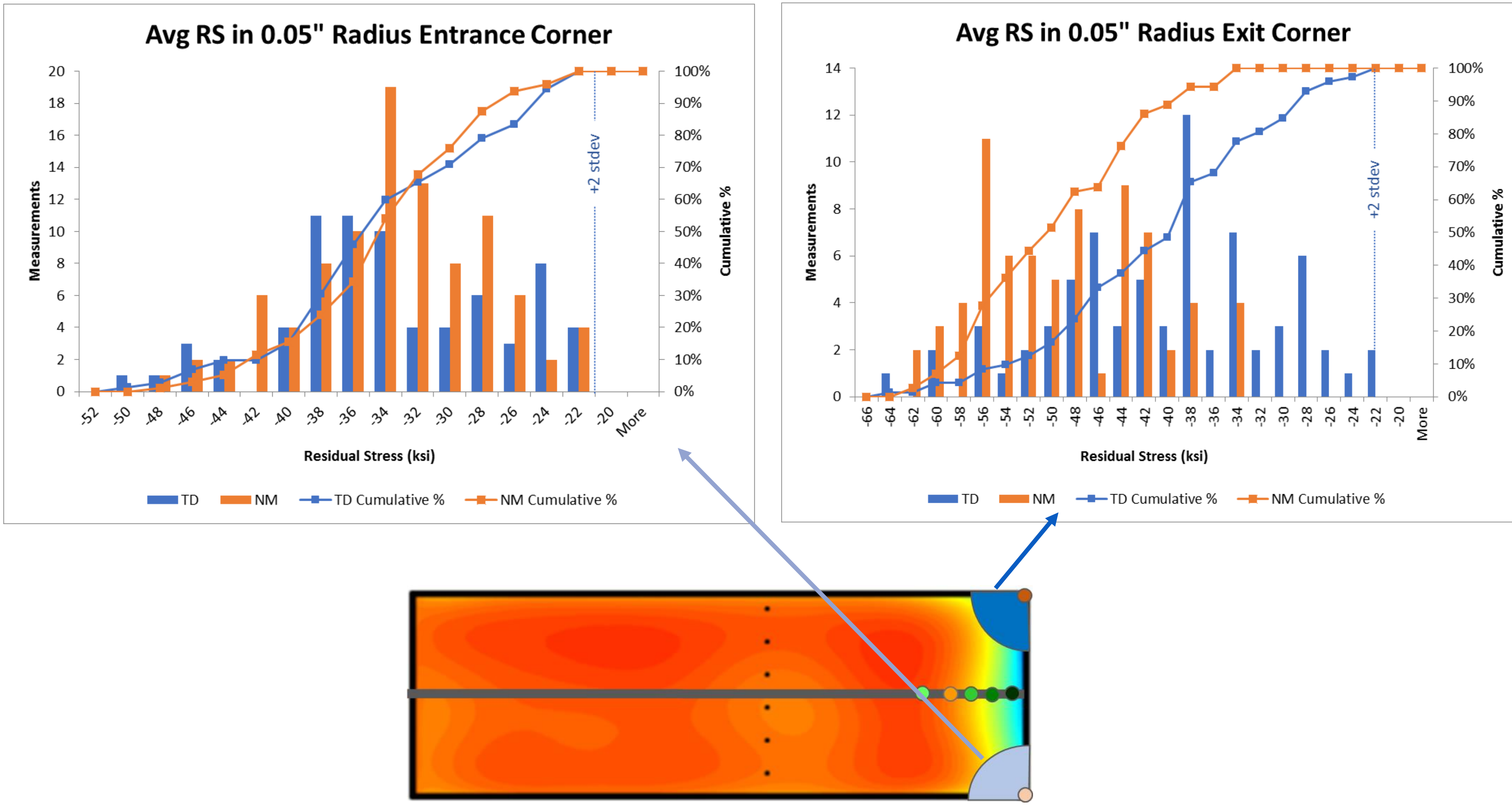
Summary o Com arisons



Conclusions

E tensive rogram com leted which rovides insight into residual stress o retired leet assets

residual stress measurements accom lished

- Teardown vs. new manufacture comparisons

Signi icant residual stress remained in all evaluated teardown locations

- No “missed Cx” locations

Initial level I com arisons com lete

- Comparable stresses observed between teardown and new manufacture coupons with significant overlap

A “Manage To” residual stress profile may be a practical approach for incorporation into SA DTAs

- +2 Stdev

MORE ORK TO DO

- Wealth of information within dataset
- How do these results impact fleet management decisions?

Measurements Su -grou date

Residual Stress Quality System

Note: this is an excerpt taken from here:

Acknowledgements

Authors: Adrian De   ald and Michael Hill

Colla orators

- Much of this work is closely linked to recent programs that involved collaboration with the following organizations and individuals
  - Pratt & Whitney: Iuliana Cernatescu, Dave Furrer, and Bob Morris
  - Arconic: Mark James, John Watton, Dave Selfridge, Dustin Bush, and Brandon Bodily
  - Lockheed Martin: Dale Ball and Mark Ryan
  - Air Force Research Laboratory: Bill Musinski, Mike Caton, and Reji John

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Residual stress in design and manu acture

Historical design a   roach: residual stress is a known unknown

- Remove where possible (thermal or mechanical stress relief)
- Conservatively manage effects on degradation (fatigue, SCC, creep)
  - Conservative assumptions (i.e., tensile residual stress fields)
  - Inspect, repair, replace
  - Costs escalate with system age
- Take minimal credit for beneficial compressive residual stress

Emerging design a   roach: residual stress   art o s eci ications

- Known residual stresses in parts (requires measurements, models, and validation metrics)
- Include residual stress in materials and process engineering
  - Trade studies
  - Quality program
- Directly account for residual stress effects on performance

Motivations or residual stress control

The ollowing are some common e am les o residual stress related concerns during   rocurement and design

Concern: tensile residual stress causing   remature/une   ected ailure

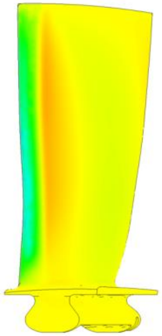
- Desire a material/part that has low-magnitude residual stress
  - I.e., avoid putting outlier residual stress parts into service

Concern: large and/or inconsistent residual stress levels im acting machining

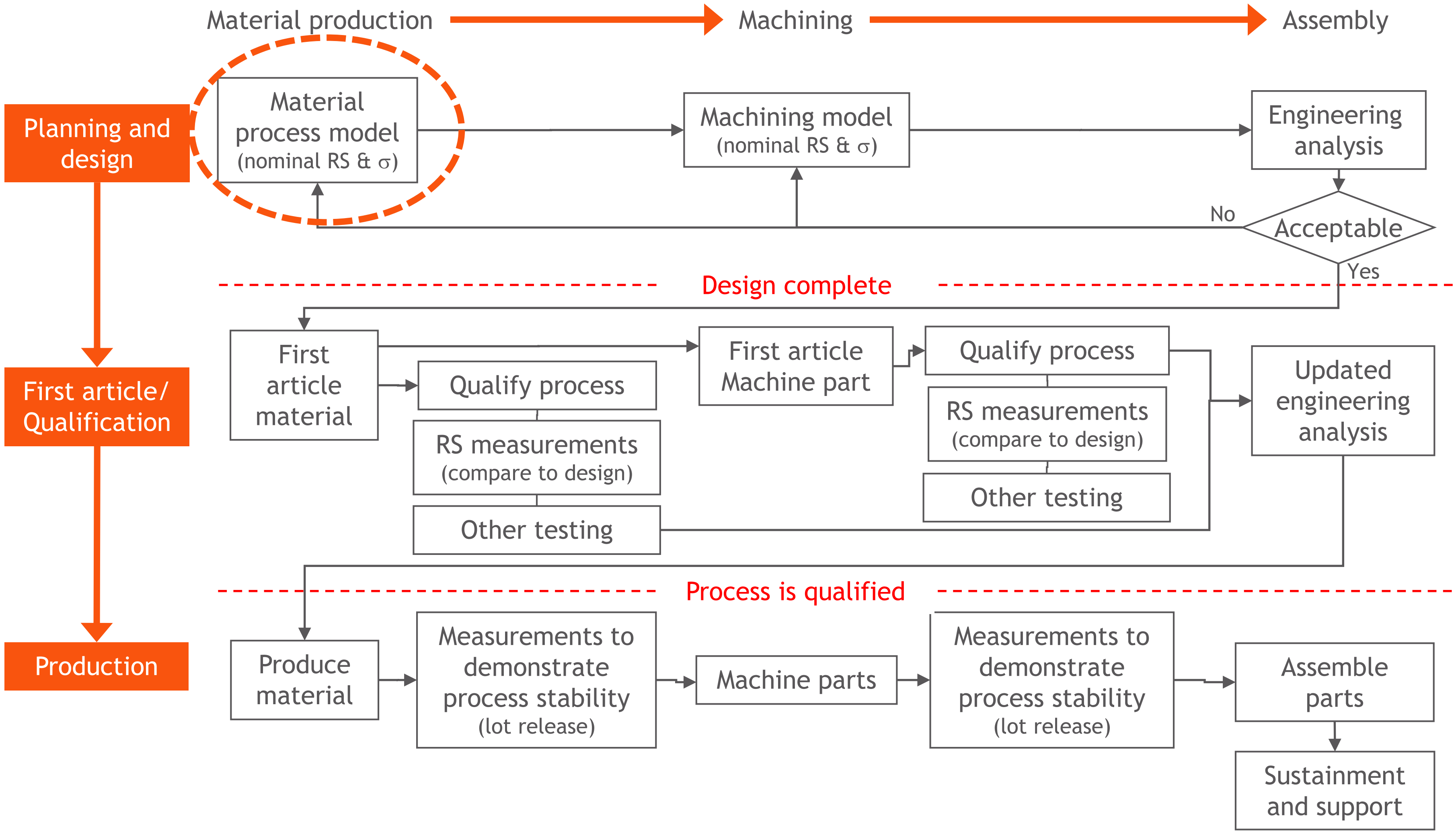
- Desire a material/part that has consistent or low-magnitude residual stress

Concern: ensure   resence o   ene icial com ressive residual stress

- Desire local regions of compressive residual stress in critical locations from engineering processes
  - Also avoid high levels of compensating tensile residual stress

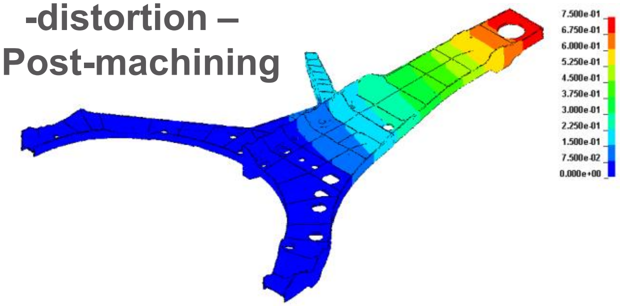


Residual stress in ormation low

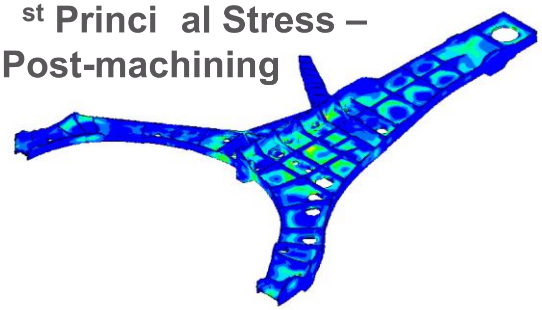


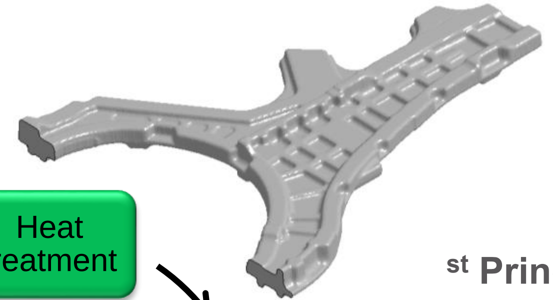
E am le: manu acturing machining models

-distortion –
Post-machining



st Princi al Stress –
Post-machining

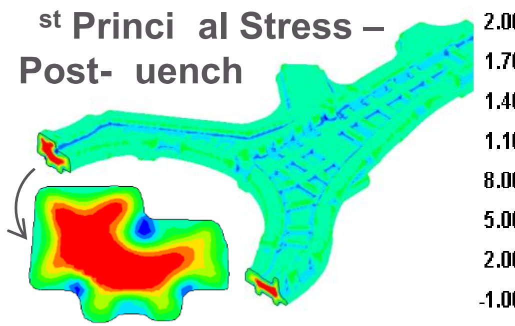




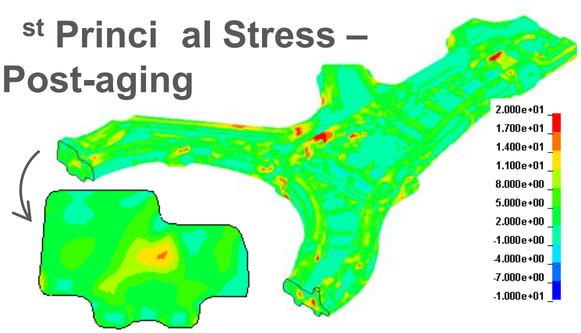
Heat treat Al
elevated tem erature

Heat treatment → Rapid quench → Cold work stress relief → Artificial Aging → Machining

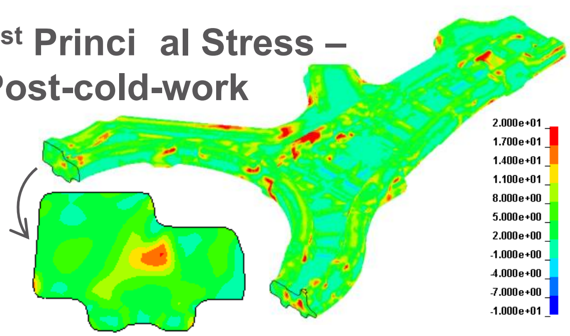
st Princi al Stress –
Post- uench



st Princi al Stress –
Post-aging



st Princi al Stress –
Post-cold-work



Process induced bulk residual stress finite-element model and validation measurements of an aluminum alloy forged and machined bulkhead, J.D. Watton, A.T. DeWald, et al., 2015 ASIP Conference, San Antonio, TX

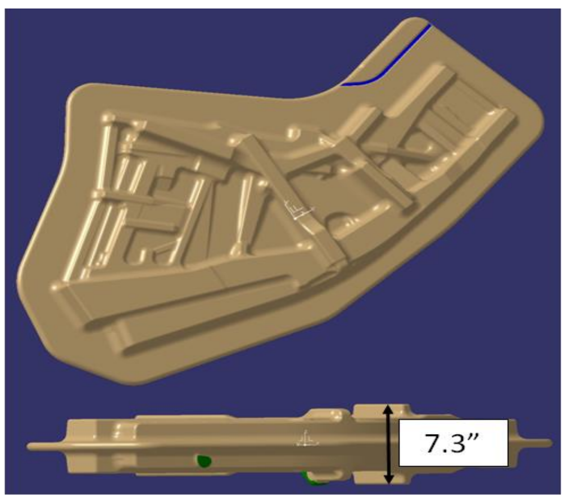
Public Release 88ABW-2015-5301

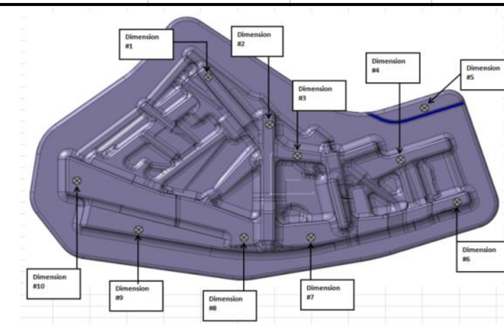
C- end itting orging

Part descri tion

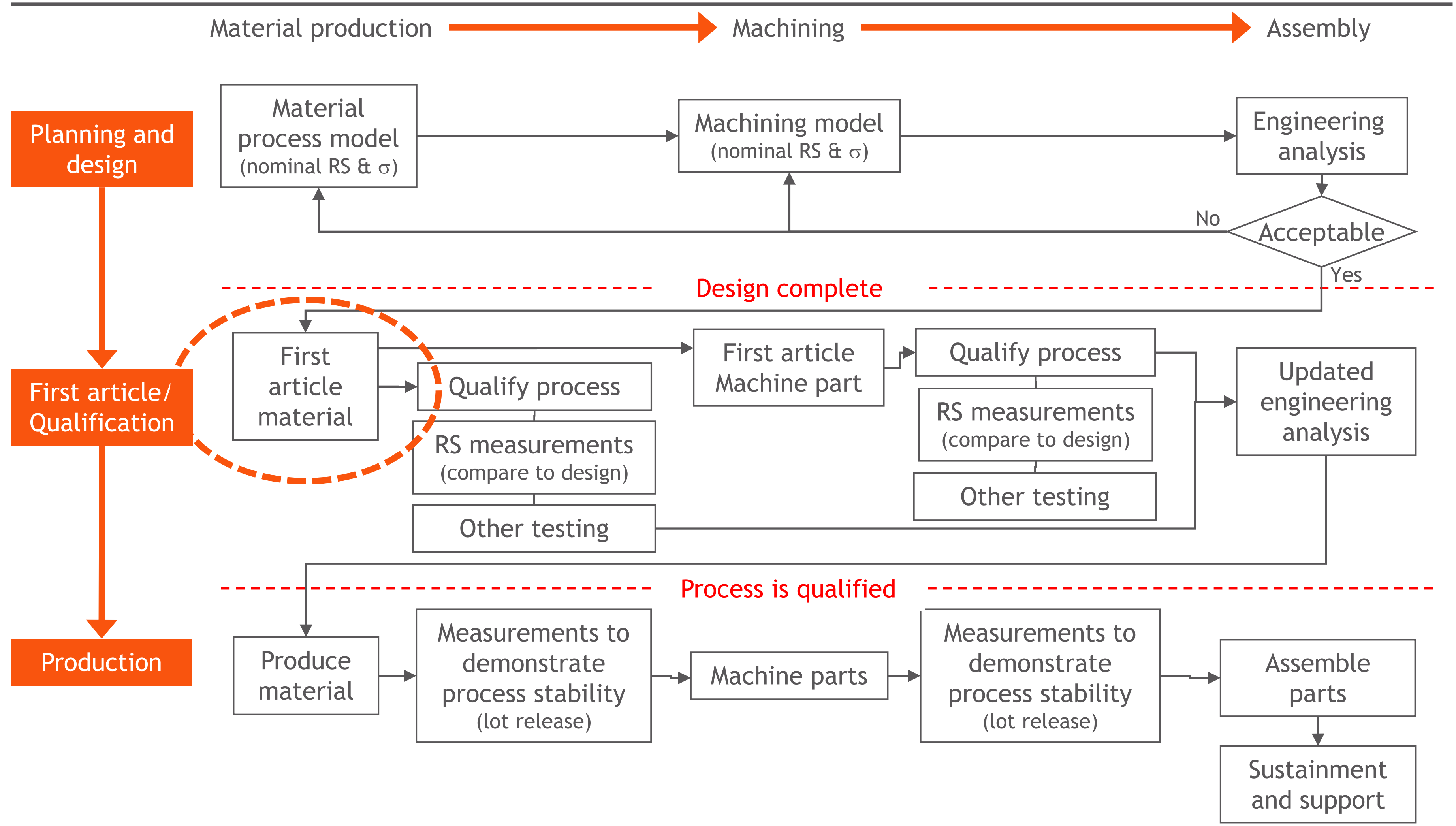
- Material: 7085-T7452
- Die-forging
- Varying amounts of cold work: 0% to 4%
  - 1% to 5% is “acceptable” for production
  - 16 parts manufactured

Part Number	Job Number	Average Cold Work	Pressure
GA120276	HM14L10	0.0%	N/A
GA120276	HM14L11	0.0%	N/A
GA020276A	HM14L07	1.4%	9.9
GA020276A	HM14L02	1.4%	9
GA020276B	HM14L01	1.6%	9.6
GA020276B	HM14L08	1.8%	10.1
GA020276	HM14L03	3.0%	14
GA020276	HM14L04	3.0%	14
GA020276	HM14L16	3.0%	14.8
GA020276	HM14L14	3.1%	14.8
GA020276	HM14L06	3.1%	14.5
GA020276	HM14L05	3.3%	14.8
GA020276	HM14L12	3.4%	14.8
GA020276	HM14L13	3.4%	14.8
GA020276C	HM14L15	3.6%	14.8
GA020276C	HM14L09	3.6%	14.8





Residual stress in ormation low



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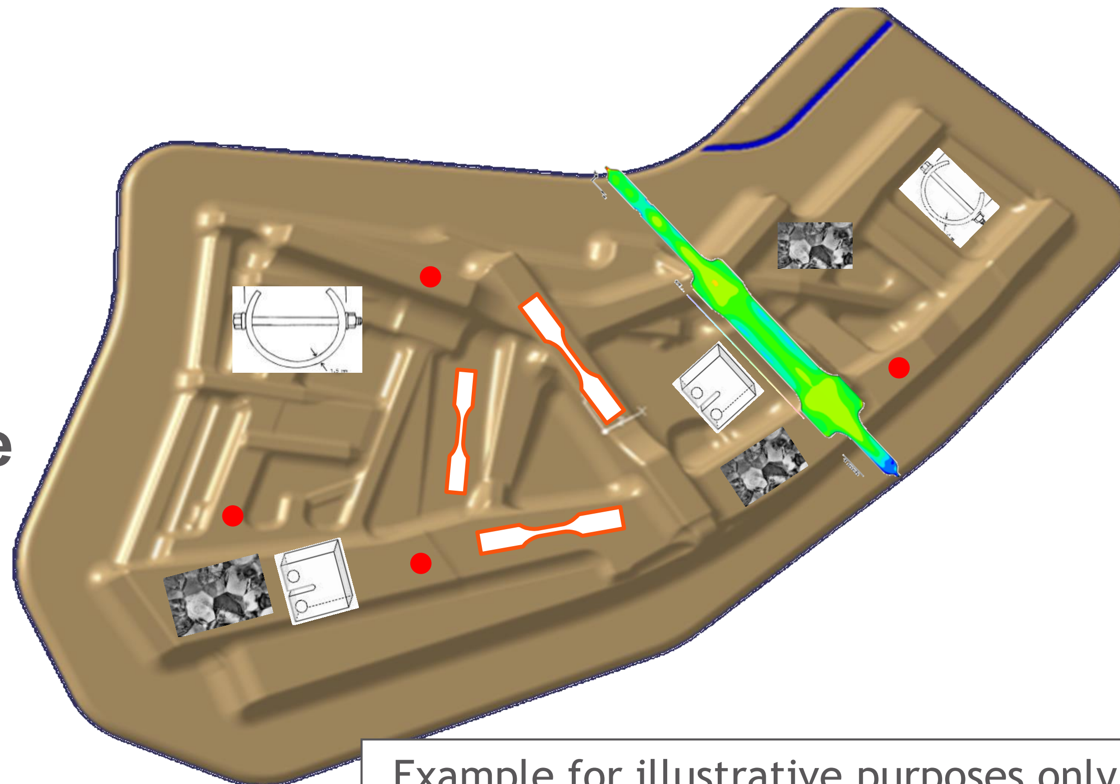
E am le: irst article uali ication

irst articles o ten re uire e tensive testing to validate critical ro erties and characteristics

- Size/dimensions
- Chemical composition
- Mechanical properties
- Stress-corrosion cracking
- Defect assessment
- Microstructure/Grain-flow

Residual stress can e handled similarly

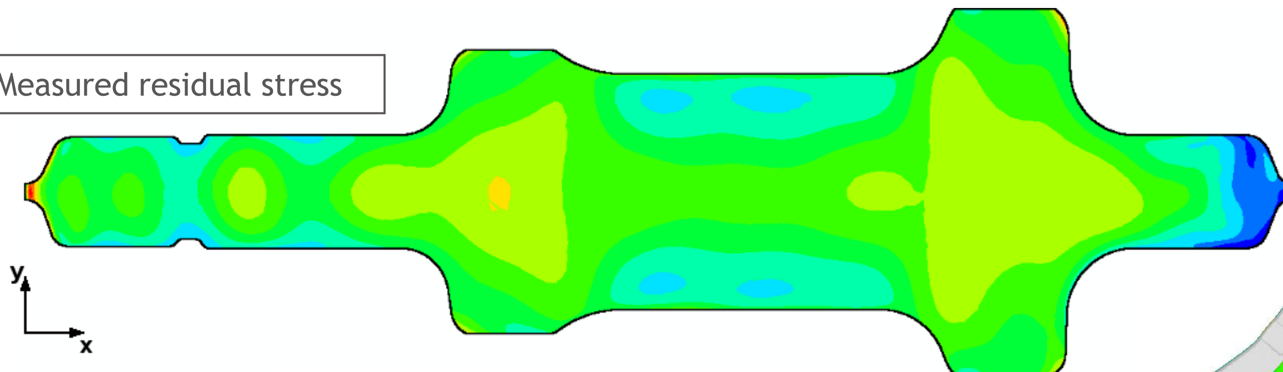


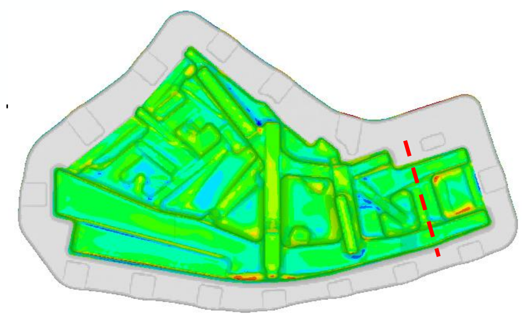
Example for illustrative purposes only

E am le: irst article uali ication validation

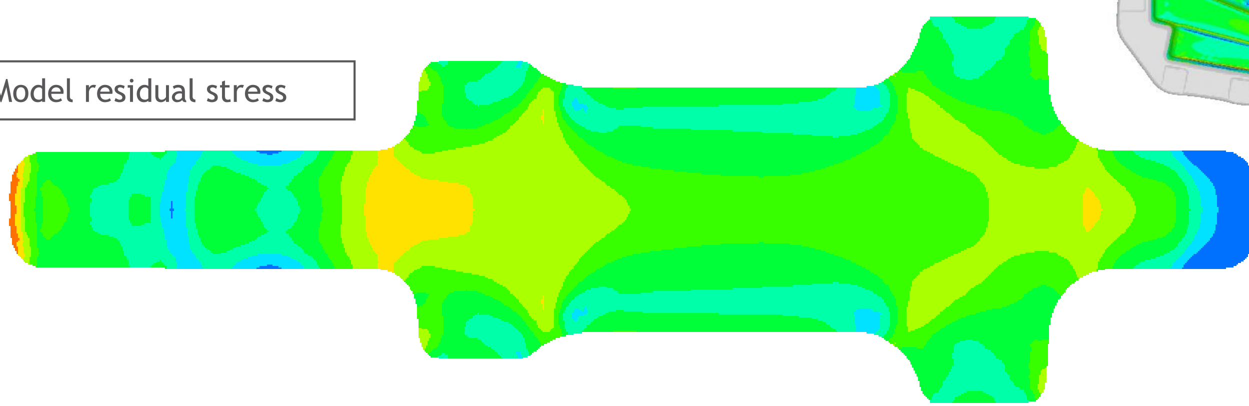
avora le com arison etween measurement and model

Measured residual stress





Model residual stress



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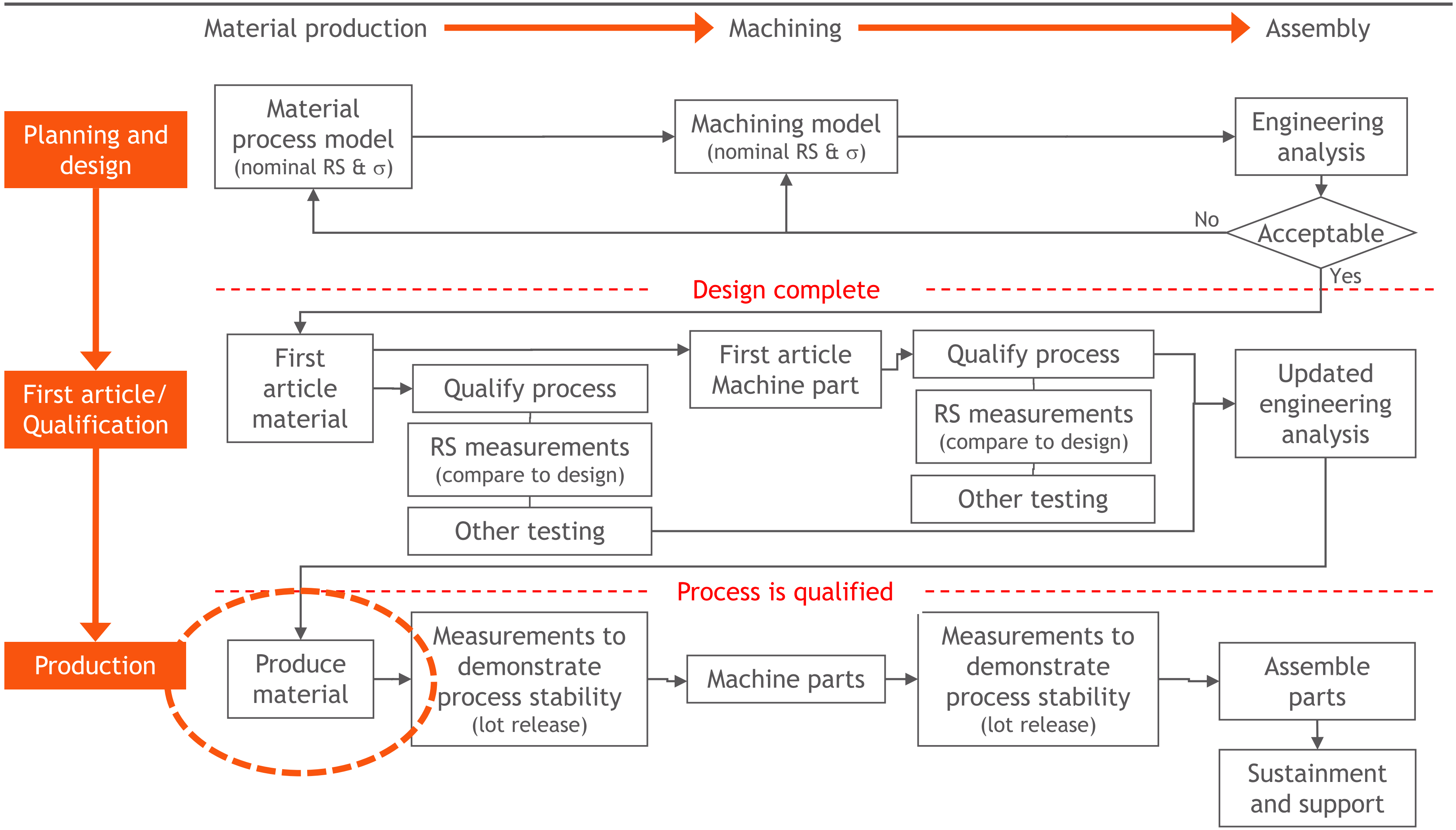
Residual stress in ormation low



E am le: roduction surveillance testing

De ine measurement locations

- Select in an intelligent manner designed to provide maximum insight and usefulness
- Often useful to perform measurements in regions of excess material

Consider the in luence o various actors

- Locations of expected tensile residual stress residing inside of machined part
- Level of sensitivity between residual stress and processing/manufacturing
- Measurement access/applicability
- Locations of likely failure (e.g., applied stress hot spots)
- Difficult to inspect

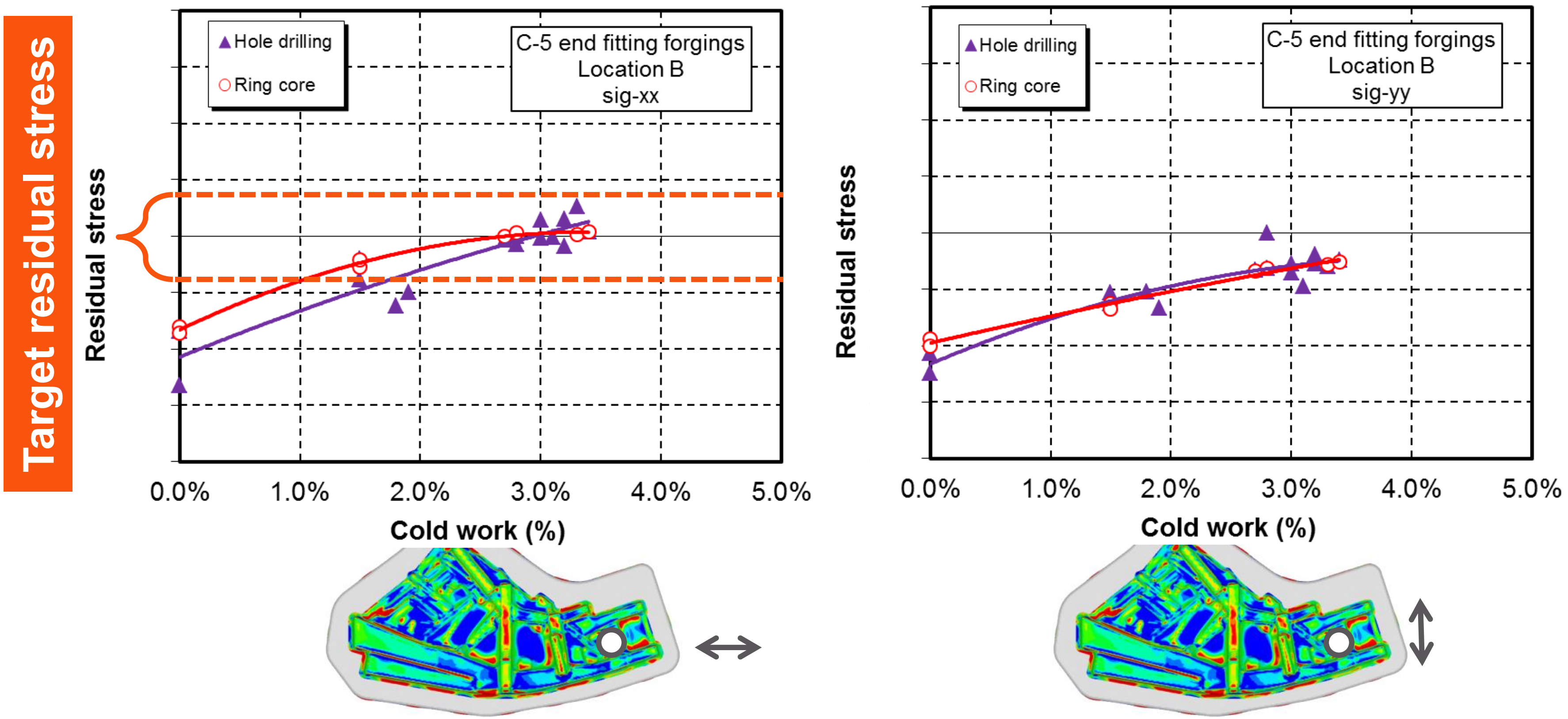
Measurement locations esta lished through colla orative discussion etween stakeholders

- OEM – understanding of locations critical to structural performance
- Material producer – understanding of locations important to manufacturing
- Testing laboratory – understanding of measurement technology/applicability

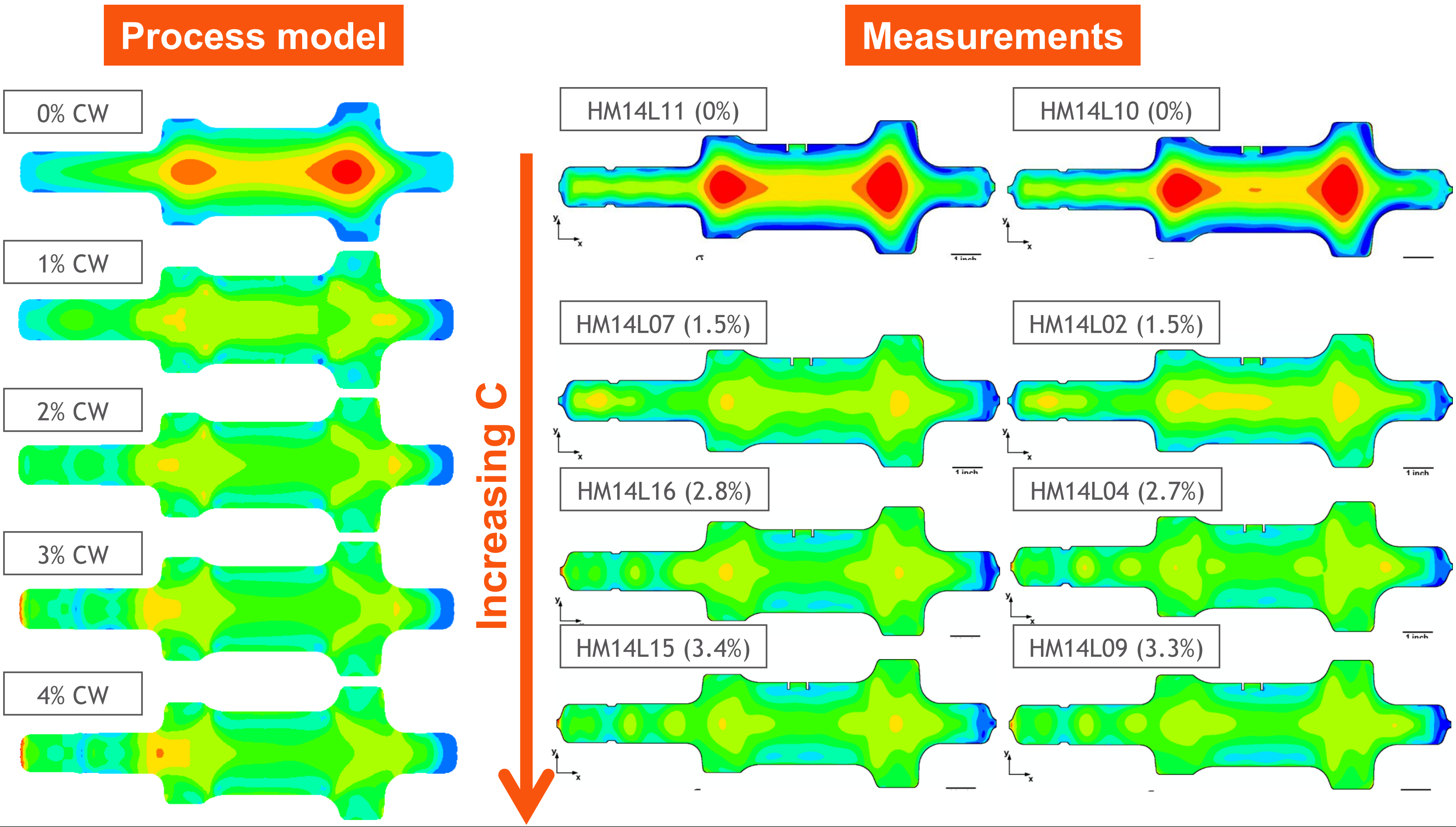
Cold work rocess sensitivity near-sur ace

Near sur ace residual stress varies with cold work

- Similar trend for hole drilling and ring core
- Confirms sensitivity between residual stress and cold work



Cold work   rocess sensitivity   ulk



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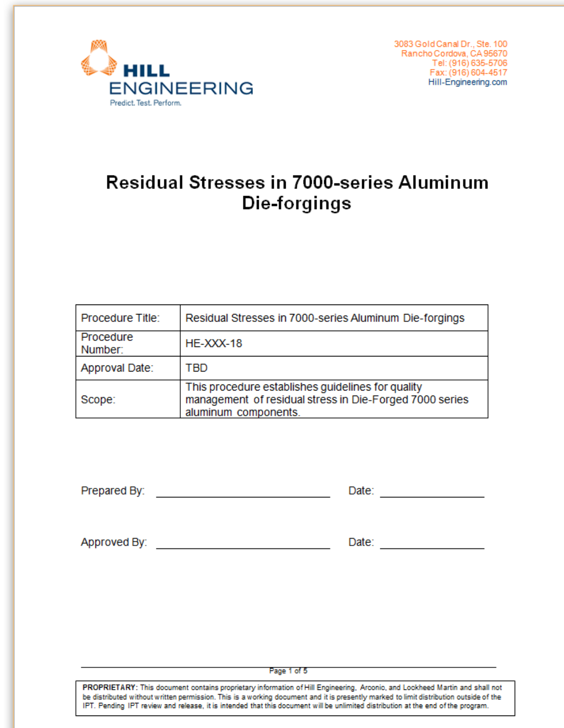
Residual stress   uality system documentation

Consistent set o language, s eci ications, and re uirements are re uired to ena le e   licit treatment o residual stress during design and   rocurement

- Developed a template for a residual stress controlled material procurement specification
- Actively working to seek updates to MIL and AMS specifications/standards

Key elements

- Residual stress requirements
  - Specified on drawings
- Process modeling plays a key role (full-field)
- Residual stress measurements at select locations
- Define first article acceptance criteria
- Define ongoing surveillance testing requirements



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Hill-Engineering.com

Residual Stresses in 7000-series Aluminum Die-forgings

Procedure Title:	Residual Stresses in 7000-series Aluminum Die-forgings
Procedure Number:	HE-XXX-18
Approval Date:	TBD
Scope:	This procedure establishes guidelines for quality management of residual stress in Die-Forged 7000 series aluminum components.

Prepared By: ____________________ Date: ____________

Approved By: ____________________ Date: ____________

Page 1 of 5

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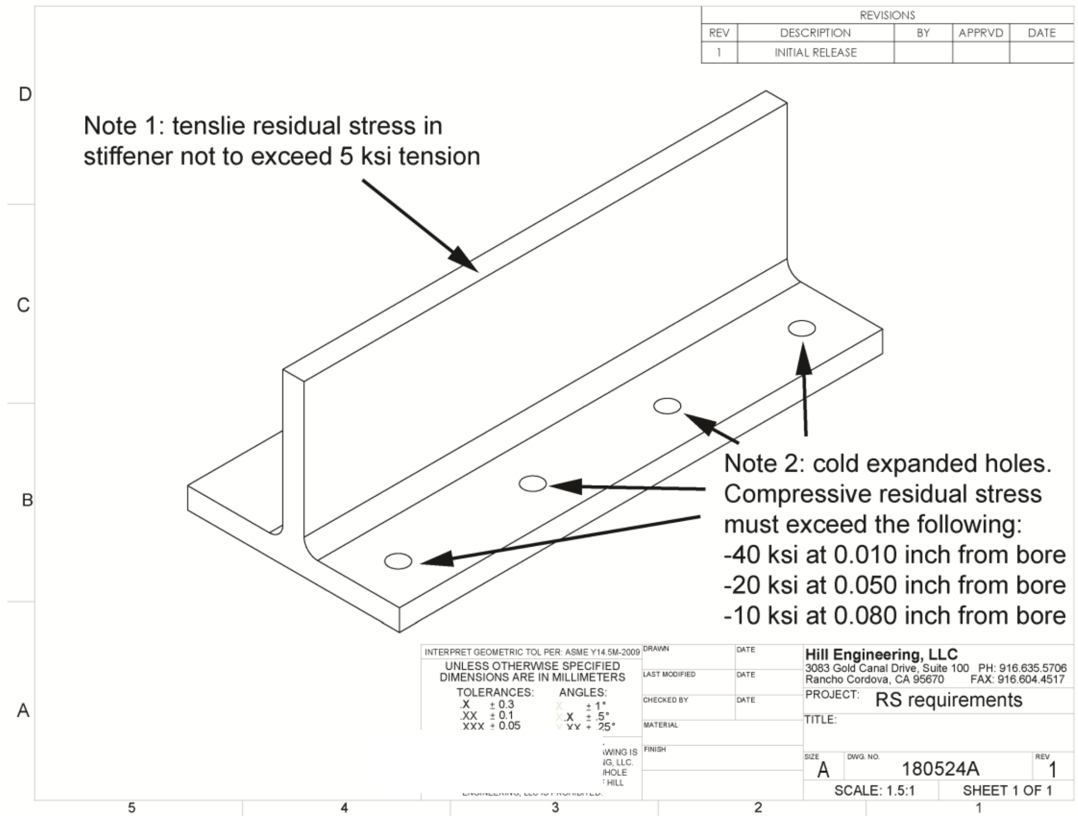
Residual stress re uirements e am le

Part s eci ic residual stress re uirements should   e s eci ied on the engineering drawing

- Simple illustration shown
- Exclude tensile residual stress where it would impact performance
- Specify compressive residual stress where necessary to meet performance requirements



here do we go rom here

Actively manage residual stress throughout the   roduct li e cycle

Tools are availa le to de ine residual stress as a com onent attri ute that is lowed throughout a su   ly-chain

- Engineering drawings contain part-specific requirements
- Specifications and standards define the general approach and requirements (internal and industry)
- Measurements and modeling quantify residual stress

Purchase raw material that has consistent residual stress

- Specify appropriate requirements and engage material producers

Methods e ist to include residual stress in   roduct li e analysis

- Need to validate the models to ensure accuracy

Develo   uality systems or residual stress and e ecute to certi y   roducts

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ERSI

Measurements Su -grou date

Large Hole CX Evaluation

Large Hole C Evaluation

O ective

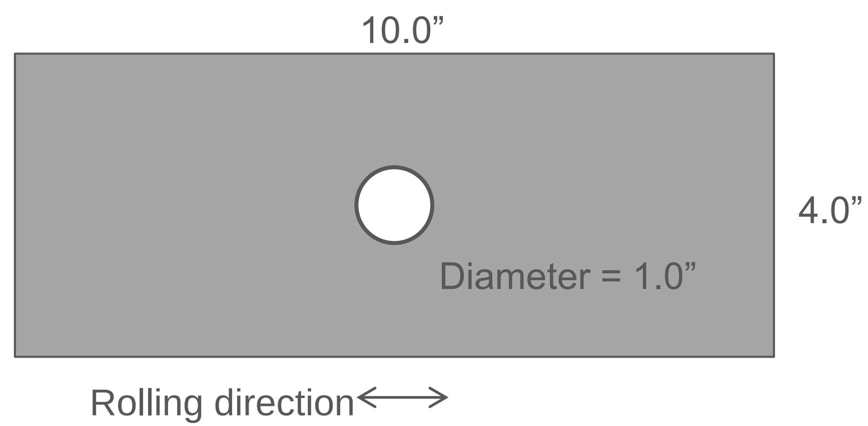
- Develop a coupon that scales-up the stress field
- Develop and interrogate measurement data

Cou on attri utes

- Large diameter
  - Maximize length scale of “near-surface” and “near-bore” regions
- Long enough to facilitate fatigue testing
- Wide enough to minimize edge margin effects

Material ty es

- 7075-T651
- 2024-T351



Large Hole C Evaluation

Current status

- Initial contour method measurements are complete
  - Residual stress consistent with scaling of geometry
  - Residual stress data is very consistent specimen-to-specimen
- Planning for next set of experimental testing is complete
  - Additional residual stress measurement methods
  - Fatigue testing

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Summary o To ics or Today

Contour Method Round Ro in

- Given the same input data, participants return results very similar to the benchmark simulation stress field
- Phase 1 complete, Phase 2 ongoing

Measurements o Stress at Legacy vs New C   Holes

- Legacy CX consistent with current production practices
- No evidence of “missed” holes

Residual Stress   uality System

- Program looked at manufacturing induced residual stress (unintended)
- Developed an approach for quality management of residual stress processes (cold working)
- Many similarities with engineered residual stress processes

Large Hole E   eriments

- Large holes with lower gradients that will be easier to measure
- Initial work is promising, continuing to evaluate further

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Thank ou

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Analytical Methods   Testing Su committees: Overview o Recent E orts

Engineered Residual Stress Implementation Workshop 2018
September 13, 2017

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Robert Pilarczyk
Group Lead – Structural Integrity
Hill Engineering, LLC

APES, INC.
analytical processes / engineered solutions

Tom Mills
Principal Engineer
APES, Inc

ERSI

Acknowledgements

- A- T- Aircra t Structural Integrity Teams
- Air orce Research La
- Analysis Methods Testing Su committee Partici ants
- ERSI orking Grou

Historical

Residual Stress is considered a ro lem or used as a *band-aid* to address design de iciencies

Emerging

Residual Stress Engineering is a *conventional technology* that assures er ormance

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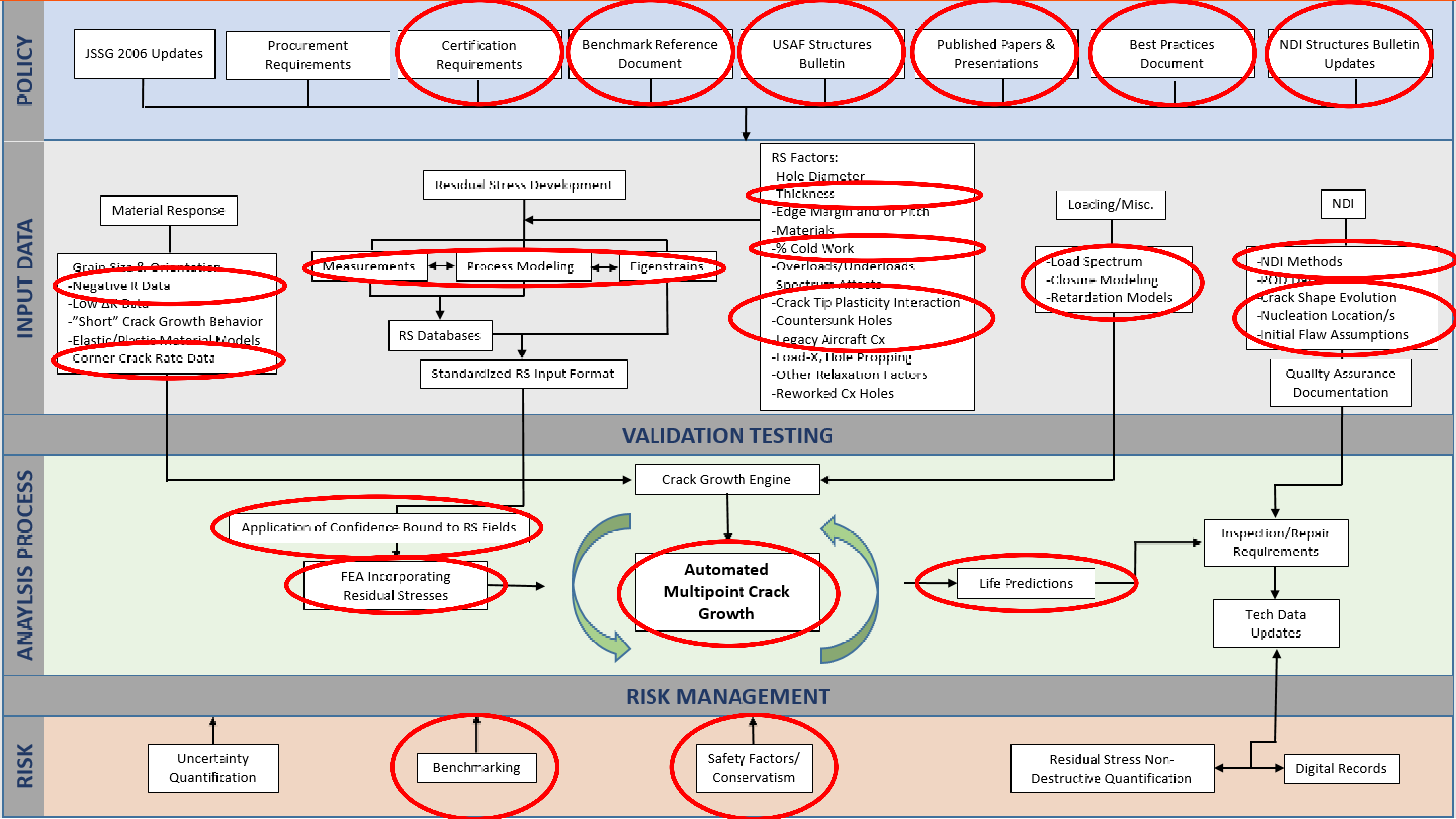
Agenda

- Round Ro in or C Holes
- Best Practices Document
- Dra t Structures Bulletin
- Engineering Im lementation o Residual Stress
- Crack Closure E ects
- 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 Ro in or C   Holes

- **Pur ose 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, <u>the focus will be on systematic uncertainties</u>, 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 <u>free to use any means to incorporate the residual stress into the DTA</u>, 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   ocus   understand analyst-to-analyst   rediction varia ility given i ed in ut data**

Round Ro in or C   Holes

- **Pur ose 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   ocus   Investigate the consistency, strengths and weaknesses o each method to de ine   est   ractices moving orward**

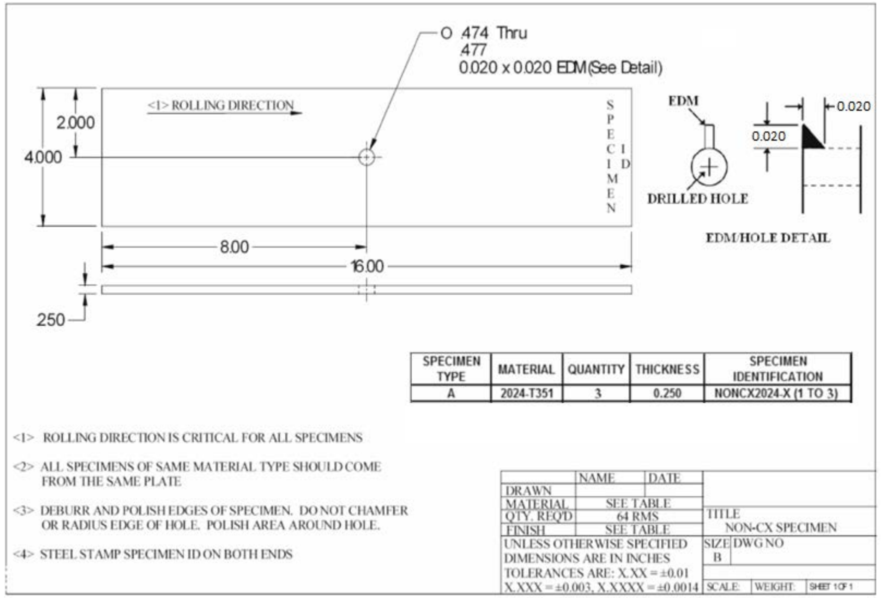
Round Ro in or C Holes

❑ 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

❑ In ut Data

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



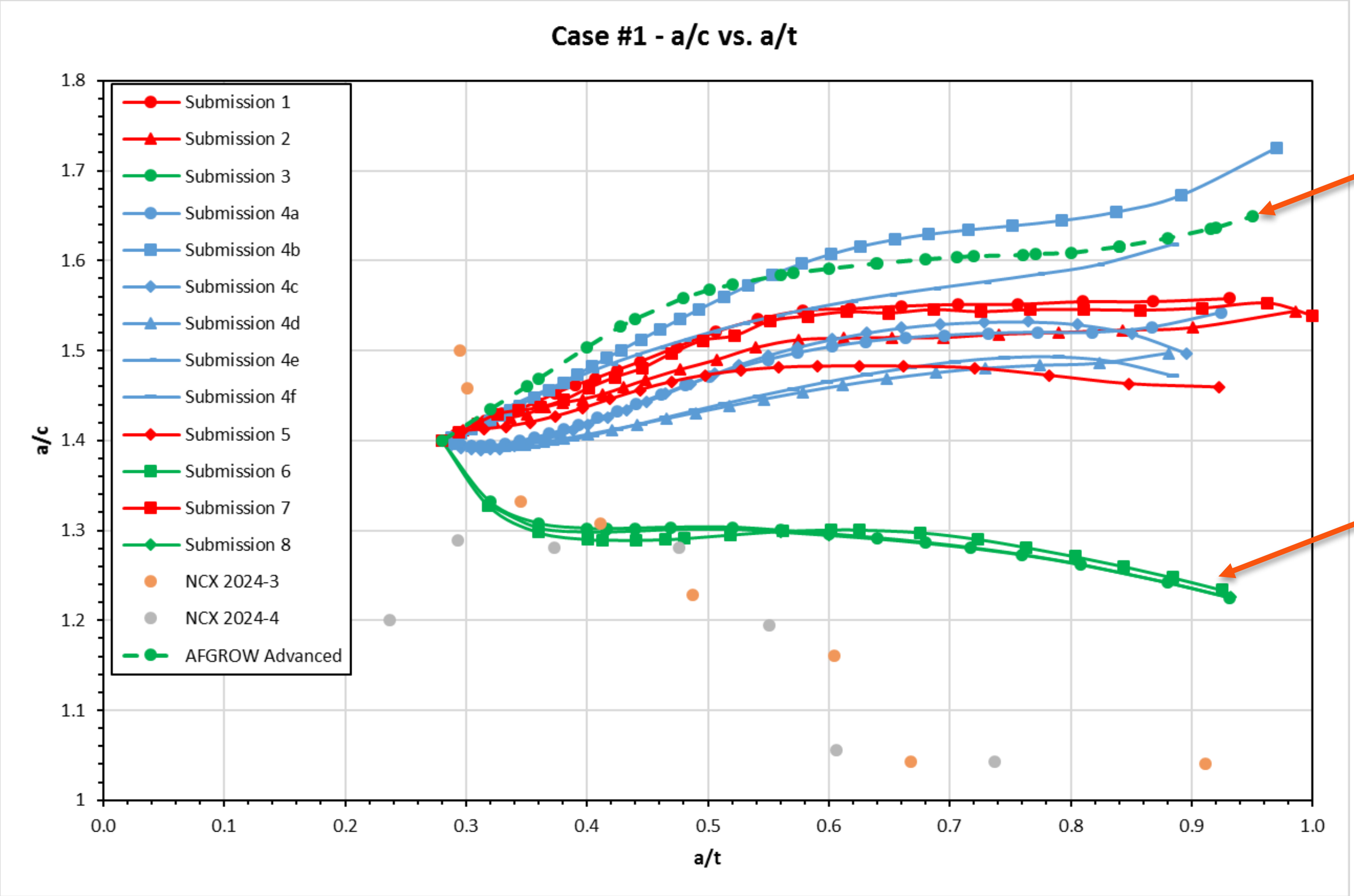
A Year of Answering the Why's???

Round Ro in or C Holes Action Items

Action Item	Title	Descri tion	ocal/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 Ro in or C Holes A GRO As ect Ratios

- Classic Newman-Ra u solutions vs. Advanced awa -Andersson



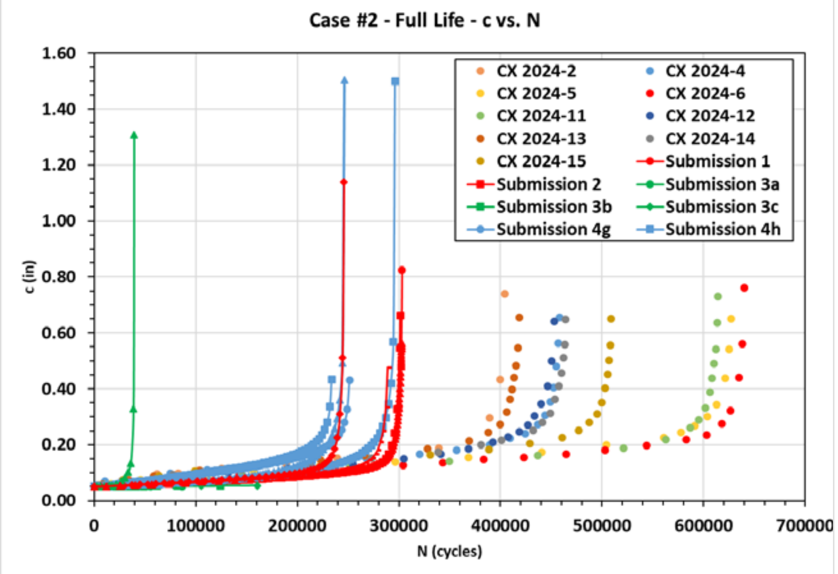
awa -Andersson

Newman-Ra u

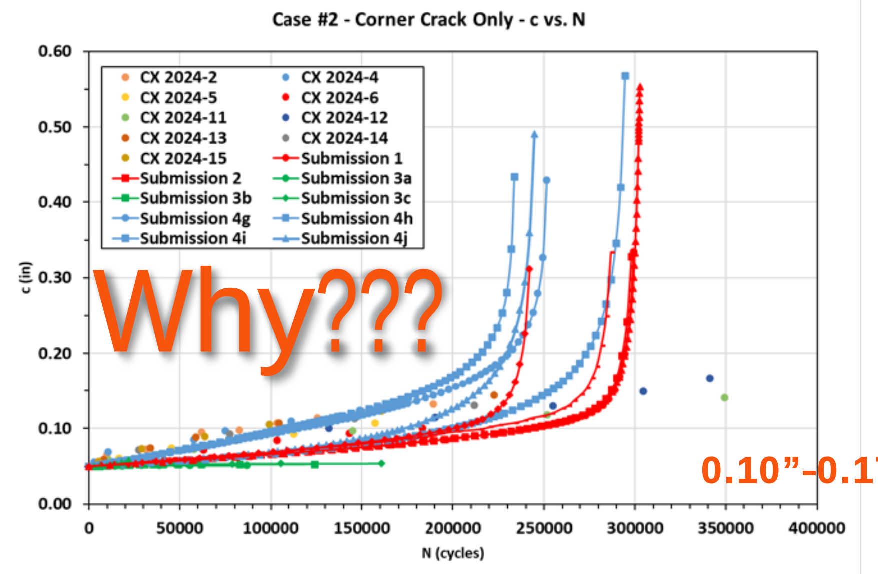
Why???

Round Ro in or C Holes Corner Thru Crack Segregation

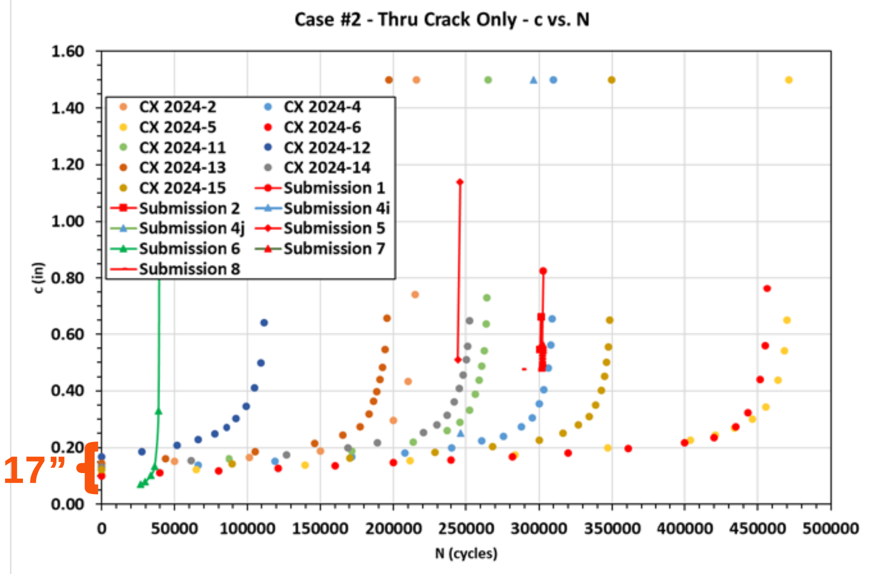
Full Life



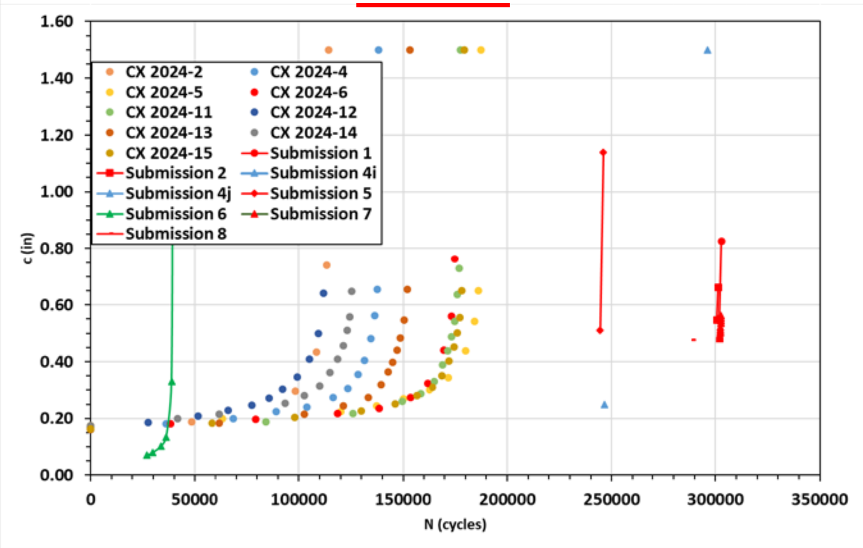
Corner Crack only



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



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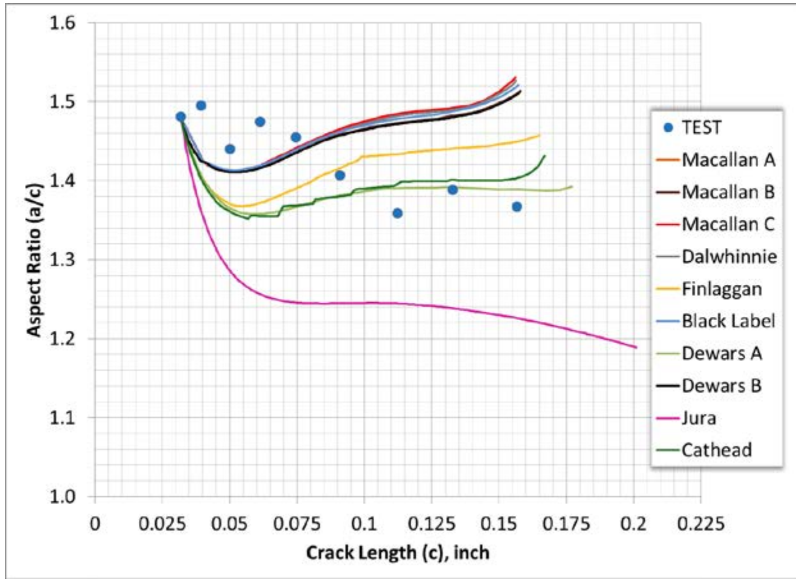
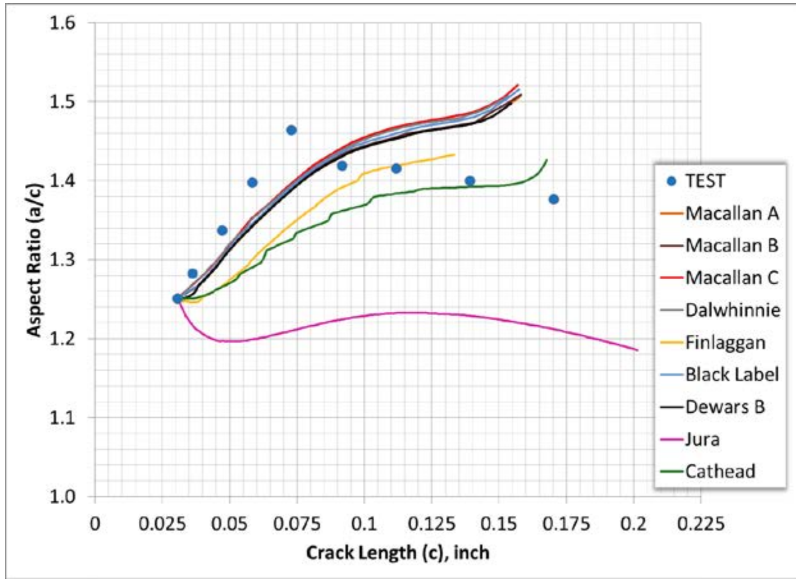
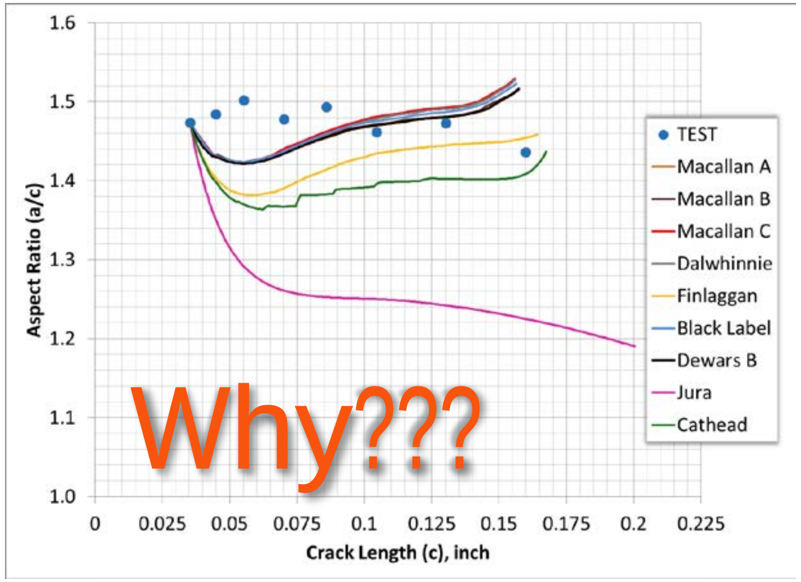
Round Ro in or C   Holes   Multi-Direction Material Pro erties

❑ A GRO   Round Ro in

- ➢ 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



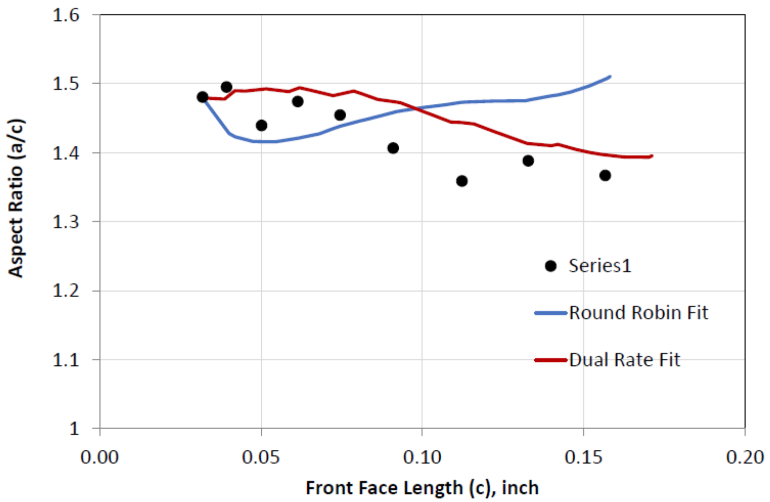


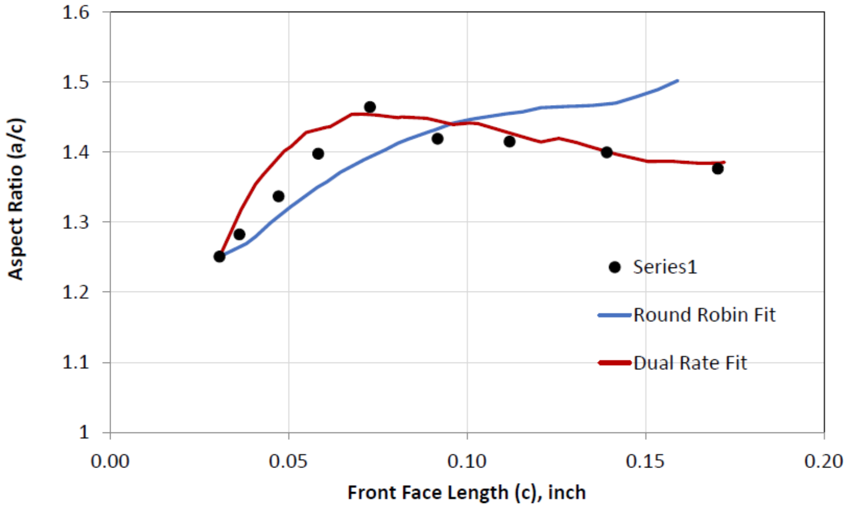


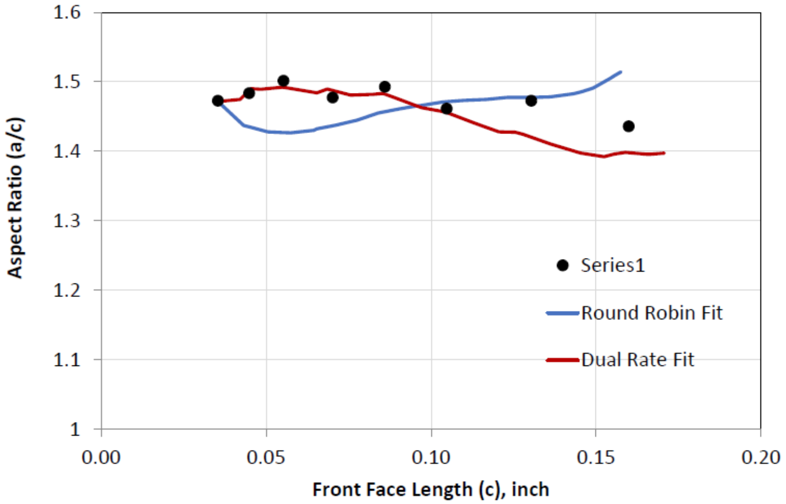
Re : Harter,   ., Case Study on Test/Prediction Correlation or Corner Cracks at Holes, Proceedings rom the   AA   S Con erence,   acksonville,   L.

Round Ro in   or C   Holes   Multi-Direction Material Pro erties

- A GRO   Round Ro in
  - Multi-directional rate data resulted in:
    - Minimal changes to life predictions
    - Better correlation to crack aspect ratio trends



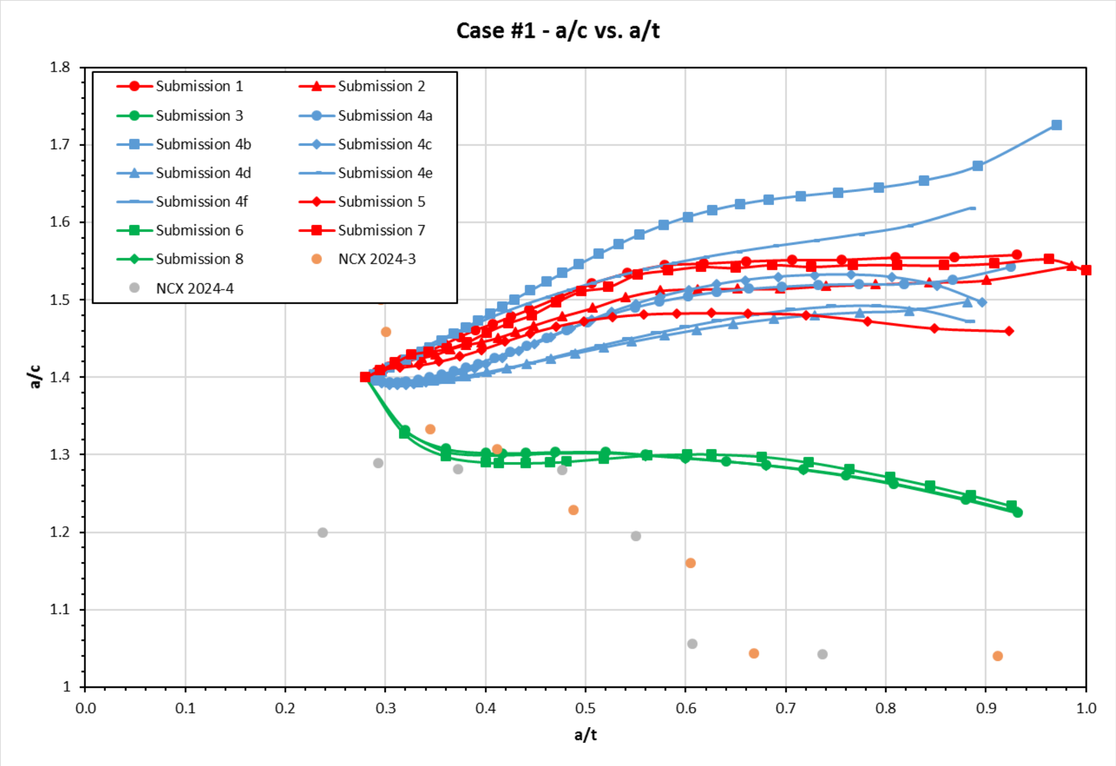


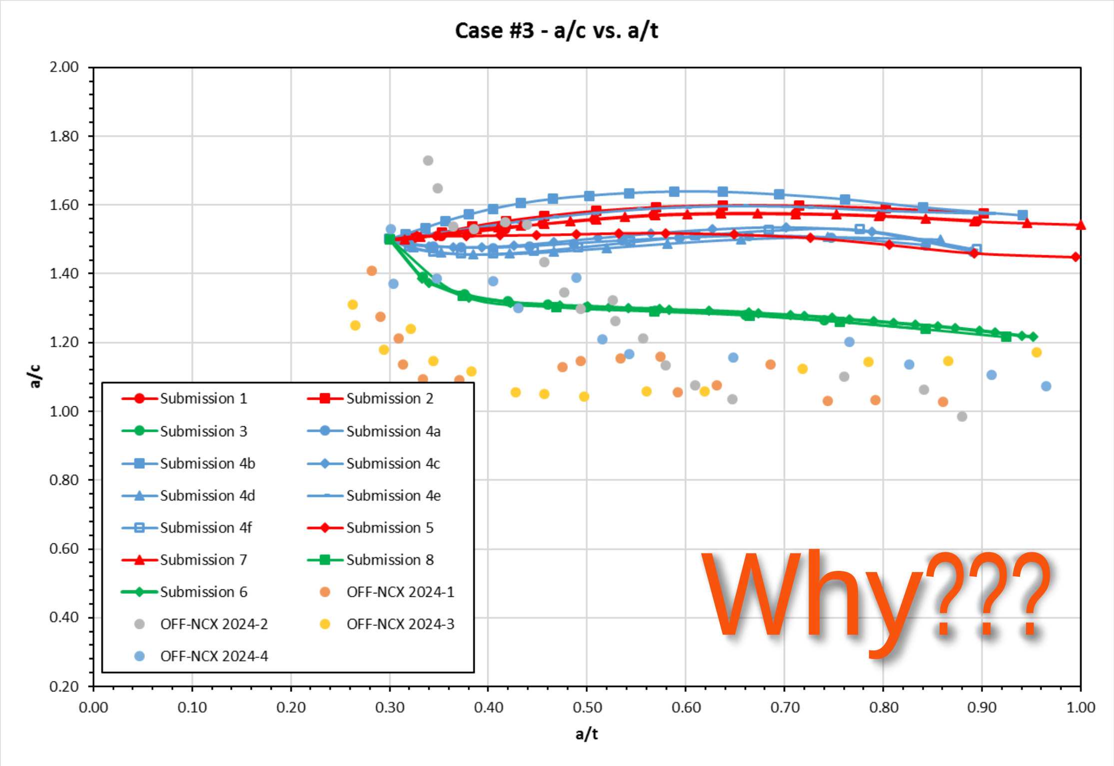


Re : Harter, ., Case Study on Test/Prediction Correlation or Corner Cracks at Holes, Proceedings rom the   AA S Con erence,   acksonville,   L.

Round Ro in or C Holes Multi-Direction Material Pro erties

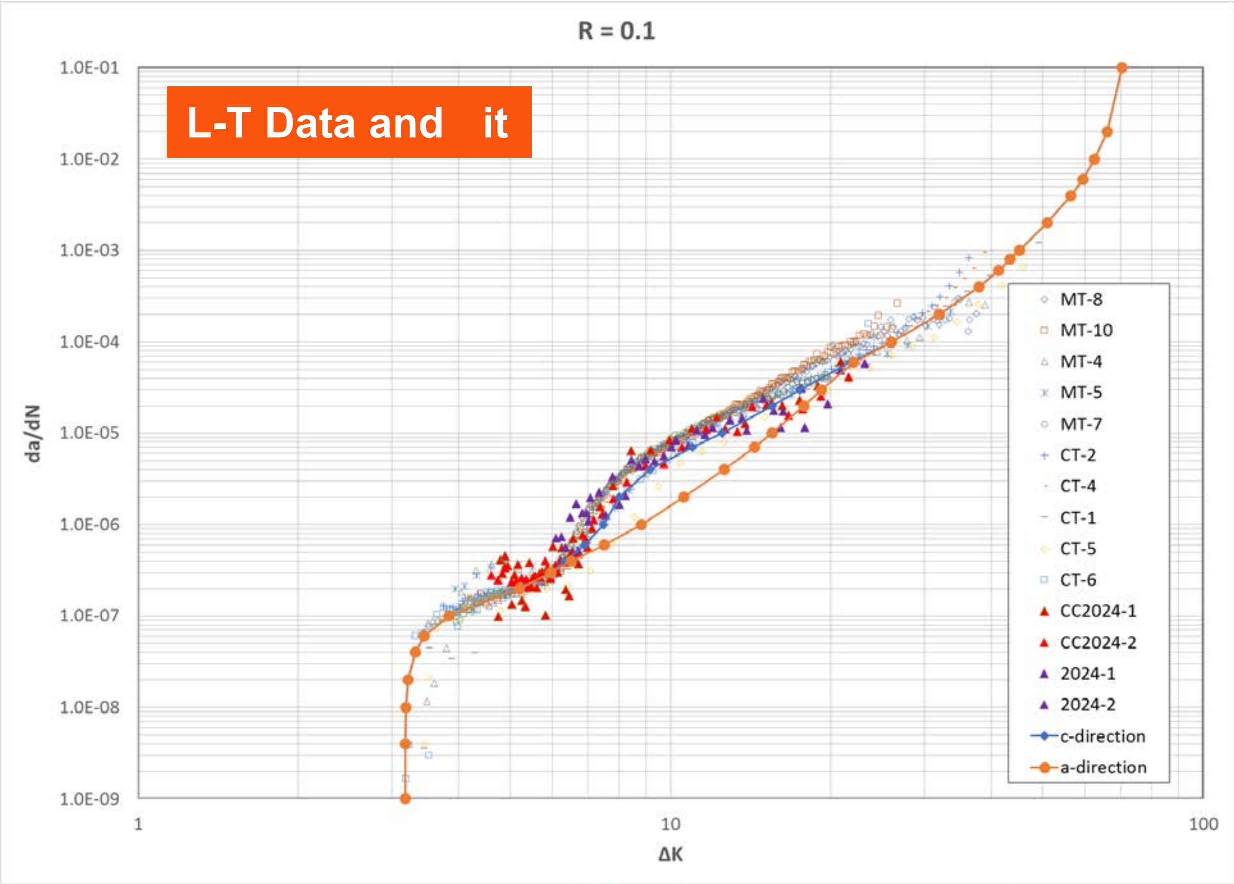
- Similar mismatch or ERSI Round Ro in

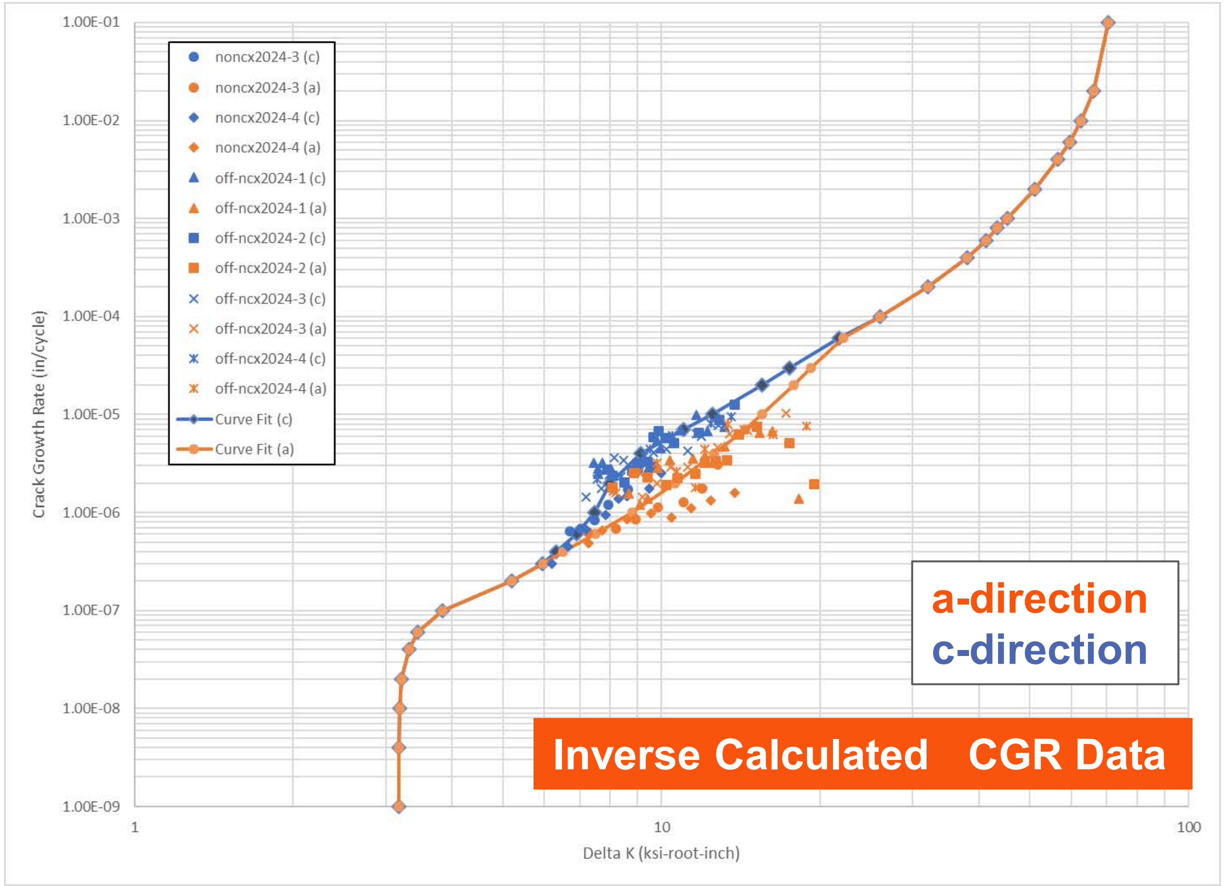




Round Ro in or C   Holes   Multi-Direction Material Pro erties

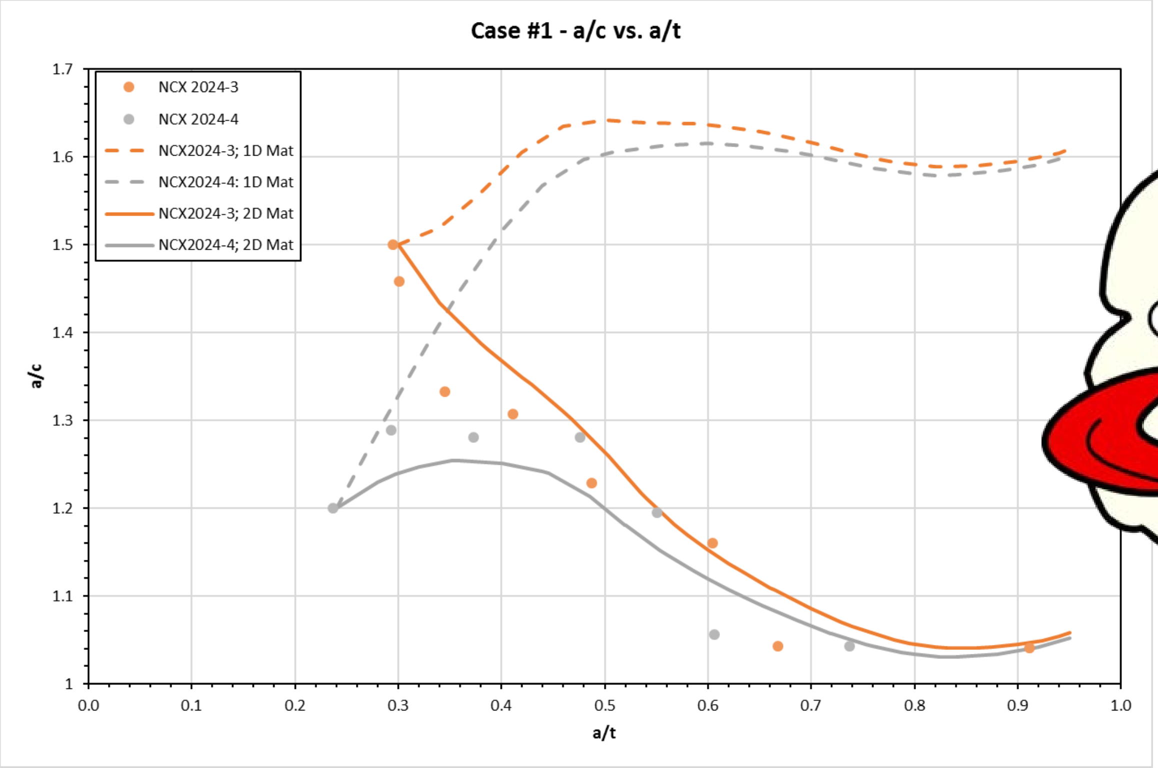
- Retrodiction o crack growth rate data in a and c direction

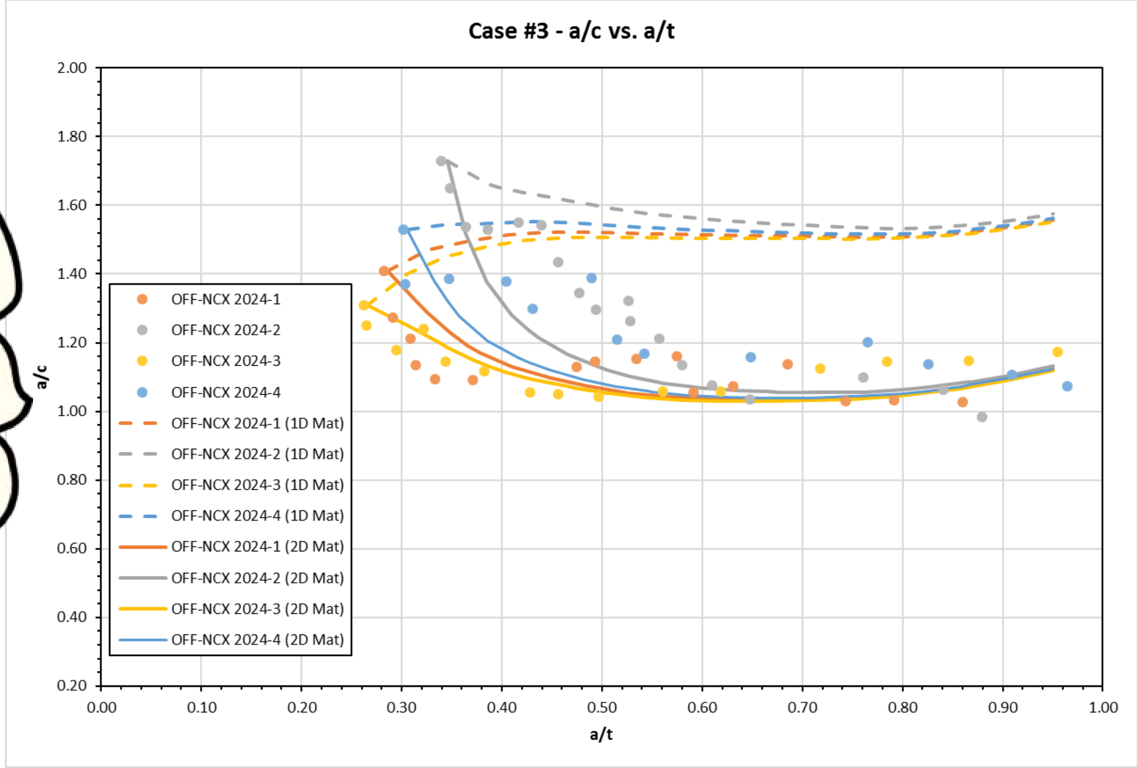




Round Ro in or C Holes Multi-Direction Material Pro erties

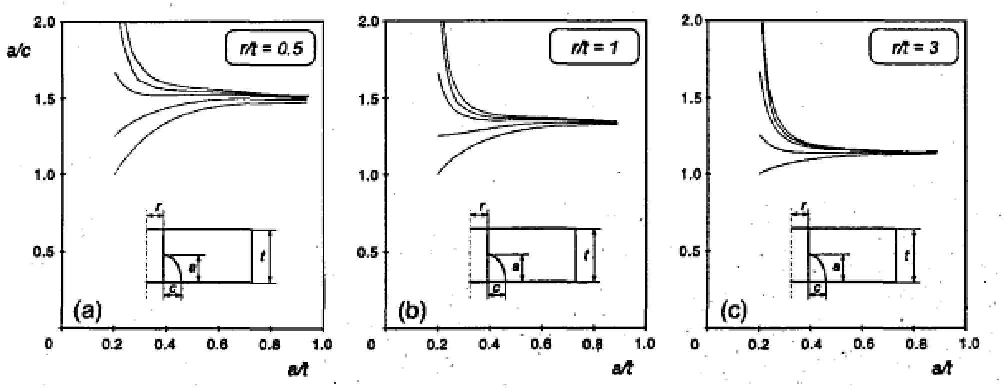
- Post-dictions with multi-directional material ro erties

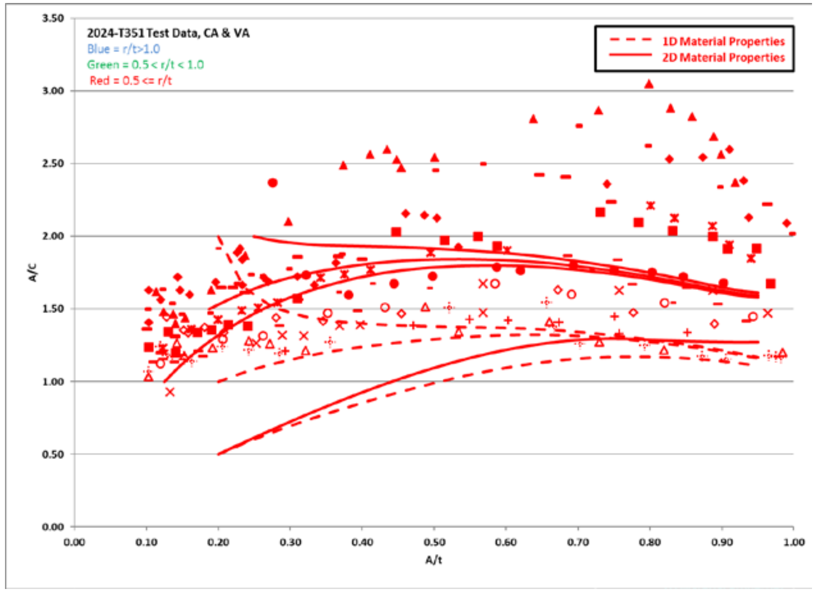


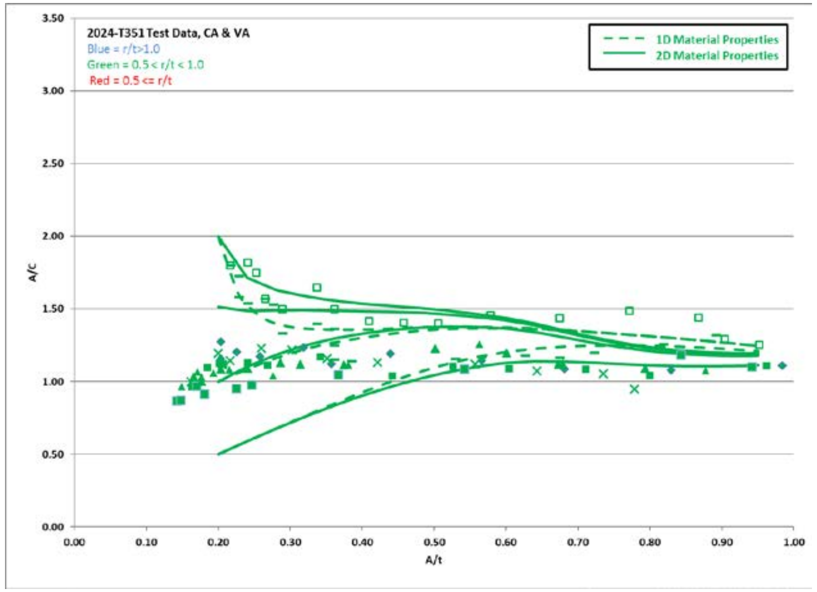


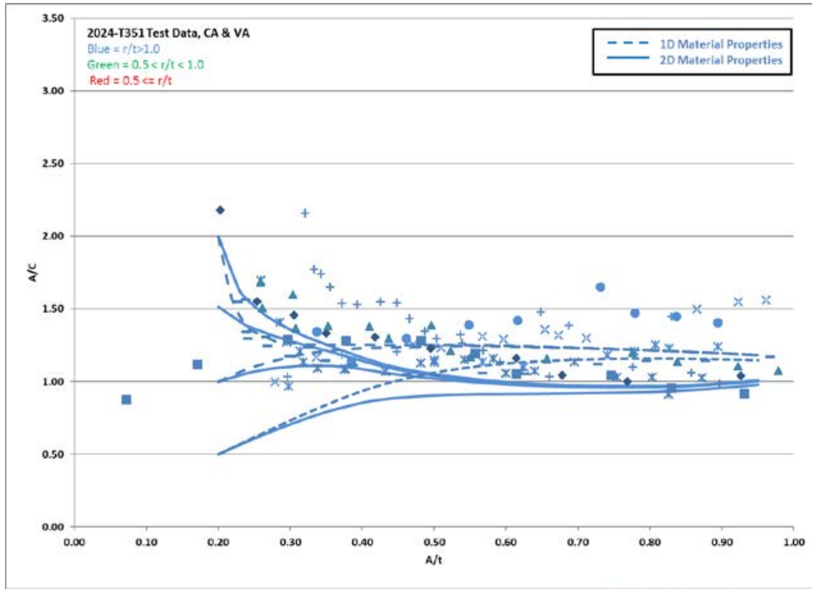
Round Ro in or C Holes Multi-Direction Material Pro erties

- D Material
  - Minimal differentiation with r/t
- D Material Pro erties
  - Distinct trend consistent with open literature and test data



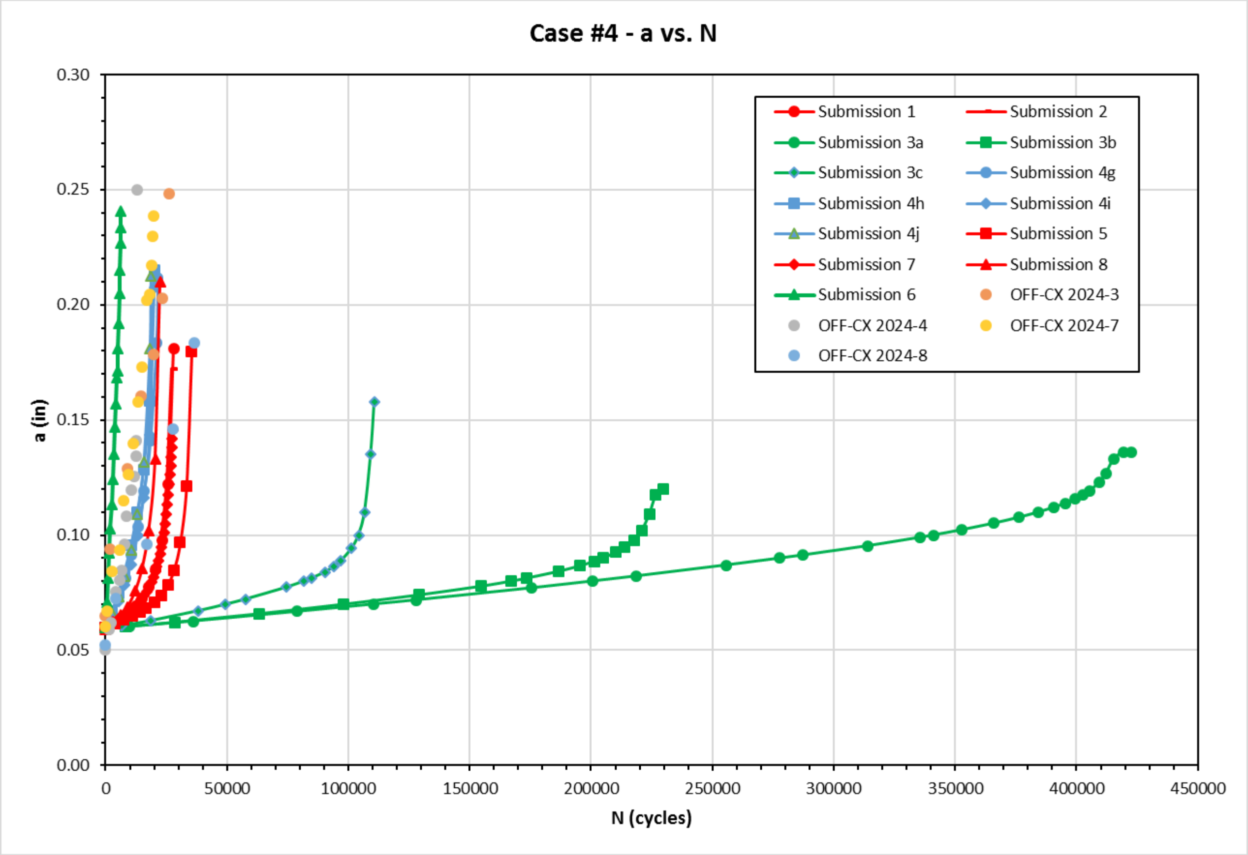


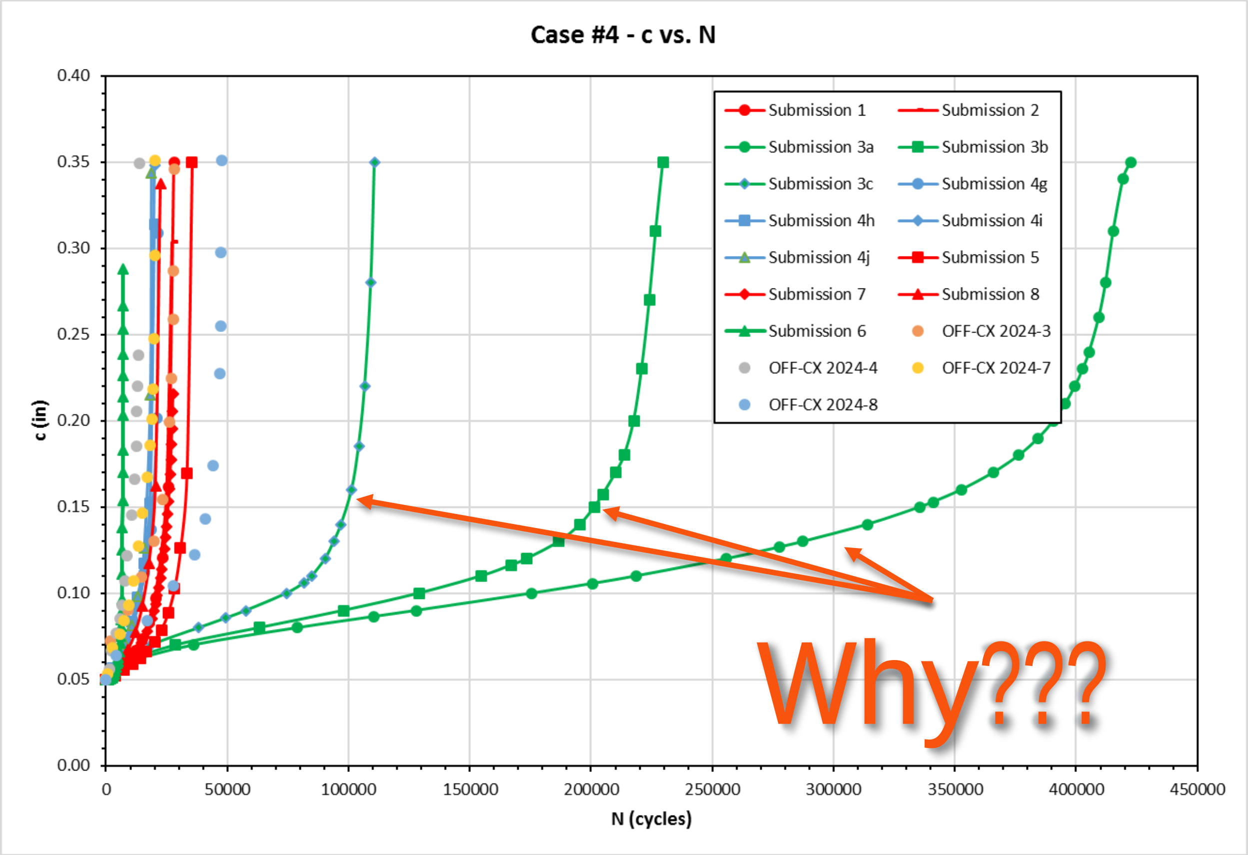




Round Ro in or C Holes A lied and Residual Stress Intensities

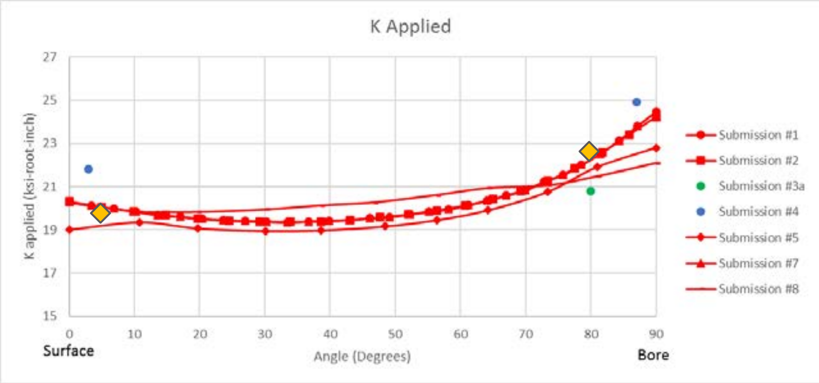
- Signi icant Over redictions rom A GRO
  - Newman-Raju solutions w/ Gaussian Integration for residual stress

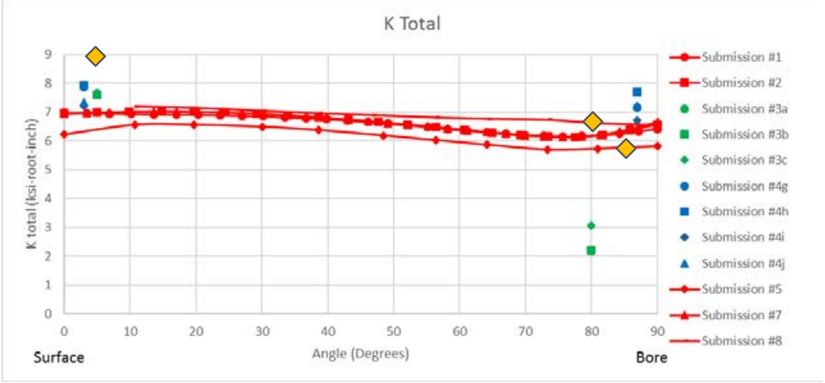


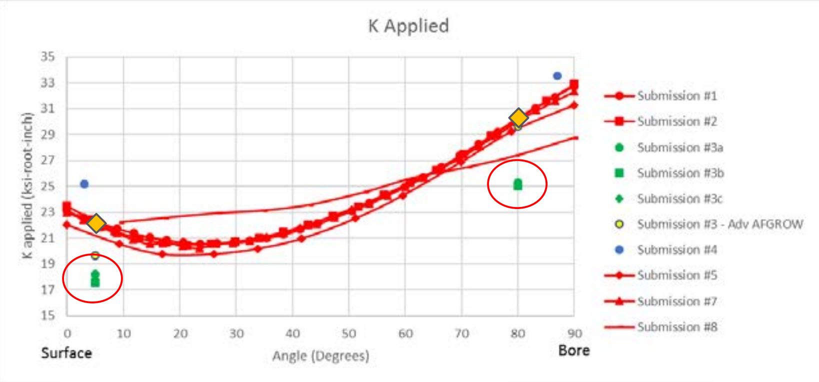


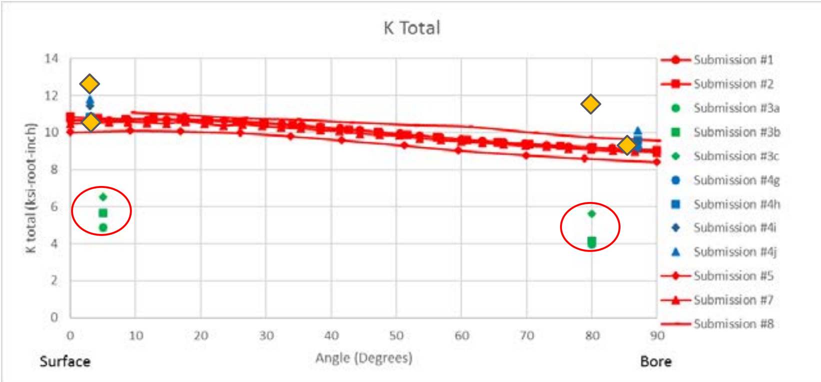
Round Ro in or C Holes A lied and Residual Stress Intensities

- Signi icant contri ution rom Newman-Ra u solutions
- Incor orated a ility to in ut RS with awa -Andersson solutions





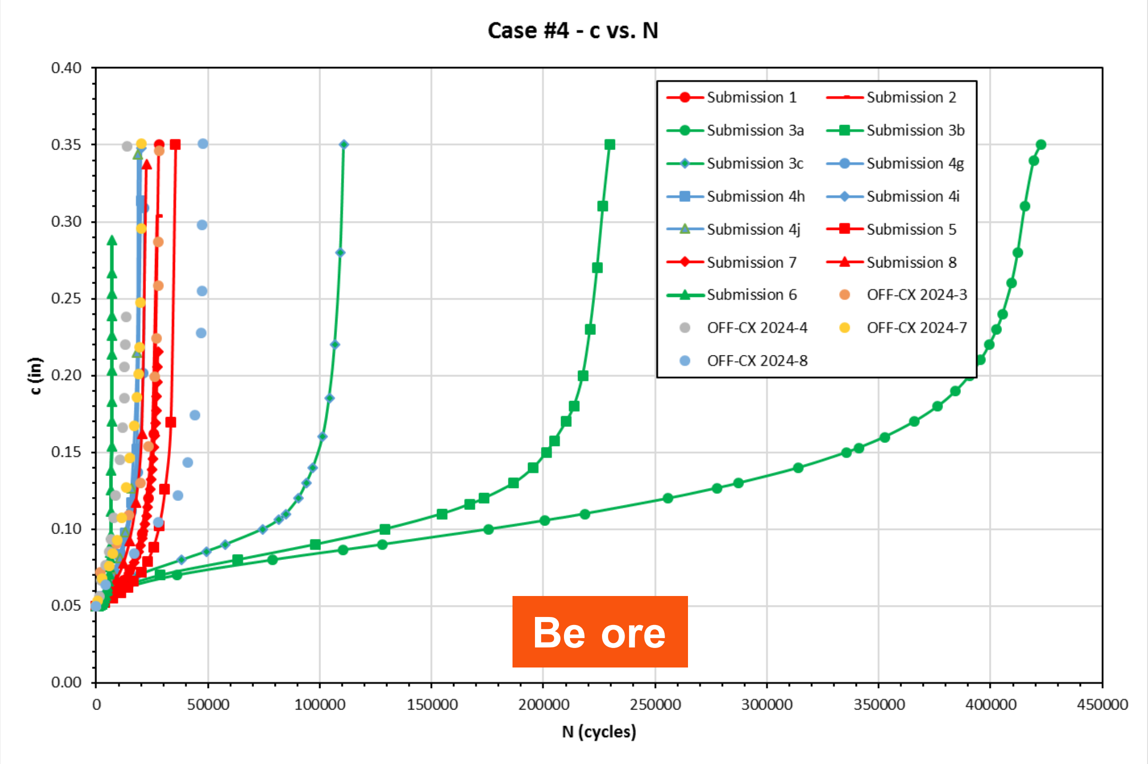


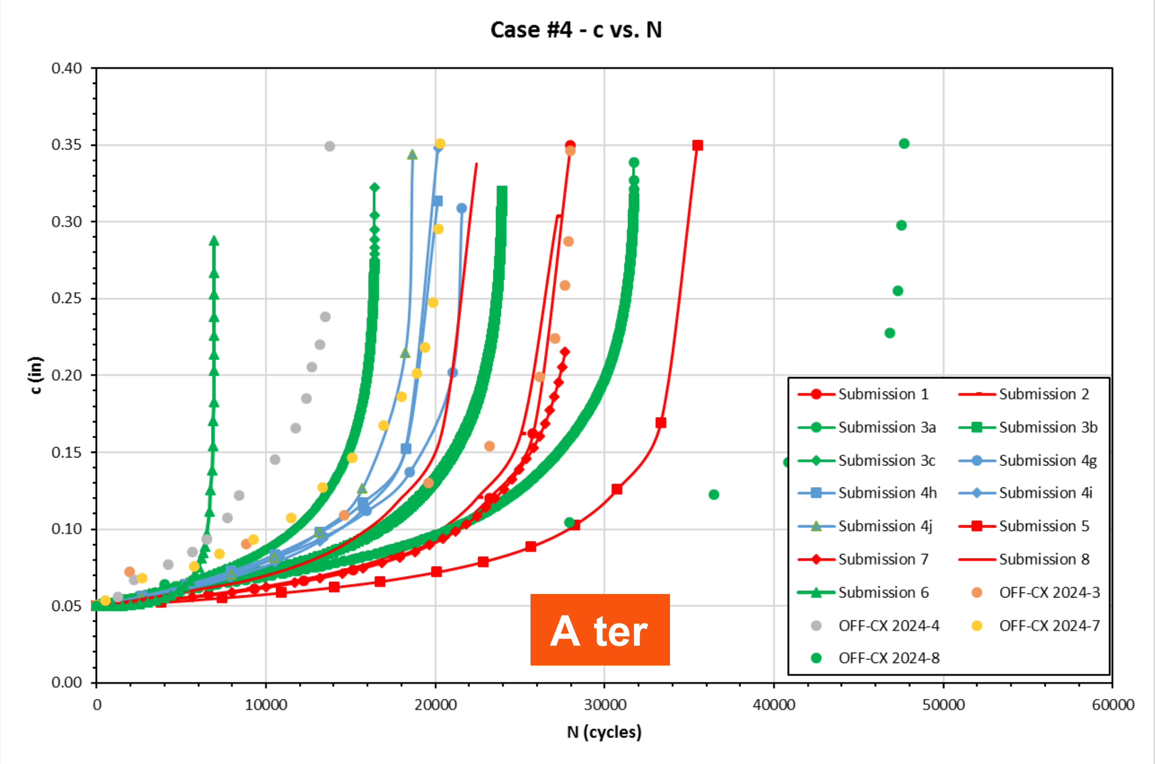


◆ Original Predictions ◆ dated Predictions

Round Ro in or C Holes A lied and Residual Stress Intensities

- Post-dictions Case





Round Ro in or C Holes A lied and Residual Stress Intensities

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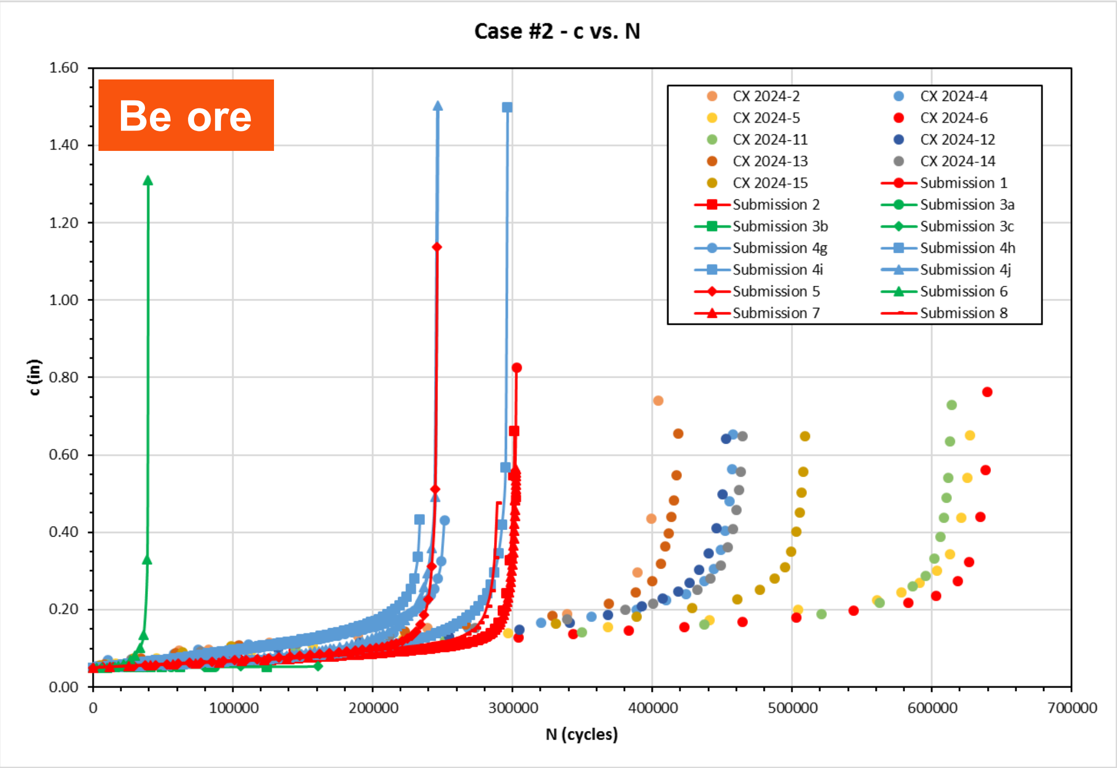
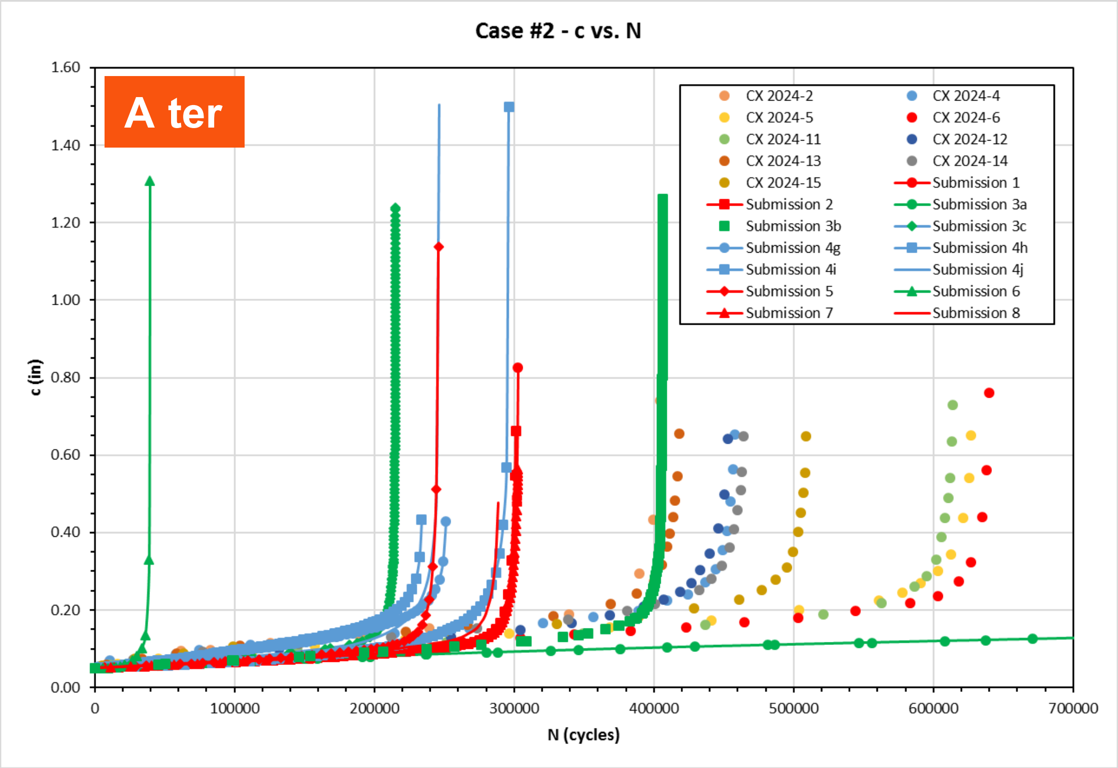


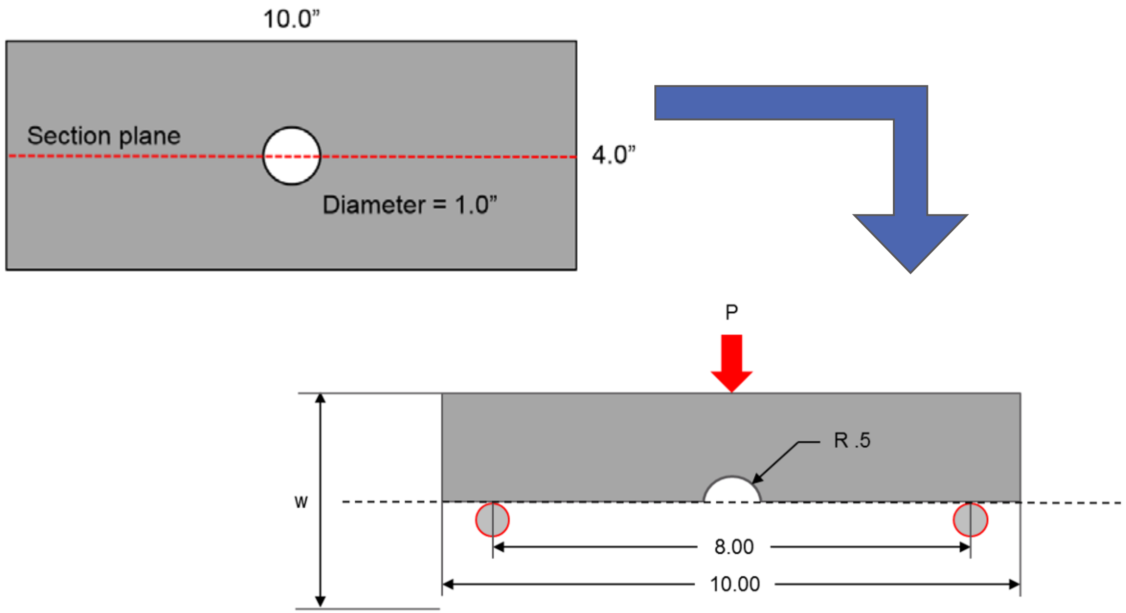


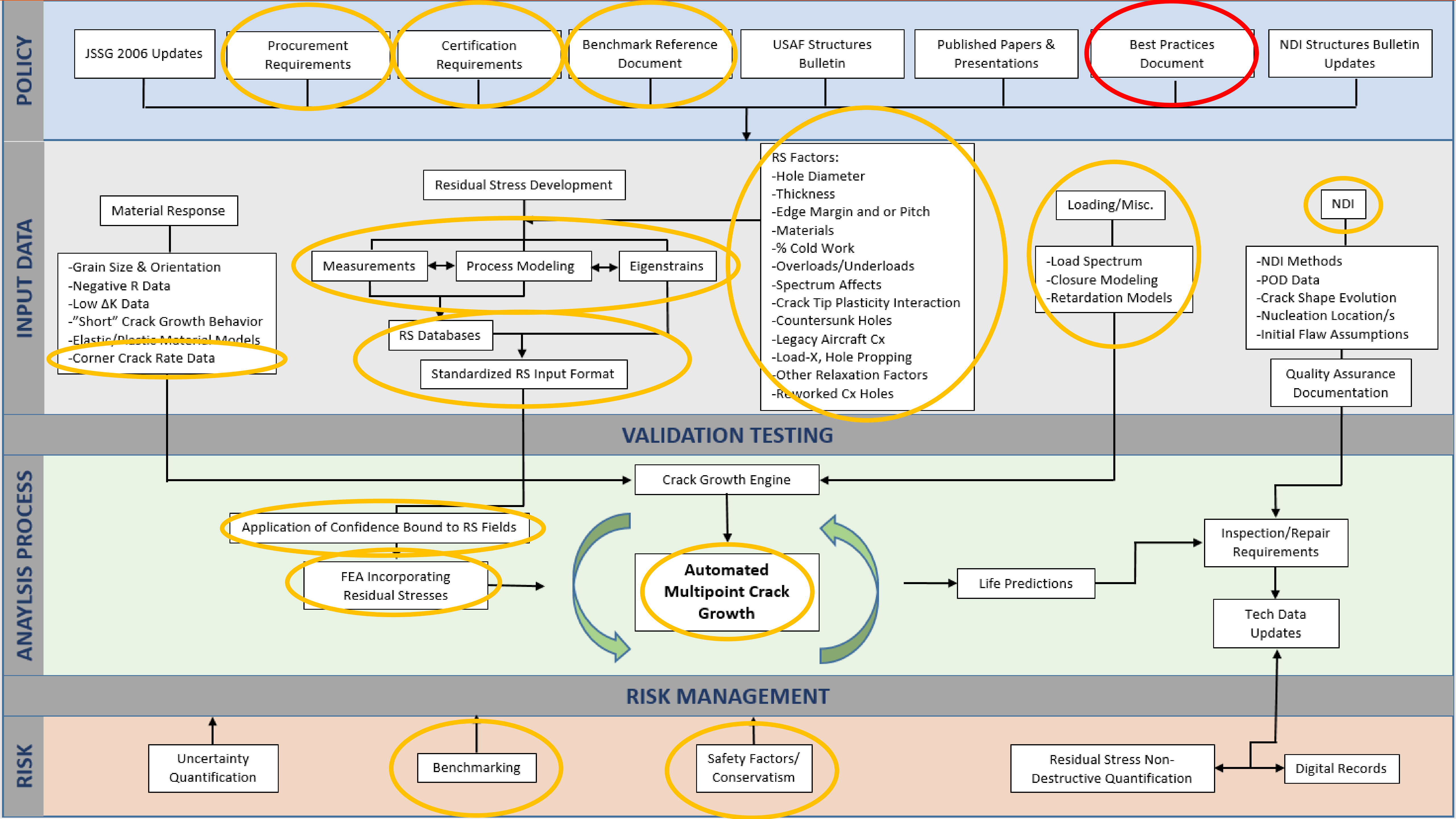
Round Ro in or C Holes - Summary

- The ear o hy s Has Been ruit ul
- Additional Action Items Need to Be Resolved
- Pu lish ournal Article
  - White paper submitted to 19th International ASTM/ESIS Symposium on Fatigue and Fracture Mechanics (42nd National Symposium on Fatigue and Fracture Mechanics)
- ollow-on Round Ro in E orts in ork

Round Ro in or C Holes Round Candidate

- **Geometrically large cou ons**
  - 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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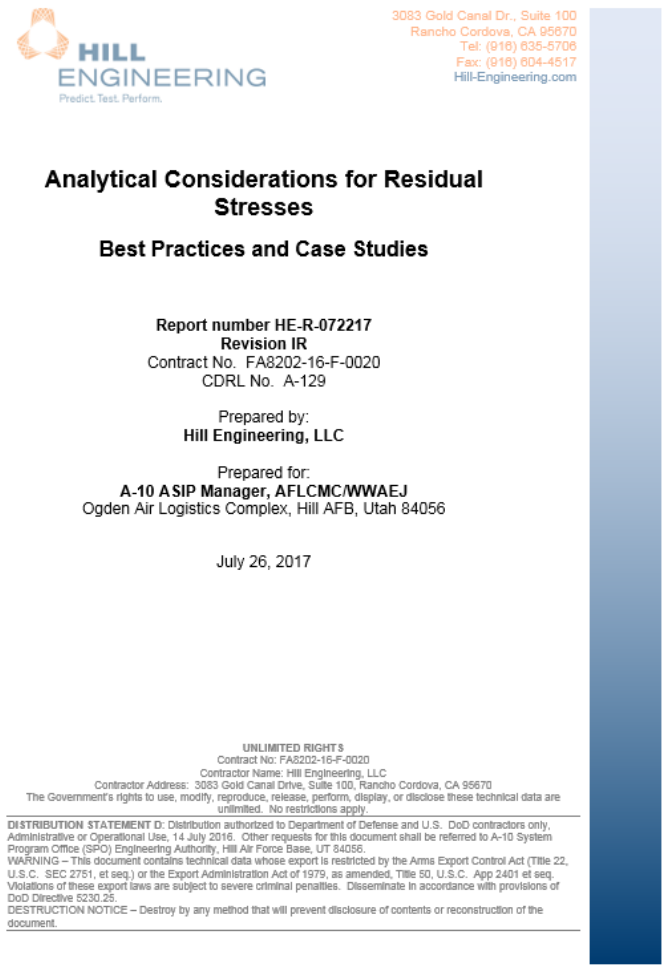
RISK MANAGEMENT
RISK
Uncertainty Quantification
Benchmarking
Safety Factors/ Conservatism
Residual Stress Non-Destructive Quantification
Digital Records

Best Practices Document

- **Pur ose**
  - Share best practices, lessons learned, and analysis methods with community
  - Document benchmarks and case studies
  - Compliment other policy documents
- **Goal O en Source Document**
- **Organi ational Structure**
  - Organized similar to AGARD documents
    - Background information
    - Best practices and lessons learned
    - Benchmark problems
    - Case studies



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Hill-Engineering.com

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:
A-10 ASIP Manager, AFLCMC/WWAEJ
Ogden Air Logistics Complex, Hill AFB, Utah 84056

July 26, 2017

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Contractor Name: Hill Engineering, LLC
Contractor Address: 3083 Gold Canal Drive, Suite 100, Rancho Cordova, CA 95670
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Best Practices Document

❑ Cha ter 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

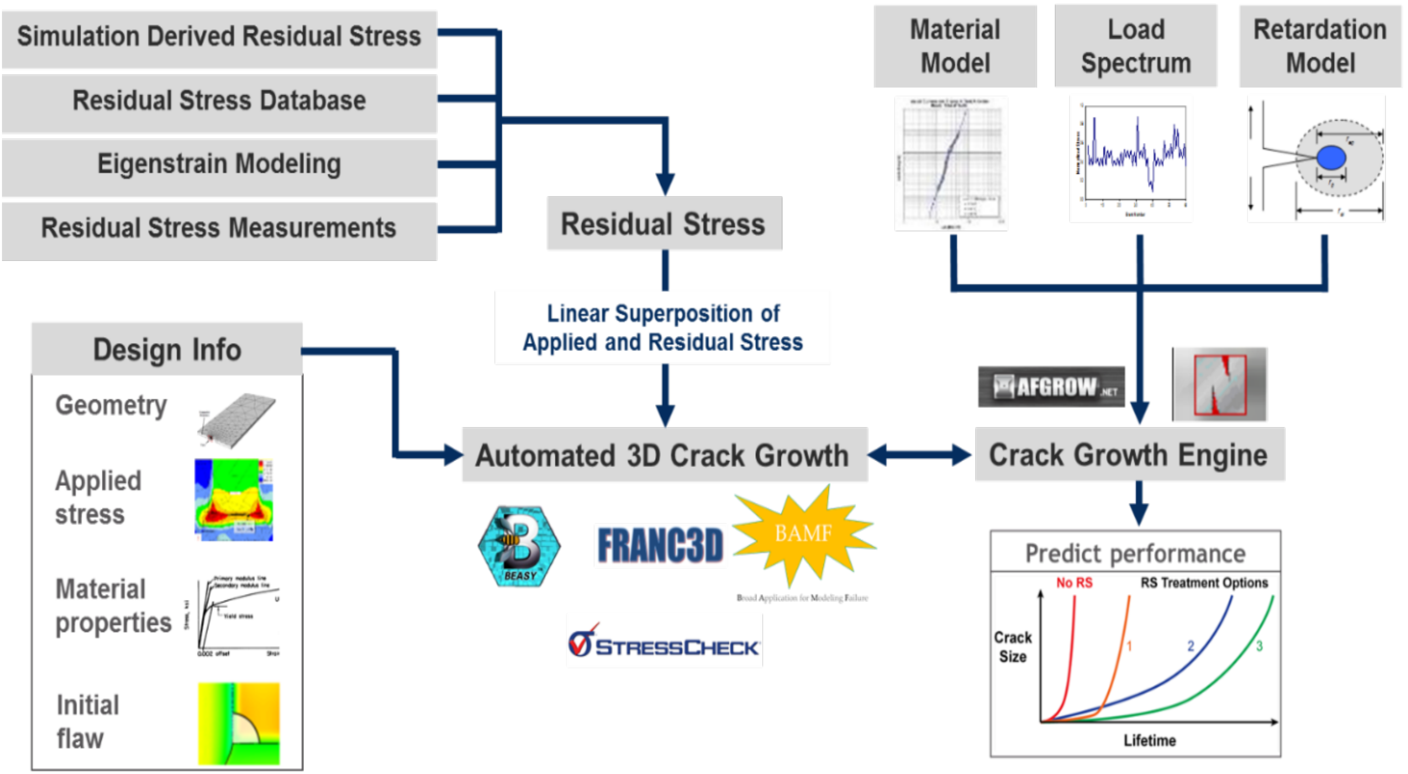
Strengths eaknesses o arious Residual Stress Measurement Techni ues

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

❑ Cha ter II Analytical Processes

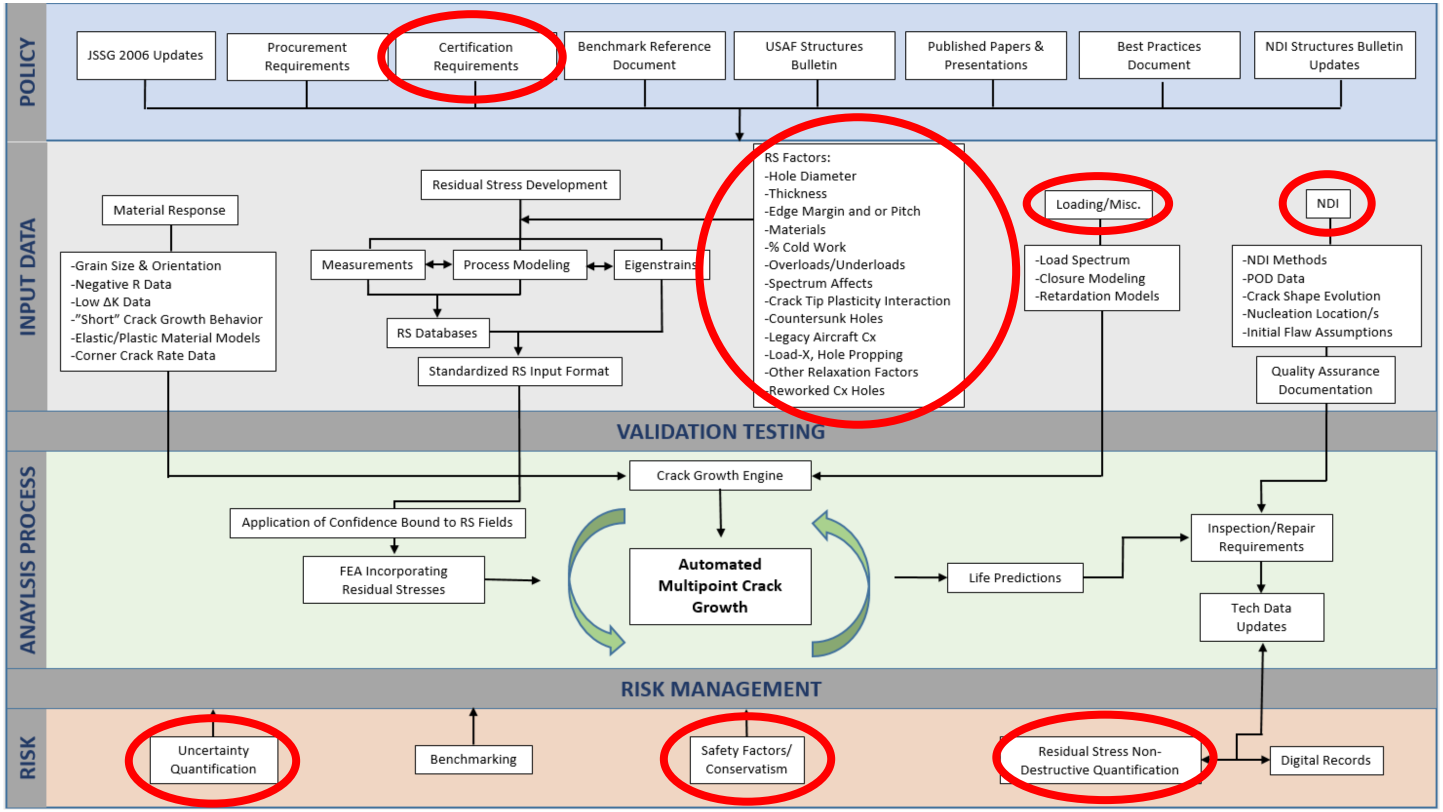
- Overview of analytical processes
- Key input data
  - Design info
  - Material models
  - Loading spectrum & retardation
  - Residual stress
- Analysis processes
  - Multi-point fracture mechanics
  - Coupled FEA
  - Other analytical approaches
- Way forward & recommendations



Best Practices Document

❑ Cha ter 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



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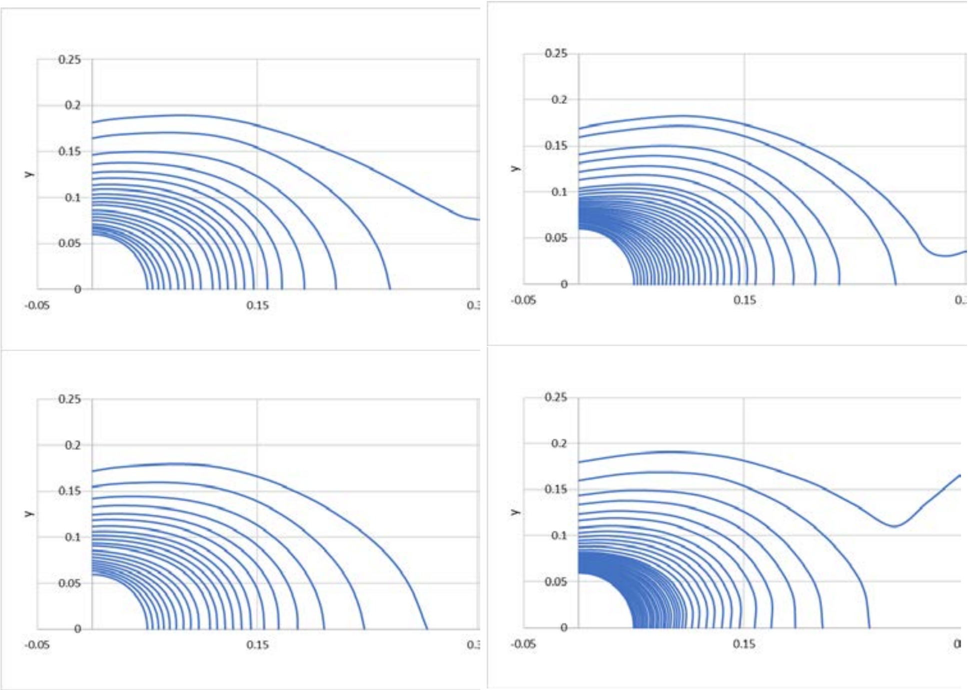
APES, INC. analytical processes / engineered solutions

ERSI

Best Practices Document

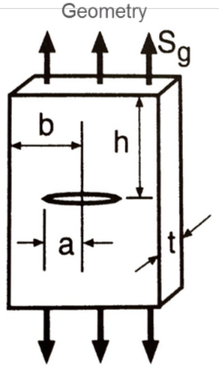
- Cha ter I Benchmark Cases
  - Handbook solutions
  - ERSI round robin results

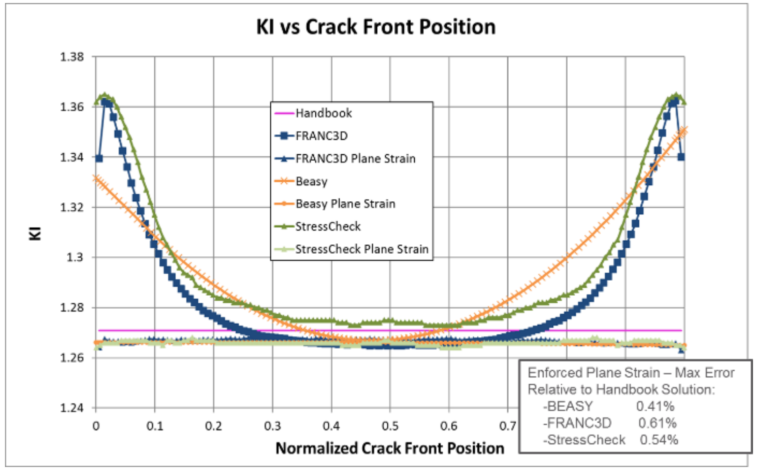


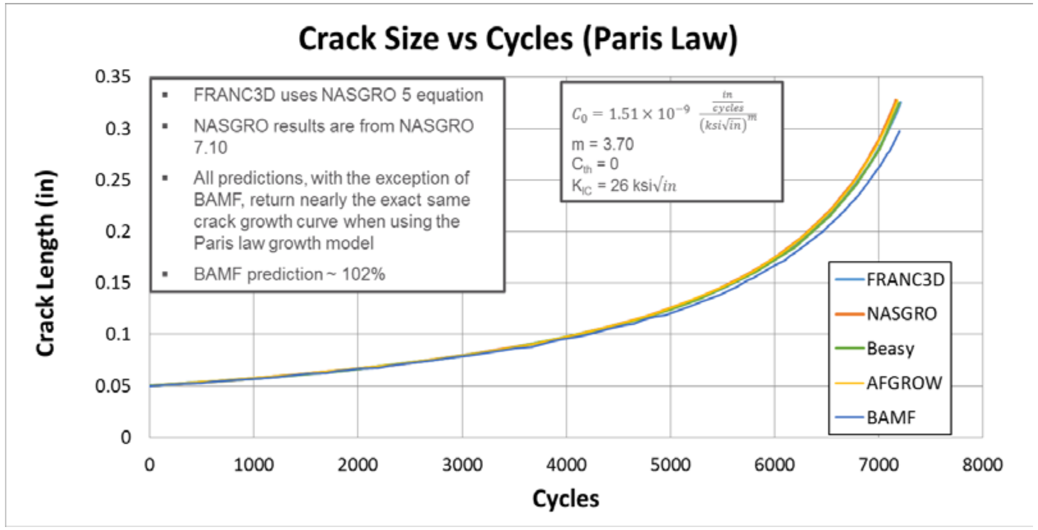
Dimensions
(inches)

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

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

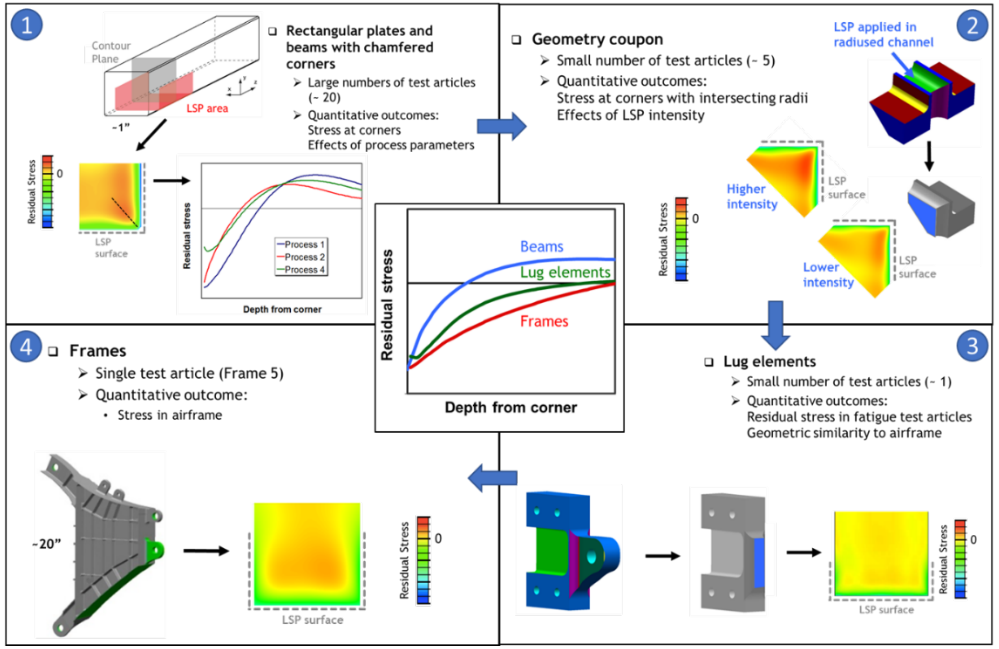


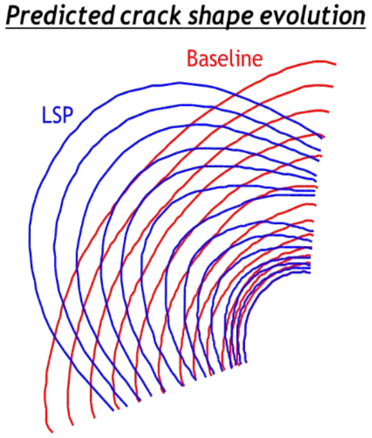


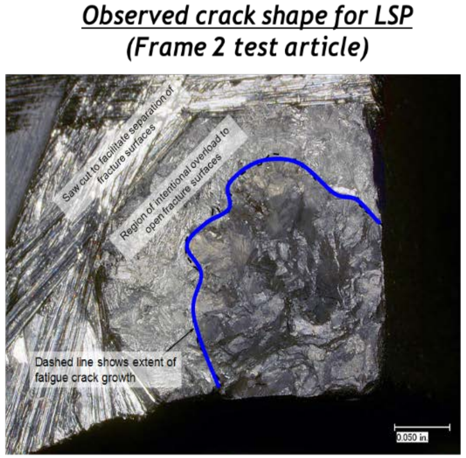


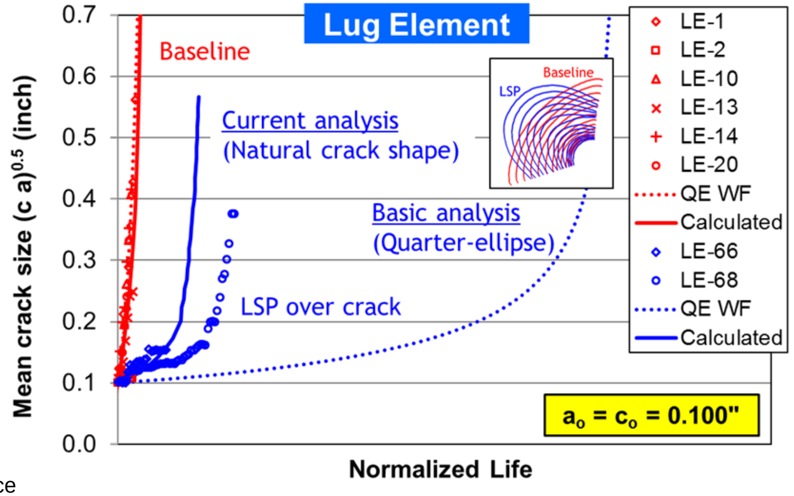
Best Practices Document

- Cha ter Case Studies
  - Laser shock peening case study
  - Cx hole case study







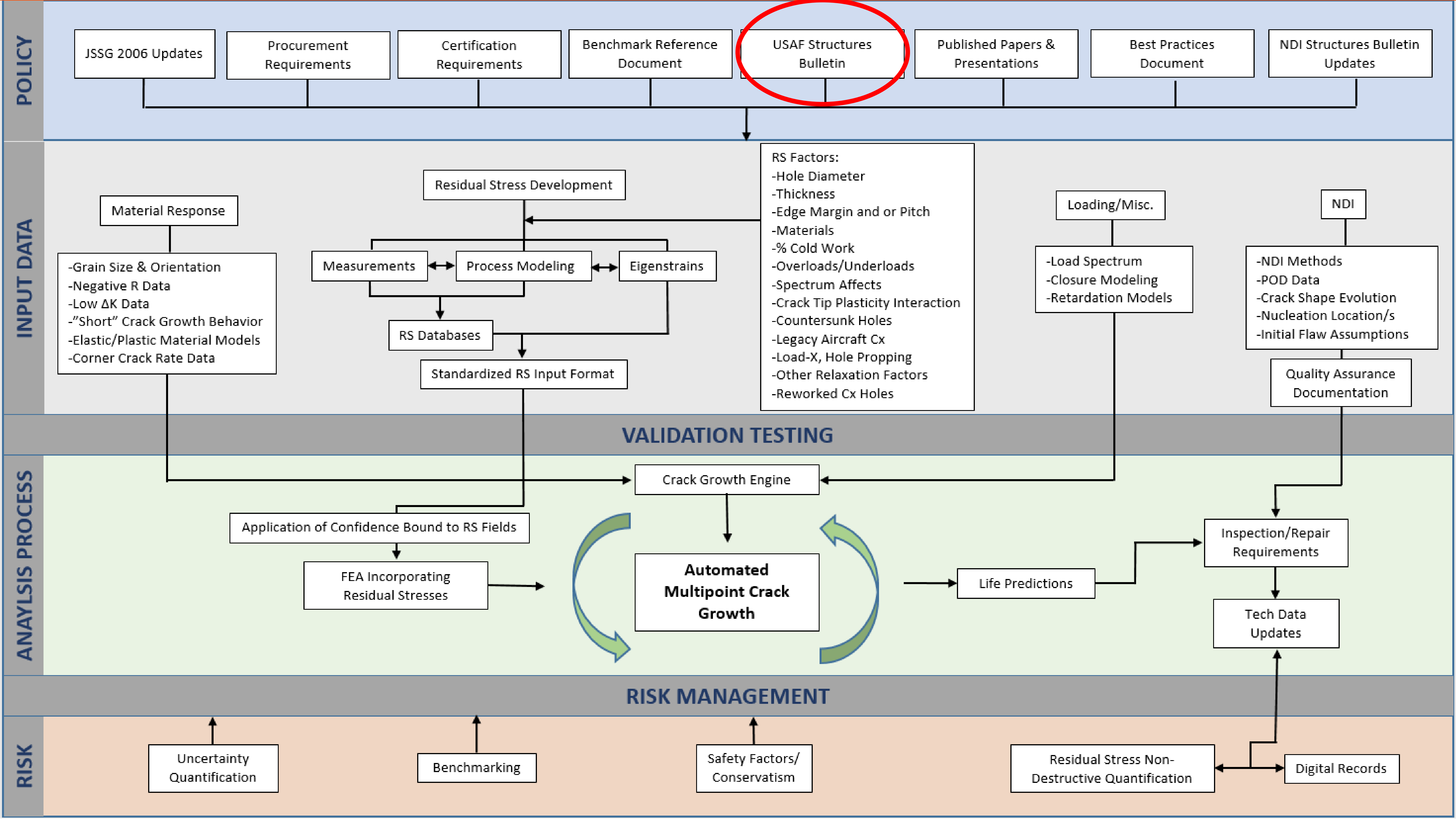


References:
Polin, L., Bunch, J., Caruso, P., McClure, J. (2011), F-22 Program Full Scale Component Tests to Validate the Effects of Laser Shock Peening, 2011 ASIP Conference
Hill, M., DeWald, A., VanDalen, J., Bunch, J., Flanagan, S., Langer, K. (2012), Design and analysis of engineered residual stress surface treatments for enhancement of aircraft structure, 2012 ASIP Conference

Best Practices Document

- **Current Status**
  - Publicly released version available (July 2018) ✓
- **Moving orward**
  - 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

E NEED O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Dra t Structures Bulletin

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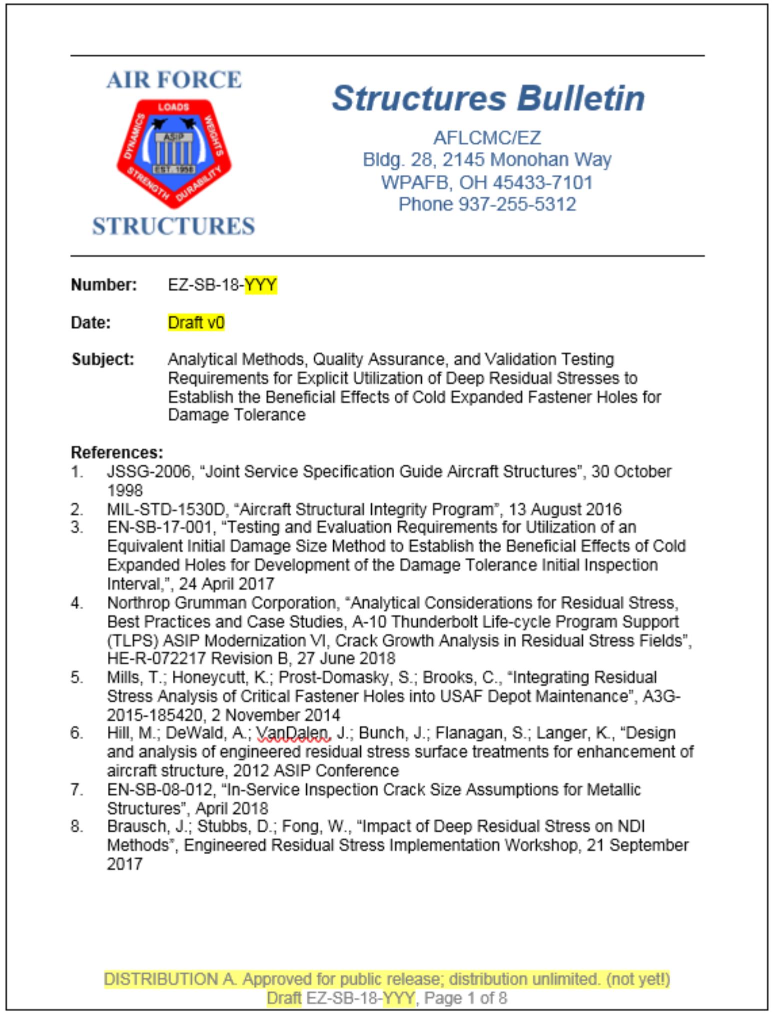
- Initial Dra t Develo ed
  - Jan-Aug 2018
- Current Status
  - USAF internal review



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Structures Bulletin

AFLCMC/EZ
Bldg. 28, 2145 Monohan Way
WPAFB, OH 45433-7101
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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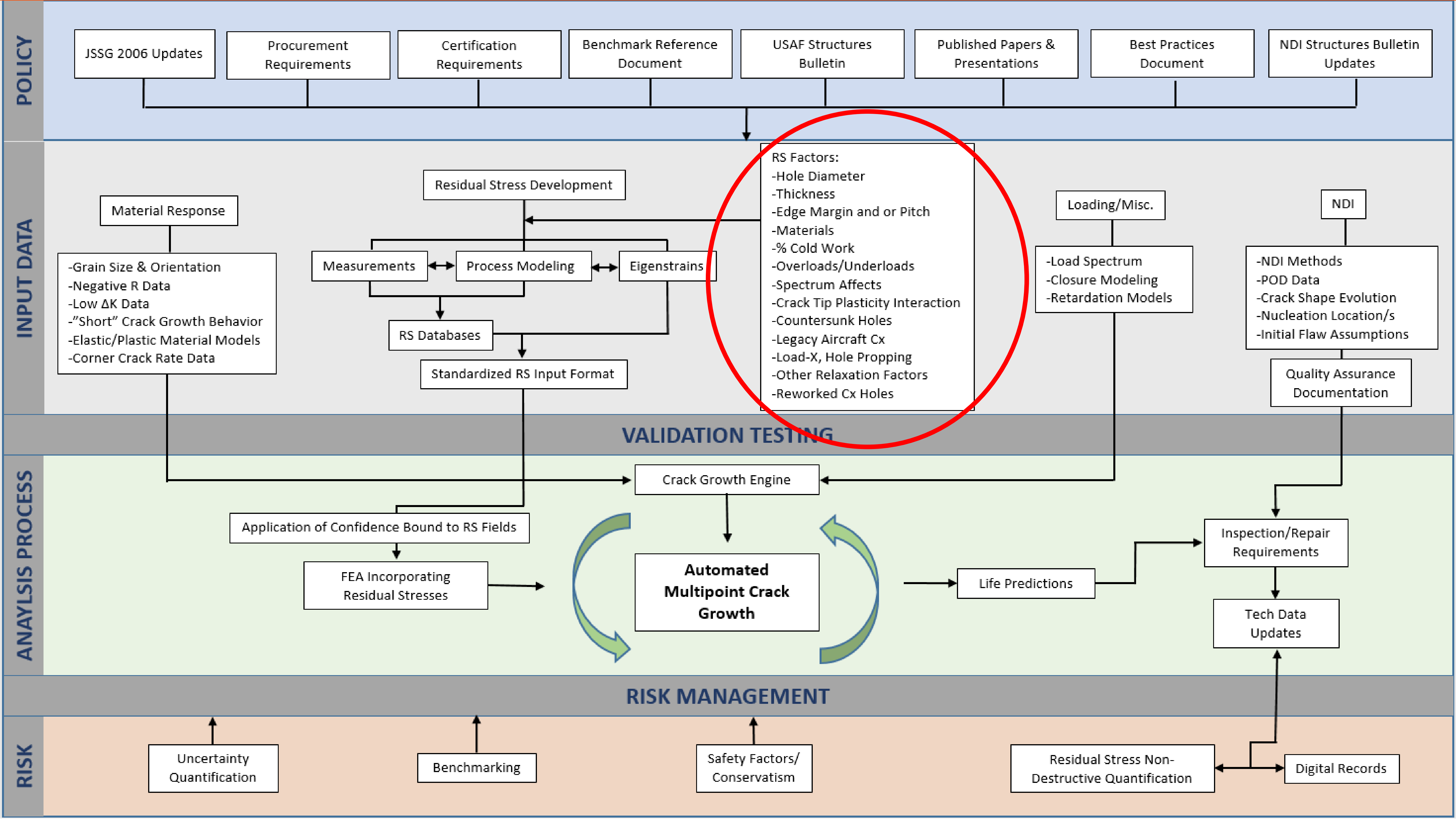

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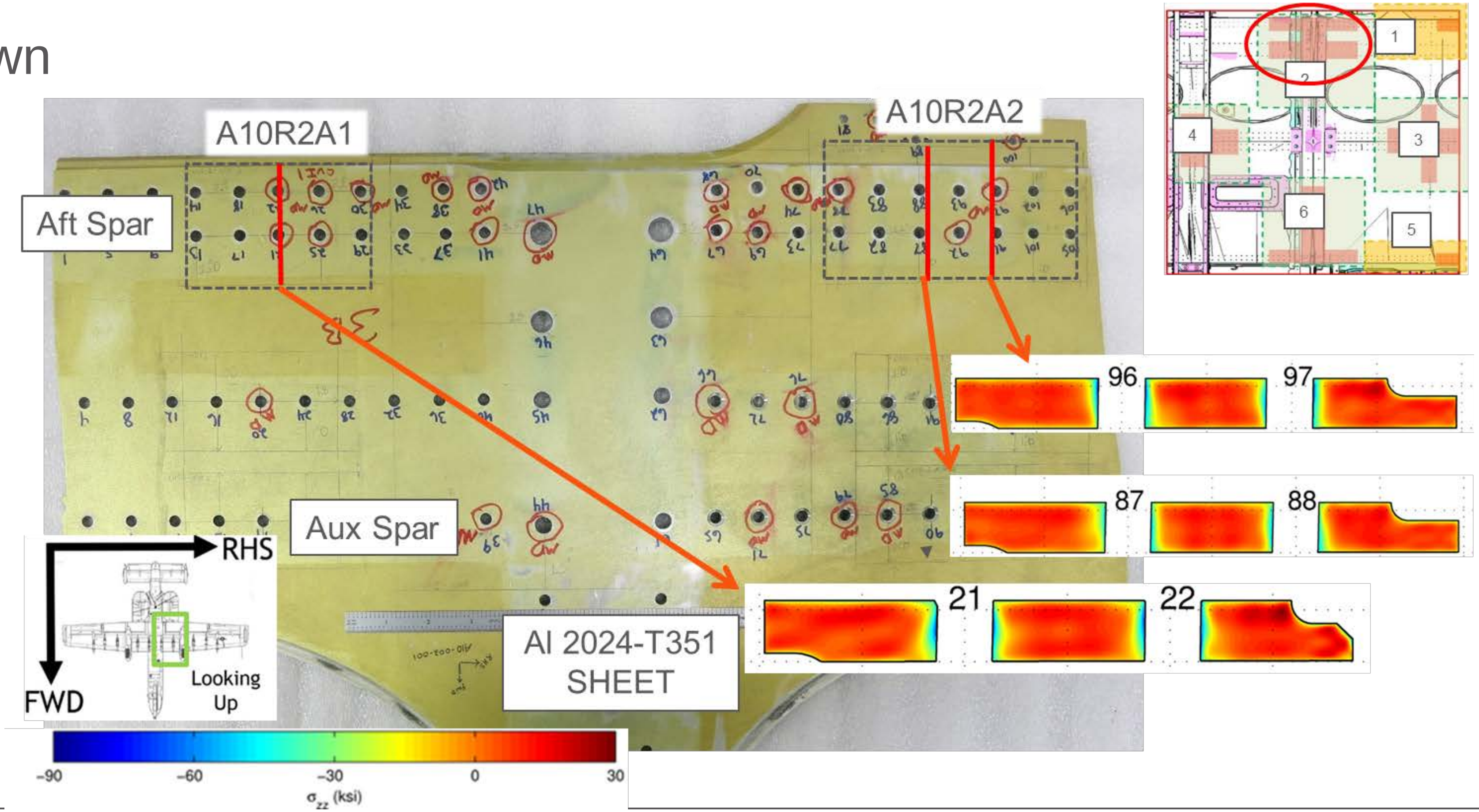
Engineering Im lementation o Residual Stress

- **Post-Service vs. New Manu acture Cou on Residual Stresses**
  - Load history / environment effects
  - Initial stress shakedown

How Should We Account for in Analyses???



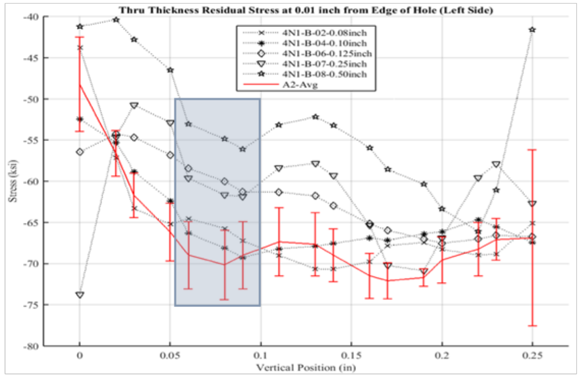
Engineering Im lementation o Residual Stress

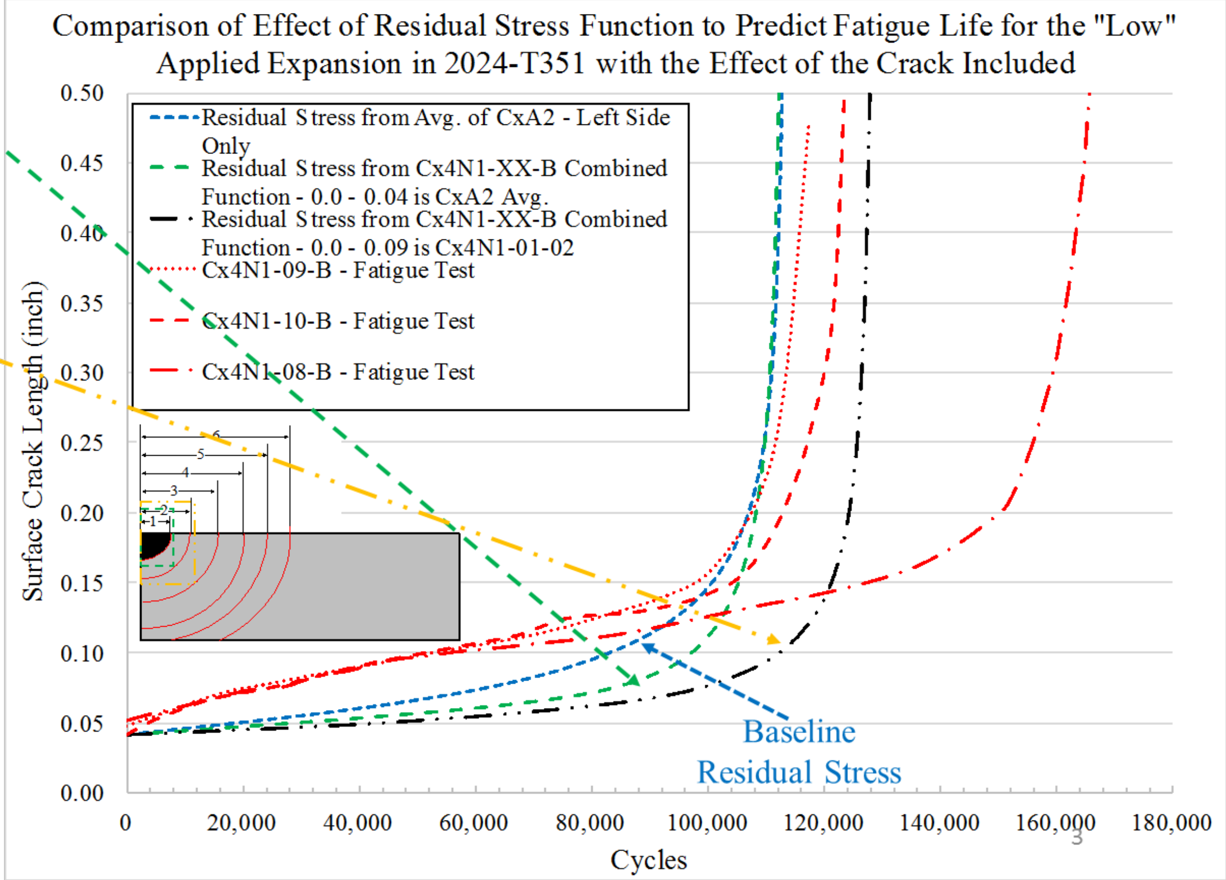
❑ Crack Ti Plasticity Interaction -T

➢ 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
1 2	Residual Stress for -01-02 (0.08inch) Crack Length	0.00 - 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





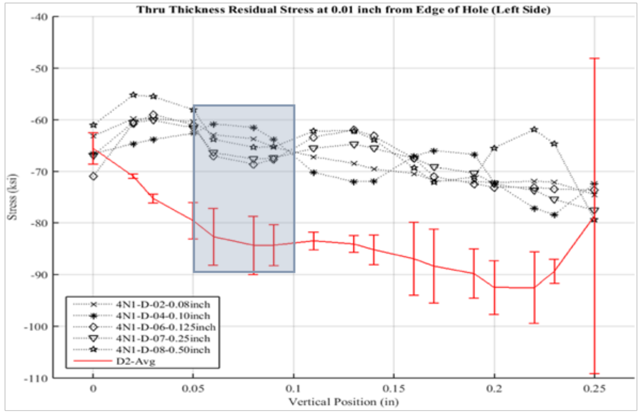
Engineering Im lementation o Residual Stress

❑ Crack Ti Plasticity Interaction -T

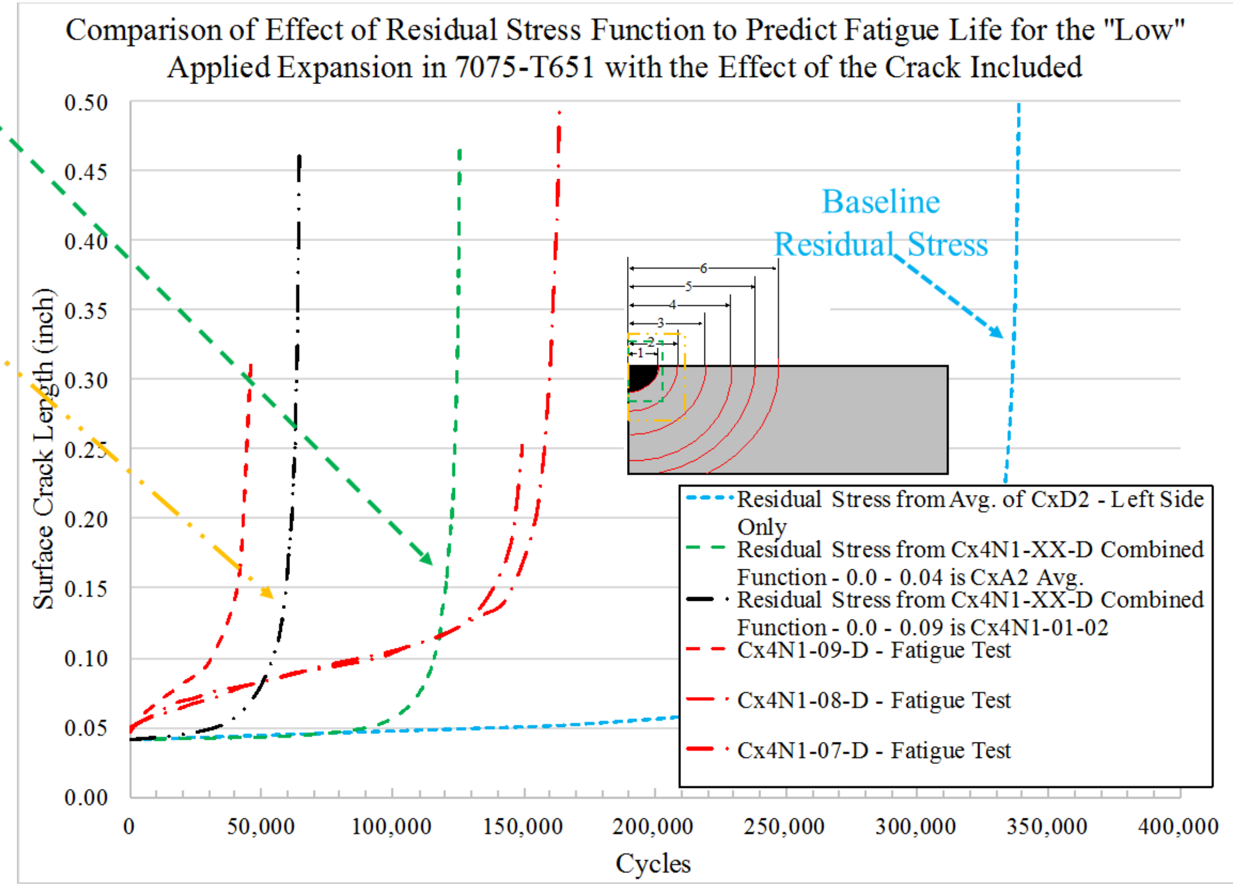
➢ Life predictions for average R.S. field – showing shift to the left, closer to average fatigue test results

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
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
1 2	Residual Stress for -01-02 (0.08inch) Crack Length	0.00 - 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



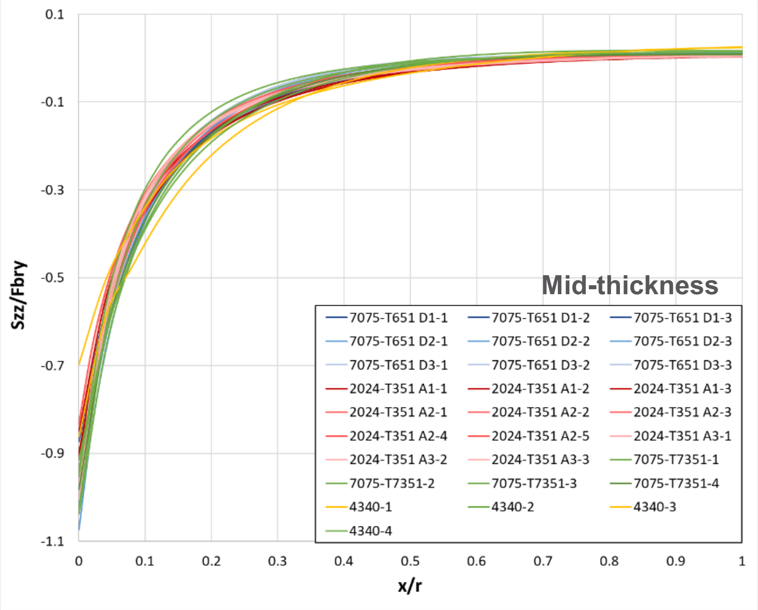
©carlson

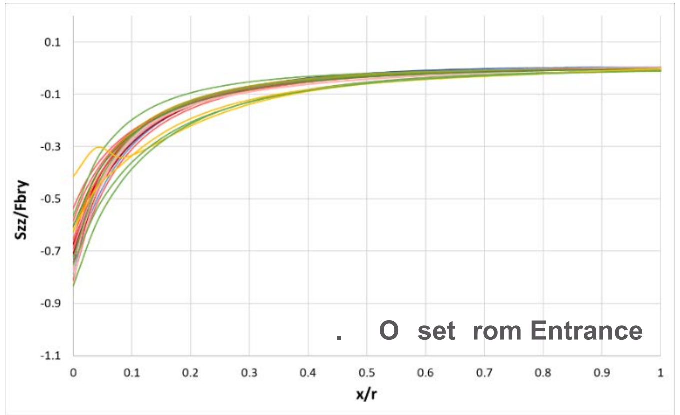


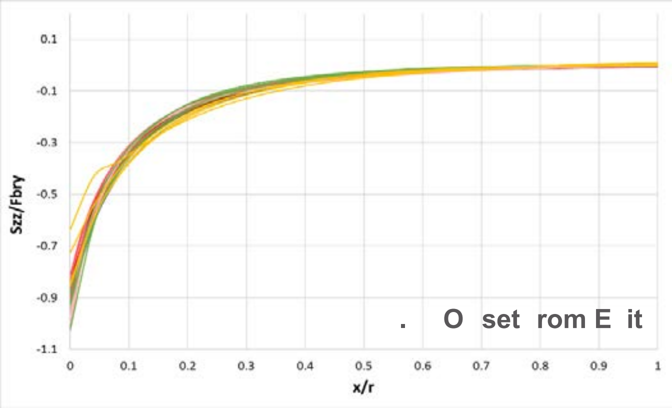
Engineering Im lementation o Residual Stress

❑ Non-Dimensional Residual Stress - The Hodge Podge

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







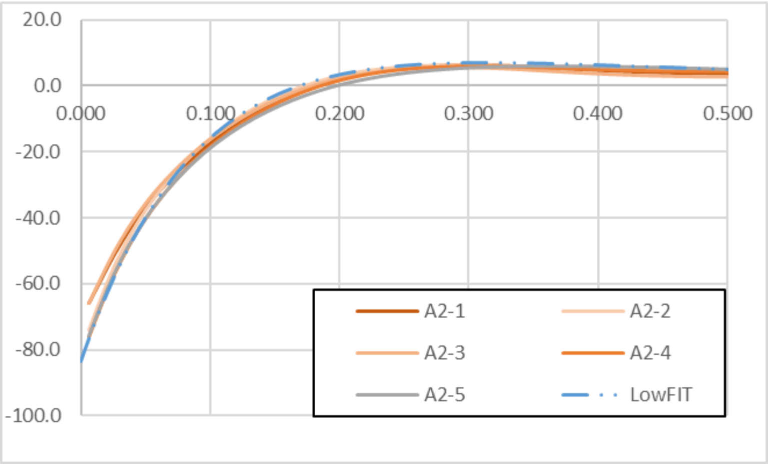
Engineering Im lementation o Residual Stress

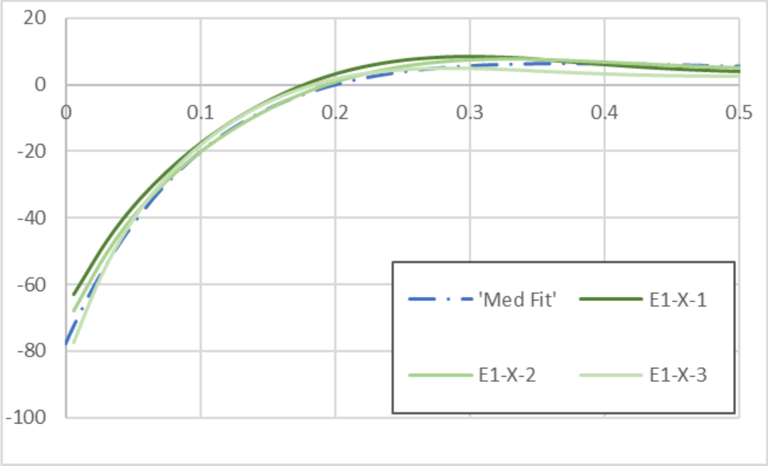
❑ Non-Dimensional Residual Stress

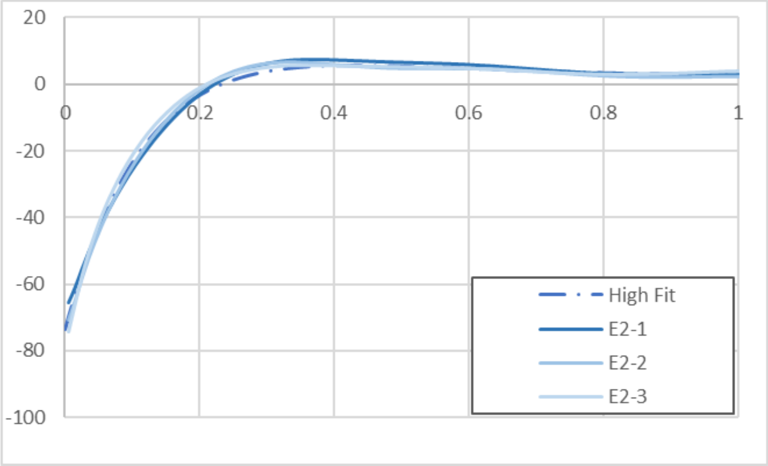
- ➢ Applied Expansion

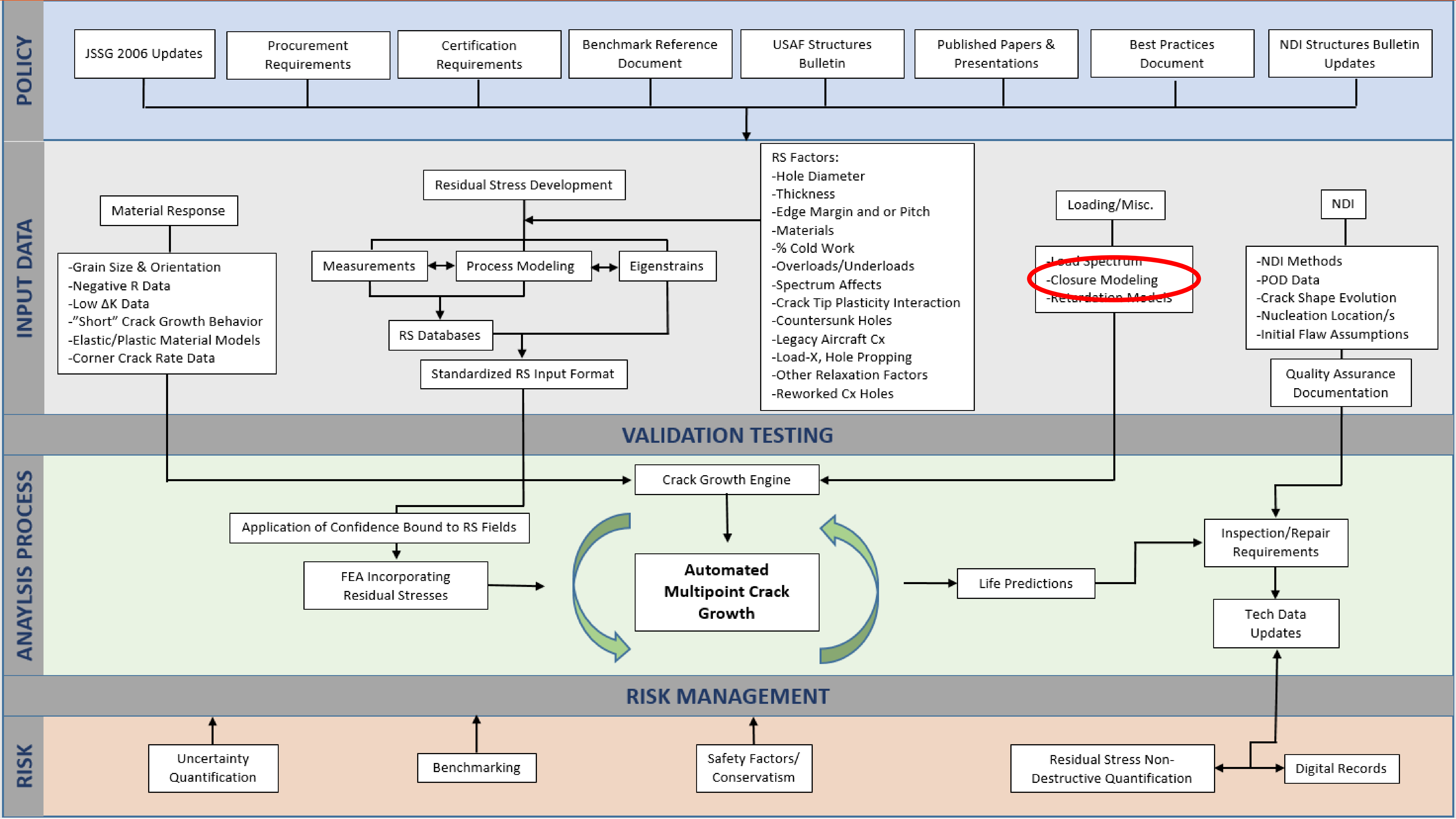
$$SzzMidthickness = e^{(\omega)x}[SzzMax + ((Vo) + (\omega)SzzMax)x] + SzzMin$$

A lied E ansion	ω	o	S Ma	S 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








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:
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-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
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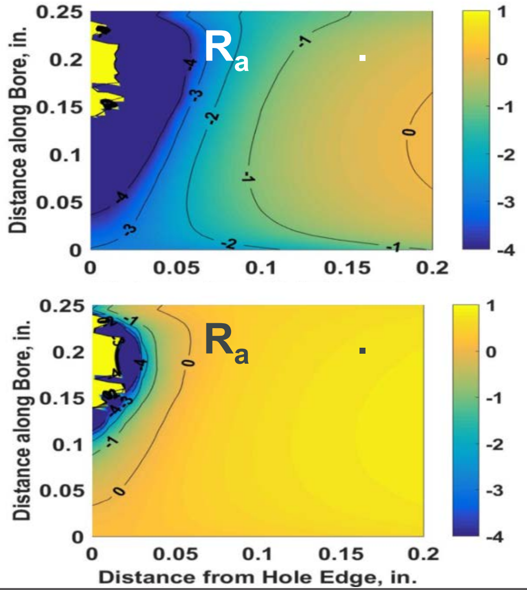
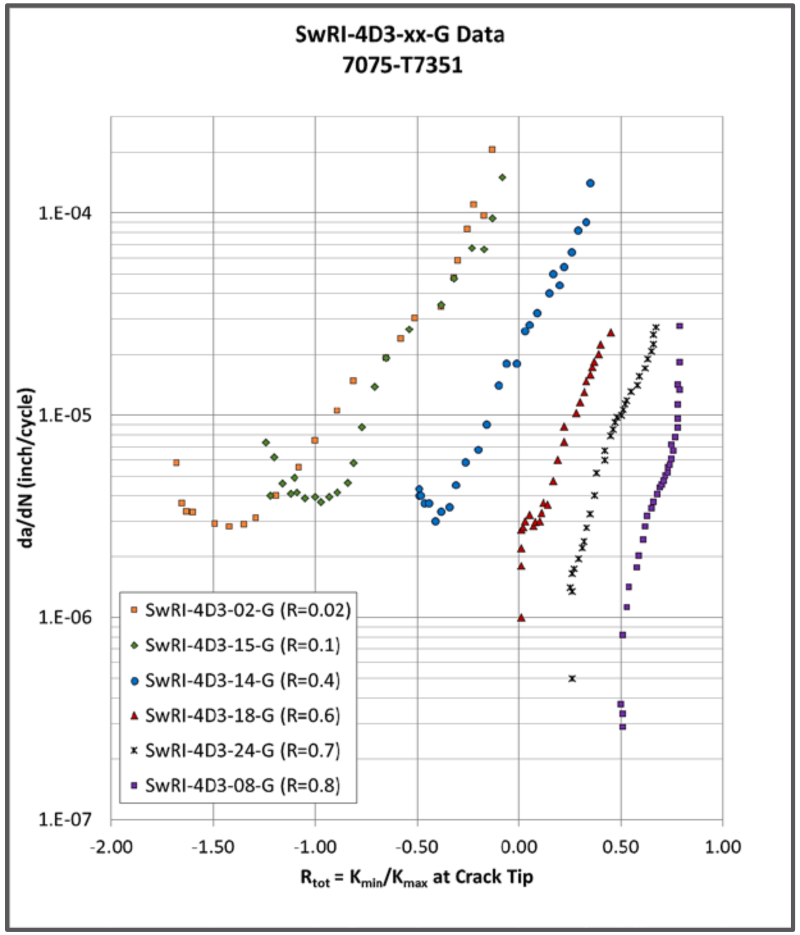
RISK MANAGEMENT
RISK
Uncertainty Quantification
Benchmarking
Safety Factors/ Conservatism
Residual Stress Non-Destructive Quantification
Digital Records

Crack Closure E ects

- E tensive evaluation o crack growth tests at C holes and various a lied R APES ESRD
- ariation o e erimentally derived da/dN growth rate as a unction o R_{tot} K_{min}/K_{ma} at the crack ti determined rom simulation
  - The ‘dip’ in the da/dN curve occurs for cracks < 0.1 inch at negative R_{tot}
- or R_{tot} , the di is not resent
  - Corresponding to R_{app} = 0.6, 0.7, 0.8





AFRL Phase III SBIR: Deep Residual Stress Methods

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Crack Closure E ects

- Modeling Closure

AFRL Phase III SBIR: Deep Residual Stress Methods

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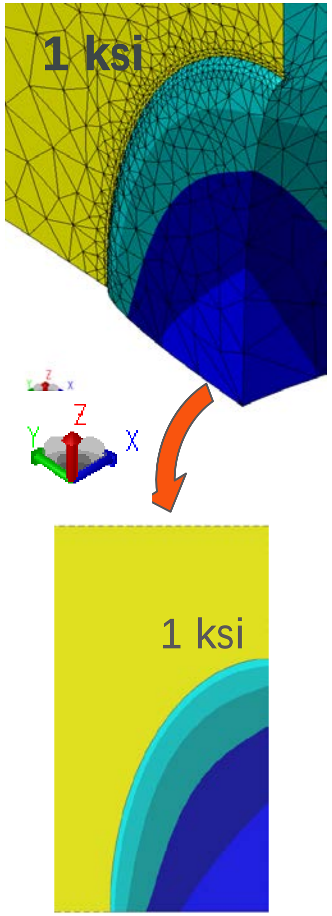
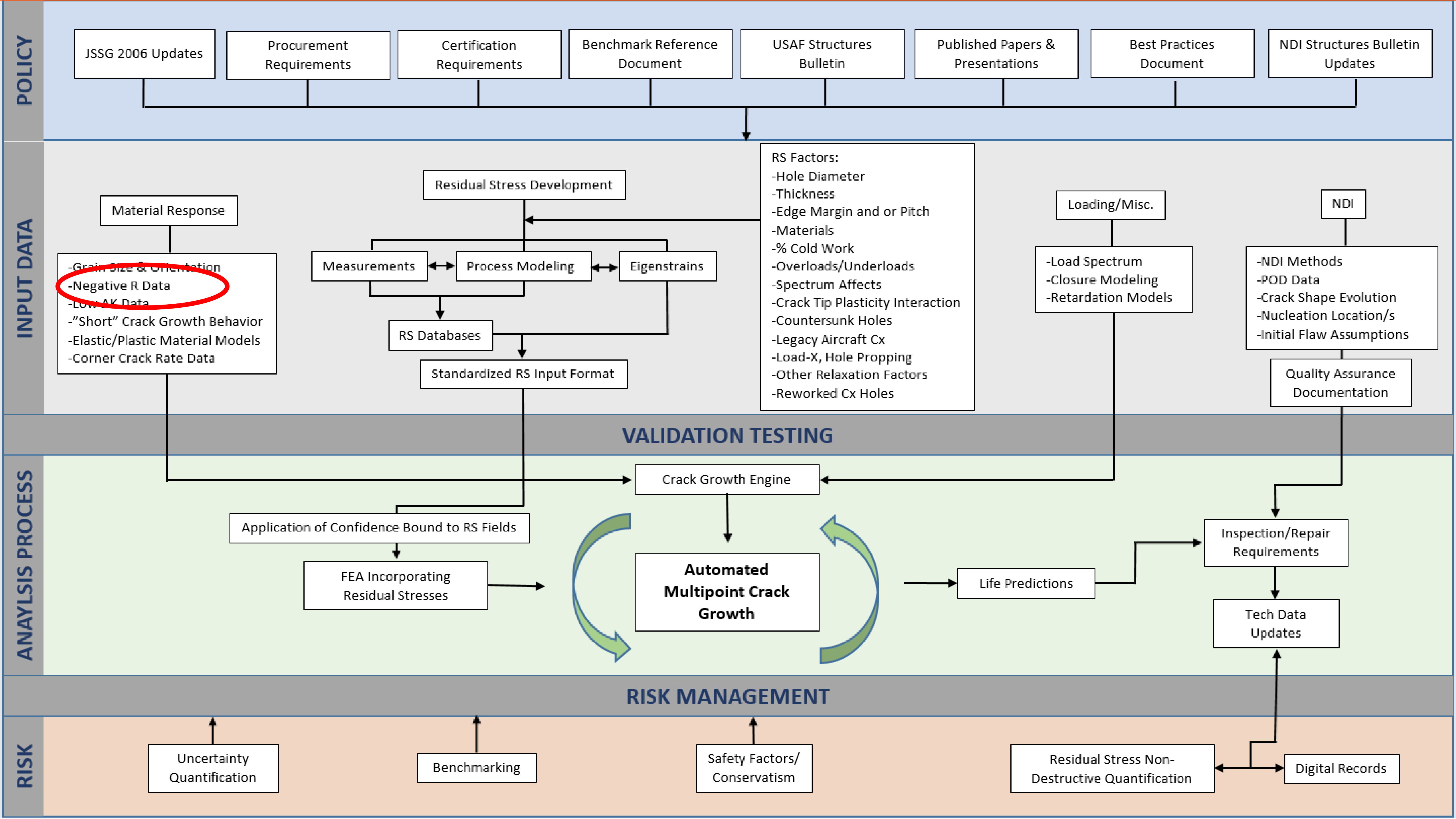


Displacement normal to the symmetry plane
Positive displacement → Crack opening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Benchmarking
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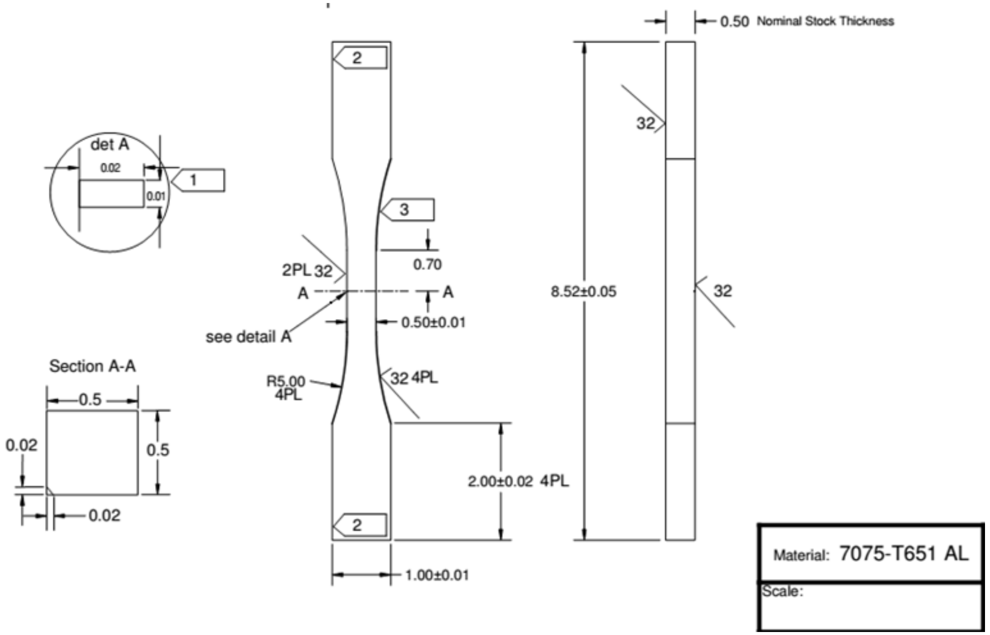
Residual Stress Non-Destructive Quantification
Digital Records

Negative R Testing

- Much o the crack growth rom C   holes can occur in regions o negative R_{tot}
- GOAL: conduct limited negative-R crack growth testing to com are to A RL historical data
  - center cracked M(T) panels (as AFRL tested)
  - part-through crack "dog-bones"
- s ecimens o   -T
  - 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
- Re eat   -s ecimen matri   or   -T



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

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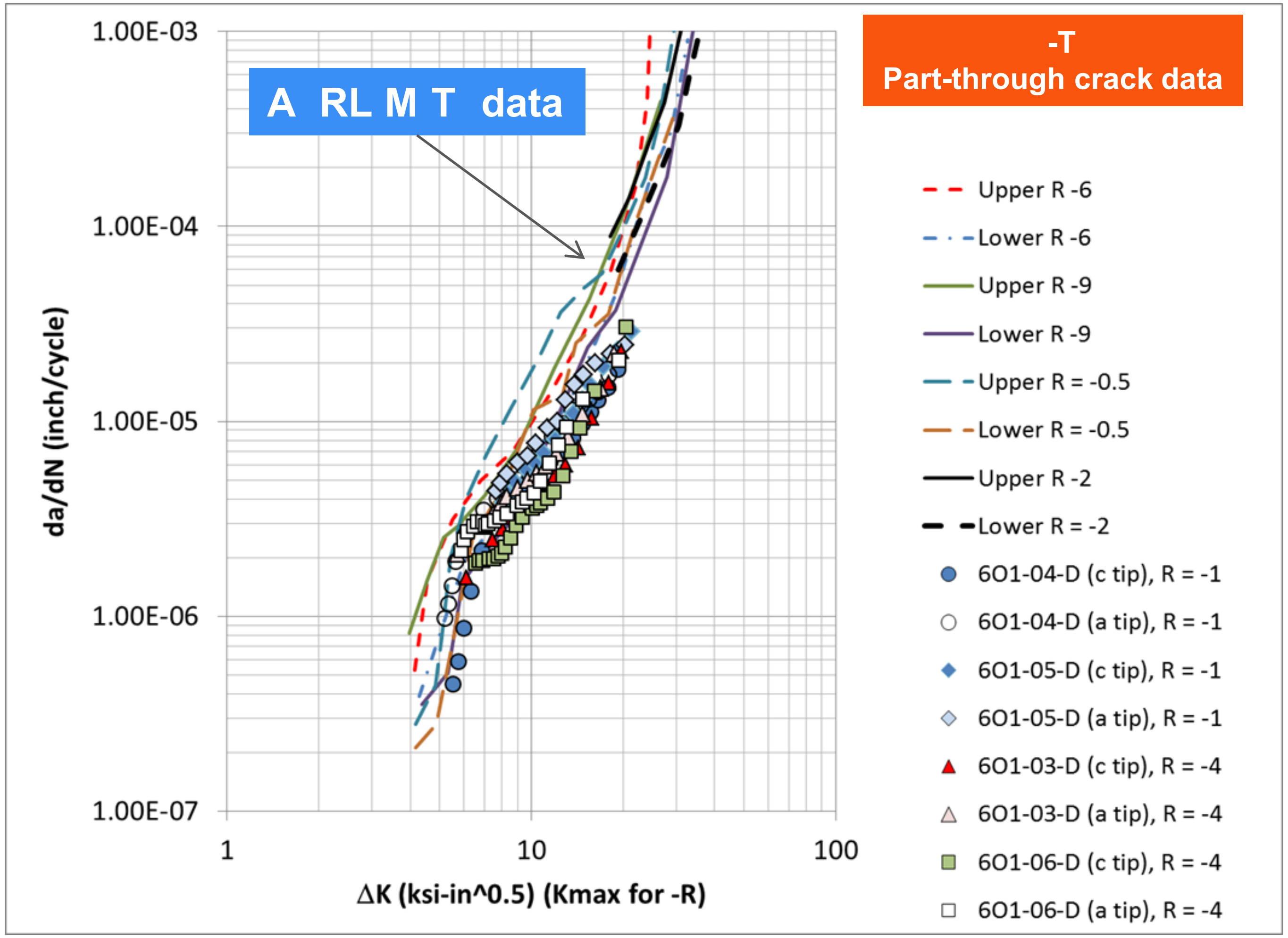
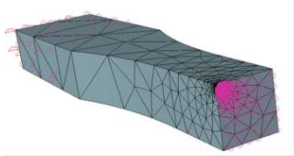
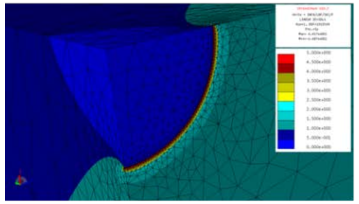
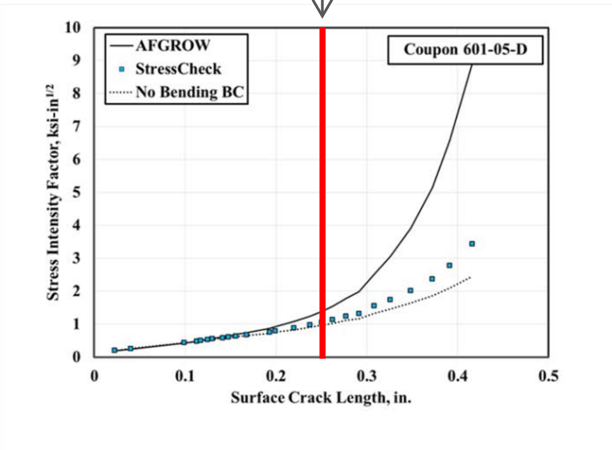
Negative R Testing



Newman-Ra u Limits
c/ .







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

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Negative R Testing coming

- S ecimen Details: Center hole, corner crack, R - , σ_{Ma} . 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
- test s ecimens have een machined out o s ecimen remnants rom the same material lot as the tests used in the round ro in
- Augment growing Negative-R data sets or art-through cracks
  - SwRI: R = -0.3 (presented data at ERSI last year)
  - APES: R = -1, R = -4
- ariety o s ecimen geometries to com are with M T long crack data

Conclusions/Summary

- **Signi icant Colla oration within Analysis Methods Su committee**
  - Thanks to those individuals that have provided inputs
- **irst C Hole Residual Stress Round Ro in Success ul**
  - (8) submissions – thank you
- **Second C Hole Residual Stress Round Ro in in Discussions**
- **Initial Best Practices Document Released**
  - Need inputs from community
- **Signi icant rogress made on understanding crack closure im lications to CG modeling in residual stress ields**
- **Negative-R crack growth data continues to e develo ed or art-through crack geometries**

uestions

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Fatigue Life Modeling in Residual Stress Fields

Negative-R Crack Growth Testing

ERSI Workshop
Layton, UT

19 June 2018

Thomas Mills, Ph.D. • Scott Prost-Domasky, D.Sc., P.E.
Kyle Honeycutt • Craig Brooks

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

Sabreliner: prime contractor

SwRI: program manager

- Lucky Smith

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Background

- Much of the crack growth from CX holes can occur in regions of negative R_{tot}.
- Do we have well-characterized negative R test data, and does it have a large impact?
- Reference AFRL negative R data from 1997**
  - These data formed basis for R-LO cut-off parameter
  - Below R-LO, which is a K value, no further shift in crack growth rate curves is modeled
- **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

** Boyd, K., Elsner, J., Jansen, D, Harter, J.: Structural Integrity Analysis and Verification for Aircraft Structures, Volume 2, Effects of Compressive Load on the Fatigue Crack Growth Rates of 7075-T651 and 2024-T3 Aluminum Alloys, WL-TR-97-3017. August 1996.

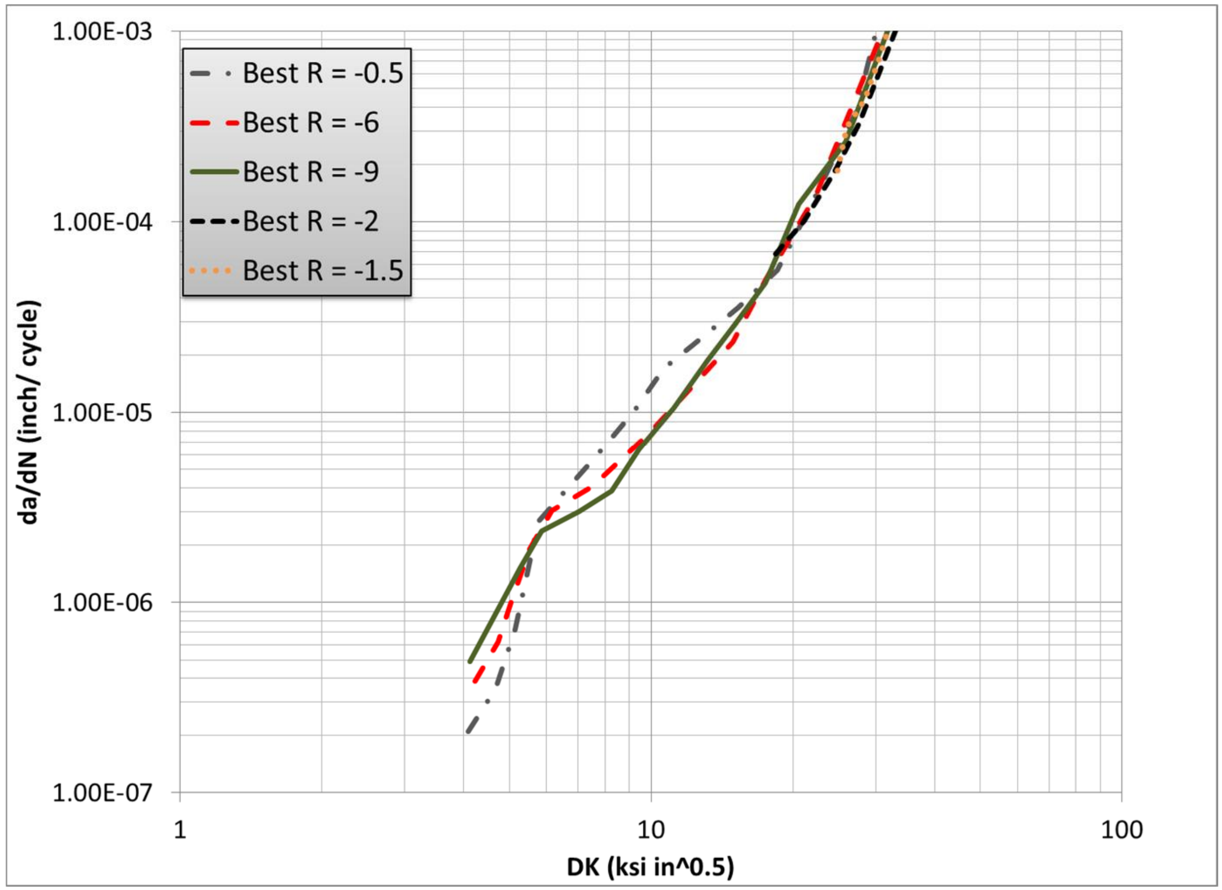
1997 AFRL Data: 7075-T651

Original test data is not available.

Had to use digitized data from pdf report.

Only R = -0.5 data seems to be unique, and only up to K of about 15

Rest of the data seems to support no further shifts in stress ratio curves at lower R



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1997 AFRL Data: 2024-T351

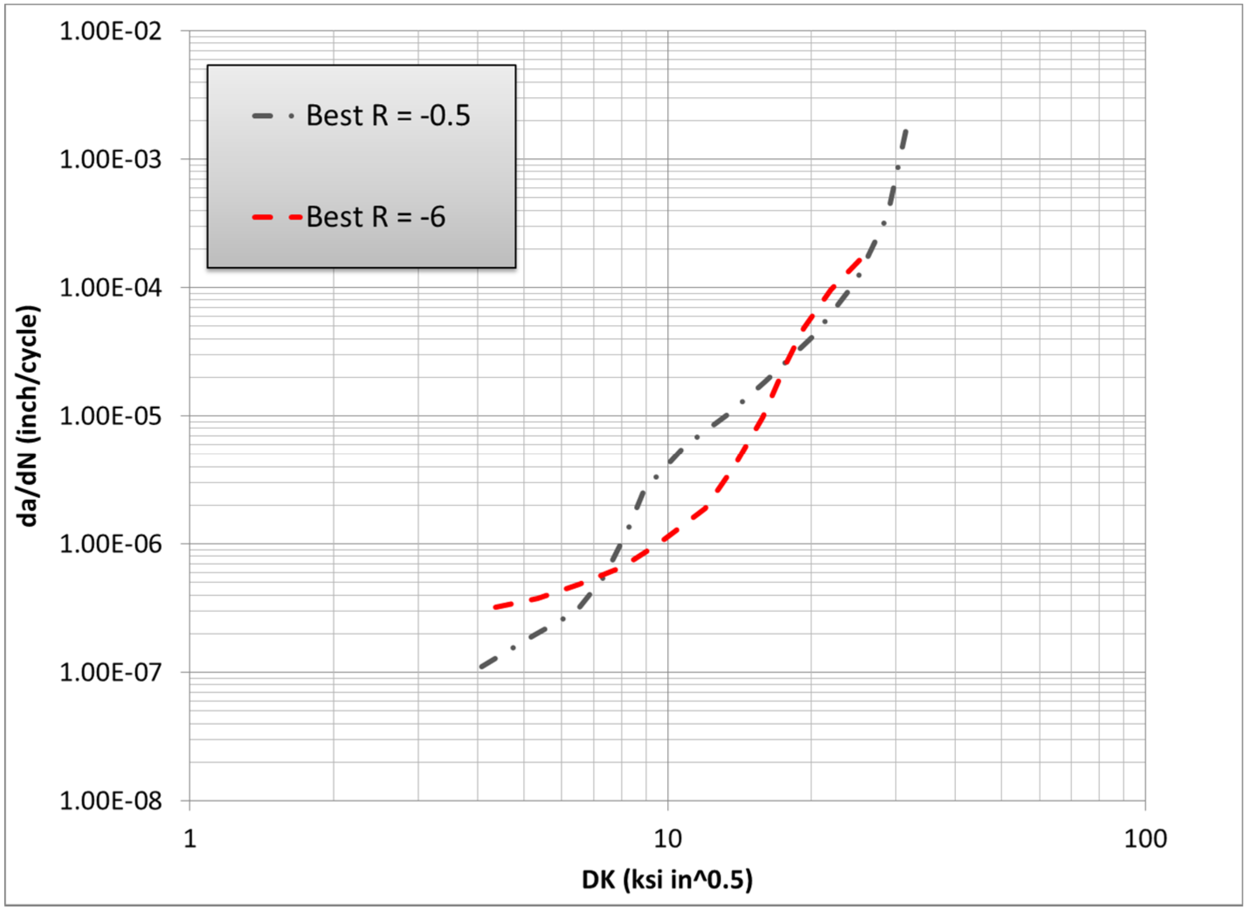
Original test data is not available.

Had to use digitized data from pdf report.

Only 2 stress ratios tested.

Appeared to have problems with plasticity

R = -6 curve suspect



Test Matrix

- 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

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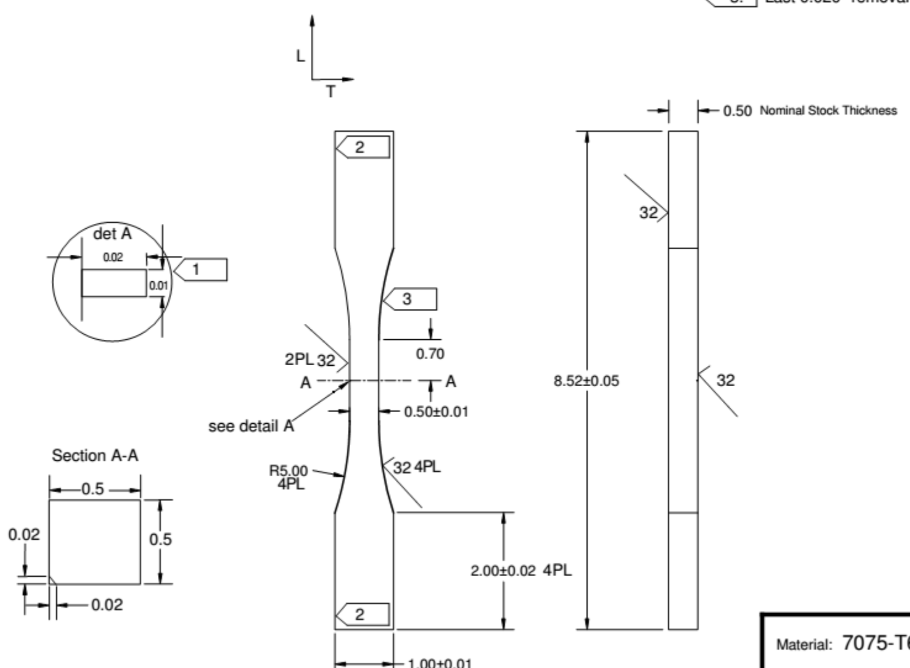
Dogbone Crack Growth Specimen

All dimensions in inches

1. Use fine saw or EDM to place notch on one corner of specimen (also see Section A-A)
2. Specimen ID: 6O1-xx-D (where xx = 01 to 06)
3. Last 0.020" removal on edges must be done in 0.005" passes.



No buckling guides required

Precrack / test loads must be balanced to avoid compressive yield for R = -4 (especially in 2024-T351)

Specimen design avoids plastic collapse in net section throughout range of reasonably collectable data

Material: 7075-T651 AL	QTY: 6	Condition:	Finish: 64 RMS unless noted
Scale:	Task: 2.10	APES, INC.	

SwRI PO-13 (A-10)

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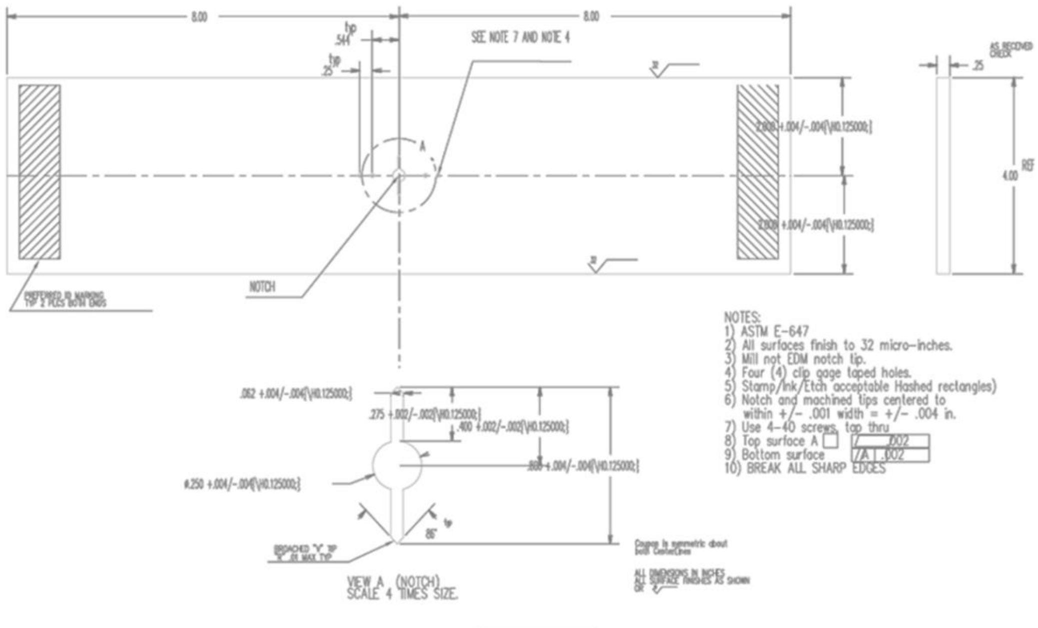
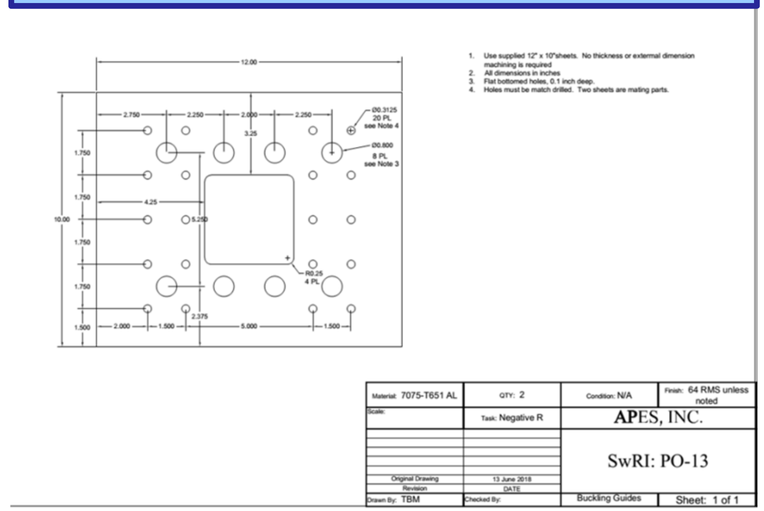
M(T) Crack Growth Specimen

Made from 0.313-inch nominal plate.



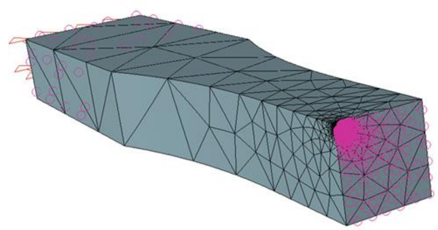
Buckling guides required.
½ inch aluminum plate
Nylon spacers used against specimen
Only 8 contact points (4 front / 4 back)

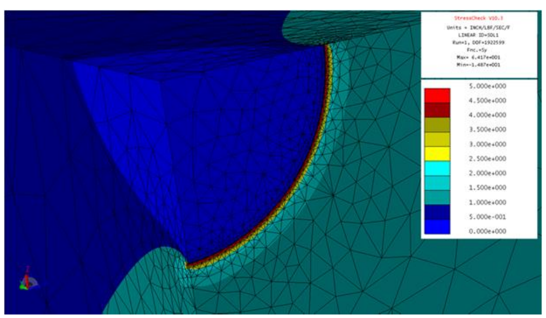


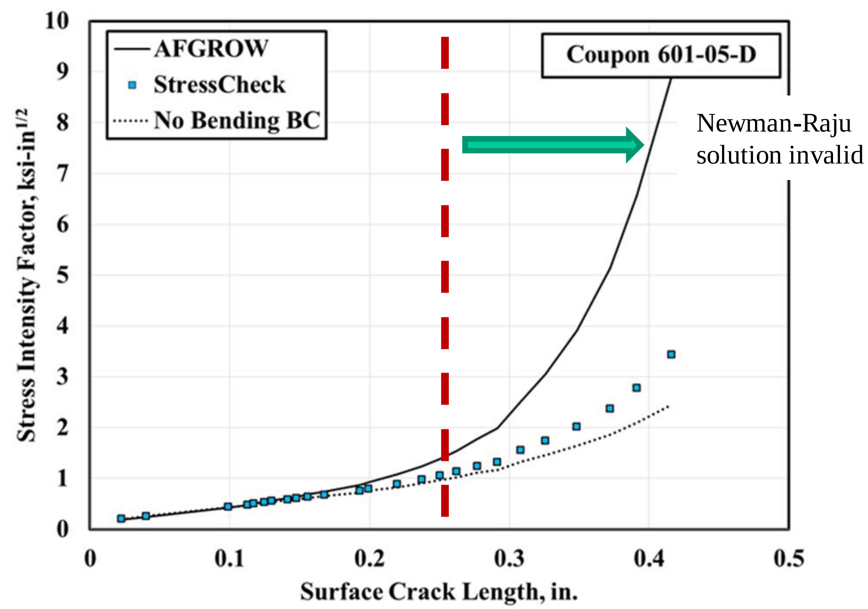
Stress Intensity Calculations

Corner crack tests go to crack sizes beyond Newman-Raju solutions in AFGROW

- Used StressCheck to compute K
- Boundary conditions: modeled full wedge grip constraint:







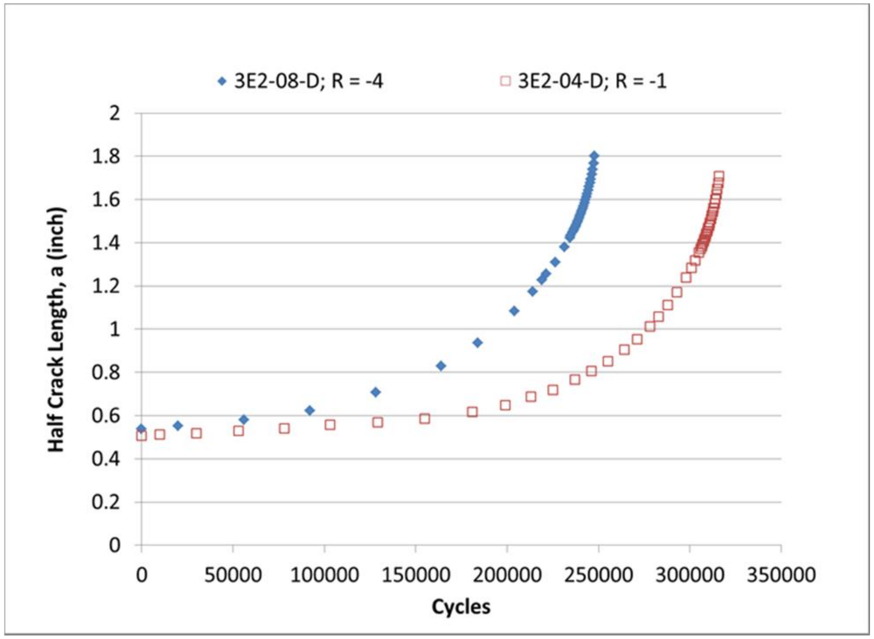
Middle-Tension Panels

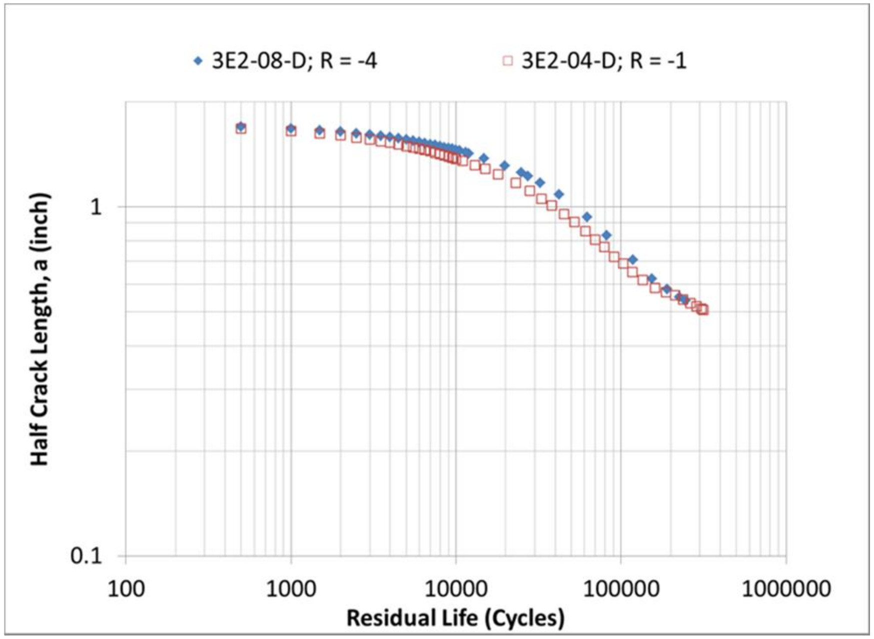
Crack Growth Data

- Crack Length vs. Cycles
- Residual Life
- Crack Growth Rate vs. K

7075-T651 M(T)

Crack Growth and Residual Life





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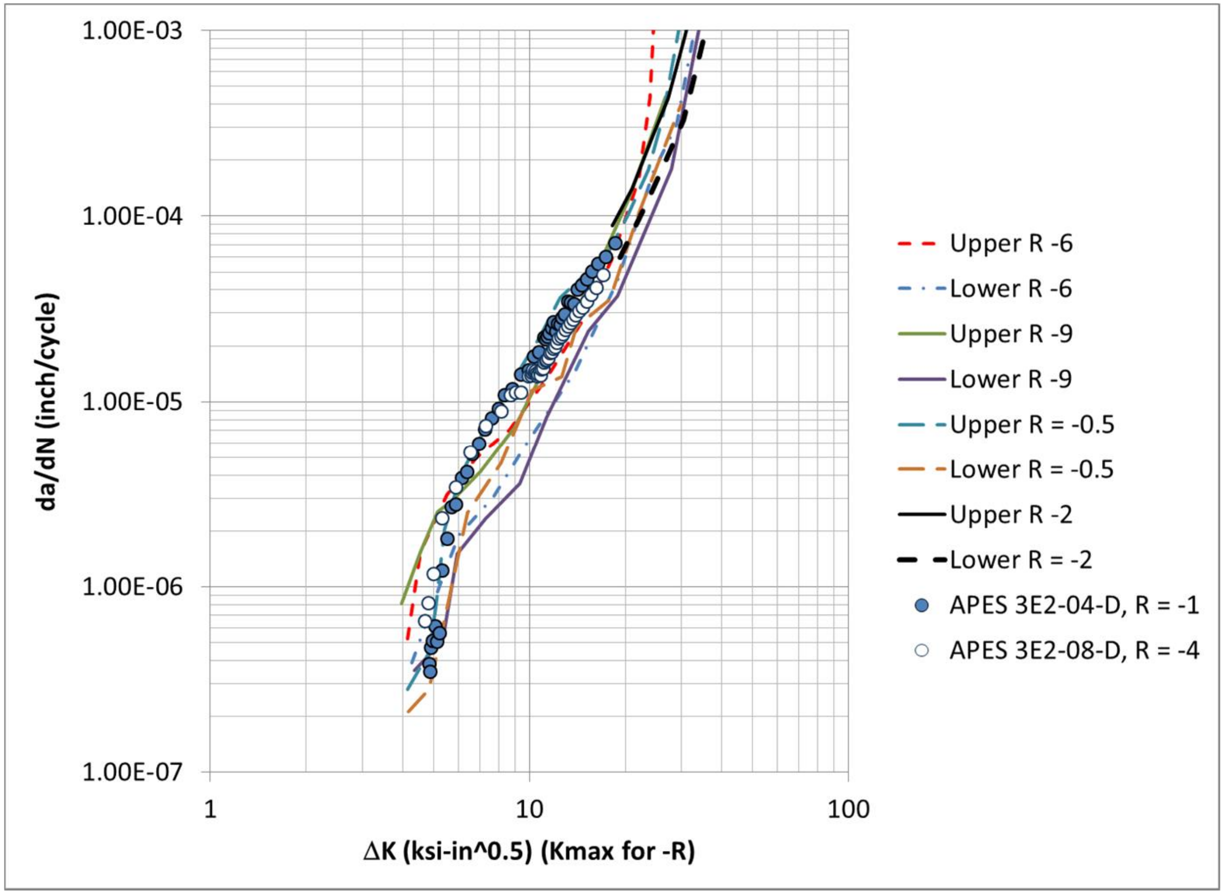
7075-T651 M(T)
Crack Growth Rate



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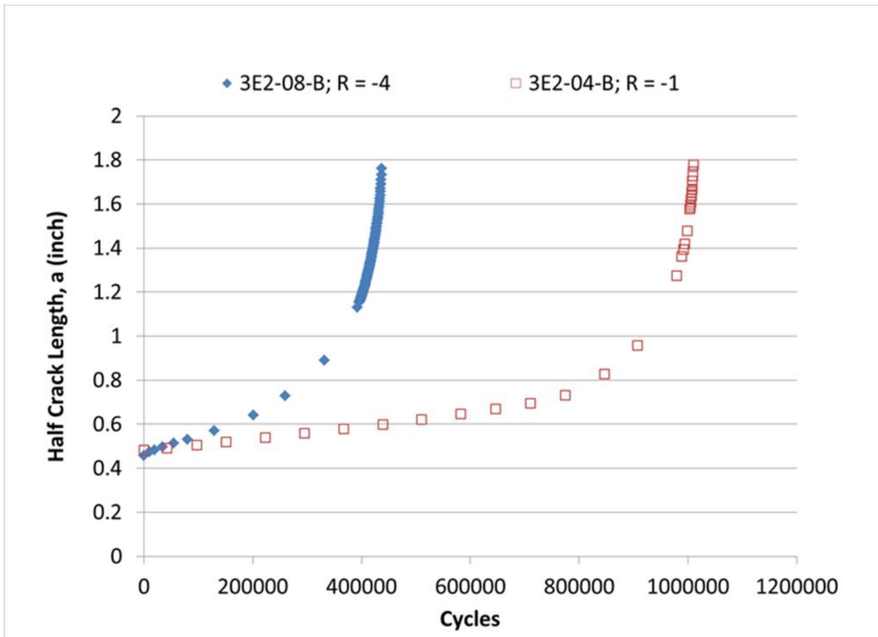
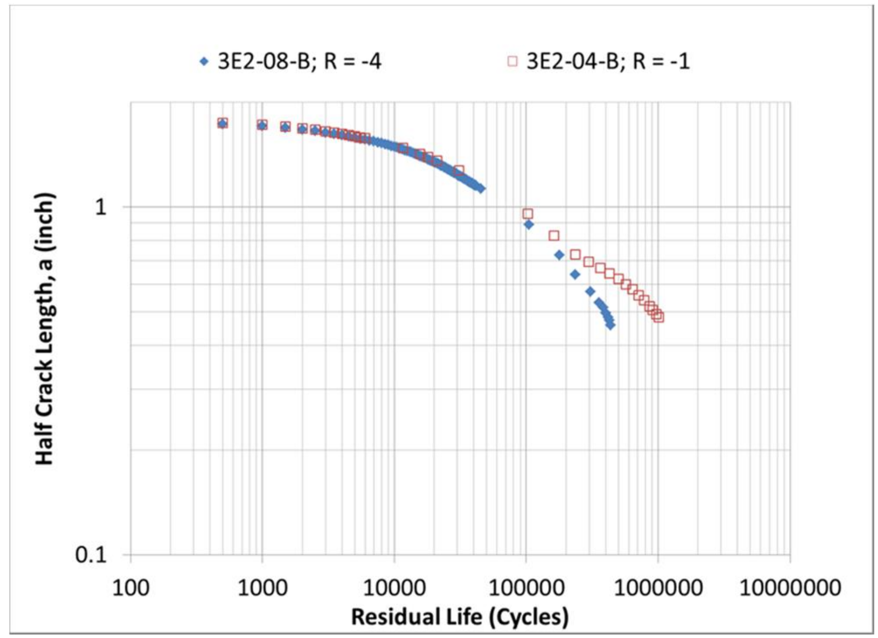
2024-T351 M(T)
Crack Growth and Residual Life





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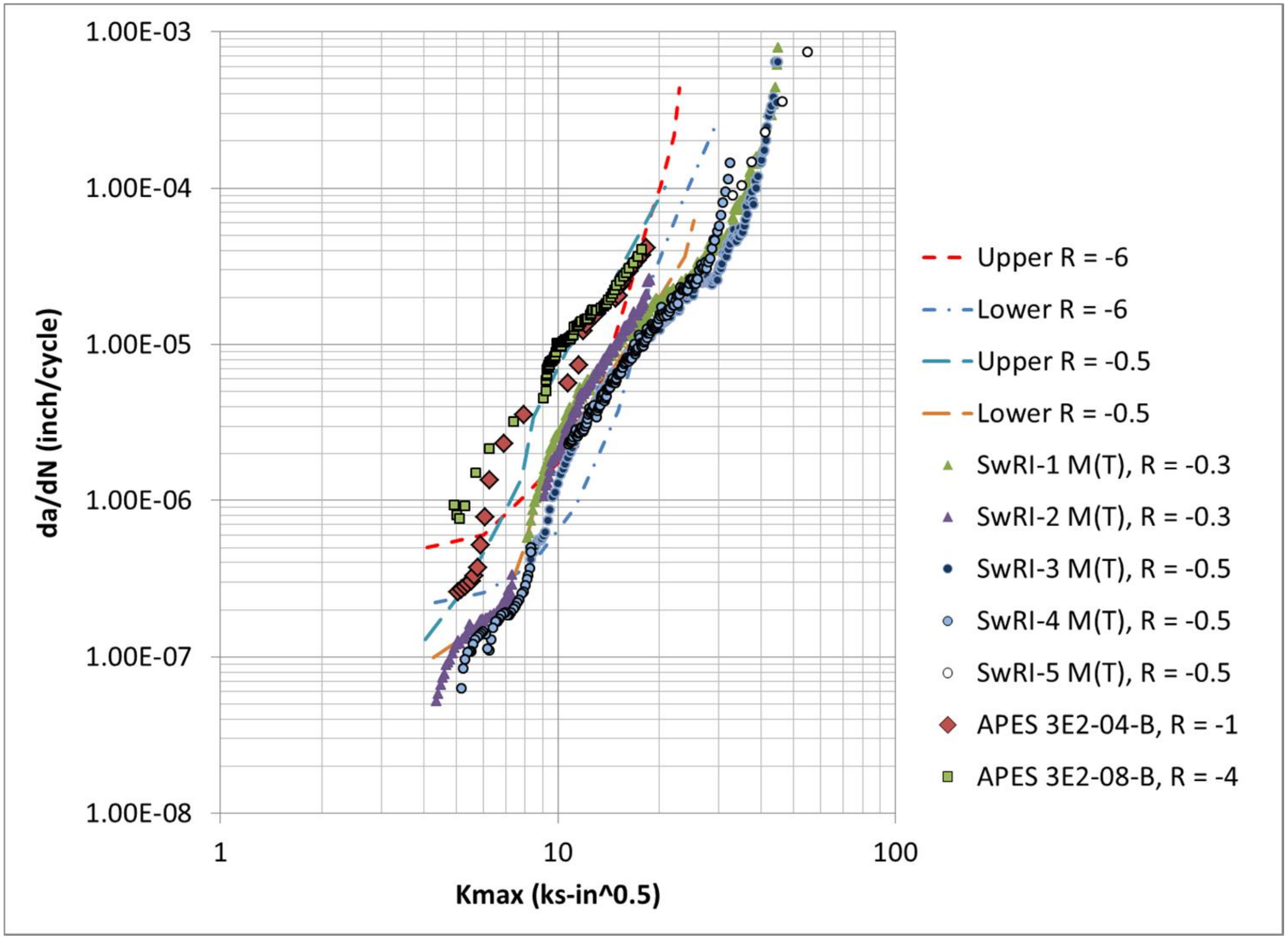
2024-T351 M(T)
Crack Growth Rate



Corner Crack (CC) Dogbone

Crack Growth Data

- Crack Length vs. Cycles
- Residual Life
- Crack Growth Rate vs. K

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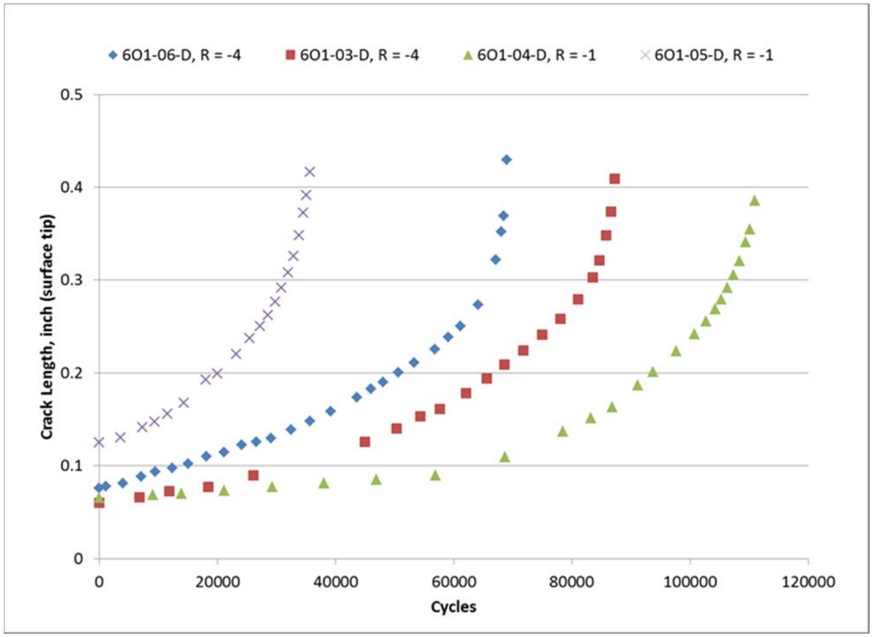
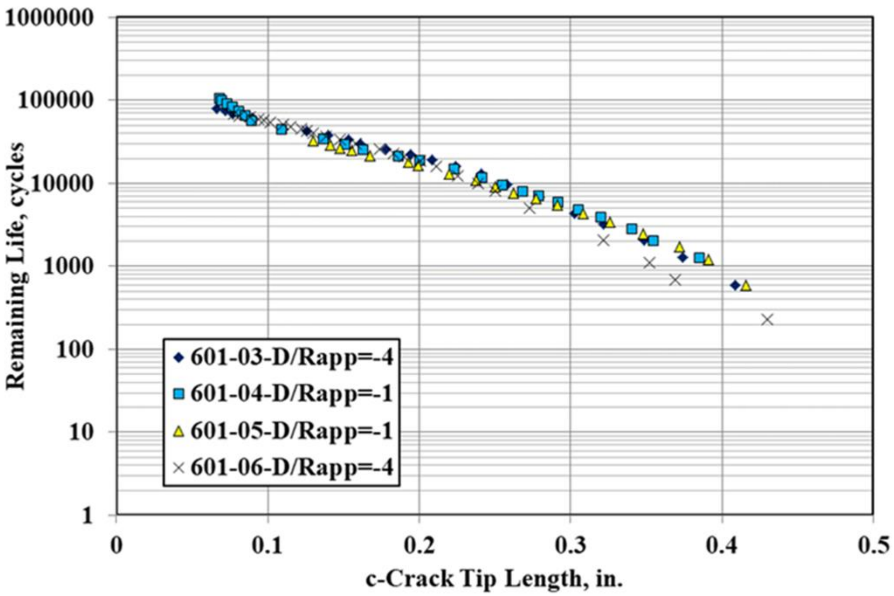
7075-T651 CC

Crack Growth and Residual Life





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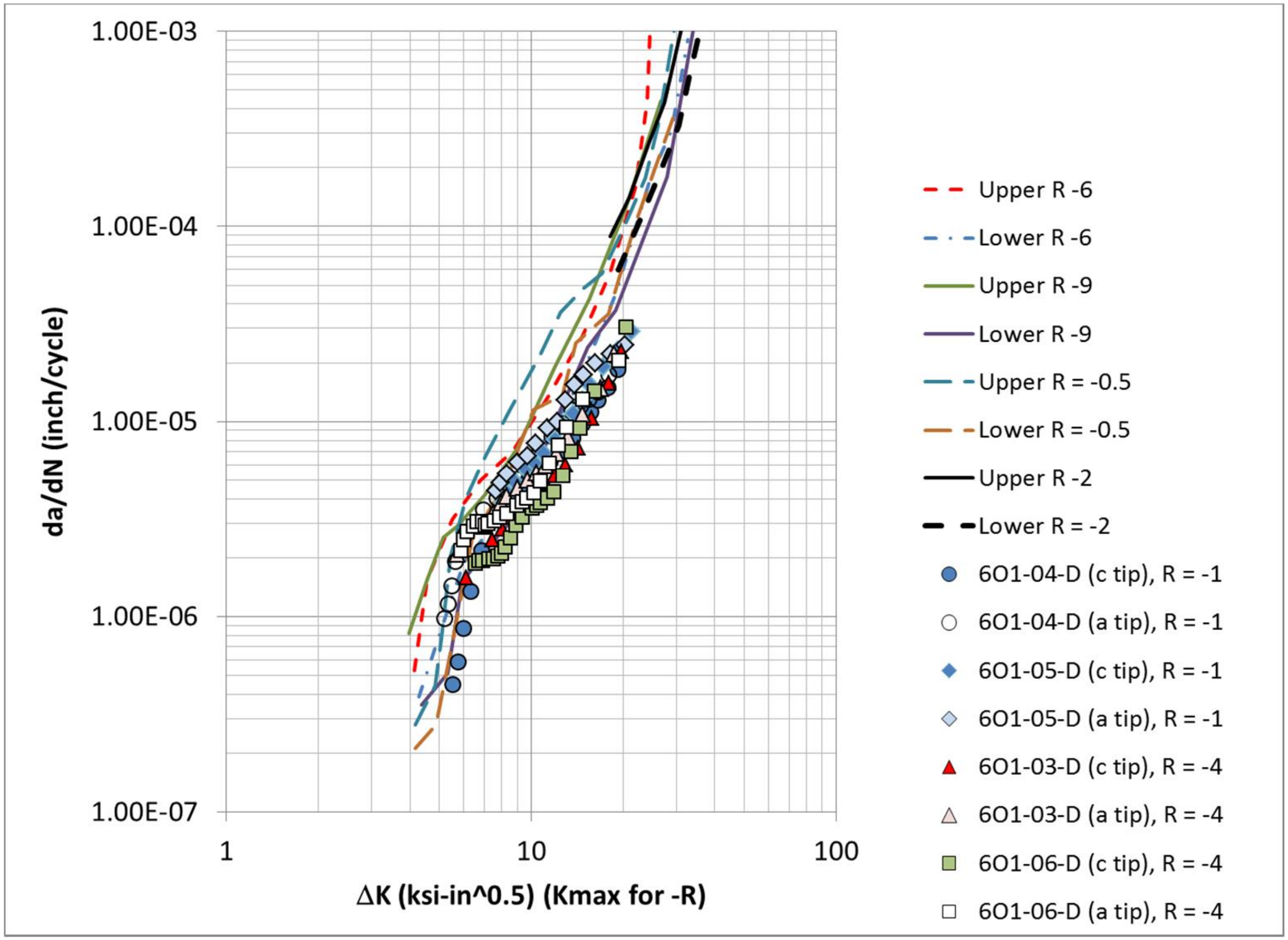
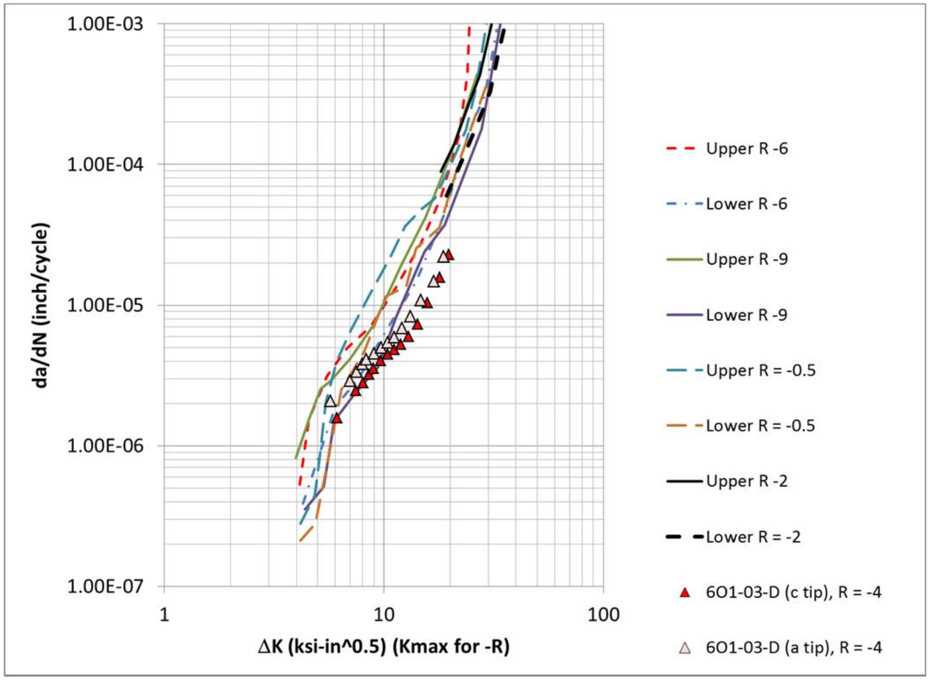
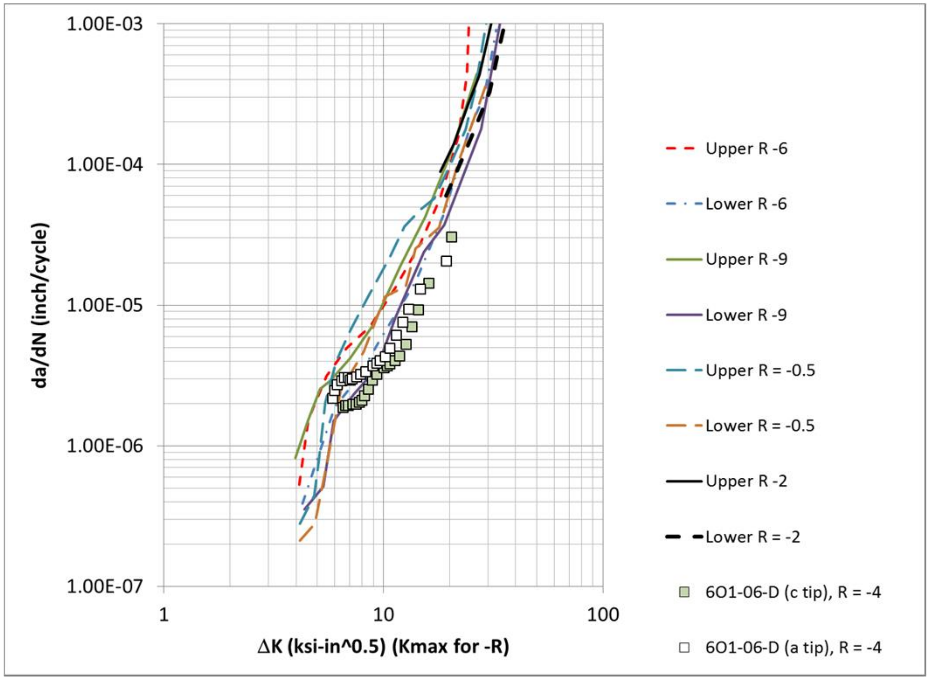
7075-T651 CC
Crack Growth Rate



7075-T651 CC (R = -4)





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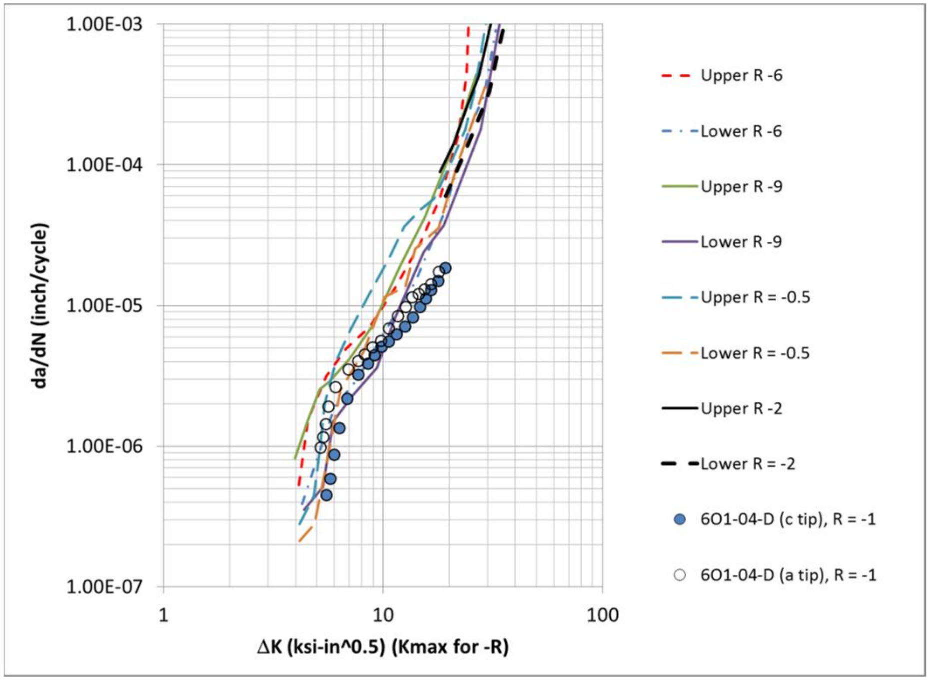
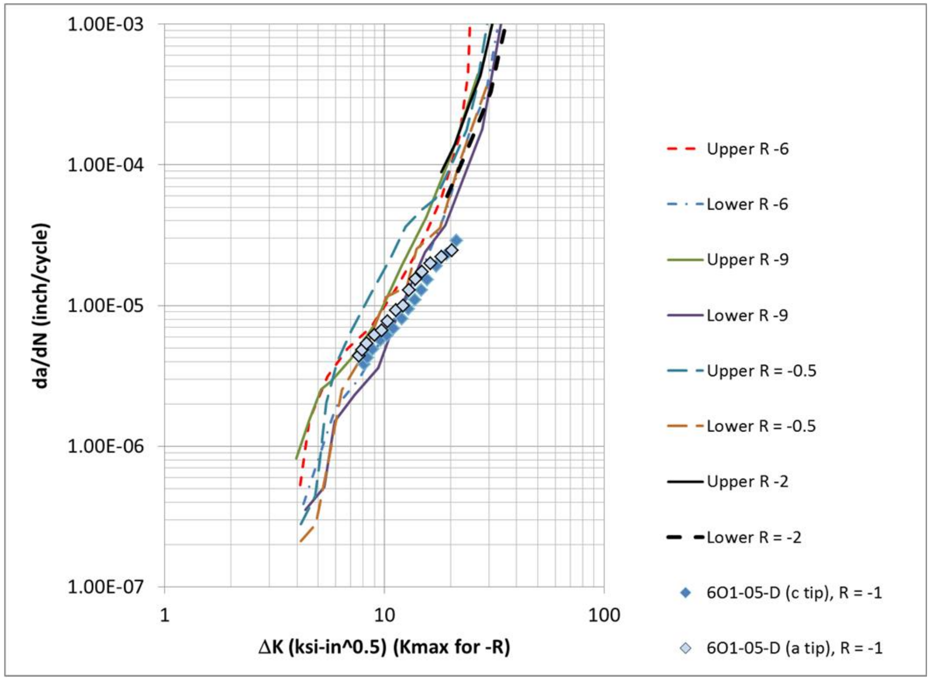
7075-T651 CC (R = -1)





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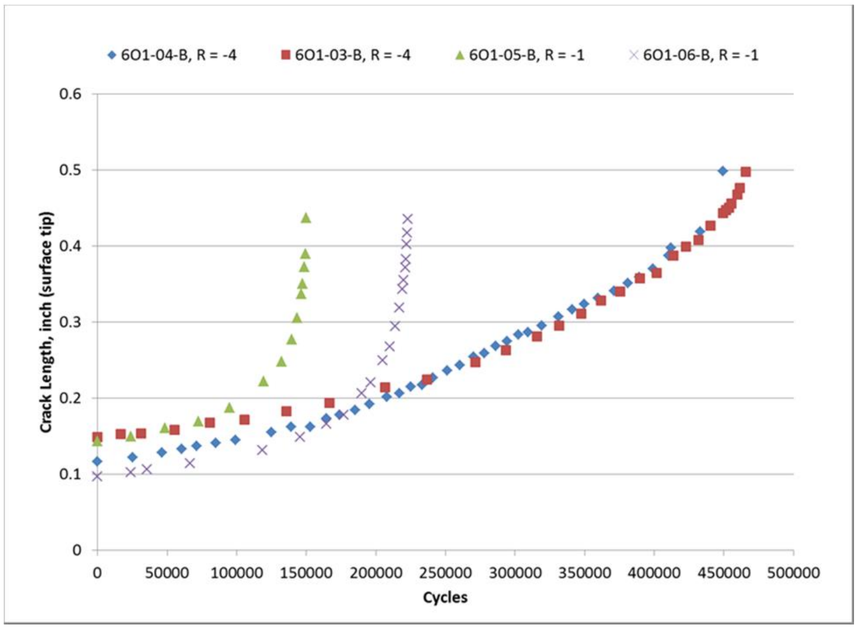
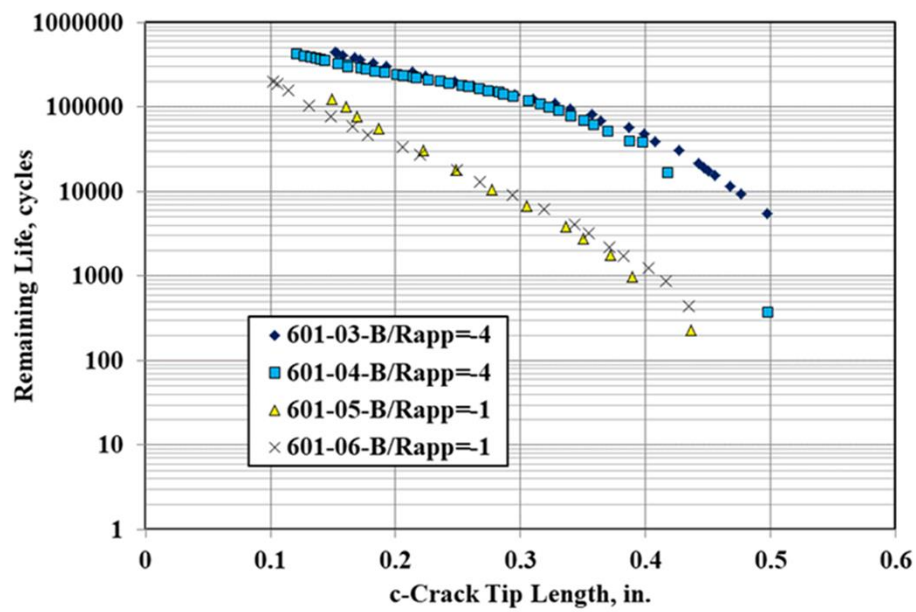
2024-T351 CC
Crack Growth and Residual Life





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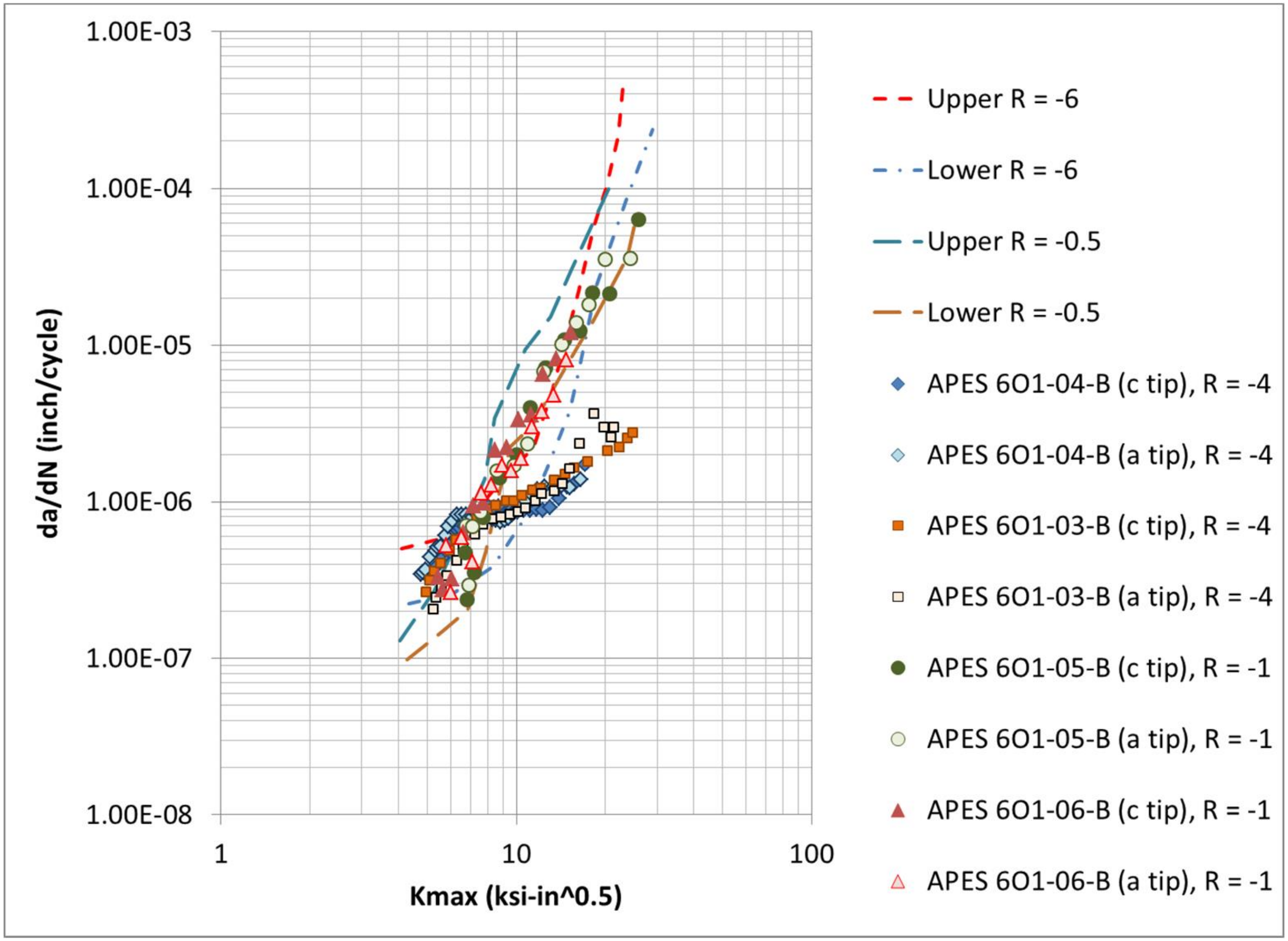
2024-T351 CC
Crack Growth Rate



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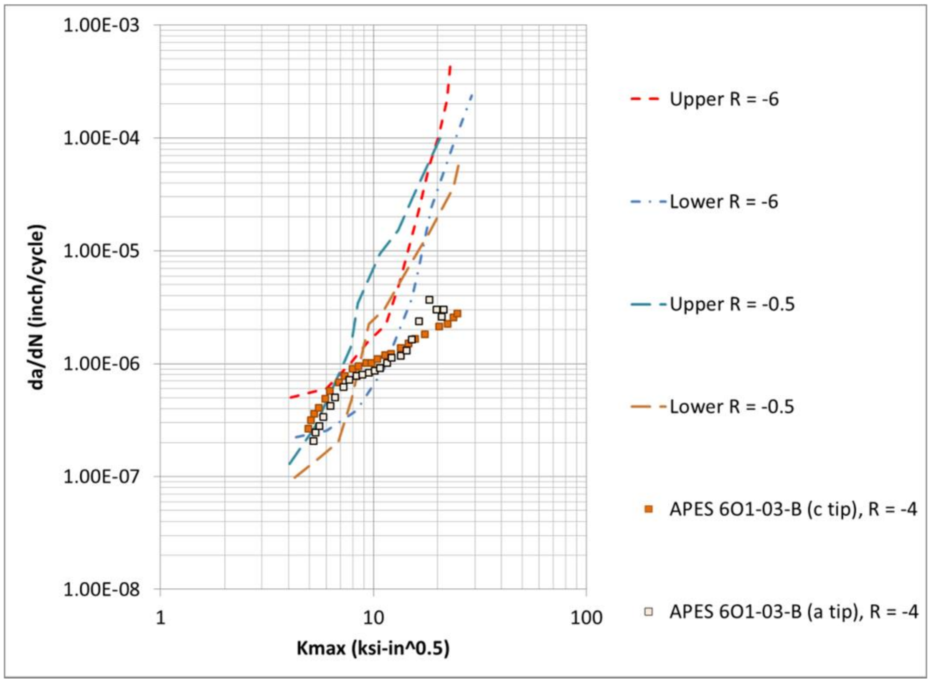
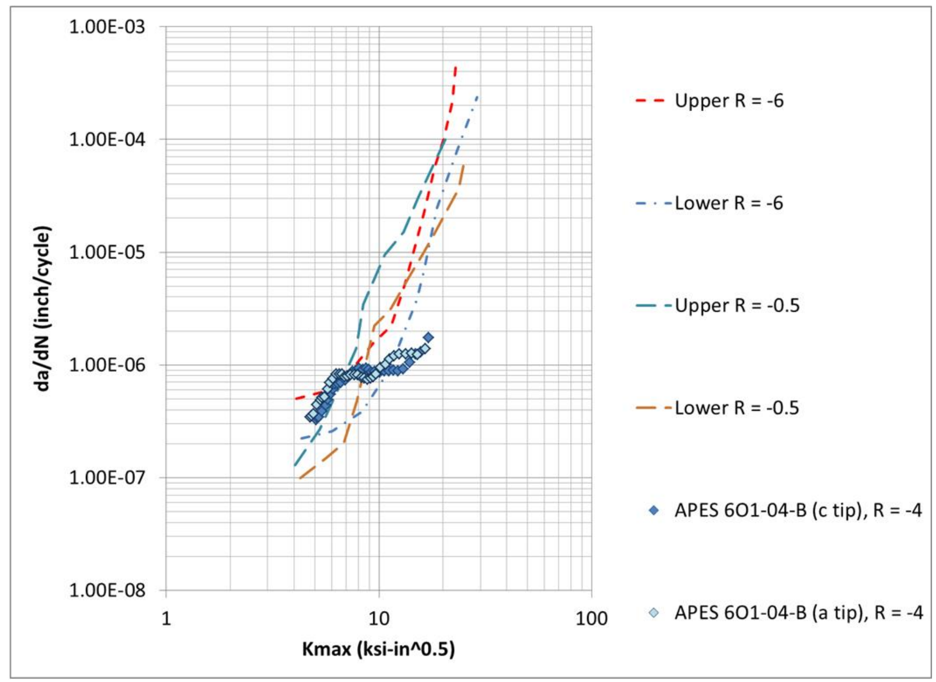
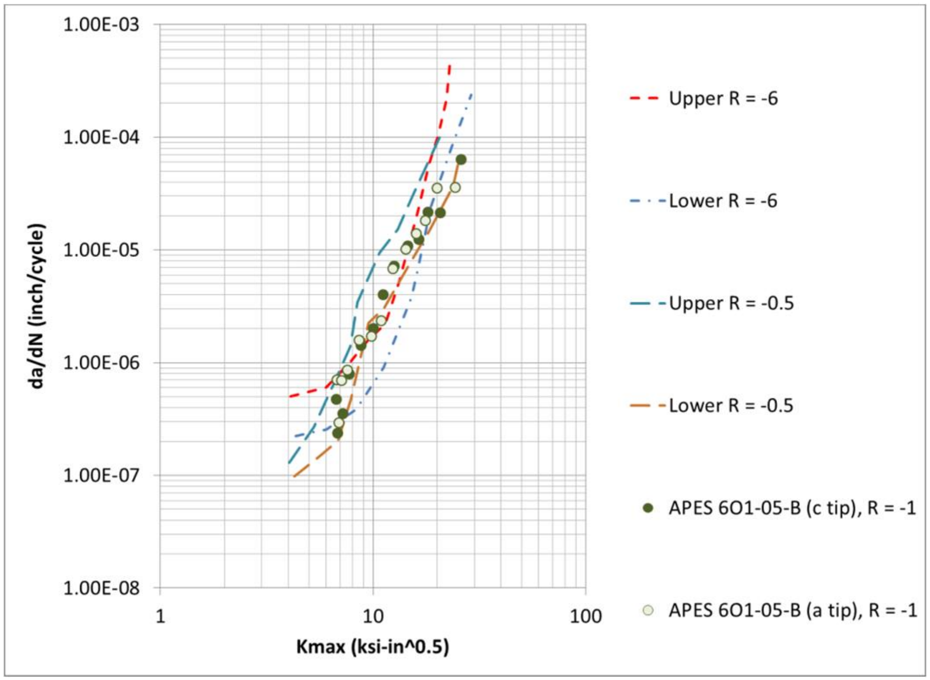
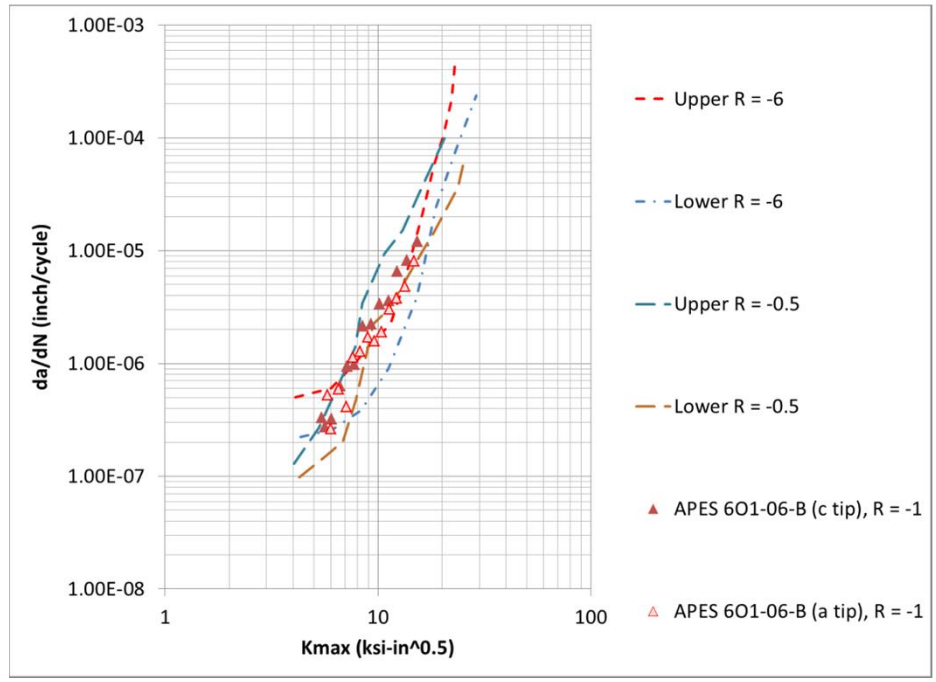
2024-T351 CC (R = -4)



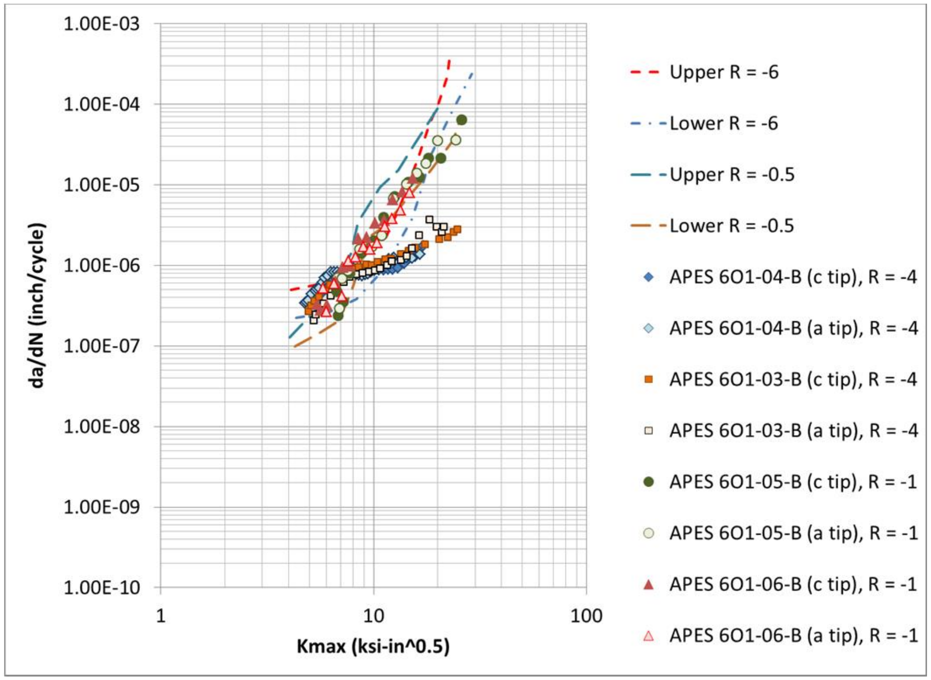


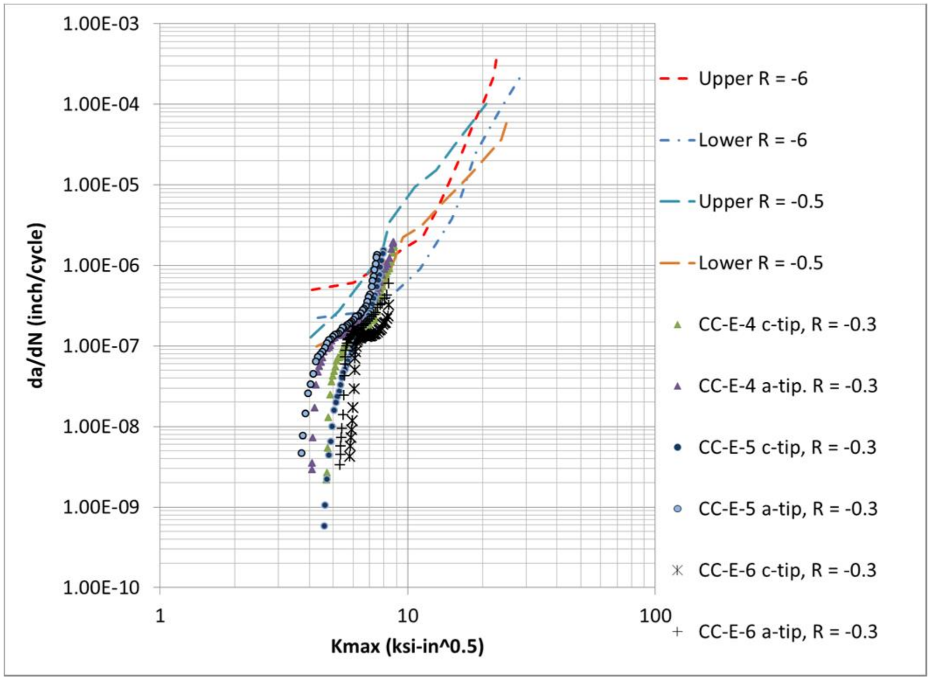
2024-T351 CC (R = -1)





Comparison of CC Growth Rates APES vs. SwRI





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Summary

7075-T651 M(T) data

- no difference between R = -4 and R = -1
- agrees well with AFRL historical data

7075-T651 CC data

- only slight difference between R = -4 and R = 1 data

2024-T351 M(T) data

- residual life curves show differences below a = 0.9 inch
- manifests as faster crack growth rates at lower K < 7 for R = -4
- rate curves completely collapse for K > 11 ksi in
- Data at K > 11 ksi in agrees well with upper bounds of AFRL historical data
- APES data categorically faster than SwRI data, which tends to lower side of AFRL data

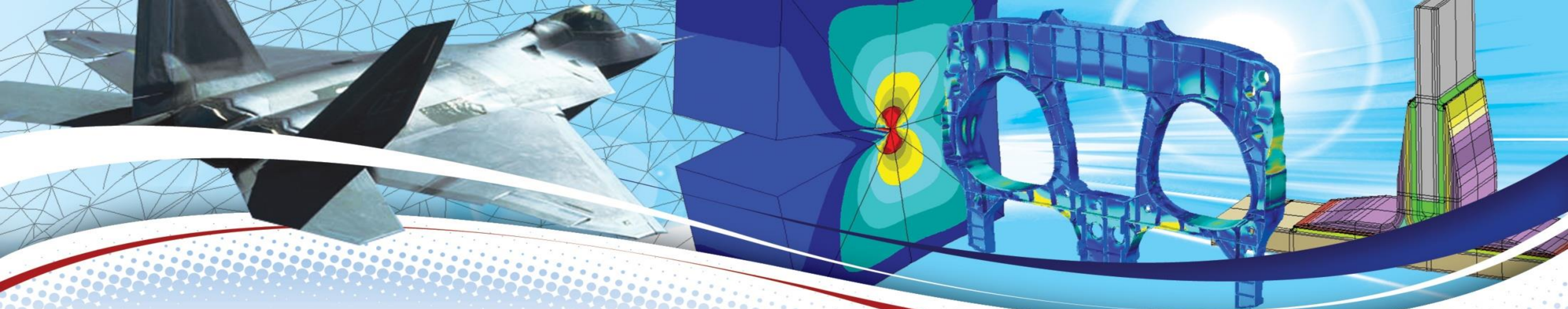
2024-T351 CC data

- residual life curves between R = -1 and R = -4 are completely different
- R = -1 data: compare favorably with AFRL historical data
- R = -4 data: the less said the better
  - compression side of cycle was 80% of compressive yield (L direction, A Basis, MMPDS, Table 3.2.3.0(b_1)
  - did this cause the problem ?
  - R = -4 tests in 7075-T651 CC specimens were only 50% of compressive yield.

Differences certainly exist between R = -1 and R = -4 in 2024-T351, but this appears to be test issue rather than true material behavior.

Questions ?

Answers ?



Engineered Residual Stress Im lementation ERSI
orksho – Clear ield, tah
Analysis Methods Su committee

RS Crack Closure

Experimental Observations and Modeling

Ricardo Actis ●Thomas Mills ● Scott Prost-Domasky ● Craig Brooks

September 2018

esrd

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- FCG data: 7075-T7351 specimens with a cold-worked hole
- Constant amplitude loading – R_{app} = 0.02, 0.10, 0.40, 0.60, 0.70, 0.80
- 24 specimen tested
- 4 for each R_{app}

EVALUATION OF EXPERIMENTAL DATA

Data Analysis

SwRI-4D3-01-G to SwRI-4D3-24-G Details

STRESSCHECK

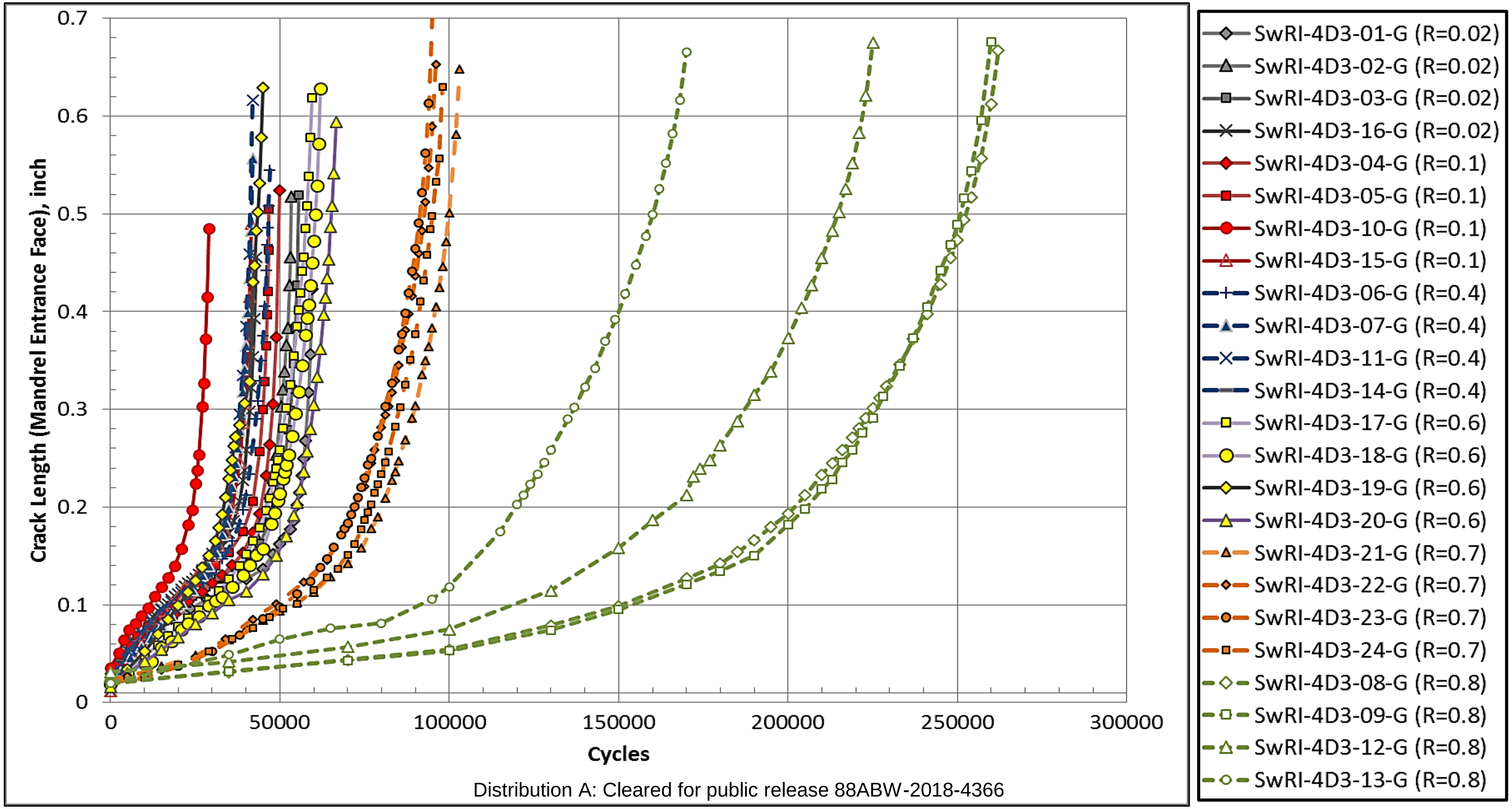
s ecimens

R_a lied

#	Coupon ID	Material	Width (in)	Thickness (in)	Diameter (in)	Edge Dist. (in)	Smax (ksi)	$R_{applied}$	Coupon Type	Initial Flaw a(in)
1	SwRI-4D3-01-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.02	Dogbone	0.0180
2	SwRI-4D3-02-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.02	Dogbone	0.0230
3	SwRI-4D3-03-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.02	Dogbone	0.0270
4	SwRI-4D3-16-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.02	Dogbone	0.0120
5	SwRI-4D3-04-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.10	Dogbone	0.0210
6	SwRI-4D3-05-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.10	Dogbone	0.0245
7	SwRI-4D3-10-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.10	Dogbone	0.0355
8	SwRI-4D3-15-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.10	Dogbone	0.0115
9	SwRI-4D3-06-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.40	Dogbone	0.0230
10	SwRI-4D3-07-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.40	Dogbone	0.0190
11	SwRI-4D3-11-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.40	Dogbone	0.0245
12	SwRI-4D3-14-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.40	Dogbone	0.0220
13	SwRI-4D3-17-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.60	Dogbone	0.0220
14	SwRI-4D3-18-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.60	Dogbone	0.0200
15	SwRI-4D3-19-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.60	Dogbone	0.0165
16	SwRI-4D3-20-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.60	Dogbone	0.0155
17	SwRI-4D3-21-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.70	Dogbone	0.0230
18	SwRI-4D3-22-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.70	Dogbone	0.0230
19	SwRI-4D3-23-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.70	Dogbone	0.0200
20	SwRI-4D3-24-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.70	Dogbone	0.0200
21	SwRI-4D3-08-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.80	Dogbone	0.0210
22	SwRI-4D3-09-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.80	Dogbone	0.0195
23	SwRI-4D3-12-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.80	Dogbone	0.0310
24	SwRI-4D3-13-G	7075-T7351	2.40	0.25	0.50	1.20	27	0.80	Dogbone	0.0200

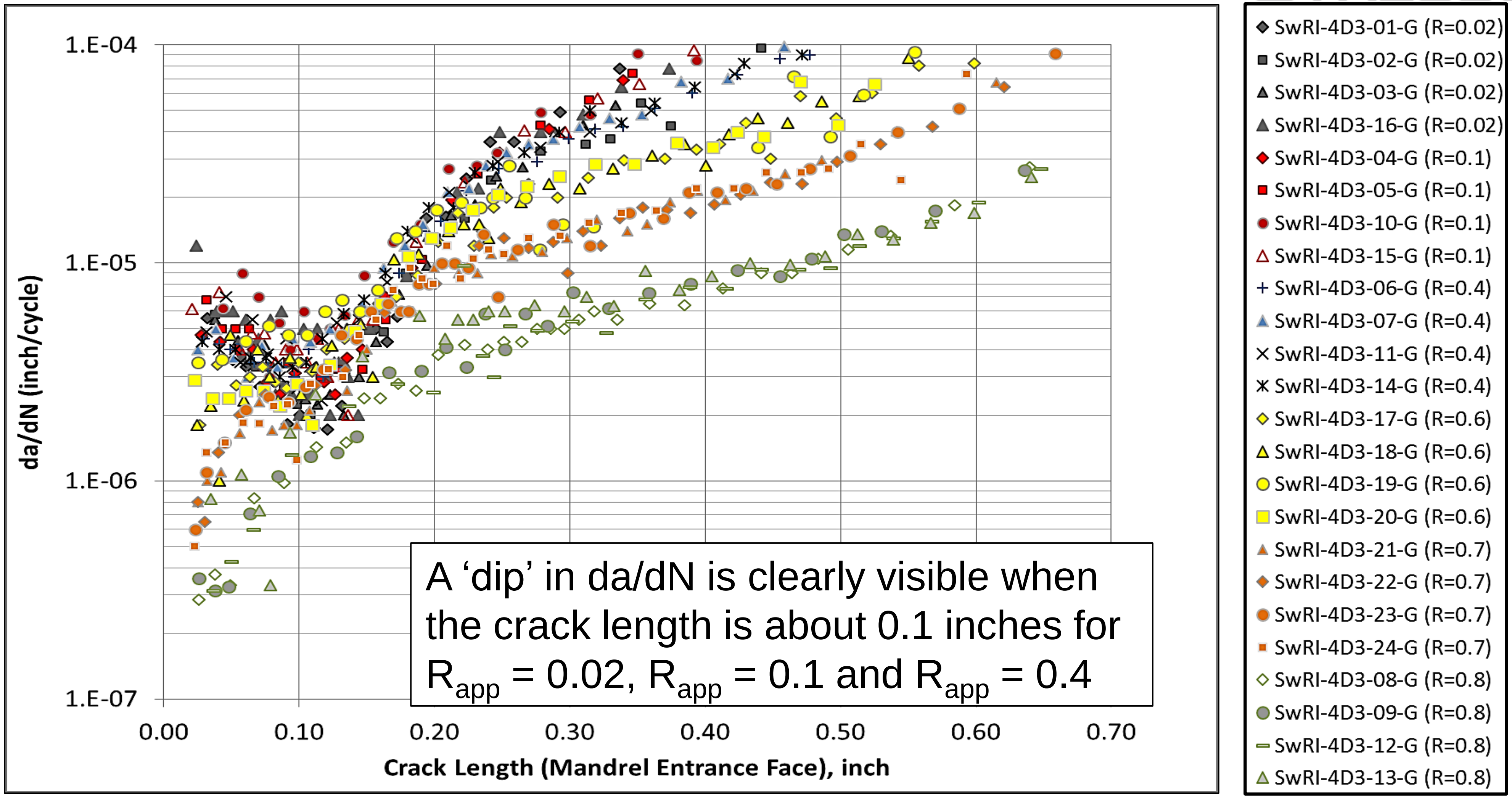
Data Analysis

All 24 Specimens: Crack Length v. Cycles



Data Analysis

All 24 Specimens: da/dN – Crack Length



A 'dip' in da/dN is clearly visible when the crack length is about 0.1 inches for R_{app} = 0.02, R_{app} = 0.1 and R_{app} = 0.4

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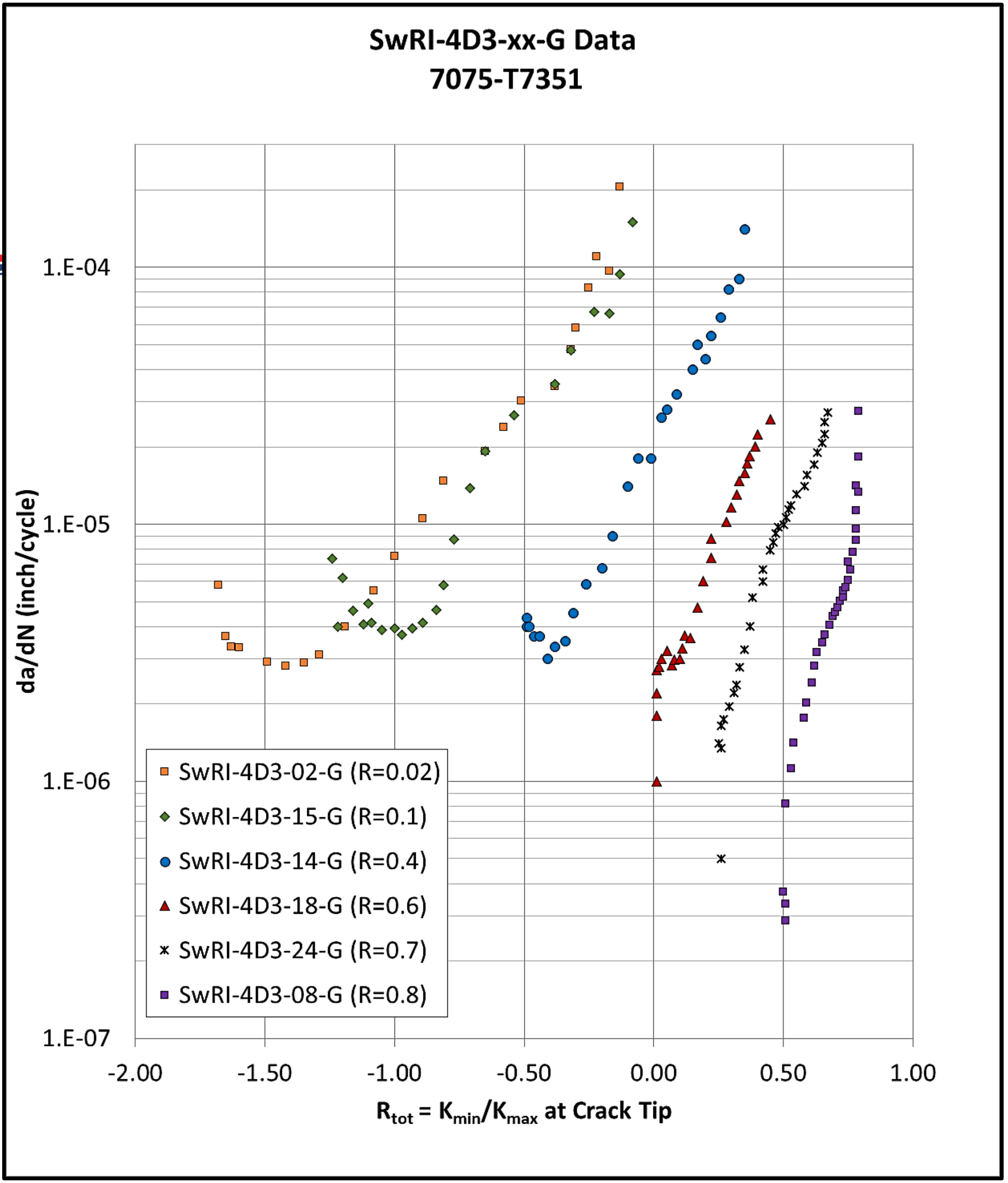
Data Analysis

da/dN – R_{tot}

- 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
  - Observation: The ‘dip’ in the da/dN curve occurs for short cracks at negative R_{tot}
- For $R_{tot} > 0$, the ‘dip’ is not present
  - This corresponds to R_{app} = 0.6, 0.7, 0.8



Examining R_{tot}

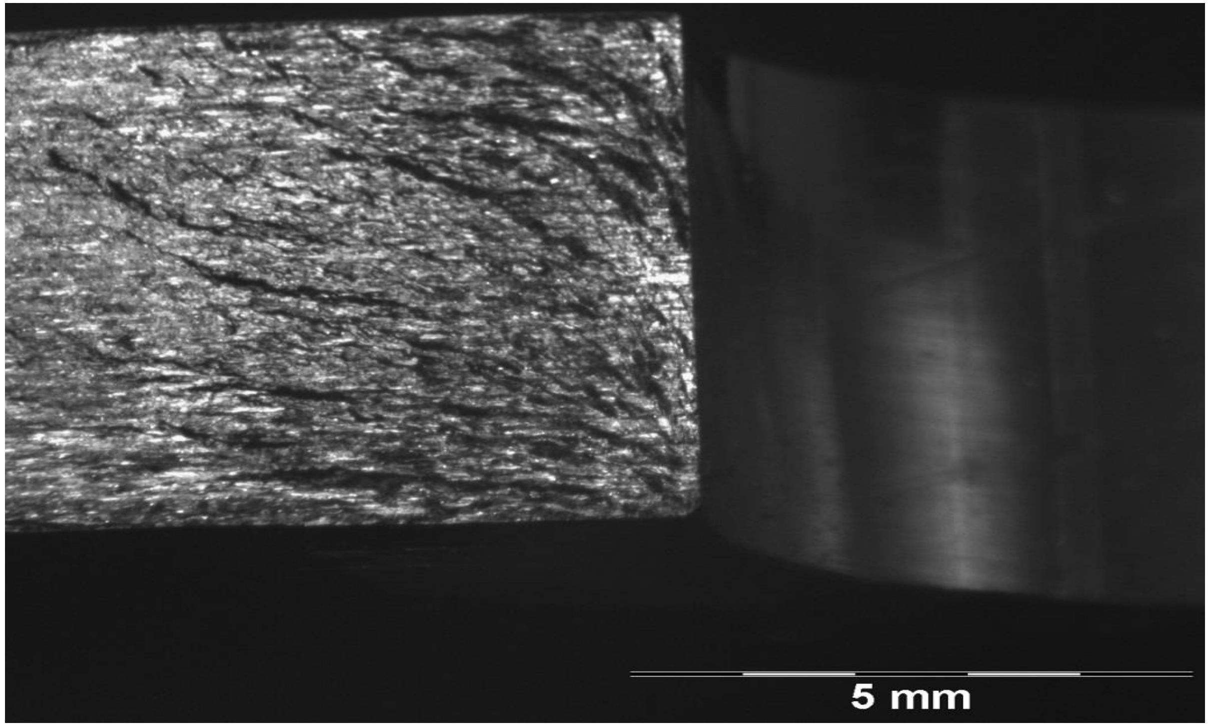
What do fracture faces tell us?

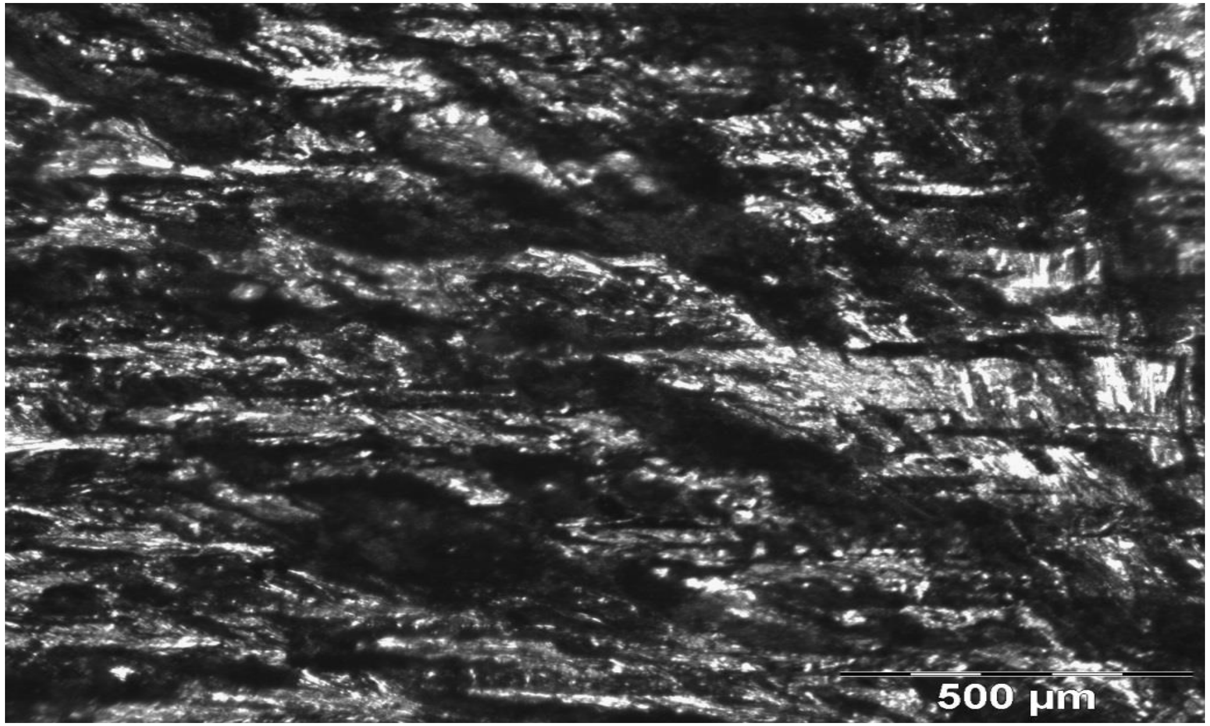
Crack origin is lower, right corner of fracture face

In higher magnification images, the origin is out of view

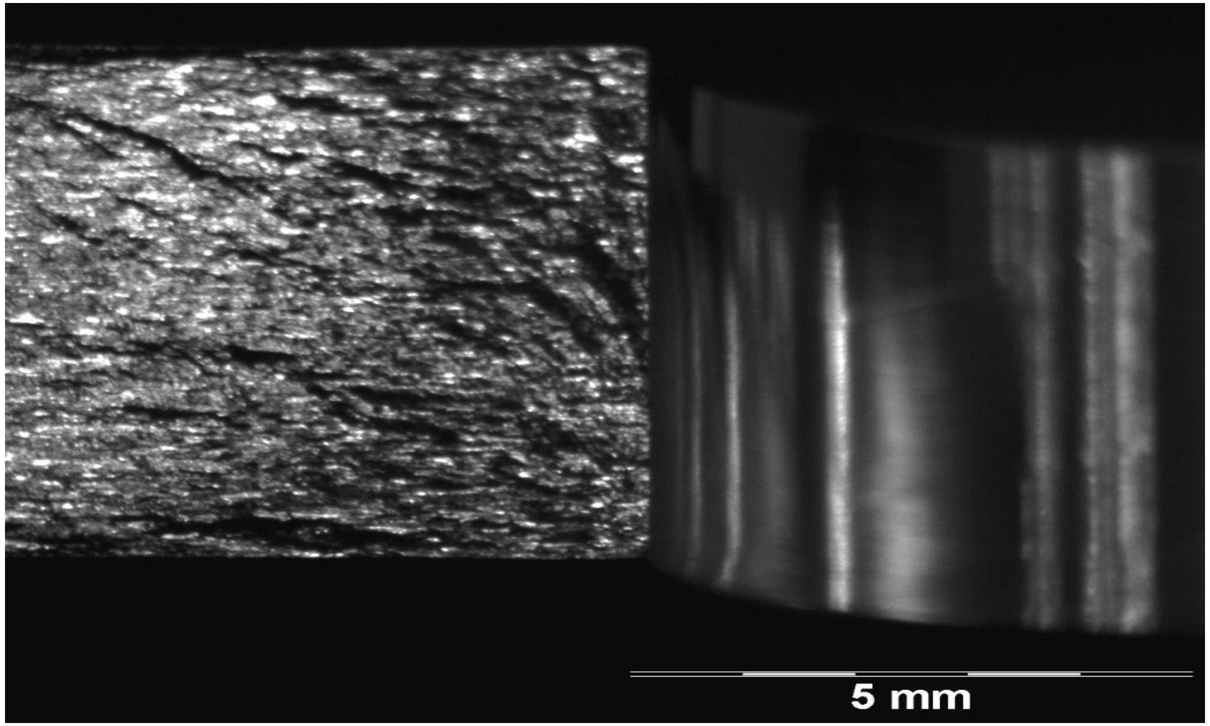
Higher magnification images centered at 0.05 x 0.05 inch from origin

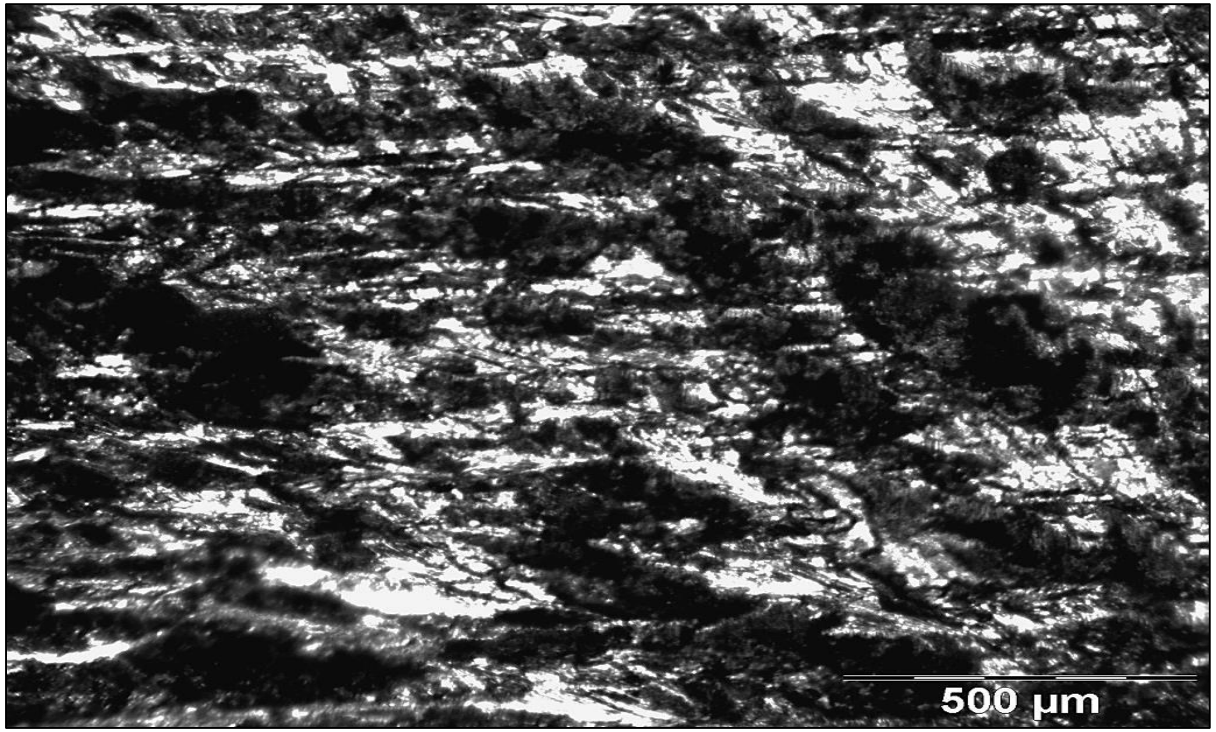
R_{app} = 0.02 Coupon (16G)



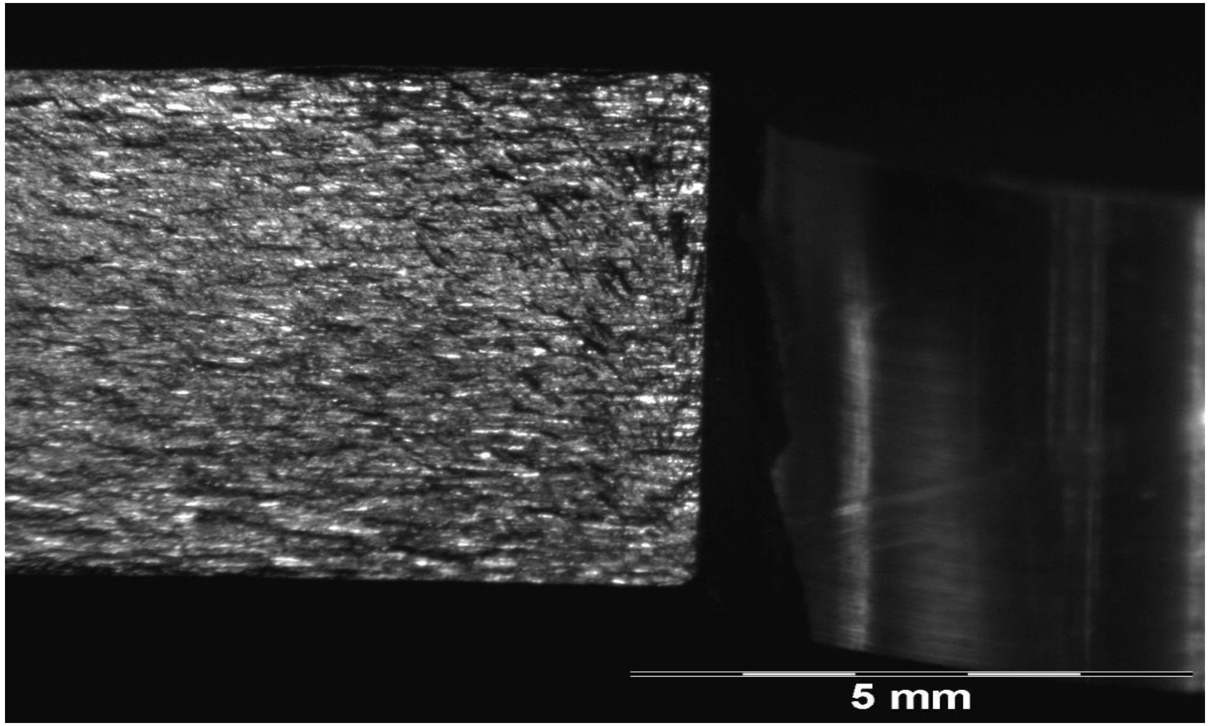


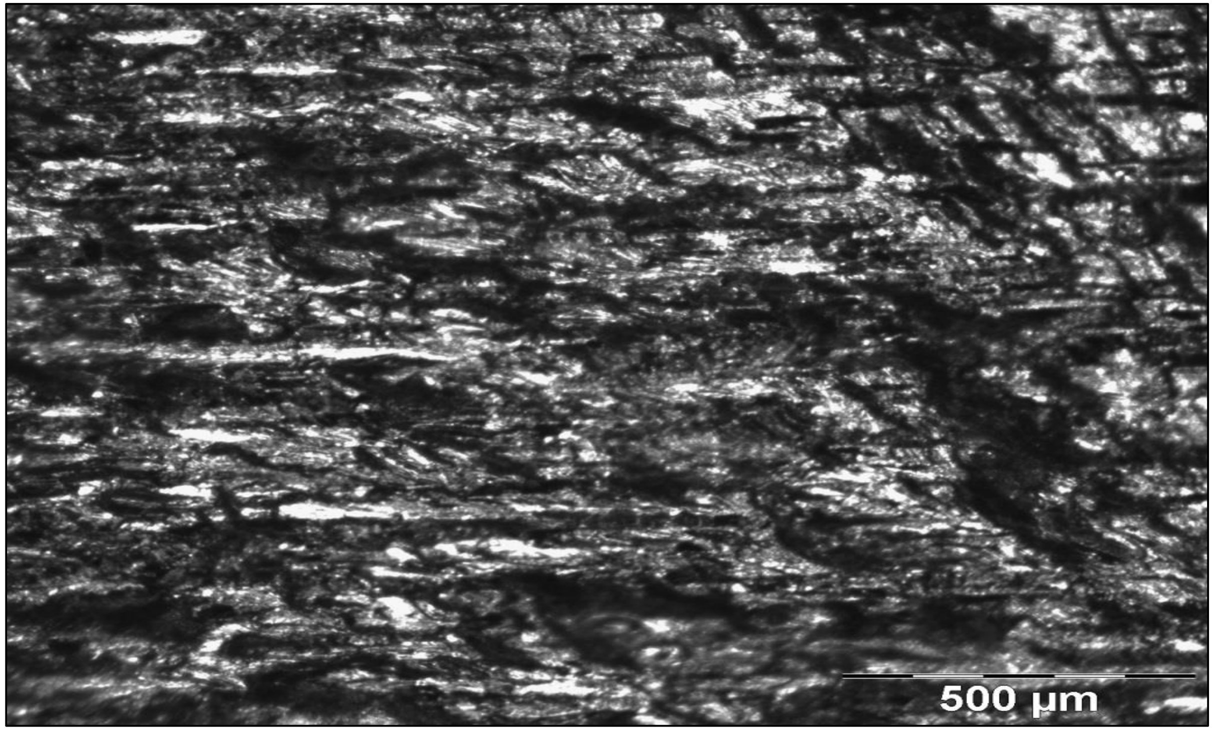
R_{app} = 0.1 Coupon (15G)



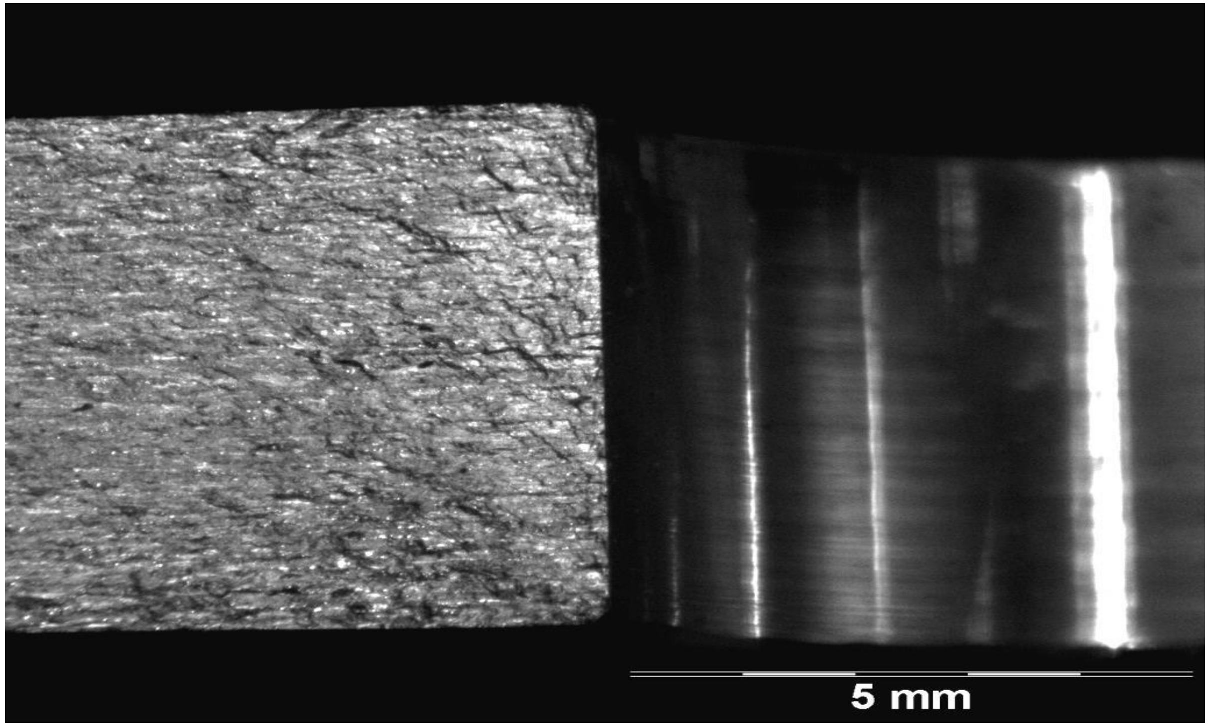


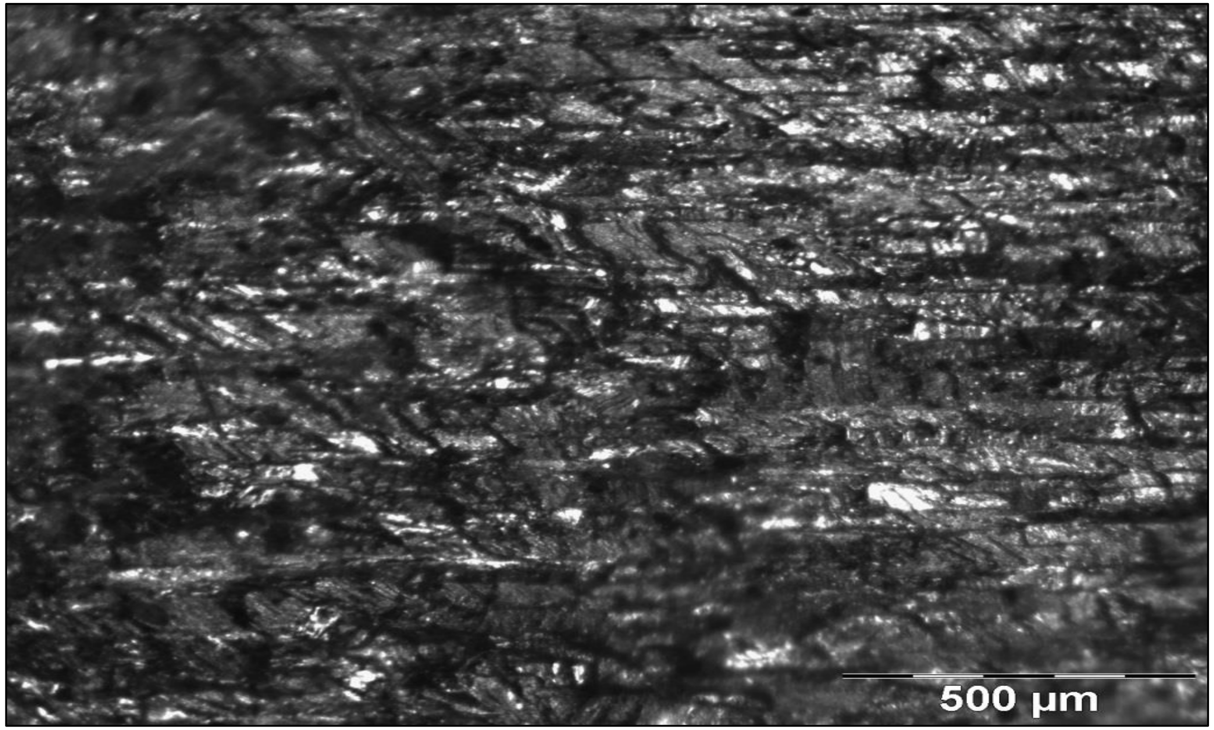
R_{app} = 0.4 Coupon (14G)





R_{app} = 0.8 Coupon (09G)



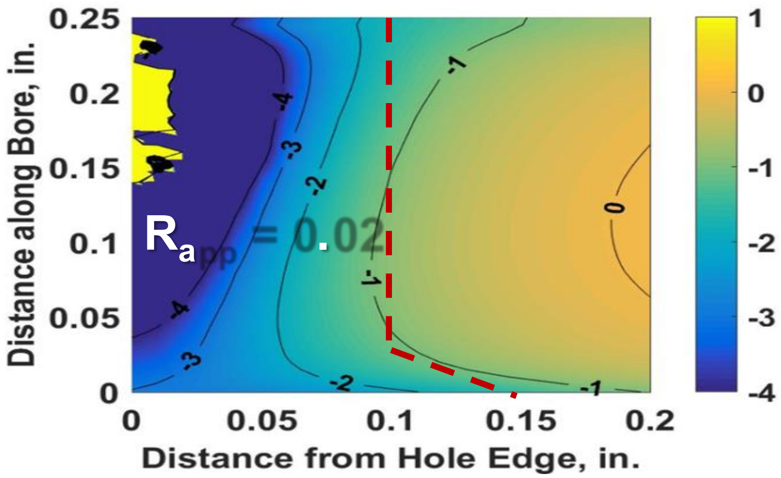


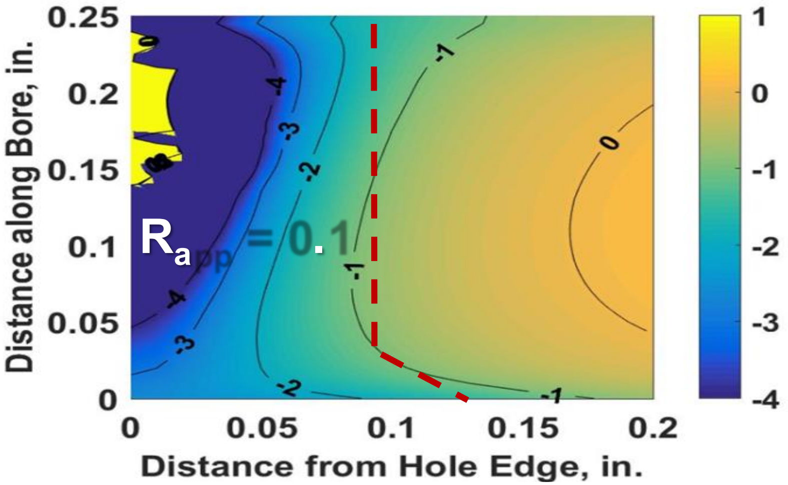
Evidence of Contact

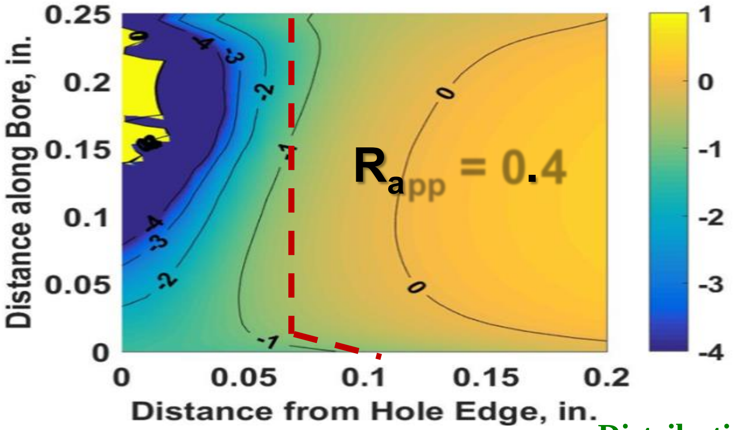
R applied	Heavy Oxide (MEF)		Heavy Oxide (Int)		Pockets of Oxide	
	Start	End	Start	End	Start	End
0.02	0	0.15	0	0.1	0.1	0.3
0.1	0	0.125	0	0.09	0.09	0.19
0.4	0	0.11	0	0.07	0.07	0.17
0.6	--	--	--	--	0.05	0.13
0.7	--	--	--	--	--	--
0.8	--	--	--	--	--	--
	Values represent distance from bore (inch)					

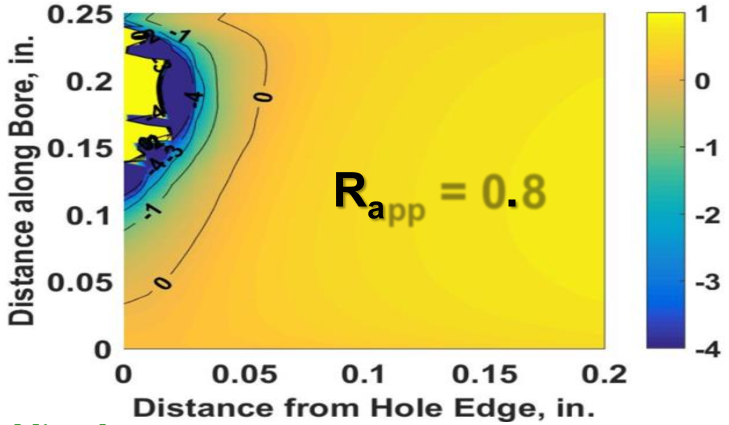
R_{tot} Contour Maps

- Qualitative observations of fracture faces correlate well with these maps
- Oxide on fractures (from contact) seem to correlate with regions of $R_{tot} < -1$









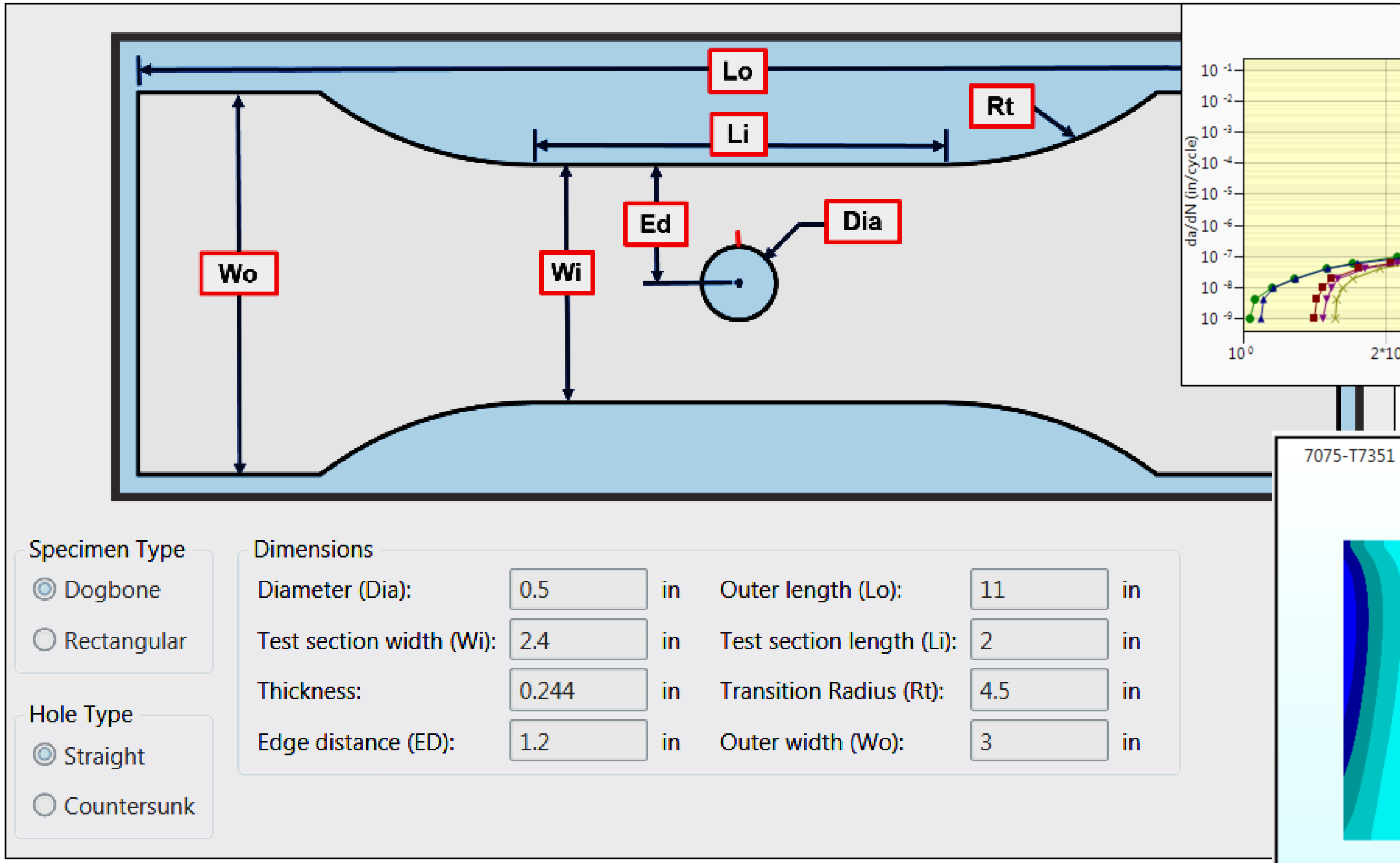
Regions to the le t o red dashed lines denote heavy o ide

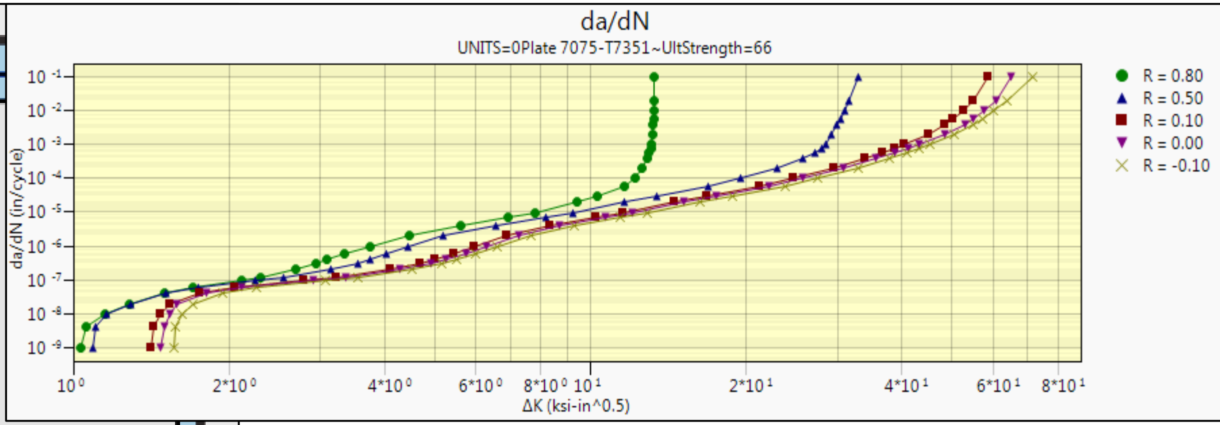
- A case for K-effective
  - Combining simulation with experimental observations

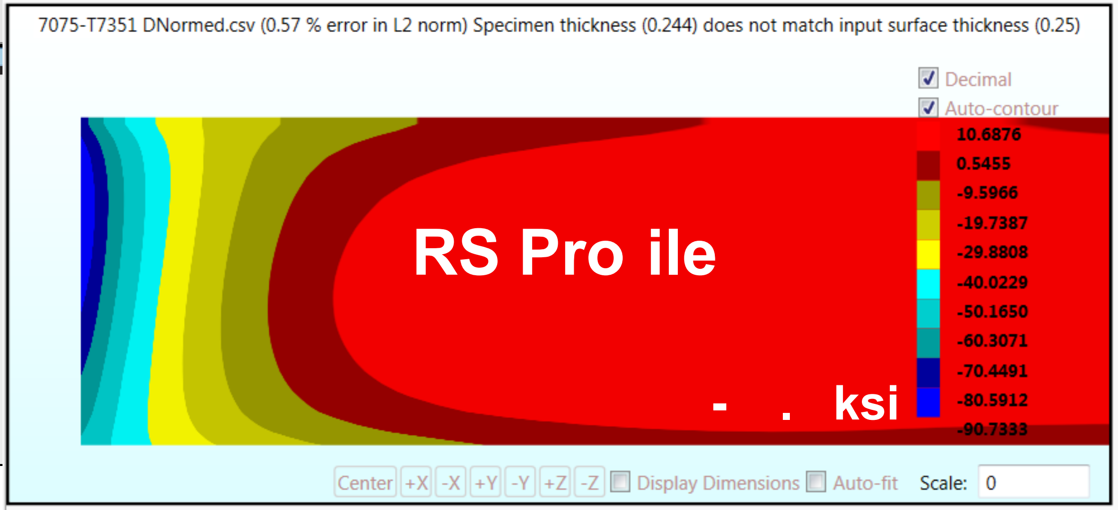
DATA ANALYSIS

Data Analysis

Specimen Dimensions & Reference RS for Simulation



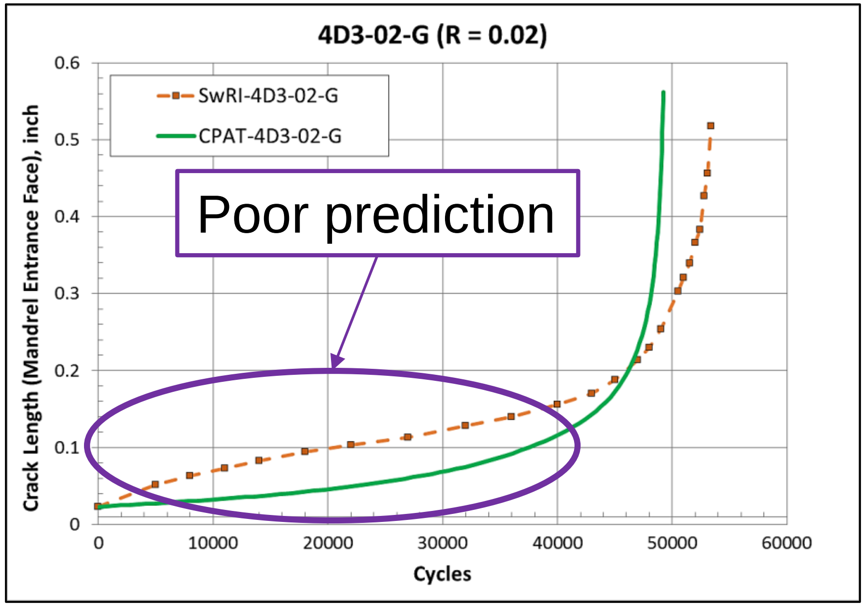


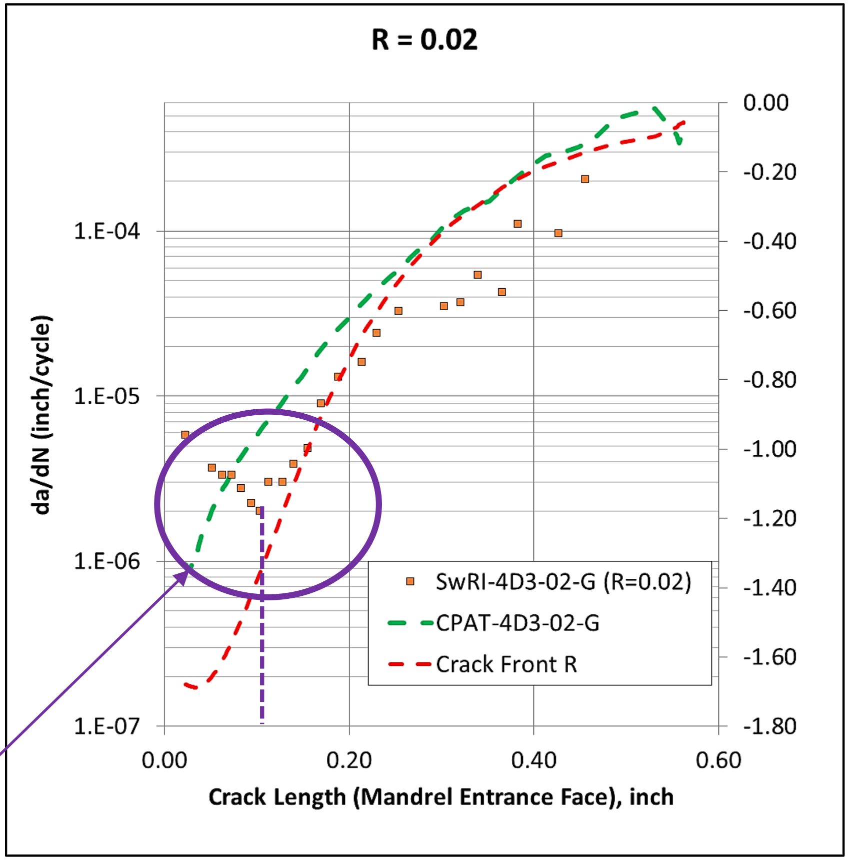


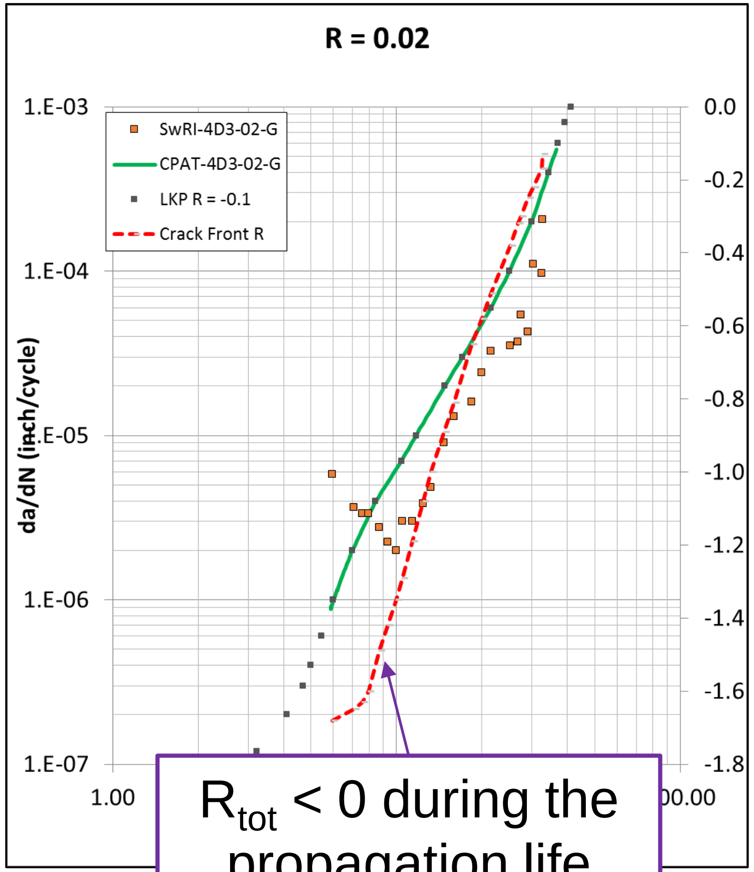
Data Analysis

Typical Prediction Using CPAT (R_{app} = 0.02)

- Simulation and test data
  - da/dN – K_{max} curve with the LKP (R = - 0.1) data. Predictions follow the R = -0.1 reference curve. Test points do not







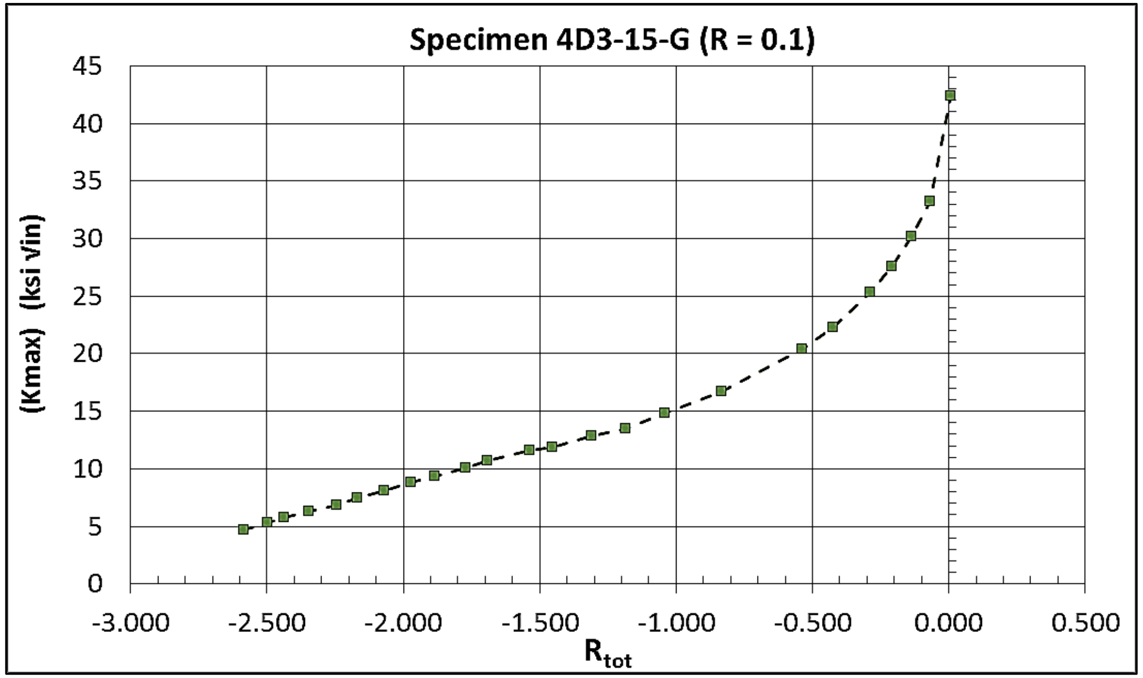
'Dip' at 0.10" crack (typical)

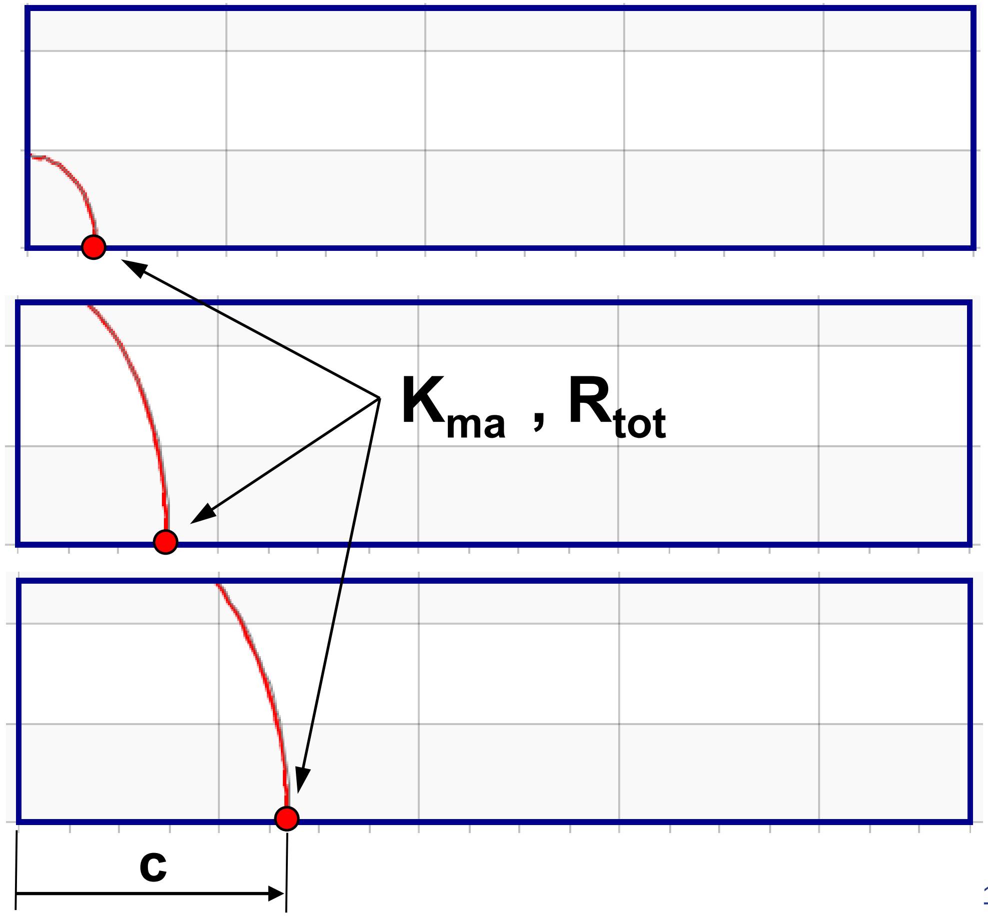
$R_{tot} < 0$ during the propagation life

Data Analysis

Computing R_{tot} and K_{max}

- Assume an elliptical crack front connecting bore and surface measurements
  - Solve in CPAT for K_{mech}, K_{res} at c-tip
  - Compute K_{max}, K_{min} and R_{tot}

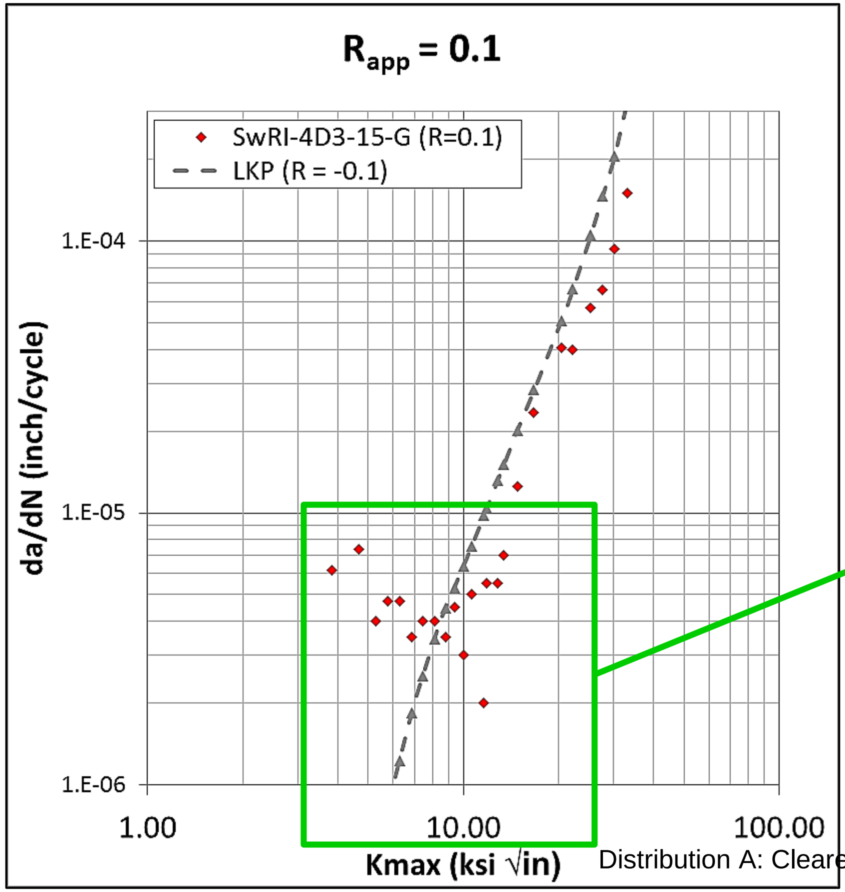


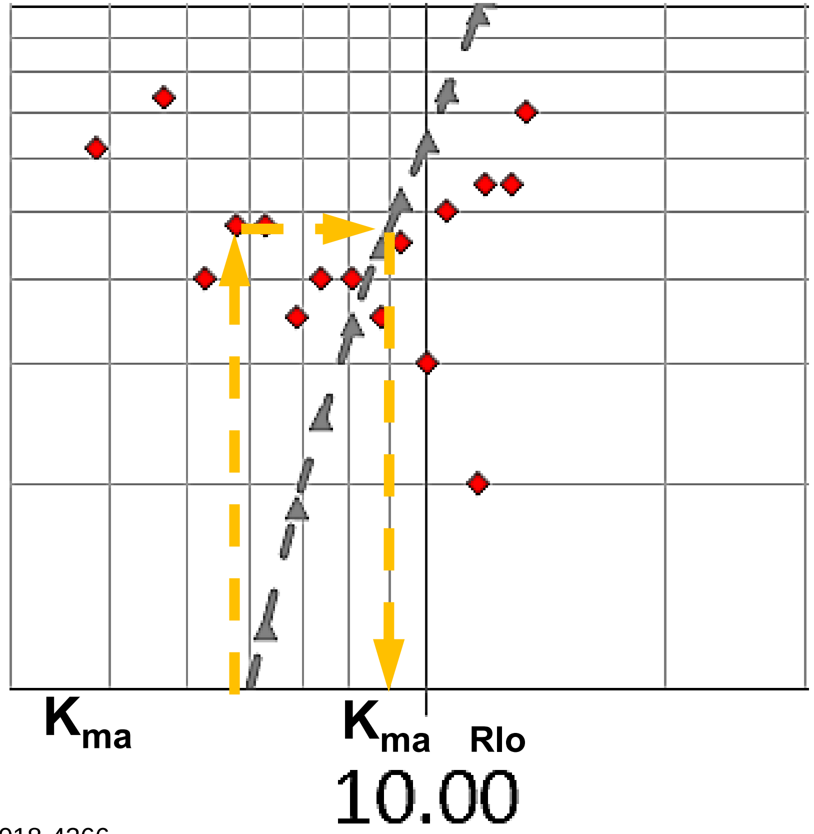


Data Analysis

Determining K-effective

- Value of K_{max} = $(K_{max})_{Rlo}$ needed to get the same $(da/dN)_{test}$ from the Rlo curve of the LKP data for each crack length





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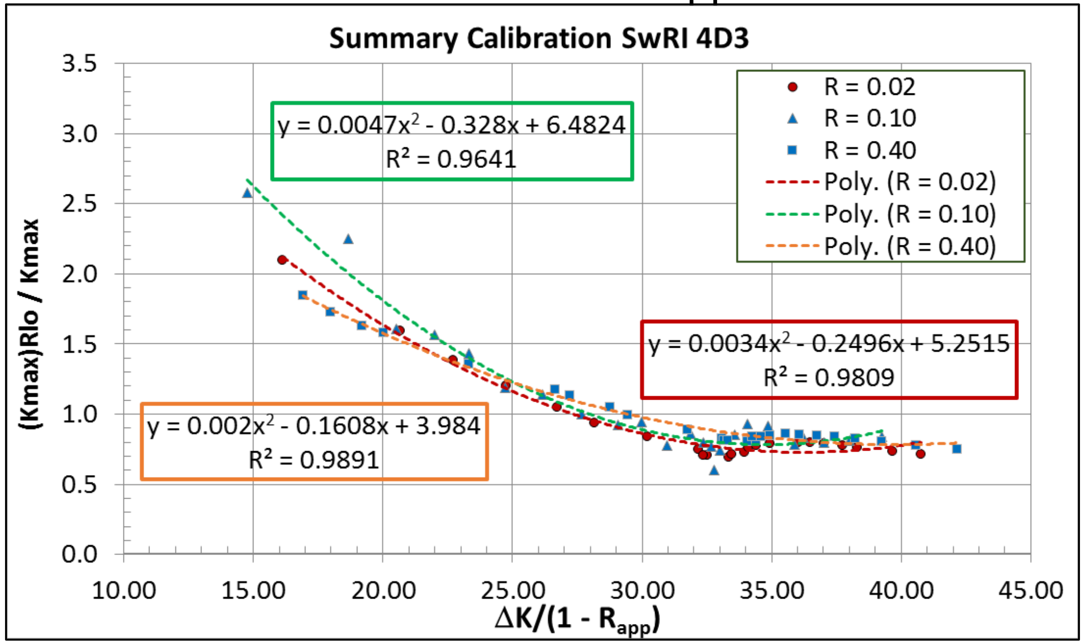
Data Analysis

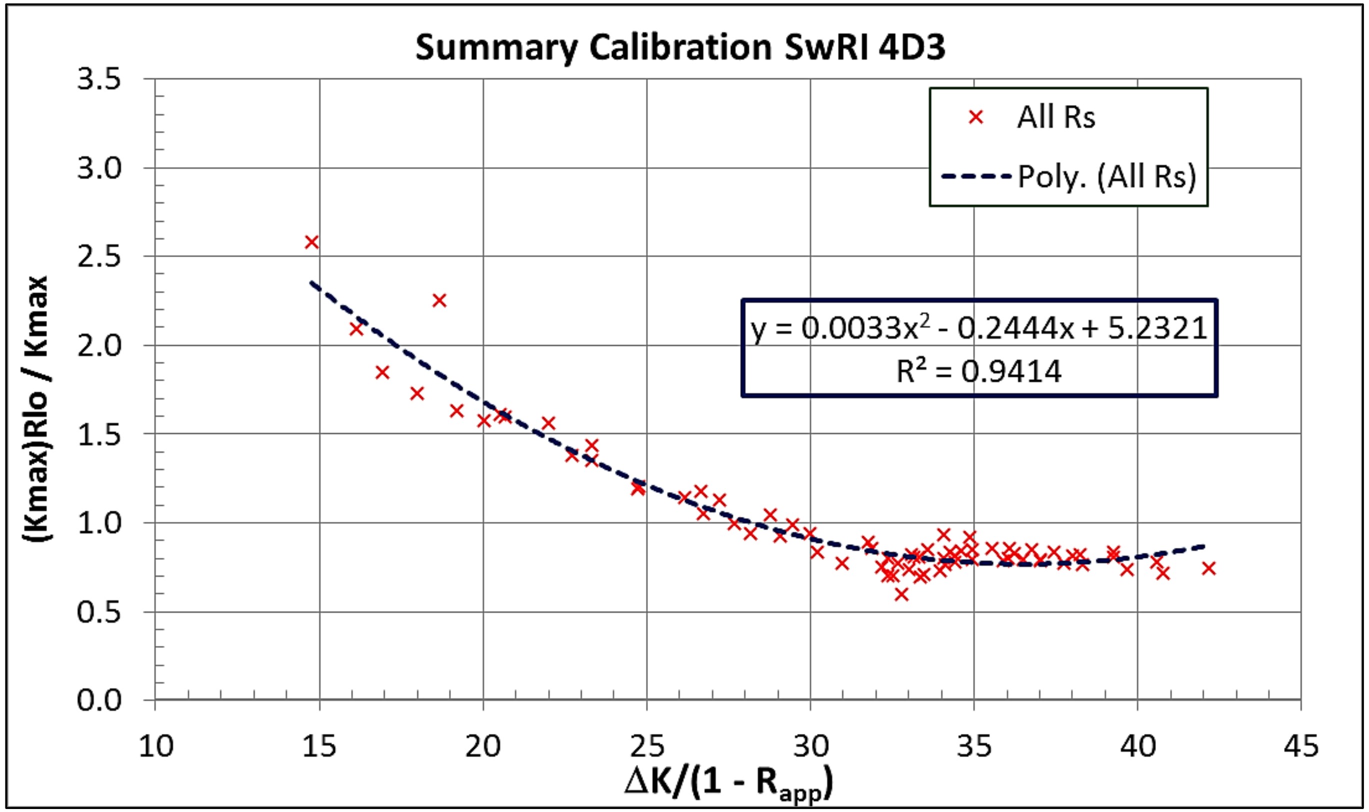
Calibration

- Applying procedure to R_{app} = 0.02, 0.10, 0.40
  - Plotting results in terms of $\Delta K / (1-R_{app})$

For each R_{app}



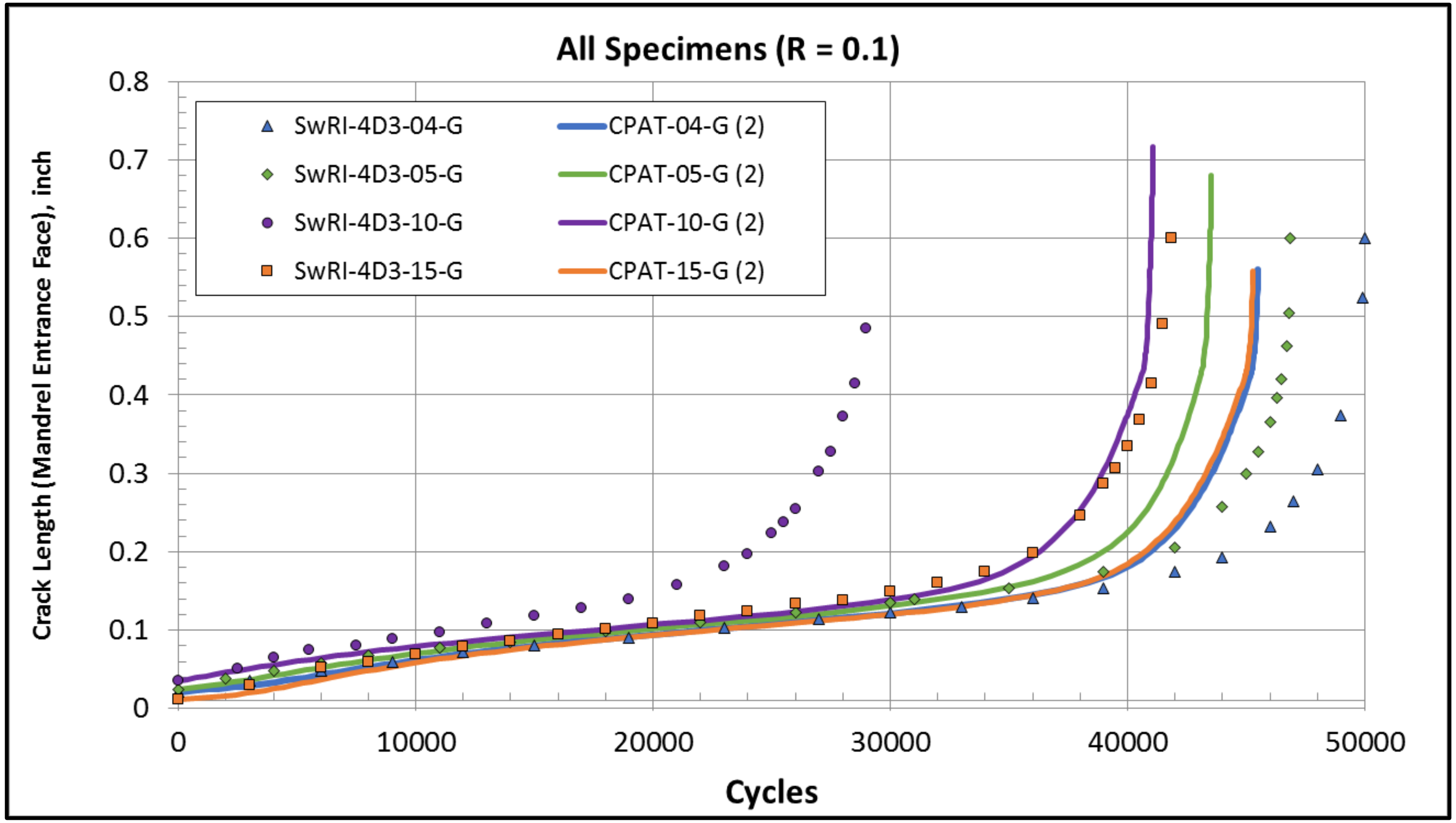
Combined

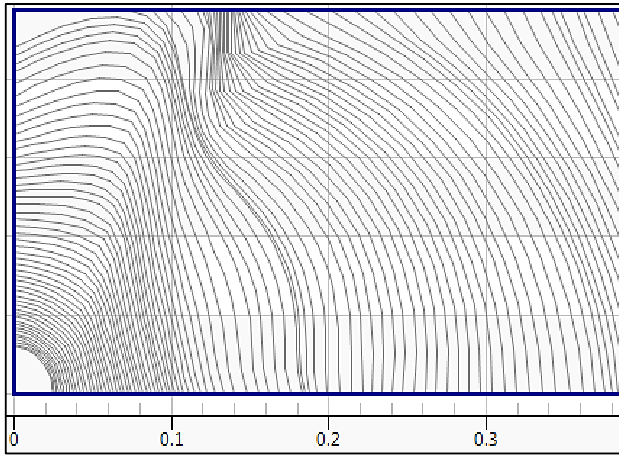


Data Analysis

Using K-effective in Predictions

- Preliminary results for $R_{app} = 0.10$

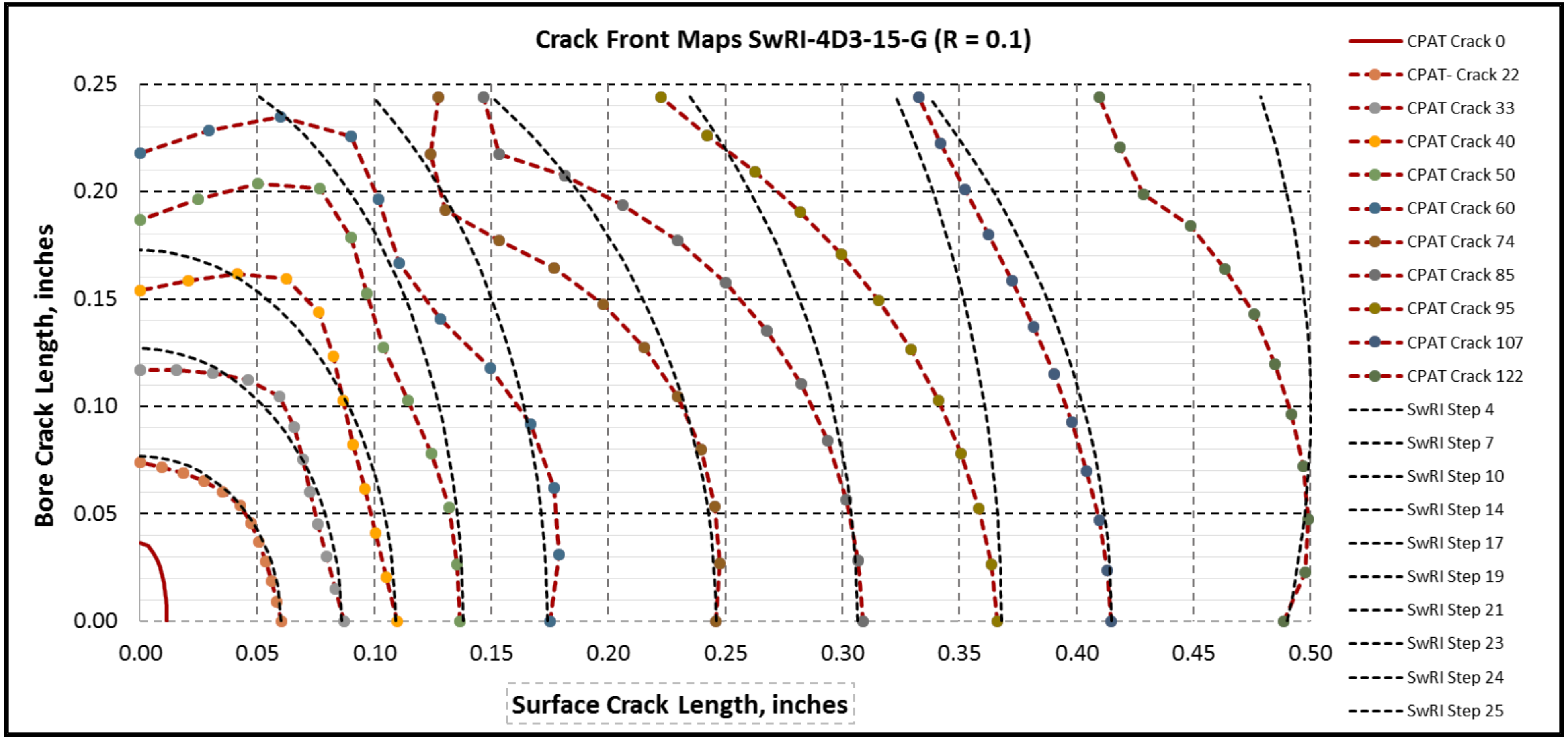




Data Analysis

Using K-effective in Predictions

- Crack Shape Specimen 4D3-15-G (Rapp = 0.10)



Summary

Data Analysis

- Using K_{max} as the dependent variable automatically incorporates the effect of the Residual Stress in the prediction
- Using $\Delta K/(1-R_{app})$ as the independent variable consolidates the calibration data for the three R_{app} considered in the study, and is independent of the RS
- Preliminary application of the calibration curve is promising, and it fits within the traditional approach of using a K-effective to account for closure effects

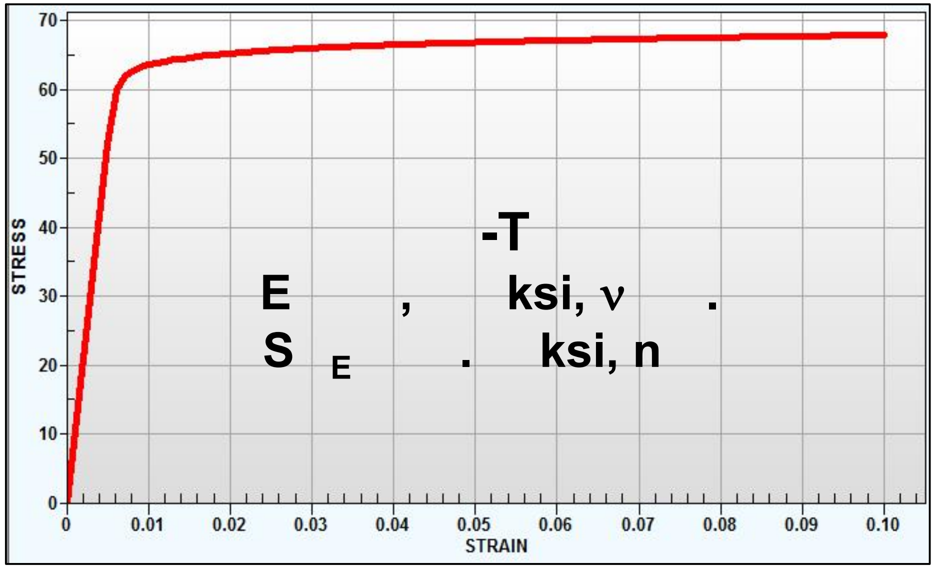
- Incremental plasticity (kinematic hardening)
- Simulation of CW + Contact + Remote Load

MODELING OF CLOSURE

Closure Model

Analysis Approach

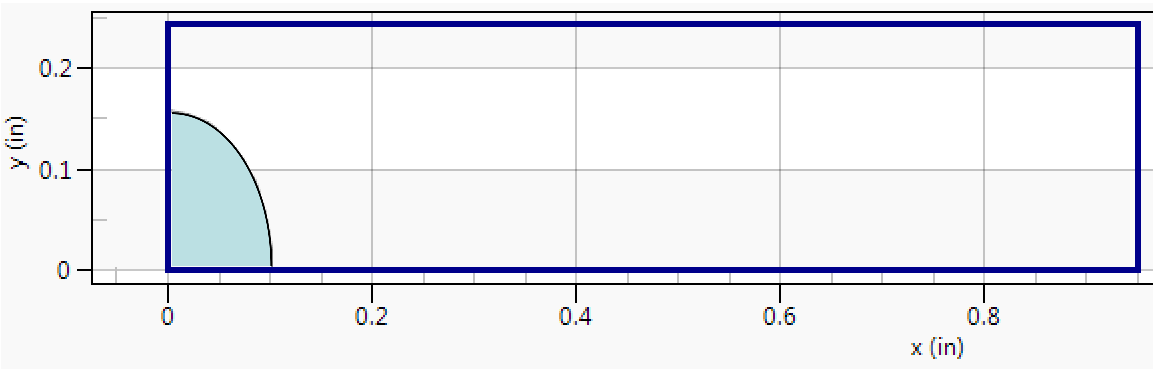
- Simulation of mandrel insertion (4%) and removal
  - Incremental plasticity – kinematic hardening
  - Ramberg-Osgood stress-strain curve
  - Distribution of residual stresses
- Introduce corner crack
  - Assume elliptical shape with dimension from test
  - Check contact effect on residual stresses
- Apply a remote load
  - Increments of 1ksi to 27 ksi
  - Check contact effect on residual stresses
  - Check crack opening as load increases



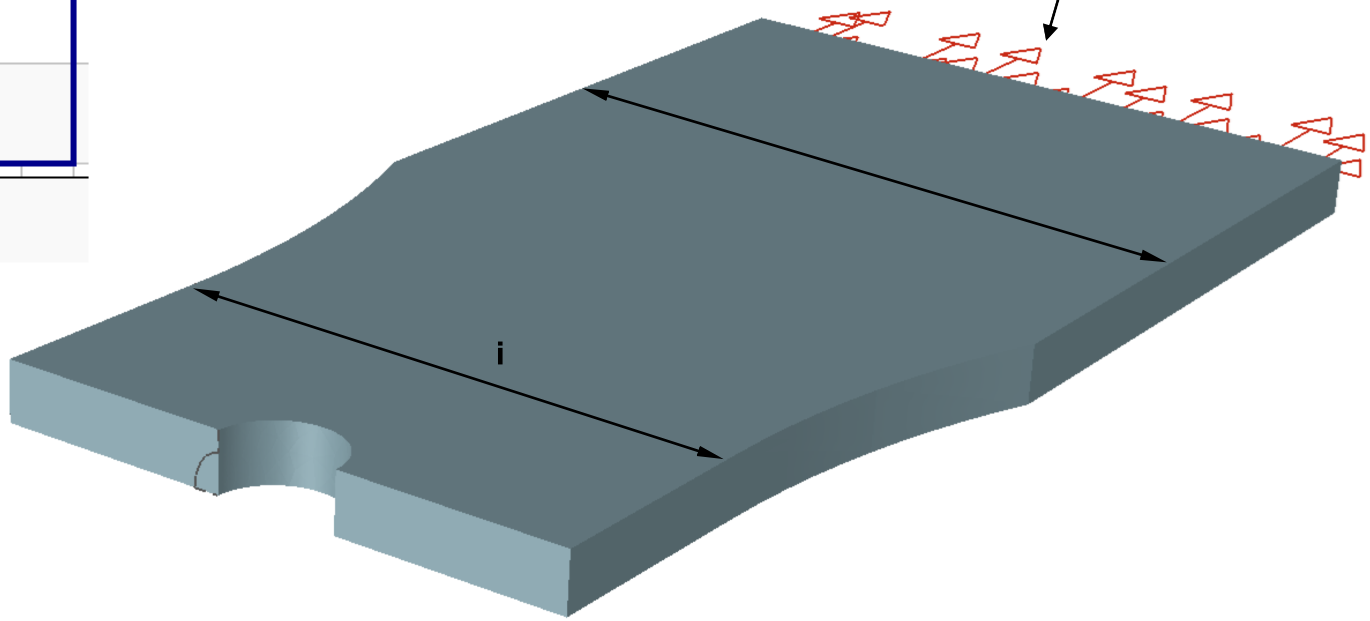
Closure Model

Crack Configuration

- 0.10 in × 0.16 in

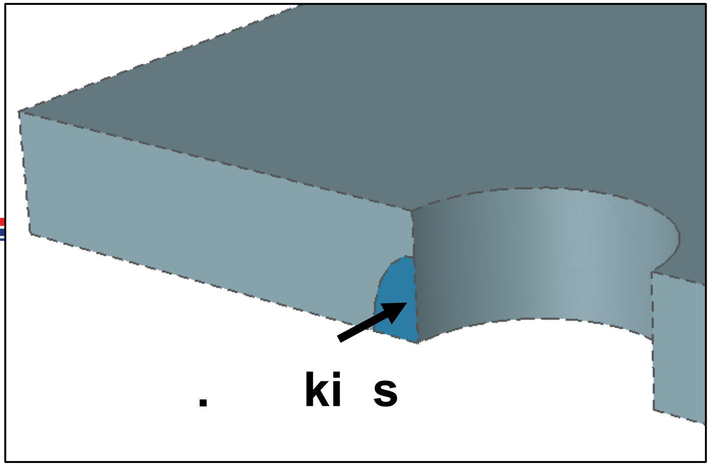


- Crack dimensions corresponding to specimen SwRI-4D3-15-G, Crack Step 9

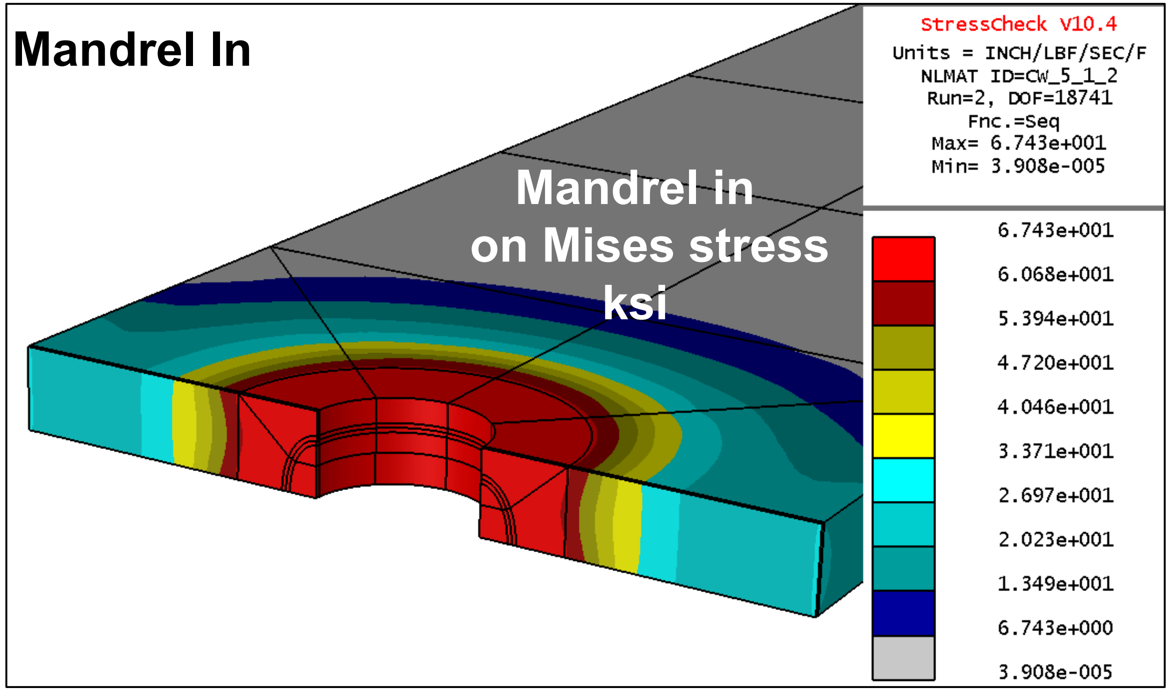


Closure Model

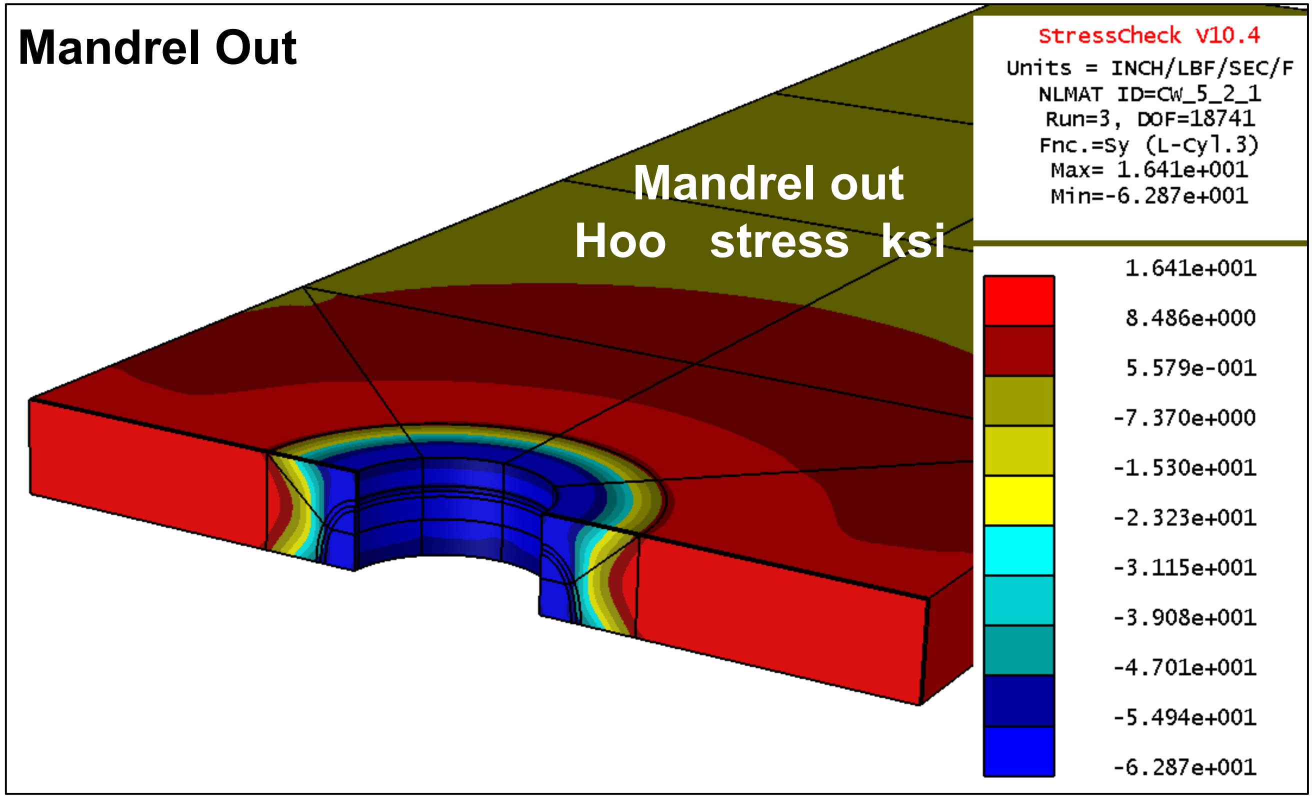
CW Simulation



orce resultant over the area o the crack-to- e a ter mandrel removal

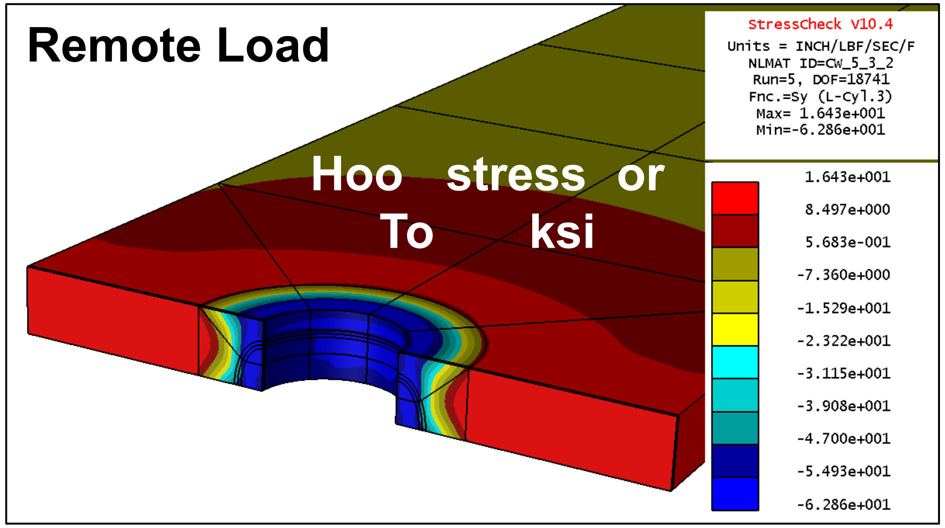


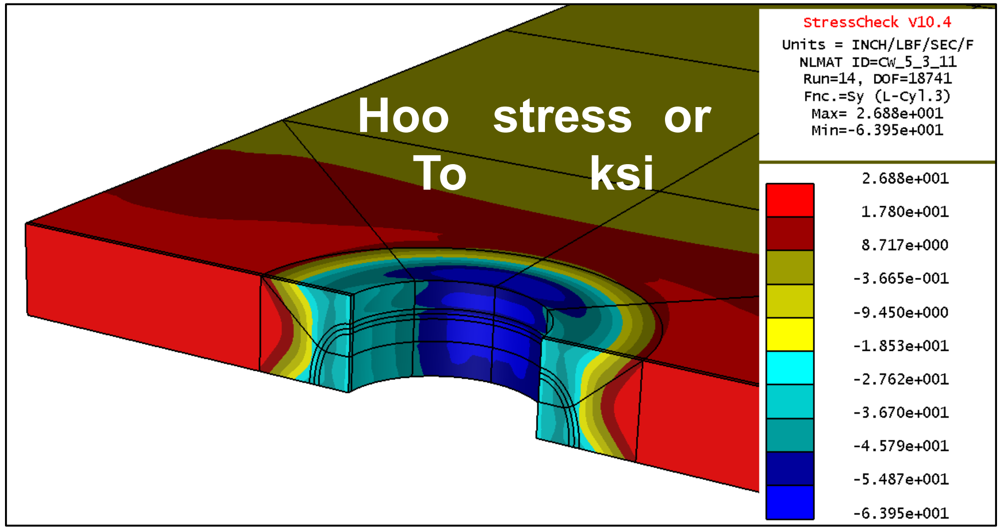
E:	1.0300e+004	v:	3.3000e-001
S70E:	6.3000e+001	n:	4.8000e+001
a(th):	0.0000e+000	beta:	1.0000e+000

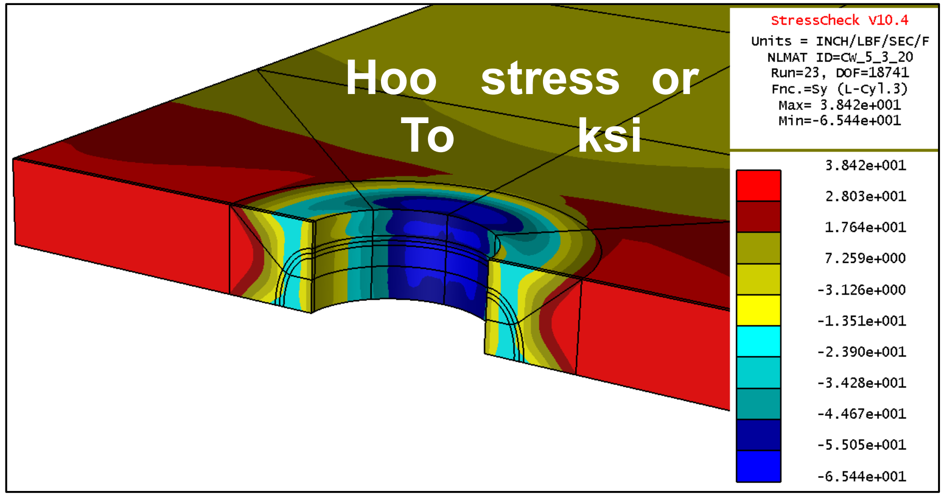


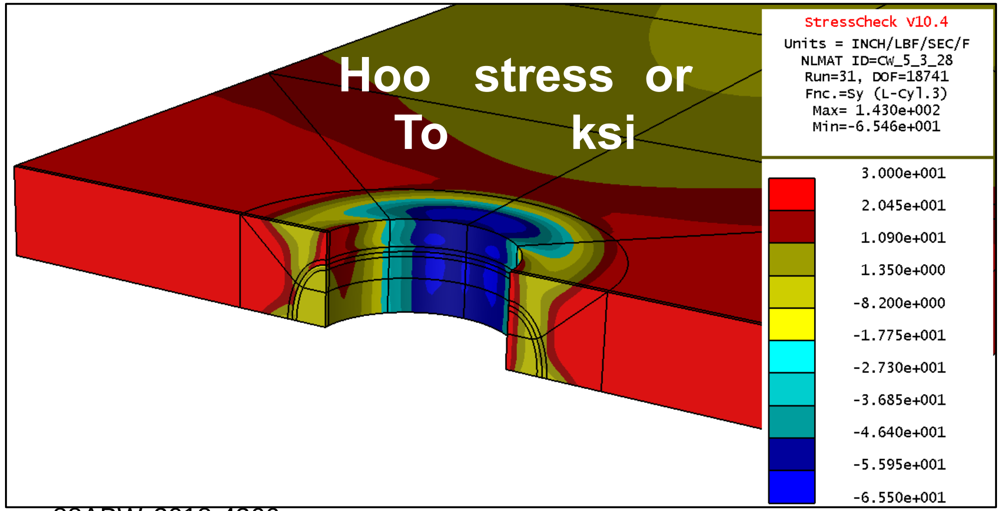
Closure Model

Contact + Remote Loading









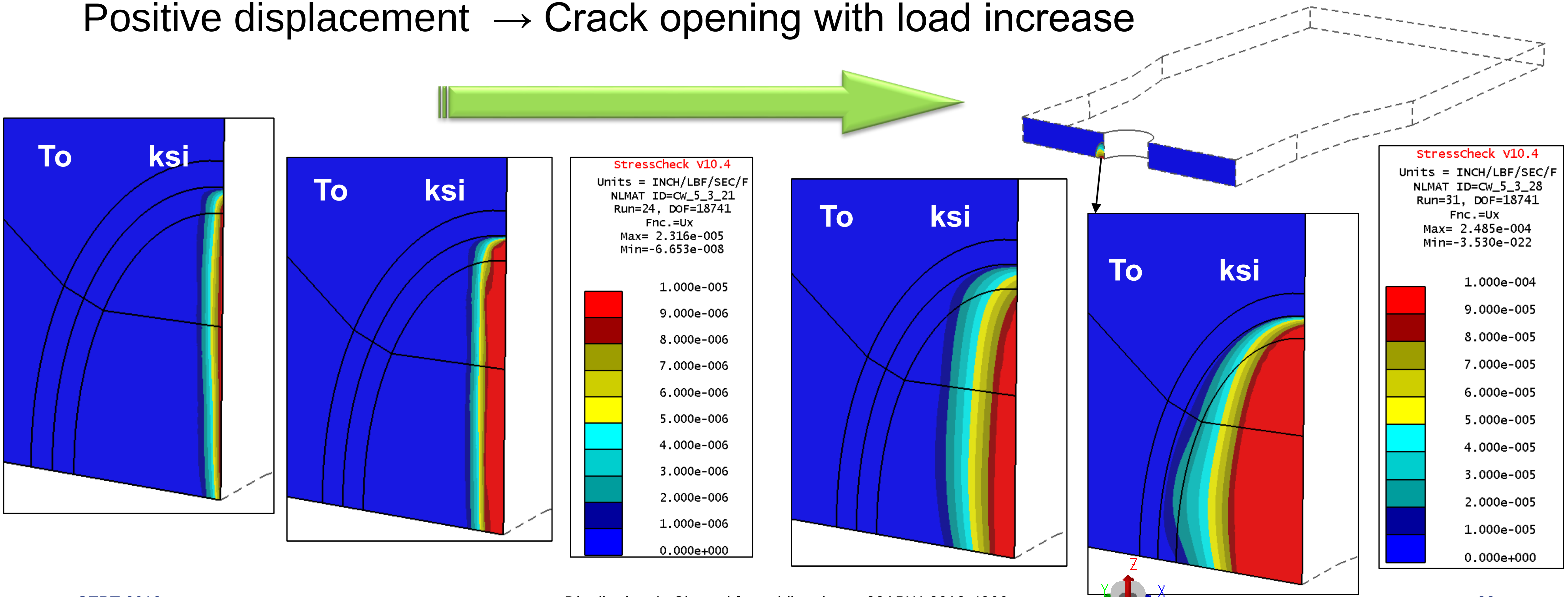
Distribution A: Cleared for public release 88ABW-2018-4366

Closure Model

Contact + Remote Loading

Displacement normal to the symmetry plane

Positive displacement → Crack opening with load increase

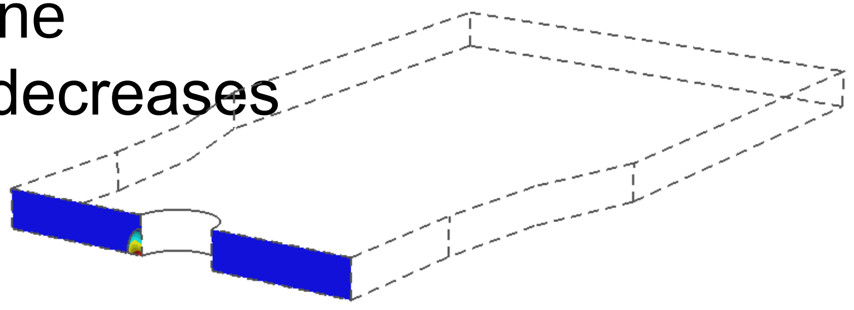


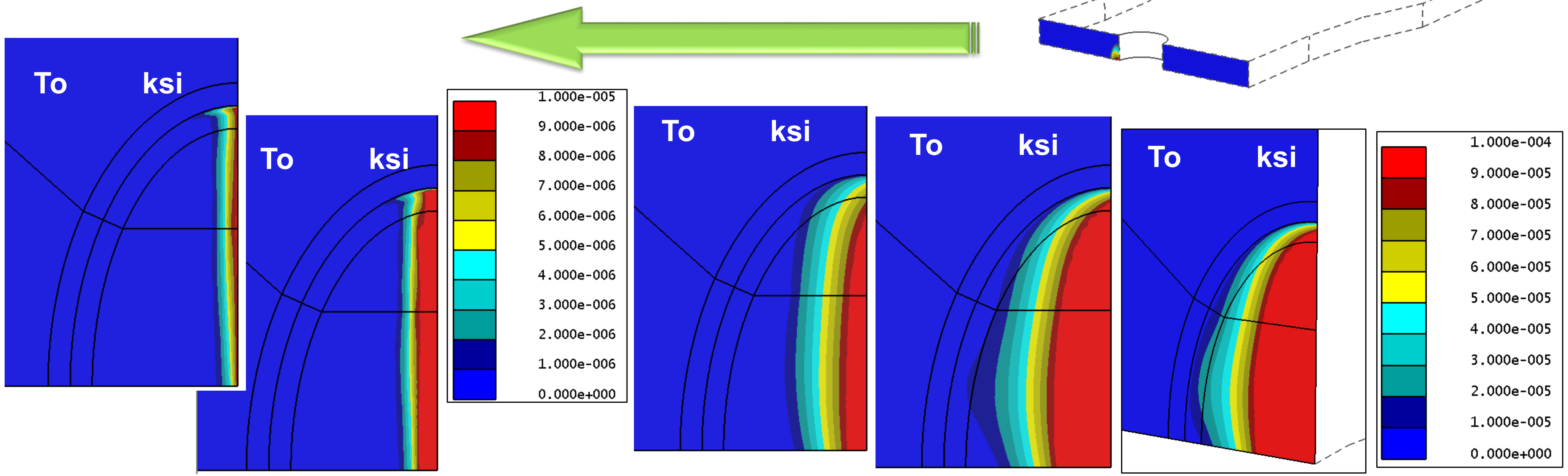
Closure Model

Contact + Remote Unloading

Displacement normal to the symmetry plane

Positive displacement → Crack closing as load decreases

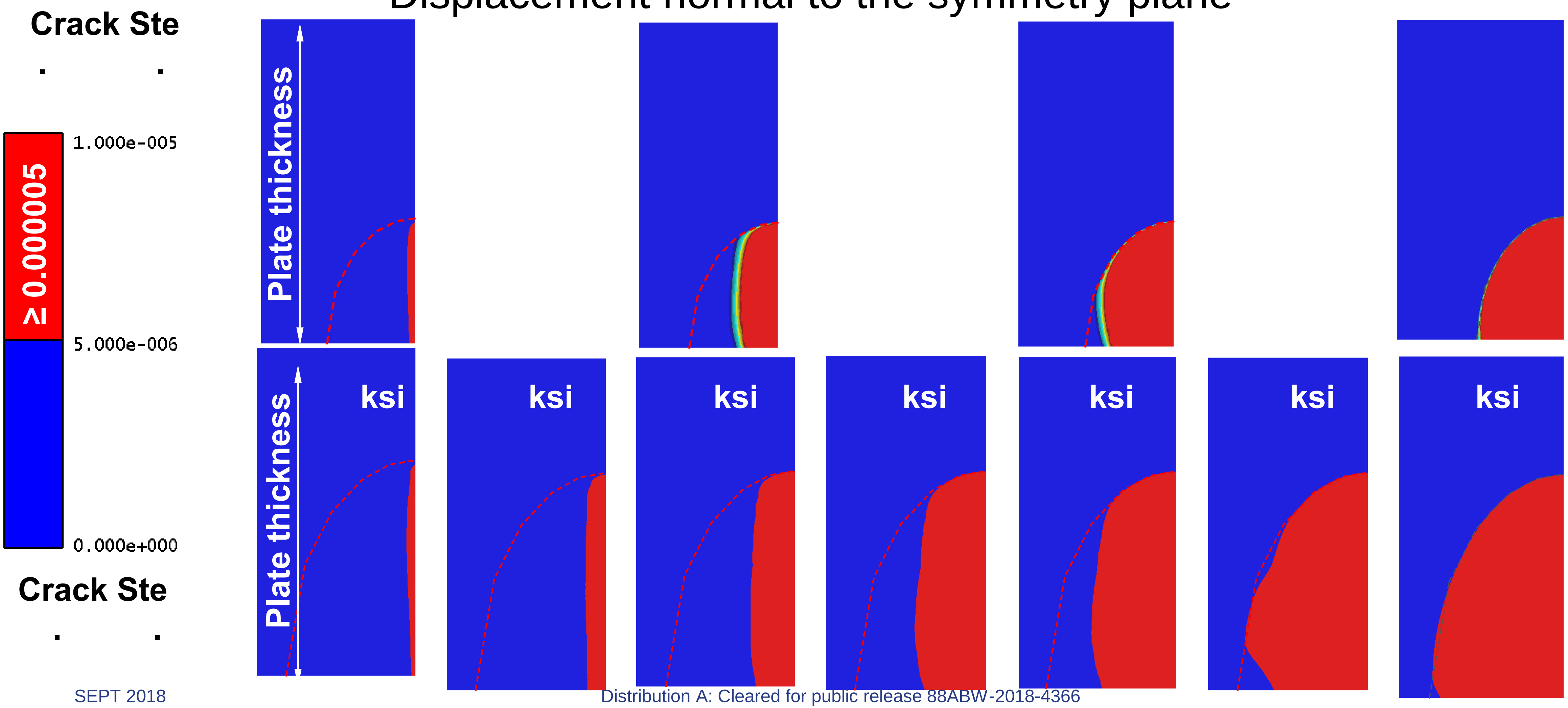




Closure Model

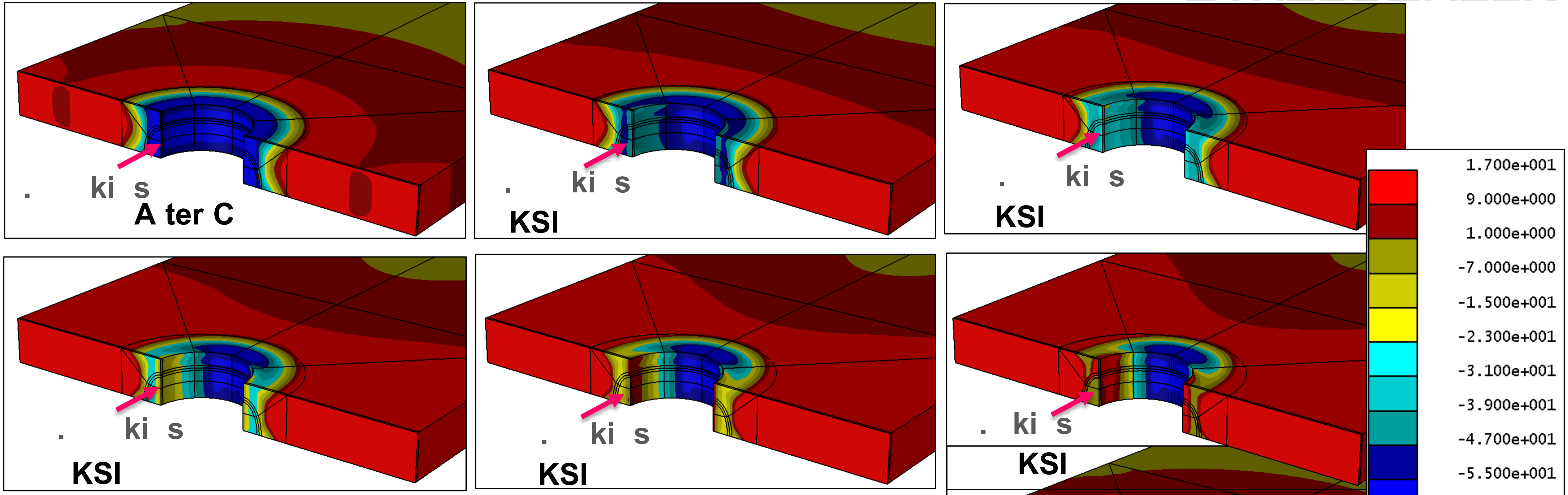
Crack Opening Summary

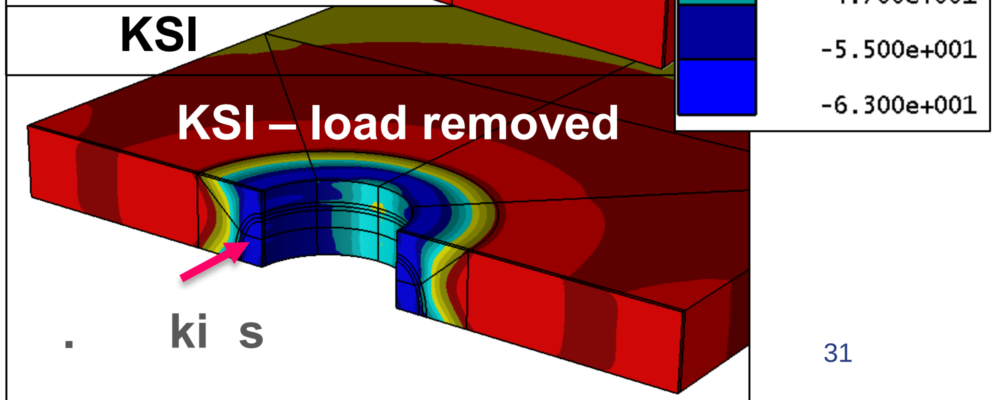
Displacement normal to the symmetry plane



Closure Model

Residual Stress Summary





Variation of the Hoop residual stress component as the load was increased to 27 KSI and then removed. All contours in the range of the CW residuals.

Summary

Future Work

- More work scheduled for FY19
- Check back with us at ERSI 2019!

Air orce Research La oratory

Nondestructive Ins ection NDI Su committee Overview

Engineered Residual Stress Im lementation ERSI   orksho

13 September 2018

John Brausch[1], Ward Fong[2]

[1]AFRL/RXSA, Systems Support Division
Materials and Manufacturing Directorate
Air Force Research Laboratory
Wright-Patterson AFB, OH 45433
[2] Ogden NDI Program Office, Hill AFB, UT

Integrity ★ Service ★ Excellence

Overview

- Summary of Current Knowledge
- Gaps
- ERSI 2017 Priorities
- Progress since 2017

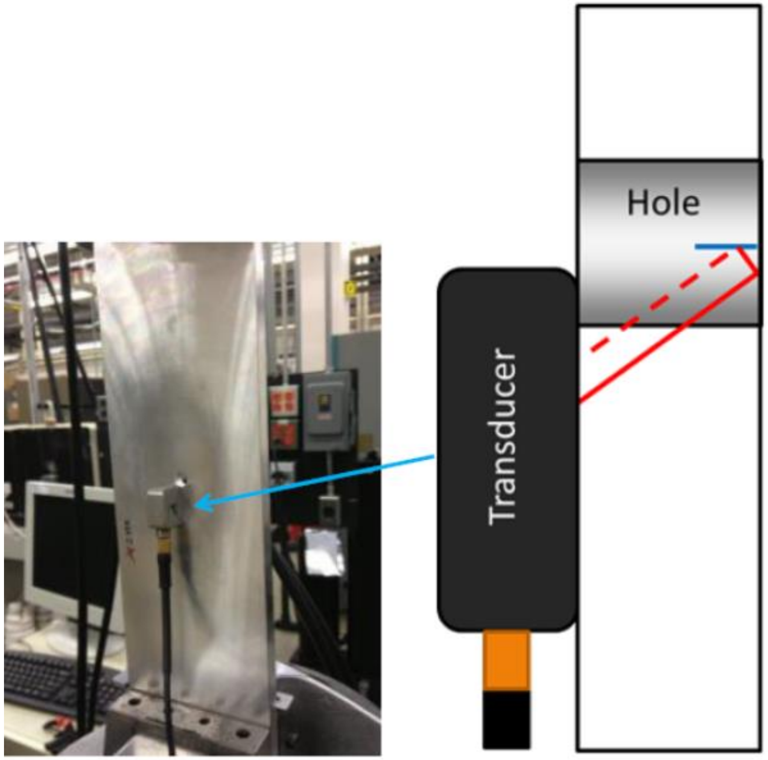
NDI Subcommittee Members

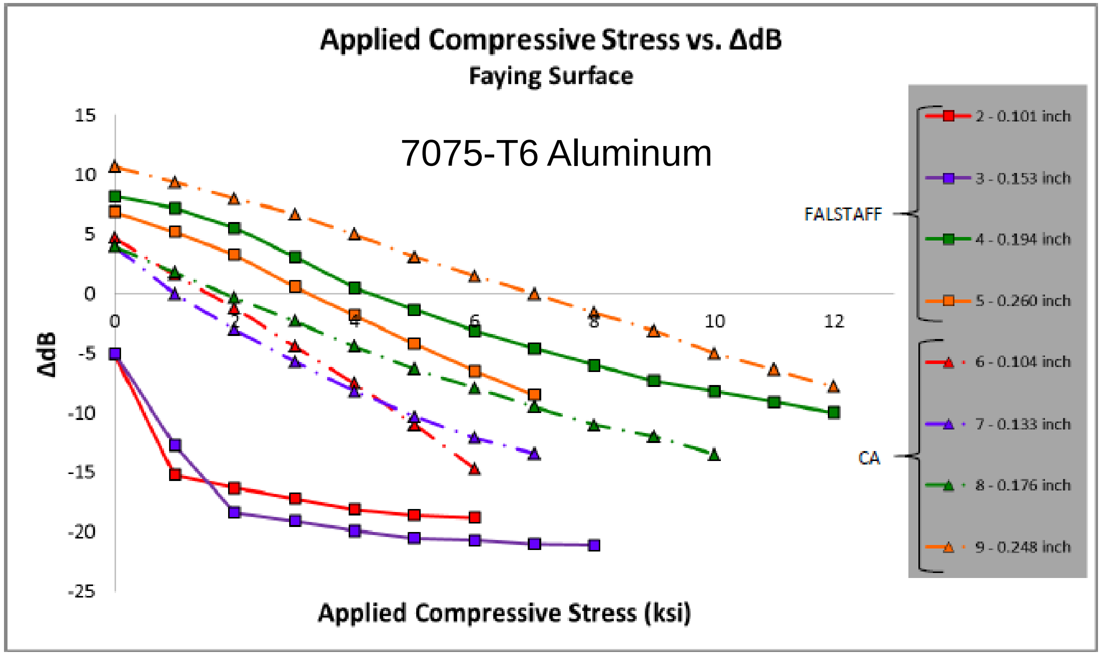
Title	First Name	Last Name	Company/Organization	Phone Number	Email Address
Mr.	John	Brausch	U.S. Air Force (AFRL - NDE Lead Engineer, Systems Support)	(937) 656-9151	john.brausch@us.af.mil
Dr.	Mike	Hill	Hill Engineering, LLC	(530) 754-6178	mrhill@hill-engineering.com
Mr.	Fred	Acosta	U.S. Marine Corp (F-5 NDI Lead)	(928) 580-5978	alfredo.acosta.ctr@usmc.mil
Mr.	Dave	Campbell	U.S. Air Force (Tinker AFB NDI Program Office Lead)	(405) 736-5008	david.campbell.2@us.af.mil
Mr.	Ward	Fong	U.S. Air Force (Hill AFB NDI Program Office Lead)	(801) 775-2483	ward.fong@us.af.mil
Mr.	Dave	Forsyth	Texas Research International (TRI) - Austin, Inc.	(512) 263-2101	dforsyth@tri-austin.com
Dr.	Carl	Magnuson	Texas Research International (TRI) - Austin, Inc.	(785) 766-8896	cmagnuson@tri-austin.com
Mr.	Tommy	Mullis	U.S. Air Force (Warner Robins AFB NDI Program Office Lead)	(478) 327-4122	Roy.Mullis@us.af.mil
Mr.	Clint	Thwing	Southwest Research Institue (SwRI)	(210) 522-3989	clinton.thwing@swri.org
Mr.	Mike	Reedy	U.S. Navy - NAVAIR - Compression Systems Engineer	(301) 757-0486	michael.w.reedy1@navy.mil
Mr.	Bryce	Harris	U.S. Air Force (F-16 ASIP Manager)	(801) 777-9381	bryce.harris@us.af.mil
Mr.	Jacob	Warner	U.S. Air Force (F-22 System Program Office - Structural Analysis)	(801) 586-8181	jacob.warner@us.af.mil
Mr.	Leo	Garza	L3 Communications - RC-135 Fleet Manager	(903) 457-4595	leo.garzaiii@L-3com.com
Dr.	Teodor	Dogaru	Southwest Research Institute (SwRI)	(210) 522-3139	teodor.dogaru@swri.org

Applied Compressive Stress

Shear-Wave Ultrasonics

Ultrasonic response from fatigue cracks under applied compressive stress.





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

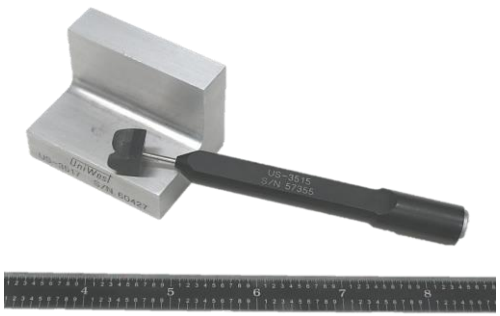
Significant Impact

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

Laser Shock Peening

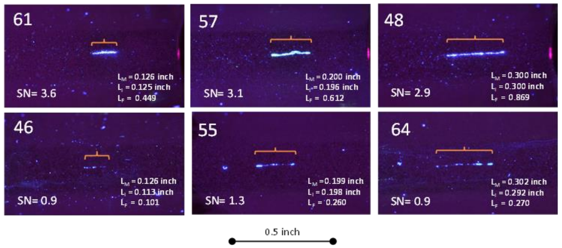
Eddy Current, Ultrasonics, Fluorescent Penetrant

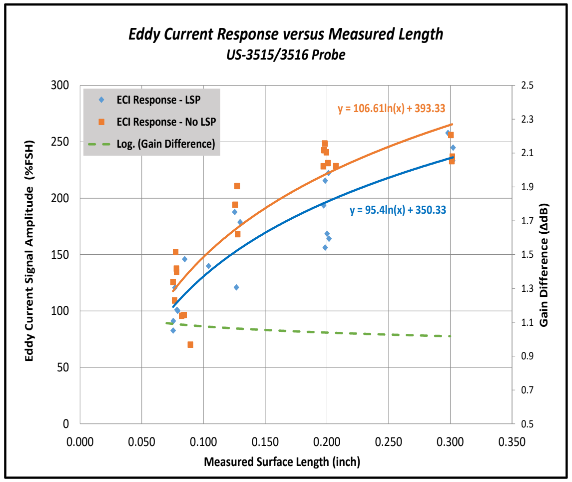
Eddy Current

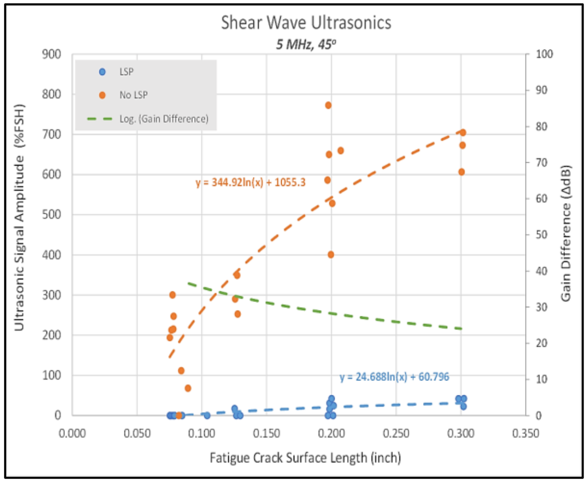


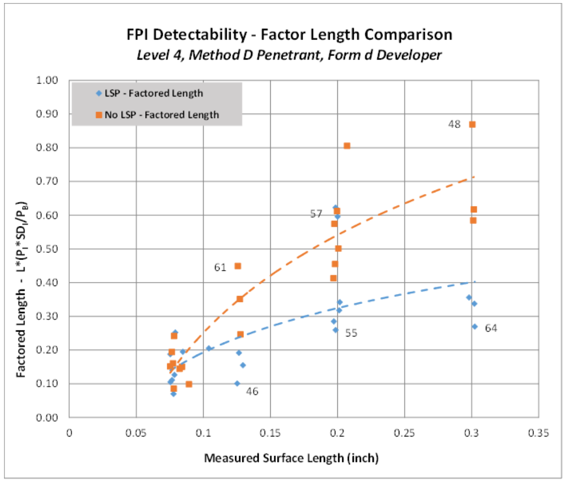
Ultrasonics

Fluorescent Penetrant









Minimal Impact

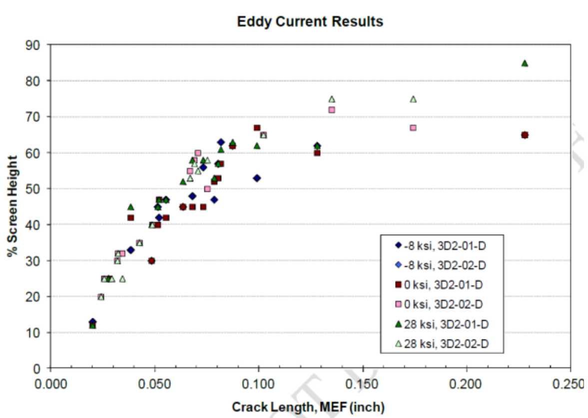
Significant Impact

Significant Impact

Hole Cold Working

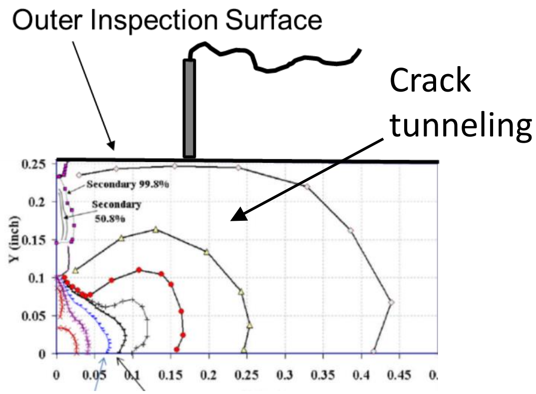
Eddy Current, Ultrasonics

Rotary Hole Eddy Current

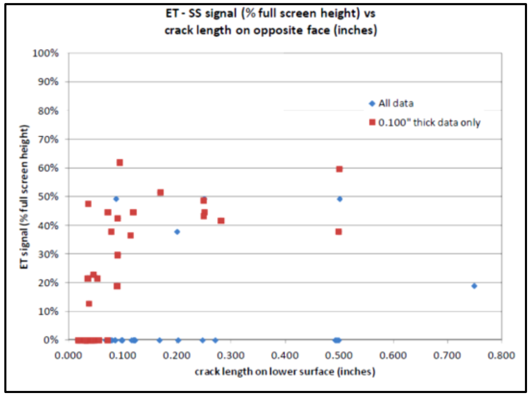


Minimal Impact

Surface Eddy Current

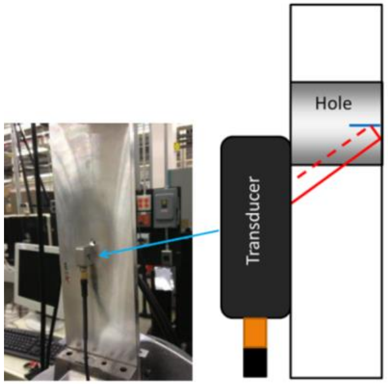


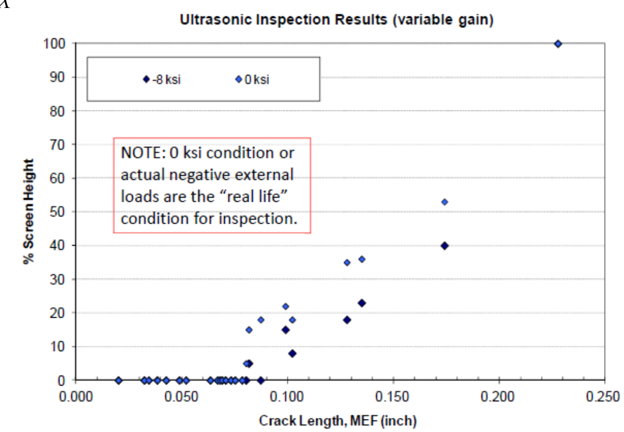
Forsythe, D., Mills, T. "Results of Study of Applied Stress and CX Process on Detectability of Fatigue Cracks"



Significant Impact

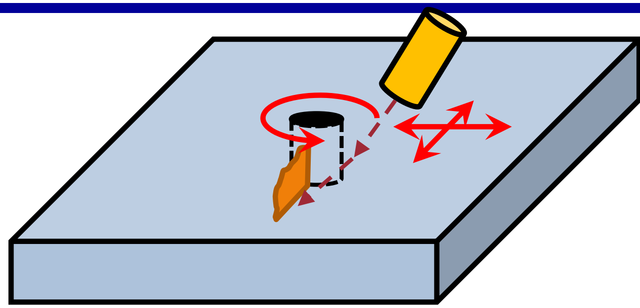
Ultrasonics

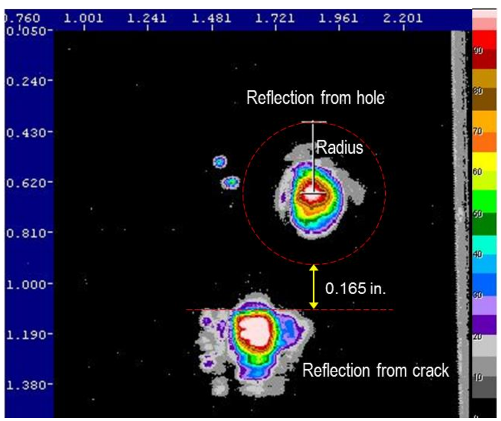


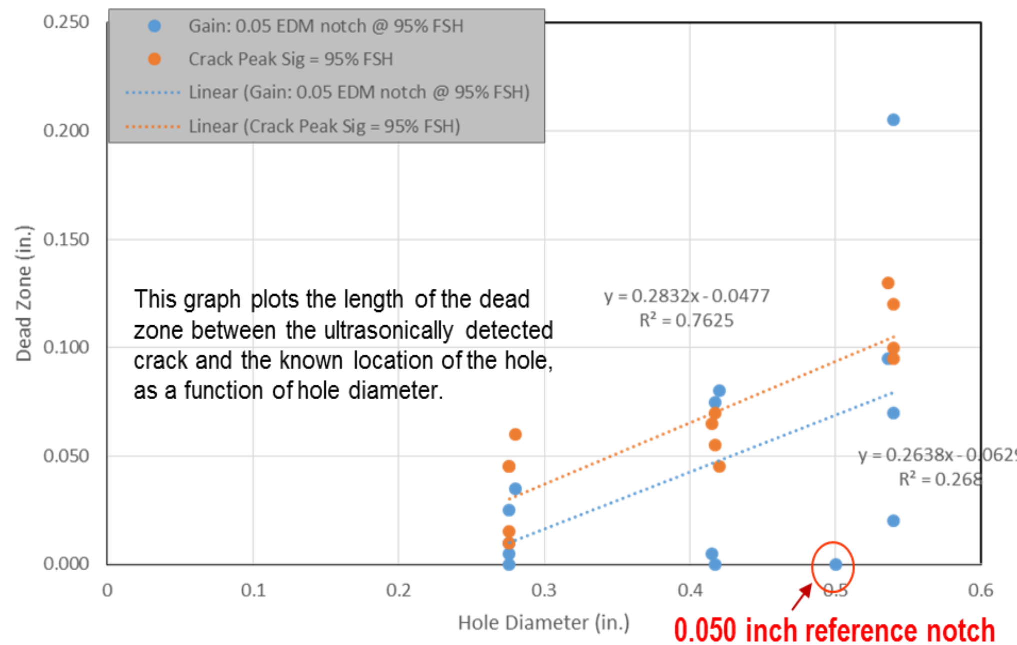


Significant Impact

Ultrasonic “Dead-Zone” in Cx Holes







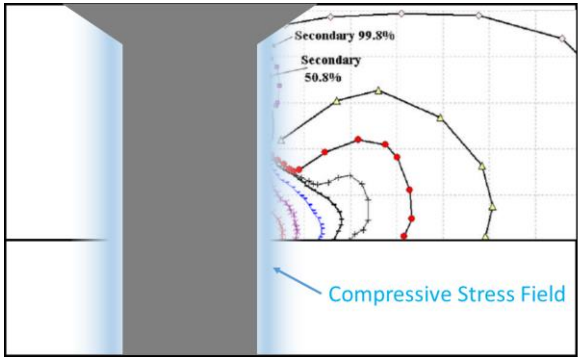
DZ = 0.3219*Diameter - 0.038

- *Dead zone proportional to hole diameter but scatter suggests other influencing factors.*
- *Use upper bound of UT dead zone estimates to correct UT POD estimates for Cx holes.*
- *Ultrasonic inspections must be designed to interrogate beyond the tangency of the hole.*

Ultrasonic “dead zone” proportional to hole diameter.

Gaps

- Ultrasonic "Dead Zone" at Cx Holes
  - Quantify UT "Dead Zone" for a range of Cx applied expansion ranges
  - Investigate causes of "Dead Zone" variability
  - *Define UT POD correction factors for Cx holes*
  - *Define optimum UT system design for Cx holes*



- Fastener Installation on UT Detectability
  - Taper-Lok fasteners
  - Interference fit fasteners
  - Interference fit fasteners installed at Cx holes
- Other ERS Surface Treatments and Materials
  - Shot peening, low plasticity burnishing – on aluminum and titanium (UT and FPI focused)
  - Laser Shock Peening (LSP) on titanium alloys

NDI Subcommittee Priorities

- **Priority I. uanti y T dead one in C holes. Develo T POD correction actors.**
  - **Ma T dead one or C holes – range o thicknesses and diameters**
  - T-38 wing skin coupons – generate cracks in aircraft skins
    - Production Cx
    - TCTO Cx
  - **Ca ture data w/ e isting T ins ection systems – alidate o timum ins ection rocess.**
    - **Rotoscan**
    - **A IS SA and Navy**
  - **Measure residual stresses in su set o s ecimens using contour method**
    - **ractogra hically si e su set o s ecimens**

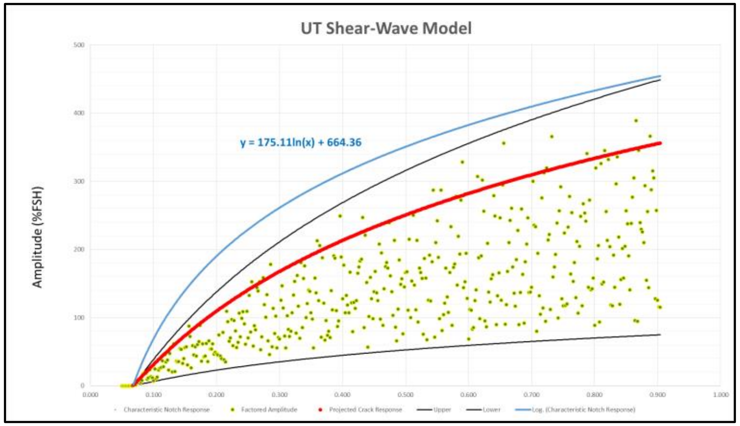
✓ **Priority II. EN-SB- - date**

- **Priority III. Investigate the im act o astener installation on ultrasonic atigue crack detecta ility**
  - **Ta er-Lok asteners – A/C rogram riority**
  - Interference fit fasteners
  - Interference fit fasteners installed in cold worked holes.

Progress Since 2017

- Published EN-SB-008-012 Rev D, April 2018
  - Impact of Cx on surface eddy current inspection
  - Impact of Cx on ultrasonic inspection of Cx fastener holes
    - Estimates of dead zone for POD correction
  - Restrictions for use of FPI and UT on Laser Peened Al structures

- Incorporated current knowledge into UT POD model
  - Applied compressive stress
  - Ultrasonic dead zone in Cx holes



- Supporting a/c program in the development of empirical ultrasonic inspection data for inspection around taper-lok fasteners – contract action pending.

QUESTIONS?

NDI/QA/Data Subcommittees
2017 Breakout Attendees

Name	Company/Organization	
Mr. John Brausch*	U.S. Air Force (AFRL - NDI Lead Engineer, Systems Support)	NDI Subcommittee Lead
Ward Fong	U.S. Air Force - Hill AFB NDI Program Manager	
Doyle Motes	Texas Research International (TRI) - Austin, Inc.	
Nick Bunnell	U.S. Air Force - Robins AFB NDI Level 3	
Tommy Mullis	U.S. Air Force - Robins AFB NDI Program Manager	
Mike Dubberly	Consultant	
Eleazar Morale	AFSC/ENSI-NDI Engineering	
Tom Driscoll	AFLCMC/LPSE - Propulsion NDI Engineering	
David Campbell	Tinker AFB NDI Program Manager	
Josh Hodges	Hill Engineering	
Mike Brauss	Proto Mfg Inc.	
Taylor Thompson	Proto Mfg Inc.	
Teodor Dogaru	SouthWest Research Institute	
Maj Joseph Wahlquist	AFRL-RXCA Branch Chief	
Eric Lindgren	AFRL-RXCA Research Lead	
Bryce Harris	F-16 ASIP Program Manager	
Leo Garza	L3 Tech	
Walt Matulowicz	AFLCMC/EZPT USAF NDI Program Office	
Mark Kassan	AFSC/ENSI	
Mike Paulk	AFLCMC/EZPT NDI Program Office - Chief	

NDI Subcommittee Refined Priorities

Priority I. uanti y T dead one in C holes. Correlate to hole D and T.

- Round Robin - Map UT dead zone for Cx holes – selected specimens
  - RXSA, RXCA, AFSC/ENSI
  - **Need stress ro iles rom al/ er Test Su committee – T. Mills**
- Measure surface stress/deformation profiles on select Cx specimens
  - PROTO via Navy SBIR, Fastener Cam via USAF SBIR
- Machine countersink, install interference fit fasteners
  - Measure stress profiles of select specimens – PROTO via Navy SBIR
  - Re-measure UT dead-zone on selected Cx specimens
- Capture data w/ existing UT inspection systems - Validate optimum inspection PAUT process – all available specimens Cx vs non-Cx AFRL/RXSA coordinates with NAVAIR/Hill AFB.
  - o Rotoscan
  - o AFIS (USAF and Navy)

NDI Subcommittee Refined Priorities

Priority II. Investigate im act o Ta er-Lok astener installation on ultrasonic atigue crack detecta ility

- **Model Ta er-Lok stress ield – Needed rom Modeling Team**
- Empirical measurements of UT response under planned a/c program effort

Priority III. Characteri e im act o laser- eening on titanium.

- Integrate measurements into planned a/c qual. programs

U.S. AIR FORCE

Quality Assurance and Data Management for the Inclusion of Residual Stresses

Hazen Sedgwick

A-10 ASIP, USAF

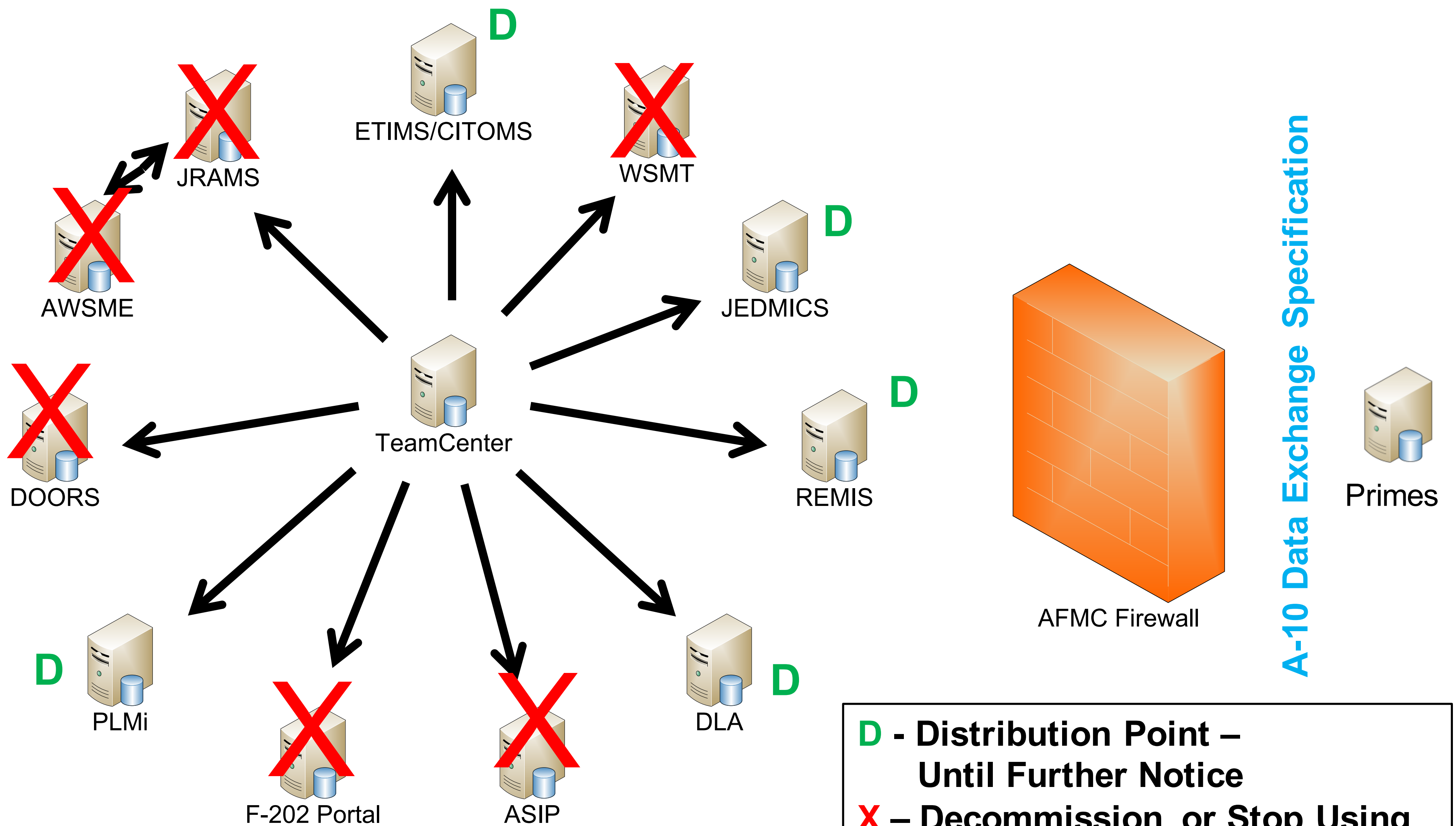
Hazen.Sedgwick@us.af.mil

13 Sept 2018

Overview

- Data management
  - A-10 PLM
  - MBD structure
  - PLM interaction tool (Nlign)
- Quality Assurance
  - Data capture at the point of maintenance

A-10 PLM Implementation



D - Distribution Point – Until Further Notice

X – Decommission or Stop Using

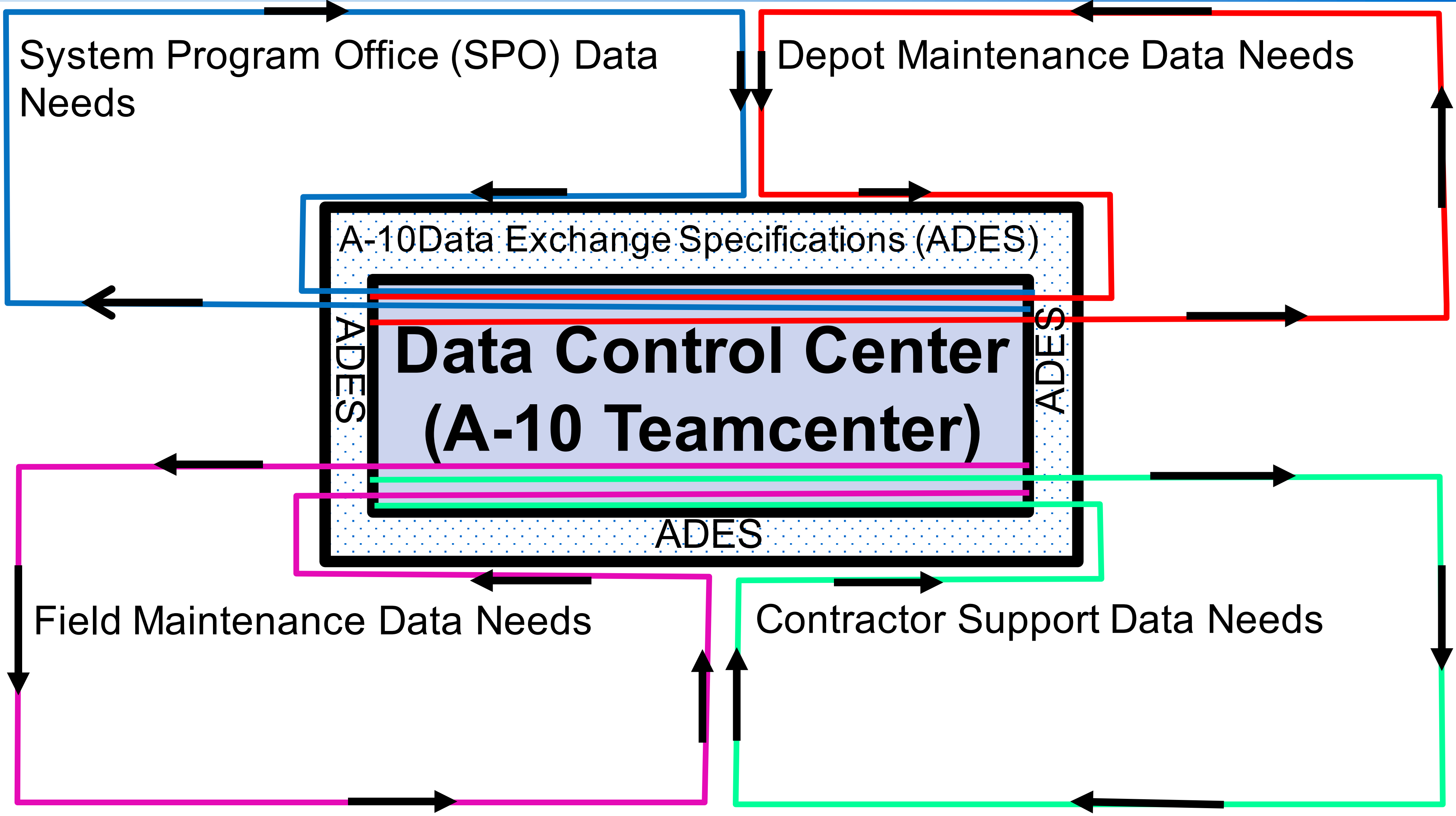
A-10 PLM Implementation

Teamcenter

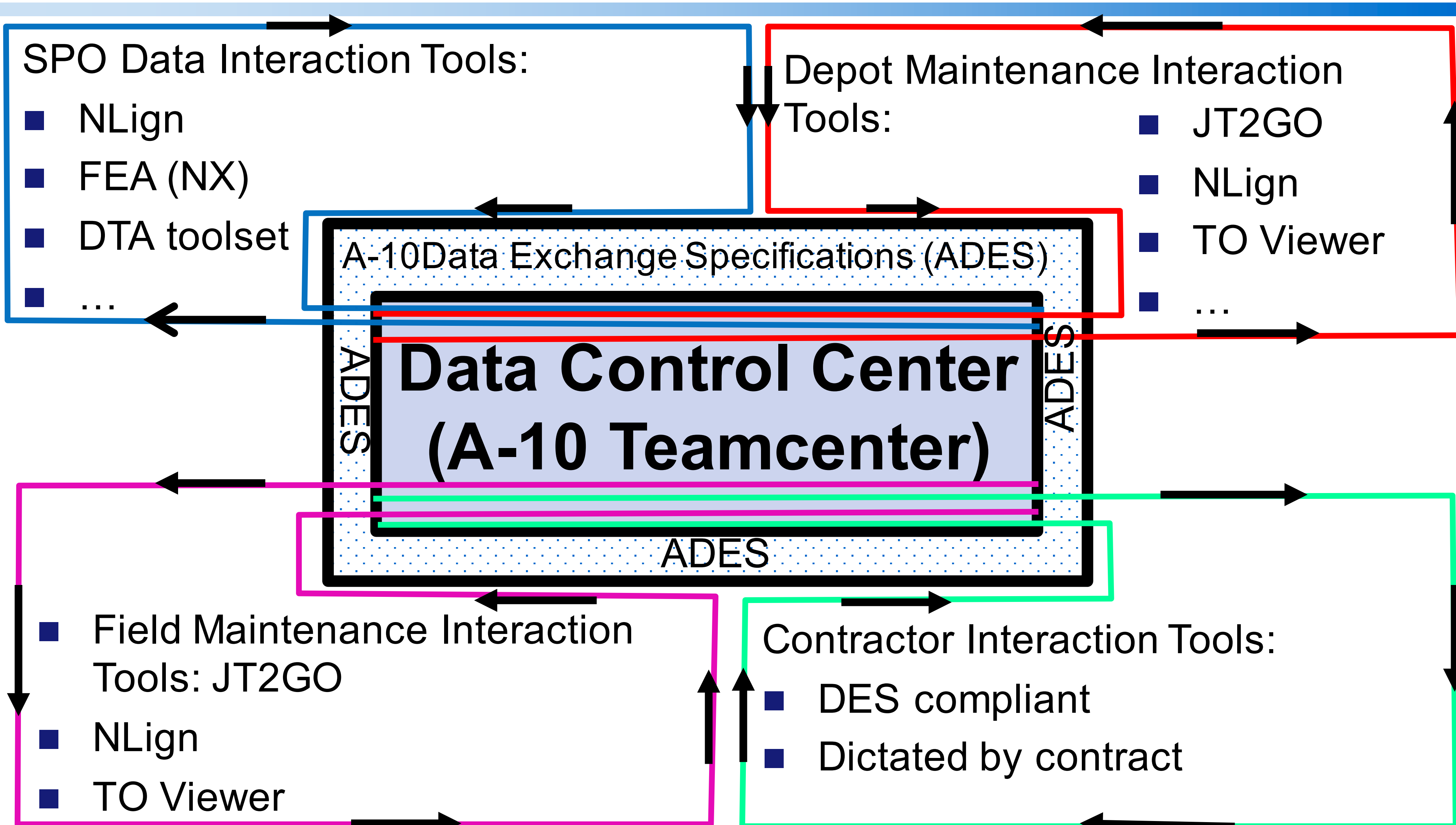
as

Single Source of Truth

A-10 PLM Implementation

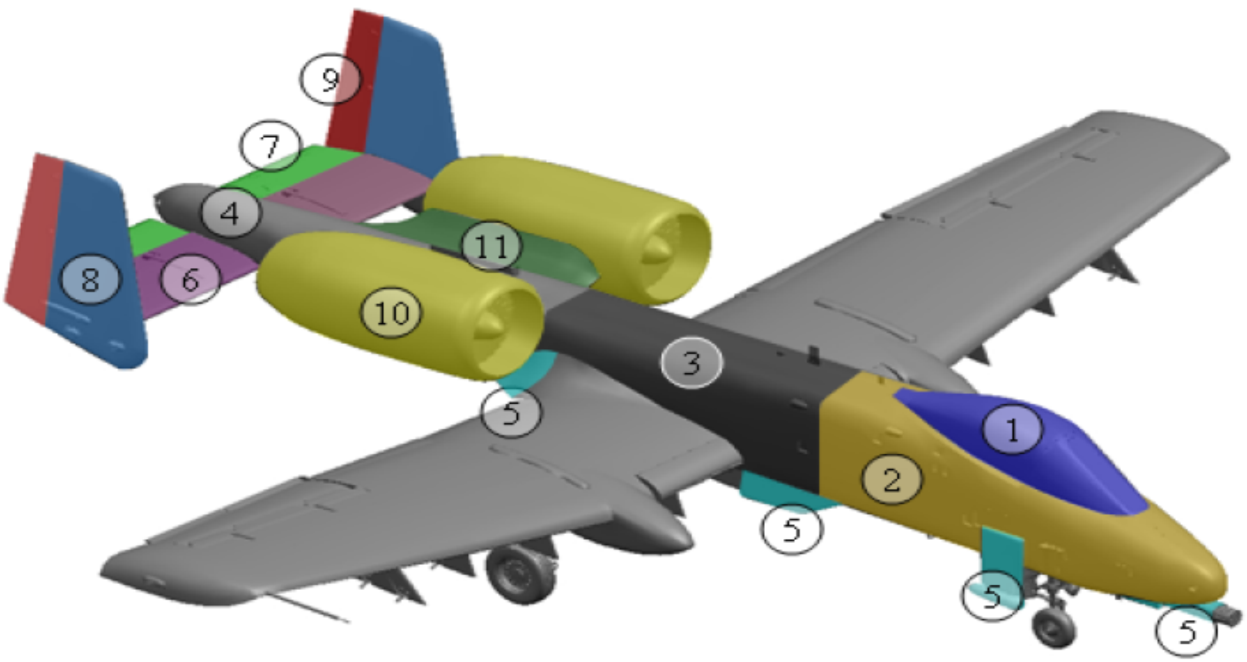


A-10 PLM Implementation



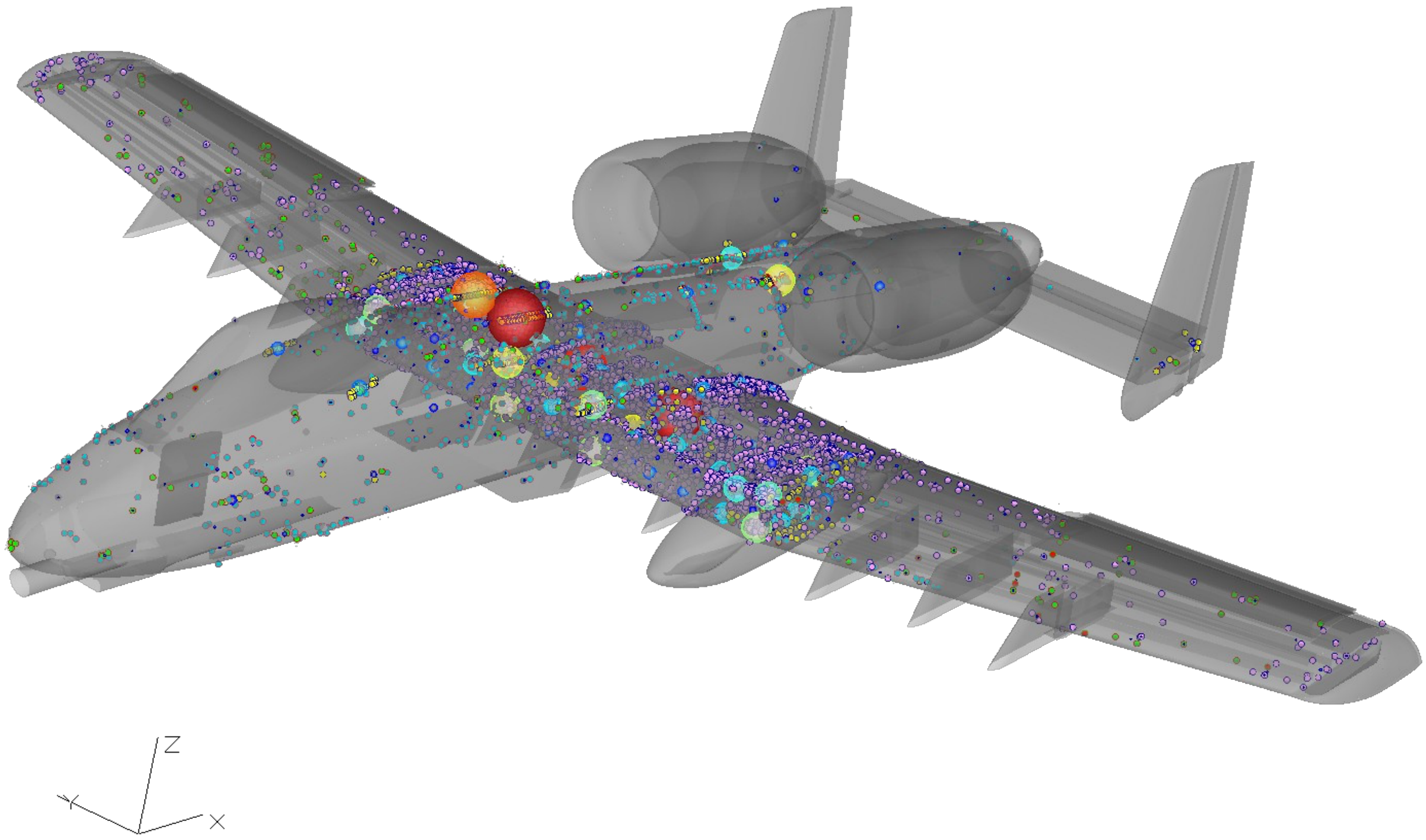
Model Based Definition (MBD)

- 3D MBD(Legacy & EWA)
  - Data managed under part number effectivity
  - Defined critical inspection locations for data management



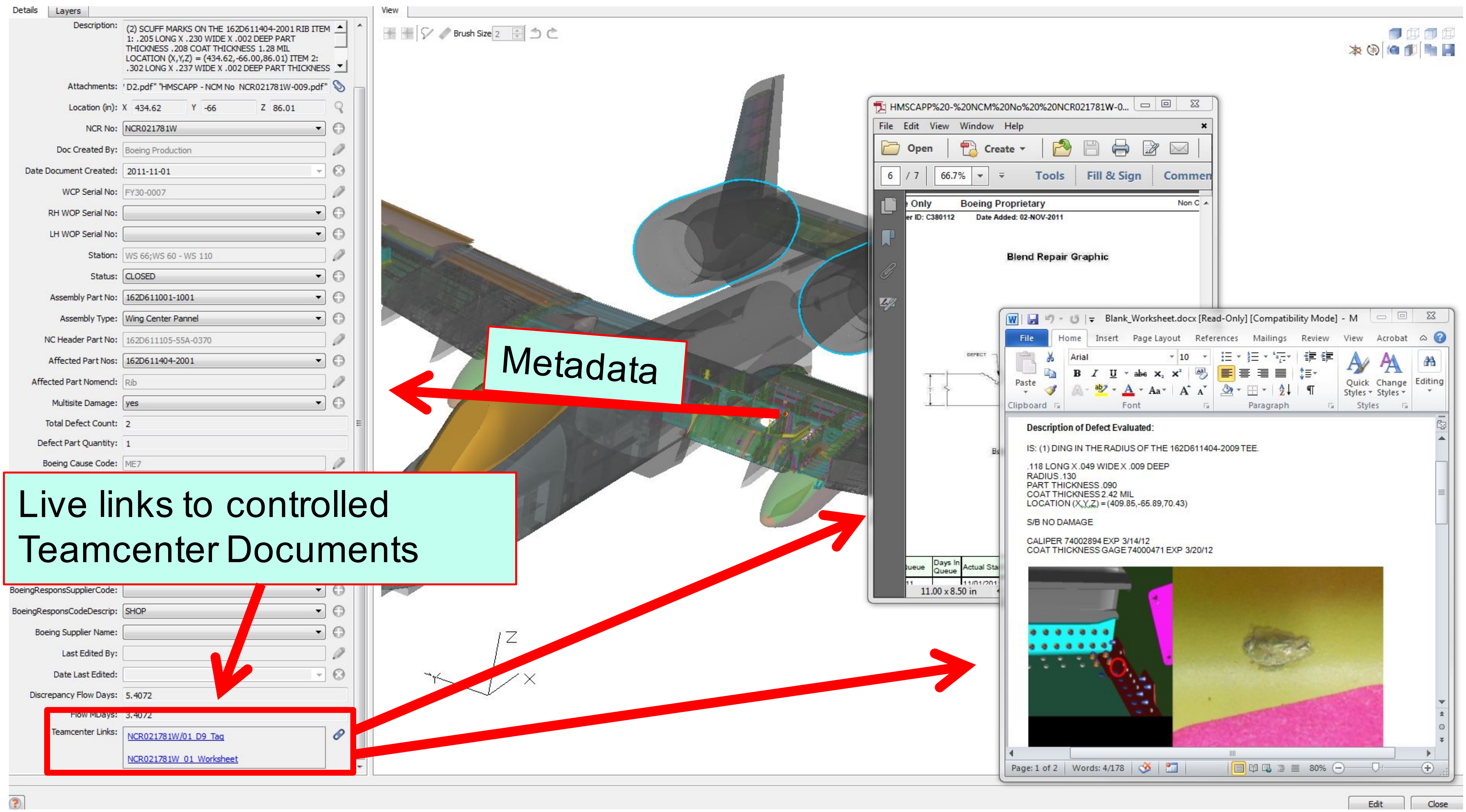
PLM Interaction Tool (NLign)

- **Visual information communication**



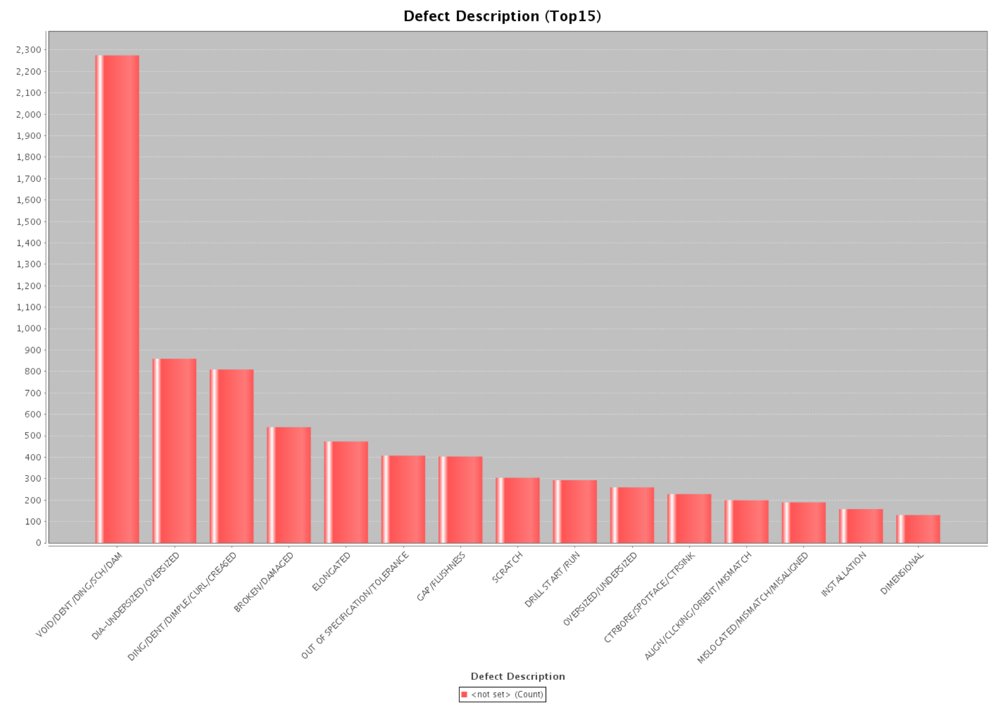
PLM Interaction Tool (NLign)

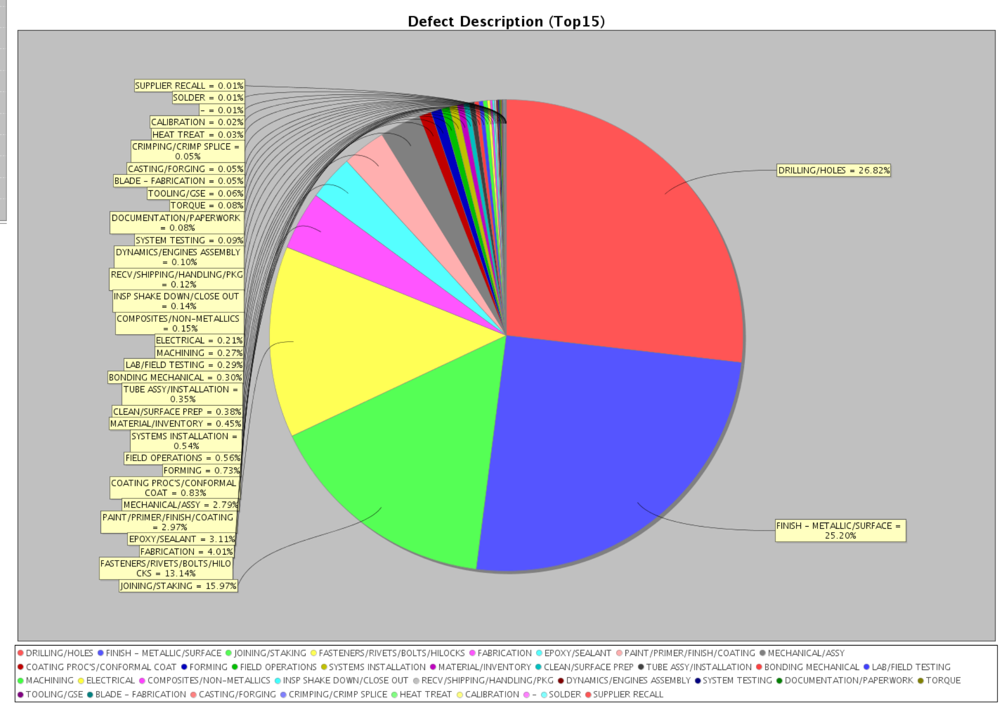
Quick data access



PLM Interaction Tool (NLign)

Live charts to quickly communicate data and feed analysis





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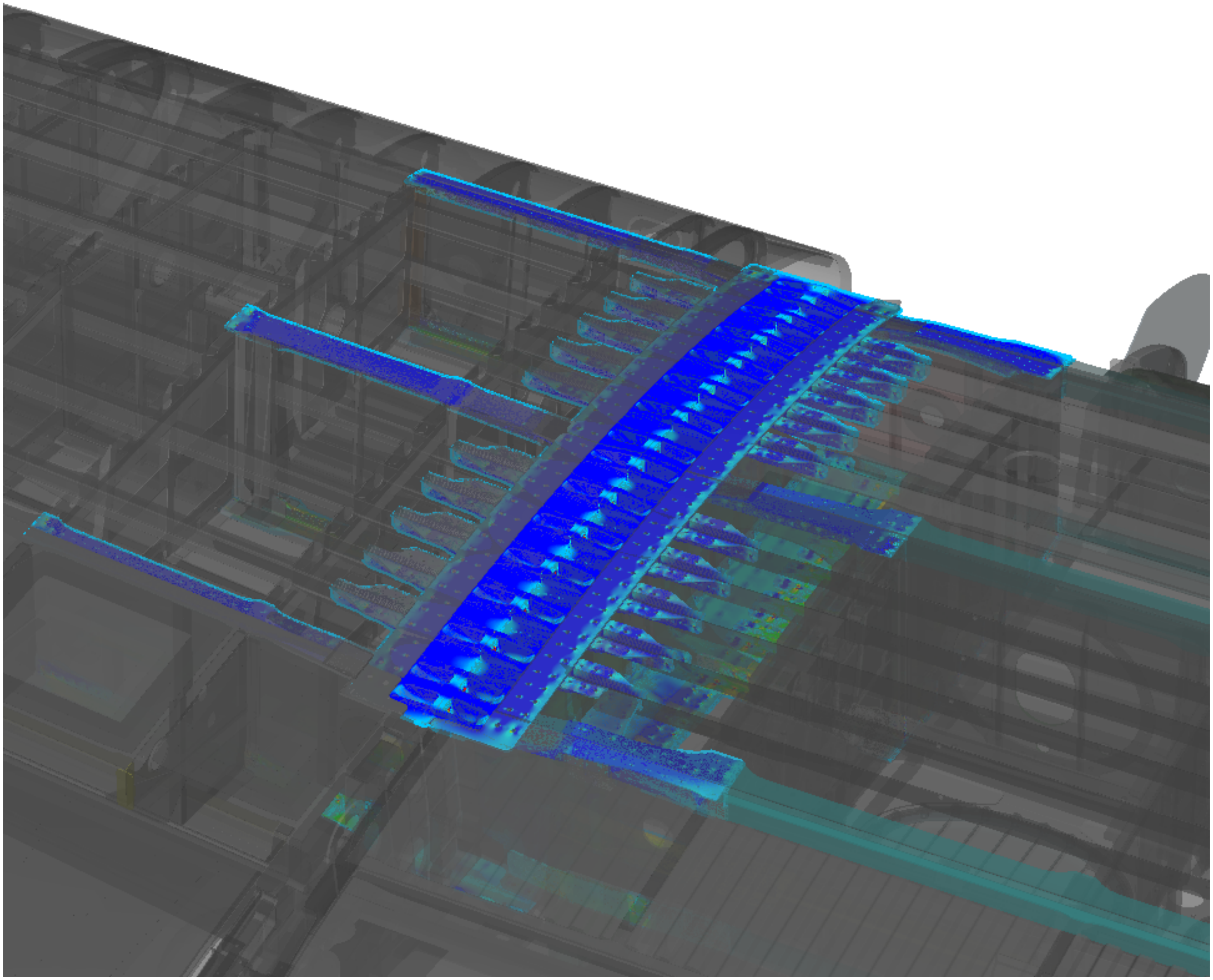
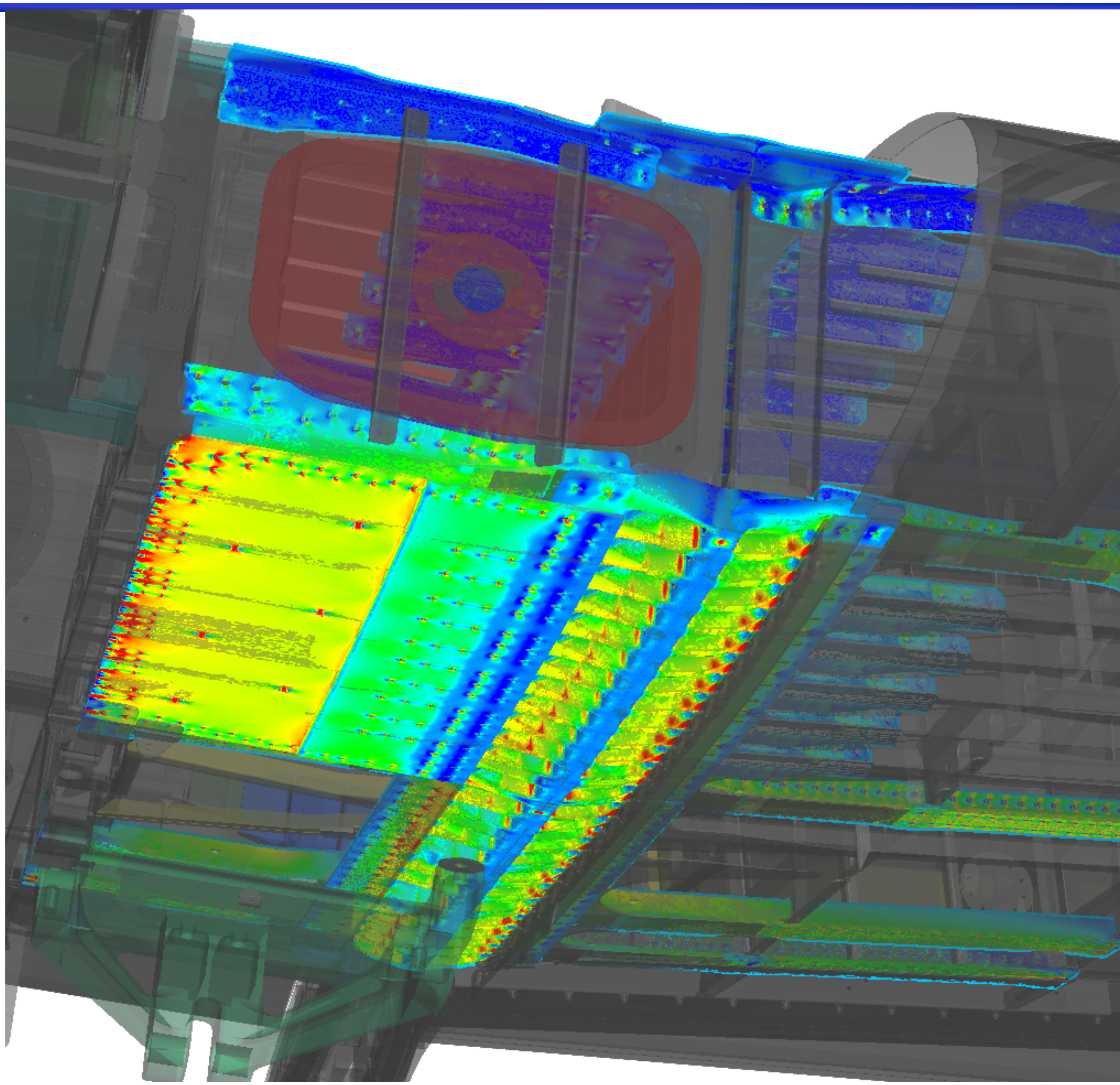
PLM Interaction Tool (NLign)



PLM Interaction Tool (NLign)



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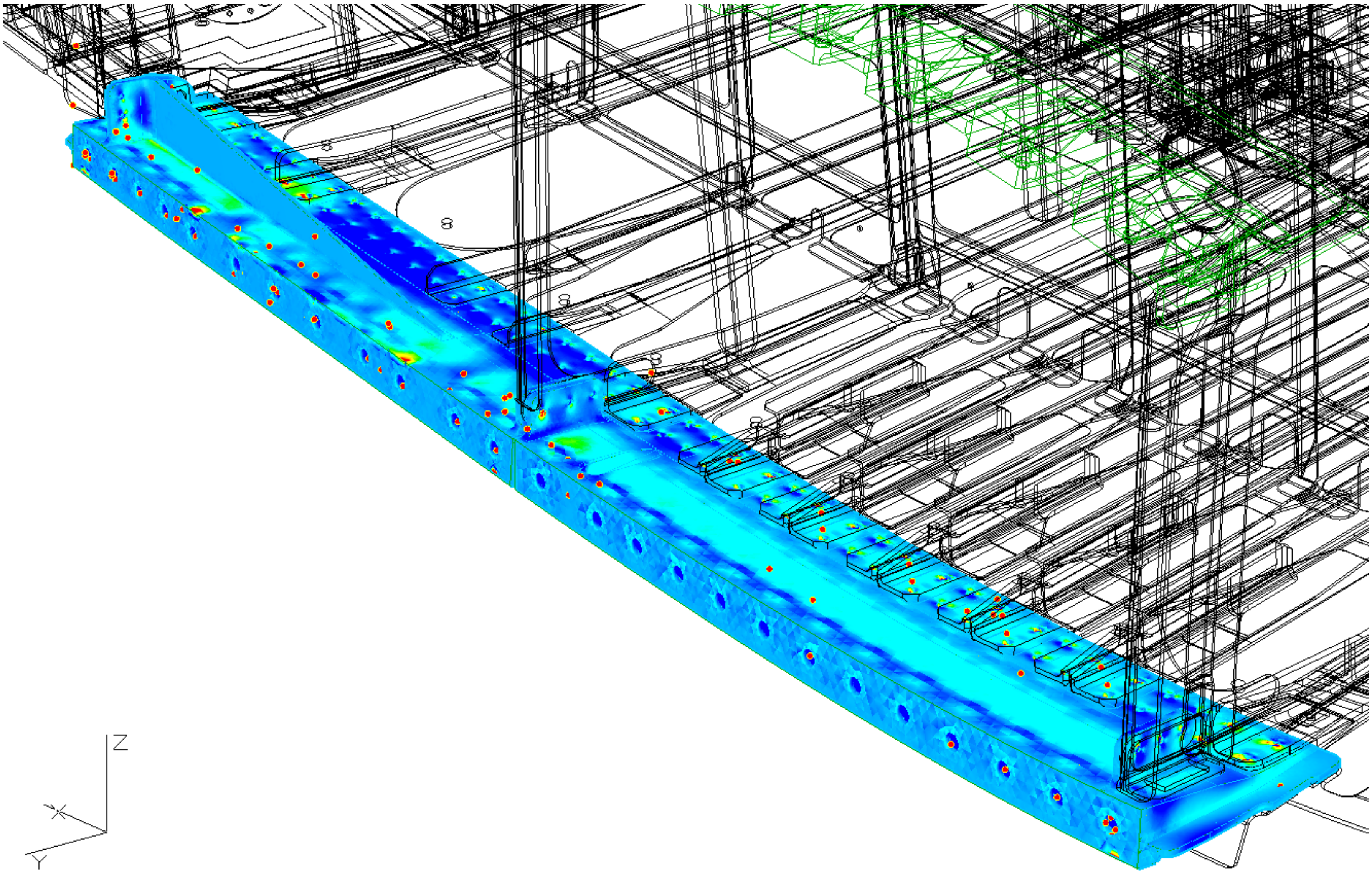

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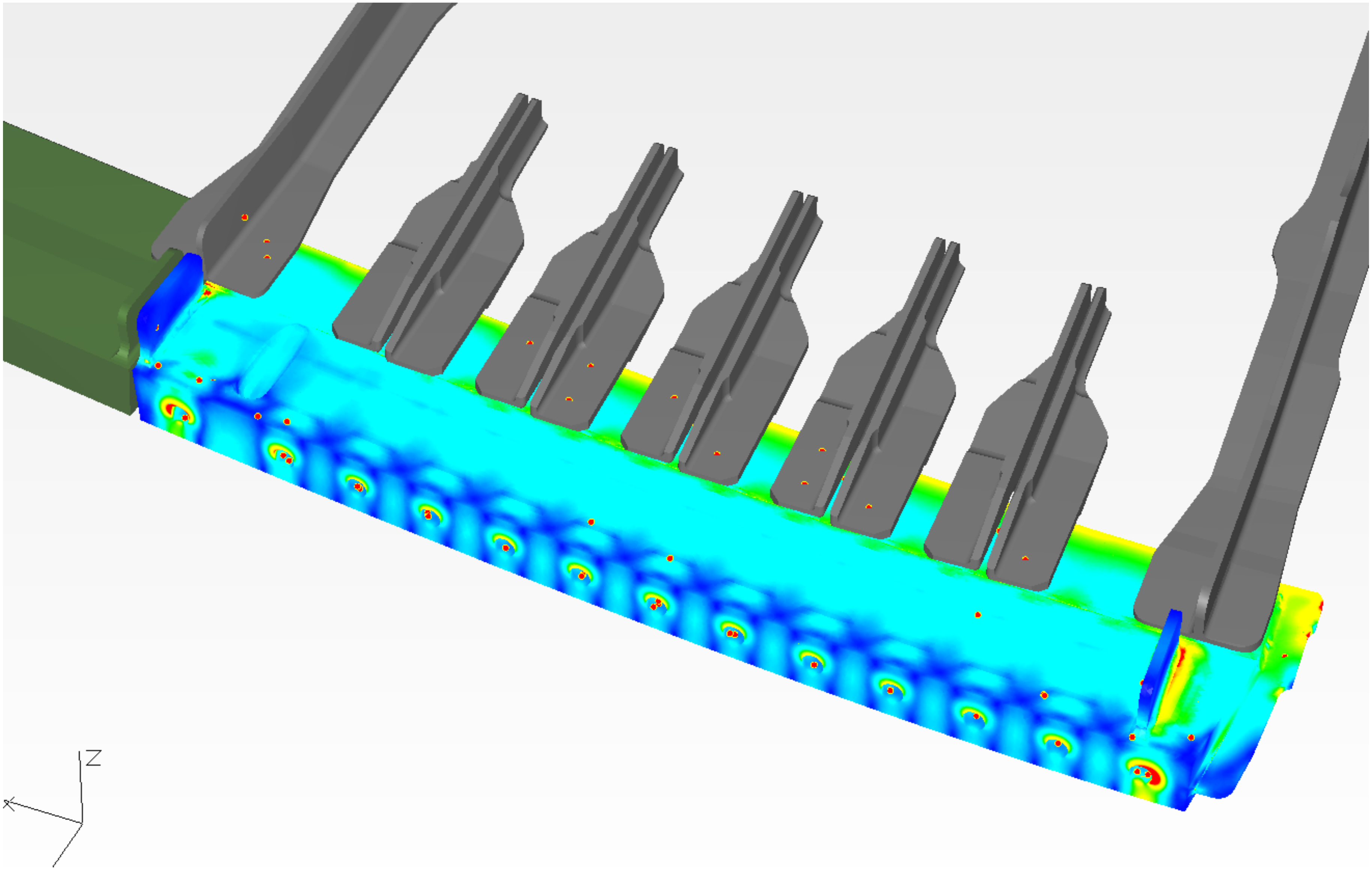
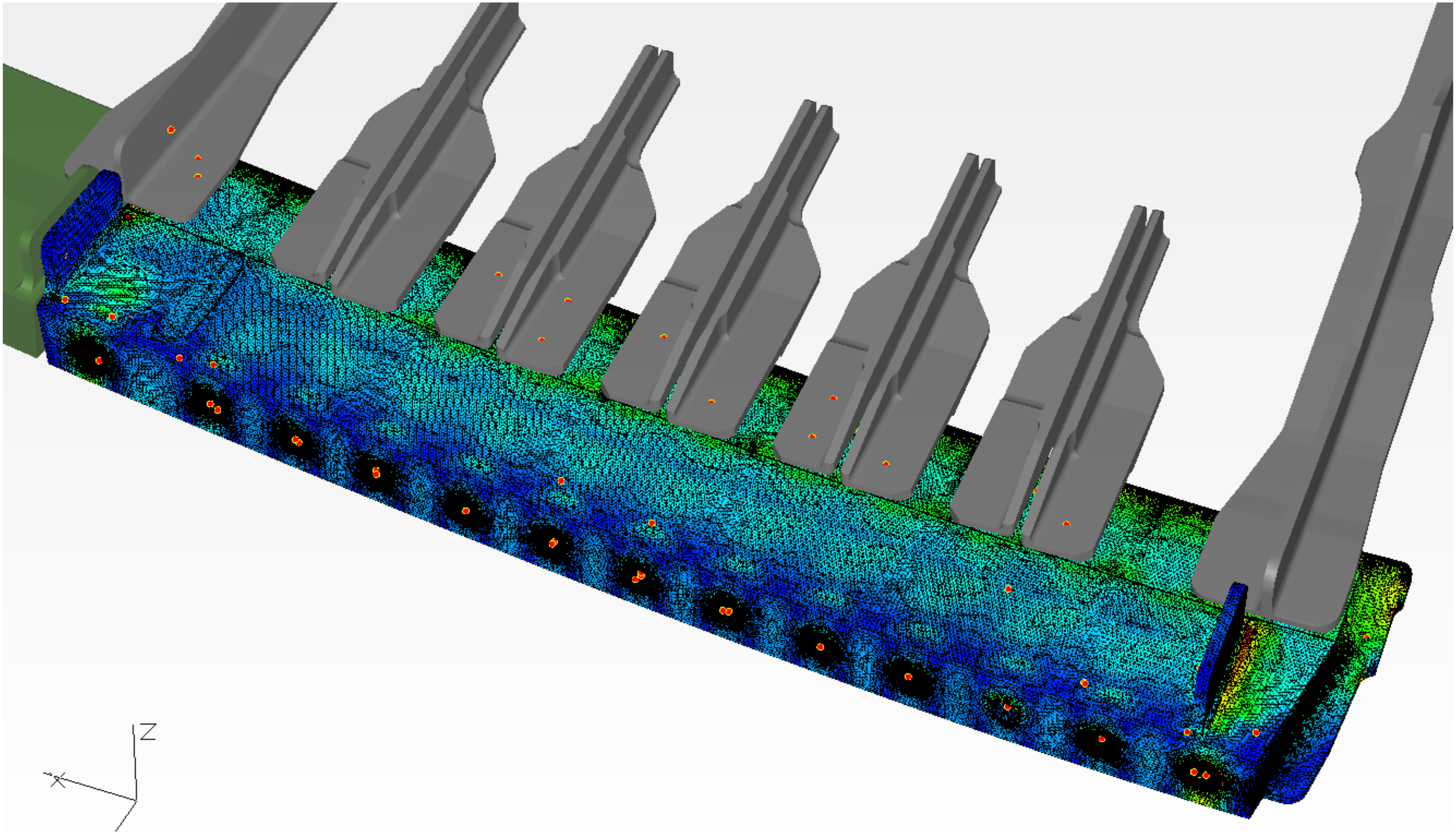


PLM Interaction Tool (NLign)



PLM Interaction Tool (NLign)

U.S. AIR FORCE

Clusters

Algorithm: Point Radius Search

Count	X	Y	Z
39	415.187	-114.86	69.063
35	433.45	-110.067	69.499
26	410.393	-110.102	68.234
21	423.858	-110.047	68.511
19	418.433	-110.072	67.941
15	429.151	-110.048	68.936
14	413.543	-110.059	68.375
8	419.979	-114.698	69.29
7	426.617	-115.123	69.857
6	431.518	-114.702	70.379
4	435.446	-110.13	70.809
3	435.766	-115.166	71.216
2	421.211	-110.351	69.245
1	423.271	-114.866	69.539
1	407.828	-114.19	68.477

Showing 15 of 15 clusters.

Isolate Selection

Display Settings

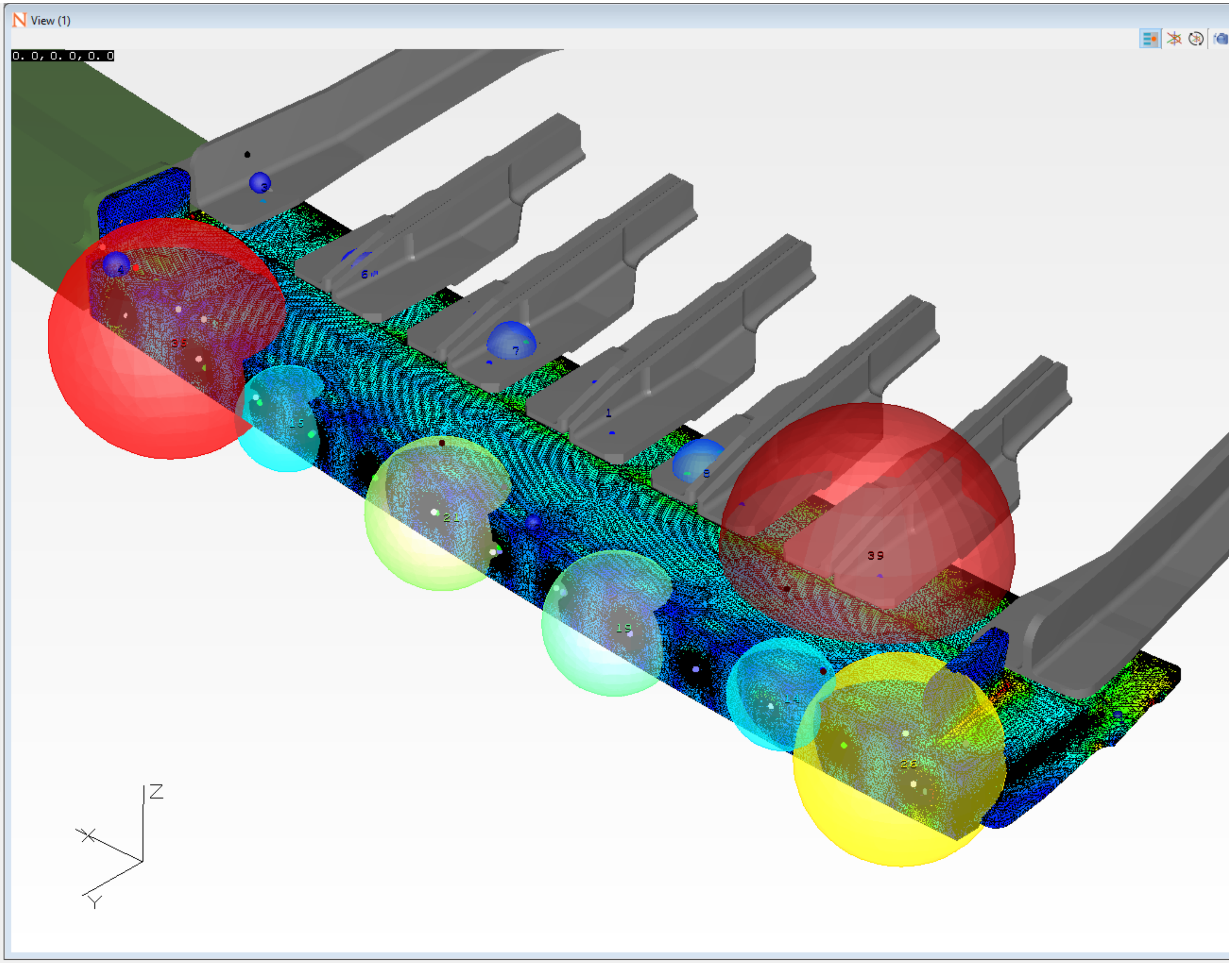
Radius: 3.00

Scale: ☑ Auto 21.53

Member Threshold: 1

Show Counts: ☑

Show Member Lines: ☐

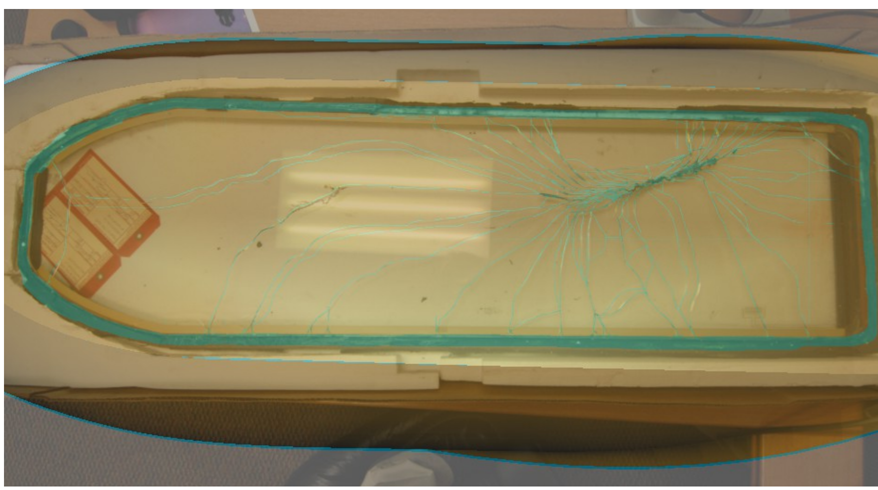


PLM Interaction Tool (NLign)

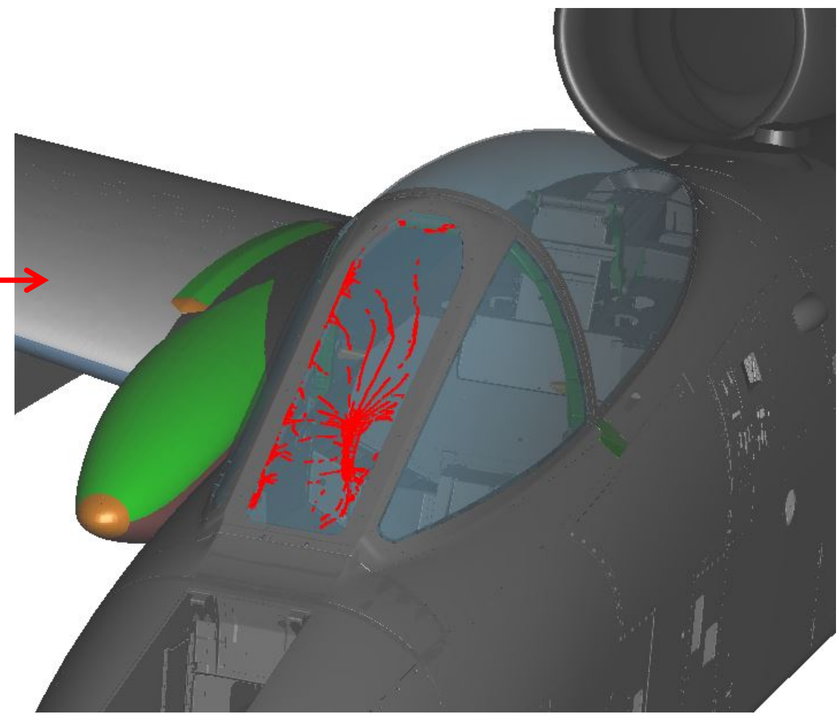
Photo of Damage

Photo alignment to Model

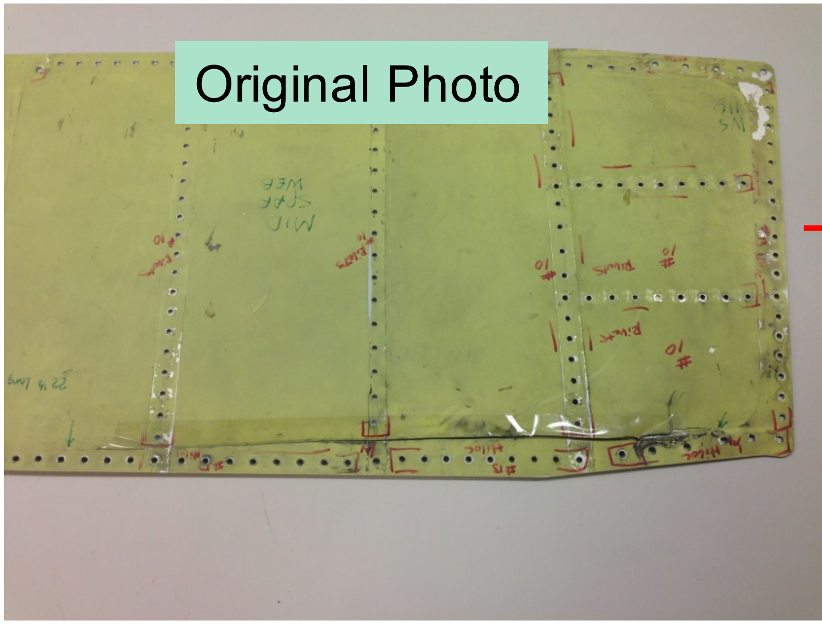
Photo Enhancements to amplify damaged regions

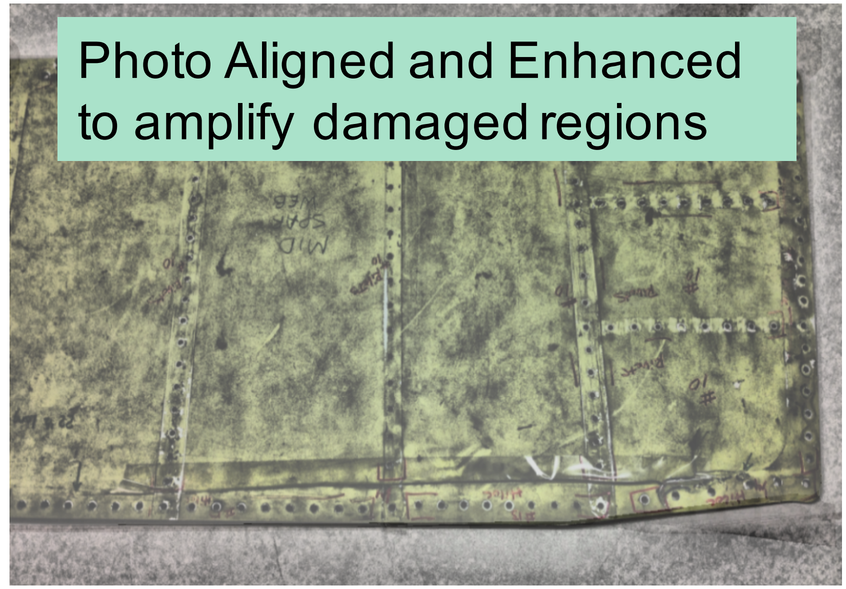


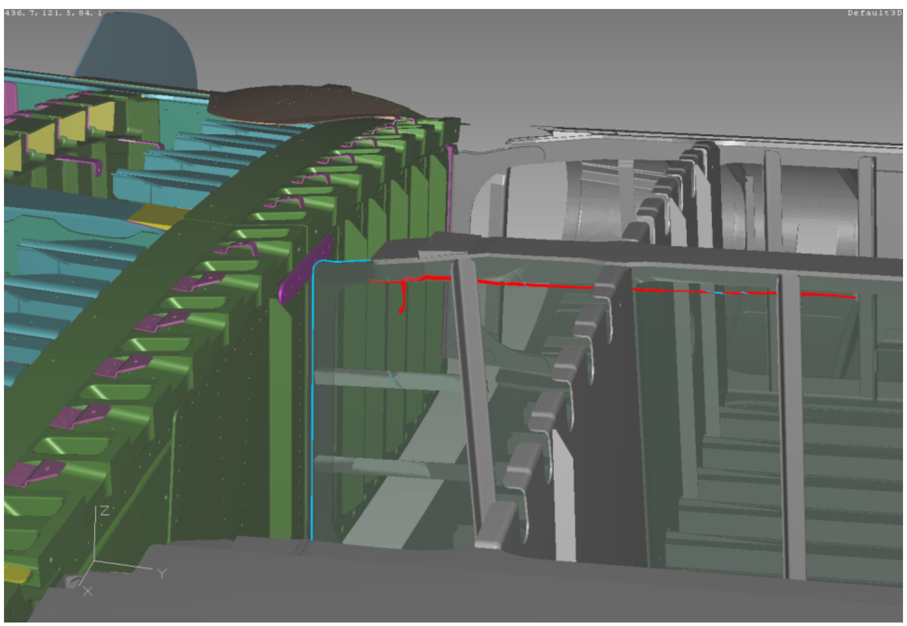
Damaged Mapped on Model for Trending

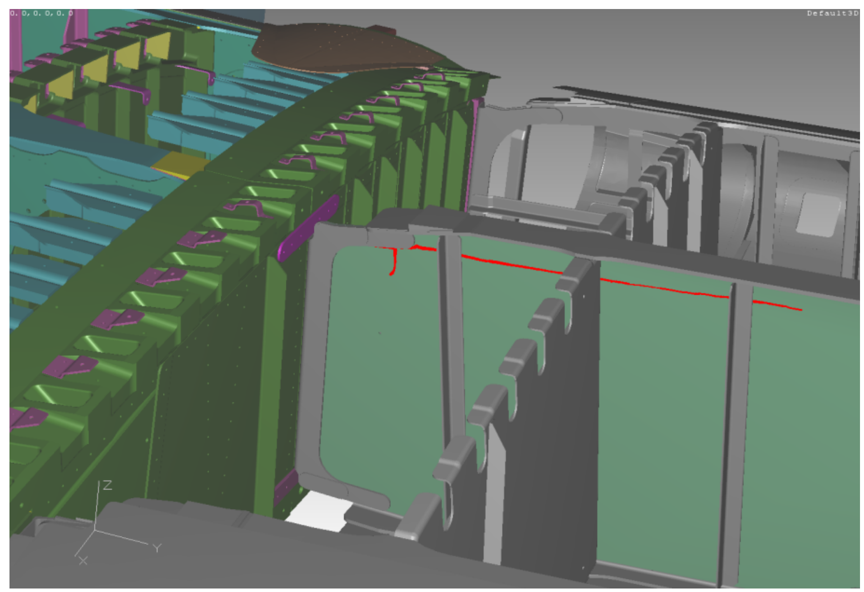


PLM Interaction Tool (NLign)









U.S. AIR FORCE

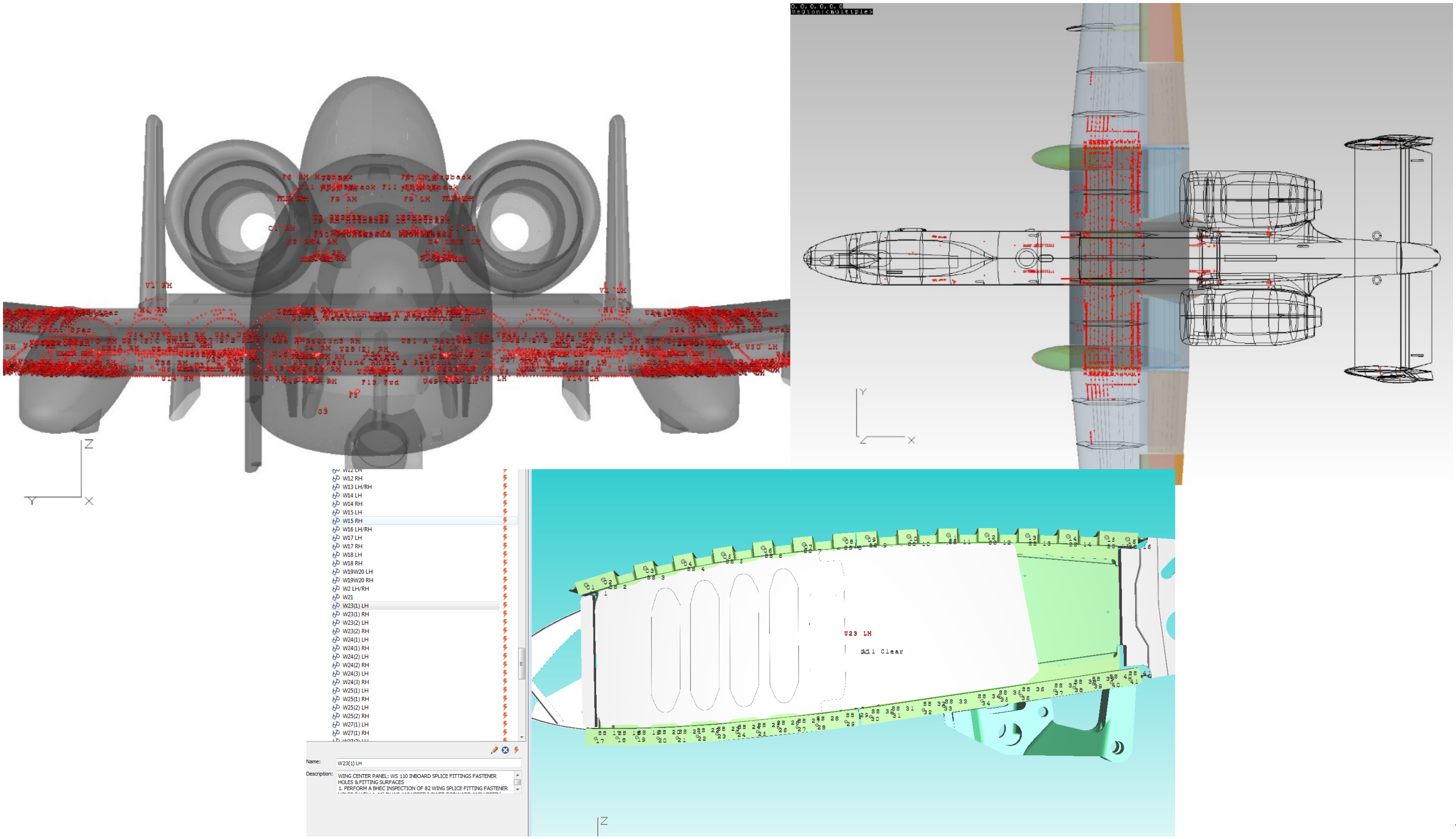
Quality Assurance

Data Capture at the Point of Maintenance

- A-10 Scheduled Structural Inspection (SSI) program.
  - Historically it takes 7-9 months from the asset induction date before Engineering sees SSI data
    - Low quality
  - No ability for engineering to address data issues while the asset is open and accessible
    - Usually asset is back on an aircraft and ready for service when the maintenance data is received
  - Engineer Tech required to manually input data into database

Data Capture at the Point of Maintenance

3D framework for quick and accurate digital inspection input



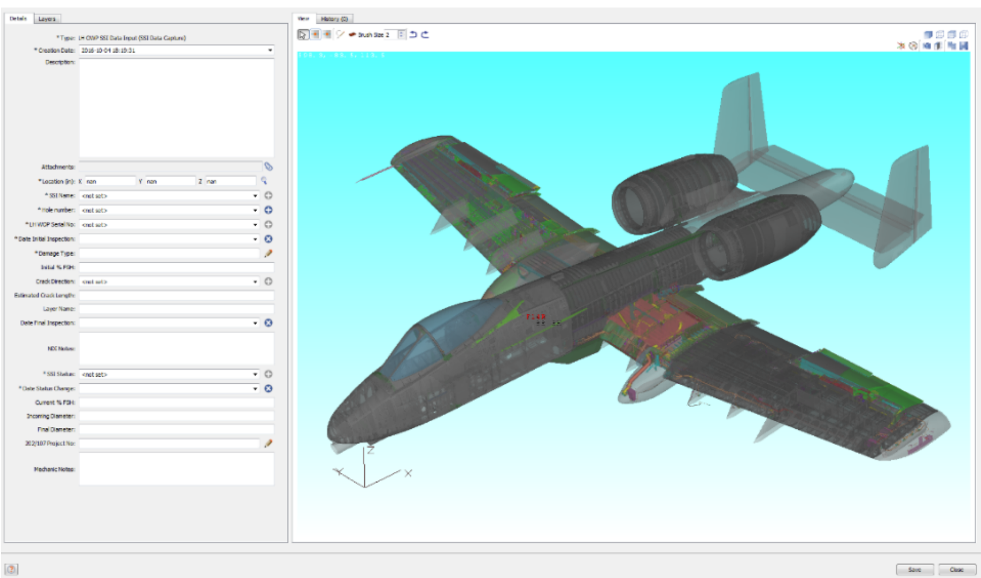
Data Capture at the Point of Maintenance

U.S. AIR FORCE

A-10 ASIP FIDUCIA NON SUPERBIA

- Aug-Sept 2016 NLign data collection test.
- Customized NLign data capture trendable per SN component type
- Developed quick 'at a glance' reporting tool
  - Keep supervisors informed
  - Keep NDI tech and Mechanic in sync to work remaining

Data input screen



Coordination Report

	A	B	C	D	E	F	G
1	RH WOP Serial No	LH WOP Serial No	SSI Name	Hole number	SSI Status	Creation Date	Date Status Change
2		00B6200627L	W50 LH	1	Complete	9/6/2016 12:29	9/6/2016
3		00B6200627L	W33R LH	SS Web	Complete	9/6/2016 9:22	9/6/2016
4		00B6200627L	W54 WS42.5 LH	1	Complete	9/6/2016 9:22	9/6/2016
5		00B6200627L	W54 WS42.5 LH	1	Complete	9/6/2016 9:22	9/6/2016
6		00B6200627L	W29 LH	SS	Complete	9/6/2016 9:03	9/6/2016
7		00B6200627L	W29 LH	SS	Complete	9/6/2016 9:03	9/6/2016
8		00B6200627L	W25(1) S11 RH	3	Complete	8/31/2016 10:27	8/31/2016
9		00B6200627L	W23(2) LH	1	Complete	8/31/2016 9:01	8/31/2016
10		00B6200627L	W25(2) OS11 LH	3	Complete	8/31/2016 9:01	8/31/2016
11		00B6200627L	W24(3) OS2 LH	2	Complete	8/30/2016 13:24	8/31/2016
12		00B6200627L	W24(3) LHOU Center Spar	7	Complete	8/30/2016 13:24	8/31/2016
13		00B6200627L	W24(3) LHOU Center Spar	5	Complete	8/30/2016 13:24	8/30/2016
14		00B6200627L	W24(3) LHOU Center Spar	4	Complete	8/30/2016 13:24	8/31/2016
15		00B6200627L	W24(3) OS7 LH	7	Complete	8/30/2016 13:24	8/31/2016
16		00B6200627L	W24(3) OS7 LH	6	Complete	8/30/2016 13:24	8/31/2016
17		00B6200627L	W24(3) OS7 LH	1	Complete	8/30/2016 13:24	8/31/2016
18		00B6200627L	W24(3) LHOU Rear Spar	1	Complete	8/30/2016 13:24	8/31/2016
19		00B6200627L	W24(2) OS15 RH	7	Complete	8/30/2016 10:44	8/30/2016
20		00B6200627L	W24(2) OS15 RH	7	Complete	8/30/2016 10:44	8/31/2016
21		00B6200627L	W24(2) OS15 RH	7	Complete	8/30/2016 10:44	8/31/2016
22		00B6200627L	W24(2) OS15 RH	7	Complete	8/30/2016 10:44	8/30/2016
23		00B6200627L	W24(2) OS12 LH	2	Complete	8/30/2016 10:44	8/30/2016
24		00B6200627L	W24(2) OS14 LH	1	Complete	8/30/2016 10:44	8/30/2016
25		00B6200627L	W45 LH	1	Complete	8/30/2016 10:44	8/30/2016
26		00B6200627L	W19W20 LH	11	Complete	8/30/2016 9:40	8/30/2016

Fuselage Report | CWP Report | OWP Report | N ...

Data Capture at the Point of Maintenance

Historic SSI Data Capture Process

=

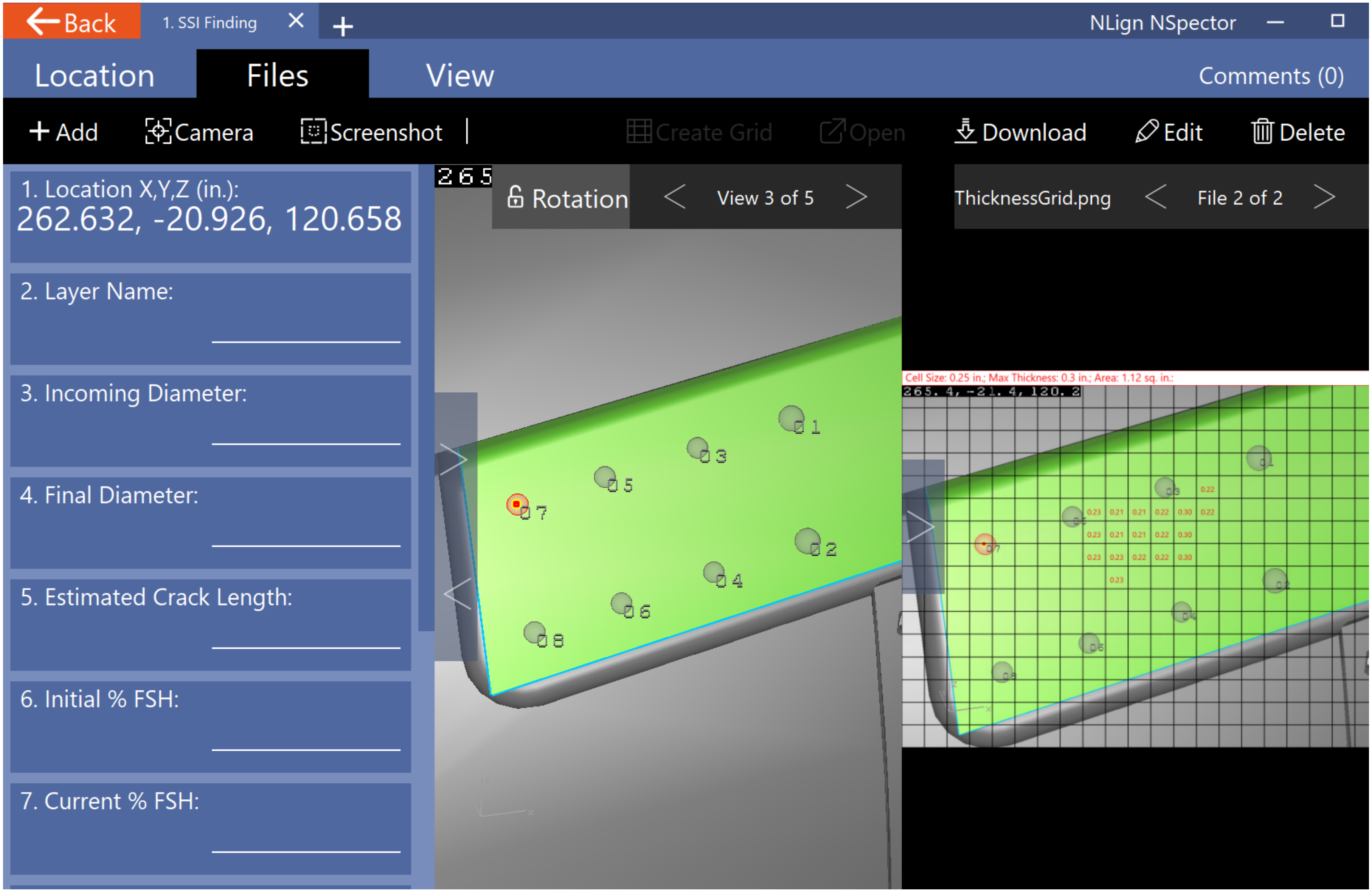
Low Quality

VS.

<u>Digital data capture with NLign</u>

- OWP 2016 test:
  - 3 weeks to complete with 100% data accuracy
  - Data available to engineers ~ 800% faster
- CWP 2017 = 2.5 months to complete with100% data accuracy
  - Data available to engineers ~ 500% faster
- 2018 full implementation of NLign on shop floor.

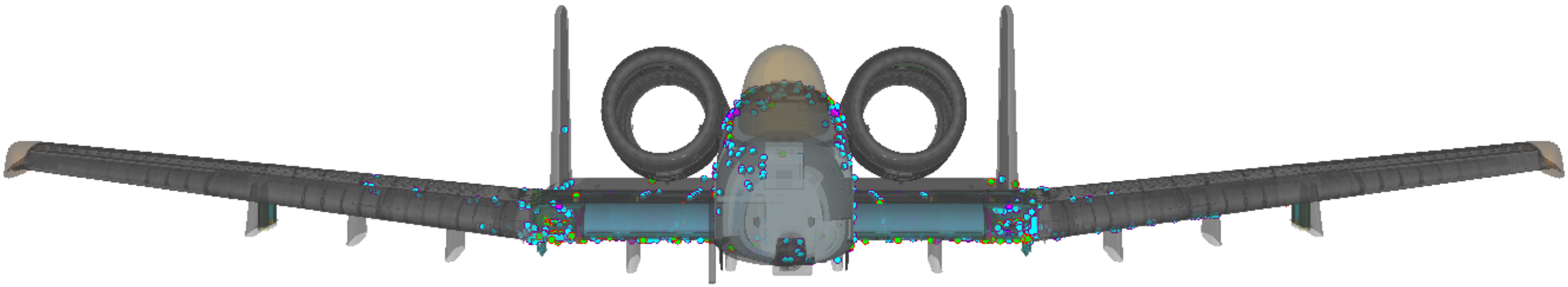
Data Capture at the Point of Maintenance

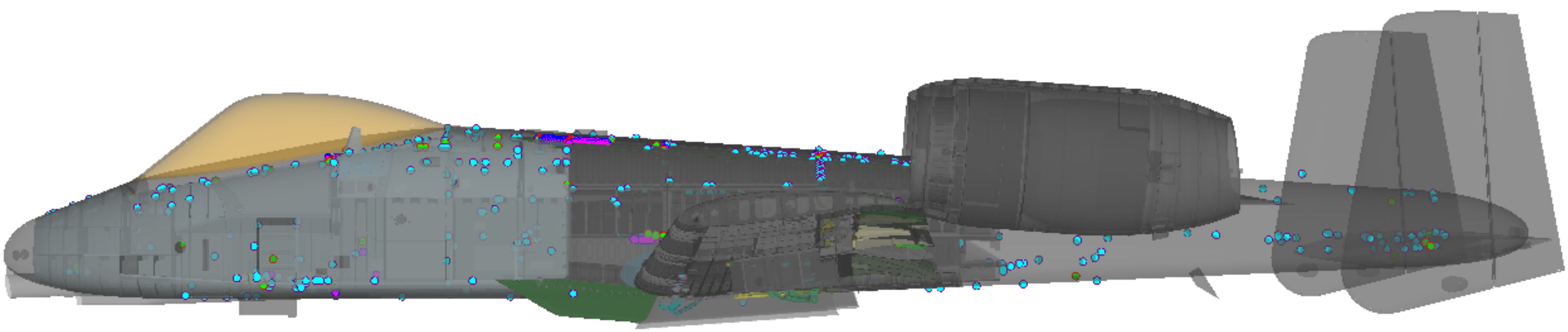


Data Spatial Positioning (DSP) System (RIF)

PEO FB/AFLCMC/LG-LZ
Requirement #: USAF-18-PEO-FB-9.K
Title: Maintenance Data Spatial Positioning (DSP) System
Military System or Acquisition Customer: Aviation Platforms - All Platforms
Description: Seeking the development of a maintenance DSP technology to provide real-time location feedback to maintainers, capture any maintenance tool data output, and communicate that data for condition-based aircraft management. This technology is building upon previous RIF efforts focused on data communication and analytics with the NLign tool, to enable a highly-effective, condition-based maintenance (CBM+) program. Venders should propose and develop the methodology, technology, and hardware for a basic spatial point locating tool, capable of capturing and associating that data to a user-defined airframe coordinate system (X,Y,Z or FS,WL,BL). Additionally, venders should propose and develop the methodology, technology, and hardware for incorporating the DSP system with existing maintenance non-destruction inspection (NDI) tools and cold expansion tools. Leveraging the NLign system from previous RIF efforts, the data positioning system will have the option to utilize pre-defined maintenance locations and provide feedback to the maintainer for location compliance. Any data output from maintenance tools should be captured with spatial coordinates and communicated to the NLign system for analysis. This tool is intended for depot or field use and to be quickly adaptable for all airframes. This effort will enhance maintenance data quality for all platforms and reduce the risk of miss-locating or missing critical maintenance operations. Also, this tool will provide the missing verification and high-fidelity data needed in CBM+ to reduce serious risk concerns that have hindered the ability to apply ‘game changing’ fleet management strategies such as residual stress benefits.
Technical POC: Hazen Sedgwick, Hazen.Sedgwick@us.af.mil (801) 586-0346, or Luke Bracken, luke.bracken@us.af.mil (801) 586-1861

Questions?





ERSI RISK AND UQ SUBCOMMITTEE ACTIVITIES

Lucky Smith
Southwest Research Institute
LSmith@swri.org

Laura Domyancic Hunt
Southwest Research Institute
LDomyancic@swri.org

Outline

- Risk and UQ Subcommittee Overview
- Short Presentations of Current Activities
  - "**Probability of Cold Expansion (POCx) Variable**," Laura Hunt, SwRI
  - "**Some Observations on the Significance of Residual Stress Variability on Fatigue Crack Growth Life**," Craig McClung, SwRI
  - "**Residual Stress Sensitivity Analysis in Probabilistic DTA**," Juan Ocampo, St. Mary's U

Committee Overview

- **GOAL**: Investigate and implement UQ methods that enhance the overall understanding of how residual stress affects life prediction analyses
- **How we can reach the goal**:
  - Uncertainty Quantification
  - Sensitivity Analysis
    - What are the most significant variables in the ERS process?
    - How can we maximize/minimize the benefits/damages of these variables?

2018 Workshop

- In the past year, the state of the art for UQ and sensitivity analysis methods were investigated
  - NASA UQ Challenge – 2014 AIAA SciTech Conference
  - Spatial statistics
  - Variance-based and local sensitivity analysis methods
  - What methods are useful for the group going forward?

- **We're here to help**
  - Our subcommittee doesn't generate data
  - We received one RS data set in the past year

"PROBABILITY OF COLD EXPANSION" VARIABLE

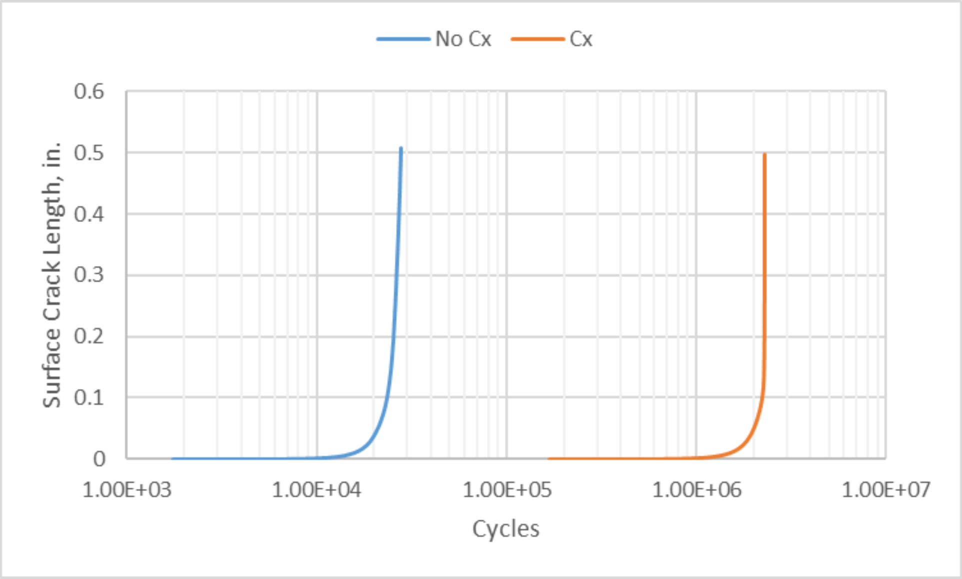
A-10 ASIP and Southwest Research Institute

POCx

- **How can we incorporate cold expansion into a PROF-type risk analysis?**
- A-10 ASIP suggested a Probability of Cold expansion (POCx) variable that acts similarly to the Probability of Inspection (POI) variable that is currently in PROF
- POCx is a singular value that represents the probability that a hole was cold-worked correctly
  - "Correctly" is a loaded term
- **This is not a final methodology, but rather a very simplified way to incorporate coldworking into current methods**

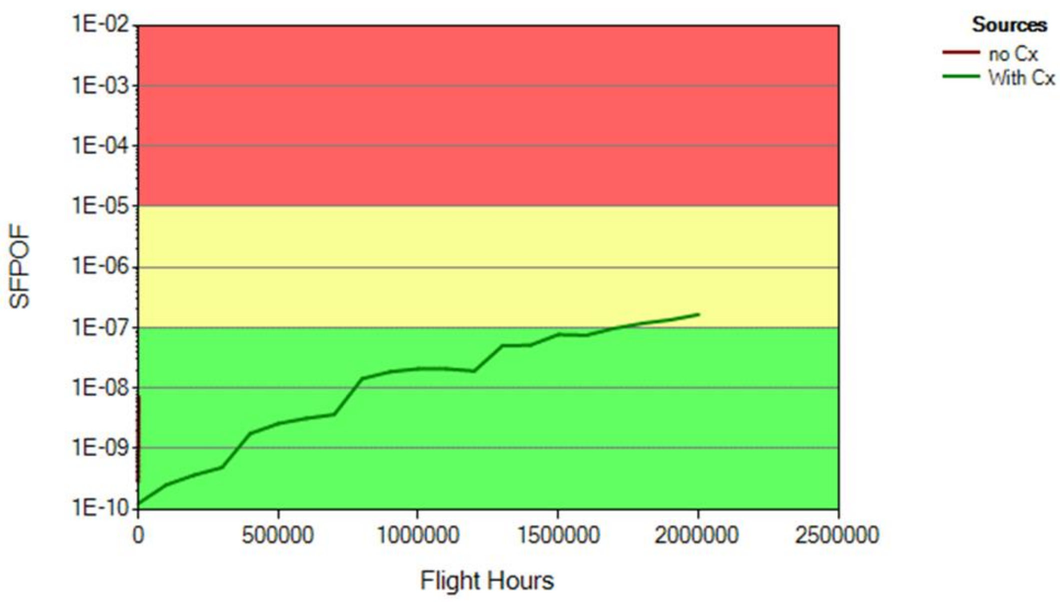
Crack Growth Life Curves

- Results from the ERSI round-robin were used as an input for the cold expanded hole case
  - Benchmark 2, 25 ksi stress
- Residual stresses were removed from the AFGROW input to create results for a theoretical non-coldworked hole case



PROF Results

- Separate PROF analyses were run for the Cx and non-Cx cases



Incorporating POCx

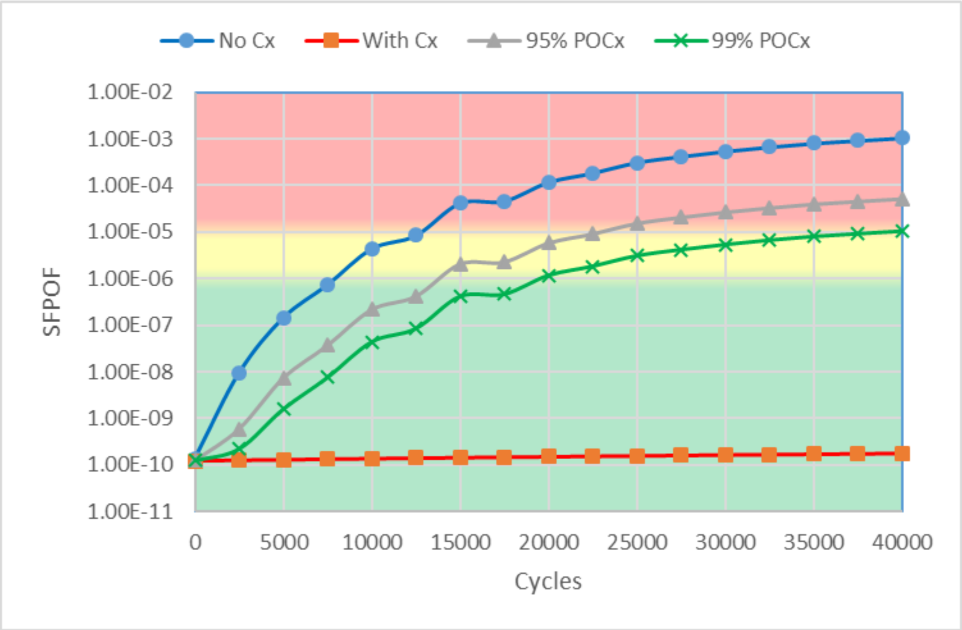
- The SFPOF results for both analyses were imported into Excel
- 95% and 99% POCx were incorporated by the formula below

board | Font | Alignment | Numb

=0.05*C2+0.95*F2

	B	C	D	E	F	G	H	I	J	K
	No Cx			With Cx				95% POCx	99% POCx	
	0	1.39E-10		0	1.24E-10		0.00E+00	1.24E-10	1.24E-10	
	2500	9.59E-09		2500	1.27E-10		2500	6.00E-10	2.22E-10	
	5000	1.46E-07		5000	1.30E-10		5000	7.40E-09	1.58E-09	
	7500	7.43E-07		7500	1.34E-10		7500	3.73E-08	7.56E-09	

POCx Risk Results



- POCx is a simple knockdown factor to incorporate residual stresses
  - Danger of becoming a "thumb-in-the-air" variable
- UQ is required to actually quantify this variable

Residual Stresses Sensitivity Analysis in Probabilistic Damage Tolerance Analysis

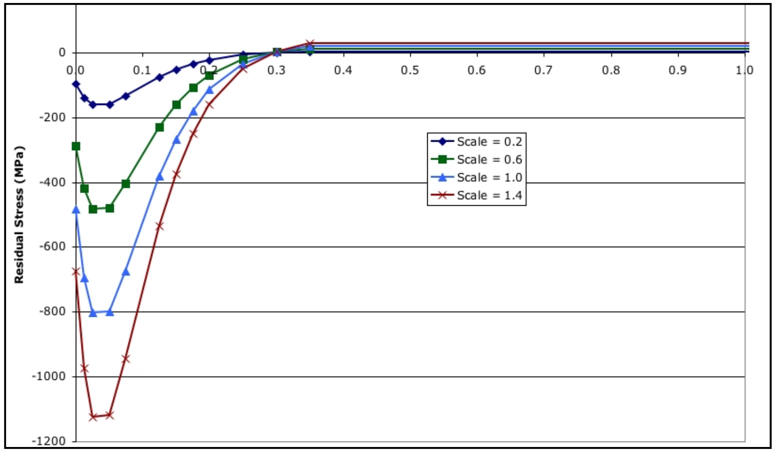
Juan D. Ocampo and Alexander Horwath
St. Mary's University
Luciano Smith and Laura Domyancic
Southwest Research Institute

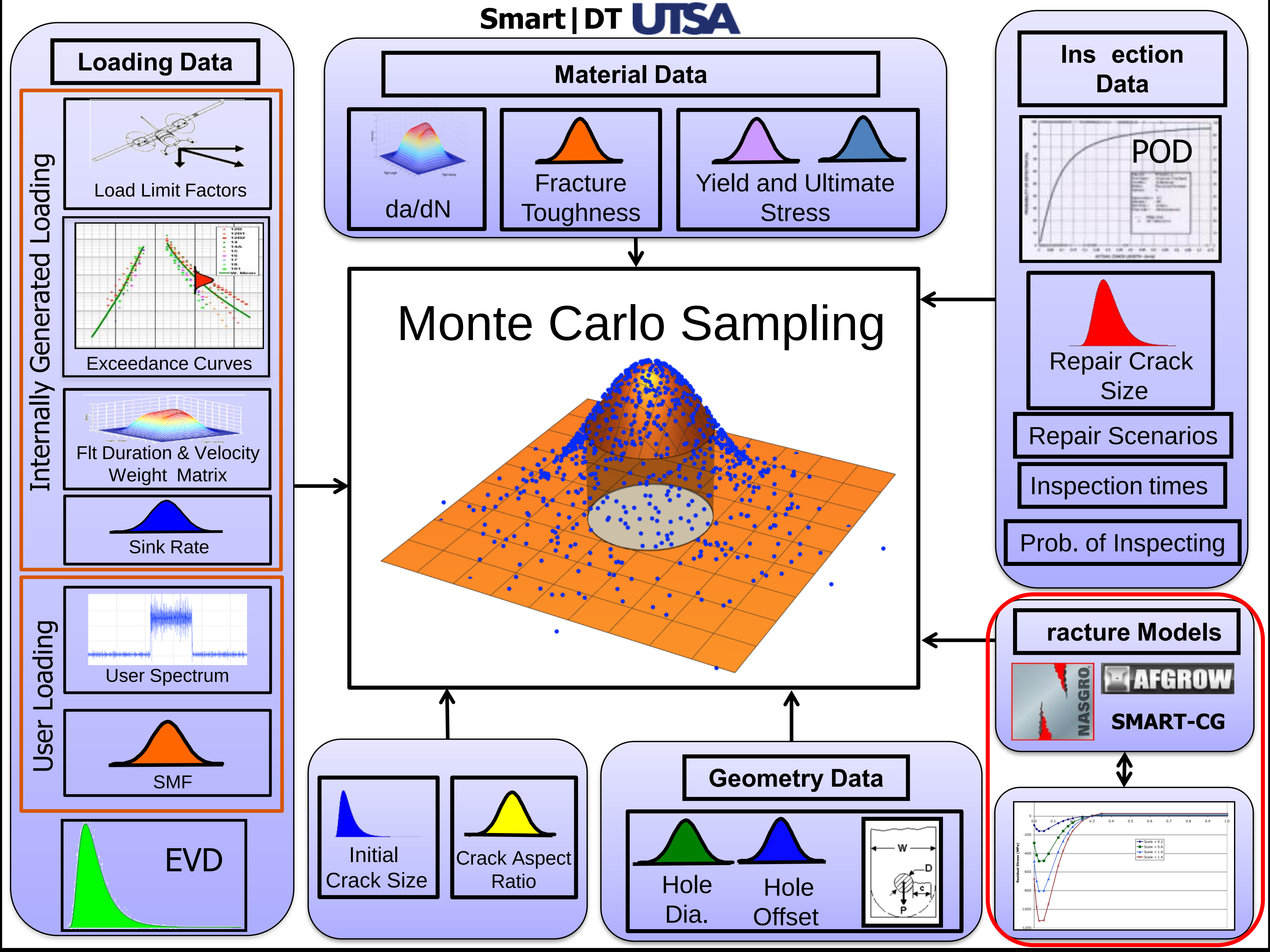
Engineered Residual Stress Implementation Workshop 2018
Salt Lake City, UT, September 13–14, 2018.

ERSI

Outline

- SMART|DT AND Residual Stresses
- Residual Stresses Modeling Software (Update)
- Residual Stresses and Inspections
- Sensitivity Analysis
- Future Plans & Group Suggestions



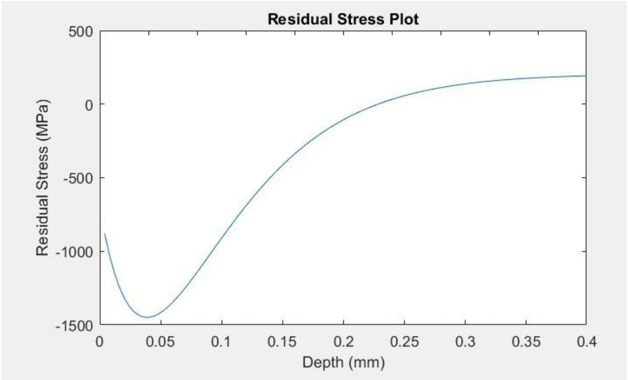


Smart | DT UTSA
Loading Data
Internally Generated Loading
Load Limit Factors
Exceedance Curves
Flt Duration & Velocity Weight Matrix
Sink Rate
User Loading
User Spectrum
SMF
EVD
Material Data
da/dN
Fracture Toughness
Yield and Ultimate Stress
Monte Carlo Sampling
Ins ection Data
POD
Repair Crack Size
Repair Scenarios
Inspection times
Prob. of Inspecting
racture Models
NASGRO
AFGROW
SMART-CG
Initial Crack Size
Crack Aspect Ratio
Geometry Data
Hole Dia.
Hole Offset
W
D
c
P

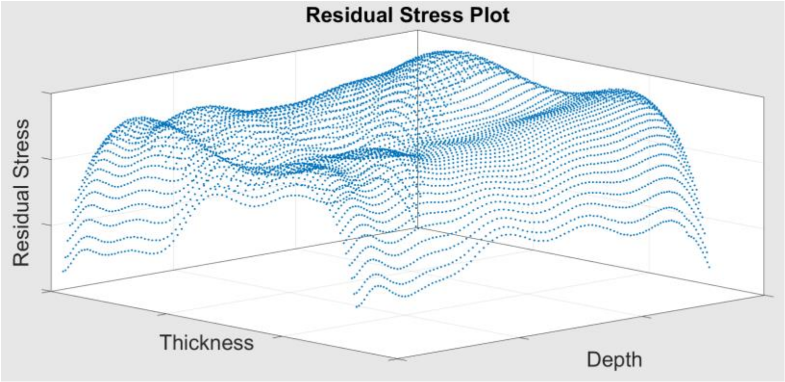
ERSI

Residual Stress Modeling Software

- Standalone executable to read experimental/ simulated data and find the best deterministic and probabilistic fit parameters.
  - 2 Models Available (Expandable)
  - 2D (Stress vs Depth) and 3D (Stress vs Depth vs Thickness).
  - Read input data in .txt & .csv format



2D



3D

ERSI

Models

- Model I*

$$\sigma(x) = (ss - si + C_1 x)Exp(-C_2 x) + si$$

$$C_1 = \frac{\{(ss - si)\left(1 - Exp(-C_2 B)\right) + siBC_2\}C_2}{(C_2 B + 1)Exp(-C_2 B) - 1}$$

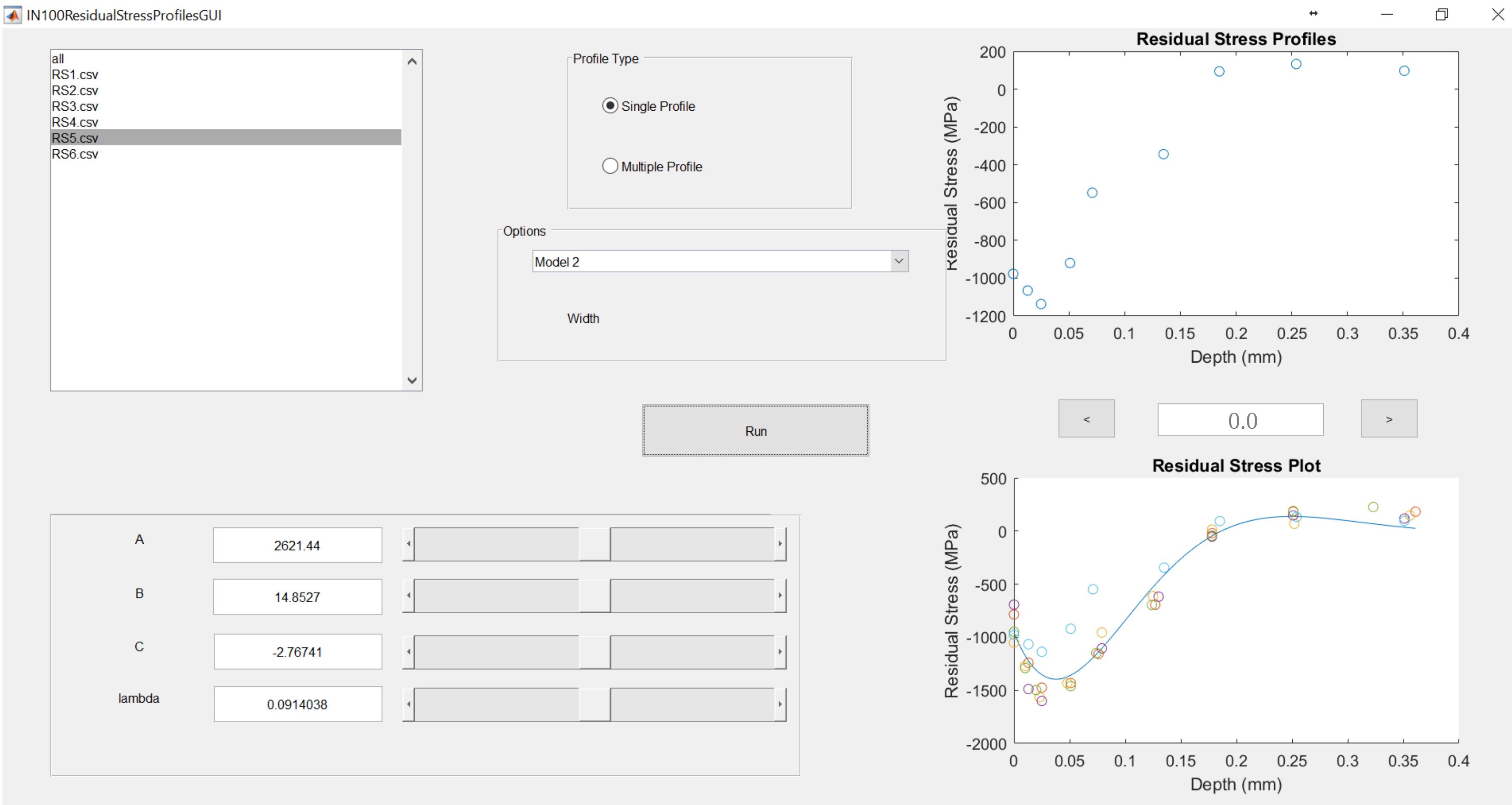
- Model II**

$$\sigma(x) = Asin(Bx + C)Exp\left(-\frac{x}{\lambda}\right)$$

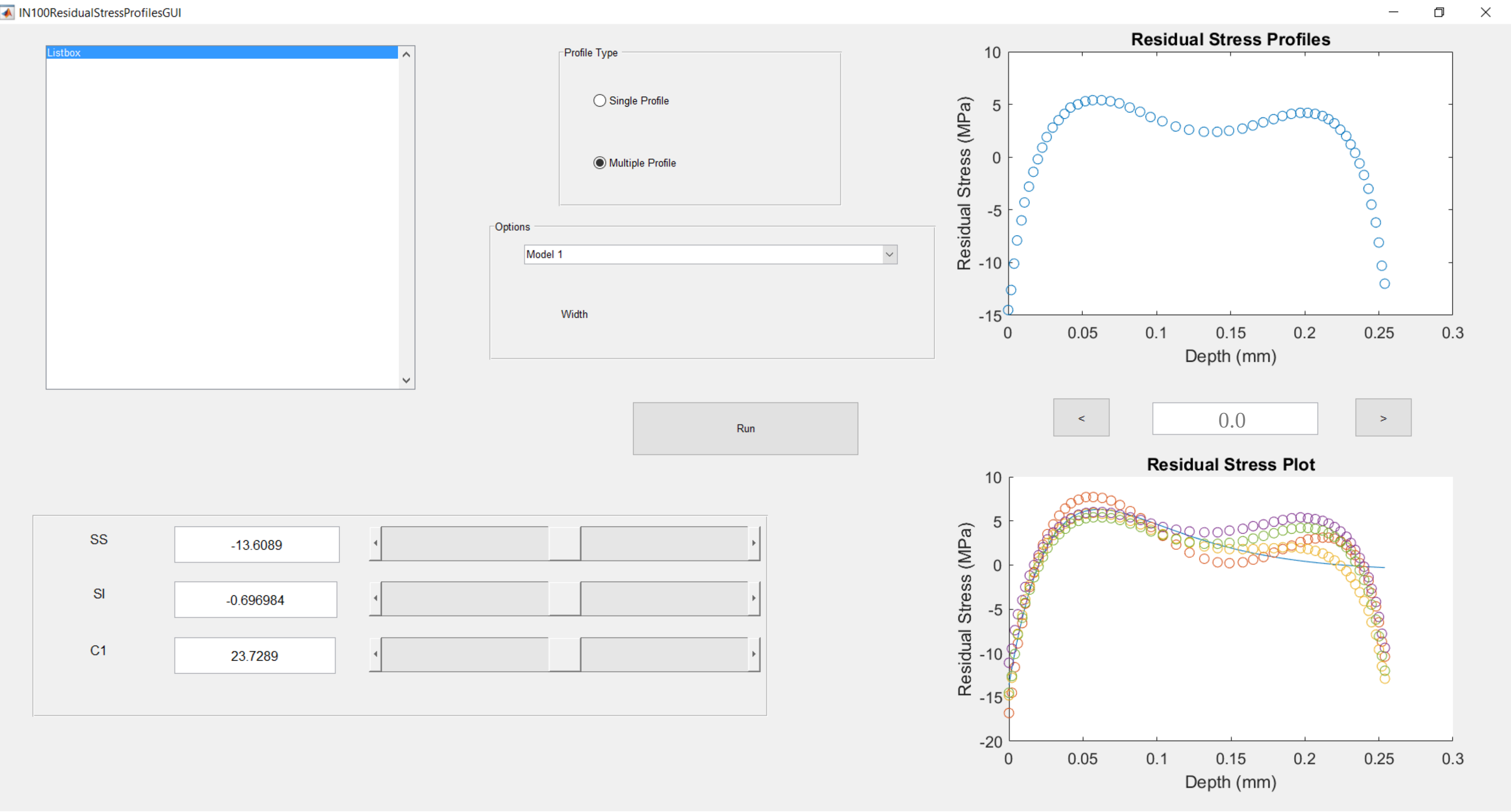
* *User Manual for ZENCRACK™ 7.1*, Zentech International Ltd., Camberley, Surrey, UK, September, 2003.

** R. VanStone, “F101-GE-102 B-1B Update to Engine Structural Durability and Damage Tolerance Analysis Final Report (ENSIP), Vol. 2,” General Electric, p. 5-2-2.

Single Profile Model I & II



Mult. Profile Model I



ERSI

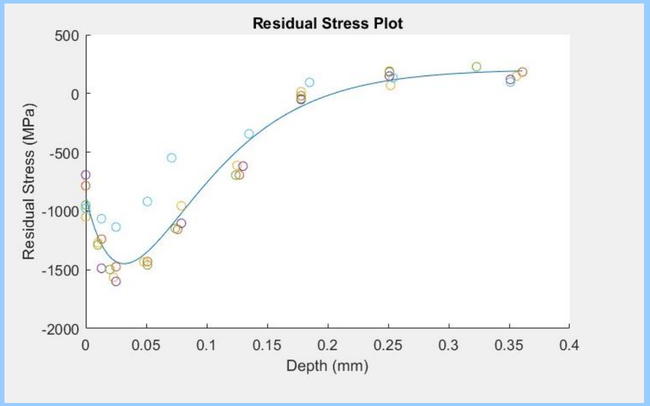
Input/Output

A2-1_stress.txt - Notepad

File Edit Format View Help

```
-1.928  0.254  0.000  -10.4
-1.928  0.000  0.000  -16.8
-1.928  0.252  0.000  -8.7
-1.928  0.250  0.000  -6.5
-1.928  0.248  0.000  -4.7
-1.928  0.245  0.000  -3.2
-1.928  0.243  0.000  -1.8
-1.928  0.240  0.000  -0.7
-1.928  0.237  0.000  0.2
-1.928  0.234  0.000  1.1
-1.928  0.231  0.000  1.7
-1.928  0.228  0.000  2.3
-1.928  0.224  0.000  2.7
-1.928  0.220  0.000  3.0
-1.928  0.216  0.000  3.1
-1.928  0.212  0.000  3.1
-1.928  0.207  0.000  3.0
-1.928  0.202  0.000  2.9
```

→ RS Mod →



Mean and Standard Deviation Parameters

	Mean	St dev
ss	-879.16	58.58
si	205.68	9.448
c2	20.872	1.050

Correlation Parameters

	ss	si	c2
ss	1	-0.214	0.402
si	-0.214	1	-0.796
c2	0.402	-0.796	1

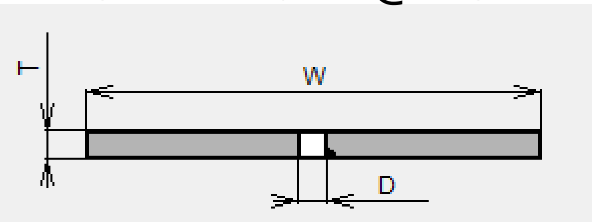
ERSI

Academic Example Problem

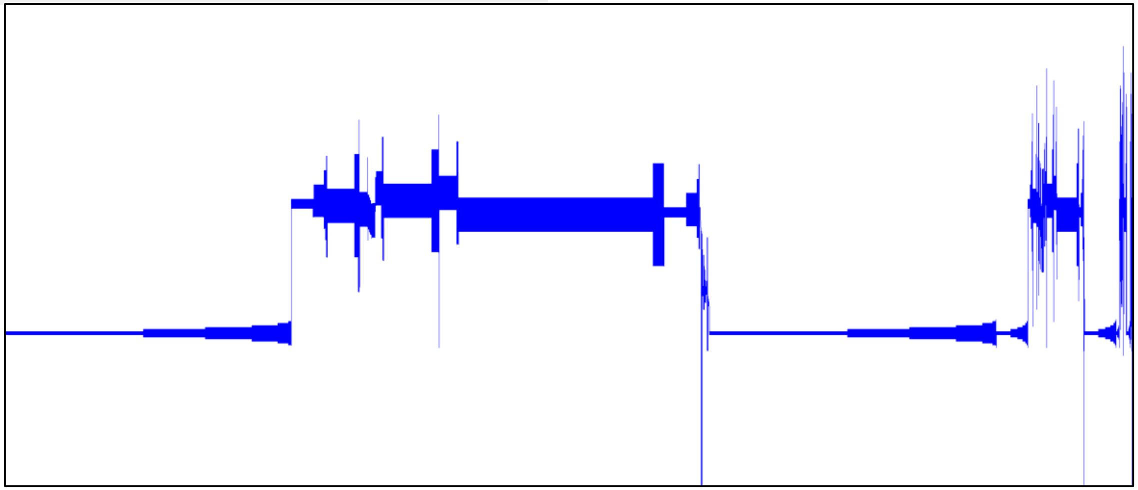
ERSI

Input Parameters

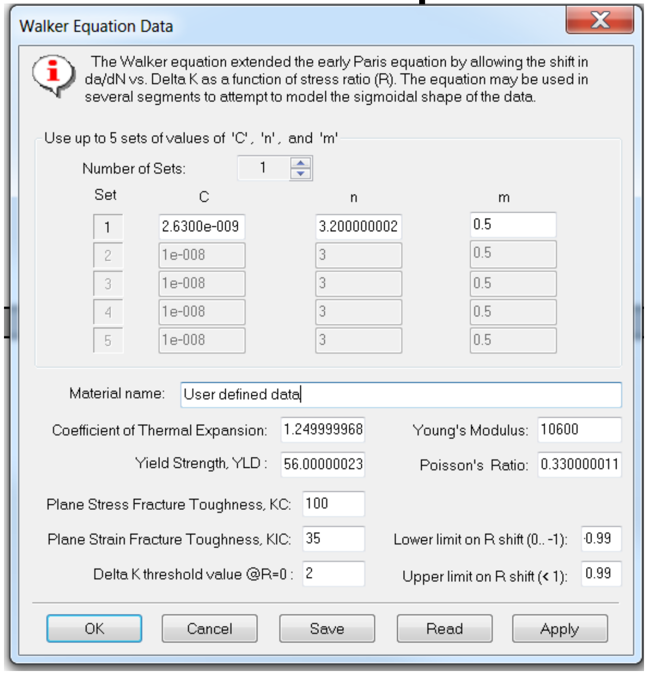
Corner crack @ hole



Parameter	Value
T	0.09 in
W	4.0 in
D	0.25 in



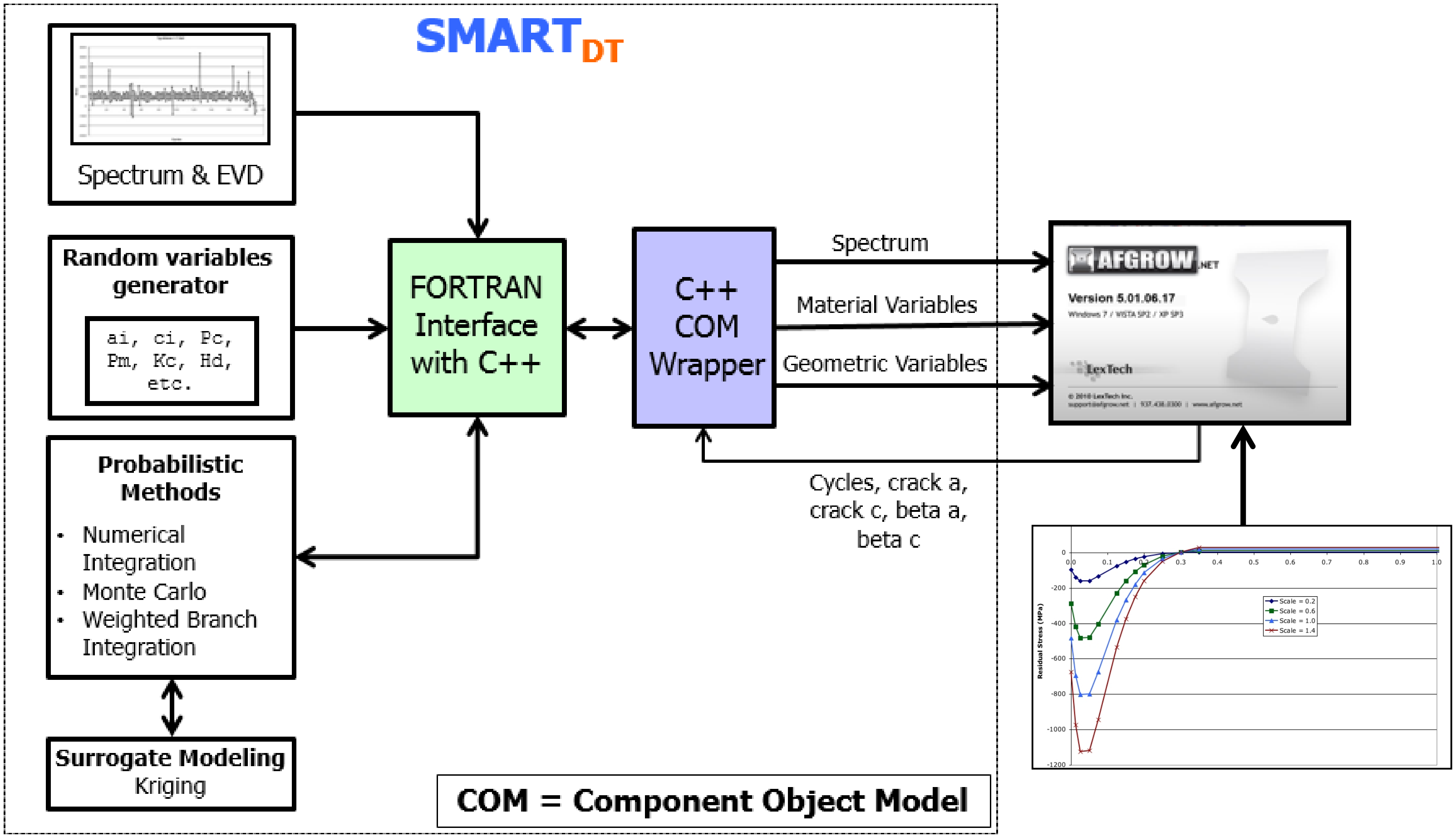
Mat. Prop.



Random Variables	Value
Fracture Toughness Distribution (Normal)	Mean = 34.5ksi√in, Standard Deviation = 3.8 ksi√in.
Initial & Repair Lognormal Size Distribution (a & c) (Lognormal)	Mean = 0.01 in, Standard Deviation = 0.001 in.
Extreme Value Distribution (Gumbel)	Location = 14.5, Scale = 0.8, and Shape = 0.0
Inspections (5,000 & 10,000)	POD Lognormal Mean = 0.07in, Standard Deviation = 0.06

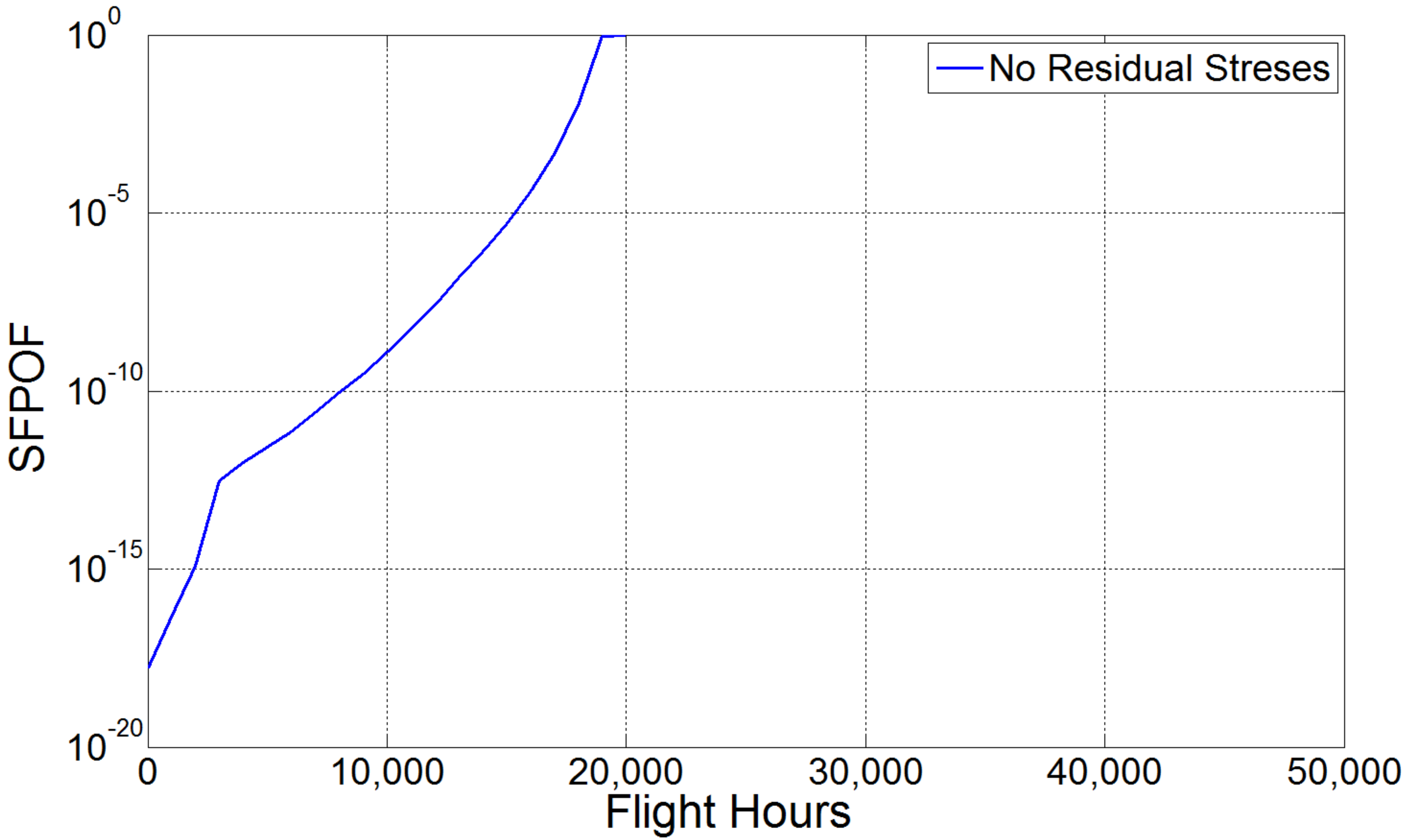
Residual Stress Effect on SFPOF

- SMART-AFGROW interface.

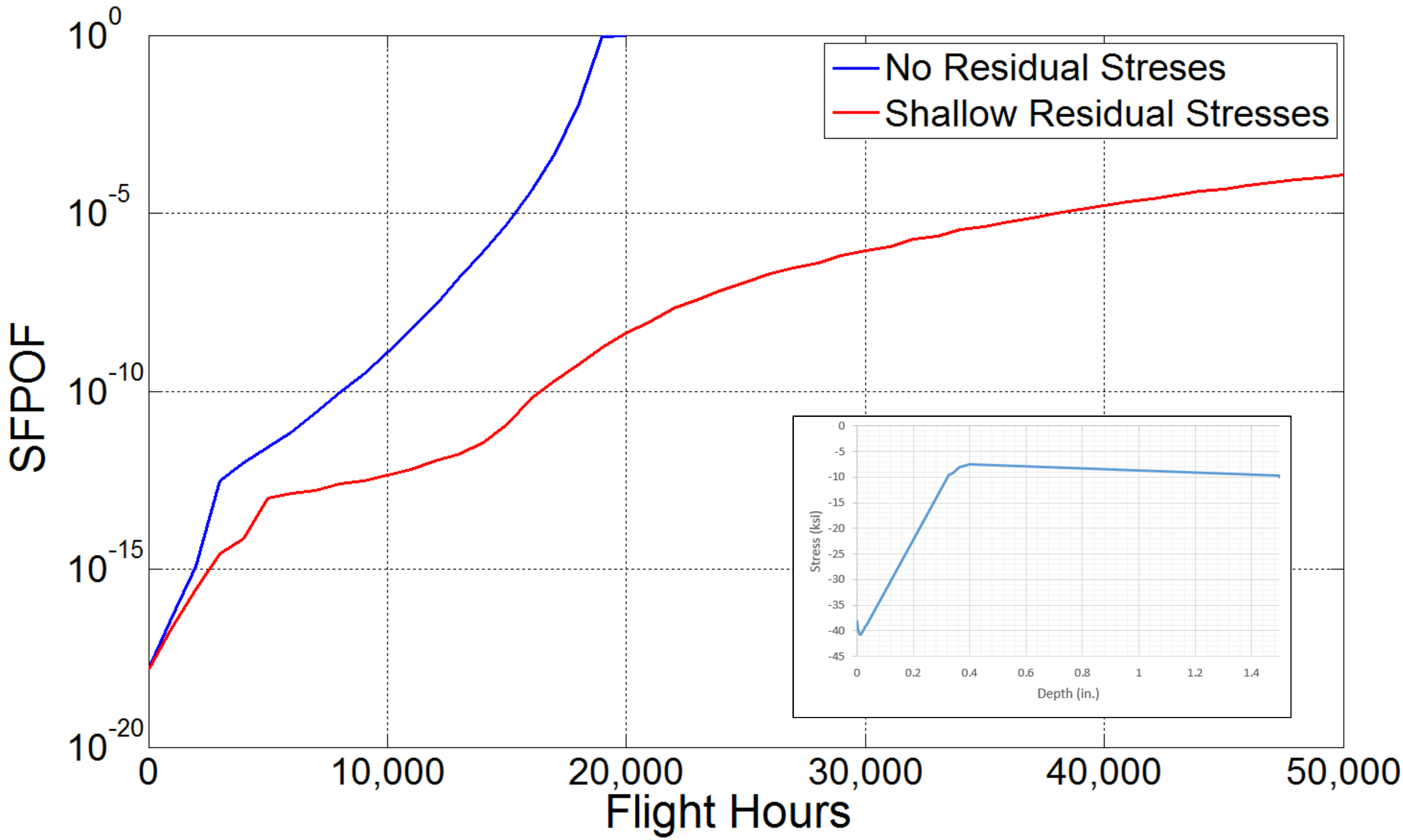


Inpections

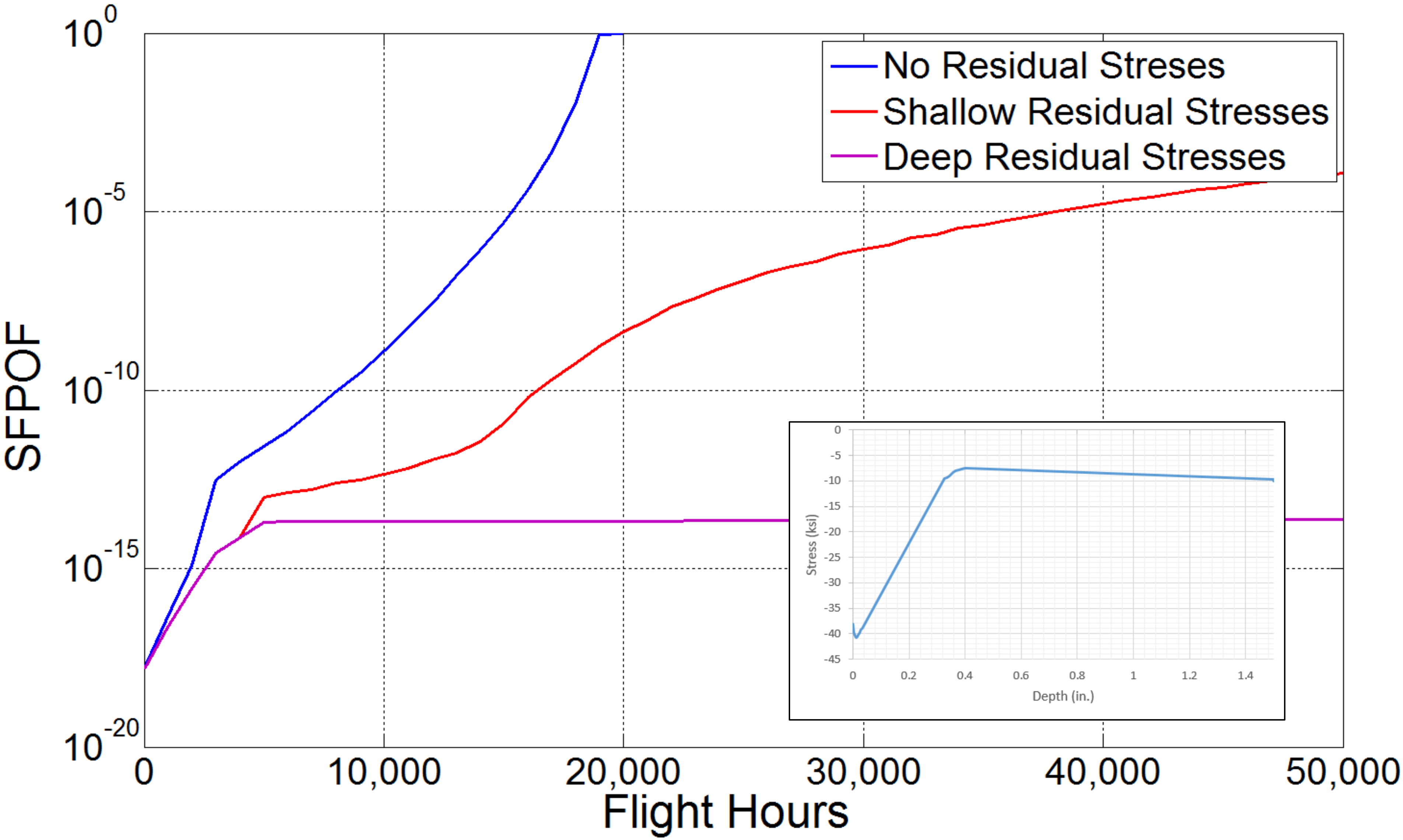
Results without Inspections



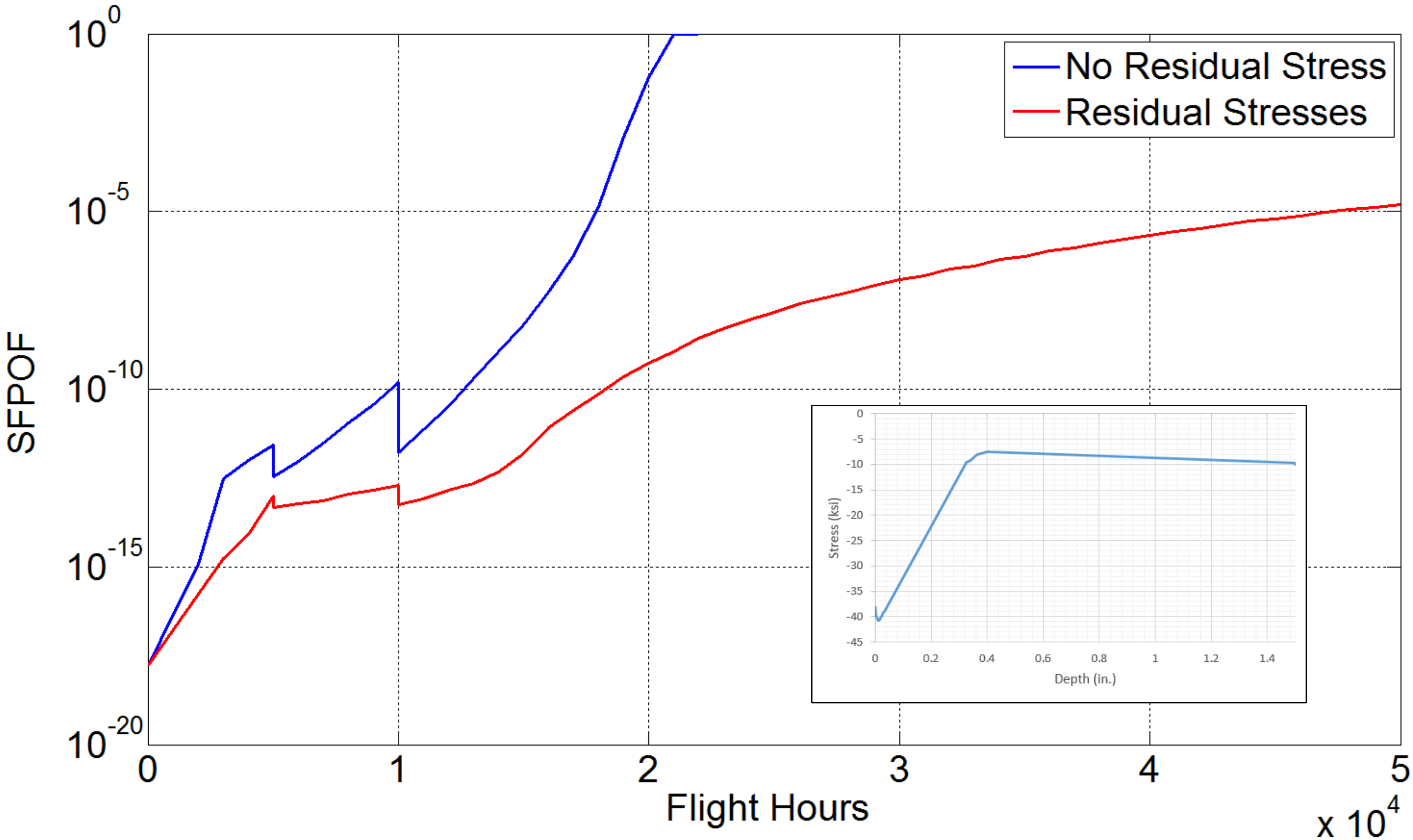
Results without Inspections



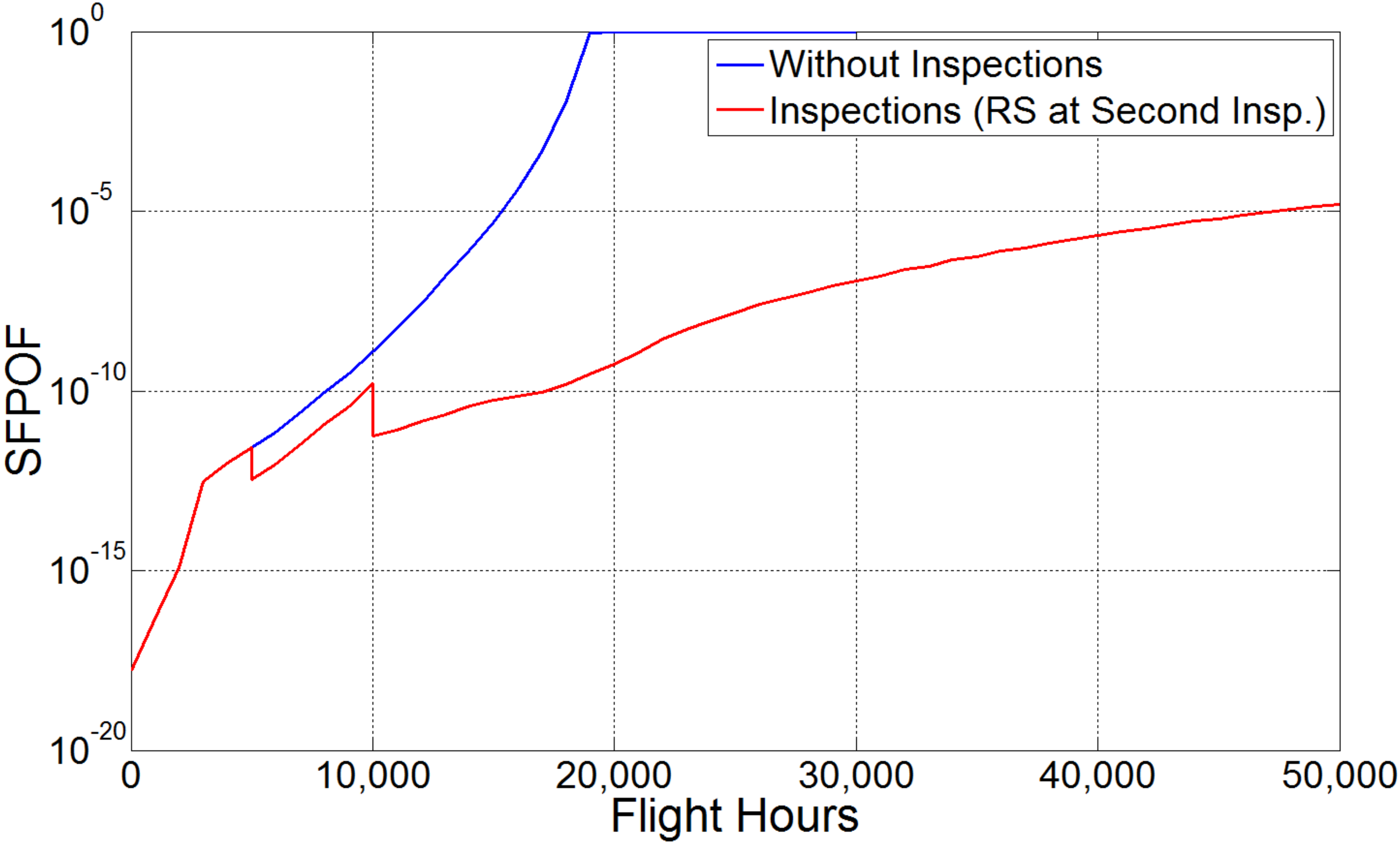
Results without Inspections



Results with Inspections

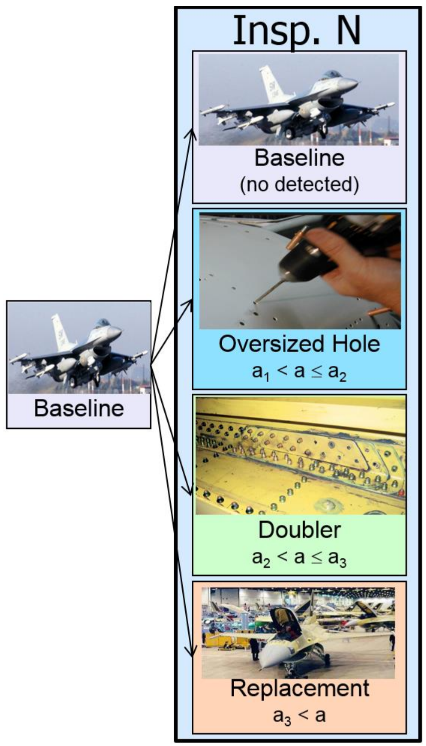


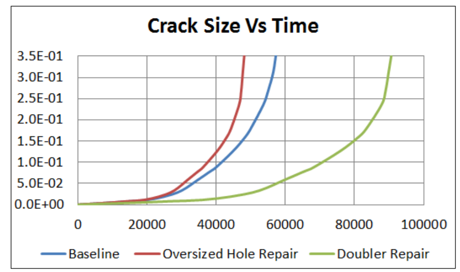
Inducing RS at the Second Inspections

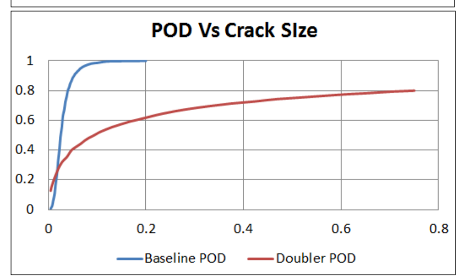


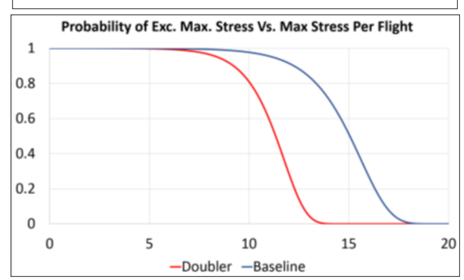
ERSI

Sensitivity Study





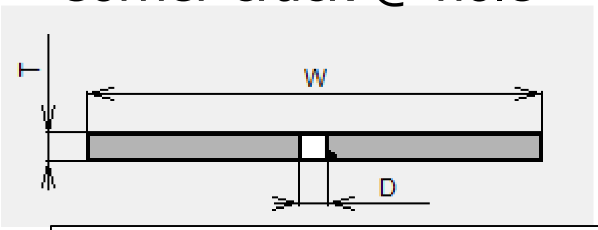




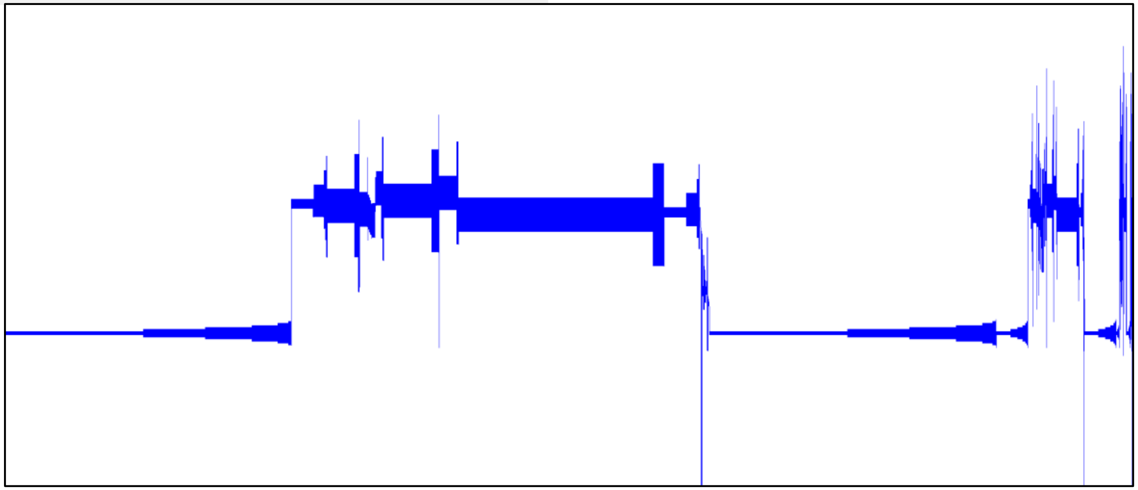
$$\bar{S}_\theta = \frac{\partial P}{\partial \theta} \cdot \theta$$

Input Parameters

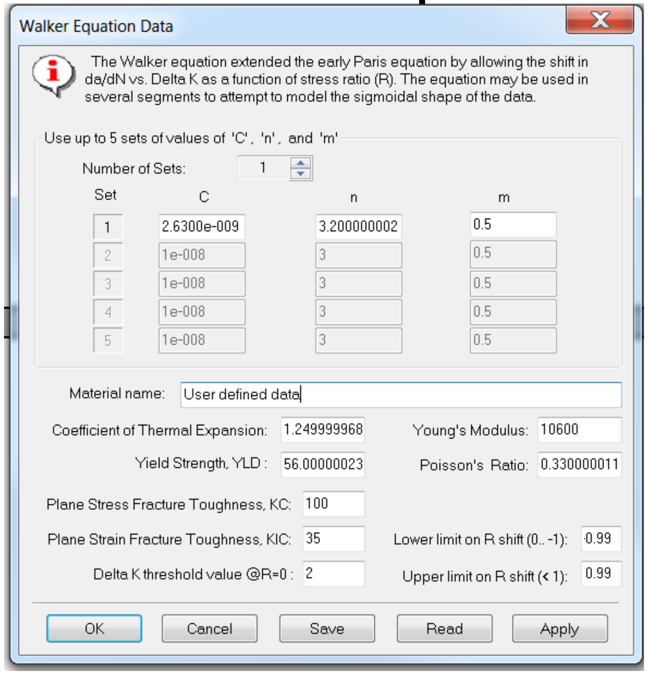
Corner crack @ hole



Parameter	Value
T	0.09 in
W	4.0 in
D	0.25 in



Mat. Prop.

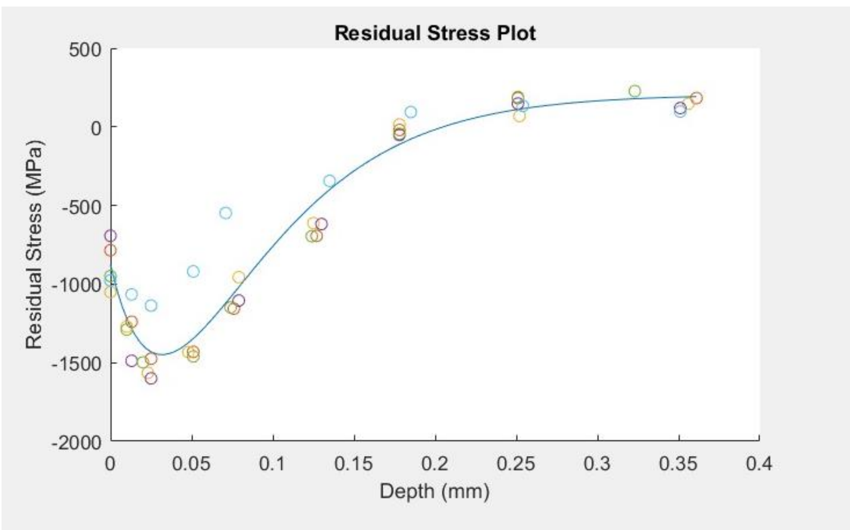


Random Variables	Value
Fracture Toughness Distribution (Normal)	Mean = 34.5ksi√in, Standard Deviation = 3.8 ksi√in.
Initial & Repair Lognormal Size Distribution (a & c) (Lognormal)	Mean = 0.005 in, Standard Deviation = 0.001 in.
Extreme Value Distribution (Gumbel)	Location = 14.5, Scale = 0.8, and Shape = 0.0

ERSI

Residual Stress Profile

➤ Shot Peening Residual Stress Profile (Random)



$$\sigma(x) = (ss - si + c_1 x)Exp[-C_2 x] + si$$

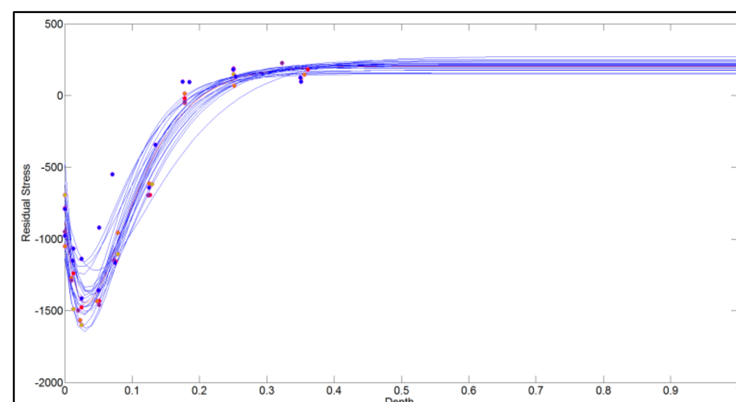
$$C_1 = \frac{\{(\sigma_s - \sigma_i)(1 - Exp[-C_2 B]) + \sigma_i B C_2\} C_2}{(C_2 B + 1)Exp[-C_2 B] - 1}$$

Mean and Standard Deviation Parameters

	Mean (Mpa)	St dev
ss	-879.16	58.58
si	205.68	9.448
c2	20.872	1.050

Correlation Parameters

	ss	si	c2
ss	1	-0.214	0.402
si	-0.214	1	-0.796
c2	0.402	-0.796	1



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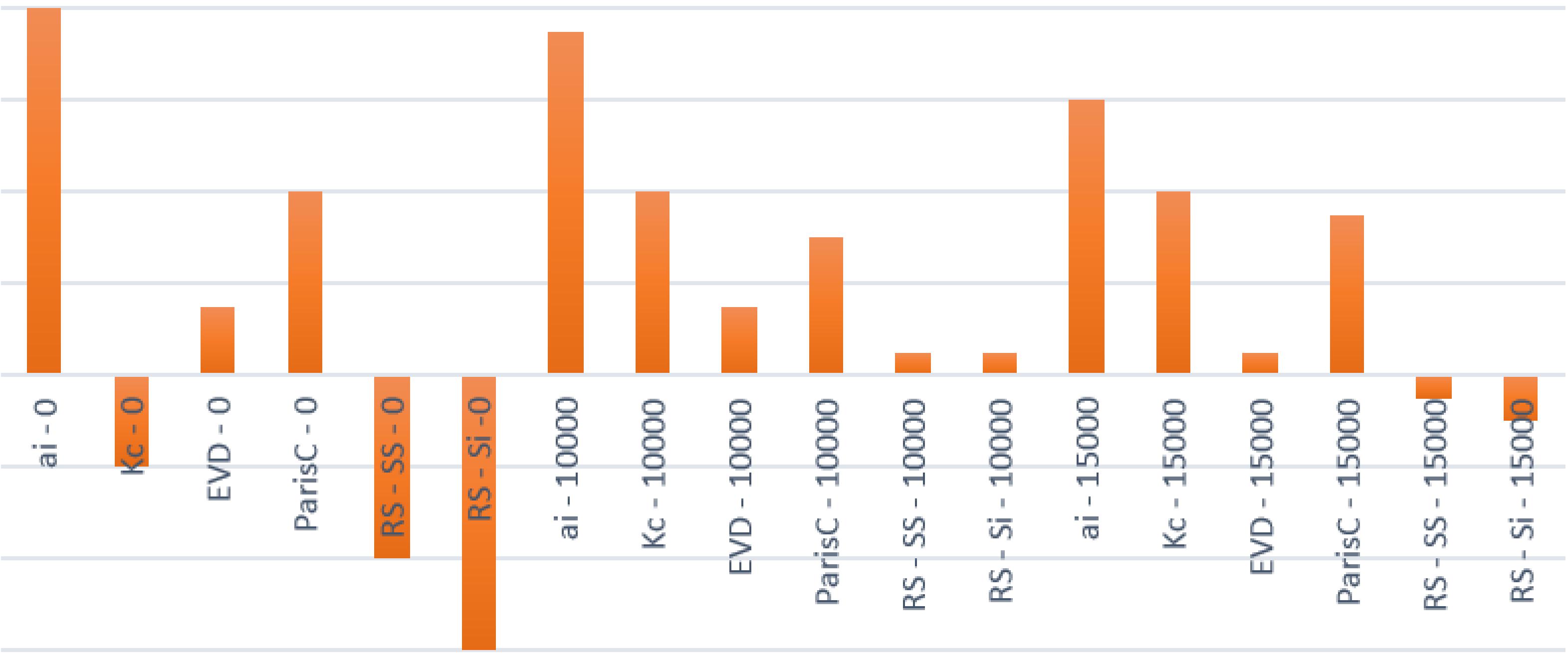
Sensitivity



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Future Work

- Compute sensitivities wrt standard deviation.
- Define handbook example problems
  - Need help from the group

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Thank you!!

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Some O servations on the Signi icance o Residual Stress aria ility on atigue Crack Growth Li e

ERSI Workshop
Layton, Utah
September 13-14, 2018

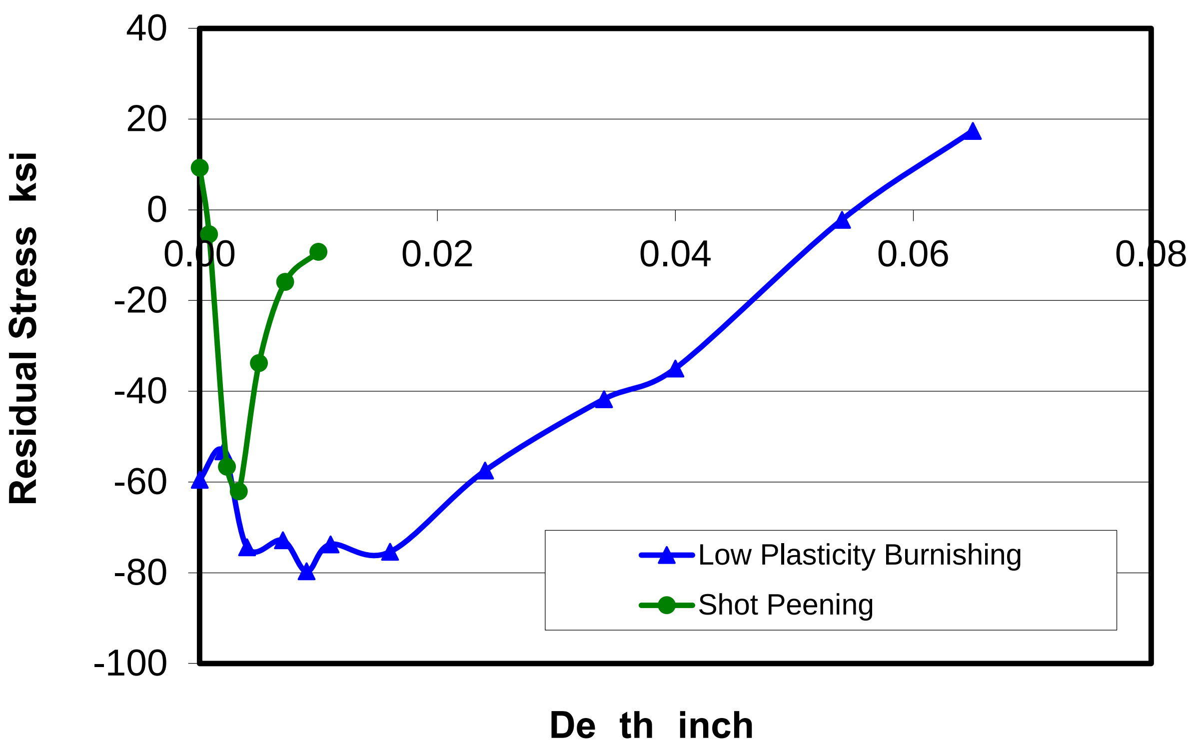
R. Craig McClung
Southwest Research Institute
San Antonio, Texas

Overview

- A few anecdotal observations are offered on the significance of variability in residual stress on fatigue crack growth lifetime
- Example 1: Relaxed surface residual stress field created by surface enhancement (shot peening or laser peening) – *data courtesy Lambda Technologies (P. S. Prevéy)*
- Example 2: Bulk residual stress field created by heat treating – *data from MAI BA-11 project*

E am le : Sur ace Engineered RS

- Surface enhancement methods such as shot peening (SP) or low plasticity burnishing (LPB) can introduce significant near-surface compressive RS fields.
- FCG analysis can be used to predict the influence of the resulting stable RS fields on fatigue life.
- In this example, alpha-beta Ti-6Al-4V laboratory coupons were subjected to SP or LPB and then thermally exposed (425°C/10 hrs) before RS profiles were measured.

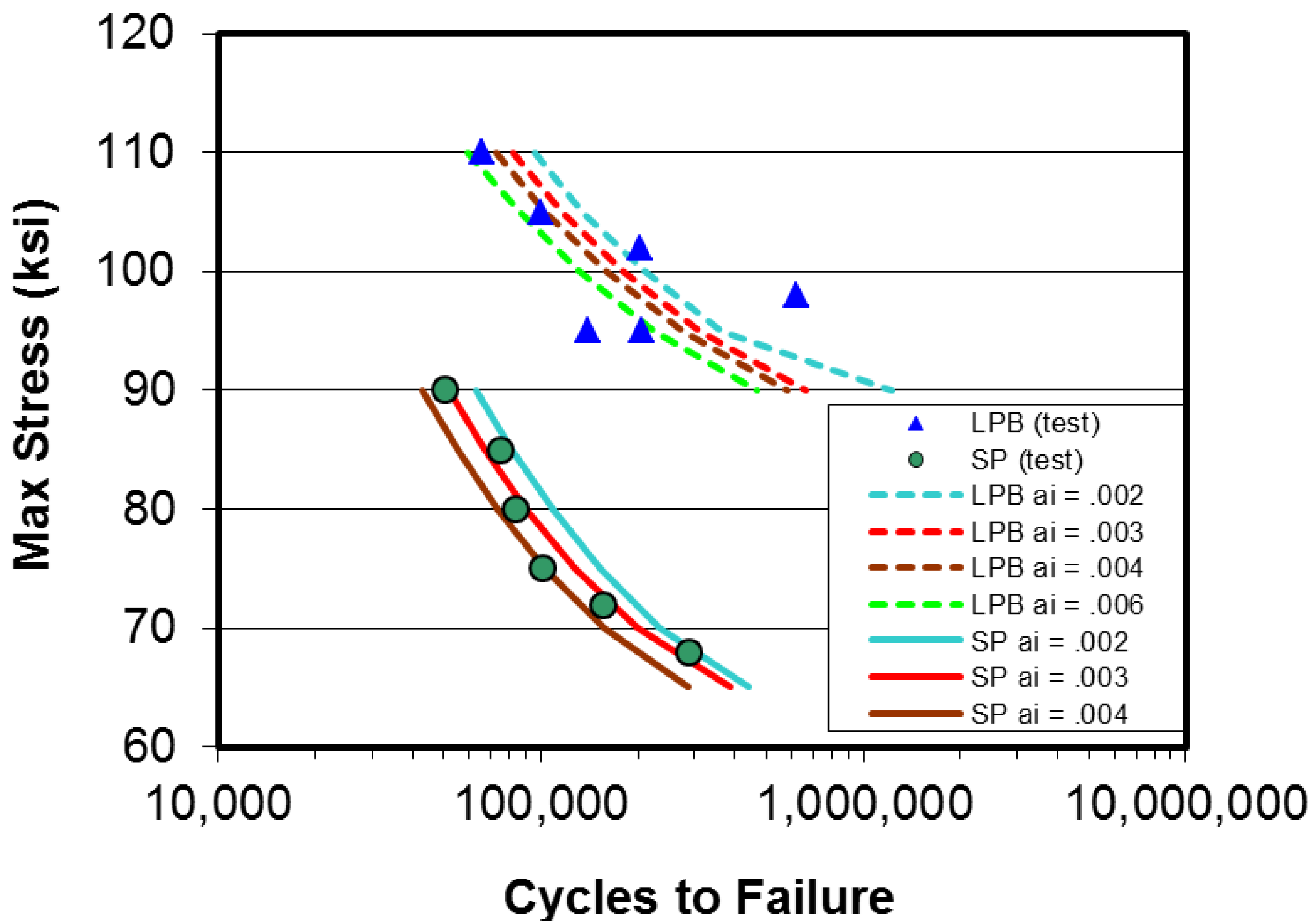


E am le : Sur ace ERS
A roach

- These RS profiles were inserted into a univariant weight function surface crack SIF solution.
- Hypothesizing that the surface enhancement could have introduced microscopic damage that would initiate fatigue cracks quickly, FCG analyses with small initial crack sizes were used to calculate total fatigue life.
- A simple El Haddad model was used to describe small-crack growth rate behavior.

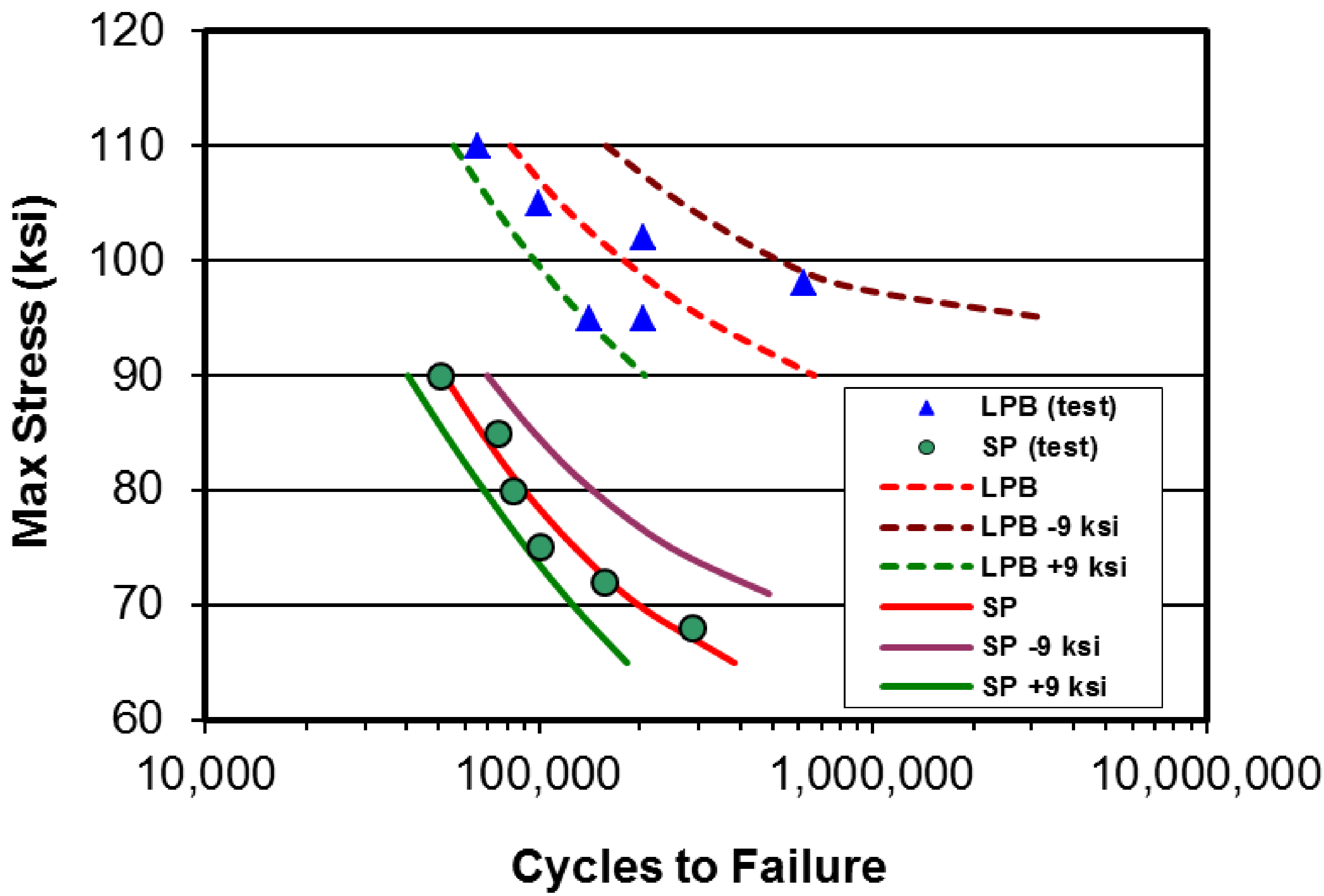
E am le : Sur ace ERS
E ect o Initial Crack Si e

- Variations in the assumed initial crack size had relatively little impact on calculated life (compare large scatter in fatigue lifetimes)



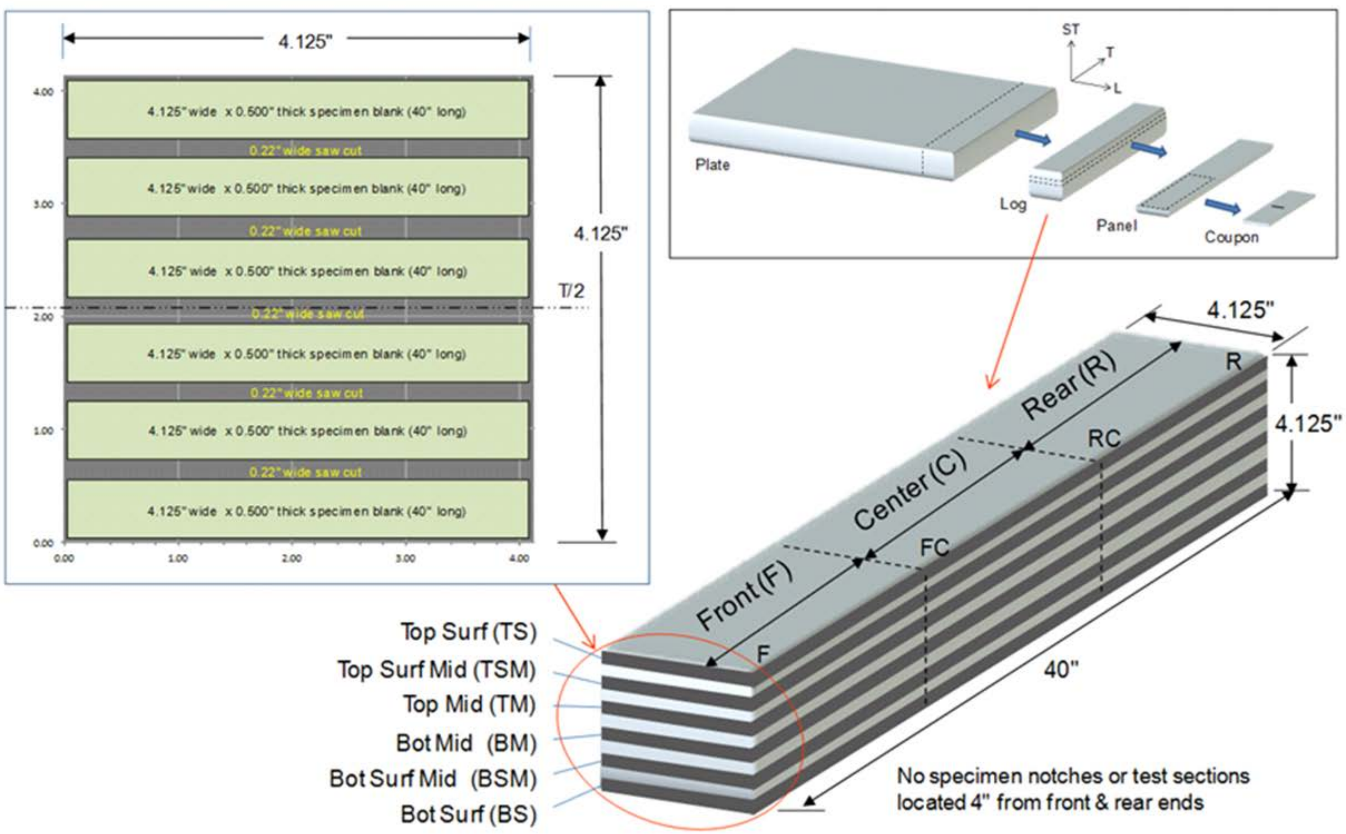
E am le : Sur ace ERS
E ect o RS aria ility

- Small shifts (±9 ksi) in the RS profiles, hypothetically arising from process variability or measurement uncertainty, had a much larger impact on calculated life and were consistent with limited data for life scatter



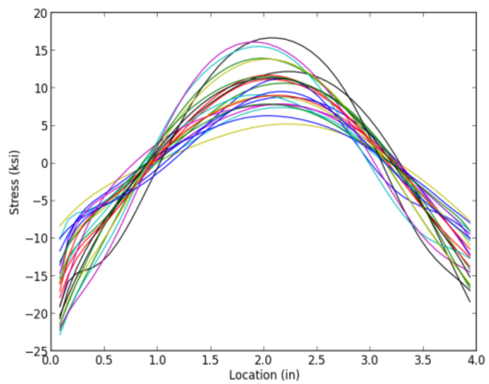
E am le : Bulk RS
Billet, Logs, Cou ons

- 7085-T74 billet cut into many ‘logs’ that were quenched and aged individually to intentionally leave significant residual stress
- Coupon blanks extracted from three longitudinal positions and six transverse positions (total of eighteen unique positions) within each log

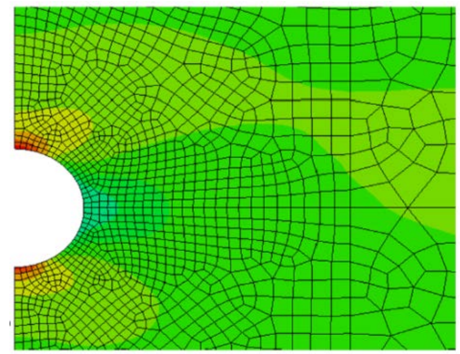


E am le : Bulk RS
A roach Overview

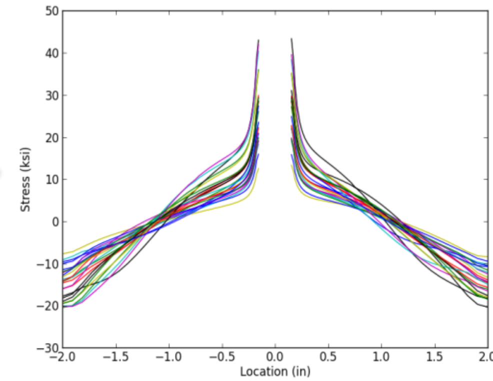
Slitting RS measurements



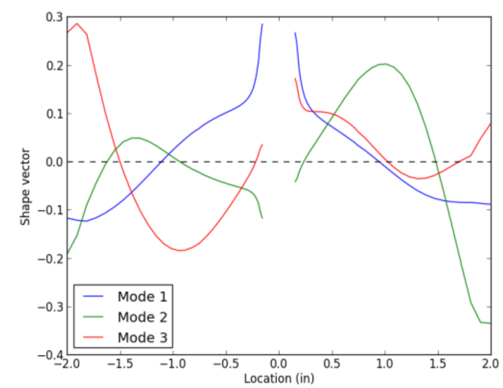
inite Element Analysis



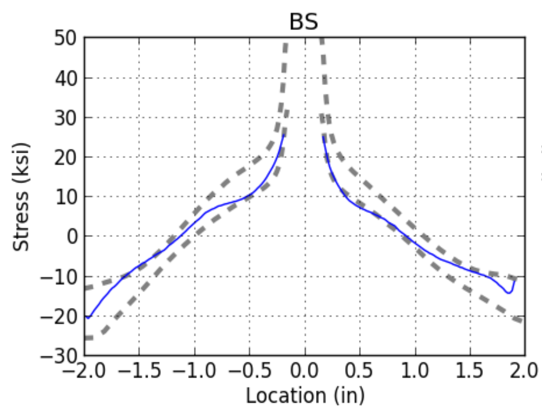
Predicted D Residual Stress



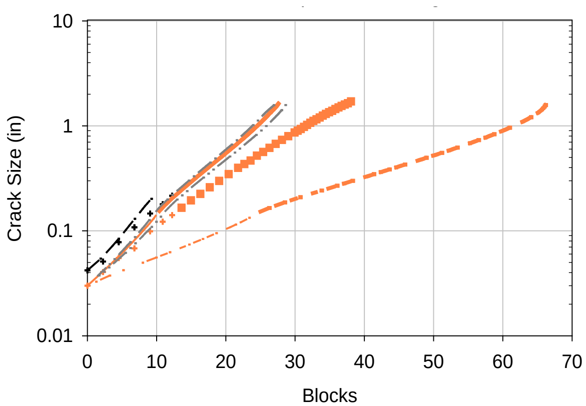
Princi al Com onents Analysis



Pro a ilistic RS Models

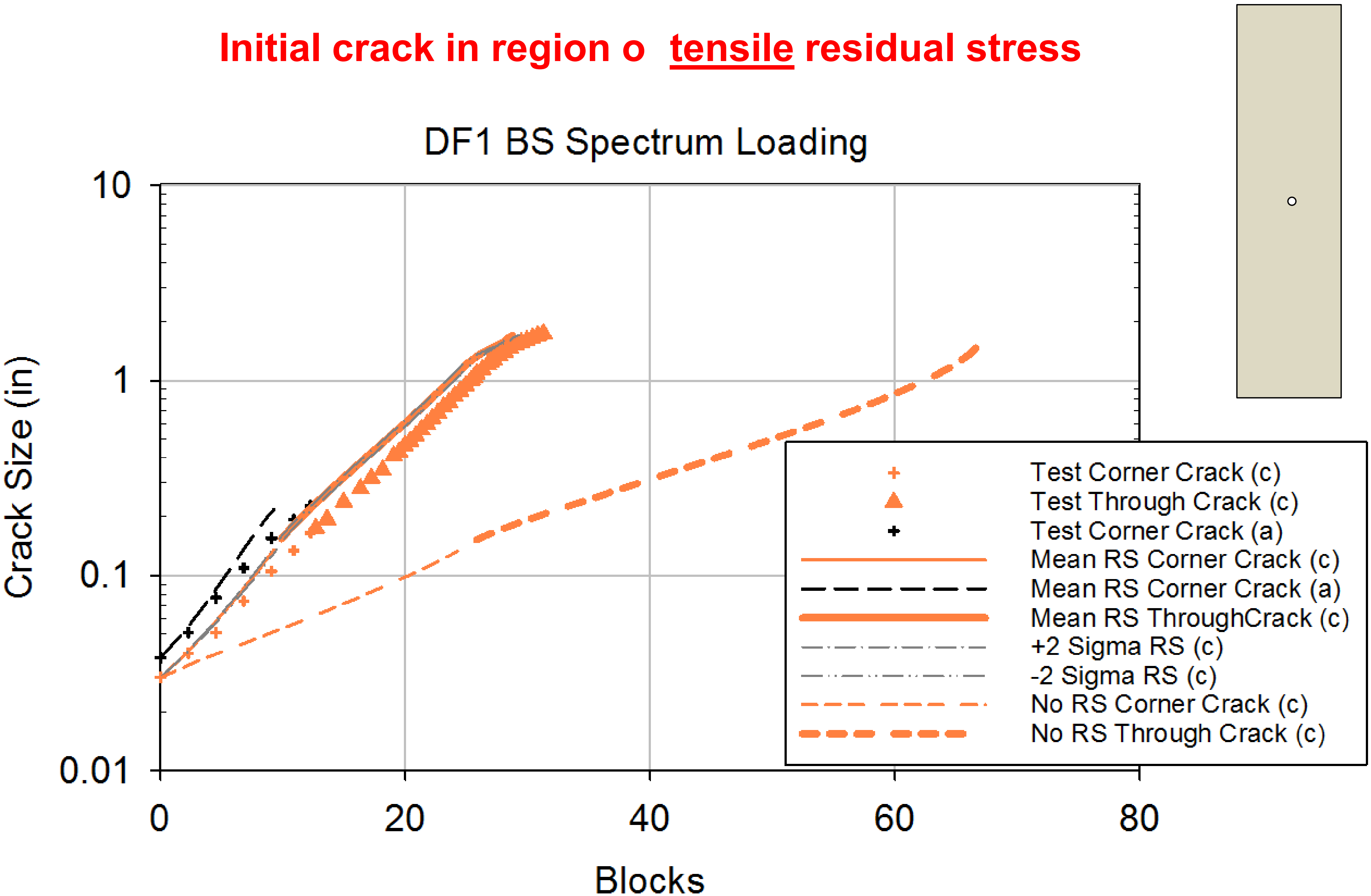


CG redictions/com arisons



E am le : Bulk RS
S ectrum Tests Tensile RS

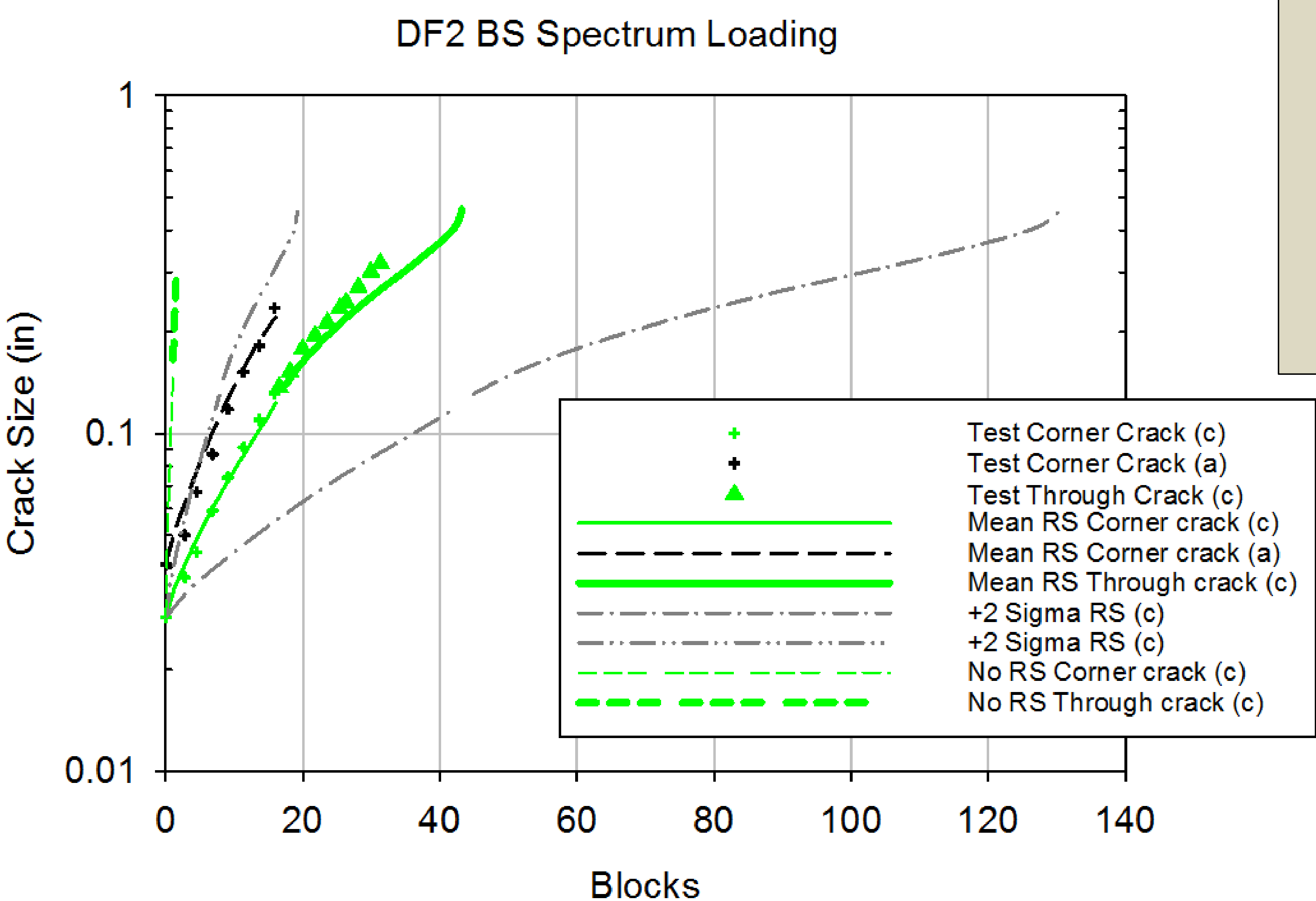
Initial crack in region o tensile residual stress

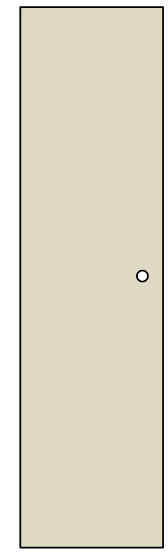


E am le : Bulk RS

S ectrum Tests Com ressive RS

Initial crack in region o com ressive residual stress





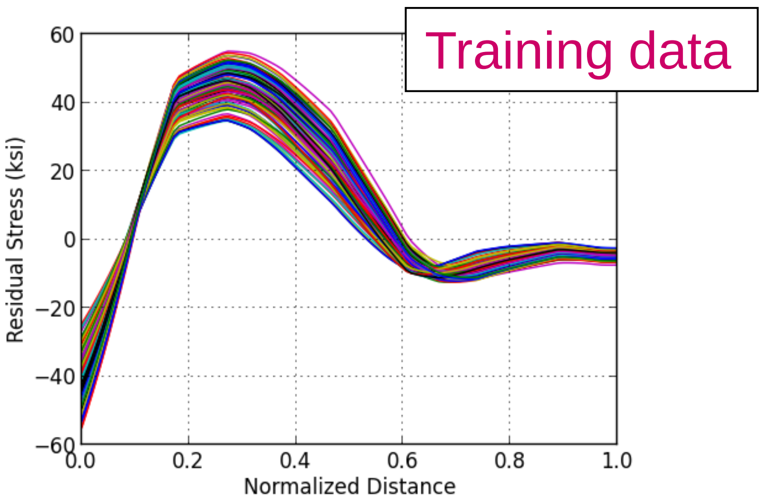
E am le : Bulk RS
O servations

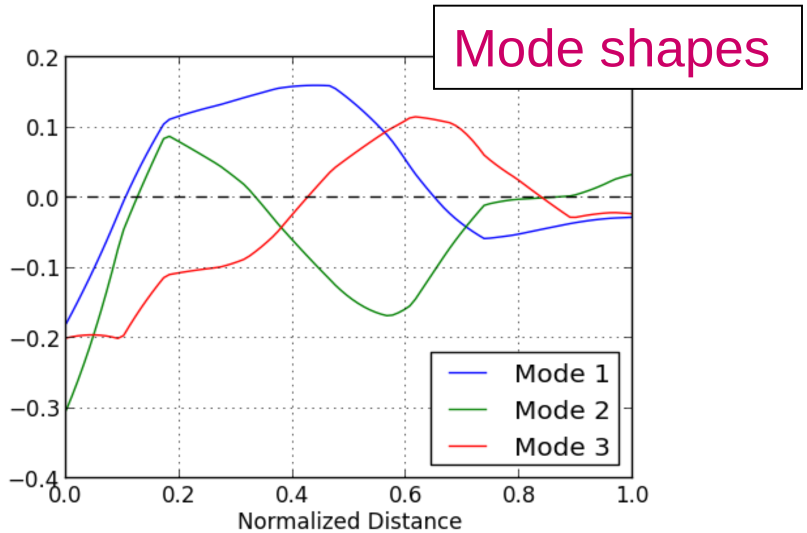
- In these tests, the RS had a significant impact on the predicted life, and predictions ignoring RS tended to be highly conservative or highly non-conservative.
- Predictions (32 tests) including mean value RS were generally accurate (±2x) with a conservative bias for constant amplitude loading, and accurate (±2x) with no bias for spectrum loading.
- How did RS scatter affect the predicted life in these tests?
  - Scatter in tensile RS generally had a very small effect
  - Scatter in compressive RS generally had a very large effect

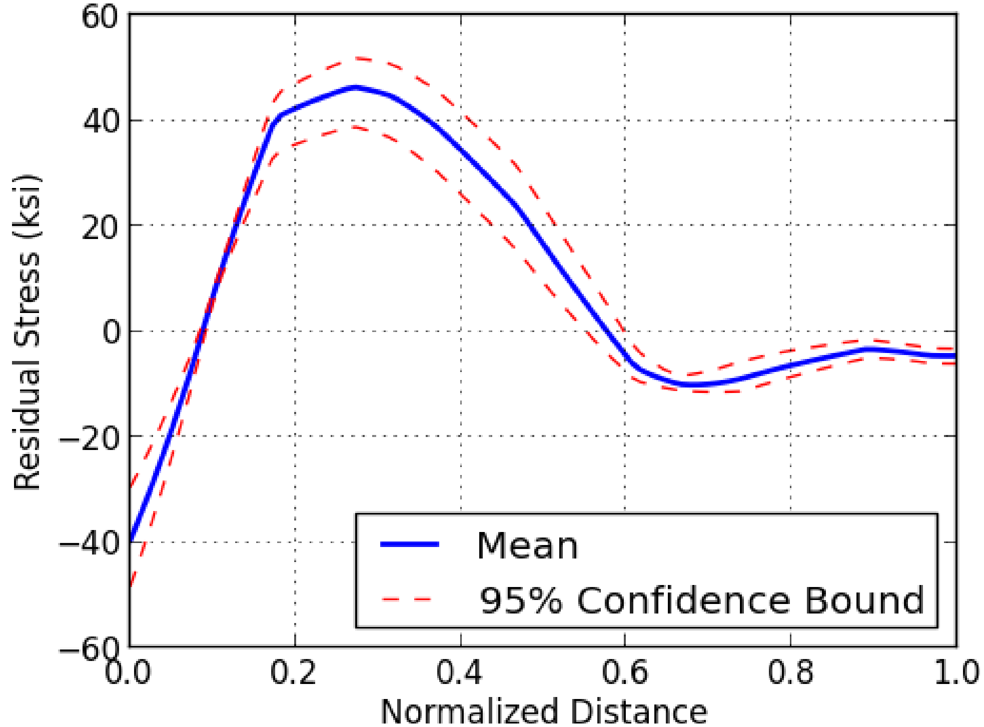
Possi le Path orward

- Use DARWIN probabilistic damage tolerance software
  - Current AFRL investment in DARWIN for AFLCMC
- Develop quantitative characterization of uncertainty in RS
  - Informed by RS models and RS measurements
- Use weight function SIF solutions to model effect of RS on crack driving force
- Perform probabilistic analysis of (uncertain) RS effects on FCG life and fracture risk

Princi al Com onents Analysis or Residual Stresses Along Crack Path

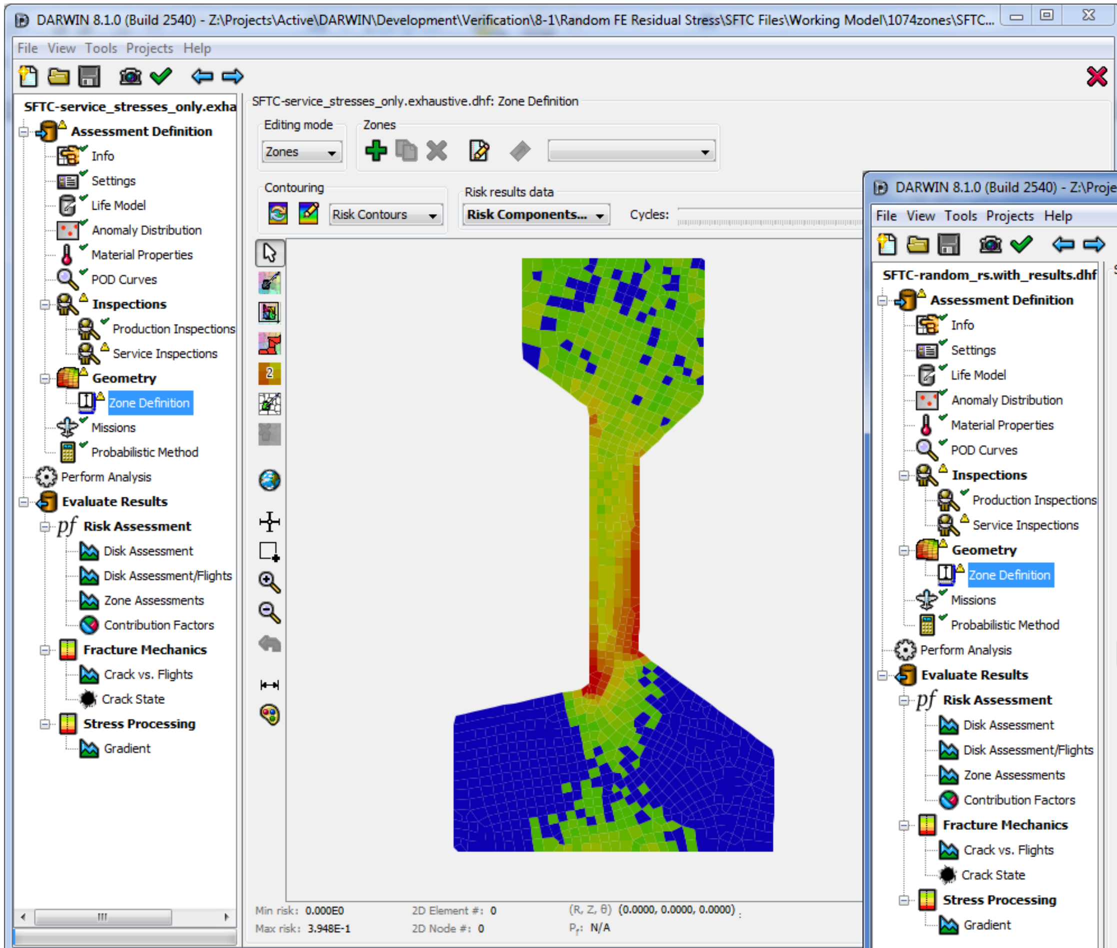




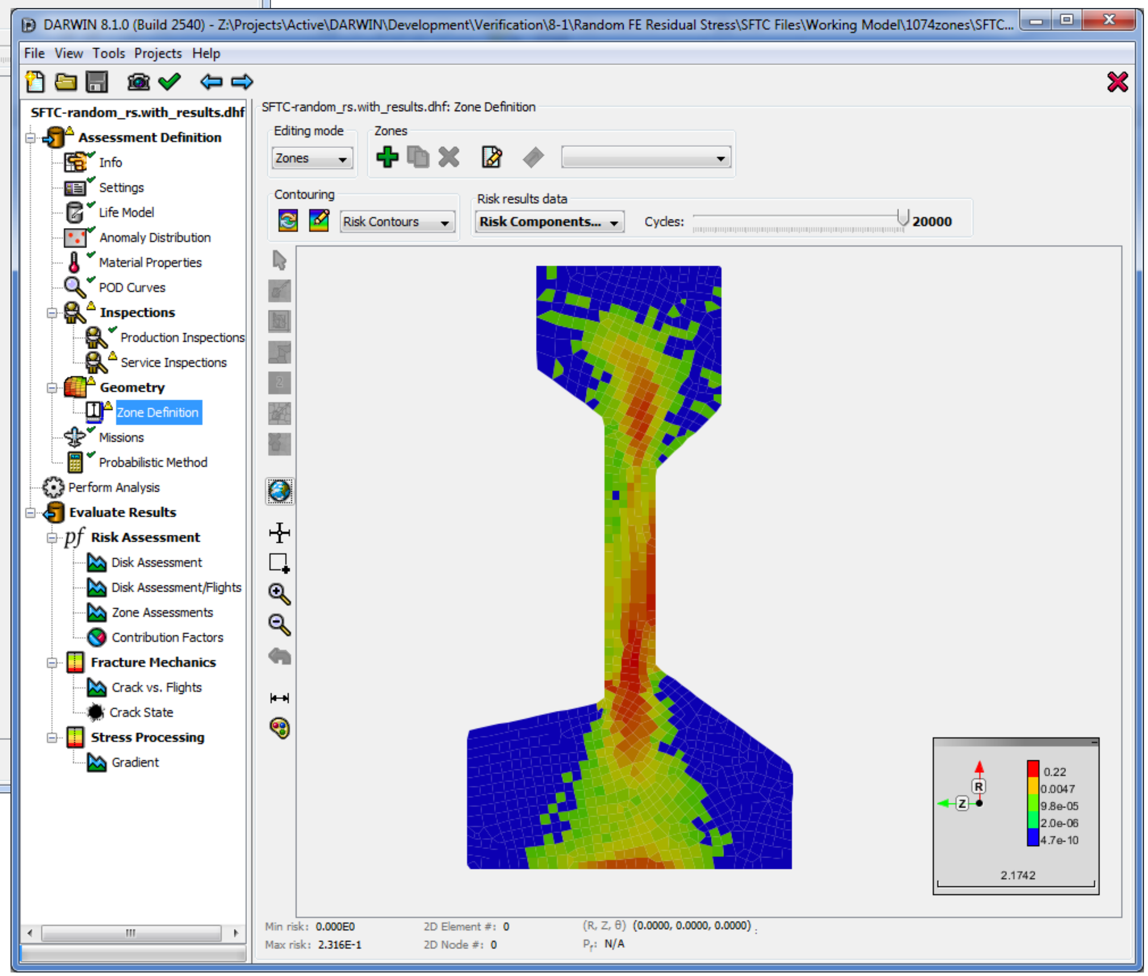


E ect o Random Residual Stress on Risk

Without Residual Stress

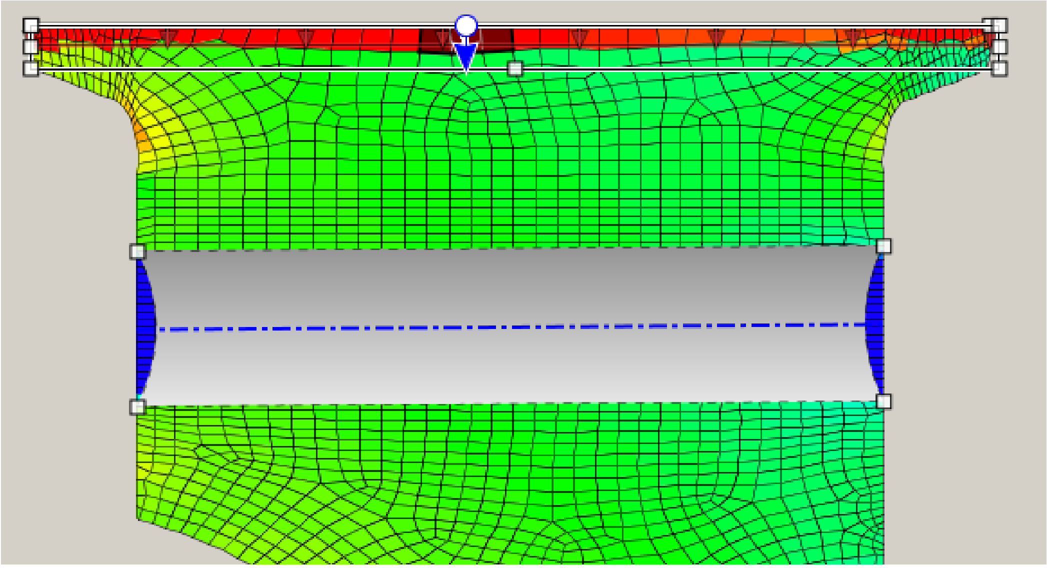


With Random Residual Stress



DAR IN Status

- Framework available to superimpose local residual stresses (e.g., surface RS at holes) with service stresses
- Univariant & bivariant WF SIF solutions available for corner/ surface/thru cracks at holes, corner/surface cracks in plates
- Probabilistic treatment of residual stress uncertainty available for bulk residual stresses in 2D finite element models
- Random RS capabilities expandable to local RS in 3D models



Closing Comments

- Relatively small variations in residual stress can have a very large impact on predicted FCG lifetime when the residual stress is compressive
- Uncertainty in tensile residual stresses appears to have relatively less effect on life variability
- A more rigorous probabilistic treatment of RS uncertainty and its effect on fracture risk appears warranted
- DARWIN software provides a potential path forward, but some enhancements are needed