Cold-Expanded Hole Tolerance Effects: Pre-Test Predictions

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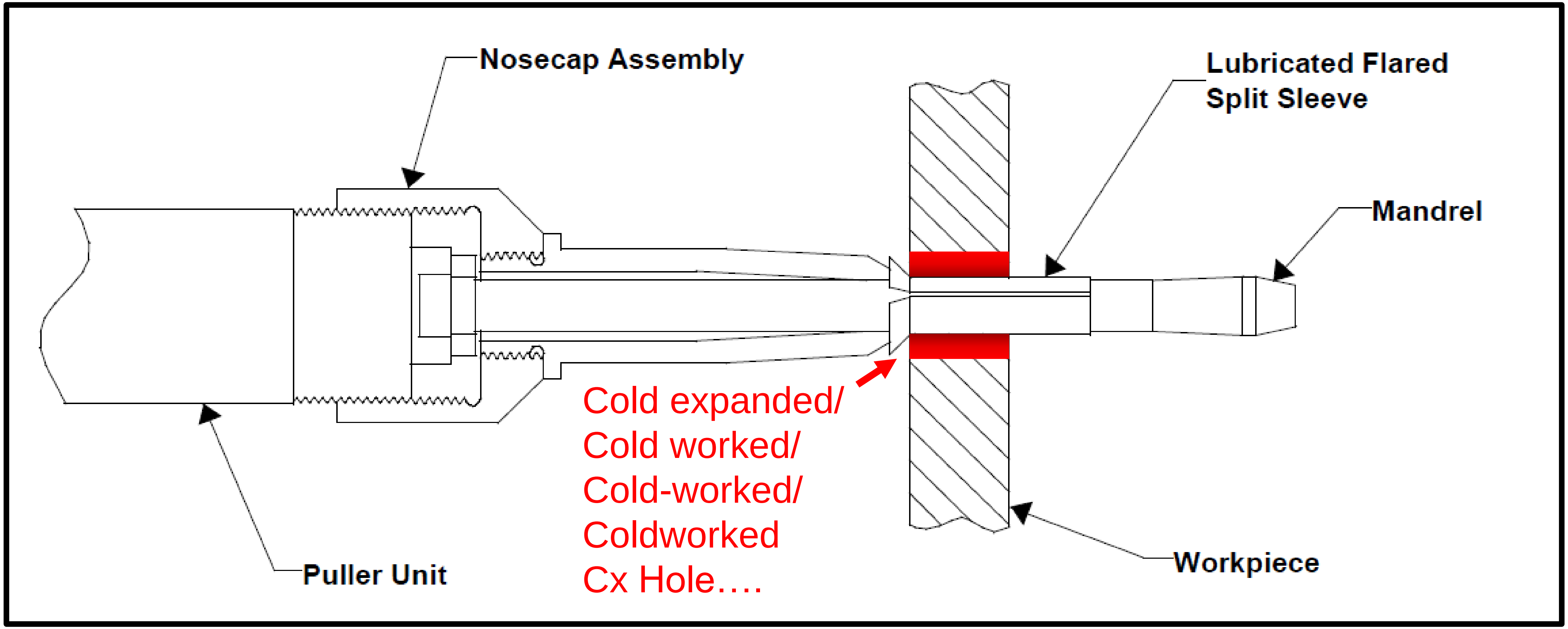
Cold Expansion (Cx) of Holes

Many holes in aircraft structure undergo a process called *cold-expansion*:

Cold Expansion (Cx) of Holes



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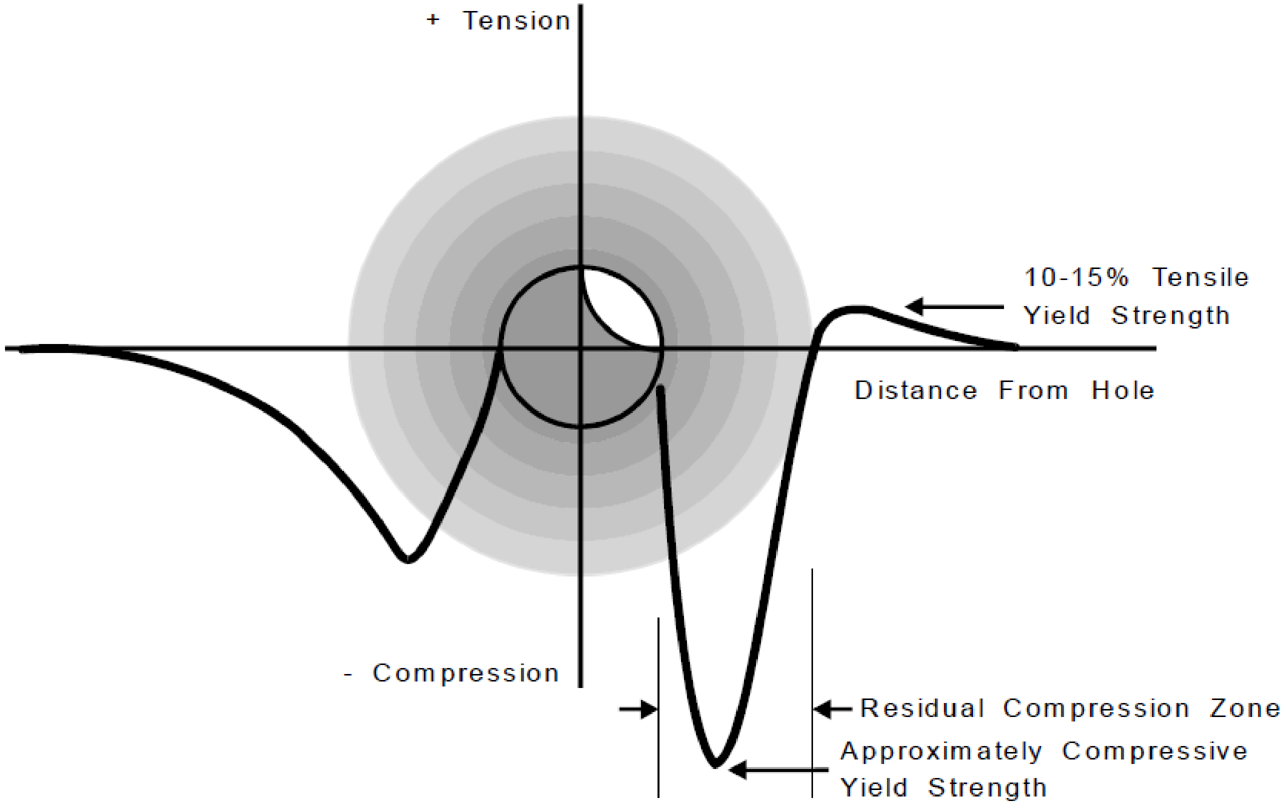

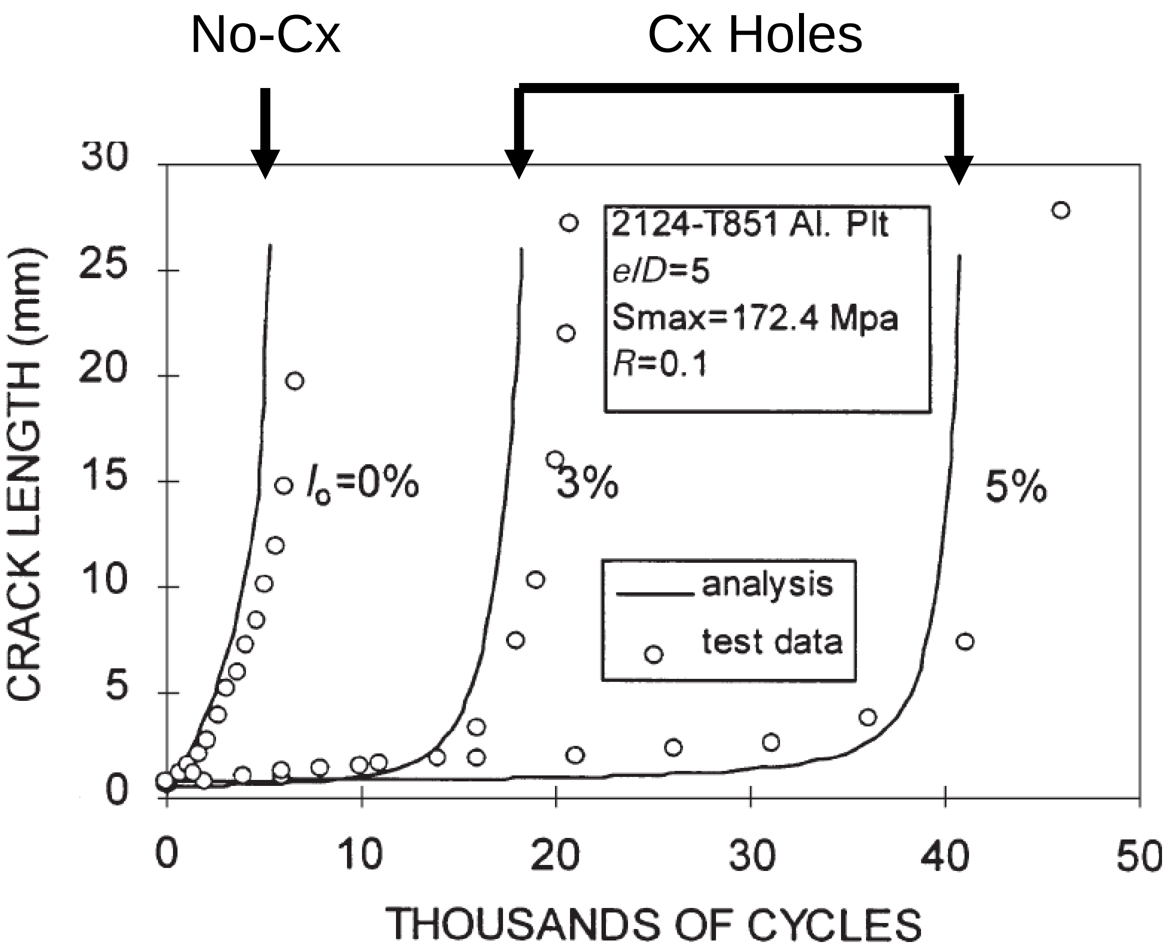

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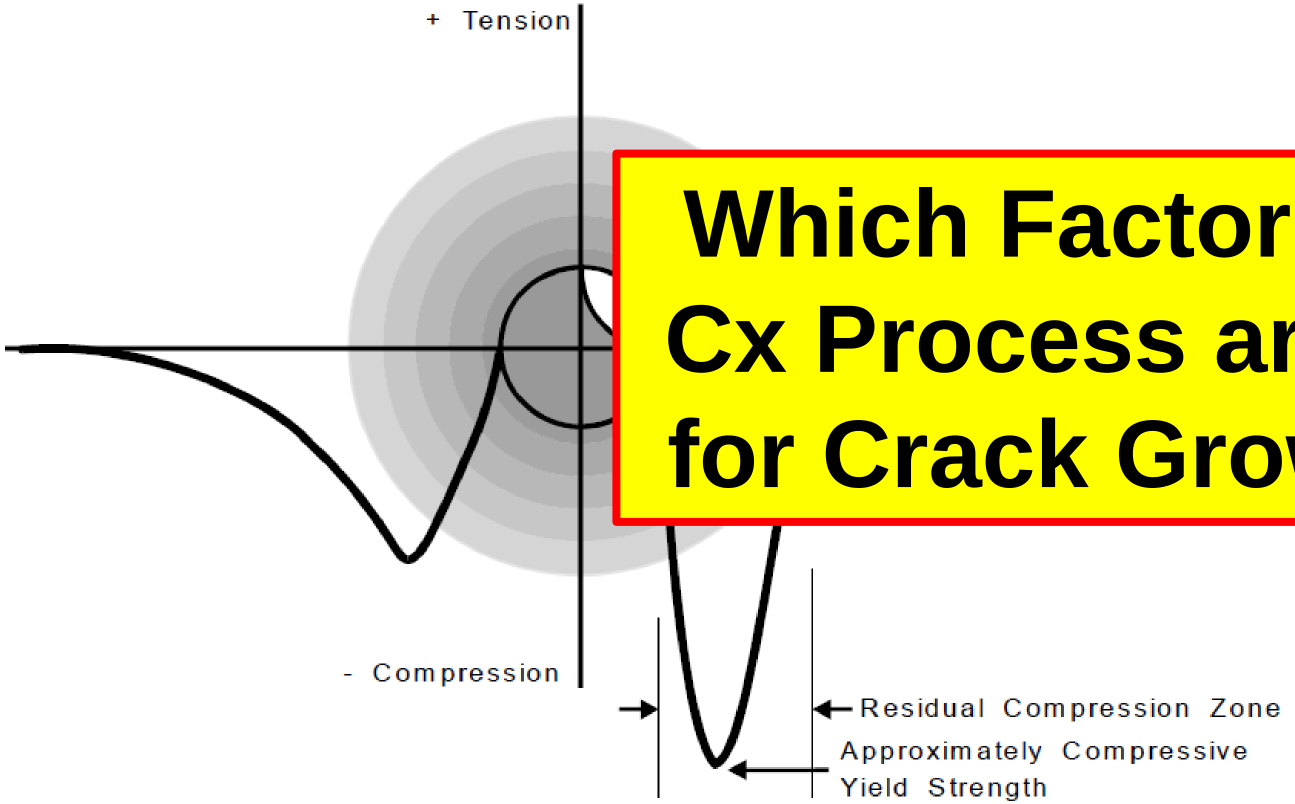
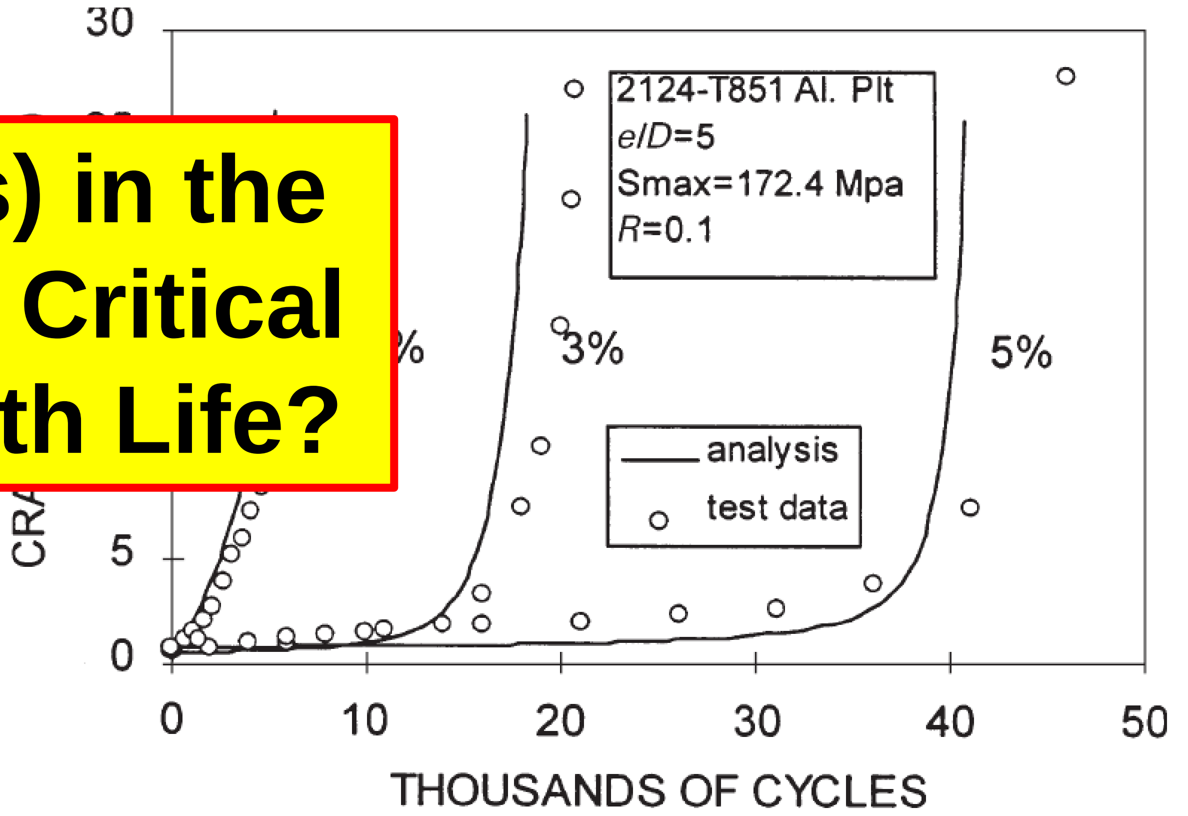


Which Factor(s) in the Cx Process are Critical for Crack Growth Life?



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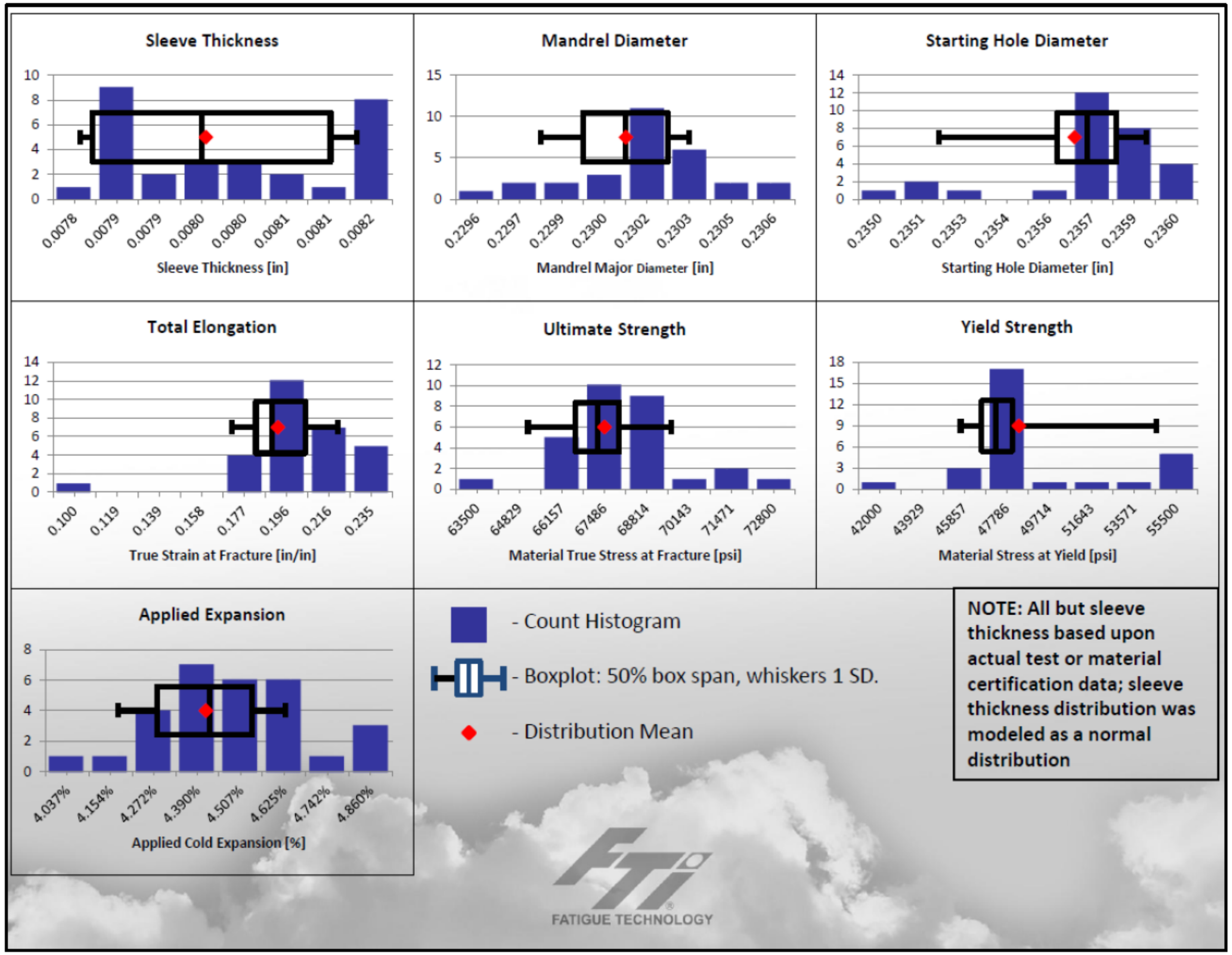
Cold Expansion (Cx) of Holes

There are several key geometric and material parameters with varying distributions:



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Cold Expansion (Cx) of Holes

These factors were examined and…

Life prediction analyses show a 95.3% correlation to applied expansion level (I_a):

Other independent factors had low correlation with life.

Run Number	Starting Hole D (inch)	Mandrel D (inch)	Sleeve T (inch)	Applied Expansion	Elongation (inch)	Ultimate Strength (psi)	Yield Strength (psi)	Predicted Life (cycles)
1	0.2357	0.230	0.008	4.383%	0.17	65950	45700	96544
2	0.2358	0.230	0.008	4.283%	0.205	67400	47300	76937
3	0.2351	0.230	0.008	4.755%	0.2	67250	46050	113056
4	0.2356	0.230	0.008	4.572%	0.22	67600	54600	101030
5	0.2358	0.230	0.008	4.504%	0.1825	67950	46900	100290
6	0.2355	0.231	0.008	4.860%	0.19	64950	46650	120566
7	0.236	0.231	0.008	4.539%	0.2	67250	46050	90015
8	0.2357	0.230	0.008	4.560%	0.1715	66450	45650	110601
9	0.2359	0.230	0.008	4.176%	0.19	67650	47300	71322
10	0.2357	0.230	0.008	4.422%	0.22	68200	53200	87129
11	0.2357	0.230	0.008	4.488%	0.235	71300	55000	91109
12	0.2358	0.230	0.008	4.526%	0.2	67250	46050	96973
13	0.2358	0.230	0.008	4.056%	0.19	72800	55500	66118
14	0.2358	0.230	0.008	4.171%	0.205	67300	47500	71010
15	0.2358	0.230	0.008	4.192%	0.175	66600	47000	71703
16	0.2357	0.230	0.008	4.431%	0.19	67650	47300	84063
17	0.2359	0.230	0.008	4.509%	0.23	69600	53800	99999
18	0.2356	0.230	0.008	4.401%	0.1875	67300	48050	85695
19	0.2356	0.230	0.008	4.494%	0.186	65400	45500	96758
20	0.2357	0.230	0.008	4.037%	0.18	68700	46800	65694
21	0.2358	0.230	0.008	4.276%	0.19	64950	46650	76644
22	0.2356	0.230	0.008	4.317%	0.19	65100	46650	79104
23	0.2351	0.230	0.008	4.629%	0.18	68050	46650	98469
24	0.2358	0.230	0.008	4.186%	0.235	71300	55000	76122
25	0.2357	0.230	0.008	4.319%	0.19	67650	47300	78047
26	0.2352	0.230	0.008	4.575%	0.2	67300	51200	98189
27	0.2357	0.230	0.008	4.281%	0.1	63500	42000	76394
28	0.235	0.230	0.008	4.755%	0.205	67300	47500	119632
29	0.236	0.230	0.008	4.288%	0.1675	67950	47400	87803
CORRELATION TO PREDICTED LIFE								
NA	-0.562	0.335	0.791	0.953	0.144	-0.217	-0.086	1.000

Applied Expansion (I_a) is given by the following formula:

$$I_a = \frac{(D + 2t - SHD) \times 100\%}{SHD}$$

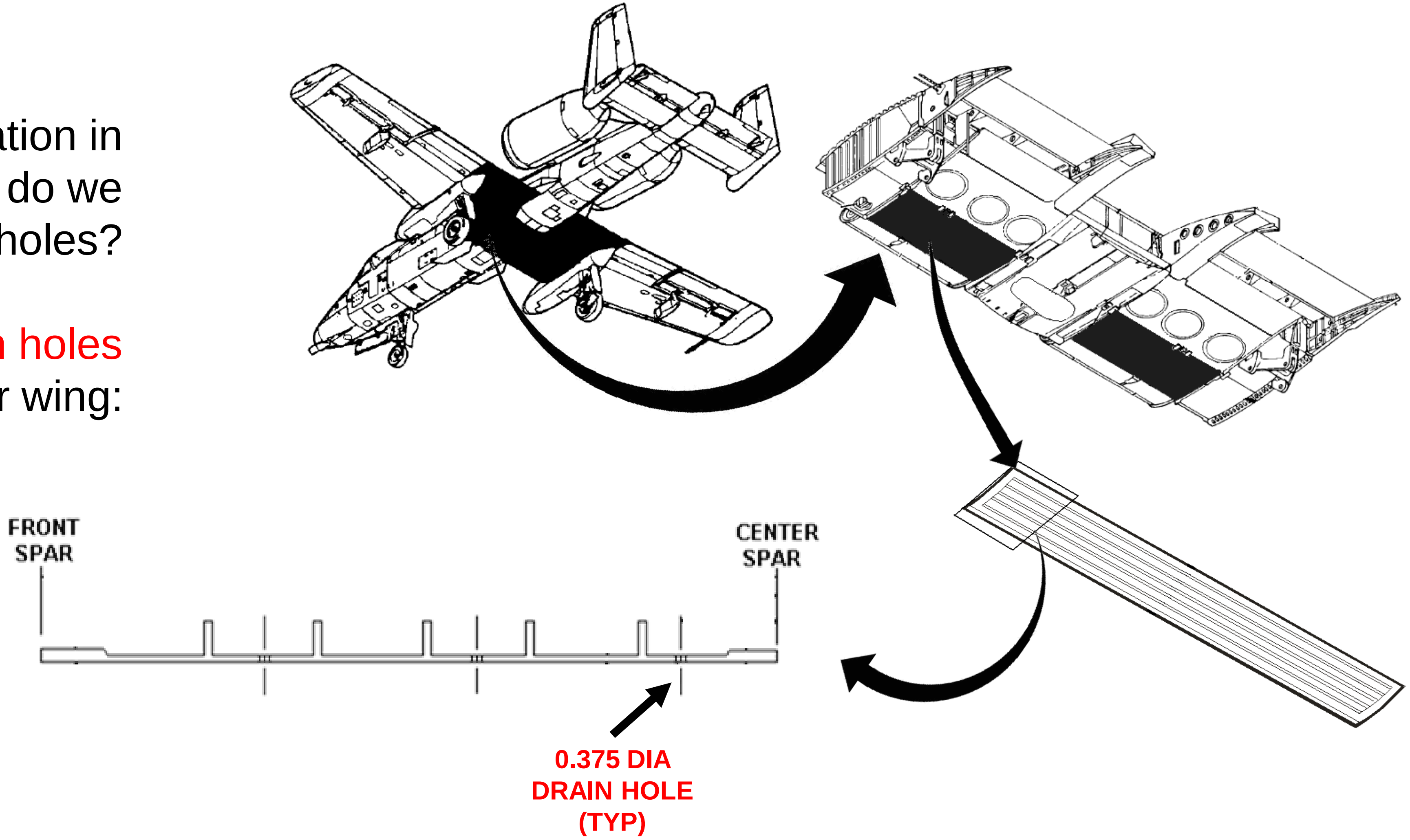
Where:

D = *Major Mandrel Diameter*
t = *Sleeve Thickness*
SHD = *Starting Hole Diameter*

Cx of A-10 Holes

How much variation in applied expansion do we expect for A-10 Cx holes?

Let's look at the drain holes in the center wing:



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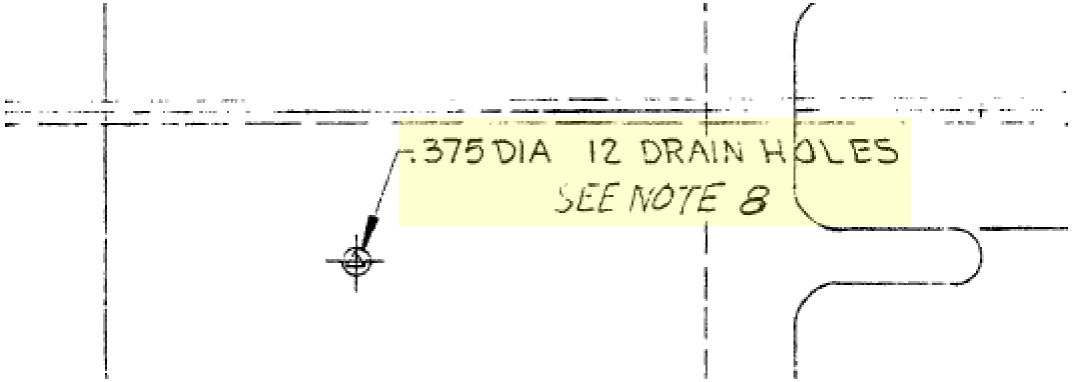
Cx of A-10 Holes

Drawing Requirements:



Note 8:

- Ream 0.359-0.362 Diameter.
- Cold work per process specification.

Process Specification:

TABLE VII. NOMINAL STARTING HOLE SIZES

Nominal Finish Hole Diameter (Inches)		Mandrel Number	Starting Hole Diameter (Inch)
Fraction	Decimal	Ref	Range
5/32	.156	4-2-N	.143-.146
3/16	.187	6-0-N	.177-.180
1/4	.250	8-0-N	.235-.238
5/16	.312	10-0-N	.297-.300
3/8	.375	12-0-N	.359-.362
7/16	.437	14-0-N	.421-.424
1/2	.500	16-0-N	.474-.477
9/16	.562	18-0-N	.537-.540
5/8	.625	20-0-N	.597-.600
11/16	.687	22-0-N	.659-.662
3/4	.750	24-0-N	.718-.721
13/16	.812	26-0-N	.782-.785
7/8	.875	28-0-N	.841-.844
15/16	.937	30-0-N	.901-.904
16/16	1.000	32-0-N	.965-.968

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Cx of A-10 Holes

Tooling Selection				Standard Tool Diameter Number	Starting Hole Diameter		Mandrel Diameters			Sleeve Thickness (6)	Gage Diameters (7)			Maximum Finished Hole Diameter Not to Exceed (8)
1A. Reference Fastener		1B. Reference Fastener					Minor	Major						
Diameter (1)	Av. Ream Allow. (2)	Diameter (1)	Av. Ream Allow. (2)		Min.	Max.	(3)	Nom. (4)	Min. (5)		A	B	C	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3/8	.005	25/64	.021	12-0-N	.359	.362	.3335	.3540	.3530	.0100	.3590	.3620	.3645	.4190
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Cx of A-10 Holes

Therefore, nominally:

SHD = 0.3590 .. 0.3605 .. 0.3620 in
t = 0.0098 .. 0.0100 .. 0.0104 in
D = 0.3530 .. 0.3540 .. 0.3542 in

Applied Expansion (I_a) is given by the following formula:

$$I_a = \frac{(D + 2t - SHD) \times 100\%}{SHD}$$

Where:

D = Major Mandrel Diameter
t = Sleeve Thickness
SHD = Starting Hole Diameter

SHD (in)	t (in)	D (in)	Ia (%)	Notes
0.3560	0.0104	0.3542	5.34	Max tol - 0.003" SHD
0.3580	0.0104	0.3542	4.75	Max tol - 0.001" SHD
0.3590	0.0104	0.3542	4.46	Max in-tol
0.3605	0.0100	0.3540	3.74	Nominal
0.3620	0.0098	0.3530	2.93	Min in-tol
0.3630	0.0098	0.3530	2.64	Min tol + 0.001" SHD
0.3650	0.0098	0.3530	2.08	Min tol + 0.003" SHD

Cx of A-10 Holes

Therefore, nominally:

SHD = 0.3590 .. 0.3605 .. 0.3620 in
t = 0.0098 .. 0.0100 .. 0.0104 in
D = 0.3530 .. 0.3540 .. 0.3542 in

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How will this variation in I_a affect the fatigue crack growth life??

SHD (in)	t (in)	D (in)	Ia (%)	Notes
0.3560	0.0104	0.3542	5.34	Max tol - 0.003" SHD
0.3580	0.0104	0.3542	4.75	Max tol - 0.001" SHD
0.3590	0.0104	0.3542	4.46	Max in-tol
0.3605	0.0100	0.3540	3.74	Nominal
0.3620	0.0098	0.3530	2.93	Min in-tol
0.3630	0.0098	0.3530	2.64	Min tol + 0.001" SHD
0.3650	0.0098	0.3530	2.08	Min tol + 0.003" SHD

Project Objectives

- **Quantify the impact of I_a variance on fatigue crack growth life and predictions for Al 2024-T351 due to in/out-of-tolerance Cx processes.**
  - **Evaluate the parameter space established by FTI in (Hitchman, 2016).**
  - **Evaluate an A-10 Cx hole configuration.**
- **Benchmark state-of-the-art Cx hole multi-point fatigue crack growth predictions utilizing a broad range of residual stress fields obtained via the contour method.**

Hitchman, K., Zimmerman, S., "Development and Use of an FEA Script for Variance and Correlation Studies of Analytical Predictions of Cold Expansion Residual Stress Fields," HOLSIP Conference 2016, Feb. 2016.

Methods Overview

- Predict crack growth behavior
  - Obtain variety of RS fields via contour method
  - Apply RS fields & simulate test specimen crack growth behavior via BAMpF

- Characterize crack growth behavior via test
  - Perform constant amplitude and spectrum-based fatigue tests.
  - In-situ marker-bands for post-mortem analysis.
  - Gather surface/bore crack lengths via travelling microscope.

- Compare predicted & actual crack growth rates/morphology.

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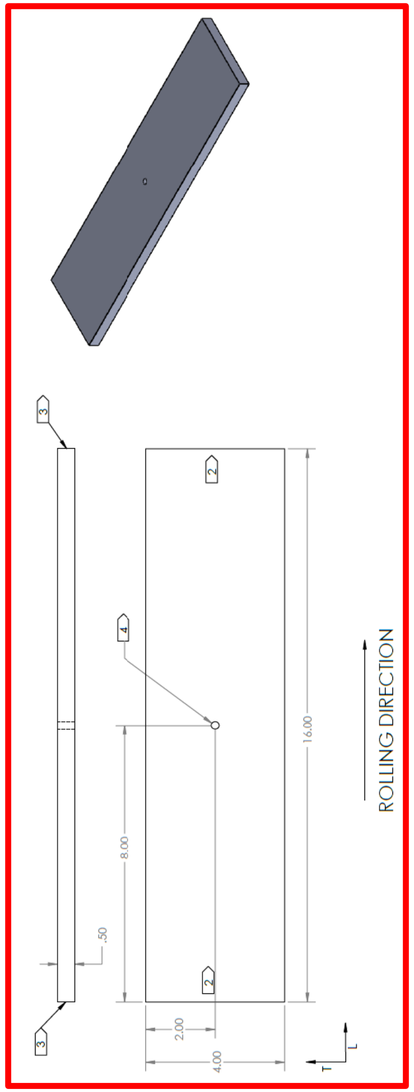
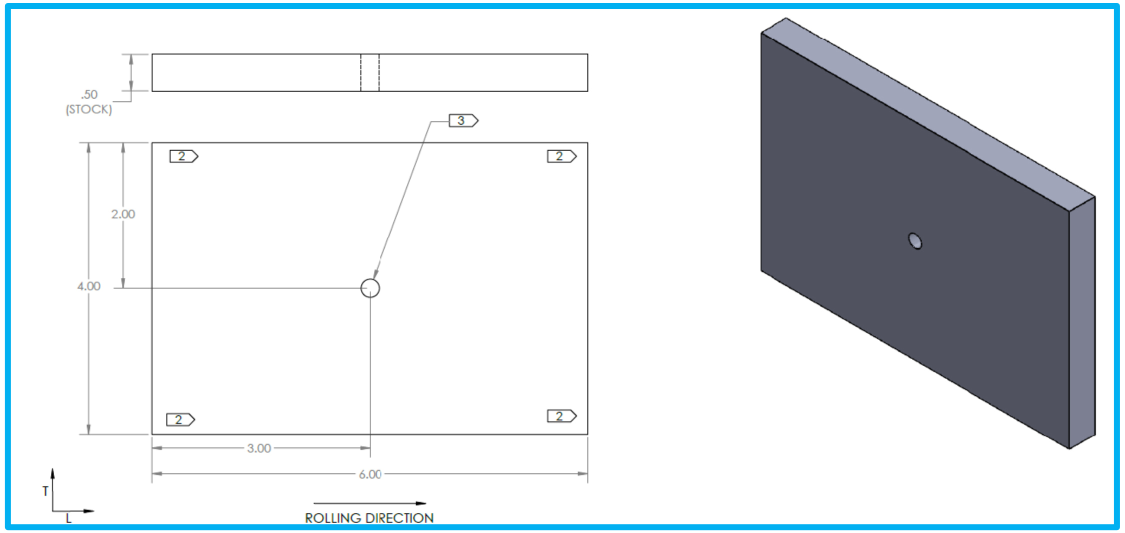
FTI Cx Configuration

Cx Tooling	Condition	Initial D (in)	T (in)	Qty	Coupon IDs
8-0-N	FTI Process Simulation (fatigue)	0.2365	0.5	3	MOD7-FTI-1 to -3
		0.2356		3	MOD7-FTI-4 to -6
		0.2346		3	MOD7-FTI-7 to -9
	FTI Process Simulation (residual stress)	0.2365	0.5	3	MOD7-FTI-RS-1 to -3
		0.2356		3	MOD7-FTI-RS-4 to -6
		0.2346		1	MOD7-FTI-RS-7



Target $I_a = $ 4.02%
4.41%
4.86%



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		0.2346		1	MOD7-FTI-RS-7

Target I_a = 4.02%
4.41%
4.86%

Coupon ID	Applied Expansion (nominal)	Applied Expansion (actual)	Expansion Error
MOD7-FTI-1	4.02%	4.10%	-0.09%
MOD7-FTI-2	4.02%	4.06%	-0.04%
MOD7-FTI-3	4.02%	4.06%	-0.04%
MOD7-FTI-4	4.41%	4.37%	0.04%
MOD7-FTI-5	4.41%	4.33%	0.09%
MOD7-FTI-6	4.41%	4.33%	0.09%
MOD7-FTI-7	4.86%	4.77%	0.09%
MOD7-FTI-8	4.86%	4.81%	0.04%
MOD7-FTI-9	4.86%	4.81%	0.04%
MOD7-FTI-RS-1	4.02%	4.10%	-0.09%
MOD7-FTI-RS-2	4.02%	4.10%	-0.09%
MOD7-FTI-RS-3	4.02%	4.10%	-0.09%
MOD7-FTI-RS-4	4.41%	4.28%	0.13%
MOD7-FTI-RS-5	4.41%	4.37%	0.04%
MOD7-FTI-RS-6	4.41%	4.37%	0.04%
MOD7-FTI-RS-7	4.86%	4.81%	0.04%

- Assuming nominal mandrel and sleeve
- We obtained an I_a variance of ~0.13% with research-grade manufacturing precision on the starting hole diameter.

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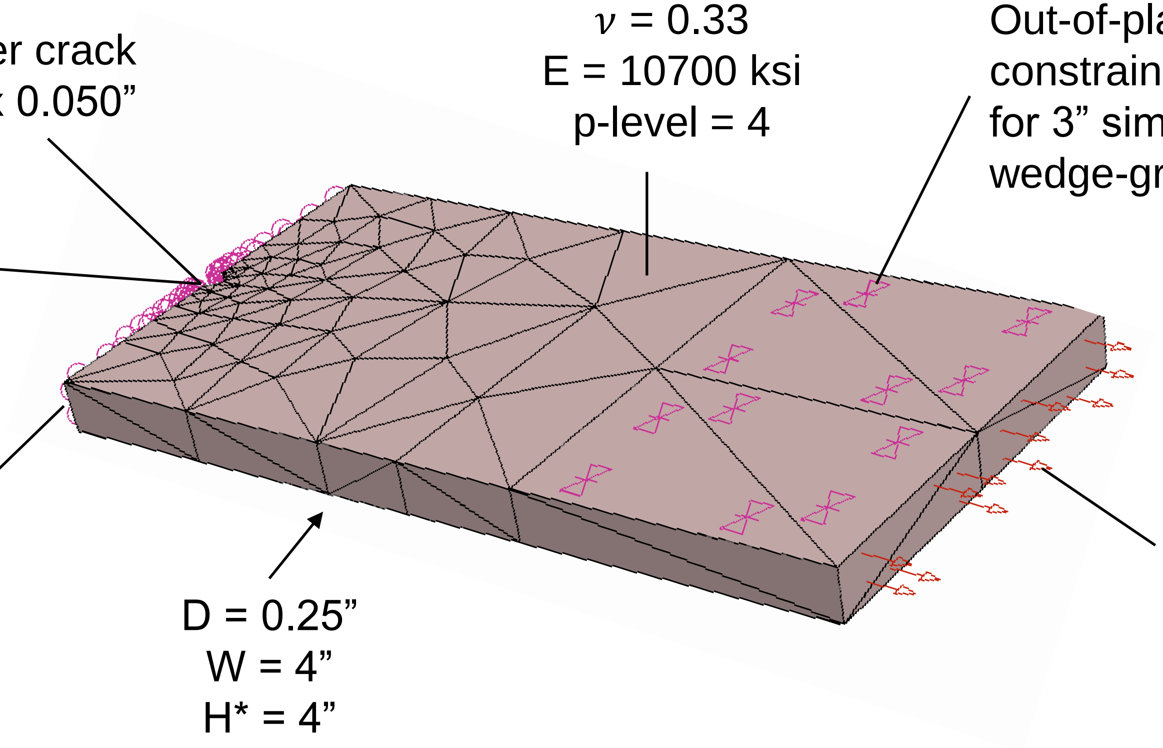
FTI Cx BAMpF Model

Al 2024-T351
ν = 0.33
E = 10700 ksi
p-level = 4

Semi-circular corner crack
0.050 x 0.050”

Out-of-plane constraint
for 3” simulating
wedge-grip height

RS applied as a
traction on crack face



Symmetry constraint
on cracking plane

SMF = 29.63 ksi
Constant Amplitude, R = 0.1
(marker band cycles not simulated)

D = 0.25”
W = 4”
H* = 4”
t = 0.5”
e/D = 8

* Model height is H; Physical specimens will be 2*H

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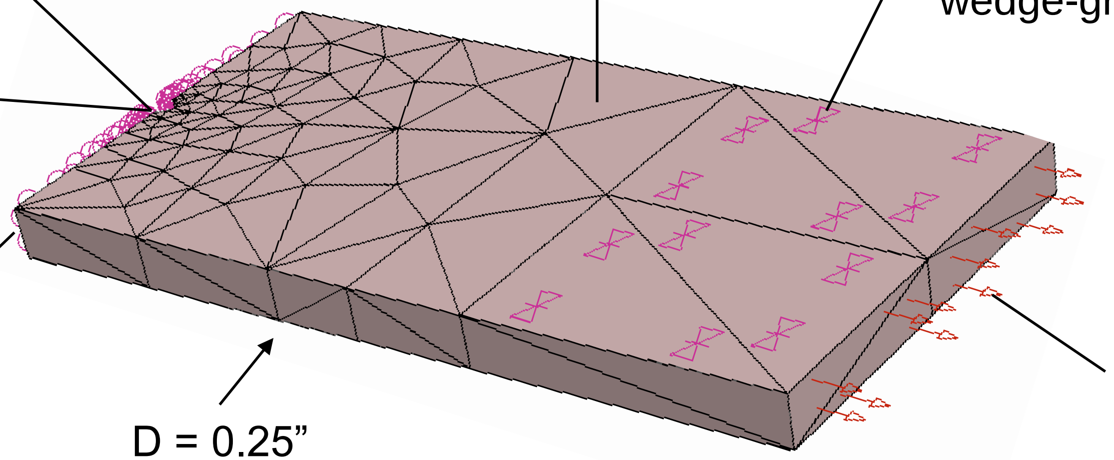

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(marker band cycles not simulated)

* Model height is H; Physical
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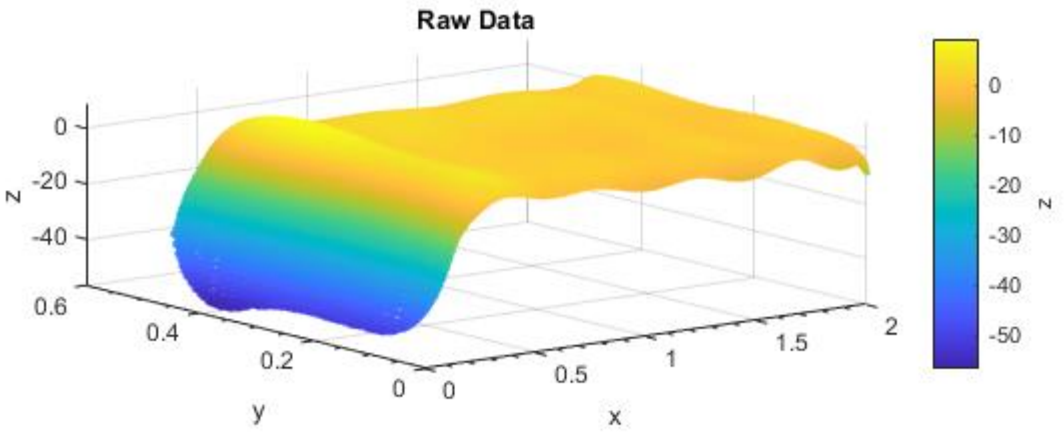
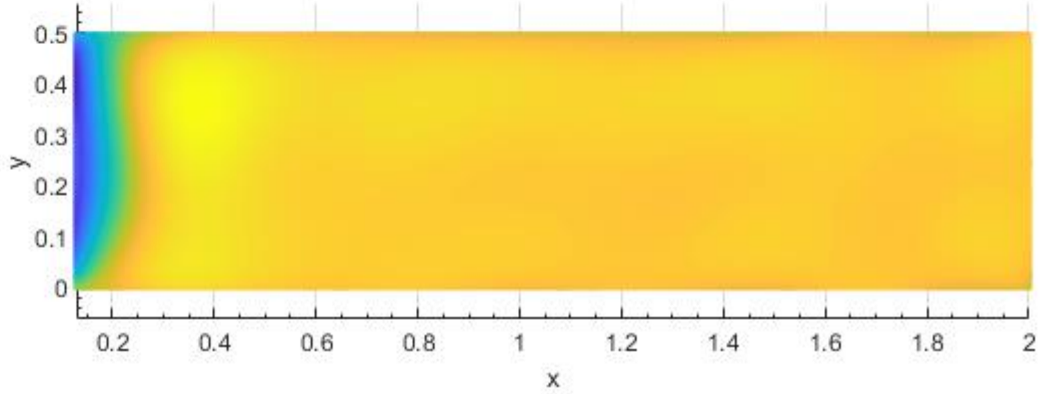
Residual Stress Analysis

Each RS dataset individually reviewed, analyzed, and archived:

Specimen ID:	RS0004_2024_T351_plt_la4.41
Serial Number:	MOD7-FTI-RS-4
Material:	Al 2024-T351 Plate, 0.50 in thk
Test Date:	2/14/2022
Test Method:	Contour Method, Residual Stress
Applied Expansion:	4.41% (nominal) 4.28% (measured)
Diameter:	0.250 in (nominal)
Edge Distance:	2.000 in (nominal)
Width:	4.000 in (nominal)
Thickness:	0.500 in (nominal)
Residual Stress Field Dimensions:	1.870 x 0.496 in





x = distance from hole edge, inches
y = distance from mandrel entry surface, inches
z = residual stress, ksi

NOTE: No lengthwise split (i.e., stress-relief cut) was performed on the 103N-1-rX-CMX samples prior to contour measurement. Splits were performed on the MOD7-FTI-RS-X and Loc1-X samples. Refer to data Serial Nos. on proceeding slides.

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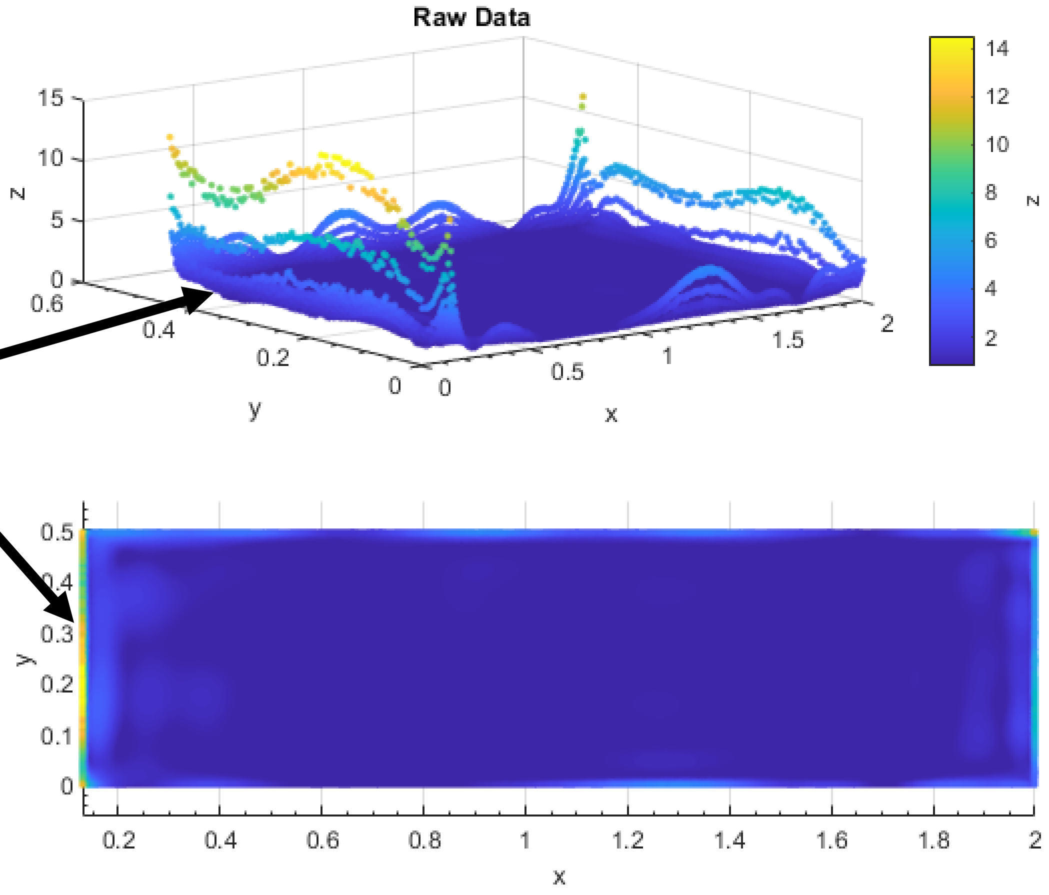
Residual Stress Analysis

Uncertainty for each RS measurement reviewed with typical results as shown:

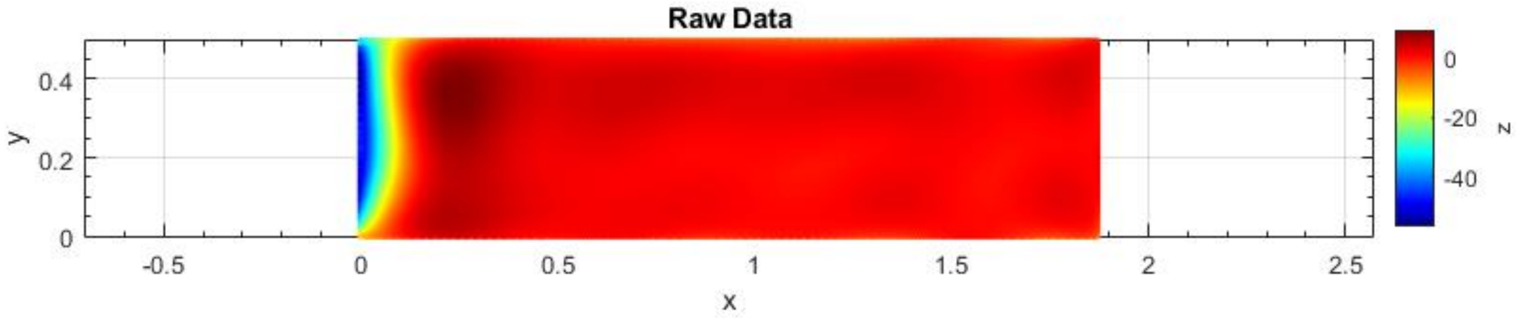
Maximum uncertainty along free edges

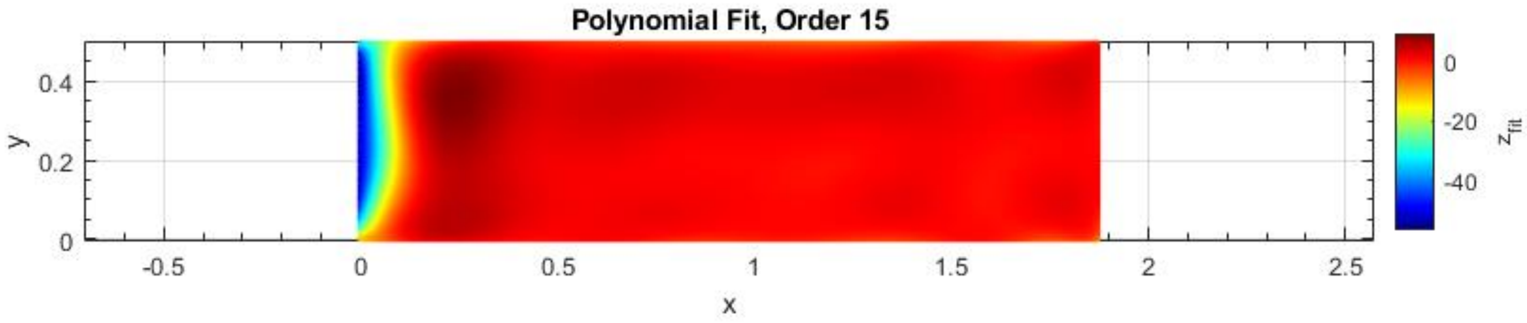


x = distance from hole edge, inches
y = distance from mandrel entry surface, inches
z = residual stress uncertainty, ksi

Residual Stress Analysis

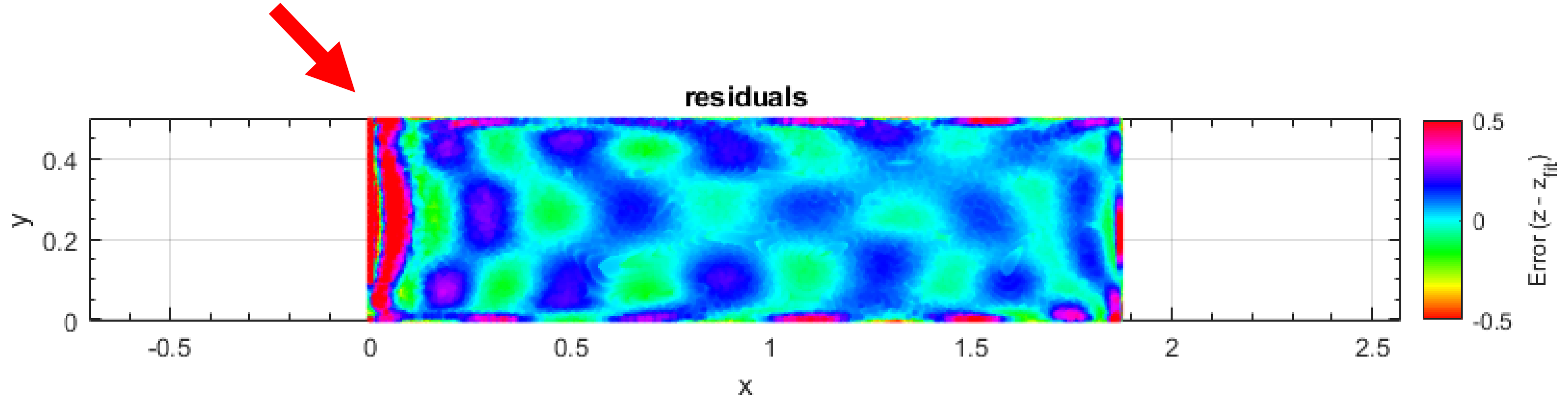
15th order polynomials fit for implementation into Stresscheck/BAMpF:

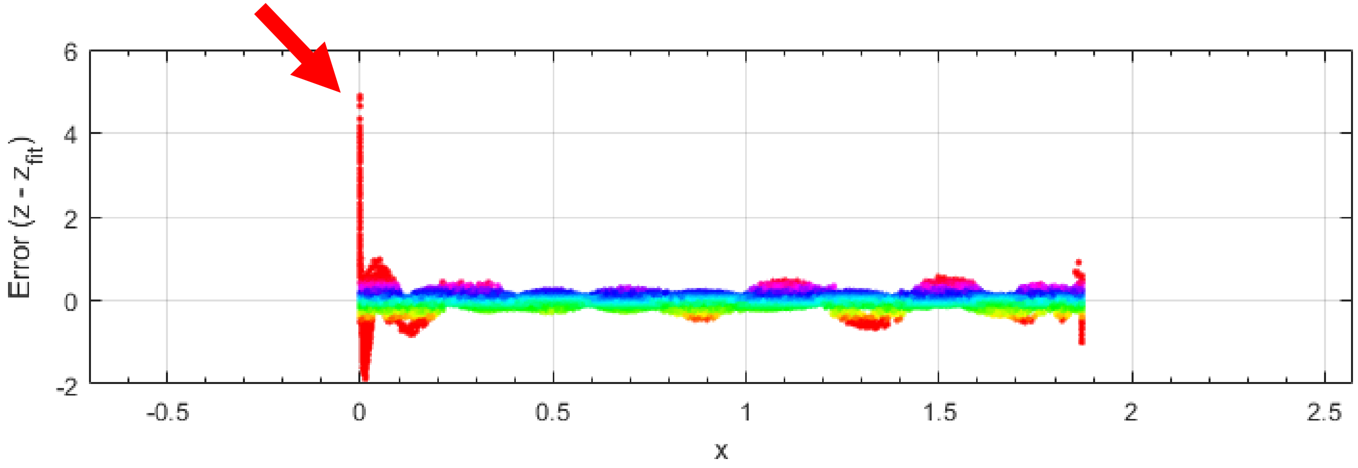




Residual Stress Analysis

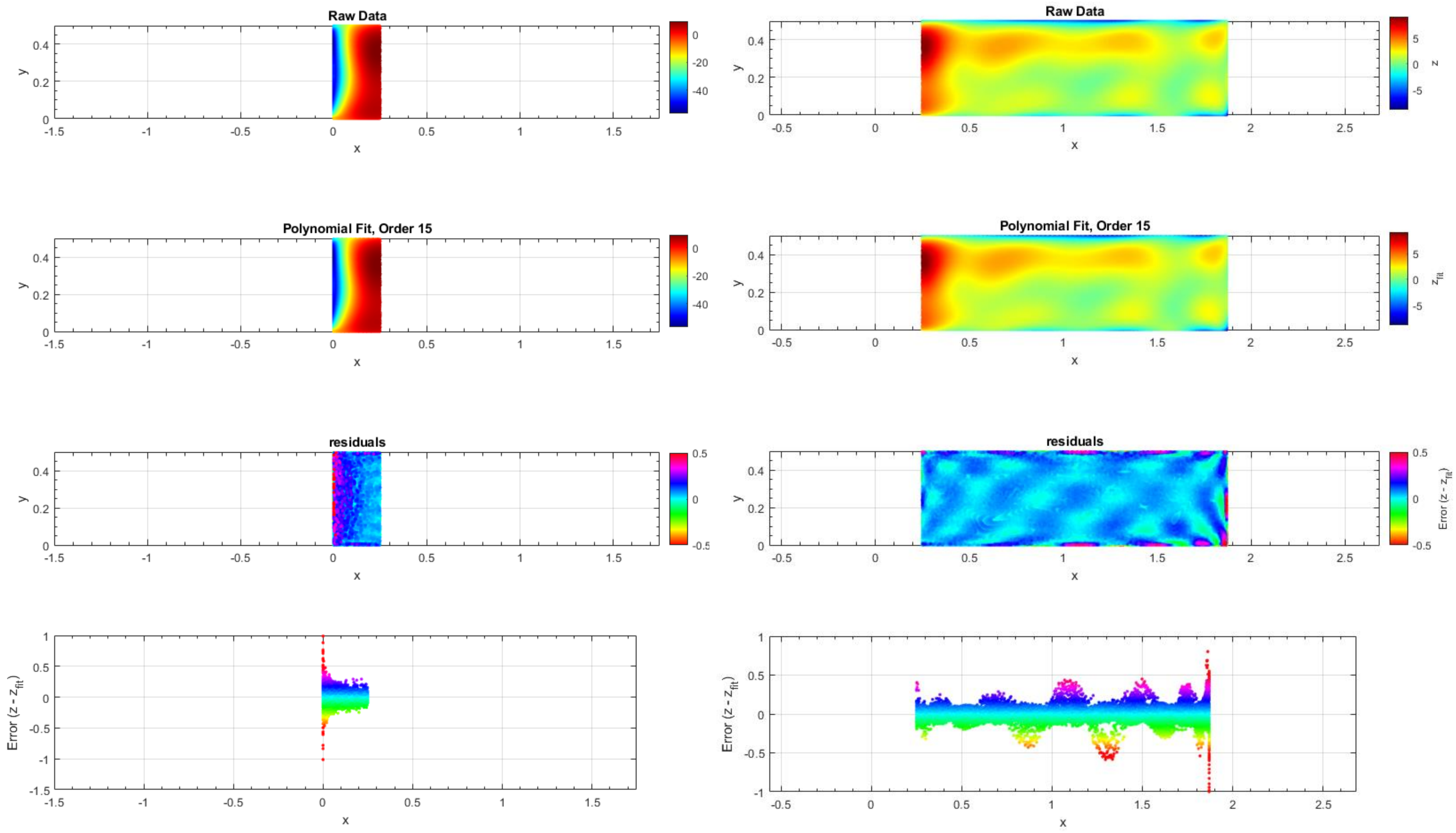
But, there is unacceptable fit error near-bore with a single stress equation:





Residual Stress Analysis

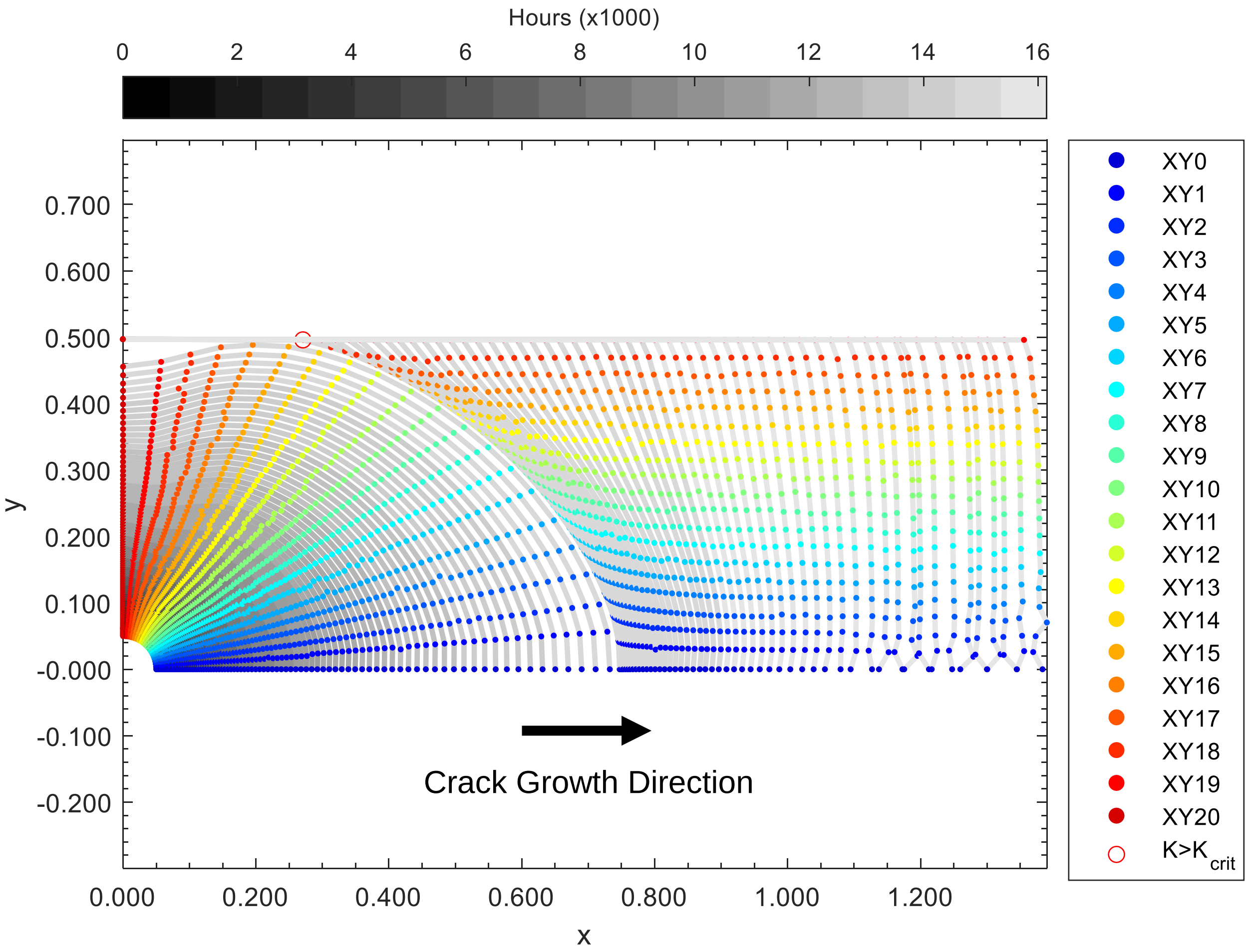
Splitting the fitting domain at 0.25” from the bore edge results in an improved max fit error of ~ +/-0.5 ksi



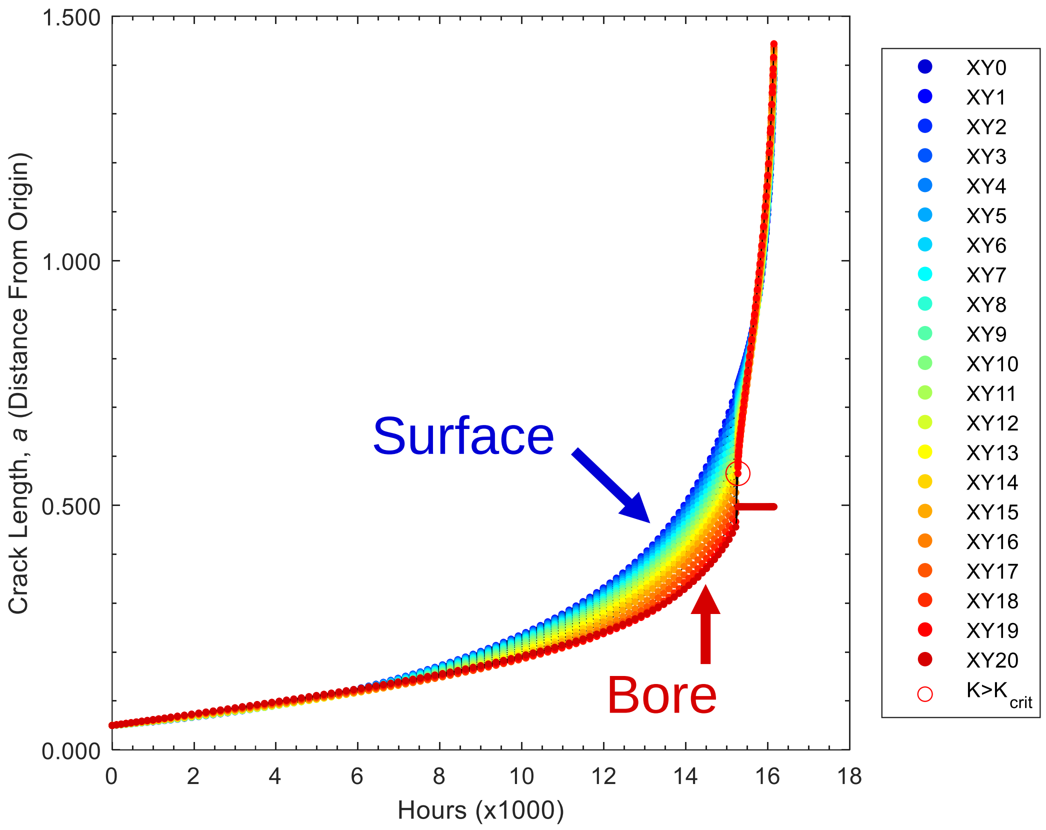
Note: Increasing the polynomial fit order to 20 further decreases fit error, but Stresscheck can’t handle the length of two 20th order equations.

BAMpF Analysis

21 evaluation points per crack front



Primary focus was the surface (XY0) and bore (XY20) growth rates

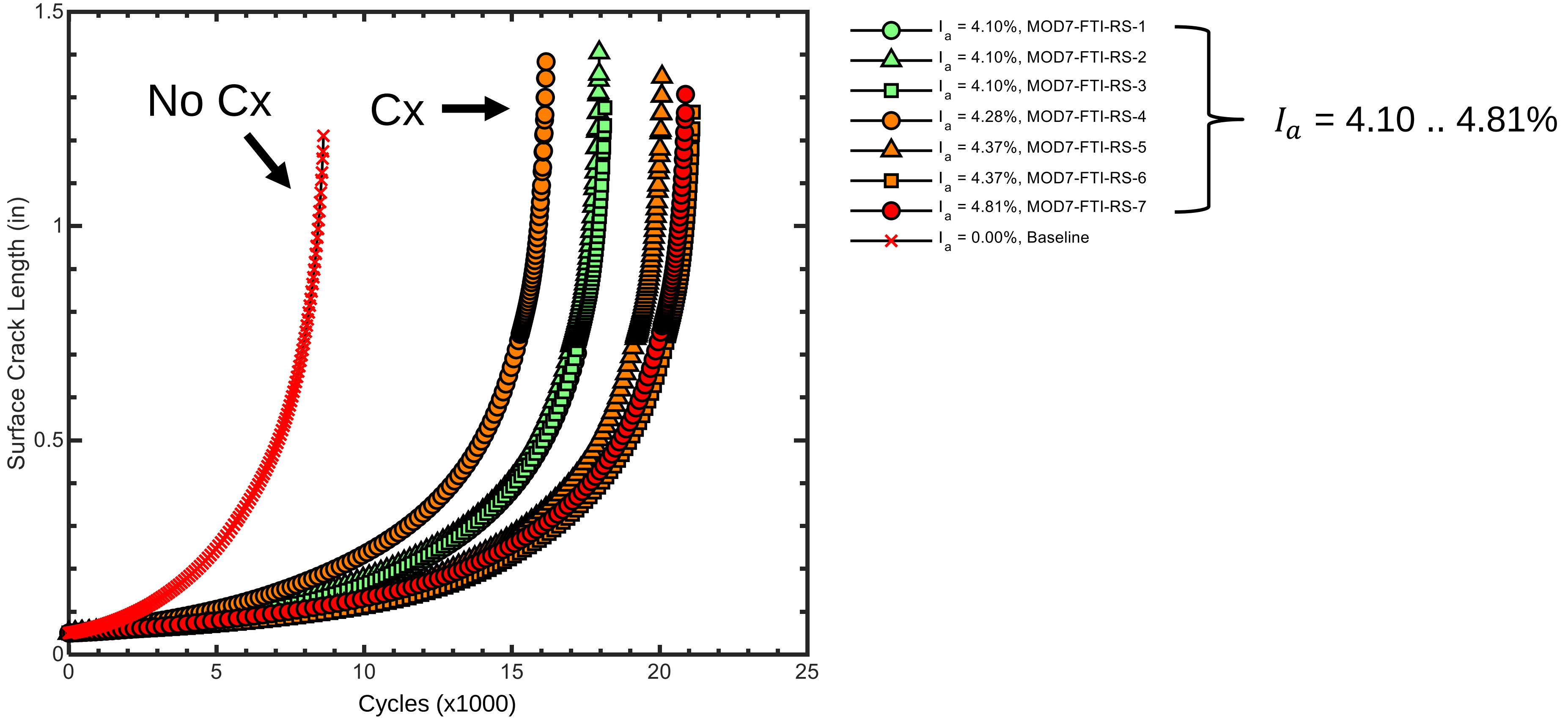


FTI Cx Prediction Results

Surface Crack Growth Behavior

With RS fields measured via contour…

The predicted LIF ranges from ~ 1.9.. 2.5 for constant amplitude loading at R = 0.1 and I_a= 4.10 .. 4.81%



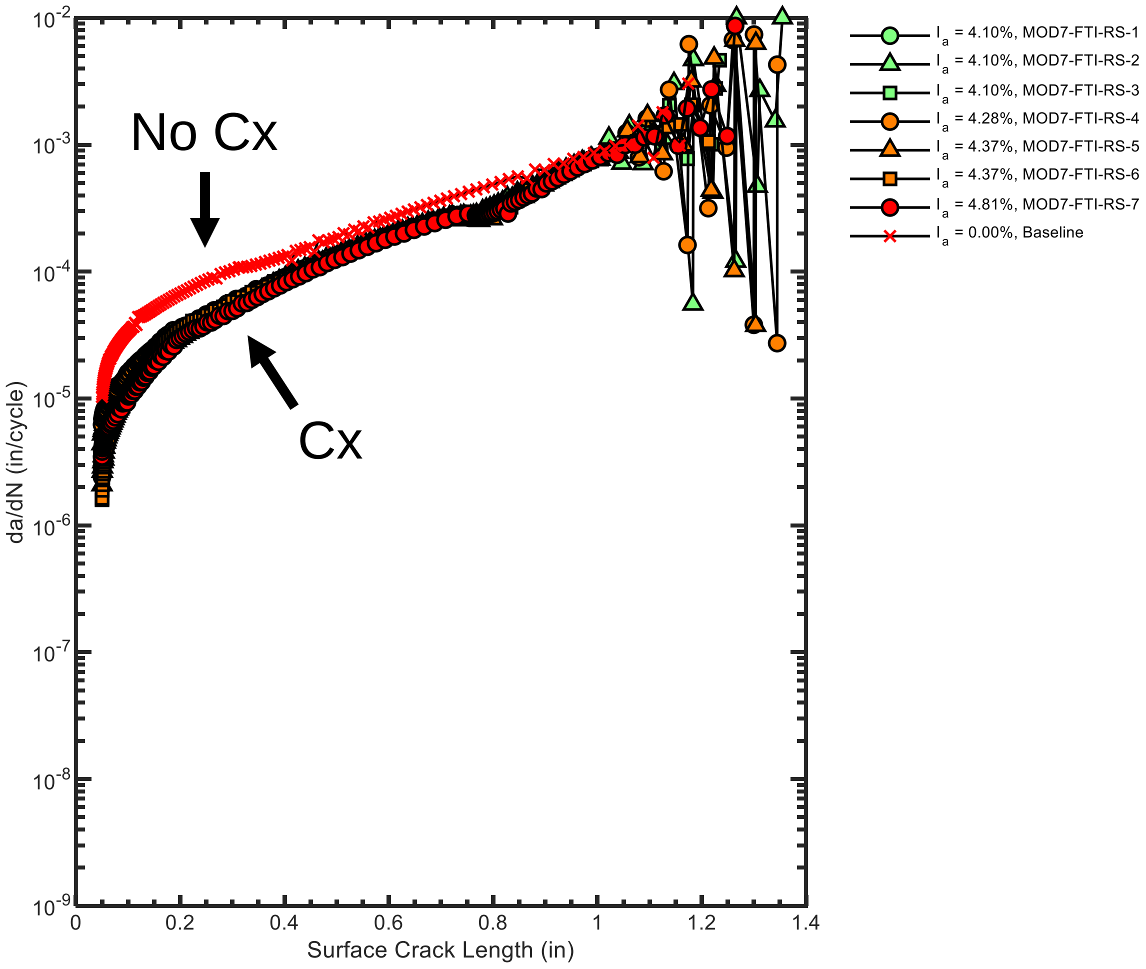
LIF = Life Improvement Factor

FTI Cx Prediction Results

Surface Crack Growth Behavior

Slight Cx crack growth rate variation primarily at *a* < 0.100”

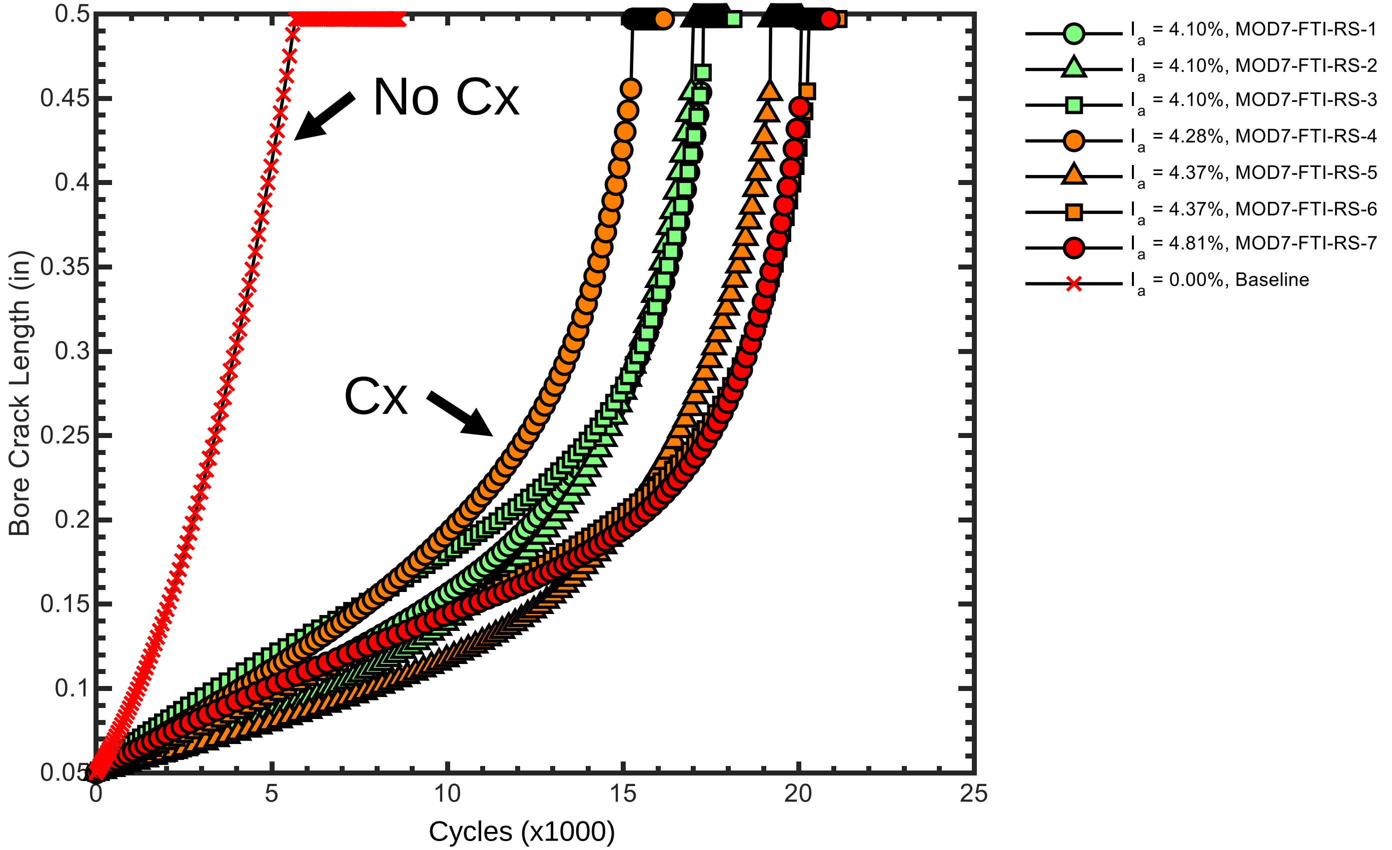
At *a* < 0.200”, Cx crack growth rate converges.



FTI Cx Prediction Results

Much more variation in the crack growth curve shape on the bore-side

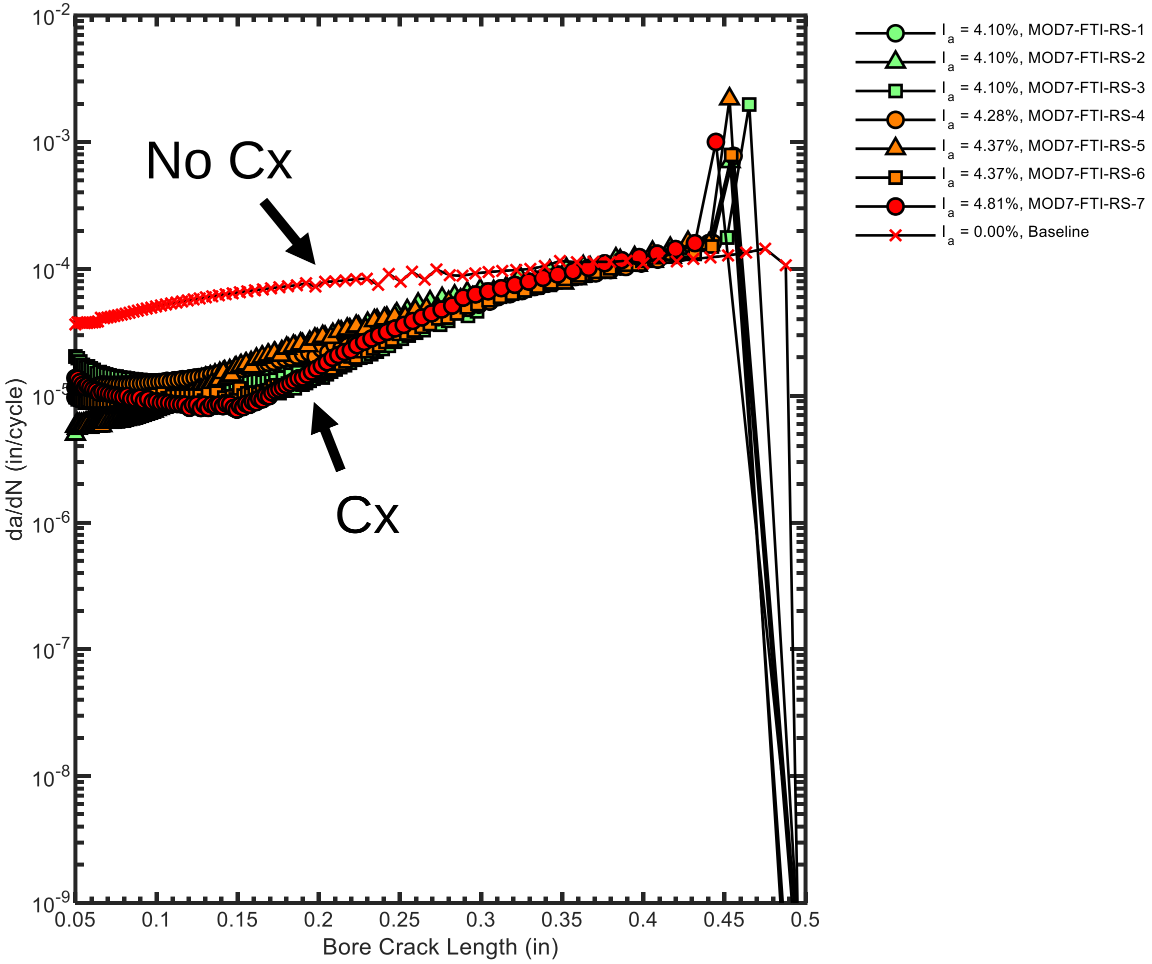
Bore Crack Growth Behavior



FTI Cx Prediction Results

Significant variation in the da/dN curve shape too, though it stays within ~0.5 order of magnitude.

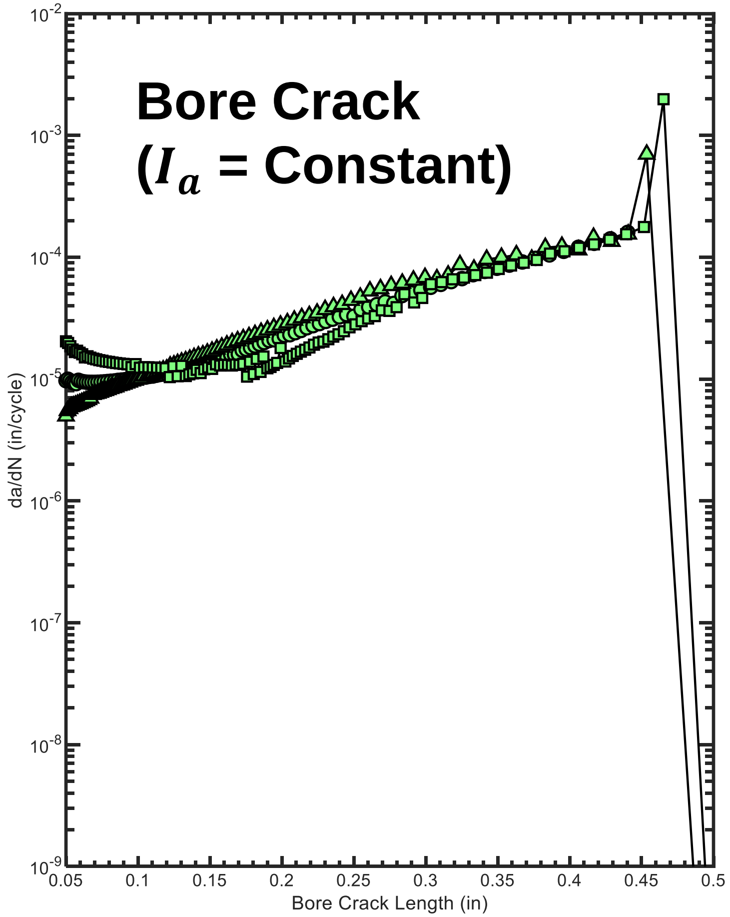
Surface Crack Growth Behavior

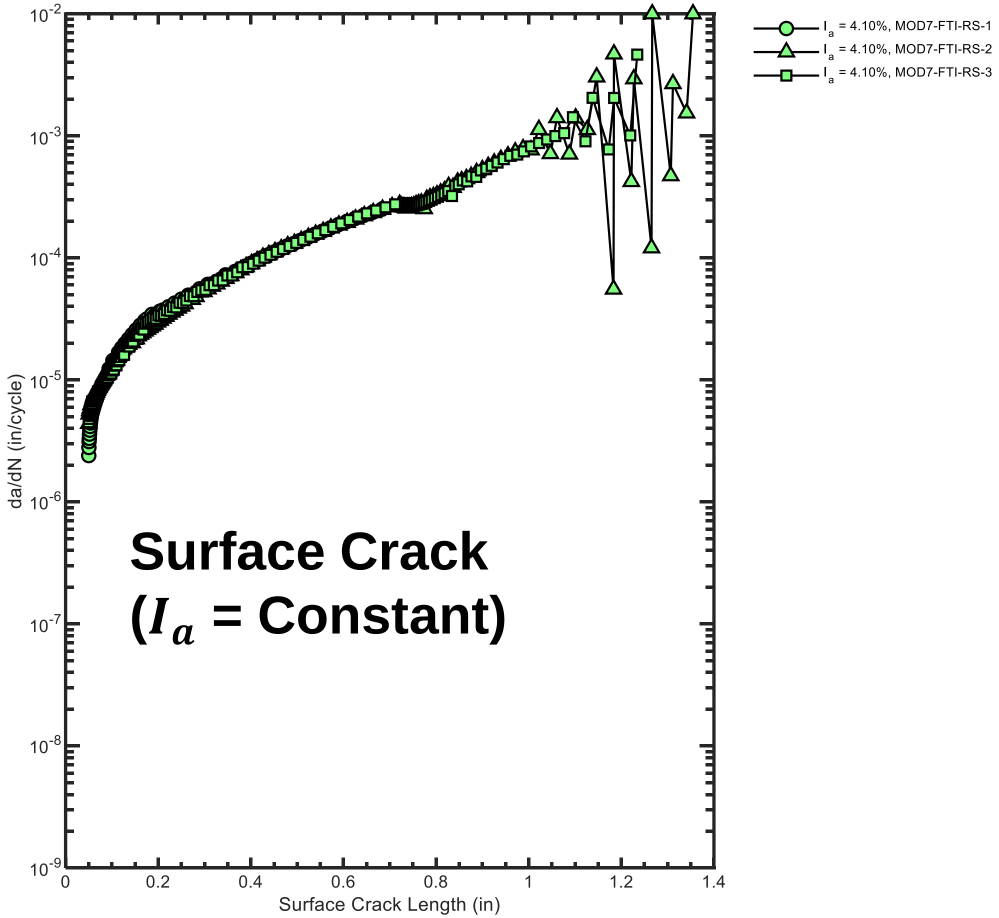


FTI Cx Prediction Results

These three contour fields have tightly replicated I_a and "surface" growth lives:

Even with tightly replicated I_a and surface growth behavior, significant differences in bore da/dN.





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FTI Cx Prediction Results

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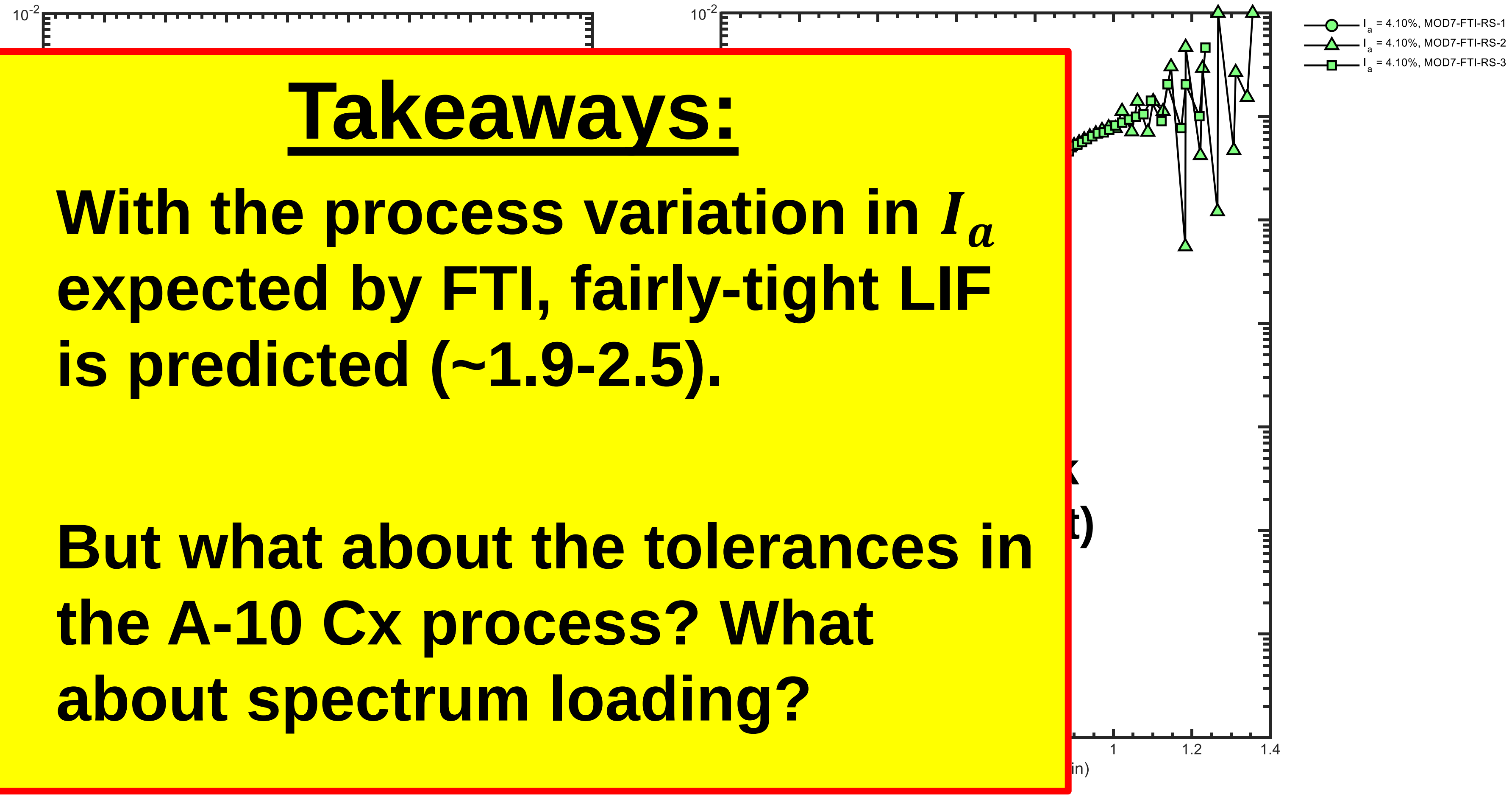
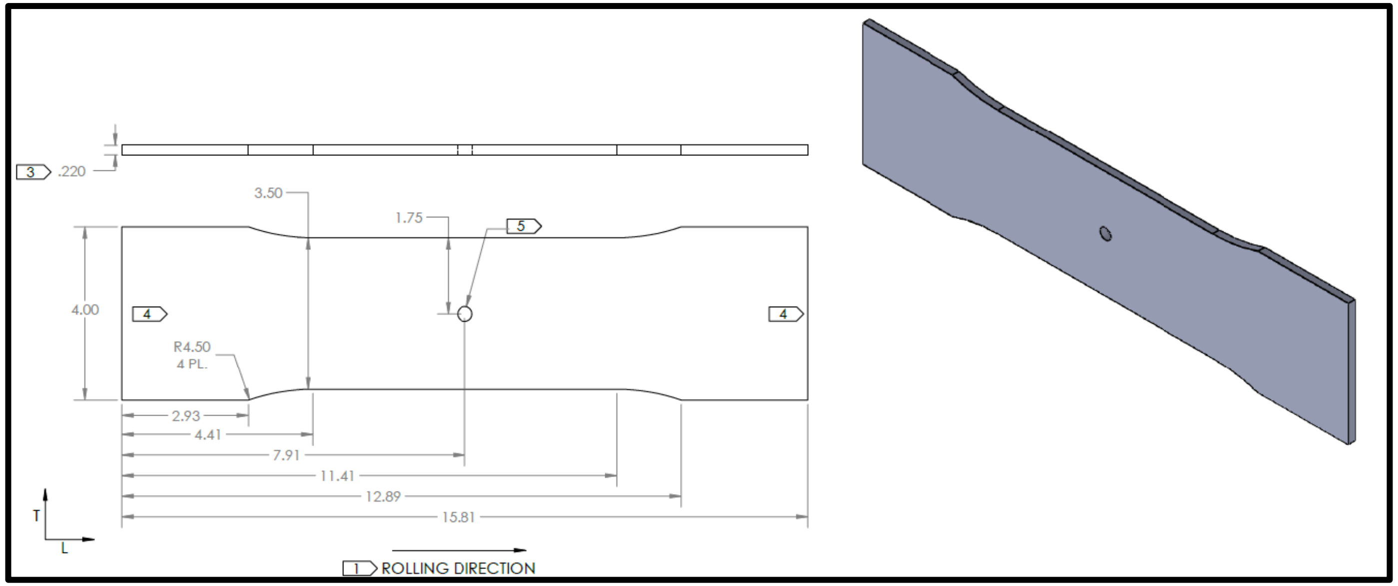


<u>Takeaways:</u>

- **With the process variation in I_a expected by FTI, fairly-tight LIF is predicted (~1.9-2.5).**
- **But what about the tolerances in the A-10 Cx process? What about spectrum loading?**

A-10 Configuration

Cx Tooling	Condition	Initial D (in)	T (in)	Qty	Coupon IDs
10-3-N	In-spec	0.3455	0.22	3	MOD7-103N-1 to -3
	Out-of-spec, over 0.001”	0.348		3	MOD7-103N-4 to -6
	Out-of-spec, over 0.003”	0.35		3	MOD7-103N-7 to -9
	Out-of-spec, under 0.001”	0.343		3	MOD7-103N-10 to -12
	Out-of-spec, under 0.003”	0.341		3	MOD7-103N-13 to -15



Target $I_a =$ 2.26%
2.84%
3.59%
4.34%
4.96%

- This specimen geometry simulates A-10 drain holes.
- RS fields supporting these tests were gathered from previous efforts, but they are representative of this sample geometry.

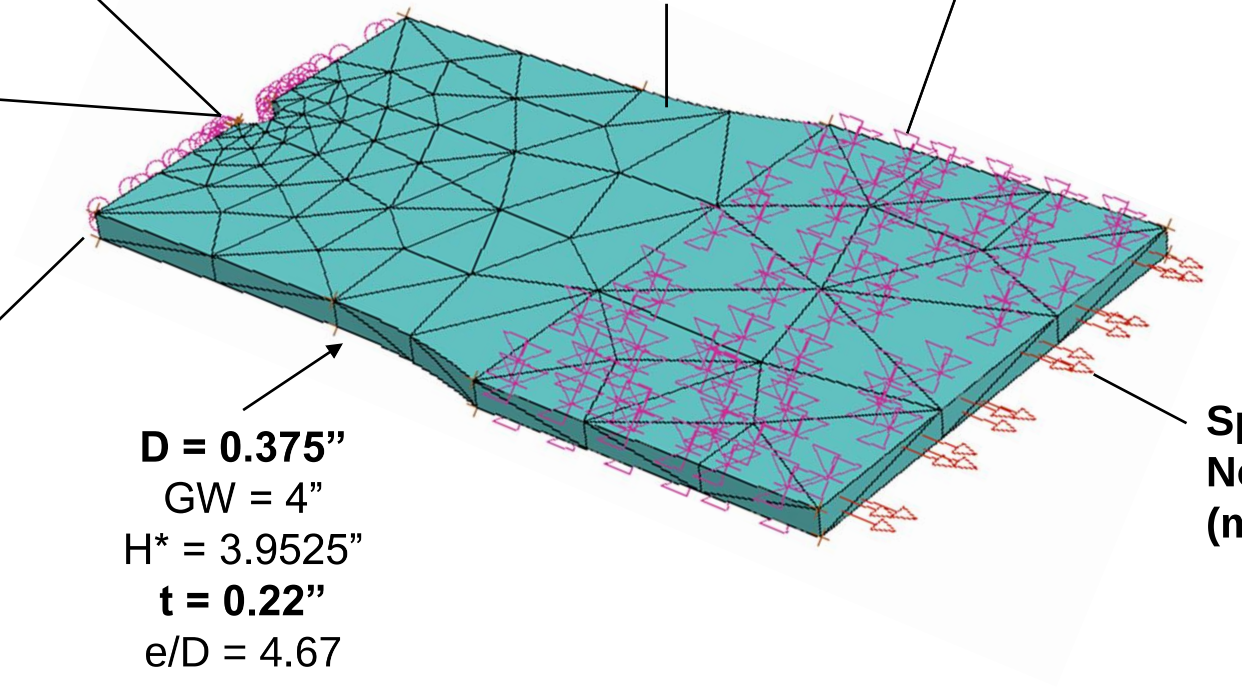
A-10 Cx BAMpF Model

Al 2024-T351
ν = 0.33
E = 10700 ksi
p-level = 4

Semi-circular corner crack
0.050 x 0.050”

Out-of-plane constraint
for 2.93” simulating
wedge-grip height

RS applied as a
traction on crack face



Symmetry constraint
on cracking plane

Spectrum Loaded
No loading retardation
(marker band cycles not simulated)

D = 0.375”
GW = 4”
H* = 3.9525”
t = 0.22”
e/D = 4.67

* Model height is H; Physical specimens will be 2*H

A-10 Prediction Results

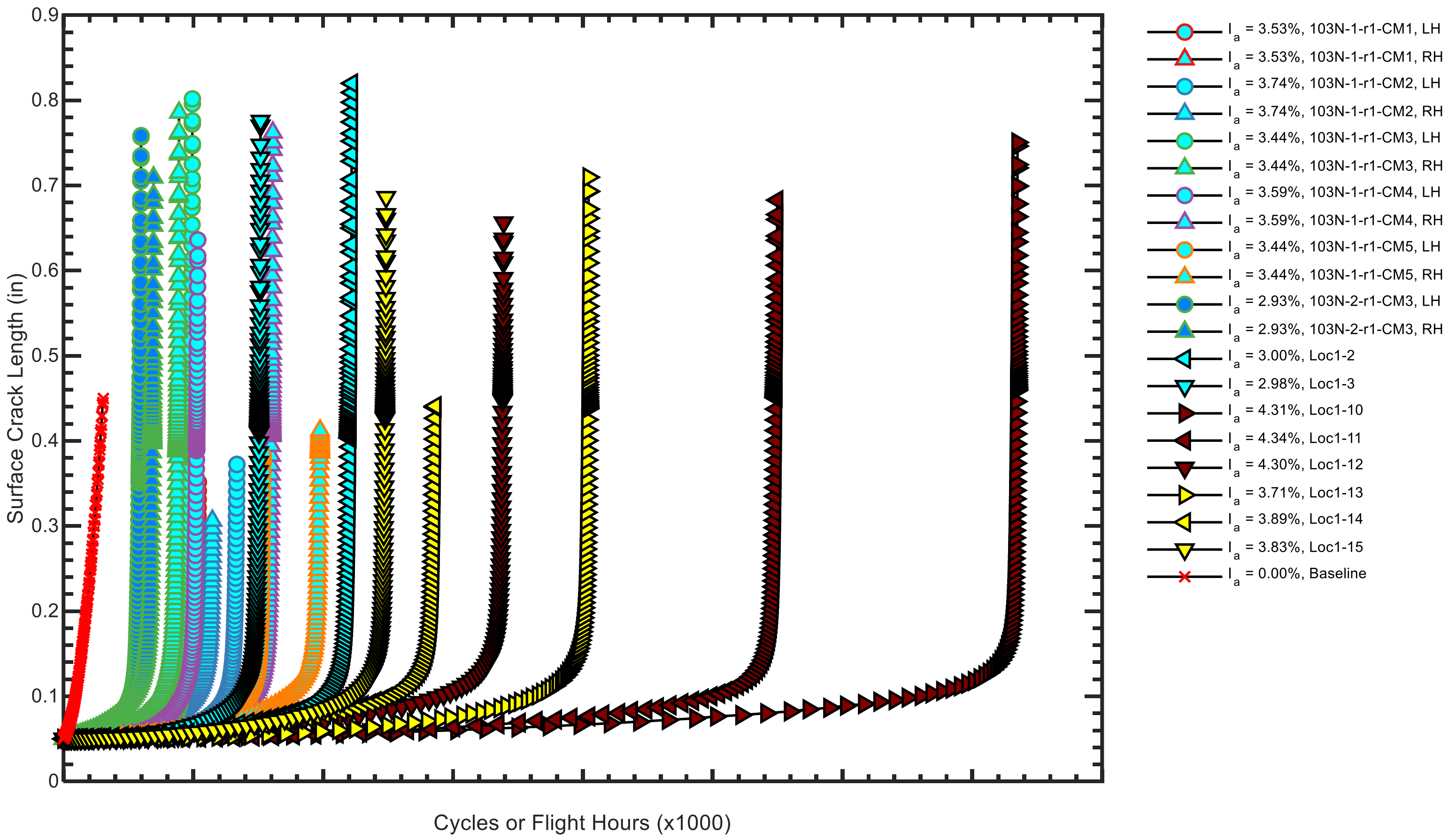
Ia (%)	Notes
5.34	Max tol - 0.003" SHD
4.75	Max tol - 0.001" SHD
4.46	Max in-tol
3.74	Nominal
2.93	Min in-tol
2.64	Min tol + 0.001" SHD
2.08	Min tol + 0.003" SHD

→ Contour data was not available for over-expanded Cx holes.

A-10 Prediction Results

Ia (%)	Notes
5.34	Max tol - 0.003" SHD
4.75	Max tol - 0.001" SHD
4.46	Max in-tol
3.74	Nominal
2.93	Min in-tol
2.64	Min tol + 0.001" SHD
2.08	Min tol + 0.003" SHD

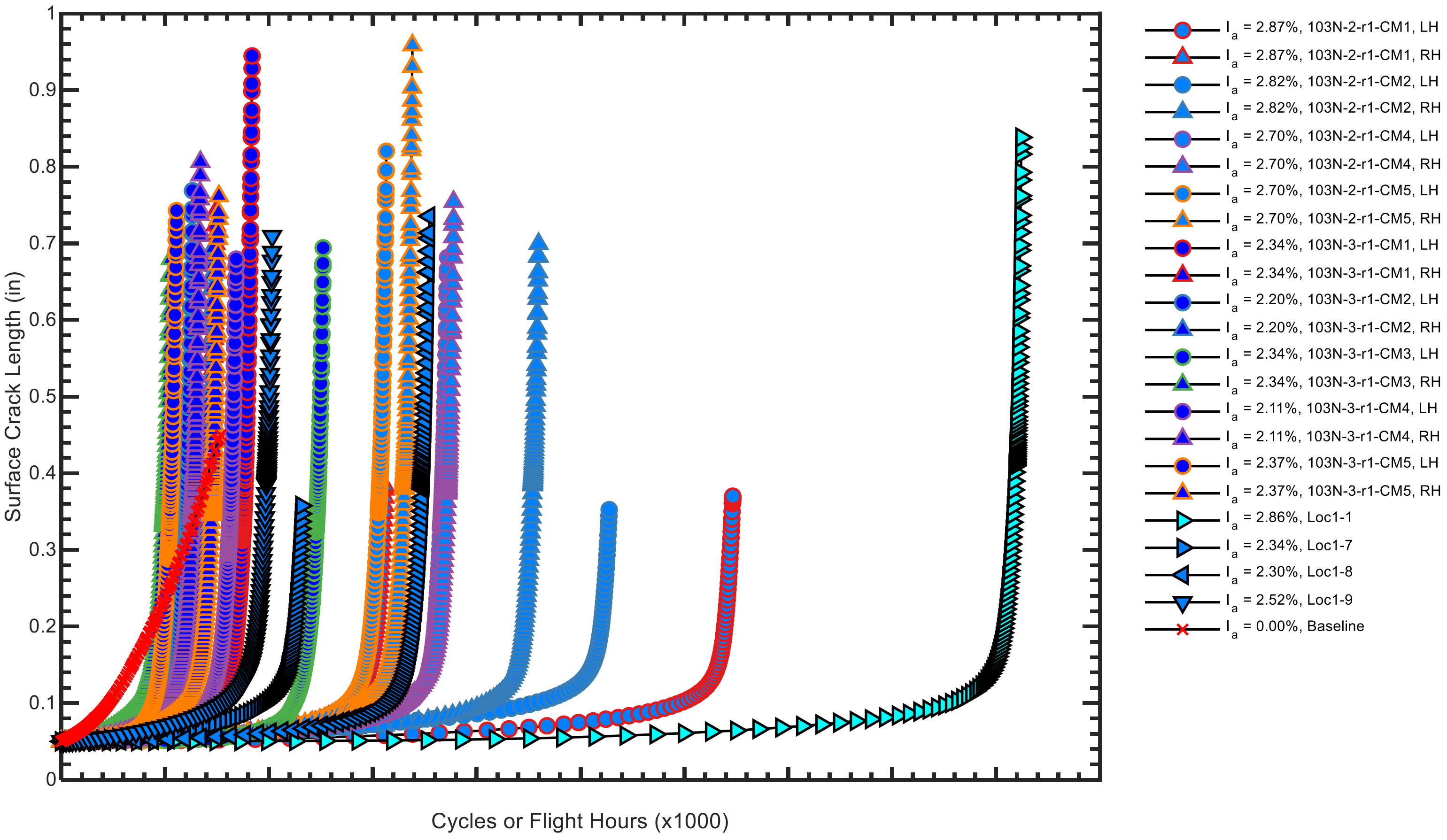
Within nominal Cx process tolerances, the predicted LIF ~ 2.5 .. 31.0 using *a* = 0.300” as a reference point:



A-10 Prediction Results

Ia (%)	Notes
5.34	Max tol - 0.003" SHD
4.75	Max tol - 0.001" SHD
4.46	Max in-tol
3.74	Nominal
2.93	Min in-tol
2.64	Min tol + 0.001" SHD
2.08	Min tol + 0.003" SHD

With holes under-expanded up to 0.003”, the predicted LIF ~ 0.83 .. 7.7 using *a* = 0.300” as a reference point:



A-10 Prediction Results

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Ia (%)	Notes
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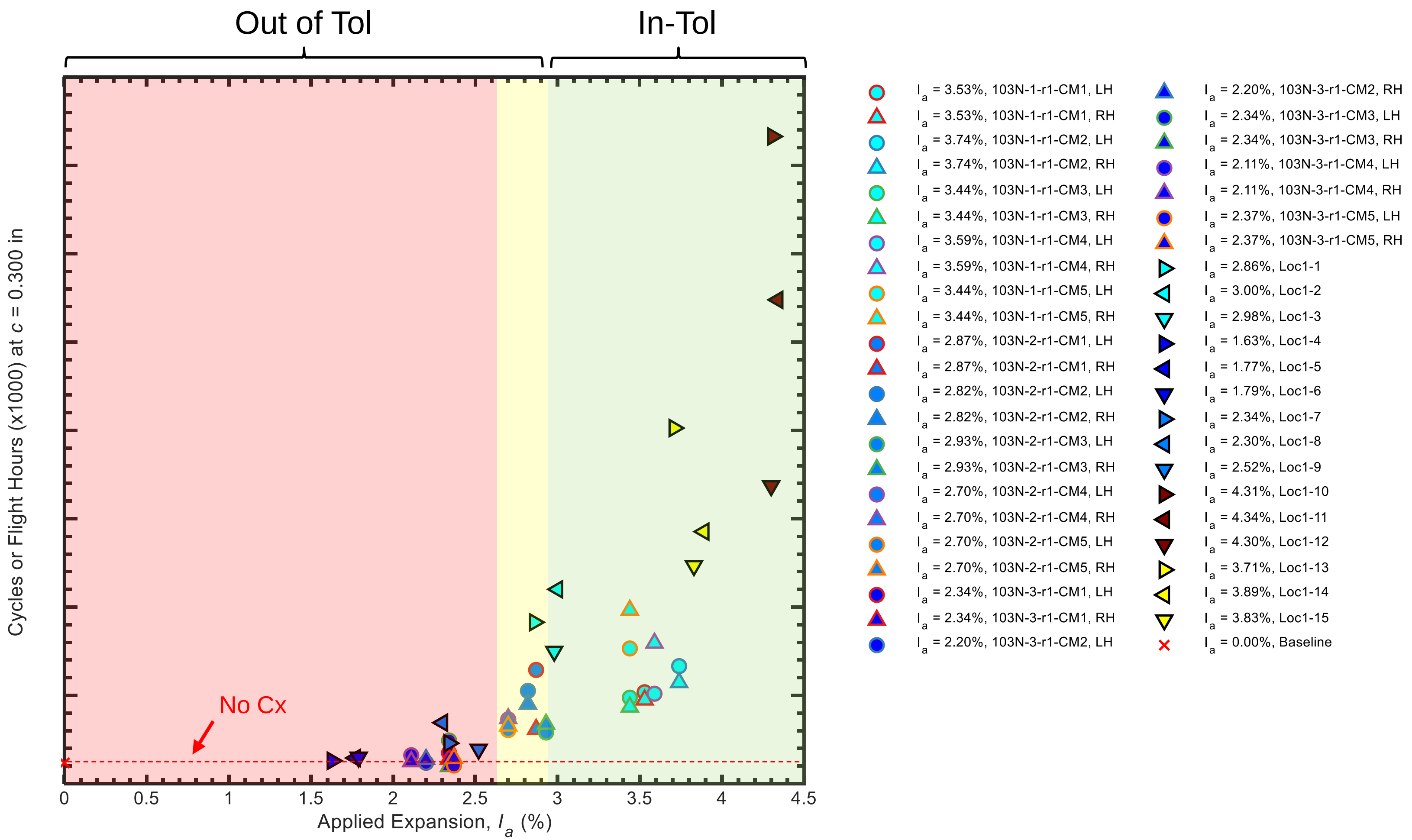
4.75	Max tol - 0.001" SHD
4.46	Max in-tol
3.74	Nominal
2.93	Min in-tol
2.64	Min tol + 0.001" SHD
2.08	Min tol + 0.003" SHD

We can summarize the spread in life predictions as shown here:

Critically, the predicted life is > "No Cx" life up to 0.001" out of tolerance



A-10 Prediction Results

Ia (%)	Notes
5.34	Max tol - 0.003" SHD
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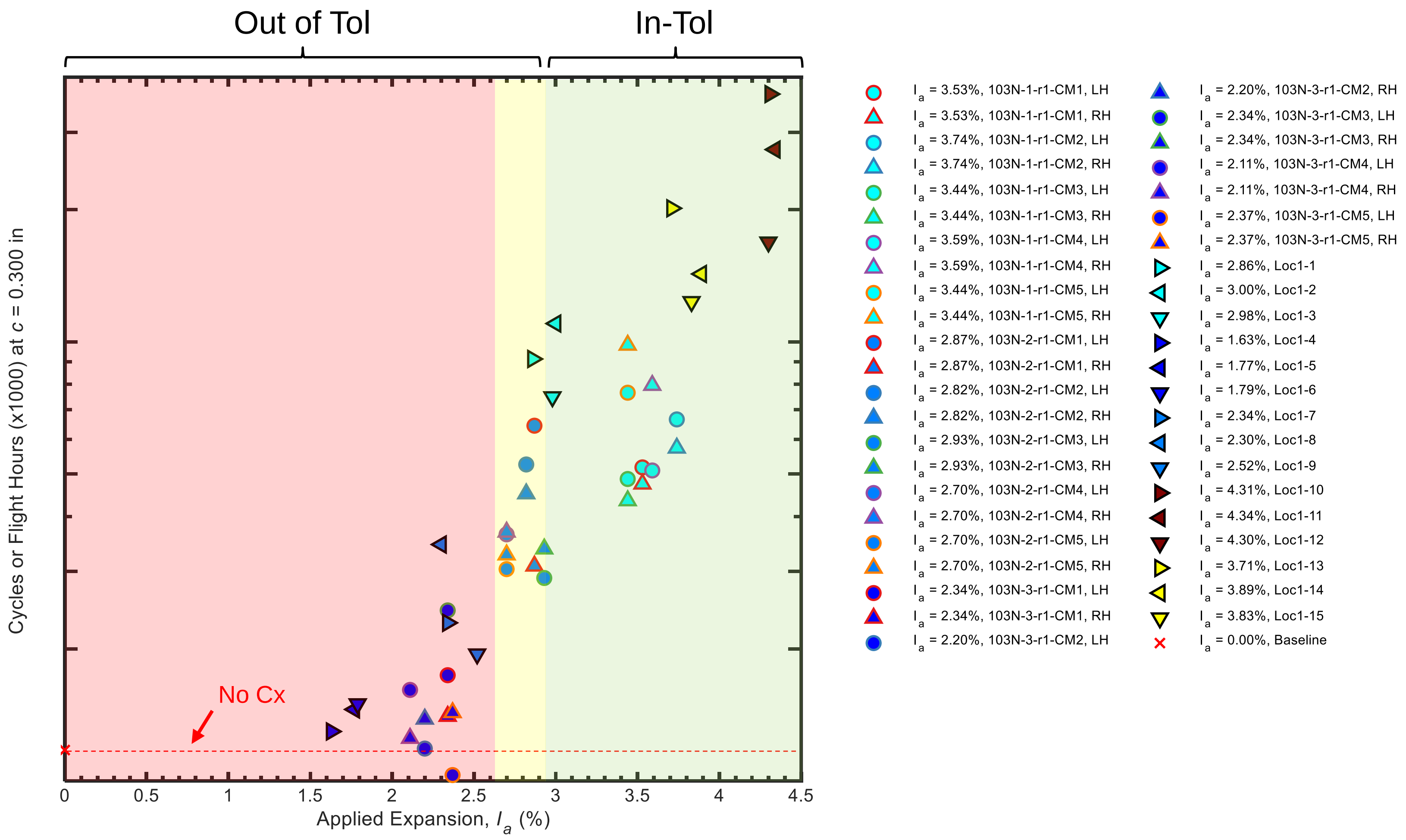
4.46	Max in-tol
3.74	Nominal
2.93	Min in-tol
2.64	Min tol + 0.001" SHD
2.08	Min tol + 0.003" SHD

Notably, we get log-linear behavior for predicted life as a function of applied expansion:

This may be useful for setting confidence bounds on life predictions, but there is significant spread!



A-10 Prediction Results

Ia (%)	Notes
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4.75	Max tol - 0.001" SHD
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3.74	Nominal
2.93	Min in-tol
2.64	Min tol + 0.001"
2.08	Min tol + 0.003"

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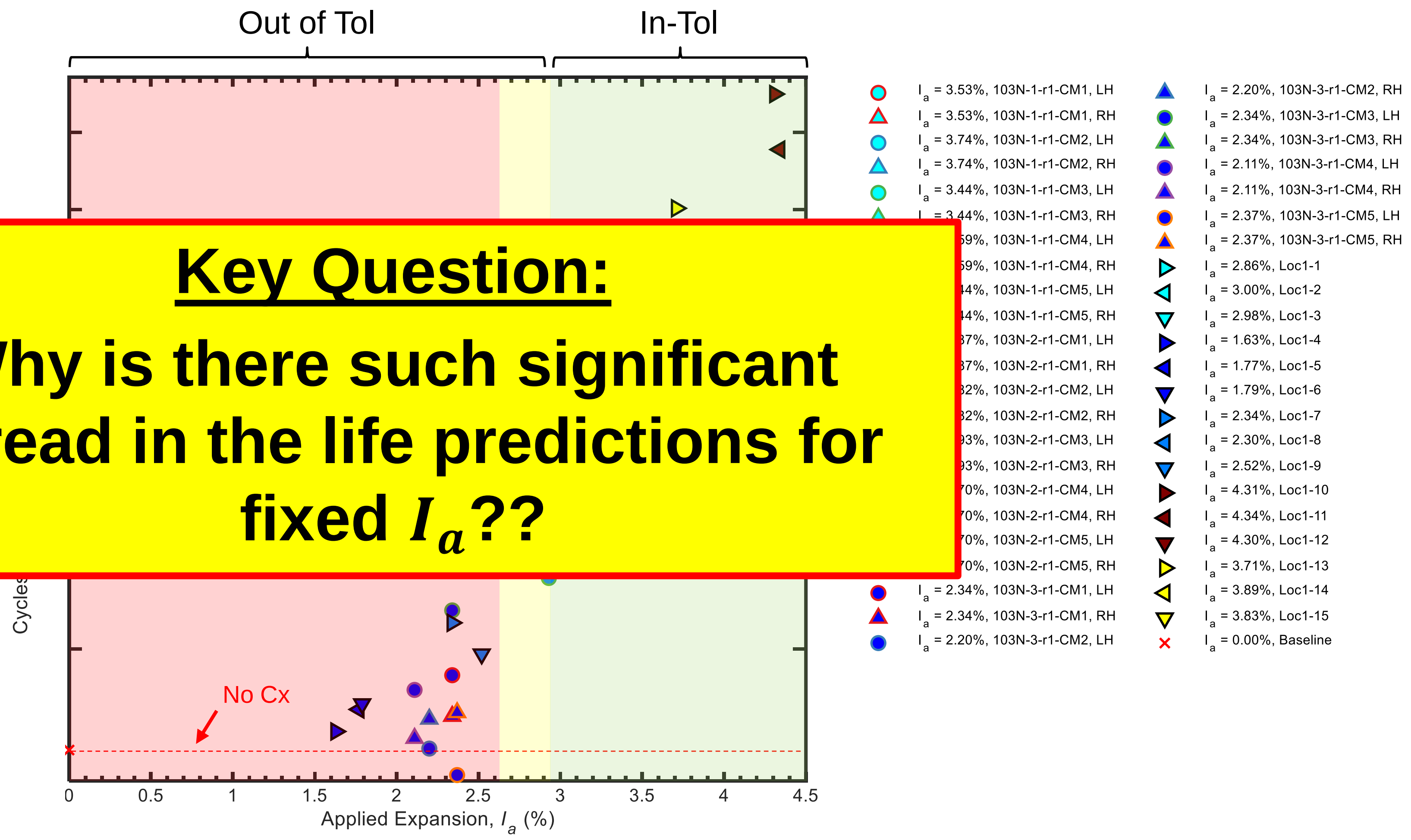


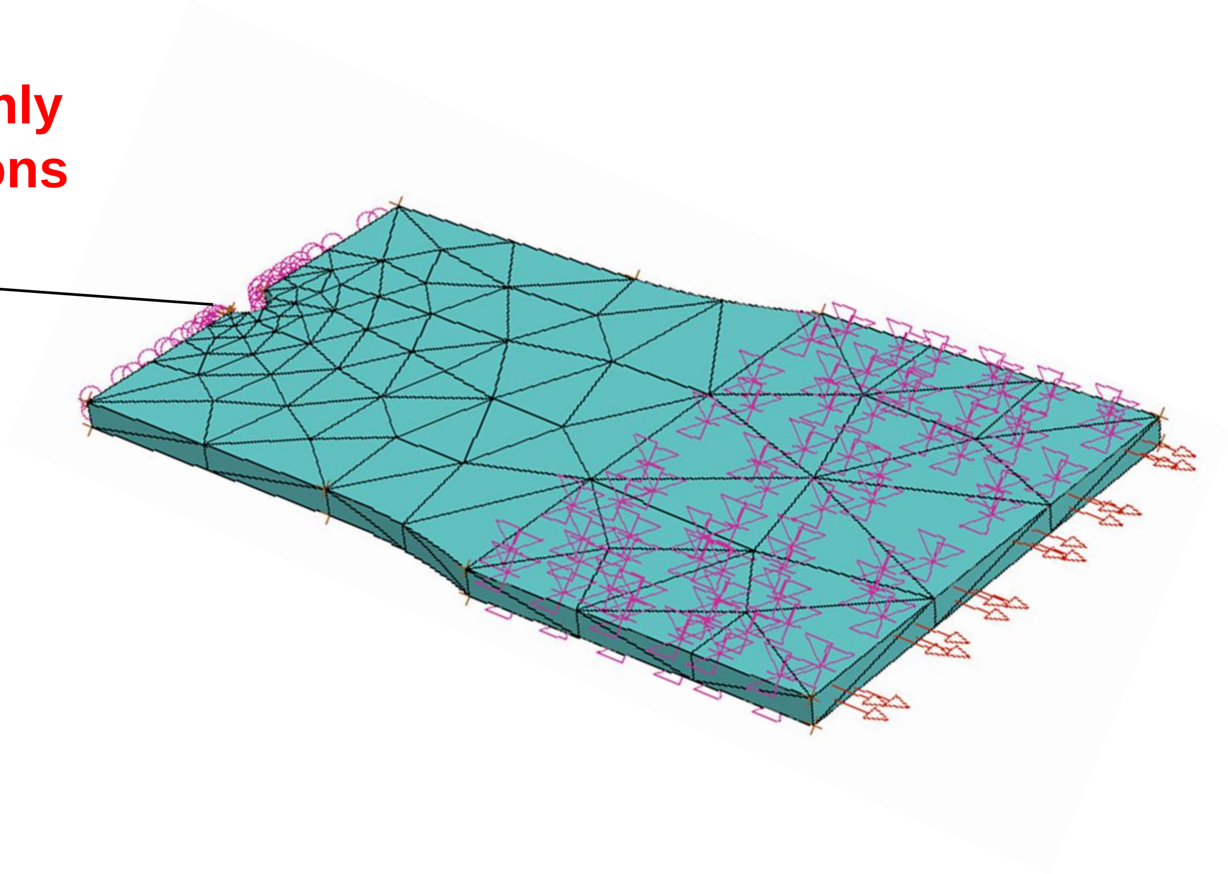
Key Question:

Why is there such significant spread in the life predictions for fixed I_a??

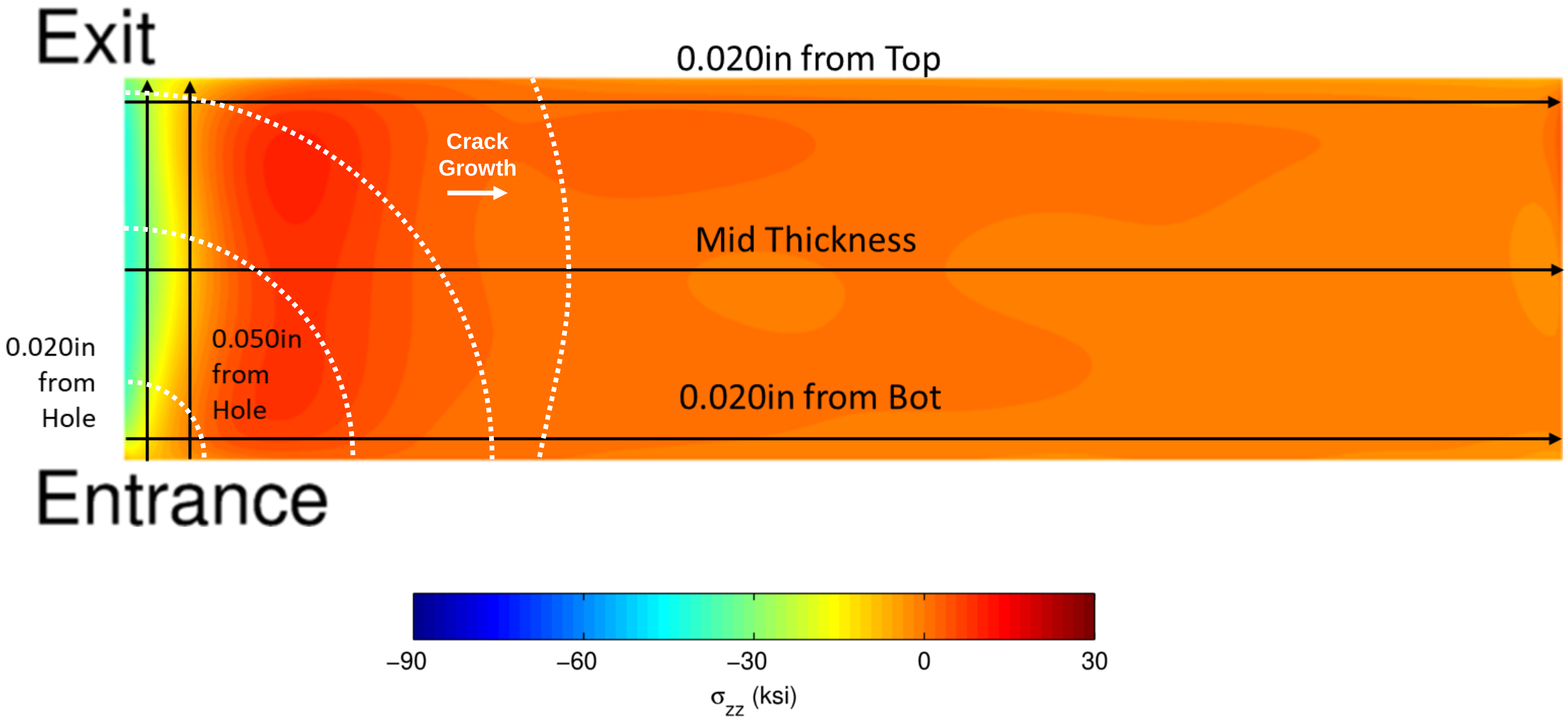
A-10 Cx BAMpF Model

The RS Field was the only variable in the simulations

RS applied as a traction on crack face

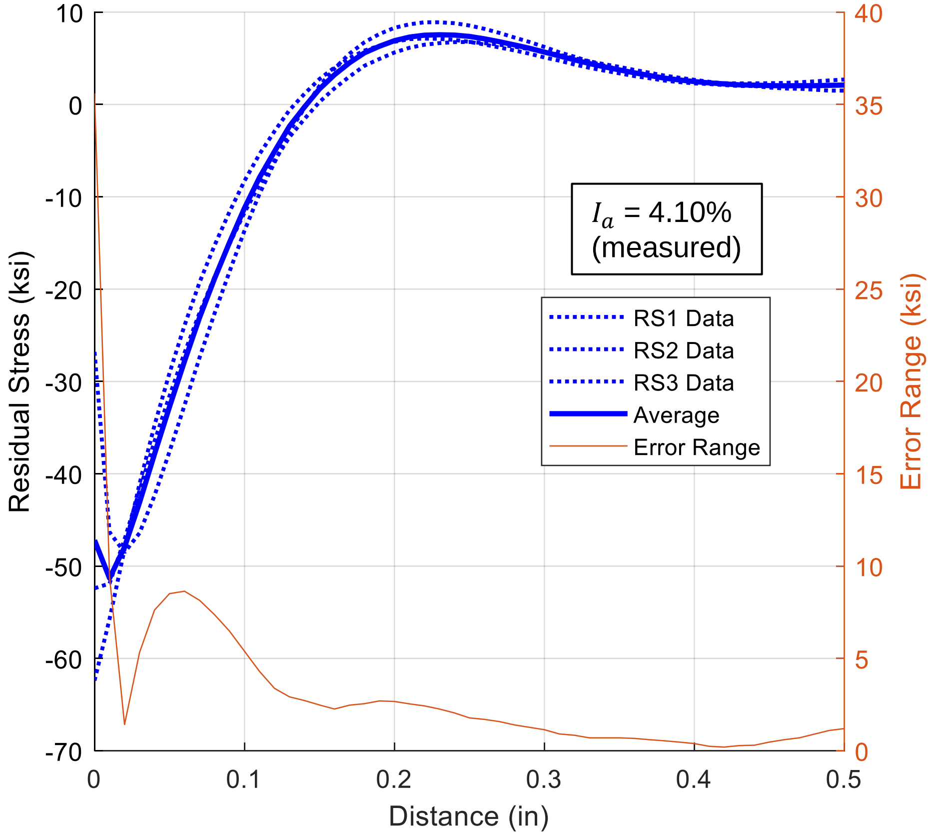


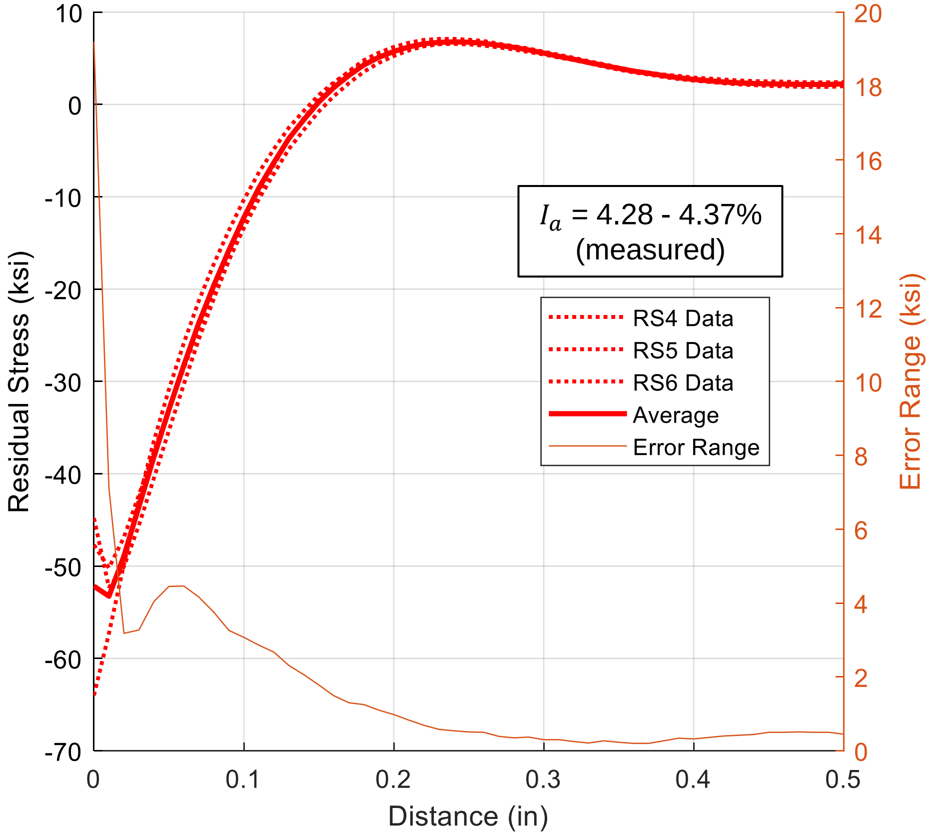
RS Field Characterization



RS Field Characterization

- Contour measurements from 6 discrete samples shown, 2 groups of target I_a
- Variance of 2-8+ ksi within 0.100” of hole bore.
- >0.100” from hole bore, 1-3 ksi variance is typical
- **Mid thickness RS tends to be the most repeatable**



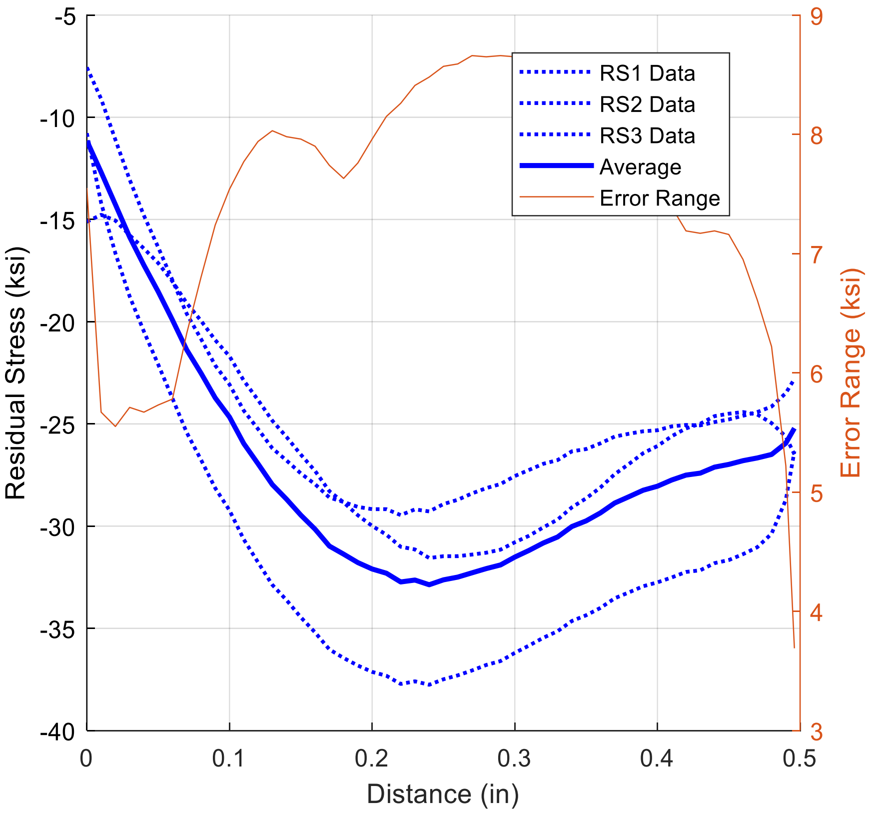


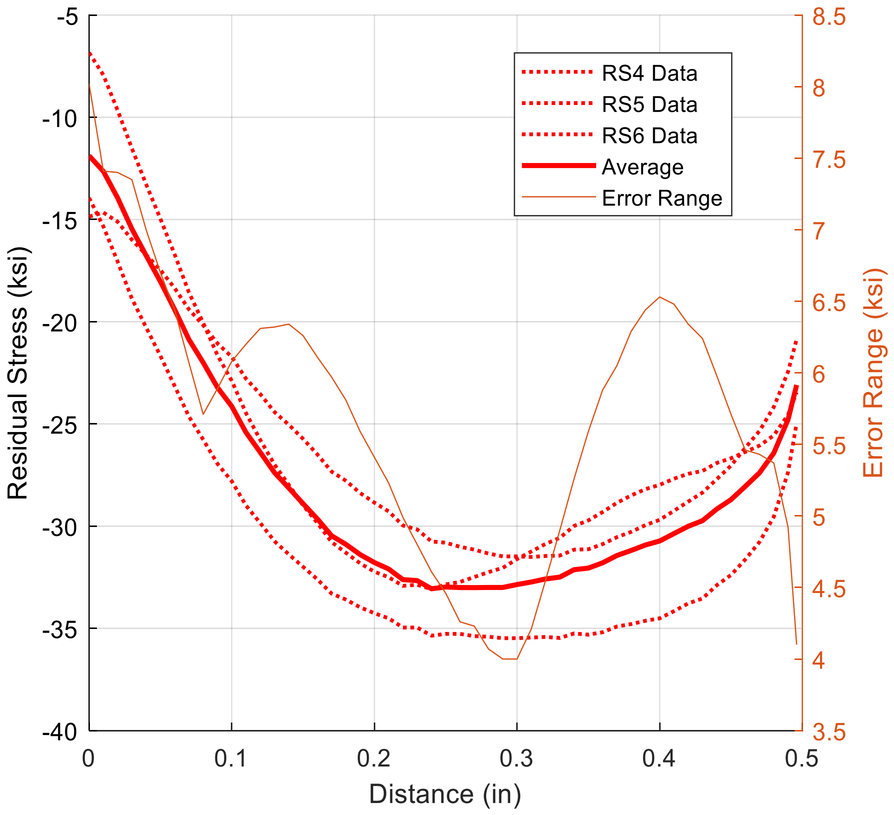
RS Field Characterization

- Variance consistently > 4 ksi for stresses 0.050” from hole bore (parallel to bore).

- **Is this just due to small variances in I_a? What about true replicate RS fields with matched I_a?**

- We can have truly “matched” I_a by looking at **<u>RS on both sides of the same hole</u>**.



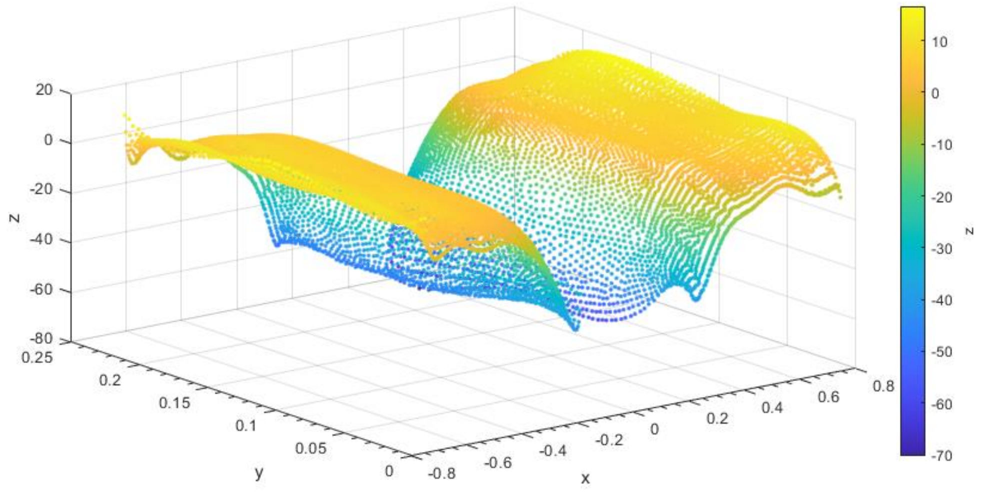


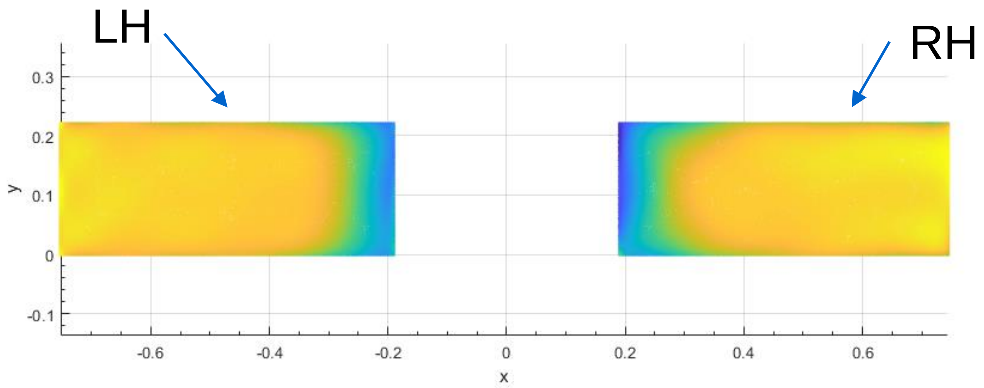
RS Field Characterization

We have double-sided RS datasets for 15 holes – equal I_a

Theoretically, the variance in RS side to side should be near the measurement uncertainty

BAMpF predictions for each side should benchmark overall differences in the fields

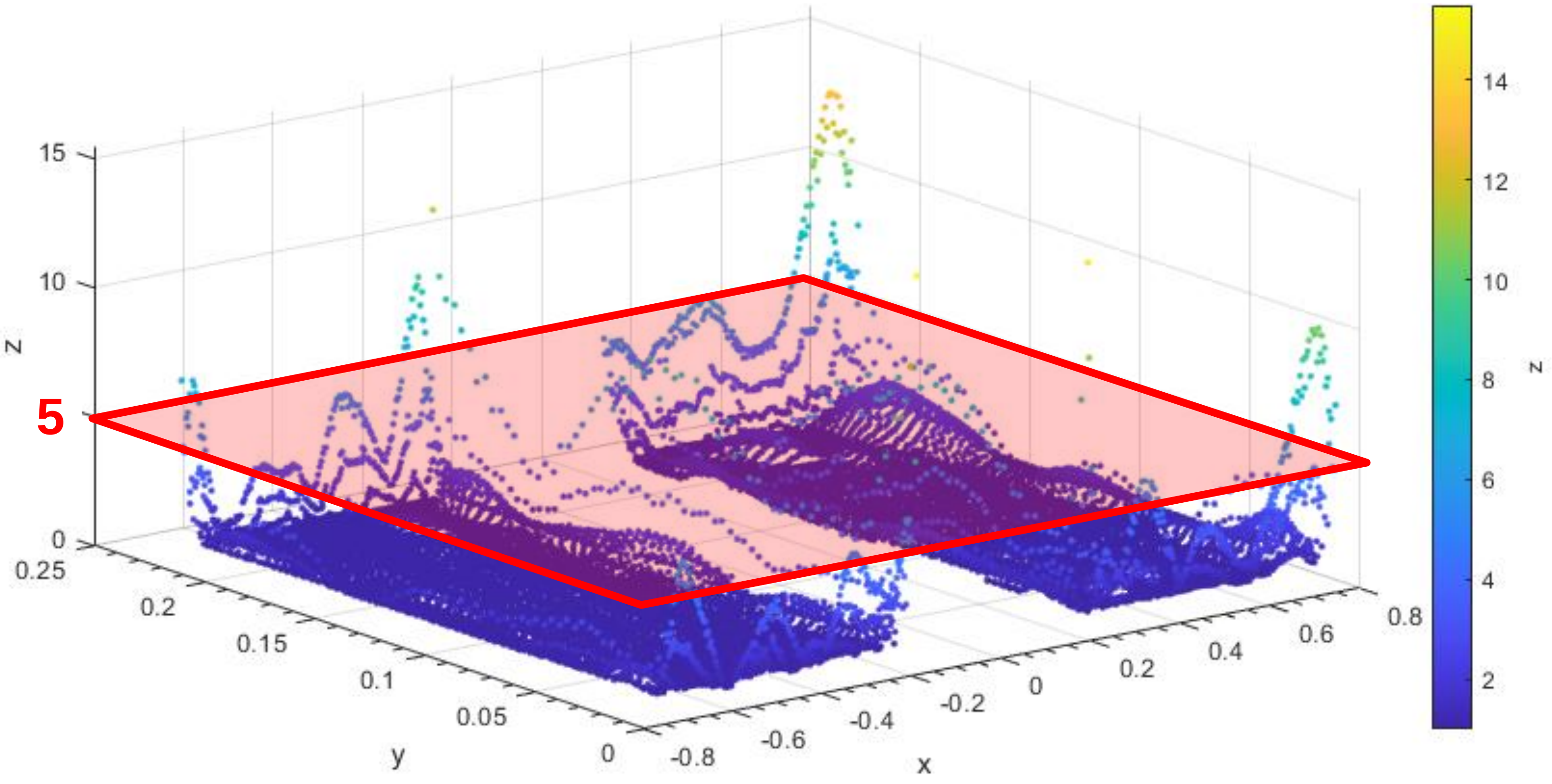




x = distance from hole edge, inches
y = distance from mandrel entry surface, inches
z = residual stress, ksi

RS Field Characterization

Based on the reported uncertainty, RS variance side-to-side should be < 5 ksi (probably less), except for nearby free-edges.



x = distance from hole edge, inches
y = distance from mandrel entry surface, inches
z = residual stress uncertainty, ksi

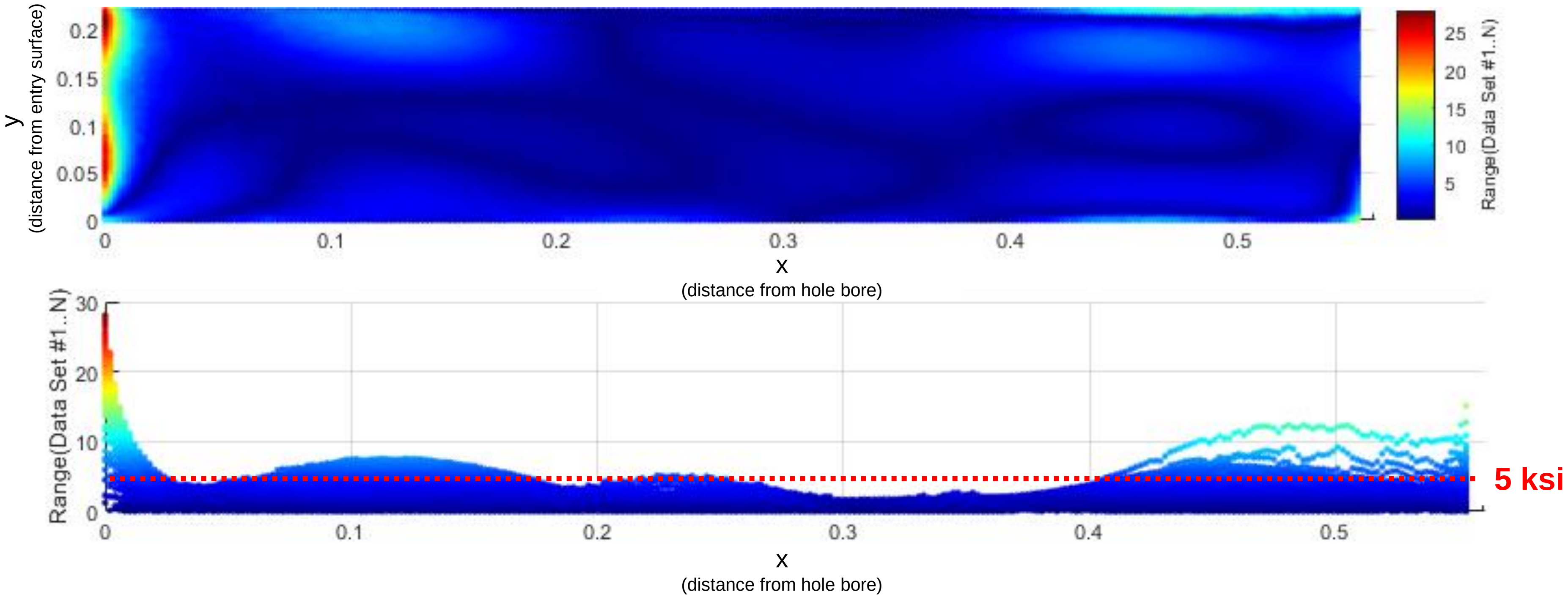
RS Field Characterization

The LH and RH fields were compared point-by-point and the range between each RS value was calculated

Rather than being < 5 ksi, the RS variance between the LH and RH side is typically ≥ 5 ksi with maximums near the bore

A similar analysis was performed for 15 other holes, these results are typical

What impact does this have on the life predictions?



RS Field Characterization

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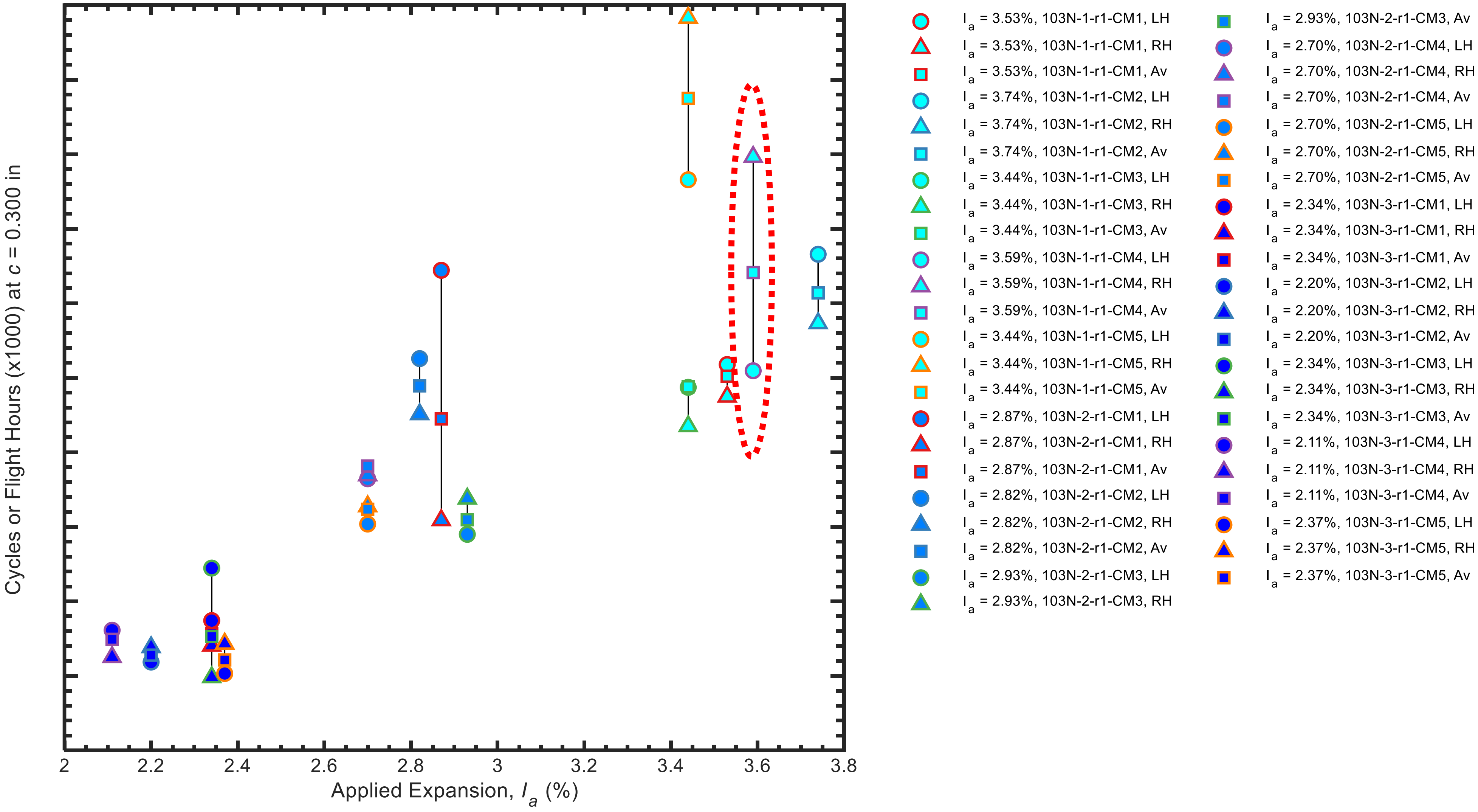
BAMpF analyses were performed for LH, RH, and averaged LH/RH RS fields:

WIDE-RANGE of crack growth life calculated for many “replicate” LH/RH RS fields.

Some were very repeatable, but others weren’t. **Is there a way we can quantify the “goodness” of a RS field??**

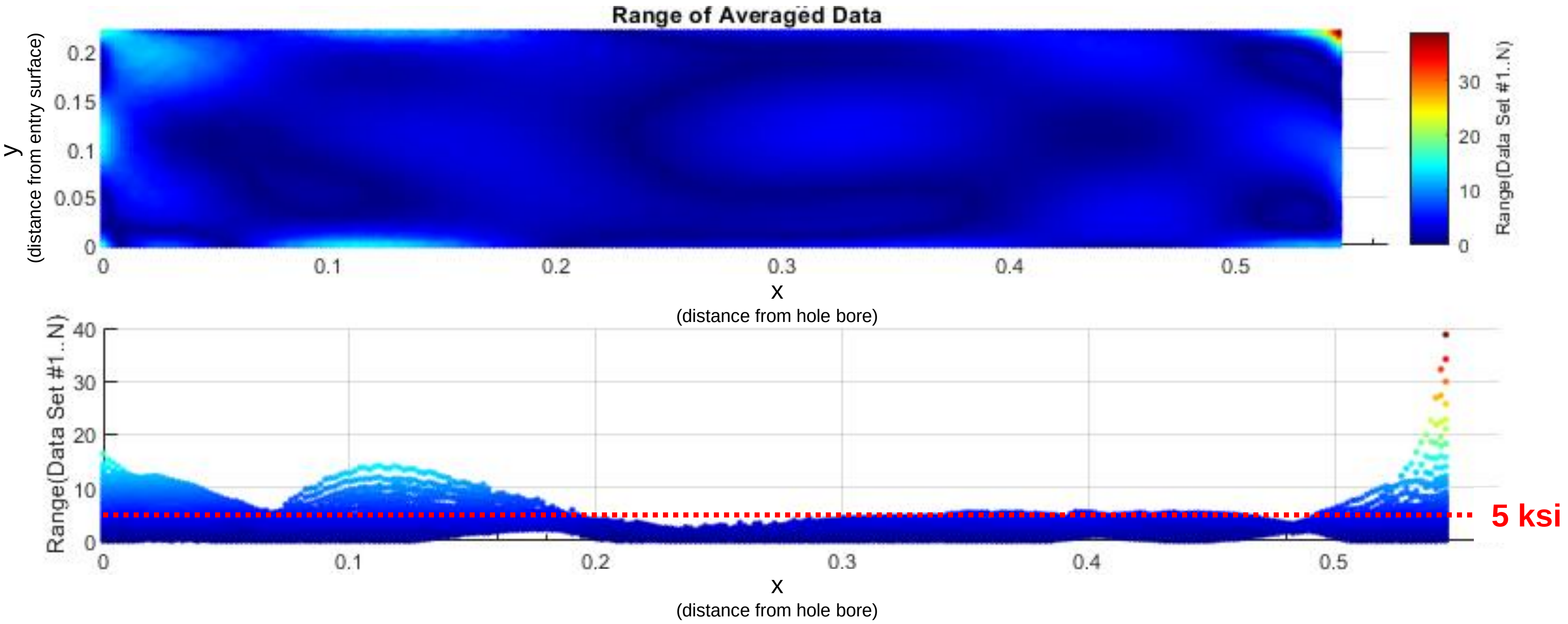
Let’s examine a poorly replicated field.

<u>NOTE</u>: No lengthwise split (i.e., stress-relief cut) was performed on these samples prior to contour measurement.



RS Field Characterization

For this dataset, the variance between the LH and RH side is consistently > 5 ksi, particularly near the hole bore

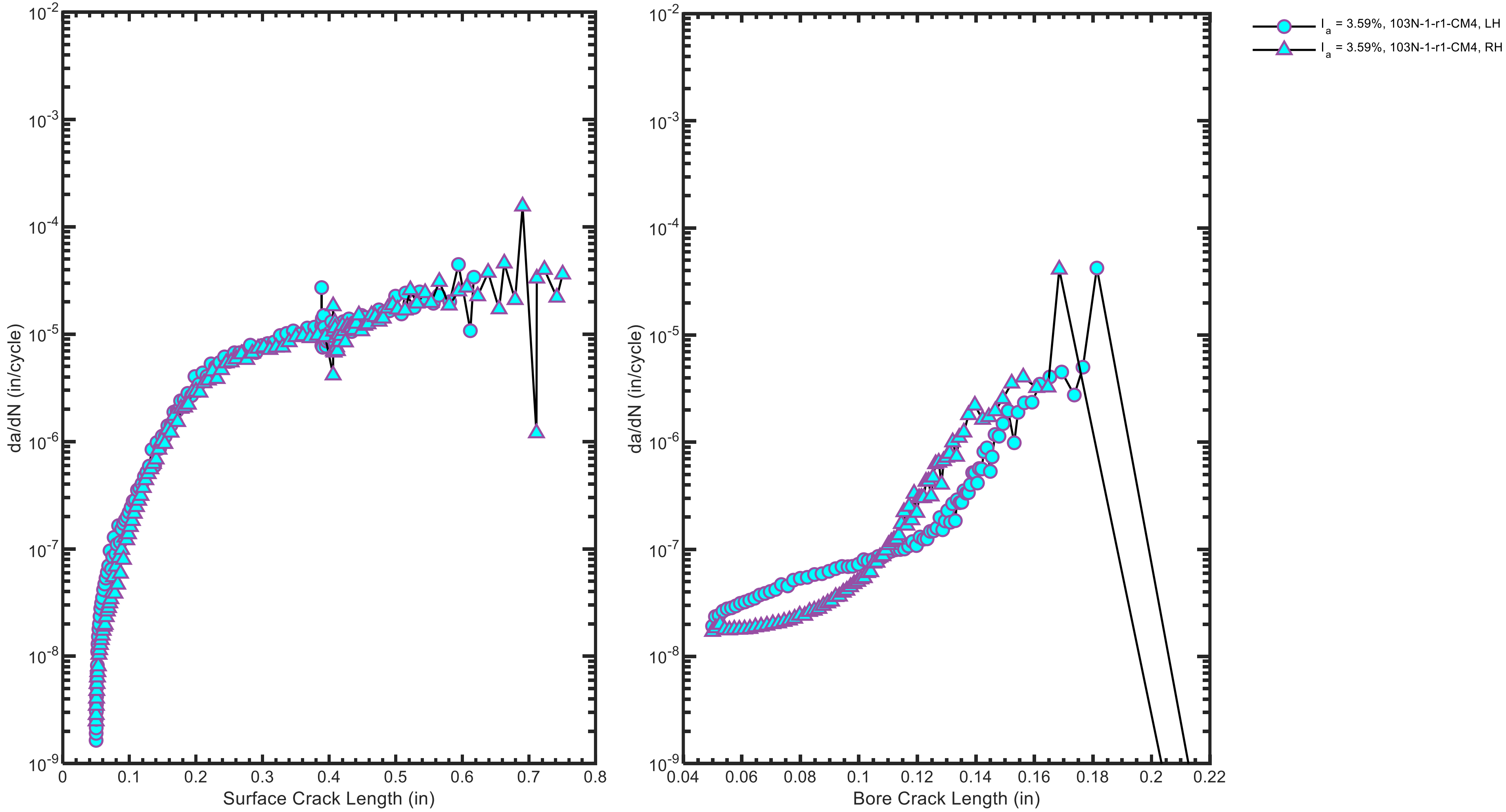


RS Field Characterization

Interestingly, the surface crack growth rate is very similar for the LH and RH sides.

But, the bore crack growth rates are very different shapes.

This indicates a key role of the bore growth behavior.

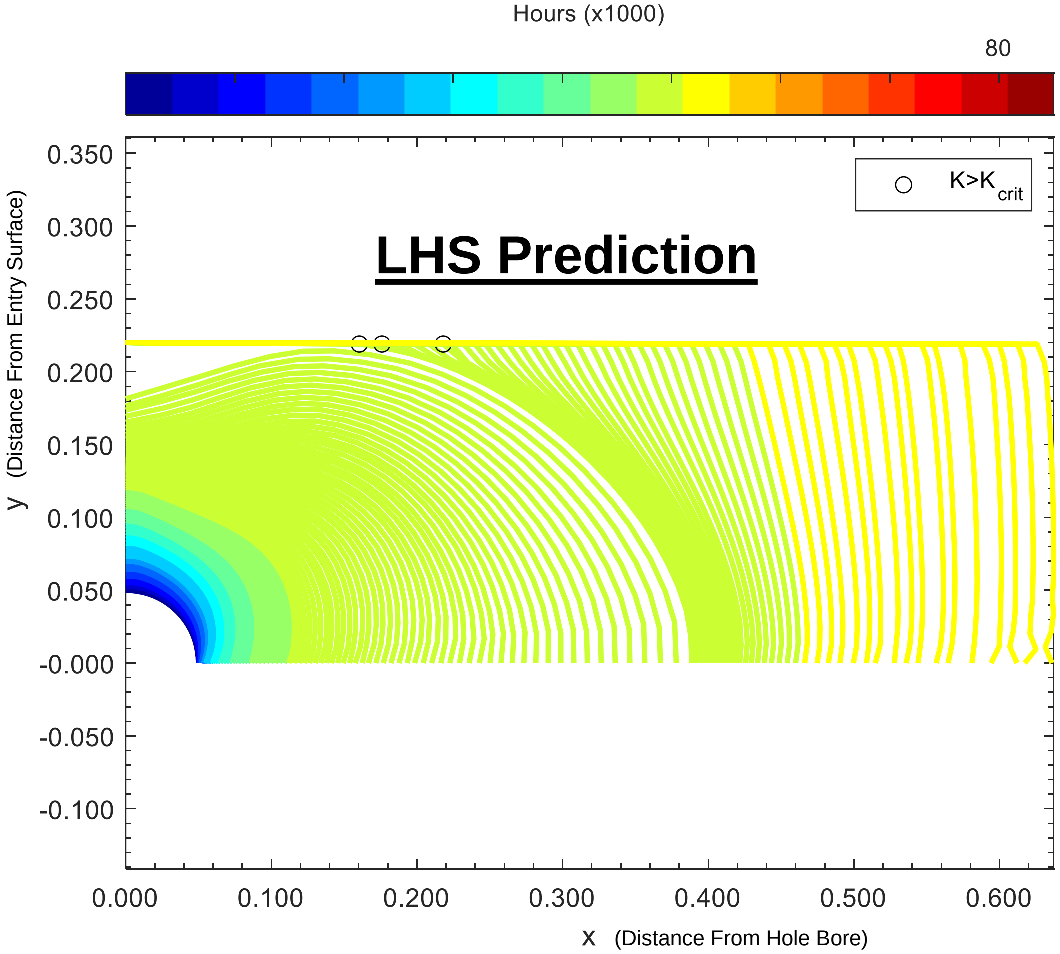


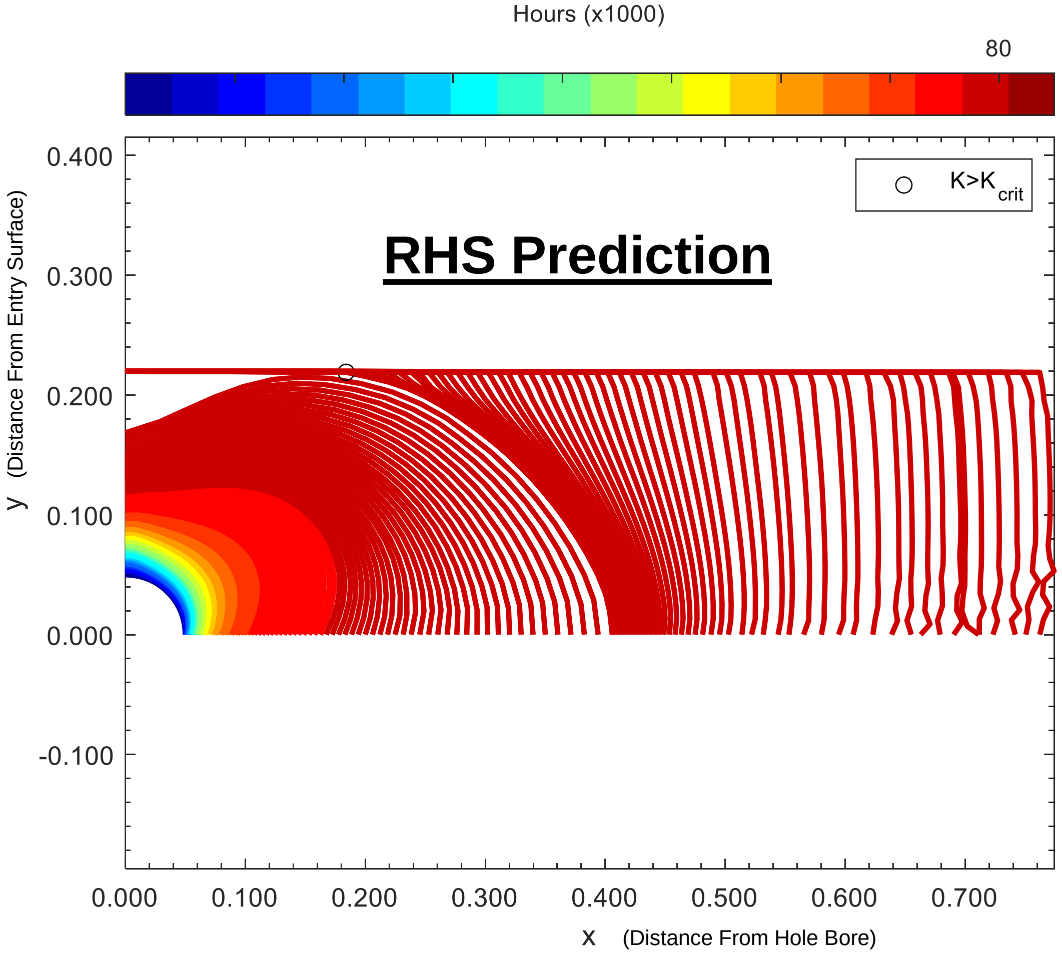
RS Field Characterization

Vast majority life is within ~0.150” of crack origin [(x,y) = (0,0)]

Since the RS field is applied as a traction on the crack face, **this ~0.150” region is key** and governs the RS impact on the life prediction.

Crack growth variations beyond this point (e.g. front shape) might be a red-herring.





Specimen ID: RS0011_2024_T351_plt_la3.59
Serial Number: 103N-1-r1-CM4

Conclusions

- **Applied expansion (I_a) variance is a key factor determining the fatigue life of cold expanded (Cx) holes.**
- **With A-10 Cx tolerances, I_a may vary from ~3.0 – 4.5%.**
- **Within the A-10 tolerance band, a life improvement factor (LIF) of 2.5 – 31 was predicted using multi-point fatigue life analysis (BAMpF) and Cx residual stress (RS) fields obtained via the contour method.**
- **This wide range of predicted LIF is partially due to the range of I_a, but significant prediction scatter was attributed to measured RS field variations.**
- **Identified poor repeatability of LH/RH side Cx hole RS fields determined via the contour method. Additional focus on replicability of contour-based Cx RS fields is required.**

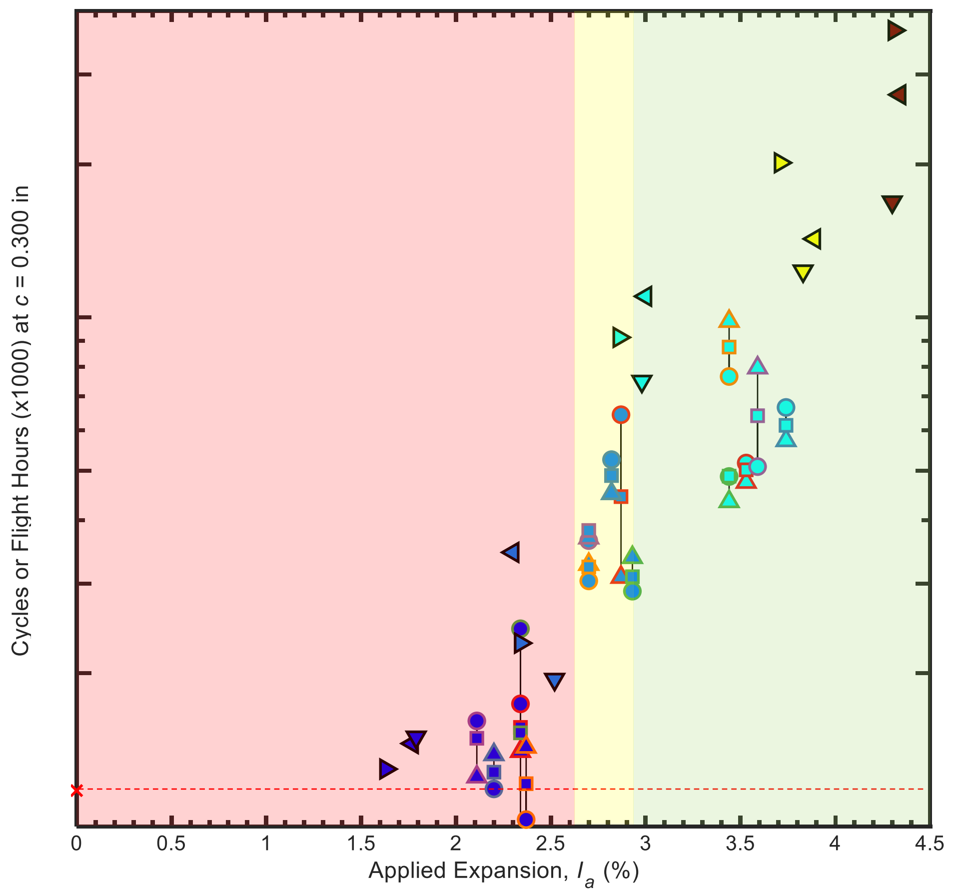
Acknowledgements

- Jake Warner

- Hill Engineering
  - Dallen Andrew
  - Josh Hodges
  - Bob Pilarczyk

- APES
  - Scott Prost-Domasky

QUESTIONS?



Cycles or Flight Hours (x1000) at c = 0.300 in
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Applied Expansion, I_a (%)