Rapid 2 Point RS Predictions

U.S. AIR FORCE

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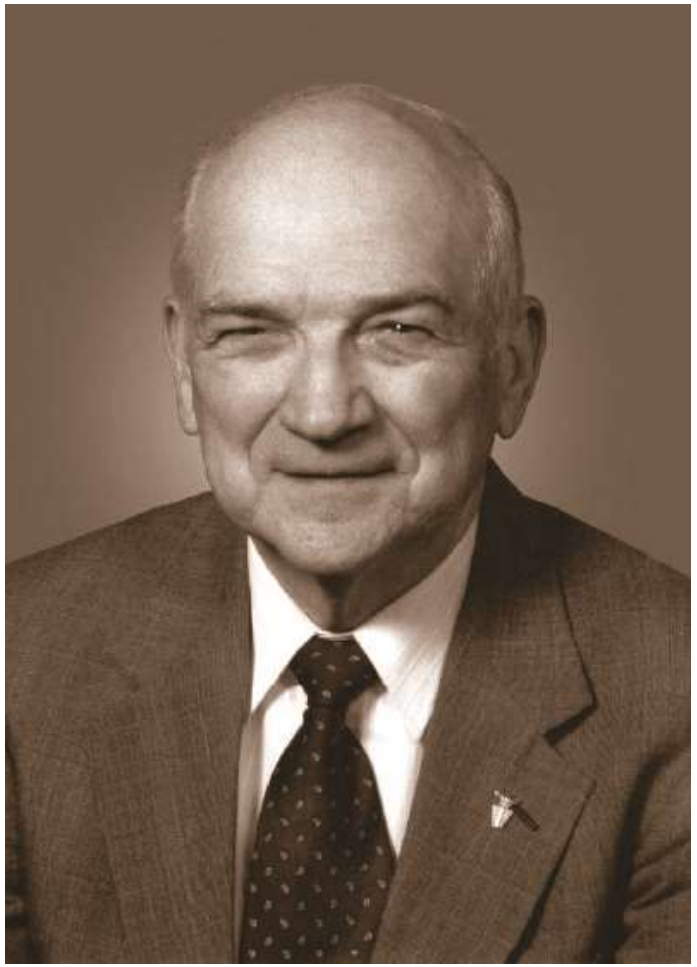
AFGROW 2021

Current Practice

- 1985, Lincoln introduced reduced initial flaw size (0.005”) approach

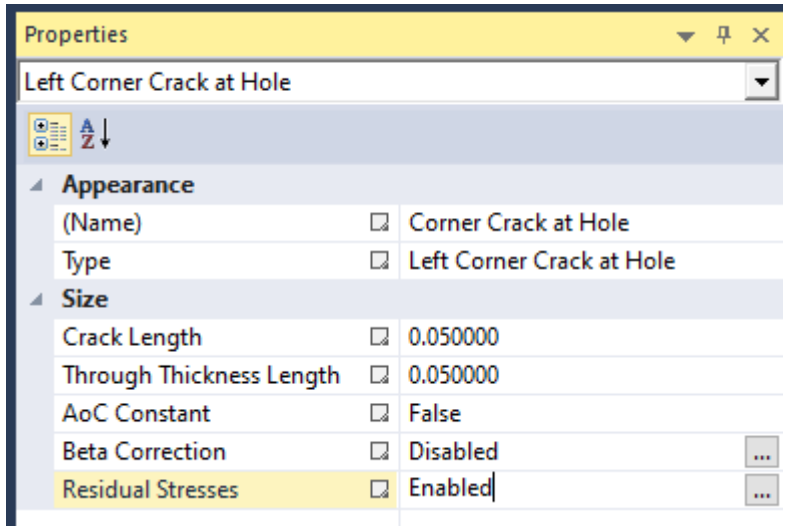
- What steps can we take to improve on 0.005”?
- Can we do better than 0.005”?
  - .005” known to have issues:
    - Severely under predicts benefit for most scenarios
    - Over predicts benefit for high stress scenarios
    - Over predicts benefit for short edge margin scenarios



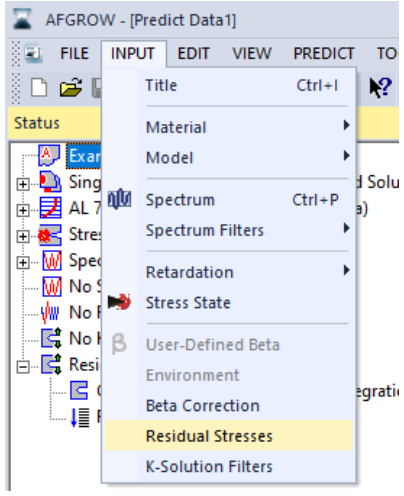
ICAF
International Committee on Aeronautical Fatigue and Structural Integrity
13th Symposium

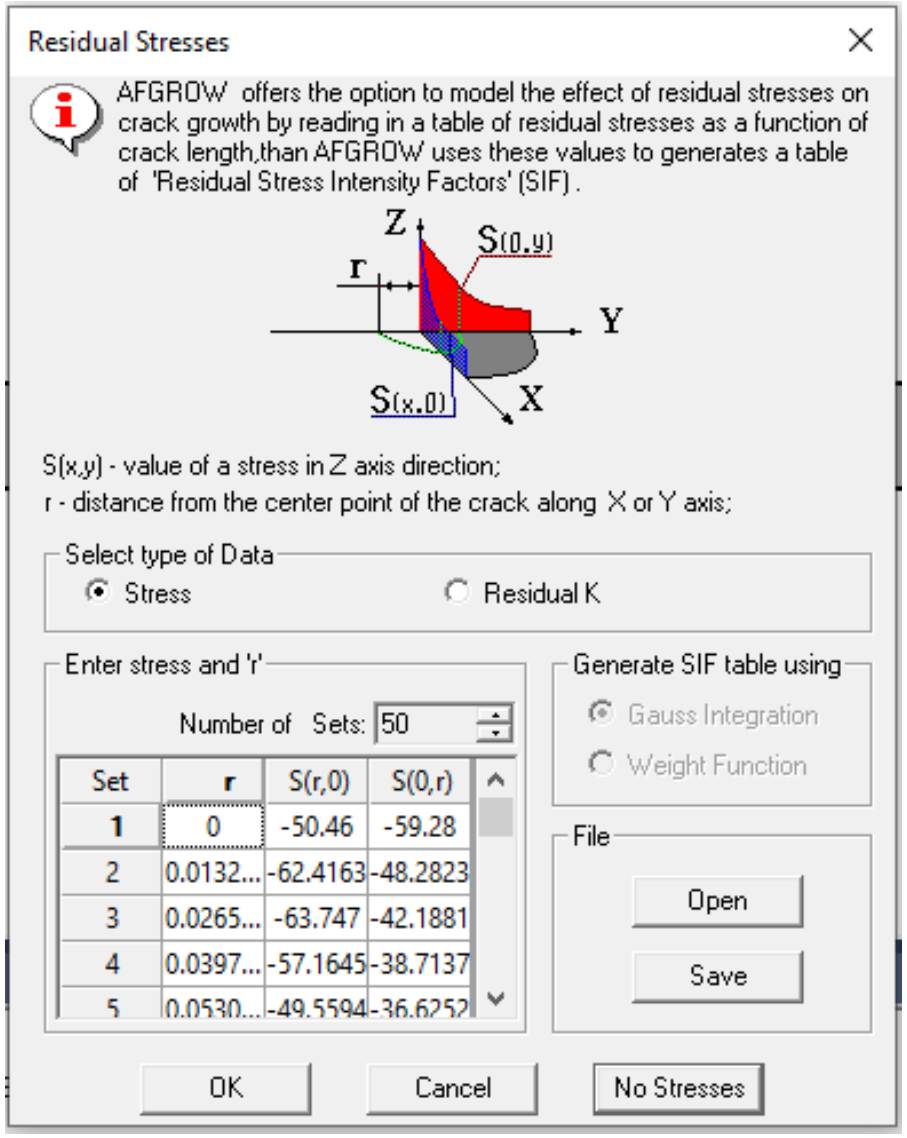
AFGROW 2 Point Menu

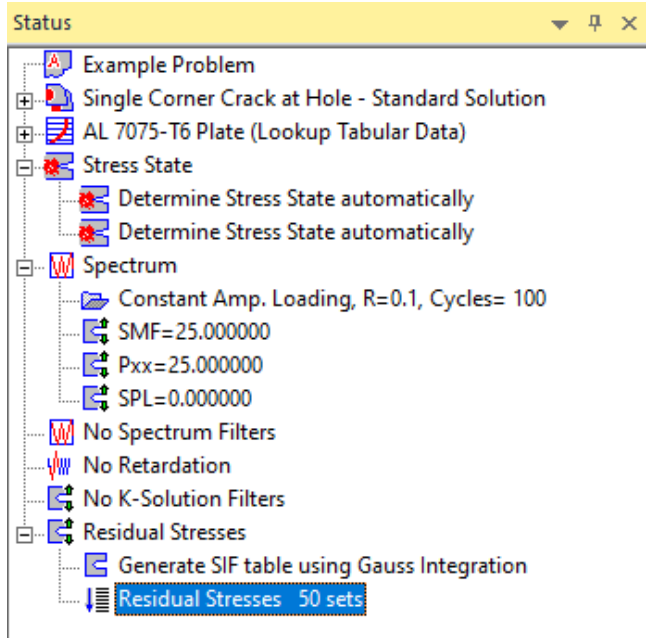
For advanced models:



For classic models:

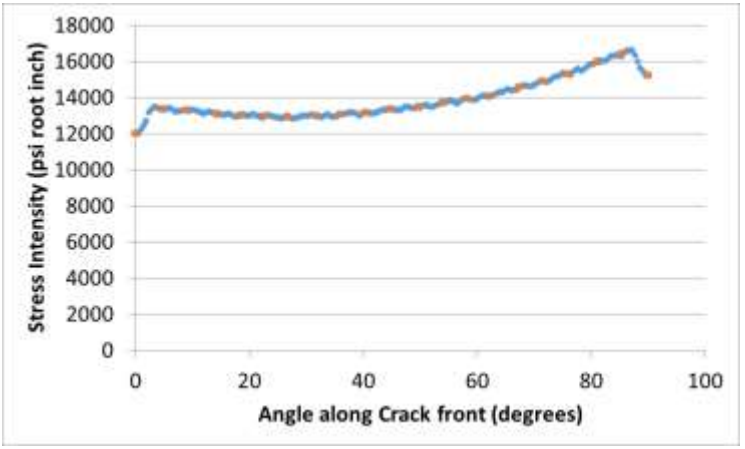


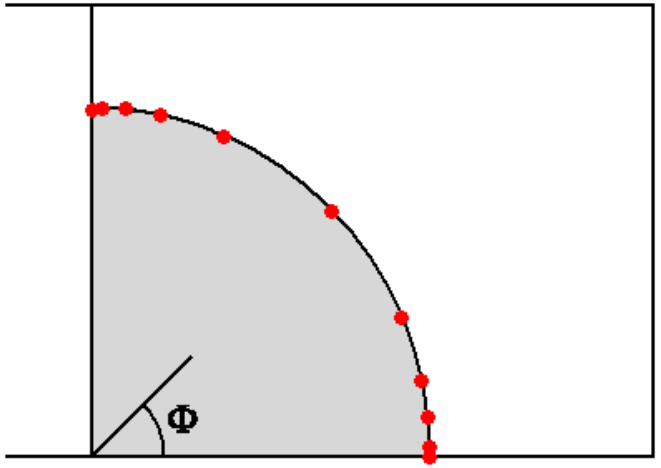


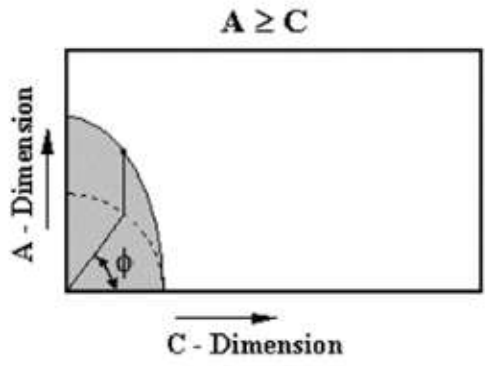


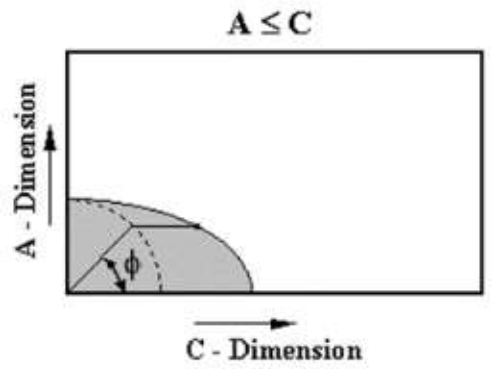
Background

- **Parametric angle definition**
  - **AFGROW simulates crack growth using 2 points, one near each free surface**
  - **Stress intensity varies along crack front**
  - **Parametric angles are the angles that define which stress intensity is used for crack growth at each surface**
- **Multi-Point analyses (BAMpF) do not use parametric angles, those analyses represent crack front with multiple points**









Hill Engineering Assessment

- Parametric angle approach
- Optimum angle was inconsistent
  - 15 degrees for CP4
  - 5 degrees for CP4T
  - 10 degrees for CP100

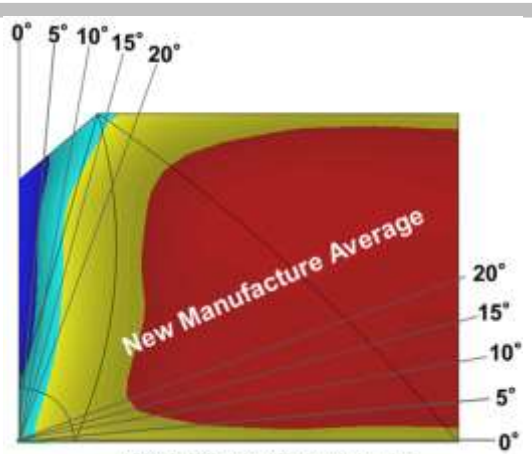


Figure 1: Residual stress extraction lines

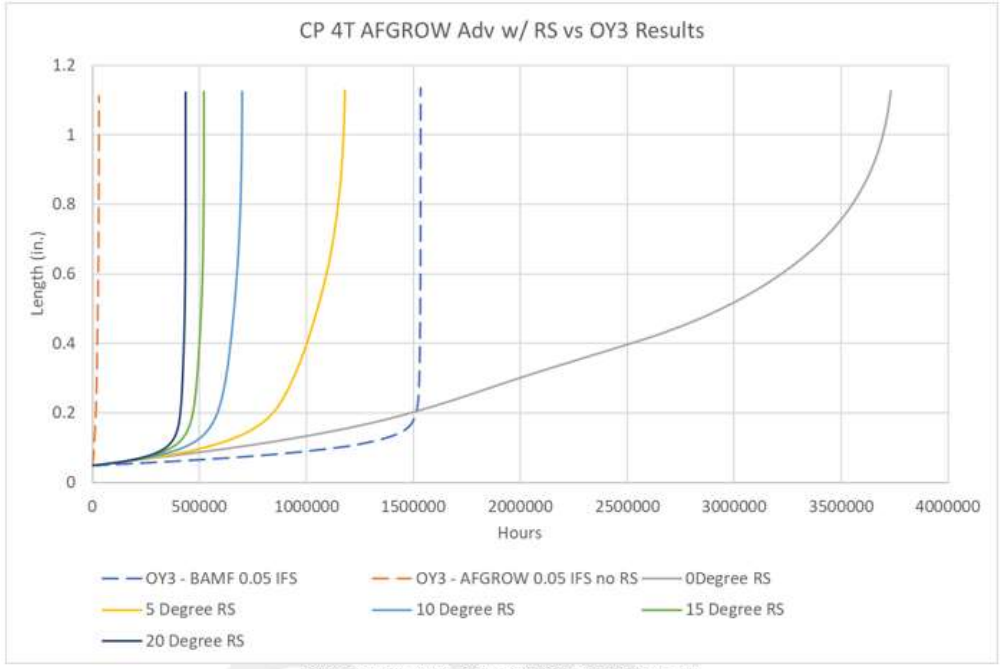
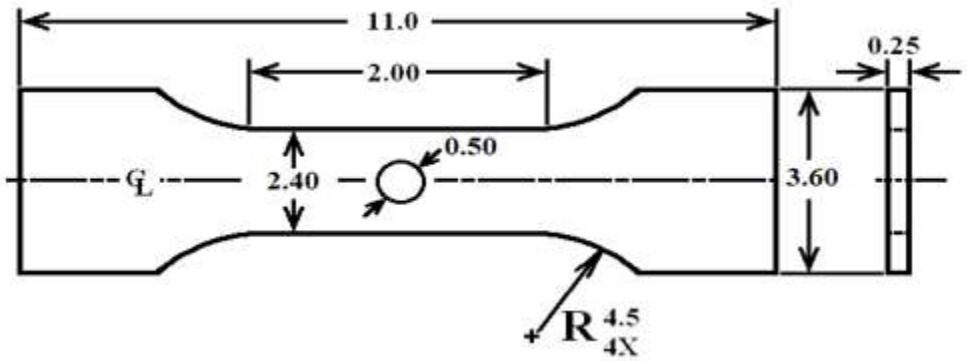


Figure 3: CP 4T Life Comparisons

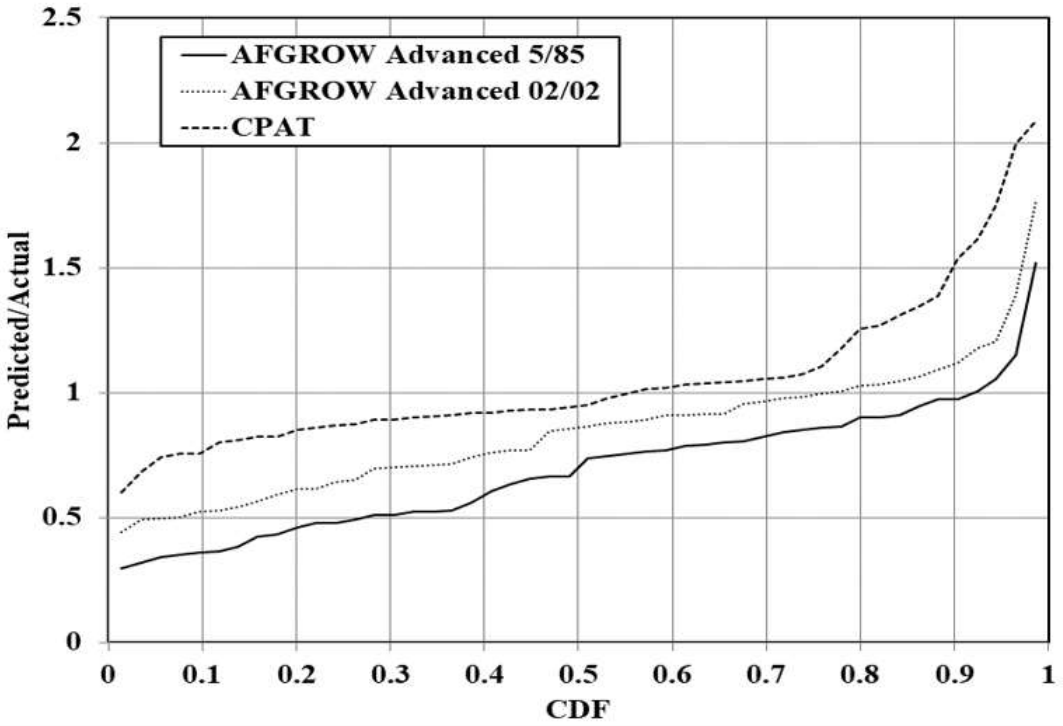
Figure 2: CP 4 Life Comparisons

APES Assessment

- Evaluated constant offset and angle approach
- 7075-T7351, same geometry for all predictions, individual contour results
- Conservative ~80% of the time

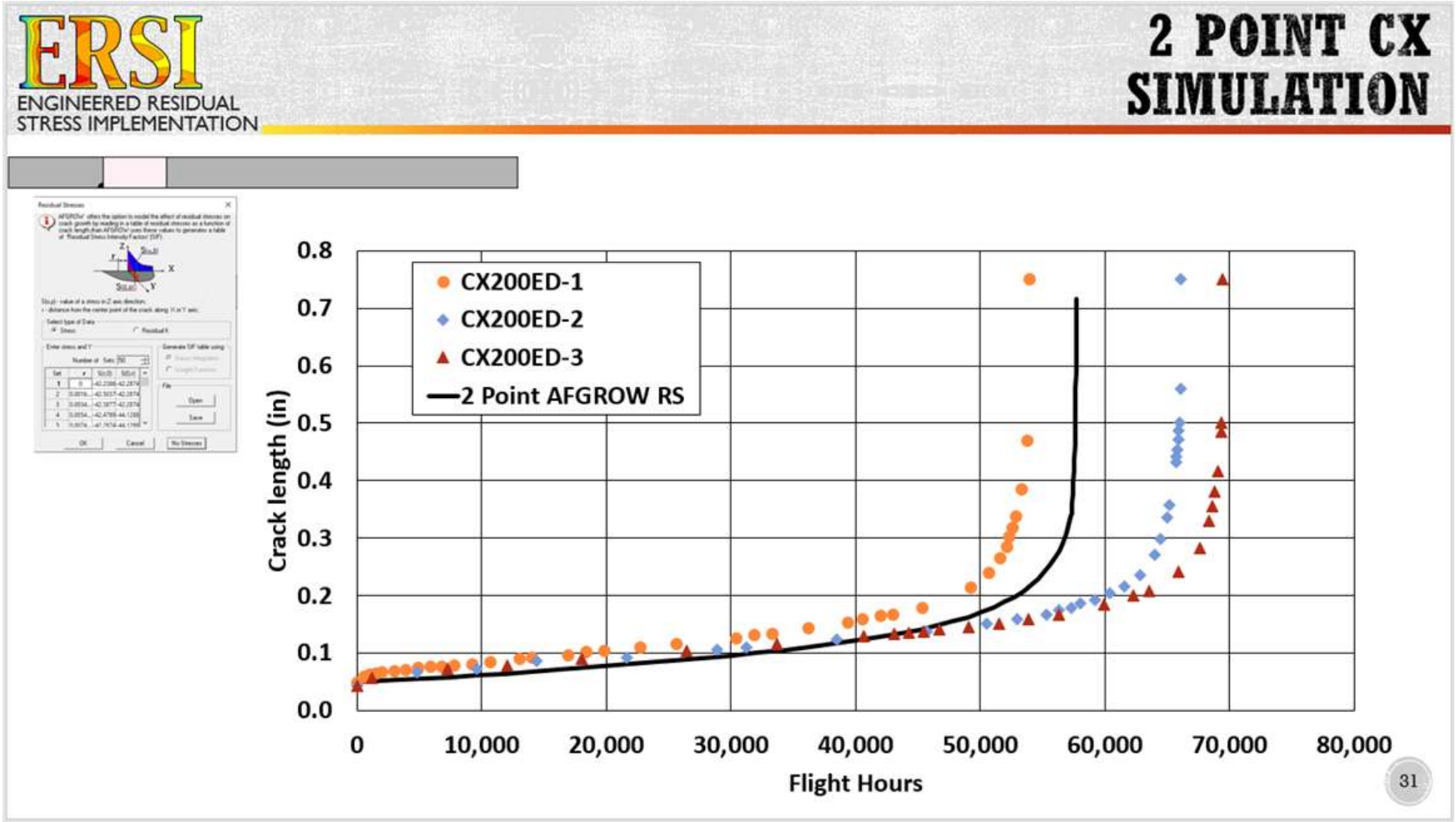


Predicted / Actual Results



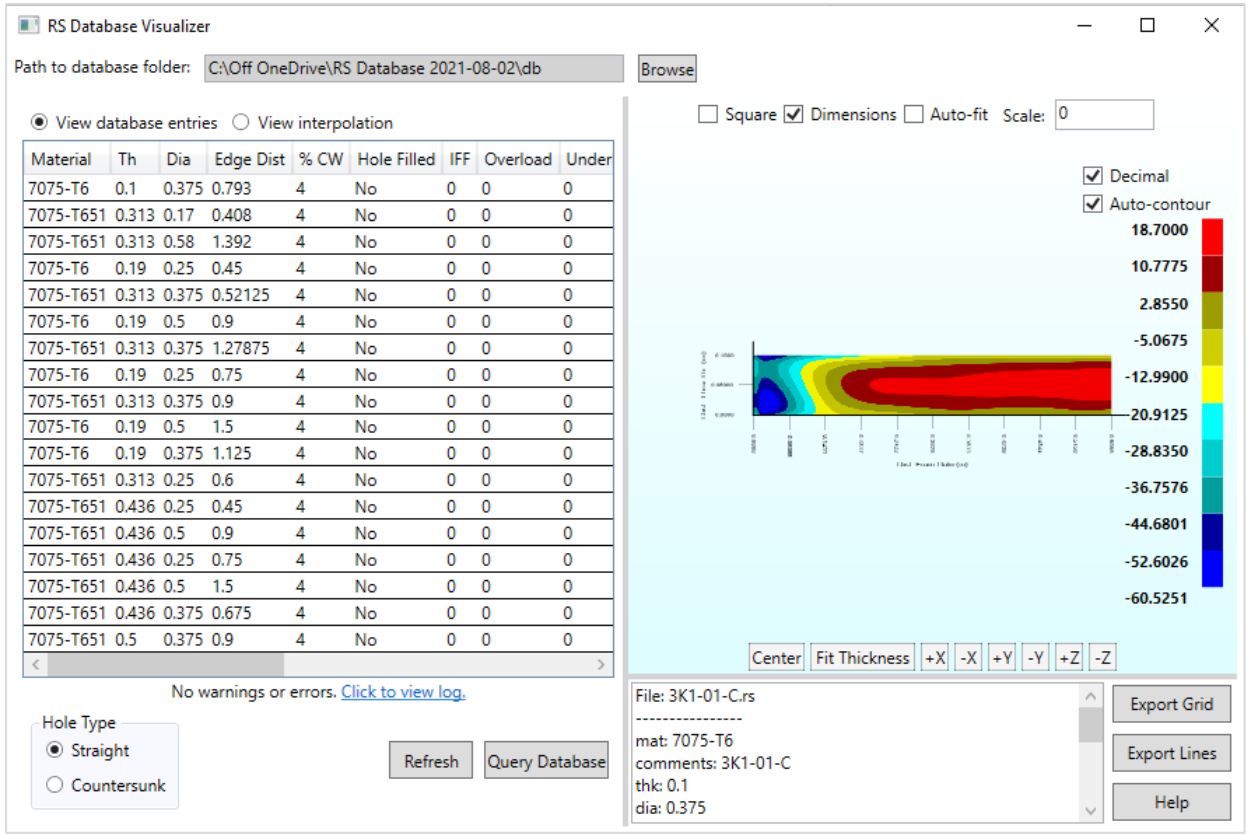
- 48 predictions with each method
- CPAT prediction mostly +/- factor of 2 with P/A = 1 crossing at 55%
- AFGROW methods more conservative but definitely show promise as rapid screening tool

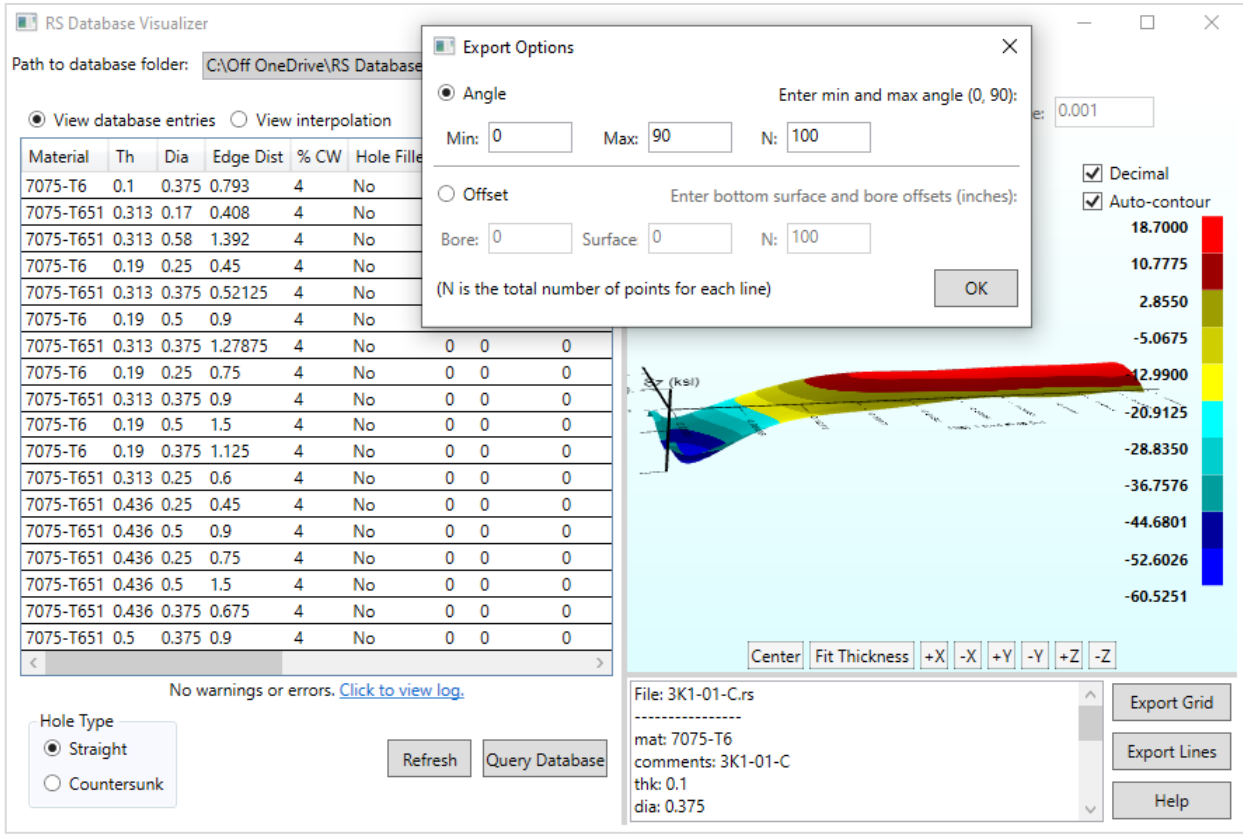
- Wing root bending loaded, 33 ksi max stress
- e/D = 2.0, ¼” plate, ½” hole



RS Database Update

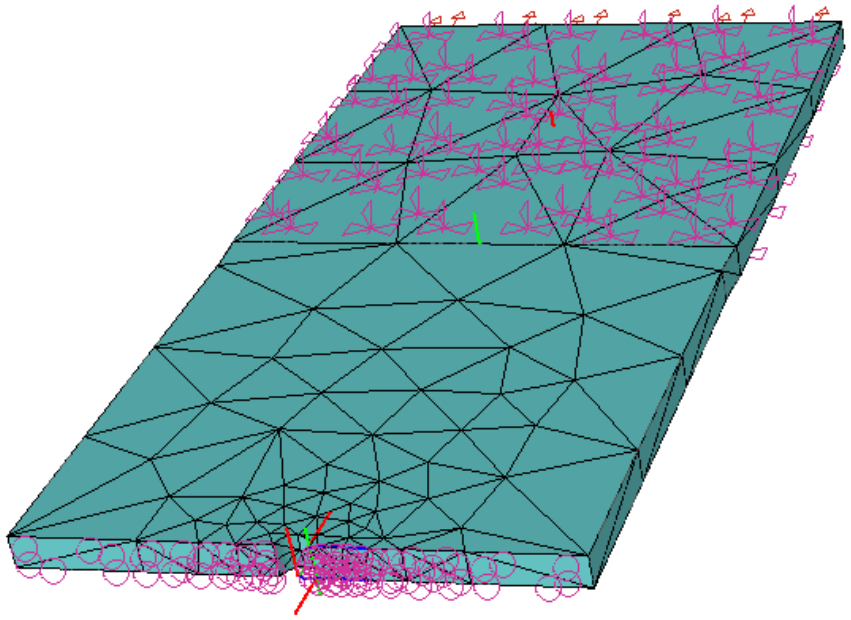
- **New RS database can directly output custom vectors for AFGROW**





RS Database Dataset

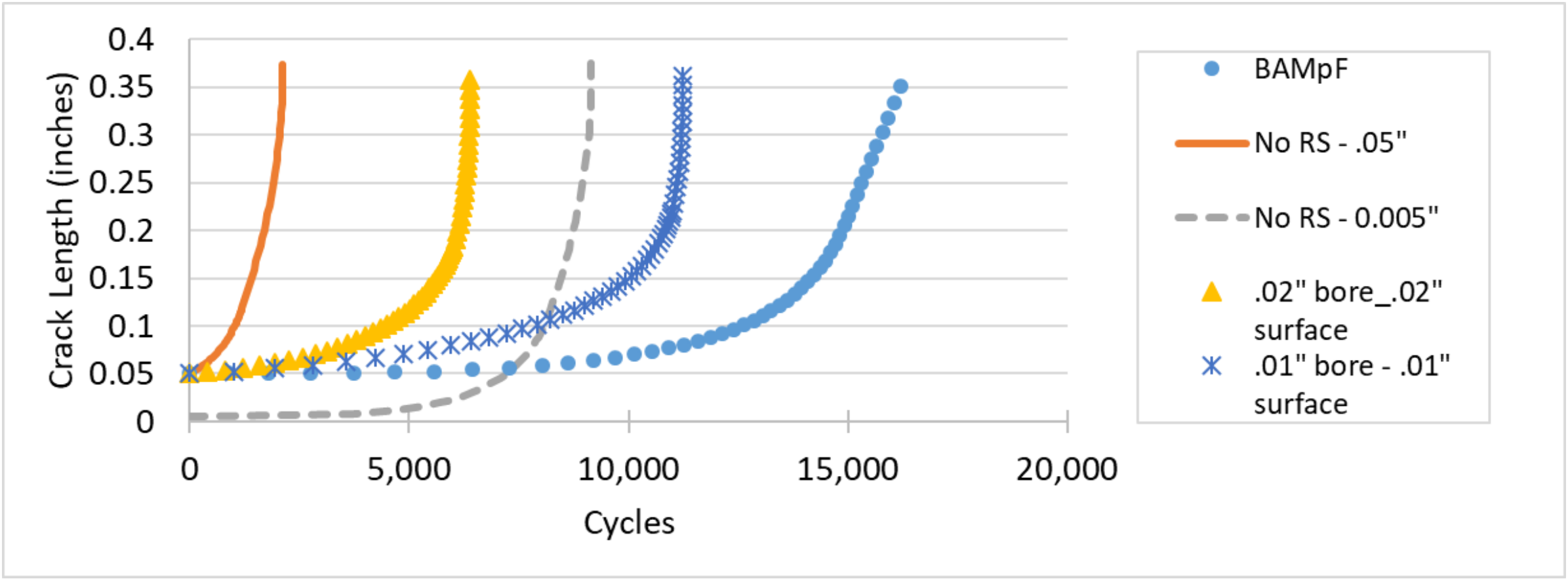
- Ran most 2024-T351 geometries available in the RS database
- 25 ksi
- R = 0.1
- 5% growth increment
- P-level = 3



	%CX	Thickness	Diameter	Edge Distance	e/D
Case1	3	0.19	0.375	0.5625	1.5
Case2	3	0.25	0.25	0.3	1.2
Case3	3	0.25	0.25	2	8
Case4	3	0.25	0.5	0.6	1.2
Case5	3	0.25	0.5	0.75	1.5
Case6	3	0.25	0.5	1	2
Case7	3	0.25	0.5	2	4
Case8	3	0.25	0.75	2	2.67
Case9	3	0.313	0.375	0.675	1.8
Case10	3	0.5	0.5	1.2	2.4
Case11	3.5	0.25	0.5	0.6	1.2
Case12	3.5	0.25	0.5	2	4
Case13	3.5	0.313	0.375	0.675	1.8
Case14	3.5	0.5	0.5	1.2	2.4
Case15	4	0.19	0.375	0.5625	1.5
Case16	4	0.19	0.4375	0.56875	1.3
Case17	4	0.25	0.5	2	4
Case18	4	0.313	0.375	0.675	1.8
Case19	4	0.5	0.5	1.2	2.4

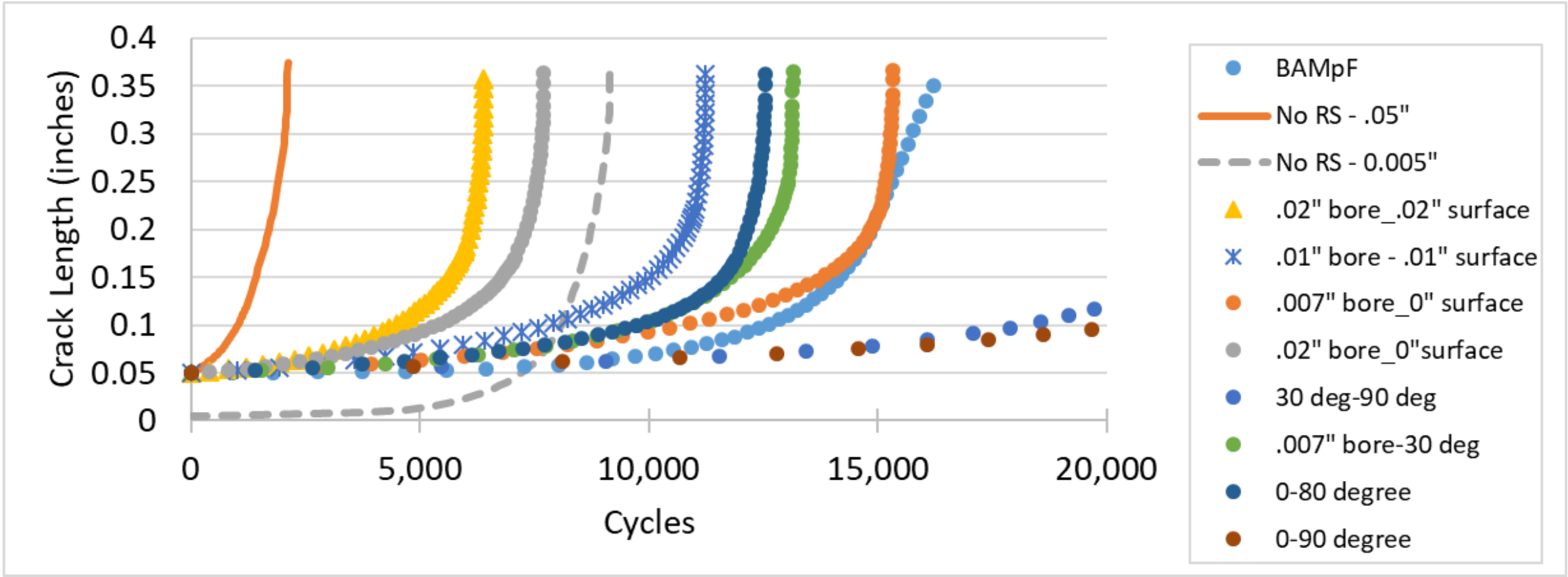
Case 1

- t = 0.19”
- D = 0.375”
- e = 0.5625”



Case 1 – All Predictions

- t = 0.19”
- D = 0.375”
- e = 0.5625”



Case 1 – All Predictions

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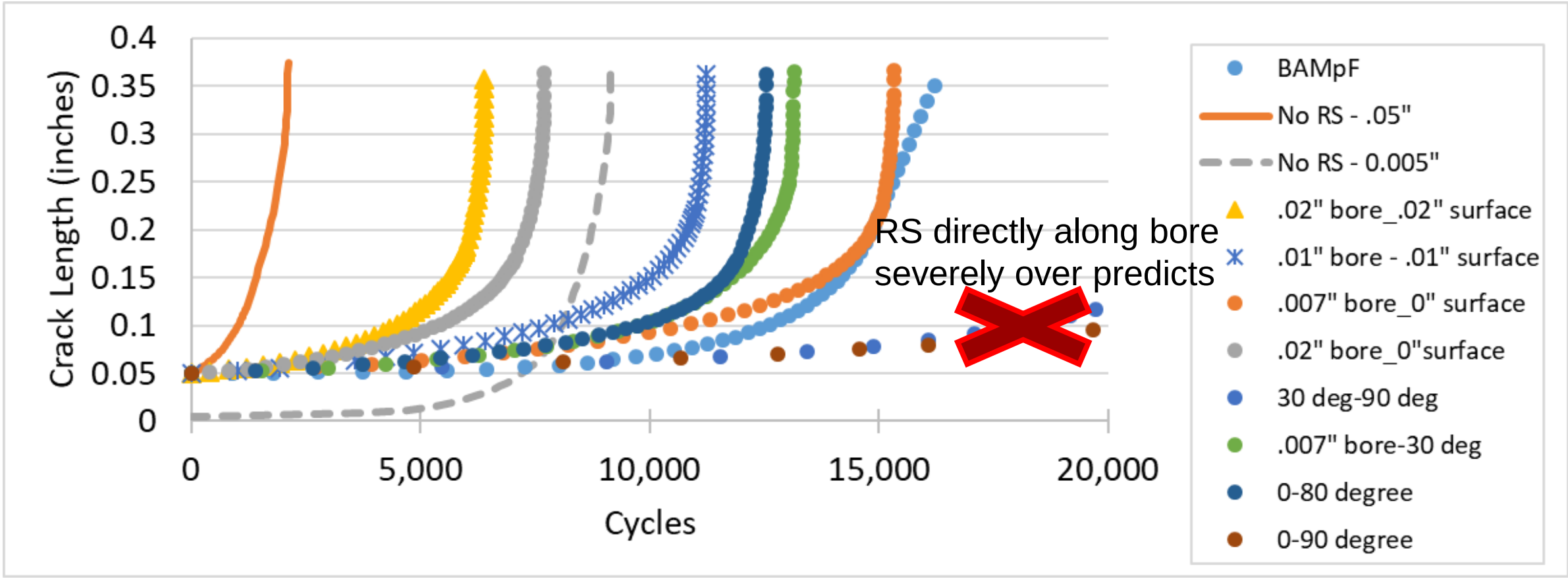
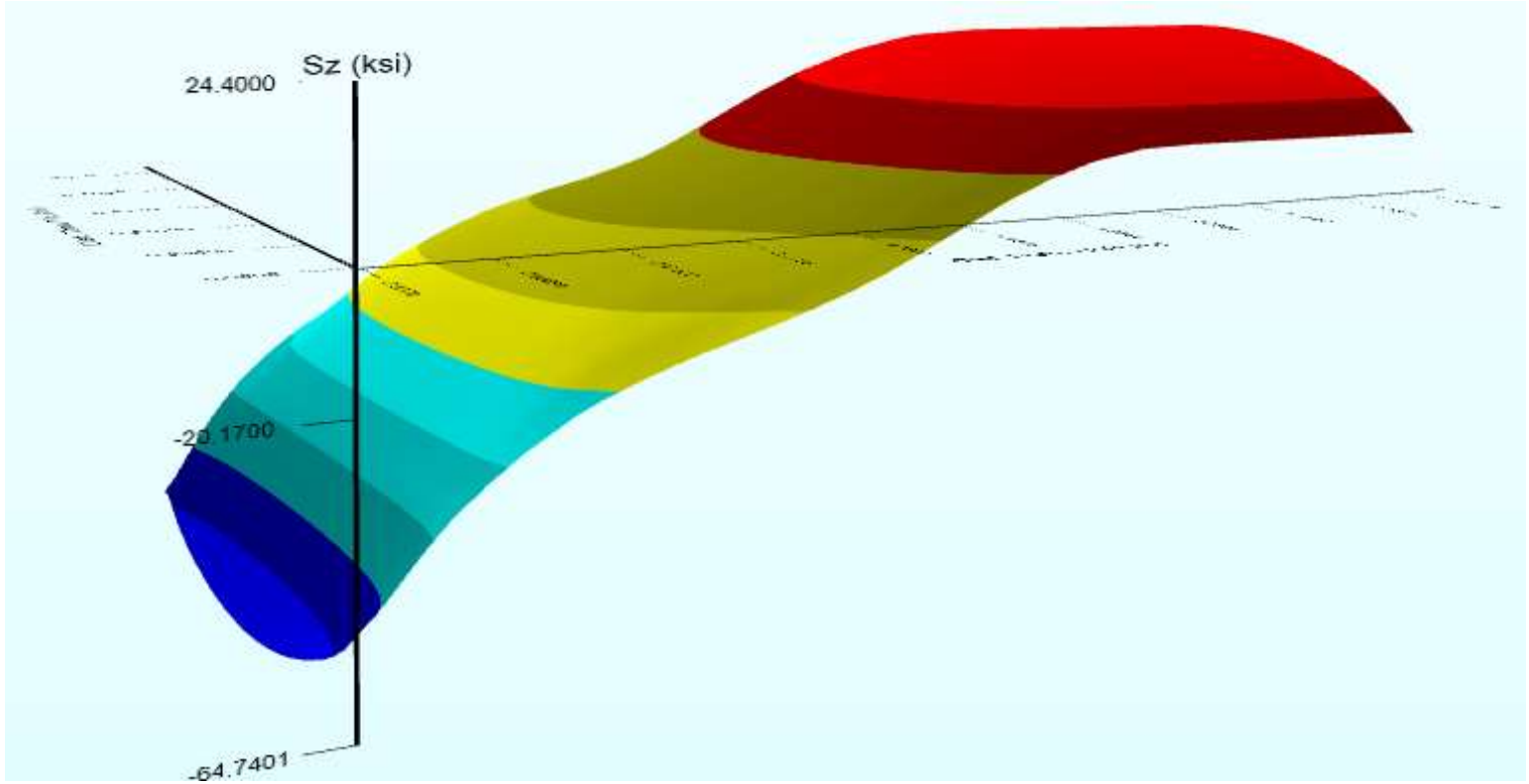


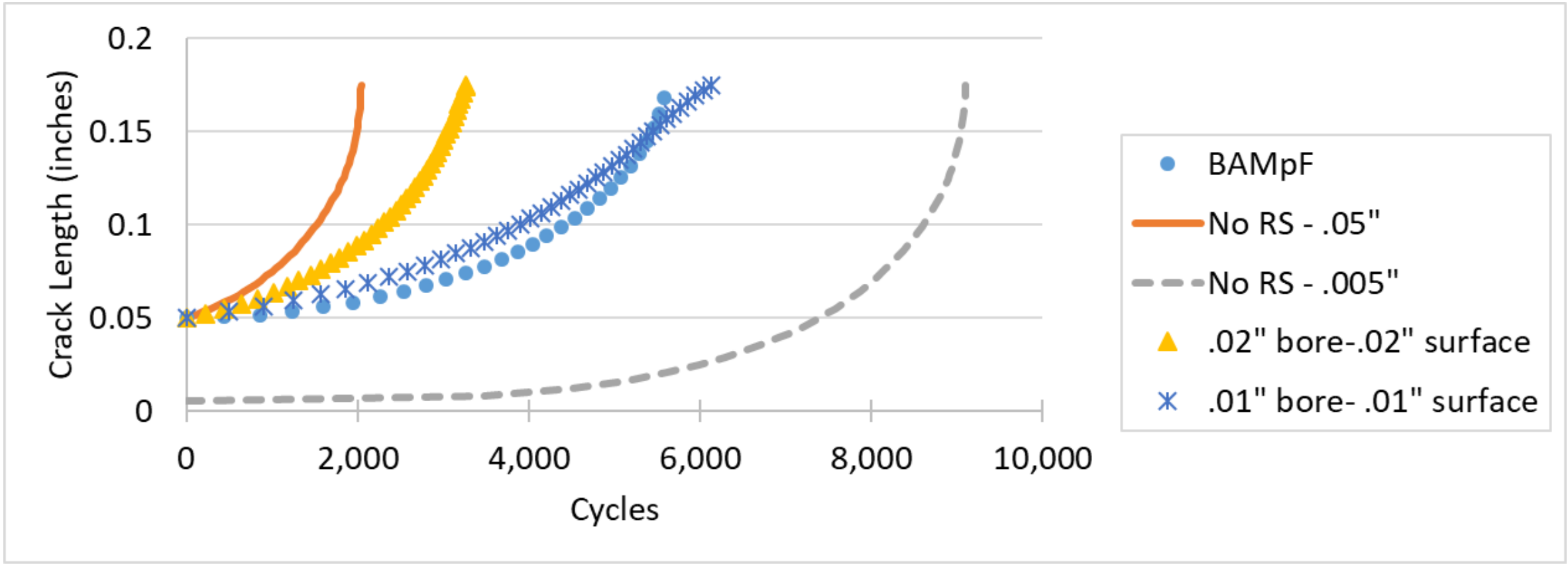
Observation – Bore RS

- RS determination right at hole bore is most often highly compressive
- Using RS immediately at hole bore results in unrealistically long life for corner cracks (for 2 point analyses)
- Surface offset generally has a minimal influence on the prediction



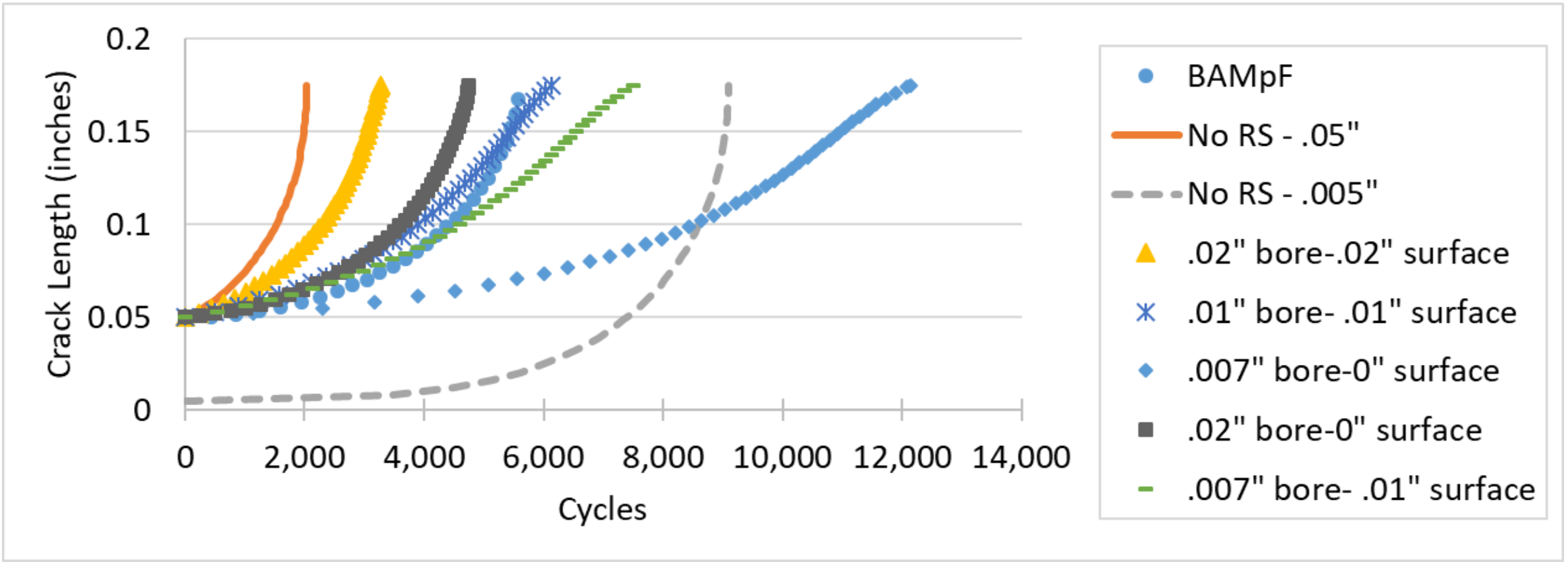
Case 2

- t = 0.25”
- D = 0.25”
- e = 0.3”



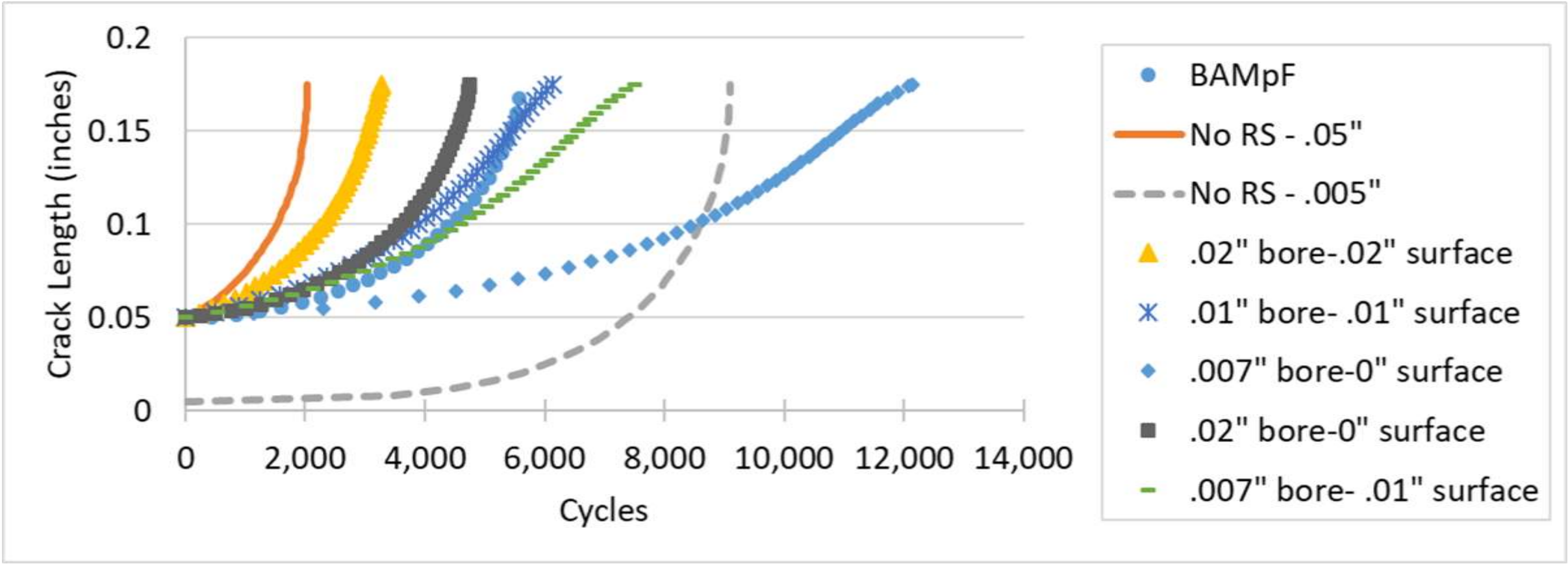
Case 2 – All Predictions

- t = 0.25”
- D = 0.25”
- e = 0.3”



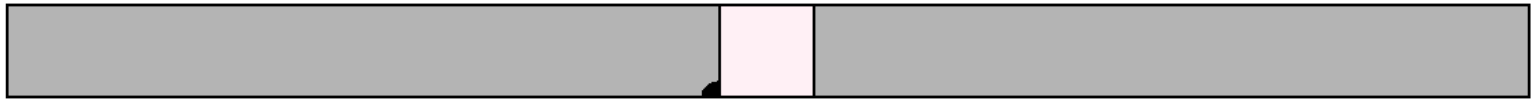
Observation – 0.005”

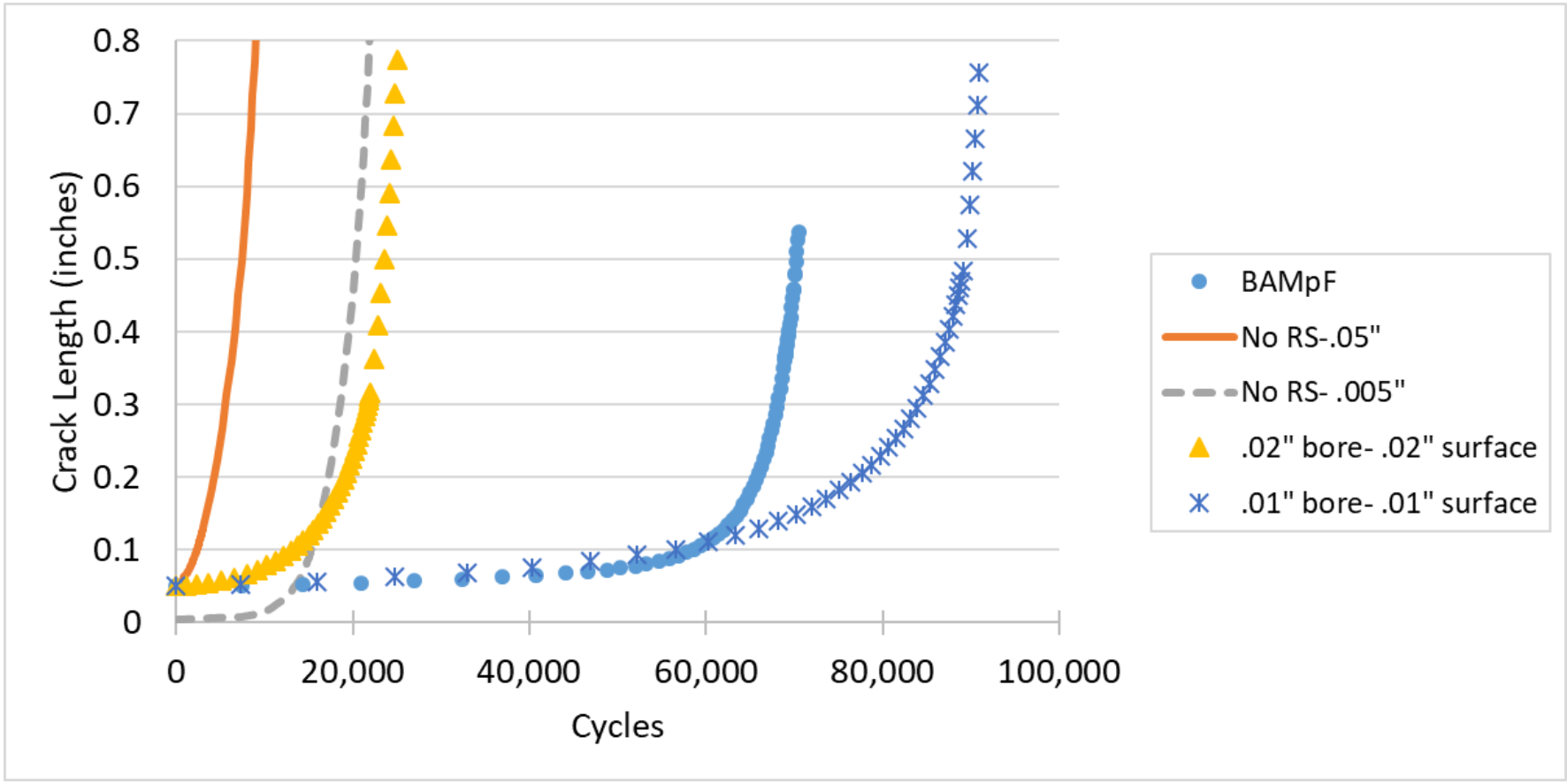
- 2 Point RS can mitigate unconservative cases of 0.005” approach
  - 0.005” approach has been shown to result in unconservative results for high stress/short edge margin



Case 3

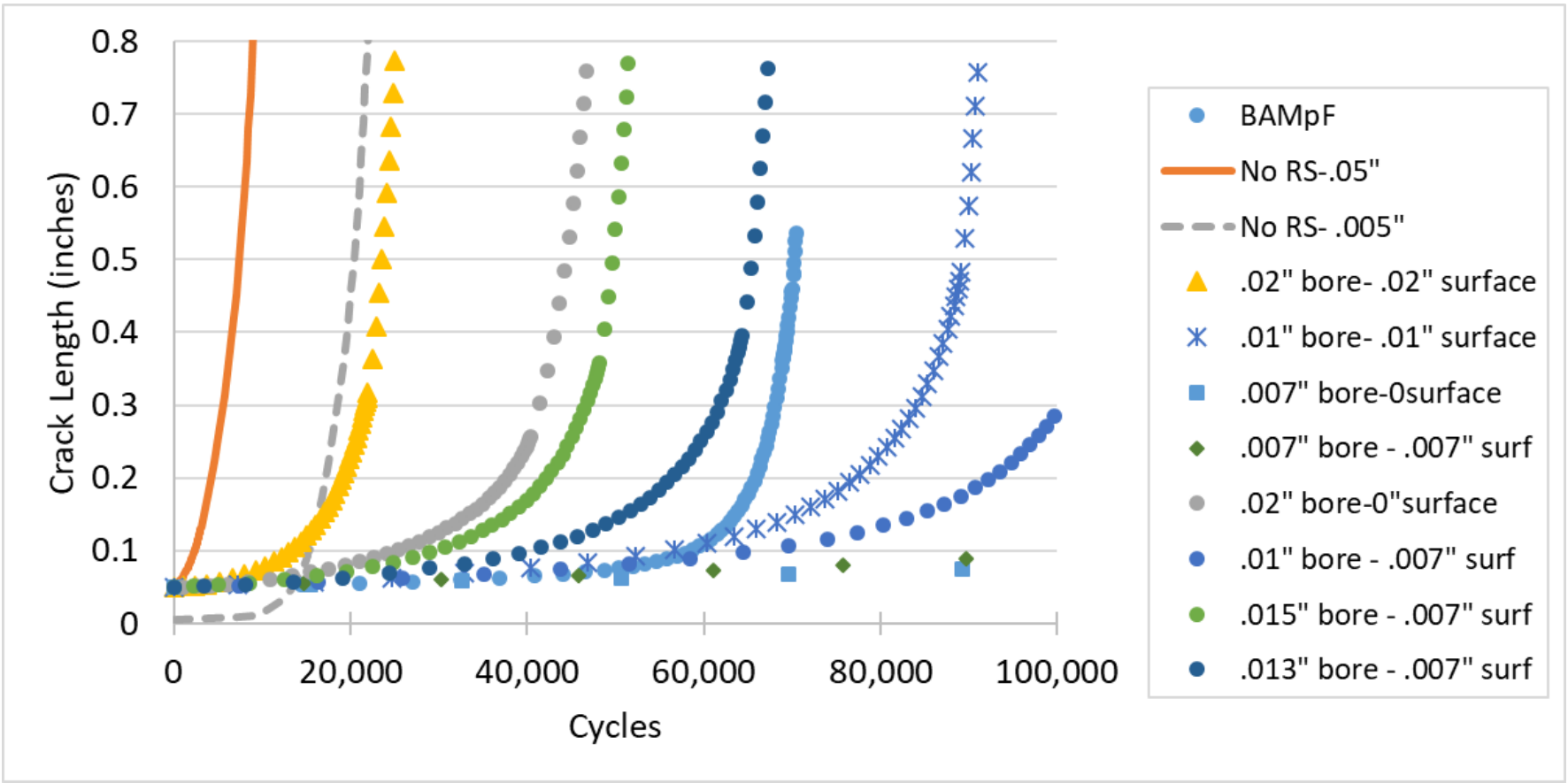
- t = 0.25”
- D = 0.25”
- e = 2”





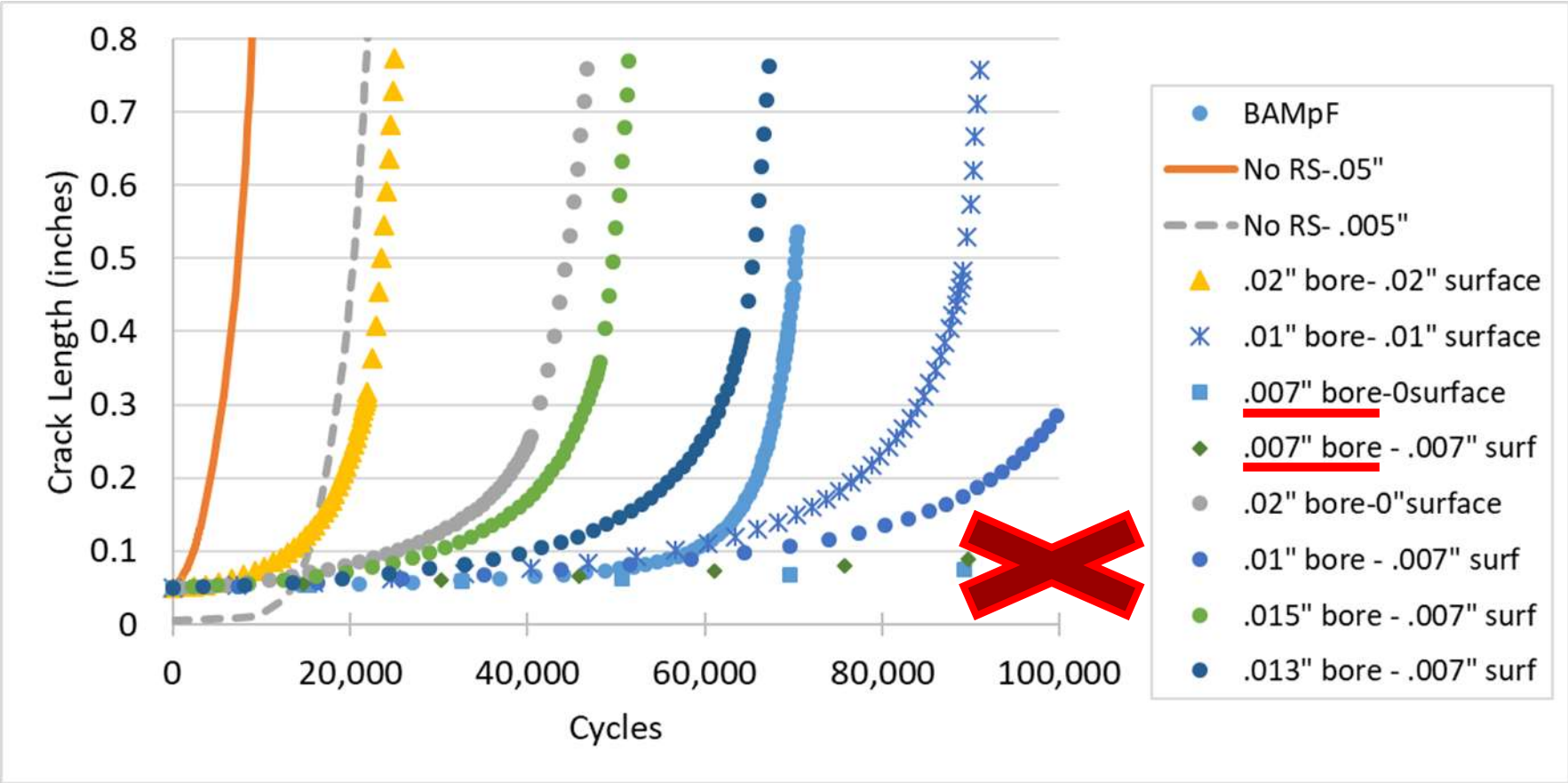
Case 3 – All Predictions

- t = 0.25”
- D = 0.25”
- e = 2”



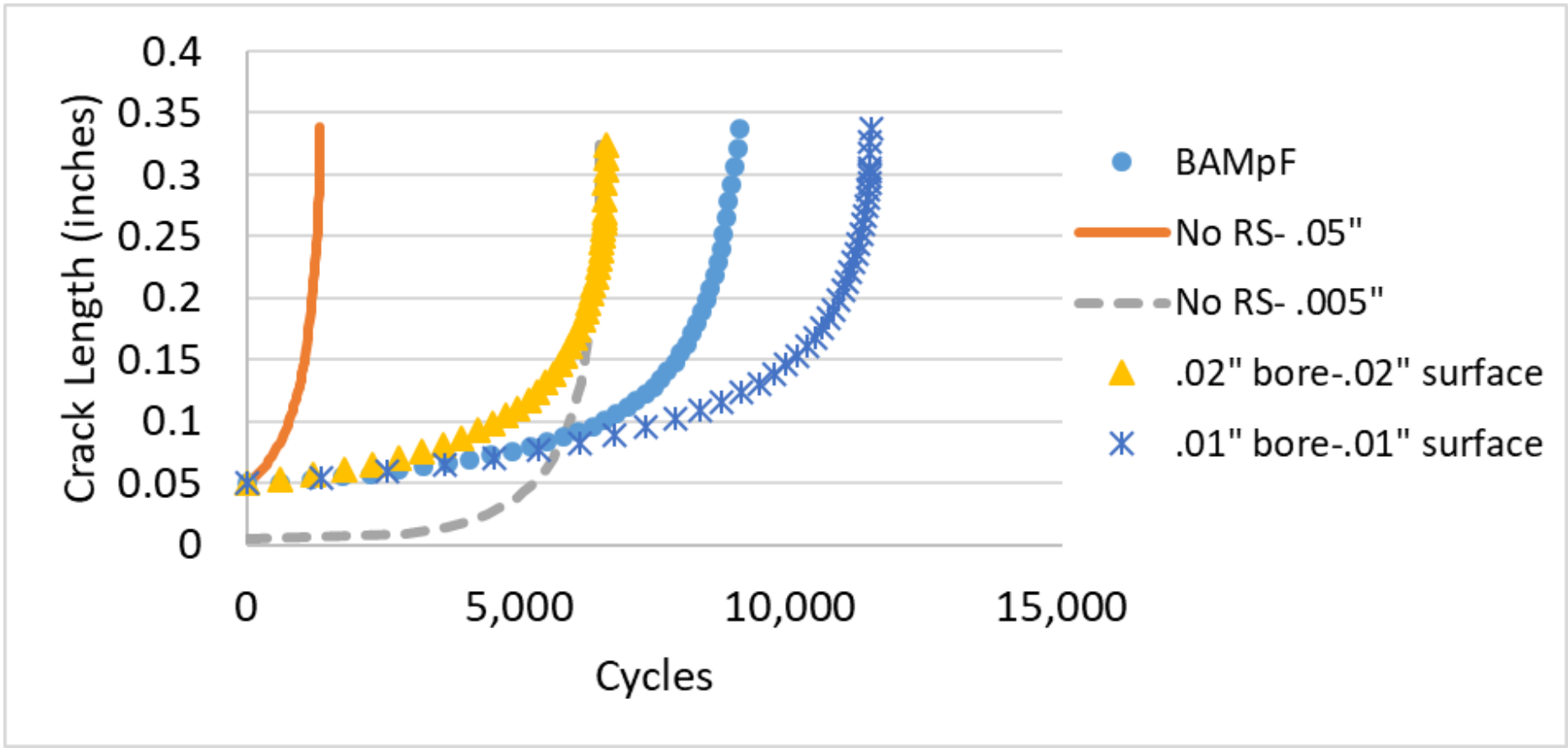
Observation – .007” bore offset

- .007” bore offset is too little, can result in excessively long life



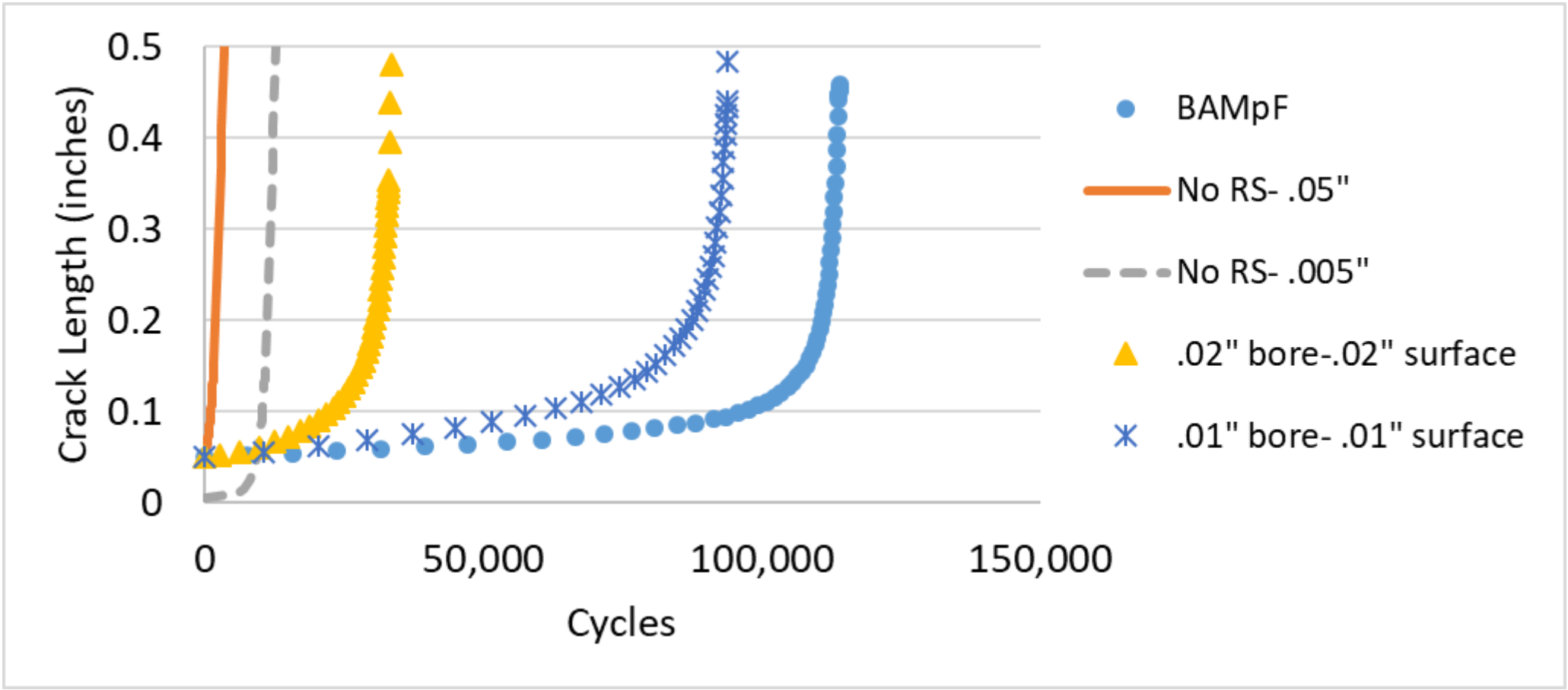
Case 4

- t = 0.25”
- D = 0.5”
- e = 0.6”



Case 7

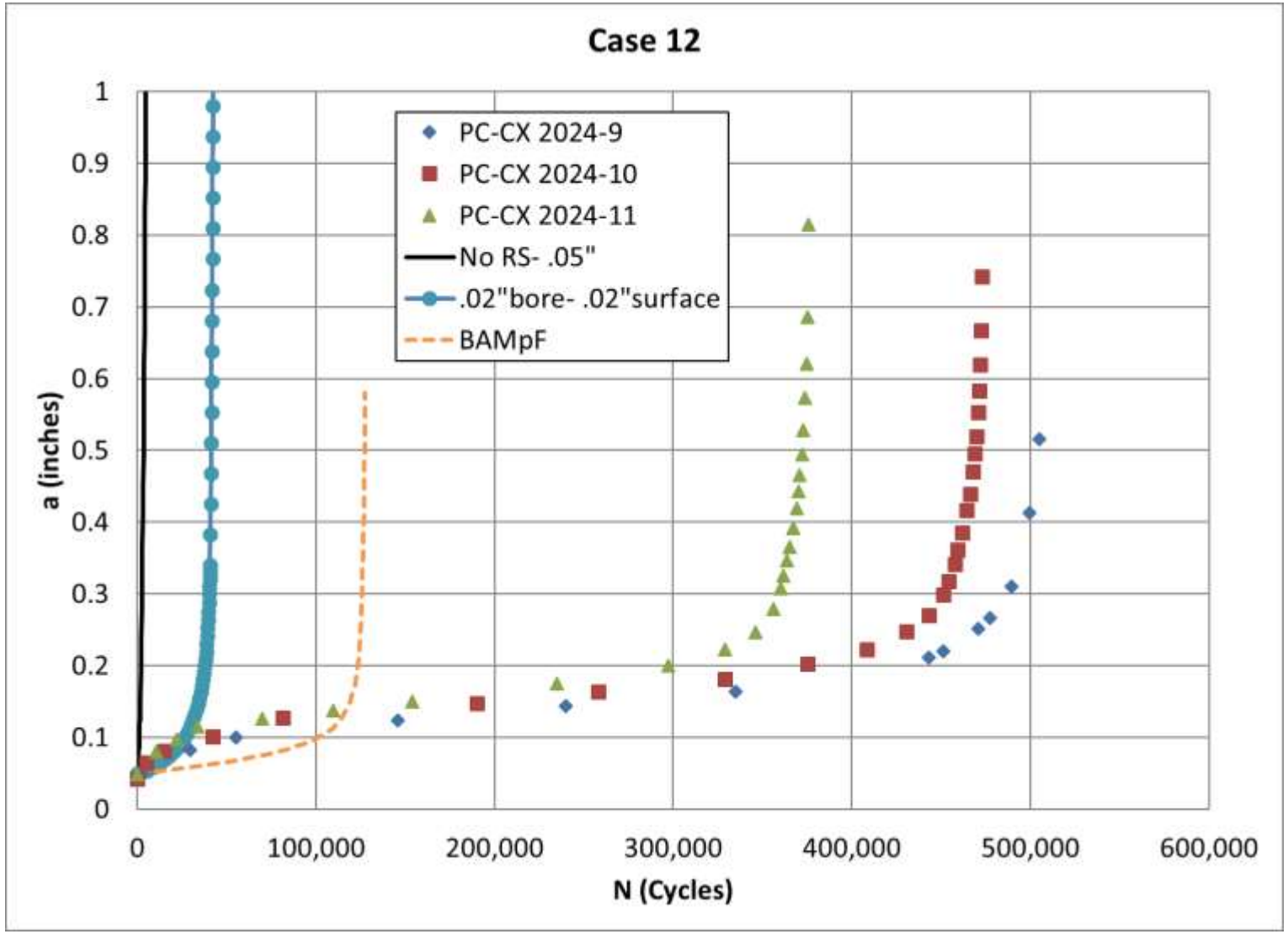
- t = 0.25”
- D = 0.5”
- e = 2”



Case 12 – Historical Validation Tests

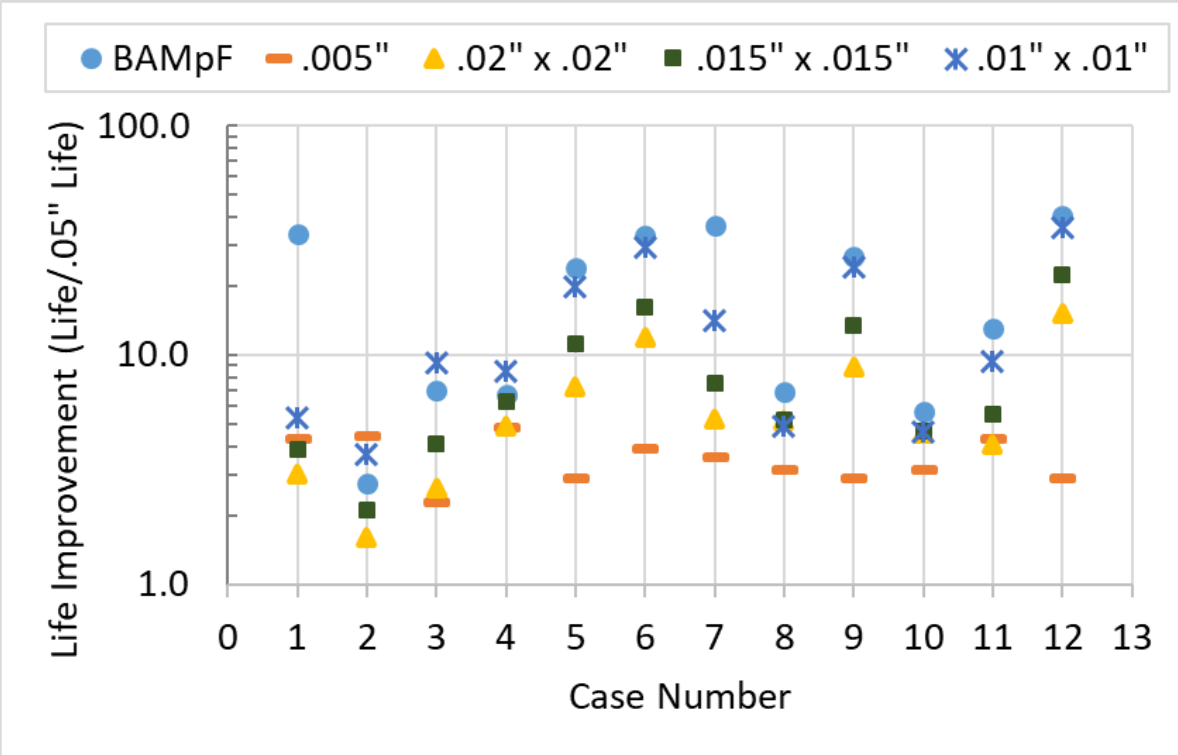
- t = 0.25”
- D = 0.5”
- e = 2”
- 3.5% CX

- Tests pre-cracked prior to cold expansion
- Some validation for comparing other cases to BAMpF



All Cases Summary

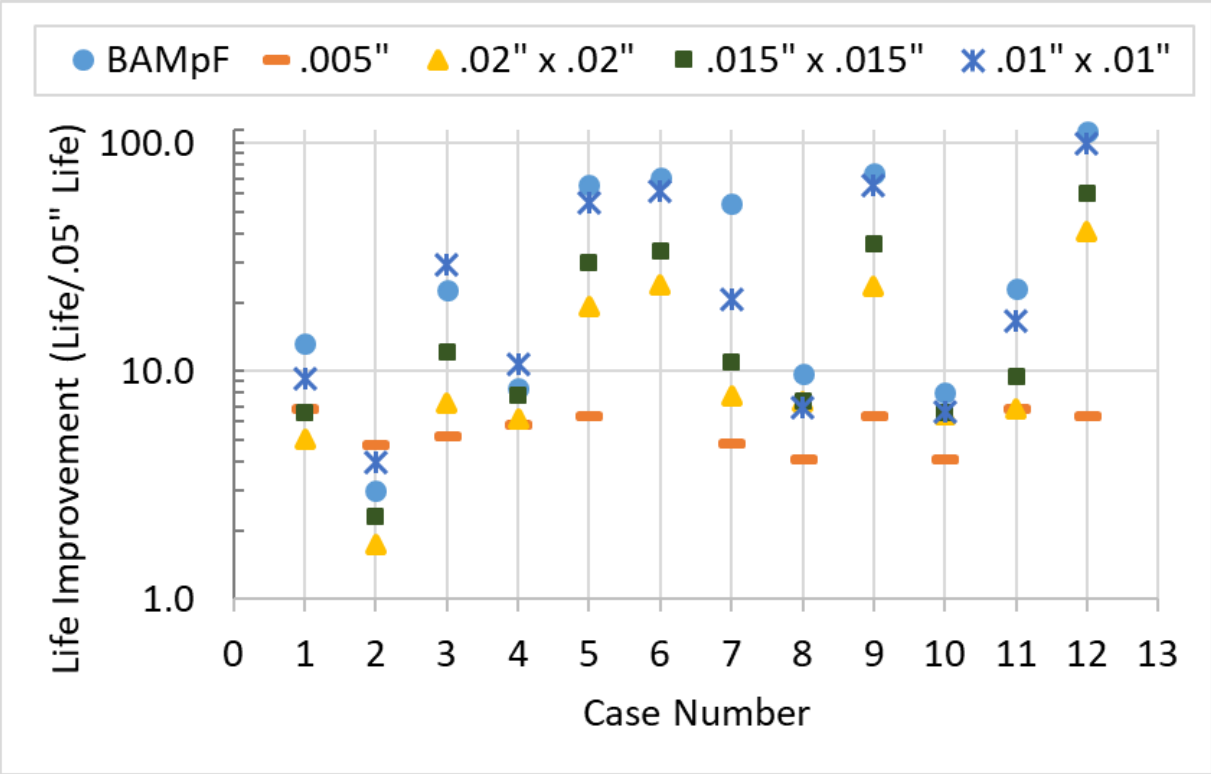
- .015” bore and surface offset conservative for all cases
- .01” bore and surface offset over predicted 4 cases
  - .012” offset conservative for 3 of those cases
- Plot and table are for surface direction



LIF	BAMpF	.005"	.02" x .02"	.015" x .015"	.01" x .01"
Case1	33.9	4.3	3.0	3.9	5.3
Case2	2.7	4.5	1.6	2.1	3.7
Case3	7.0	2.3	2.6	4.1	9.2
Case4	6.8	4.8	4.9	6.2	8.5
Case7	23.8	2.9	7.2	11.2	19.9
Case8	33.3	3.9	11.9	16.2	29.6
Case9	36.8	3.6	5.3	7.5	14.1
Case10	6.9	3.2	5.2	5.2	4.9
Case12	26.7	2.9	8.9	13.5	24.0
Case14	5.7	3.2	4.6	4.7	4.6
Case15	13.0	4.3	4.1	5.5	9.4
Case17	40.4	2.9	15.1	22.2	36.0

All Cases Summary – Bore Direction

- Trends for bore direction match the surface direction
- Same cases that over predicted surface benefit over predicted bore benefit



Bore LIF	BAMpF	.005"	.02" x .02"	.015" x .015"	.01" x .01"
Case1	13.1	6.9	5.0	6.6	9.2
Case2	3.0	4.7	1.7	2.3	4.0
Case3	22.5	5.2	7.2	12.1	29.2
Case4	8.5	5.8	6.1	7.8	10.7
Case7	65.9	6.3	19.2	30.0	54.4
Case8	71.0	0.0	23.8	33.4	61.9
Case9	54.0	4.8	7.7	11.0	20.6
Case10	9.7	4.1	7.3	7.3	6.9
Case12	73.5	6.3	23.6	36.3	65.4
Case14	8.1	4.1	6.5	6.6	6.6
Case15	22.9	6.9	6.8	9.4	16.5
Case17	112.0	6.3	40.9	60.6	98.9

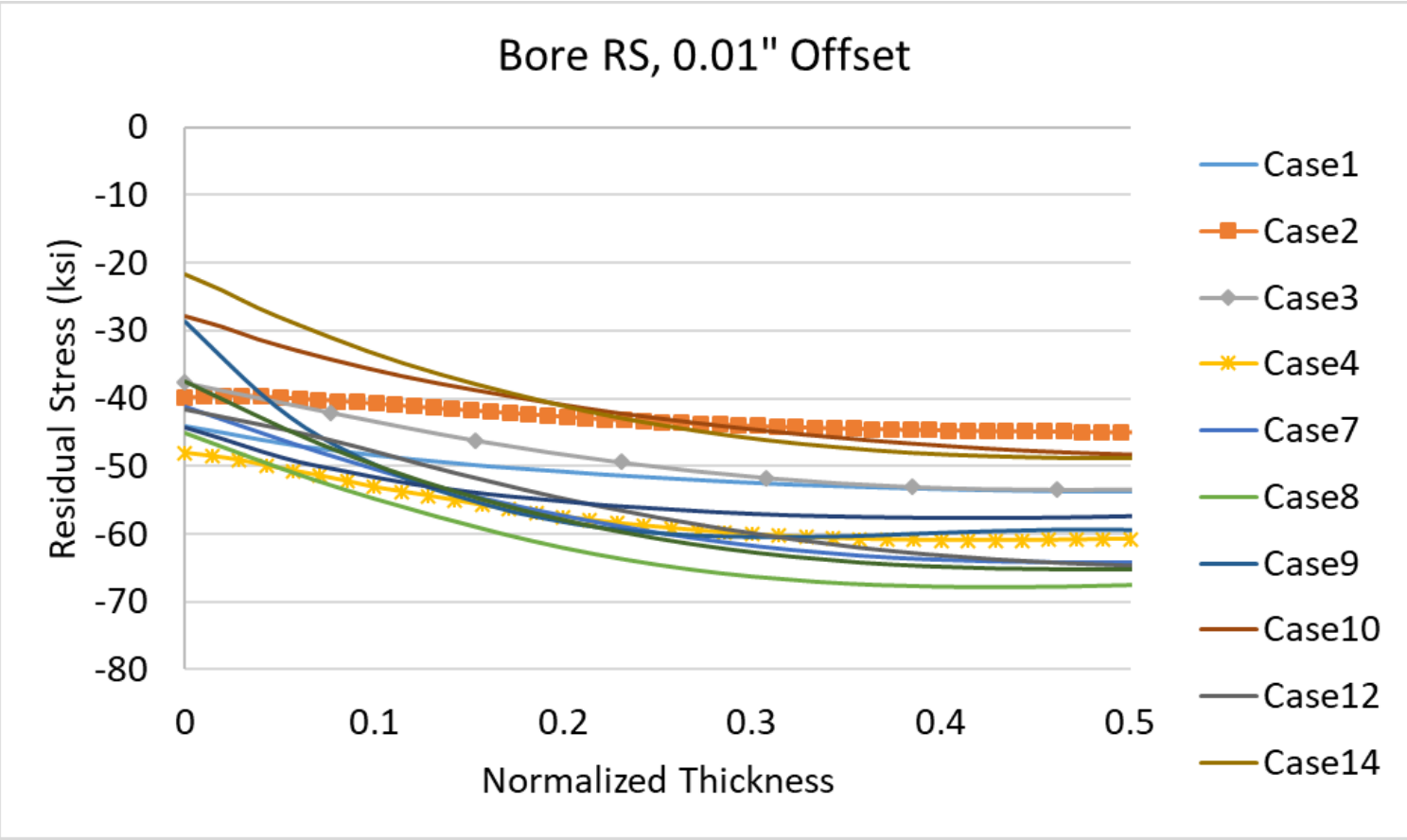
Over Predicted Cases With .01” Offset

- **No apparent geometry commonality for .01” offset being unconservative**

	%CX	Thickness	Diameter	Edge Distance	e/D
Case1	3	0.19	0.375	0.5625	1.5
Case2	3	0.25	0.25	0.3	1.2
Case3	3	0.25	0.25	2	8
Case4	3	0.25	0.5	0.6	1.2
Case7	3	0.25	0.5	2	4
Case8	3	0.25	0.75	2	2.67
Case9	3	0.313	0.375	0.675	1.8
Case10	3	0.5	0.5	1.2	2.4
Case12	3.5	0.25	0.5	2	4
Case14	3.5	0.5	0.5	1.2	2.4
Case15	4	0.19	0.375	0.5625	1.5
Case17	4	0.25	0.5	2	4

.01” Offset, RS Comparisons

- Case 2 has a nearly constant thru thickness RS
- Case 3 follows trend of other cases
- Case 4 starts most compressive, remains highly compressive



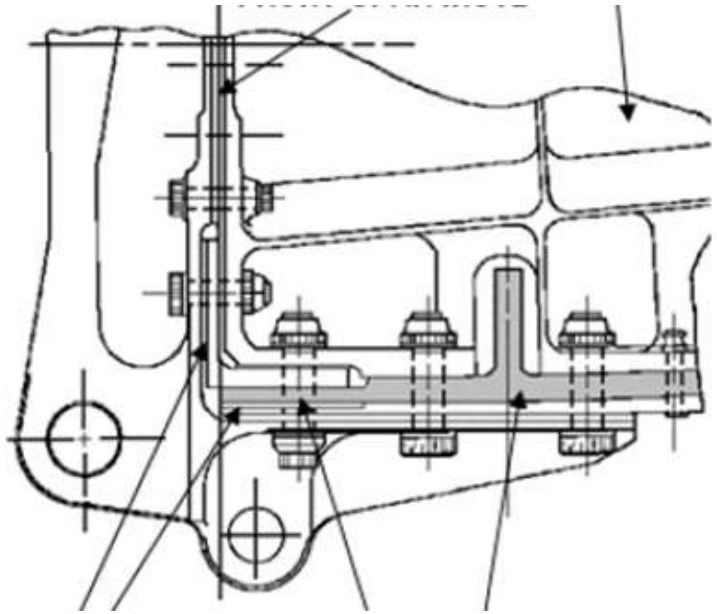
Study Summary

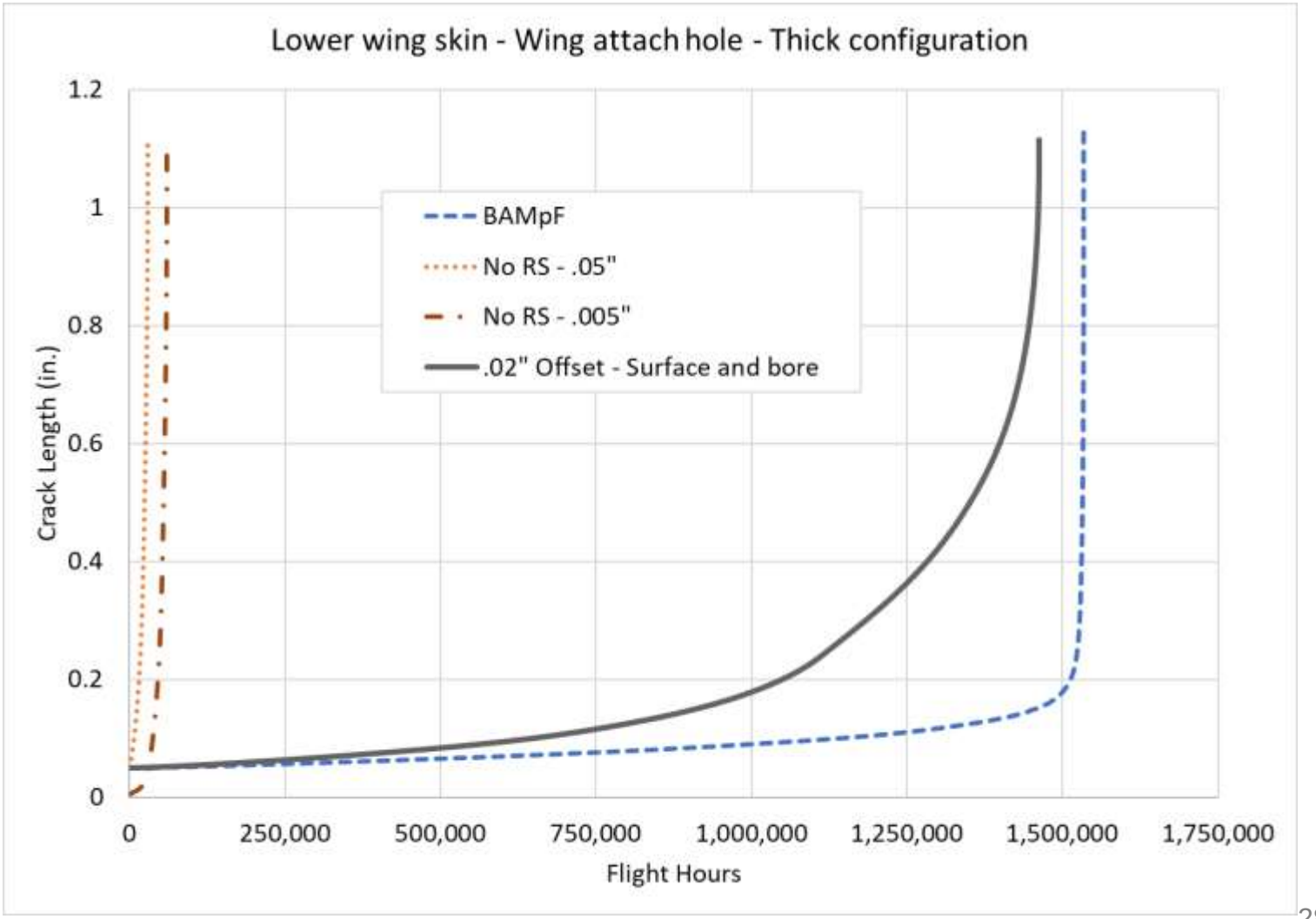
- .01” x .01” offset appears to work quite well, though not always conservative compared to BAMpF
- .02” x .02’ offset always conservative, though significantly under predicts benefit for many cases
- .015” x .015” offset always conservative, still under predicts many cases significantly

- This was all constant amplitude, does spectrum perform similarly?

HE Assessment Revisited

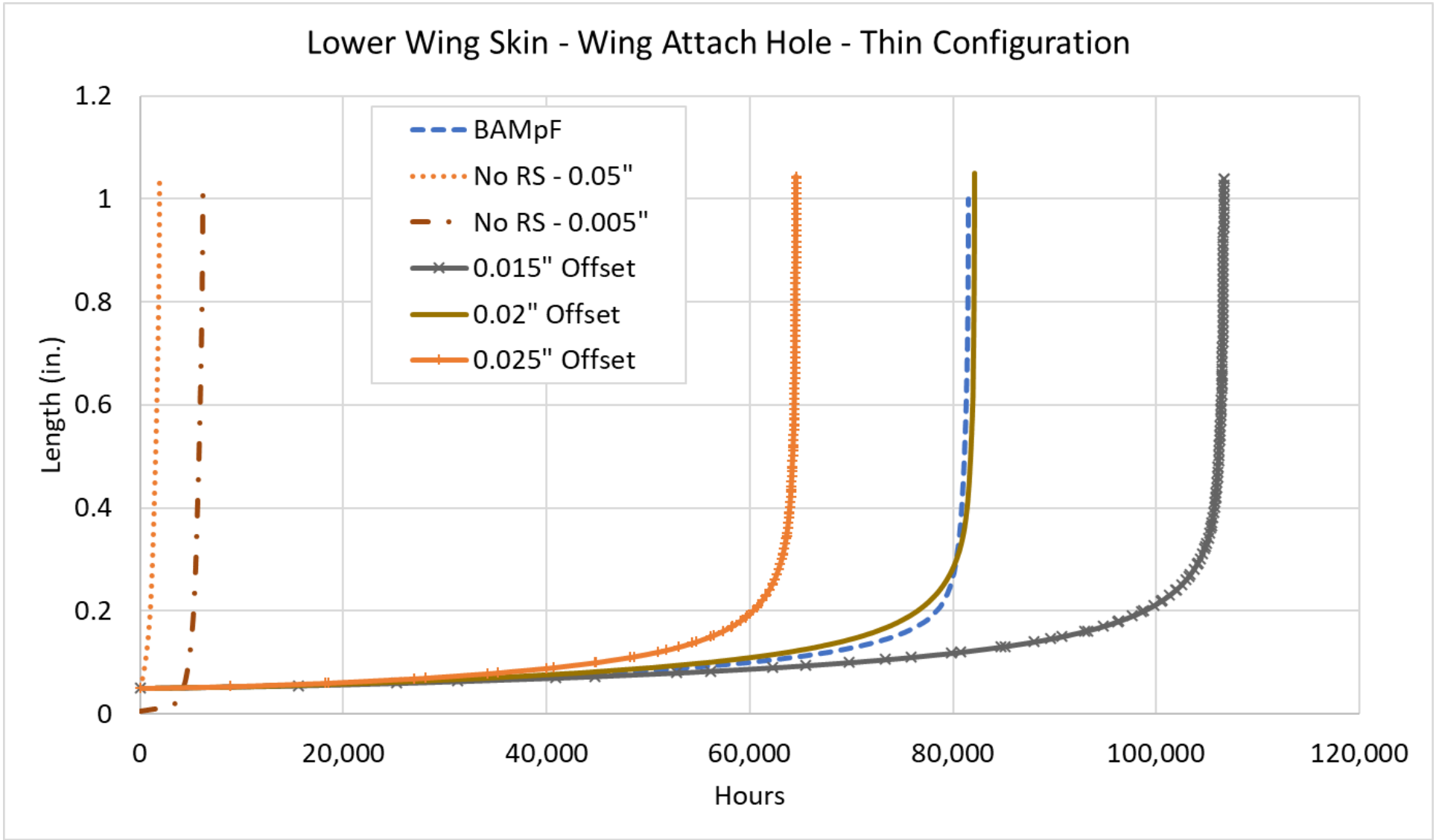
- Evaluate .02” offset for HE analyses of A-10 CPs
- No retardation used
  - With or without RS





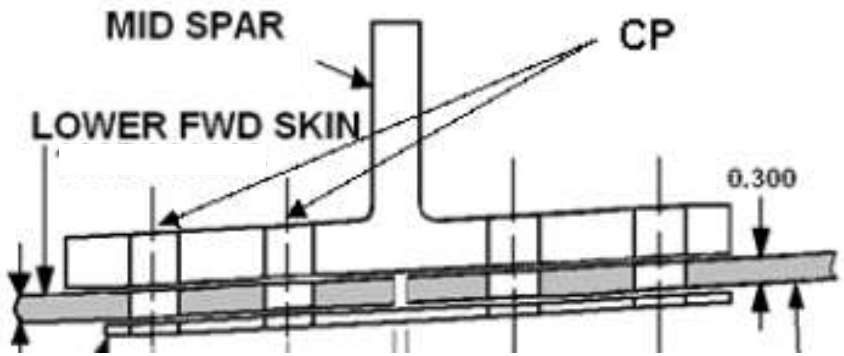
HE Assessment Revisited (2 of 3)

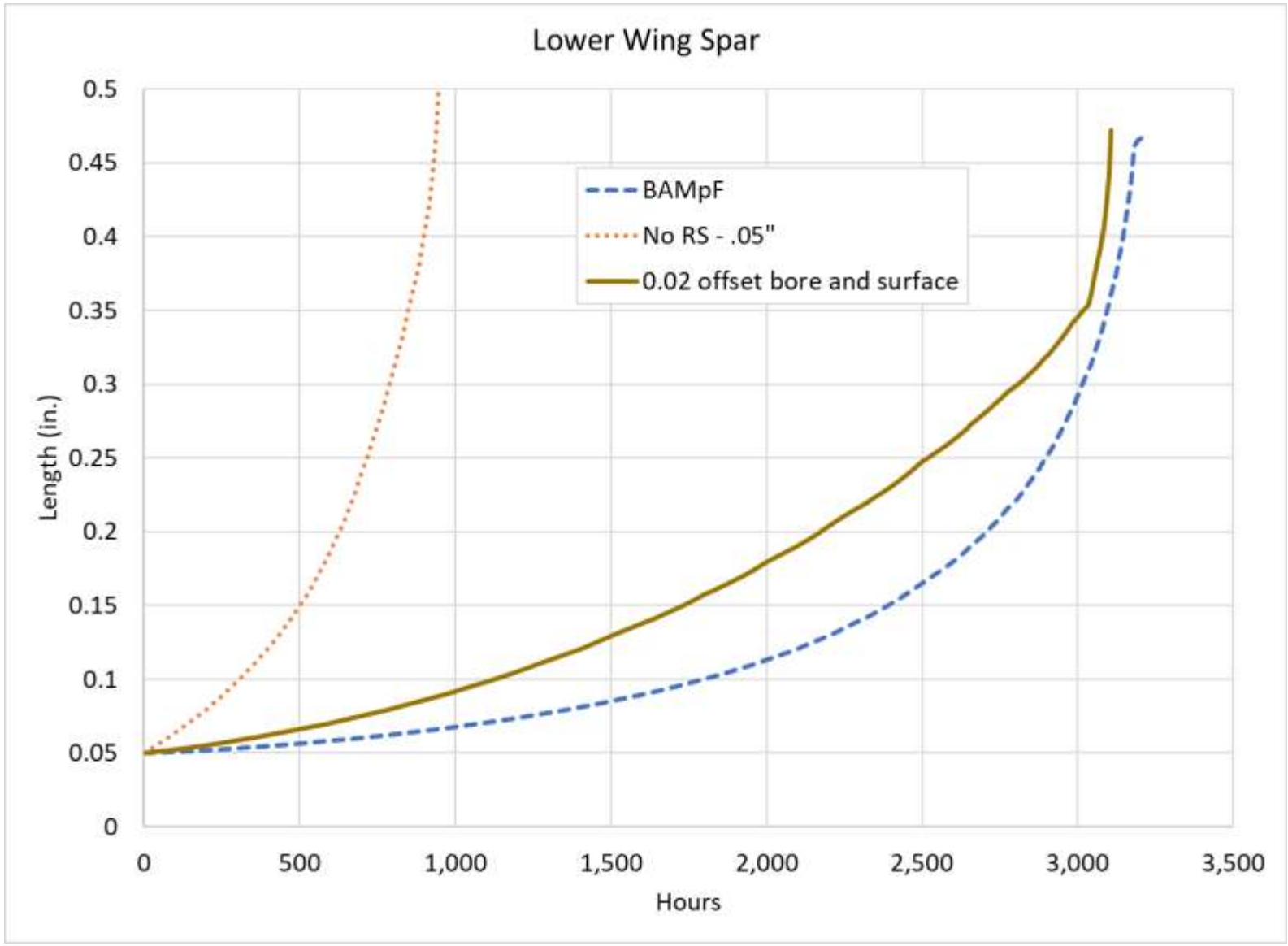
- Thin skin
  - .015” offset over predicts
  - .02” offset matches well



HE Assessment Revisited (3 of 3)

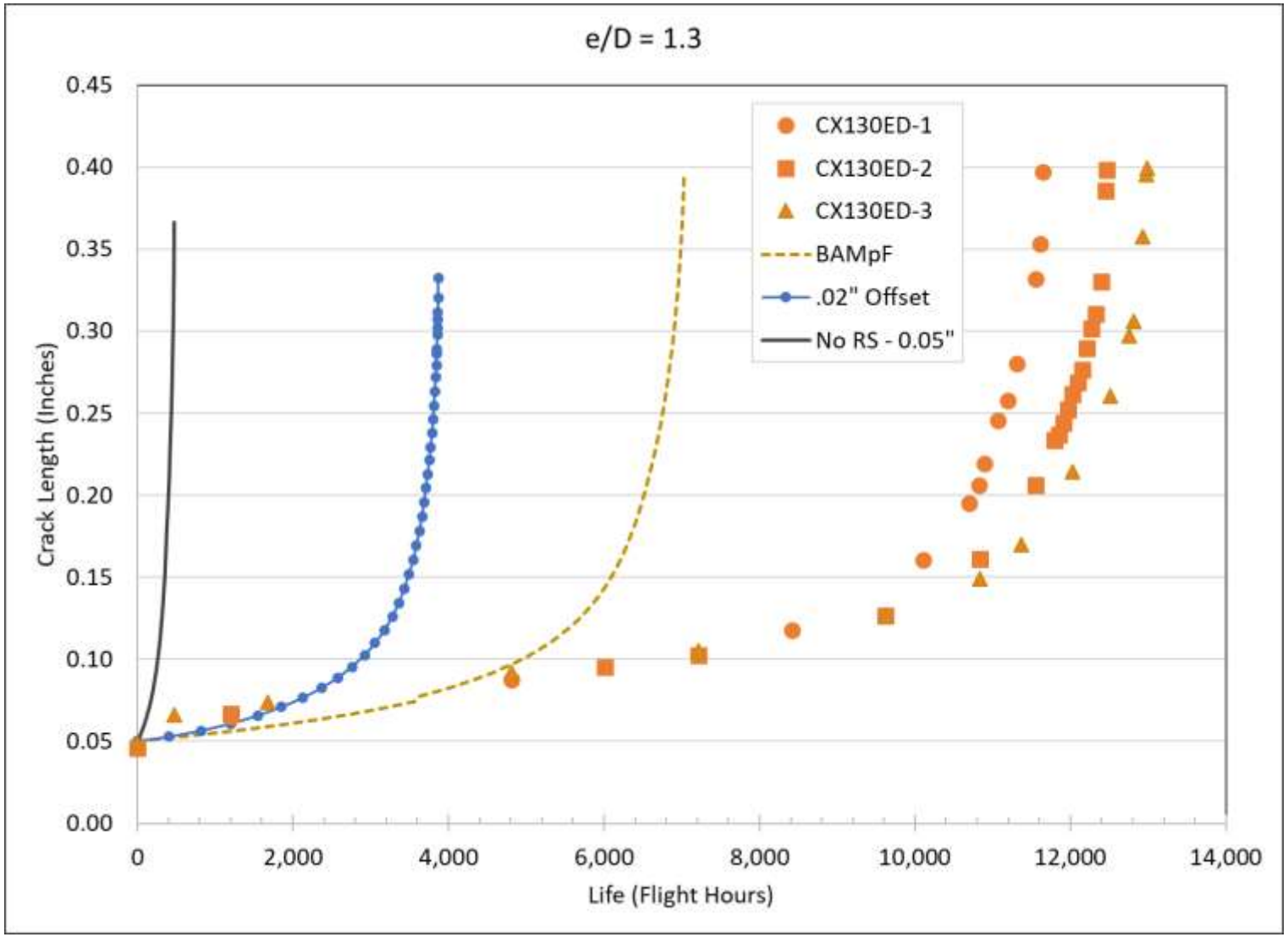
- Lower wing spar to skin joint
- 0.02” offset shows good agreement





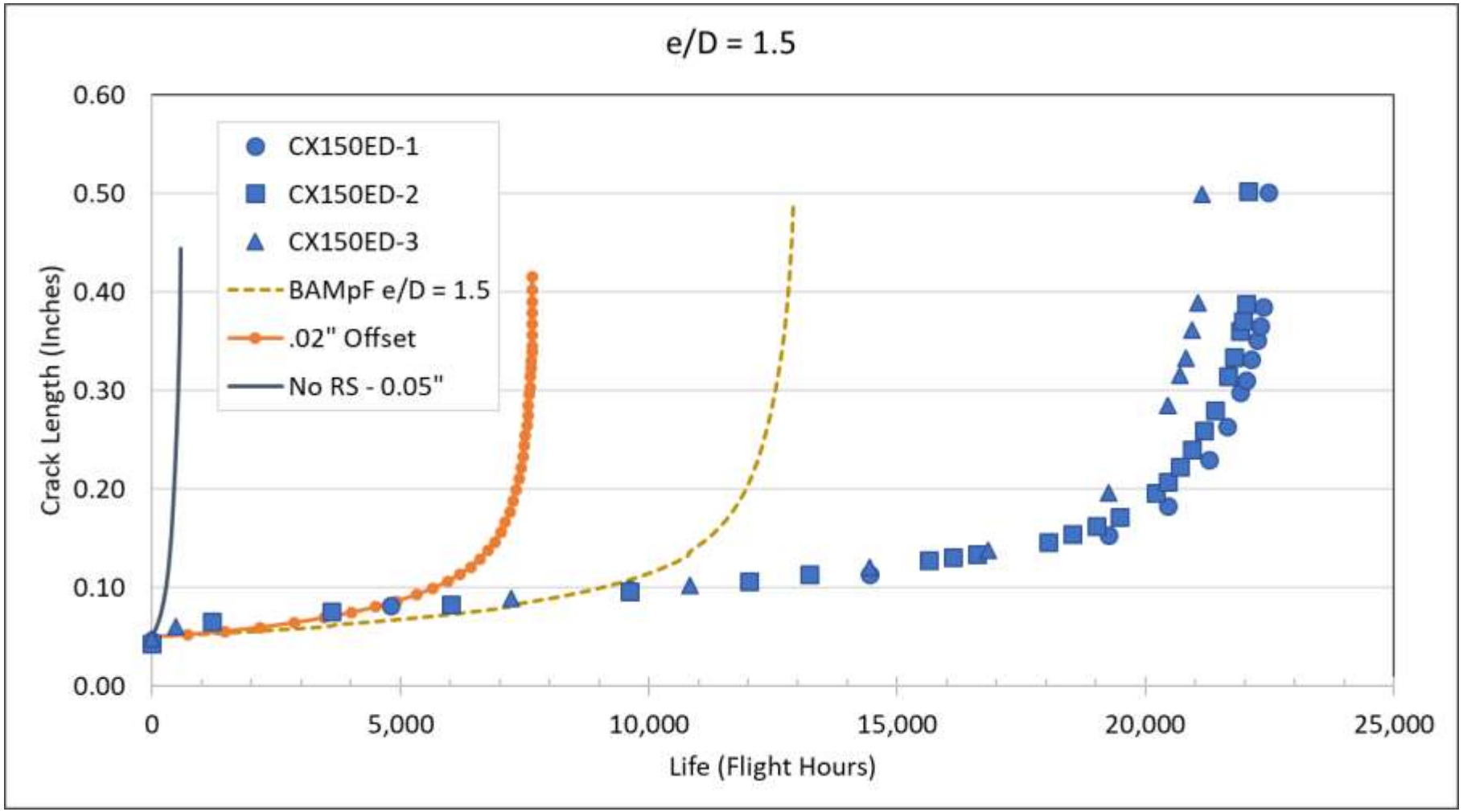
Evan Ross Thesis Data

- t = .25”
- D = .5”
- e = 0.65”
- e/D = 1.3
- Wing root spectrum
- 33 ksi max stress



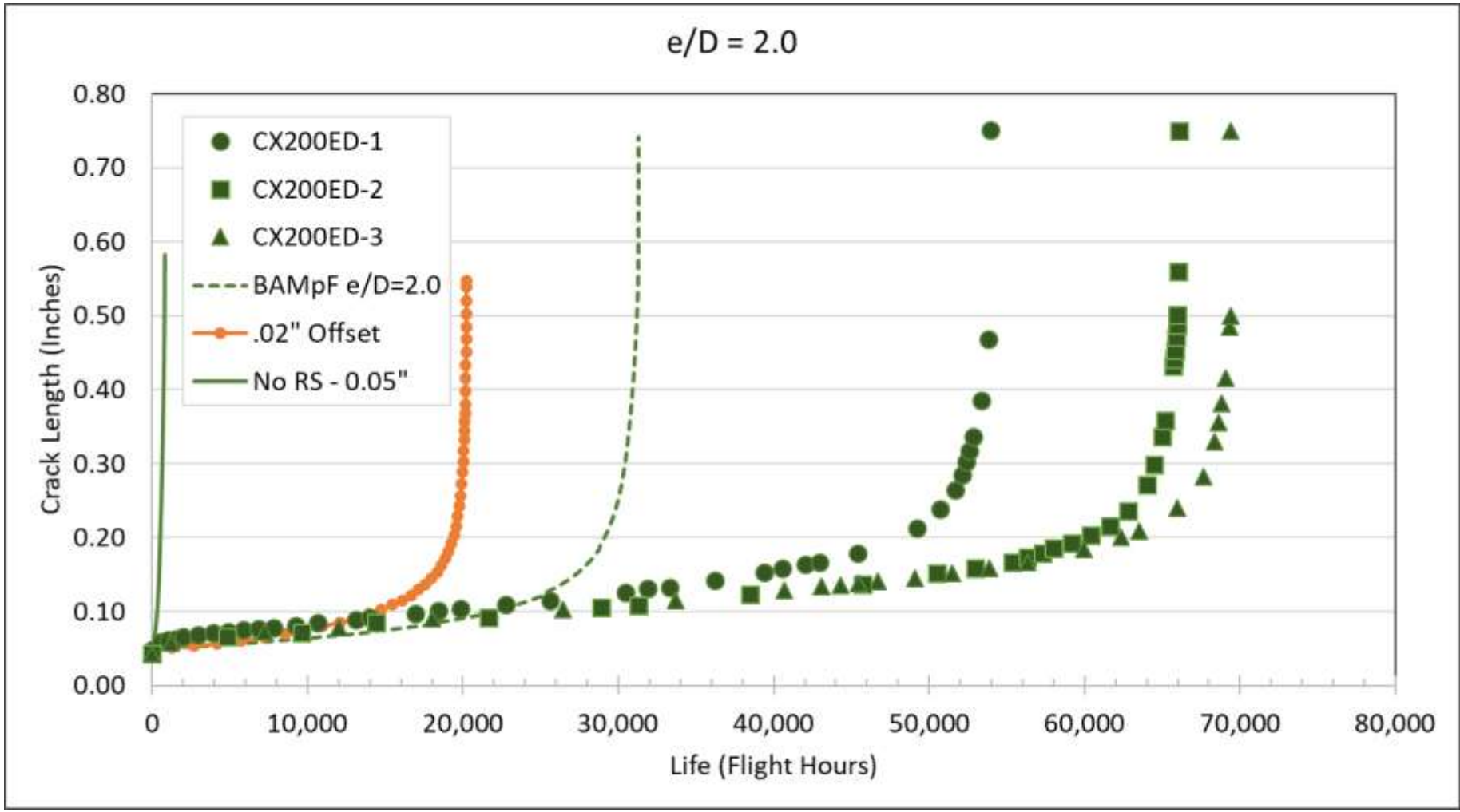
Evan Ross Thesis Data (2 of 3)

- t = .25”
- D = .5”
- e = .75”
- e/D = 1.5
- Wing root spectrum
- 33 ksi max stress



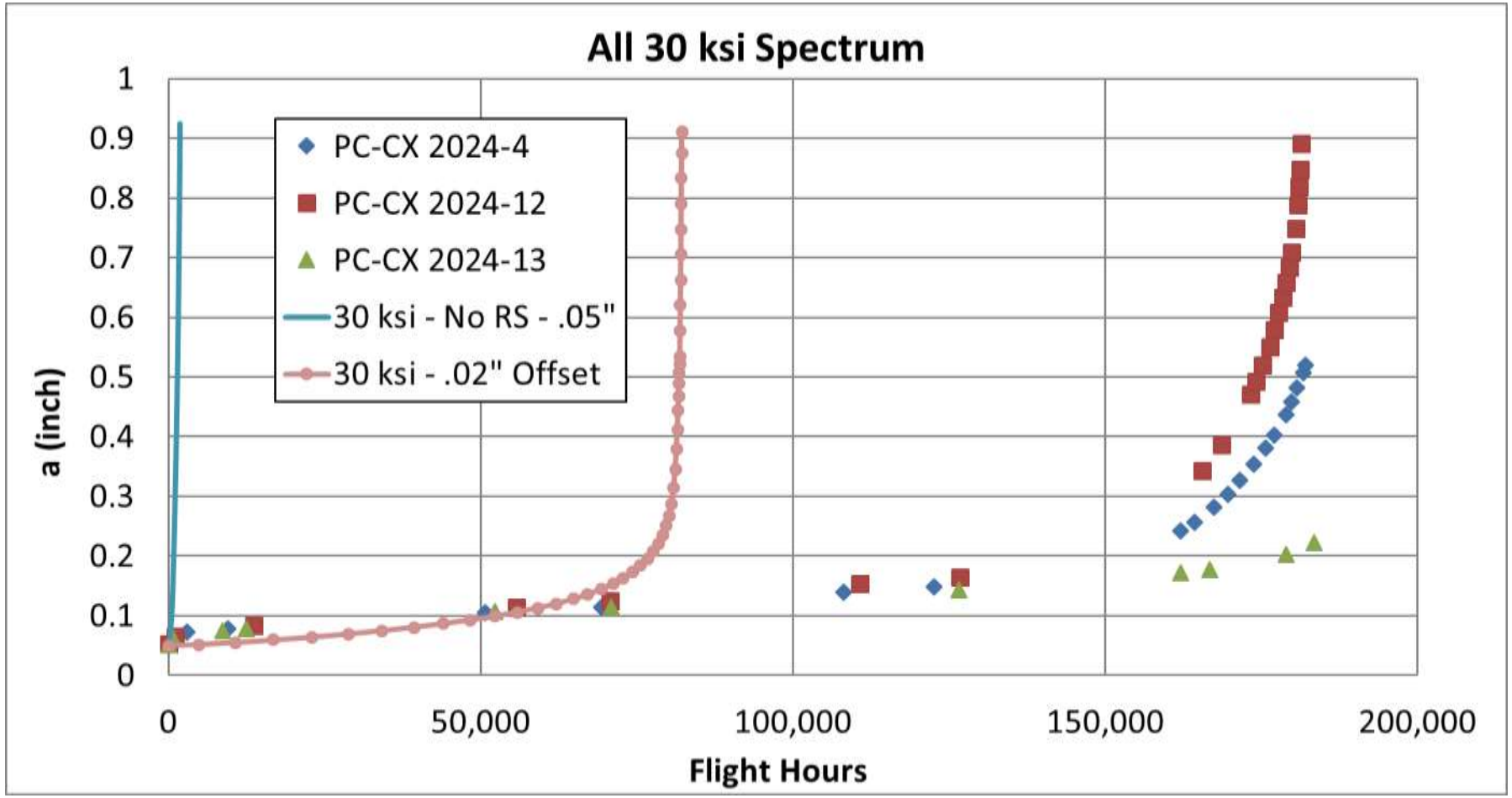
Evan Ross Thesis Data (3 of 3)

- t = .25”
- D = .5”
- e = 1”
- e/D = 2
- Wing root spectrum
- 33 ksi max stress



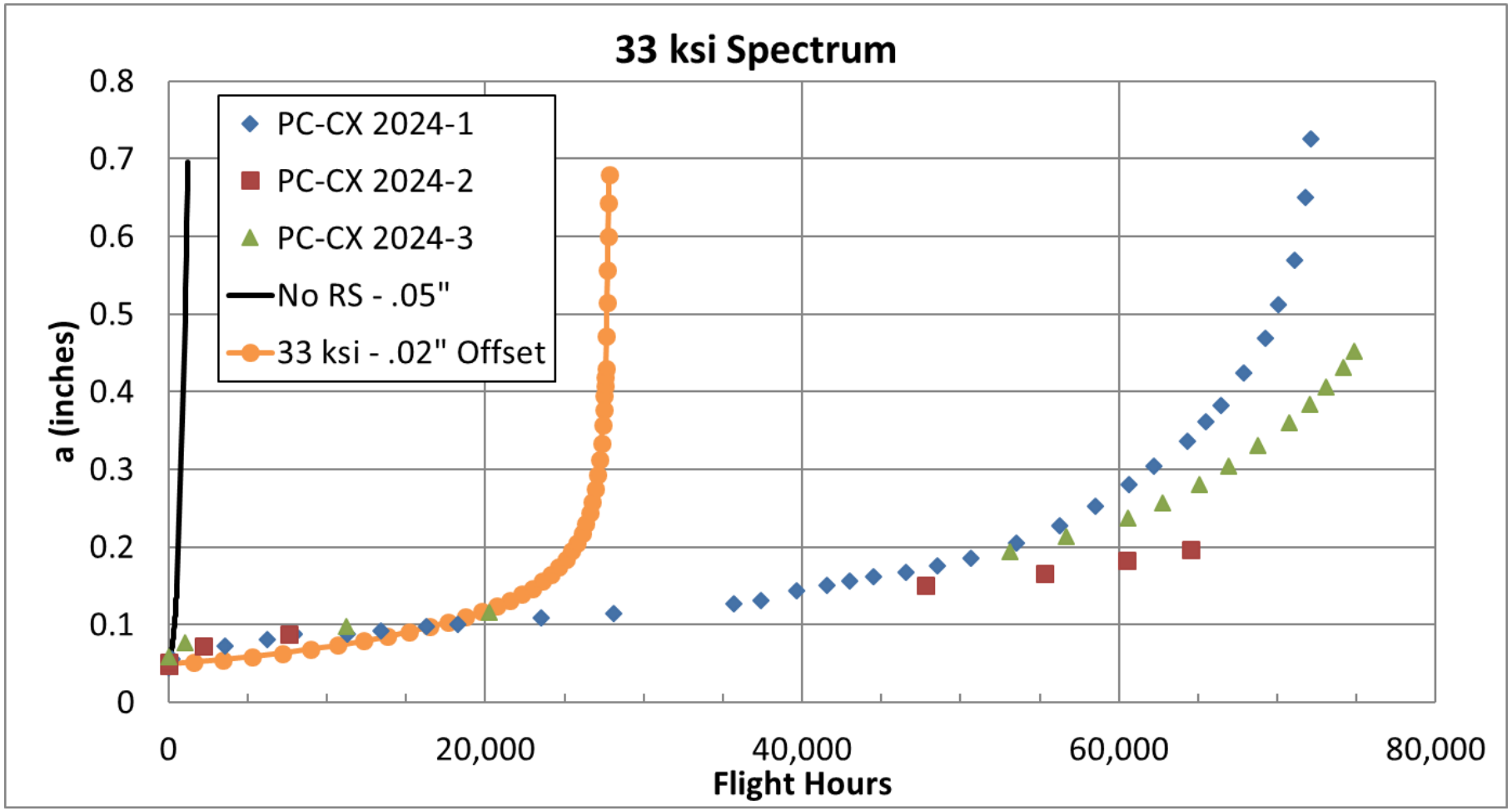
Center Hole Test Data

- t = .25”
- D = .5”
- e = 1”
- e/D = 2
- Wing root spectrum
- 30 ksi max stress



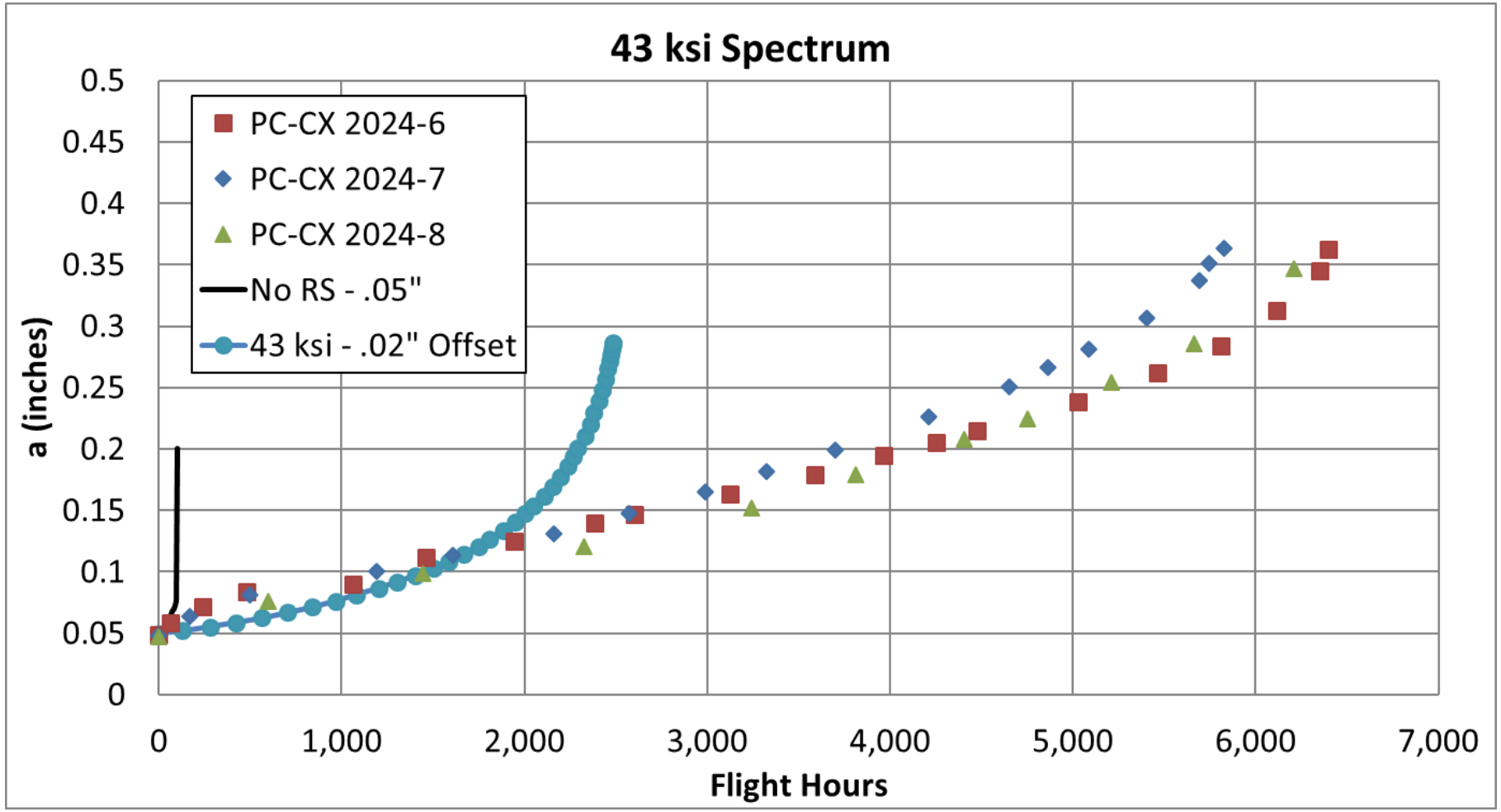
Center Hole Test Data (2 of 3)

- t = .25”
- D = .5”
- e = 1”
- e/D = 2
- Wing root spectrum
- 33 ksi max stress



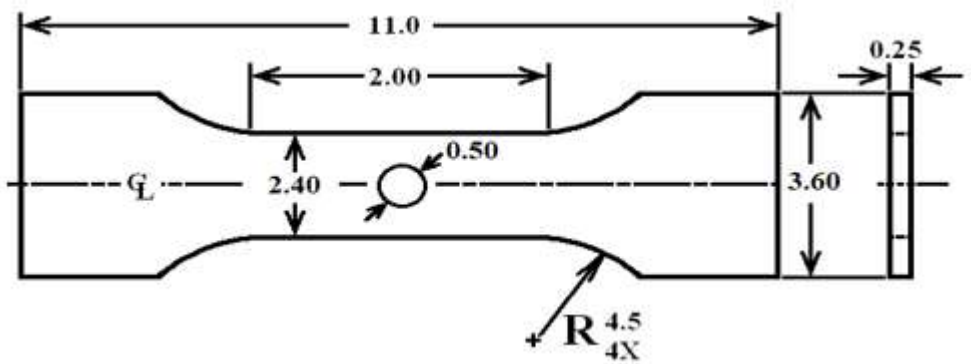
Center Hole Test Data (3 of 3)

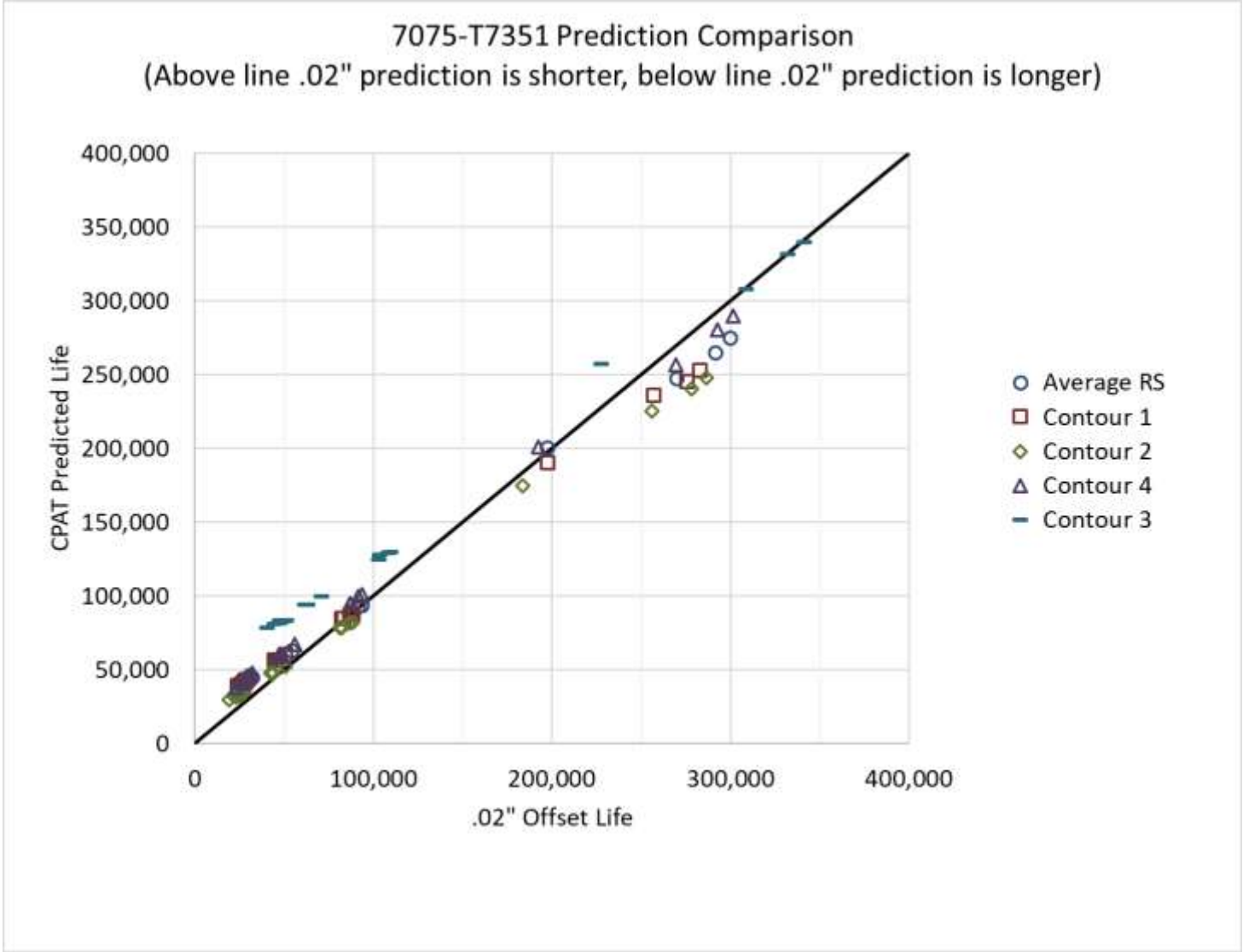
- t = .25”
- D = .5”
- e = 1”
- e/D = 2
- Wing root spectrum
- 43 ksi max stress



7075-T7351 Analysis

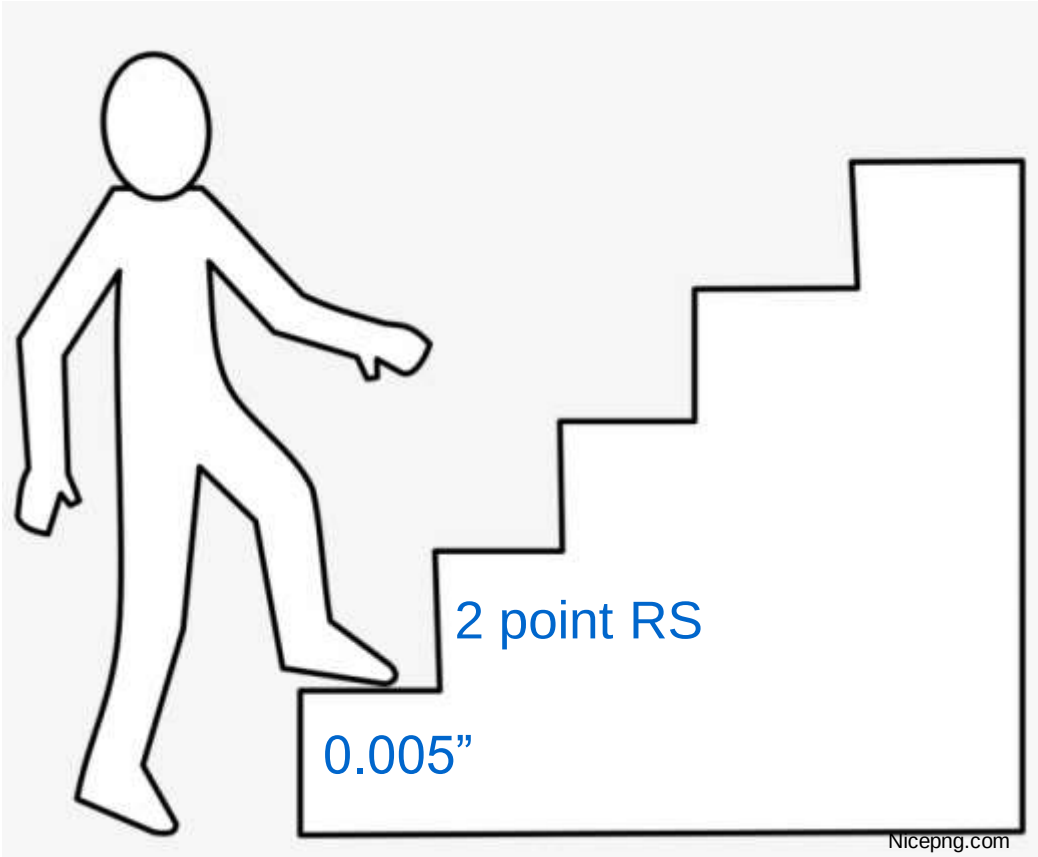
- 240 total predictions
- 27 ksi at R= 0.02, 0.1, 0.4, 0.6, 0.7, 0.8
- T = 0.25”, D = 0.5”, center hole
- 4 different starting crack lengths
- 5 different RS profiles





Conclusions

- 2 point analysis with RS is superior to 0.005” approach
  - Predicts significantly more benefit for most scenarios
  - Does not over predict for high stress, short e/D scenarios
- Study was limited to:
  - 2024-T351
    - Constant amplitude and spectrum loading
    - Multiple stress levels
    - Multiple geometries
  - 7075-T7351
    - 6 stress ratios
    - 4 starting crack lengths
    - 5 RS profiles



Recommendations

- Do not use vectors directly along surface, severely over predicts life
- Constant value offset performs better than parametric angle approach
- Recommend using 0.02” offset for bore and surface
  - Application specific validation recommended

- Future work:
  - Investigate mid thickness RS for surface direction
  - Investigate closed form solution to define RS field as a function of yield strength
  - Further studies to identify if 0.02” offset is best approach for more scenarios
  - Apply to additional materials

Questions?