



**U.S. AIR FORCE**

# Bearing Loaded Offset Holes

## Comparing Solutions Between AFGROW and StressCheck (BAMpF)

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# Abstract



The A-10 System Program Office (SPO) engineering team is continually working to modernize their analysis methods for fleet management. One aspect of this modernization effort is to account for the benefit of residual stress at a cold worked hole during fatigue life predictions. Currently this benefit is captured using 3D finite element solutions for stress intensity—utilizing StressCheck within the framework of the multi-point crack growth program known as BAMpF. As part of validating these BAMpF models, the A-10 SPO compares baseline AFGROW and BAMpF models (no residual stress) to ensure that the solutions between models match or are correlated in a predictable way. A recent observation during analysis noted that non-bearing loaded models usually compared well, but bearing loaded models had larger differences than expected. A study was conducted that compared solutions between AFGROW and BAMpF across a variety of plate widths and hole offsets to better understand where AFGROW and BAMpF bearing loaded models align or diverge. Additional investigations were made to propose underlying reasons for any observed divergence in solutions.



# Acknowledgements



- **Jake Warner (USAF)**
- **Joshua Hodges (Hill Engineering)**
- **Jim Harter (LexTech Inc)**
- **Adrian Loghin (Simmetrix)**



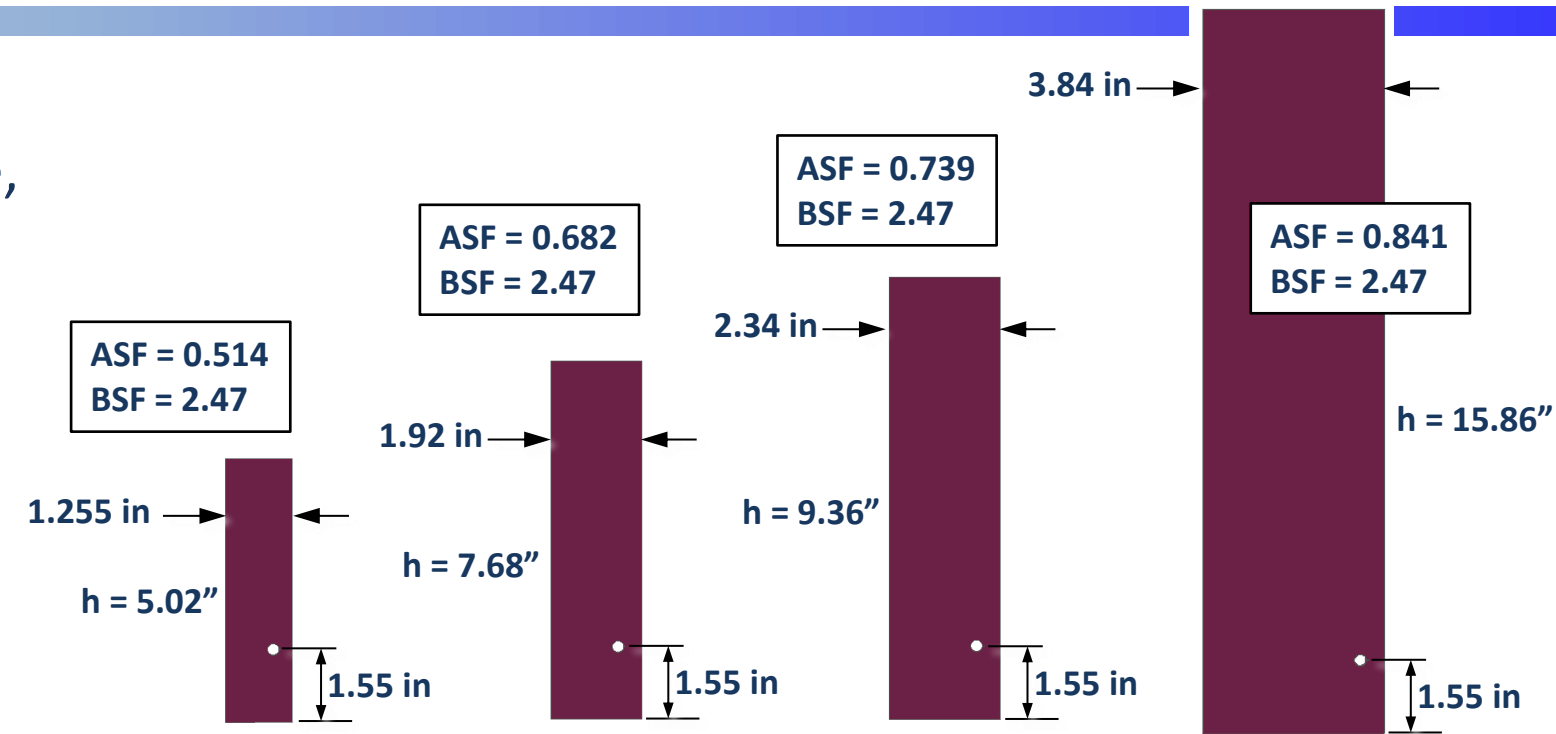
- **Motivation for Study**
- **Outline of Study: Range of Applicability, Assumptions, Etc**
- **Summary of %-Differences in Predicted Life (AFGROW vs BAMpF)**
- **Additional Investigations**
  - **“Infinite” Width Model(s)**
  - **SIF (Beta) Checks—Corner Crack and Thru-Crack**
  - **Plane Stress vs Plane Strain Assumptions**
- **Concluding Remarks**



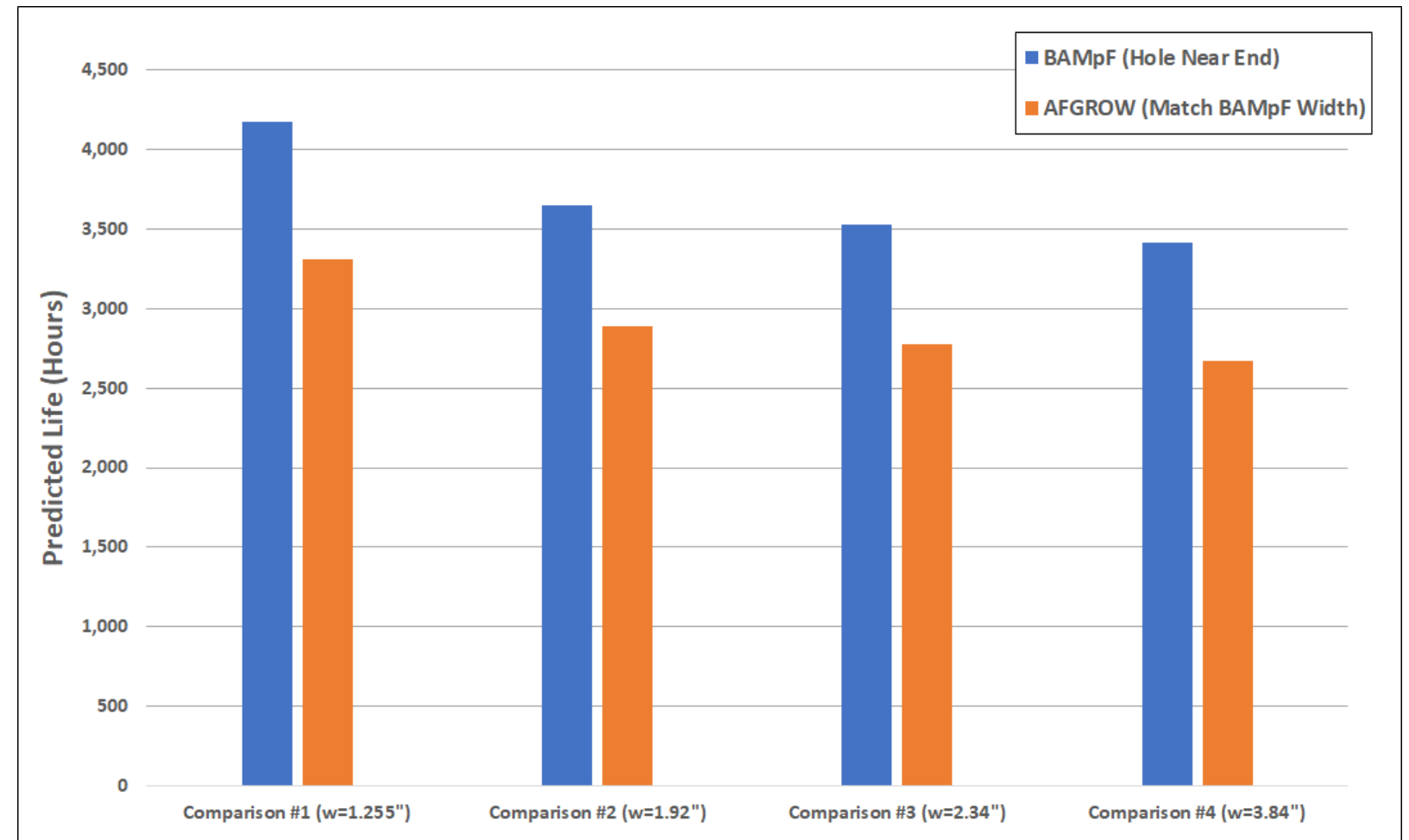
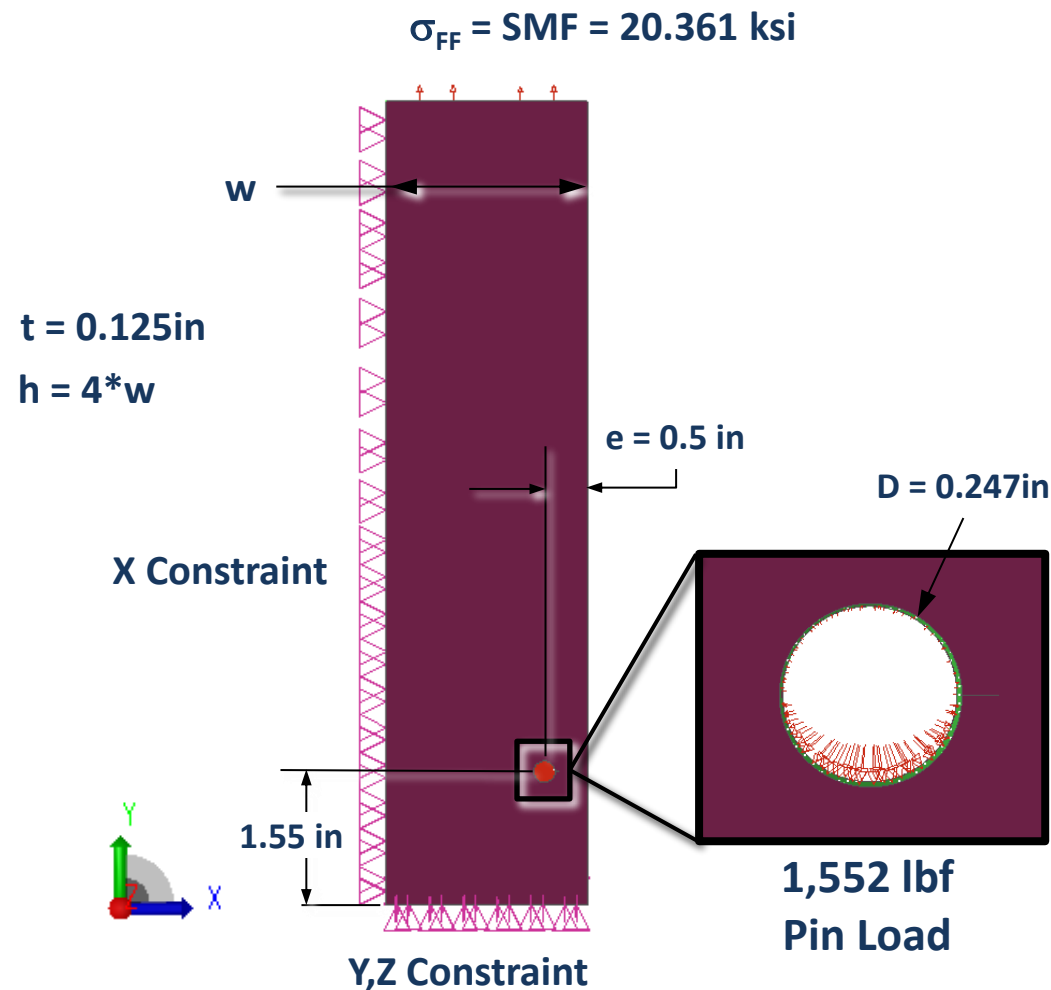
# Motivation for Study



**Background:** while trying to correlate a BAMpF model to an AFGROW solution for a plate having a bearing-loaded, offset hole, several different 3D FEA (StressCheck) models were built and compared to AFGROW models having the same width, thickness, material, hole offset, SMF, and BSF. ASF allowed to vary. In all these cases (shown on right), the crack growth life predicted by BAMpF was about 26%-27% higher than the AFGROW result.



## Typical StressCheck Model





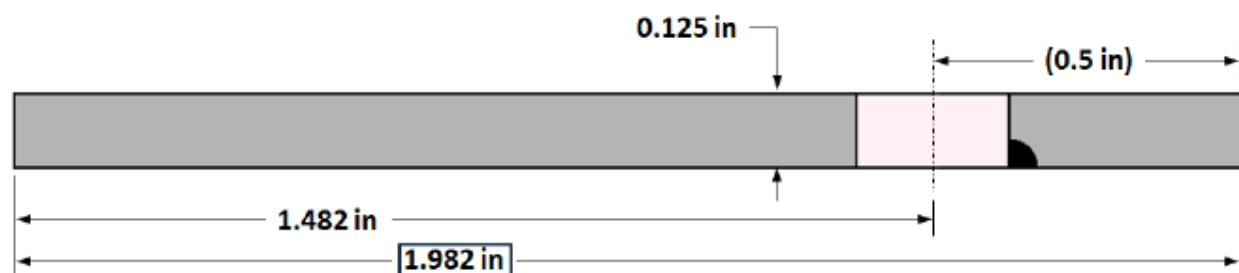


# Motivation for Study

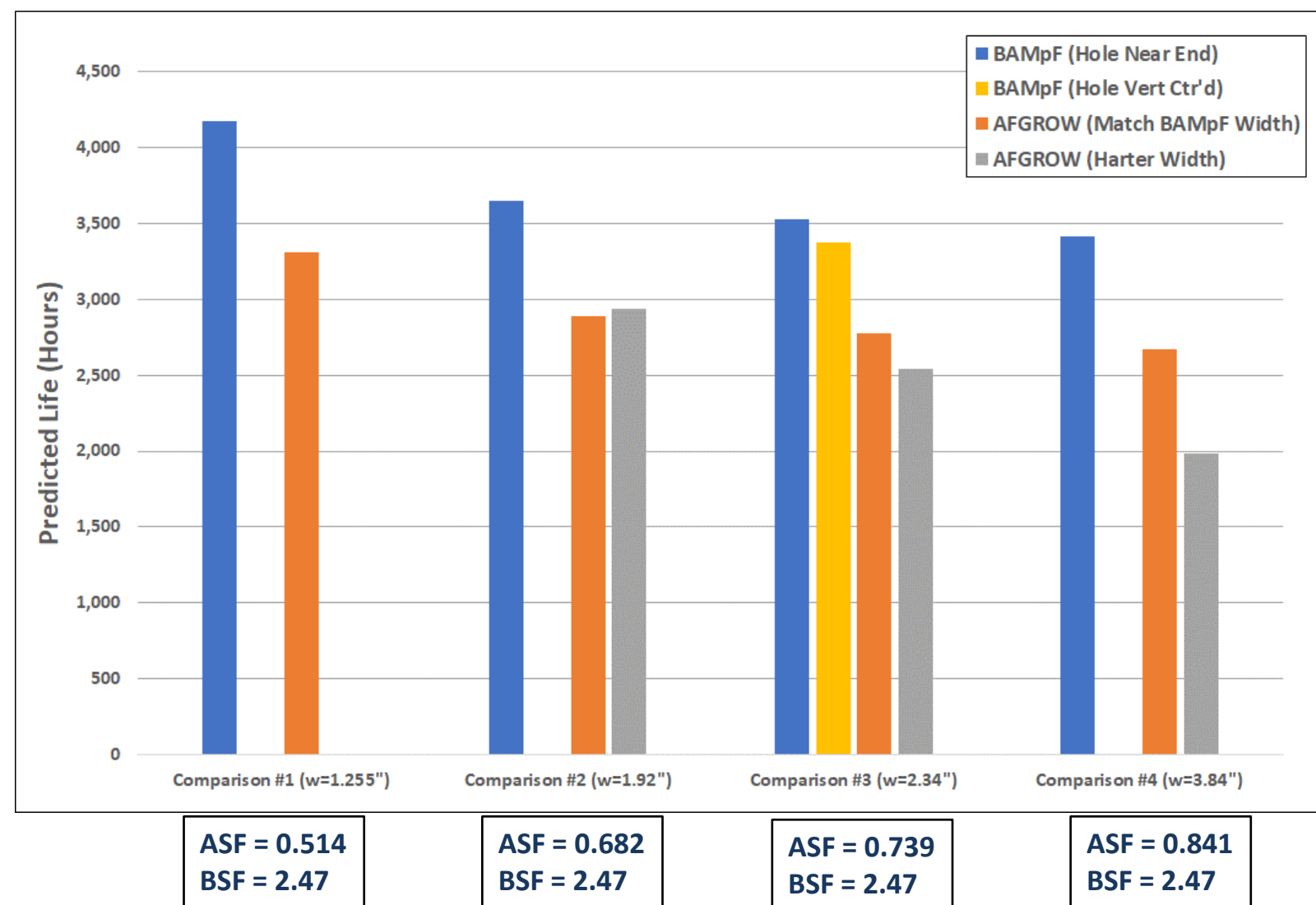
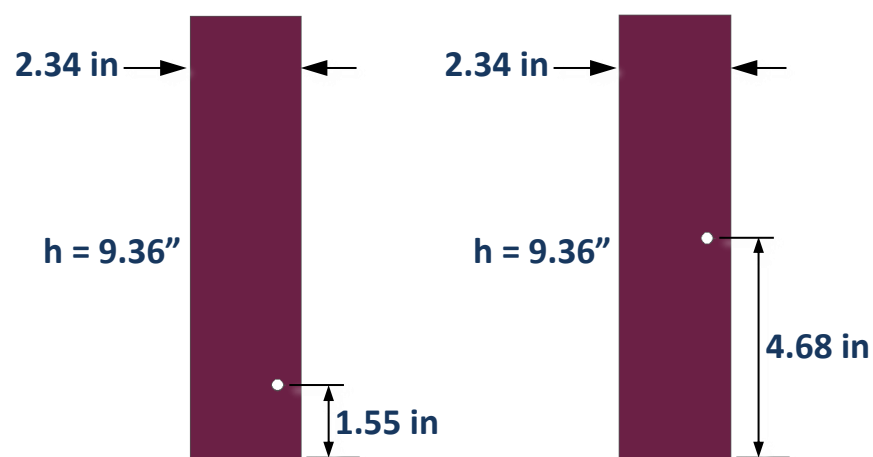
**Background (cont'd):** two different modifications, described below, were checked. However, neither improved the correlation between AFGROW and BAMpF.

- For applicable models, modify the width per recommendation in white paper “Modeling Bearing Load in Wide Panels Using AFGROW” by James A. Harter: “When modeling wide/offset plates with combined loads, it is therefore recommended to adjust the panel width so that the hole is not more than 6D from either edge.”

See grey-colored bars in chart



- Second, a BAMpF analysis was performed using a StressCheck FEM having the hole centered vertically to check for edge effect. See gold-colored bar.





# Outline of Study



- To limit size of the study, thickness ( $t$ ), hole diameter ( $d$ ), material, and load spectrum were held constant

- $t = 0.125''$
- $d = 0.25''$
- 7075-T6751 Aluminum
- A-10 Spectrum for CP 47
- SMF = 20 ksi\*

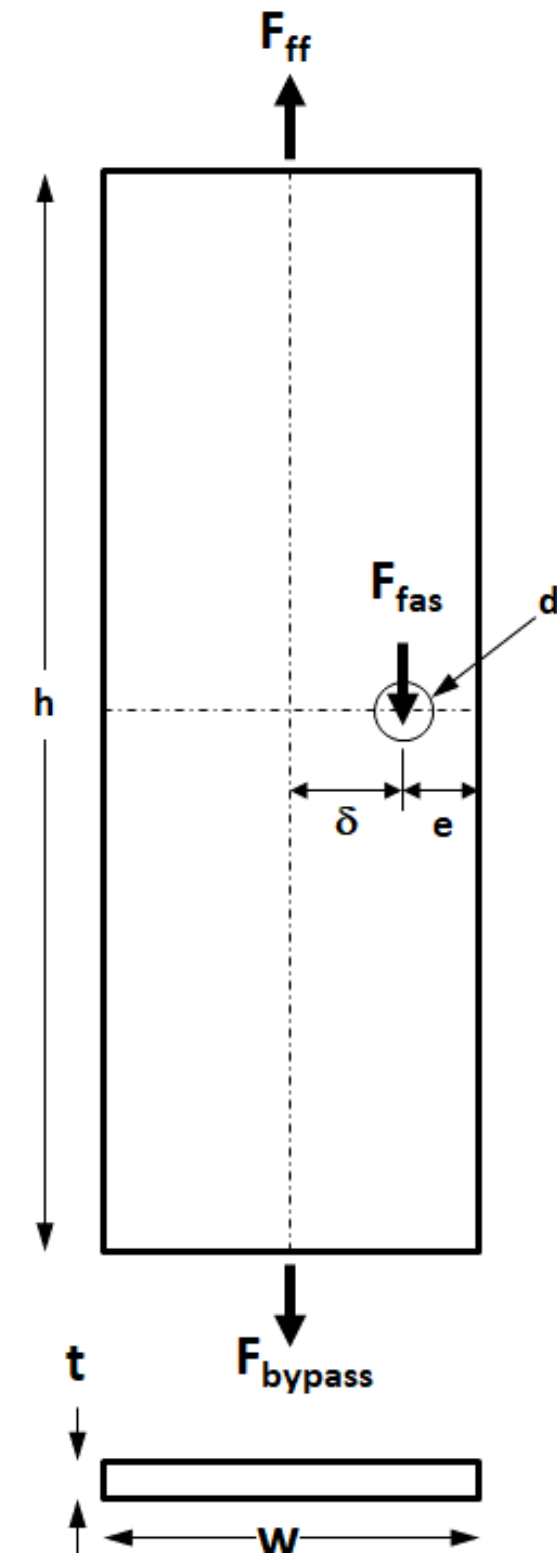
- Plate width ( $w$ ) used in the study:  $0.5 \leq w \leq 4$

- $2 \leq w/d \leq 16$
- Offsets:  $0.05 \leq \delta/w \leq 0.4438$

- Where possible, BSF held constant at 2.5\*

- Requires ASF to vary as needed

w (in)	w/d		$\delta/w$	ASF	BSF	SMF (ksi)
0.5	2	Centered Holes	0	1	0	10
		Offset Holes	0.05, 0.1	0.25	1.5	
0.75	3	Centered Holes	0	1	0	20
		Offset Holes	0.05, 0.1, 0.15, 0.2	0.167	2.5	
1	4	Centered Holes	0	1	0	20
		Offset Holes	0.05, 0.1, 0.15, 0.2, 0.2525	0.375	2.5	
1.5	6	Centered Holes	0	1	0	20
		Offset Holes	0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35	0.584	2.5	
2	8	Centered Holes	0	1	0	20
		Offset Holes	0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.3875	0.6875	2.5	
3	12	Centered Holes	0	1	0	20
		Offset Holes	0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.40, 0.425	0.7917	2.5	
4	16	Centered Holes	0	1	0	20
		Offset Holes	0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.40, 0.4438	0.84375	2.5	

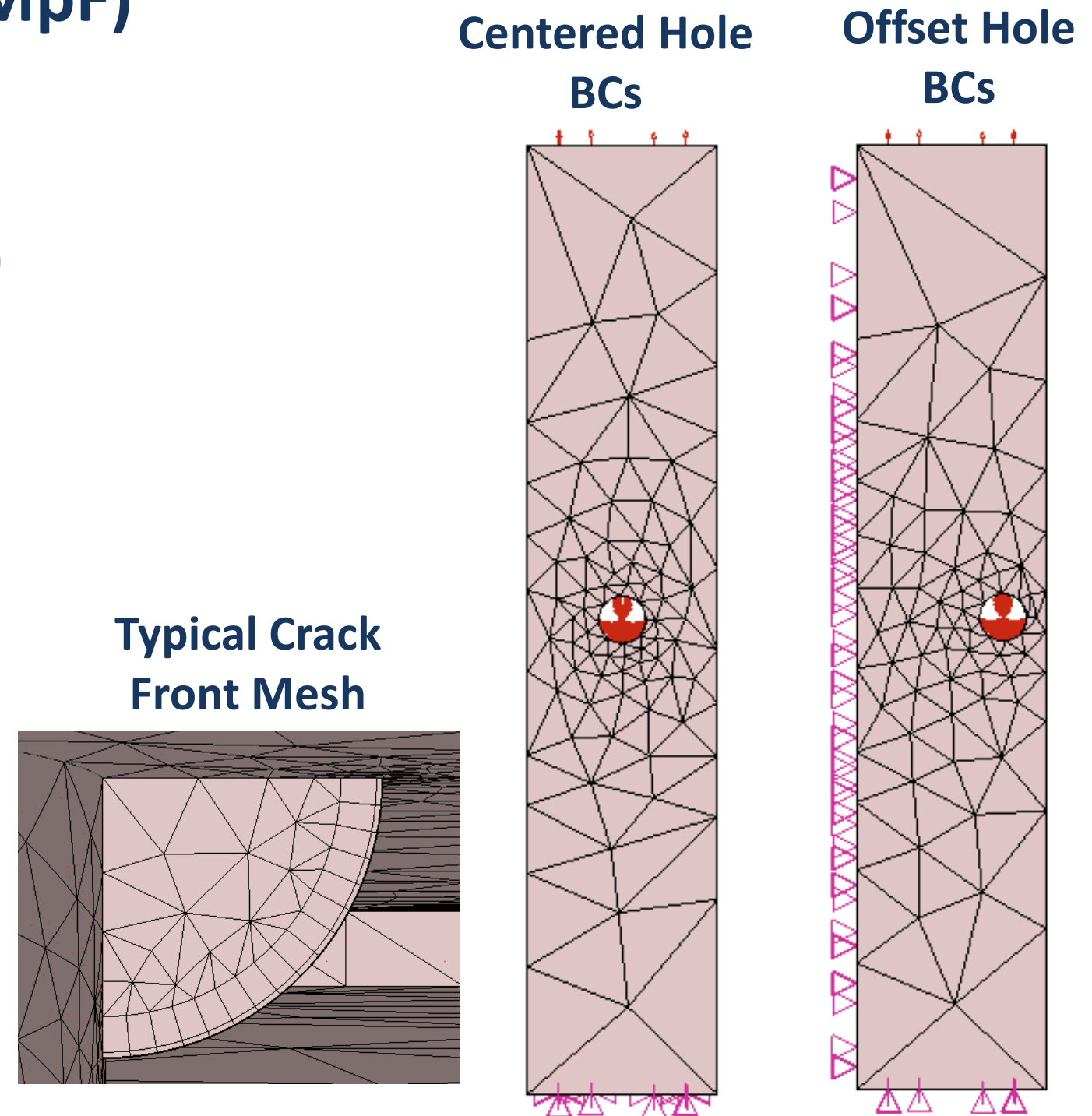




# Outline of Study



- Primary comparison is overall life prediction between AFGROW and multi-point 3D FEM (StressCheck via BAMpF)
  - Starting from 0.05" x 0.05" corner crack
- AFGROW Advanced Models (version 5.4)
  - Run both N-R and H-T width corrections
  - No retardation
  - No residual stress
  - Check  $K_{max}$  and Net Section Yield Checks
- StressCheck Models
  - Height (h) set to five times width
  - No lateral face constraint for centered hole
  - "Crack Front" mesher utilized for crack
  - Solver p-level = 4







# Summary of %-Difference in Predicted Life



- The table below summarizes the %-difference in overall life prediction for BAMpF vs AFGROW for all models studied (+ means BAMpF overpredicts AFGROW—i.e. AFGROW conservative)
- The large %-differences in life were unexpected, *especially for centered open (no bearing) holes*
- General trends
  - Loaded Offset Holes: correlation (%-diff) gets worse with decreasing width (w/d) and increasing offset ( $\delta/w$ )
  - Centered Holes: %-difference switches from positive (BAMpF overpredicts AFGROW) to negative with increasing width *for both unloaded and loaded holes*
  - Also note sharp jump in %-difference as we switch from centered hole ( $\delta/w=0$ ) to slight offset ( $\delta/w>0$ )

Centered Holes      Increasing Offset

		Centered Holes ( $\delta/w = 0$ )		Offset Holes ( $\delta/w$ )													
		No Bearing Load	With Bearing Load	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.3875	0.4	0.425	0.4438			
Increasing Width 	w	w/d															
	Initial Study	0.5	2	20.7%	100.2%	87.6%											
		0.75	3	27.3%	17.2%	71.1%	105.4%	148.3%	324.6%								
		1	4	15.9%	2.6%	43.5%	52.9%	72.1%	109.6%	138.9%							
		1.5	6	4.9%	-7.5%	12.9%	18.8%	25.5%	39.6%	48.1%	88.9%	328.6%					
		2	8	0.4%	-9.0%	7.8%	10.6%	14.1%	19.4%	25.1%	42.8%	82.2%	89.2%				
		3	12	-3.8%	-2.5%	6.0%	*	18.5%	*	37.9%	*	*		*	71.1%		
4		16	-5.5%	-11.9%	0.8%	5.8%	*	5.5%	*	3.9%	*		26.5%		*		

\* BAMpF model not yet run

Blue text cells are situations where Harter "6d" width limitation may apply

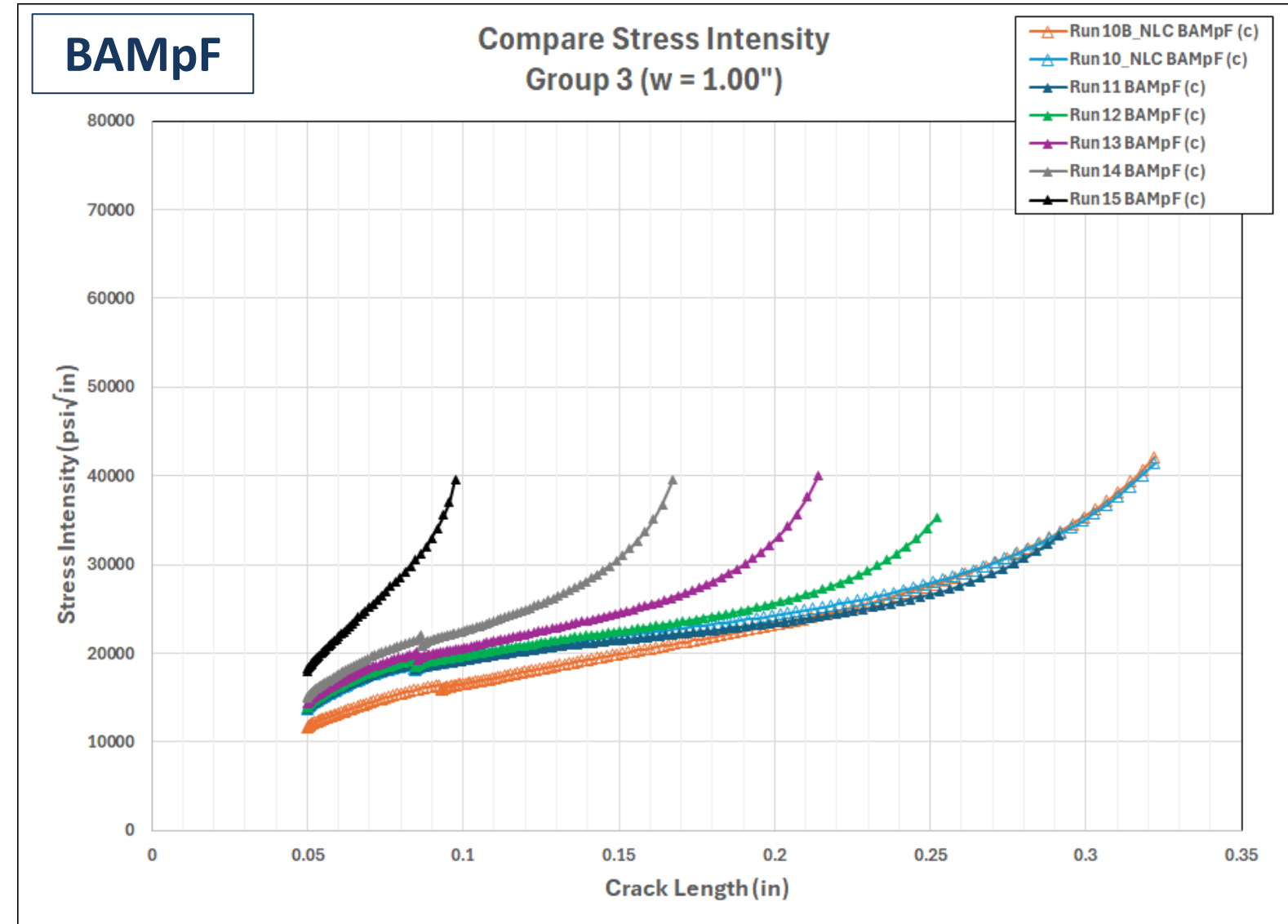
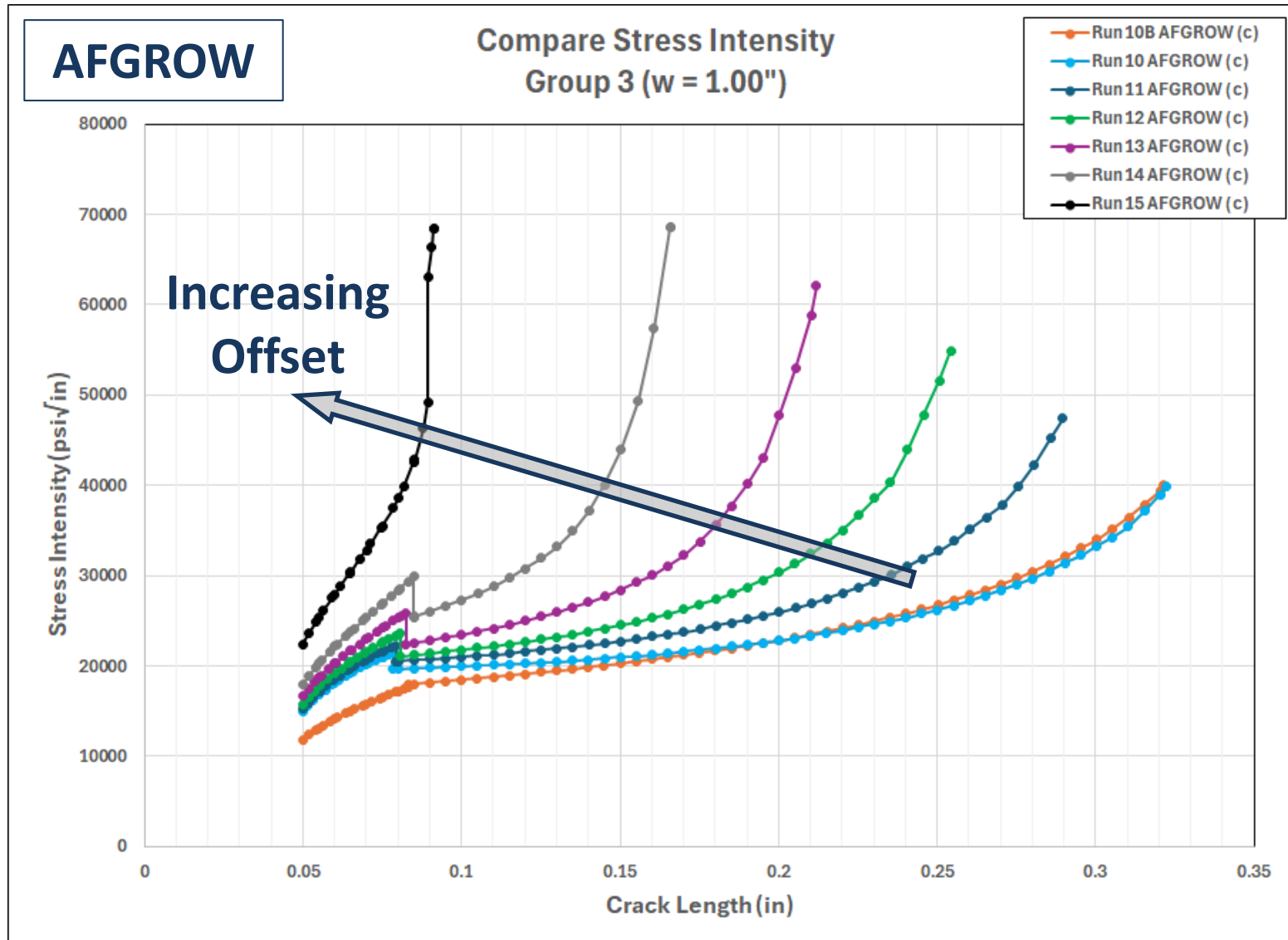


# Offset Holes SIF Comparison Example



- Group 3 ( $w = 1.00''$ ,  $w/d = 4$ ) used here as example to illustrate via c-crack SIFs the reason for difference in life predictions

w	w/d	Centered Holes ( $\delta/w = 0$ )		Offset Holes ( $\delta/w$ )													
		No Bearing Load	With Bearing Load	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.3875	0.4	0.425	0.4438			
Initial Study	0.5	2	20.7%	100.2%	87.6%												
	0.75	3	27.3%	17.2%	71.1%	105.4%	148.3%	324.6%									
	1	4	15.9%	2.6%	43.5%	52.9%	72.1%	109.6%	138.9%								
	1.5	6	4.9%	-7.5%	12.9%	18.8%	25.5%	39.6%	48.1%	88.9%	328.6%						
	2	8	0.4%	-9.0%	7.8%	10.6%	14.1%	19.4%	25.1%	42.8%	82.2%	89.2%					
	3	12	-3.8%	-2.5%	6.0%	*	18.5%	*	37.9%	*	*		*	71.1%			
	4	16	-5.5%	-11.9%	0.8%	5.8%	*	5.5%	*	3.9%	*			26.5%			*

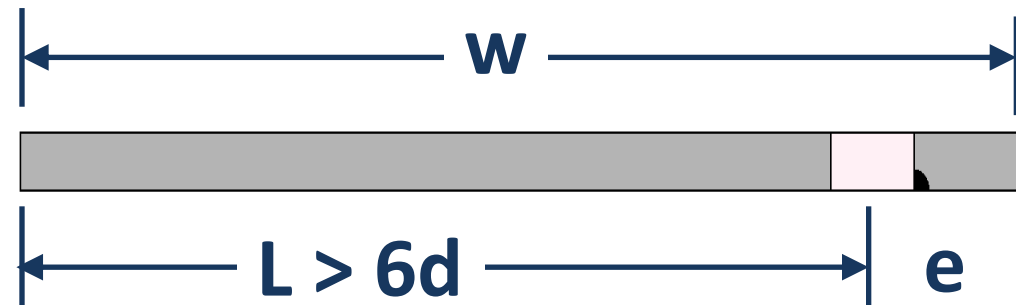




# “6D Rule” Modified Width AFGROW Check



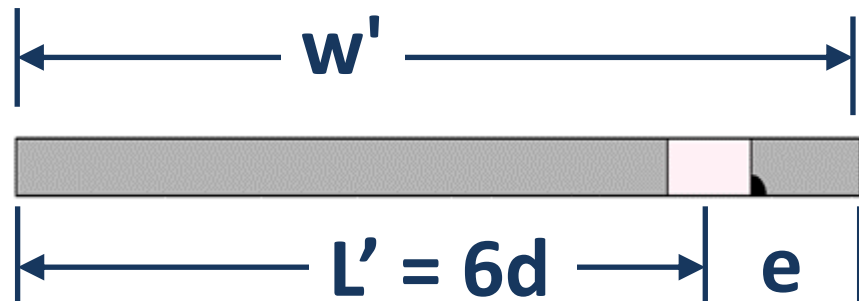
- Applying the “6D Rule” seemed to help at more extreme offsets, but was not universally an improvement



		Offset Holes ( $\delta/w$ )										
$w$	$w/d$	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.3875	0.4	0.425	0.4438
Initial Study	0.5	2	87.6%									
	0.75	3	71.1%	105.4%	148.3%	324.6%						
	1	4	43.5%	52.9%	72.1%	109.6%	138.9%					
	1.5	6	12.9%	18.8%	25.5%	39.6%	48.1%	88.9%	328.6%			
	2	8	7.8%	10.6%	14.1%	19.4%	25.1%	42.8%	82.2%	89.2%		
	3	12	6.0%	*	18.5%	*	37.9%	*	*		*	71.1%
	4	16	0.8%	5.8%	*	5.5%	*	3.9%	*		26.5%	

\* BAMpF model not yet run

Blue text cells are situations where Harter "6d" width limitation may apply



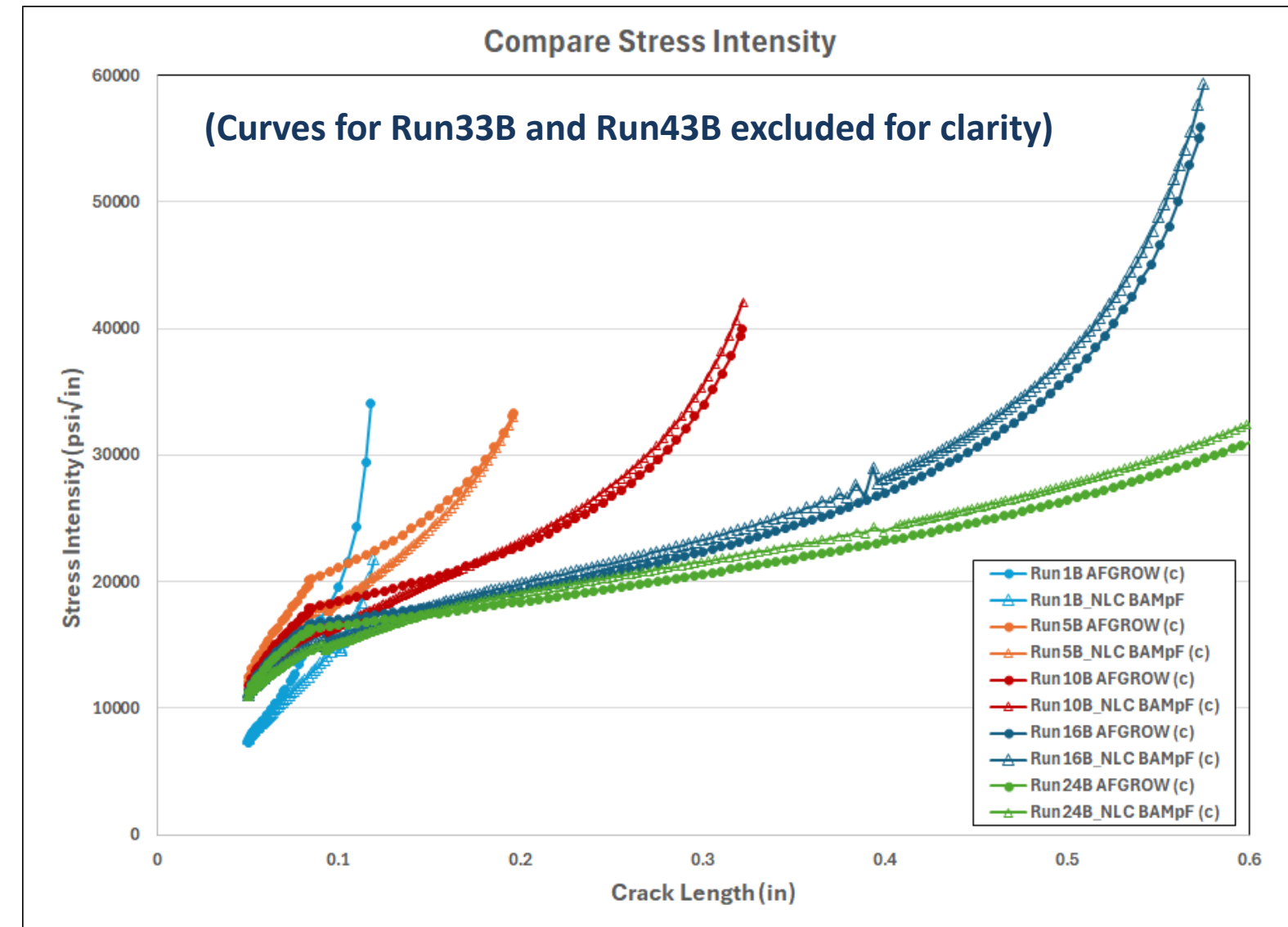
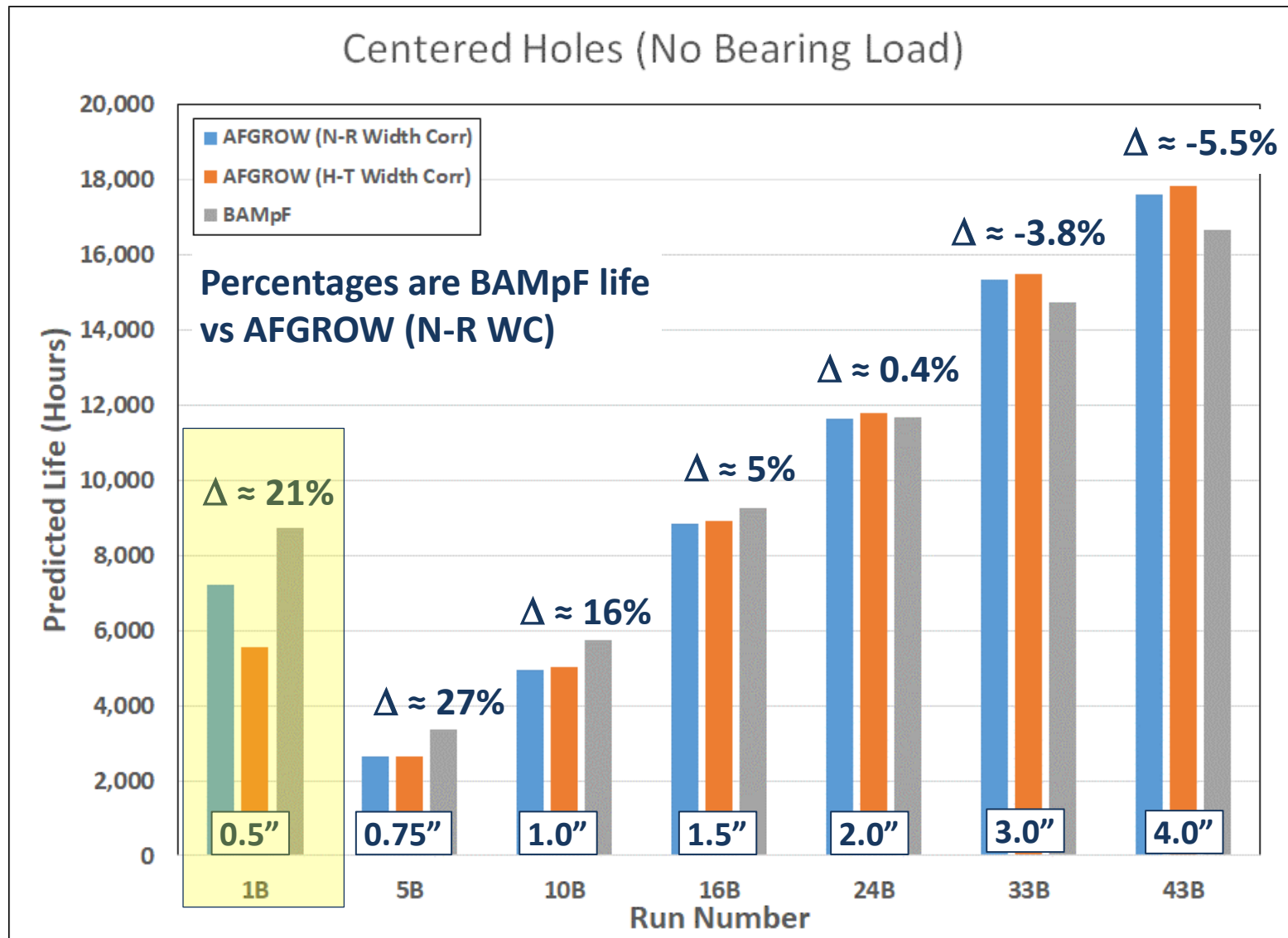
		Offset Holes ( $\delta/w$ )										
$w$	$w/d$	0.05	0.1	0.15	0.2	0.25	0.3	0.35	0.3875	0.4	0.425	0.444
Initial Study	0.5	2	87.6%									
	0.75	3	71.1%	105.4%	148.3%	324.6%						
	1	4	43.5%	52.9%	72.1%	109.6%	138.9%					
	1.5	6	12.9%	18.8%	25.5%	39.6%	48.1%	88.9%	328.6%			
	2	8	7.8%	10.6%	14.1%	19.4%	25.1%	-34.4%	-12.7%	0.1%		
	3	12	-52.4%	*	-44.1%	*	-30.6%	*	*		*	3.3%
	4	16	0.8%	5.8%	*	-46.4%	*	-42.6%	*		-21.2%	



# Centered Holes with No Bearing Loads



- The bar chart below compares overall life prediction AFGROW vs BAMpF
- The line plots compare K-solutions (surface crack) vs crack length
  - Stress intensity solutions, and therefore life predictions, vary more dramatically for narrow plates—i.e. less than 1.5" (w/d = 6)
  - AFGROW conservative compared to BAMpF for  $w/d \leq 6$



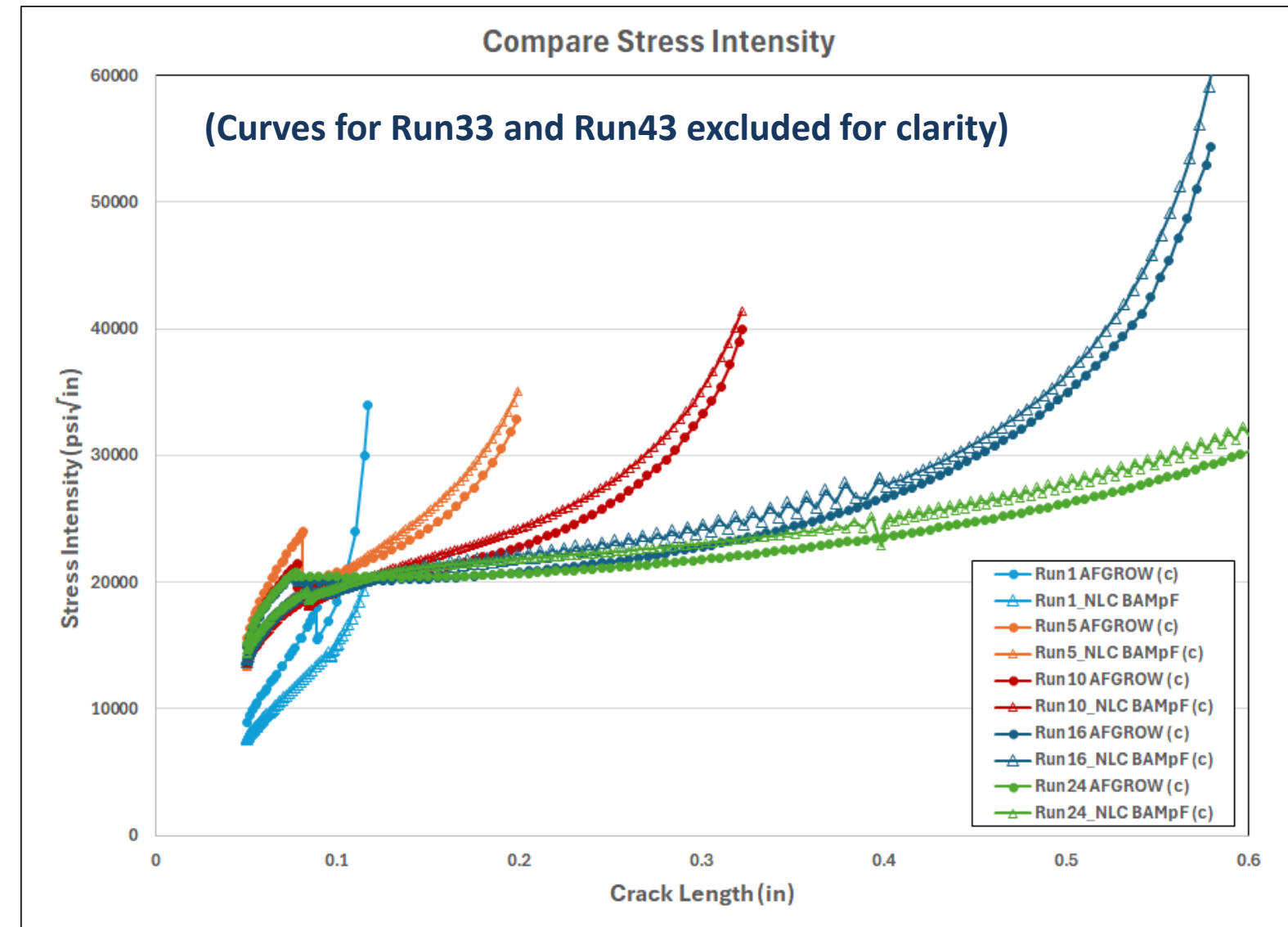
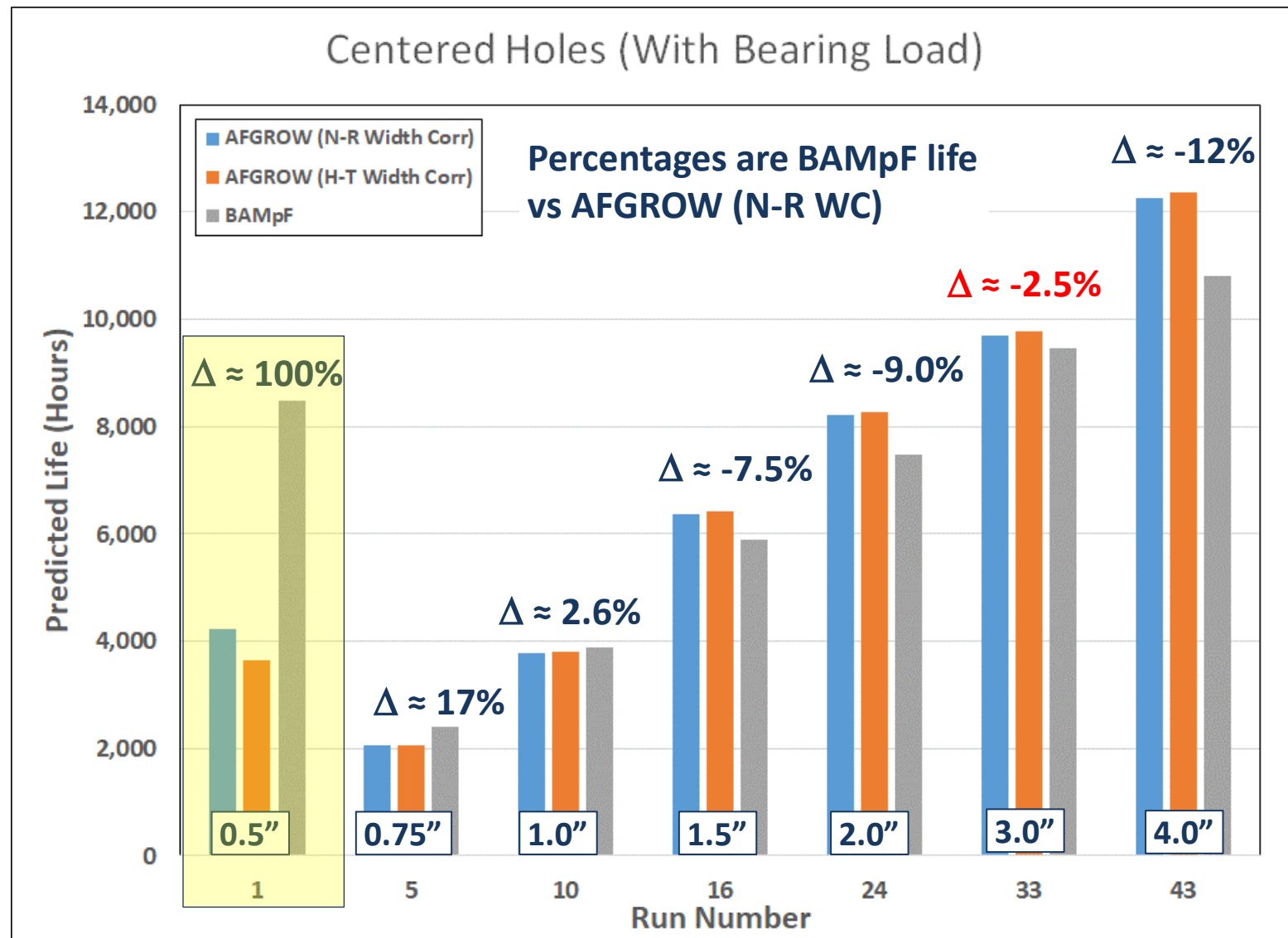




# Centered Holes with Bearing Loads



- The bar chart below compares overall life prediction AFGROW vs BAMpF
- The line plots compare K-solutions (surface crack) vs crack length
  - Noticeable difference in K-solution for corner-crack region and transition to thru-crack
  - AFGROW less conservative compared to BAMpF for  $w/d \geq 6$







# Need Additional Investigation!



- **The correlation results between AFGROW and BAMpF for the offset bearing loaded holes were worse than anticipated**
  - **%-differences are likely a combination of confounding factors**
    - **Finite width**
    - **Hole offset**
    - **Bearing**
- **However, we were surprised by the correlation trends seen in the unloaded center hole models**
  - **Finite width effects only which we assumed were accounted**
  - **Decided to investigate in more detail**



# Additional Wide Plate Centered Hole Models



- Additional wider plate models with unloaded centered holes, up to an “infinite width” ( $w = 25$ ”) were run to examine the correlation trend

		Centered Holes ( $\delta/w = 0$ )		
w	w/d	No Bearing Load	With Bearing Load	
Initial Study	0.5	2	20.7%	100.2%
	0.75	3	27.3%	17.2%
	1	4	15.9%	2.6%
	1.5	6	4.9%	-7.5%
	2	8	0.4%	-9.0%
	3	12	-3.8%	-2.5%
	4	16	-5.5%	-11.9%

w	w/d	No Bearing Load	At C-crack Length (in)	
Added	6	24	-9.0%	1.972
	8	32	-9.3%	1.890
	12	48	-9.7%	1.985
	16	64	-9.9%	1.983
	20	80	-8.3%	1.730
	25	100	-10.1%	1.985



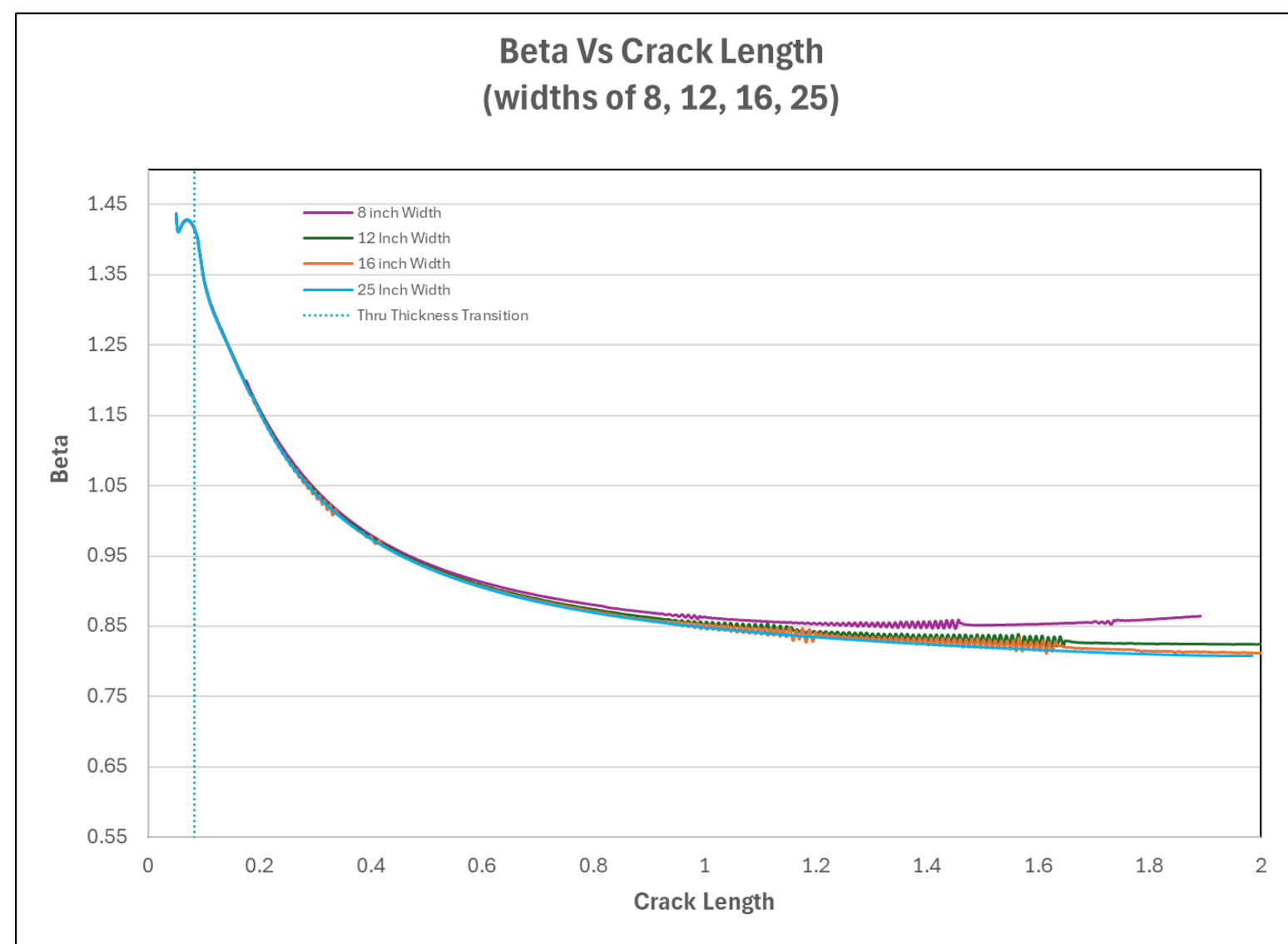
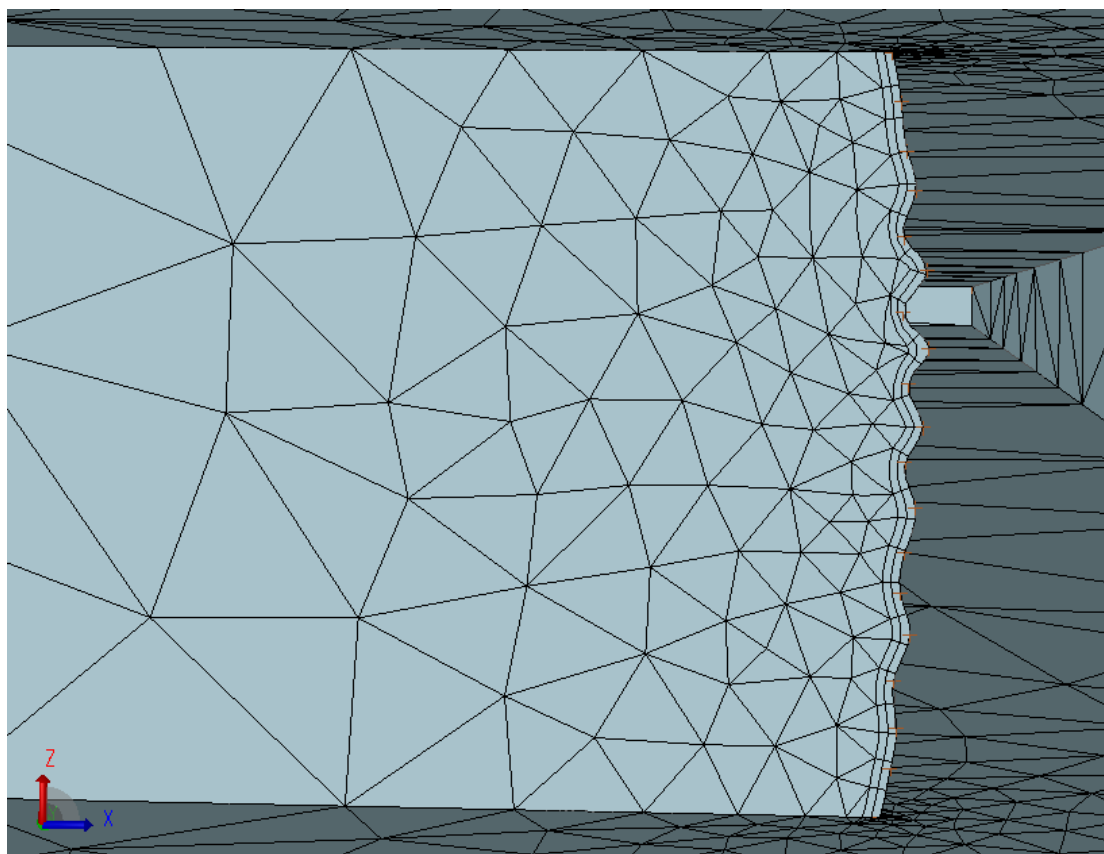
- Note: the %-difference would continue to trend more and more negative, but the result shown here flat-line due to issues in BAMPF that limited the maximum crack length to about 2” → see next slide for more detail



# Wide Plate Centered Hole Comparisons



As the crack length increases in BAMpF the % growth increment needs to reduce to get a crack front that does not have oscillations in it. At a crack length of 2 inches, it is hard to get much more out of BAMpF. So, the 8 inch wide and wider models all stopped near a crack length of 2 inches. Because of how wide the plate is, the edge does not influence the stress intensity solution much up to this 2-inch crack length. So, the variation in life at that length would be about the same for each model ran.



This means the growth increment needs to be reduced.



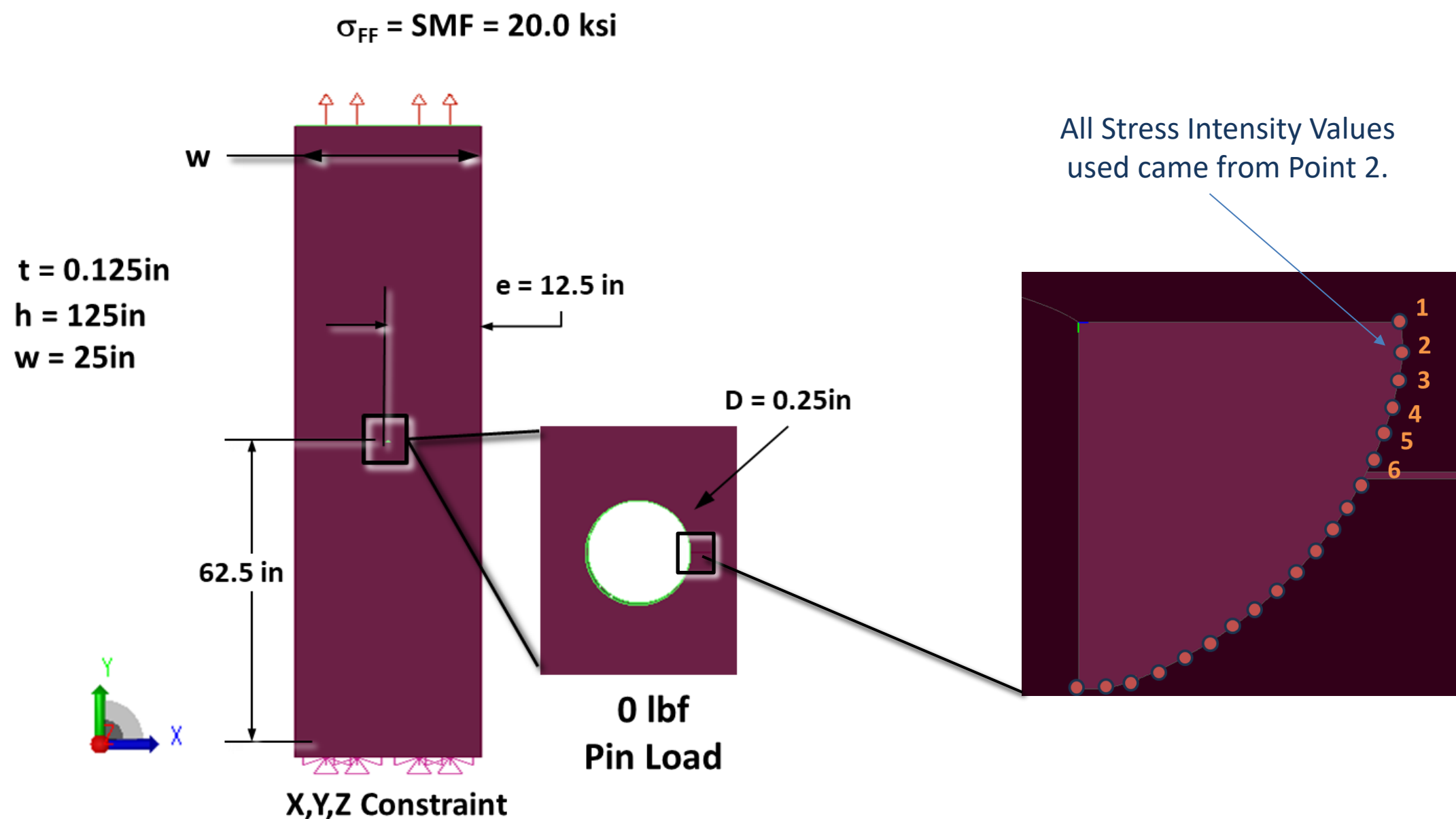


# Infinite Width Beta Solution Checks



With the variations seen as a function of width, it was decided to check an infinite width case to remove the question of the finite width correction.

## Infinite Width StressCheck Model





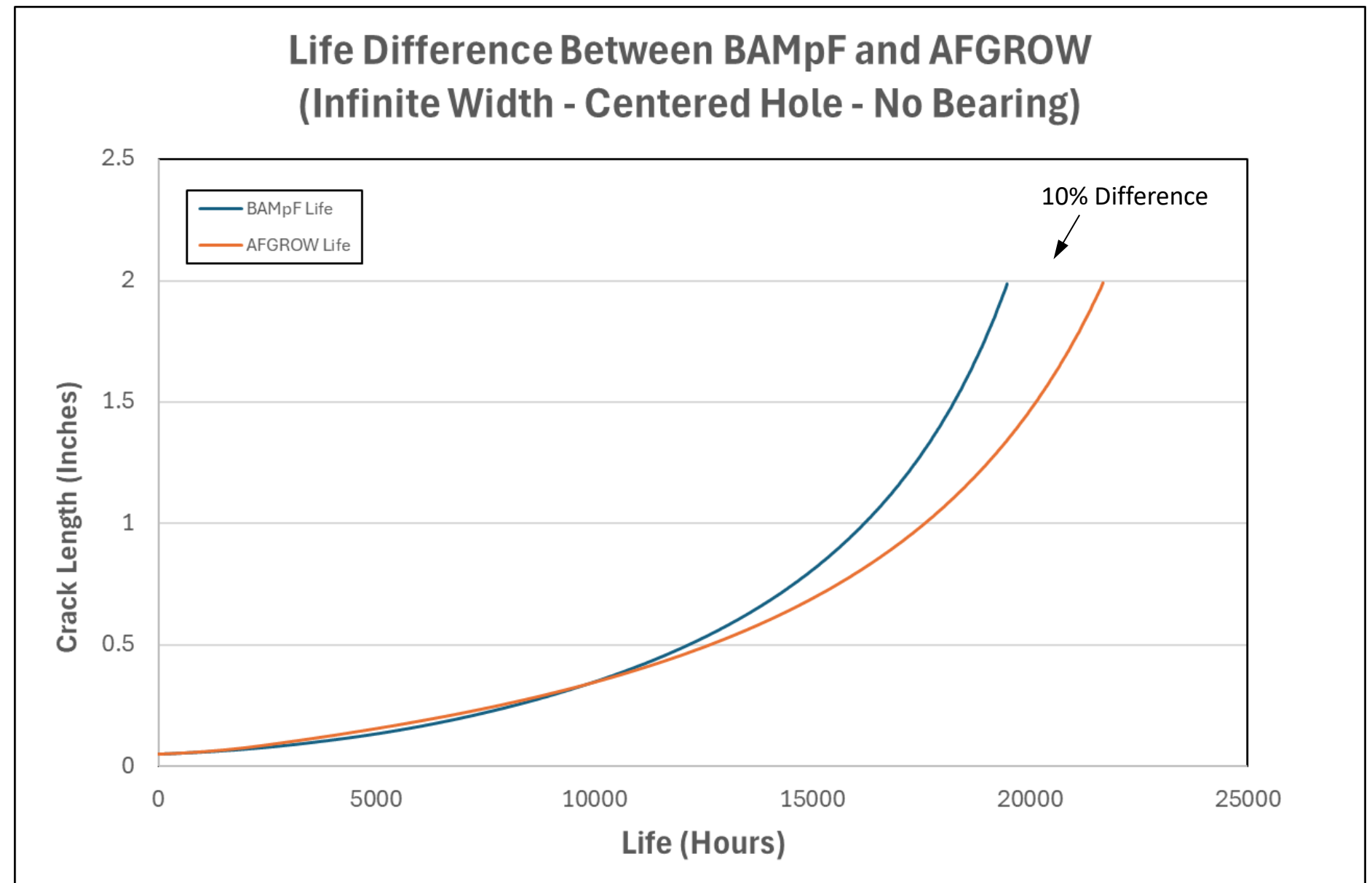
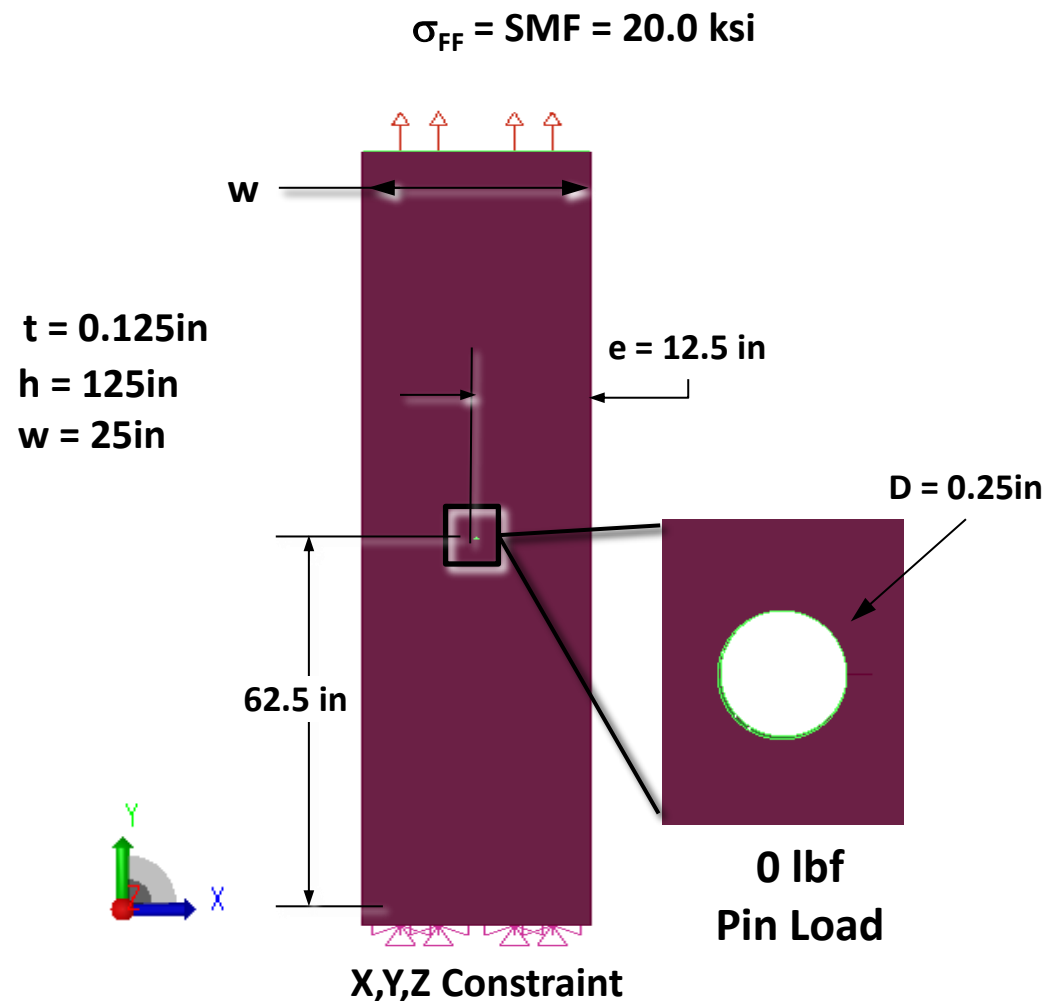
# Infinite Width Beta Solution Checks



It was expected that the life difference between AFGROW and BAMpF would be less than this for a centered hole infinite width plate with no bearing. The finite width correction is removed, the offset hole correction is removed and there is no bearing to worry about. Why is there a difference?

As a note: the critical crack length is 6 inches, but BAMpF struggled to get to 2" so that is where the comparison stopped.

## Infinite Width StressCheck Model





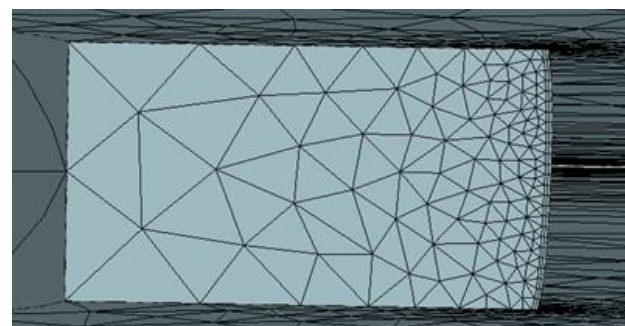
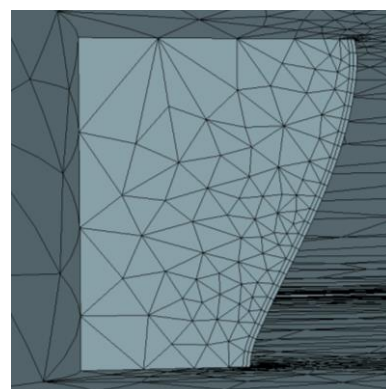


# Infinite Width Beta Solution Checks

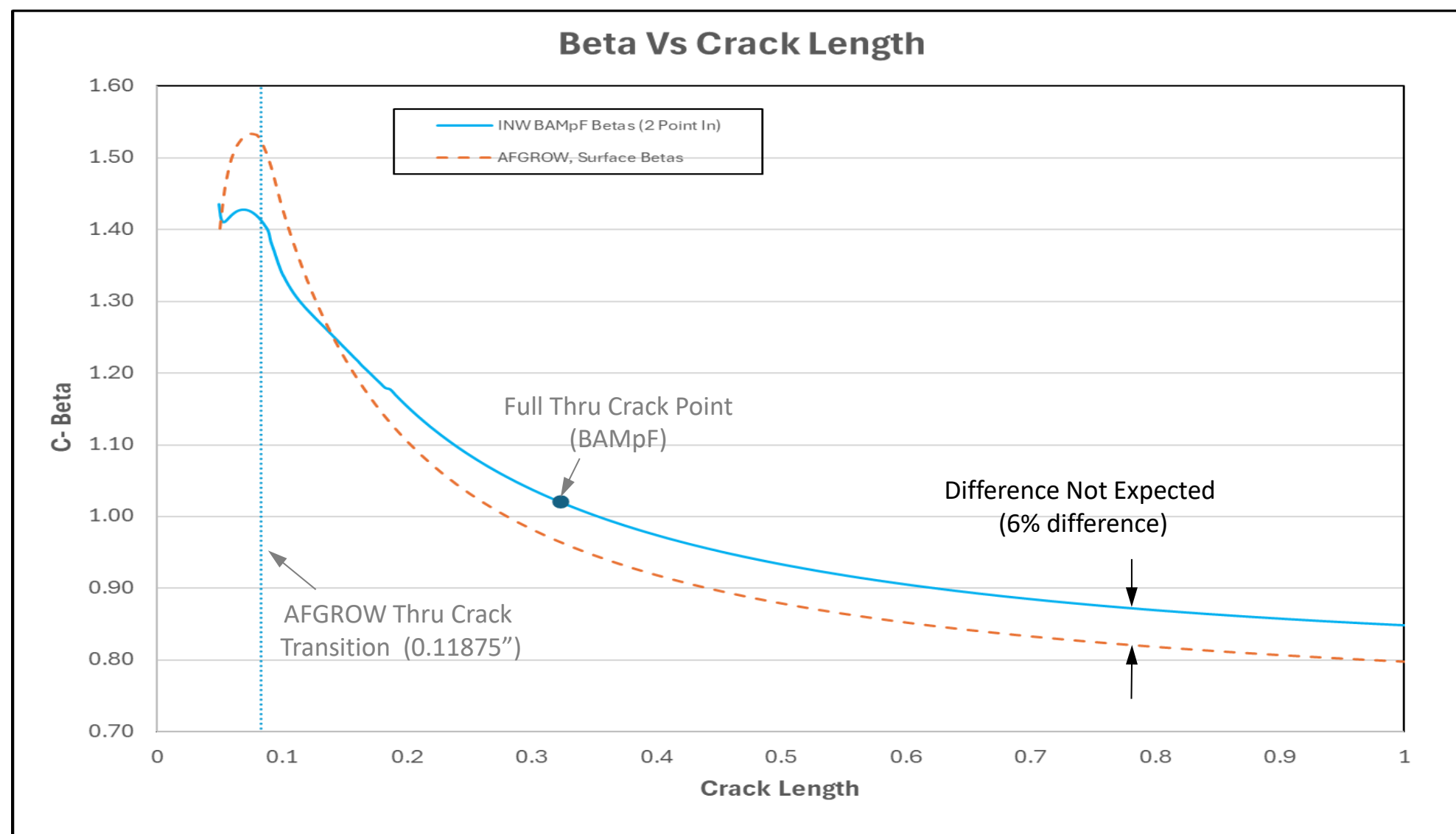
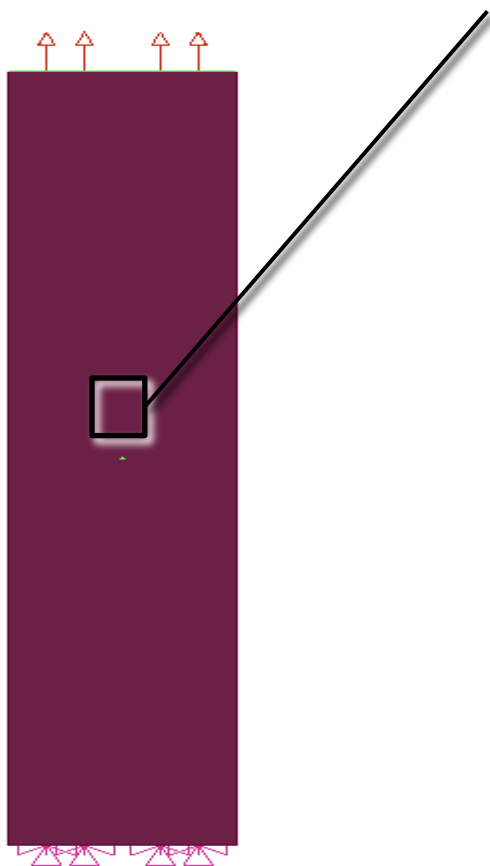


Stress Intensity value vs crack length are different. The difference is not significant, but it was not expected. Constant 6% difference between solutions occurs at the point where the full thru crack starts (i.e. back face crack length and front face crack length are the same).

3D Corner Crack at a Hole  
StressCheck Model



Full Thru Crack Point  
(BAMpF)



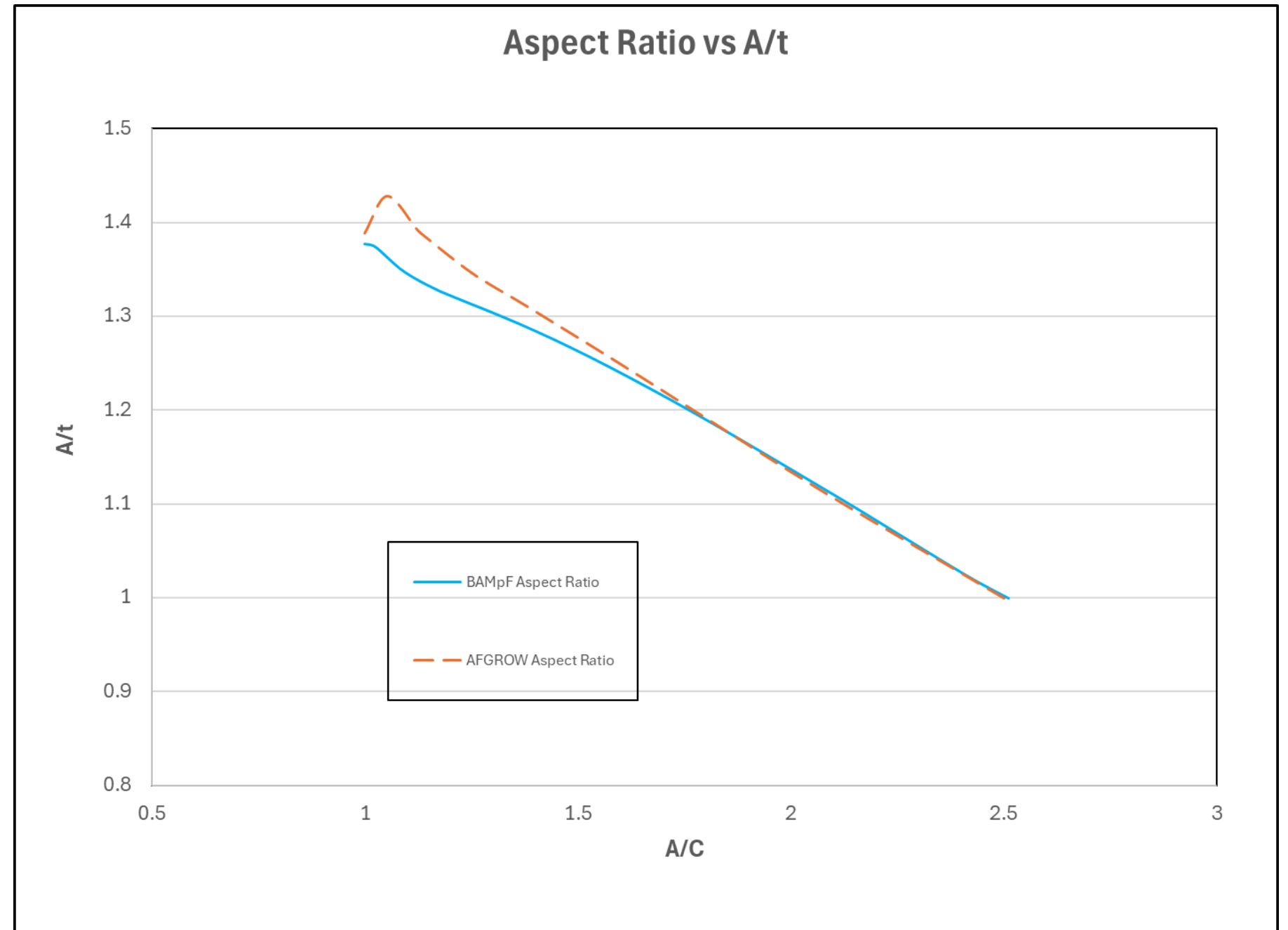
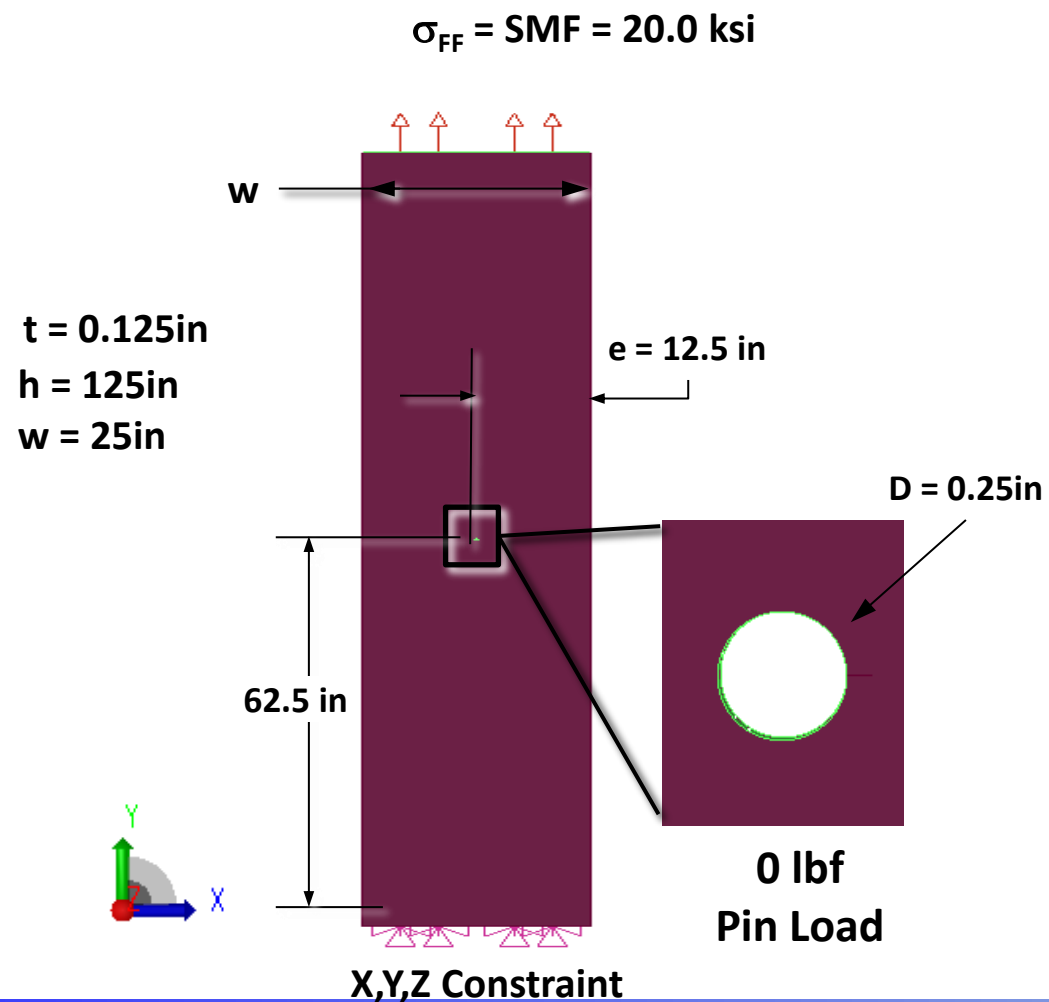


# Infinite Width Beta Solution Checks



Aspect Ratio Between BAMpF and AFGROW are fairly similar. There is difference, so the aspect ratio does contribute some to the differences in the corner crack realm.

## Infinite Width StressCheck Model



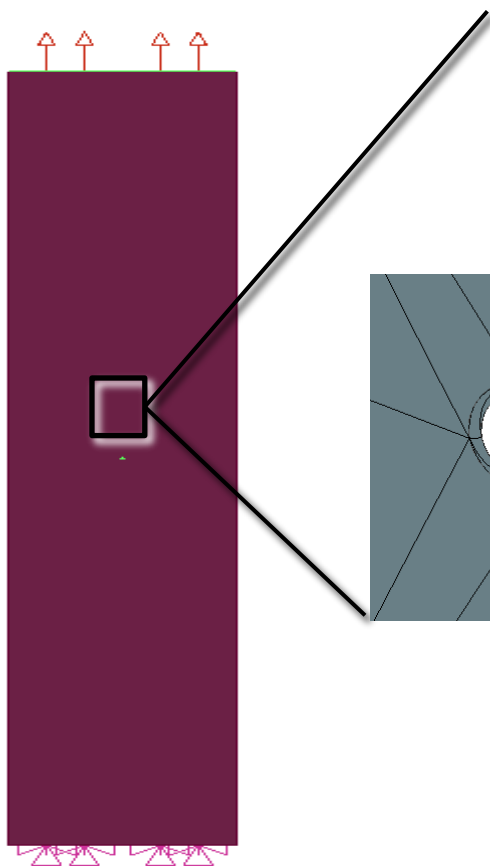
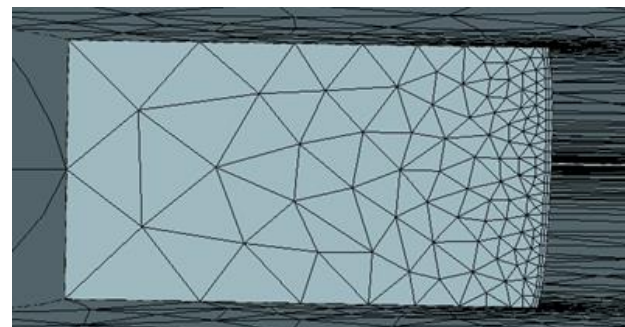
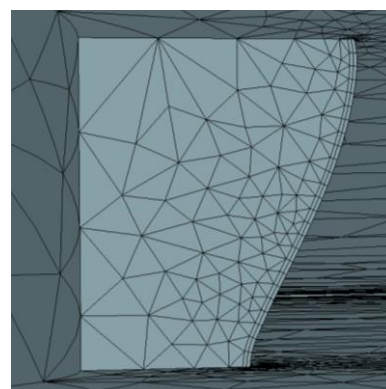


# Infinite Width Beta Solution Checks

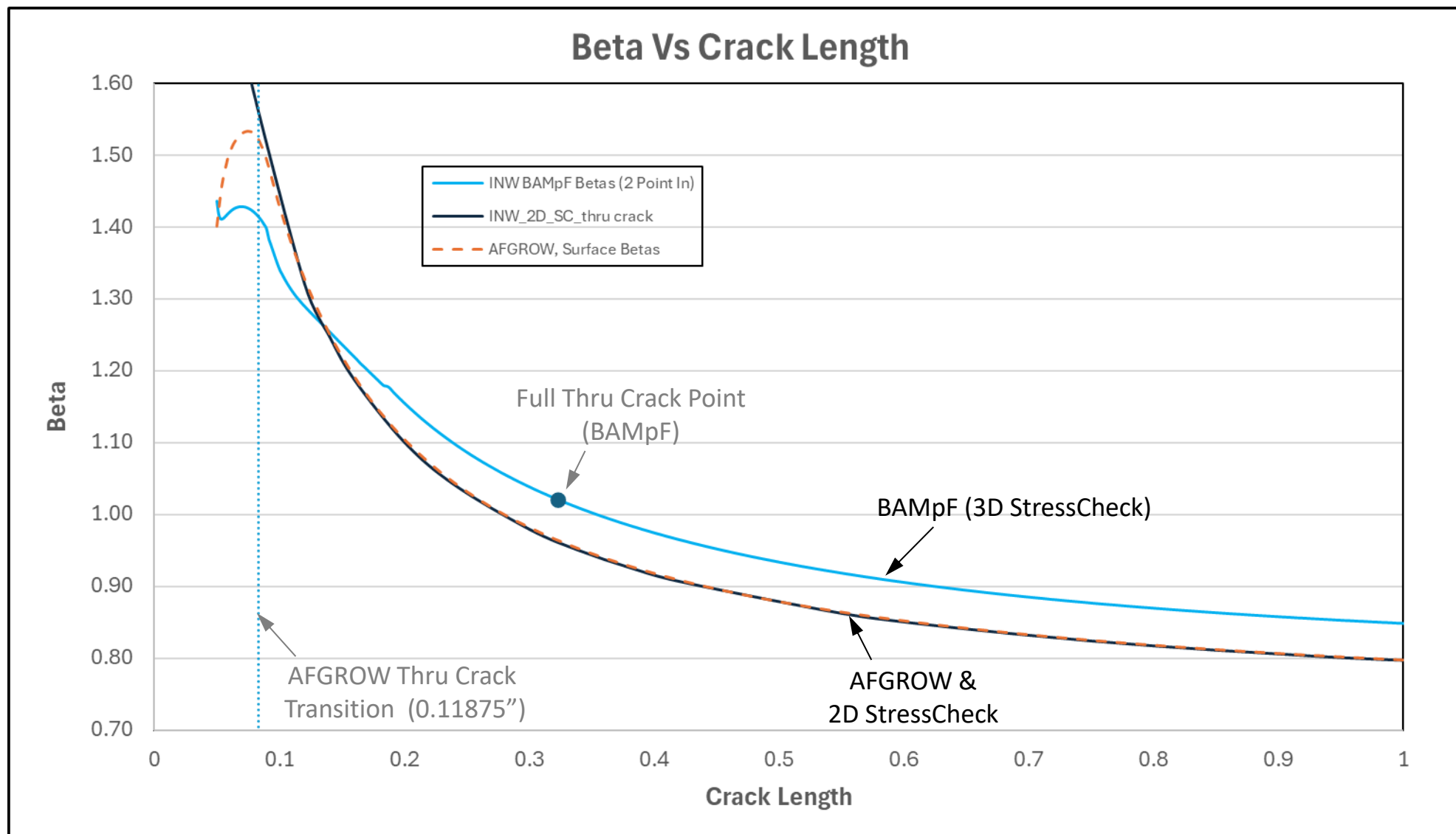
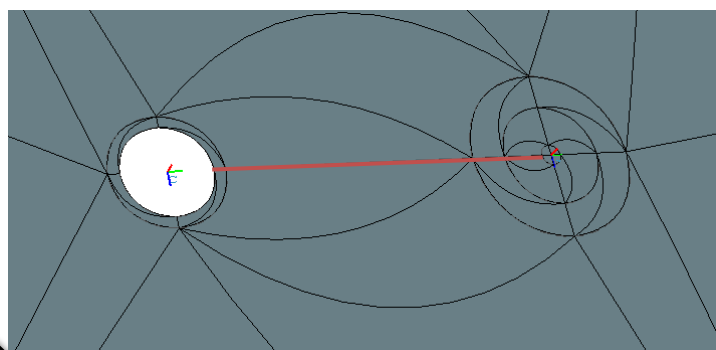


Betas for AFGROW and 2D StressCheck Models match up almost exactly. However, the BAMpF 3D StressCheck model again does not match up. So, there is a difference between betas from a 2D StressCheck model and a 3D StressCheck model. Why is there difference?

3D Corner Crack at a Hole StressCheck Model



2D Thru Crack at a Hole StressCheck Model





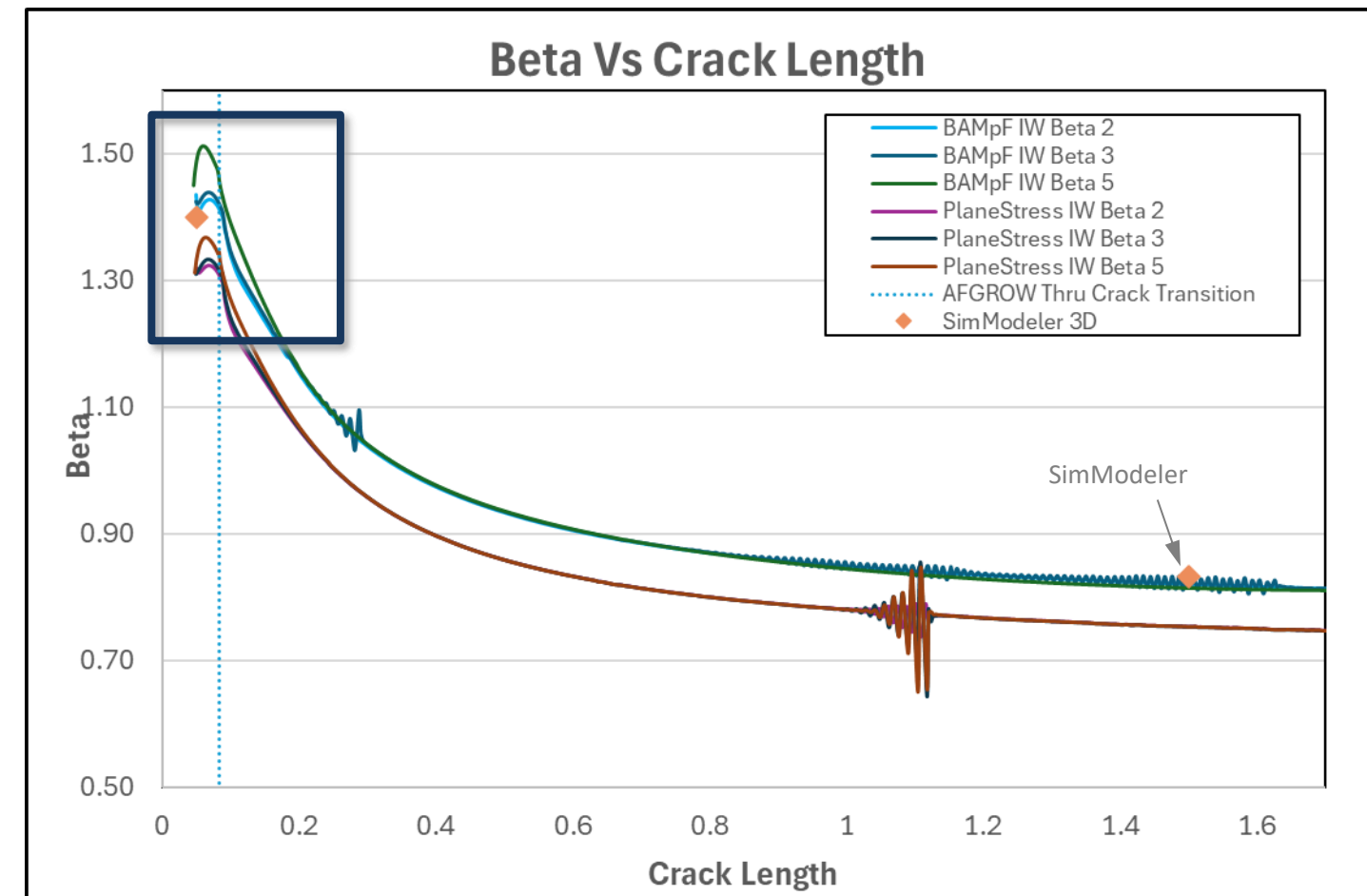
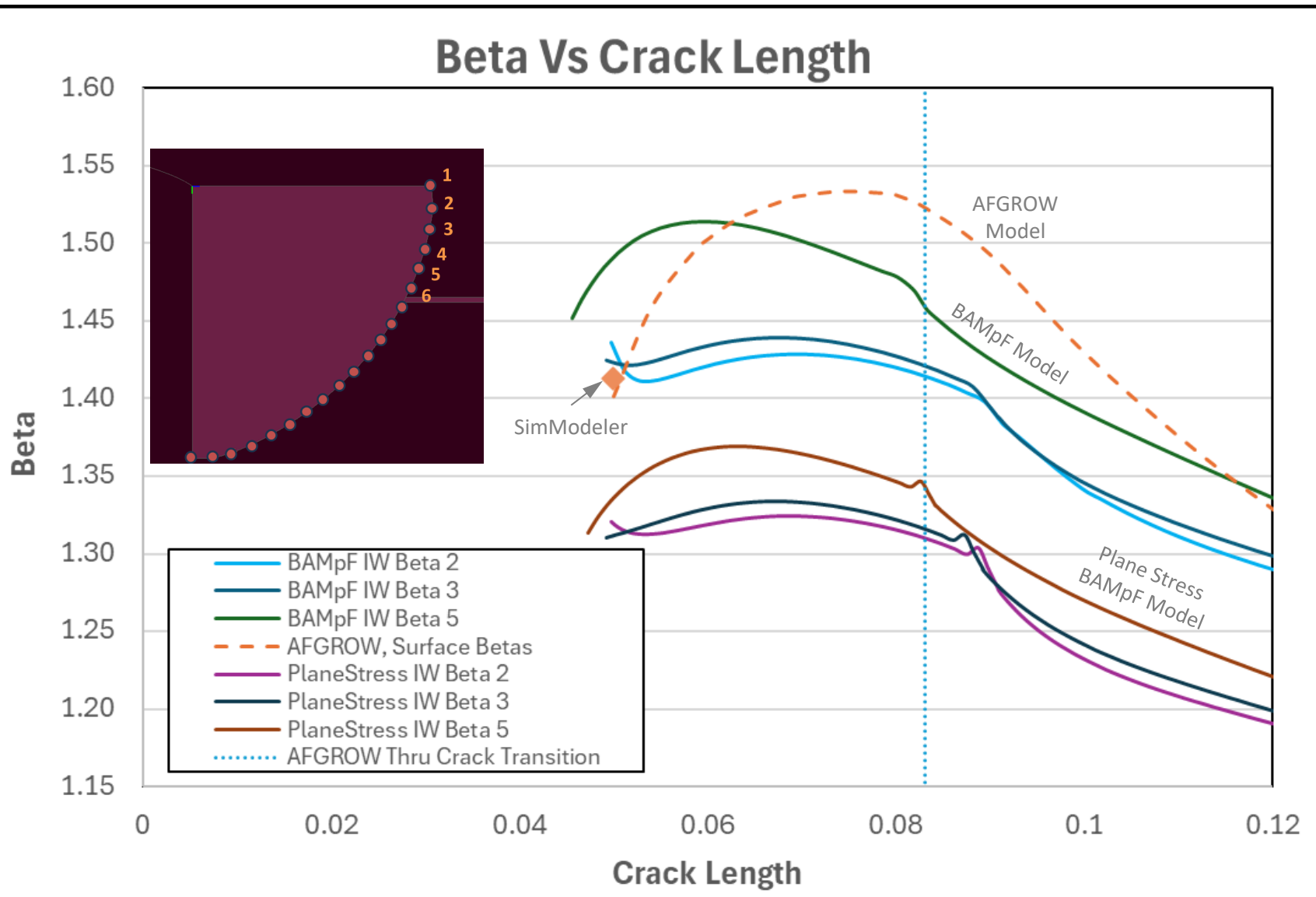
# Plane Stress or Plane Strain?



## Corner Crack

Comparison of BAMpF models run nominally and BAMpF models run with plane stress requirement enforced. The corner crack realm shows the nominal plane stress models are even further away from the AFGROW runs. Can also enforce plane strain, but results were not much different than StressChecks default

Note: 3D FEM transitions plane strain to plane stress as the crack grows, similar to AFGROW.







# Plane Stress or Plane Strain?

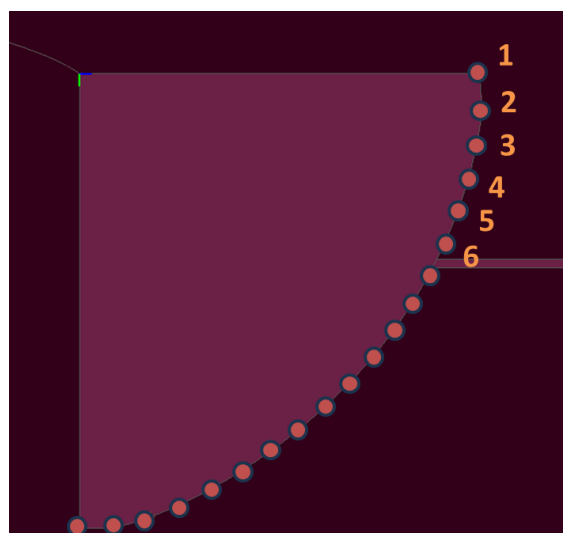


## 3D Thru Crack

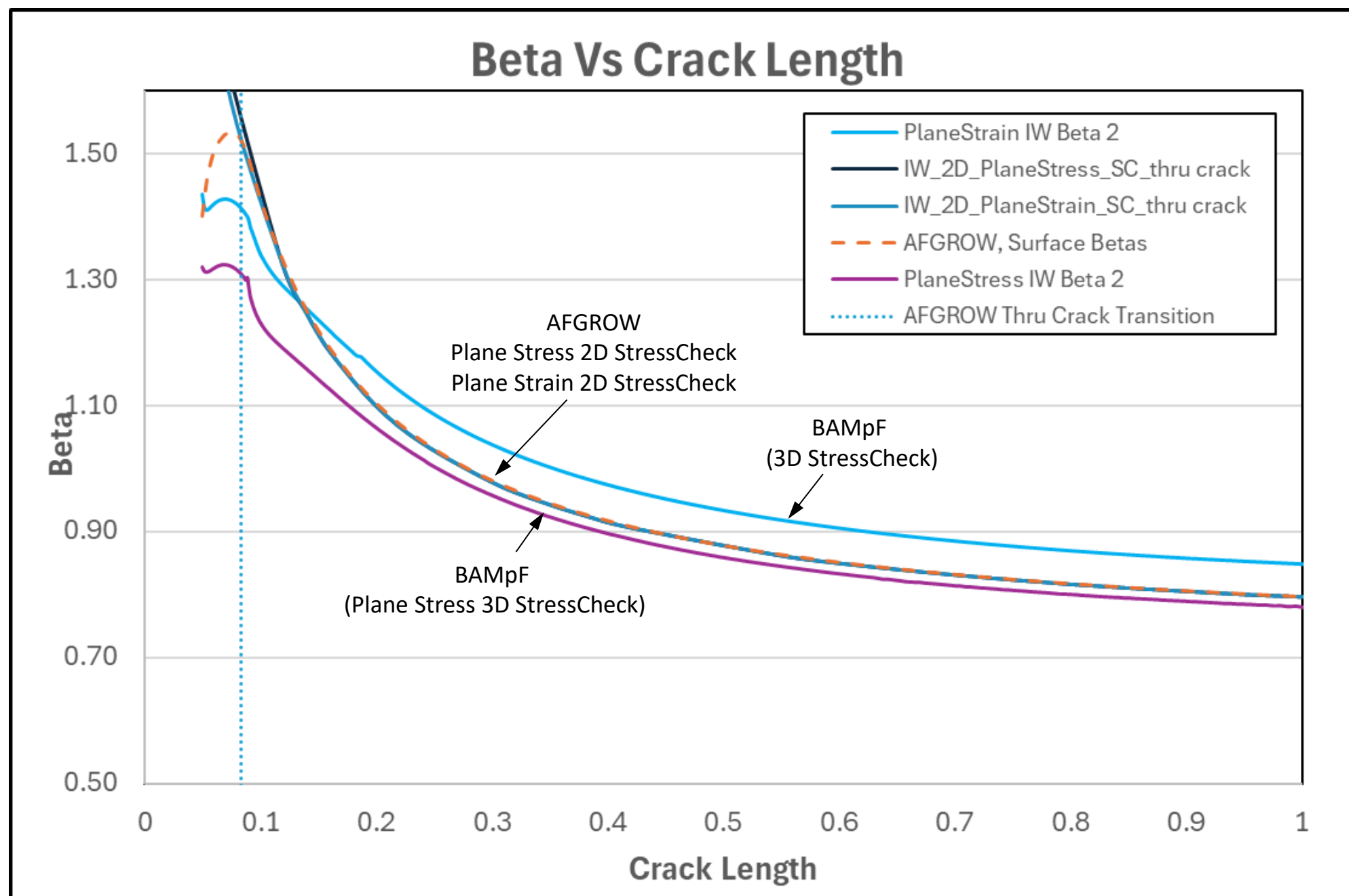
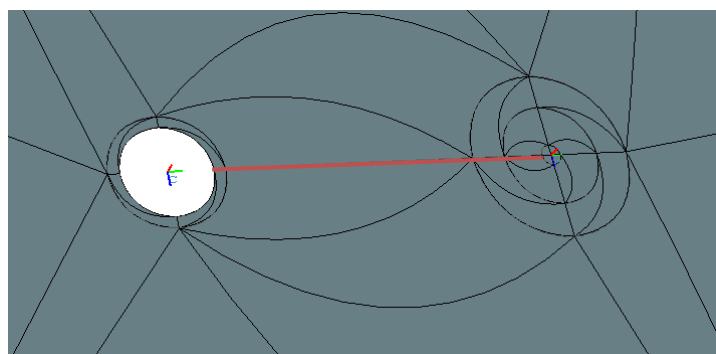
Comparison of BAMpF models run with auto stress state and BAMpF models run with plane stress enforced.

-The thru crack realm shows that the plane stress model is closer, but not quite on top of the AFGROW beta curve. So, there still is a difference between 2D StressCheck and 3D StressCheck with plane stress enforced.

Note: Default for 2D StressCheck is plane stress.



2D Thru Crack at a Hole  
StressCheck Model







# Concluding Remarks



- **Offset Holes with Bearing:**
  - Correlation between AFGROW and BAMpF was poor for all offsets in narrow plates ( $w/d < 6$ ) and poor in wider plates (up to  $w/d = 12$ ) having  $\delta/w > 0.15$
  - Modifying the AFGROW model width based on the “6D rule” may improve the correlation, but not universally
- **Take-away: exercise extreme caution with narrow plates having offset holes loaded in bearing**
- **Centered Holes:**
  - In the thru-crack portion of crack growth in IW model:
    - 2D FEA (StressCheck)  $\beta$  solution matches AFGROW exactly
    - The 3D FEA relying on automatic stress state definition has a consistently higher  $\beta$  solution
    - The 3D FEA with forced plane stress condition aligns more closely to 2D and AFGROW, but does not match either
  - In the corner crack portion of crack growth in IW model, none of the 3D FEA models tested were able to match AFGROW.
- **Take-away: Why? What the heck?**



# Questions?