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AFGROW Workshop 2022

Solution for Combinations of Corner and Straight Through Cracks At a Hole

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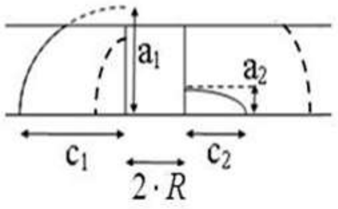
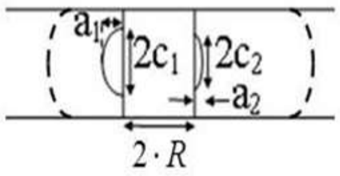
Advanced Crack At Hole Solutions in AFGROW

- The world's largest stress intensity factor database
- Created by Börje Andersson and sponsored by CAStLE
- 3 Years of super-computer number crunching
- Improved the Fawaz – Andersson unequal double corner crack at hole tabular data solution from 2003
- The 2017 release adds more solutions:
  - Corner crack – oblique crack at hole
  - Two unequal semi-elliptical crack at hole
  - Semi-elliptical crack - oblique crack at hole
  - Two unequal oblique crack at hole
  - Single corner crack, semi-elliptical crack and oblique crack at hole

Joint Type Analysed	Parameter Values				Total Number of Scenario
	c/a	*a/t*	*R/t*	*b/t*	
	25	23	30	1	4.32 *M*
	25	23	30	1	4.32 *M*

Parameter	Values
c/a	0.1, 0.111, 0.125, 0.1428, 0.1667, 0.2, 0.25, 0.333, 0.5, 0.667, 0.75, 0.8, 1.0, 1.25, 1.333, 1.50, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0
a/t	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 0.95, 0.975, 0.99, 1.05, 1.15, 1.50, 1.75, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0
R/t	0.075, 0.1, 0.111, 0.125, 0.1428, 0.1667, 0.2, 0.25, 0.333, 0.4, 0.4444, 0.5, 0.5714, 0.667, 0.75, 0.8, 1.0, 1.25, 1.333, 1.50, 1.75, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0

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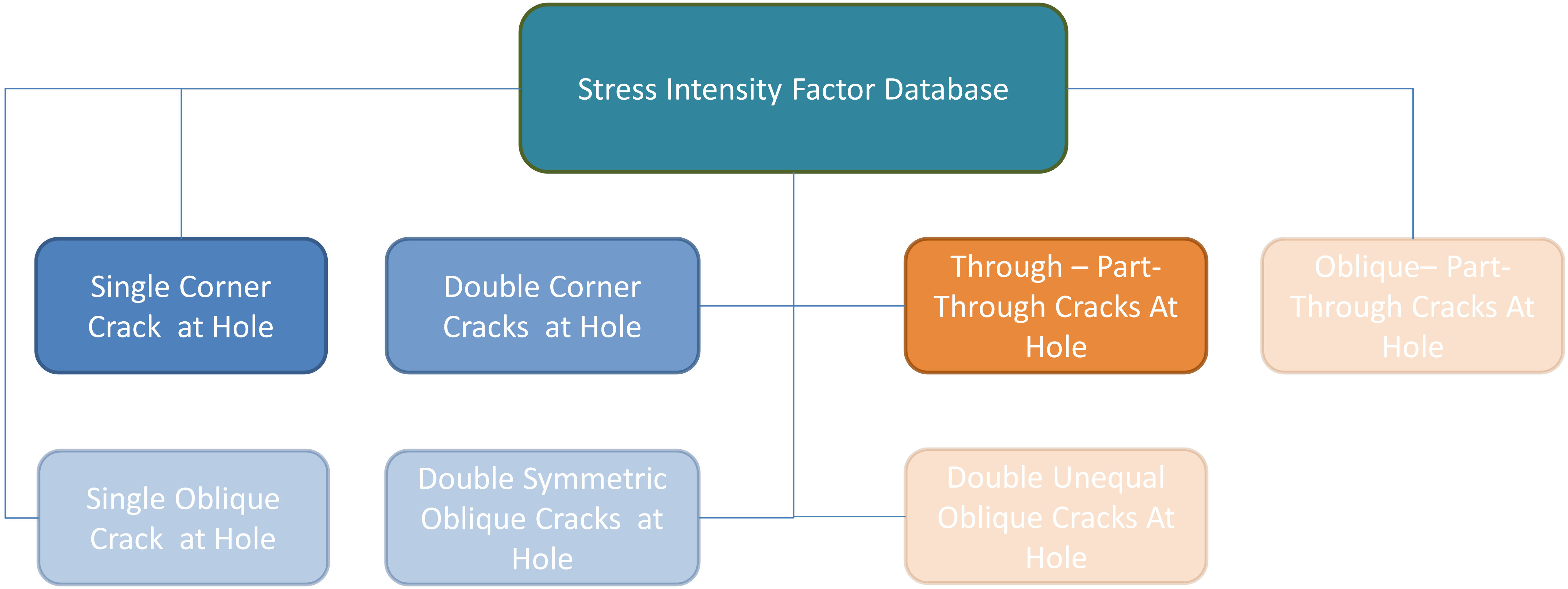
Advanced Crack at a Hole Solution Database



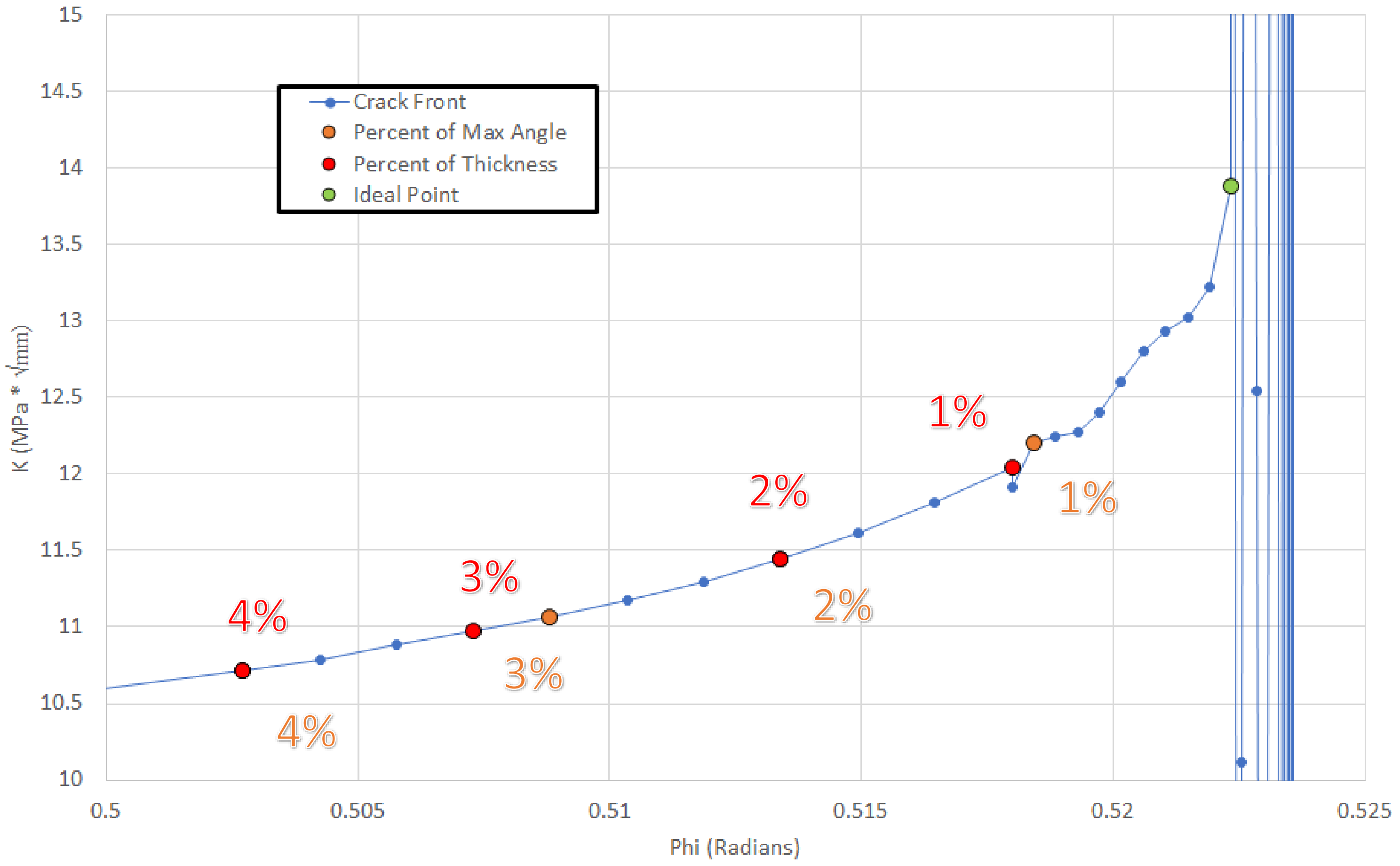
Solution for Combinations of Corner and Straight Through Cracks at Hole

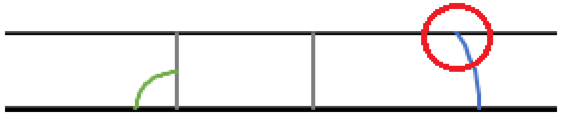
- Was developed out of necessity because we have not been able to determine a way to find beta values for the Ct direction and develop the Combination of Corner and Oblique Through Cracks at Hole solution
- We tried 3 different methods of finding Beta Ct:
  - % of the thickness
  - % of the parametric angle
  - The closest point to the free edge (“ideal” point on the graphs)
- All 3 methods produced very disappointing results

Validation of Ability to Consistently Find Vertices

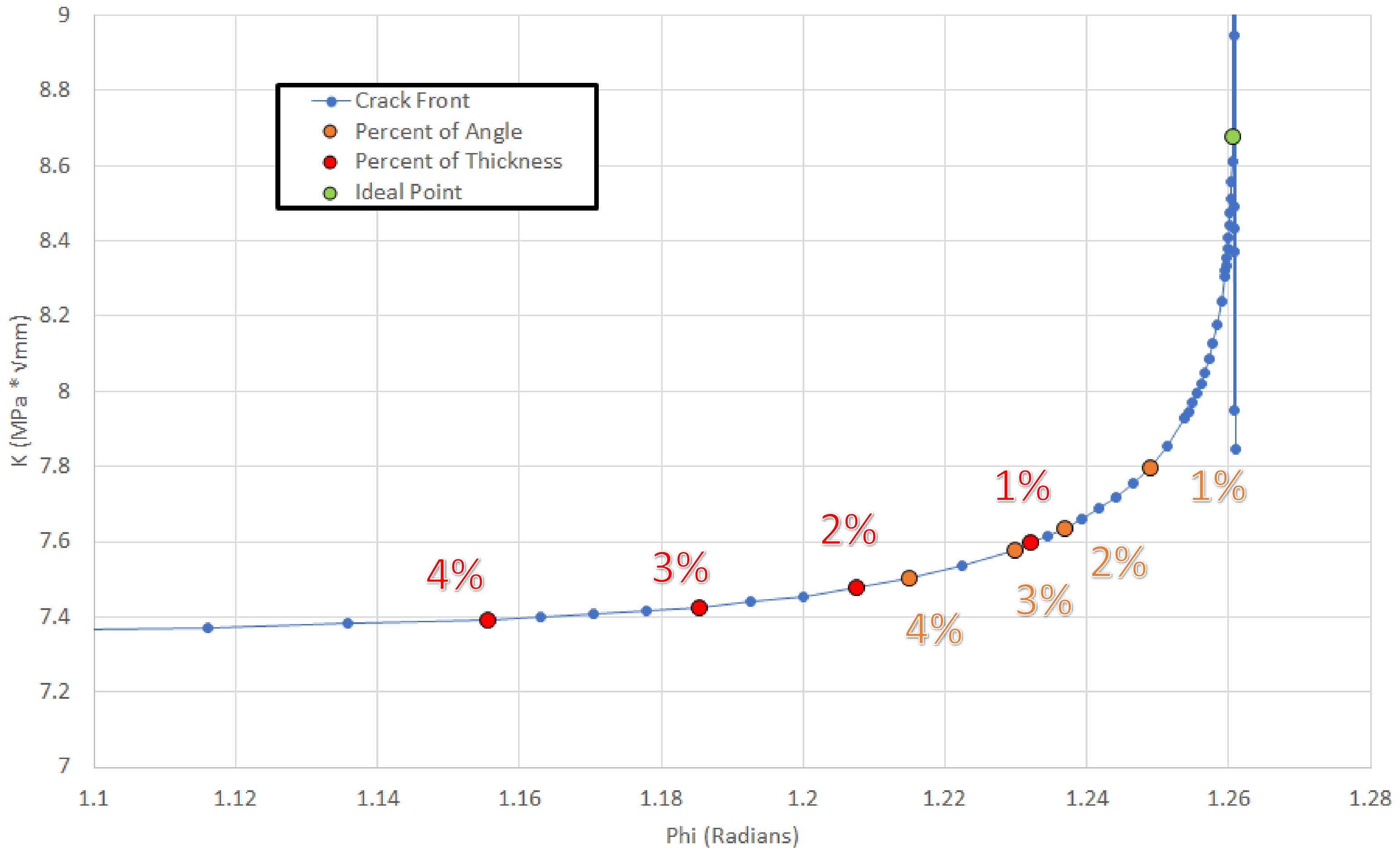
- There is no issue with finding vertices for A and C crack direction
- We were not able to determine a way to find Beta values for the Ct direction. There is no clearly defined local maximum on the neighborhood of the surface, similar to C and A directions. The K (Beta) starts wild oscillations when approaching the surface
- We tried 3 different methods of finding Beta Ct:
  - % of the thickness
  - % of the parametric angle
  - The closest point to the free edge ("ideal" point on the graphs)
- All 3 methods produced very disappointing results

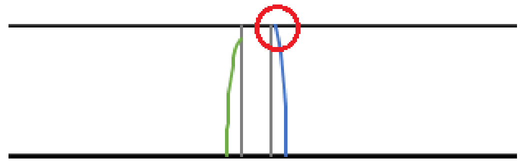
r/t=0.8, a1/c1=1.0, a1/t=0.5, a2/c2=1.0, a2/t=2.0



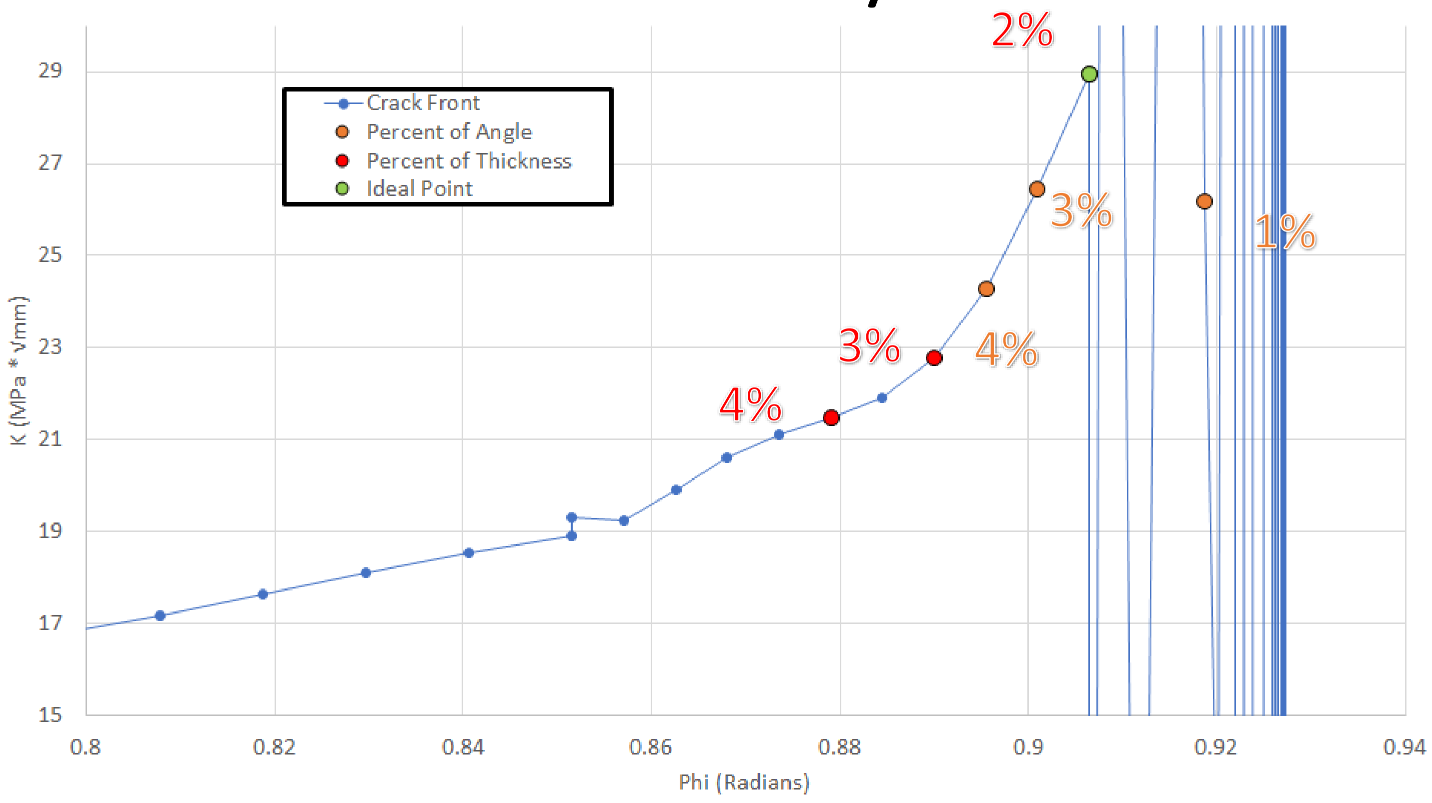


r/t=0.1, a1/c1=9.0, a1/t=0.9, a2/c2=10.0, a2/t=1.05





r/t=1.0, a1/c1=1.0, a1/t=0.5, a2/c2=0.1, a2/t=1.25



1% not pictured, (0.9141, 41.1)

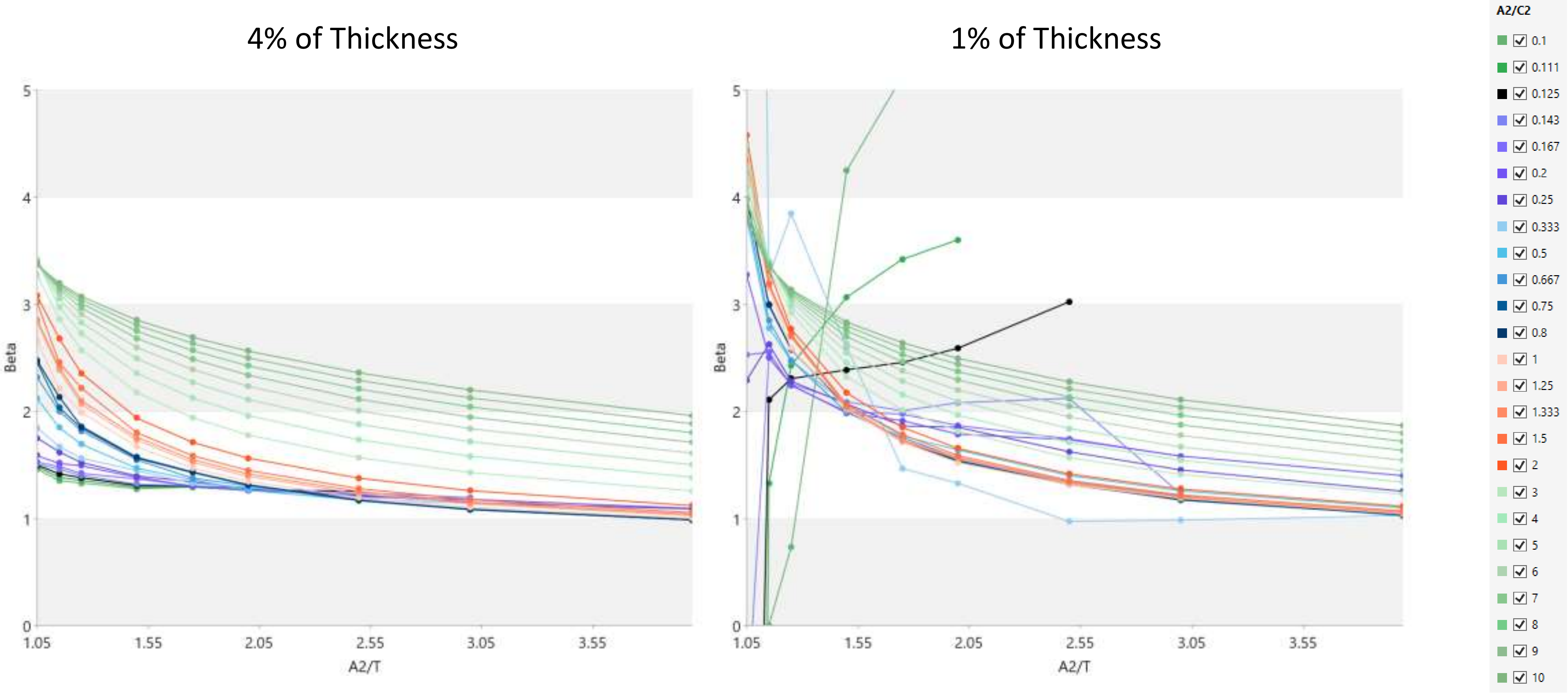
2% not pictured, (0.90952, 40.77)

Very Wide Oblique Crack

Percent Method Vertices
r/t=1.0, a1/c1=1.0, a1/t=0.5

4% of Thickness

1% of Thickness



Generating Part-Through/Through Vertices

- The data for the Part-Through crack would remain unchanged
- Need a method to generate beta values for the Through crack on the opposite side of the hole
- We decided to use the steepest possible Oblique crack available for each C length, to best approximate the Part-Through/Through crack case

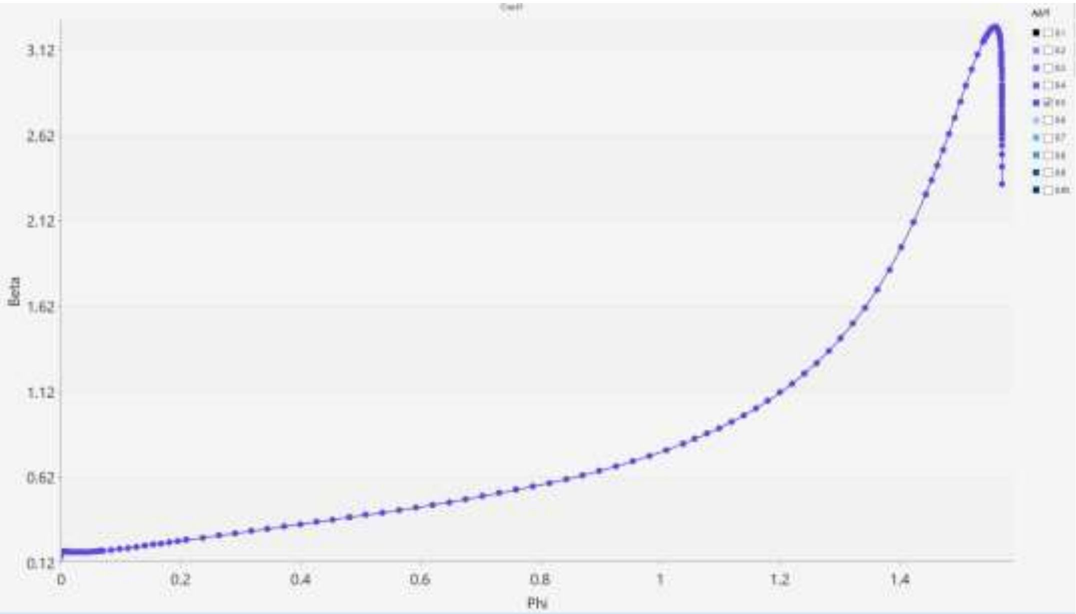
Steps To Generate Part-Through/Through Crack Data

The 5 step approach to generate accurate Part-Through/Through Crack Data that covers all required r/t, a1/c1 and c1/a1

- Step 1: Locate vertices
- Step 2: Find the Oblique Crack with the highest virtual A-Length
- Step 3: Correct data inconsistencies
- Step 4: Extrapolating data to create a complete set
- Step 5: Use spline interpolation to generate equally spaced data points

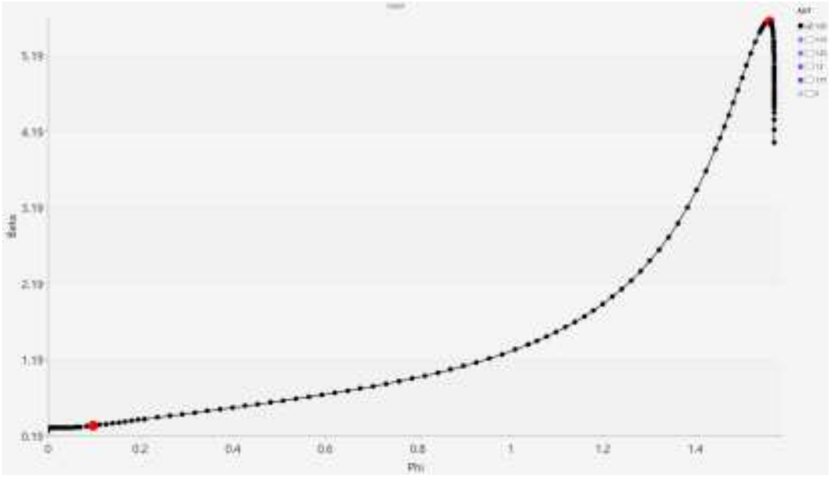
Step 1 – Generate Vertices

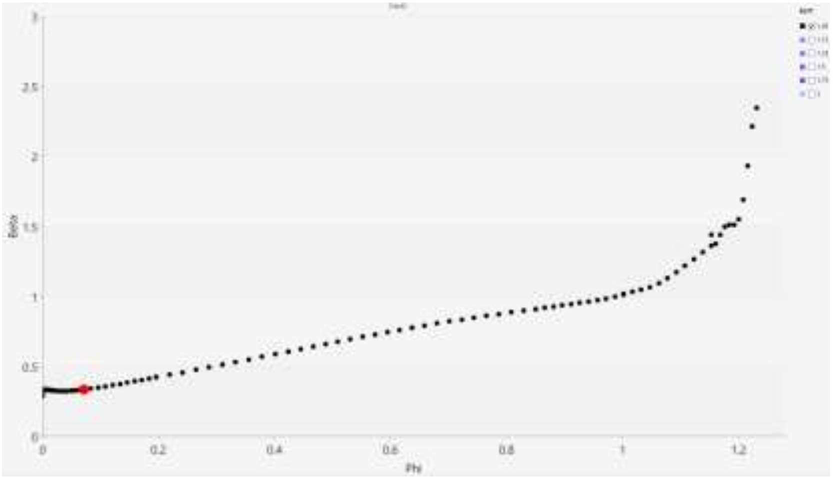
- The original data set comes in a large file that contains many solutions.
- The parameters for the data are r/t, a1/c1, a1/t, a2/c2, and a2/t
- For each of these cases, K values are provided along the entire crack front
- A typical beta distribution is shown on the right



Step 1 – Generate Vertices, Continued

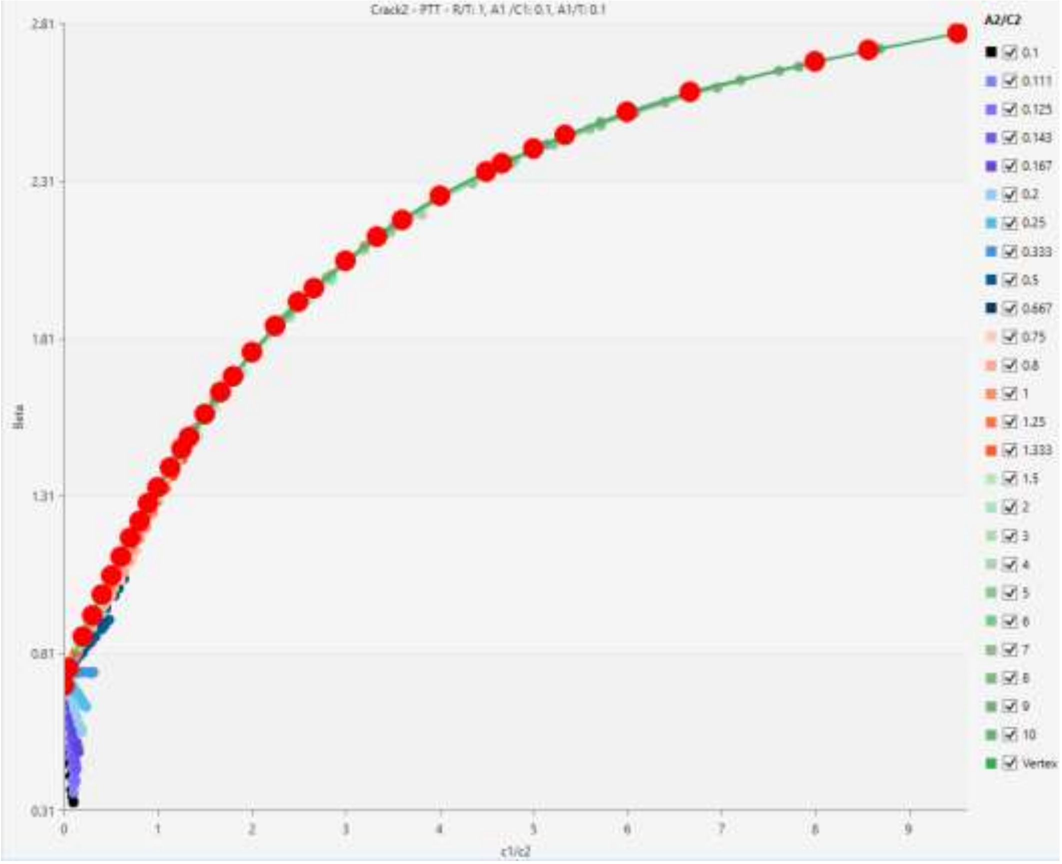
- The local maximum on each end of the curve were used to determine the vertices
- For Part-Through/Through cracks, we extracted vertex values for Crack 1 in A and C-directions, and for the C-direction for the Oblique crack (Crack 2)
- The Ct-direction for Crack 2 was ignored





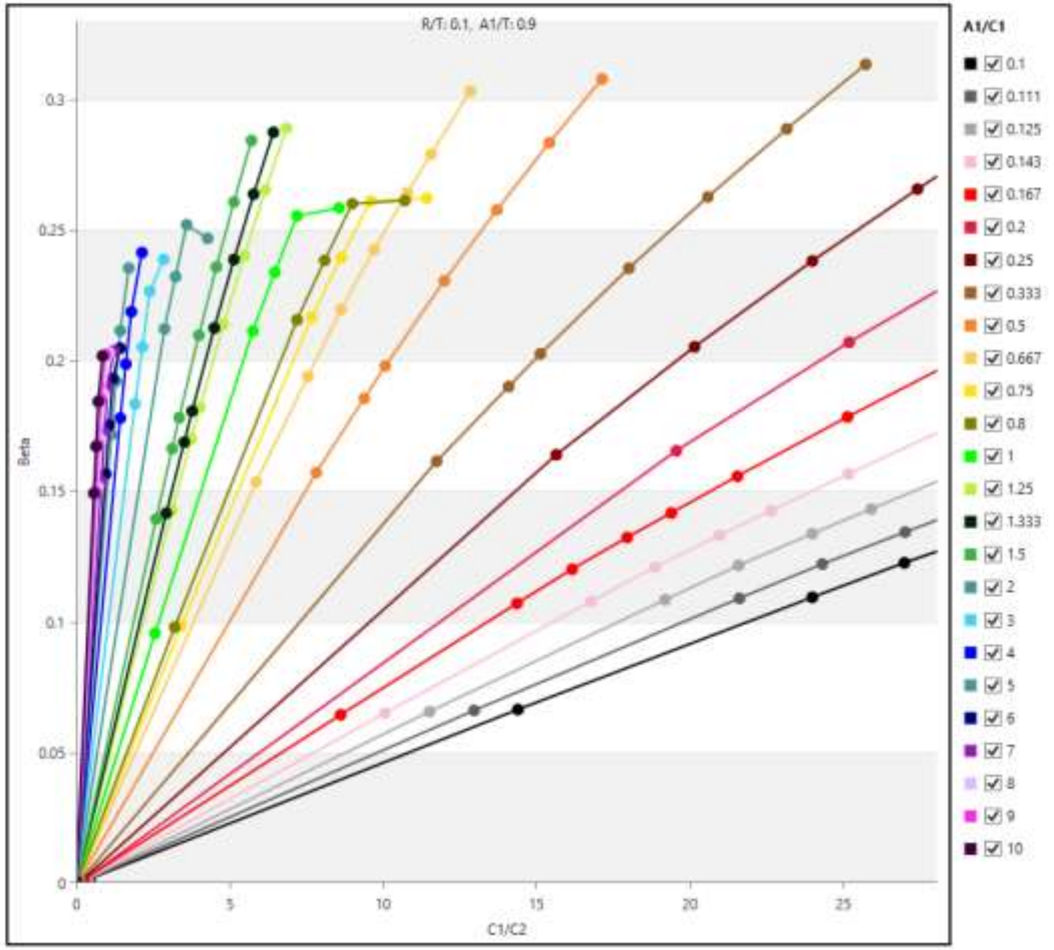
Step 2 – Finding the Highest Virtual A-Length for the Oblique Cracks

- The beta values for the C2 direction were re-plotted vs. C1/C2 for each A2/C2
- The upper limit for the A2/C2 curves are used to determine the through crack (C2) betas
- The resulting through crack beta-values are shown by red dots



Step 3 – Correcting Data Inconsistencies

- When applicable, interpolation methods were used to correct individual points or lines that did not correspond with the trend of the data
- When interpolation could not be used, points were hand fit to better align with the trend of the data
- Each line in the figure represents one beta curve, that was shown in red on the previous slide



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Step 4 – Extrapolating Data To Have A Complete Set

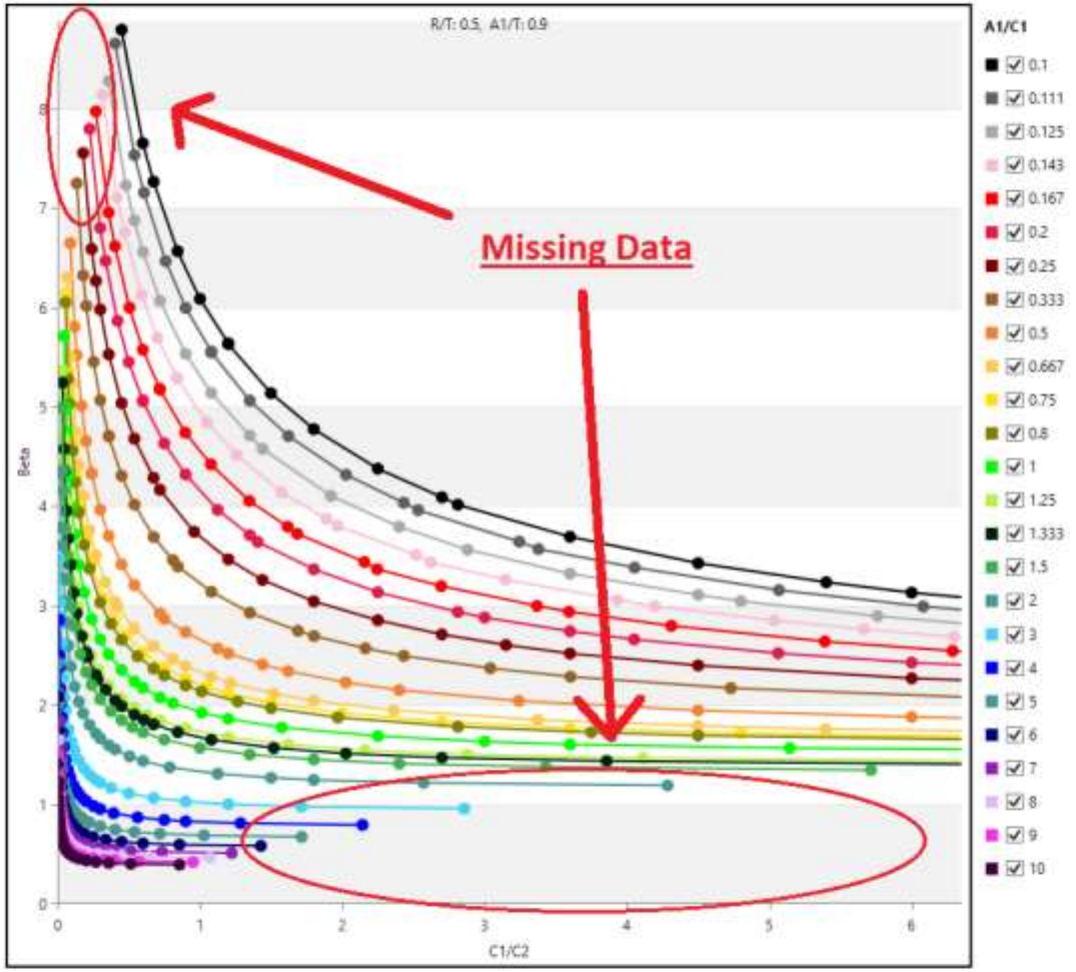
- The goal is to have a complete set of data in the following ranges:

  $0.0 < A1/T \leq 0.95$

  $0.1 \leq A1/C1 \leq 10$

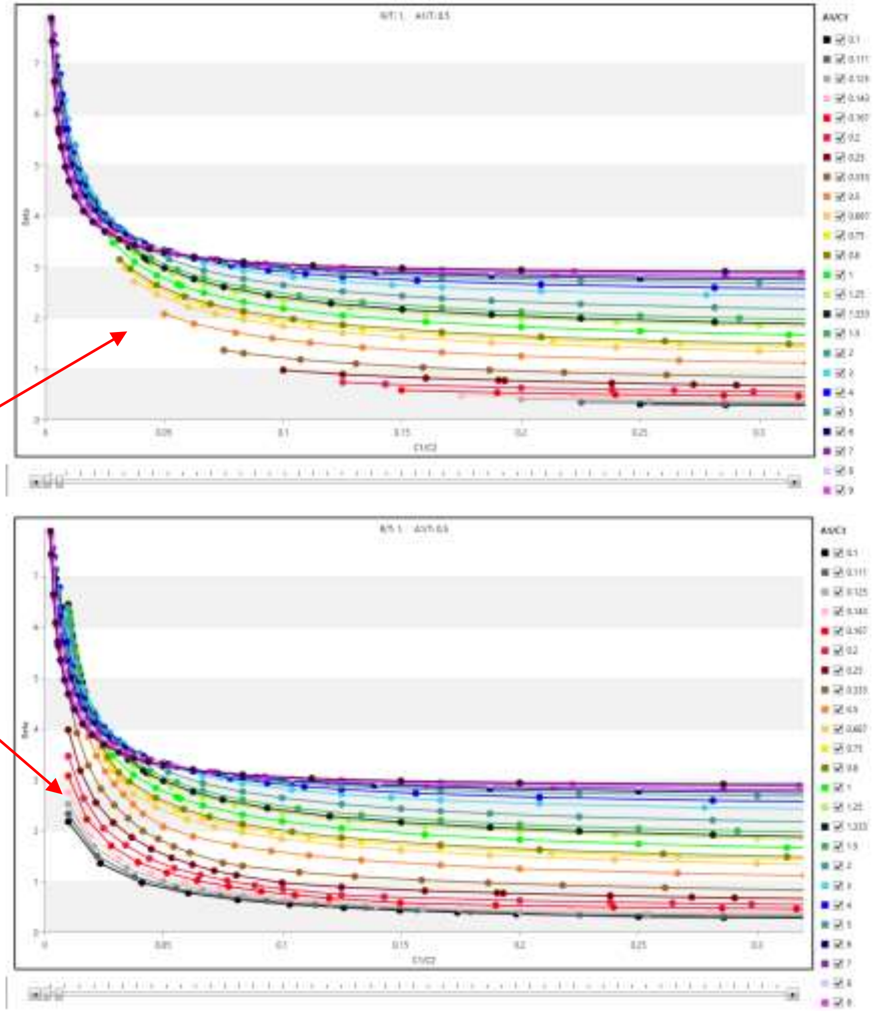
  $0.01 \leq C1/C2 \leq 6.0$

- Most accurate interpolation method requiresa full matrix
- The original data did not cover the required range 0.01 <= C1/C2 <= 6 and A1/T < 0.1.
- To extend these data, we had to use multiple interpolation methods which will be detailed in the following slides



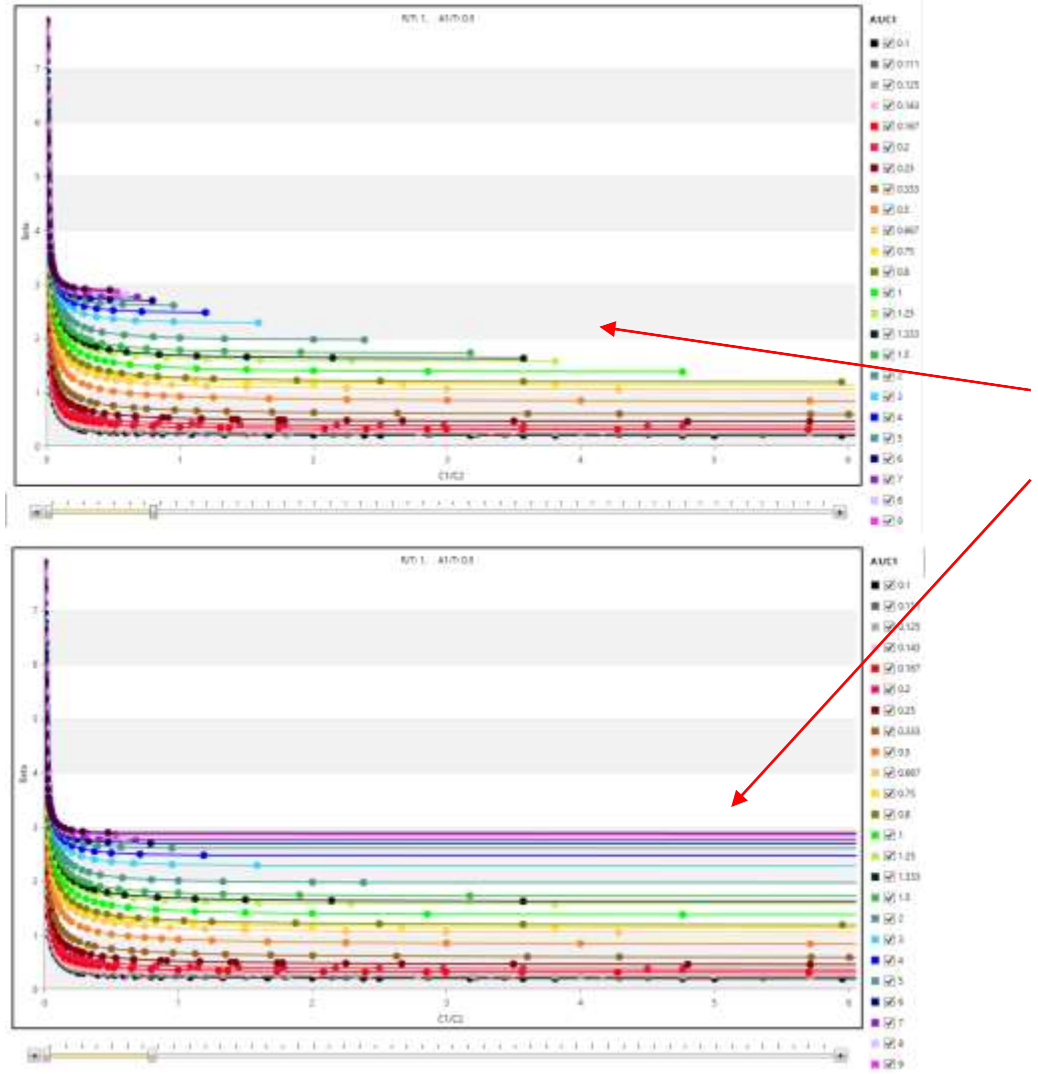
Extending Crack 1 A/C-Direction Data To C1/C2=0.01 (Tension)

To extend the Part-Through cracks to C1/C2=0.1, we used the AFGROW Advanced Model (wide plate with a slot and corner crack) to outline the borders of the solution for a given R/T and A1/T



Extending Crack 1 A/C-Direction Data To C1/C2=6 (Tension)

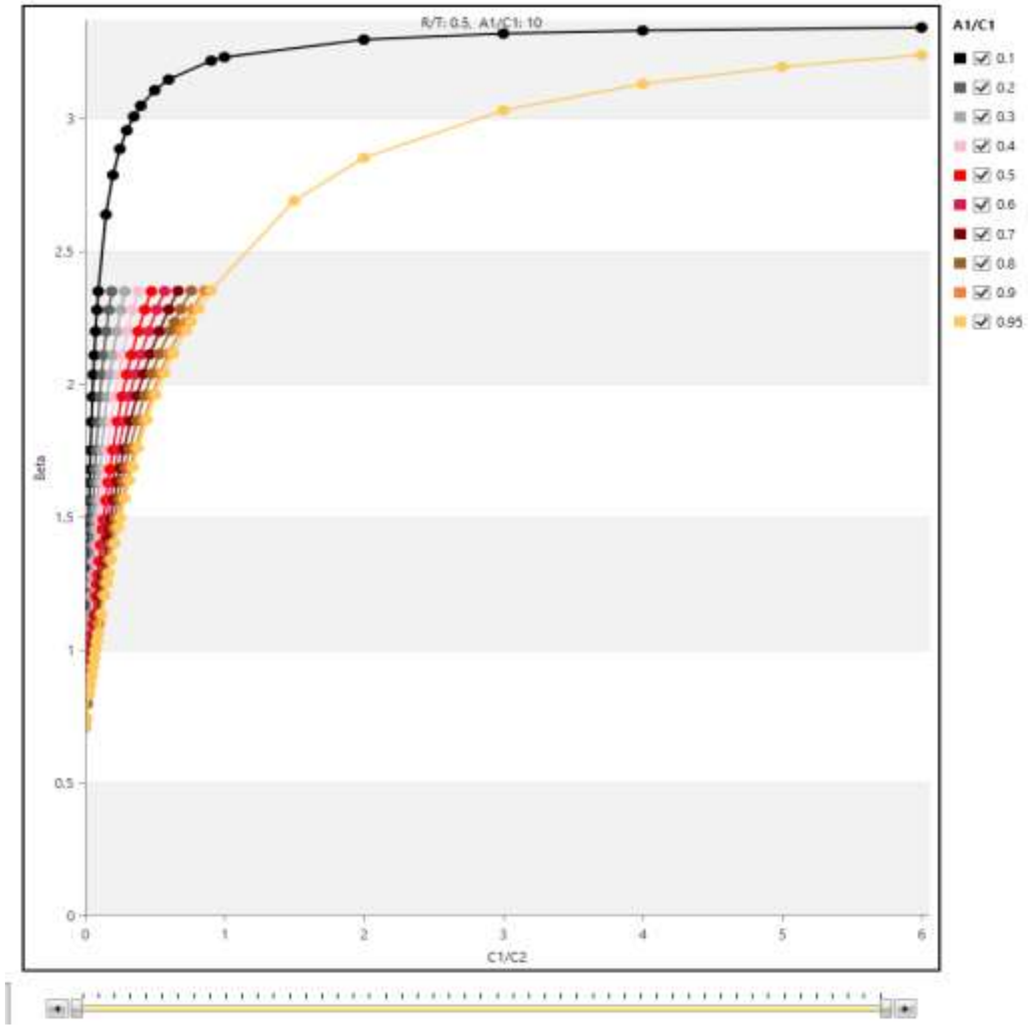
- When C1/C2 = 6, the Part-Through crack is much larger than the Through Crack, so the Through Crack was ignored
- We used the Single Corner Crack at a hole model to calculate the betas for this case

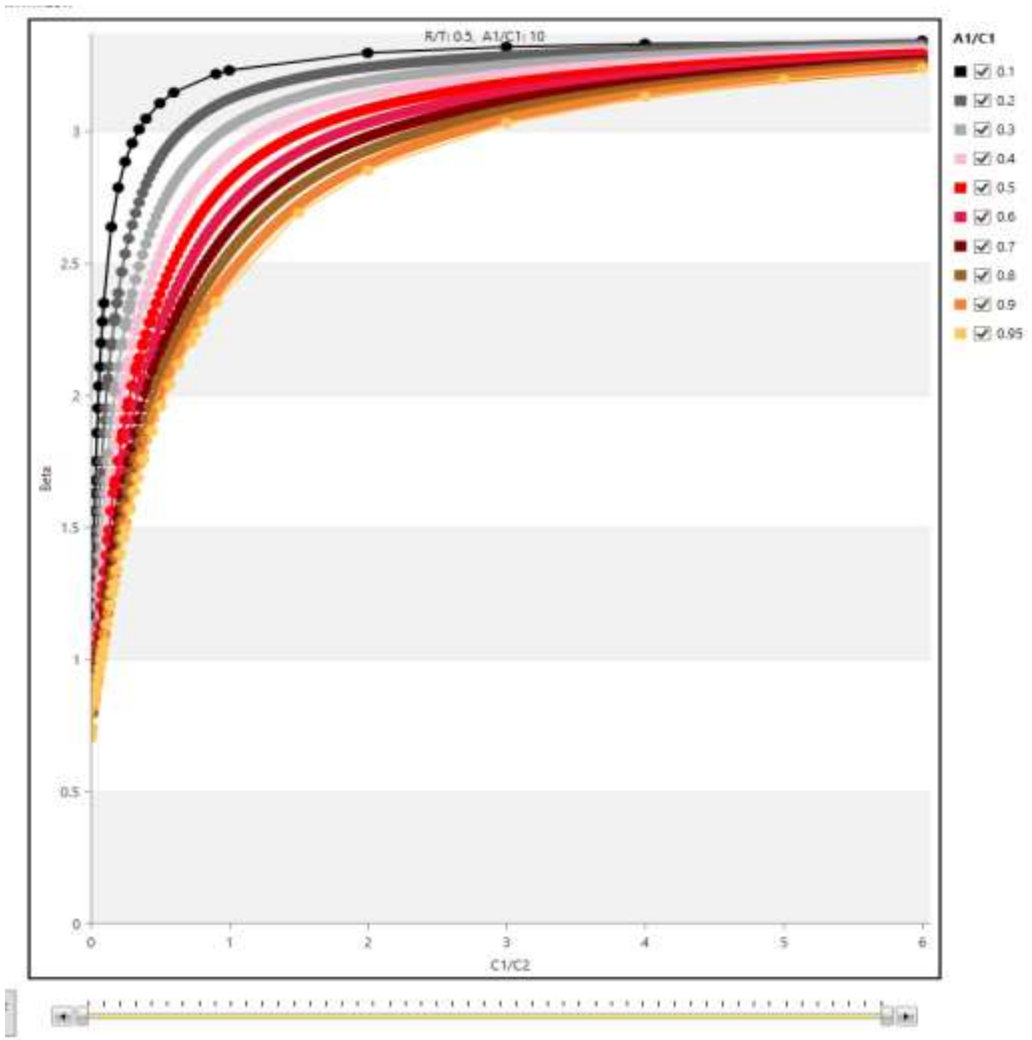


Extending Through Crack Data (Crack 2) To C1/C2=6

- We used a through crack at hole AFGROW model to generate data for cases where A1/T = 0.1 and 0.95 (single and double through crack(s))
- All other values were filled using different interpolation methods in MATLAB
- Graph explaining this process will be shown in next slide

Extending Through Crack Data (Crack 2) To C1/C2=6

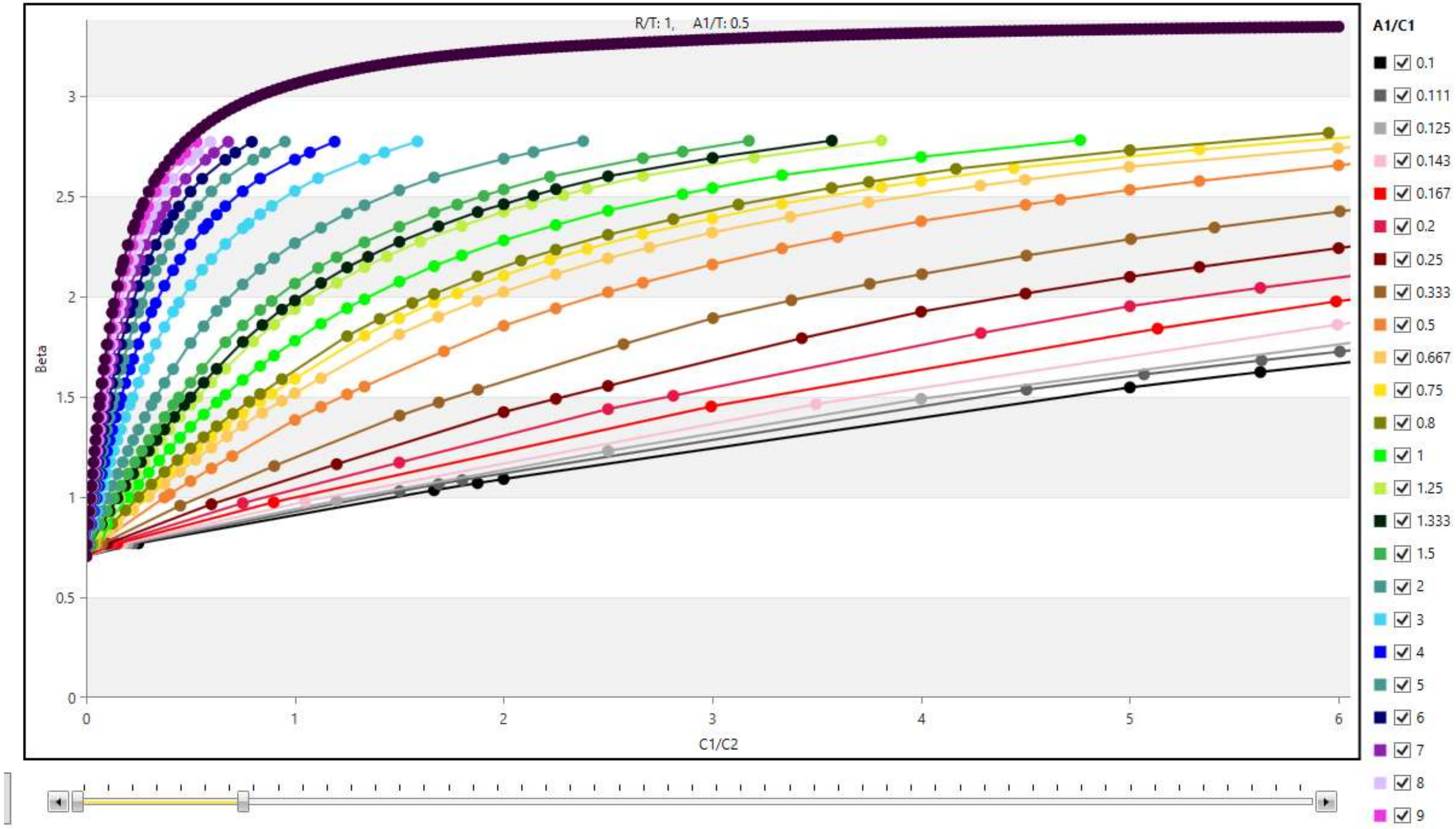




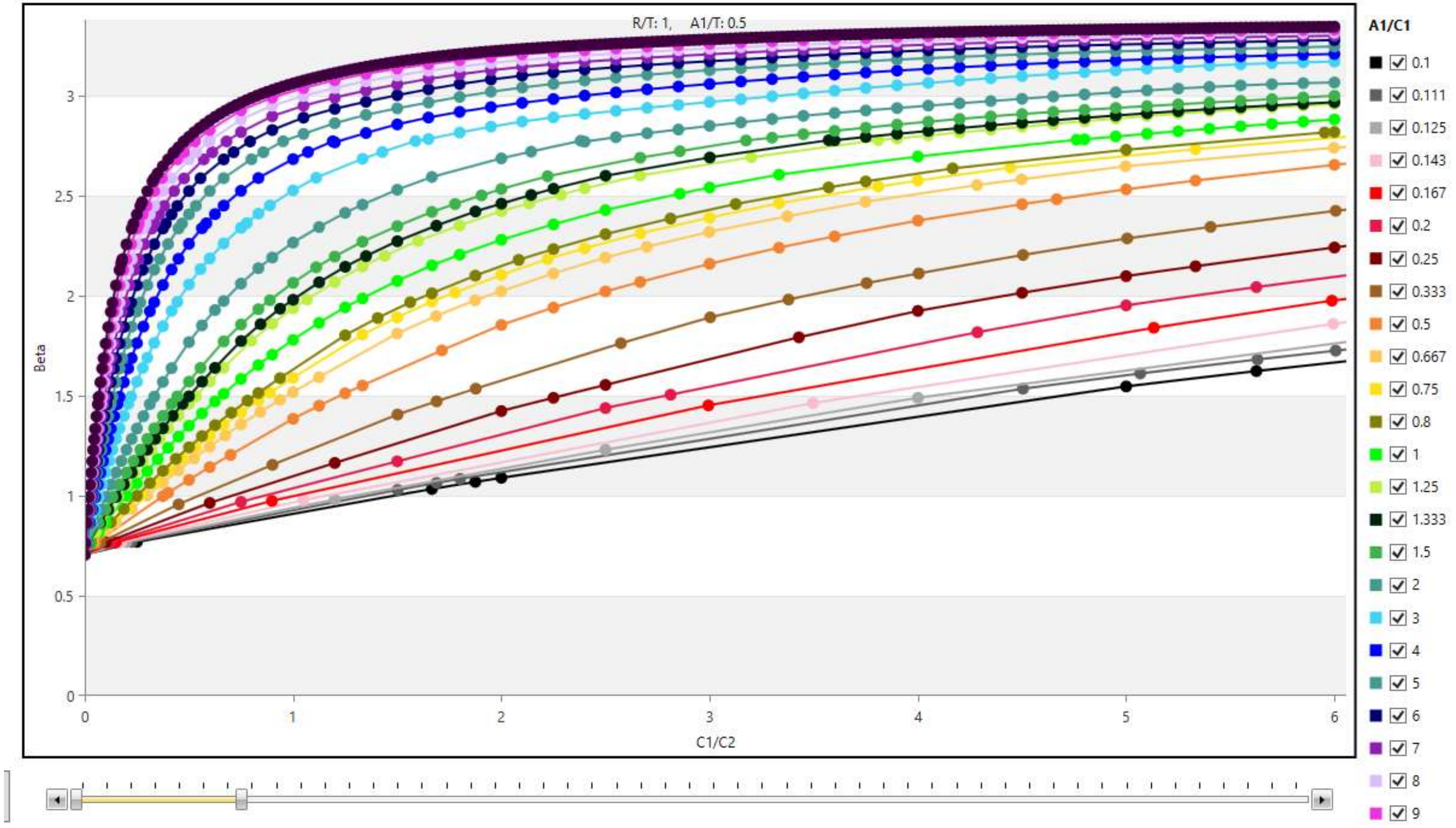
Extending Crack 2 C-Direction Data To C1/C2=6

- The last step is to fill the the data in the A1/T range: 0.2-0.9.
- Built-in MATLAB methods were used to fill the remaining data for each R/T
- The results of the fitting are demonstrated on the two next slide

Extending Crack 2 to C1/C2=6



Extending Crack 2 to C1/C2=6



Extending Crack 2 C-Direction Data to A1/T=0

- The beta for three different loading cases (axial, bearing and bending) all converge to different values as A1/T approaches 0
- This is based on the through crack solution limit as the crack length goes to infinity
- For the Axial loading we used the beta value 0.7071
- For Bearing we used 0.0
- For Bending we used a range of values around 0.4

Extending Crack 1 A1/T to 0

- The different MATLAB extrapolation methods were used to extrapolate the data
- After the extrapolation, the data were reviewed to ensure that the existing trends were followed

Making The Data Uniform

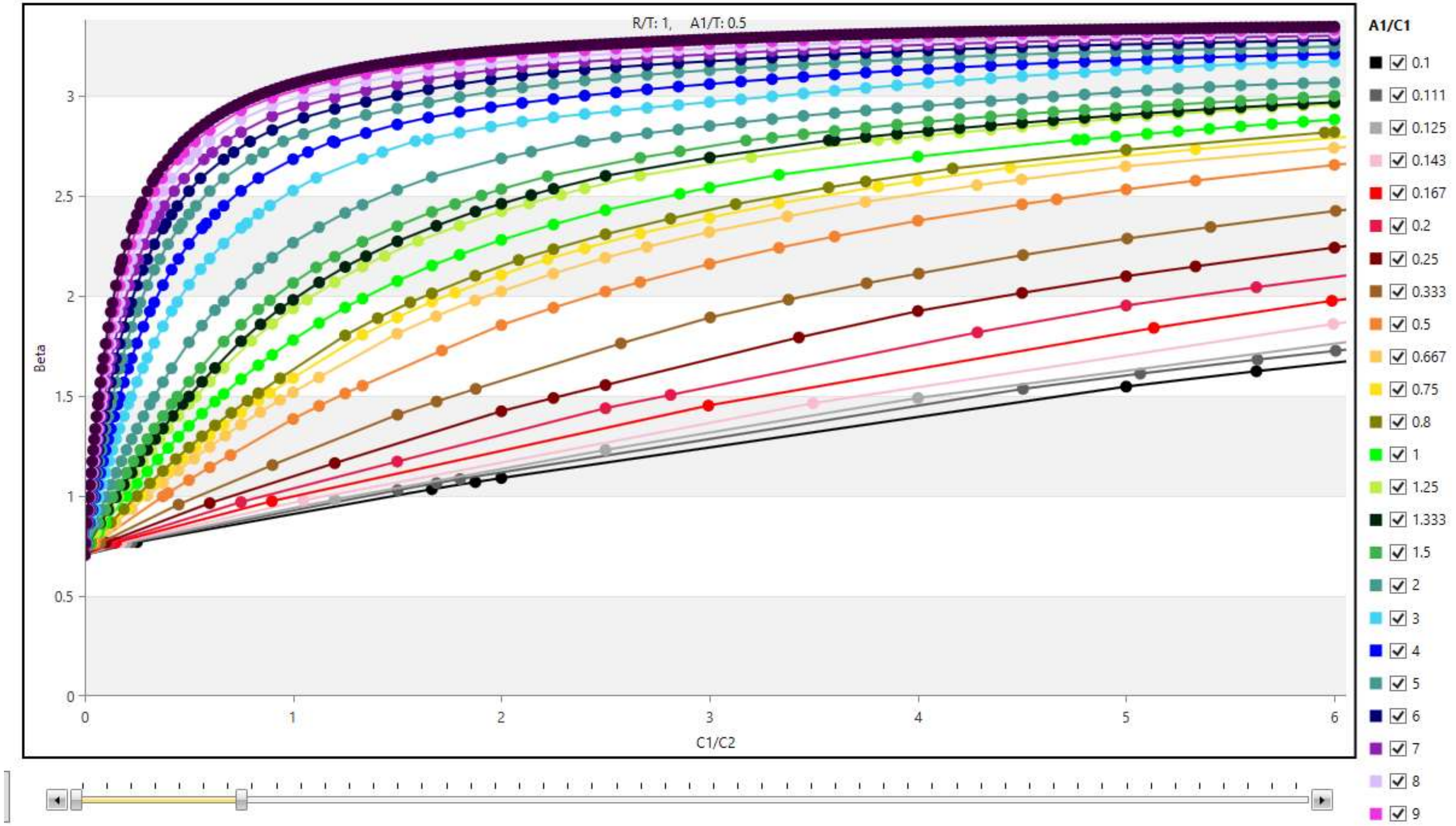
- This step ensures that that data is in an interpolation friendly format and covers the required range

  $0.0 < A1/T \leq 0.95$

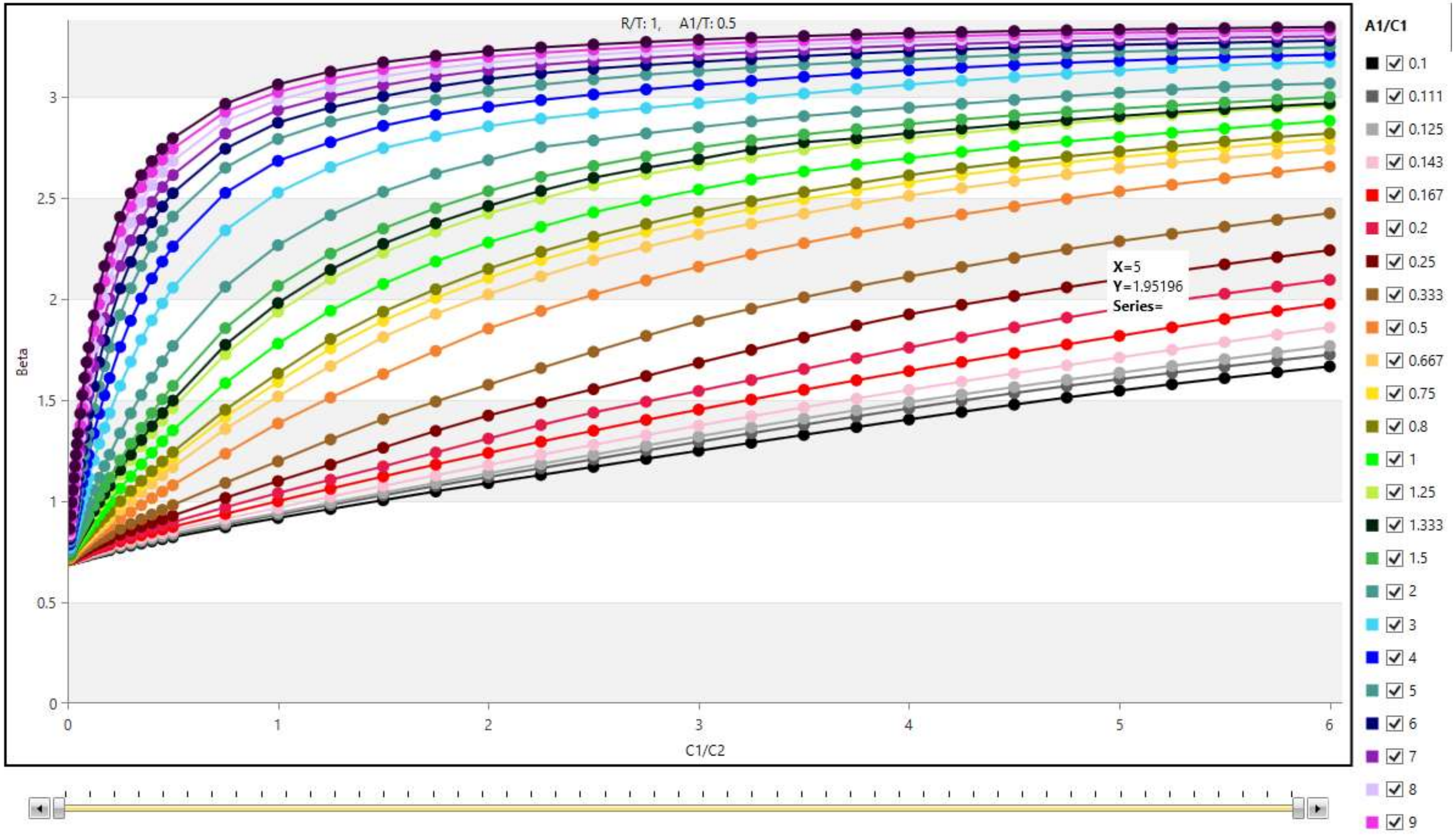
  $0.1 \leq A1/C1 \leq 10$

  $0.01 \leq C1/C2 \leq 6.0$

Before Making Data Uniform



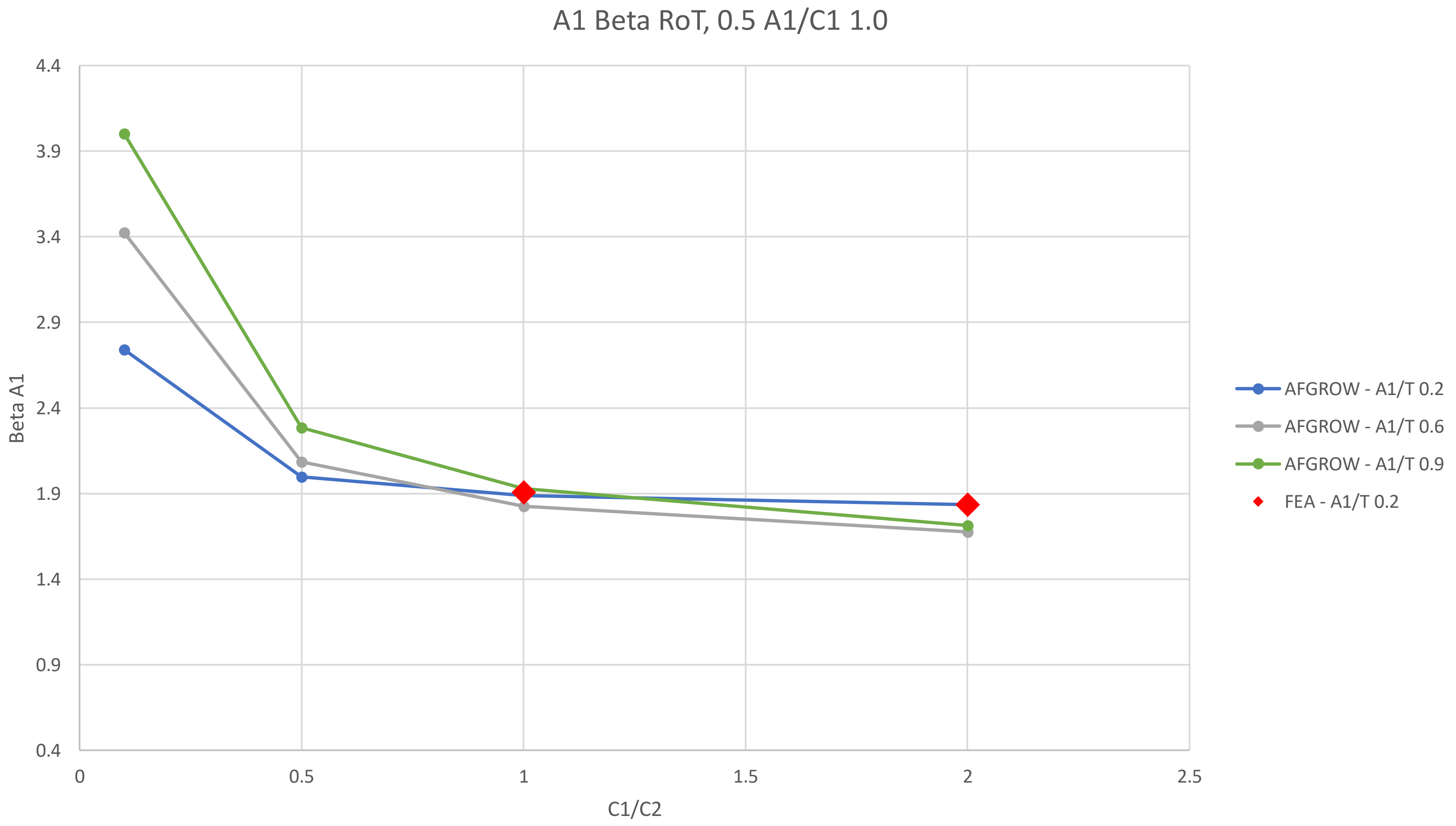
After Making Data Uniform



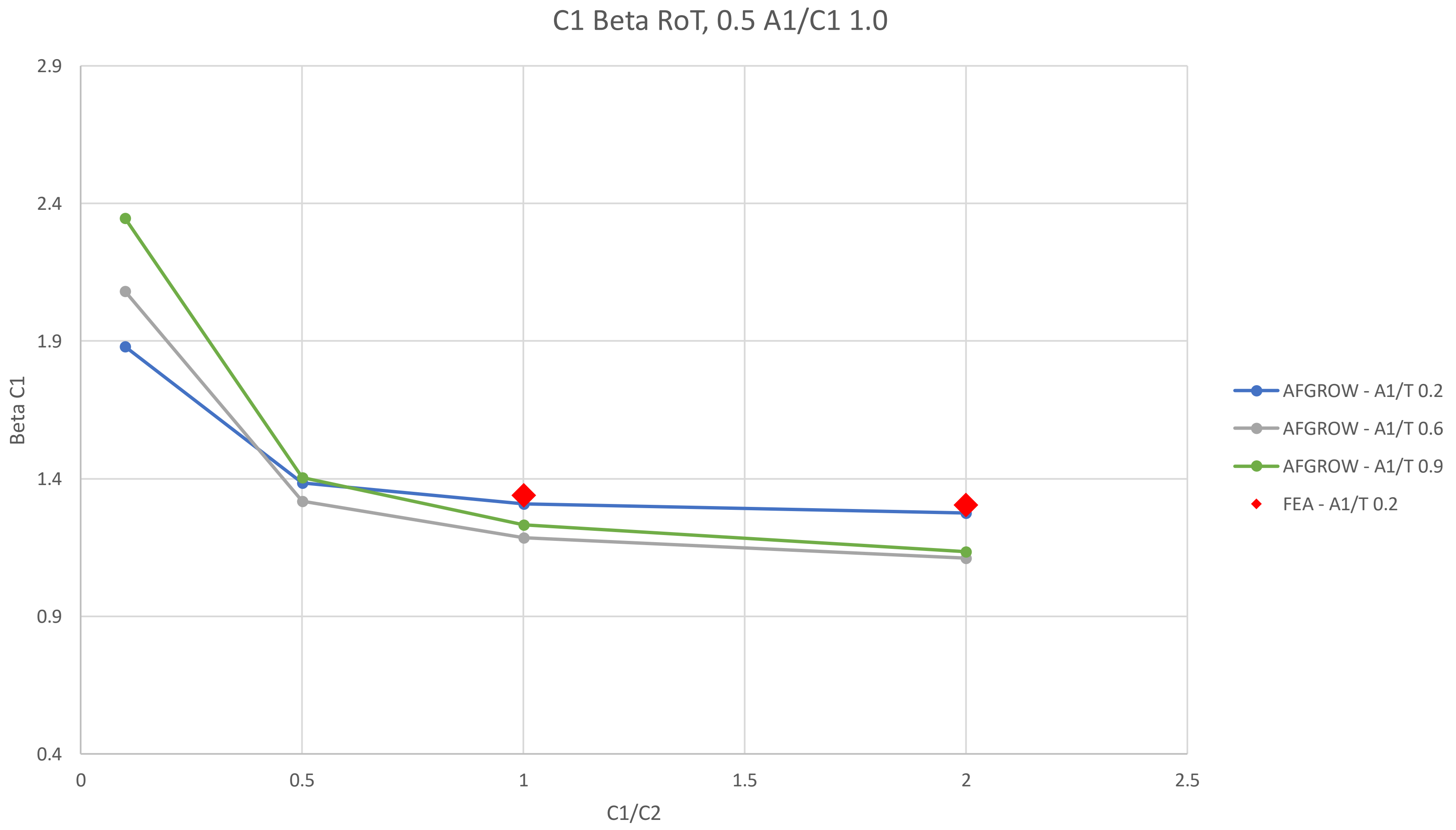
Solution Validation

- The following slides will compare our AFGROW new part through/through solution with FEA results generated by APES Inc. using StressCheck.
- The AFGROW new solution also compared with the beta generated by other currently available solution label "OAS" (Other Available Solution)
- The AFGROW solution is represented by bold line with circular data points and the FEA results are shown as large red diamonds

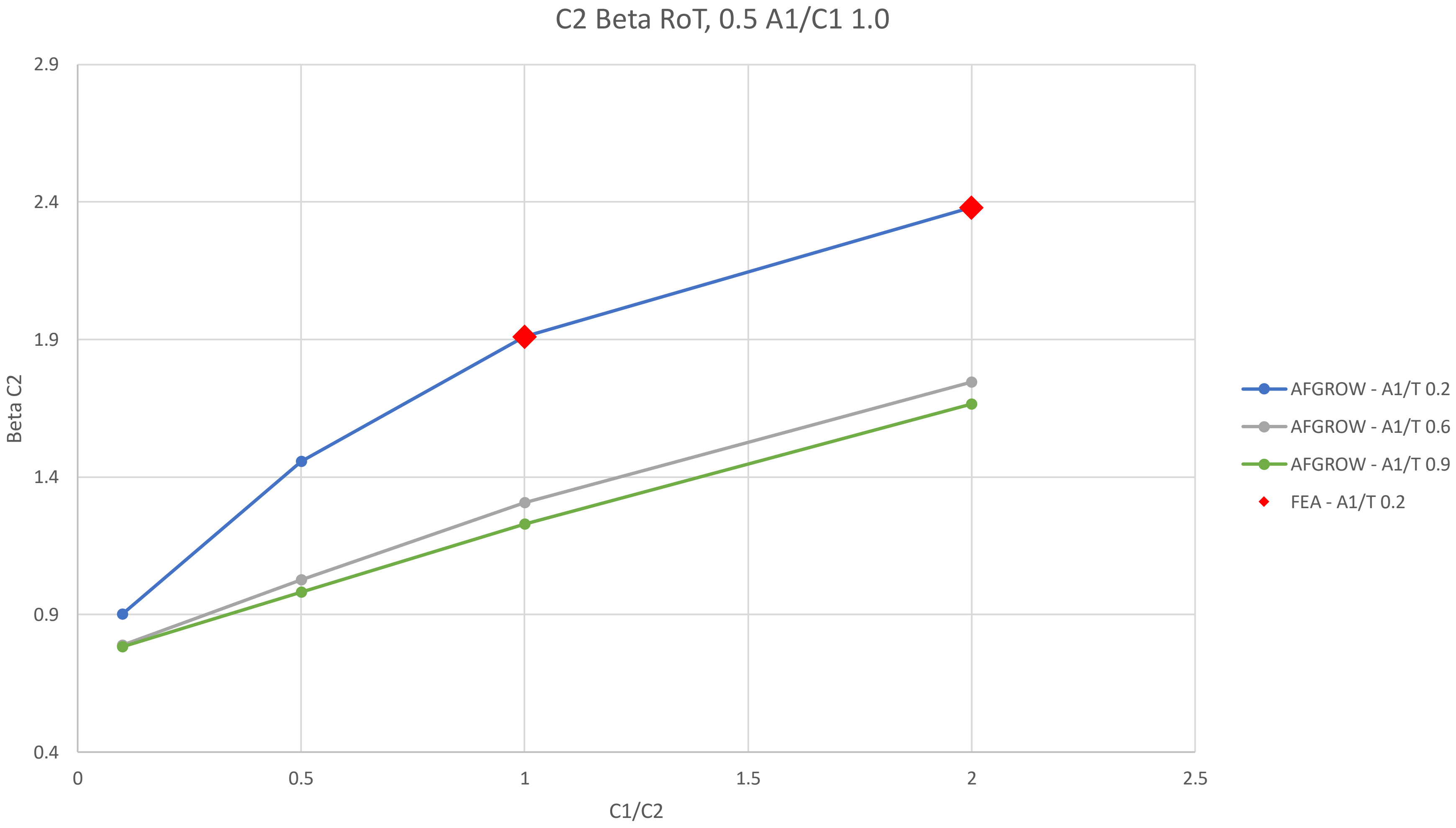
A1 Axial Loading



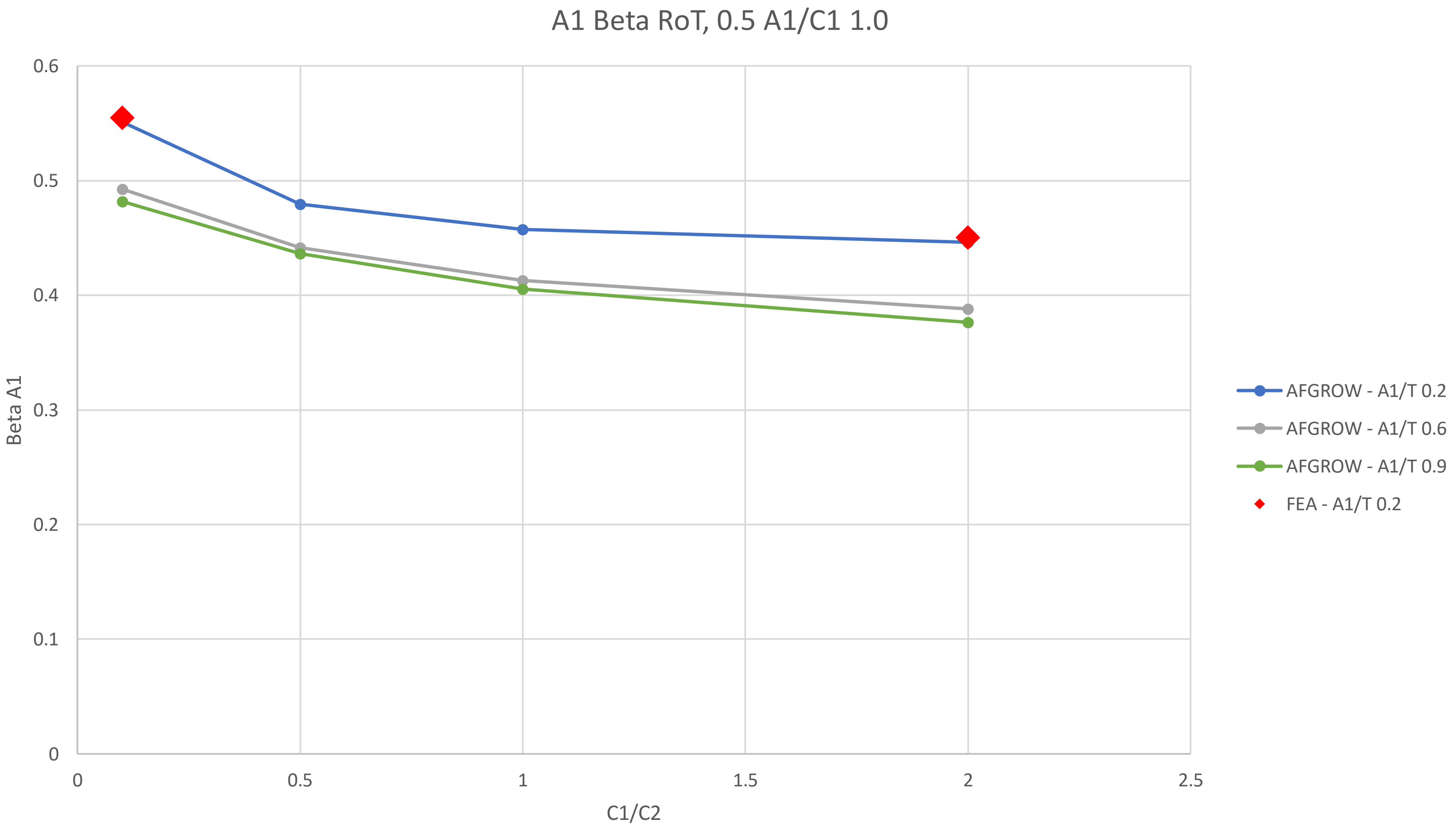
C1 Axial Loading



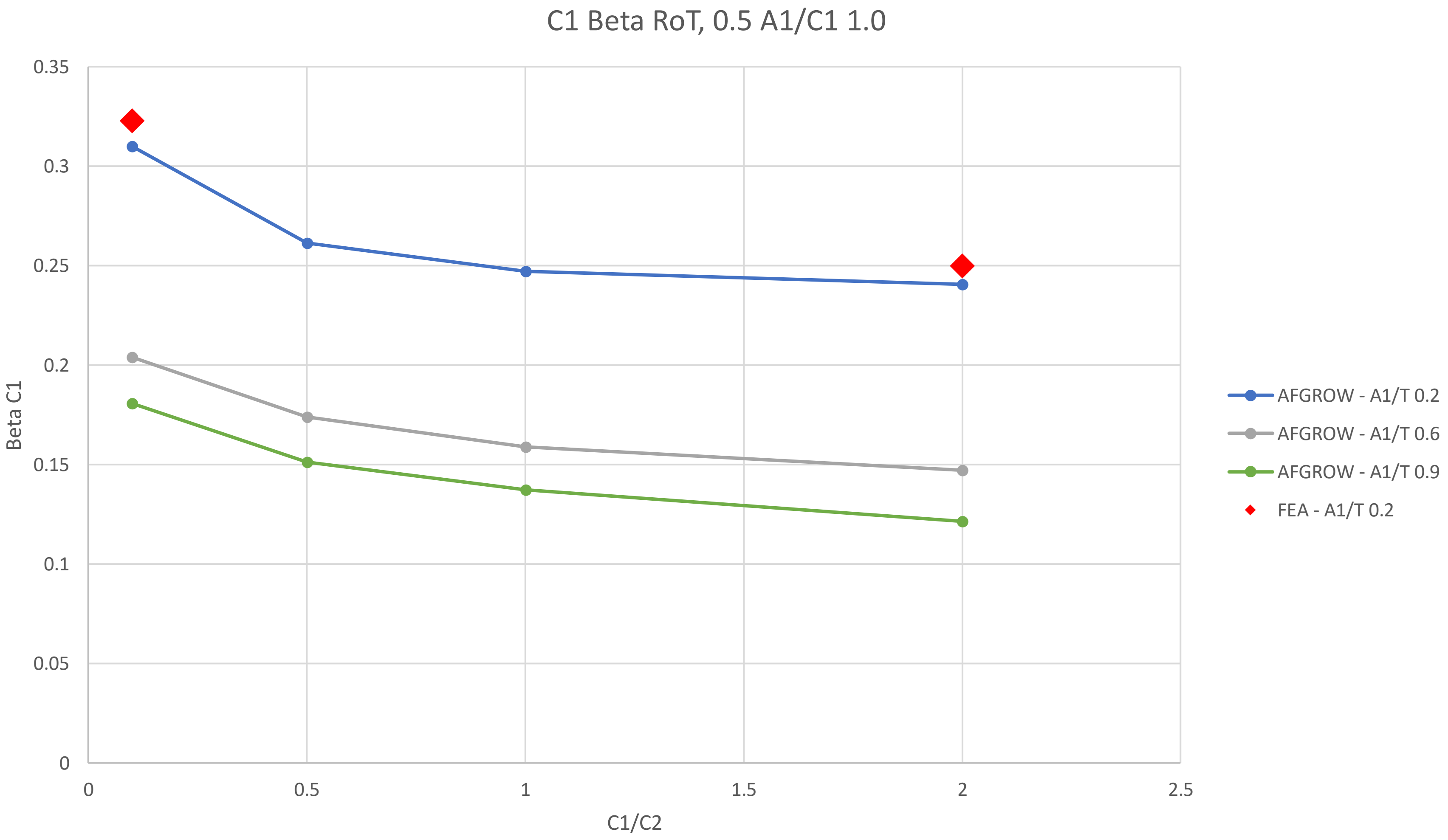
C2 Axial Loading



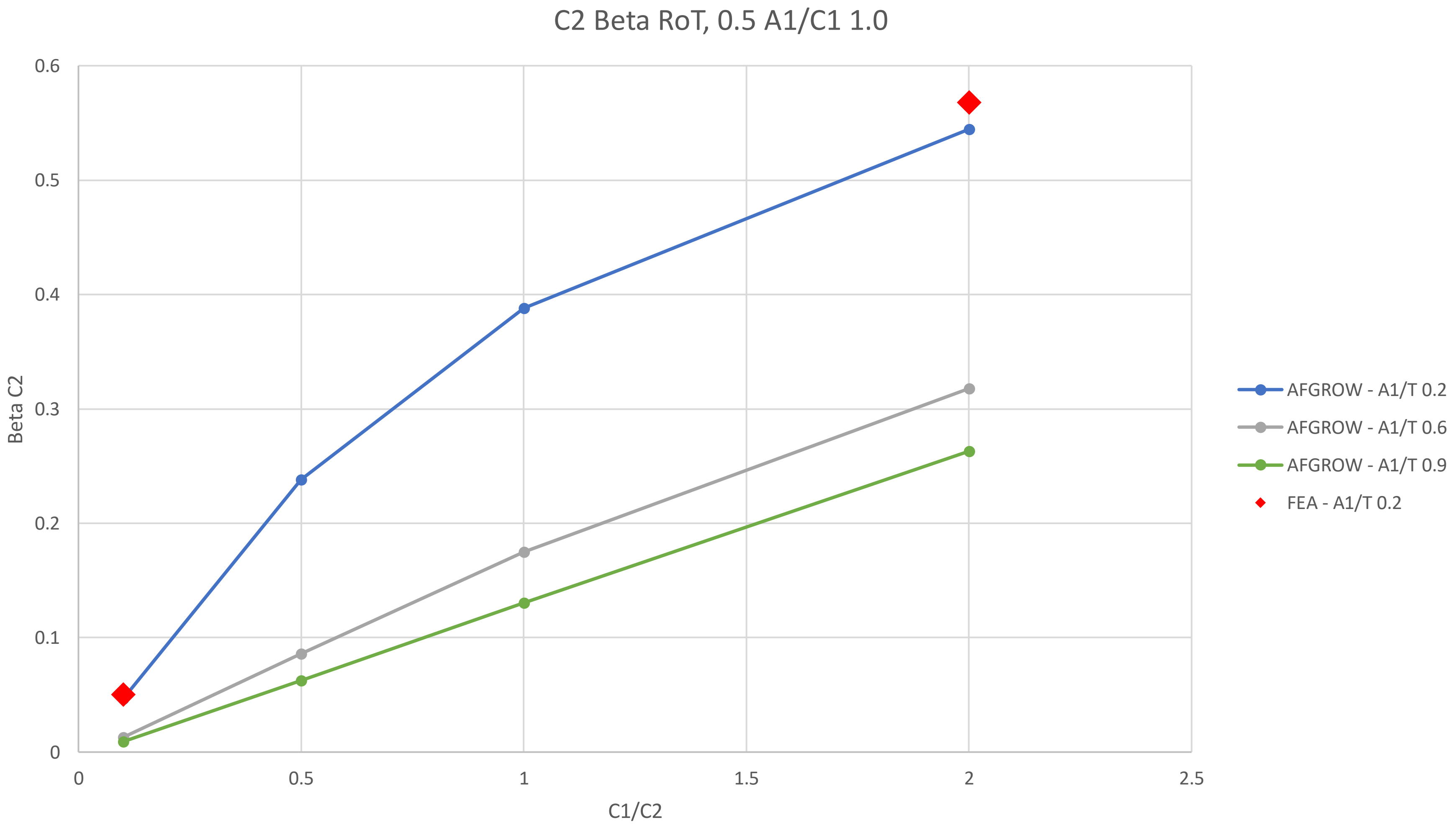
A1 Bearing Loading



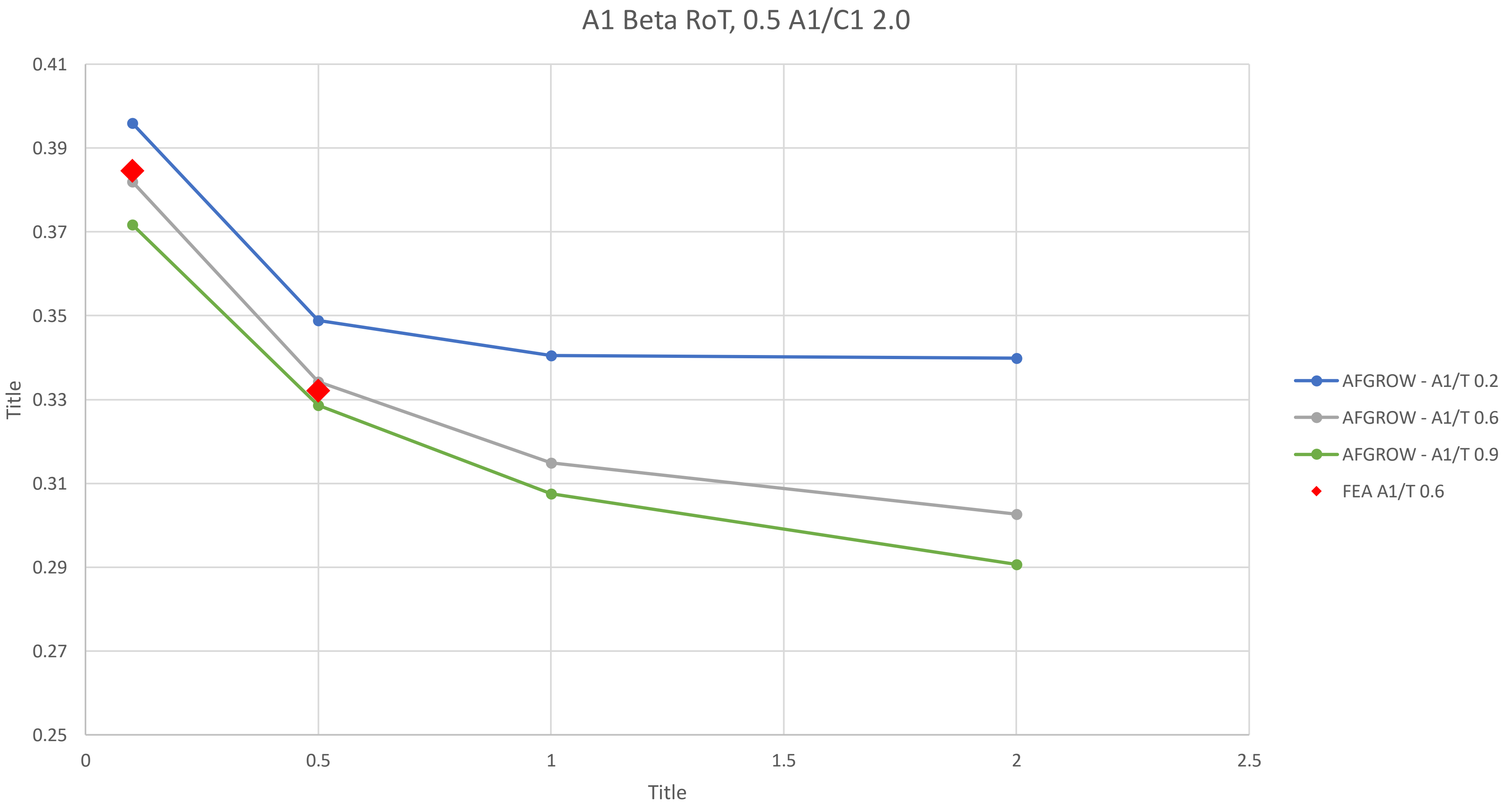
C1 Bearing Loading



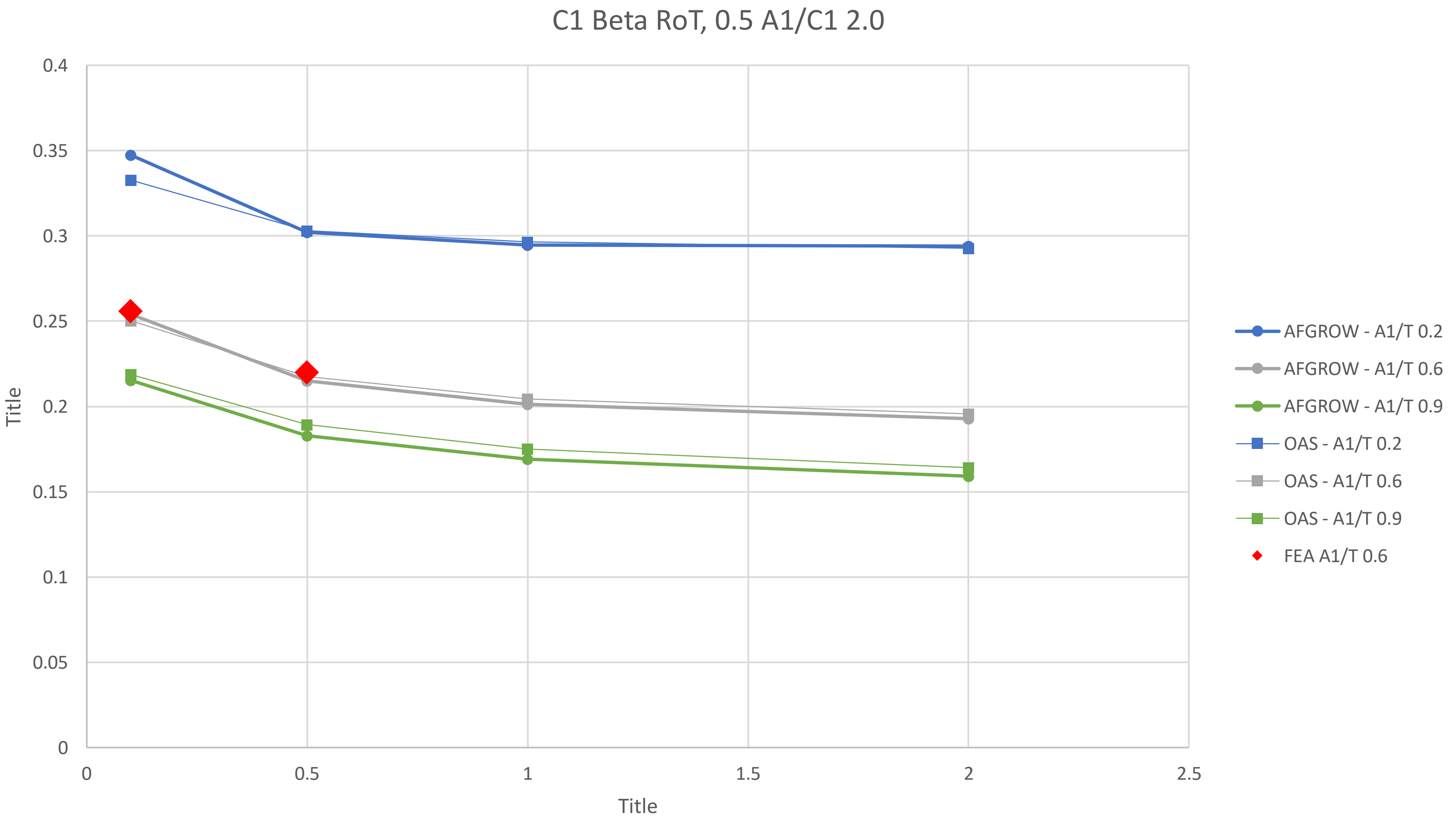
C2 Bearing Loading



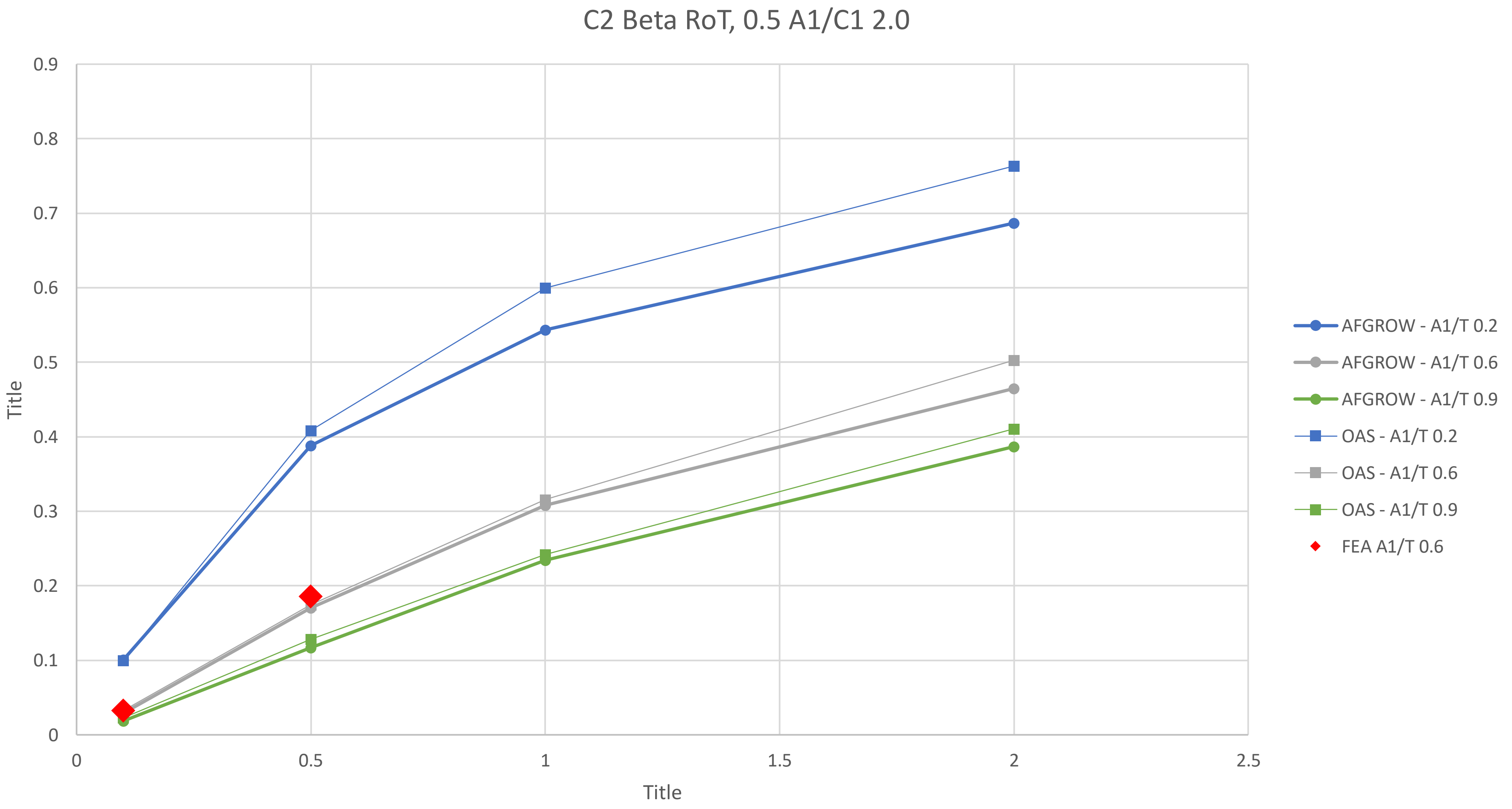
A1 Bearing Loading



C1 Bearing Loading



C2 Bearing Loading



Axial All Cases FEA Comparisons

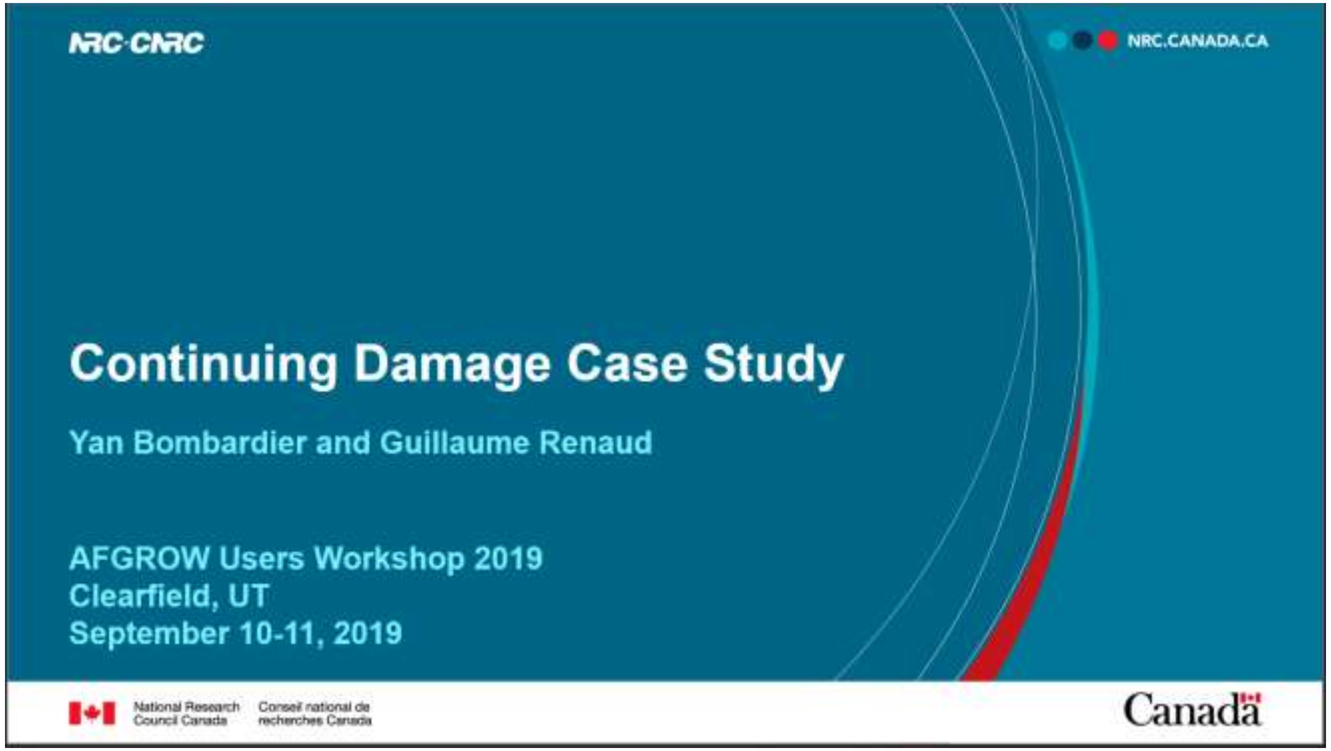
Geometry				AFGROW			FEA			% Diff AFGROW		
RoT	A1/C1	A1/T	C1/C2	A1	C1	C2	A1	C1	C2	A1	C1	C2
0.5	0.5	0.2	0.1	3.9543	1.7382	0.8166	3.9613	1.7536	0.8133	0%	1%	0%
0.5	0.5	0.2	0.5	2.5717	1.1518	1.1359	2.6061	1.1789	1.1244	1%	2%	1%
0.5	1	0.2	1	1.8870	1.3085	1.9110	1.9062	1.3398	1.9093	1%	2%	0%
0.5	1	0.2	2	1.8361	1.2757	2.3793	1.8343	1.3038	2.3789	0%	2%	0%
0.5	2	0.2	1	1.3715	1.3558	2.3798	1.3852	1.3828	2.3732	1%	2%	0%
0.5	2	0.2	2	1.3688	1.3530	2.7444	1.3713	1.3675	2.7546	0%	1%	0%
1	0.5	0.6	0.1	4.8854	2.4012	0.7939	4.9369	2.4757	0.7491	1%	3%	6%
1	0.5	0.6	0.5	2.9730	1.5214	1.0386	2.9783	1.5456	1.0412	0%	2%	0%
1	1	0.2	2	1.9922	1.6108	2.7863	2.0147	1.6446	2.7353	1%	2%	2%
1	1	0.6	0.1	3.1391	2.2693	0.8461	3.1597	2.3249	0.8466	1%	2%	0%
1	2	0.2	2	1.4278	1.6098	3.0187	1.4458	1.6325	2.9701	1%	1%	2%
1	2	0.6	0.1	1.8862	1.8895	0.9527	1.9032	1.9301	0.9499	1%	2%	0%

Bearing All Cases FEA Comparisons

Geometry				AFGROW			FEA			% Diff AFGROW		
RoT	A1/C1	A1/T	C1/C2	A1	C1	C2	A1	C1	C2	A1	C1	C2
0.5	0.5	0.2	0.1	0.6544	0.1923	0.0204	0.6560	0.2017	0.0230	0%	5%	11%
0.5	0.5	0.2	2	0.5171	0.1394	0.3891	0.5223	0.1463	0.4129	1%	5%	6%
0.5	1	0.2	0.1	0.5512	0.3100	0.0466	0.5551	0.3230	0.0501	1%	4%	7%
0.5	1	0.2	2	0.4462	0.2406	0.5446	0.4504	0.2498	0.5681	1%	4%	4%
0.5	2	0.6	0.1	0.3820	0.2539	0.0293	0.3846	0.2560	0.0327	1%	1%	10%
0.5	2	0.6	0.5	0.3342	0.2151	0.1705	0.3321	0.2200	0.1856	1%	2%	8%
1	0.5	0.6	0.1	0.7063	0.2428	0.0150	0.7134	0.2535	0.0147	1%	4%	2%
1	0.5	0.6	0.5	0.6306	0.2064	0.0927	0.6308	0.2127	0.0934	0%	3%	1%
1	1	0.2	2	0.4963	0.3607	0.6768	0.4996	0.3684	0.6776	1%	2%	0%
1	1	0.6	0.1	0.5772	0.3395	0.0316	0.5725	0.3496	0.0325	1%	3%	3%
1	2	0.2	1	0.3604	0.3832	0.6781	0.3646	0.3911	0.6769	1%	2%	0%
1	2	0.2	2	0.3602	0.3830	0.7680	0.3643	0.3883	0.7529	1%	1%	2%

Solution Validation

Our goal is to use a new model to reproduce the life prediction for a Ligament Failure Scenario that was presented by Yan Bombardier, National Research Council Canada (NRC) at AFGROW User Workshop 2019 and compare the results.

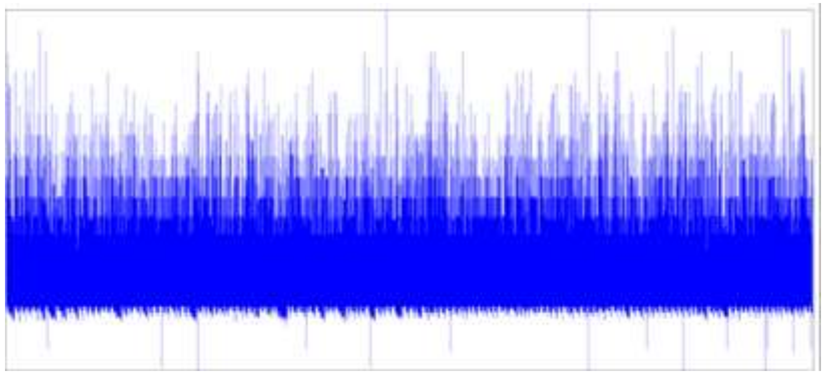


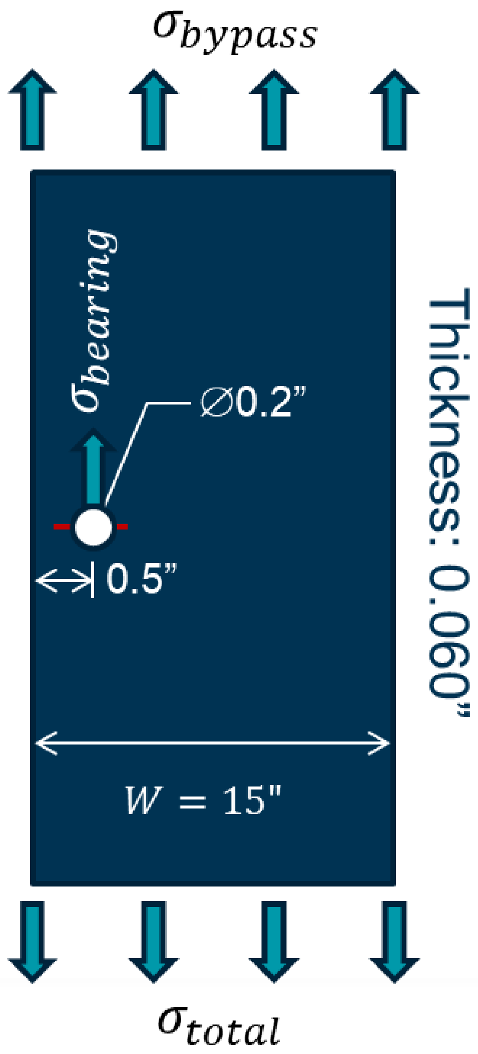
Solution Validation: Problem Definition

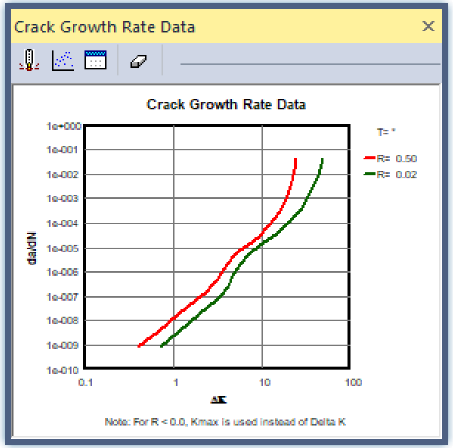
Geometry, Loading, Material

– **Offset hole in a plate**

- Material: 7075-T6, Tabular Lookup (R = 0.02, R = 0.5)
- Retardation: Willenborg (SOLR = 1.7)
- Spectrum: Variable amplitude (A-10)



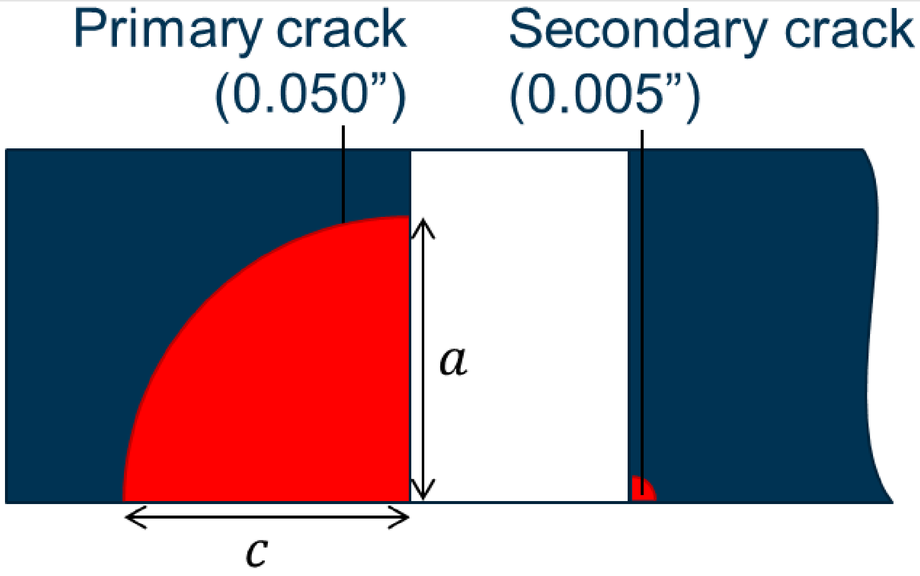




Solution Validation: Problem Definition

Crack Size, Shape, Sequence

- Quarter-circular cracks (fixed a/c ratio)
  - Primary crack: c_o = 0.050”
  - Secondary crack: c_o = 0.005”
  - Bearing load lost after ligament failure
  - Transition to through crack: 95% of thickness[1]

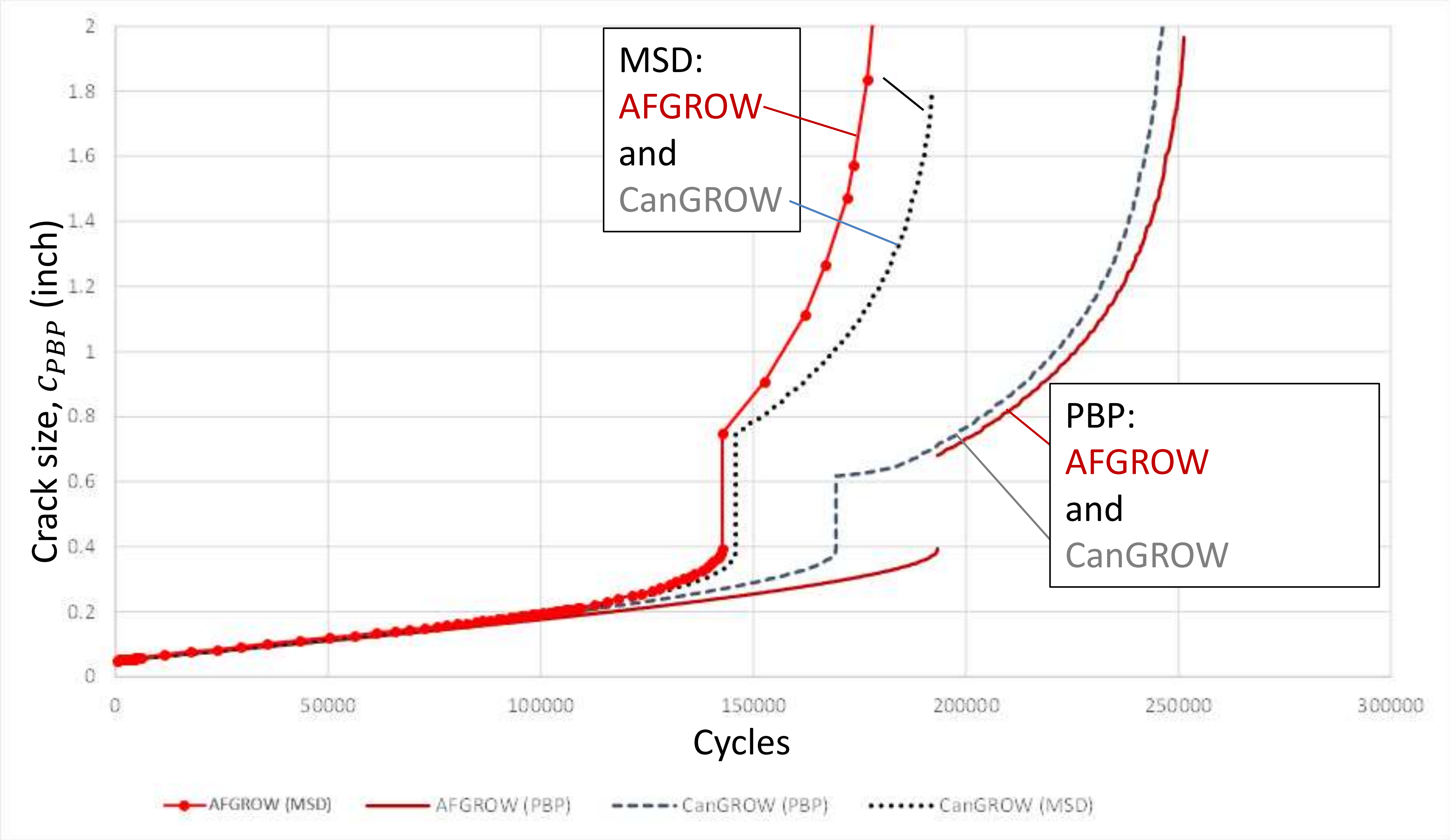


Model	Bypass stress fraction	Bearing stress fraction
Diametrical crack	0.90	1.969
Edge crack	1.00	0.000

[1] Current CanGROW implementation: 100% of thickness. It is planned to be updated (e.g. transition when plastic zone reached the surface).

Simultaneous Crack Growth

Crack Growth Results – Lead Crack



Approach	Life (cycles)
PBP/AFGROW	251,279
MSD/AFGROW	178,377
PBP/CanGROW	246,357
MSD/CanGROW	193,797

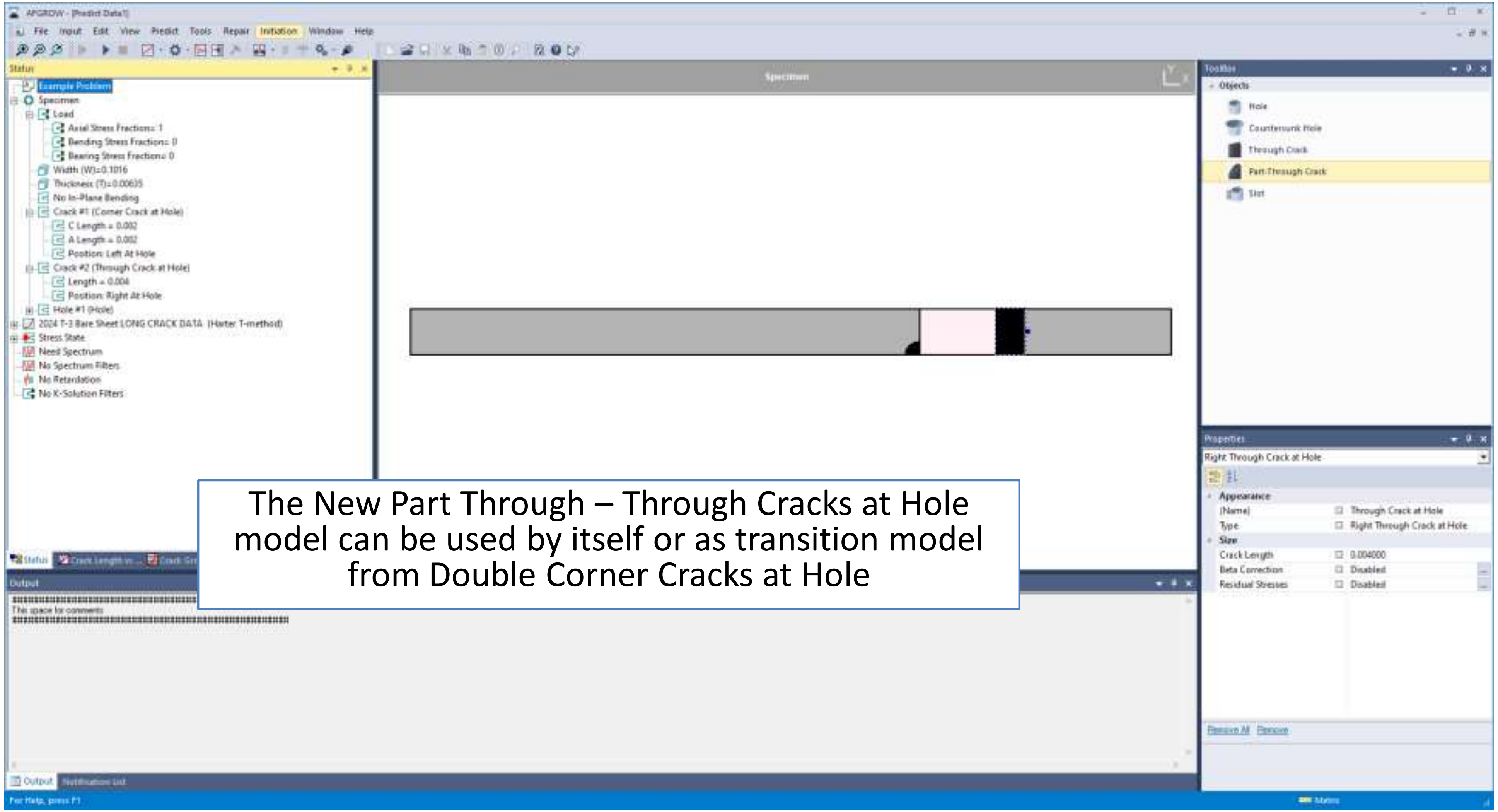
Approach	Cont. Crack
PBP/AFGROW	0.681”
MSD/AFGROW	0.749”
PBP/CanGROW	0.618”
MSD/CanGROW	0.746”

Canada

LexTech

AFGROW.NET

Implementing the Data Into AFGROW



The New Part Through – Through Cracks at Hole model can be used by itself or as transition model from Double Corner Cracks at Hole