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AFGROW European Workshop

Solution for Combinations of Corner and Straight Through Cracks At Hole

Jun 23, 2022

ZHAW School of Engineering
Centre for Aviation

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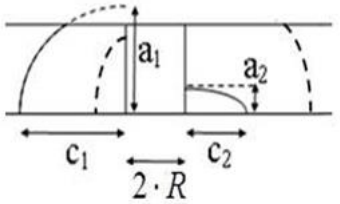
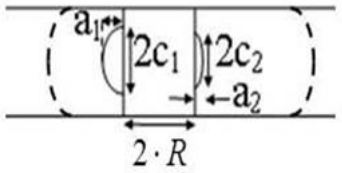
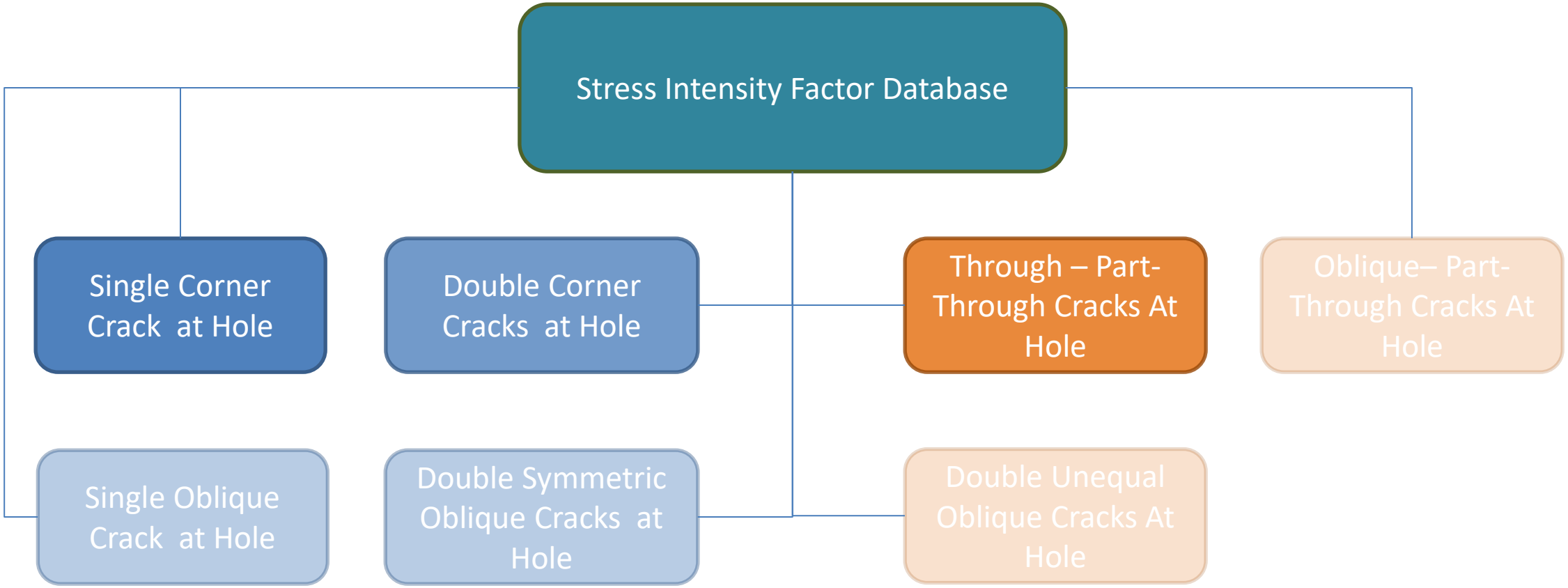
Advanced Crack At Hole Solutions in AFGROW

- 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

Advanced Crack at a Hole Solution Database



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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

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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

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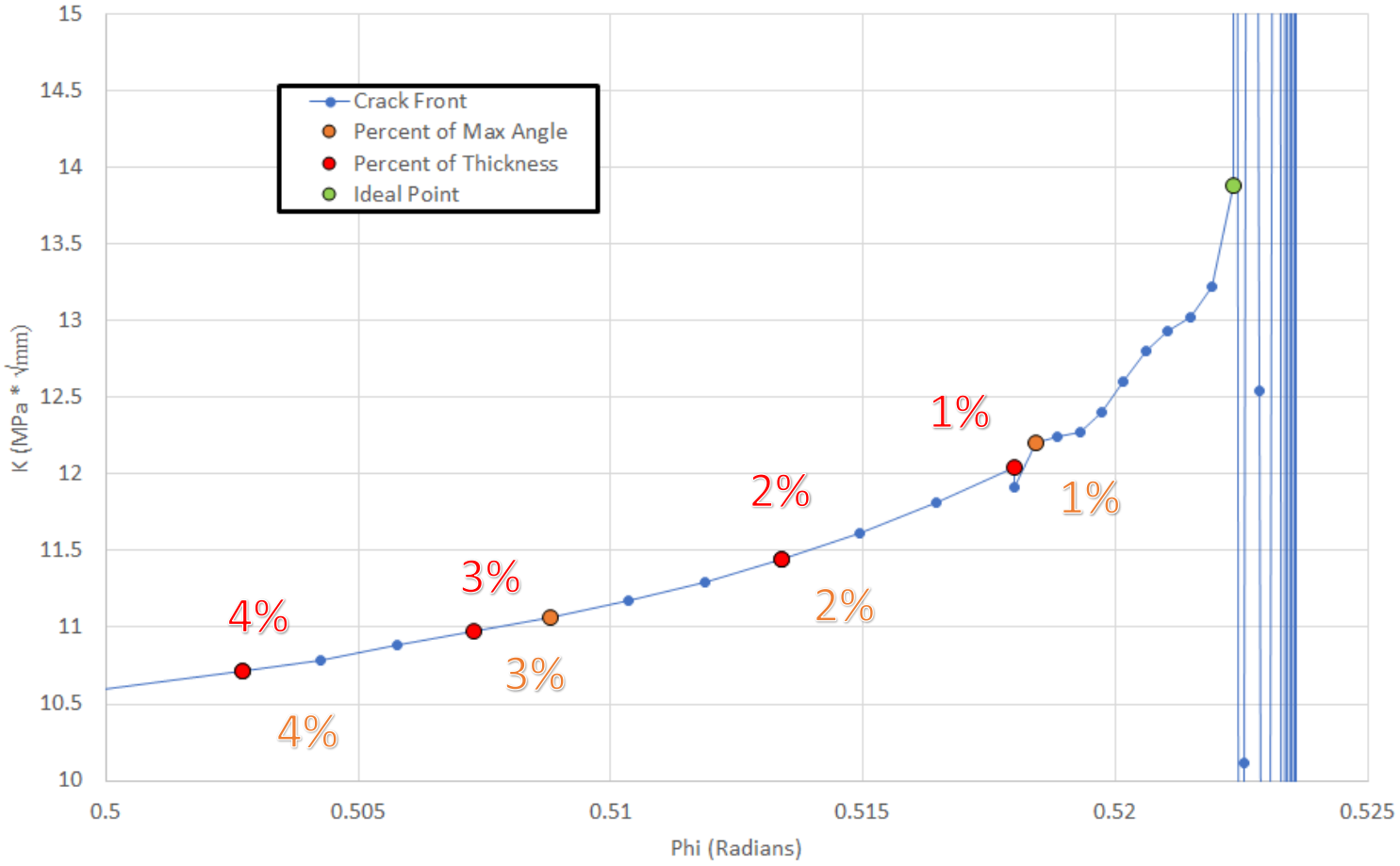
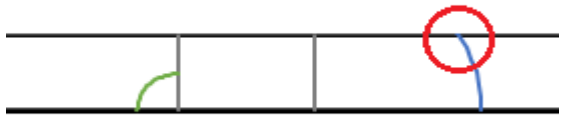
r/t=0.8, a1/c1=1.0, a1/t=0.5, a2/c2=1.0, a2/t=2.0





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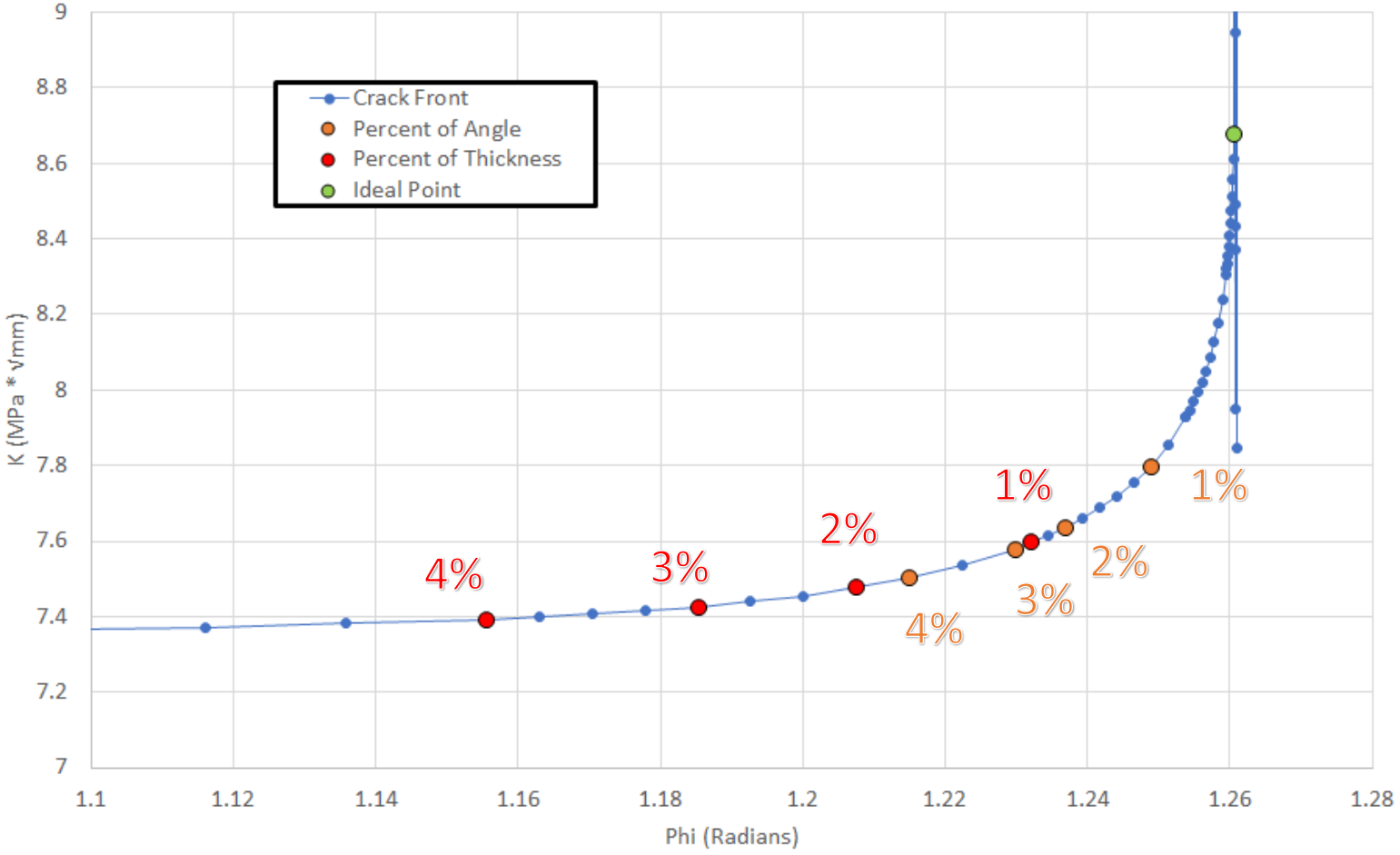
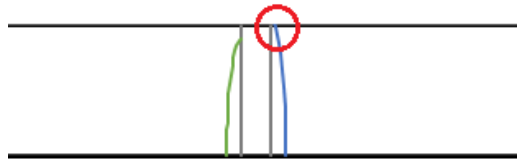
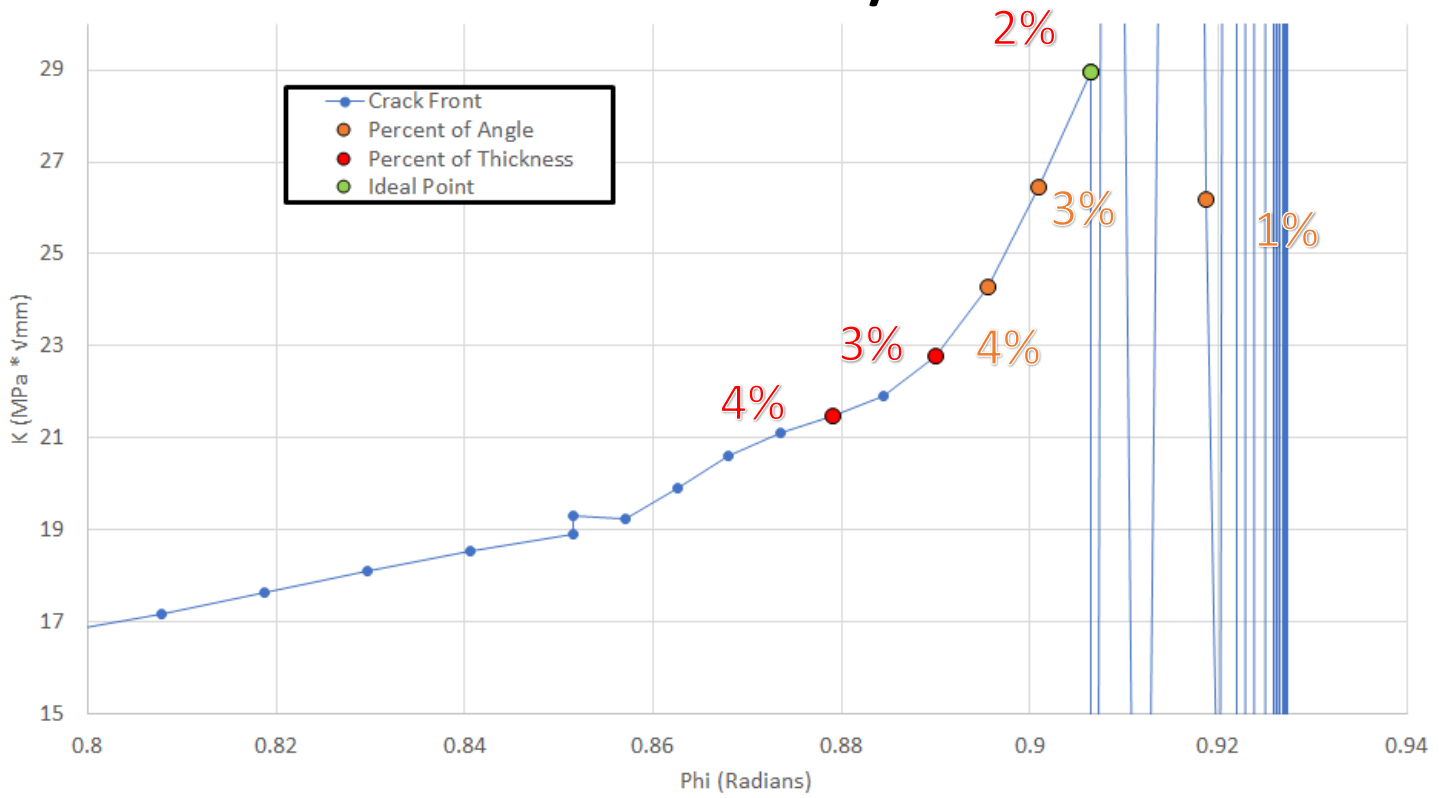
r/t=0.1, a1/c1=9.0, a1/t=0.9, a2/c2=10.0, a2/t=1.05





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



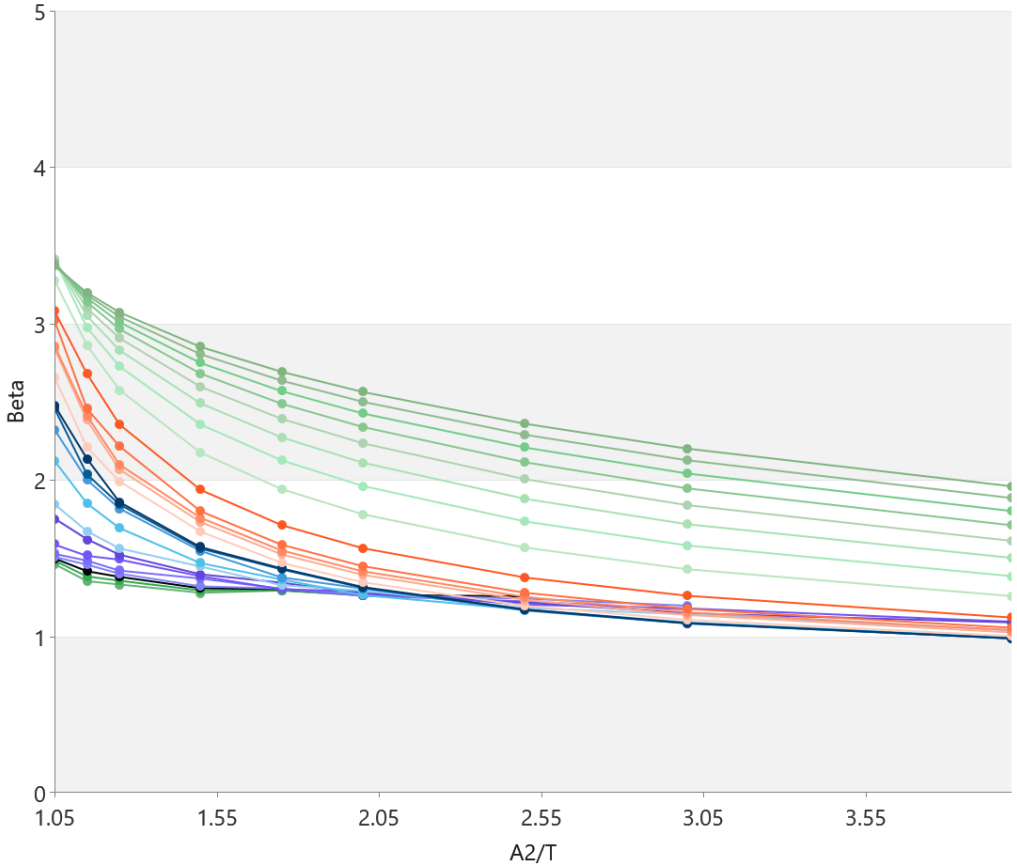
1% not pictured, (0.9141, 41.1)

2% not pictured, (0.90952, 40.77)

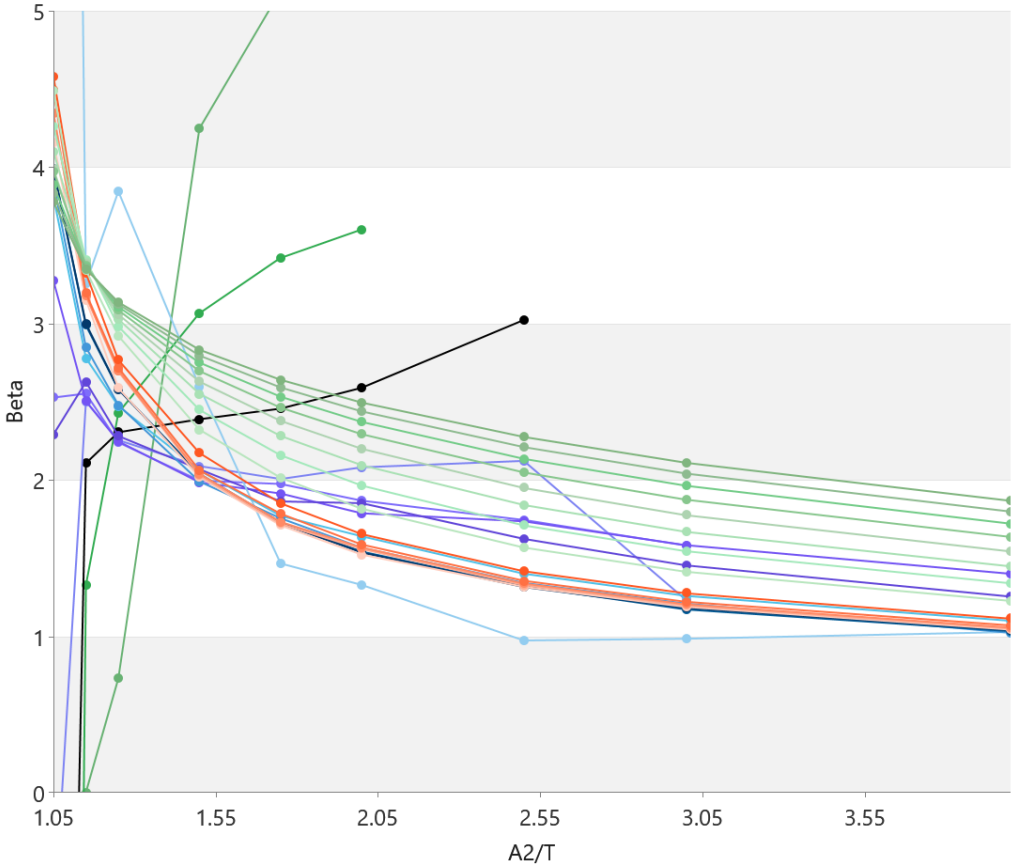
Very Wide Oblique Crack

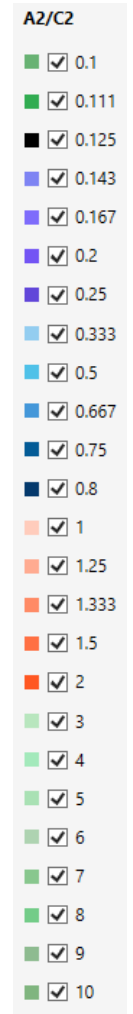
Percent Method Vertices
r/t=1.0, a1/c1=1.0, a1/t=0.5

4% of Thickness



1% of Thickness





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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

Bellow are the 5 general steps approach to produce accurate Part-Through/Through Crack Data that covers all required r/t, a1/c1 and c1/a1

- Step 1: Generating Vertices
- Step 2: Filter For The Most Steep Oblique Cracks
- Step 3: Correcting Data Inconsistencies
- Step 4: Extrapolating Data To Have A Complete Set
- Step 5: Make The Data Uniform

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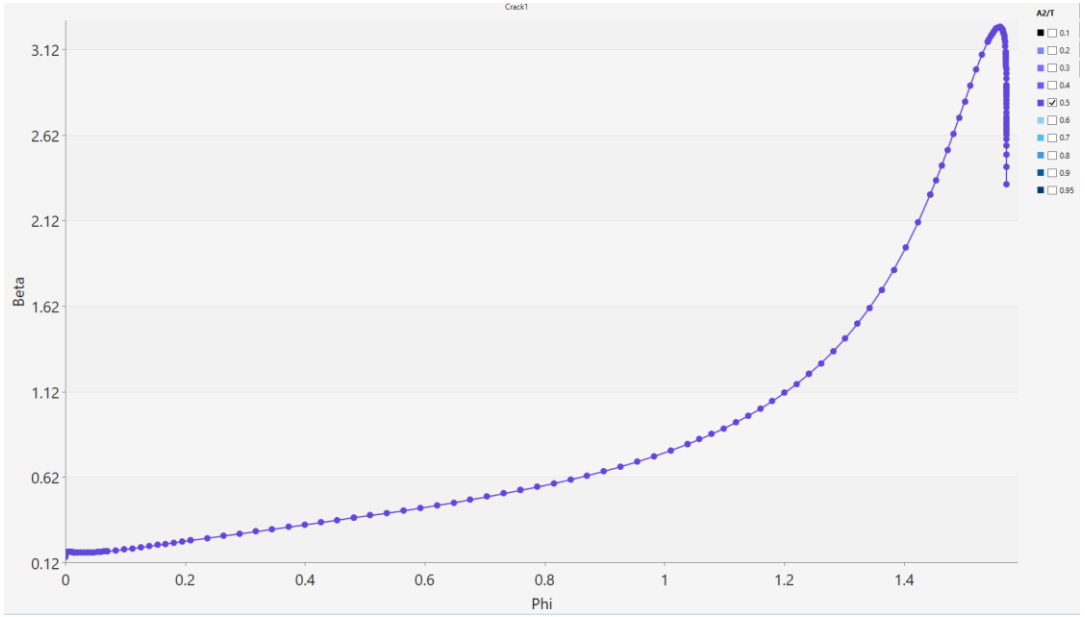
Step 1 – Generate Rough Vertices

- 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 one of these cases, there are two crack front data tables, that contain K values along the entire crack front
- Example on right is a Part-Through crack front after converted to beta values



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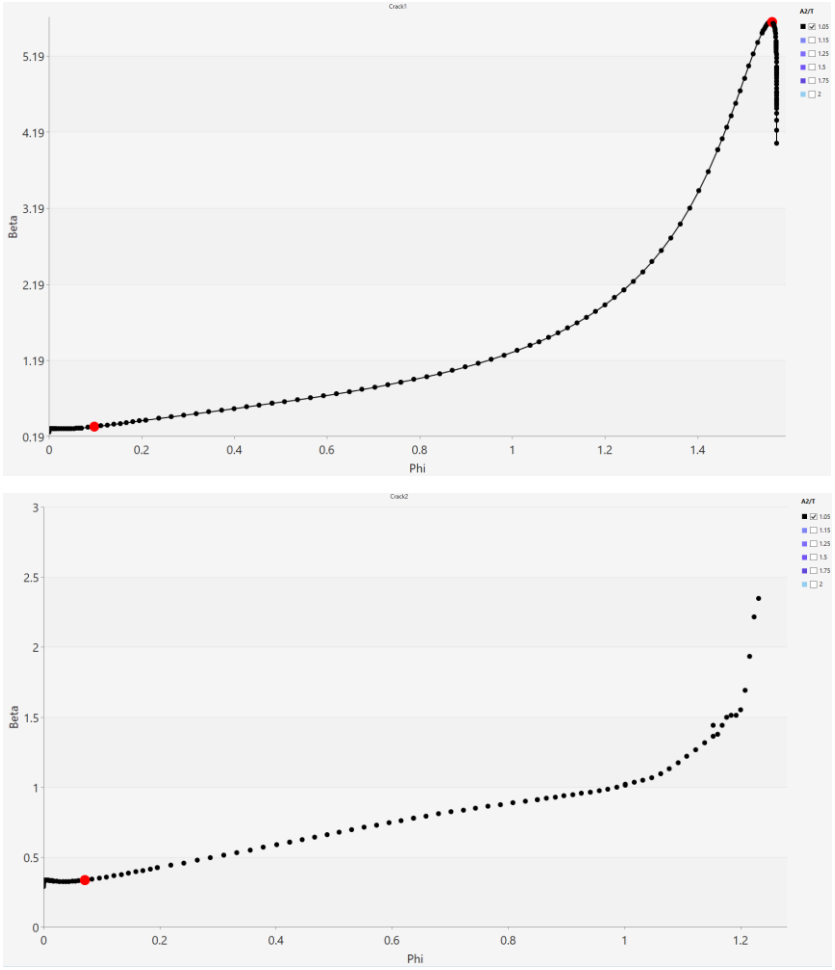
Step 1 – Generate Rough Vertices

- The local maximum on each side of the curve were to determine the vertices
- For Part-Through/Through, we extracted vertices values in C and C directions, and for Crack 2 only in the C direction
- The Ct-direction for crack 2 was ignored



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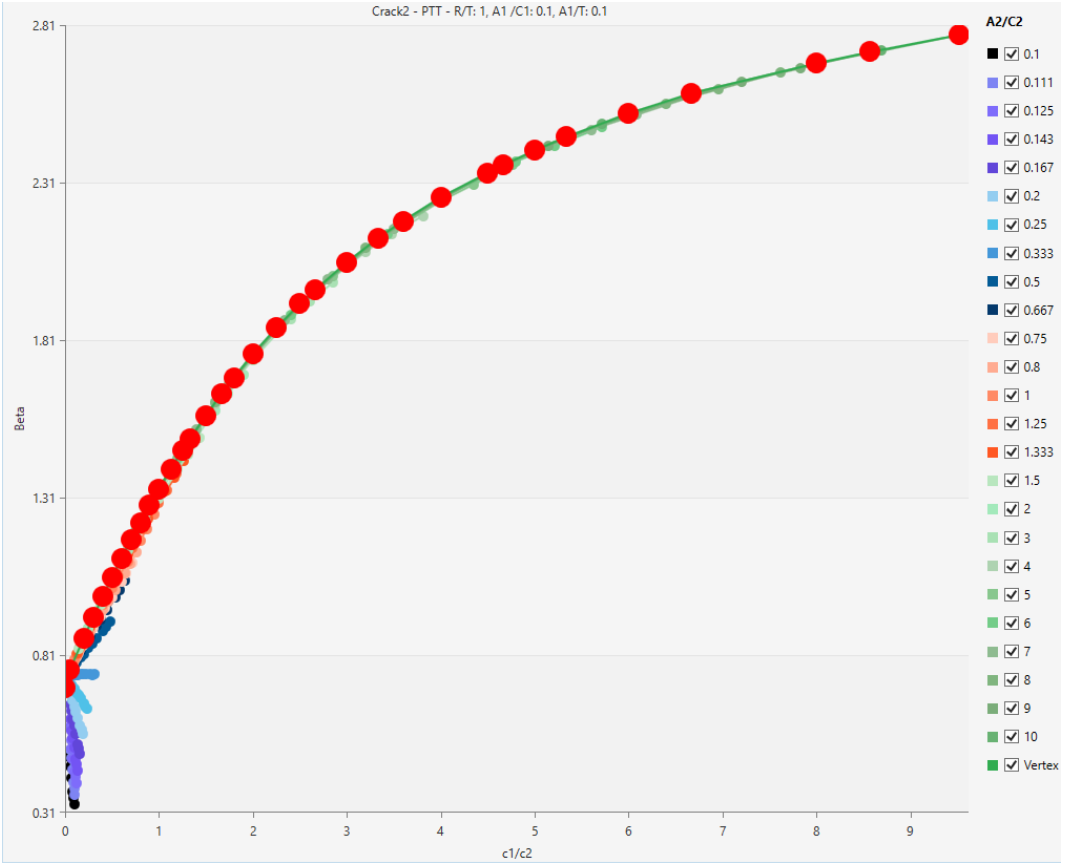
Step 2 – Filter for the most steep oblique cracks

- The c2 direction betas were re-plotted in Beta vs. c1/c2 coordinates for all a2/c2
- Then, the highest, outermost edge of this graph is used to determine thex through crack (c2) betas
- For any given c1/c2, the highest beta value for the oblique crack is used, which should be eaqual or extremely close to the beta value of the through crack
- The selected through crack beta curve are shown by red dots in the figure



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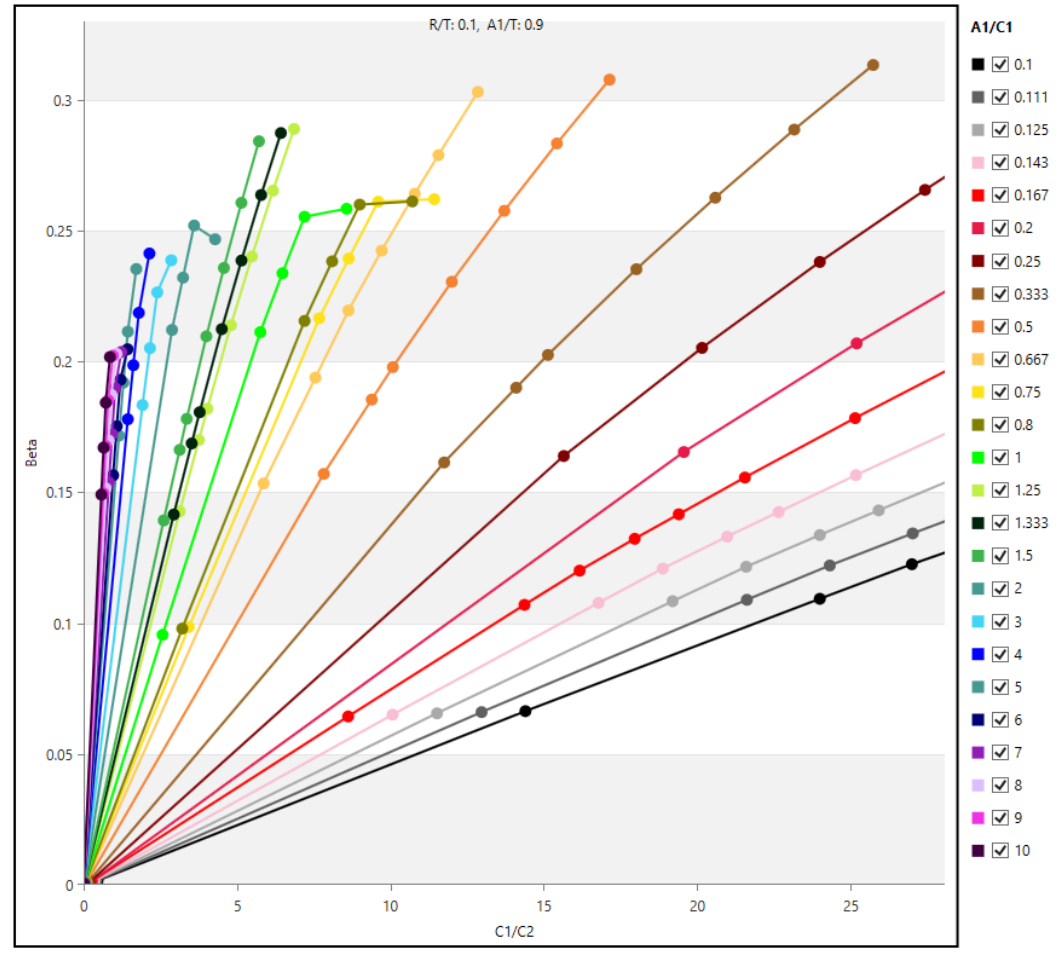
Step 3 – Correcting Data Inconsistencies

- The newly generated beta curves for the through needed to be reviewedand corrected if necessery
- 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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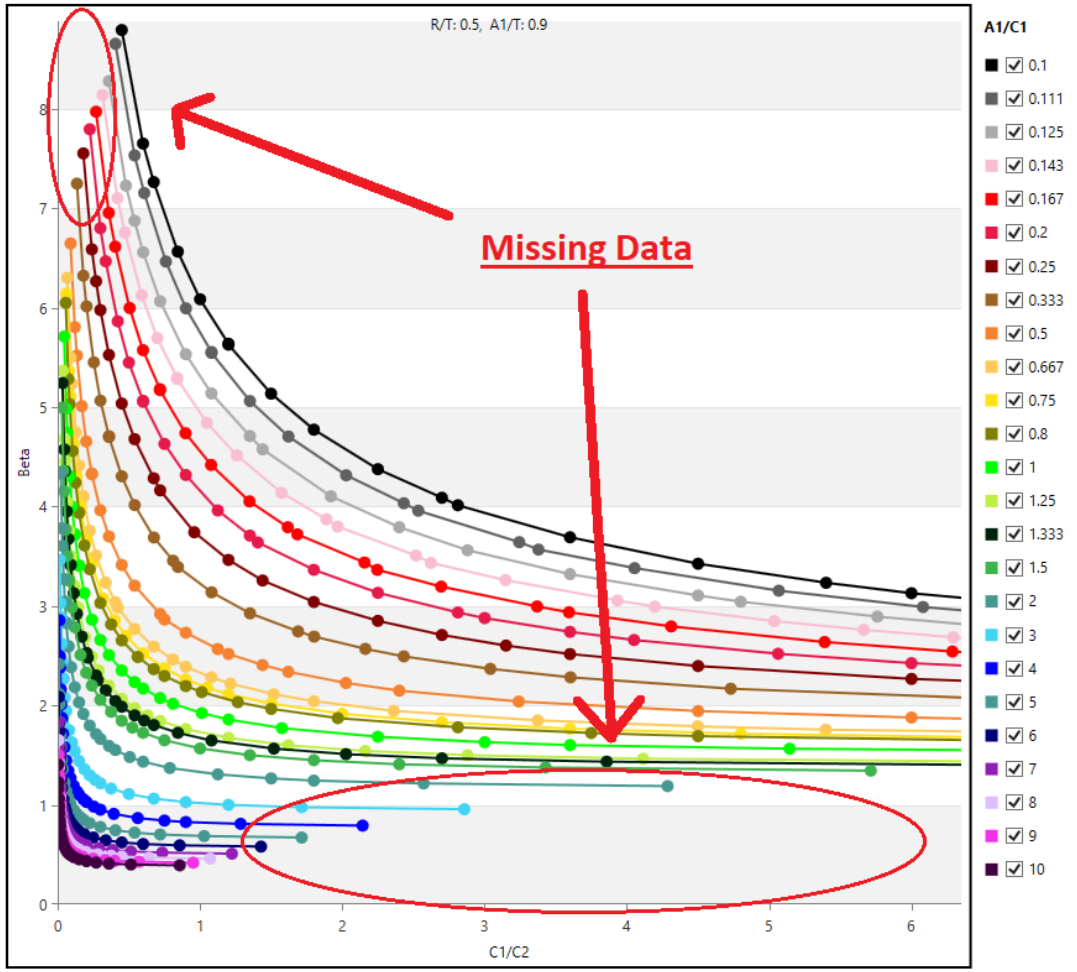
Step 4 – Extrapolating Data To Have A Complete Set

- Our goal is to have a complete set of data in the 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 methods require “square” matrix
- The original data did not have all of the data needed in order to fill the range of C1/C2 values from 0.01 to 6.
- The original data also did not have a/t values for Crack 1 below a/t = 0.1
- To extend the data we had to use multiple methods which that will be detailed in the following slides



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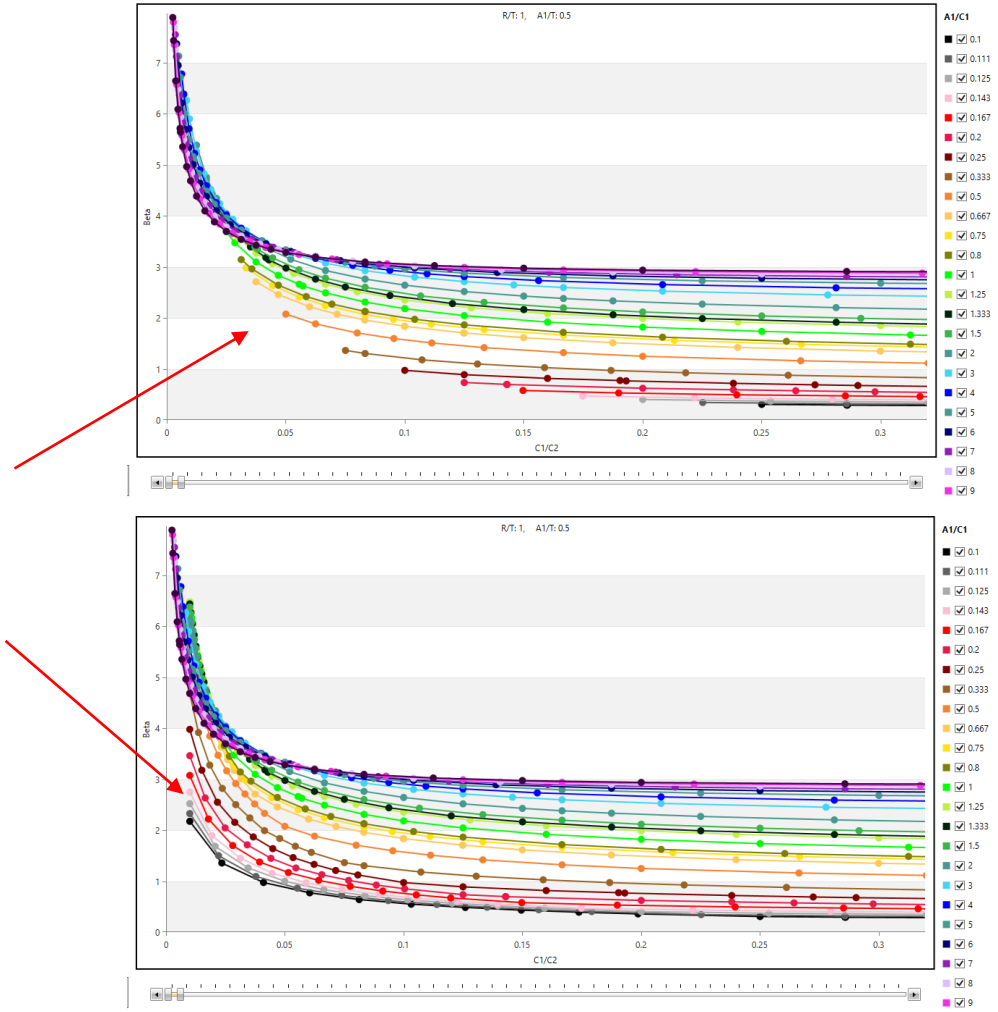
Extending Crack 1 A/C-Direction Data To C1/C2=0.01 (Tension)

- To extend the Part-Through cracks to C1/C2=0.1, we used the AFGROW Advanced Model to outline the borders of the solution for a given r/t and a/t
- The Model used was a wide plate with a slot, and a corner crack



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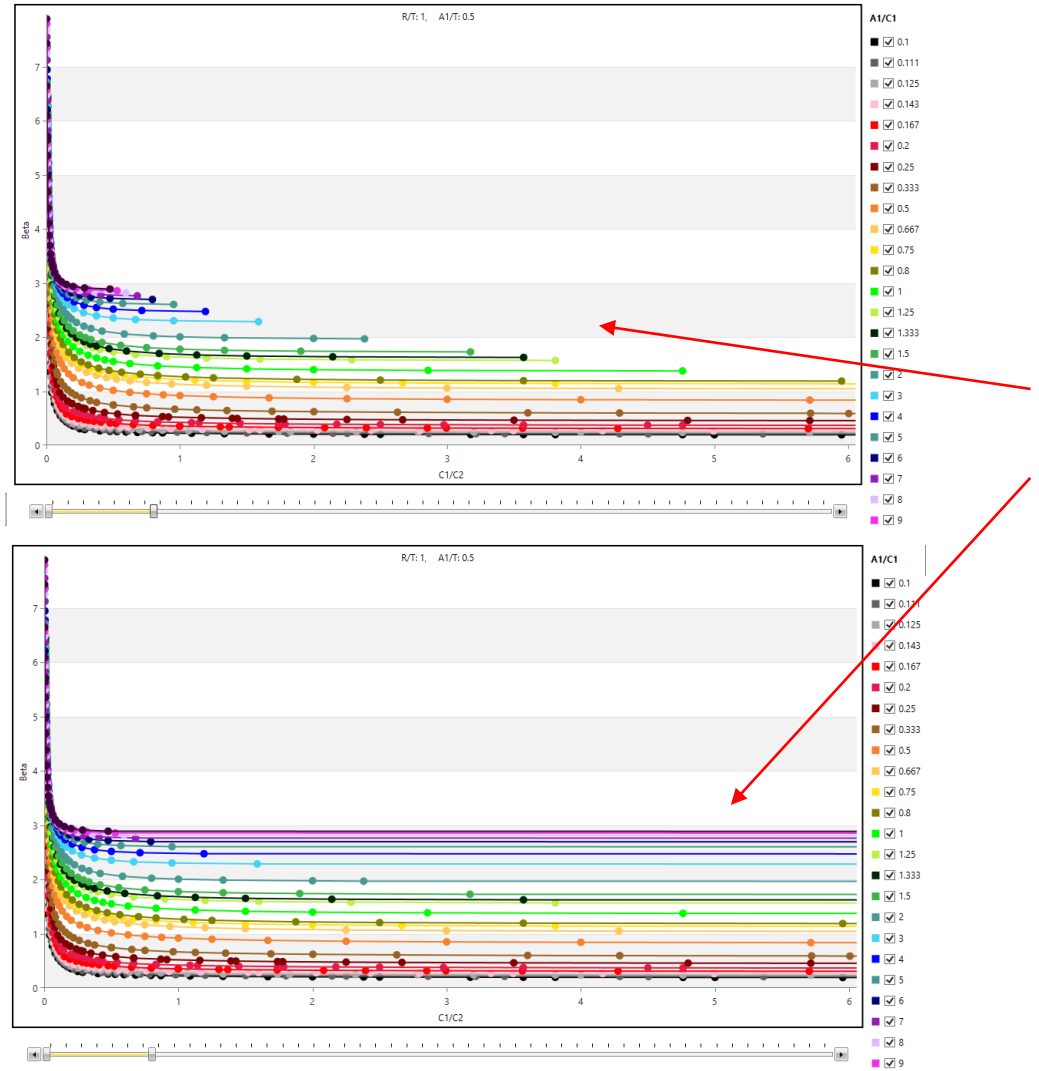
Extending Crack 1 A/C-Direction Data To C1/C2=6 (Tension)

- When c1/c2 equal to 6, the Part-Through crack is much larger than the Through crack and influence of Corner Crack on Through Ctack in neglectable
- We used single crack at hole AFGROW model to calculate the betas in this case



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

- We used a through crack at hole AFGROW models to generate data for cases where A1/T = 0.1 and 0.95
- All other values were filled using different interpolation methods in MatLab
- Graphs of this process will be demonstrated in the next few slides

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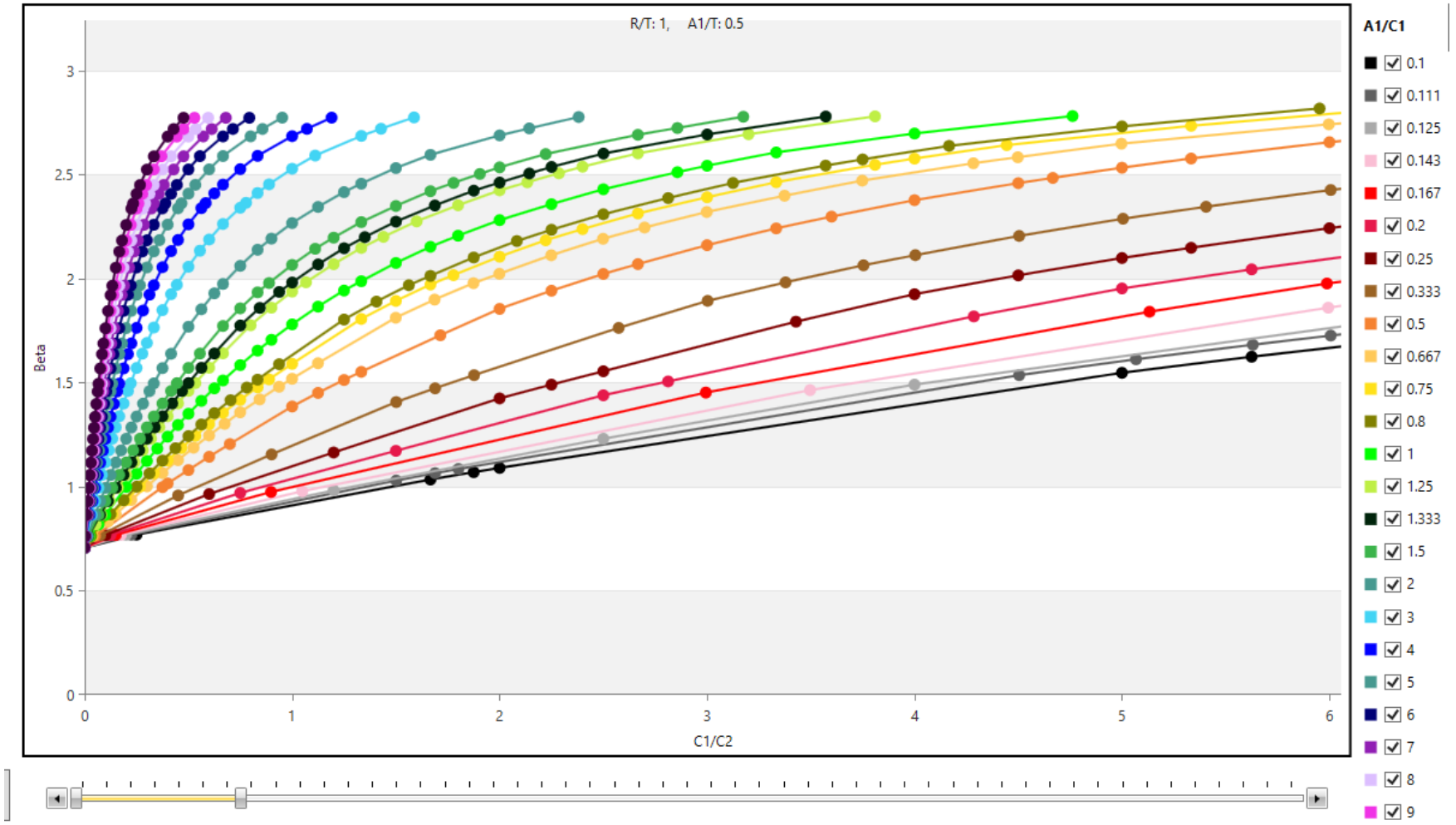
Extending Crack 2 to C1/C2=6



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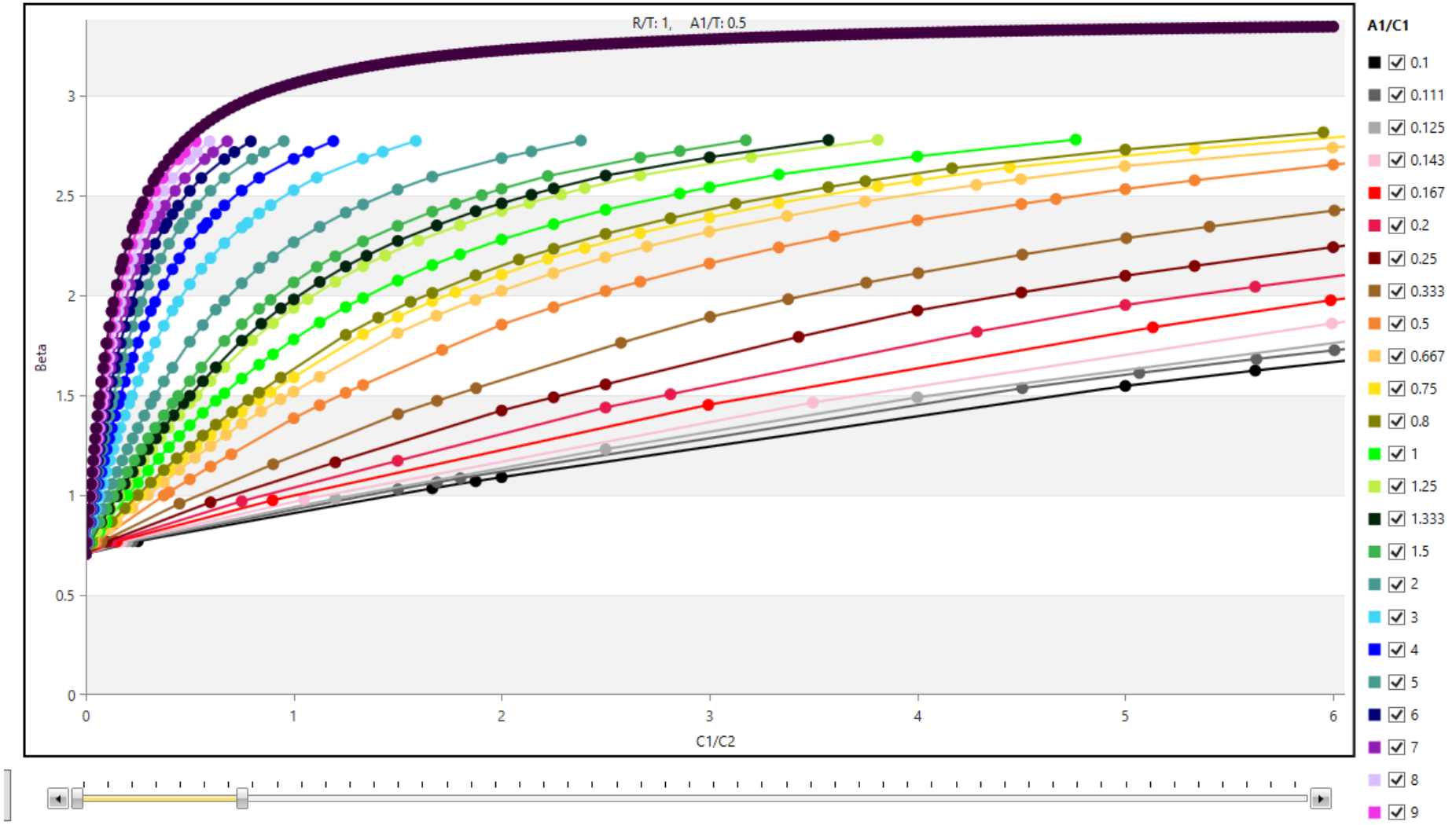
Extending Crack 2 to C1/C2=6



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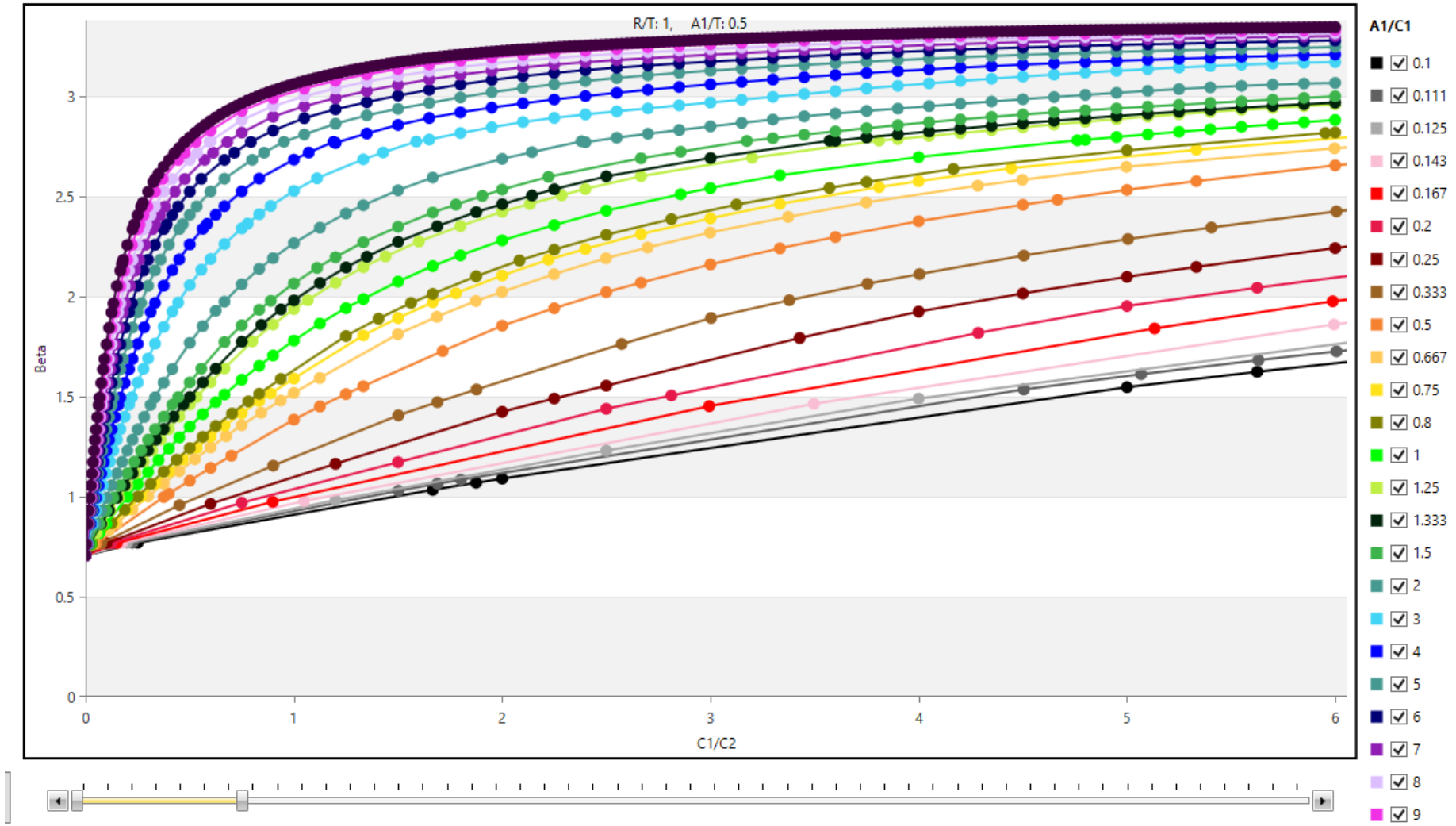
Extending Crack 2 to C1/C2=6



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Extending Crack 2 C-Direction Data to a1/t=0

- The beta for three different loading cases (axial, bearing and bending) all go to different points when a1/t approaches 0
- The values are determined by what value a through crack approaches as it length reaches 0.
- 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

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Extending Crack 1 A1/T to 0

- The different MatLab extrapolation methods were used to extrapolate the data
- After the the extrapolation, the data warre reviewed to insure that the existing trends were followed

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Step 5 – Making The Data Uniform

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

$$0.0 < A1/T \leq 0.95$$

$$0.1 \leq A1/C1 \leq 10$$

$$0.01 \leq C1/C2 \leq 6.0$$

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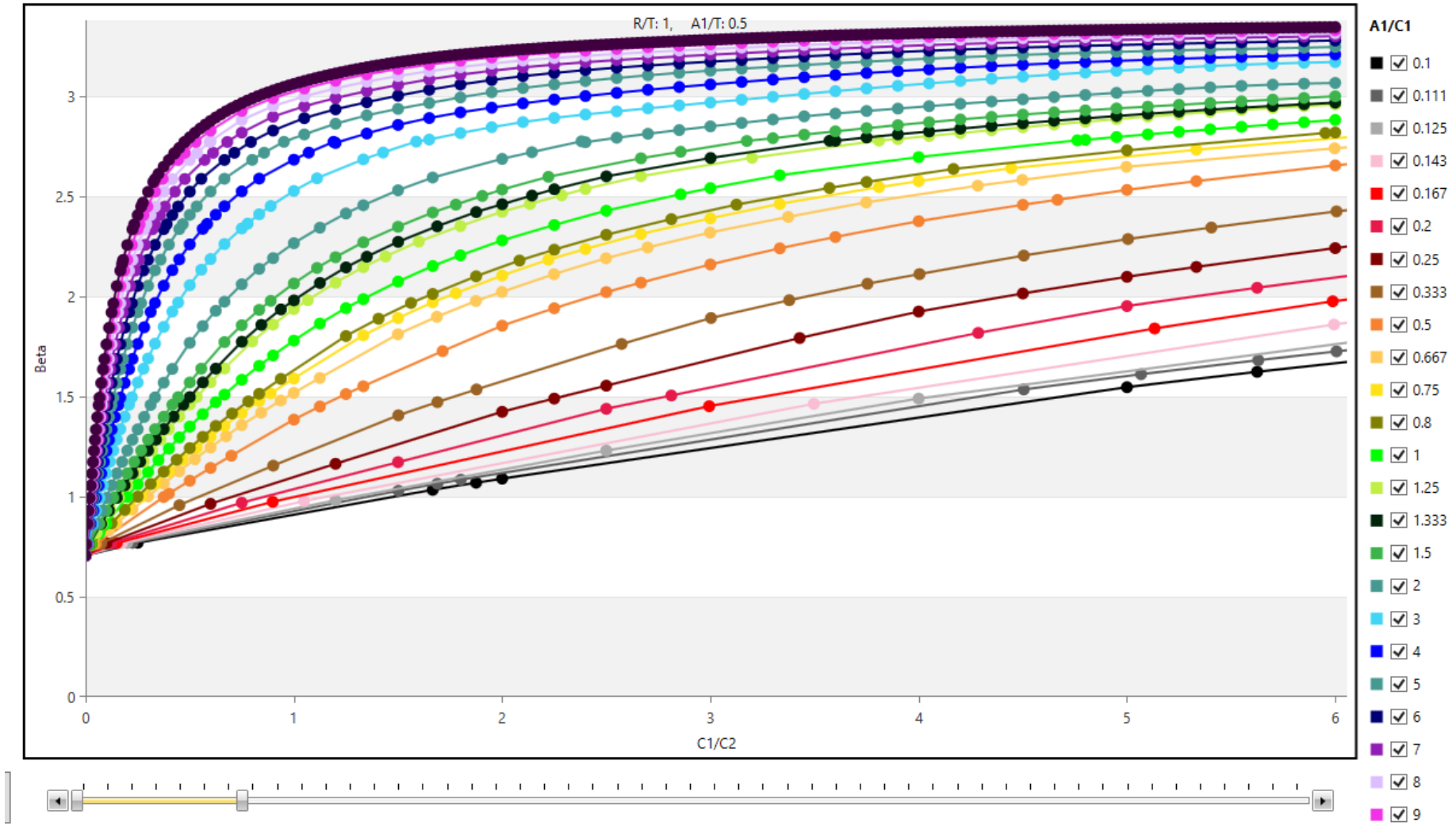
Before Making Data Uniform



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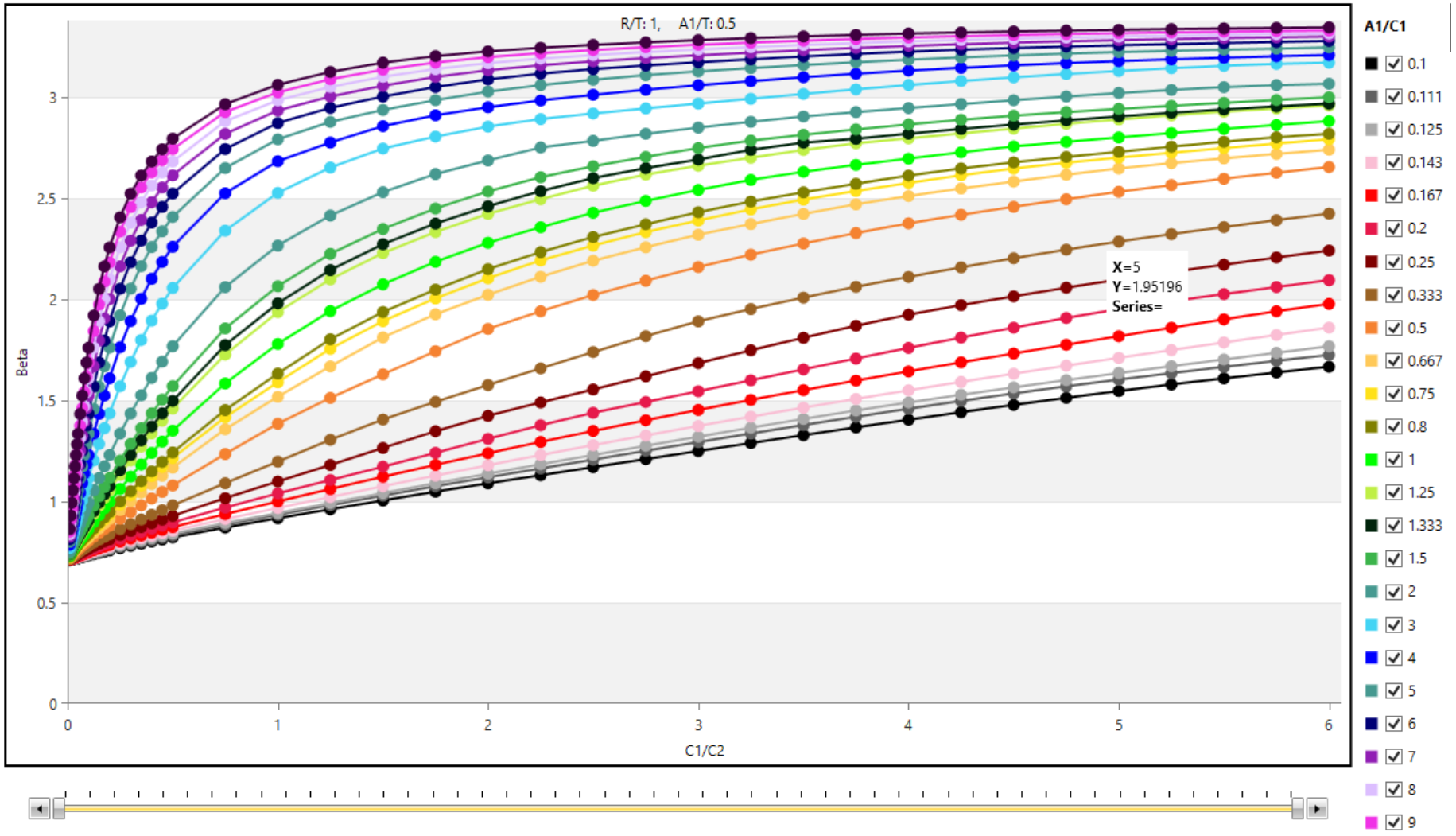
After Making Data Uniform



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Data 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 markers
- The OAS solution is represented by thin line with square markers
- The FEA results are shown as large red diamonds

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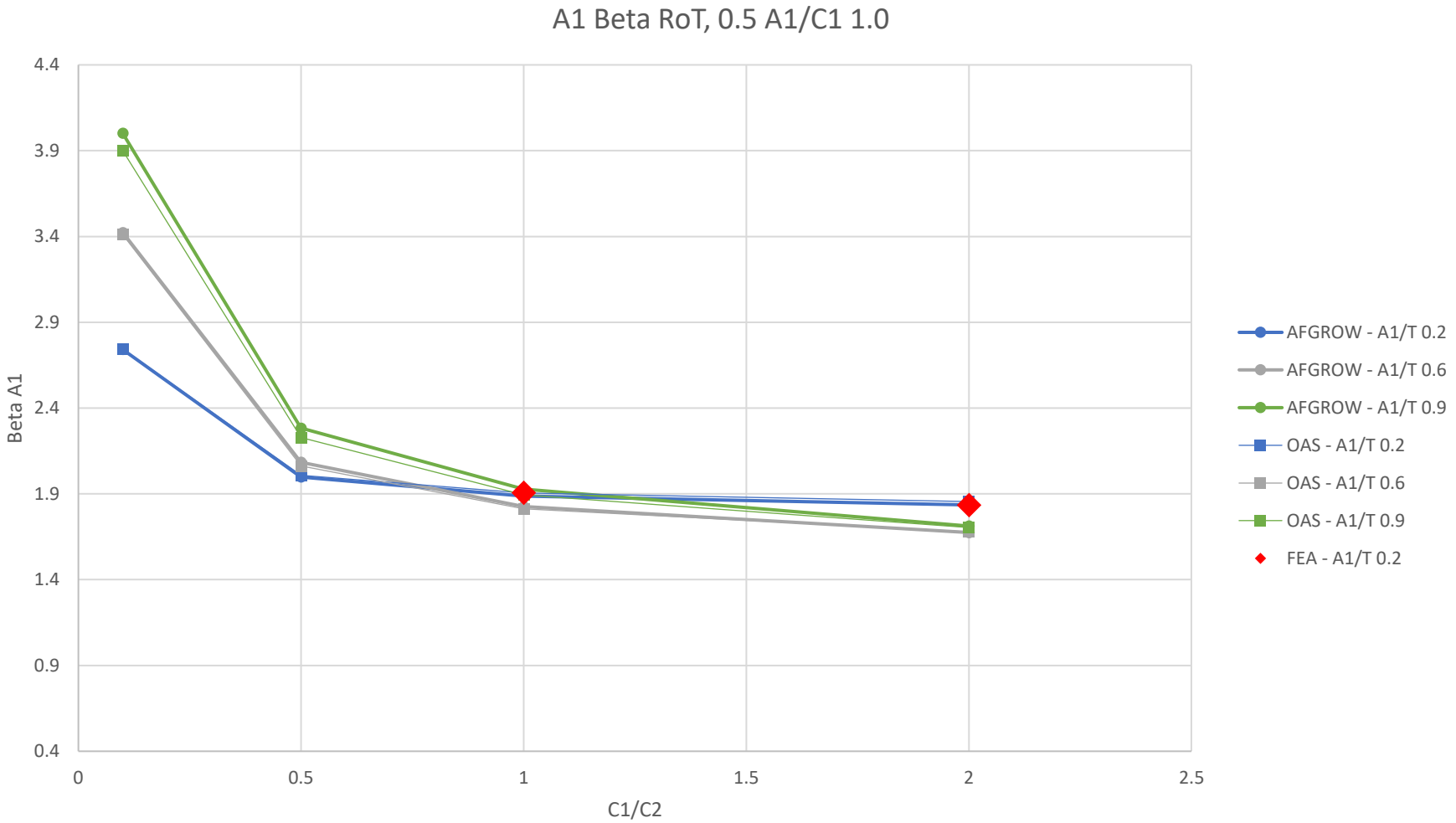
A1 Axial Loading



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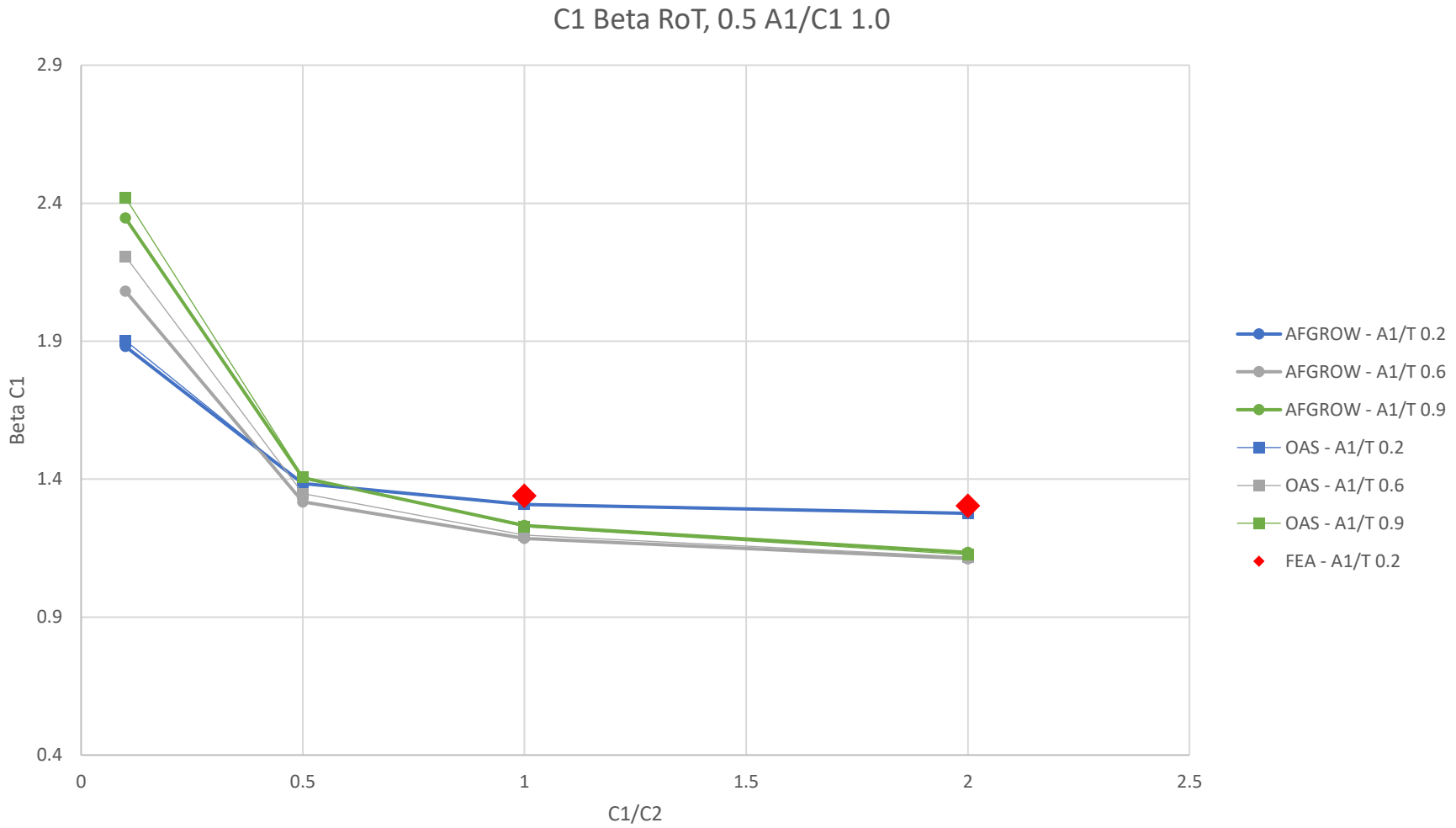
C1 Axial Loading



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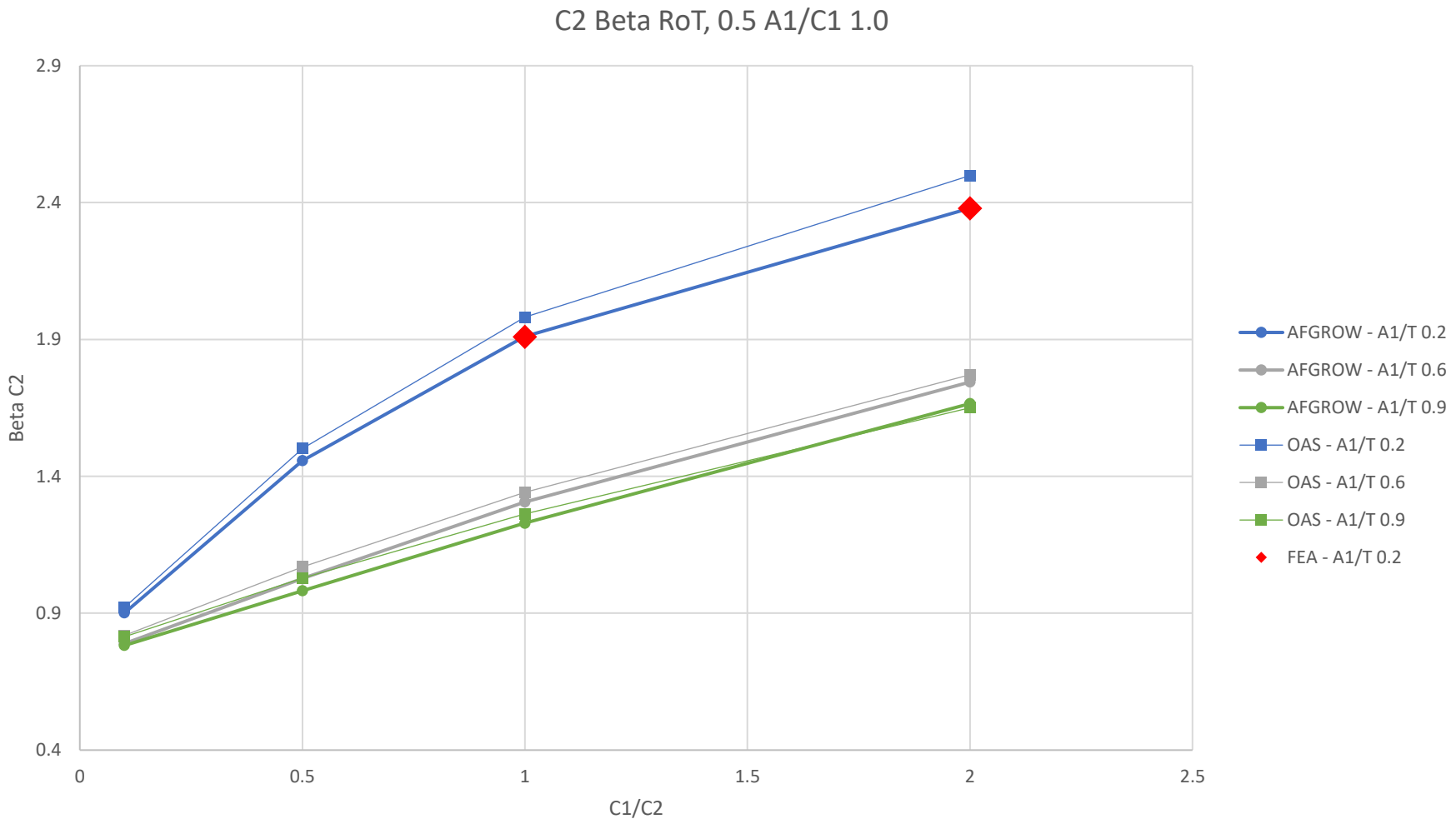
C2 Axial Loading



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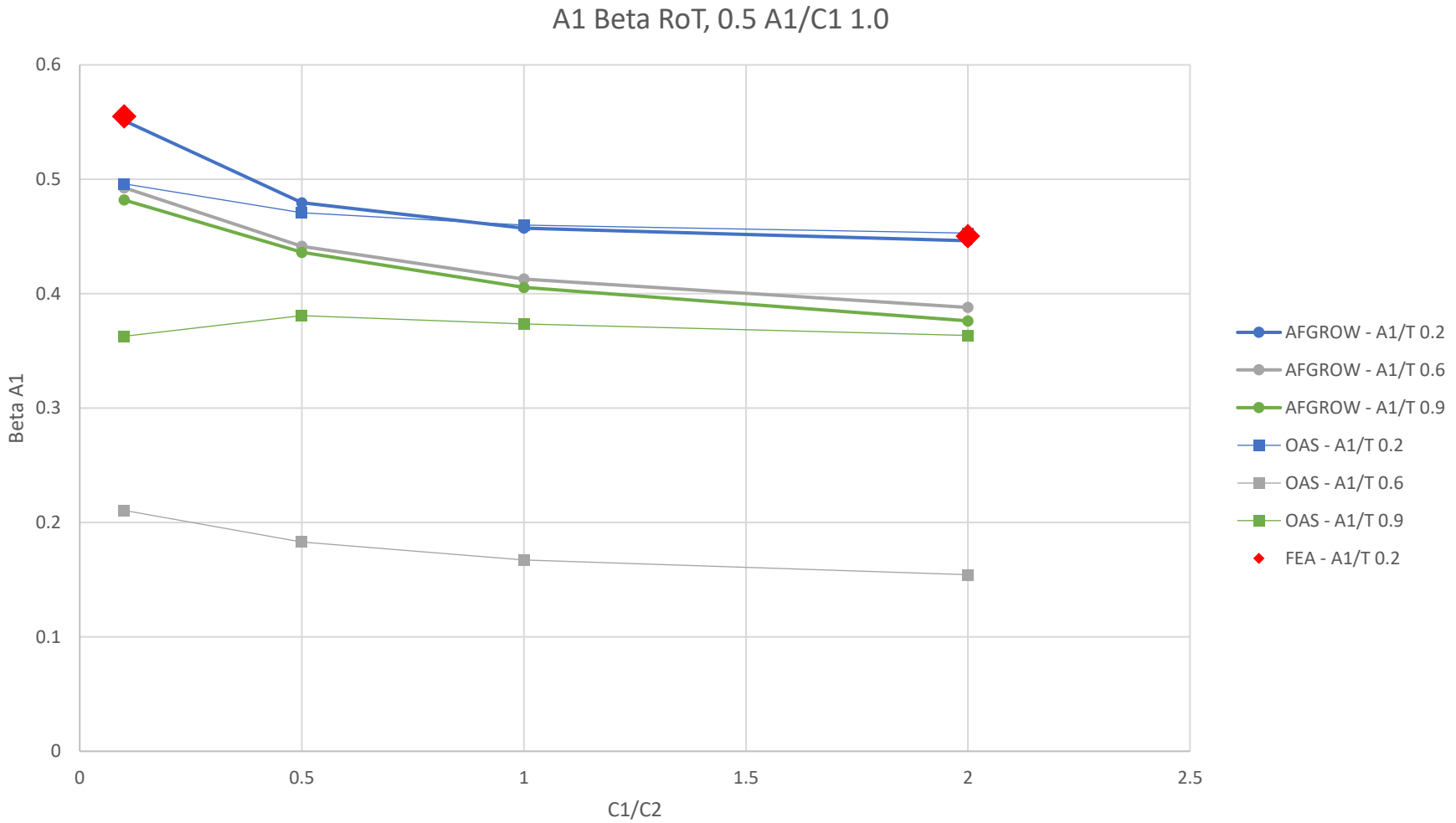
A1 Bearing Loading



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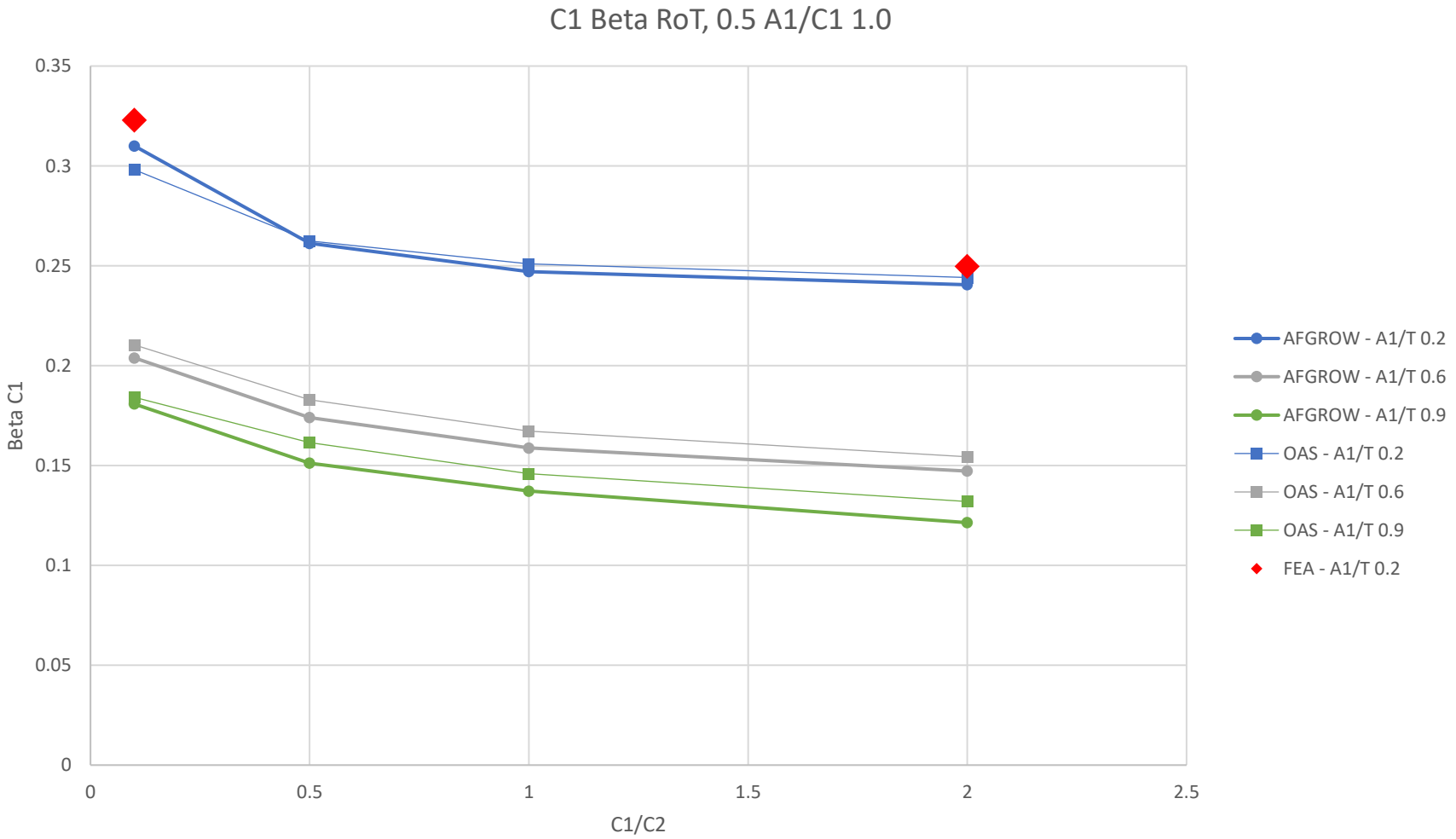
C1 Bearing Loading



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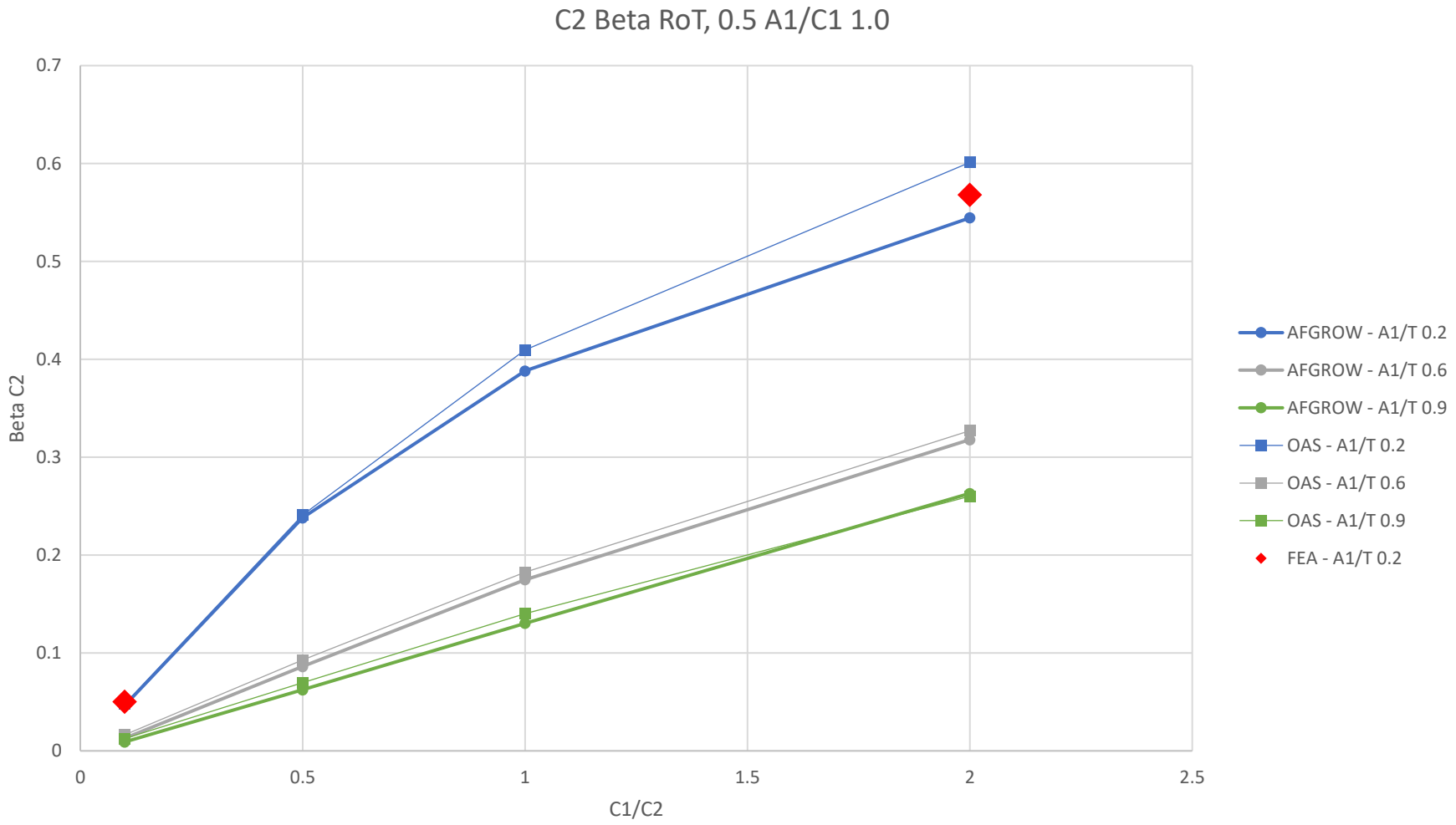
C2 Bearing Loading



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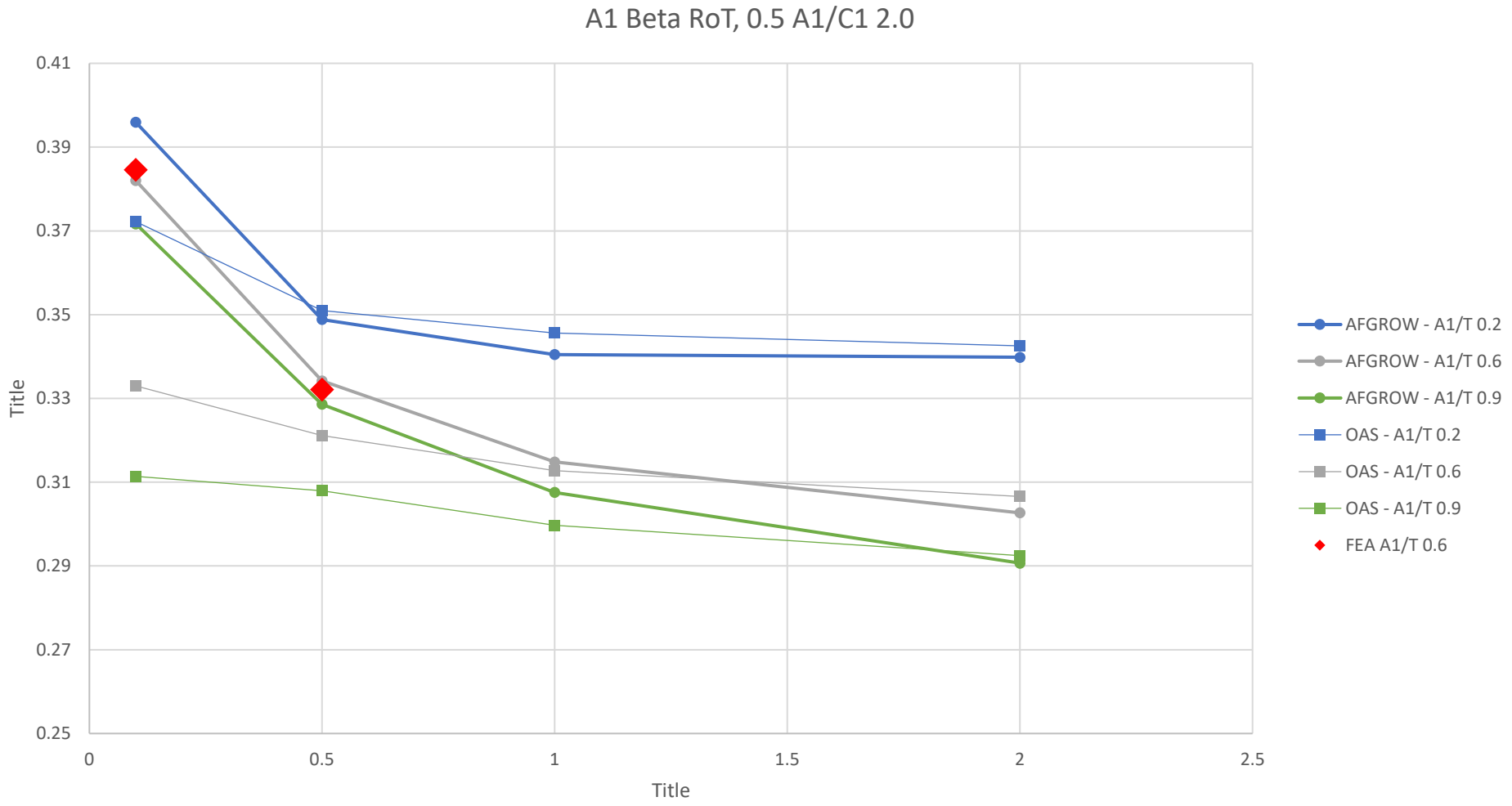
A1 Bearing Loading



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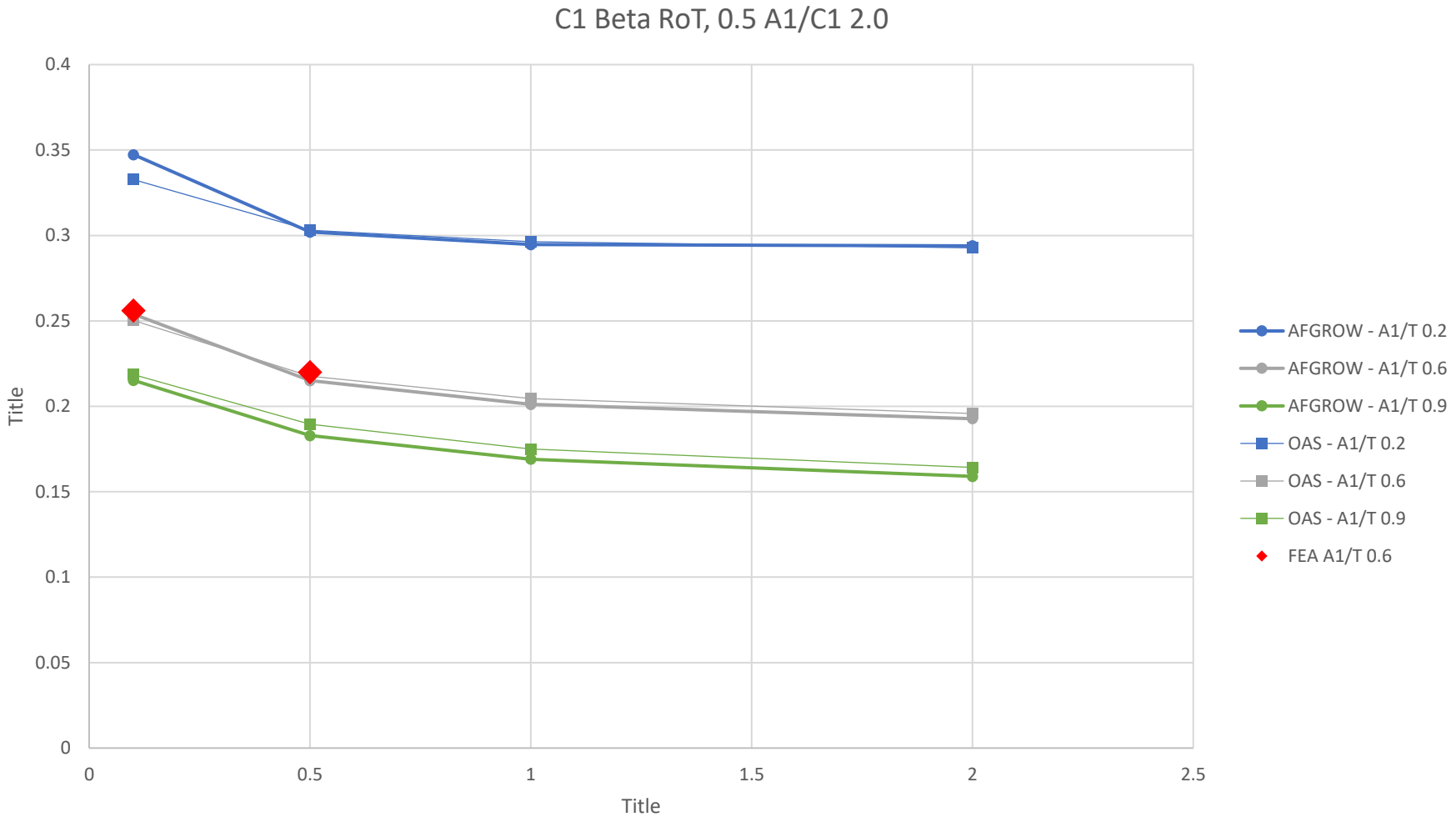
C1 Bearing Loading



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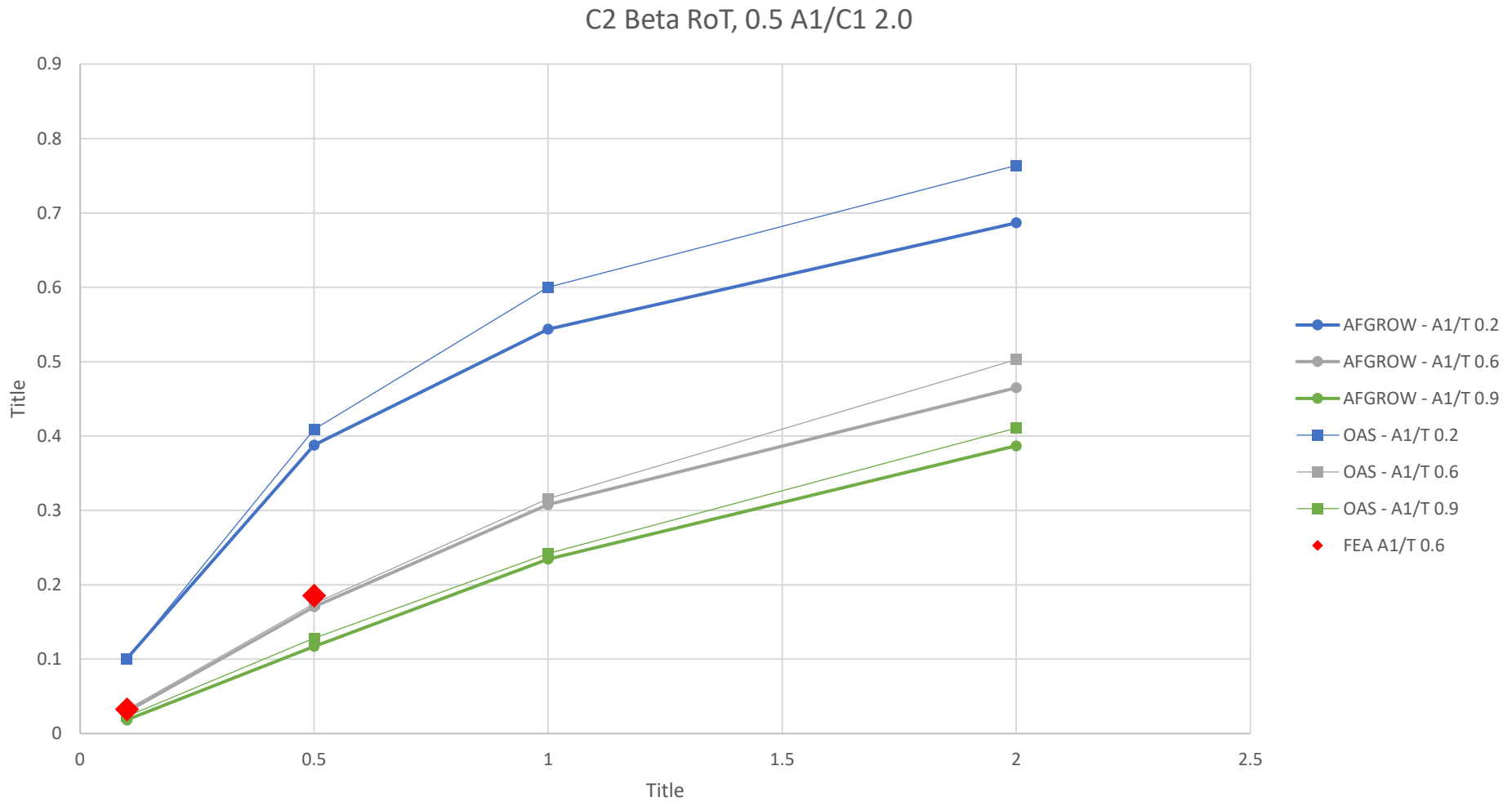
C2 Bearing Loading



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Axial All Cases FEA Comparisons

Geometry				AFGROW			OAS			FEA			% Diff AFGROW			% Diff OAS		
RoT	A1/C1	A1/T	C1/C2	A1	C1	C2	A1	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	3.9694	1.8397	0.8364	3.9613	1.7536	0.8133	0%	1%	0%	0%	5%	3%
0.5	0.5	0.2	0.5	2.5717	1.1518	1.1359	2.5629	1.1886	1.1632	2.6061	1.1789	1.1244	1%	2%	1%	2%	1%	3%
0.5	1	0.2	1	1.8870	1.3085	1.9110	1.9048	1.3105	1.9812	1.9062	1.3398	1.9093	1%	2%	0%	0%	2%	4%
0.5	1	0.2	2	1.8361	1.2757	2.3793	1.8559	1.2770	2.4988	1.8343	1.3038	2.3789	0%	2%	0%	1%	2%	5%
0.5	2	0.2	1	1.3715	1.3558	2.3798	1.3848	1.3584	2.4954	1.3852	1.3828	2.3732	1%	2%	0%	0%	2%	5%
0.5	2	0.2	2	1.3688	1.3530	2.7444	1.3678	1.3423	2.9172	1.3713	1.3675	2.7546	0%	1%	0%	0%	2%	6%
1	0.5	0.6	0.1	4.8854	2.4012	0.7939	4.9033	2.5730	0.8295	4.9369	2.4757	0.7491	1%	3%	6%	1%	4%	11%
1	0.5	0.6	0.5	2.9730	1.5214	1.0386	2.9443	1.5575	1.0705	2.9783	1.5456	1.0412	0%	2%	0%	1%	1%	3%
1	1	0.2	2	1.9922	1.6108	2.7863	2.0073	1.6132	2.9184	2.0147	1.6446	2.7353	1%	2%	2%	0%	2%	7%
1	1	0.6	0.1	3.1391	2.2693	0.8461	3.1375	2.3214	0.8762	3.1597	2.3249	0.8466	1%	2%	0%	1%	0%	3%
1	2	0.2	2	1.4278	1.6098	3.0187	1.4315	1.6085	3.1952	1.4458	1.6325	2.9701	1%	1%	2%	1%	1%	8%
1	2	0.6	0.1	1.8862	1.8895	0.9527	1.8808	1.8915	0.9825	1.9032	1.9301	0.9499	1%	2%	0%	1%	2%	3%

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Bearing All Cases FEA Comparisons

Geometry				AFGROW			OAS			FEA			% Diff AFGROW			% Diff OAS		
RoT	A1/C1	A1/T	C1/C2	A1	C1	C2	A1	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	0.5573	0.1927	0.0224	0.6560	0.2017	0.0230	0%	5%	11%	15%	4%	2%
0.5	0.5	0.2	2	0.5171	0.1394	0.3891	0.5197	0.1463	0.4115	0.5223	0.1463	0.4129	1%	5%	6%	0%	0%	0%
0.5	1	0.2	0.1	0.5512	0.3100	0.0466	0.4960	0.2981	0.0478	0.5551	0.3230	0.0501	1%	4%	7%	11%	8%	5%
0.5	1	0.2	2	0.4462	0.2406	0.5446	0.4530	0.2441	0.6011	0.4504	0.2498	0.5681	1%	4%	4%	1%	2%	6%
0.5	2	0.6	0.1	0.3820	0.2539	0.0293	0.3330	0.2502	0.0324	0.3846	0.2560	0.0327	1%	1%	10%	13%	2%	1%
0.5	2	0.6	0.5	0.3342	0.2151	0.1705	0.3212	0.2176	0.1745	0.3321	0.2200	0.1856	1%	2%	8%	3%	1%	6%
1	0.5	0.6	0.1	0.7063	0.2428	0.0150	0.5849	0.2558	0.0209	0.7134	0.2535	0.0147	1%	4%	2%	18%	1%	42%
1	0.5	0.6	0.5	0.6306	0.2064	0.0927	0.5969	0.2235	0.0983	0.6308	0.2127	0.0934	0%	3%	1%	5%	5%	5%
1	1	0.2	2	0.4963	0.3607	0.6768	0.5281	0.3757	0.7791	0.4996	0.3684	0.6776	1%	2%	0%	6%	2%	15%
1	1	0.6	0.1	0.5772	0.3395	0.0316	0.5174	0.3437	0.0371	0.5725	0.3496	0.0325	1%	3%	3%	10%	2%	14%
1	2	0.2	1	0.3604	0.3832	0.6781	0.3855	0.4002	0.7785	0.3646	0.3911	0.6769	1%	2%	0%	6%	2%	15%
1	2	0.2	2	0.3602	0.3830	0.7680	0.3837	0.3980	0.8918	0.3643	0.3883	0.7529	1%	1%	2%	5%	2%	18%

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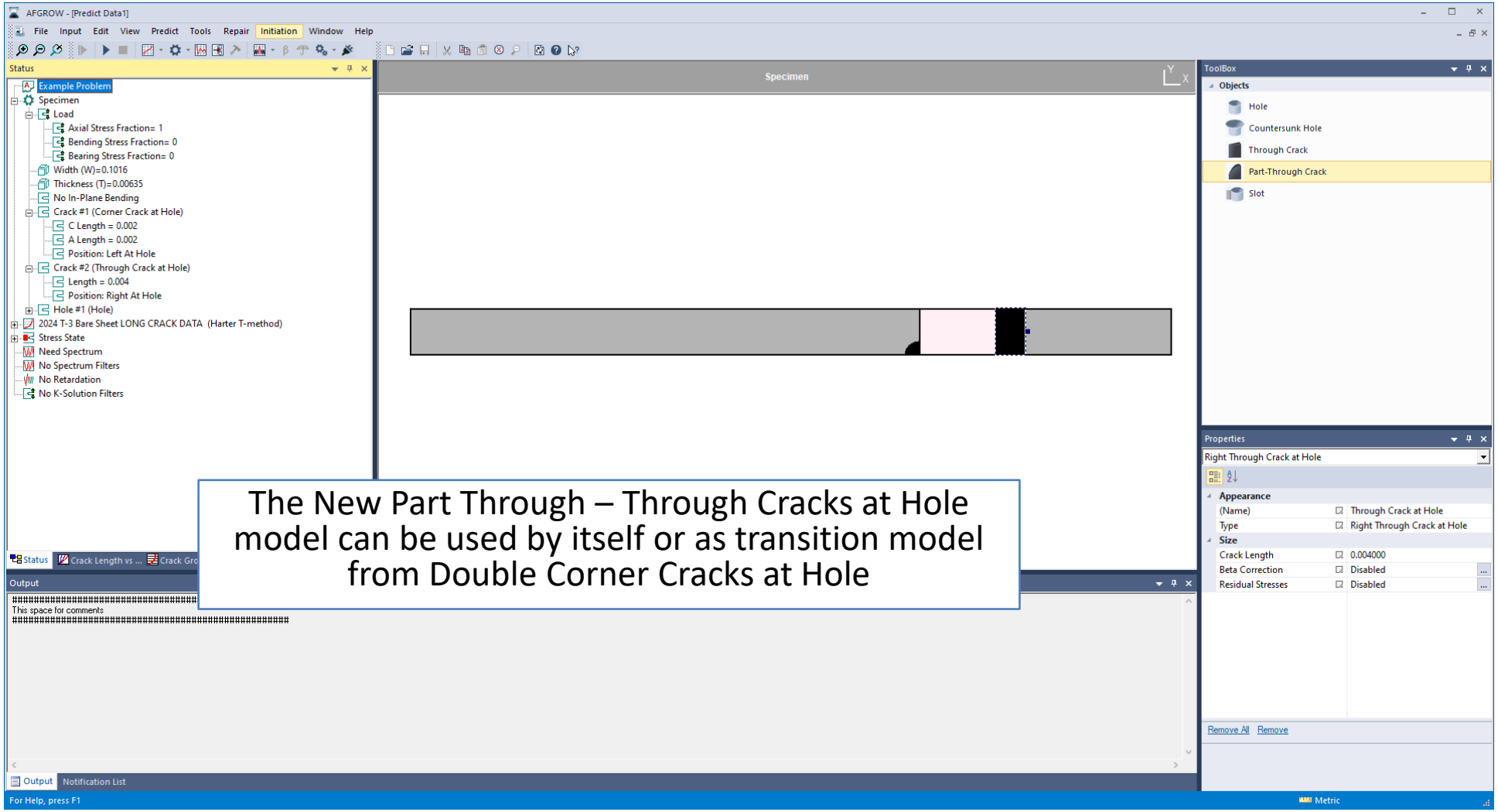
Implementing the Data Into AFGROW



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

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