AFGROW Workshop 2021

AFGROW Release 5.4 Overview

Alex Litvinov, James Harter, James Lambert, Ryan Teeters, Matthew Gross, Evgeniy Saltovets

LexTech, Inc .

Outline

- List of user issues and suggestions for enhancement from Workshop 2020 and progress to completion
- Upcoming release 5.4 details
- Validation and verification of the Fawaz – Andersson 2017 – 2018 K-solution database

List of User Issues and Suggestions for Enhancement

User issues and suggestions from the 2020 AFGROW Users Workshop are listed below (number represents the priority level from 1 to 10):

Task/Issue	Completion
Validate a filled hole correction for part-through cracks (10)	
Oblique/Part Through Corner Cracks at Hole (10)	50%
Double Oblique Crack at Hole (10)	50%
Bearing solution for corner crack(s) at a countersunk hole (9) (Recommend 3 c/s depths)	
Add a check box to put output in the same file as input. Also, allow the same file names for each type. (9)	100%
Add a stiffened panel solution? (8) (Bulging factors)	
Spectrum Severity Comparison (7)	
Integrate Cycle Counter into Spectrum Manager (6)	
Ability to read uncounted data in the Spectrum Manager (6)	
Improved Undo/Redo in Spectrum Manager (5)	
Ability to use beta correction with a weight function solution (5)	
Incorporate Effective width in the bearing beta calculation (5) (Add check box to update bearing load case width)	
Make changes to allow the use of spectra with three load channels (5)	
Combining exceedance curves (4)	
Include a log file with the Spectrum Manager (list of what was done) it would need to be dated and maintained each time the spectrum is opened. Maybe a separate log file? Like a log used to track changes for software development. (3)	100%
Scott Fawaz would like the font size for the R & Delta plot and axes to be changed for reporting purposes (3)	100%
Investigate a 3-D integration method for beta correction (2)	
Double and Single Semi-elliptical Cracks at hole (2)	
Oblique/Part Through Semi-elliptical Cracks at Hole (2)	
Add different retardation parameters for the different growth directions (2)	
HDF5 binary format for AFGROW database (1)	30%
Look into notifications for exceeding limits for a corner crack at a C/S knuckle (1)	

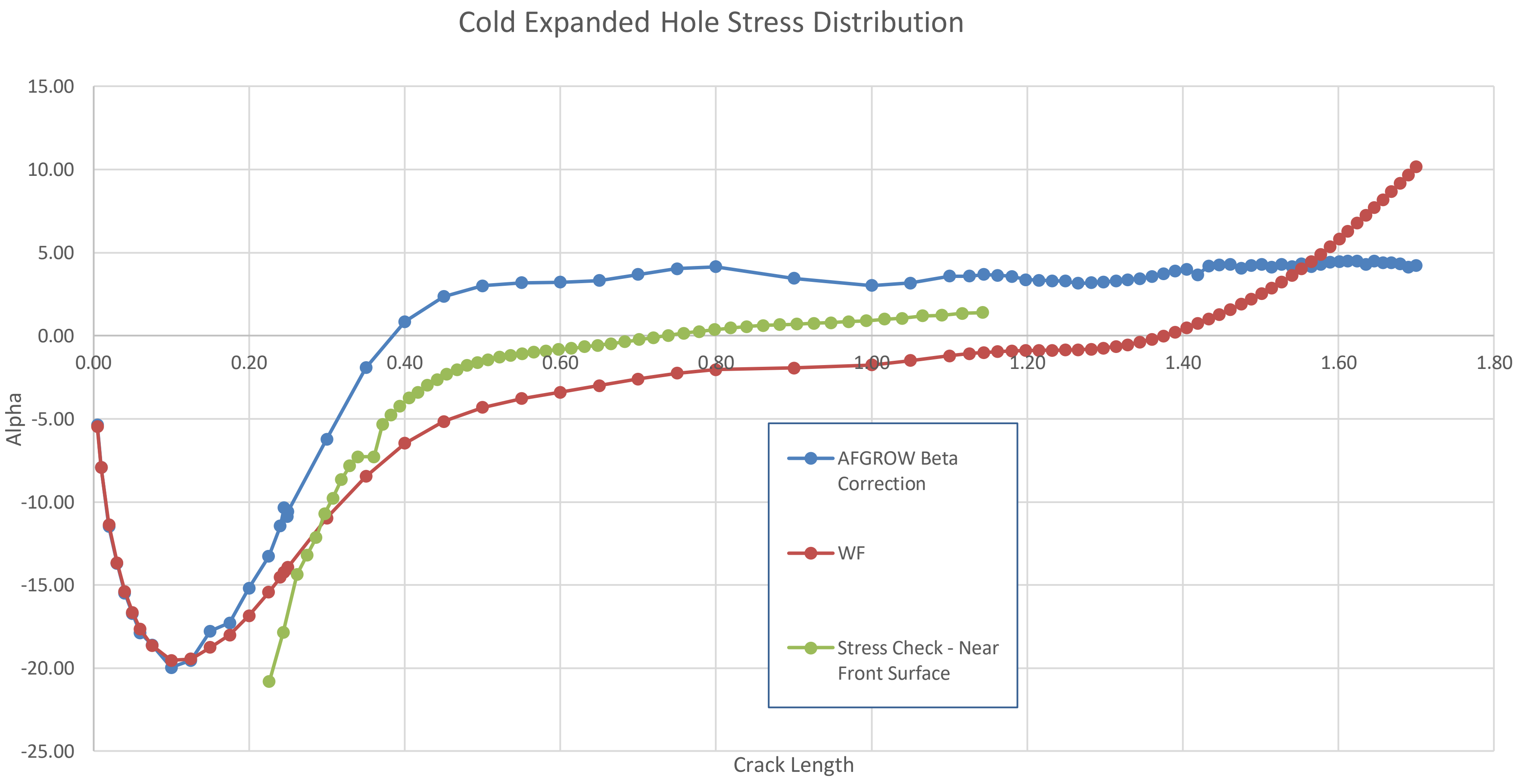
Release 5.04.01.25

- New/Enhanced Advanced Crack At Hole Solutions (single corner crack at hole and combination of a corner crack and through crack at a hole)
- MSD models
- New width correction to a crack(s) at a hole models
- New single and double through crack at a hole weight function solutions
- Local material database in tabular-lookup format
- 35 new crack initiation material data sets
- Option to open material data file through COM
- Investigate/fix small crack combination (a/t < 0.1) for advanced corner cracks at hole.
- Modify output preferences: Add a check box to put output file in the same folder as input file. Allow the for each output file type to have the same name as an input file
- Option to use plugin from COM
- Better handling life in hours output. Output intervals printed in "hours" if the option to display life in hours is selected in the Output Intervals tab, the crack length plots also should be converted to hours
- Print NASGRO material name in the output
- Fix JavaScript Engine
- Add correction for filled unloaded hole to advanced models
- Access retardation metadata via COM and Plug-in Interface

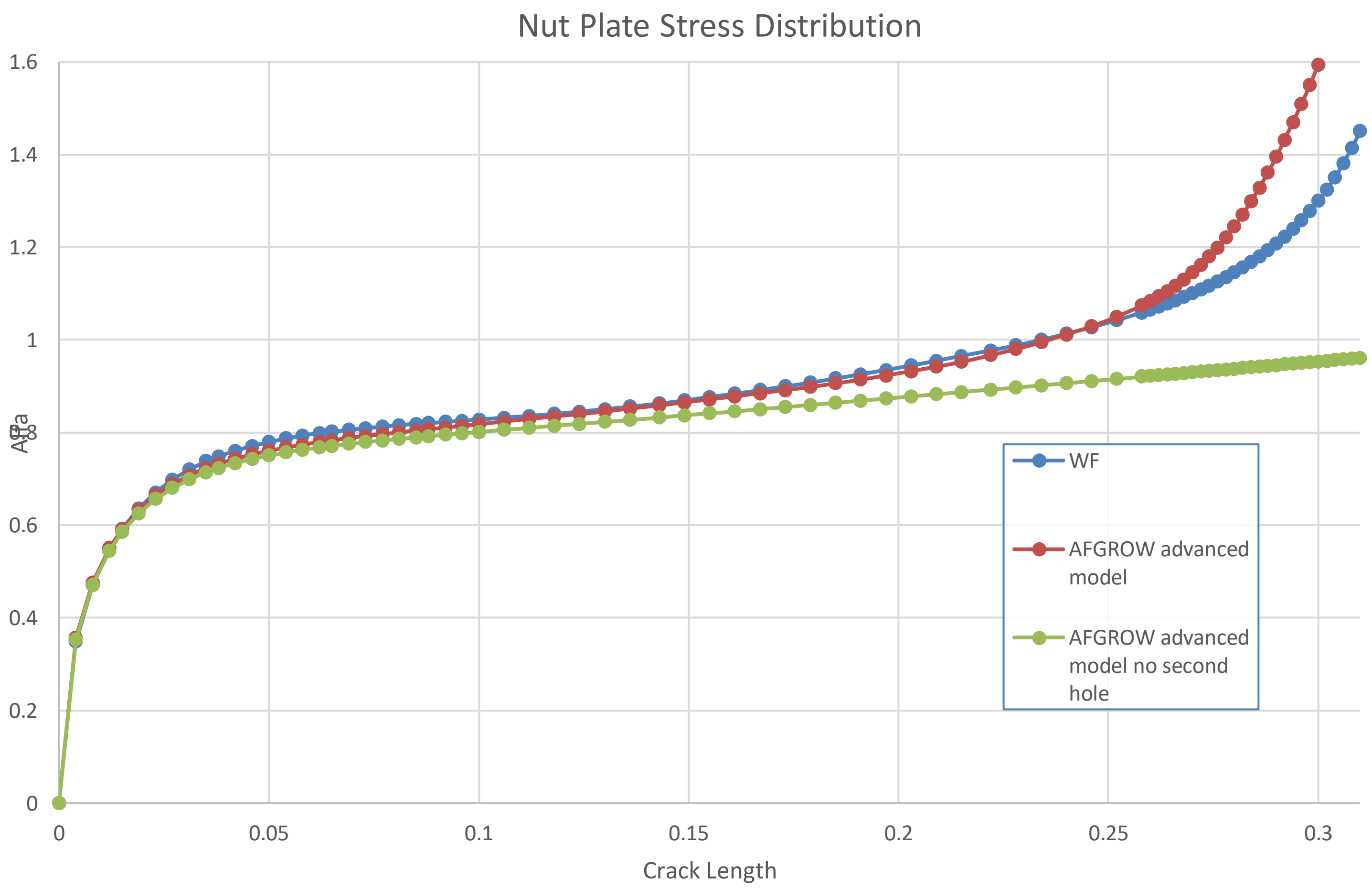
Single and Double Through Crack at Hole Weight function Solutions

Based on Jihwi Kim, Michael R. Hill (*Department of Mechanical and Aerospace Engineering, University of California*) paper: "*Weight functions for a finite width plate with single or double radial cracks at a circular hole*" that was published in Engineering Fracture Mechanics and also presented at AFGROW Workshop 2016

Single Through Crack at a Hole Weight Function Solution Verification - Case 1

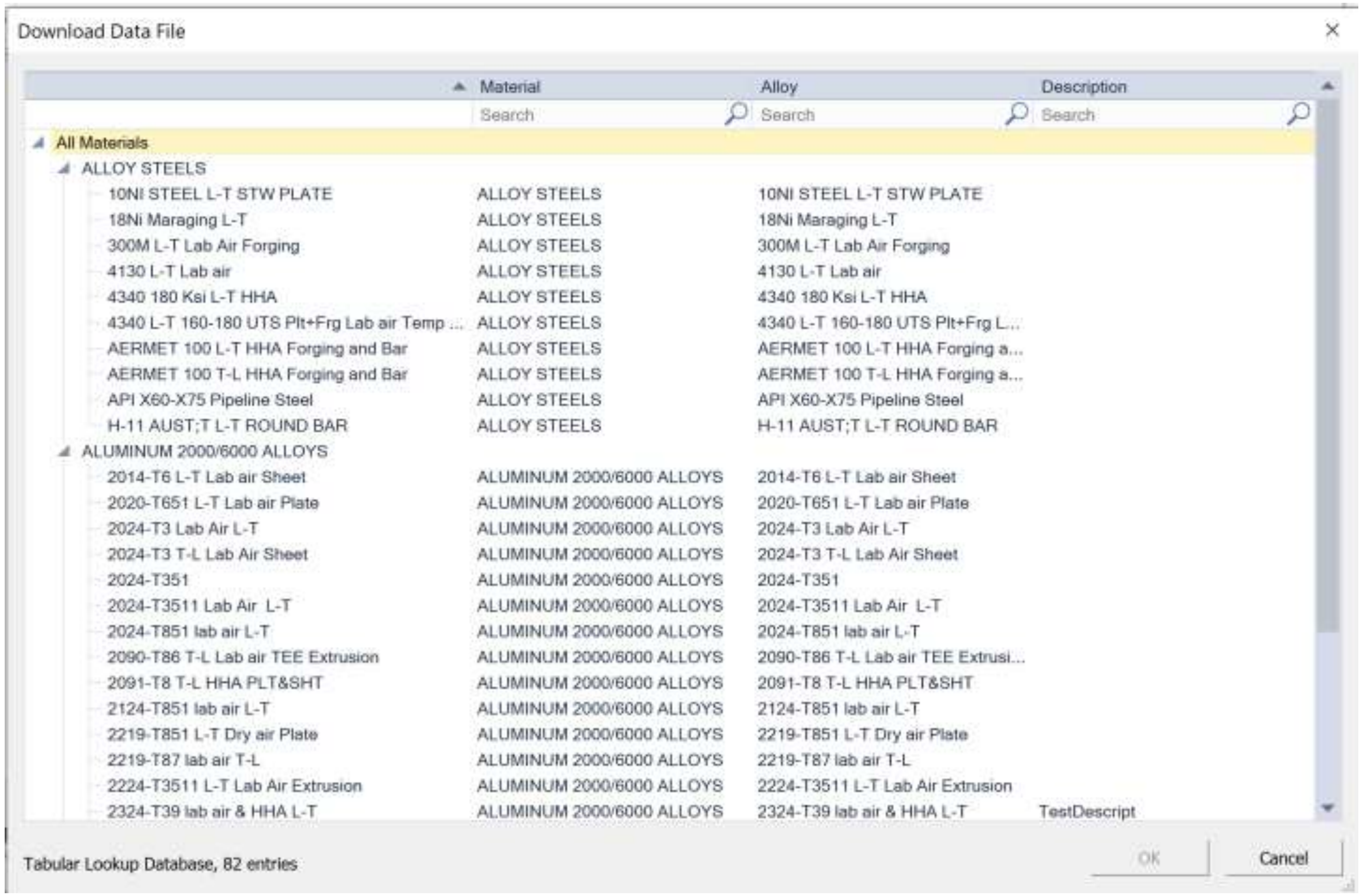


Single Through Crack at Hole Weight Function Solution Verification - Case 2



Local Material Database in the Tabular-Lookup format

- Based on AFMAT Data
- Searchable by material name and material type
- Data can not be modified
- AFGROW can be configured to be used the database on local computer, network server or company intranet


Download Data File

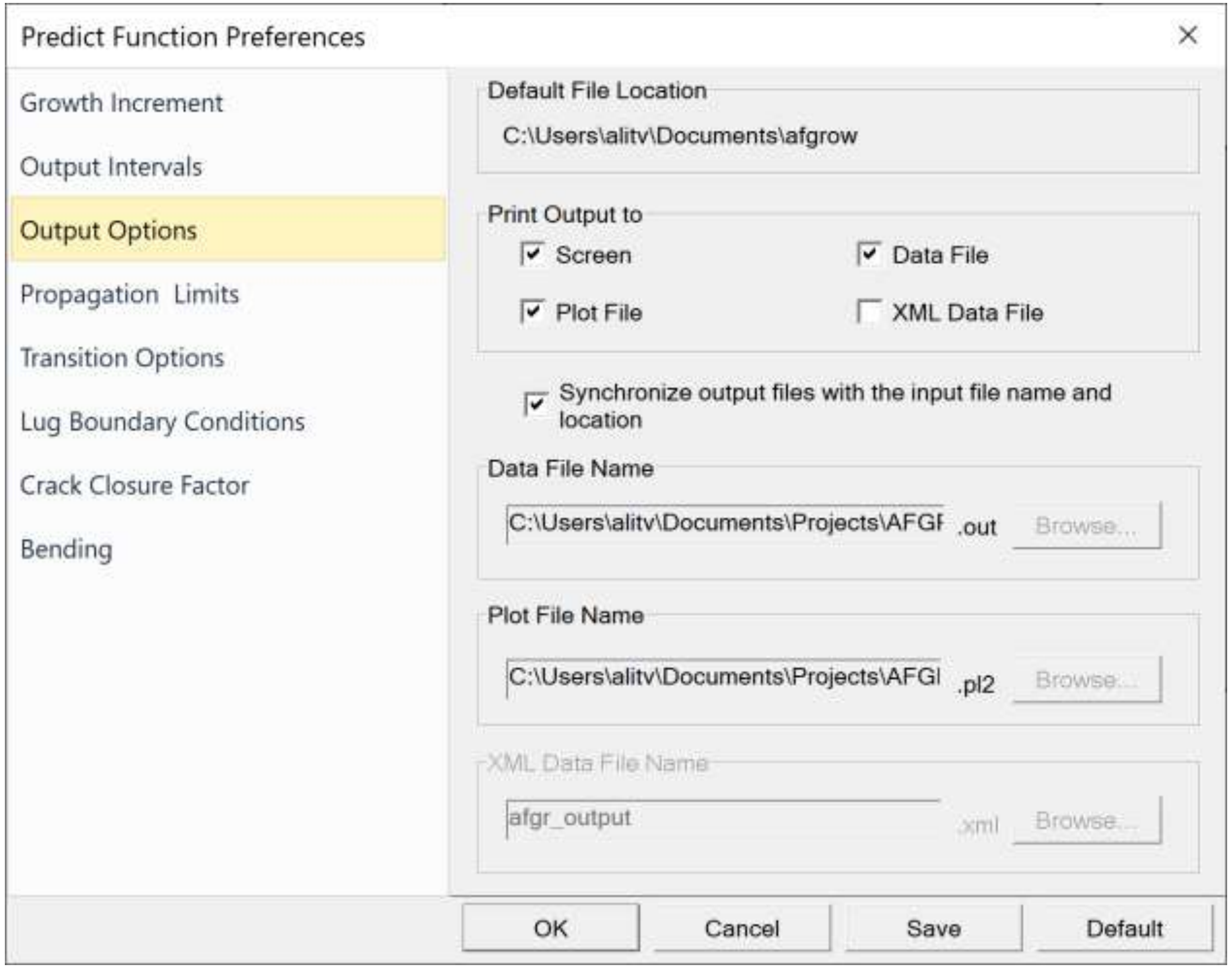
	Material	Alloy	Description
	Search	Search	Search
All Materials			
ALLOY STEELS			
10NI STEEL L-T STW PLATE	ALLOY STEELS	10NI STEEL L-T STW PLATE	
18Ni Maraging L-T	ALLOY STEELS	18Ni Maraging L-T	
300M L-T Lab Air Forging	ALLOY STEELS	300M L-T Lab Air Forging	
4130 L-T Lab air	ALLOY STEELS	4130 L-T Lab air	
4340 180 Ksi L-T HHA	ALLOY STEELS	4340 180 Ksi L-T HHA	
4340 L-T 160-180 UTS Plt+Frg Lab air Temp ...	ALLOY STEELS	4340 L-T 160-180 UTS Plt+Frg L...	
AERMET 100 L-T HHA Forging and Bar	ALLOY STEELS	AERMET 100 L-T HHA Forging a...	
AERMET 100 T-L HHA Forging and Bar	ALLOY STEELS	AERMET 100 T-L HHA Forging a...	
API X60-X75 Pipeline Steel	ALLOY STEELS	API X60-X75 Pipeline Steel	
H-11 AUST;T L-T ROUND BAR	ALLOY STEELS	H-11 AUST;T L-T ROUND BAR	
ALUMINUM 2000/6000 ALLOYS			
2014-T6 L-T Lab air Sheet	ALUMINUM 2000/6000 ALLOYS	2014-T6 L-T Lab air Sheet	
2020-T651 L-T Lab air Plate	ALUMINUM 2000/6000 ALLOYS	2020-T651 L-T Lab air Plate	
2024-T3 Lab Air L-T	ALUMINUM 2000/6000 ALLOYS	2024-T3 Lab Air L-T	
2024-T3 T-L Lab Air Sheet	ALUMINUM 2000/6000 ALLOYS	2024-T3 T-L Lab Air Sheet	
2024-T351	ALUMINUM 2000/6000 ALLOYS	2024-T351	
2024-T3511 Lab Air L-T	ALUMINUM 2000/6000 ALLOYS	2024-T3511 Lab Air L-T	
2024-T851 lab air L-T	ALUMINUM 2000/6000 ALLOYS	2024-T851 lab air L-T	
2090-T86 T-L Lab air TEE Extrusion	ALUMINUM 2000/6000 ALLOYS	2090-T86 T-L Lab air TEE Extrusi...	
2091-T8 T-L HHA PLT&SHT	ALUMINUM 2000/6000 ALLOYS	2091-T8 T-L HHA PLT&SHT	
2124-T851 lab air L-T	ALUMINUM 2000/6000 ALLOYS	2124-T851 lab air L-T	
2219-T851 L-T Dry air Plate	ALUMINUM 2000/6000 ALLOYS	2219-T851 L-T Dry air Plate	
2219-T87 lab air T-L	ALUMINUM 2000/6000 ALLOYS	2219-T87 lab air T-L	
2224-T3511 L-T Lab Air Extrusion	ALUMINUM 2000/6000 ALLOYS	2224-T3511 L-T Lab Air Extrusion	
2324-T39 lab air & HHA L-T	ALUMINUM 2000/6000 ALLOYS	2324-T39 lab air & HHA L-T	TestDescript

Tabular Lookup Database, 82 entries

OK Cancel

Enhanced Output Preferences

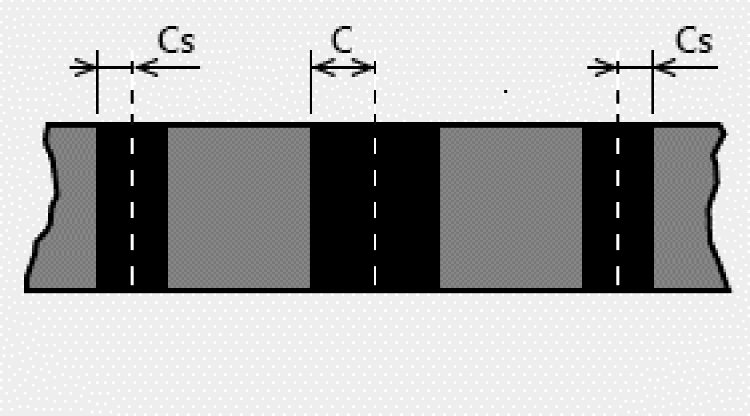
- Add a check box to put output file in the same folder as input file.
- Allow the for each output file type to have the same name as an input file.



Multiside Damage Solutions (MSD)

Multiple Through Cracks in an Infinite Plate

- Axial load case
- 3 to 9 cracks Multiple Holes in an Infinite Plate (Continuing Damage)

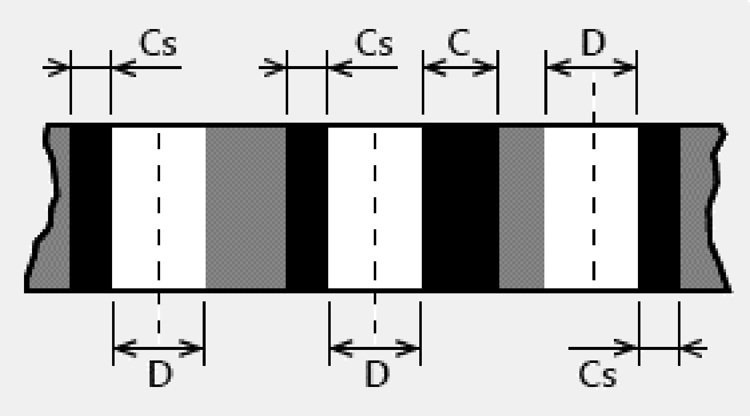


Axial and bearing load cases

- Primary and Secondary Crack at the Center Hole
- Single Secondary Crack on Outside of each adjacent hole (2, 4, 6, or 8 holes)

Multiple Holes in an Infinite Plate (Multisite Damage)

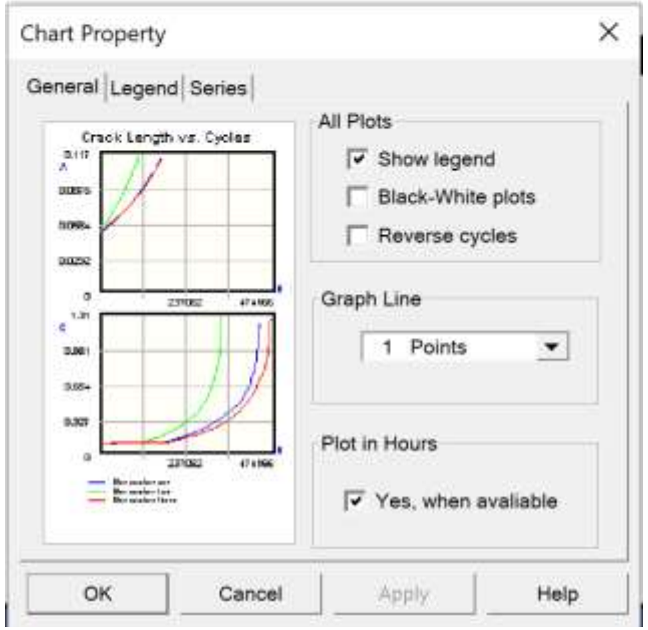
- Axial and bearing load cases
- Primary and Secondary Crack at the Center Hole
- Single Secondary Crack on Outside of each adjacent hole (2, 4, 6, or 8 holes)



Life in Hours Output – What Do We Do with a Time Dependent Spectrum?

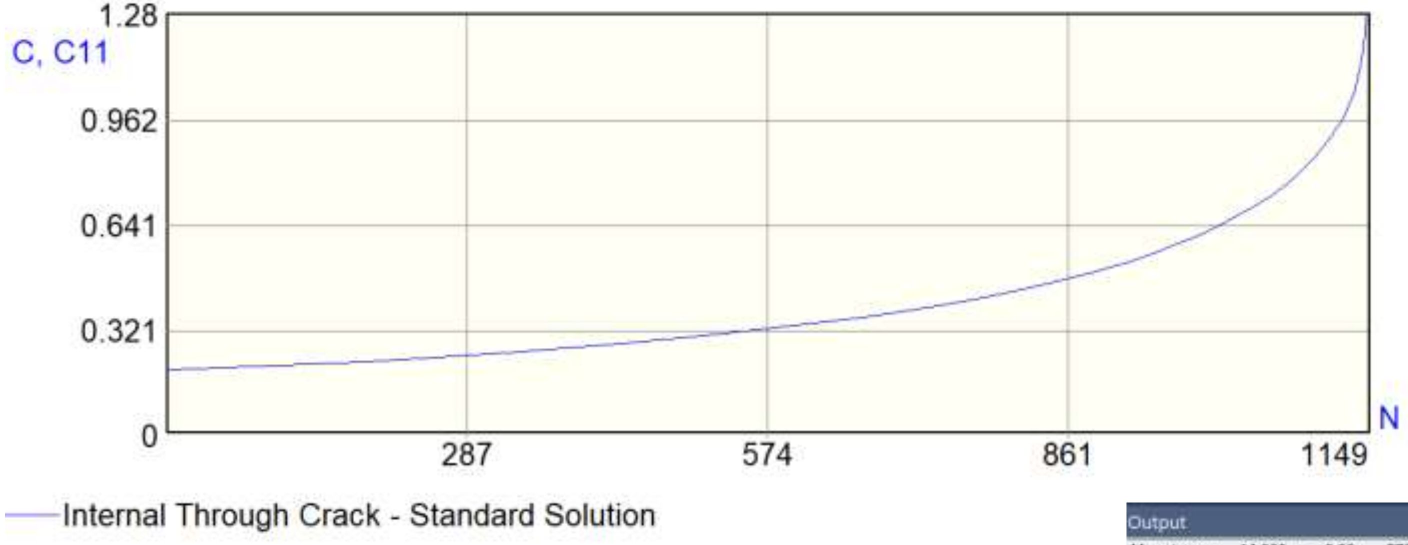
Print hours and cycles

```
C  Crack size=    1.089  Beta Tension= 1.2170 Beta Compression= 1.2170  R(k)= 0.0000  R(final)= 0.0000          Delta k=3.1513e+01  D()/DN=3.0626e-04
Max stress =    14.000  r = 0.00      57100  Cycles  Subspectra:      0  Pass:  572    Hours: 1142

C  Crack size=   1.1196  Beta Tension= 1.2498 Beta Compression= 1.2498  R(k)= 0.0000  R(final)= 0.0000          Delta k=3.2816e+01  D()/DN=4.4571e-04
Max stress =    14.000  r = 0.00      57200  Cycles  Subspectra:      0  Pass:  573    Hours: 1144

C  Crack size=   1.1642  Beta Tension= 1.2498 Beta Compression= 1.2498  R(k)= 0.0000  R(final)= 0.0000          Delta k=3.3463e+01  D()/DN=5.5443e-04
Max stress =    14.000  r = 0.00      57300  Cycles  Subspectra:      0  Pass:  574    Hours: 1146

C  Crack size=   1.2196  Beta Tension= 1.3171 Beta Compression= 1.3171  R(k)= 0.0000  R(final)= 0.0000          Delta k=3.6095e+01  D()/DN=2.1559e-03
Max stress =    14.000  r = 0.00      57400  Cycles  Subspectra:      0  Pass:  575    Hours: 1148
```



- Let user decide what to see in the plot view.
- “Crack Length vs. Cycles” graph will be in hours only if “Yes” button is checked in and plots are covetable to hours

New Life in Hours Output Options



The crack length plots converted to hours if the option to display life in hours is selected

Output intervals printed in "hours" if the option to display life in hours is selected

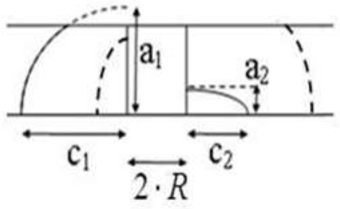
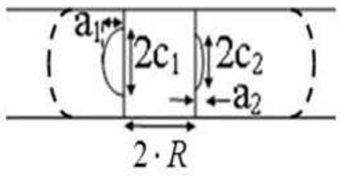
```
Output
Max stress =   14.000  r = 0.00    57000  Cycles  Subspectra:     0  Pass:  571   Hours: 1140

 C  Crack size=    1.089  Beta Tension= 1.2170 Beta Compression= 1.2170  R(k)= 0.0000  R(final)= 0.0000        Delta k=3.1513e+01  D()/DN=3.0626e-04
Max stress =   14.000  r = 0.00    57100  Cycles  Subspectra:     0  Pass:  572   Hours: 1142

 C  Crack size=   1.1196  Beta Tension= 1.2498 Beta Compression= 1.2498  R(k)= 0.0000  R(final)= 0.0000       Delta k=3.2816e+01  D()/DN=4.4571e-04
Max stress =   14.000  r = 0.00    57200  Cycles  Subspectra:     0  Pass:  573   Hours: 1144

 C  Crack size=   1.1642  Beta Tension= 1.2498 Beta Compression= 1.2498  R(k)= 0.0000  R(final)= 0.0000       Delta k=3.3463e+01  D()/DN=5.5443e-04
Max stress =   14.000  r = 0.00    57300  Cycles  Subspectra:     0  Pass:  574   Hours: 1146

 C  Crack size=   1.2196  Beta Tension= 1.3171 Beta Compression= 1.3171  R(k)= 0.0000  R(final)= 0.0000       Delta k=3.6095e+01  D()/DN=2.1559e-03
Max stress =   14.000  r = 0.00    57400  Cycles  Subspectra:     0  Pass:  575   Hours: 1148

*********Fracture based on ' Kmax' Criteria (current maximum stress)
 C  Crack size=   1.2821  Beta Tension= 1.3677 Beta Compression= 1.3677  R(k)= 0.0000  R(final)= 0.0000       Delta k=3.8429e+01  D()/DN=1.0000e-02
Max stress =   14.000  r = 0.00    57429  Cycles  Subspectra:     0  Pass:  575   Hours: 1148.58

Stress State in the 'C' direction (PSC): 2
Fracture has occurred- run time:  0 hour(s)  0 minute(s)  1 second(s)
1148.5800 hours have passed
```

LexTech

AFGROW .NET

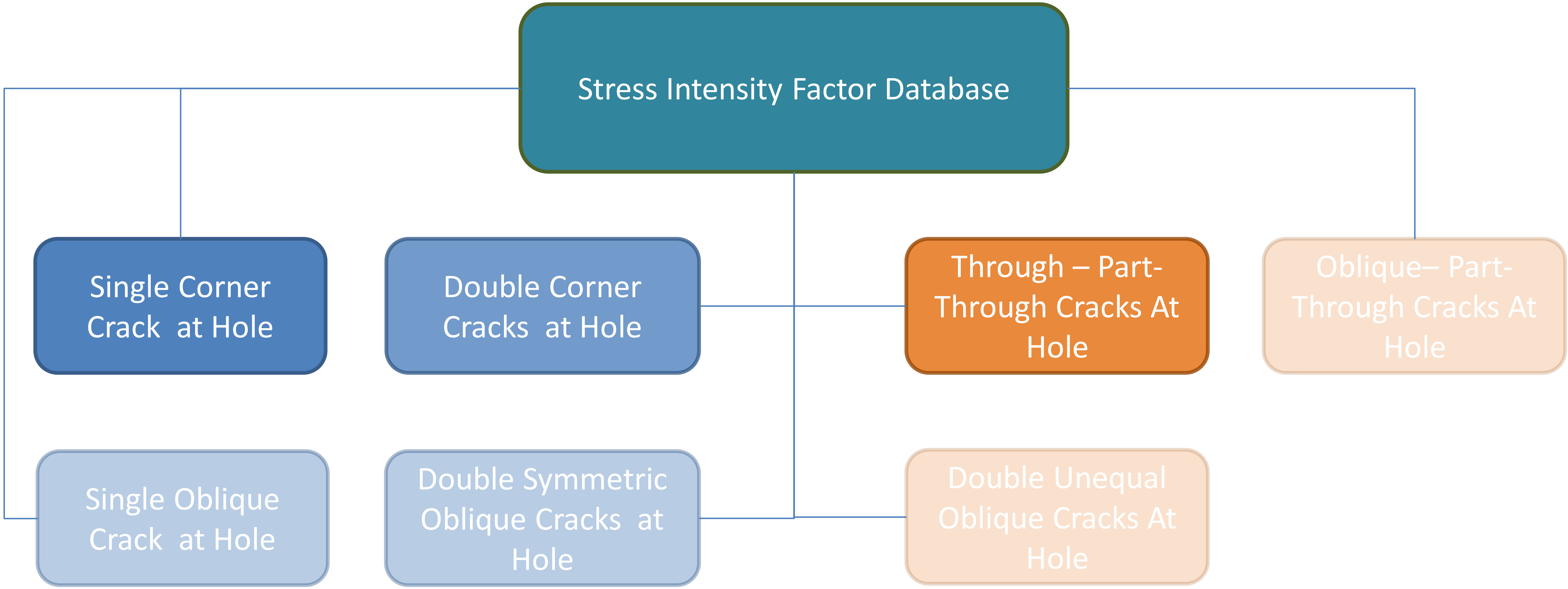
Advanced Crack At Hole Solutions in AFGROW

- 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



Verification vs. Validation

- Verification - the process of establishing the truth, accuracy.
- Validation - the action of making or declaring something legally or officially acceptable

Tabular K Solution Implementation Process

- Verify the raw data – make sure that there are no missing data and that the data are inside the acceptance bounds, and visual inspection of the data plots.
- Validate the raw data, when possible – compare data to known analytical/data solutions.
- Generate data necessary for the tabular K solution set.
- Verify the tabular K solution – visual inspection, test data using penalized regression splines (cubic spline fitting).
- Validate the tabular K solution – compare to known solutions and FEA.

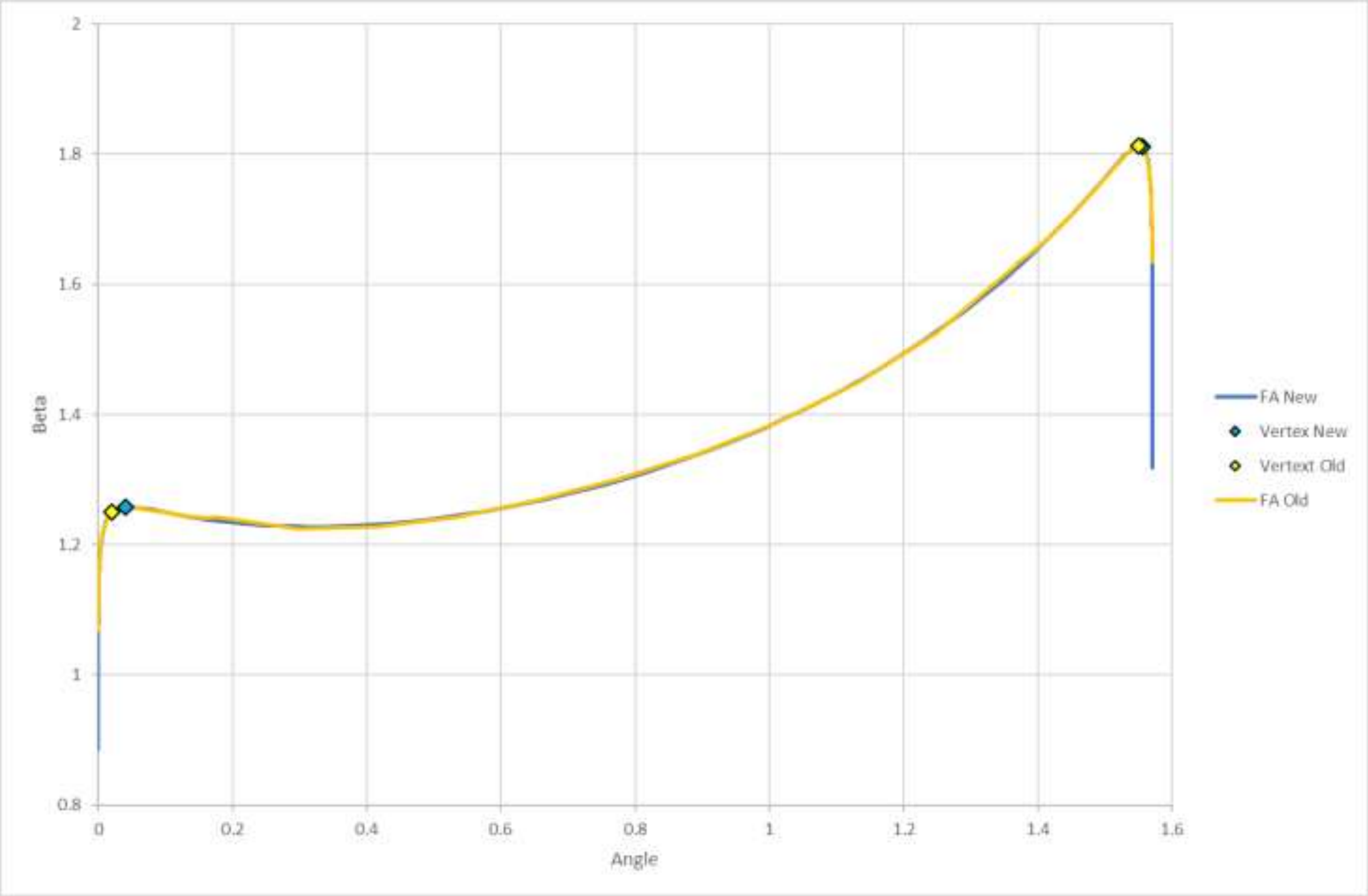
Single Corner Crack At a Hole

Axial

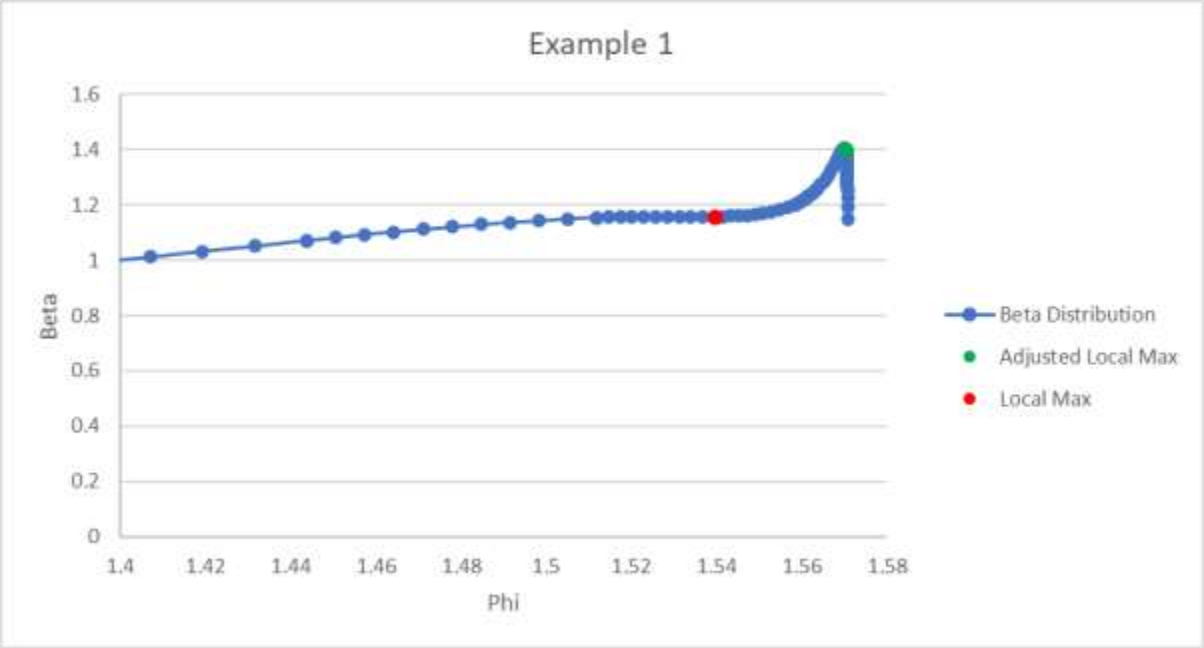
r/t	a/c	a/t
0.5	1	0.2

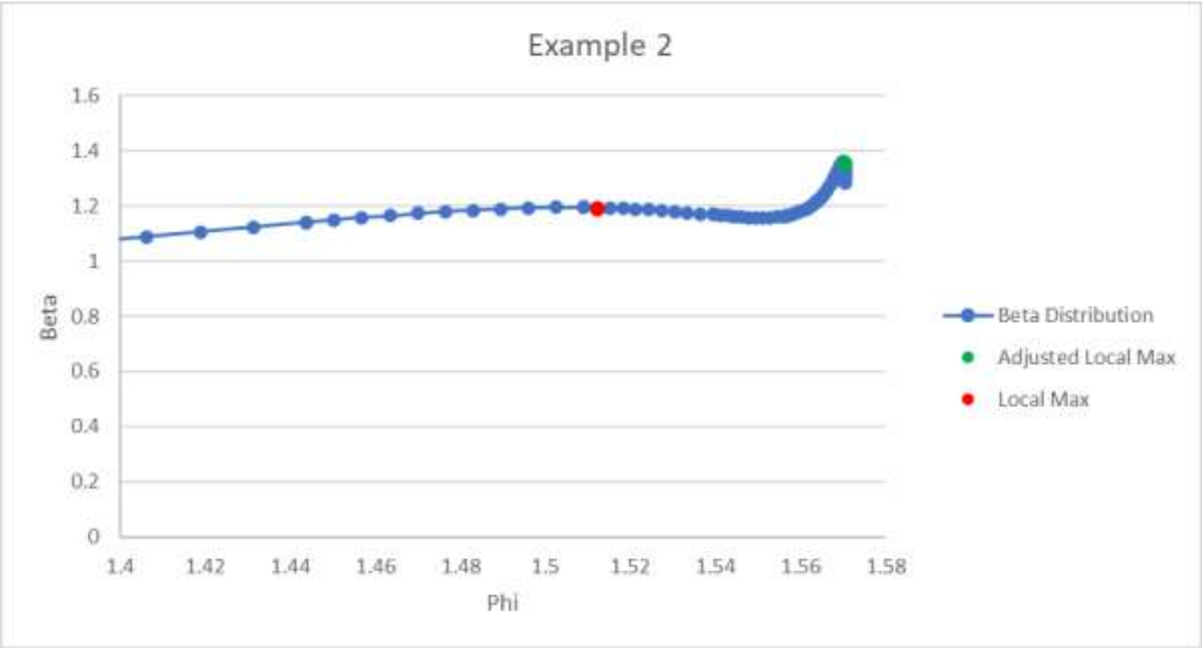
- All cases cases plotted and reviewed
- Found issues related to multiple local maximums in the area of vertices
- Modified vertex extraction code to fix the issue

Beta Distribution Along Crack Front



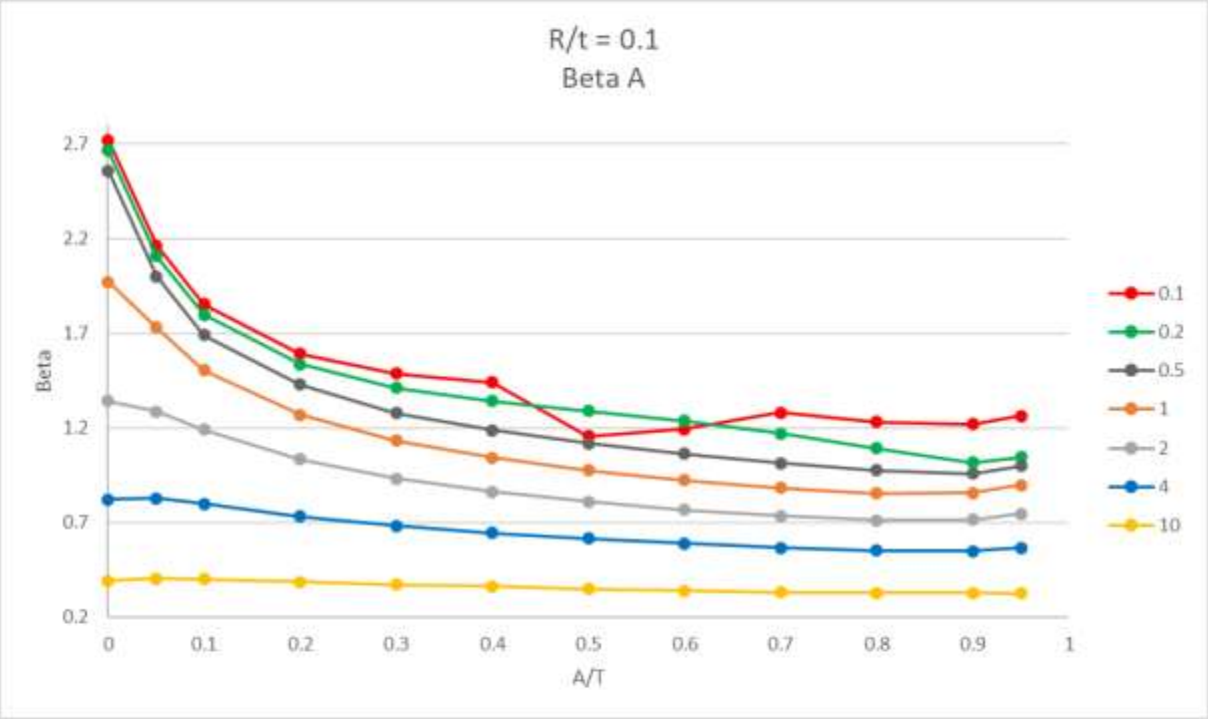
Single Corner Crack at Hole - Local Maximum Versus Adjusted Local Maximum

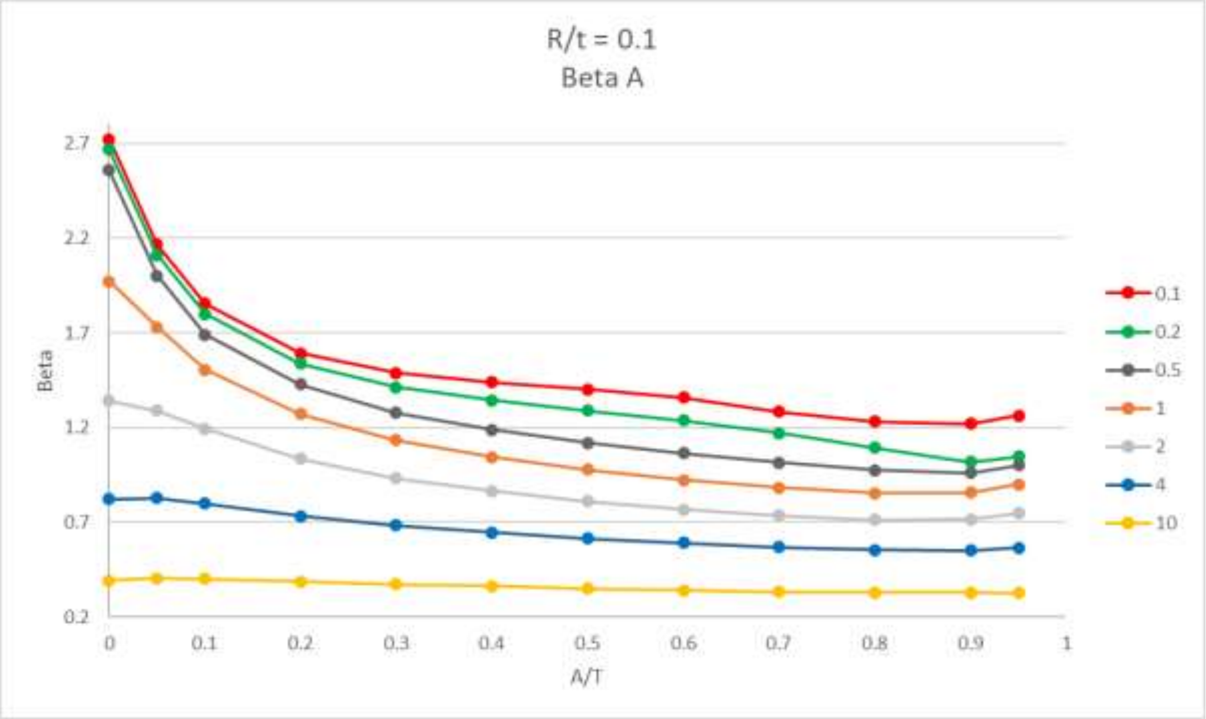




These images demonstrate local maximums before and after the adjustment was mad

Single Crack Corner Crack at Hole - Local Maximum Vertices Compared





These images demonstrate local maximums before and after the adjustment was mad

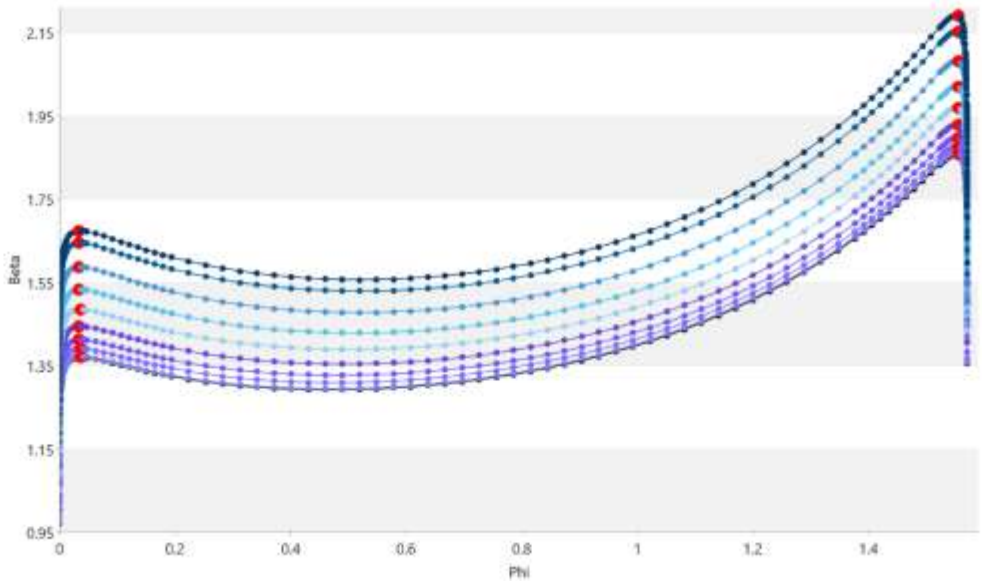
Double Corner/Oblique Cracks at Hole Verification - Introduction

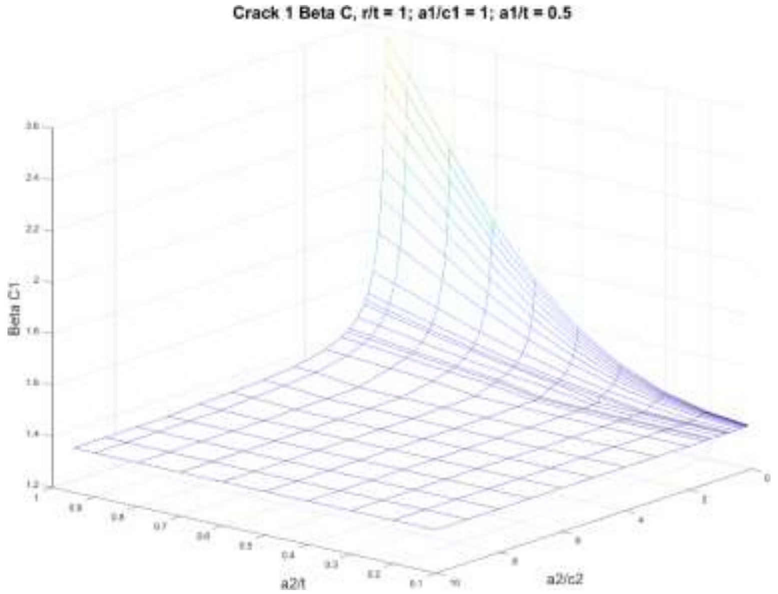
- Describe verification goals
- Review verification methodology
- Discuss the results
- This work covers only data verification for an axial loading however the bending and bearing data were reviewed and have a similar behavior.

What We Were Trying to Verify

- Ability to consistently find vertices for C and A and Ct (oblique crack) directions. Methodology is established and used in the 2003 Fawaz/Andersson solutions

- Smoothness of the two dimensional beta distribution with coordinates A2/C2, A2/t and Beta. Methodology proposed by LexTech and discussed in the next slide.





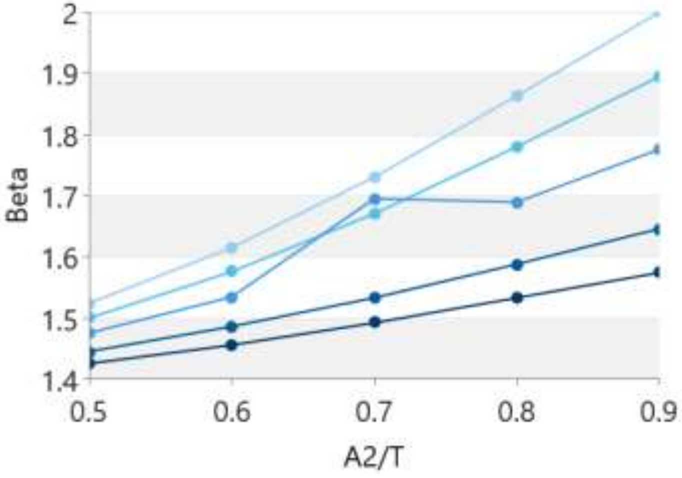
Smoothness of the Two Dimensional Beta Distribution Data Verification Methodology

Iterate through each data point in the distribution and validate it, by:

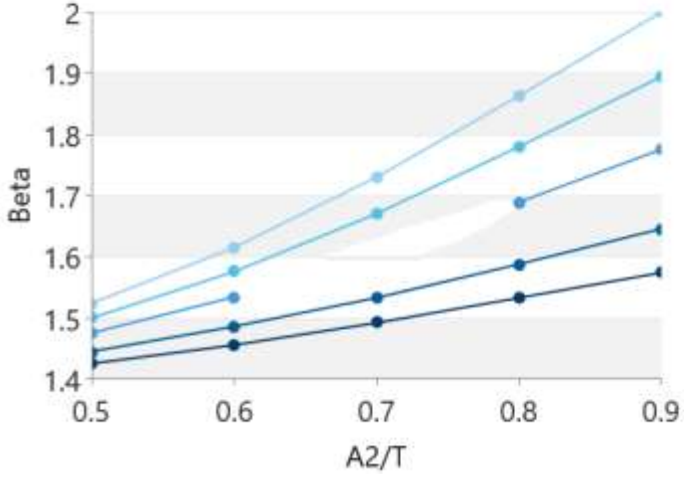
- Removing the point from the distribution
- Using two dimensional Radial Basis Function (RBF) to fit the rest of the data
- Using fitted data to recalculate Beta in the removed point
- The recalculated Beta value with more than 10% difference from the original was considered problematic.

Verification Methodology Example

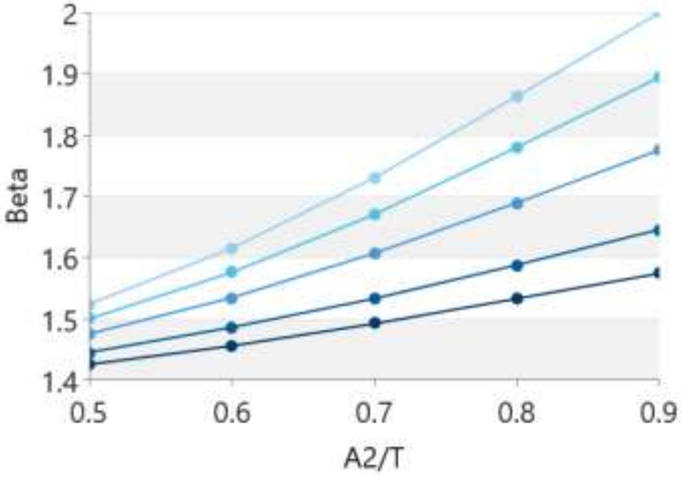
1. Original Point



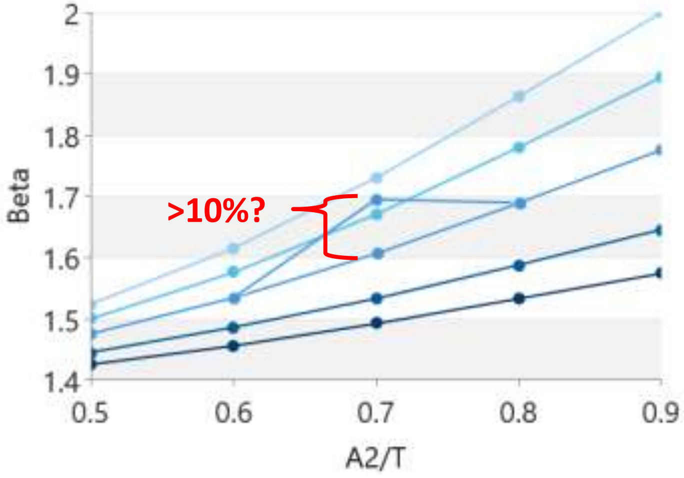
2. Original Point Removed



3. Fit Data and Calculate New Beta



4. Compare to Original



Validation of the Two Dimensional Beta Distribution Smoothness

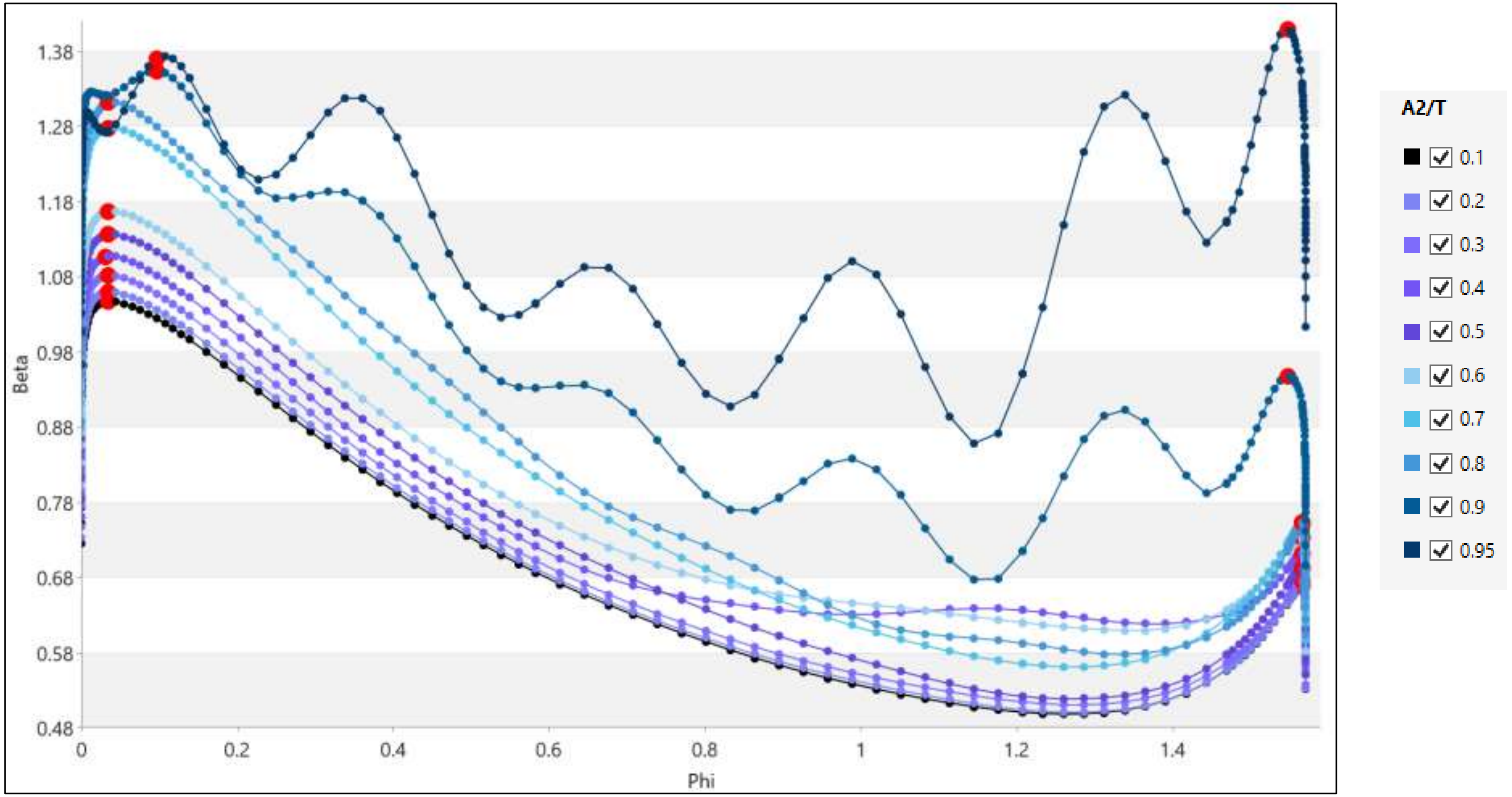
- On average, the data are acceptable
- There are a significant number of reported issues in the low r/t areas
- We found a lot of systematic errors that we believe could be related to FEA meshing
- This problem is not critical, however, it is not visible to fix that many cases manual and we are investigating the possibility of fixing data programmatically

Double Corner Cracks at Hole Error Report Overview

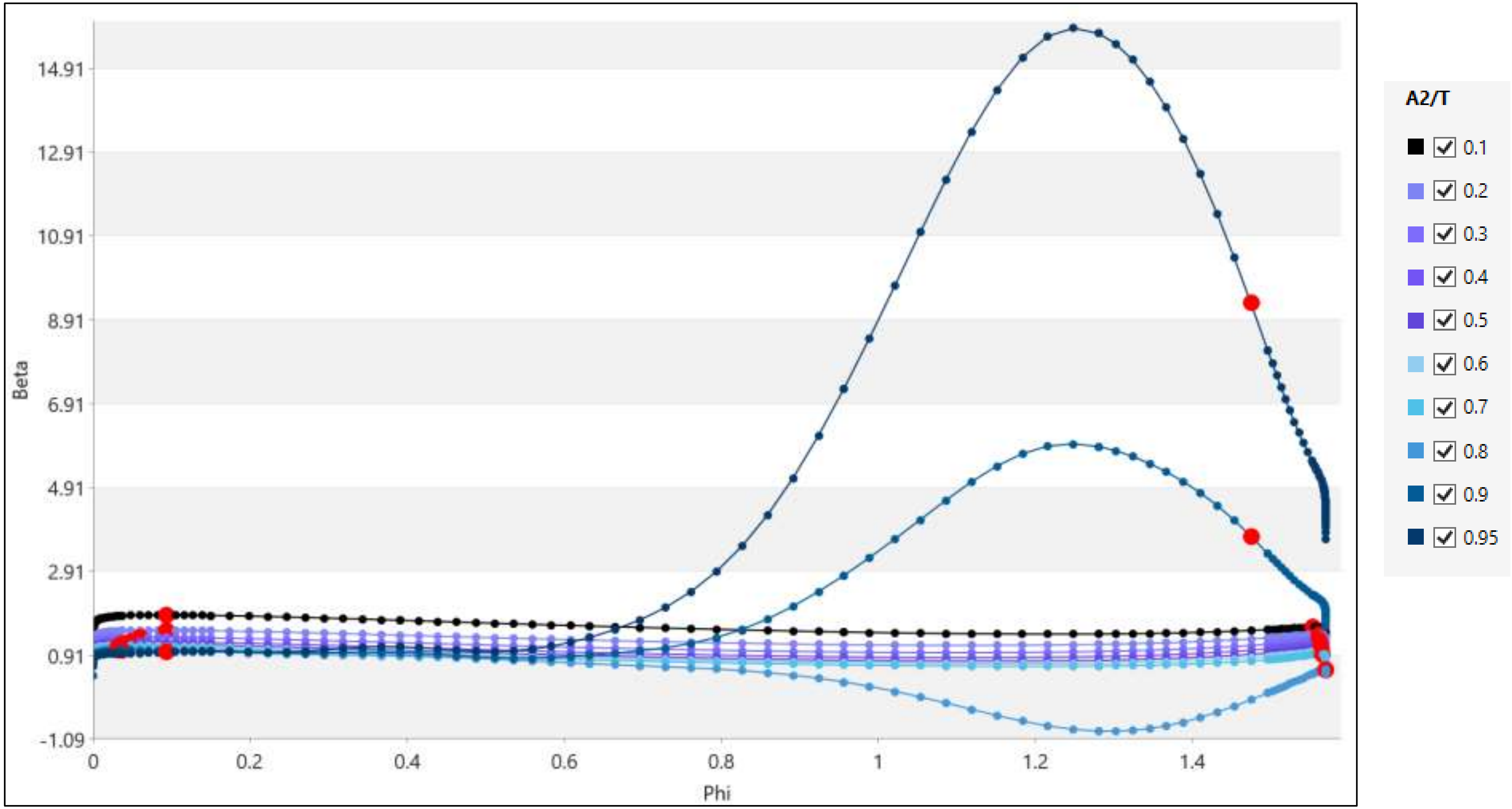
r/t	Estimated Bad Cases
0.1	2205
0.111	1771
0.125	1565
0.2	236
0.333	15
0.667, 0.8, 1	<3 each
2.25*	16913
Total (not including 2.25)	5796

*2.25 was removed from our final dataset because of how prevalent errors were

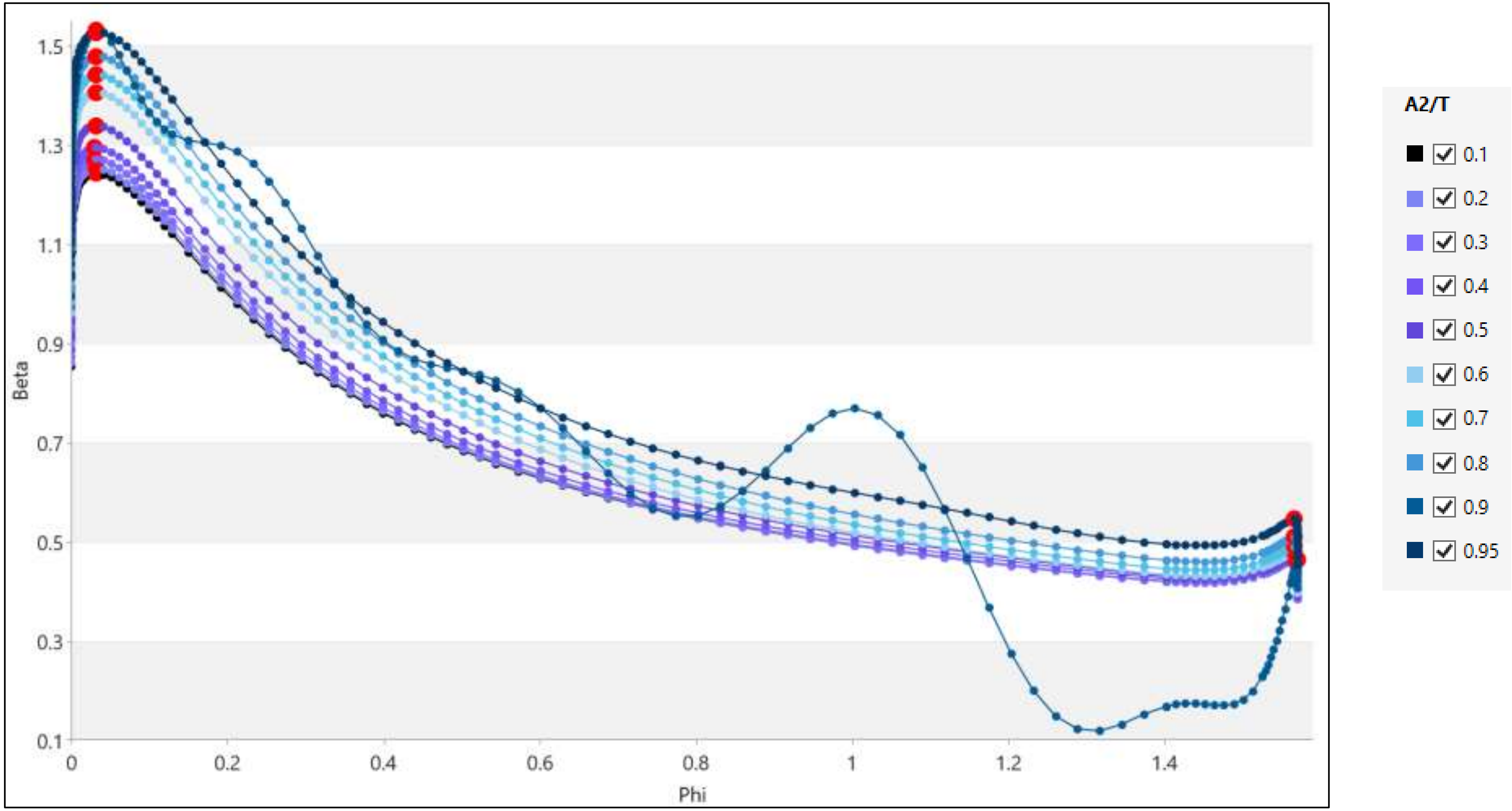
r/t=0.125, a1/c1=3.0, a1/t=0.8, a2/c2=2.0
Crack 1 Face



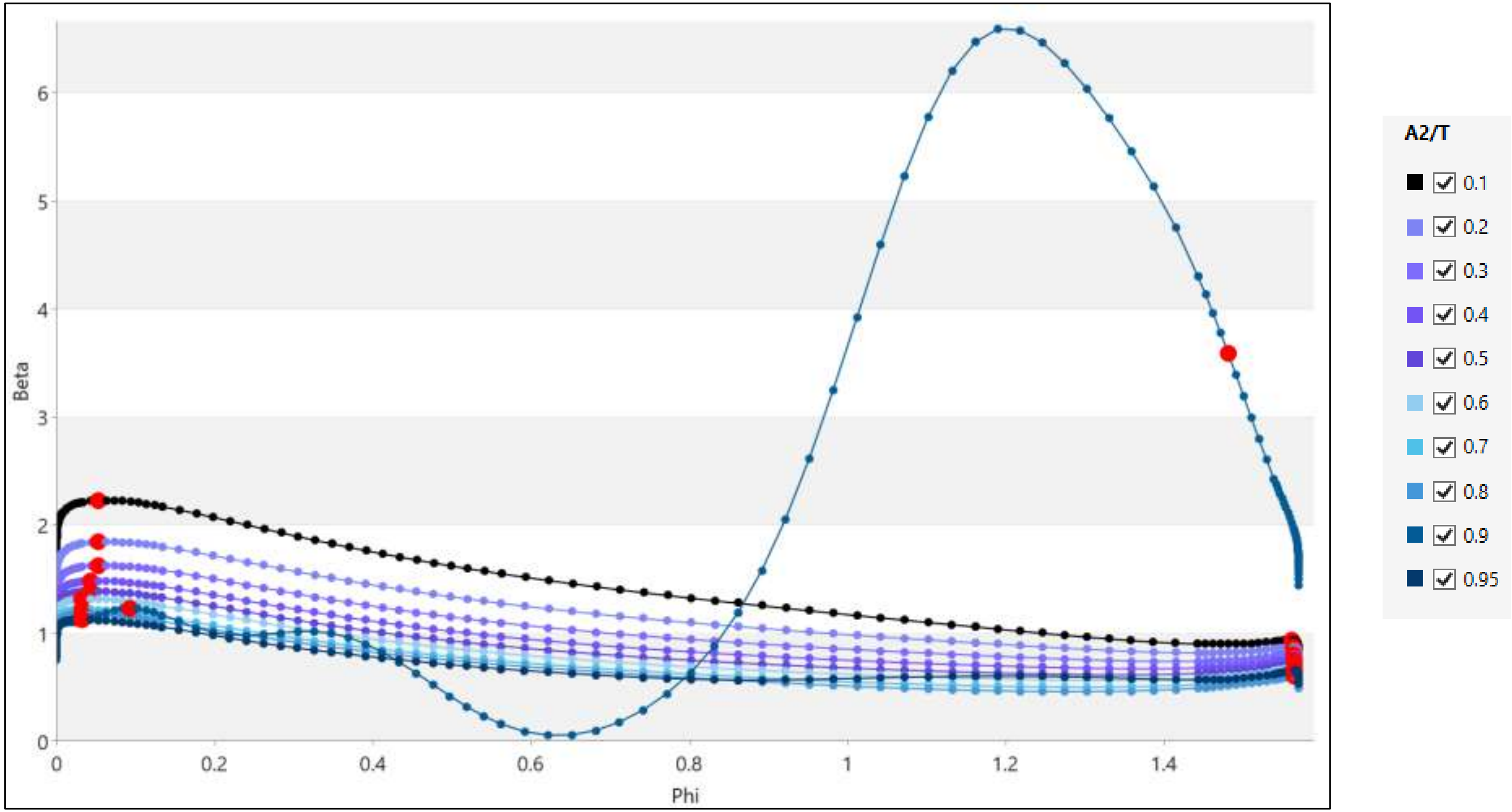
r/t=0.125, a1/c1=3.0, a1/t=0.8, a2/c2=2.0
Crack 2 Face



r/t=0.111, a1/c1=6.0, a1/t=0.8, a2/c2=4.0
Crack 1 Face



r/t=0.111, a1/c1=6.0, a1/t=0.8, a2/c2=4.0
Crack 2 Face

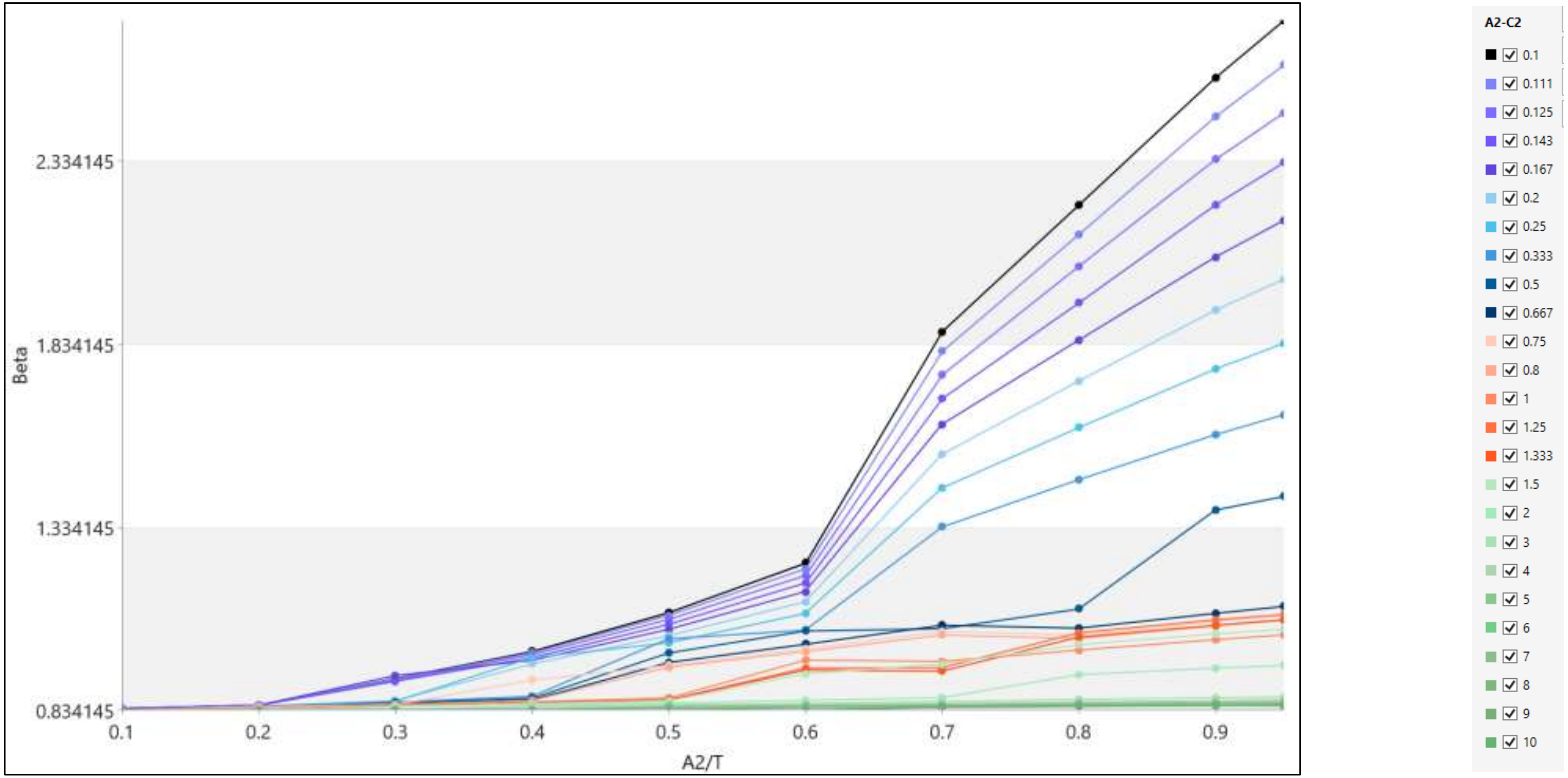


Systematic Errors

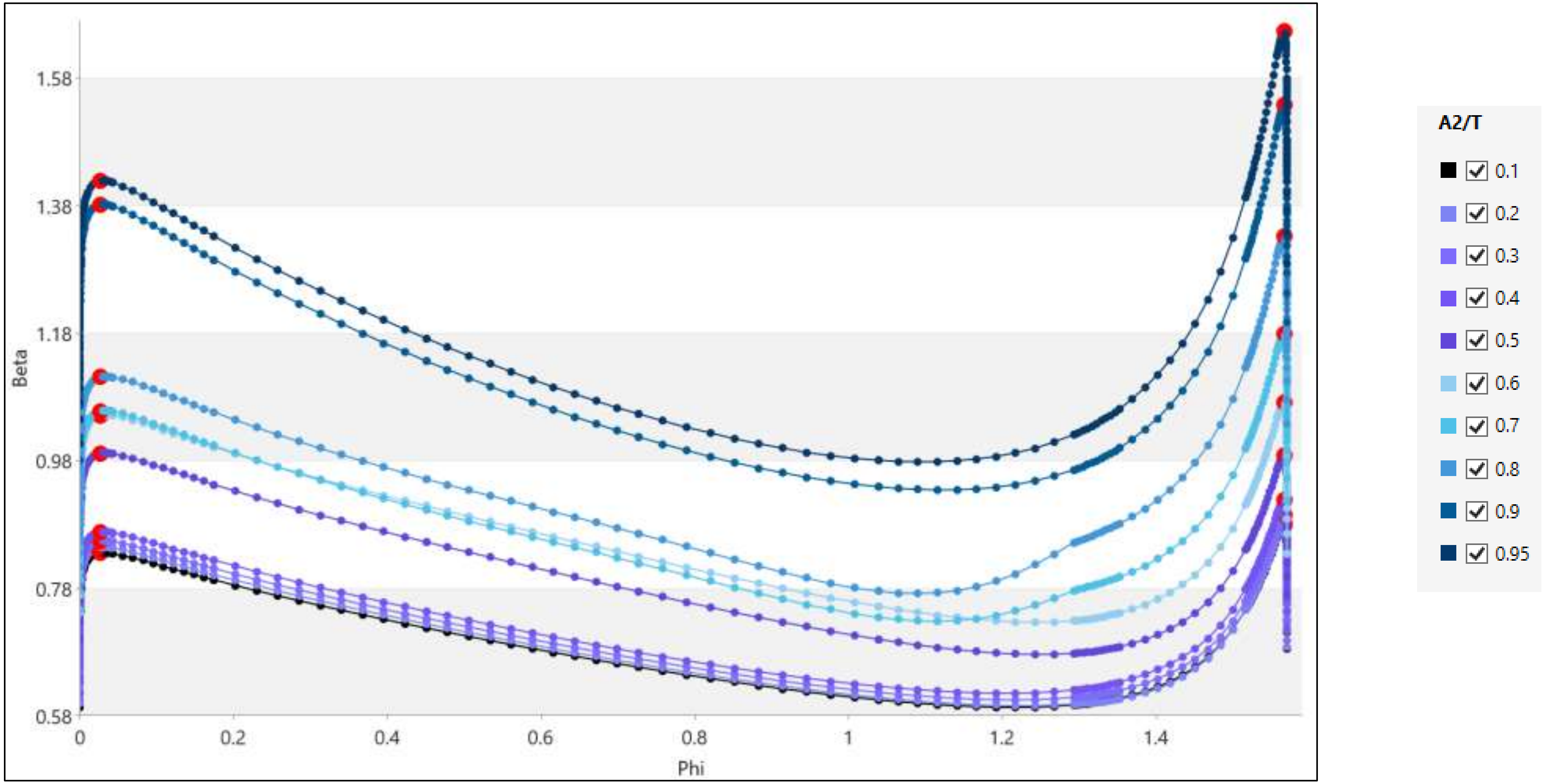
The following examples represent systematic errors. Systematic errors are when each individual crack front plot looks acceptable, but these cases have issues that span across multiple different parameter combinations.

These examples will have an overview showing the patterns of inconsistencies in the vertices compared to cases with similar parameters, followed by graphs that show the original crack front curves and the points that were picked for the vertices.

r/t=0.125, a1/c1=1.25, a1/t=0.8
Crack 1 Vertex C

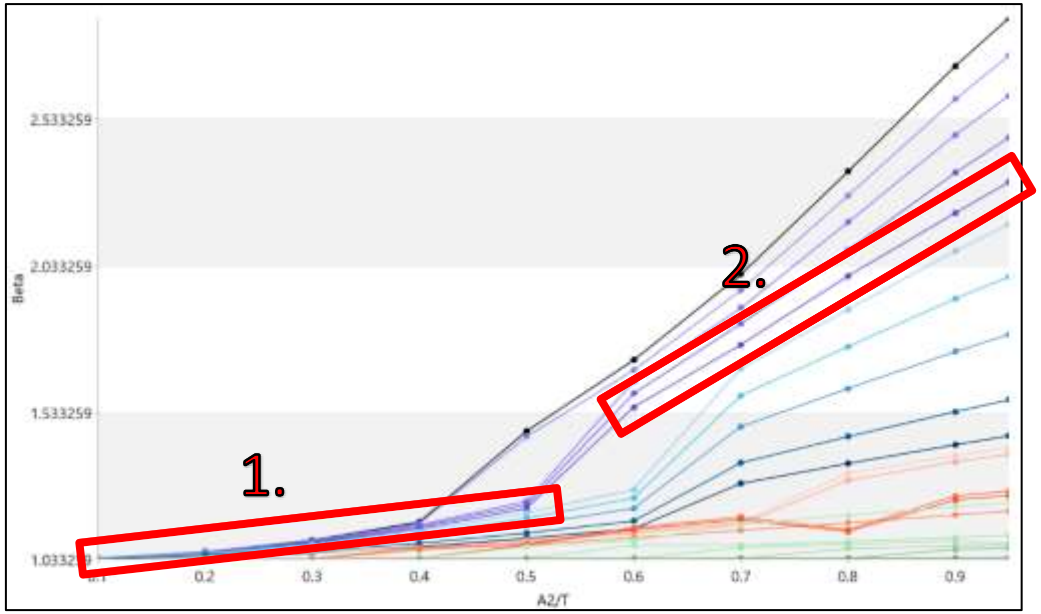


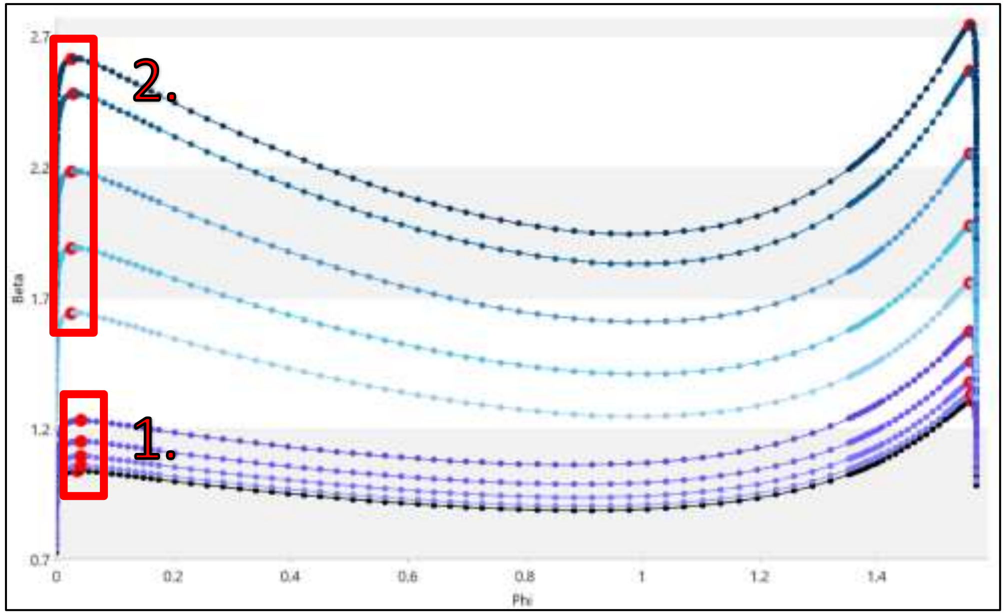
r/t=0.125, a1/c1=1.25, a1/t=0.8, a2/c2=0.5
Crack 1



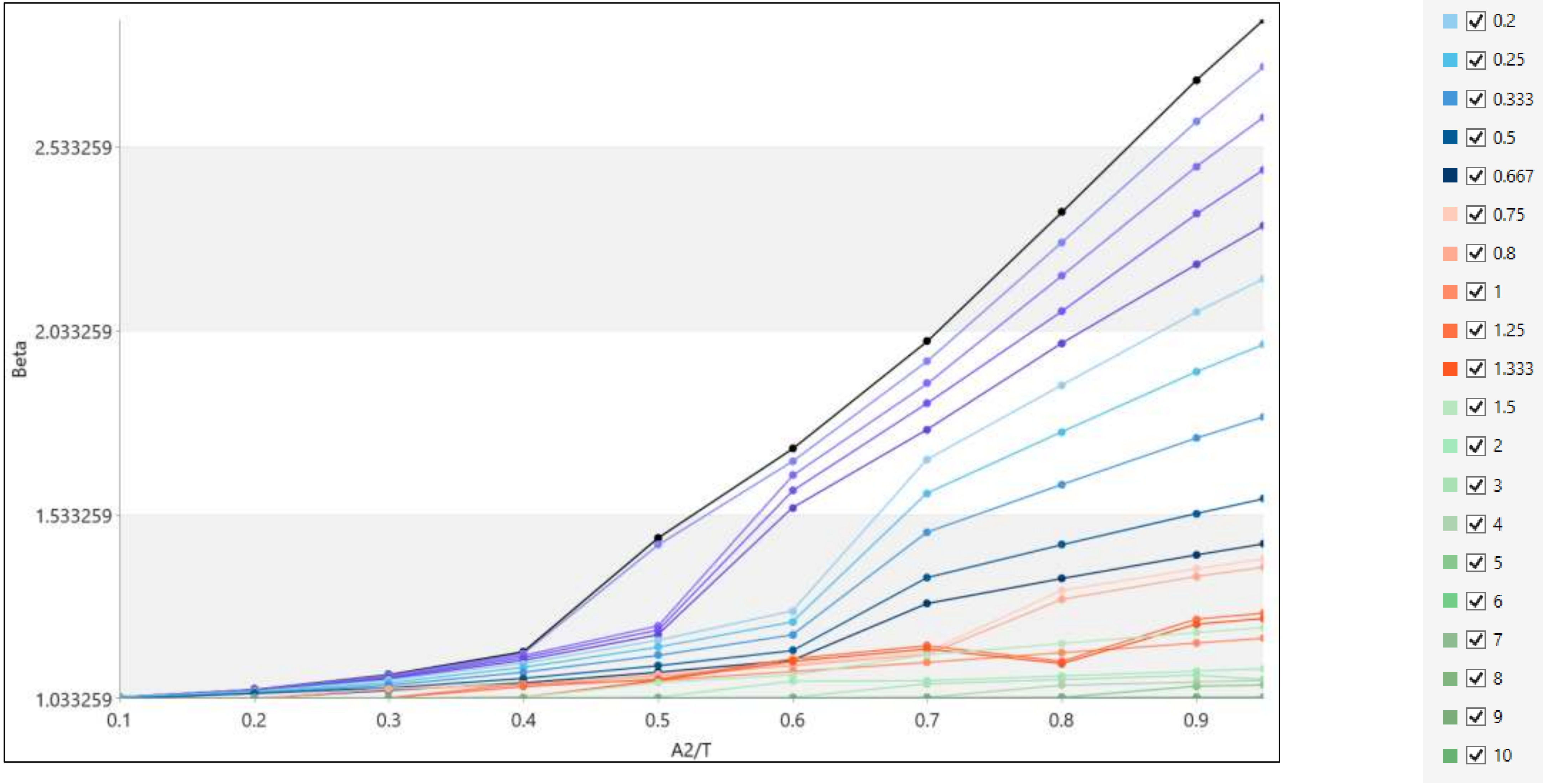
r/t=0.333, a1/c1=1.25, a1/t=0.6

Crack 1 Vertex C / Crack 1 Face



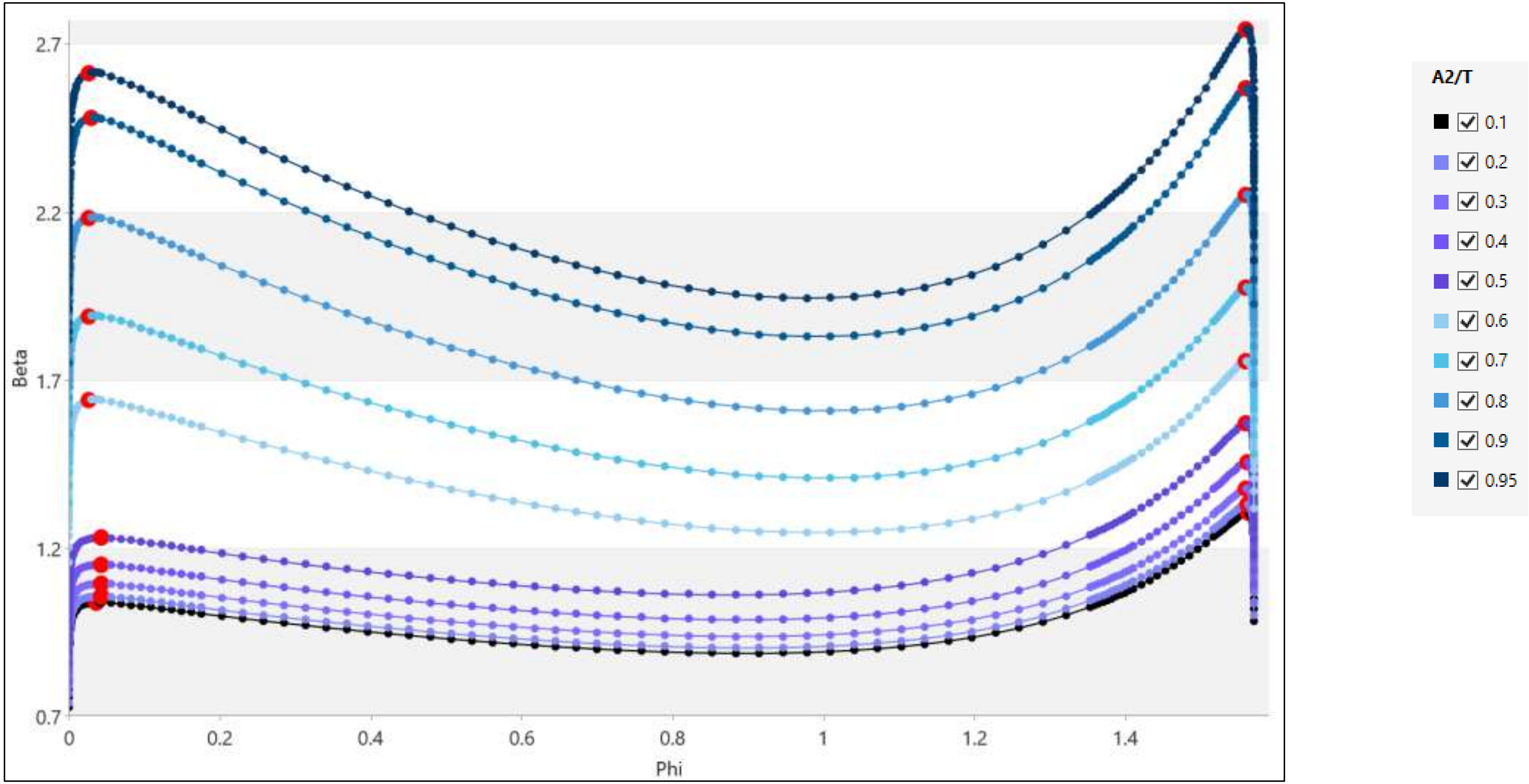


r/t=0.333, a1/c1=1.25, a1/t=0.6
Crack 1 Vertex C

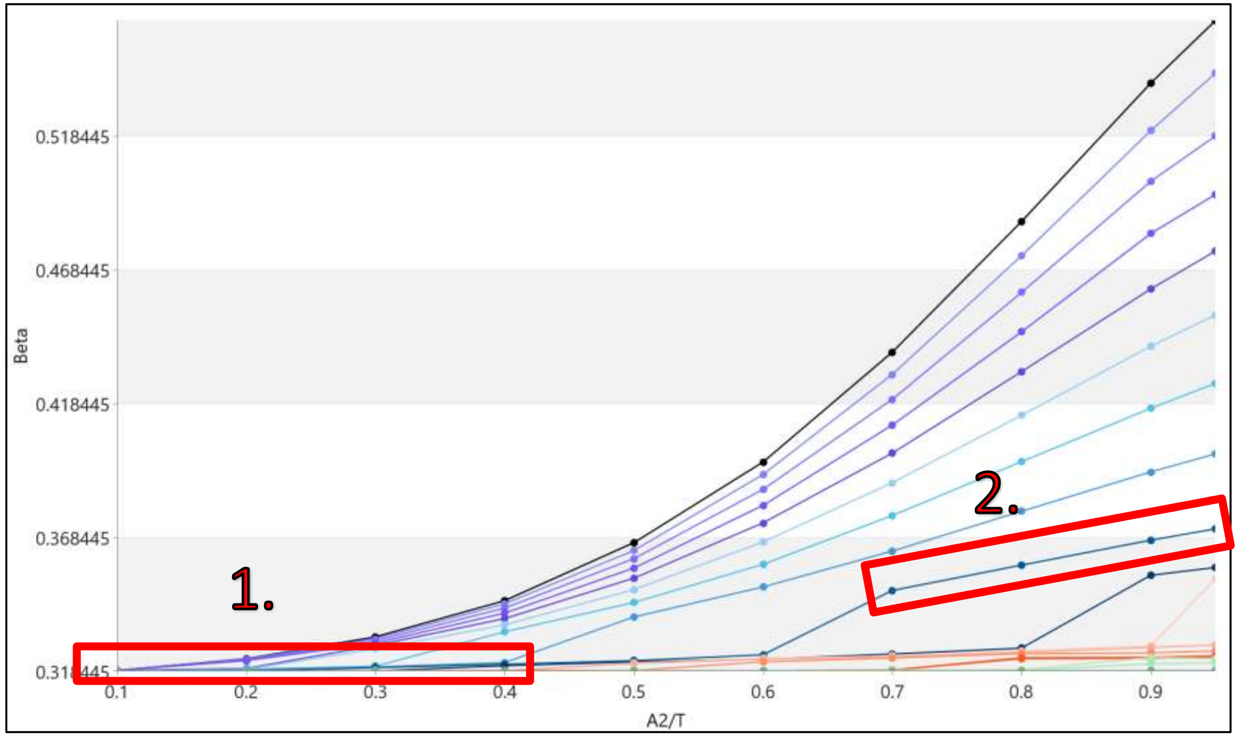


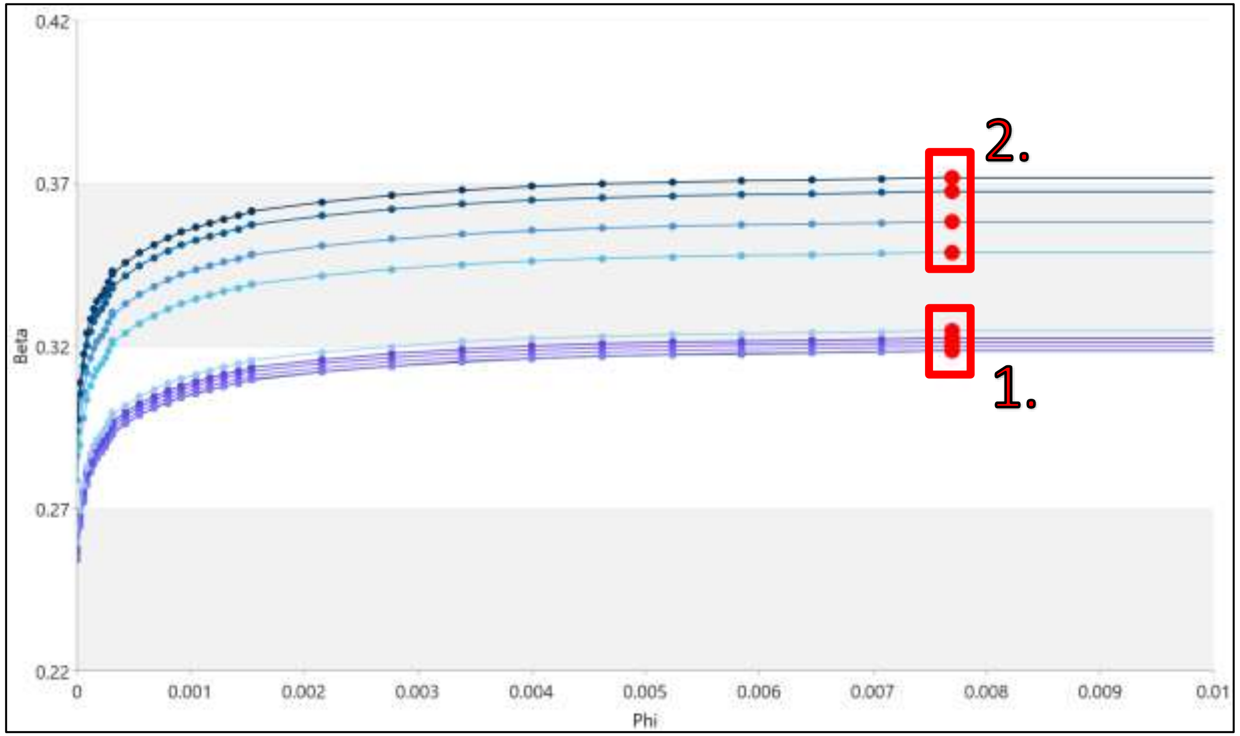
r/t=0.333, a1/c1=1.25, a1/t=0.6, a2/c2=0.125

Crack 1

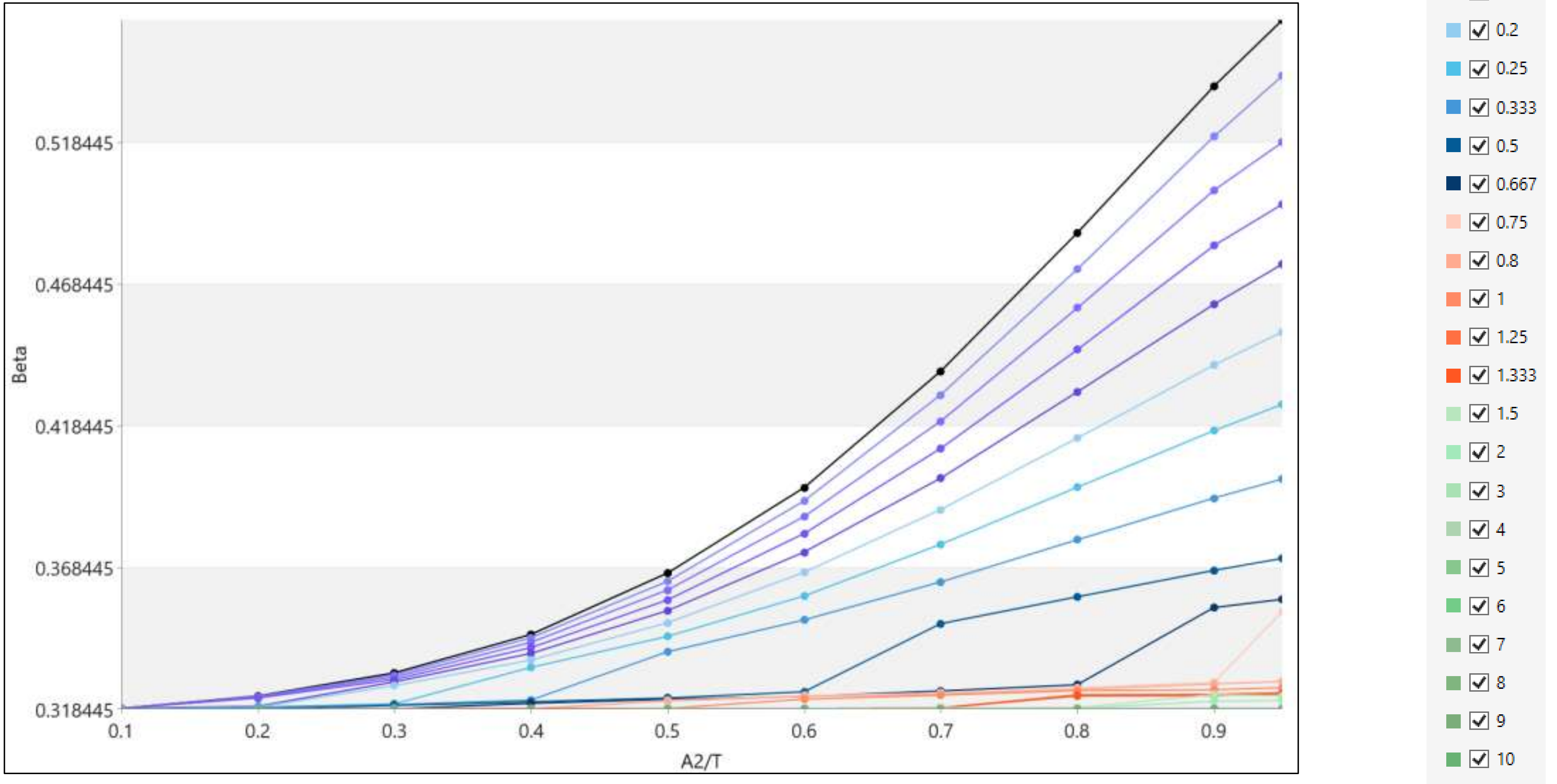


r/t=1.0, a1/c1=0.2, a1/t=0.3
Crack 1 Vertex C / Crack 1 Face (zoom)

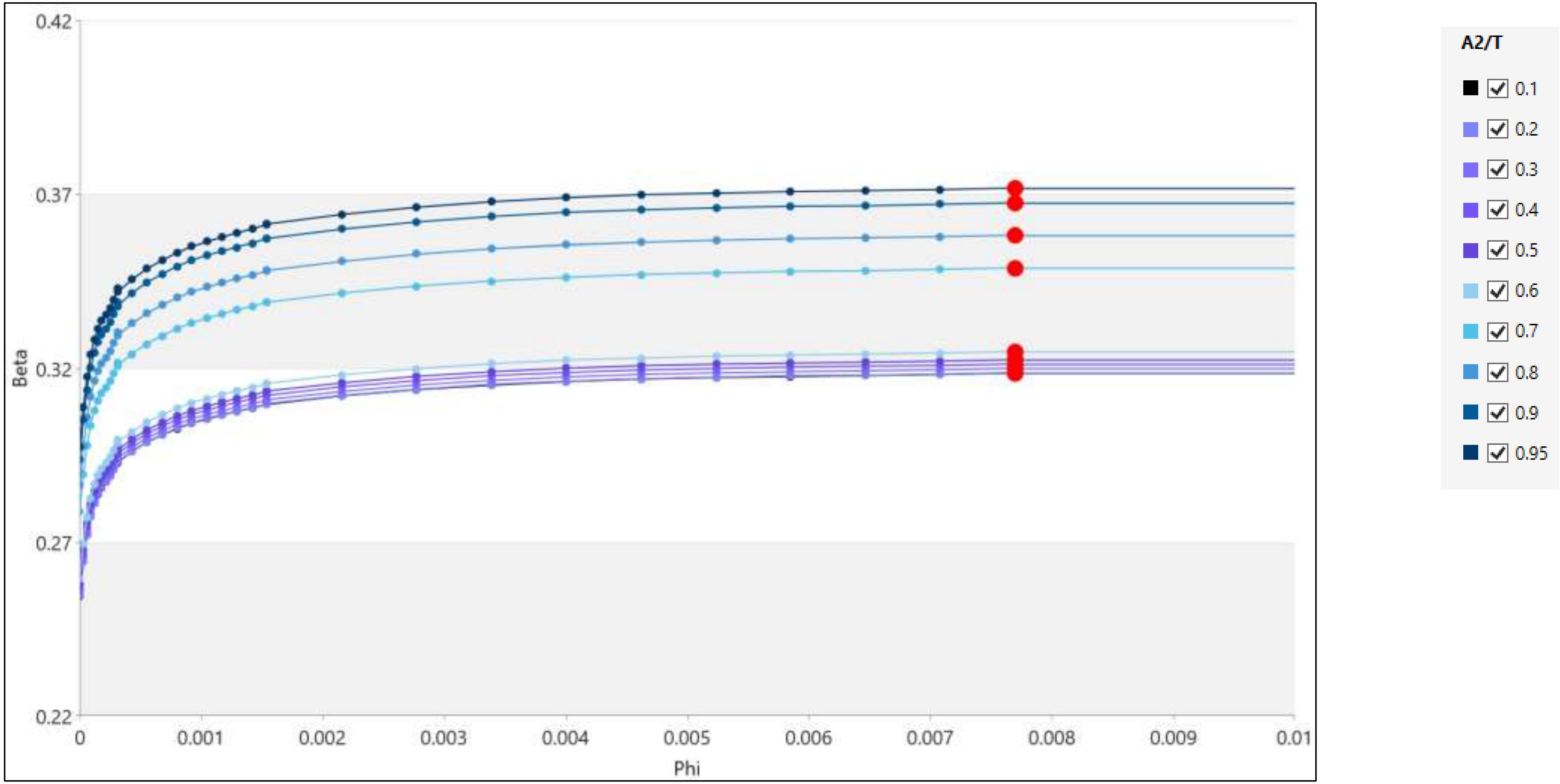




r/t=1.0, a1/c1=0.2, a1/t=0.3
Vertex 1 C

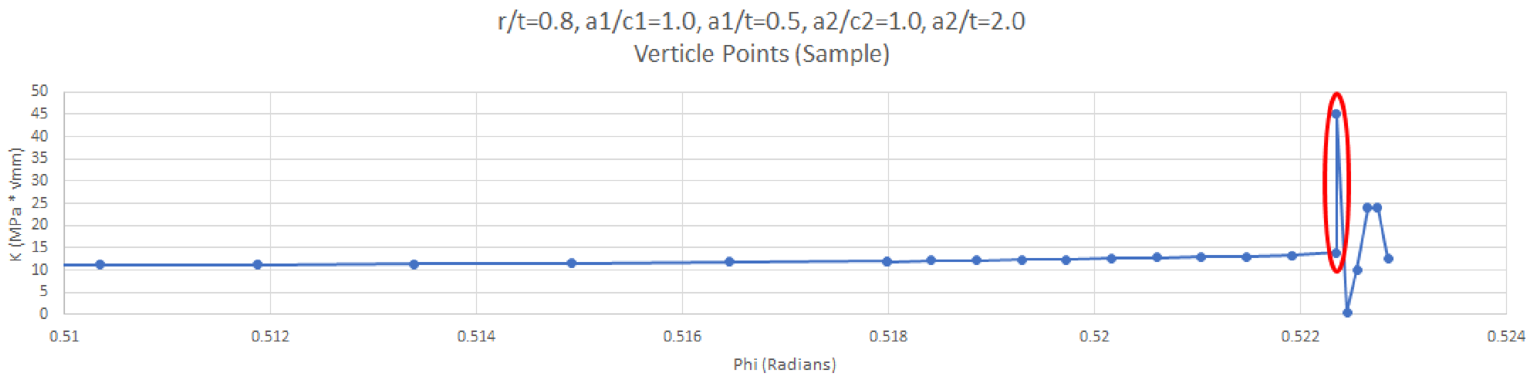


r/t=1.0, a1/c1=0.2, a1/t=0.3, a2/c2=0.5
Crack 1 C (phi 0-0.01)



Vertical / Duplicate Points

- Throughout the data, there are data points that are duplicated, but with different K values.
- In Many of these cases, the difference is negligible, but in some cases there is a significant difference.
- Much of the time this vertical point is between regular and irregular sections of the crack front curve



Validation of Ability to Consistently Find Vertices

- There is no issue with finding vertices for A and C crack direction
- We have not been 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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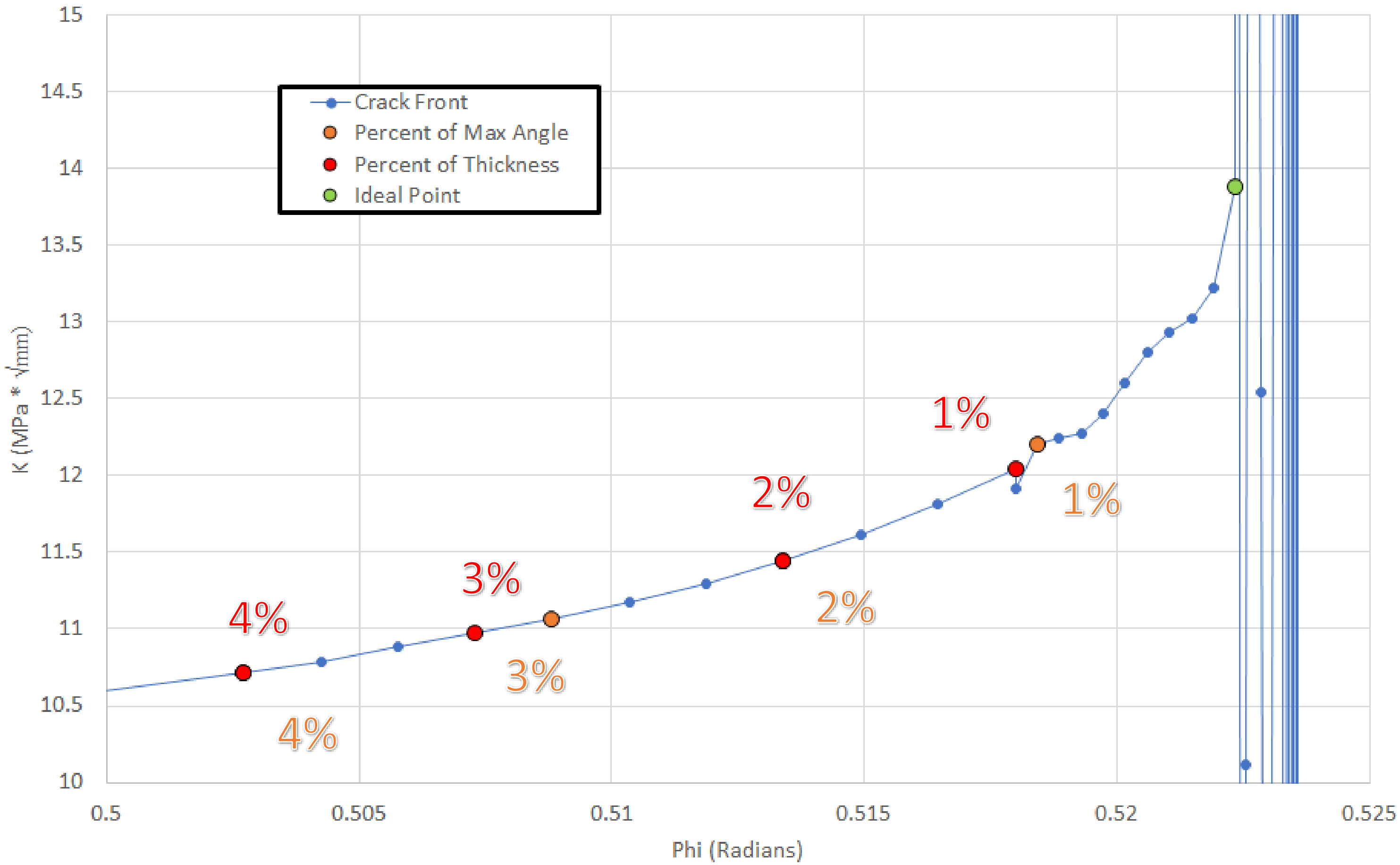
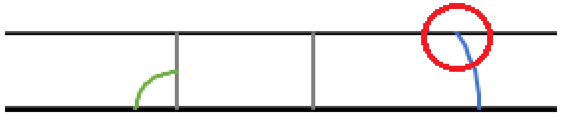
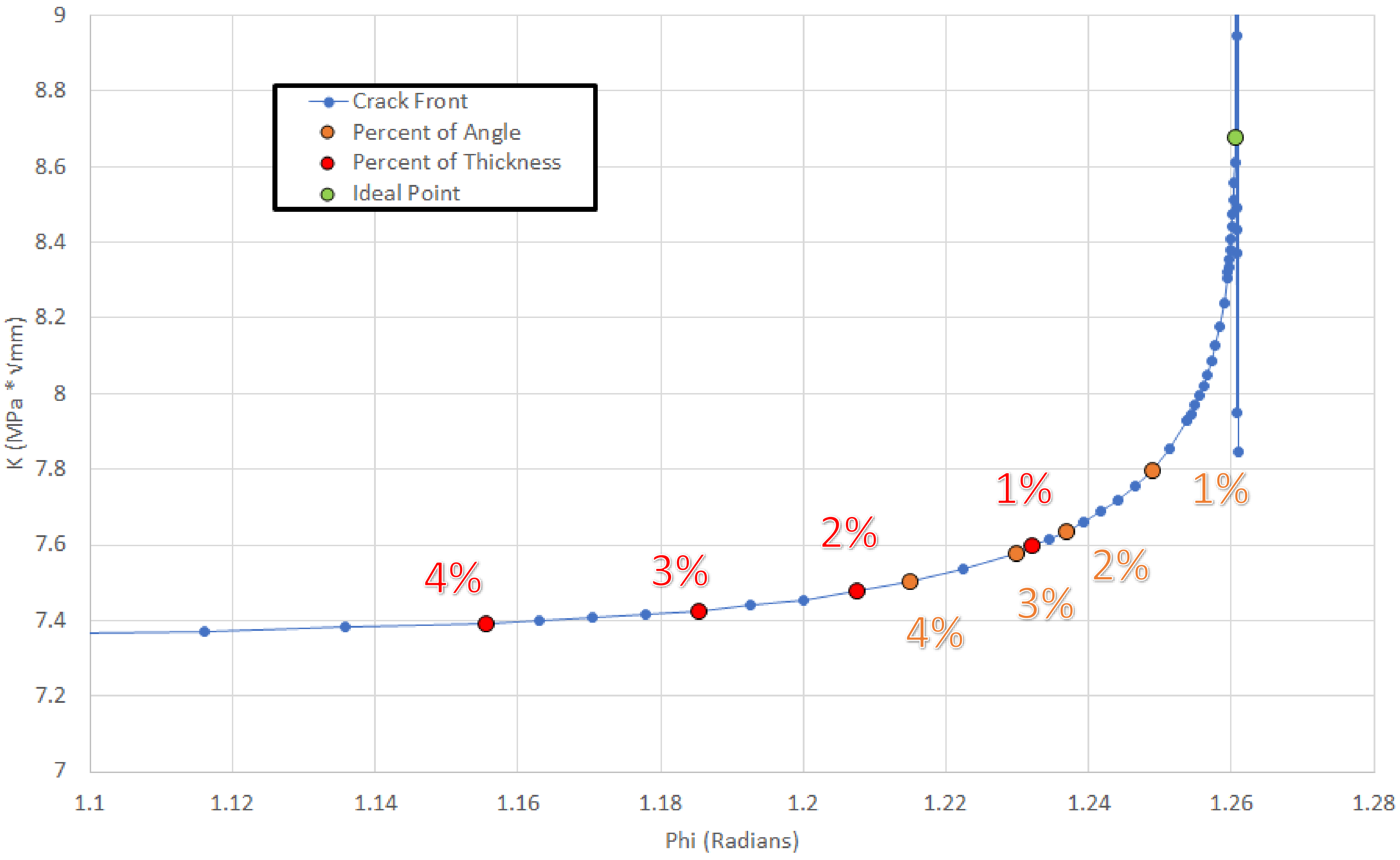
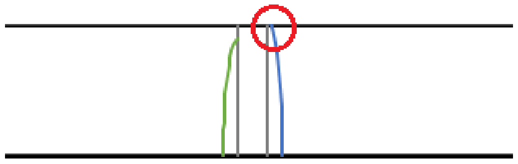
r/t=0.8, a1/c1=1.0, a1/t=0.5, a2/c2=1.0, a2/t=2.0



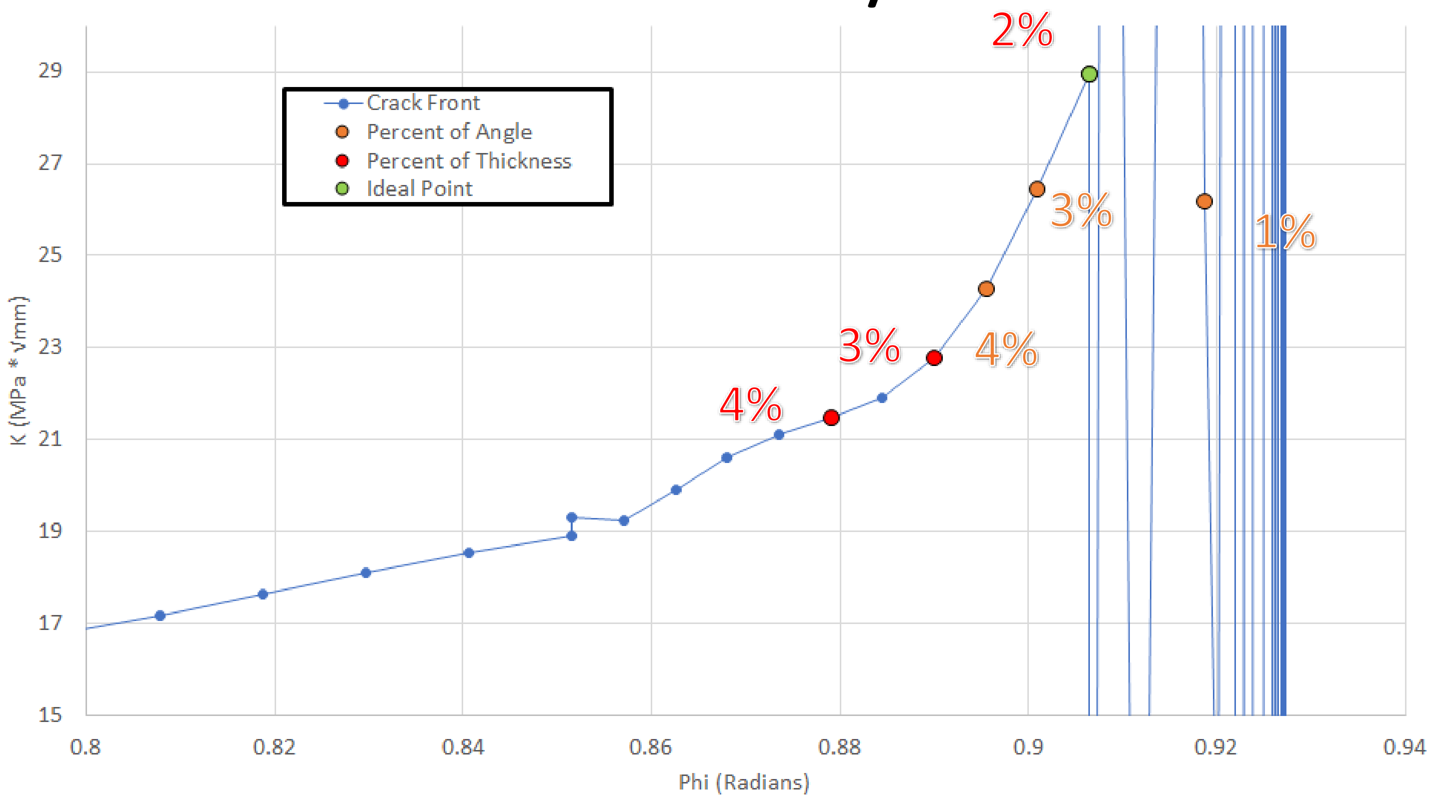


r/t=0.1, a1/c1=9.0, a1/t=0.9, a2/c2=10.0, a2/t=1.05





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

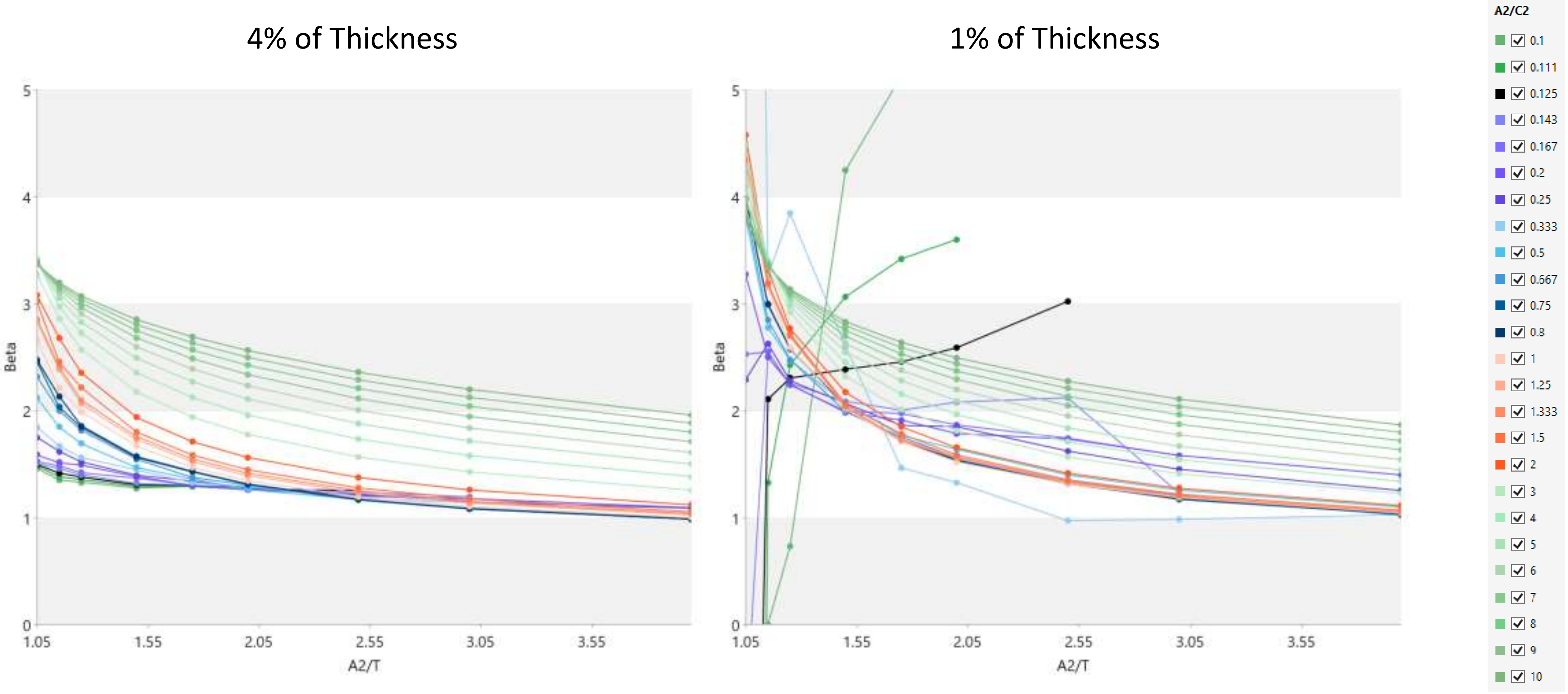


1% not pictured, (0.9141, 41.1)

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

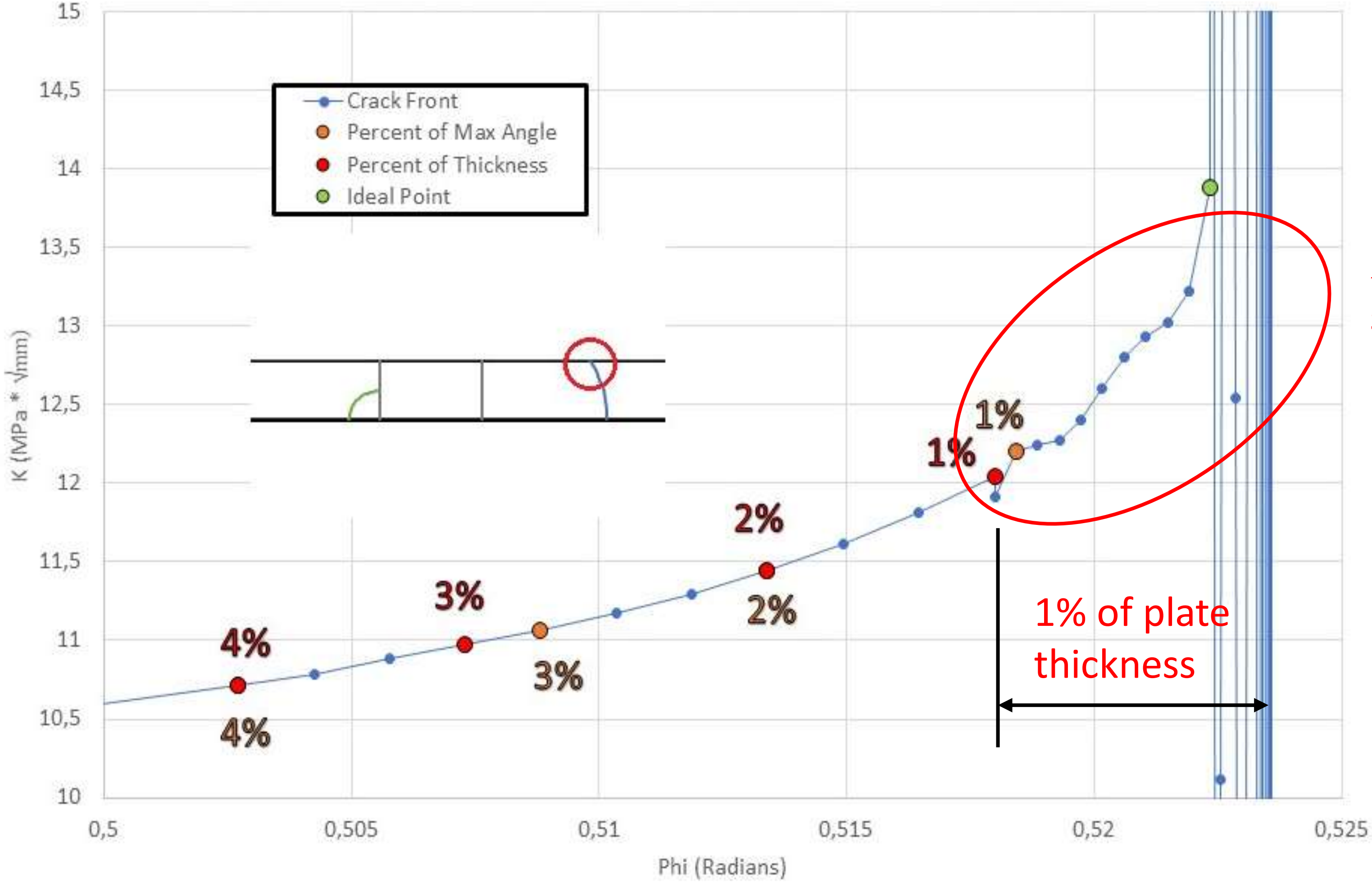


Vertices: Slides for your AFGROW lecture

Börje Anderssson

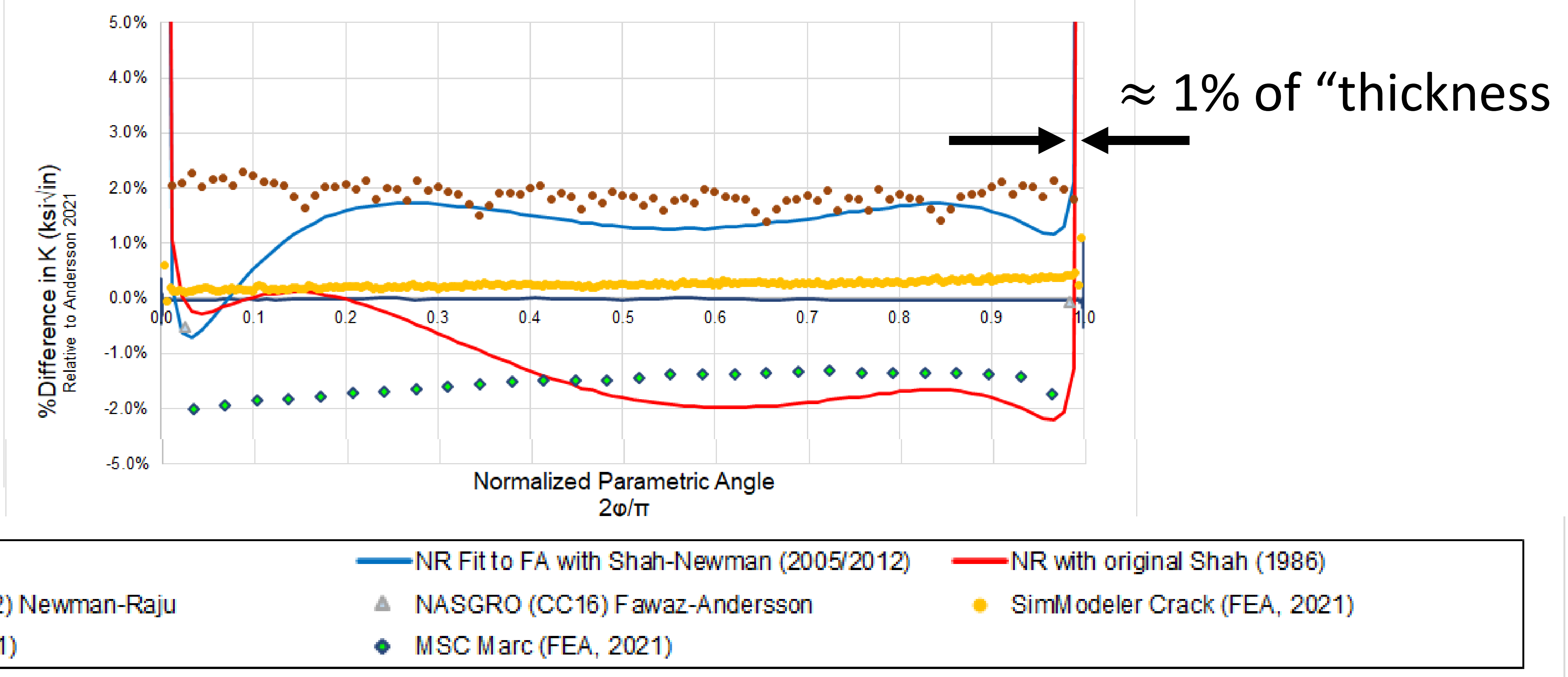
12 Sept 2021

The stress intensity functions $K_I(\phi)$ shows in most cases a very complex behavior near vertices due to the assumption that crack fronts are in form of ellipses. In most cases will K go to infinity for through thickness cracks, something which is difficult to calculate accurately (see Figure below). However, with insight in the mathematical theory for vertices, and proper software (FE-code STRIPE) we can calculate K arbitrary close to the vertex with high precision.

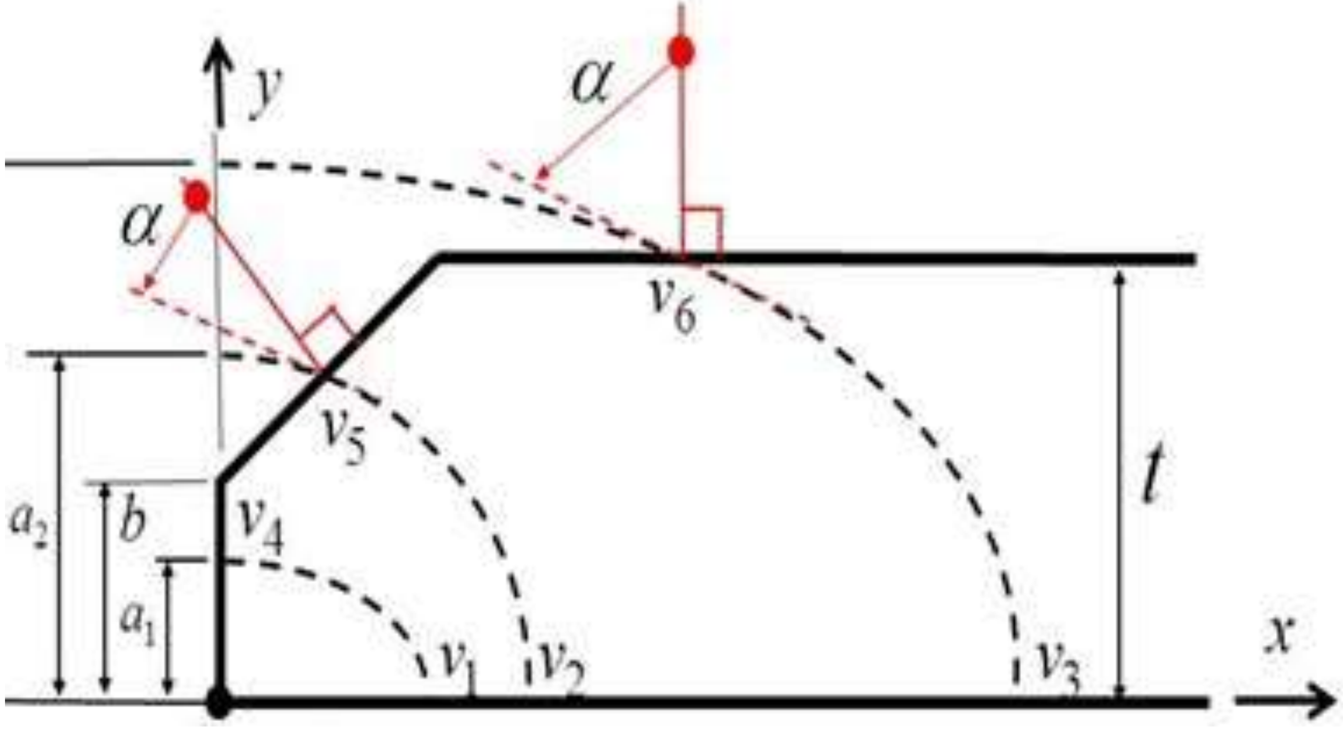


$K_I(\phi)$ from the FE-solutions shows sometime this fuzzy behavior very near the surface.

The figure below is from Robert Pilarczyk's lecture on the ERSI K-benchmark today. We show it to emphasize the challenge in deriving accurate K-solutions at over $\approx$ 100 million vertices where $K_I(\phi) \rightarrow \infty$. The standard approaches for K-calculation that was used in the benchmark did not capture the K-behavior in the region of "1% of the thickness".



Accurate determination of $K_I(\phi)$ near vertices $v_1, v_2, \ldots v_6$.



$$x = c \cdot \cos(\phi)$$
$$y = a \cdot \sin(\phi)$$

K is near any vertex v_i (defined by the angle α only) given by,

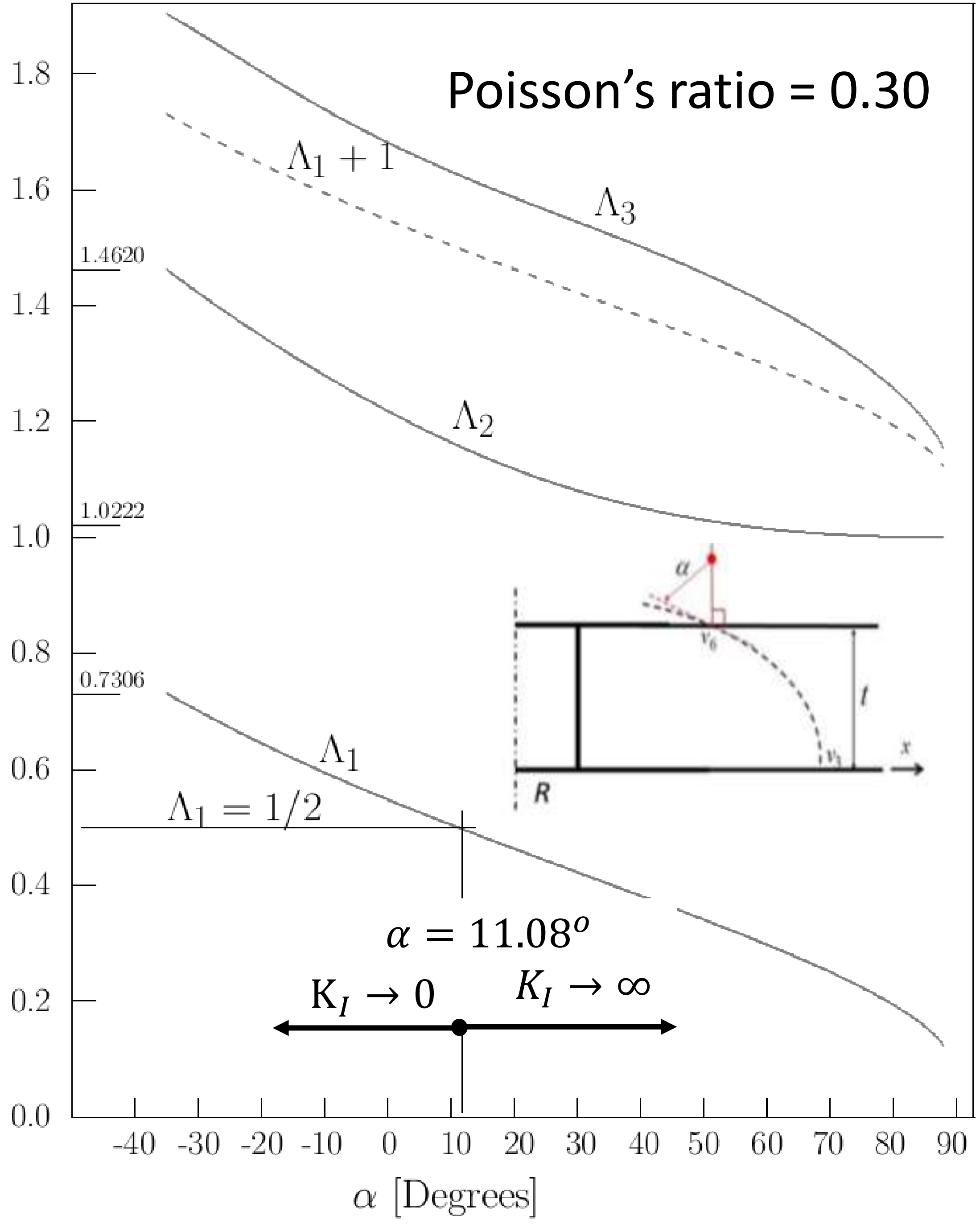
$$K(s) = \sum_{I=0}^{I=\infty} \sum_{i=1}^{i=\infty} S_{i,I} \cdot s^{\Lambda_i - 1/2 + I}$$

$S_{\{i,I\}}$ are unknown constants, $\Lambda_i(\alpha)$ known constants and $s(\phi)$ the crack front arc length.

The vertex singularities $\Lambda_i(\alpha)$ depend only on Poisson's ratio for the material.
The angle α determines if Λ_1 is smaller or larger than ½, that is, will K_I go to zero or infinity at the vertex. How do we determine $S_{i,I}$ in the formula,

$$K(s) = \sum_{I=0}^{I=\infty} \sum_{i=1}^{i=\infty} S_{i,I} \cdot s^{\Lambda_i - 1/2 + I}$$

Solution: we simply select $S_{i,I}$ in such a way that the formula above is in closest possible agreement with the available finite element solutions for K_I over a part of the crack front.



Numerics to determine $K(s) = \sum_{I=0}^{I=\infty} \sum_{i=1}^{i=\infty} S_{i,I} \cdot s^{\Lambda_i - 1/2 + I}$

The arc length from the vertex is,

$$s(\phi) = a \cdot \int_0^\phi \sqrt{1 - (1 - (c/a)^2) \cdot sin^2(\varphi)} d\varphi$$

Do a least square fit of $K(s)$ to the finite element solution over part of the crack by minimizing the following function,

$$\{\int_{s0(\phi)}^{s1(\phi)} (K_{FEM}(\tau) - \sum_{I=0}^{I=1} \sum_{i=1}^{i=3} S_{i,I} \cdot \tau^{\Lambda_i - 1/2 + I})^2 d\tau\}$$

For simplicity use discrete values of the FEM-solution in the minimization,

$$\{\sum_{j=j1}^{j=j2} (K_{FEM}(\tau_j) - \sum_{I=0}^{I=1} \sum_{i=1}^{i=3} S_{i,I} \cdot \tau_j^{\Lambda_i - 1/2 + I})^2\}$$

The accuracy of the least square fit is measured with the *Err* function.

$$Err = \{\sum_{j=j1}^{j=j2} \| K_{FEM}(\tau_j) - \sum_{I=0}^{I=1} \sum_{i=1}^{i=3} S_{i,I} \cdot \tau_j^{\Lambda_i - 1/2 + I} \|\} / (j2 - j1 + 1)$$

Example, consider a straight shank hole data base for single crack with *R/t*=1. There are 236 cracks that have a through thickness crack. The function *Err* is given in the table below in %. The approximation is over 10-50% of thickness. Maximum value of *Err* is only 0.17%.

a/t

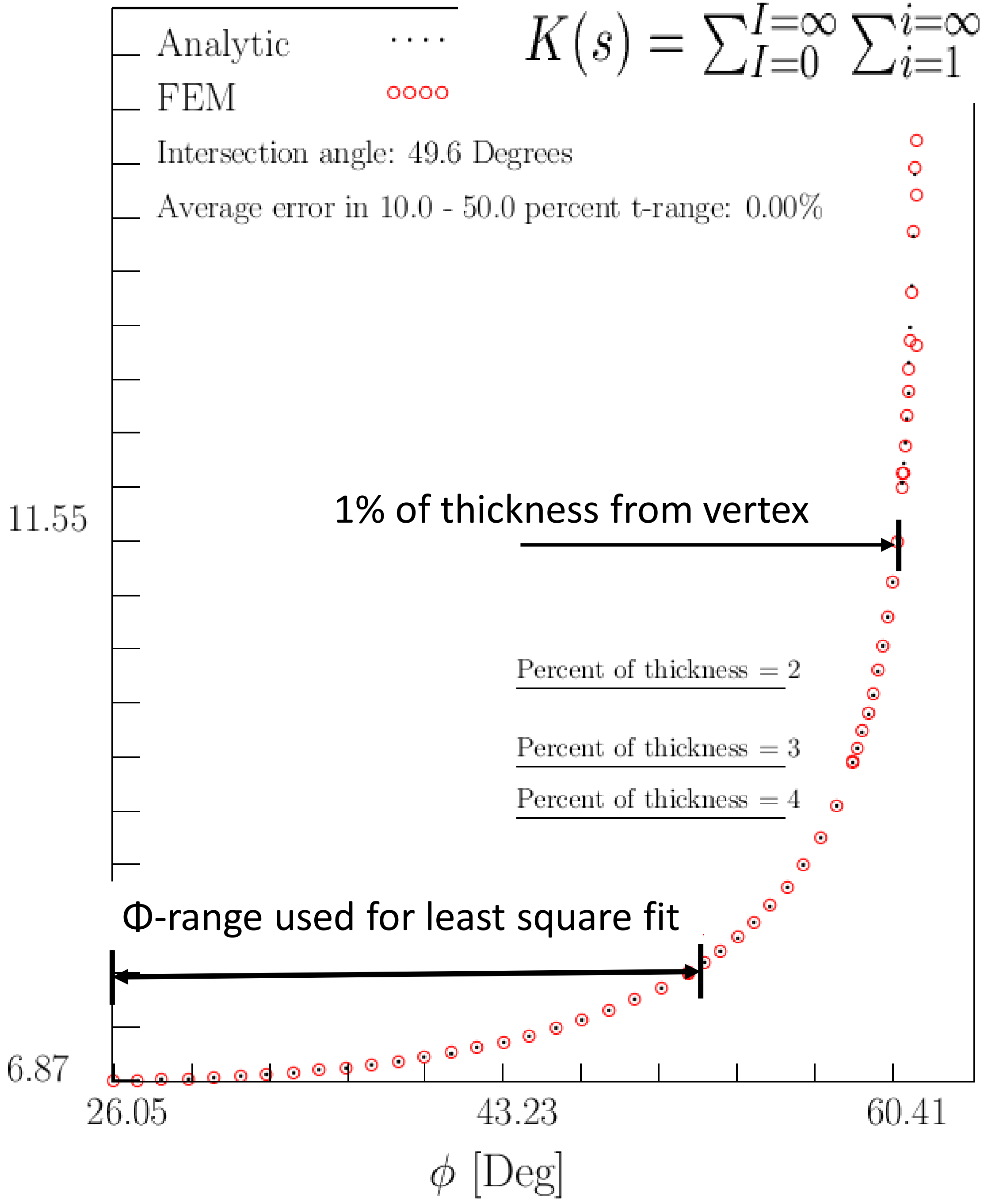
a/c

a/c	1.05	1.15	1.25	1.50	1.75	2.00	2.50	3.00	4.00	5.00	6.00	8.00	10.00
0.10	0.14	0.17	0.15	0.09	0.12	0.11							
0.11	0.15	0.15	0.13	0.08	0.10	0.08							
0.12	0.17	0.13	0.12	0.08	0.08	0.08	0.04						
0.14	0.15	0.10	0.09	0.07	0.06	0.07	0.03	0.03					
0.17	0.15	0.09	0.10	0.07	0.05	0.07	0.02	0.03					
0.20	0.14	0.09	0.09	0.05	0.03	0.04	0.01	0.02	0.02				
0.25	0.07	0.06	0.06	0.03	0.03	0.02	0.03	0.02	0.02	0.02			
0.33	0.08	0.03	0.02	0.03	0.03	0.03	0.04	0.04	0.03	0.03	0.02		
0.50	0.03	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01
0.67	0.03	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.01	0.01	0.01	0.01
0.75	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.03	0.02	0.02	0.01	0.01
0.80	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.01
1.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.02	0.02	0.02	0.01	0.02
1.25	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.01	0.02	0.02
1.33	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.03	0.02
1.50	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.02
2.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02
3.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5.00	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
6.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7.00	0.01	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8.00	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10.00	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00

$$K(s) = \sum_{I=0}^{I=\infty} \sum_{i=1}^{i=\infty} S_{i,I} \cdot s^{\Lambda_i - 1/2 + I}$$

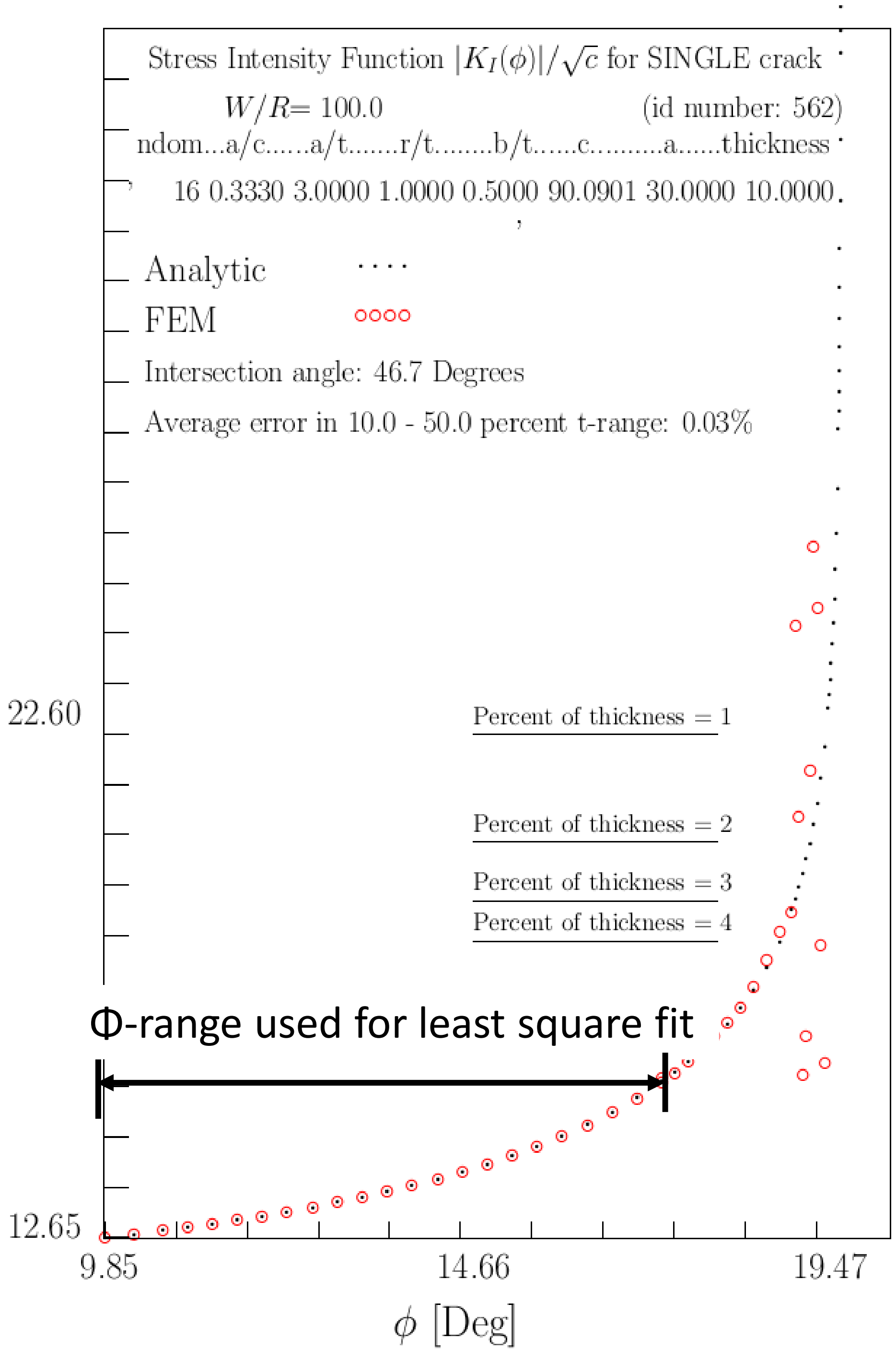
Example 1 The vast majority of the solutions show no fuzzy behavior except extremely close to the vertex. The figure to right exemplify that. The analytic solution is in very close agreement with the FEM-solution for all ϕ inside and outside the range used for the least square fit.

The *K*-values at exactly 1%, 2%... of the thickness from the vertex is calculated from the analytic formula.



Example 2 The *FEM*-solution for this very large crack (*c/R*=9) shows a fuzzy behavior close to the vertex. The analytic solution is in very close agreement with the FEM-solution for ϕ inside the range used for the least square fit. Just outside this range, the agreement is also excellent.

The control of millions of K-solutions with this semi-analytic approach is ongoing.



Selecting Vertex With Assistance of Borje's Program

- To help solve the problem of irregular data near the crack free edge, Borje has developed an analytic formula to determine accurate K's near the free edge
- This method should be able to produce accurate Vertex K's using the data we already have
- This method is likely to also solve the vertical points issue shown on the previous slide.
- The next slides will demonstrate how Borje's Analytic formula compares to the FEM in some of the samples we were previously having issues with.

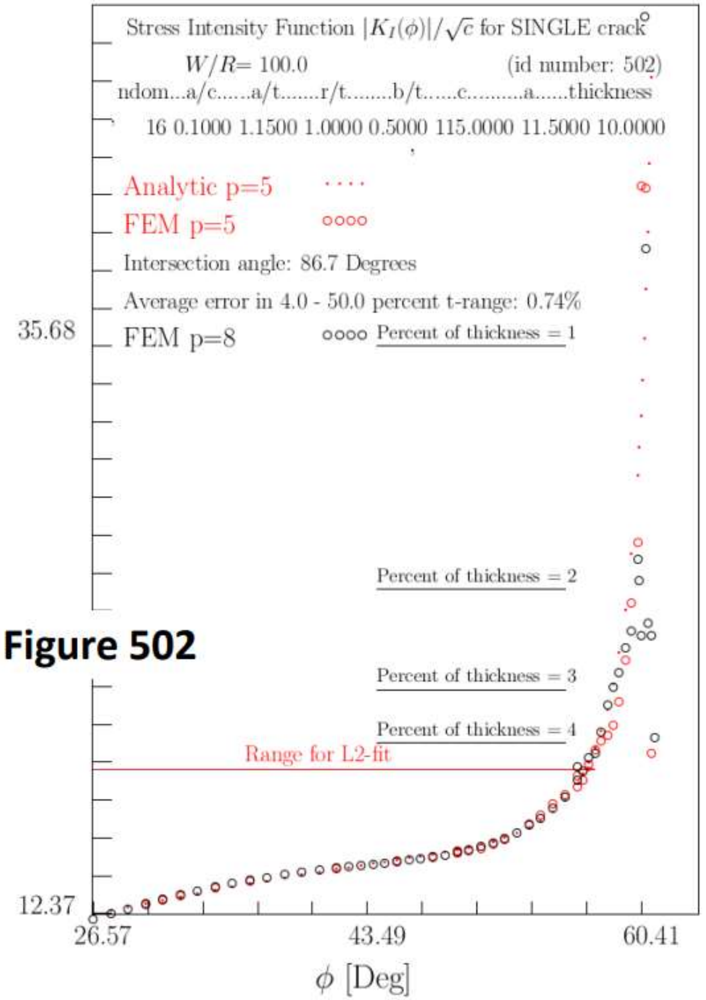
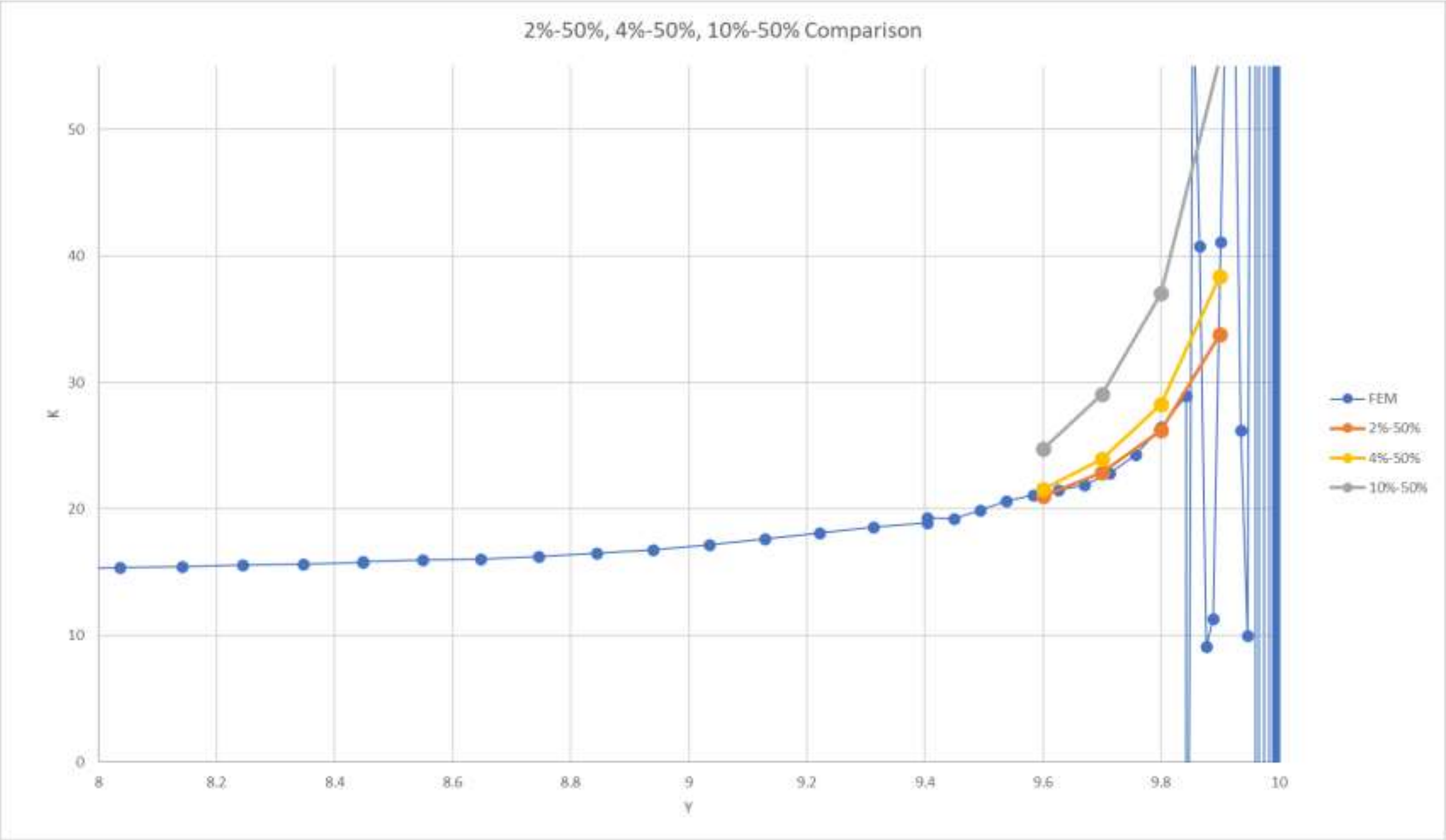
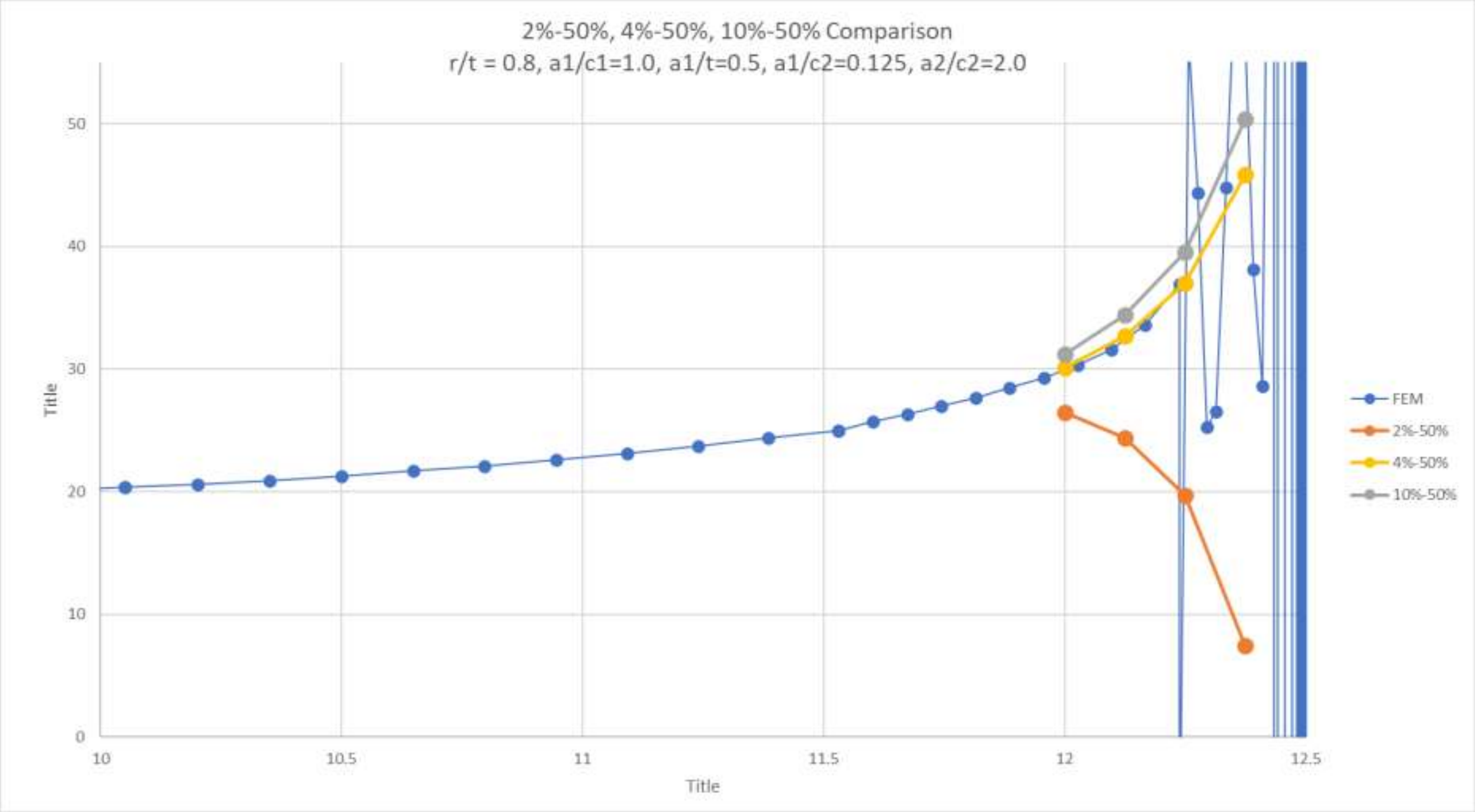


Figure 502

Borje's Analytic Formula Compared to FEM Data 1

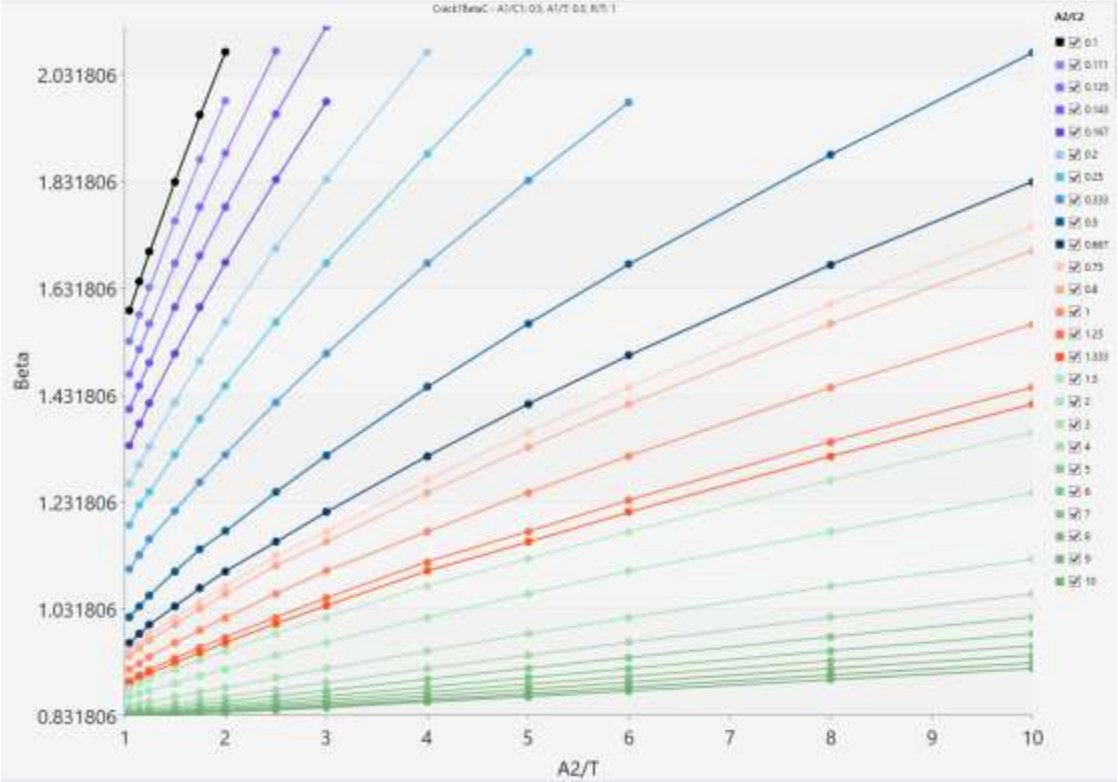


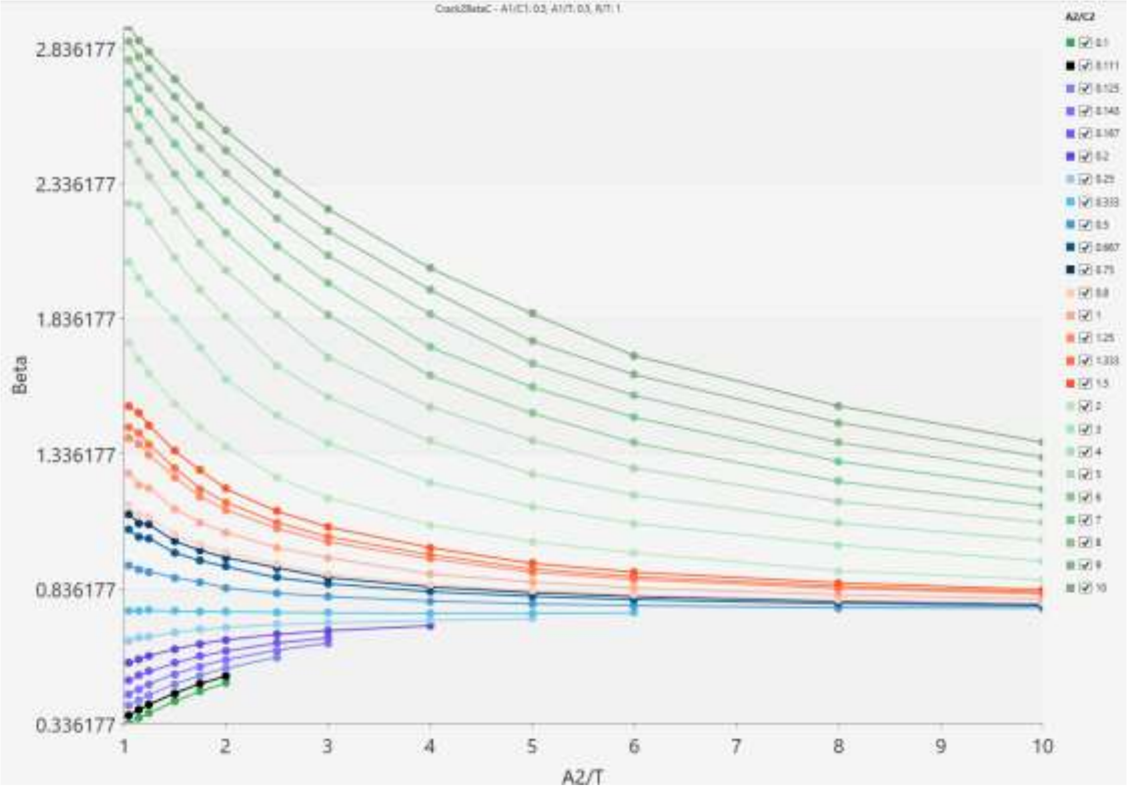
Borje's Analytic Formula Compared to FEM Data 2



Corner Crack - Through Crack at Hole Solution

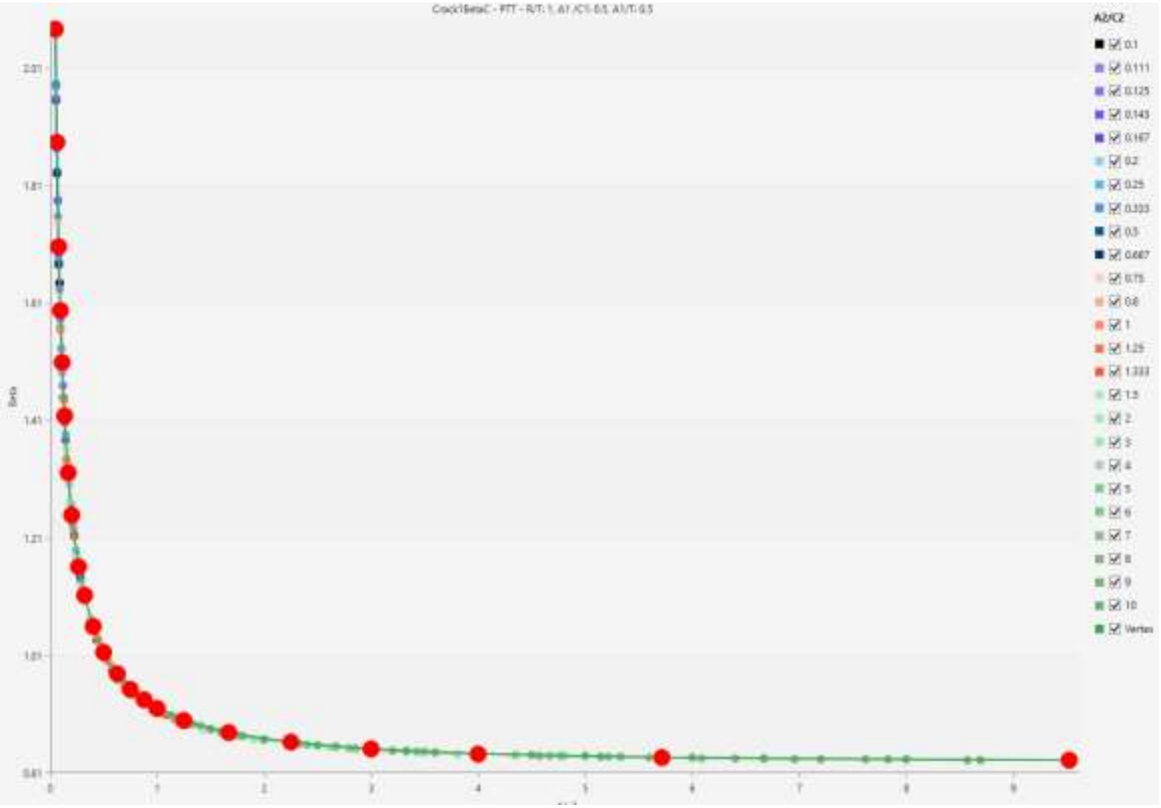
Adapt corner crack- oblique crack at hole data - by using the C1,A1, and C2 vertices

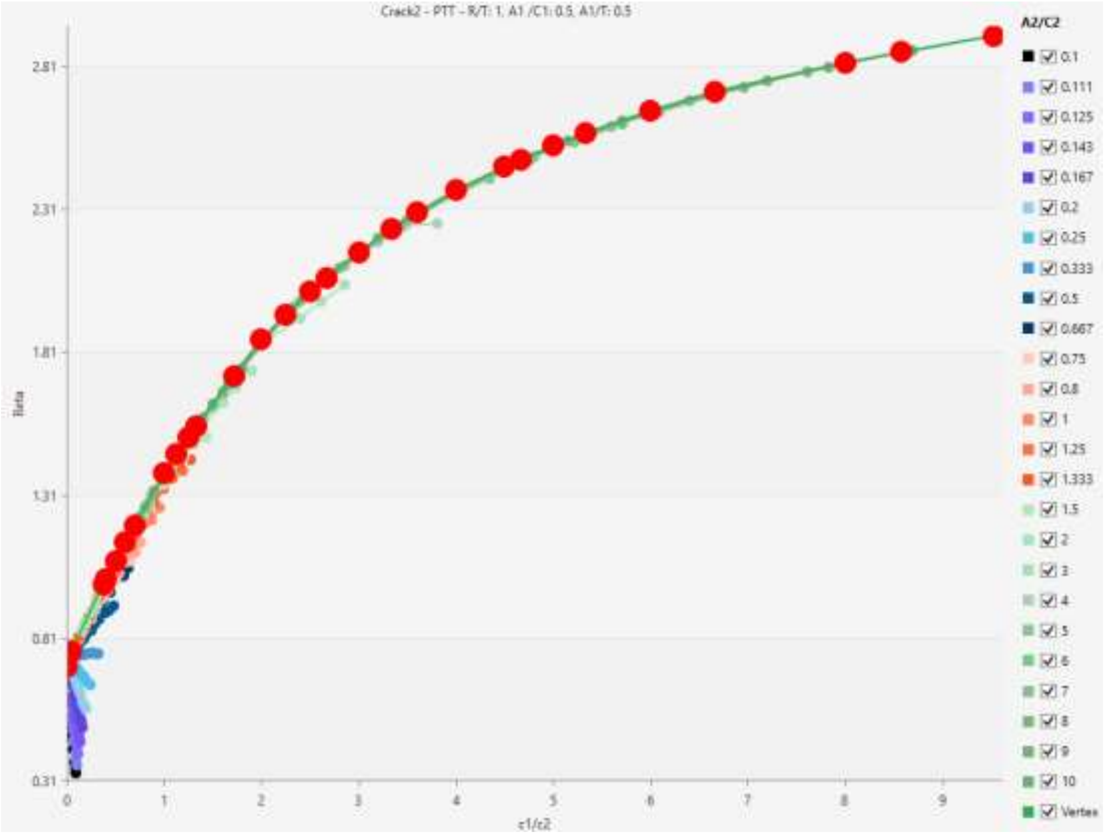




Corner Crack - Through Crack at Hole Solution

Different view of the same data





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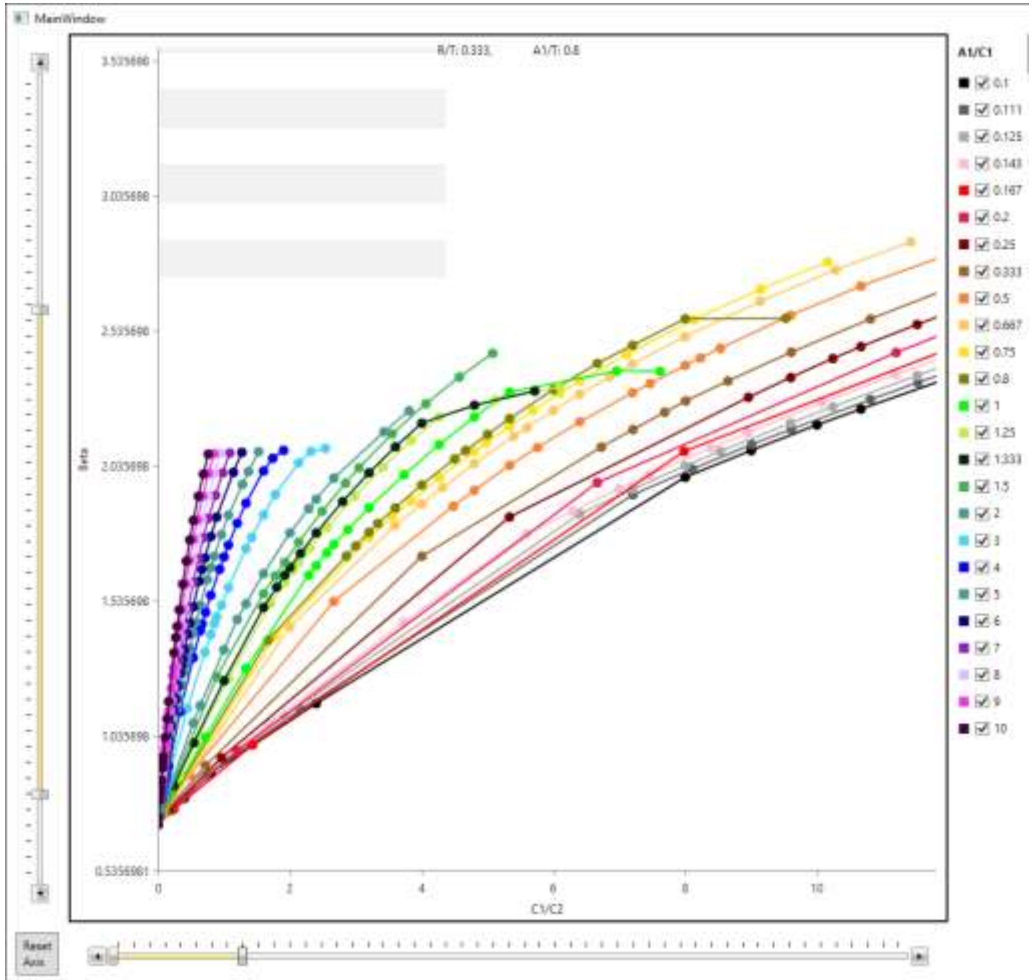
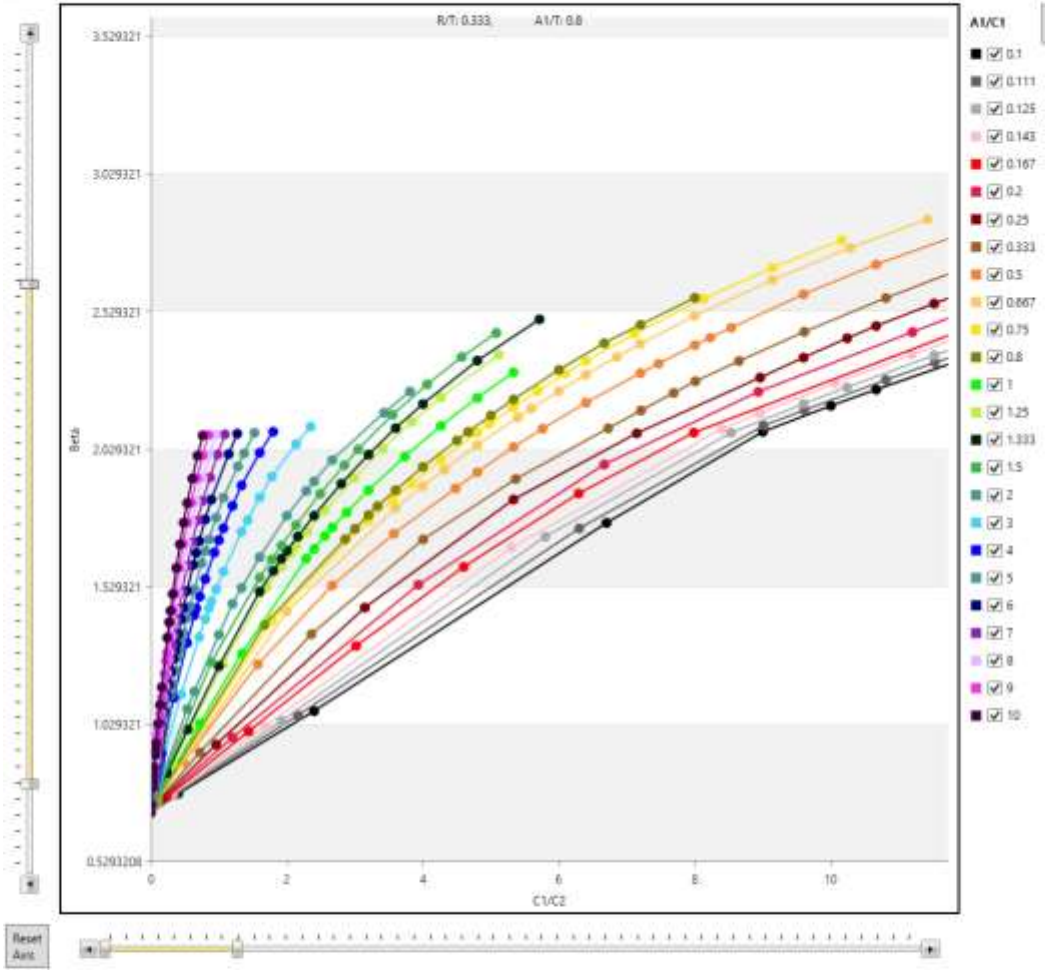
Corner Crack - Through Crack at Hole Solution Current Vertex Extraction Process

- Extract Data and calculate vertices for Beta C1, A1, and C2.
- Beta C1 and A1 are verified with minor corrections and then made into a uniform grid for future interpolation
- Beta C2 goes through an automatic smoothing process before each case is verified and corrected by hand if necessary
- Then data is extended to fill the parameters being a minimum C1/C2 of 0.01, and a maximum C1/C2 of 6.
- C2 is made into a uniform grid through the same process as C1 and A1
- Finally, C1, A1, and C2 are combined into a common database.

Corner Crack - Through Crack Hole Solution
Manually Correcting Cases



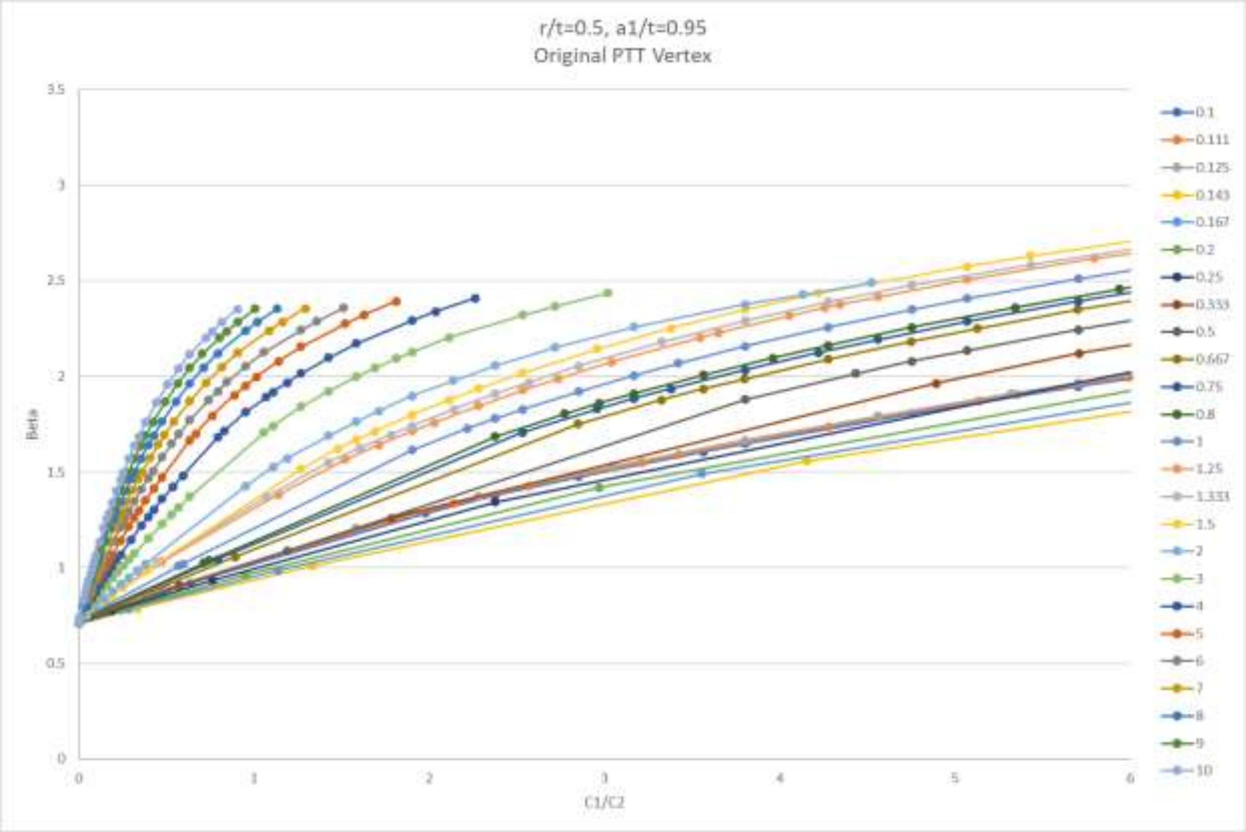


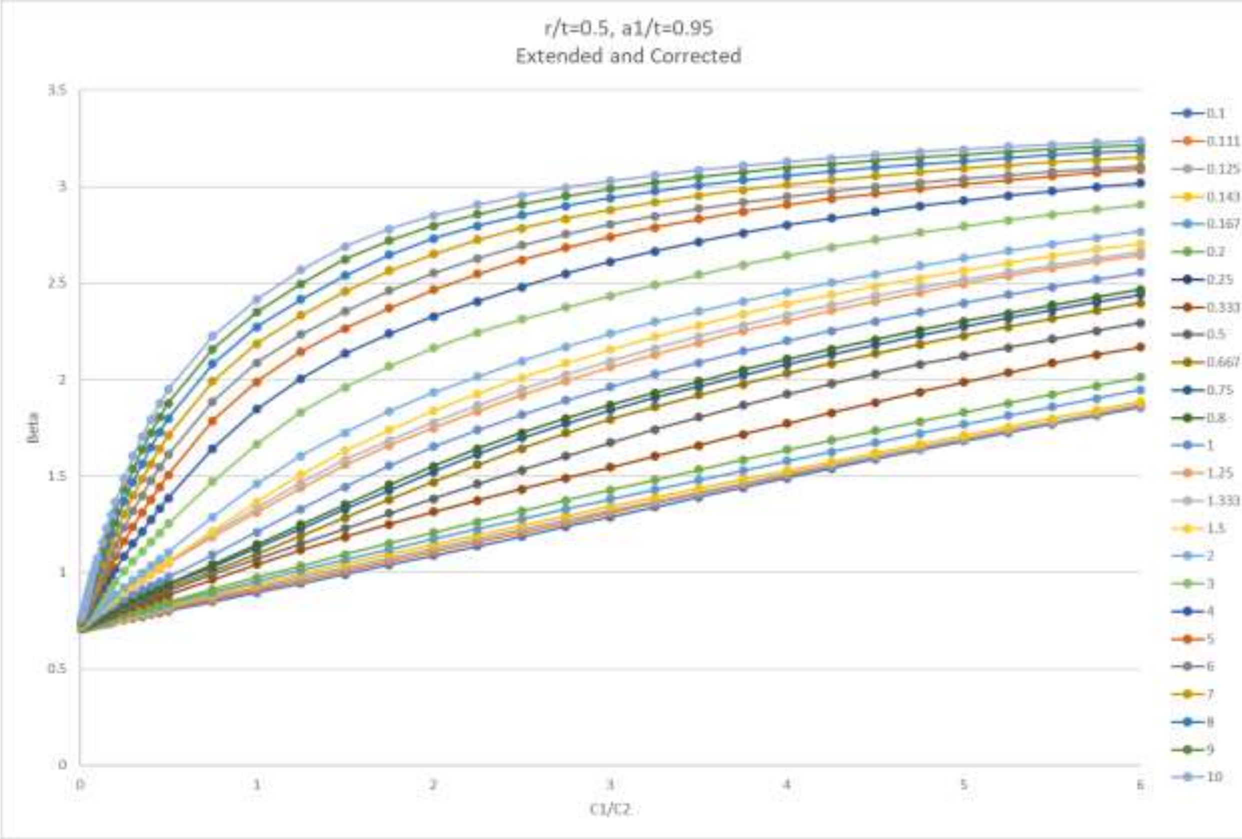
Corner Crack - Through Crack at Hole Solution Extending Data

- We use various methods to extend the data so that it always includes $0.01 \leq c1/c2 \leq 6.0$
- These methods are repeatable. Steps in this process involve using already know comparable crack solutions along with interpolation methods provided with MATLAB

Corner Crack - Through Crack Hole Solution Data Correction and Extension

The two graphs below demonstrate the extracted vertices before and after hand correction and extension of the original data.





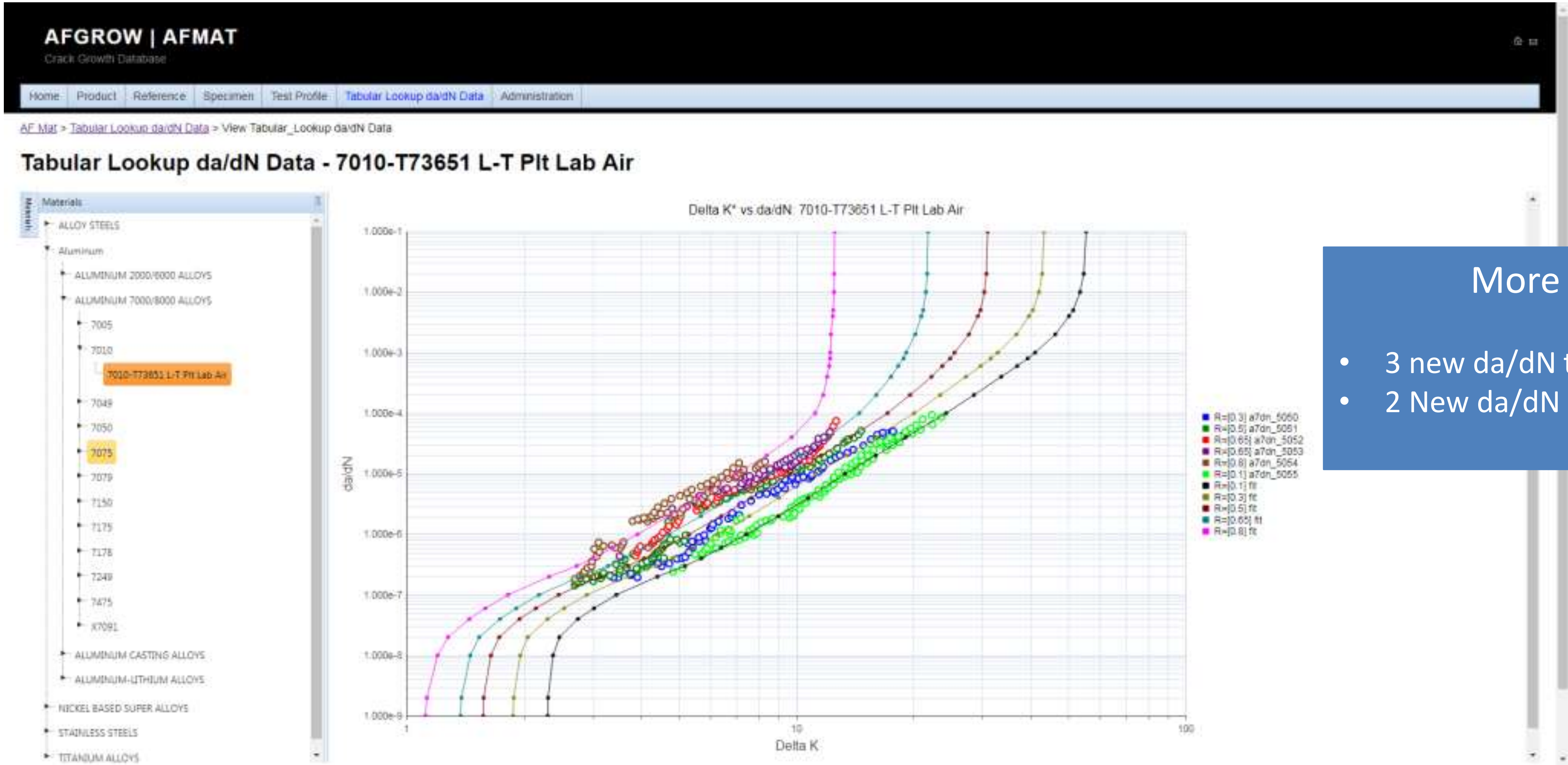
Corner Crack - Through Crack Hole Solution Vertex Extraction Process Challenges

- Manually correcting the data takes a large amount of time and resources
- Manually correcting data means including a human element to the shape of data
- This process is tedious, and requires knowledge of the history of the project

Corner Crack - Through Crack Hole Solution Progress and Next Steps

- We have extracted, corrected, and processed r/t=0.5, 0.667, 0.75 and 1.0.
- We incorporated these data into an AFGROW solution
- We will continue to expand the scope of the corner crack - through crack hole solution to both higher and lower r/t ranges.

AFMAT updates since September 2020



More data

- 3 new da/dN test data sets
- 2 New da/dN curve fits

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Acknowledgements

- A-10 and T-38 Structural Integrity and Analysis Group
- ASIMIS
- AFGROW Customers and Consortium Members

Questions