MEASUREMENT SYSTEMS  MEASUREMENT SERVICES

Investigating SIF Extractions using Solver Agnostic Tools

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Outline

- Background
- Models
  - Crack Detail
  - Model Summaries
- Displacement Integral Method (DIM)
- Contour Integral Method (CIM)
  - Background
  - Math
  - Process for Single Extraction
  - Extension to Entire Crack Front
- CIM vs. DIM
- Benchmark and Additional Problems
  - FT01
  - FT02
  - Countersink Model
  - Round Robin Problems

Acknowledgements

- USAF
  - Nathan Phillips
  - Dr. Mark Thomsen
- Hill Engineering
  - Josh Hodges
  - Robert Pilarczyk

Introduction

- The Stress Intensity Factor (SIF or “K”) concept has proven its utility in various fracture mechanics problems and approaches
- SIFs have a direct relation to the energy release rate at the crack tip during expansion
- Properties needed to determine SIFs are readily available in most FEA packages
  - Displacement, stress, strain, strain energy density, etc.
- Many FEA packages have SIF extraction capability through various methodologies (J integral, Contour Integral, Domain Integral, etc.)
  - Abaqus, ANSYS, FRANC3D, MARC (PATRAN add-on), StressCheck
- Siemens NX/Simcenter has no SIF extraction capability
  - Simcenter has numerous other features making it desirable for many FEA projects

- Problem statement: Can a solver-agnostic tool be developed that extracts SIFs from *any* FEA package?

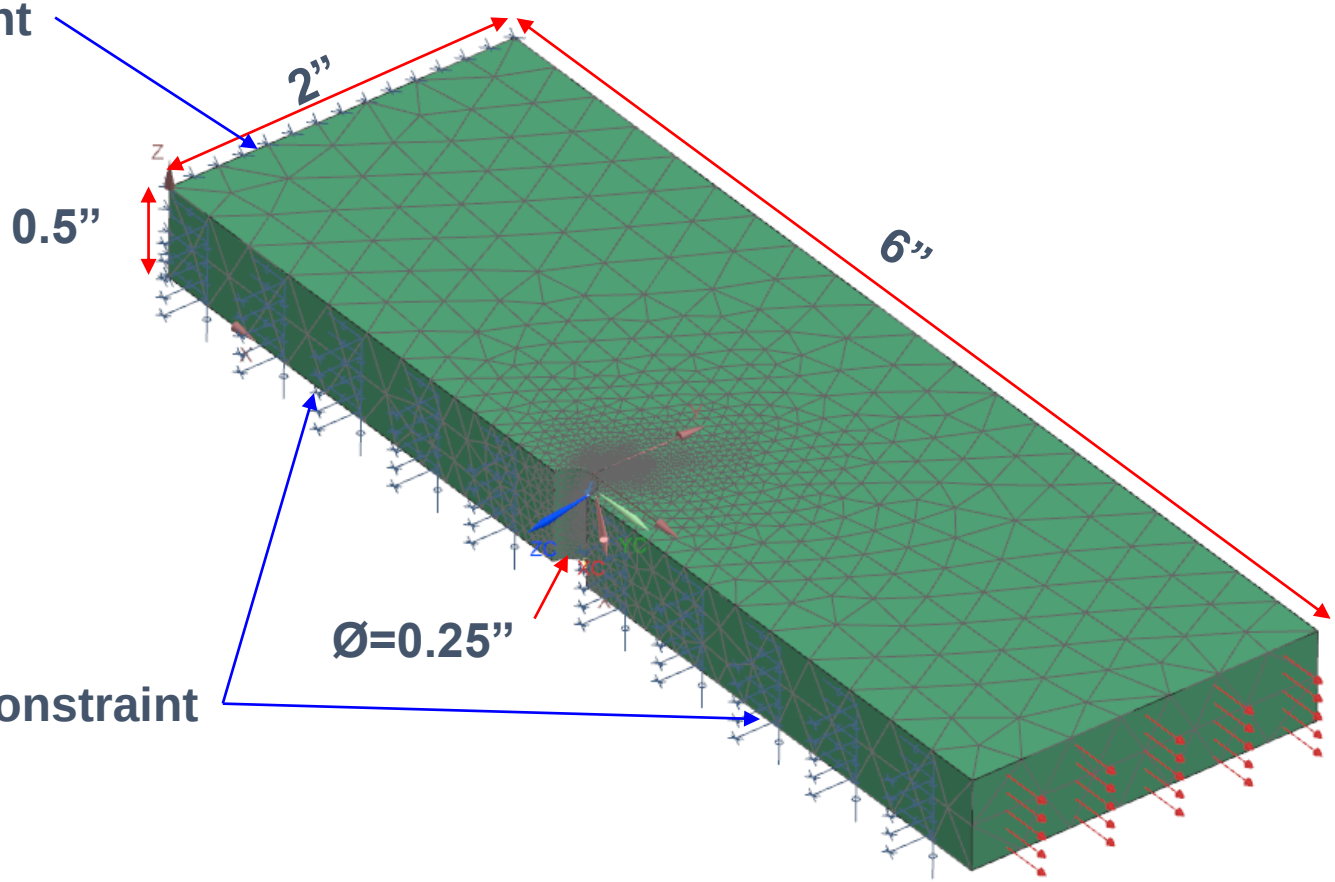
Introduction

- Two SIF extraction methods were investigated:
  - Displacement Interpretation Method (DIM)
  - Contour Integral Method (CIM)
- Many other extraction methods exist but were not investigated:
  - J-integral
  - Disk integral
  - Domain integral
  - Crack tip opening displacement
  - Crack closure integral (various forms)
  - Virtual crack extension
  - Crack tip elements
  - Hybrid elements
- Problem requirement: use standard elements readily accessible by most (all) FEA packages
  - No p-elements
  - No crack tip elements
  - No quarter-point elements
  - H-elements only

Models

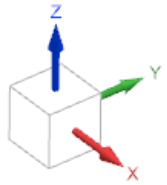
Models

Fixed Constraint



Symmetric Constraint

F=500 lbs (σ=0.5ksi)

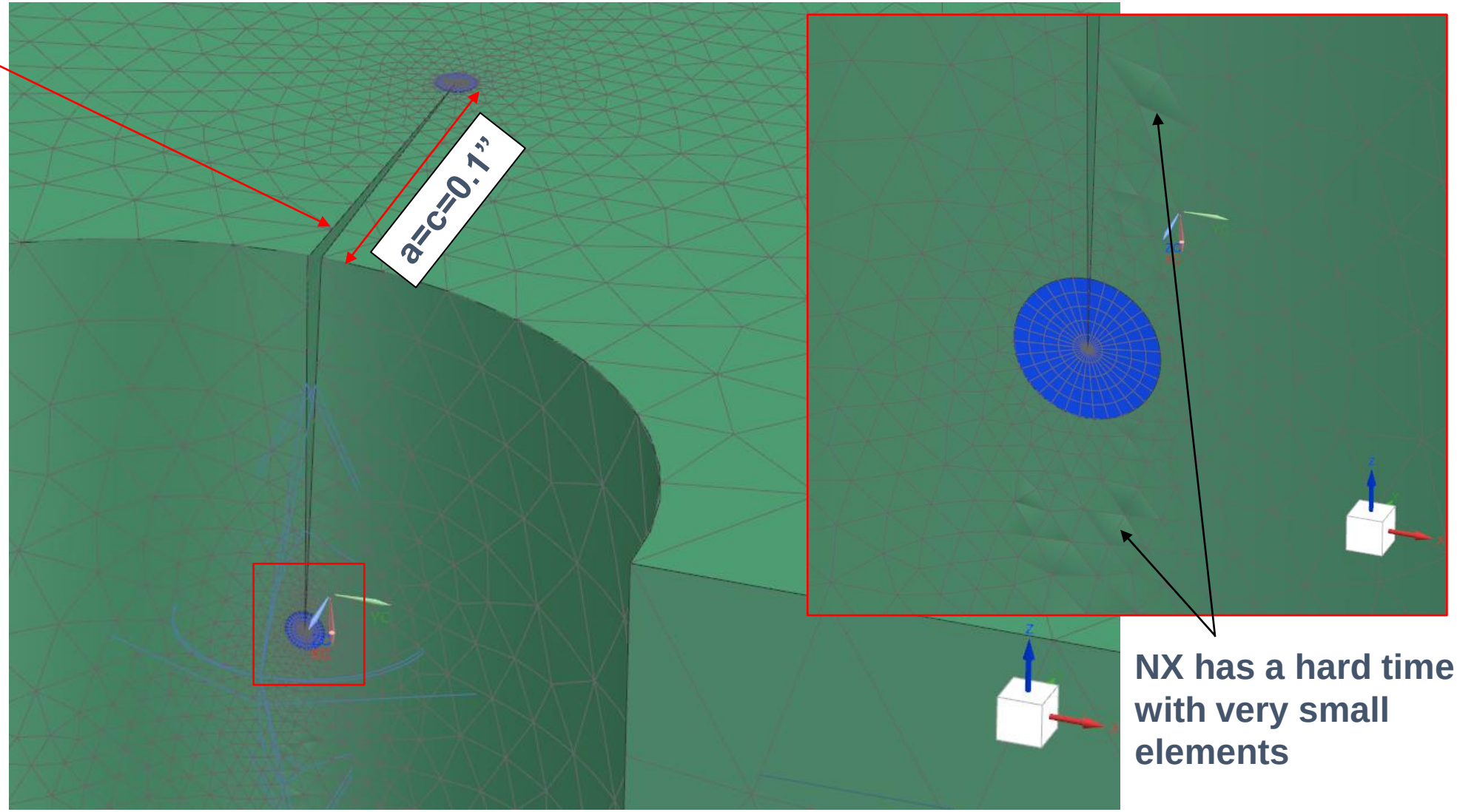


Models

"Slice" subtracted from body
Opening = 2°

5 rings, seed face size = 0.001"

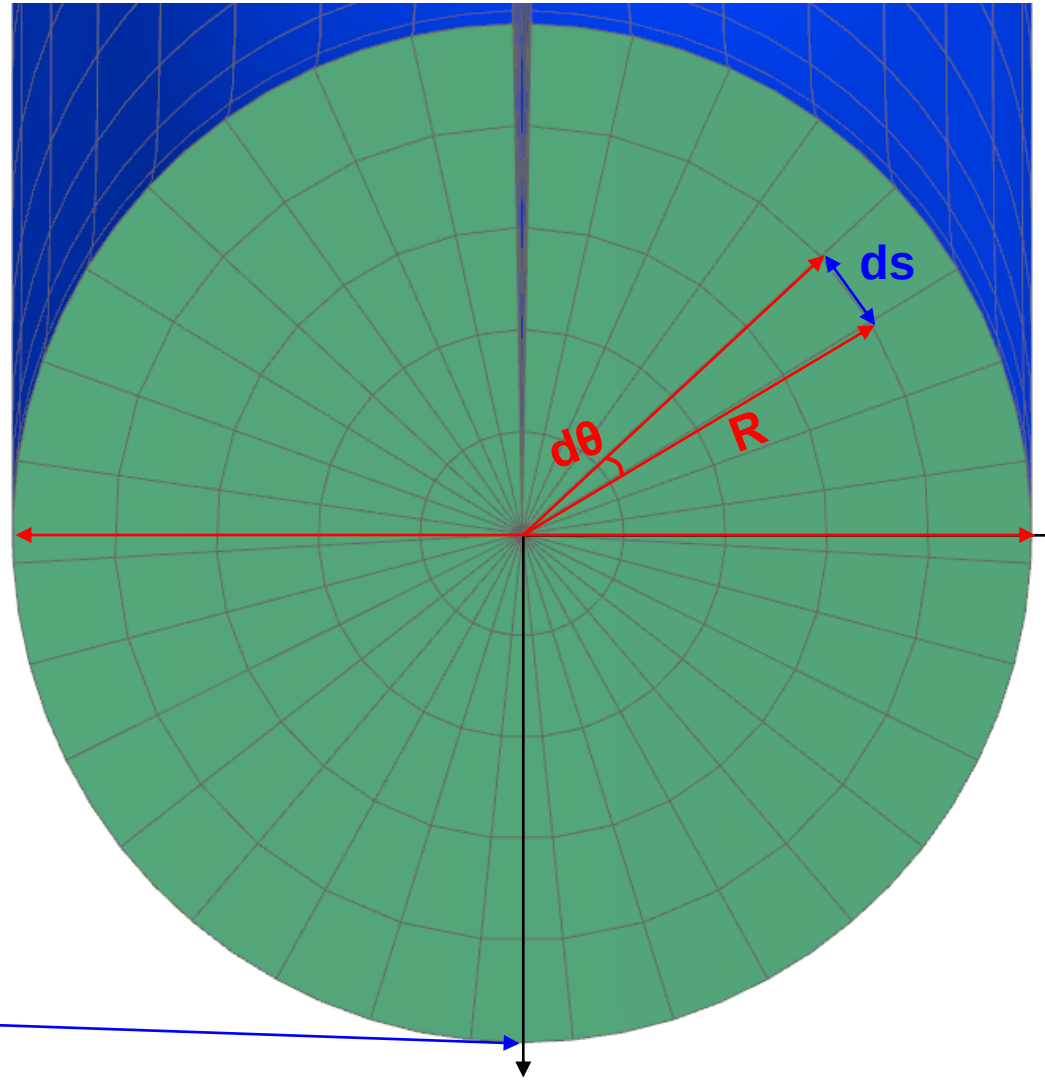
~element length = 0.005"



NX has a hard time with very small elements

Crack Detail: Example

Model 1: NX makes
31 elements radially

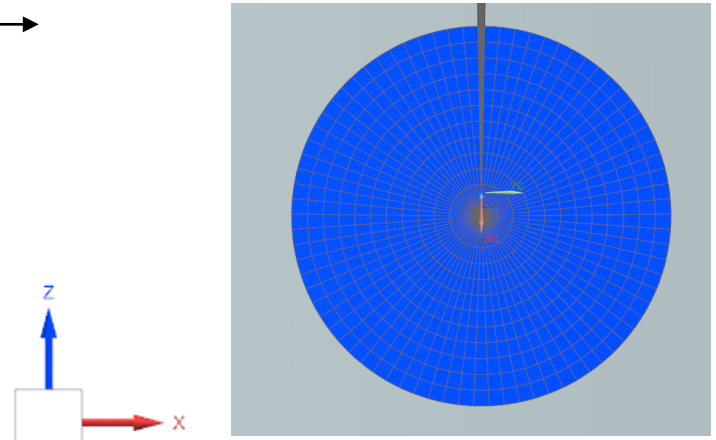


$$ds = Rd\theta = \frac{2\pi R}{\#\ elements}$$

Ring 1: rad_c = 0.001”, ds = 0.00002027”
Ring 2: rad_c = 0.002”, ds = 0.00004054”
Ring 3: rad_c = 0.003”, ds = 0.00006081”
Ring 4: rad_c = 0.004”, ds = 0.00081073”
Ring 5: rad_c = 0.005”, ds = 0.00101342”

Max Radius of Integration:
Ø=0.01” (0.1*c)
$rad_{c,max}$=0.005”

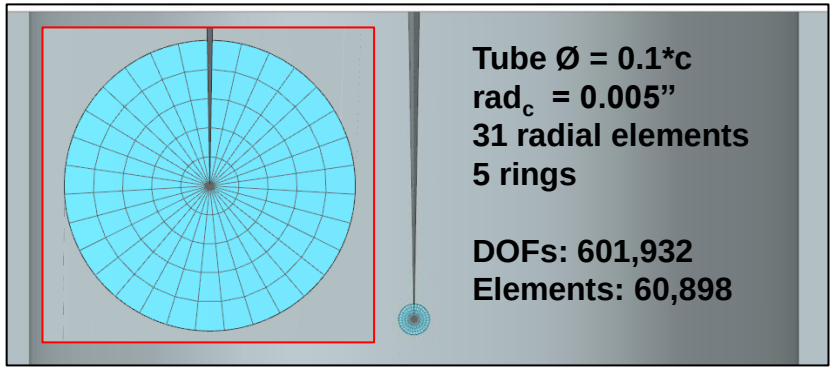
Note: cleaner to have element edge/face on x1 vector (not as pictured)



Model 2: NX makes 77 elements circumferentially
Ø=0.02475” (0.2475*c)
$rad_{c,max}$=0.012375”

Model Summaries

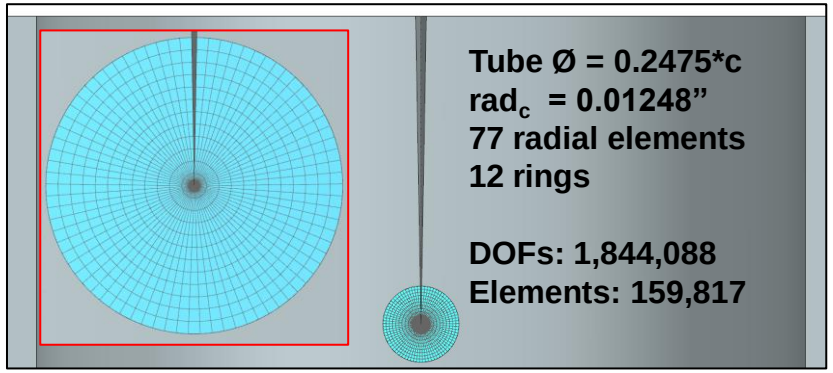
Model 1



Tube Ø = 0.1*c
rad_c = 0.005”
31 radial elements
5 rings

DOFs: 601,932
Elements: 60,898

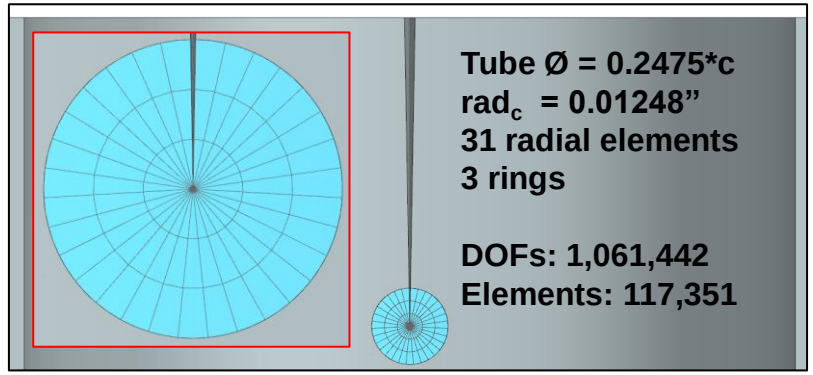
Model 2



Tube Ø = 0.2475*c
rad_c = 0.01248”
77 radial elements
12 rings

DOFs: 1,844,088
Elements: 159,817

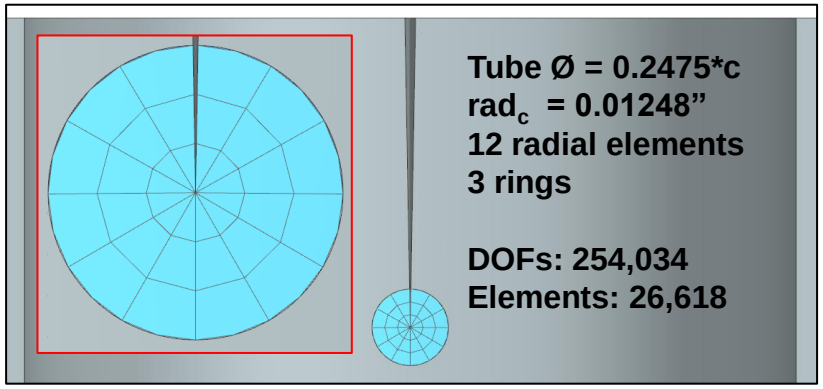
Model 3



Tube Ø = 0.2475*c
rad_c = 0.01248”
31 radial elements
3 rings

DOFs: 1,061,442
Elements: 117,351

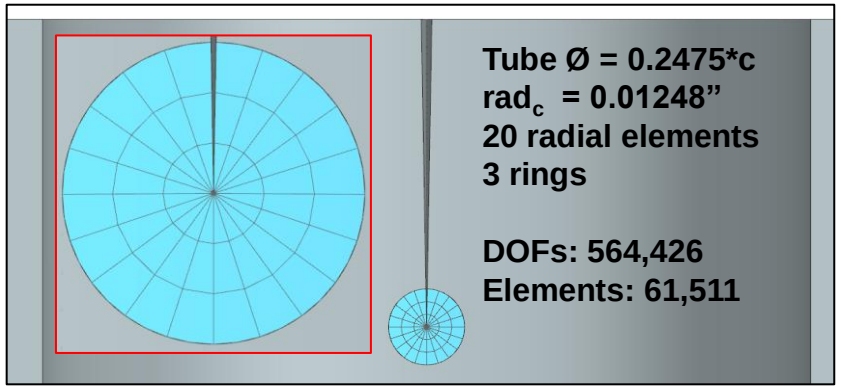
Model 4



Tube Ø = 0.2475*c
rad_c = 0.01248”
12 radial elements
3 rings

DOFs: 254,034
Elements: 26,618

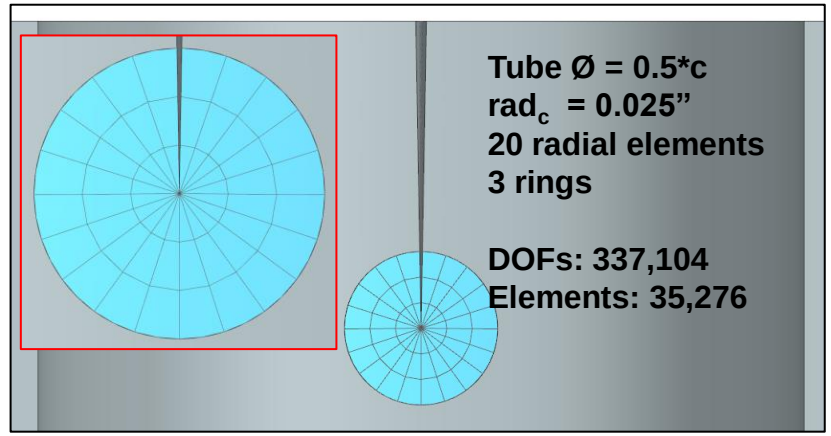
Model 5



Tube Ø = 0.2475*c
rad_c = 0.01248”
20 radial elements
3 rings

DOFs: 564,426
Elements: 61,511

Model 6



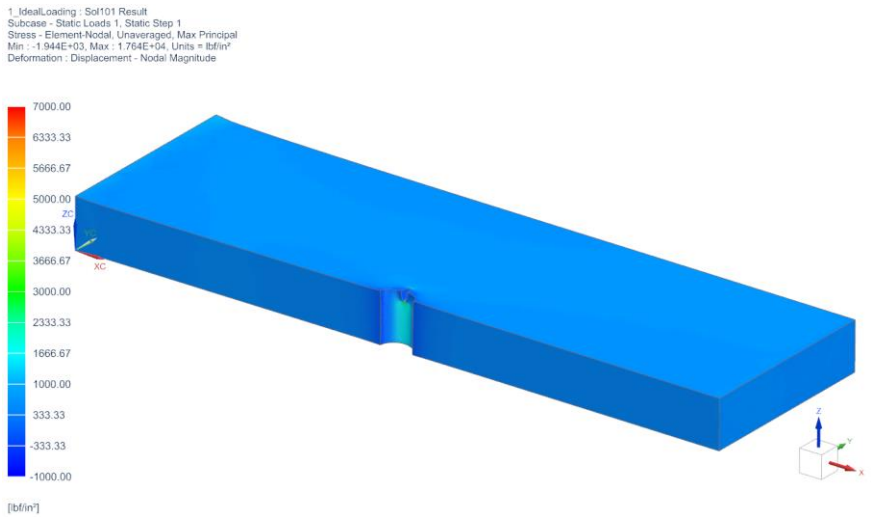
Tube Ø = 0.5*c
rad_c = 0.025”
20 radial elements
3 rings

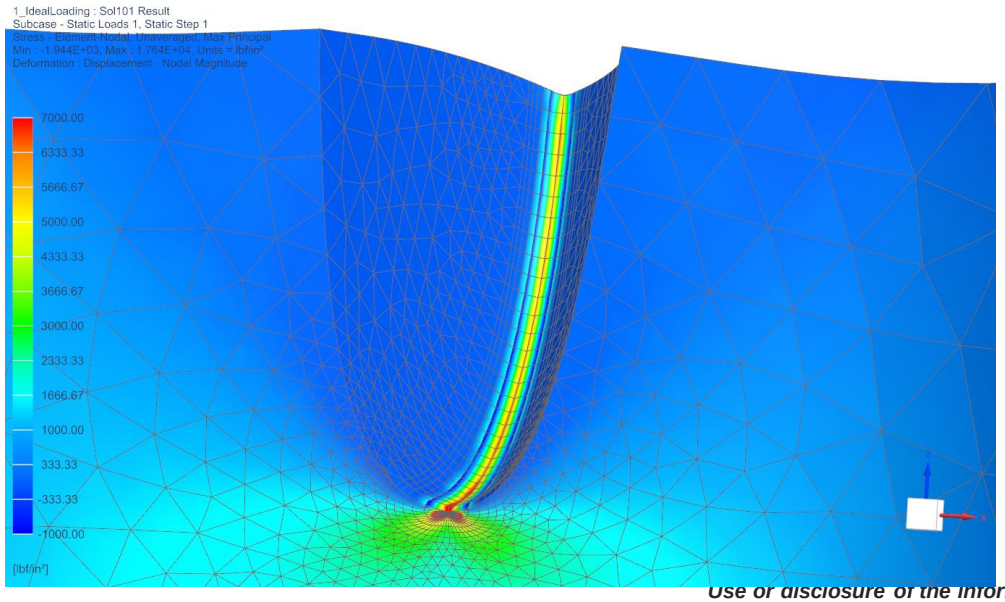
DOFs: 337,104
Elements: 35,276

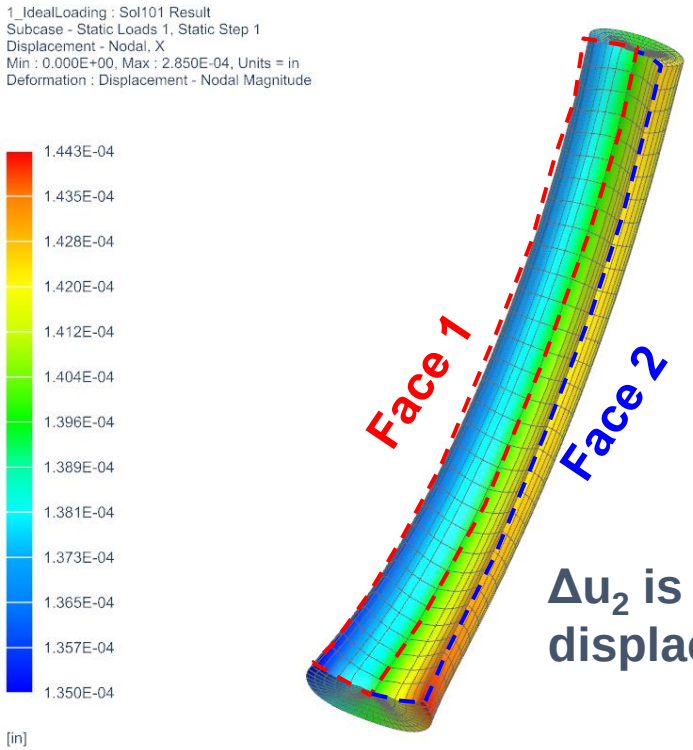
All large images are approximately to scale

Displacement Interpretation Method (DIM)

Displacement Interpretation Method (DIM)







$$K = \lim_{r^* \to 0} u_2^{FEM}(r^*, \theta = \pi) \frac{E'}{4} \sqrt{\frac{2\pi}{r^*}}$$

-OR-

$$K = \lim_{r^* \to 0} \Delta u_2^{FEM}(r^*, \theta = \pi) \frac{E'}{8} \sqrt{\frac{2\pi}{r^*}}$$

$$E' = E \ (plane\ stress)$$

$$E' = \frac{E}{(1 - \nu^2)} \ (plane\ strain)$$

Δu_2 is the relative crack opening displacement

$\Delta u_2 = \Delta u_{2,Face2} - \Delta u_{2,Face1}$

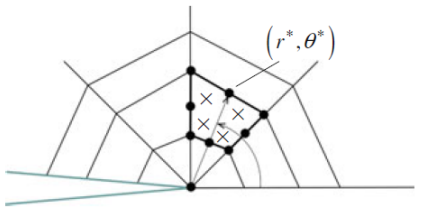


Fig. 5.3 Evaluation of the FEM solution at a node (r^*, θ^*)

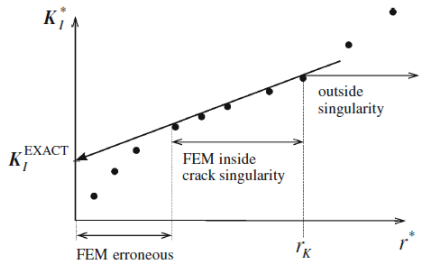
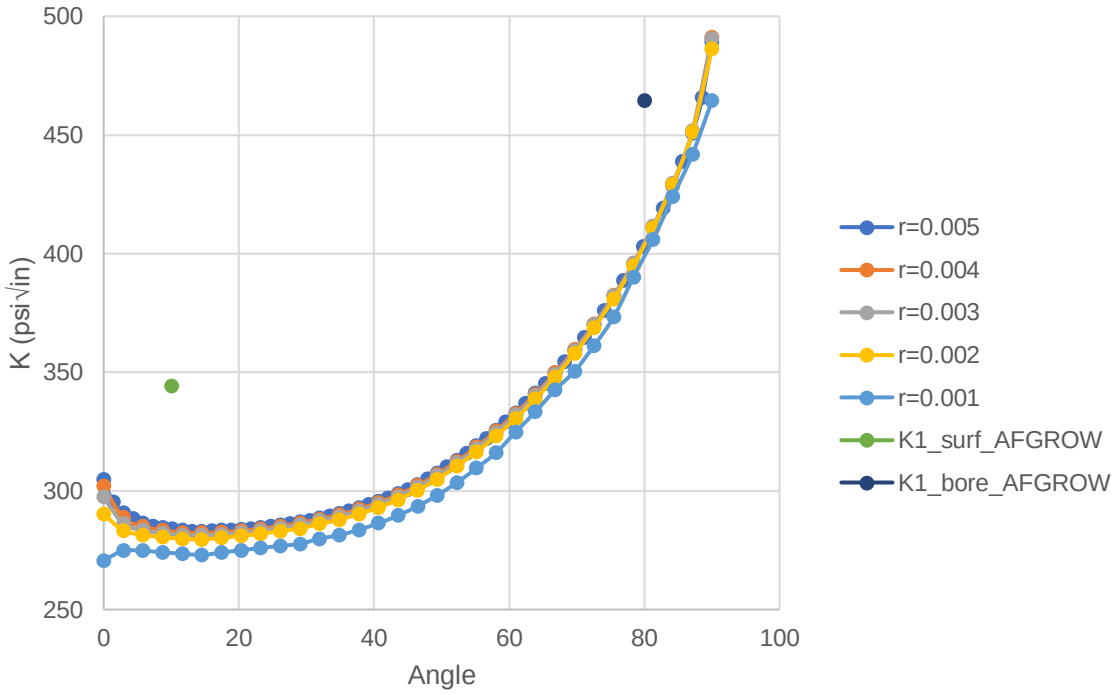


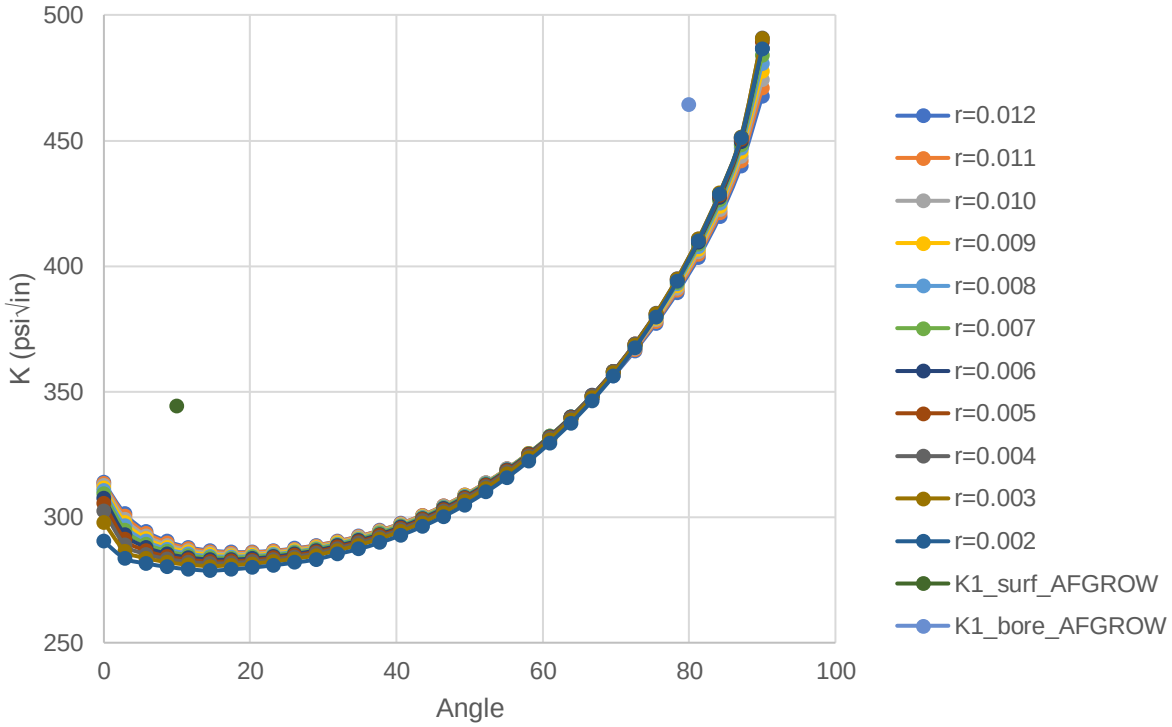
Fig. 5.4 Validity range of the FEM interpretation

From *Finite Elements in Fracture Mechanics*, M. Kuna, page 195

Displacement Interpretation Method (DIM)



Model 1
(5 layers, r* max = 0.005”)



Model 2
(12 layers, r* max = 0.012375”)

Added layers do not necessarily guarantee convergence!

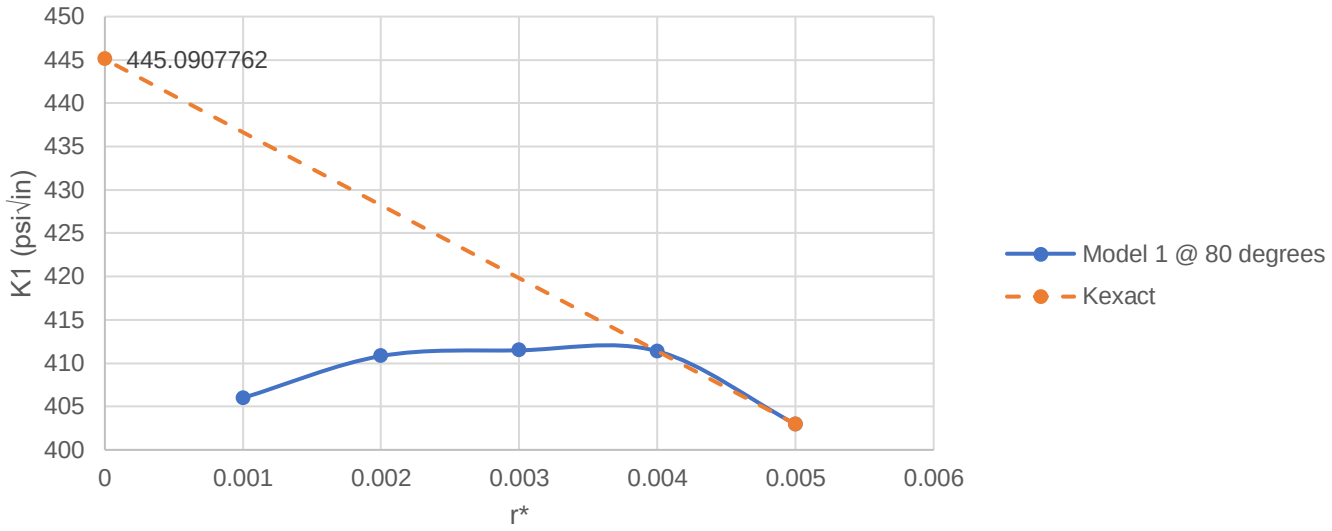
Displacement Interpretation Method (DIM)

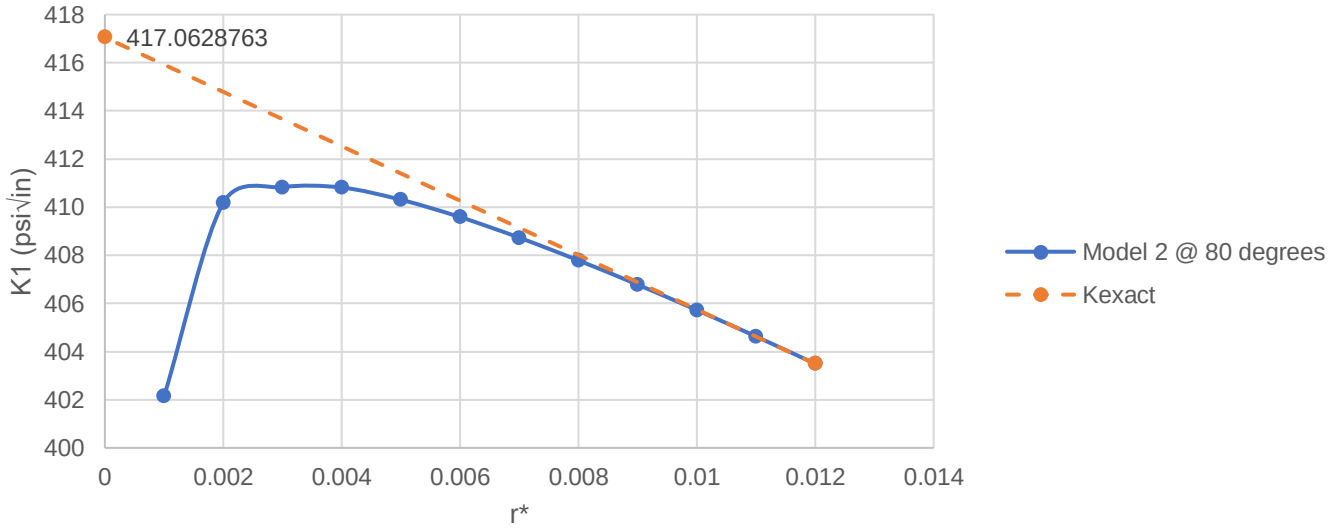
Model 1 @ 80 degrees	
r	K1
0.005	402.97997
0.004	411.40213
0.003	411.48723
0.002	410.82536
0.001	405.985

Model 2 @ 80 degrees	
r	K1
0.012	403.5041
0.011	404.634
0.01	405.7271
0.009	406.7818
0.008	407.7878
0.007	408.73
0.006	409.5838
0.005	410.3015
0.004	410.8074
0.003	410.8214
0.002	410.1709
0.001	402.1453

Fit with Model 1			
r*	Slope	K/Intercept	% error
0.005		402.98	-13.23%
0	-8422.16	445.0908	-4.16%

Fit with Model 2			
r*	Slope	K/Intercept	% error
0.012		403.5041	-13.12%
0	-1129.9	417.0629	-10.20%





Displacement Interpretation Method (DIM)

- Method requirements:
  - Requires matching nodes on opposite sides of crack faces
  - Hex mesh along crack front *not necessarily* required (but does make matching nodes easier)
  - Extrapolation to r* = 0 required for all geometries
  - Ignore mid-nodes (makes post-processing easier, does not affect result)

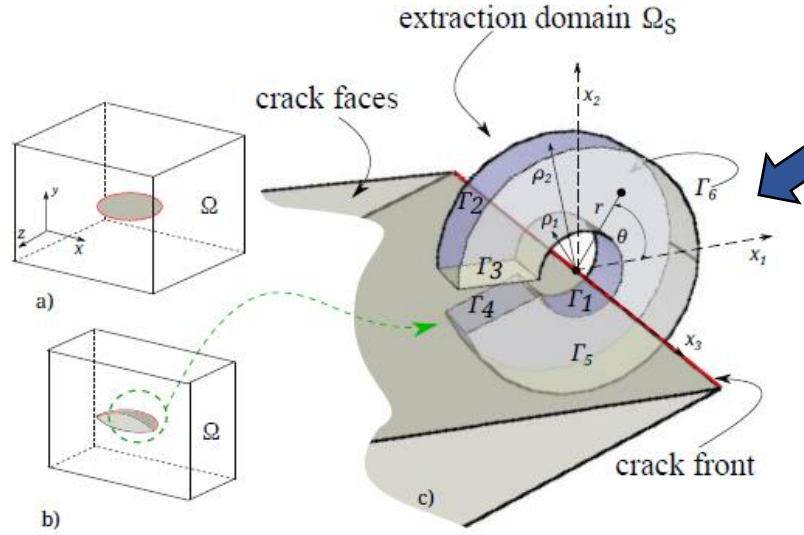
- Benefits
  - Using relative displacement of nodes allows use of Boolean (subtract) features instead of creating non-manifold geometry (i.e. StressCheck crack face designation)
  - No special elements needed
  - Only one CSYS at crack origin is needed
  - Similar method to calculate K_{II} and K_{III}
  - Only needs displacement
  - Easy!

- Drawbacks
  - Need many layers of crack refinement
  - Engineering judgement for “far away enough”

Contour Integral Method (CIM)

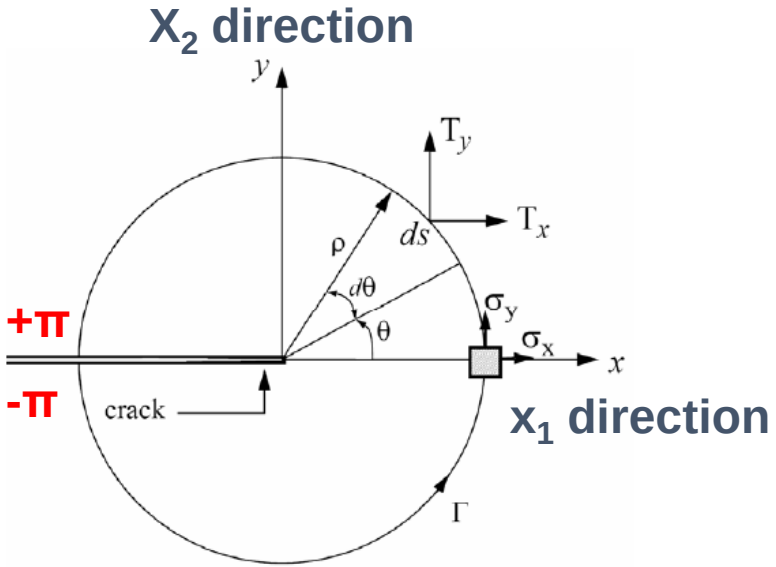
Contour Integral Method (CIM)

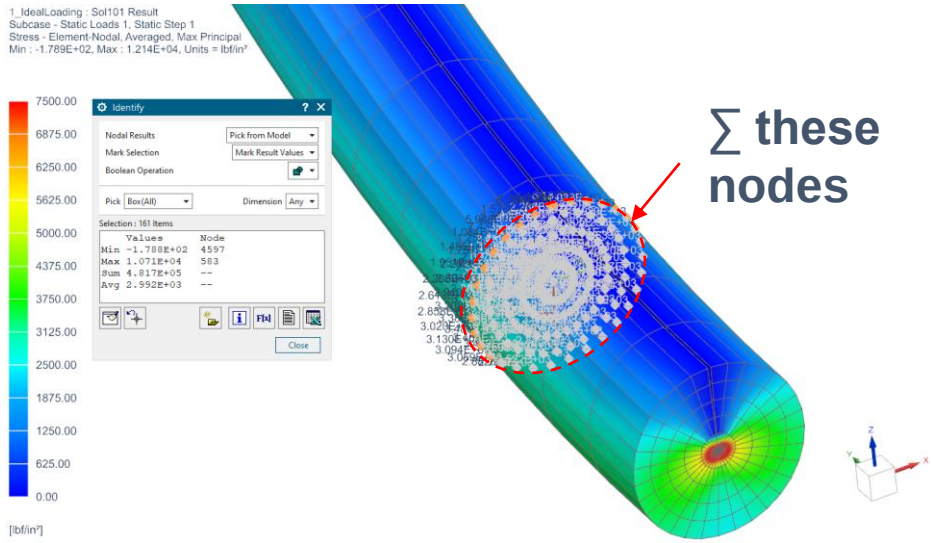
- StressCheck uses CIM
  - ANSYS uses a similar Domain Integral Method
- CIM denigrates to a “line integral”
- Sum up nodal values on a common plane and radius, negating the need for a specified path of integration (departure from classical CIM technique)



Line Integral

Domain Integral





From *Extraction of Stress Intensity Factors for the Simulation of 3-D Crack Growth with the Generalized Finite Element Method*, J. Garzon, C.A. Duarte, and J.P. Pereira, Key Engineering Materials Vol. 560
doi:10.4028/www.scientific.net/KEM.560.1

Contour Integral Method (CIM)

$$\begin{bmatrix} K_1 \\ K_2 \end{bmatrix} = \sqrt{2\pi} \begin{bmatrix} A_1^{(1)} \\ A_1^{(2)} \end{bmatrix}$$ **Where A is asymptotic expansion at the crack tip**

$$A_1^{(m)} \approx \oint_{\Gamma} \left(W_m T_{FE} - u_{FE} T^{(W_m)} \right) ds$$ **Where the exact solution exists as ds→0, m denotes Mode I or II**

$$\oint_{\Gamma} \left(W_m T_{FE} - u_{FE} T^{(W_m)} \right) ds = \oint_{-\pi}^{+\pi} \left(W_m T_{FE} - u_{FE} T^{(W_m)} \right) R d\theta$$ **in local coordinates at crack tip node of interest**

$$T_{FE} = \begin{bmatrix} T_x \\ T_y \end{bmatrix}_{FE} = \begin{bmatrix} \sigma_x \cos\theta + \tau_{xy} \sin\theta \\ \tau_{xy} \cos\theta + \sigma_y \sin\theta \end{bmatrix} = \begin{bmatrix} \sigma_{11} \cos\theta + \sigma_{12} \sin\theta \\ \sigma_{12} \cos\theta + \sigma_{22} \sin\theta \end{bmatrix}$$ **in local coordinates at crack tip node of interest**

$$u_{FE} = \begin{bmatrix} u_x & u_y \end{bmatrix}_{FE} = \begin{bmatrix} u_{x,node} - u_{x,R=0} & u_{y,node} - u_{y,R=0} \end{bmatrix}$$ **in local coordinates at crack tip node of interest**

W_m and $T^{(Wm)}$ are extraction functions:

$$W_m = \frac{R^{\frac{-1}{2}}}{D^{(m)}} \begin{bmatrix} \Psi_1^{(m)}(\theta) & \Psi_2^{(m)}(\theta) \end{bmatrix} \qquad T^{(Wm)} = -\frac{GR^{\frac{-3}{2}}}{D^{(m)}} \begin{bmatrix} Y_1^{(m)}(\theta) \\ Y_2^{(m)}(\theta) \end{bmatrix}$$

Contour Integral Method (CIM)

$D^{(1)} = \pi(2\kappa - 1)$ **For Mode I**

$D^{(2)} = \pi(2\kappa + 3)$ **For Mode II**

$\kappa_1 = 3 - 4\nu$ **plane-strain**

$\kappa_2 = \dfrac{3 - \nu}{1 + \nu}$ **plane-stress**

Determined at R & θ = 0 for StressCheck
Determined at R = $rad_{c,max}$, θ = 0 in next slides

To account for stresses in 3D:

$$\gamma = \left|\frac{\sigma_z}{\sigma_x + \sigma_y}\right| = \left|\frac{\sigma_{33}}{\sigma_{11} + \sigma_{22}}\right|$$

$$\kappa = \kappa(\gamma) = \kappa_1 + (\kappa_2 + \kappa_1)\left(\frac{2\gamma}{0.1} + 1\right)\left(1 - \frac{\gamma}{0.1}\right)^2$$ **For γ ≤ 0.1**

$\kappa = \kappa_1 = 3 - 4\nu$ **For γ > 0.1**

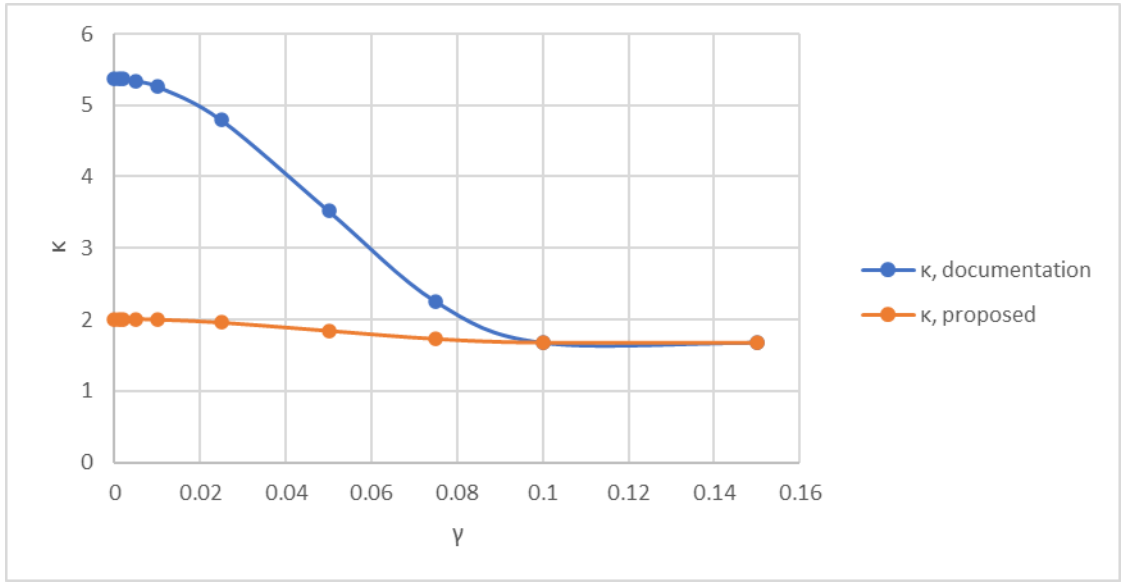
Contour Integral Method (CIM)

- κ(γ) is supposed to transition from κ_1 to κ_2, but documentation says:

$$\kappa = \kappa(\gamma) = \kappa_1 + (\kappa_2 + \kappa_1)\left(\frac{2\gamma}{0.1} + 1\right)\left(1 - \frac{\gamma}{0.1}\right)^2$$

- Proposed:

$$\kappa = \kappa(\gamma) = \kappa_1 + (\kappa_2 - \kappa_1)\left(\frac{2\gamma}{0.1} + 1\right)\left(1 - \frac{\gamma}{0.1}\right)^2$$



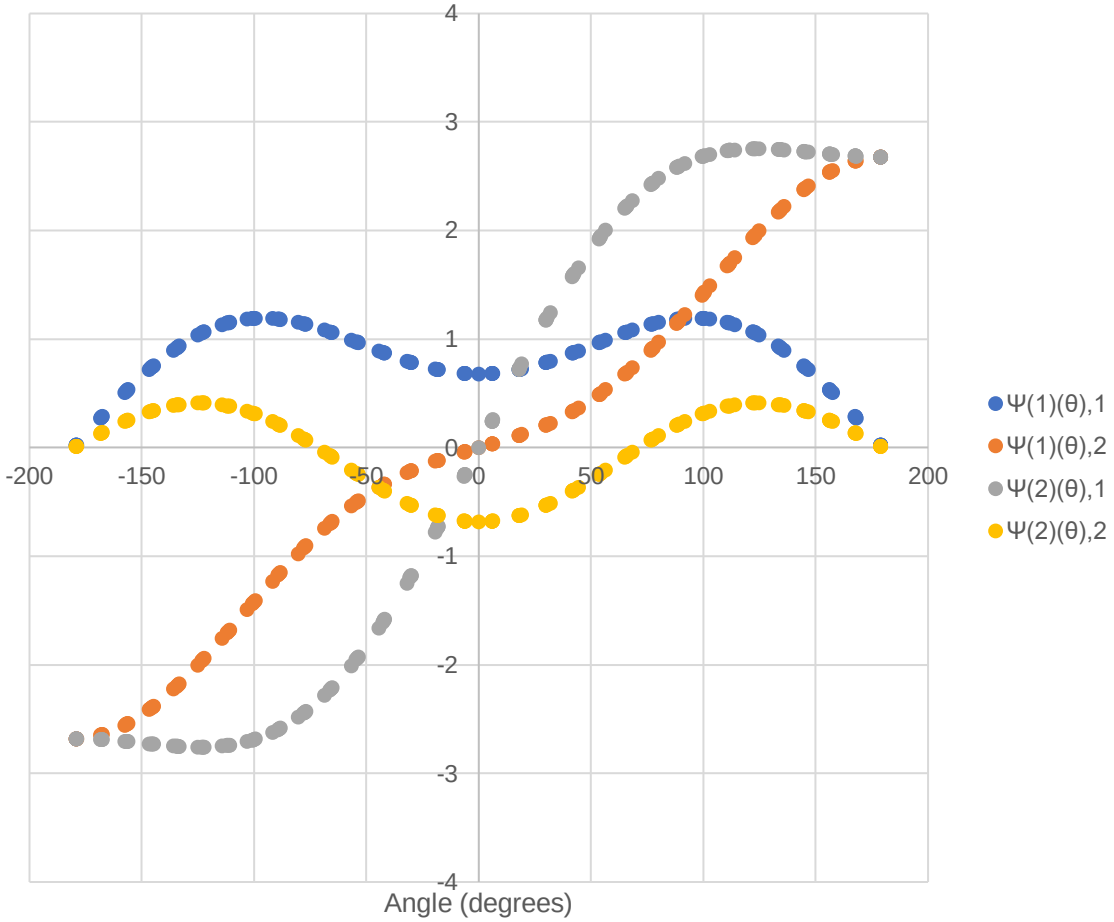
Contour Integral Method (CIM)

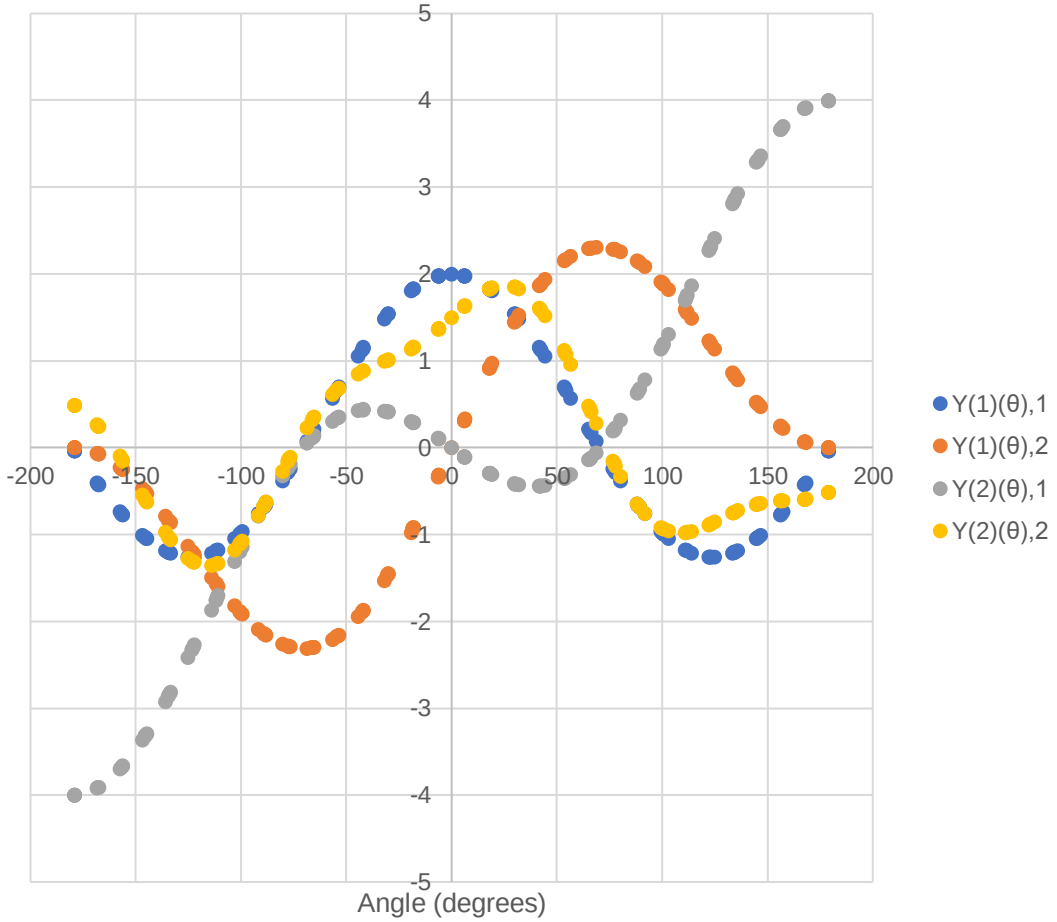
$$\Psi^{(1)}(\theta) = \begin{bmatrix} \left(\kappa - \frac{1}{2}\right)\cos\left(\frac{\theta}{2}\right) - \frac{1}{2}\cos\frac{3\theta}{2} \\ \left(\kappa + \frac{1}{2}\right)\sin\left(\frac{\theta}{2}\right) - \frac{1}{2}\sin\frac{3\theta}{2} \end{bmatrix} \qquad \Psi^{(2)}(\theta) = \begin{bmatrix} \left(\kappa + \frac{3}{2}\right)\sin\left(\frac{\theta}{2}\right) + \frac{1}{2}\sin\frac{3\theta}{2} \\ -\left(\kappa - \frac{3}{2}\right)\cos\left(\frac{\theta}{2}\right) - \frac{1}{2}\cos\frac{3\theta}{2} \end{bmatrix}$$

$$Y^{(1)}(\theta) = \begin{bmatrix} \left(\frac{3}{2}\cos\left(\frac{\theta}{2}\right) + \frac{1}{2}\cos\left(\frac{5\theta}{2}\right)\right)\cos(\theta) + \left(\frac{1}{2}\sin\left(\frac{5\theta}{2}\right) - \frac{1}{2}\sin\left(\frac{\theta}{2}\right)\right)\sin(\theta) \\ \left(\frac{1}{2}\sin\left(\frac{5\theta}{2}\right) - \frac{1}{2}\sin\left(\frac{\theta}{2}\right)\right)\cos(\theta) + \left(\frac{5}{2}\cos\left(\frac{\theta}{2}\right) - \frac{1}{2}\cos\left(\frac{5\theta}{2}\right)\right)\sin(\theta) \end{bmatrix}$$

$$Y^{(2)}(\theta) = \begin{bmatrix} \left(-\frac{7}{2}\sin\left(\frac{\theta}{2}\right) - \frac{1}{2}\sin\left(\frac{5\theta}{2}\right)\right)\cos(\theta) + \left(\frac{1}{2}\cos\left(\frac{5\theta}{2}\right) + \frac{3}{2}\cos\left(\frac{\theta}{2}\right)\right)\sin(\theta) \\ \left(\frac{1}{2}\sin\left(\frac{5\theta}{2}\right) + \frac{3}{2}\cos\left(\frac{\theta}{2}\right)\right)\cos(\theta) + \left(-\frac{1}{2}\sin\left(\frac{\theta}{2}\right) + \frac{1}{2}\sin\left(\frac{5\theta}{2}\right)\right)\sin(\theta) \end{bmatrix}$$

Contour Integral Method (CIM)





At 80° from surface (fully plane-strain)

Denmar Technical Services

Results for a Single Slice at 80° from Surface (10° from Bore)

Contour Integral Method (CIM)

Contour Integral Method (CIM)

- Build Excel sheet to search and sum all nodes within a certain radial "window" (80 degrees from surface)
- Model 1:

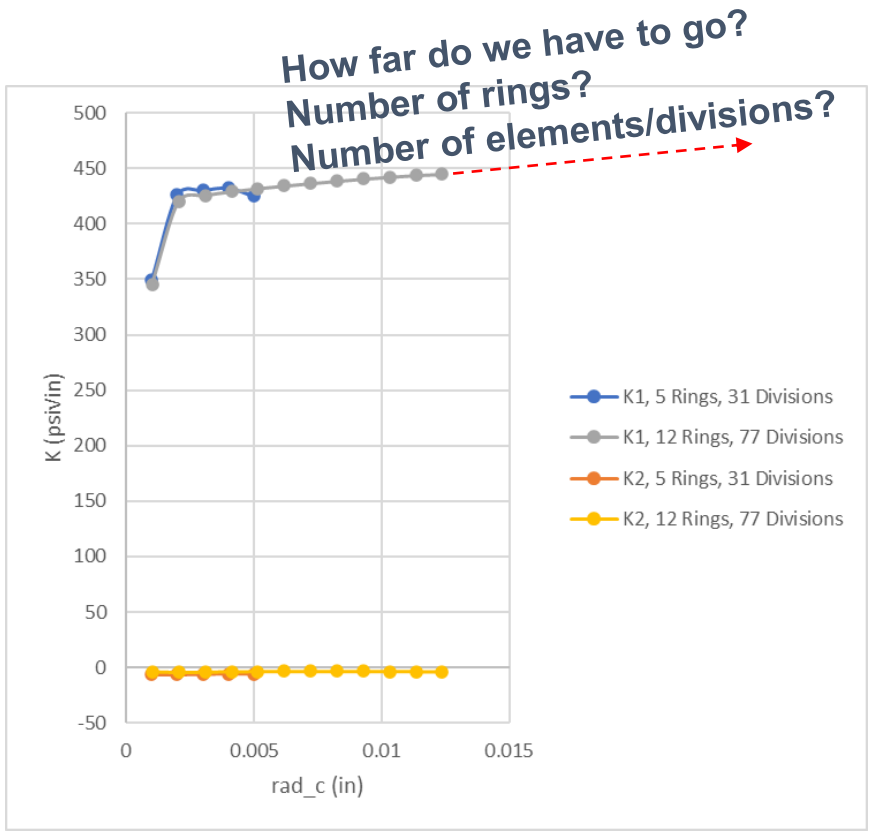
rad_c	ds	r_{min}	r_{max}	Σ, all	A1(1)	A1(2)	K1	K2
0.001	0.000203	0.0005	0.0015	**Σ, R=0.001**	139.47	-2.37	349.59	-5.93
0.002	0.000405	0.0015	0.0025	**Σ, R=0.002**	170.01	-2.38	426.15	-5.98
0.003	0.000608	0.0025	0.0035	**Σ, R=0.003**	171.55	-2.31	430.00	-5.79
0.004	0.000811	0.0035	0.0045	**Σ, R=0.004**	172.43	-2.26	432.22	-5.66
0.005	0.001013	0.0045	0.0055	**Σ, R=0.005**	169.56	-2.30	425.03	-5.76

  - At R=0.004", underestimates by 6.9%

- Model 2:

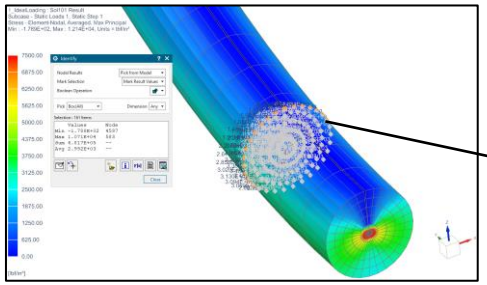
rad_c	ds	r_{min}	r_{max}	Σ, all	A1(1)	A1(2)	K1	K2
0.00103	0.000084	0.00052	0.00155	**Σ, R=0.001**	137.79	-1.42	345.39	-3.56
0.00206	0.000168	0.00155	0.00258	**Σ, R=0.002**	167.56	-1.53	420.00	-3.84
0.00309	0.000252	0.00258	0.00361	**Σ, R=0.003**	169.81	-1.48	425.64	-3.71
0.00413	0.000337	0.00361	0.00464	**Σ, R=0.004**	171.13	-1.44	428.96	-3.60
0.00516	0.000421	0.00464	0.00567	**Σ, R=0.005**	172.25	-1.41	431.76	-3.52
0.00619	0.000505	0.00567	0.00670	**Σ, R=0.006**	173.21	-1.39	434.17	-3.48
0.00722	0.000589	0.00670	0.00773	**Σ, R=0.007**	174.10	-1.39	436.40	-3.47
0.00825	0.000673	0.00773	0.00877	**Σ, R=0.008**	174.92	-1.39	438.47	-3.48
0.00928	0.000757	0.00877	0.00980	**Σ, R=0.009**	175.69	-1.40	440.40	-3.50
0.01031	0.000841	0.00980	0.01083	**Σ, R=0.010**	176.41	-1.41	442.19	-3.53
0.01134	0.000926	0.01083	0.01186	**Σ, R=0.011**	177.01	-1.42	443.71	-3.56
0.01238	0.001010	0.01186	0.01289	**Σ, R=0.012**	177.44	-1.46	444.77	-3.65

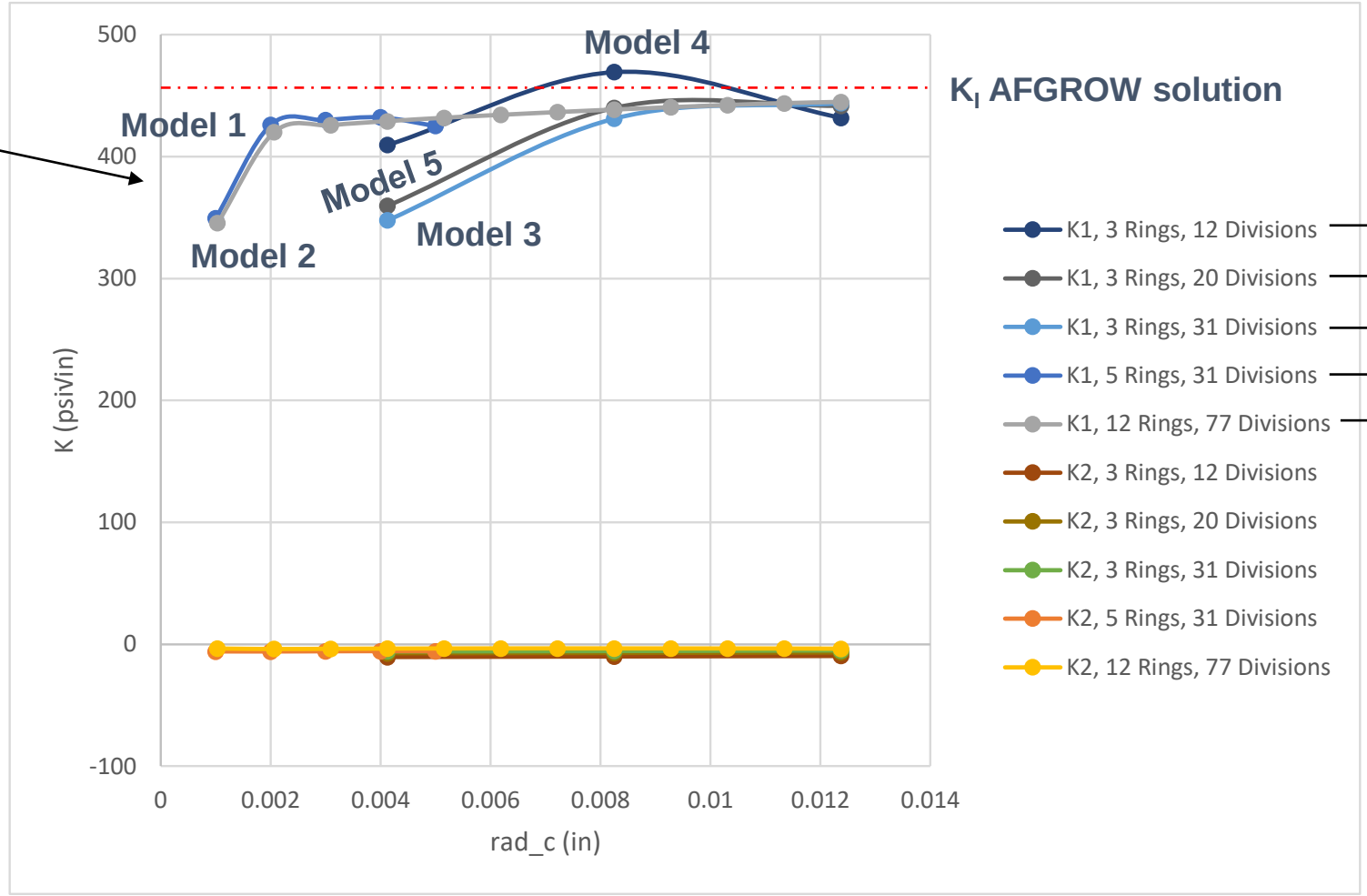
  - At R=0.0124", underestimates by 4.1%



Contour Integral Method (CIM)

- With two models built, what happens if we increase the radius of integration and add more layers of refinement?

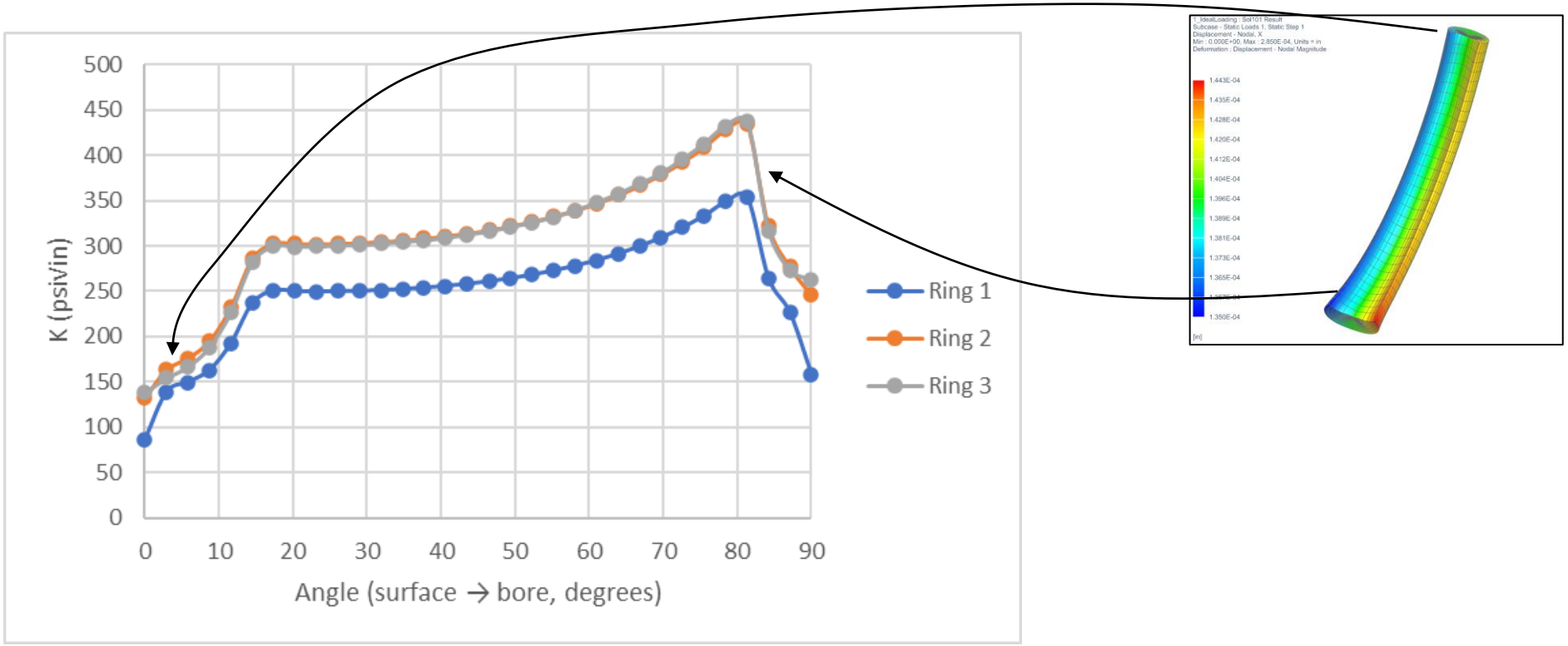




Model 5 looks "pretty good"

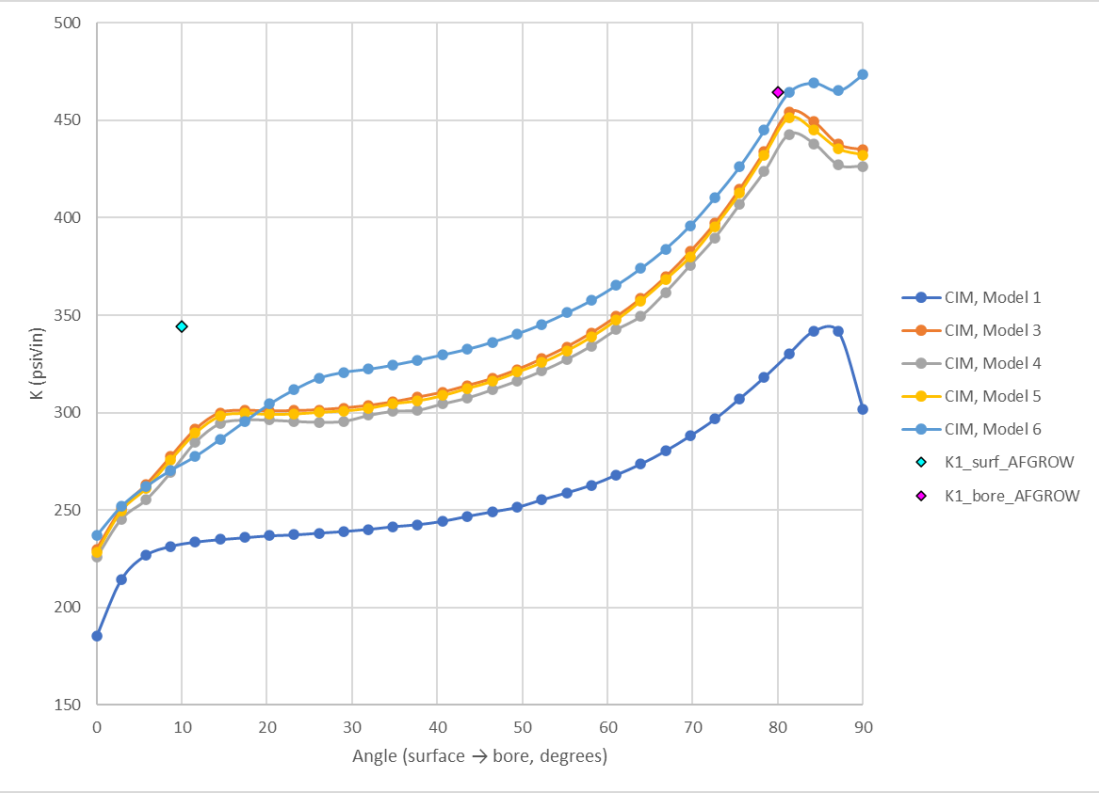
Contour Integral Method (CIM)

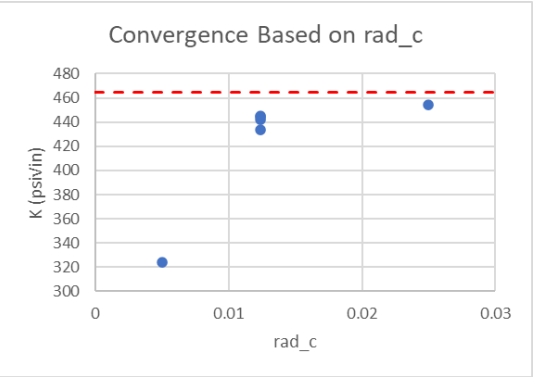
- Now that a baseline for a single “slice” at the crack front has been developed:
  - Expand method to handle global coordinates and translate based on a crack origin CSYS with the crack plane on the local X-Z axis
  - Look at the entire crack front results
  - Transforming into individual extraction coordinate systems using ***documented*** κ(γ) (Model 5, $rad_{c,max}$ = 0.01248”):

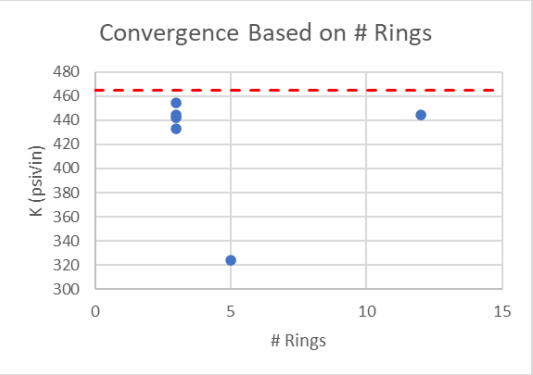


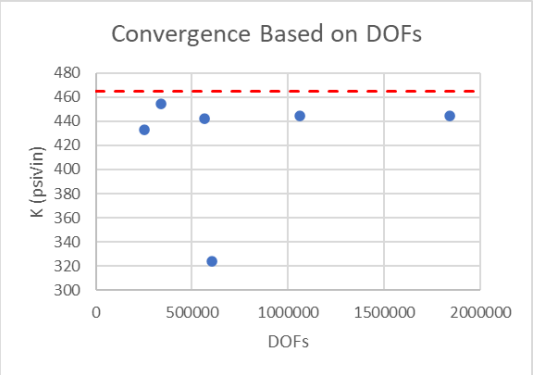
Contour Integral Method (CIM)

- Convergence study (initial) using ***proposed*** κ(γ)
  - Add one more model (Model 6, $rad_{c,max}$ = 0.025”) with an increased radius of integration
  - Look at maximum radius of integration results and plot against others
  - Note: Model 2 ignored due to very large solution file









Contour Integral Method (CIM)

- Method requirements:
  - Requires nodes on or near plane of interest
  - Hex mesh along crack front *not necessarily* required (but does make matching planes easier)
  - Use averaged values and sum per node
  - Ignore midnodes unless element lengths are large (until a more elegant solution is implemented)

- Benefits
  - Allows use of Boolean (subtract) features instead of creating non-manifold geometry (i.e. StressCheck crack face designation)
  - No special elements needed
  - K_{II} calculated alongside K_I
  - Only needs displacement and stress in the local CSYS

- Drawbacks
  - Not easy
  - Underpredicts K_I bore without a sufficient radius of integration
  - Underpredicts K_I surface (surface "pinning" discussed by J. Hodges, et. al. AFGROW 2020?)
  - May overpredict at smaller crack sizes or thinner materials (ESRI Round Robin, presented AFGROW 2021)

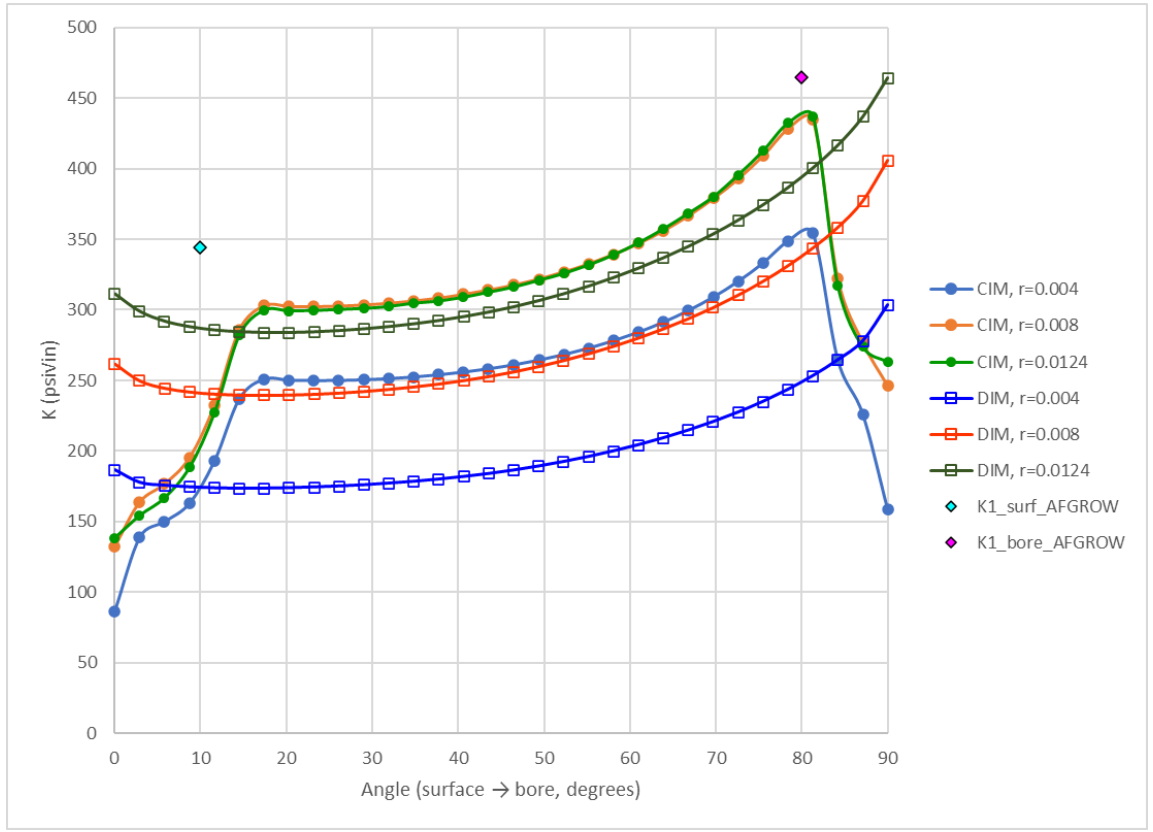
CIM vs. DIM

CIM vs. DIM (Model 5)

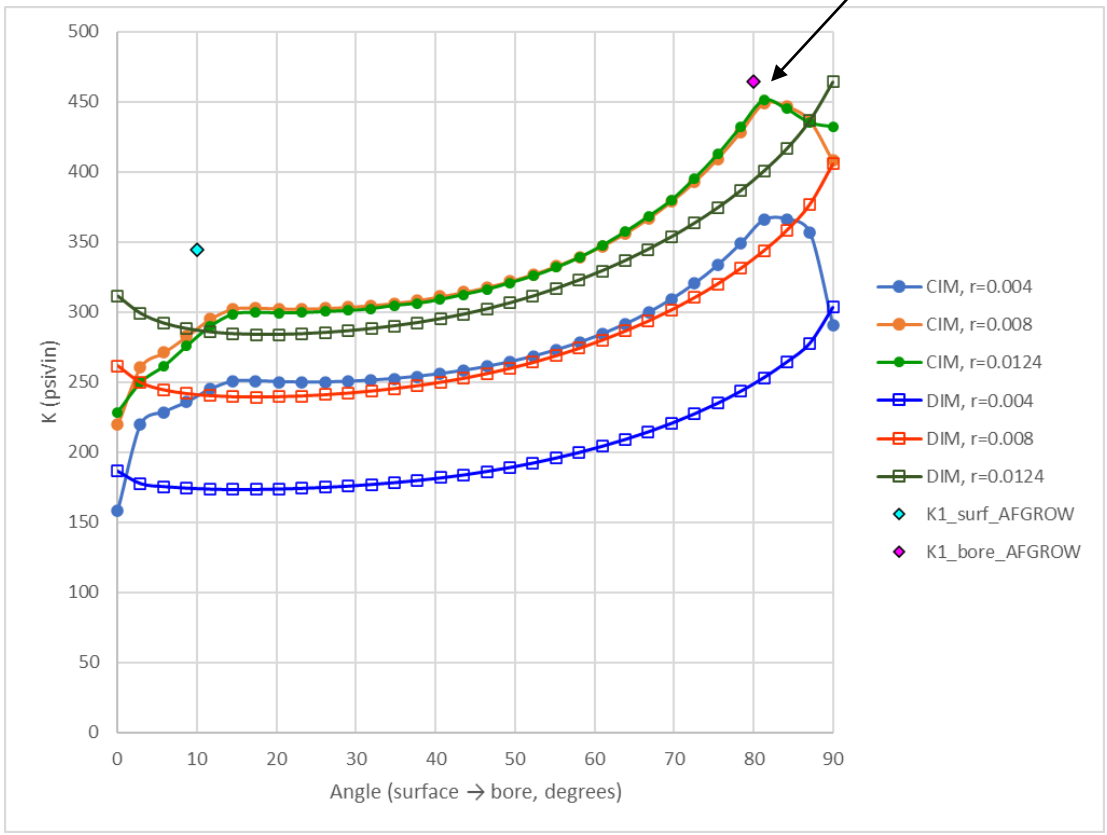
rad_c max = 0.012375”

CIM Underpredicts by 3.3%

Using documented κ(γ)



Using proposed κ(γ)

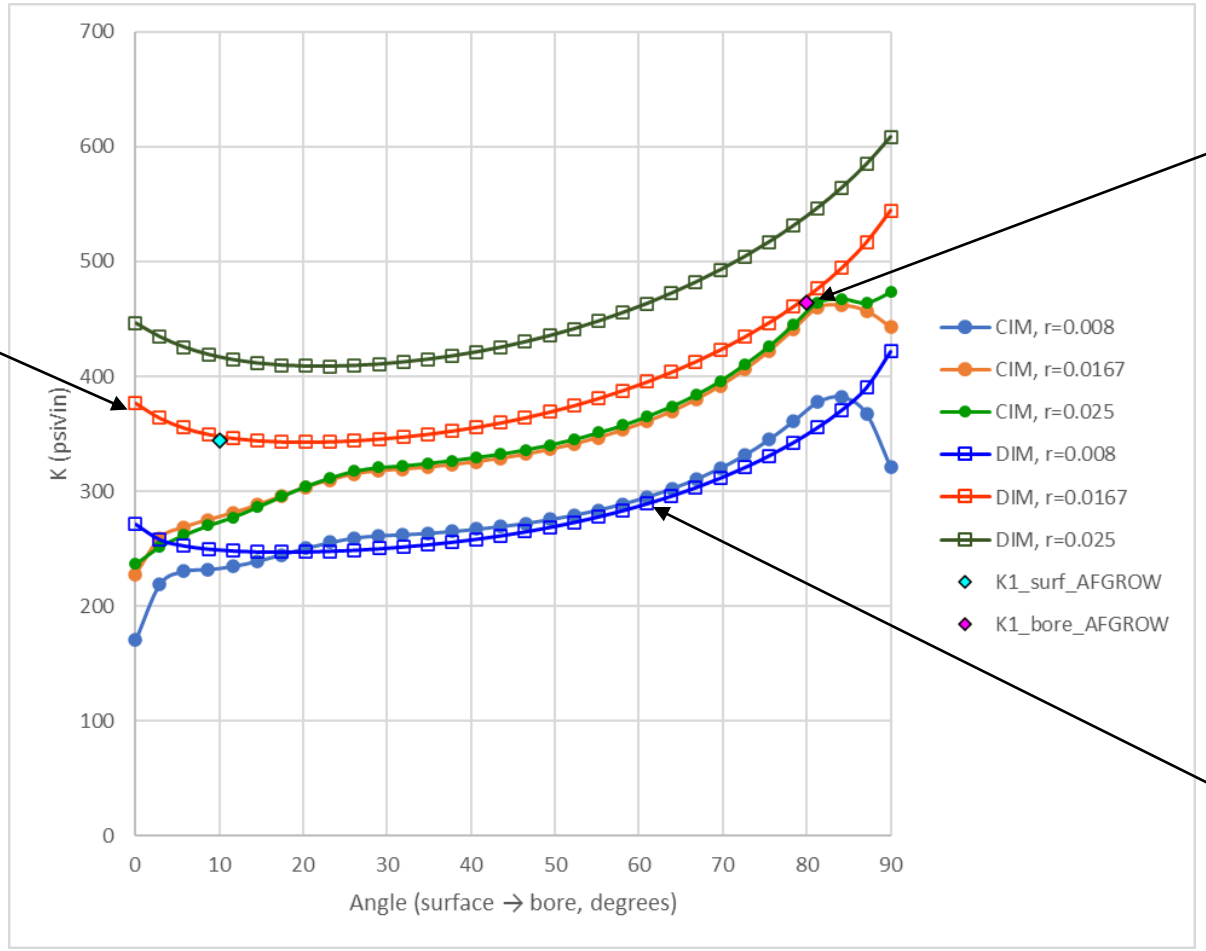


But maybe we’re not converged. Look at a larger rad_c (next slide)…

CIM vs. DIM (Model 6)

rad_c max = 0.025”

Using proposed κ(γ)

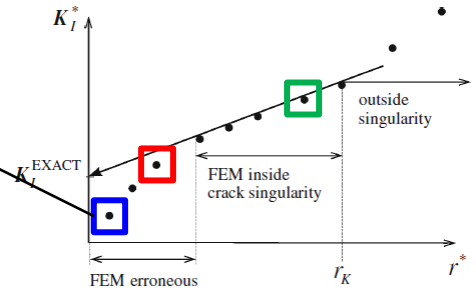


CIM underpredicts by 2.1%

Need more layers to determine appropriate DIM value.

-But-

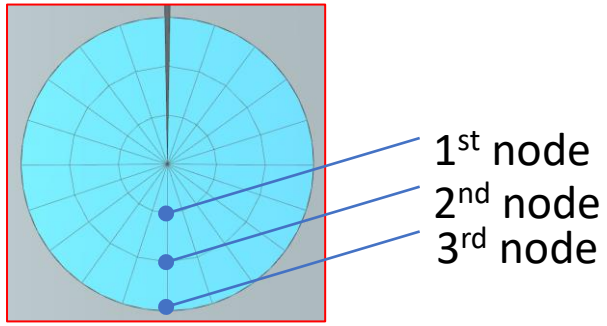
Significantly increases model size and run time.



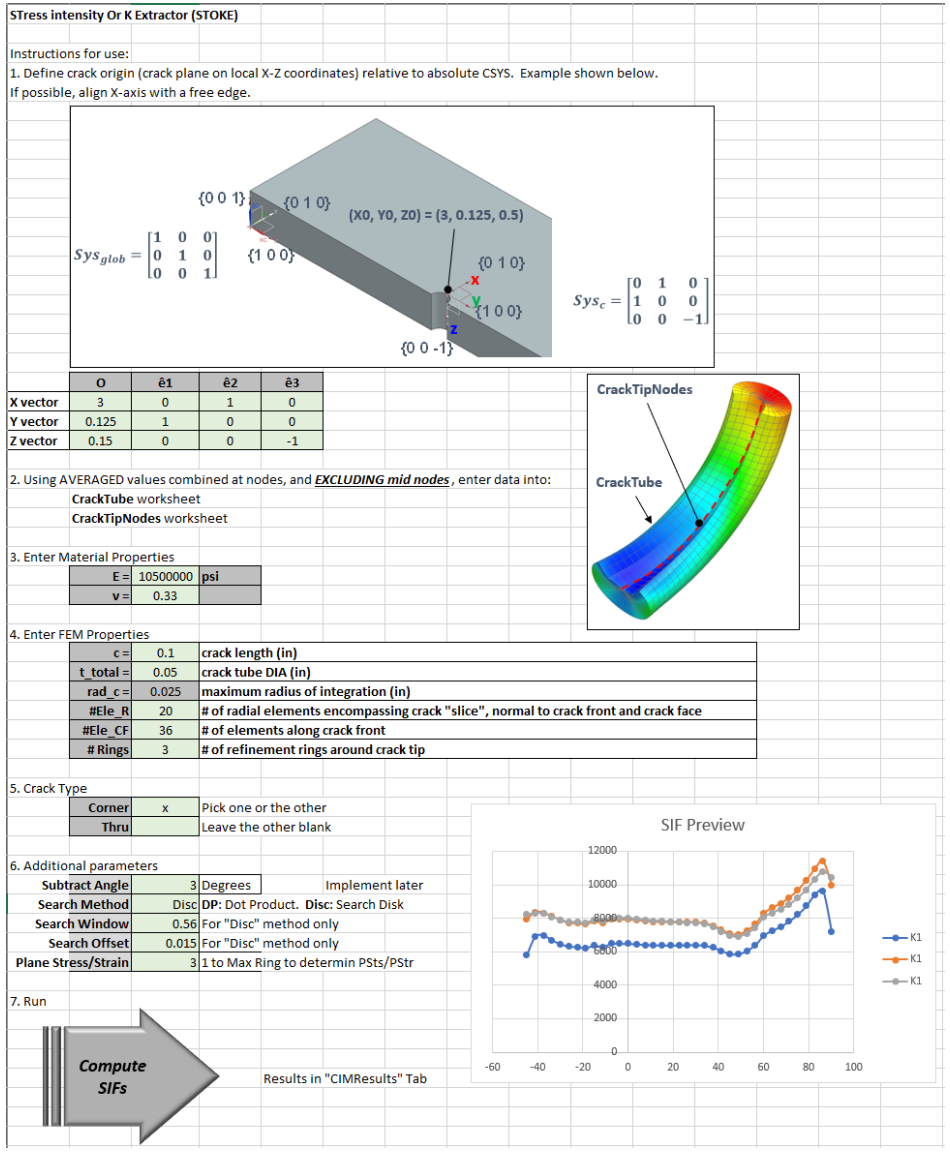
Introducing…

STress intensity Or K Extractor (STOKE)

- Tool that works with any FE package
- User extracts “crack tube” of structured mesh of node numbers, positions, displacement, and stresses
- User defines:
  - crack origin and directions
  - materials
  - crack properties
  - crack type
  - crack tip node numbers
  - κ derivation node



- All extractions in remainder of presentation use STOKE to pull from the FE solution

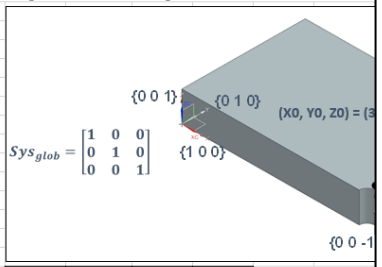


Step 1: Enter global info

STress intensity Or K Extractor (STOKE)

Instructions for use:

1. Define crack origin (crack plane on local X-Z coordinates) relative to abs
If possible, align X-axis with a free edge.



	O	ê1	ê2	ê3
X vector	3	0	1	0
Y vector	0.125	1	0	0
Z vector	0.15	0	0	-1

2. Using AVERAGED values combined at nodes, and ***EXCLUDING mid nodes***
CrackTube worksheet
CrackTipNodes worksheet

3. Enter Material Properties

E =	10500000	psi
v =	0.33	

4. Enter FEM Properties

c =	0.1	crack length (in)
t_total =	0.05	crack tube DIA (in)
rad_c =	0.025	maximum radius of integration (in)
#Ele_R	20	# of radial elements encompassing crack
#Ele_CF	36	# of elements along crack front
# Rings	3	# of refinement rings around crack tip

5. Crack Type

Corner	x	Pick one or the other
Thru		Leave the other blank

6. Additional parameters

Subtract Angle	3	Degrees	Implement later
Search Method	Disc	DP: Dot Product. Disc: Search Disk	
Search Window	0.56	For "Disc" method only	
Search Offset	0.015	For "Disc" method only	
Plane Stress/Strain	3	1 to Max Ring to determin PSts/PStr	

7. Run

Compute SIFs

Results in "CIMResults" Tab

Step 2: Enter nodal info

		Position (in)			Global Displacements (in)			Global Stresses (psi)					
Node	X Coord	Y Coord	Z Coord	u_x	u_y	u_z	s_xx	s_yy	s_zz	s_xy	s_yz	s_xz
1	2.994591	0.124882	0.41576	0.000132	-8.1E-06	-7.33734E-07	24.03989	-5.68031	209.8218	-6.03796	-8.82788	-156.983
2	2.997295	0.124971	0.407877	0.000134	-7.6E-06	-3.4307E-07	-336.749	5.05019	256.3075	-25.1053	41.68149	24.42403
3	2.989998	0.124598	0.413342	0.000132	-7.5E-06	-1.42942E-06	161.2902	-18.4897	367.4069	12.63	-41.3456	-467.065
4	2.994995	0.1249	0.406668	0.000134	-7.2E-06	-9.67103E-07	-162.388	-49.6216	645.6294	-5.07604	0.76738	-652.284
5	2.986365	0.124254	0.409638	0.000133	-6.9E-06	-1.80522E-06	619.3142	-16.0663	315.2767	75.07208	-83.6169	-734.078
6	2.993172	0.124813	0.404816	0.000135	-6.8E-06	-1.31282E-06	508.5444	-89.2513	445.6161	50.01293	-44.6557	-1142.26
7	2.984041	0.123977	0.404996	0.000134	-6.5E-06	-1.86843E-06	1219.78	0.592888	144.0365	168.9152	-100.674	-783.065
8	2.992004	0.124744	0.402495	0.000136	-6.4E-06	-1.39289E-06	1360.578	-111.132	37.35446	124.0826	-69.1306	-1223.19
9	2.983272	0.123876	0.399856	0.000135	-6.1E-06	-1.68396E-06	1757.805	16.38111	10.53266	248.6845	-79.0703	-614.274
10	2.991617	0.124719	0.399925	0.000137	-6.1E-06	-1.25926E-06	2082.931	-123.96	-280.954	190.2973	-60.1217	-930.673
11	2.98414	0.12399	0.394732	0.000136	-5.9E-06	-1.33701E-06	2106.641	21.75479	9.15655	279.3395	-35.1744	-324.327
12	2.992054	0.124747	0.397363	0.000137	-5.9E-06	-9.815E-07	2488.676	-133.372	-335.365	220.8143	-24.9284	-447.795
13	2.986542	0.124273	0.390131	0.000137	-5.7E-06	-9.1513E-07	2233.888	15.89272	158.8468	248.1596	3.448416	-37.7538
14	2.993262	0.124818	0.395062	0.000138	-5.8E-06	-6.38112E-07	2543.791	-142.528	-110.347	206.3676	15.99203	-3.28179
15	2.990235	0.124617	0.386486	0.000138	-5.6E-06	-5.12023E-07	2177.225	1.627045	403.8932	175.1358	18.06758	132.2972
16	2.995114	0.124904	0.39324	0.000139	-5.6E-06	-3.11662E-07	2364.363	-150.474	268.1715	154.2699	46.19865	226.4254
17	2.994867	0.124895	0.384142	0.000139	-5.6E-06	-2.20455E-07	2055.04	-7.31541	634.2371	86.43948	13.58088	130.0834
18	2.997433	0.124973	0.392068	0.000139	-5.6E-06	-7.95678E-08	2153.943	-155.123	608.6251	82.66189	61.04967	195.5255

Home | CrackTube | CrackTipNodes | CIMResults

Step 3: Enter crack tip nodes

Node
185
372
375
376
377
378
379
380
381
382
383
384
385
386
387
388
389
390
391

Home | CrackTube | CrackTipNodes | CIMResults

Step 4: Compute SIFs

Benchmark and Additional Problems

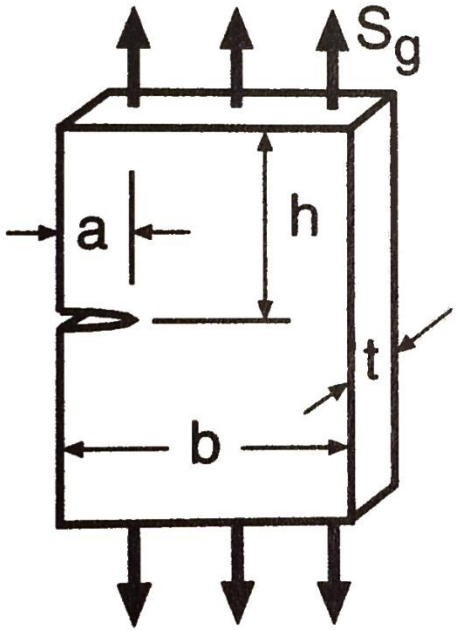
Benchmark Models

- FT01 and FT02 have same CAD geometry, only boundary conditions change

FT01/TC02 Geometry

Dimensions
h = ~~5~~ 10
b = 5
a = 0.5
t = 5

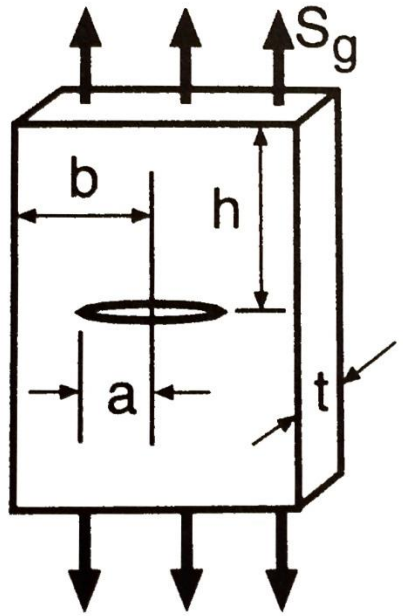
Material: E = 3.0e7, v = 0.30
Loading: Uniform unit stress



FT02/TC01 Geometry

Dimensions
h = ~~5~~ 10
b = 5
a = 0.5
t = 5

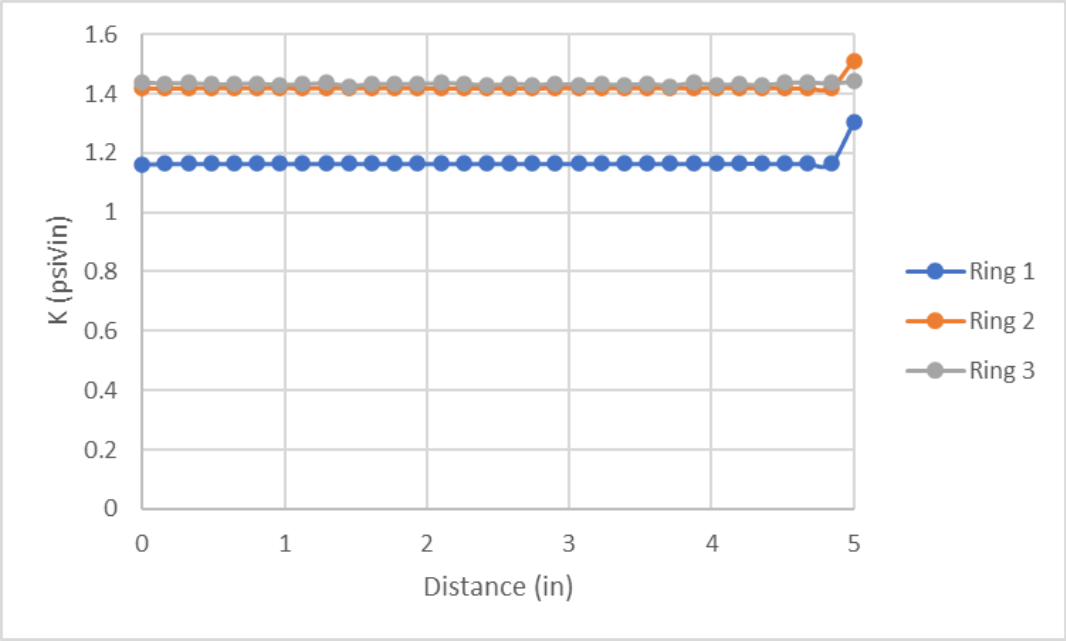
Material: E = 3.0e7, v = 0.30
Loading: Uniform unit stress



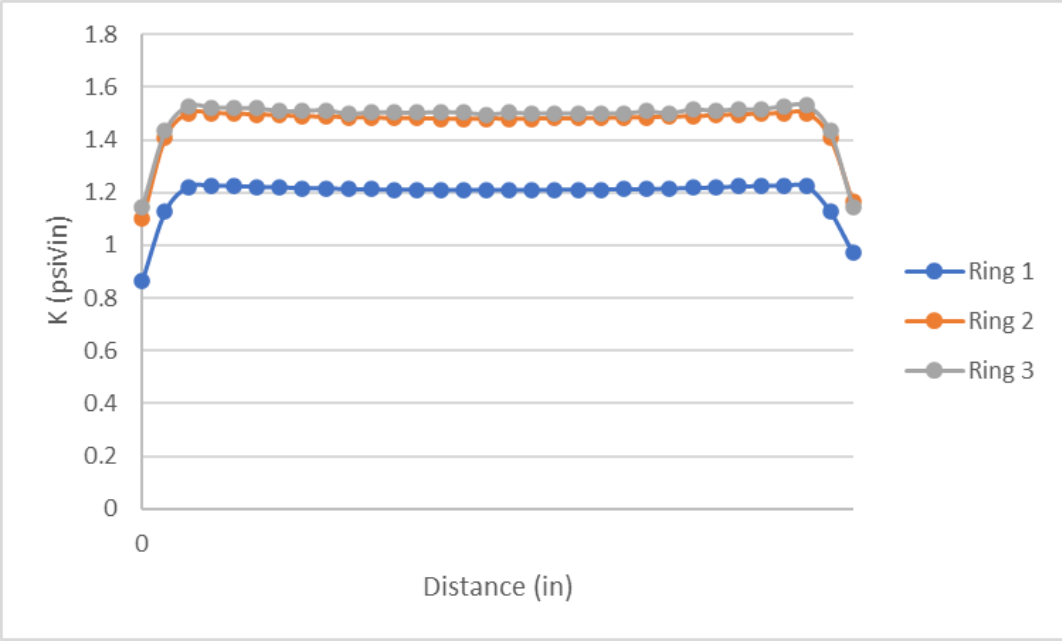
Benchmark Models

- FT01

Forced Plane Strain

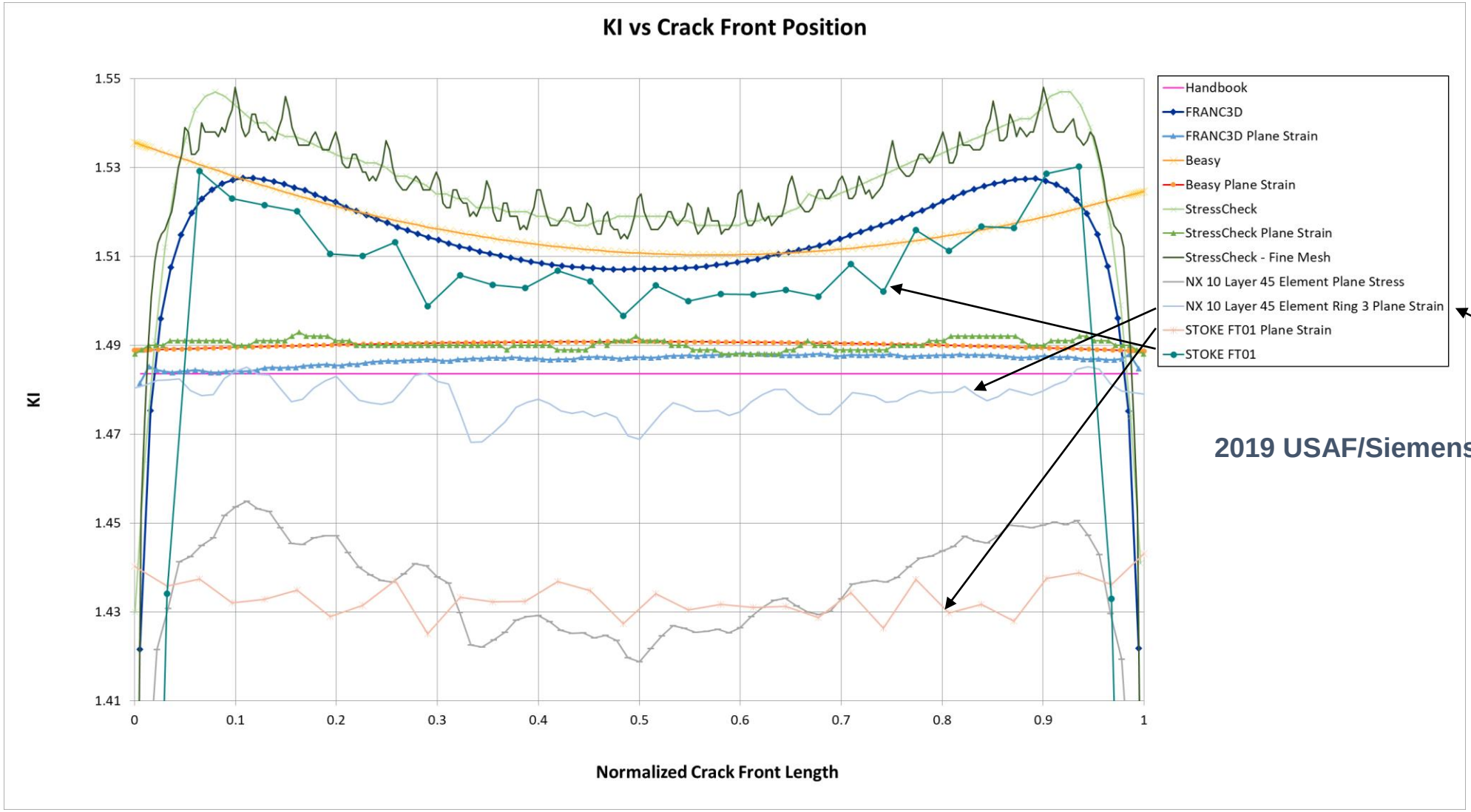


Plane Stress



Benchmark Models

- FT01

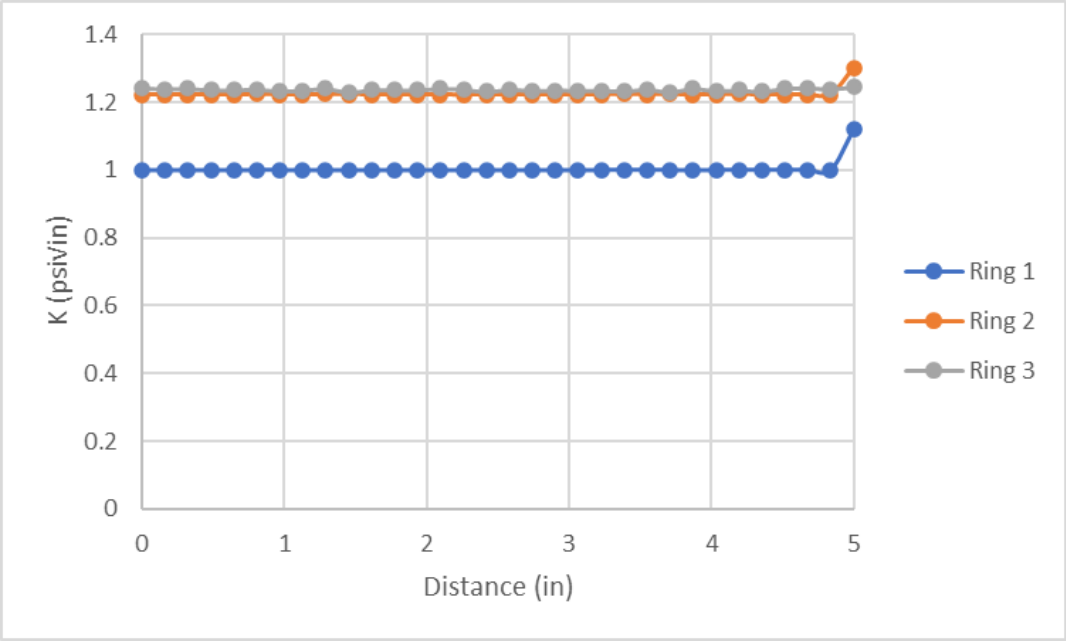


2019 USAF/Siemens effort

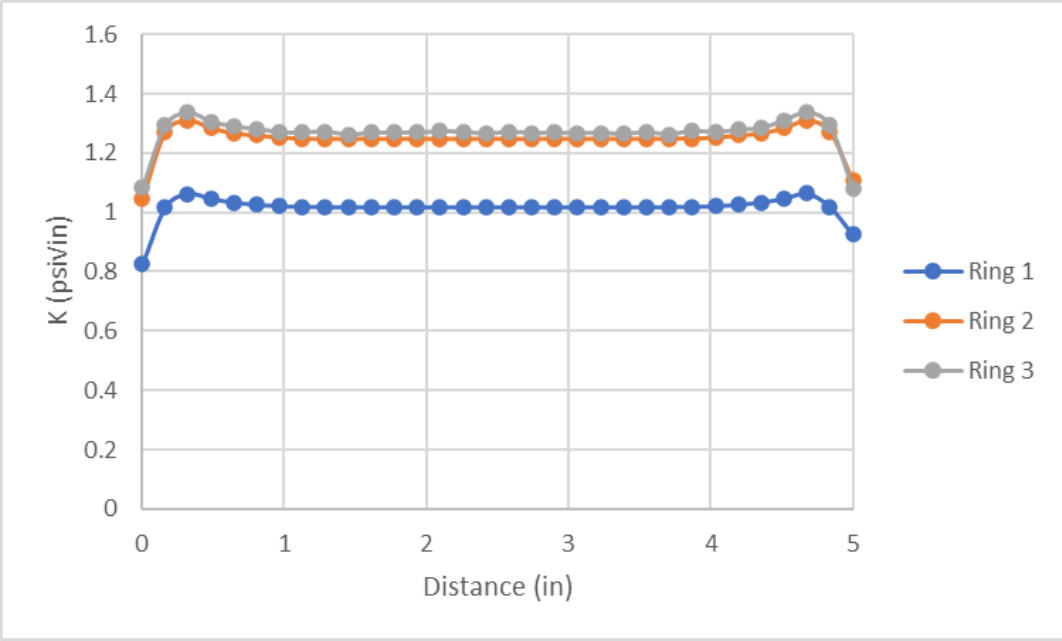
Benchmark Models

- FT02

Forced Plane Strain

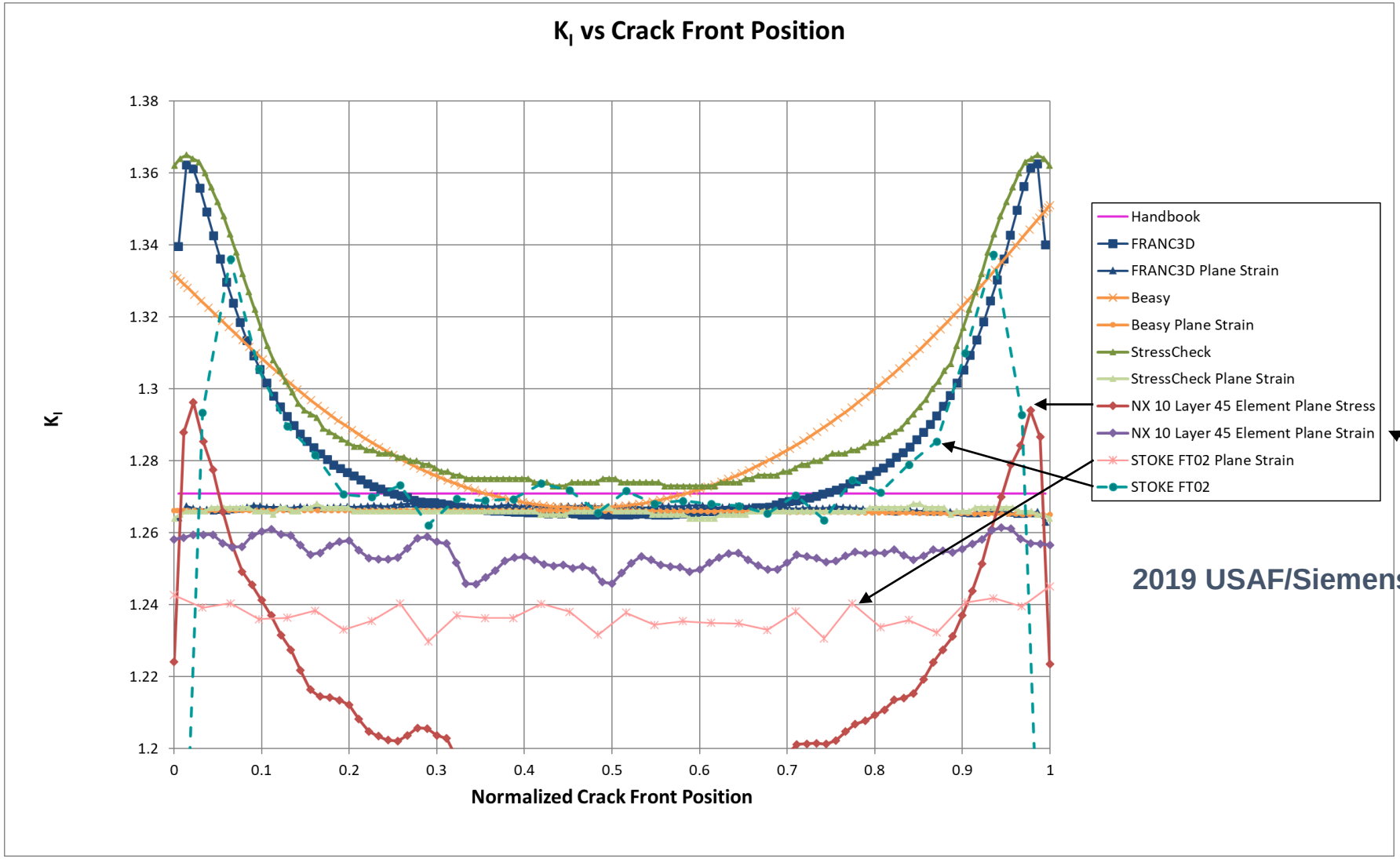


Plane Stress



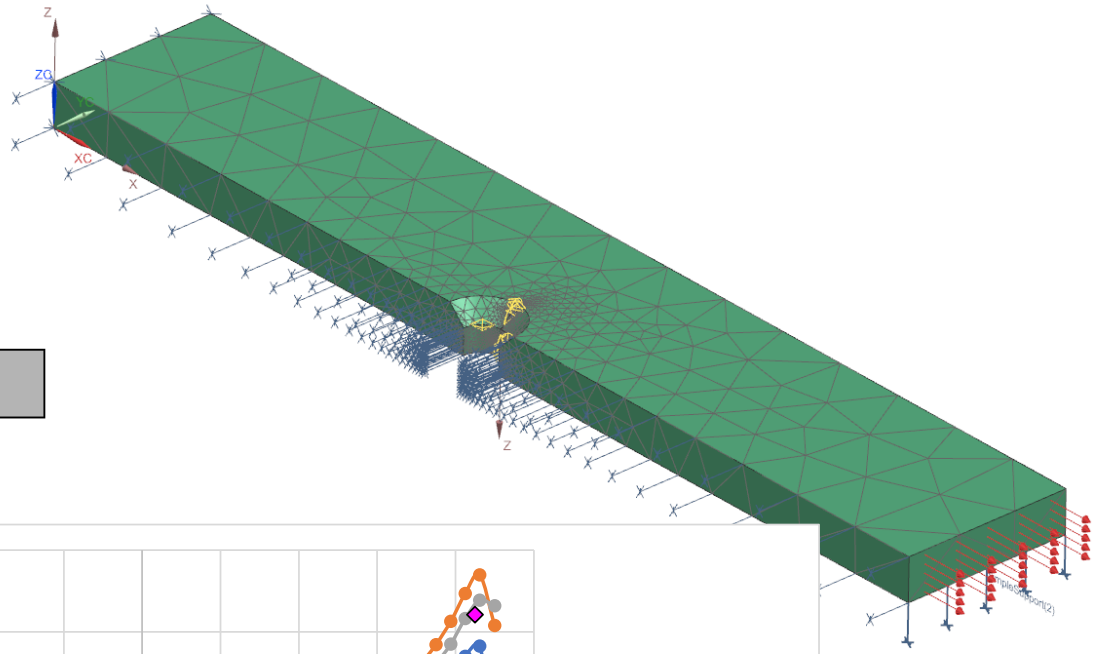
Benchmark Models

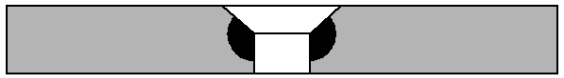
- FT02

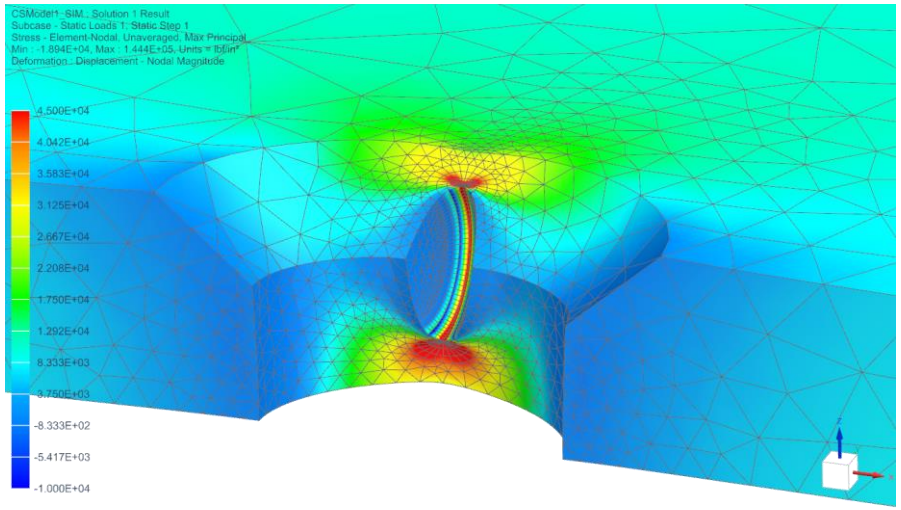


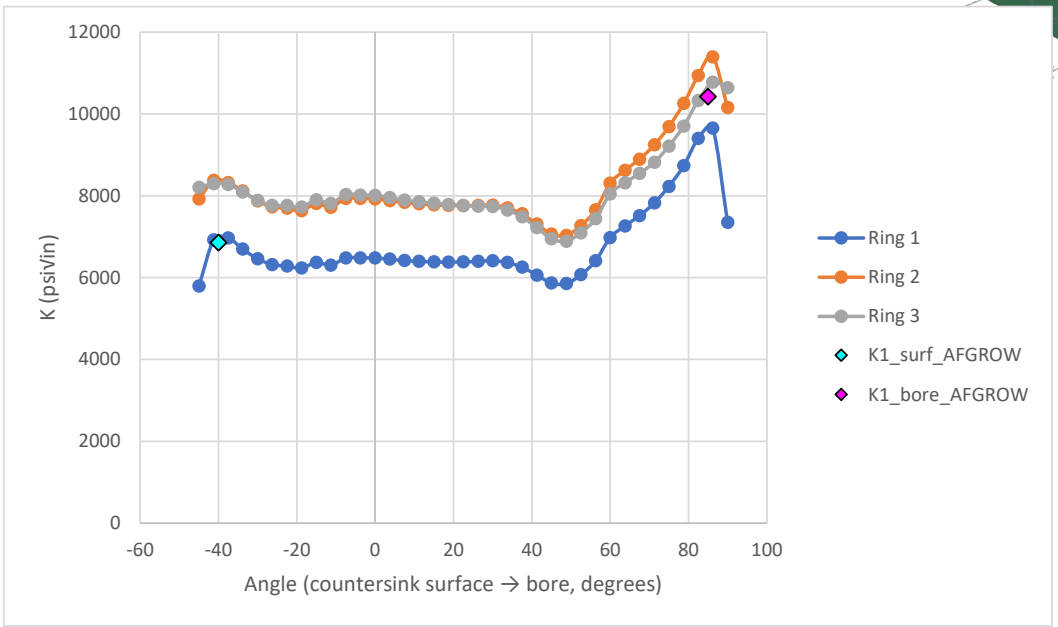
Additional Problems: Countersink Model Example

- c=0.1”, t_total=0.5*c
- Radial elements: 20
- Crack front elements: 38
- 3 layers
- Load: 2500 lbs, 10ksi
- Half width = 1in
- thickness =0.25in
- diameter =0.25in
- CS depth = 0.1”, 45 degrees







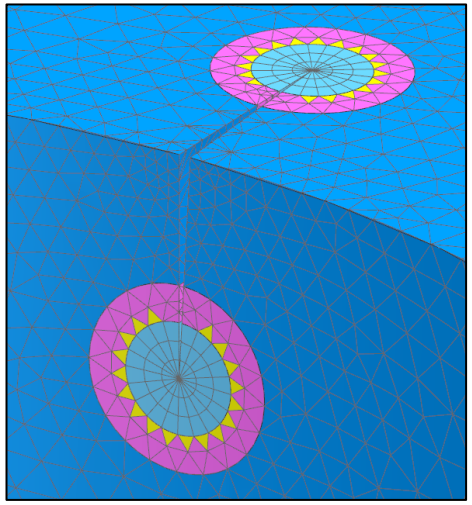


To Do

- DIM:
  - Convergence studies
  - Optimization of meshing techniques
  - Automate extraction
  - Incorporate displacement transformation from global CSYS to crack origin local CSYS
  - Plane-stress to plane-strain conversion

- CIM:
  - More convergence studies
  - Optimization of meshing techniques (better technique discovered during ESRI Round Robin)
  - Larger integration radius requires fewer crack front elements (due to math formulation…for now)

- Both:
  - Implement in NX Open?
  - Refine VBA



t_{total}=0.5*c
Buffer size = t_{total}/3

Conclusion

- CIM and DIM can be used to approximate SIFs using conventional FEA packages with no additional add-ons, special elements, or output requests
- Meshing methods are the **single most important factor** in the accuracy of extracting SIFs
- More example cases are needed to determine best practices and limitations
- Robust crack tube refinement desired, but FEA package developers are unlikely to offer (for now)
- Methods that interpolate between nodal values may offer a more elegant and accurate solution (recently implemented)
- STOKE provides an experimental environment to assess SIF extractions from any FEA solver

Questions?

Backup

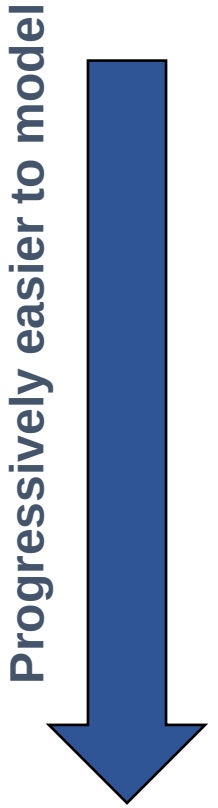
Notes on Models

Initial Models

- Both models are exceptionally large:
  - Model 1
    - 5 “rings” over Ø0.01”, 31 radial elements
    - DOFs: 601,932
    - Elements: 60,898
    - Solution file: 150MB
  - Model 2
    - 12 “rings” over Ø0.02475”, 77 radial elements
    - DOFs: 1,844,088
    - Elements: 159,817
    - Solution file: 435MB
- What is the best combination of number of layers, crack tube diameter, and element size?

Follow-on Models

- Model 3
  - 3 “rings” over Ø0.02475”, 31 radial elements
  - DOFs: 1,061,442
  - Elements: 117,351
  - Solution file: 273MB
- Model 4
  - 3 “rings” over Ø0.02475”, 12 radial elements
  - DOFs: 254,034
  - Elements: 26,618
  - Solution file: 64MB
- Model 5
  - 3 “rings” over Ø0.02475”, 20 radial elements
  - DOFs: 564,426
  - Elements: 61,511
  - Solution file: 88MB (only requested displacement and stress)

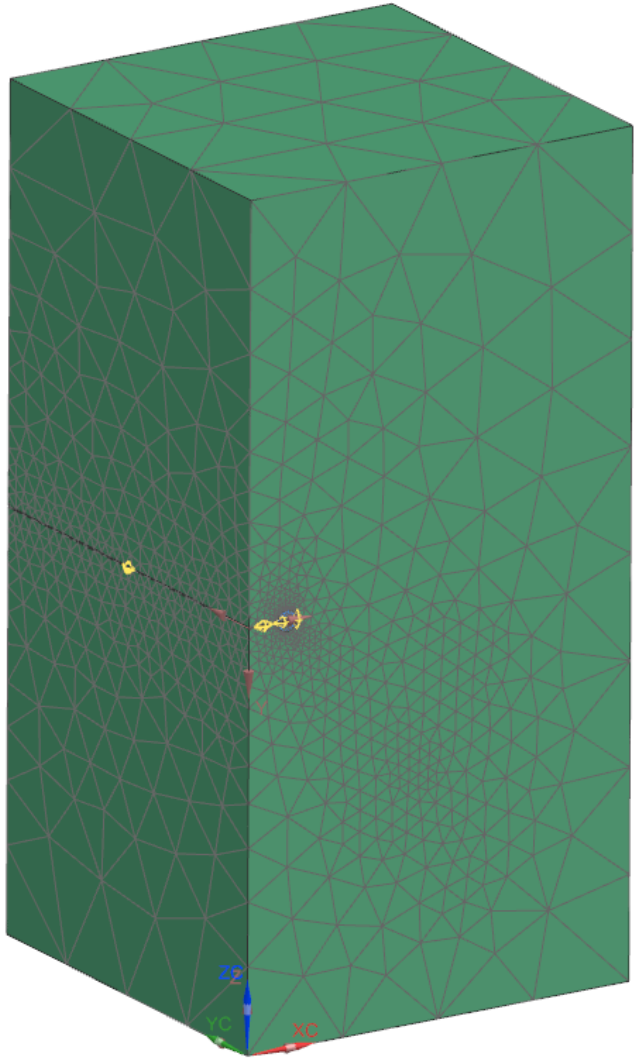


Notes on Models

Follow-on Models

- Model 6
  - 3 “rings” over Ø0.05”, 20 radial elements
  - DOFs: 337,104
  - Elements: 35,276
  - Solution file: 52MB (only requested displacement and stress)

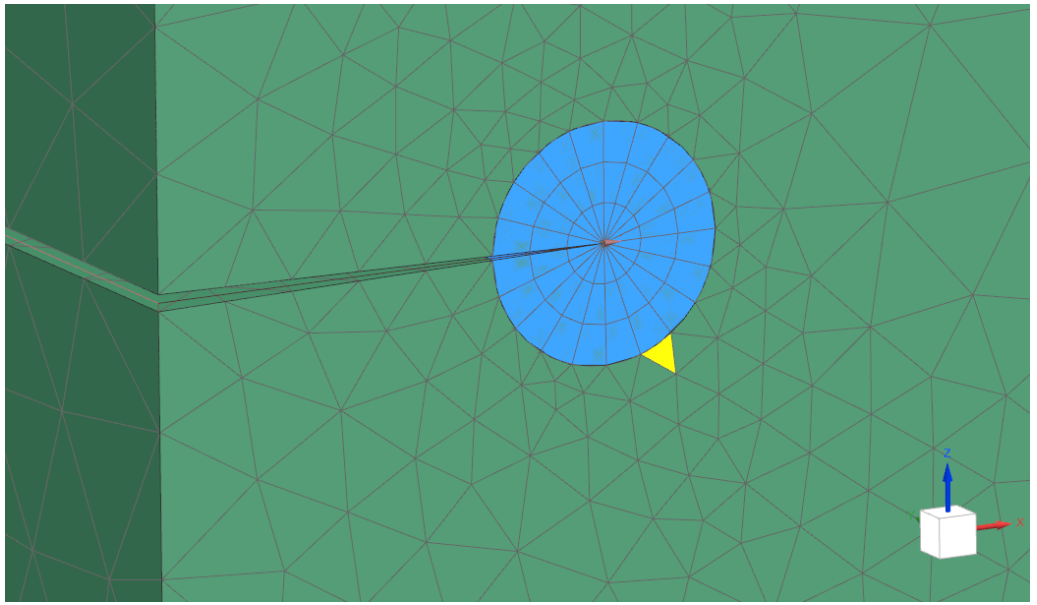
Benchmark Models

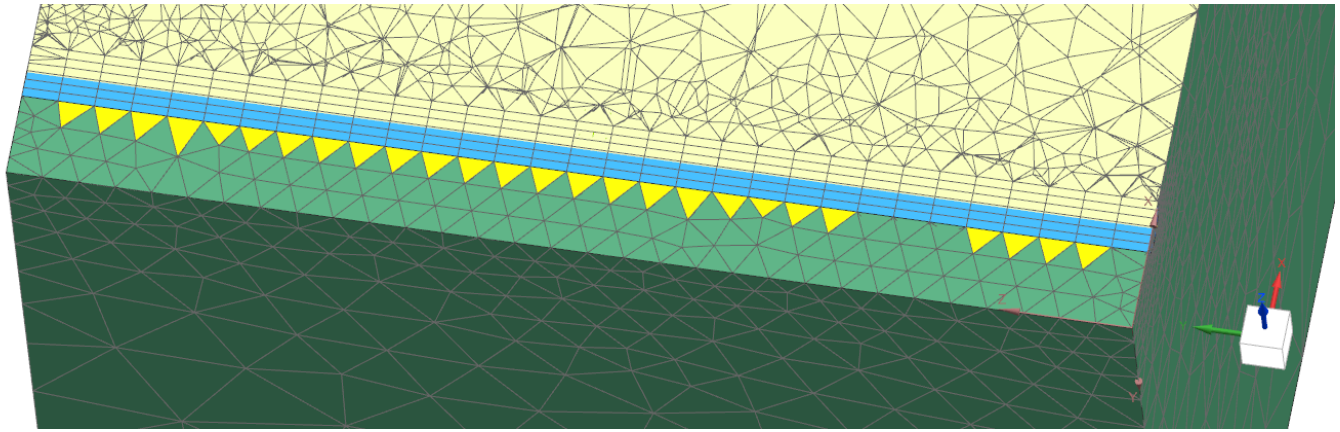


t_{total} = 0.5*c per previous slides (0.25”)

rad_c = 0.125”

31 elements along front





Benchmark Models