QUANTIFICATION OF THE IMPACT OF THE CRACK SHAPE CONSTRAINT ASSUMPTION ONTO PREDICTED REMAINING USEFUL LIFE

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Motivation

- **Industry is relying on two-degree of freedom K_I solutions (reduced order models - ROM, assuming an elliptical crack front shape) for damage tolerant life assessment.**

- **Robust meshing procedures for crack insertion and propagation are available for multi-degree of freedom solutions (the crack front ellipticity constraint is removed).**

- **Validation requirements are often challenging to achieve due to numerical and experiment uncertainties. An assumed crack front increment shape can be a contributing factor.**

- **Impact of an assumed crack front increment needs to be quantified by providing 3D FEA based remaining useful life (RUL) solutions using 1. elliptical crack front increments and, 2. no crack front shape constrains**

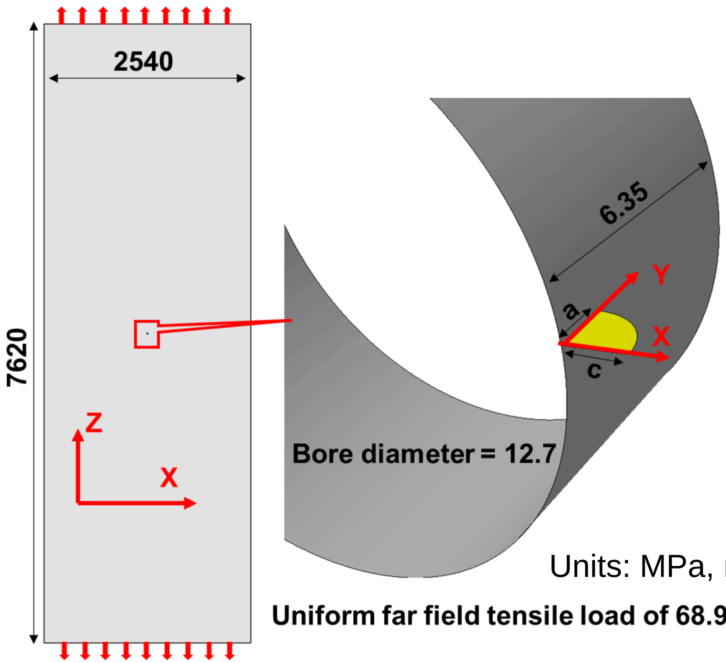
3D FEA modeling capabilities used in this study

- **Robust remeshing capabilities to show solution convergence**
  - ✓ Create crack front meshes of 100, 200, 300 … 8000 element edges along crack front
  - ✓ Perform crack propagation simulation using increments of different magnitudes and crack front mesh refinements
- **Full control of advancement process**
  - ✓ Multi-degree of freedom crack advancement (no crack front shape constraint)
  - ✓ Two-degree of freedom (enforce elliptical crack front increments)
- **CAD-Mesh continuous associativity**
  - ✓ Efficient model definition throughout the entire fatigue crack growth simulation
- **Compatible with commercial FEA packages**
  - ✓ Accurate, physics-based 3D FE models
- **Scripting availability**
  - ✓ Use tabular crack growth rate as an input
  - ✓ Efficiently use meshing API functionality with commercial FEA scripting
- **Automatic 3D fatigue crack growth**
- **SimModeler Crack is used to generate all 3D FEA solutions**

K_I solution accuracy

- In the ERSI Round Robin Challenge[1] seven generic corner crack at hole geometries were considered. Nine participants used different methods to compute K_I values.
- Accuracy of K_I calculation used in this study was demonstrated on the seven geometries in the Round Robin Challenge[1].
- Second case[1] is selected to demonstrate the K_I accuracy with a convergence study.

ERSI Round Robin Challenge – Case #2



Units: MPa, mm.

Uniform far field tensile load of 68.9 MPa

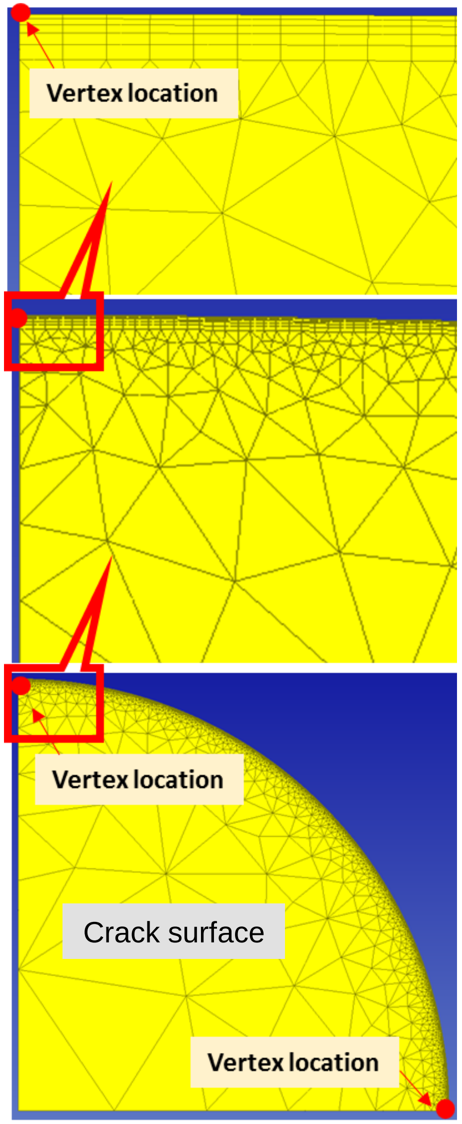
[1]Robert Pilarczyk, "Cross-Comparisons of Stress Intensity Factors from Various Sources. The Pathway to Improved SIF Solutions", AFGROW Workshop 2021, https://afgrow.net/workshop/documents/2021/Robert_Pilarczyk_Cross-Comparisons_of_Stress_Intensity_Factors_from_Various_Sources-Workshop-2021.pdf

Seven benchmark problems[1] are used to satisfy K_I verification requirements

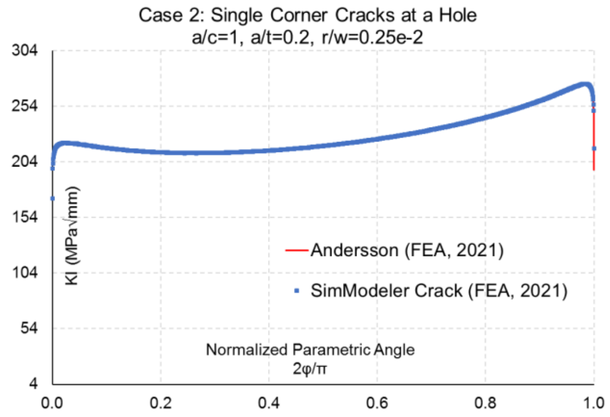
K_I solution accuracy – sensitivity study

- Seven uniform meshes are considered: 100, 200, 300, 1000, 2000, 3070, 8200 element edges along crack front.
- Metric for accuracy assessment: average of relative difference (absolute values) between K_I values at the same normalized parametric angle.
- All meshes provide very good K_I solutions when compared to the semi-analytic reference[1].

Mesh refinement: 2000 element edges along crack front



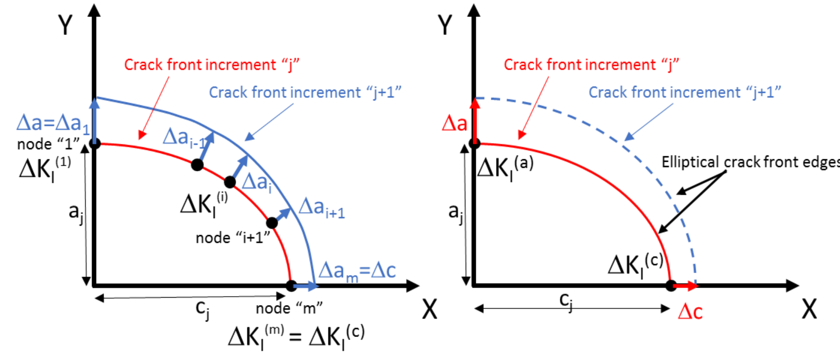
No. element edges along crack front	Average of relative differences (absolute values) using Andersson' semi-analytic solution as reference	
	0.01 < 2*phi/pi < 0.99	0.001 < 2*phi/pi < 0.999
100	0.42%	
200	0.15%	
300	0.23%	
1000	0.13%	0.13%
2000	0.14%	0.14%
3070	0.19%	0.19%
8200	0.18%	0.18%

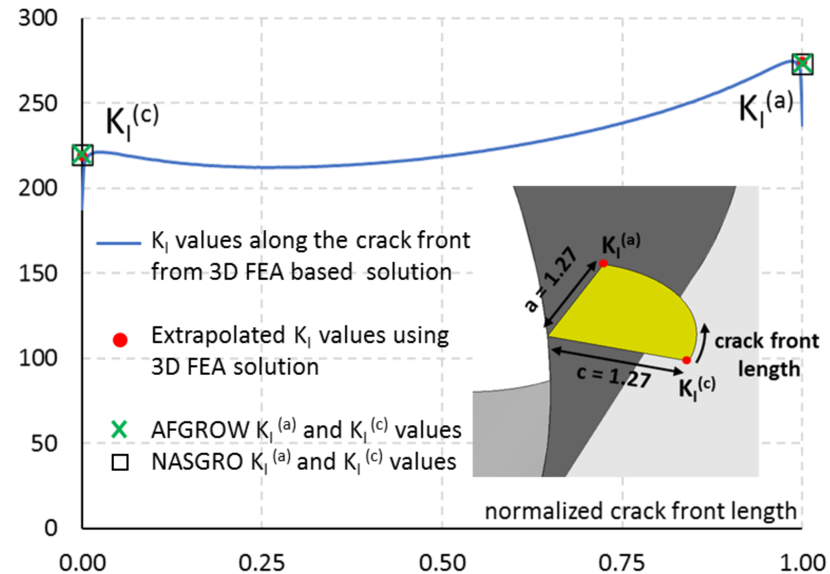


K_I verification requirements are reached

Fatigue crack growth: two degree vs. multi-degree of freedom modeling

- Modeling procedures used for damage tolerance assessments[2]:
  - A two degree of freedom solution uses two locations to track crack size under the assumption that each crack front increment has an elliptical shape
  - A multi-degree of freedom solution does not constrain crack front increments to any shape.
- Similar to a reduced order model, a two-degree of freedom procedure is implemented in a 3D FE modeling process:
  - Only the ΔK_I values at each crack front increment end are used in the procedure
- K_I verification[3] against third party solutions is satisfied.





[2]Branco, R., Antunes, F.V., Costa, J.D., 2015. "A review on 3D-FE adaptive remeshing techniques for crack growth modelling". Engineering Fracture Mechanics, Vol. 141, pp. 170-195

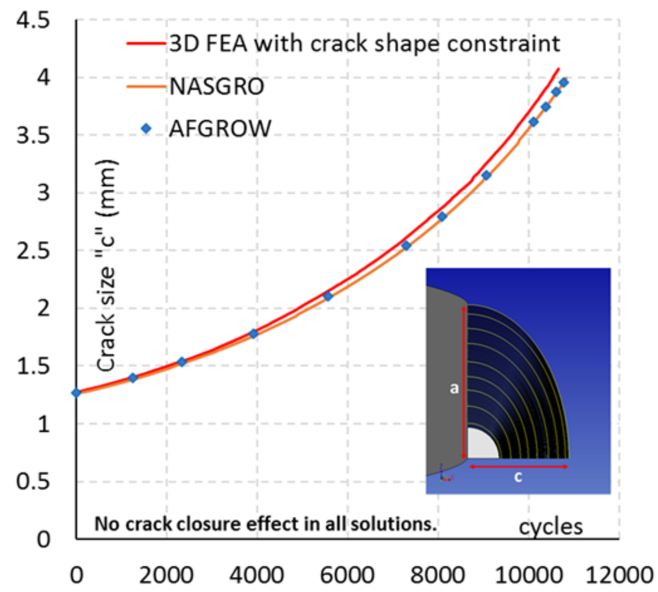
[3]Adrian Loghin, Comparison of fatigue crack growth life assessment predictions using different simulation tool, ERSI meeting, April 2021. NASGRO solution (CC16, betaR=off) provided by Shak Ismonov, Jacobs Tech. AFGROW (Advanced Model) solution provided by James Harter.

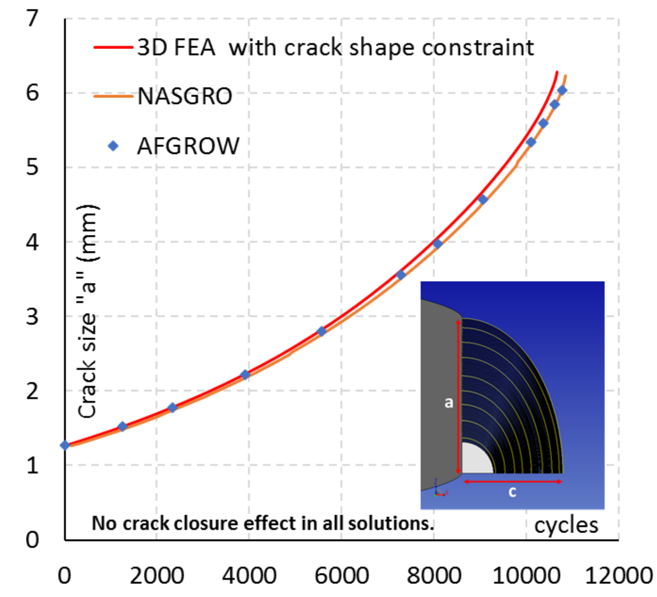
A multi-degree of freedom 3D FEA based modeling process was modified to a two-degree of freedom

Fatigue crack growth: two degree of freedom solutions

- Two reduced order modeling fatigue crack growth life assessment solutions (AFGROW, NASGRO) are used as references for verification purposes.
- The 3D FEA based two-degree of freedom solution is within 2.8% from the reduced order modeling solution.
- This solution comparison serves as a verification for the two-degree of freedom 3D FEA modeling procedure

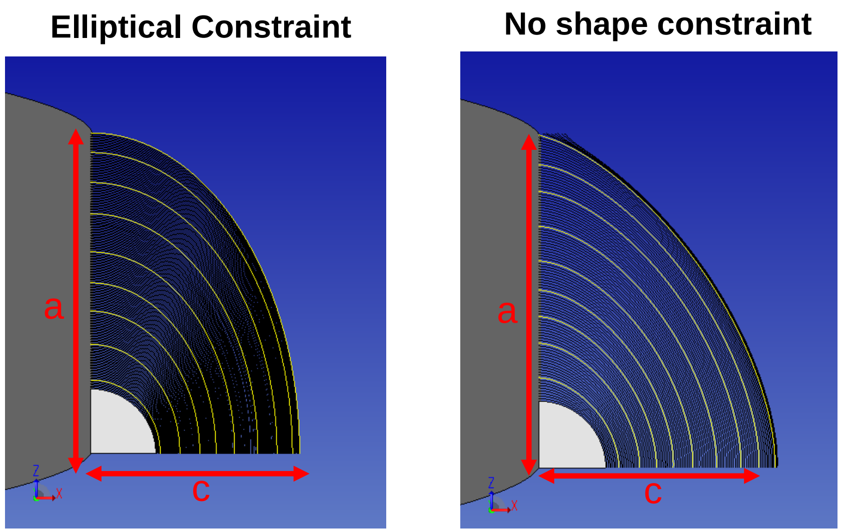
Remaining useful life (RUL) verification requirements are satisfied

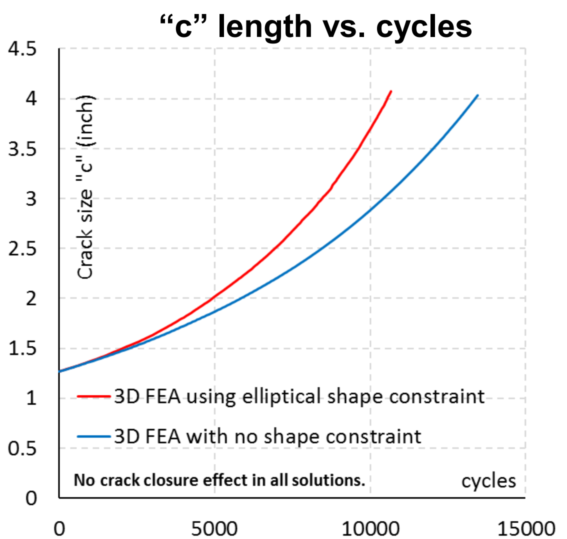


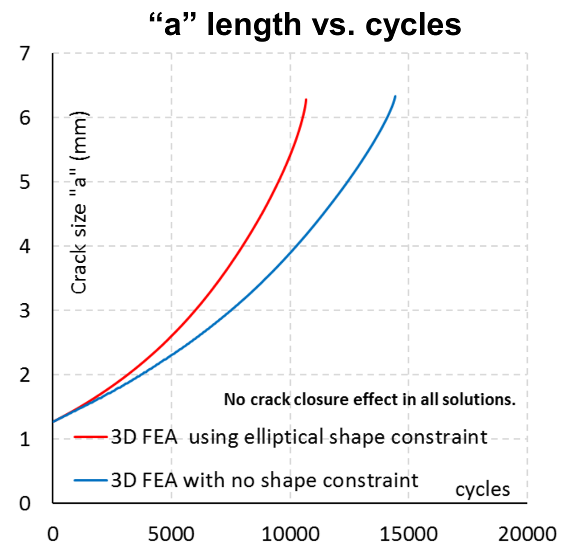


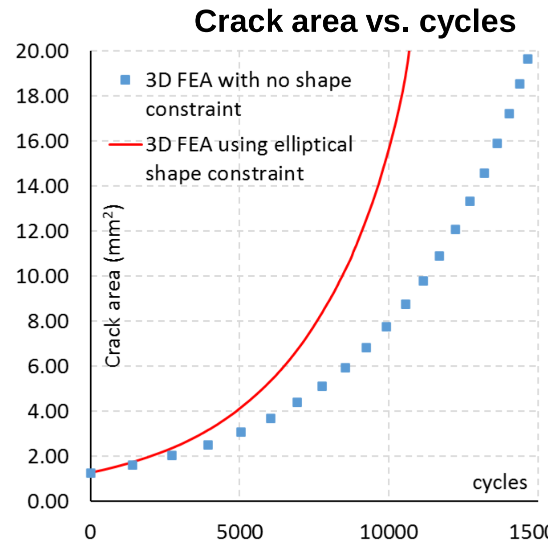
Fatigue crack growth: two degree vs. multi-degree of freedom modeling

- A comparison between the two modeling procedures (elliptical vs. non-constrained crack front shape) can be achieved.
  - Same mesh density for each increment
  - Same FE model (geometry, boundary conditions)
  - Same method to compute K_I values







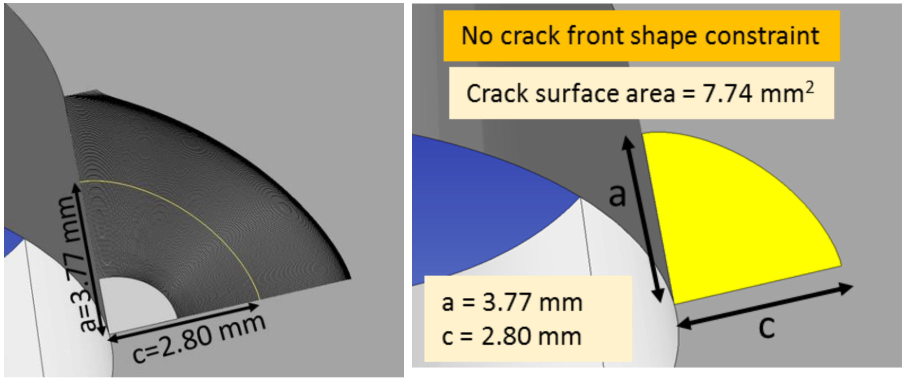


For this generic case, a 36% RUL difference is recorded

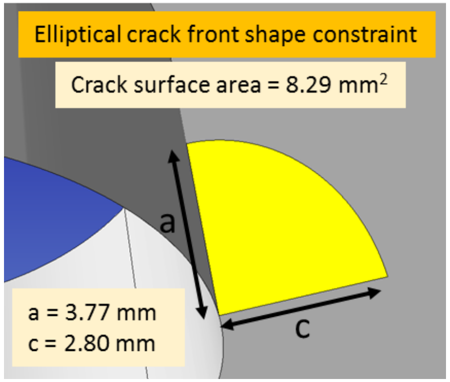
Fatigue crack growth: two degree vs. multi-degree of freedom modeling

- A comparison between the two modeling processes is conducted for a crack defined by two parameters: {a, c}:
  - One of the crack fronts generated by the modeling procedure where no shape is enforced
  - An elliptical crack front definition
- The crack surface area is larger for the elliptical crack definition.
- The K_I values used in the two degree of freedom model are larger than the correspondent values generated in the modeling procedure where no shape constraint is used. This leads to a lower remaining useful life recorded in the two-degree of freedom modeling procedure.

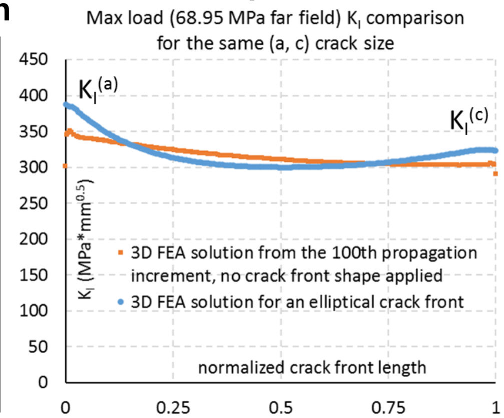
Selected crack front increment



Elliptical crack representation



K_I comparison between the two procedures

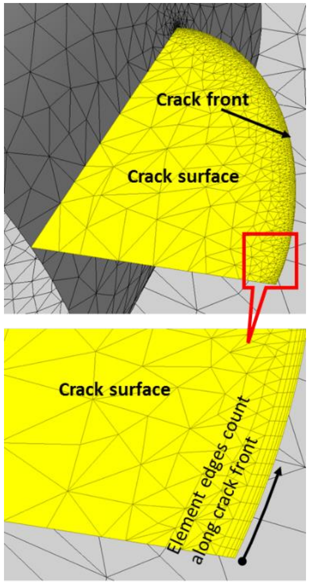


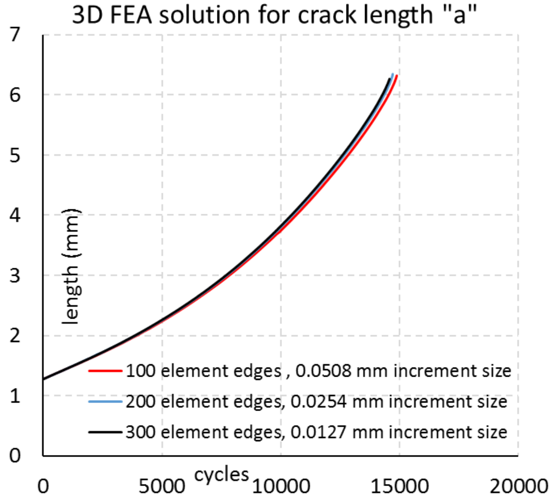
For the same {a, c} dimensions, the two-degree of freedom procedure uses a larger crack size representation

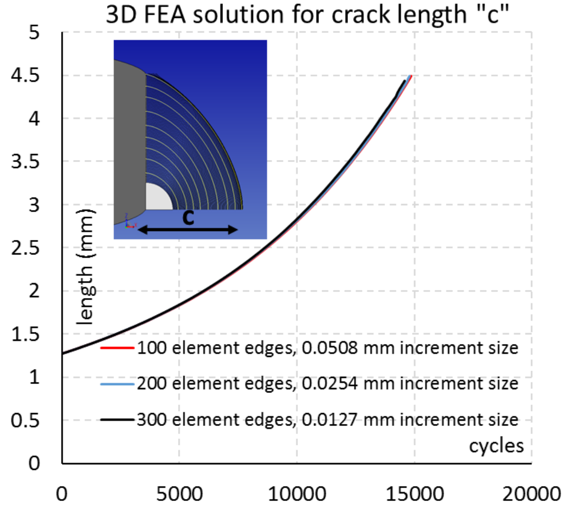
Multi-degree of freedom solution convergence

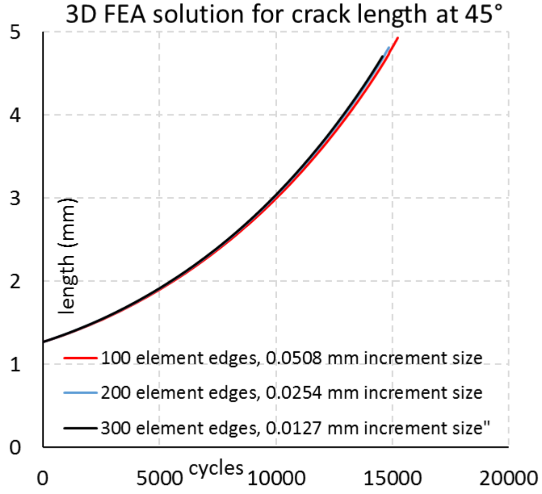
- For the multi-degree of freedom procedure, a convergence study is performed to demonstrate that the mesh density and the increment size does not introduce additional numerical uncertainty.

- Three solutions using {100, 200, 300} element edges along the crack front that correspond to {0.0508, 0.0254, 0.0127} mm max. increment size are provided.





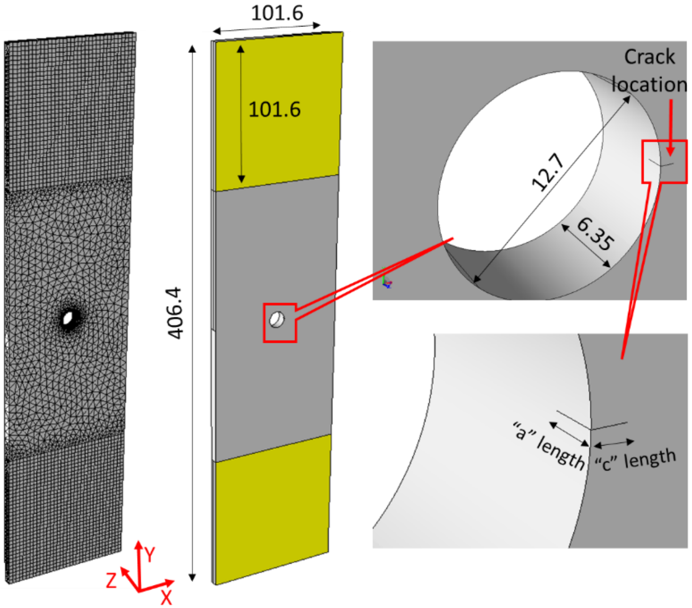




Solution convergence is demonstrated

Modeling validation: two vs. multi-degree of freedom solutions

- A second ERSI Round Robin Challenge[4] is used as a reference for modeling validation purposes.
  - Specimen: flat panel (material: Al. alloy 7075-T651) containing a hole
  - Corner crack is initiated at the bore
- Three fatigue crack growth experimental measurements are used as a reference for 3D FEA based solutions.
  - Entire specimen geometry captured in the FE representation
  - Same loading mission (cycle block, max. and min. load) as in the experimental procedure
  - Tabular fatigue crack growth rate used in the numerical procedure instead of the Paris' relationship



da/dN (mm/cycle)	ΔK (MPa*mm$^{0.5}$)
1.14E-05	147.19
5.59E-05	218.26
2.29E-04	352.63
4.32E-04	448.26
6.10E-04	521.23
8.26E-04	625.47
1.08E-03	712.34
1.52E-03	816.59
2.54E-03	924.31
5.08E-03	1025.08
1.02E-02	1138.01
2.54E-02	1303.07
5.08E-02	1398.63
2.54E-01	1563.68
5.08E-01	1615.81

Units: MPa, mm.

Specimen ID	initial "c" length (mm)	initial "a" length (mm)
PC-CX-7075-1	0.81	1.20
PC-CX-7075-2	0.78	0.97
PC-CX-7075-3	0.90	1.32

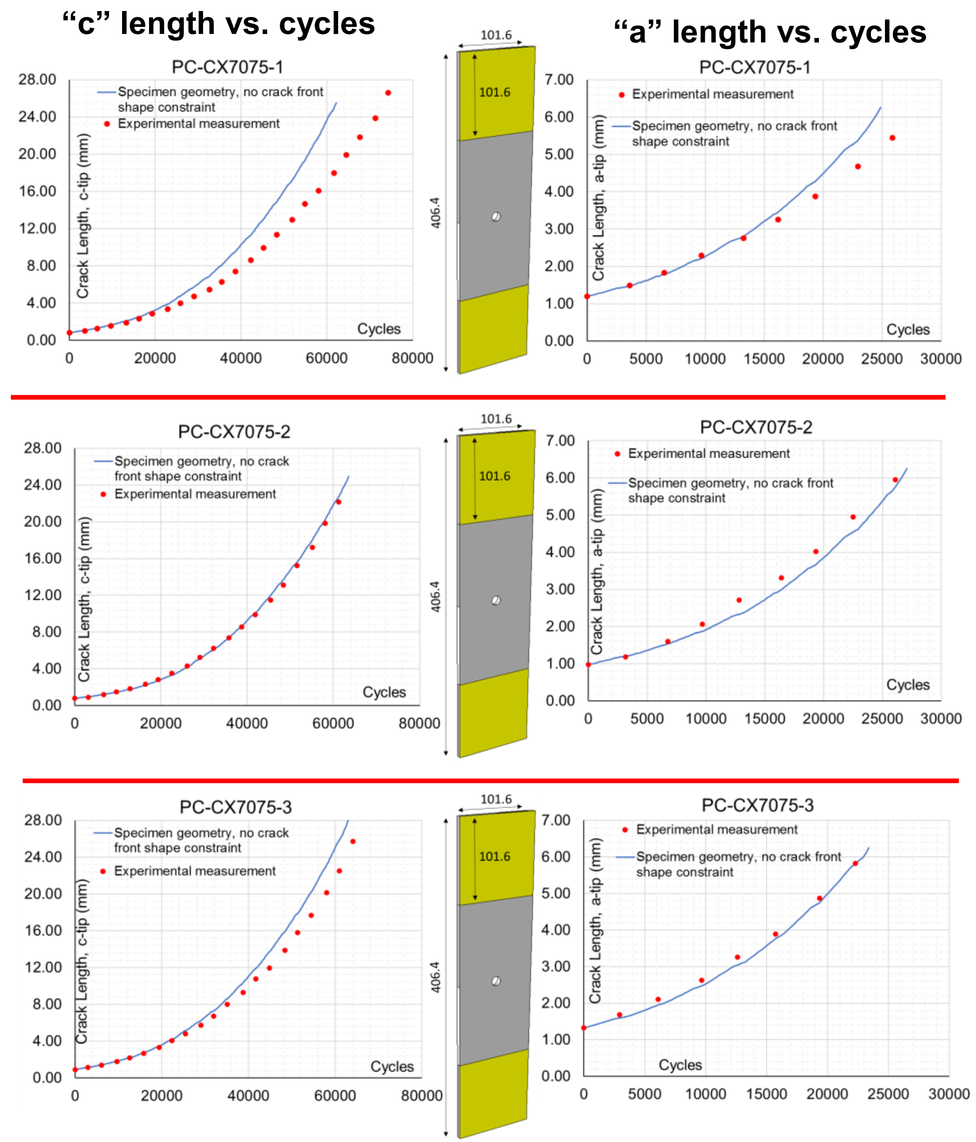
Max Load (MPa)	Min Load (MPa)	Cycles	
82.74	8.27	2500	
66.19	6.62	100	9 times
66.19	6.62	10	
66.19	6.62	100	
82.74	8.27	2500	
66.19	6.62	100	3 times
66.19	6.62	10	
66.19	6.62	100	
82.74	8.27	2500	
66.19	6.62	100	5 times
66.19	6.62	10	
66.19	6.62	100	

The 3D FEA multi-degree of freedom captures experimental conditions for all three specimens

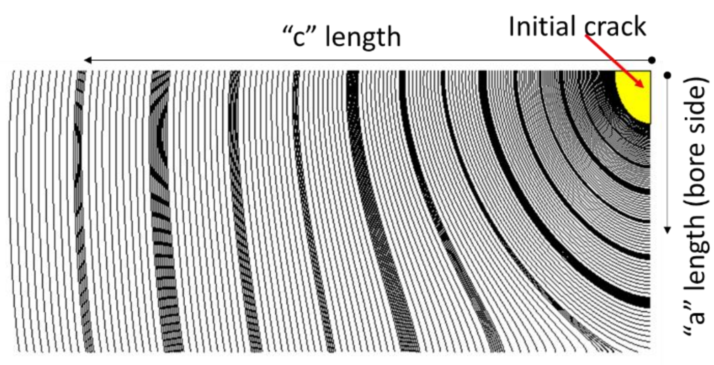
[4]Fawaz, S.A and Mills, T., 2017. "Round-Robin Testing, Fractography and Crack Growth Rate Data". AFGROW Workshop. https://afgrow.net/workshop/workshop2017.aspx…

Modeling validation: multi-degree of freedom solutions

- Very good agreement is obtained between the 3D FEA based solution (no crack front shape constraint) and experimental measurements.
  - Numerical solutions along the bore (“a” length) are 0% (PC-CX7075-3), 2% (PC-CX7075-2) and 11% (PC-CX7075-1)
  - Numerical solutions along the side of the sample are 15% for PC-CX7075-1, 1% for PC-CX7075-2 and 5% for PC-CX7075-3
  - No crack closure effects are considered



Numerical solution: crack front increments



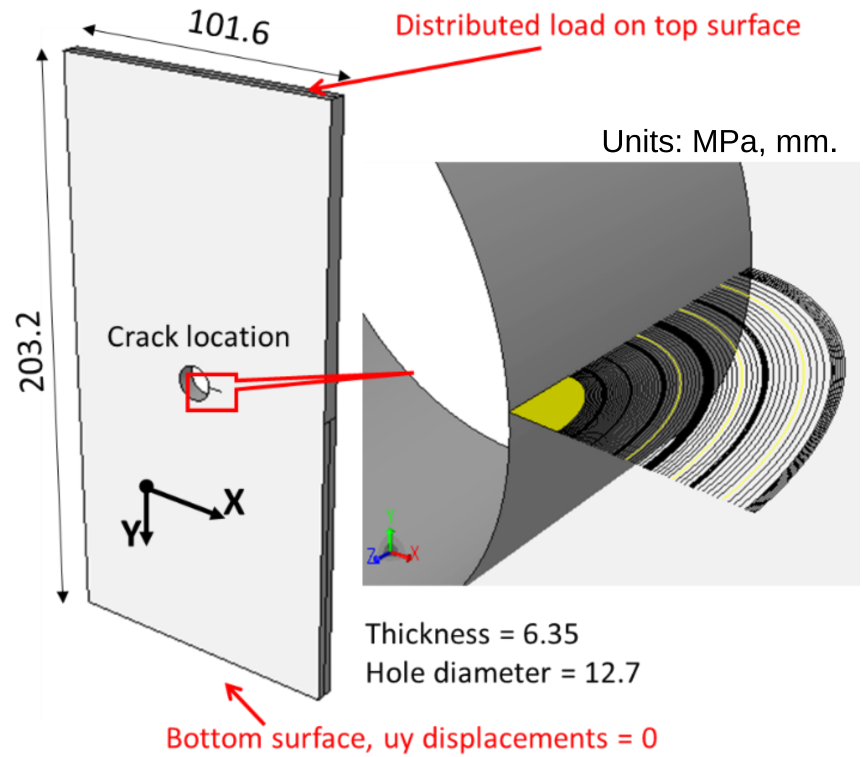
Validation requirements are achieved

Modeling validation: multi-degree of freedom solutions

- Gauge section geometry under uniform tensile loading could be considered as a representative model.

- For two-degree reduced order models, gauge section representation of the specimen is a typical modeling choice since a predefined model is available.

- A similar multi-degree of freedom solution can be pursued to:
  - Compare the simplified model (gauge only) results with the entire specimen representation
  - Provide a better reference for the two- vs. multi-degree of freedom comparison



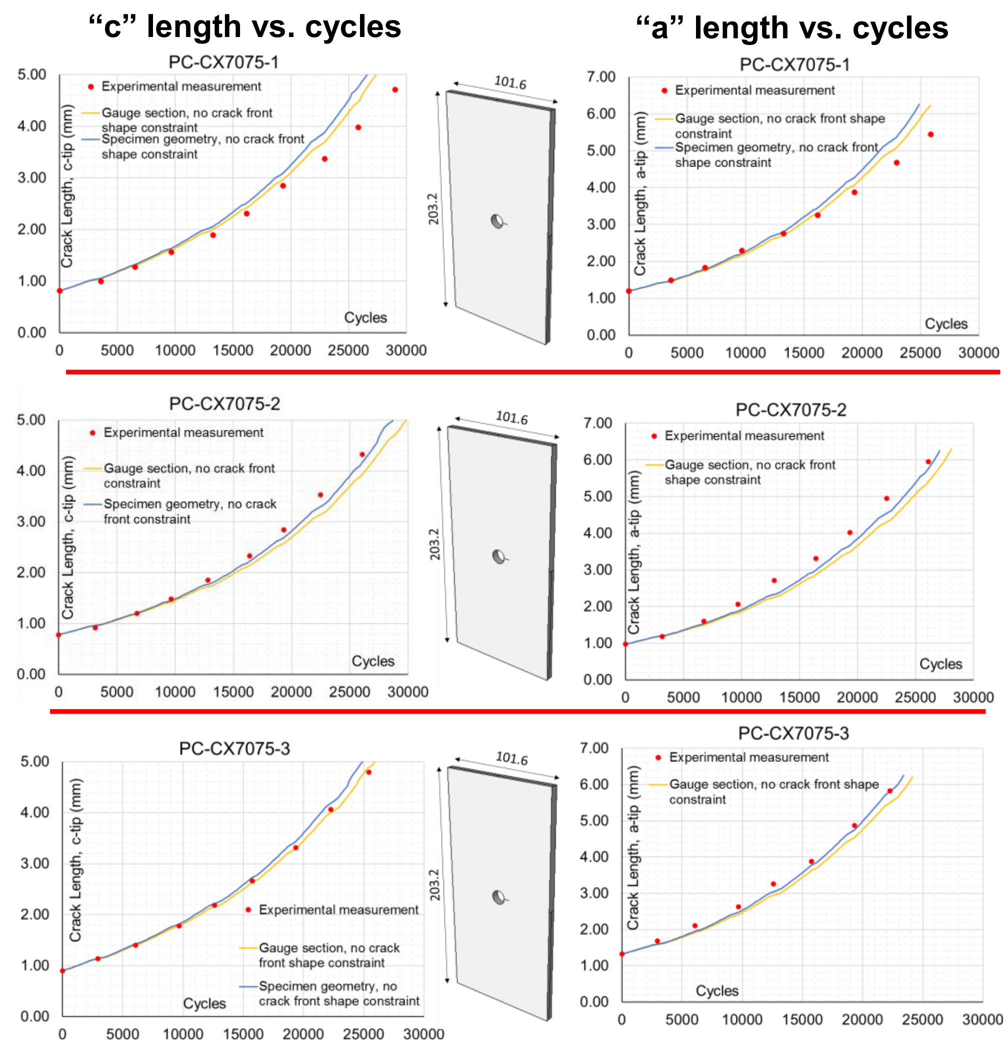
A multi-degree of freedom solution is pursued for a simplified FE model

Modeling validation: multi-degree of freedom solutions

- The multi-degree solutions from the simplified model and the entire specimen representation capture accurately the measurement data.

- Low difference (within 3%) between the two numerical solutions indicate that the simplified model is a valid representation of the entire specimen (geometry, loading mission).

- In general, simplification of geometry and loading conditions could be a source of numerical uncertainty.



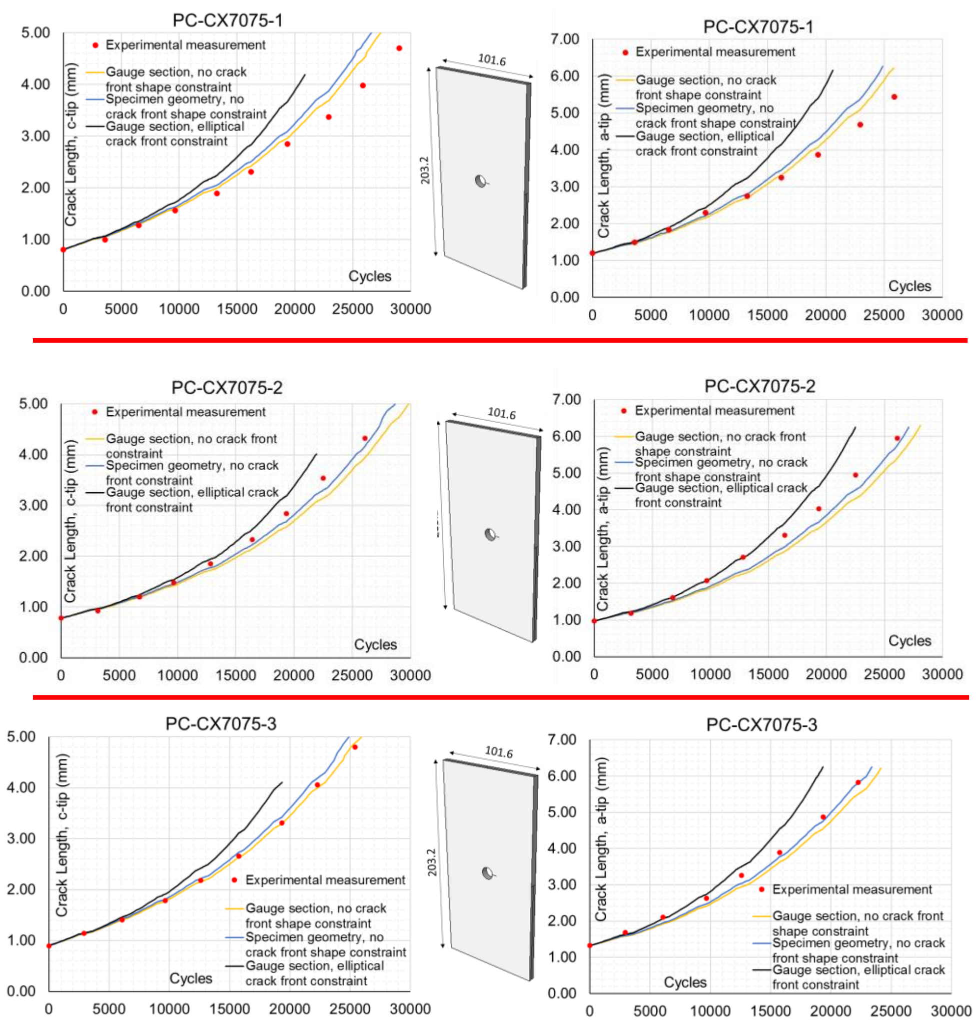
Gauge only (simplified) model provides a solution within 3% to the entire specimen representation

Modeling validation: two- vs. multi-degree of freedom solutions

- Using the simplified model, a two-degree vs. a multi-degree comparison can be achieved

- When compared to the experimental measurements, the multi-degree of freedom procedure provides a more accurate solution than the two-degree of freedom.
  - For the largest "a" measured length, the error of the two degree of freedom solutions relative to the experimental data ranges between 16% and 25%
  - The error of the specimen level multi-degree of freedom solutions relative to the experimental data are 0% (PC-CX7075-3), 2% (PC-CX7075-2) and 11% (PC-CX7075-1)

"c" length vs. cycles **"a" length vs. cycles**



Better performance shown by the multi-degree of freedom modeling procedure

Conclusions

- 3D FEA was used to develop a two-degree of freedom fatigue crack growth modeling procedure that resembles the correspondent procedure based on reduced order models. Two-degree of freedom solution verification was achieved.

- A two-degree of freedom fatigue crack growth model that assumes an elliptical crack front shape introduces numerical uncertainty. For a generic corner crack at a hole geometry under uniform far field tensile loading, a 36% difference is recorded between a two-degree of freedom solution and an unconstrained crack front shape (multi-degree of freedom).

- When the two 3D FEA solution types (elliptical crack vs. no shape constraint) are compared to experimental measurements for validation purposes, the multi-degree of freedom solution has a better performance as expected.

Questions?

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