AFGROW .NET

AFGROW Workshop 2023

Developing Plugin Models for Off-Axis Loaded Lug Geometry

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Motivation

- Continuous need to extend AFGROW's model database
- Continuous need to provide more accurate models to AFGROW's users
- Provide modeling capabilities that complement customer's design and analysis flow
- Shorten new model implementation time or allow users to define their own reduced order model

Current AFGROW K_I Solutions

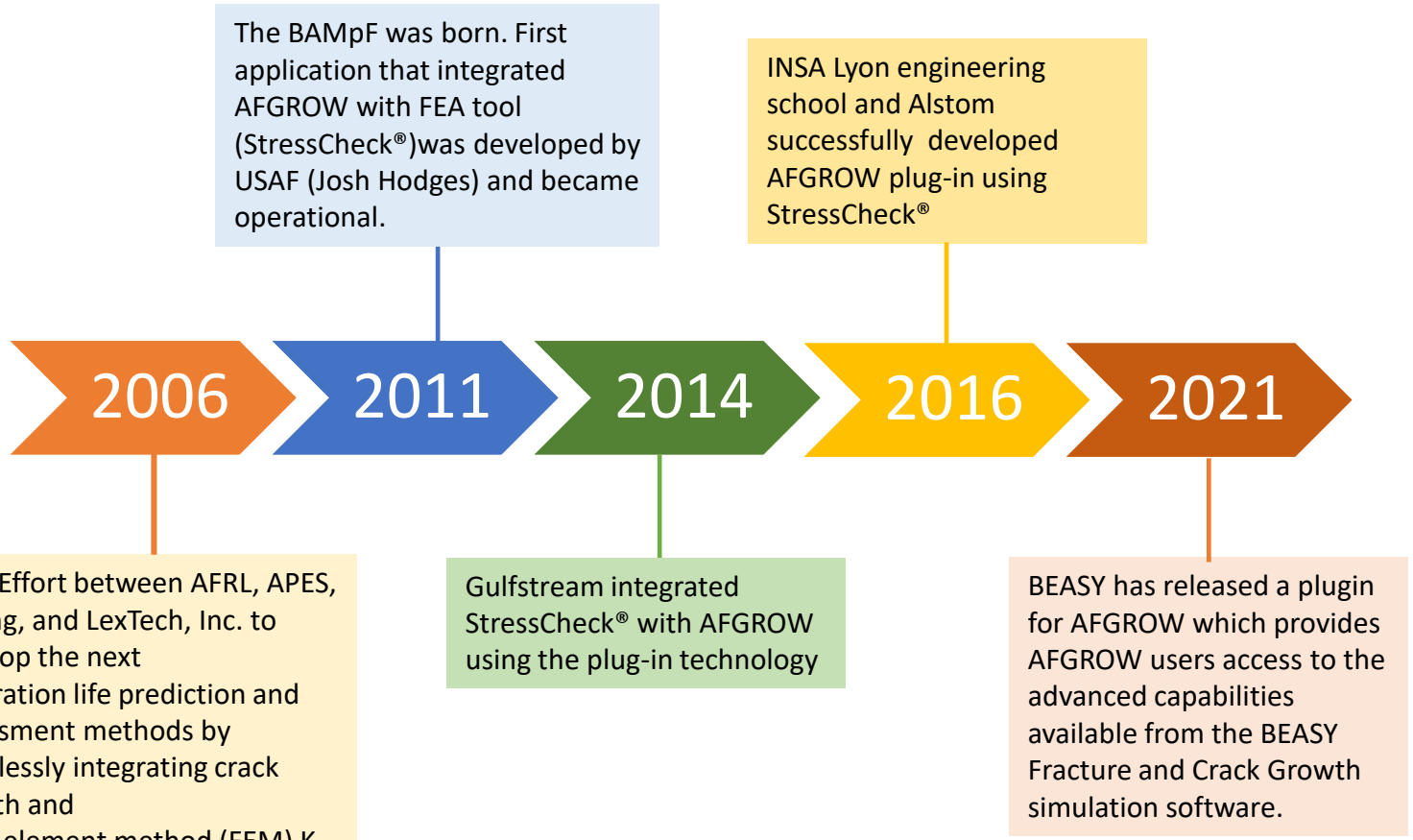
- **Closed-form, tabular or combination of both solution:** Uniform stress distribution, idealized model geometry, covers wide rage of geometry variations (r/t for example).
- **Weight function solution or beta correction applied on existing closed-form or tabular solution:** Non-uniform stress distribution, idealized model geometry, covers wide rage of geometry variations.
- **User-defined solution:** Non-uniform stress distribution, real model geometry, limited to only one set geometric properties and one or two interconnected crack grows direction.
- **Using on demand FEA tool to calculate K_I:** Non-uniform stress distribution, real model geometry, multiple crack and crack directions

AFGROW has the capability to add additional K solutions by using the COM plug-in.

Plug-ins allow user-defined custom solutions

- Proprietary
- Closed-Form
- Tabular / Interpolative / Extrapolative
- External-K_I

AFGROW FEA plug-in capability overview



2006 — Joint Effort between AFRL, APES, Boeing, and LexTech, Inc. to develop the next generation life prediction and assessment methods by seamlessly integrating crack growth and finite element method (FEM) K-solver programs.

Used the framework of AFGROW and StressCheck®

2011 — The BAMpF was born. First application that integrated AFGROW with FEA tool (StressCheck®)was developed by USAF (Josh Hodges) and became operational.

2014 — Gulfstream integrated StressCheck® with AFGROW using the plug-in technology

2016 — INSA Lyon engineering school and Alstom successfully developed AFGROW plug-in using StressCheck®

2021 — BEASY has released a plugin for AFGROW which provides AFGROW users access to the advanced capabilities available from the BEASY Fracture and Crack Growth simulation software.

- AFGROW FEA based K solver plug-in capability is a mature and proven technology that was successfully applied to solve the complex fracture mechanics problems
- Only organizations that can have access the modern FEA packages can benefit from this AFGROW functionality
- The development of the interface between plugin and FEA package require significant investment of time and manpower as well as FEA analyst expertise
- The original goal of developing Handbook of FEA crack growth solutions in AFGROW in unfulfilled

Handbook of FEA Crack Growth Solutions in AFGROW

Joint effort of Simmetrix and LexTech with an objective to develop a Handbook of FEA models for a relatively simple structural geometries and load conditions that are to complex or too time consuming to implement otherwise.

Goals

- Integrate AFGROW with the help of plug-in with SimModeler™ software tool.
- Demonstrate that it is possible to create a crack growth analysis tool that will benefit from using on demand FE analysis without require the user to be an FEA expert
- Ensure that this tool could be accessible (affordable) to a wide range of AFGROW users

SimModeler™ is a pre-processing tool that streamlines the generation of analysis input decks for a variety of analysis packages starting from geometric data. It can be easily customized and extended to produce run-ready input for additional solvers.

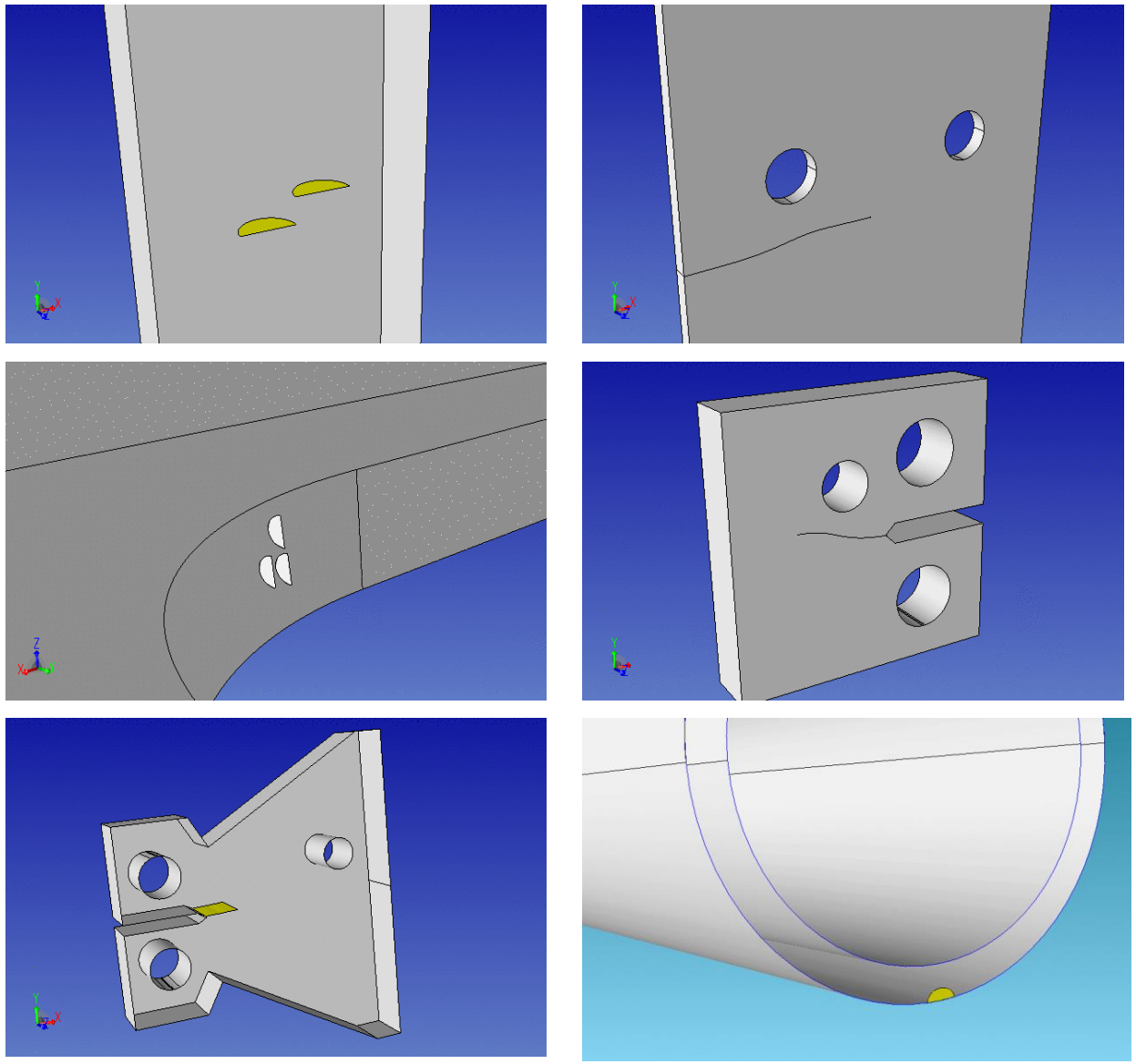
AFGROW will direct SimModeler™ via plug-in to generate the mesh of the model geometry and re-mesh the model as crack grows. The input from it can be used as an input to multiple FEA solvers such as ANSYS, Abaqus and CalculiX.

SimModeler Crack

AFGROW.NET

Capabilities:

- ✓ uses CAD geometry or existing meshes in the modeling process
- ✓ mature development for crack insertion and meshing
- ✓ automatic crack propagation simulation process
- ✓ tested on large variety of component geometries and crack configurations (includes propagation)
- ✓ GUI access and script-based modeling process
- ✓ Passed many V&V benchmarks for planar as well as mixed-mode cases



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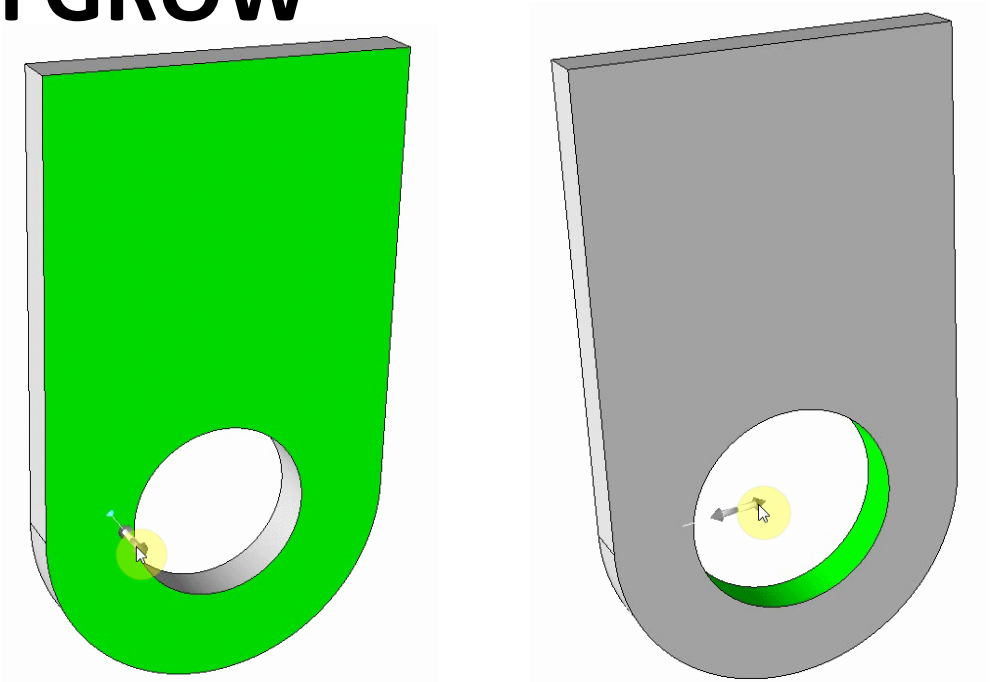
Meet the needs: SimModeler functionality embedded into AFGROW

SimModeler capabilities provide:

- ✓ Access to parametric geometry definition
- ✓ Access to crack modeling API functionality
- ✓ Access to different solvers to support any loading and boundary condition configuration



AFGROW Plugin will deliver:

- ✓ A process to add new fatigue crack growth models into the AFGROW solution library and, improve or extend limits of existing models
- ✓ The new models will work in a similar fashion as the closed-form models. Based on user's input (dimensions, loading conditions) the functionality will create the model and perform the simulation with no additional input from the user.
- ✓ Verification benchmarking is an integral part of the new model development

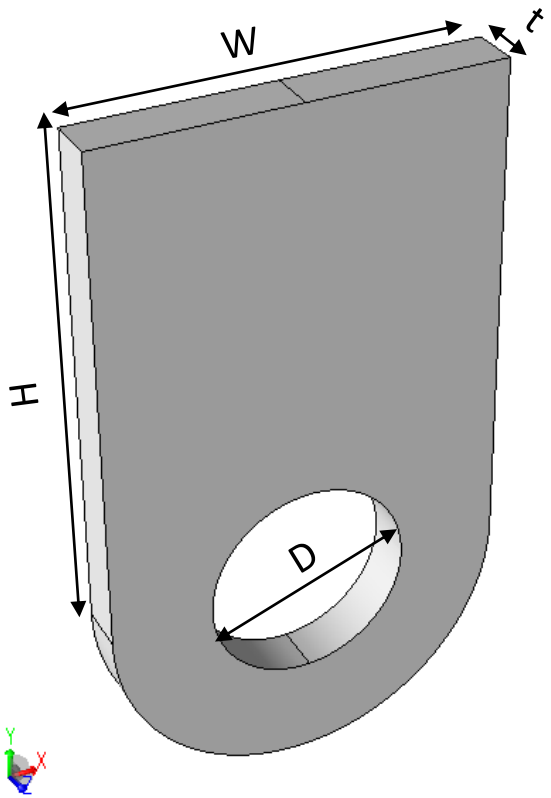
Overview

1. New AFGROW model development: corner crack in a lug geometry under off-center axis loading
2. Case studies:
   - $\theta = 0^{o}$ (loading direction along the lug centerline)
   - $\theta = 30^{o}$
   - $\theta = 45^{o}$
   - $\theta = 90^{o}$
3. Solution verification benchmarking
4. New AFGROW model definition and availability

Problem Definition

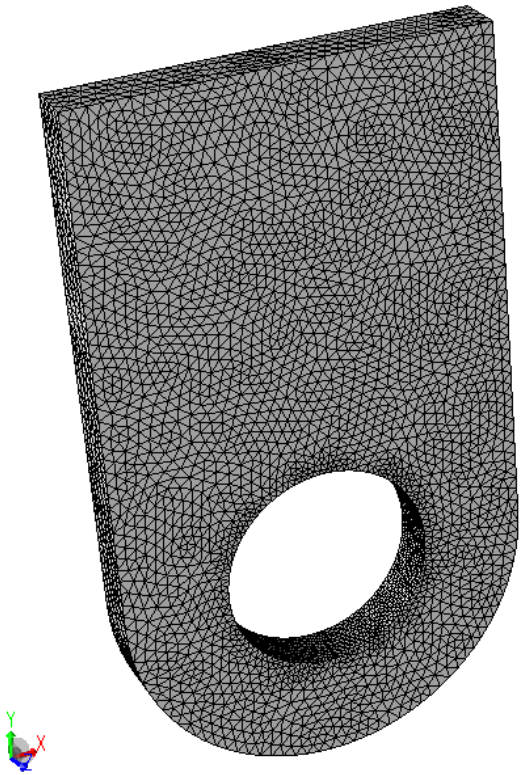
- **AFGROW model development: corner crack in a lug geometry under off-center axis loading**

Lug Geometry



- Four parameter lug geometry: {H, W, D, t}
- Parametric geometry definition

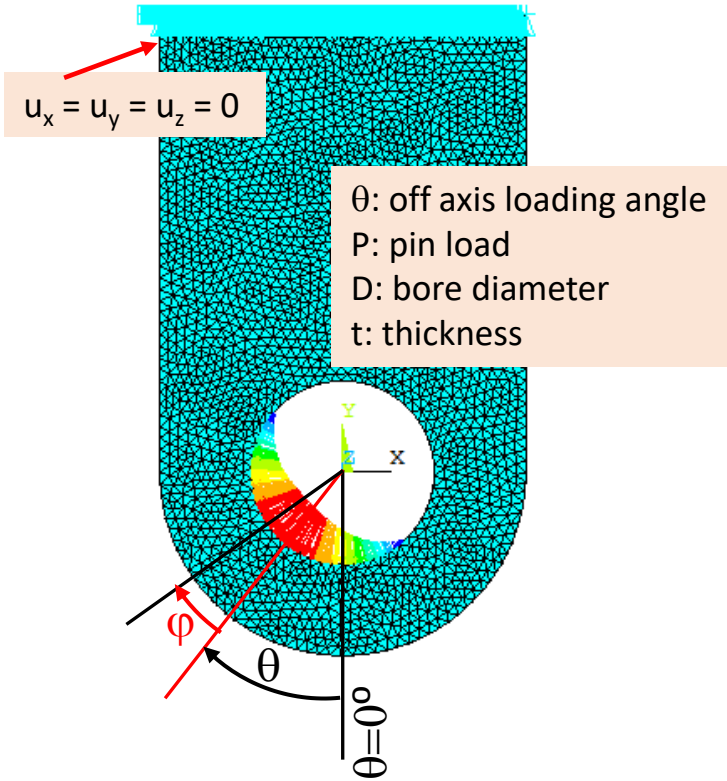
Mesh



- User control mesh refinement
- Geometry based meshing size assignment

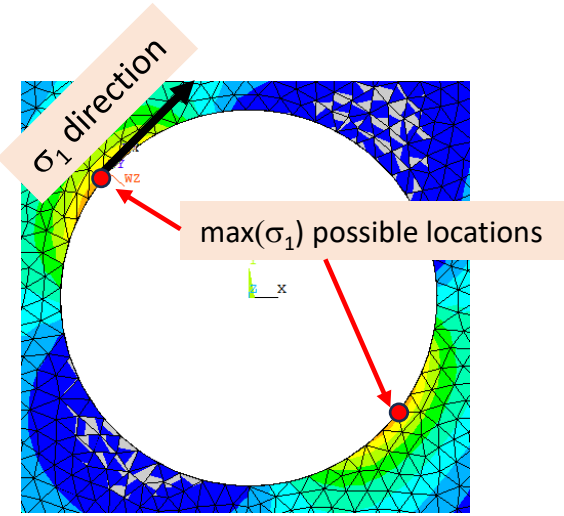
Loading

$$presure(\varphi) = \cos(\varphi) * \frac{4P}{D * \pi * t}$$



- Pressure loading defined using a cosine function, $\varphi = [-\pi/2, \pi/2]$
- Parametric loading definition: {P, θ}

Corner crack location and orientation

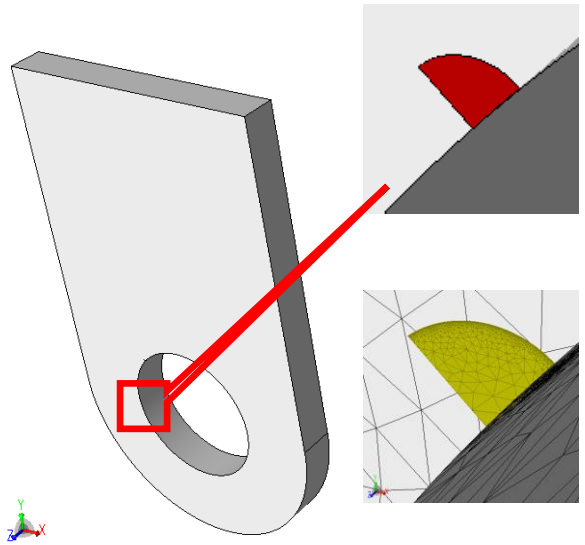


- Location and orientation of the crack is identified using max(σ_1) along the bore

Problem Definition

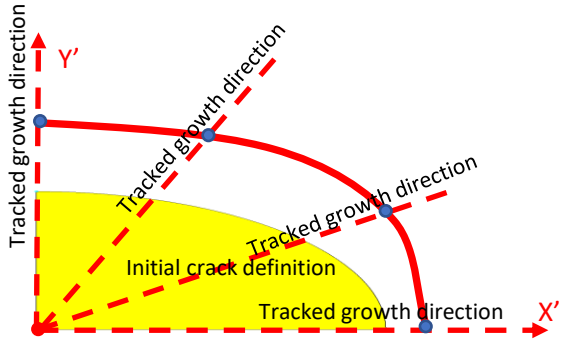
- **AFGROW model development: corner crack in a lug geometry under off-center axis loading**

Initial crack front definition



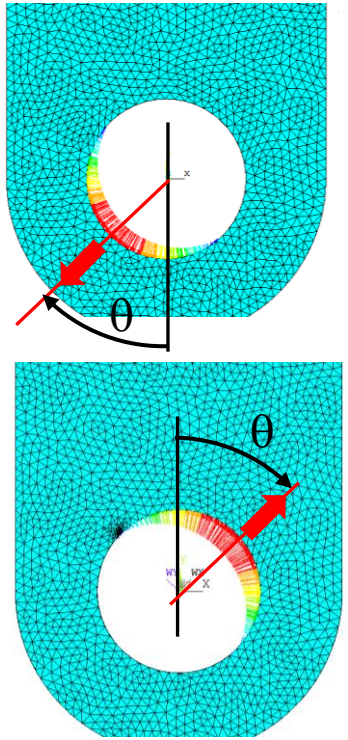
- Elliptical or B-spline shape used for the initial crack front definition
- Geometry-mesh association for each model
- Mesh size along the front and on the crack surface is adjustable

Crack front increments



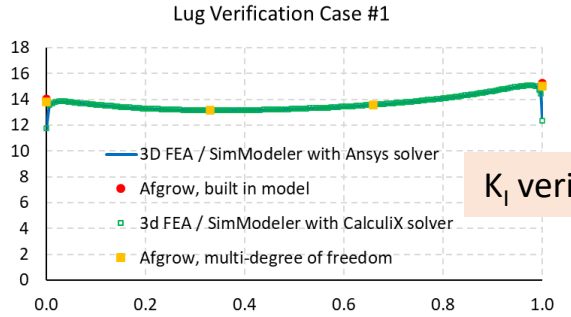
- Predefined-degree of freedom crack growth solution

Loading cycle

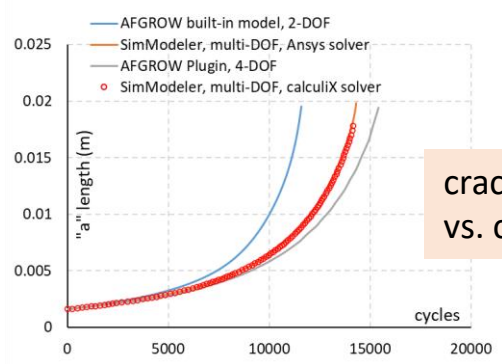


- Alternating loading mission

Typical solution and Verification Benchmarking



K_I verification



crack length vs. cycles

- Solution comparison between the predefined-degree of freedom modeling procedure performed via AFGROW and an FEA multi-degree (controlled by the mesh density along the crack front)

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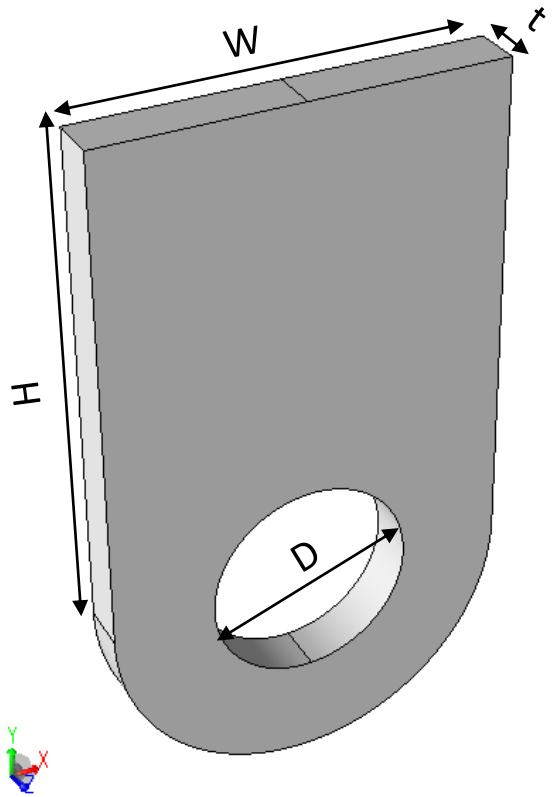
3D FEA solution

Case study: Loading Axis at θ = 0°

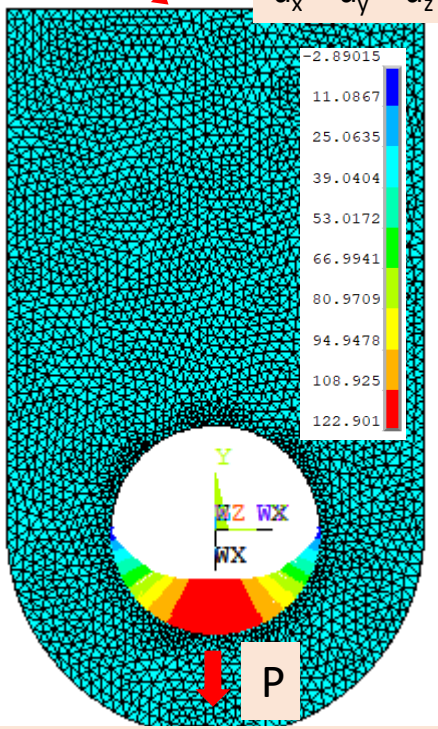
AFGROW.NET

Lug Geometry



W = 160 mm
t = 20 mm
D = 80 mm
H = 200 mm

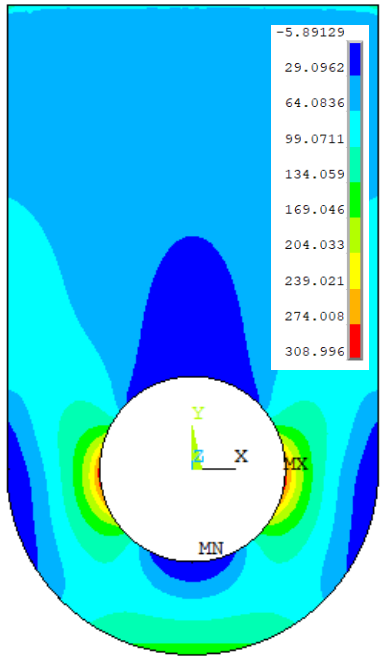
FE Model



$$presure(\varphi) = \cos(\varphi) * \frac{4P}{D * \pi * t}$$

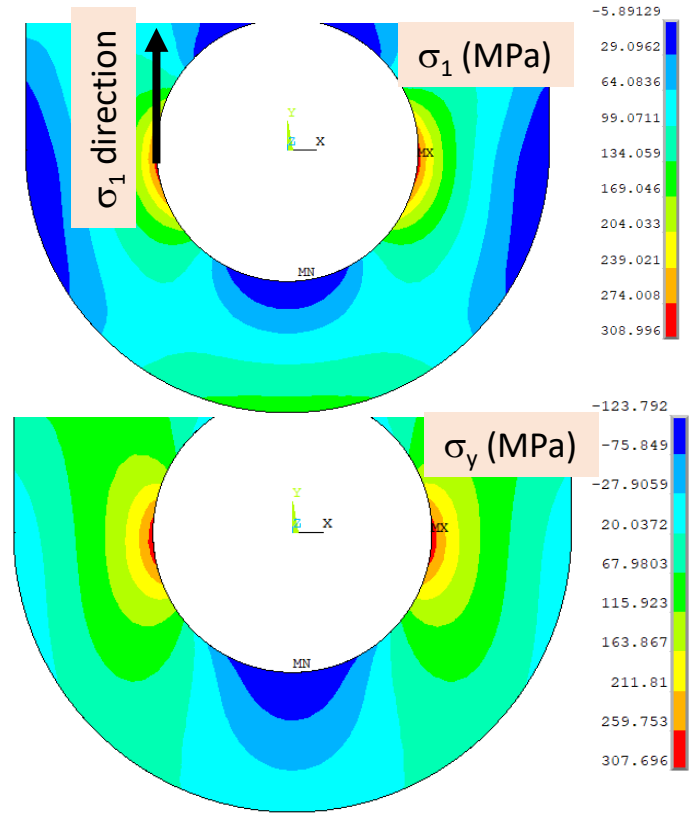
Pin equivalent load = 96.5266 MPa
P [N] = Pin equivalent load * W*t
Young's Modulus =72395 MPa
Poisson's Ratio =0.33

FE Solution



Model symmetry.
max(σ_1)=309 MPa on both sides of the bore

Corner crack location and orientation



σ_1 along loading direction, σ_1 normal to the bore radial direction
One or two cracks could be considered.

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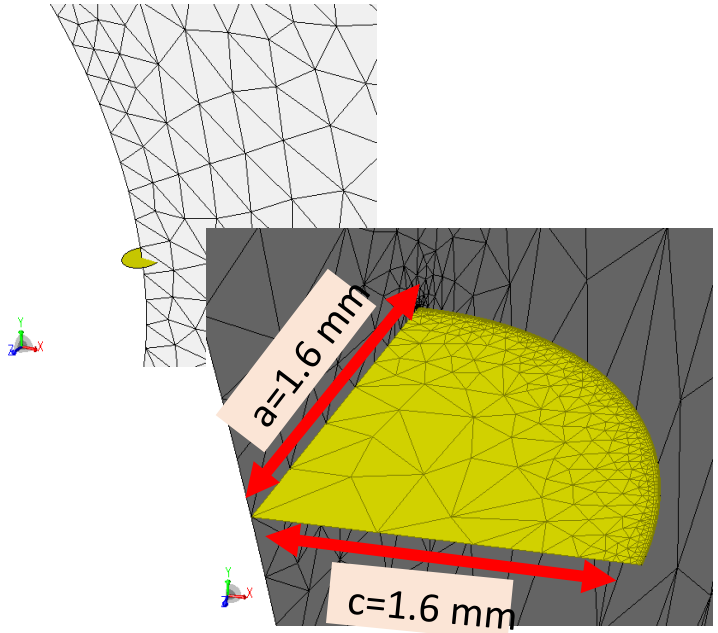
Case study: Loading Axis at θ = 0°

Initial crack front definition



Crack surface can be defined geometrically:

- as an elliptic surface;
- as a planar surface bounded by a B-spline edge (crack front). A set of points (degrees of freedom) is used to define the B-spline.

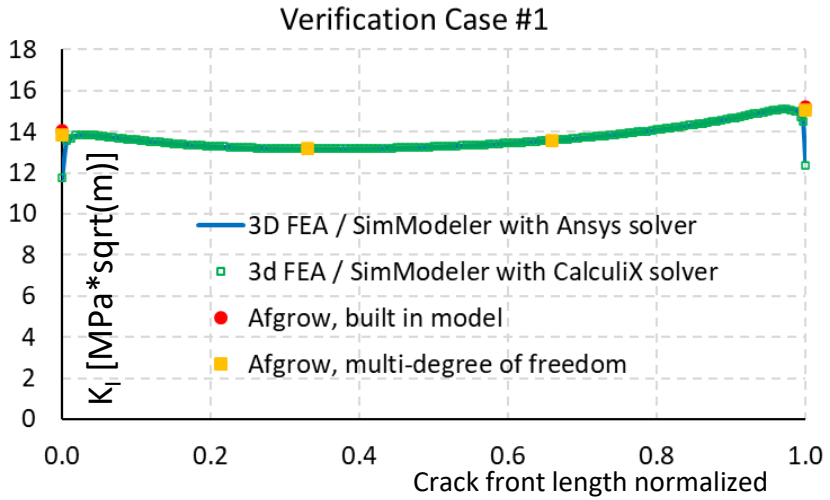
K_I Solutions

K_I solutions can be achieved by:

1. Solving the 3D multi-DOF (mesh dependent) finite element model using SimModeler and Ansys as a solver
2. Solving the 3D multi-DOF finite element model using SimModeler and calculiX as a solver to assess the differences between the two solvers
3. Using a B-spline definition of the crack front (AFGROW controlled) and perform a calculiX batch mode solution using Simmetrix' modeling capabilities (geometry, meshing, pre- and post-processing)
4. Using the two-DOF built-in AFGROW model

K_I solution verification is reached

Verification Benchmarking



Verification assessment:

- a difference of less than 0.25% (except at the end vertices) between Ansys and calculiX based multi-DOF solutions is observed
- a difference of less than 1.7% between the built-in AFGROW solution (two-DOF) and a four-DOF solution (calculiX solver)

3D FEA solution

Case study: Loading Axis at θ = 30°

AFGROW.NET

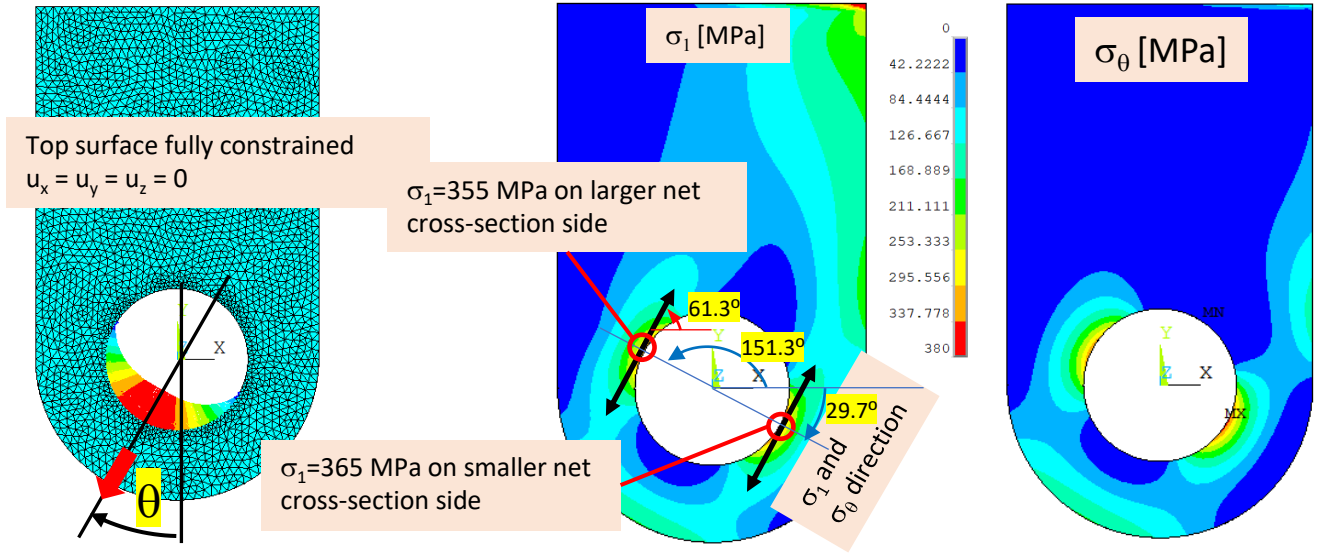
Same Lug Model, only the loading direction is modified

FE Model

FE Solution

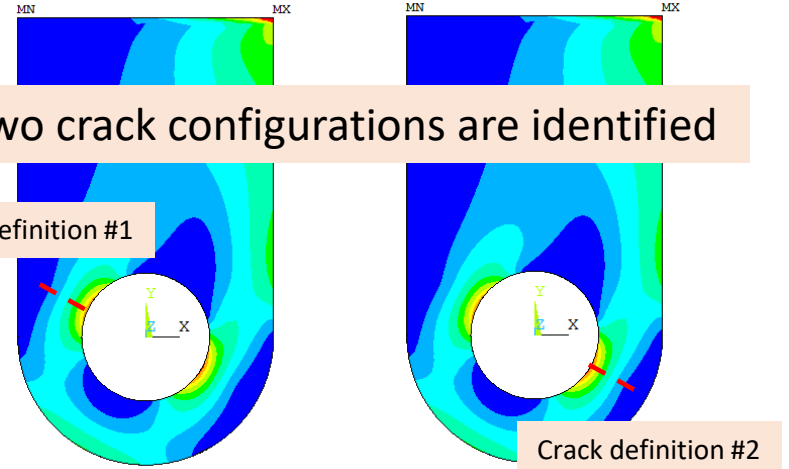
Definition of corner crack location and orientation

Loading step #1



Crack location on the larger cross-section side

Crack location on the short cross-section side

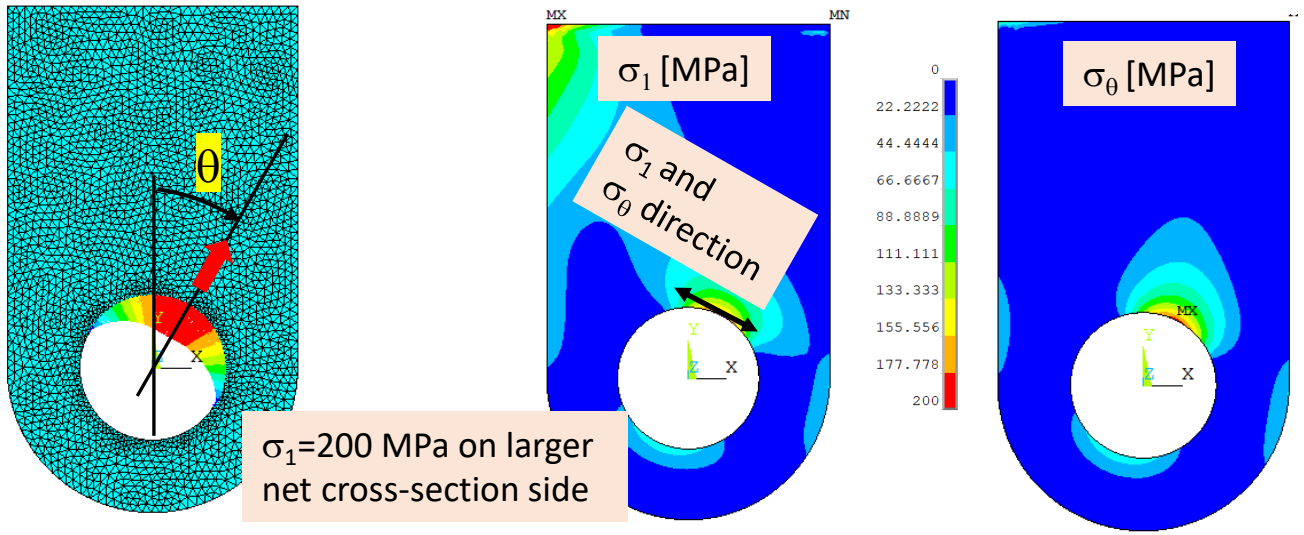


Two crack configurations are identified

Crack definition #1

Crack definition #2

Loading step #2 Reverse loading



- σ_1 magnitude is 40% lower than σ_1 values at the bore from loading step #1

This crack location is not considered in the modeling procedure

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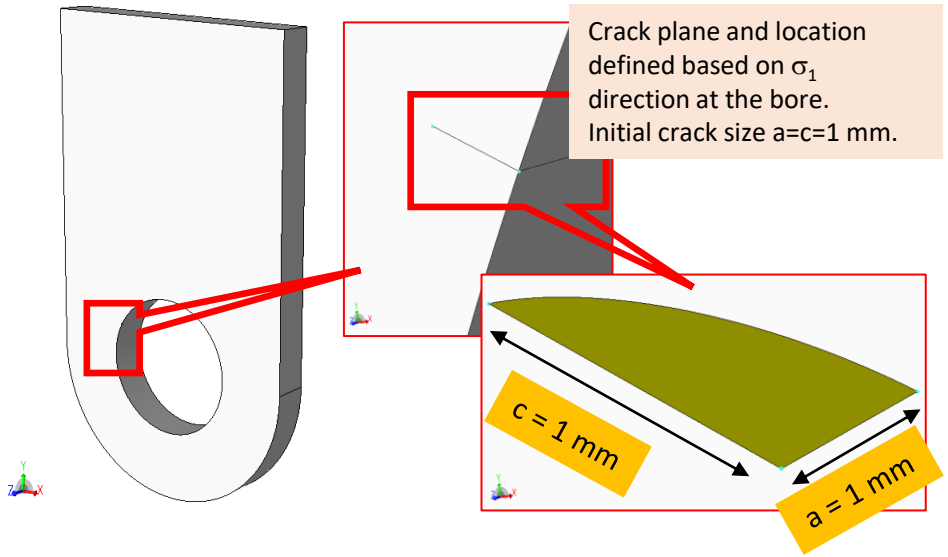
K_I, K_{II}, K_{III} solution assessment

Case study: Loading Axis at θ = 30°

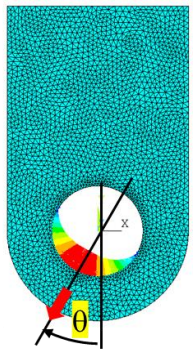
Corner crack location and orientation

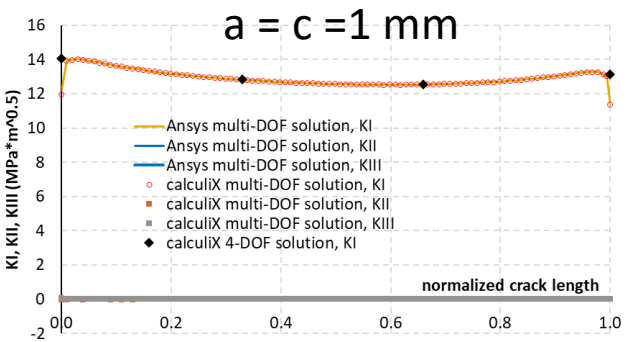
Crack Definition #1



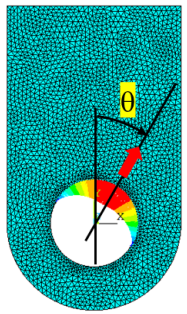
Crack plane and location defined based on σ_1 direction at the bore. Initial crack size a=c=1 mm.

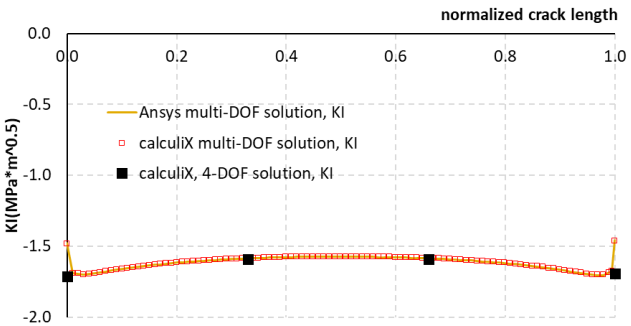
Loading step #1



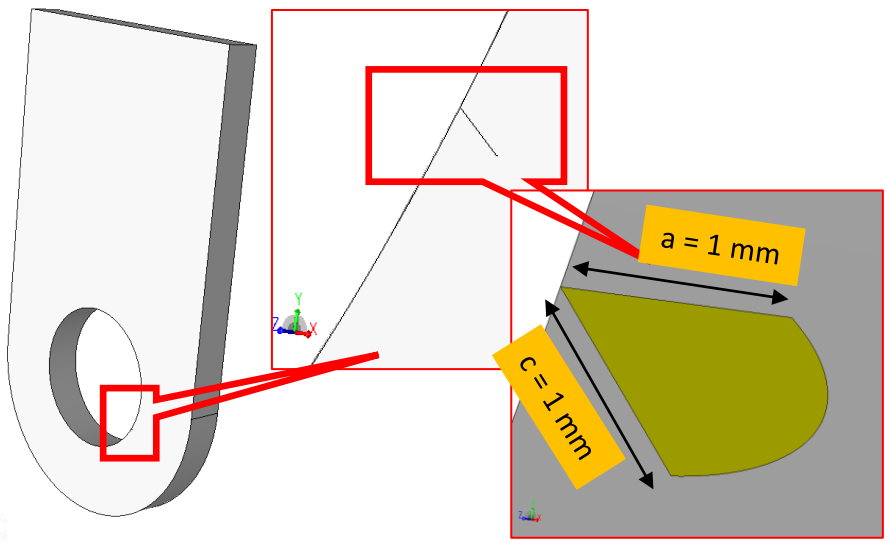


Loading step #2

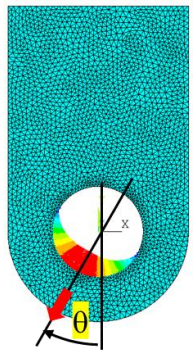


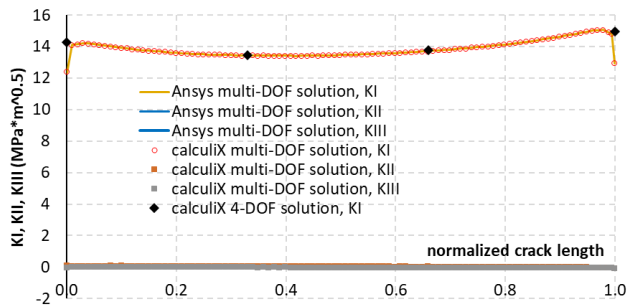


Crack Definition #2



Loading step #1





Ansys runtime: 20 sec

Verification benchmarking is reached.

Take aways:

- K_{II} and K_{III} are negligible in comparison to K_I indicating a mode I crack growth
- Using 100 element edges along the crack front, calculiX based solution is within 0.4% (except vertex locations) from Ansys counterpart
- The 4-DOF solution (obtained via calculiX solver and AFGROW Plugin) matches the multi-DOF solutions
- For a reverse loading configuration (along larger net section i.e. loading step #2), K_I becomes negative indicating contact between crack faces while K_{II} and K_{III} are negligible.
- For both crack configurations, reverse loading (loading step #2) can be neglected since will not contribute to the ΔK magnitude

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3D FEA solution

Case study: Loading Axis at θ = 45°

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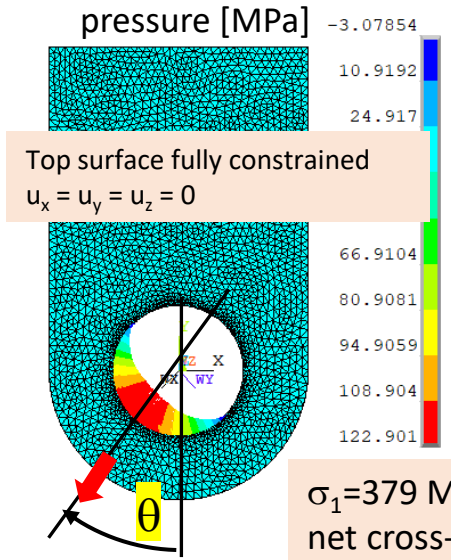
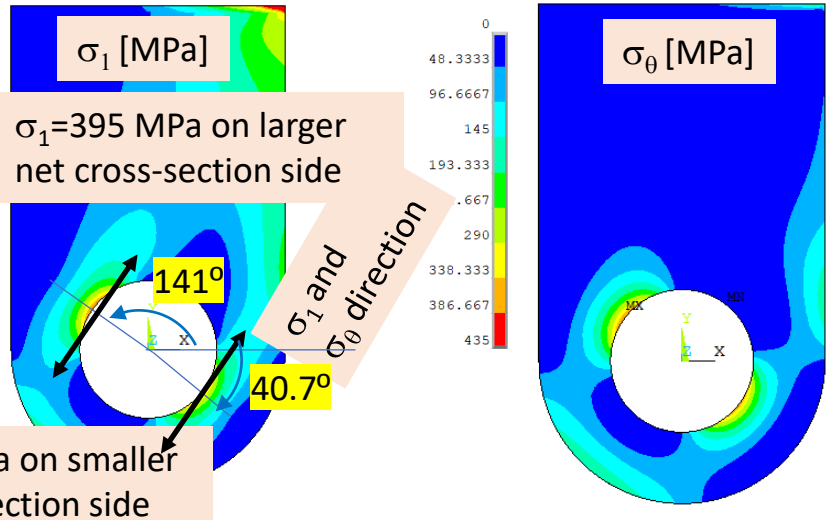
Same Lug Model, only the loading direction is modified

Loading step #1

FE Model



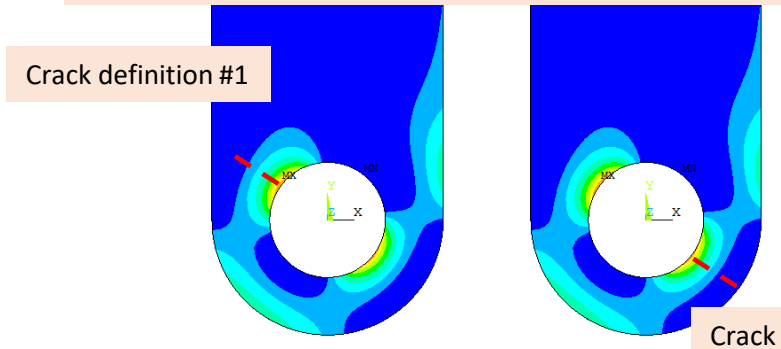
FE Solution



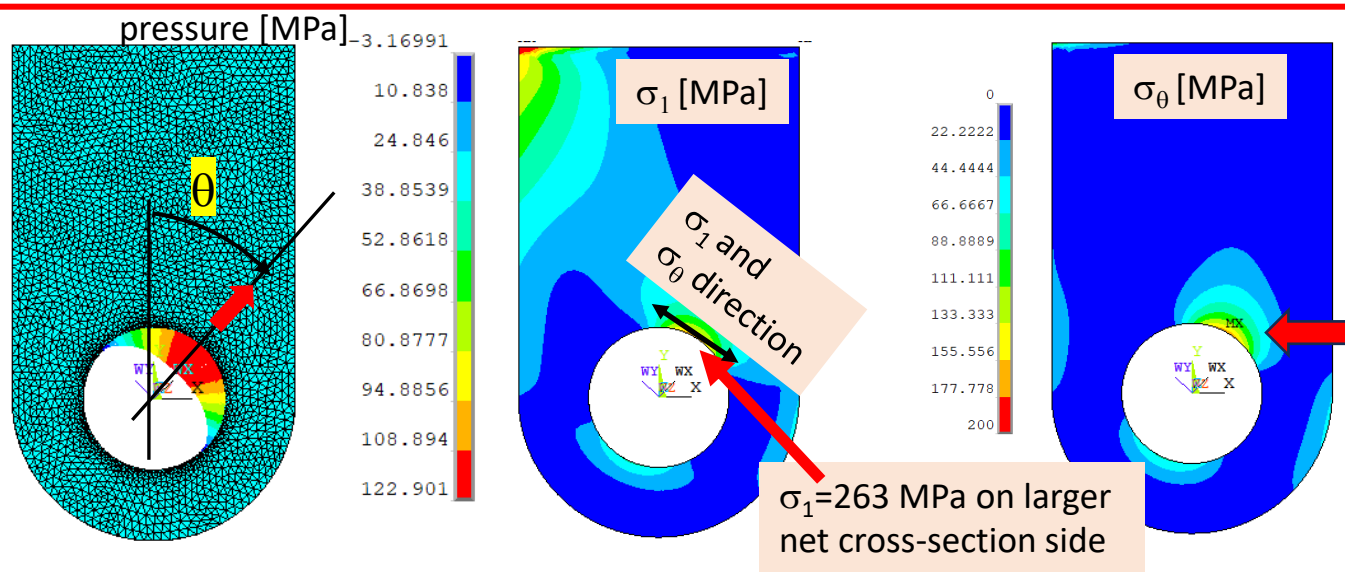
Definition of corner crack location and orientation

Crack location on the larger cross-section side | **Crack location on the short cross-section side**

Two crack configurations are identified



Loading step #2



- σ_1 magnitude is 30% lower than σ_1 values at the bore from loading step #1

This crack location is not considered in the modeling procedure

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K_I, K_{II}, K_{III} solution assessment

Case study: Loading Axis at θ = 45°

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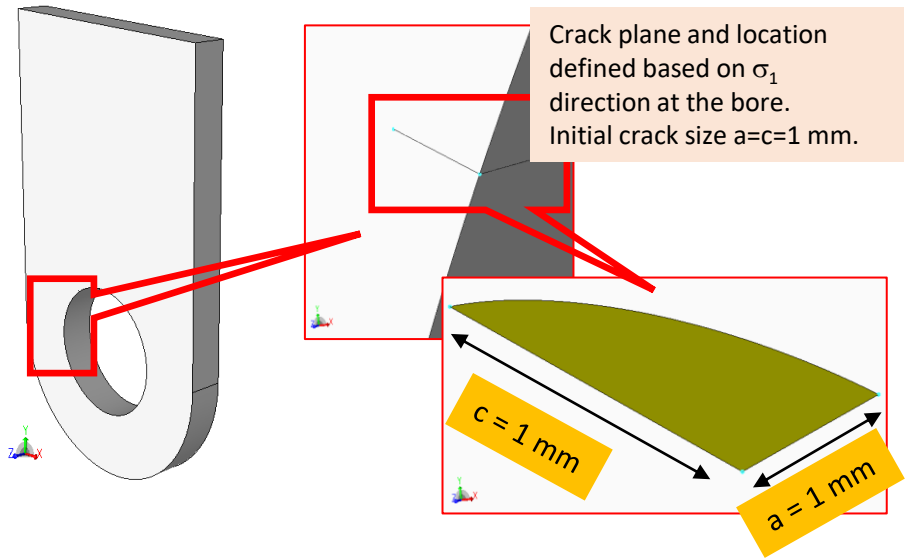
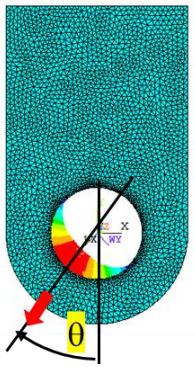
Corner crack location and orientation

Crack Definition #1

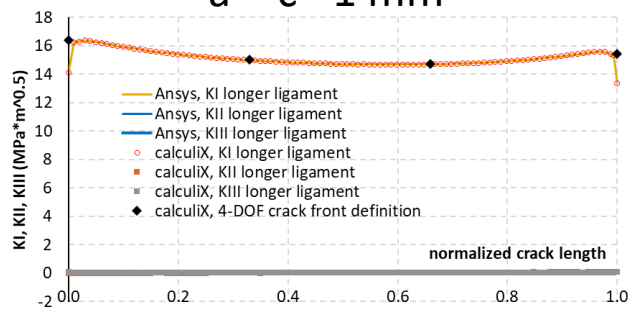


Crack plane and location defined based on σ_1 direction at the bore. Initial crack size a=c=1 mm.

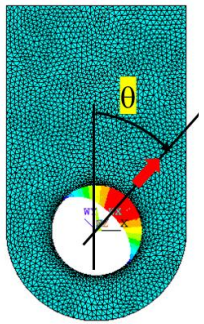
Loading step #1

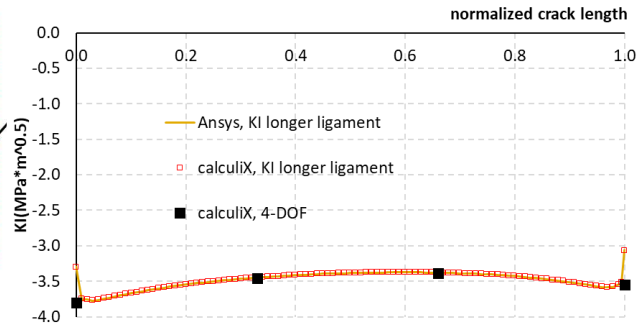


a = c =1 mm

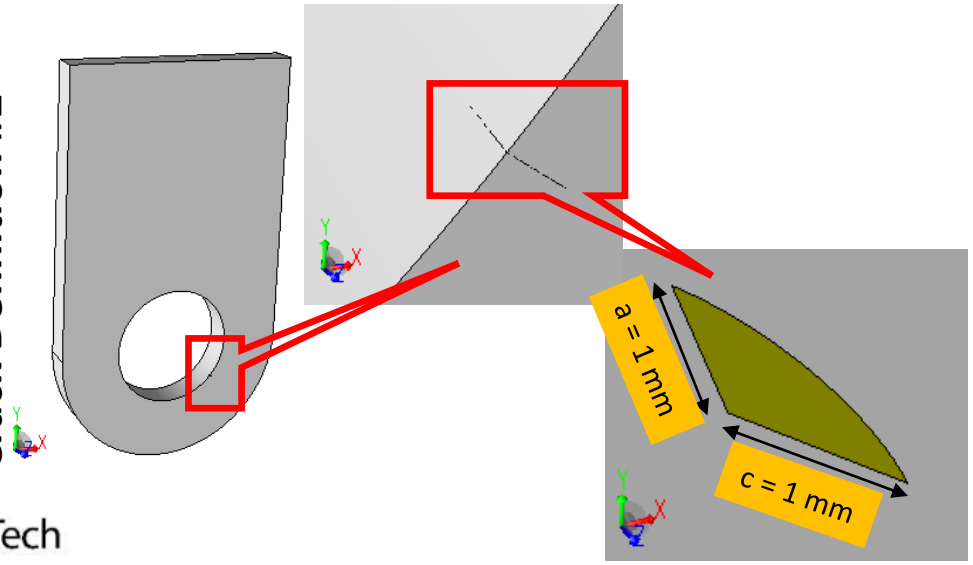


Loading step #2

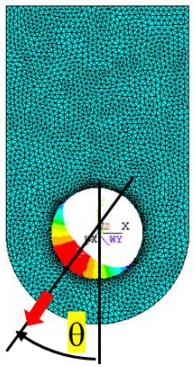


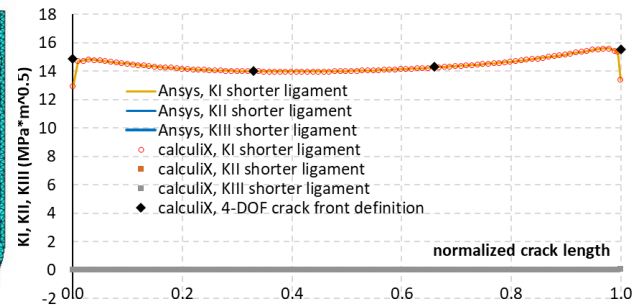


Crack Definition #2



Loading step #1





Verification benchmarking is reached.

Take aways:

- same as the θ = 30° case

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3D FEA solution

Case study: Loading Axis at θ = 90°

AFGROW.NET

Same Lug Model, only the loading direction is modified

FE Model

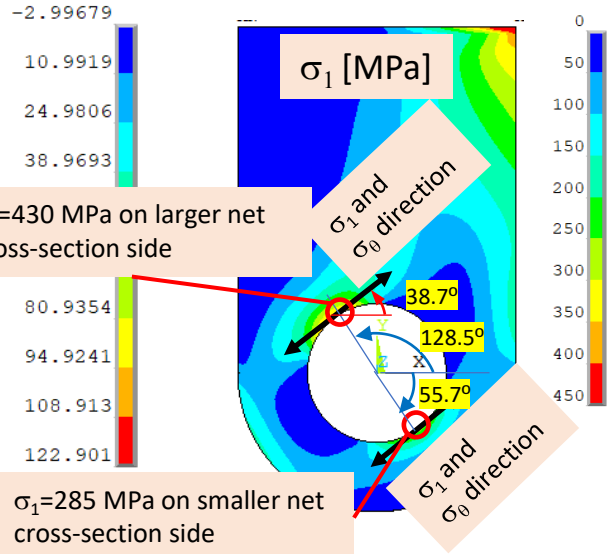
FE Solution

Definition of corner crack location and orientation

Loading step #1

Top surface fully constrained
$u_x = u_y = u_z = 0$

θ



σ1=430 MPa on larger net cross-section side

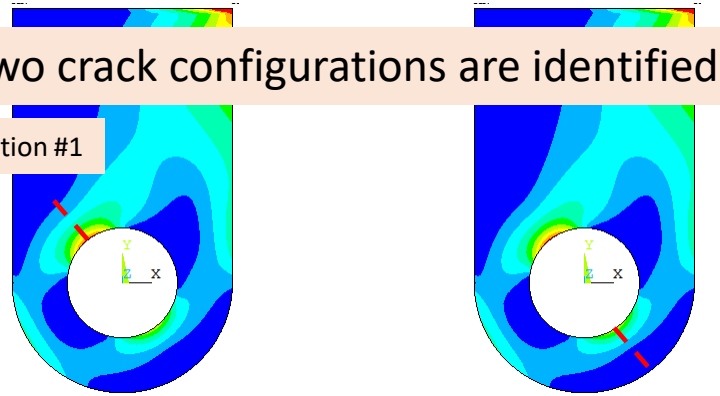
σ1=285 MPa on smaller net cross-section side

Crack location on the larger cross-section side

Crack location on the short cross-section side

Two crack configurations are identified

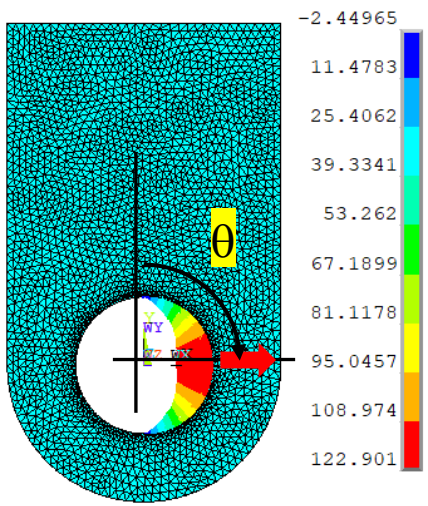
Crack definition #1

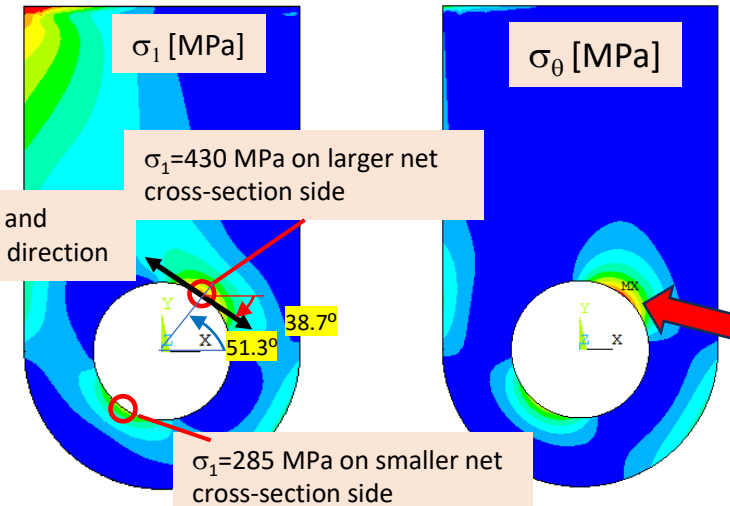


Crack definition #2

Loading step #2

θ





σ1=430 MPa on larger net cross-section side

σ1=285 MPa on smaller net cross-section side

- When load is reversed, the stress contours are mirrored wrt centerline
- The two locations identified above are sufficient (symmetric geometry wrt centerline). The two crack locations are maintained to be consistent with other off-axis loading cases

This crack location is not considered in the modeling procedure

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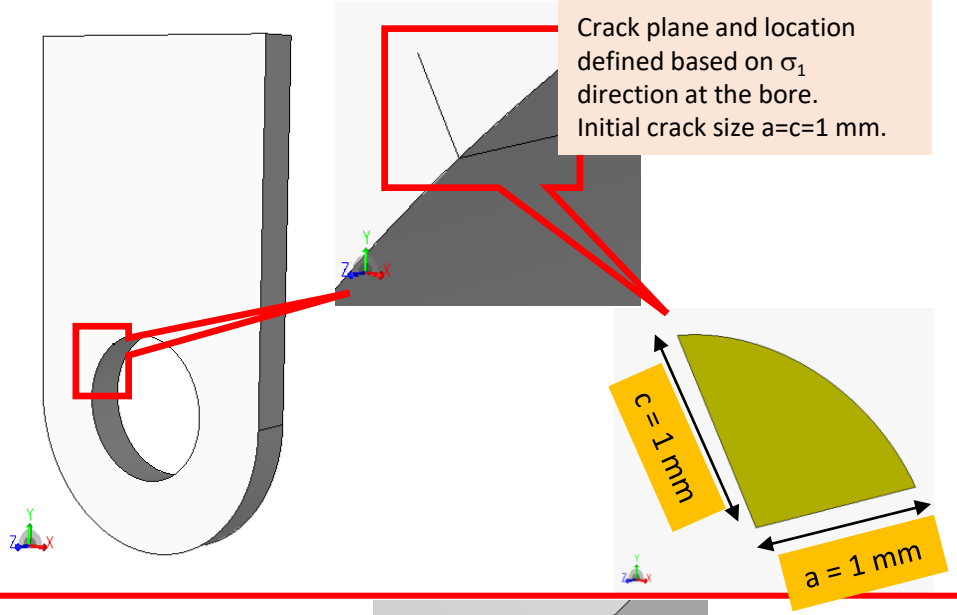
Case study: Loading Axis at θ = 90º

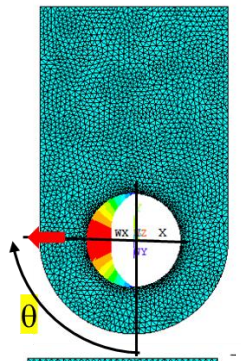
Corner crack location and orientation

Crack Definition #1

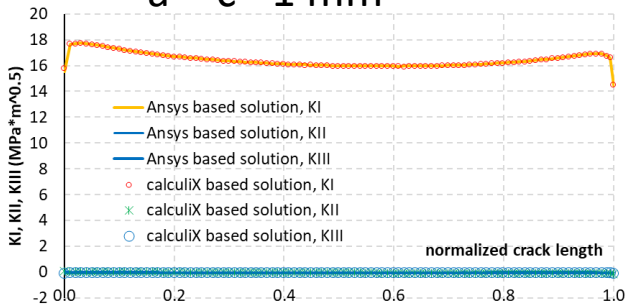
Crack plane and location defined based on σ_1 direction at the bore.
Initial crack size a=c=1 mm.



Loading step #1



a = c =1 mm



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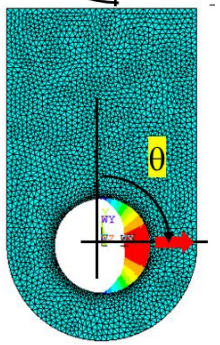
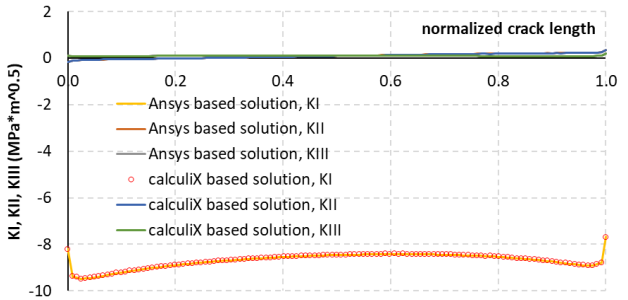
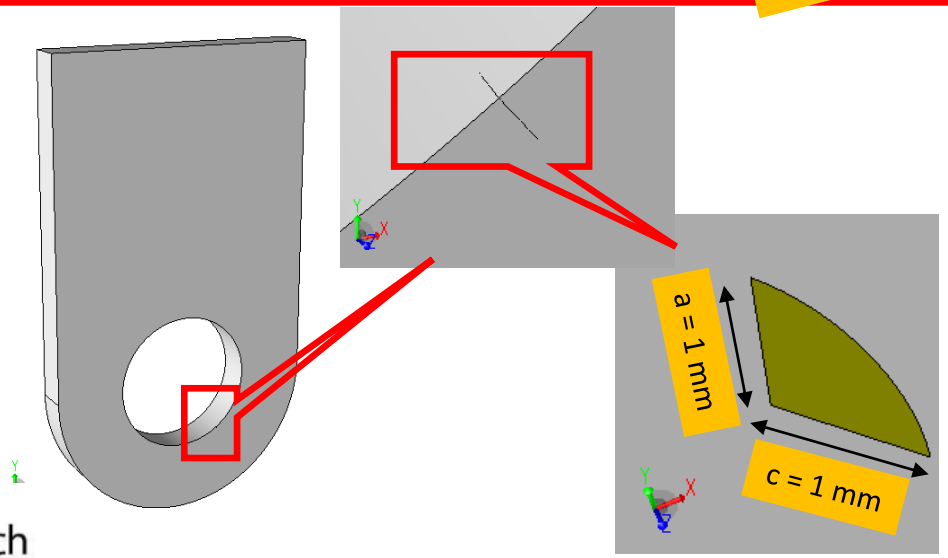
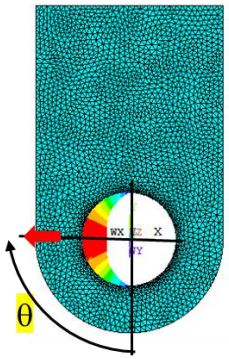


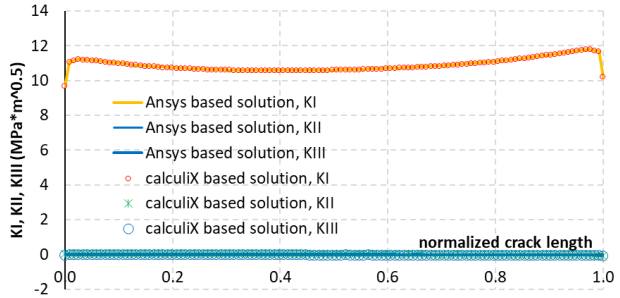


Crack Definition #2



Loading step #1





Verification benchmarking is reached.

Take aways:

- same as the θ = 30º, 45º cases
- AFGROW 4-DOF solution to follow
- maximum K_I solution difference between calculiX and Ansys is 0.25% (includes the vertex locations)

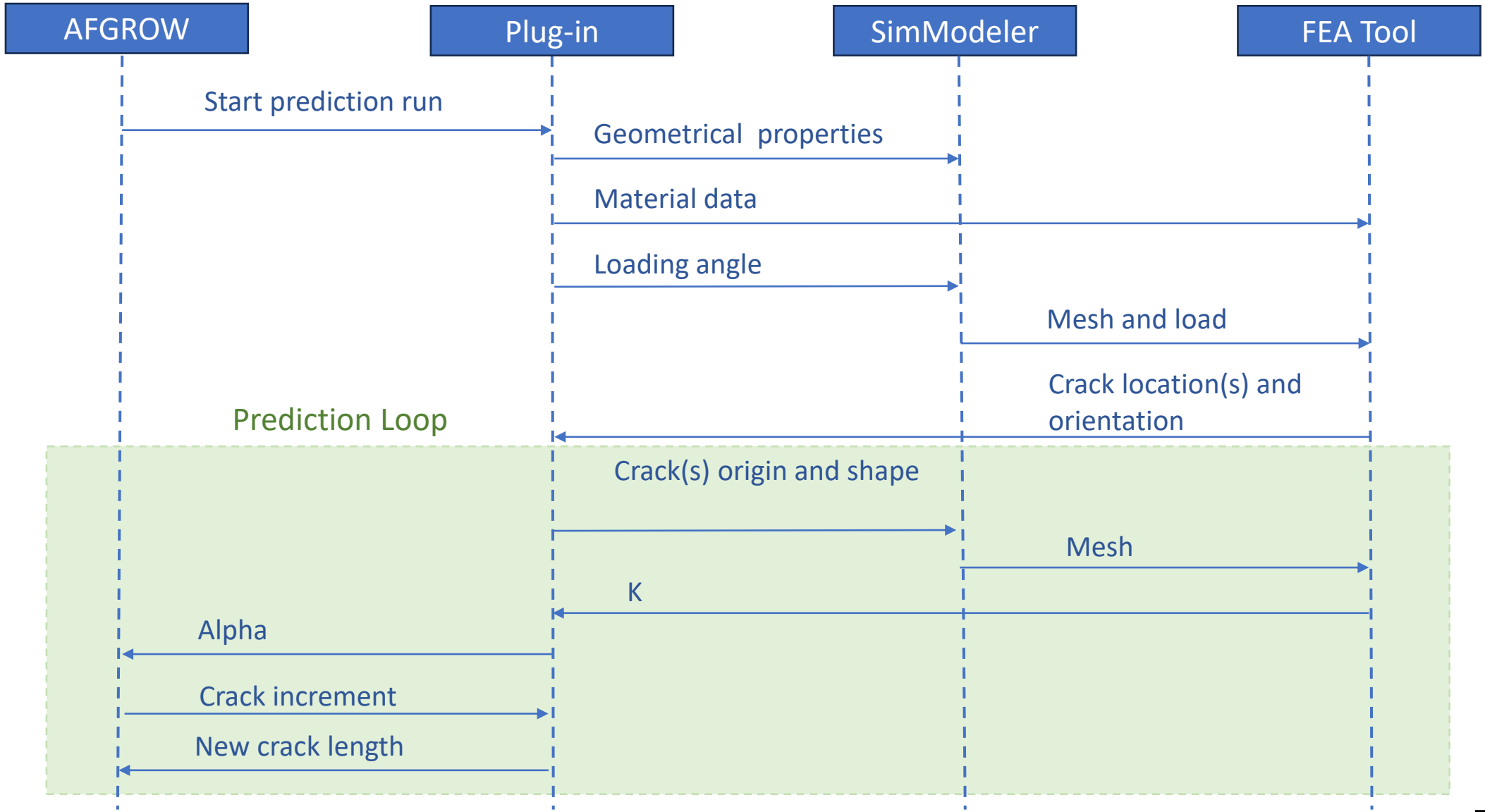
Take-aways, partial conclusions

1. Two location scenarios, single crack definition implementation:
   - Crack location on the short ligament side
   - Crack location on the long ligament side
2. The reverse loading solution does not need to be considered in the modeling procedure since $K_I < 0$. With contact between crack faces, $K_I = 0$.
3. For a given load and crack location/orientation based on location/direction of $\max(\sigma_1)$, K_{II} and K_{III} magnitudes are very low compared to K_I values for all solutions. No mixed-mode conditions were identified for crack propagation.
4. These models comply to a Mode I fatigue crack growth modeling procedure.

Next:

1. Verification benchmarking: crack propagation solution (length vs. cycles along predefined directions). Comparison between multi-DOE (two solvers) and a 4-DOE solutions obtained via AFGROW Plugin.
2. Loading cycle considered for the verification benchmarking: 0-max.

Implementation in AFGROW



Problem Setup

Model Properties

Width
Thickness
Hight
Hole Diameter
Crack Length (C Direction)
Crack Length (A Direction)
Loading Angle

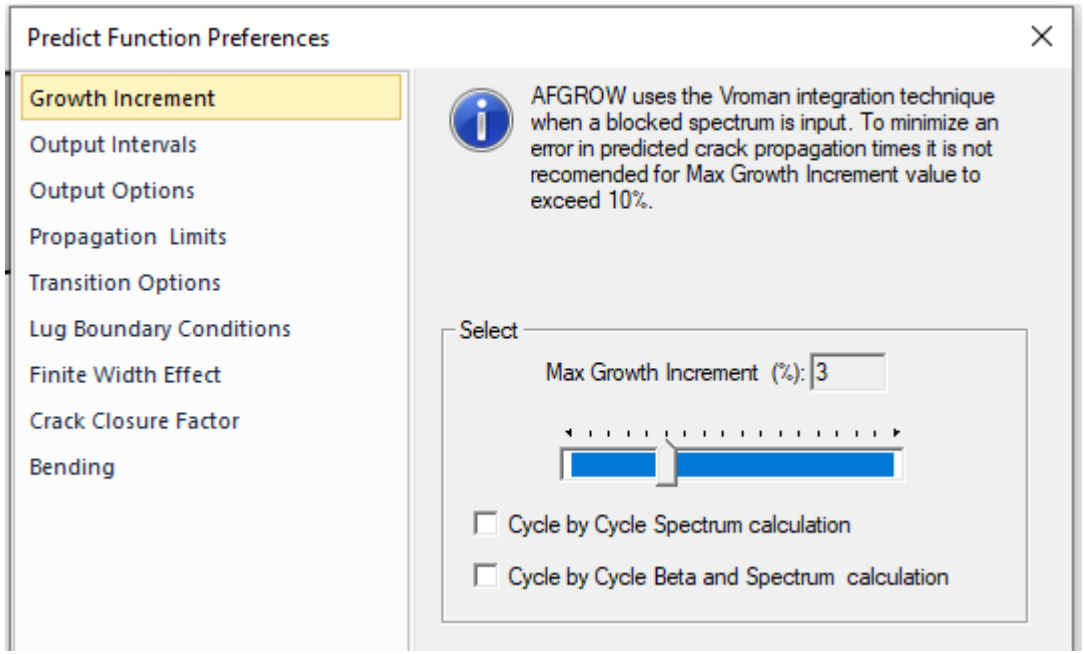
Crack front has four different crack directions:

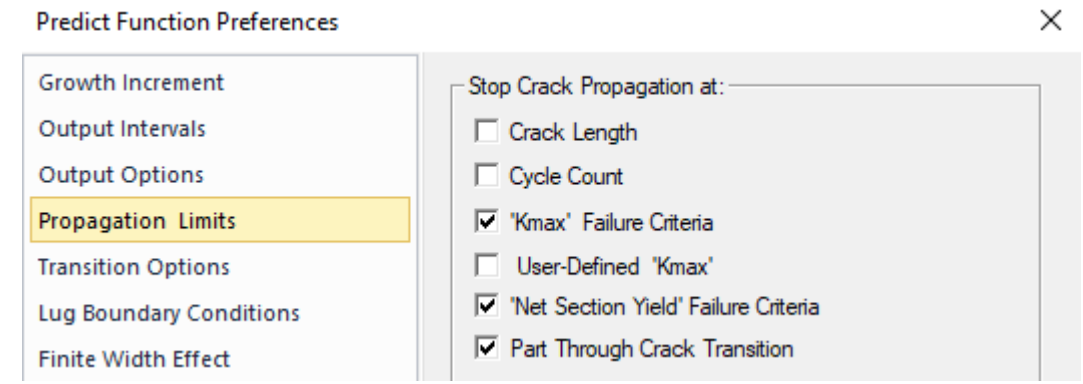
1. 0 ° (C)
2. 30 °
3. 60 °
4. 90 ° (A)

The angles are parametric. Every delta length increment applied perpendicularly to the crack front.

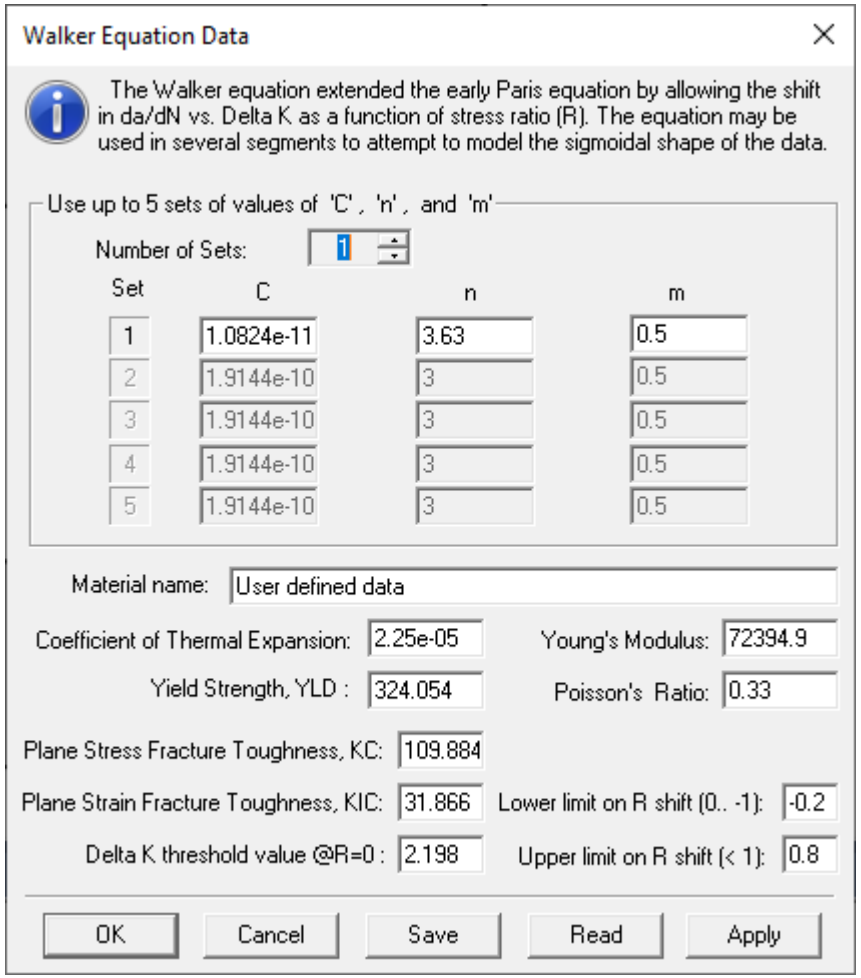
Constant Amplitude Load

Predict Preferences



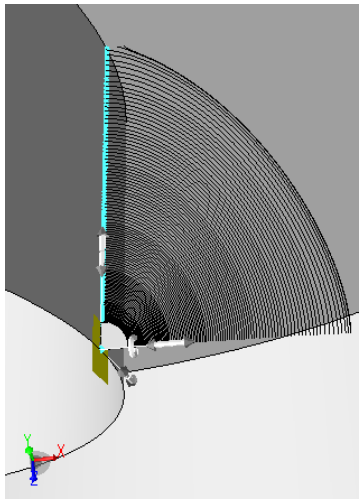


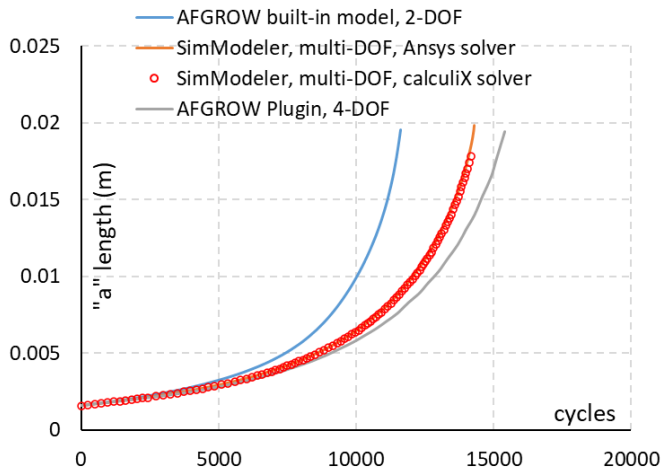
Material (Paris Equation)

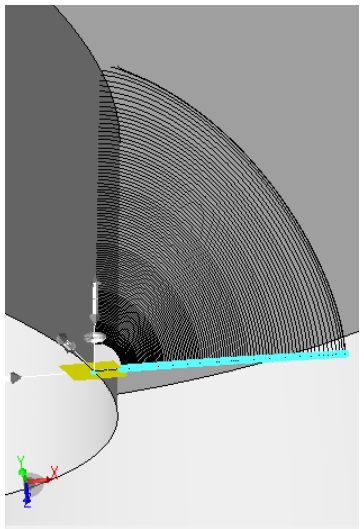


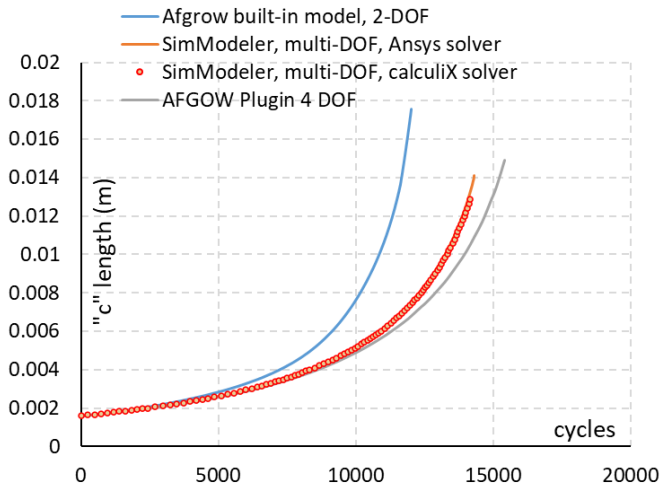
Verification benchmarking
Crack growth solution

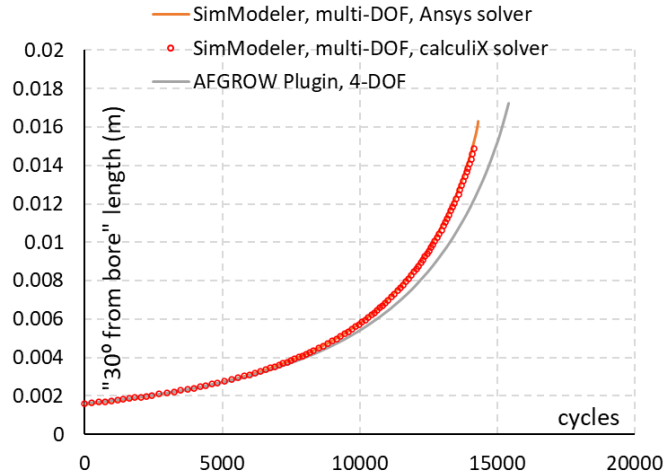
Case Study: Loading Axis at θ = 0°

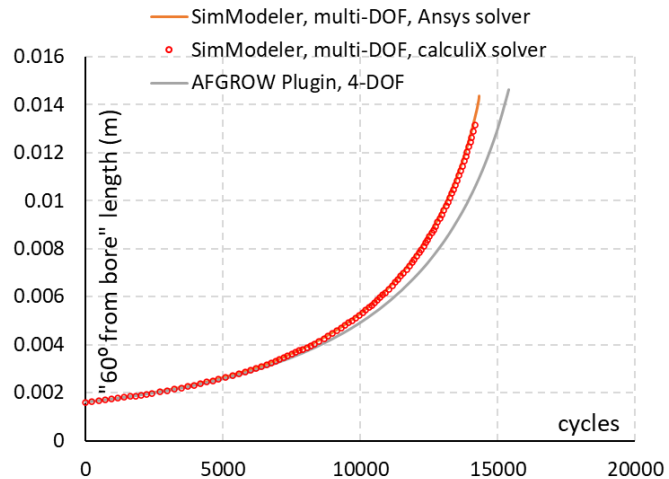


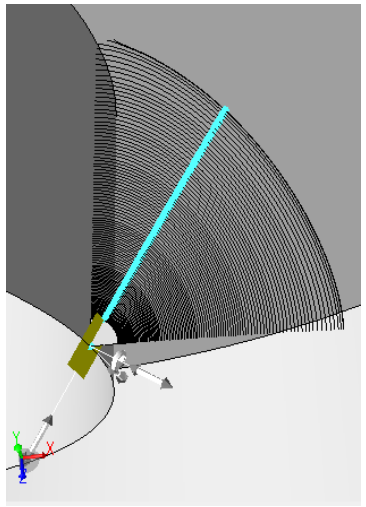


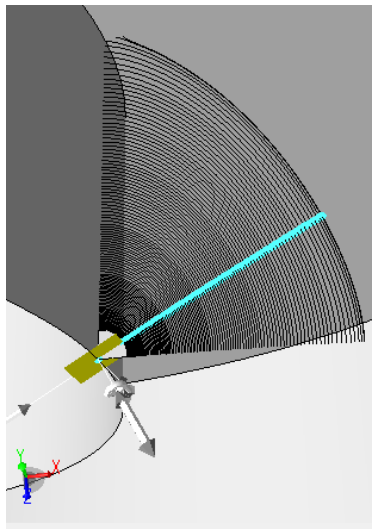












- Using the same mesh refinement for each crack front increment, the solutions based on calculiX and Ansys solvers are consistent
- The 4-DOF solution obtained via AFGROW Plugin, is within 8% from the multi-DOF solutions (Ansys and calculiX solvers)
- The built-in 2-DOF AFGROW solution is within 18% from the multi-DOF solutions

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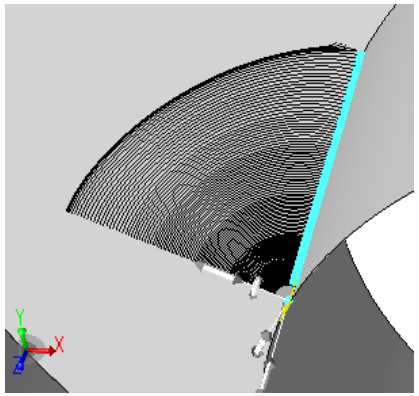
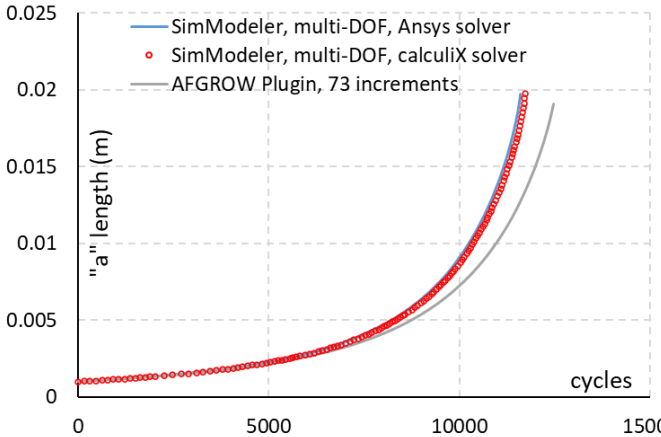
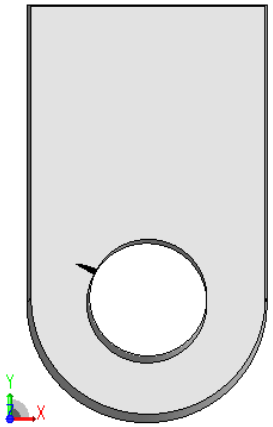
Verification benchmarking
Crack growth solution

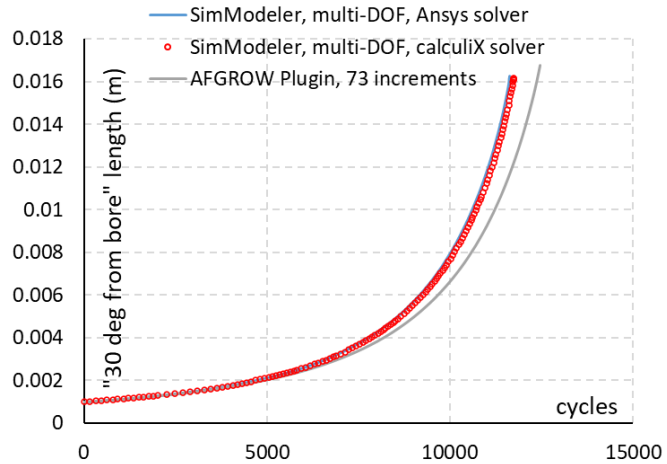
Case Study: Loading Axis at θ = 30°

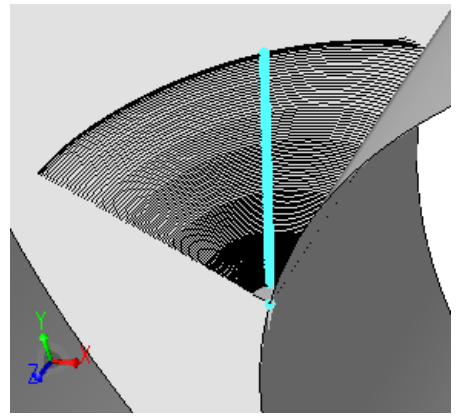
Long Ligament

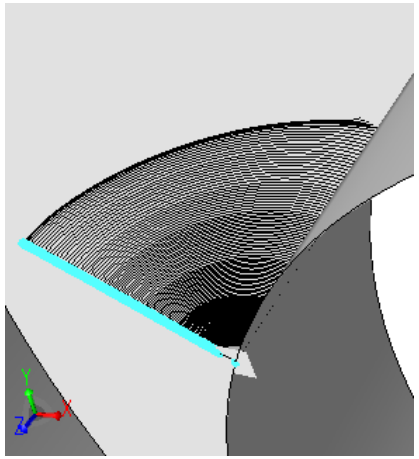


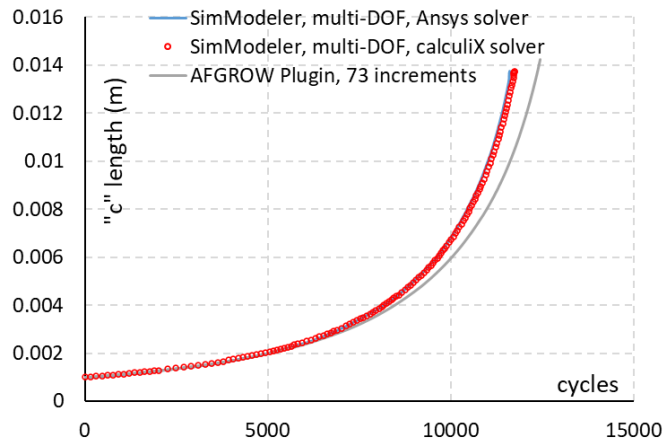


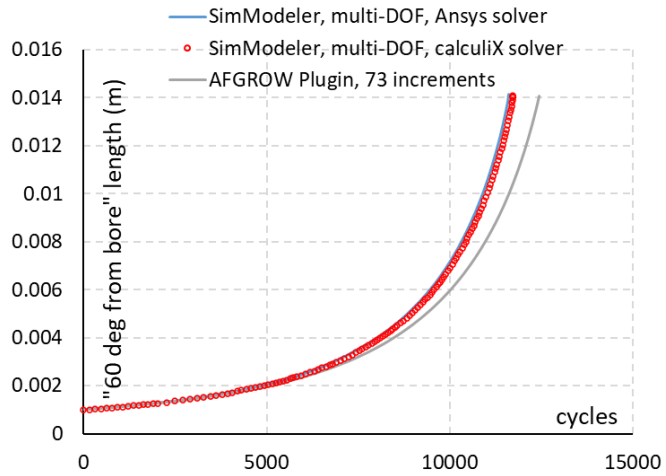


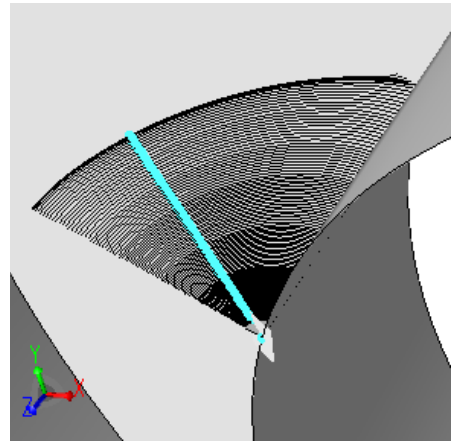










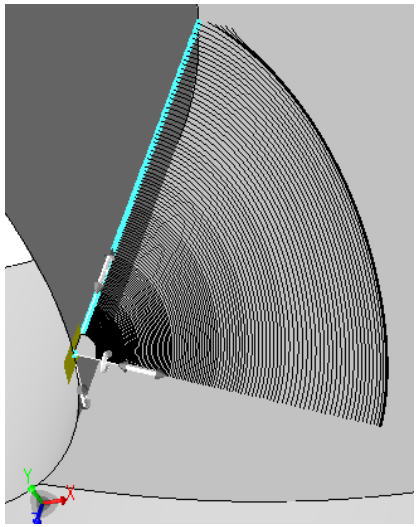


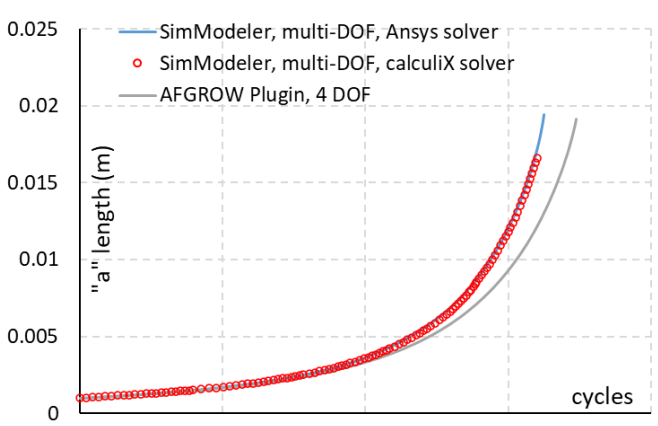
- This solution is consistent with the θ = 0° solution
- Very low error between the multi-DOF Ansys based solution and the calculiX equivalent
- The 4-DOF solution obtained via AFGROW Plugin, is within 6% from the multi-DOF solutions (Ansys and calculiX solvers)

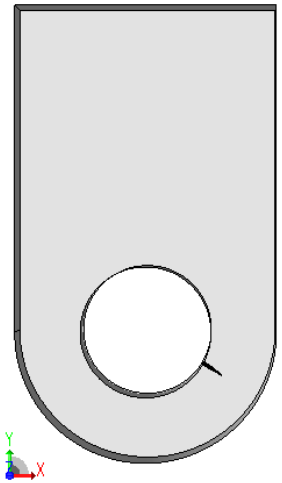
Verification benchmarking
Crack growth solution

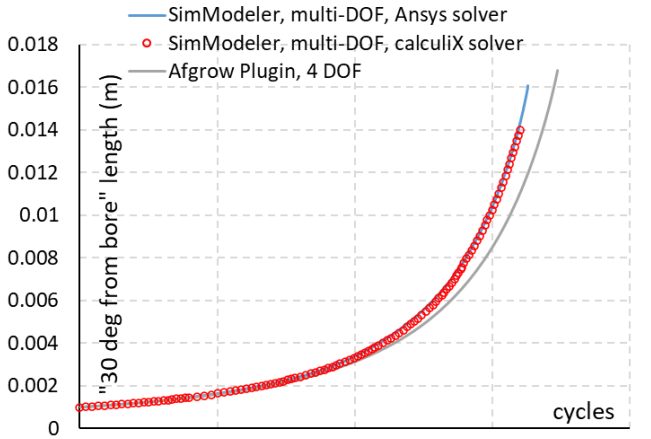
Case Study: Loading Axis at θ = 30º

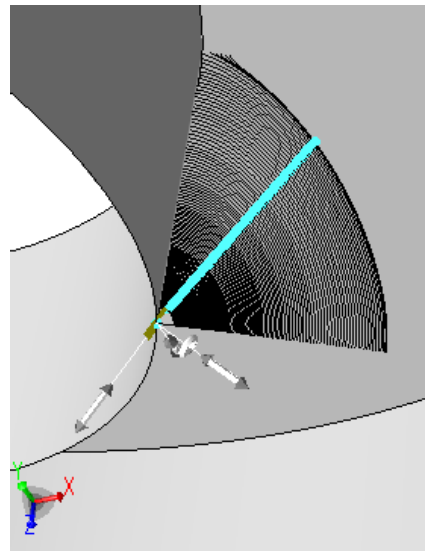
Short Ligament

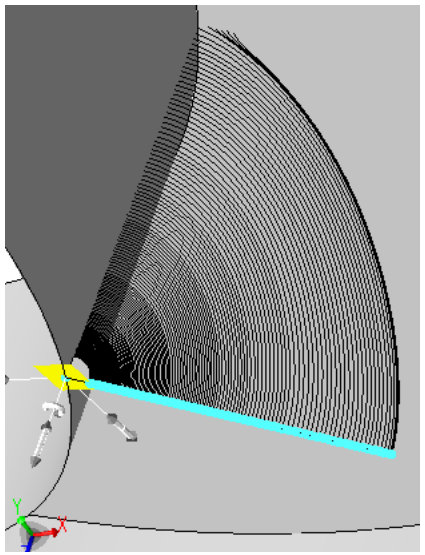


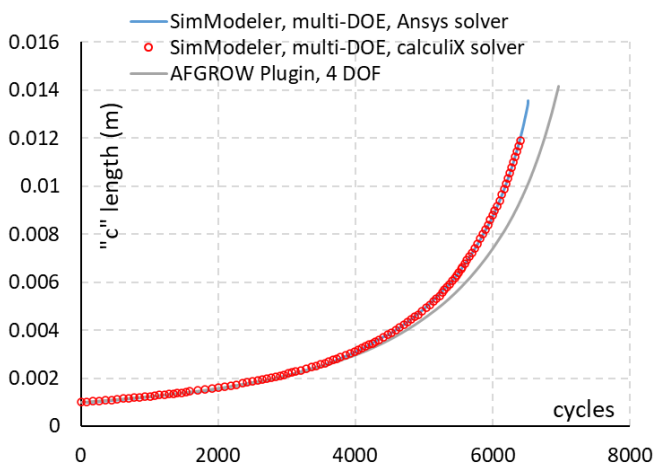


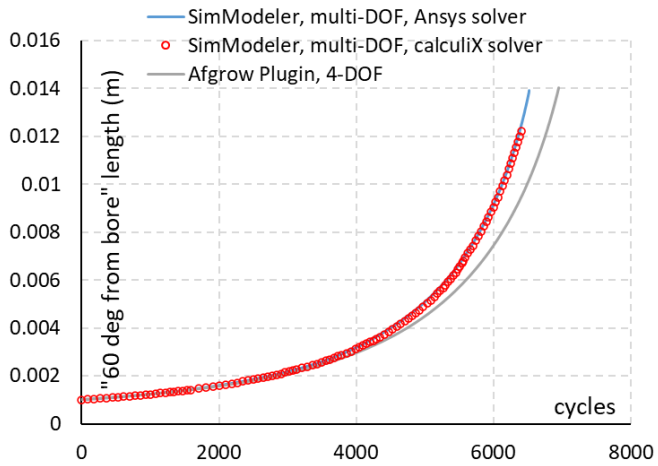


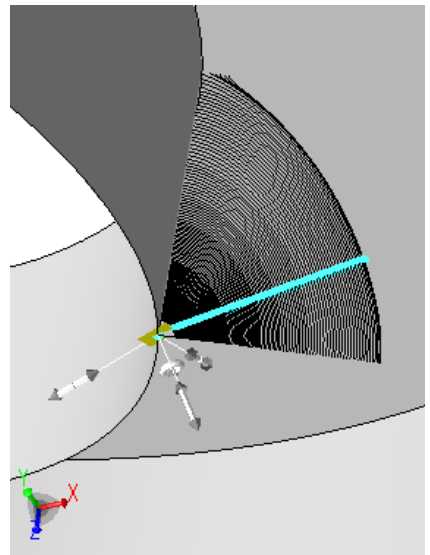










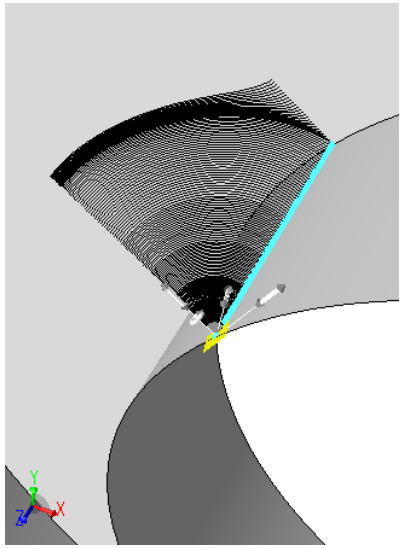


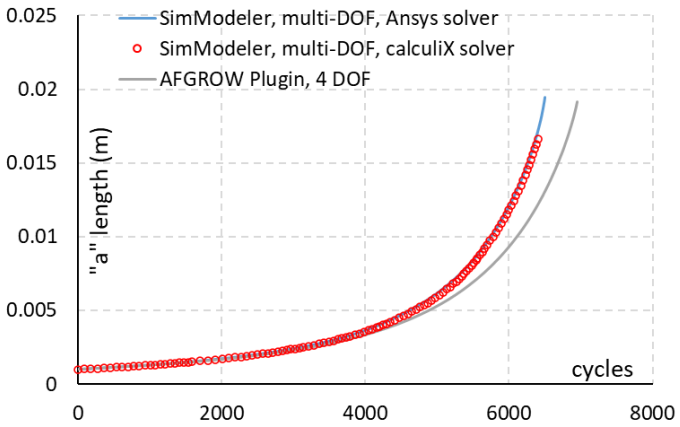
- This solution is consistent with the θ = 30º long ligament solution
- Same conclusions

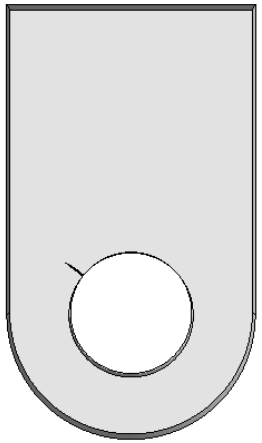
Verification benchmarking
Crack growth solution

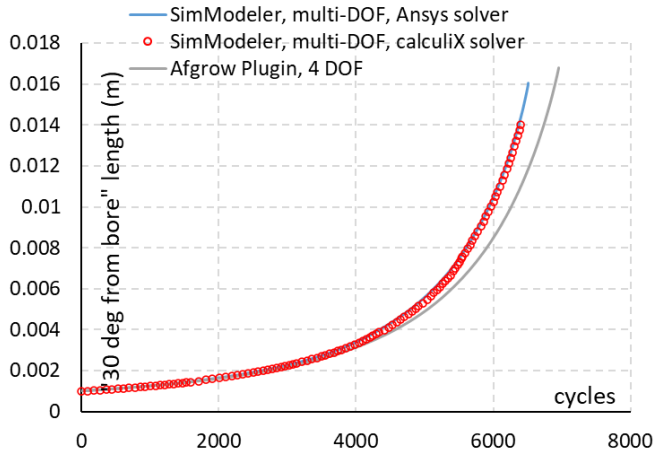
Case Study: Loading Axis at θ = 45°

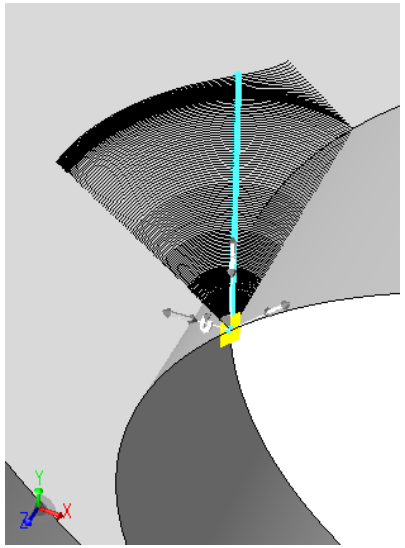
Long Ligament

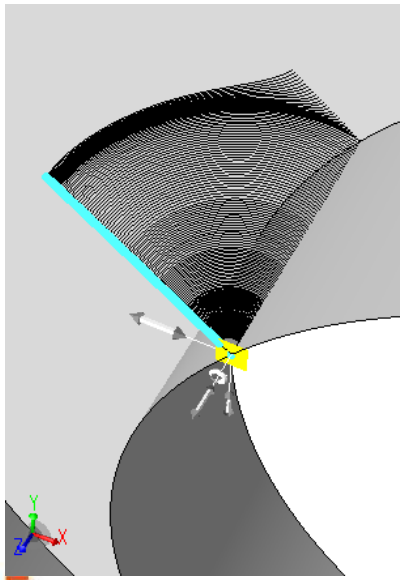


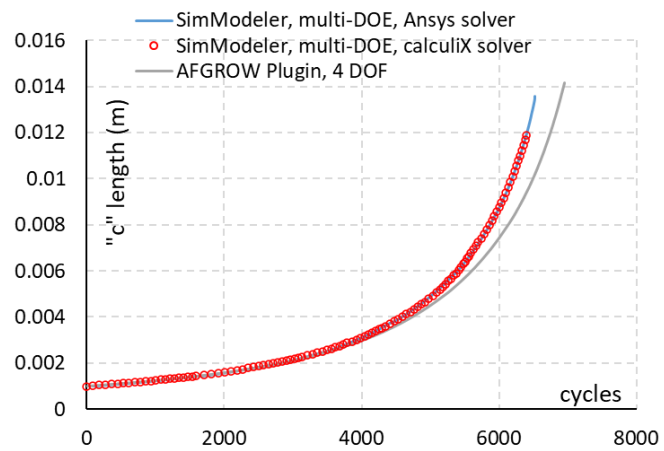


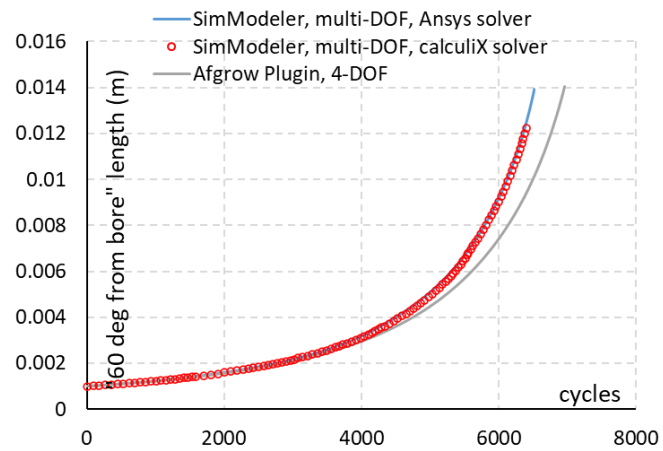


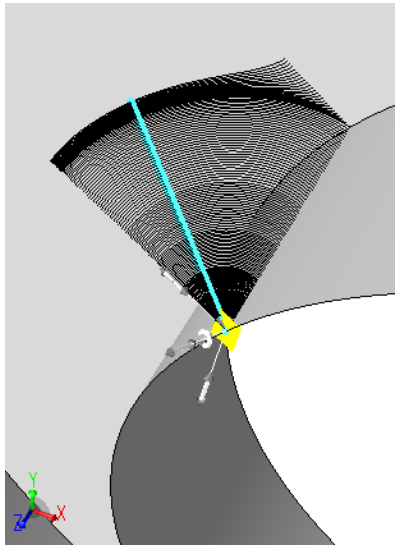










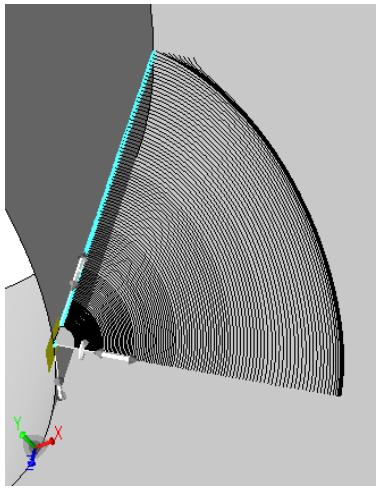


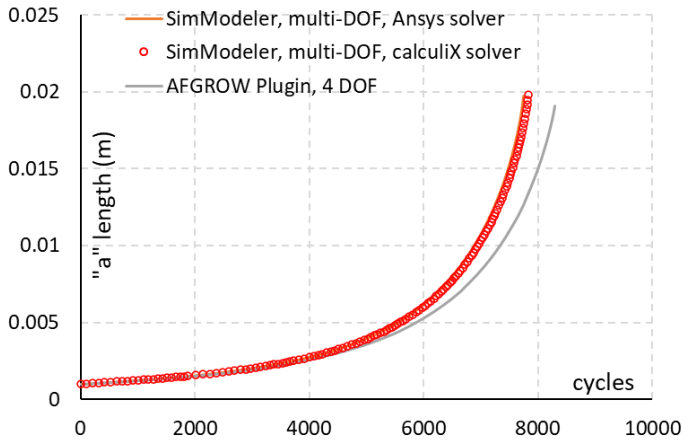
- This solution is consistent with the θ = 30° solution
- Same conclusions

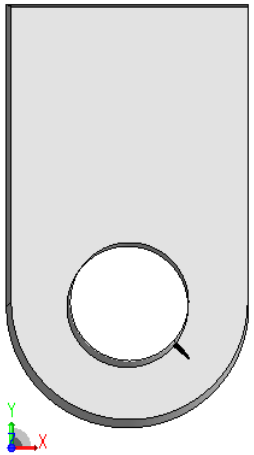
Verification benchmarking
Crack growth solution

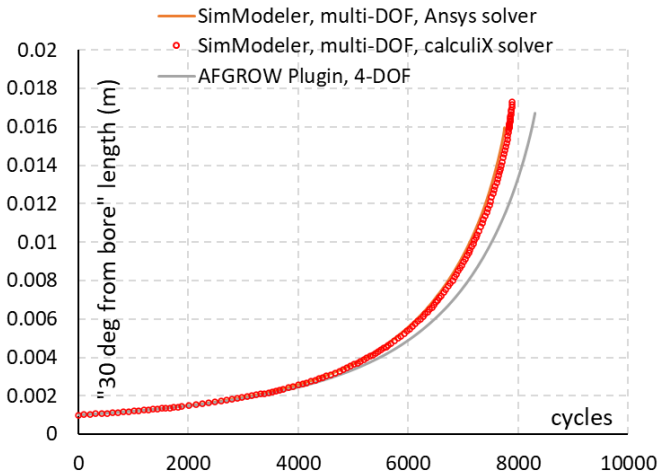
Case Study: Loading Axis at θ = 45°

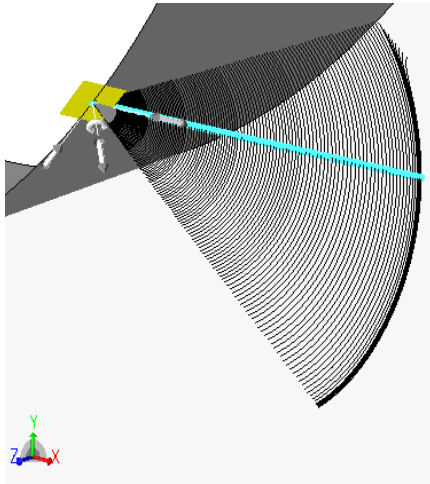
Short Ligament

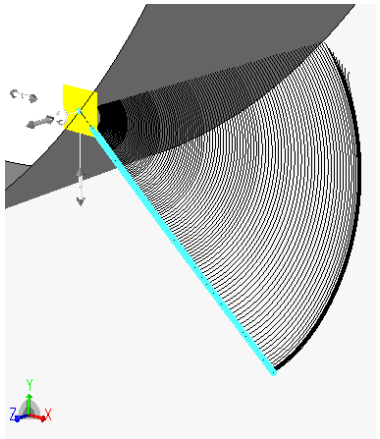


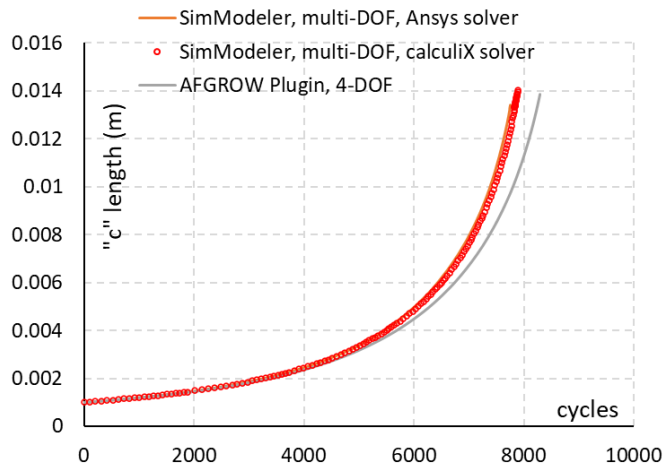


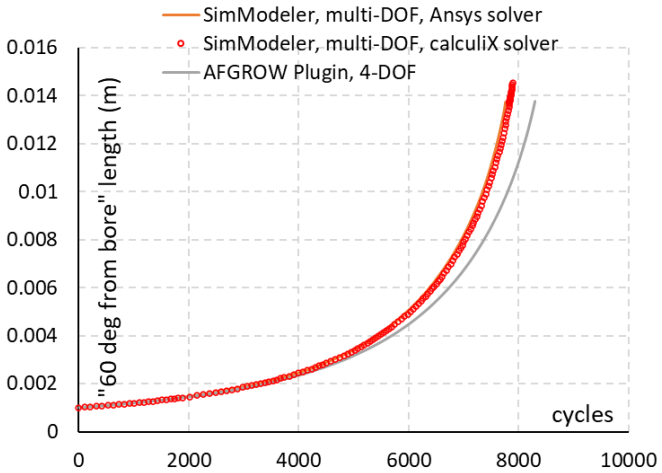


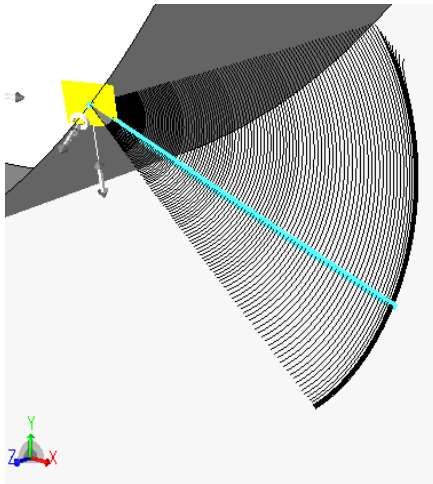










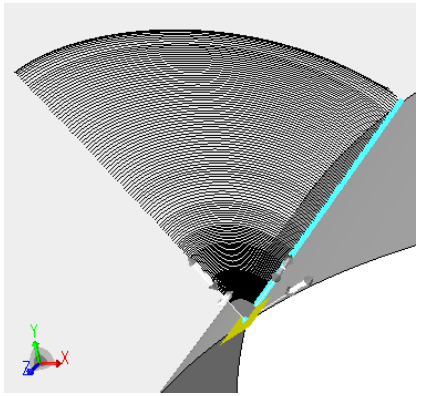


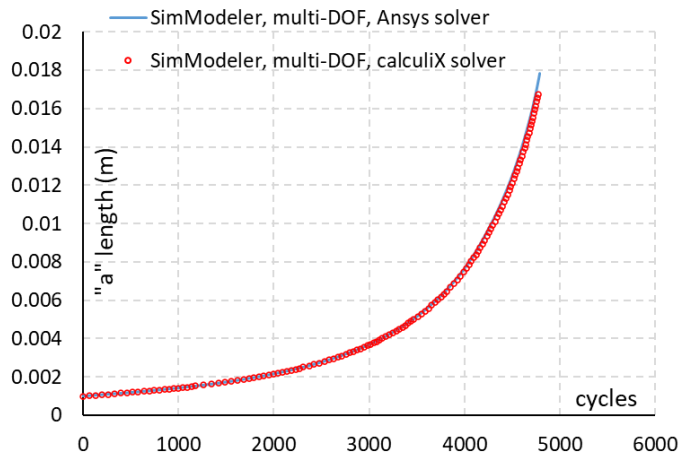
- This solution is consistent previous examples. Same conclusions

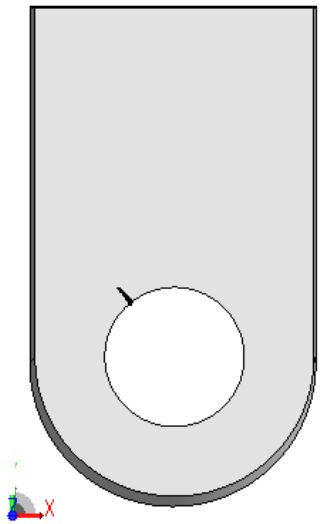
Verification benchmarking
Crack growth solution

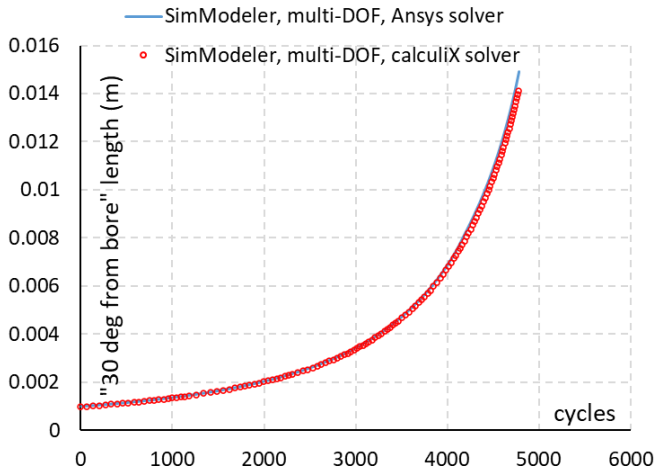
Case Study: Loading Axis at θ = 90°

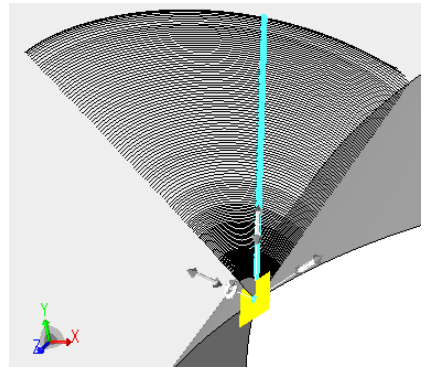
Long Ligament

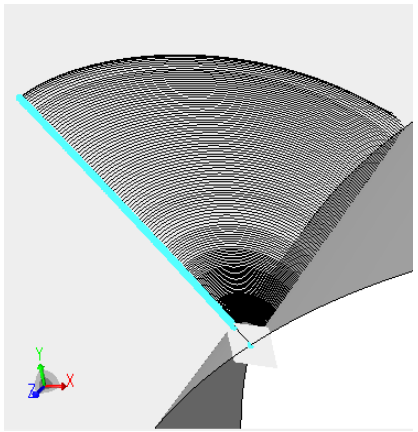


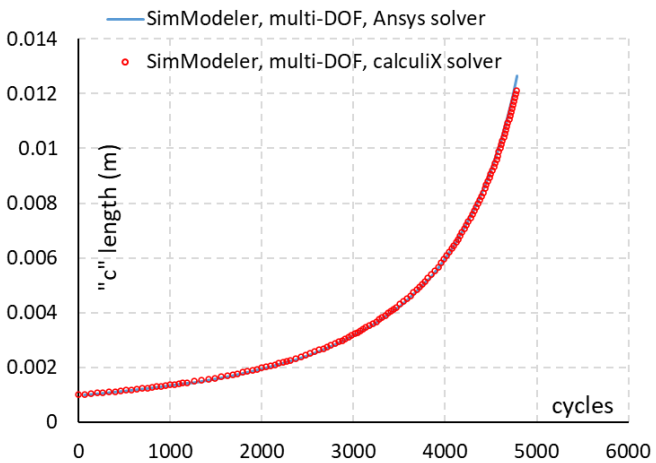


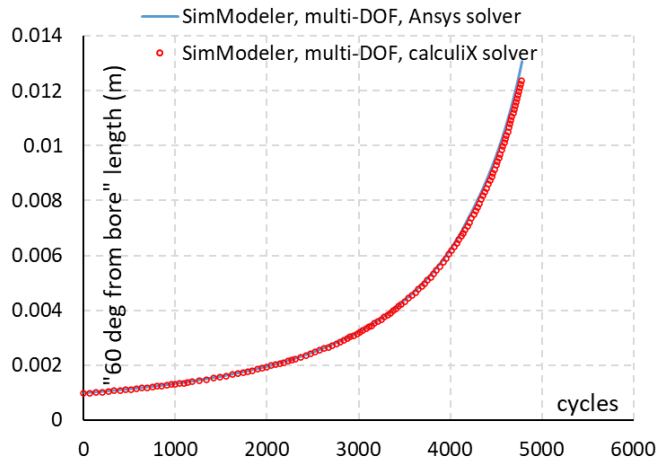


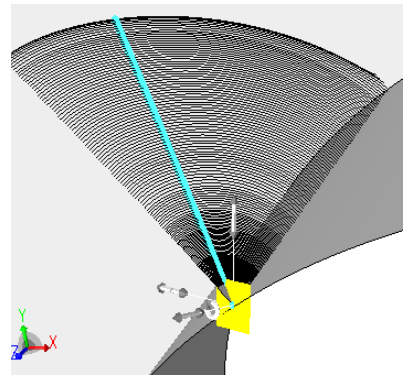












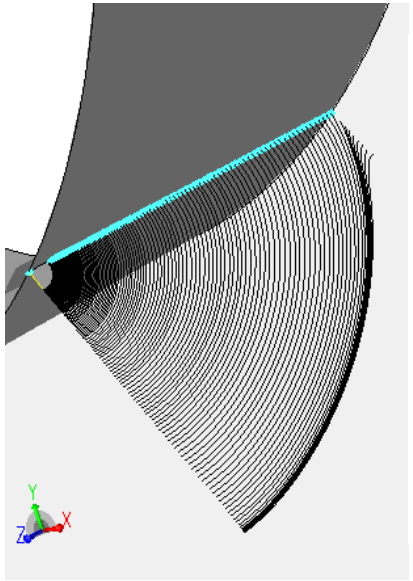
- This solution is consistent previous examples.
- AFGROW Plugin solution to follow

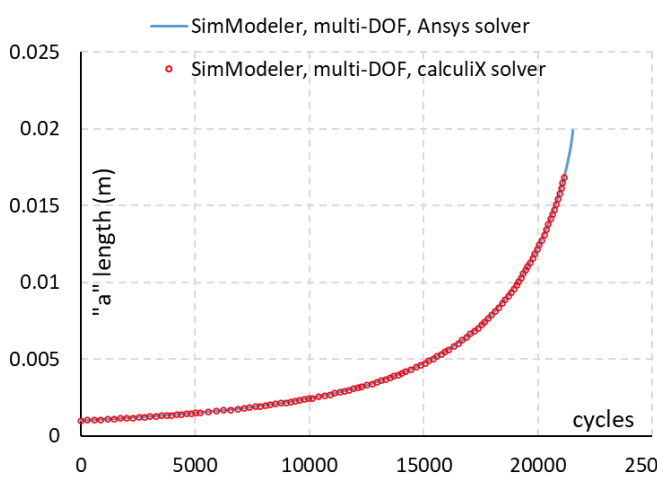
Verification benchmarking
Crack growth solution

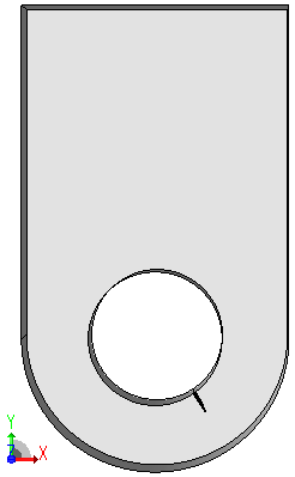
Case Study: Loading Axis at θ = 90°

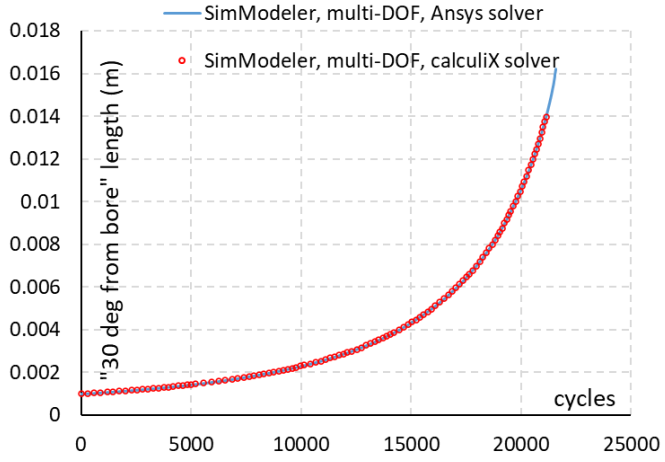
AFGROW.NET

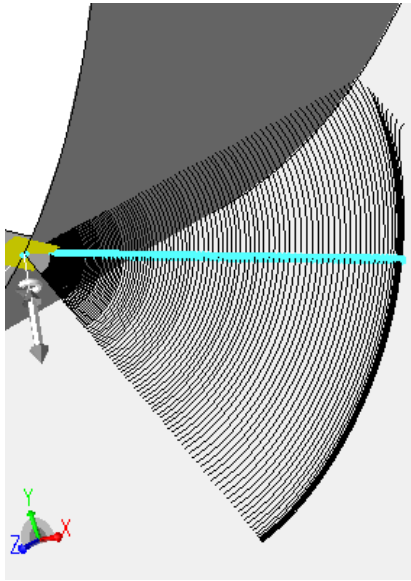
Short Ligament

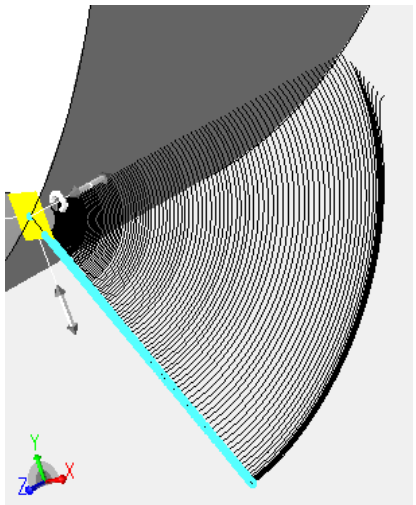


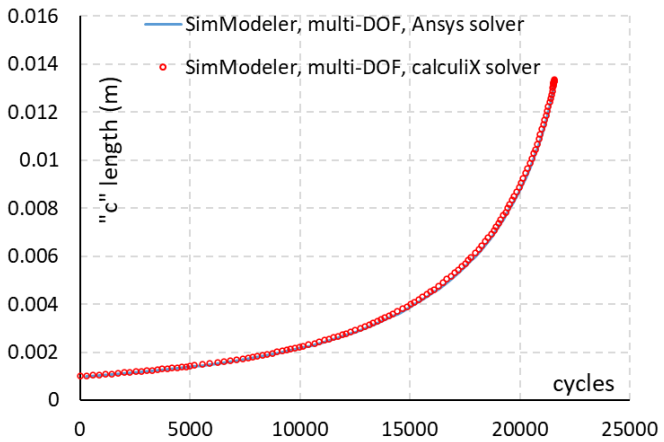


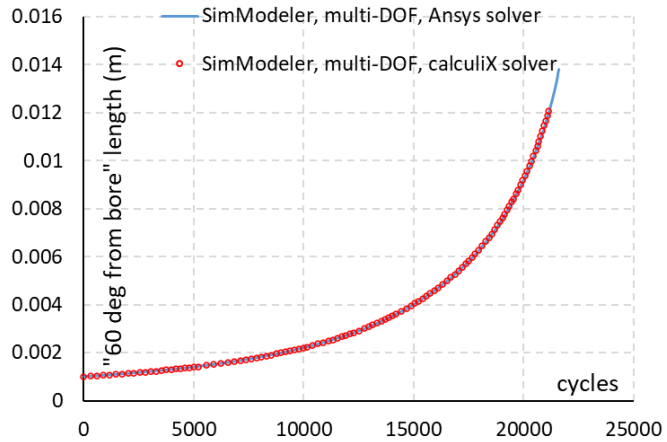


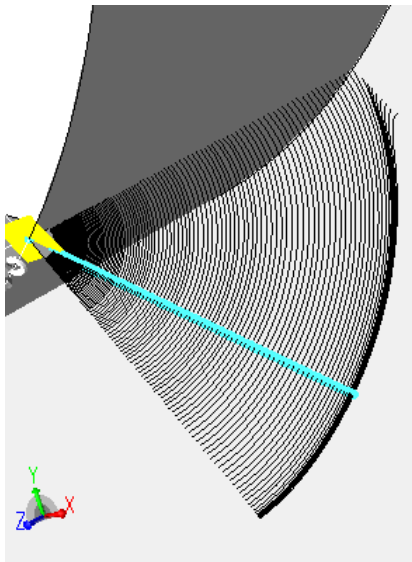












- This solution is consistent previous examples.
- AFGROW Plugin solution to follow

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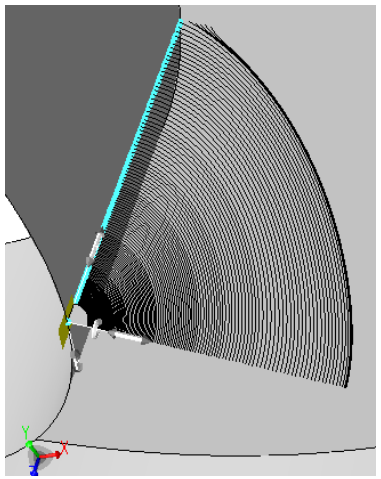
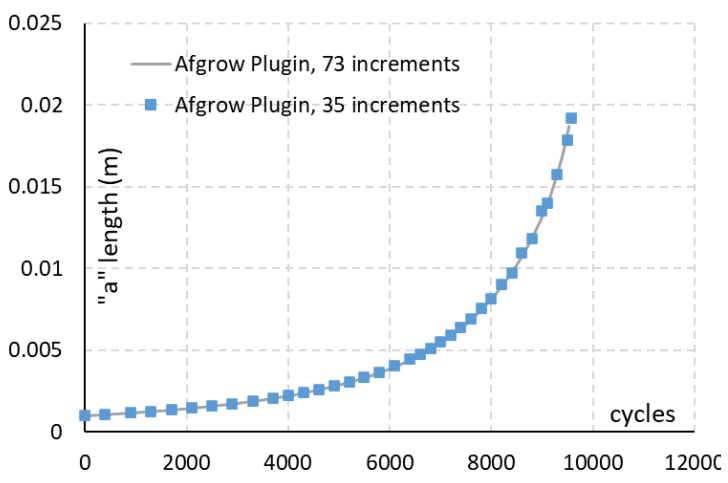
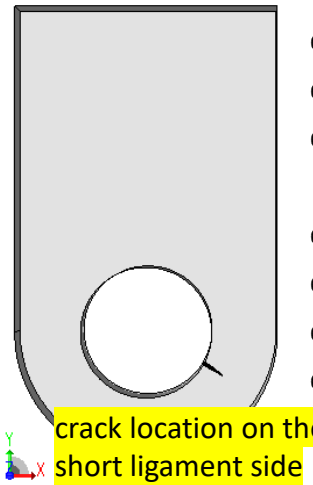
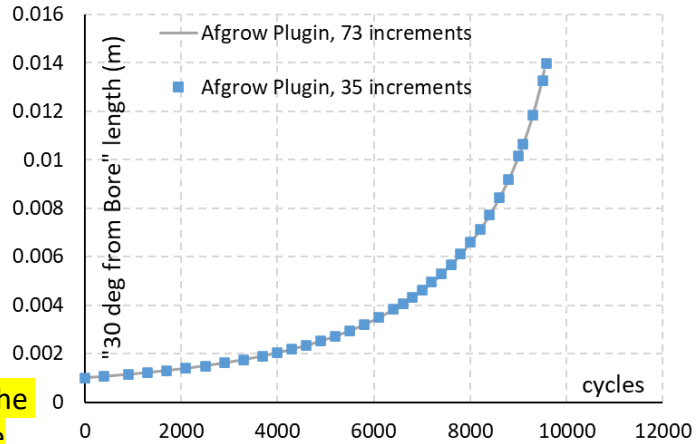
Verification benchmarking
Crack growth solution

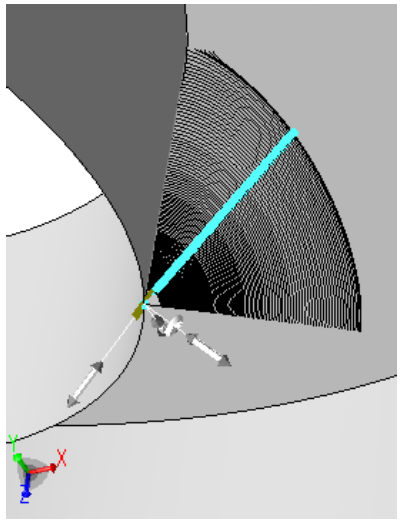
4-DOF Solutions: Quick Convergence Study

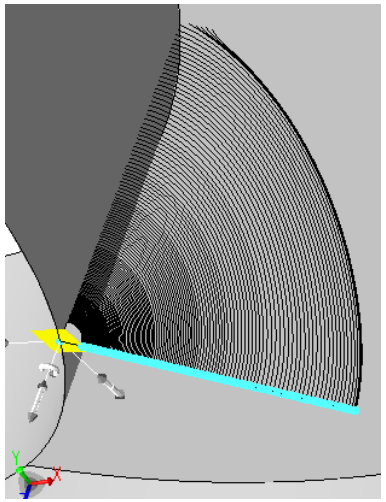


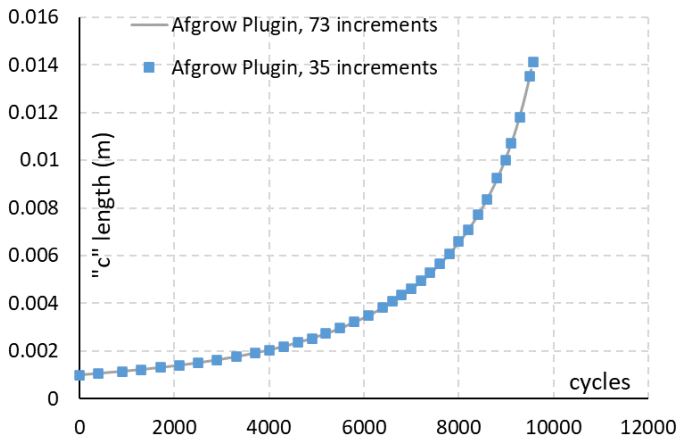


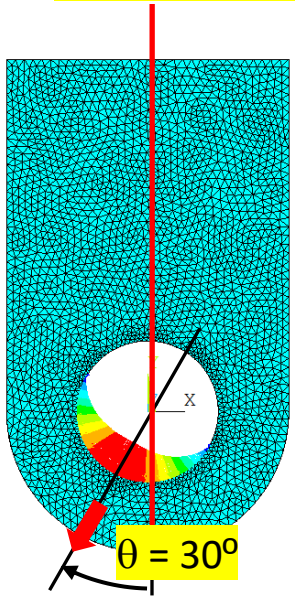


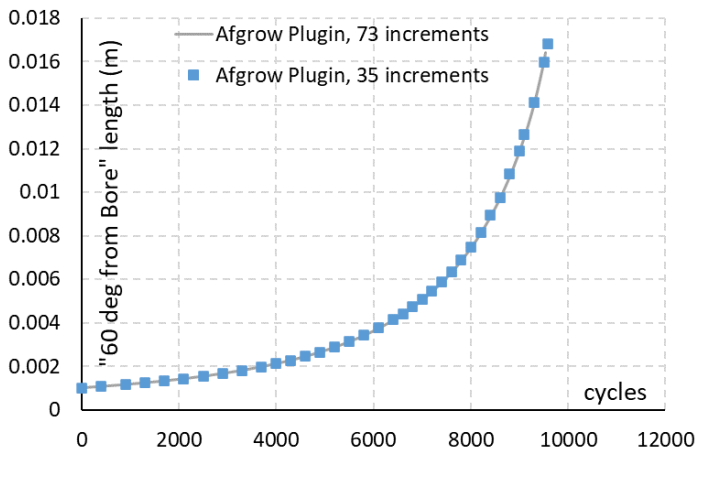


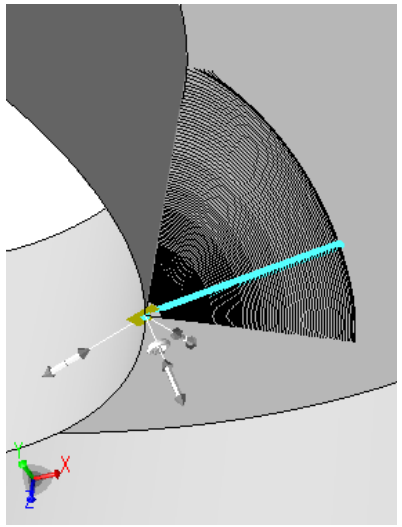










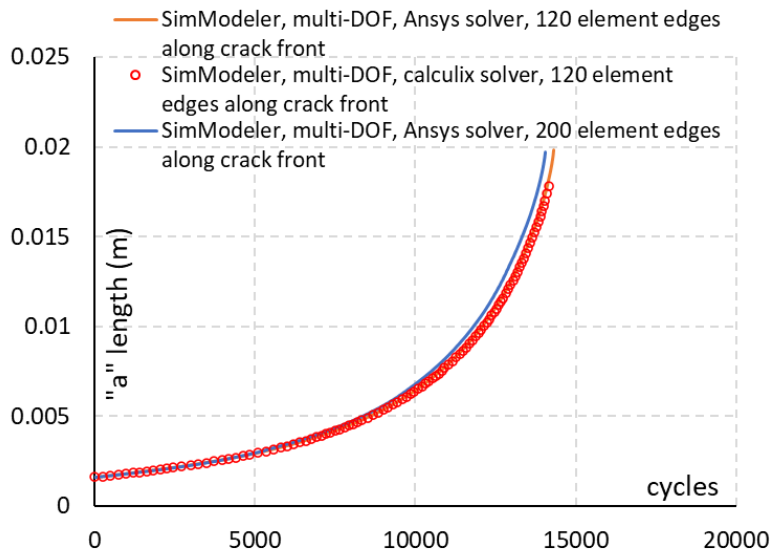


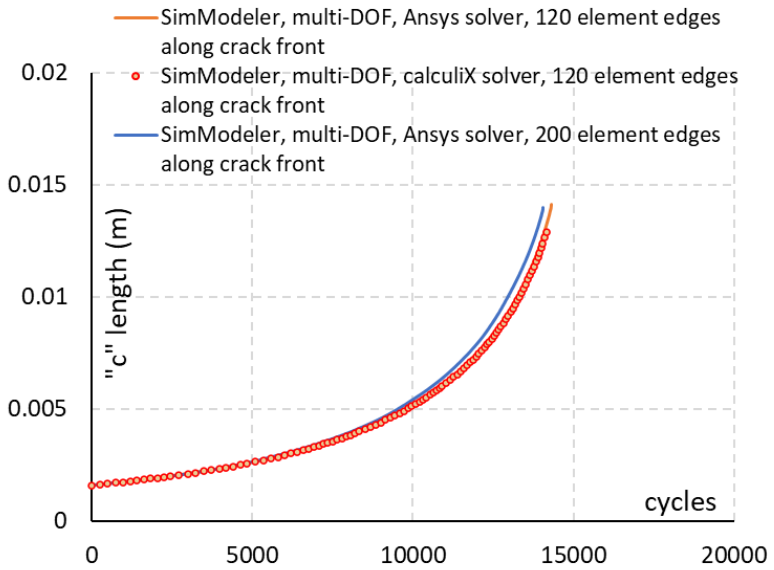
- Two 4-DOF solutions are performed: 35 and 73 increments.

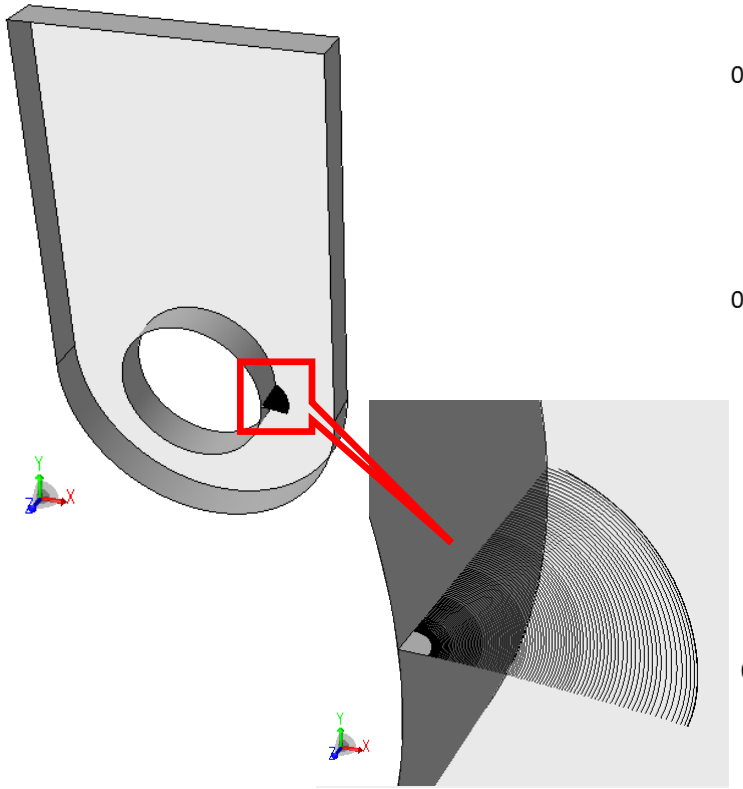
AFGROW Plugin 4-DOF solution convergence is demonstrated

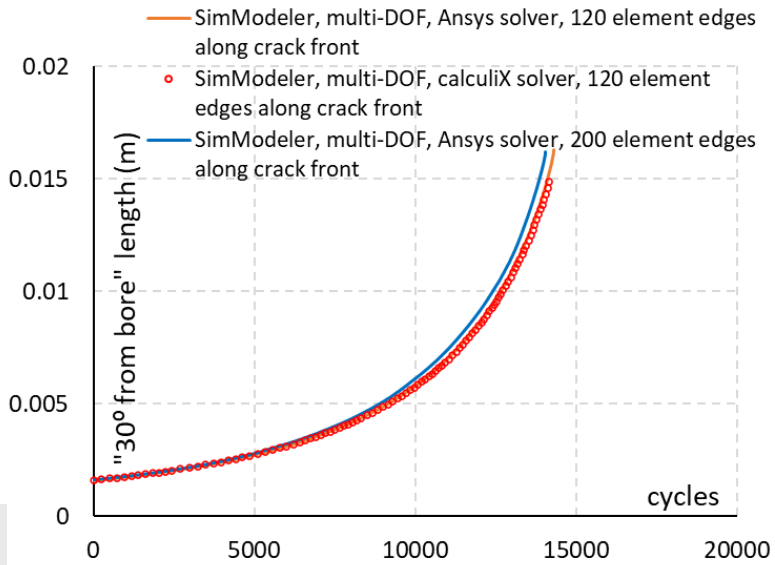
Verification benchmarking
Crack growth solution

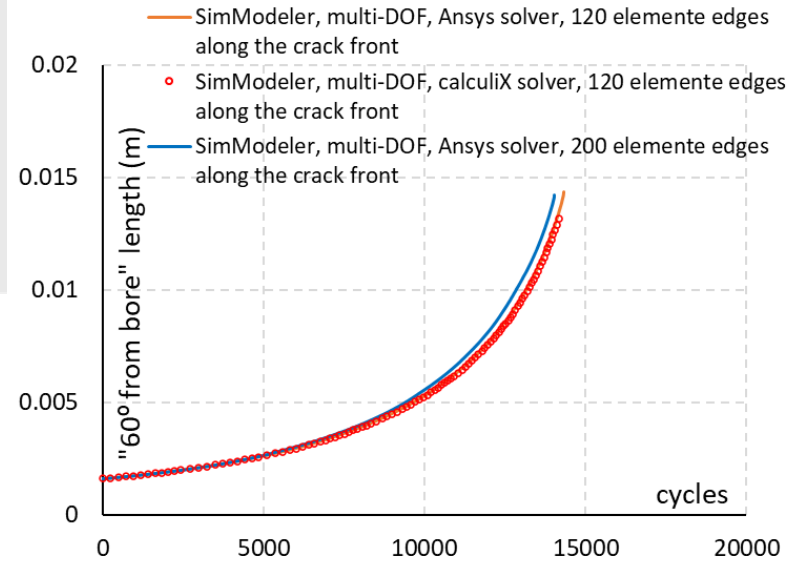
Multi-DOF Solutions: Quick Convergence Study











- Two multi-DOF solutions are performed: 120 and 200 element edges along crack front for each increment
- Very low difference (<2%) between the two crack front mesh refinements

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Conclusions

AFGROW model development: corner crack in a lug geometry under off-center axis loading

1. Baseline cases for a new AFGROW lug model implementation were developed.
2. Solution verification benchmarking was addressed for K_I calculation and remaining useful life. The multi-DOF solutions from two solvers were used as a reference for the 4-DOF Ansys Plugin solutions.

Overall:

1. Implementation is agnostic to the geometry. Component level geometries can be used in the Plugin.
2. AFGROW Plugin uses calculiX solver but, with a minimal update, Ansys or Abaqus solvers can be added as different processors.