AFGROW Users Workshop 2024

Automatic MultiDoF FEM Based Solutions Within AFGROW Tapered Lug Model Implementation

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Simmetrix Inc.

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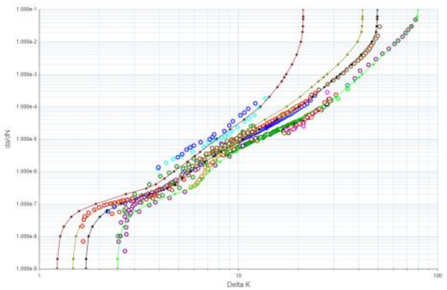
LexTech, Inc.

Agenda

- About AFGROW
- Handbook of FEA Crack Growth Solutions as organic growth of AFGROW capabilities
- SimModeler - Mesh/Pre/Post Engine behind AFGROW's Parametric multi-DoF modeling capability
- New Model Implementation: Corner crack in a tapered lug under off-axis tensile loading
- Overview of the previously completed work
- Problem setup and project goals
- Convergence study by increasing number of points on the crack front (DoFs)
- Oblique crack propagation verification
- Where do we go from here?

AFGROW: user-friendly and run-time efficient Linear Elastic Fracture Mechanics (LEFM) based crack growth life prediction tool that serves industry damage tolerance analysis needs

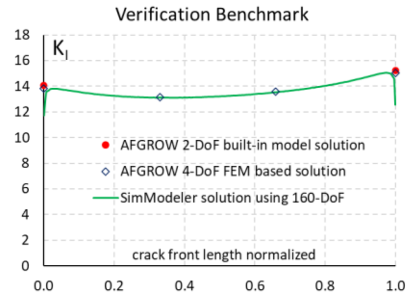


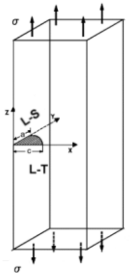
AFMAT

- Model based fits to FCGR datasets (Forman, Walker, NASGRO, Harter-T)
- Tabular entries for 100 materials
- User defined FCGR

V&V Benchmarking

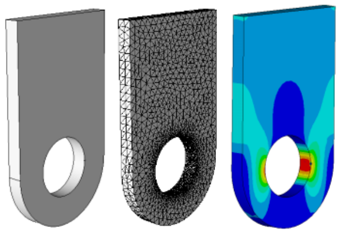
- Crack propagation life solution vs. experimental measurement
- K_I solution comparison against other solutions
- Solution convergence





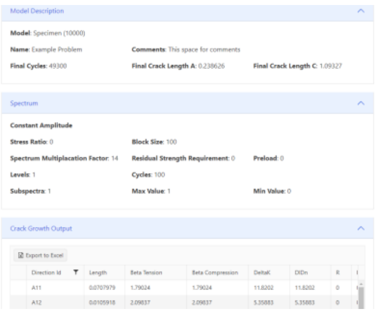
Modeling Capabilities

- 1-DoF and 2-DoF models (precompiled database, analytical formulations, user input - β table)
- Parametric Multi-DoF models (automatic 3D FEA based solution directly from AFGROW)
- Retardation models



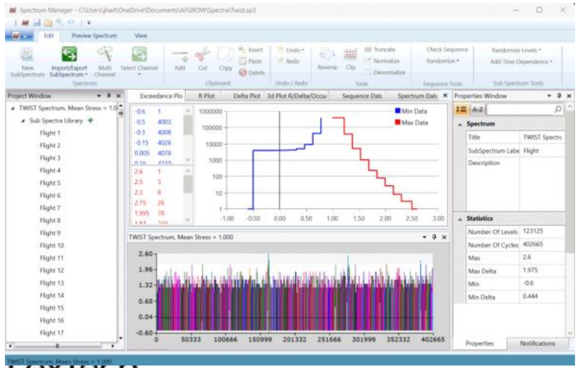
Output

- Postprocessor
- Plots/Reports
- Crack growth evolution graphics



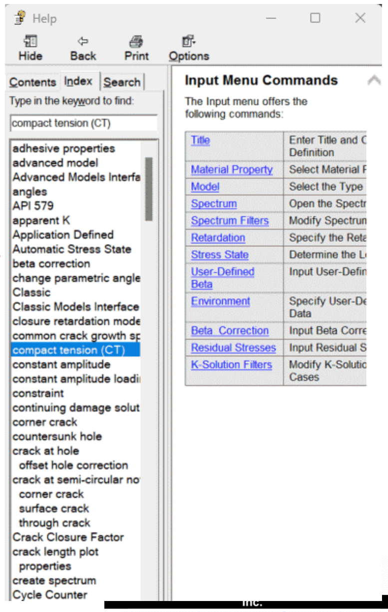
Spectrum Manager

- GUI
- Flight specific spectrum definition
- Loading spectrum generation & editing



Documentation

- Public access to all Workshop presentations
- Examples/Training
- Manuals/Context Sensitive Help



COM Interface

User Application

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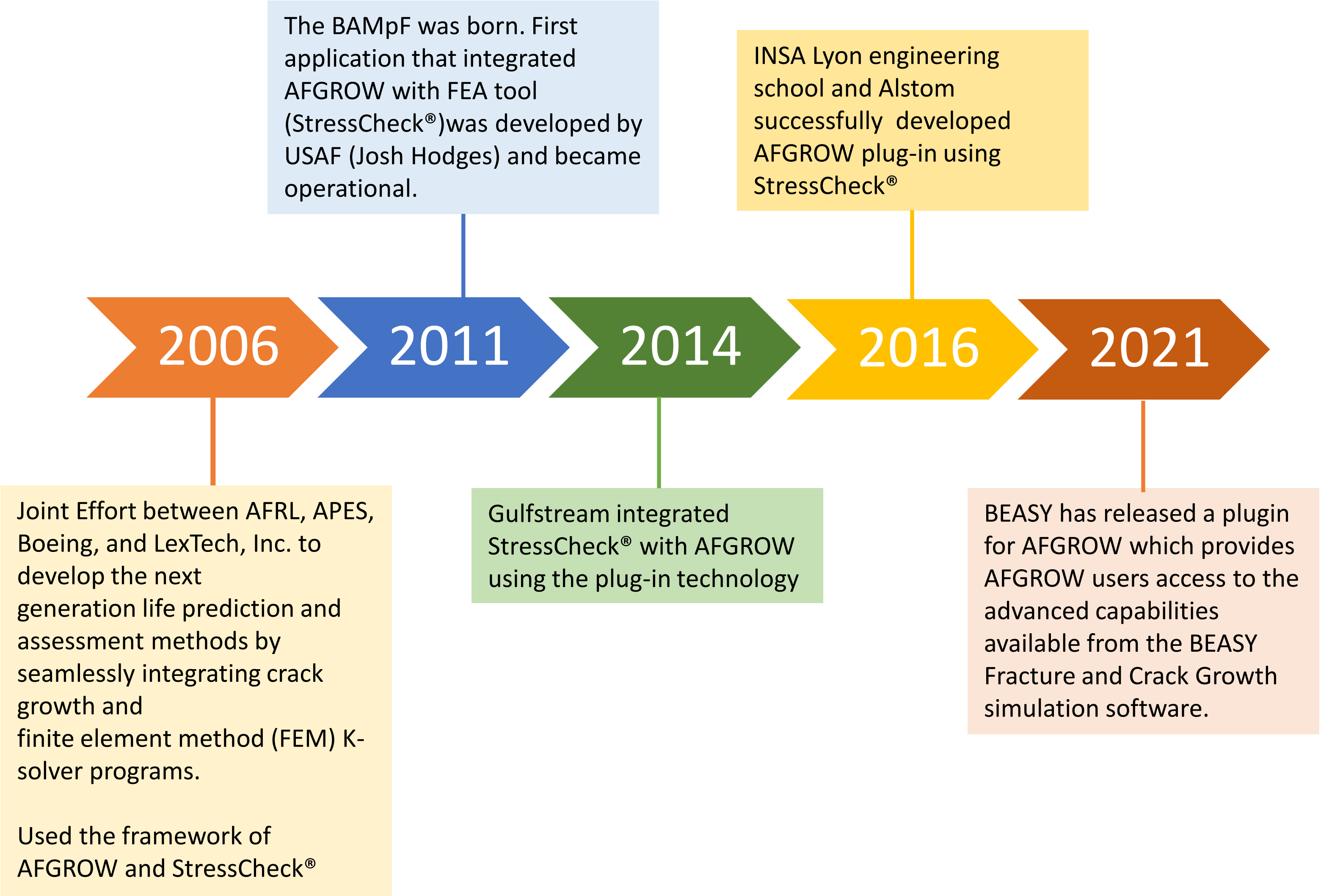
AFGROW FEA plug-in capability overview



- 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

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AFGROW: Extension of Modeling Capabilities

AFGROW .NET

Desired

- An AFGROW embedded modeling capability designed to easily extend the model database, improve solution accuracy and provide an easy user access.
- Automatic solution.

Benefits

- Reduce time-consuming new model development or additions to existing models.
- Improve solution accuracy by using multi-DoF crack front definition
- Geometry agnostic.
- Eliminate some modeling error sources due to curve fitting and analytical formulations.
- Same methodology can be used to automatically perform a fatigue crack growth solution or generate β-tables.

- Building of 3D geometry w/ and w/o crack definition using a parametric definition
- Control of number of DoF in crack front definition
- Robust mesh generation
- Input deck generation for model processing

3D model generation for each crack growth increment

Solver access & Batch Processing

FEM Solution Post-processing

- Model based identification of crack location and orientation
- FE solution-based K_I calculation
- Linkage with AFGROW functionality
- Crack front increment definition

Modeling Capabilities

Parametric multi-DoF modeling

AFGROW

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.

The Mesh/Pre/Post Engine behind AFGROW's Parametric multi-DoF Modeling Capability

AFGROW.NET

AFGROW's multi-DoF capability takes advantage of the fatigue crack growth modeling and general CAE modeling functionality developed over the past 20 years at Simmetrix Inc.

Geometry

- **Direct interface to CAD geometry**
- **Demonstrated component level functionality for crack insertion and propagation**
- **Geometry-mesh associativity maintained for crack growth solutions**

Meshing

- **Unstructured meshing and automatic compatibility with structured meshes**
- **Structured meshing process: boundary layer, thin-section, extrusion**
- **Automatic surface and volumetric meshing**
- **Meshing capabilities demonstrated for: single and multiple crack propagation simulation, crack at material interface, generic surface for crack definition in a solid model**

Interface

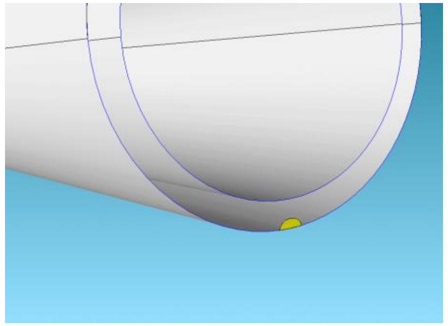
- **Plugins for different structural solvers: Abaqus, Ansys, calculiX**
- **Customers can write plugins to extend SimModeler to support specific modeling workflows**

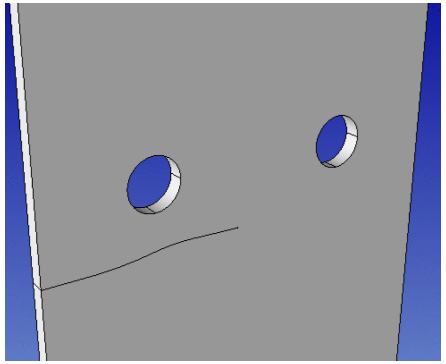
V&V

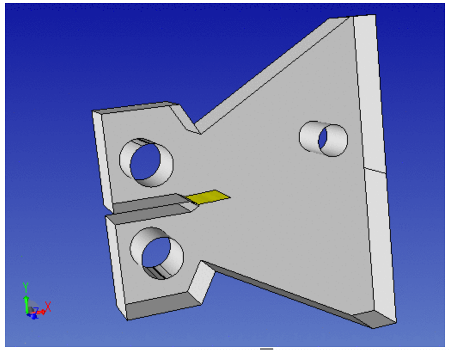
- https://afgrow.net/workshop/documents/2021/Robert_Pilarczyk_CrossComparisons_of_Stress_Intensity_Factors_from_Various_Sources-Workshop-2021.pdf
- https://www.arctosmeetings.com/agenda/airworthiness/2021/proceedings/presentations/P21320.pdf
- https://www.arctosmeetings.com/agenda/asip/2021/proceedings/presentations/P21624.pdf

More info

- https://www.researchgate.net/publication/325695699_LIFE_PREDICTION_MODELING_CAPABILITIES_FOR_FE_APPLICATIONS#fullTextFileContent
- **For more information, please send email to: loghin@simmetrix.com or info@simmetrix.com**







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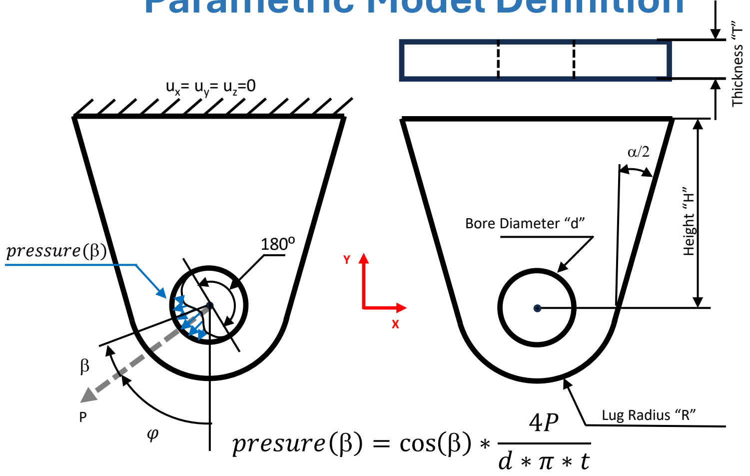
AFGROW: Extension of Modeling Capabilities

AFGROW .NET

Example of New Model Implementation: Corner Crack in a Tapered Lug under Off-axis Tensile Loading

Automatic FEM based crack propagation solution: How everything works

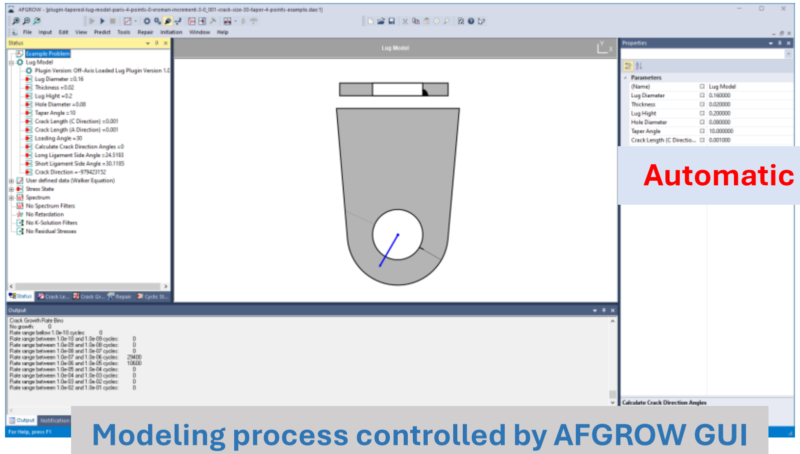
Parametric Model Definition



$$presure(\beta) = \cos(\beta) * \frac{4P}{d * \pi * t}$$

β = [-π/2, π/2] relative to the direction of the equivalent pin-bore concentrated load "P"

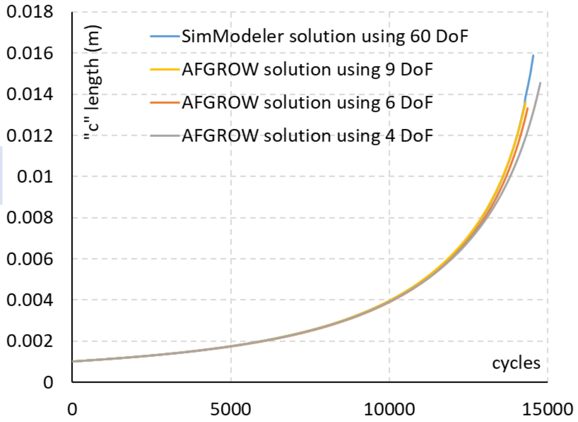
AFGROW user interface



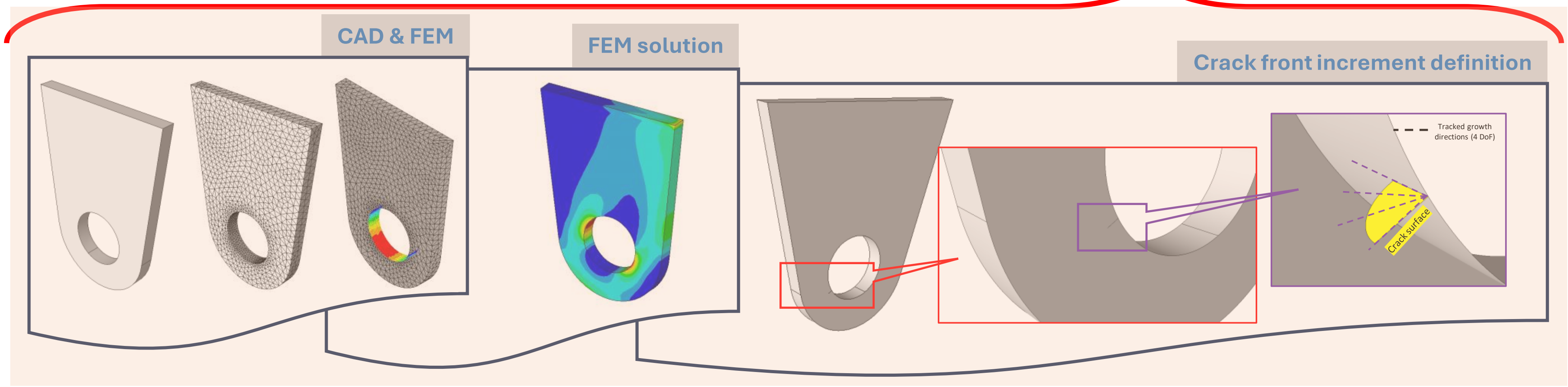
Automatic crack growth solution

Modeling process controlled by AFGROW GUI
Transparent to the end-user

Solution postprocessing



- Runtime: 1 min / crack growth increment
- Verification & solution convergence



Same modeling process is followed for a different geometry or loading definition

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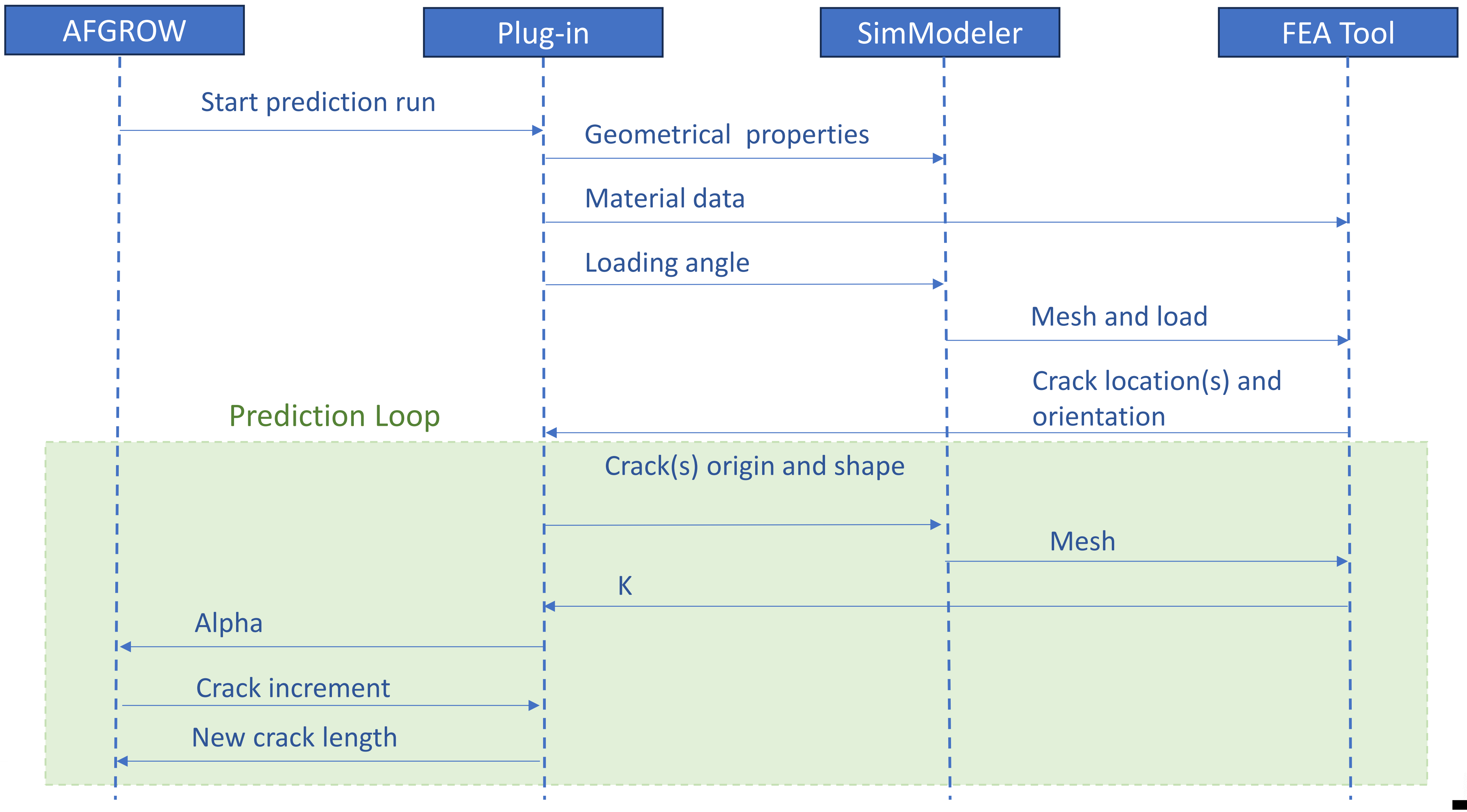
Plugin Model Implementation in AFGROW

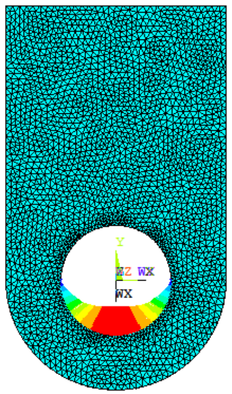


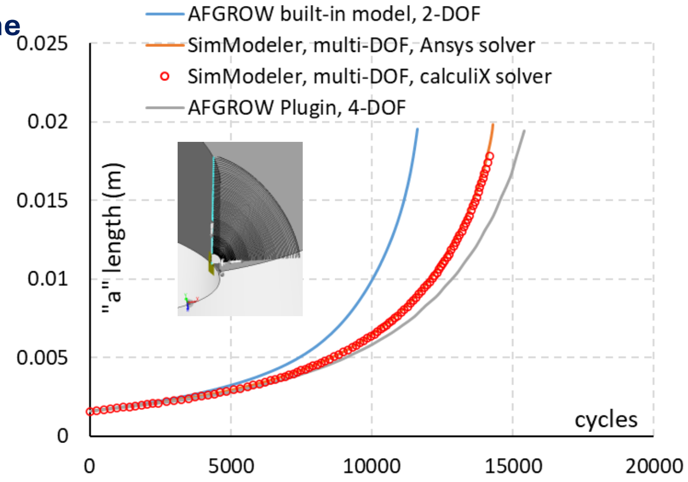
AFGROW: Extension of Modeling Capabilities

AFGROW Workshop 2023 - Review of last year's presentation

- ✓ New lug model development was introduced.
- ✓ Verification of K_I solution from new 3DFEA-based model implementation was made against the legacy 2-DoF solution
- ✓ Four baseline cases (one straight lug geometry, four different loading directions), were used to pass K_I and remaining useful life verification benchmarking for a 4-DoF AFGROW solution (multi-DoF 3DFEA/SimModeler used as a reference)
- ✓ All verification conclusions were made only for part-through cracks (up to transition to an oblique-edge crack shape)
- ✓ Both long-ligament and short-ligament crack locations were used for verification benchmarking purposes
- ✓ Solution convergence was demonstrated for the 4-DoF AFGROW solution as well as the multi-DoF 3DFEA/SimModeler solution
- ✓ Using two solvers (calculiX, Ansys), it was demonstrated that the remaining useful life solution (using the multi-DoF 3DFEA) does not change. AFGROW Plugin uses calculiX solver but, with a minimal update, Ansys or Abaqus solvers can be added as different processors.
- ✓ Automatic AFGROW modeling process using 3DFEA-based modeling process was reported (up to crack shape transition, from corner to edge)

Loading Axis at 0º from the symmetry plane





More development was added in the past year

Current Development Goals

- Integrate a Tapered Lug in the modeling process into AFGROW GUI
- Automate locations and propagation planes (short/long ligament sides) are identification
- Use SimModeler as independent verification tool
- Demonstrate solution convergence with an increased number of points on the crack front (DoFs)
- Verify corner crack transition to oblique crack and oblique crack propagation

Problem Setup

AFGROW .NET

Model Properties

(Name)	Lug Model
Lug Diameter	0.160000
Thickness	0.020000
Lug Hight	0.200000
Hole Diameter	0.080000
Taper Angle	30.000000
Crack Length (C Direction)	0.001000
Crack Length (A Direction)	0.001000
Loading Angle	30.000000
Calculate Crack Direction Angles	Enabled
Long Ligament Side Angle	0.000000
Short Ligament Side Angle	0.000000
Crack Direction	Short Ligament Side

Constant Amplitude Load

Predict Preferences

Predict Function Preferences

- Growth Increment
- Output Intervals
- Output Options
- Propagation Limits
- Transition Options
- Lug Boundary Conditions
- Finite Width Effect
- Crack Closure Factor
- Bending

AFGROW uses the Vroman integration technique when a blocked spectrum is input. To minimize an error in predicted crack propagation times it is not recomended for Max Growth Increment value to exceed 10%.

Select

Max Growth Increment (%): 3

- [ ] Cycle by Cycle Spectrum calculation
- [ ] Cycle by Cycle Beta and Spectrum calculation

Stop Crack Propagation at:

- [ ] Crack Length
- [ ] Cycle Count
- [x] 'Kmax' Failure Criteria
- [ ] User-Defined 'Kmax'
- [ ] 'Net Section Yield' Failure Criteria
- [ ] Part Through Crack Transition

Material (Paris Equation)

Walker Equation Data

The Walker equation extended the early Paris equation by allowing the shift in da/dN vs. Delta K as a function of stress ratio (R). The equation may be used in several segments to attempt to model the sigmoidal shape of the data.

Use up to 5 sets of values of 'C', 'n', and 'm'

Number of Sets: 1

Set	C	n	m
1	1.0824e-11	3.63	0.5
2	1.9144e-10	3	0.5
3	1.9144e-10	3	0.5
4	1.9144e-10	3	0.5
5	1.9144e-10	3	0.5

Material name: User defined data

Coefficient of Thermal Expansion: 2.25e-05   Young's Modulus: 72394.9

Yield Strength, YLD : 324.054   Poisson's Ratio: 0.33

Plane Stress Fracture Toughness, KC: 109.884

Plane Strain Fracture Toughness, KIC: 31.866   Lower limit on R shift (0.. -1): -0.2

Delta K threshold value @R=0 : 2.198   Upper limit on R shift (< 1): 0.8

OK   Cancel   Save   Read   Apply

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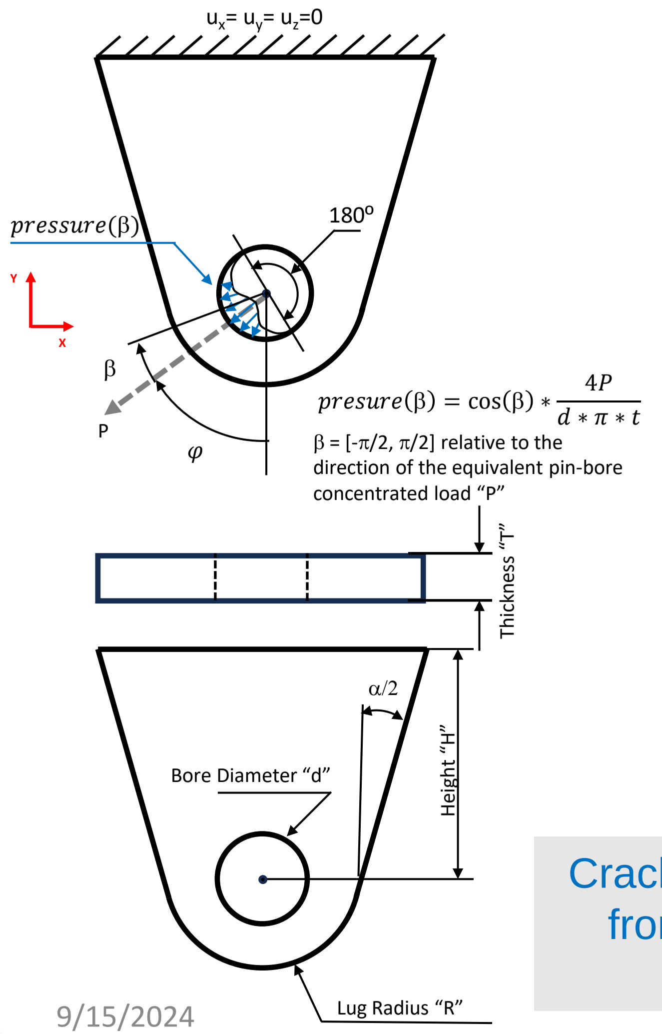
AFGROW: Extension of Modeling Capabilities

Example of New Model Implementation: Corner Crack in a Tapered Lug under Off-axis Tensile Loading

Automatic model creation

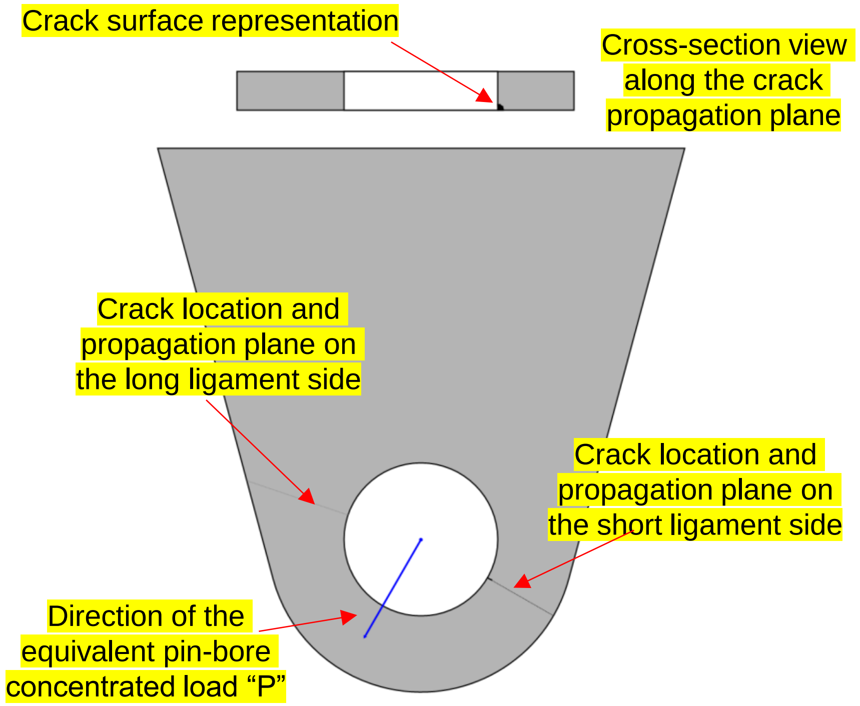
Parametric Model Definition



User's access to model definition

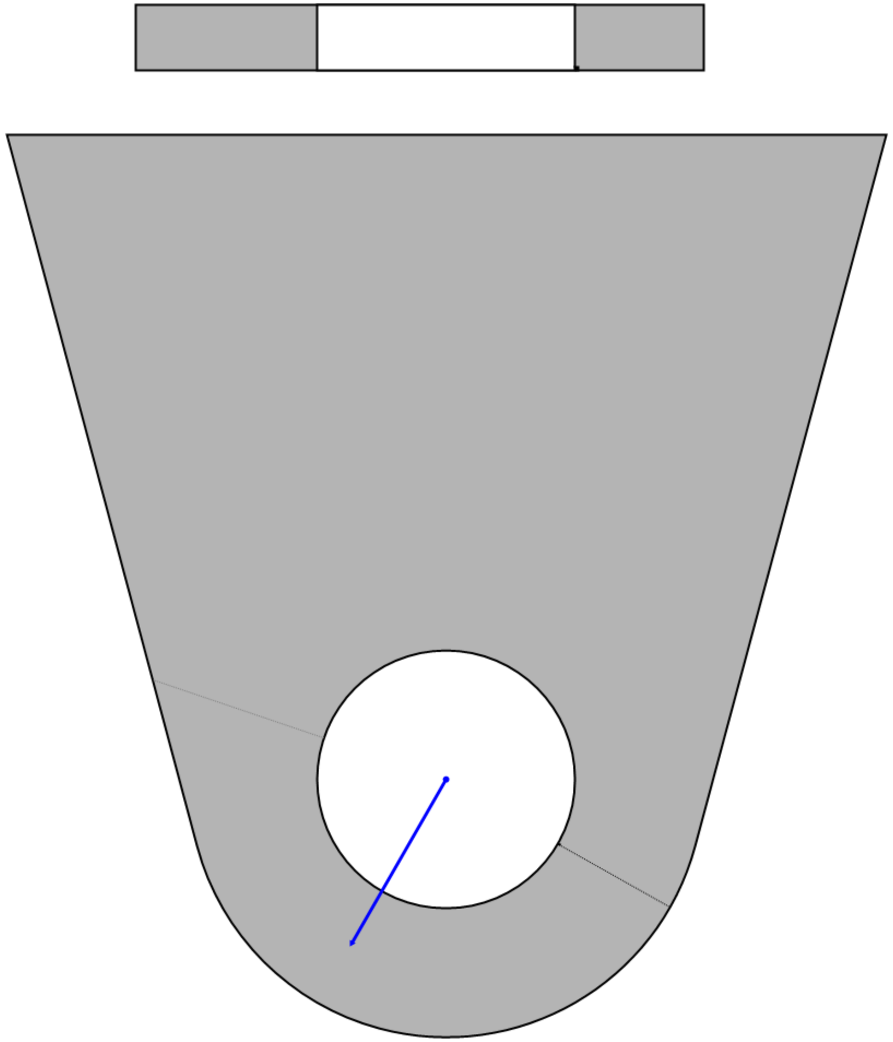
Parameters	
(Name)	Off-Axis Loaded Lug
Lug Diameter	0.160000
Thickness	0.020000
Lug Hight	0.204000
Hole Diameter	0.080000
Taper Angle	**30.000000**
Crack Length (C Dir...	**0.003000**
Crack Length (A Dir...	**0.003000**
Loading Angle	**30.000000**
Calculate Crack Dir...	Enabled
Long Ligament Sid...	18.632690
Short Ligament Sid...	30.103925
Crack Direction	Short Ligament Side

Graphical feedback for the end-user



Crack locations and propagation planes (short/long ligament sides) are identified automatically from a 3D FEA solution. Any error associated with an analytical formulation between crack plane and loading direction is eliminated.

Solution Convergence Demonstration



Parametric angles of the points on the crack front

4 points:
0 °, 30°, 60°, 90°.

6 points:
0°, 10°, 30°, 60°, 80°, 90°.

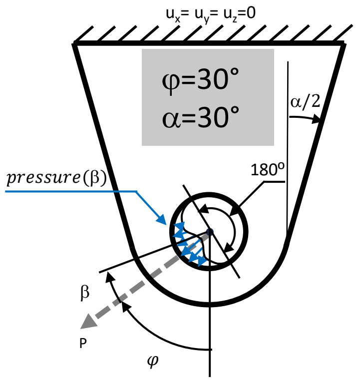
9 points:
0°, 10°, 20°, 30°, 45°, 60°, 70, 80 °, 90°

AFGROW: Extension of Modeling Capabilities

Example of New Model Implementation: Corner Crack in a Tapered Lug under Off-axis Tensile Loading

Automatic crack growth modeling process

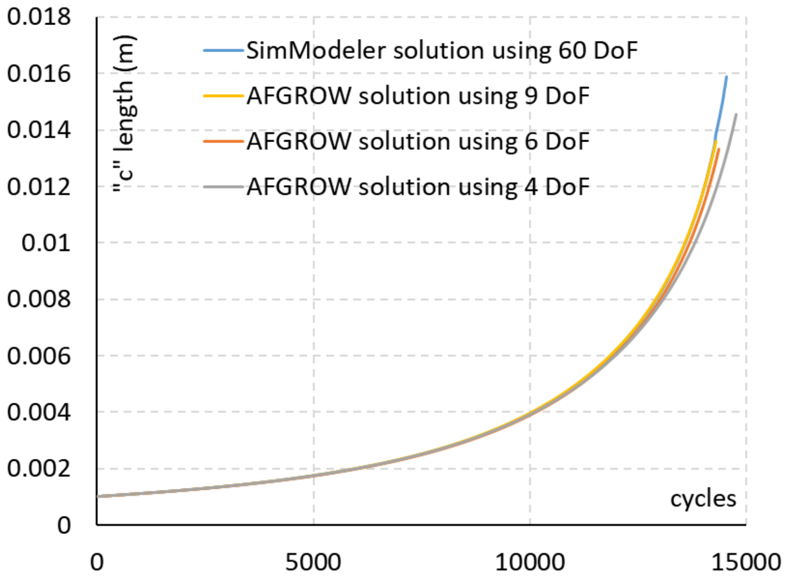
Convergence study to demonstrate solution convergence with an increased number of DoFs

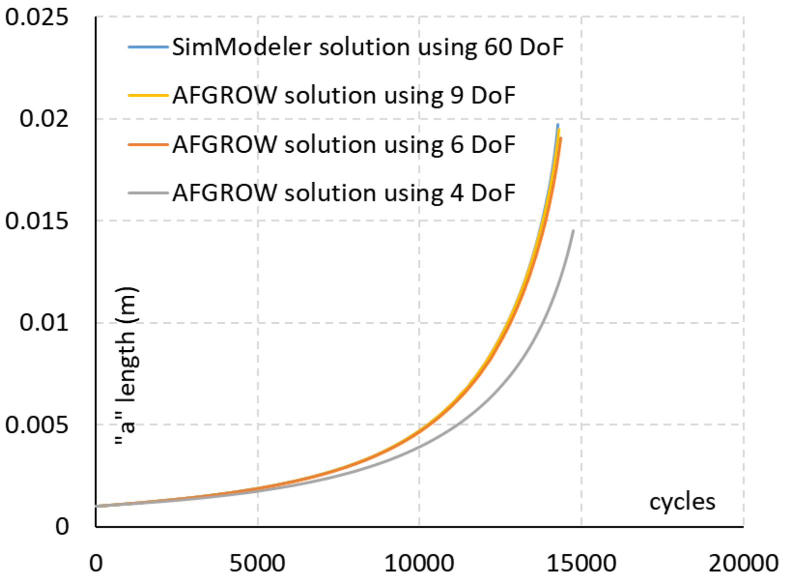


Parameters	
(Name)	Lug Model
Lug Diameter	0.160000
Thickness	0.020000
Lug Hight	0.200000
Hole Diameter	0.080000
Taper Angle	30.000000
Crack Length (C Direction)	0.001000
Crack Length (A Direction)	0.001000
Loading Angle	90.000000
Calculate Crack Direction Angles	Enabled
Long Ligament Side Angle	0.000000
Short Ligament Side Angle	0.000000
Crack Direction	Short Ligament Side

Length [m] {C, n} = {1.0825e-11, 3.63}

Angle [deg] Units: ΔK [MPa*m^0.5], da/dN [m/cycles]





Some conclusion

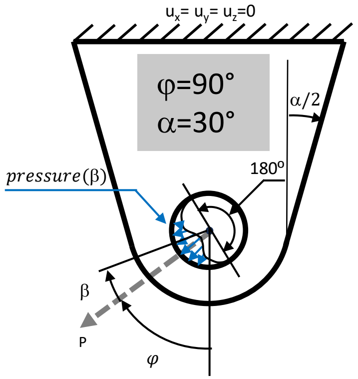
AFGROW: Extension of Modeling Capabilities

AFGROW .NET

Example of New Model Implementation: Corner Crack in a Tapered Lug under Off-axis Tensile Loading

Automatic crack growth modeling process: AFGROW Model Verification (φ=90°, α=30°)

Model input



Parameters	
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Hole Diameter	0.080000
Taper Angle	30.000000
Crack Length (C Direction)	0.001000
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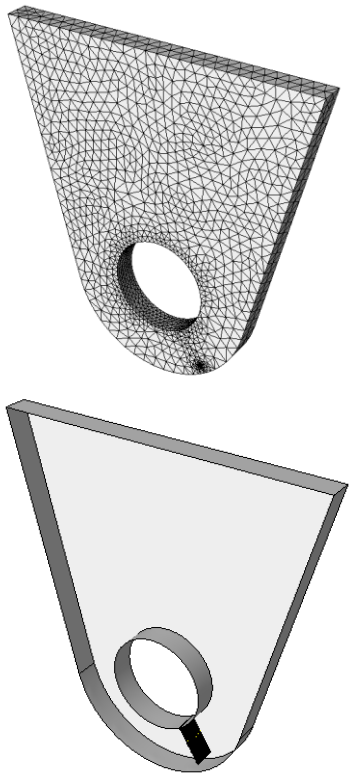
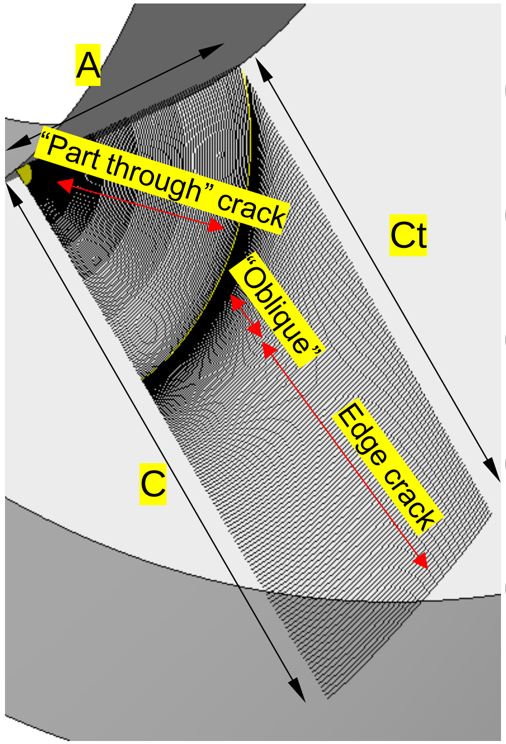
Loading Angle	90.000000
Calculate Crack Direction Angles	Enabled
Long Ligament Side Angle	0.000000
Short Ligament Side Angle	0.000000
Crack Direction	Short Ligament Side

Length [m]
Angle [deg]

{C, n} = {1.0825e-11, 3.63}
Units: ΔK [MPa*m^0.5], da/dN [m/cycles]

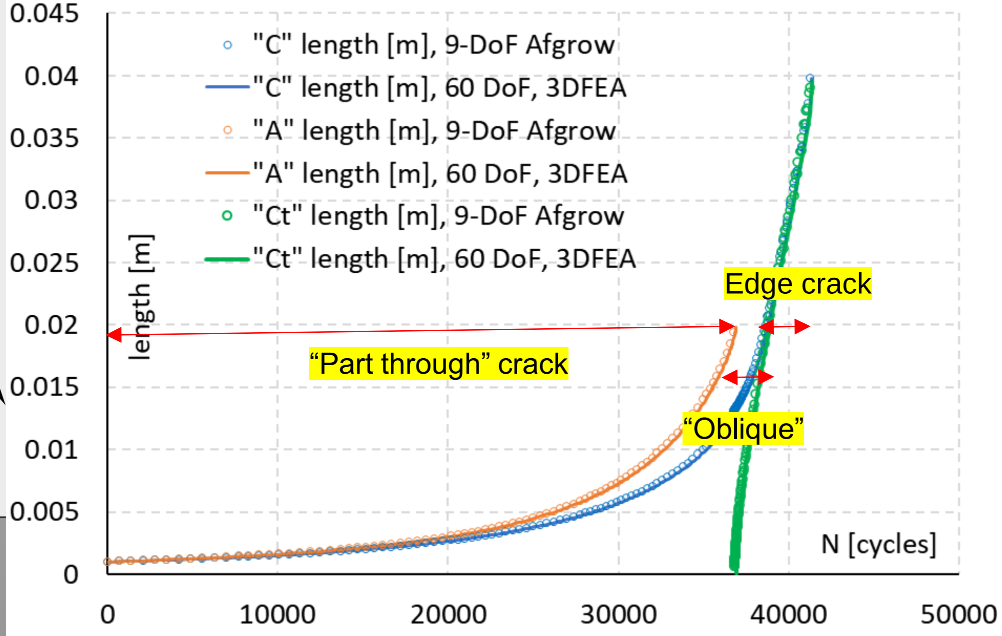
3D FEA Solution used as a reference





Runtime/increment = 15 sec

9-DoF AFGROW solution vs. 60-DoF 3DFEA Solution verification



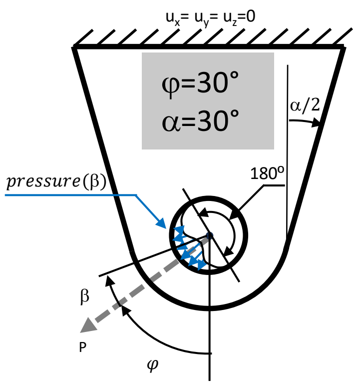
For the same mesh density, AFGROW's 9-DoF solution captures accurately the 60-DoF solution (SimModeler)

AFGROW: Extension of Modeling Capabilities

Example of New Model Implementation: Corner Crack in a Tapered Lug under Off-axis Tensile Loading

Automatic crack growth modeling process: AFGROW Model Verification (φ=30°, α=30°)

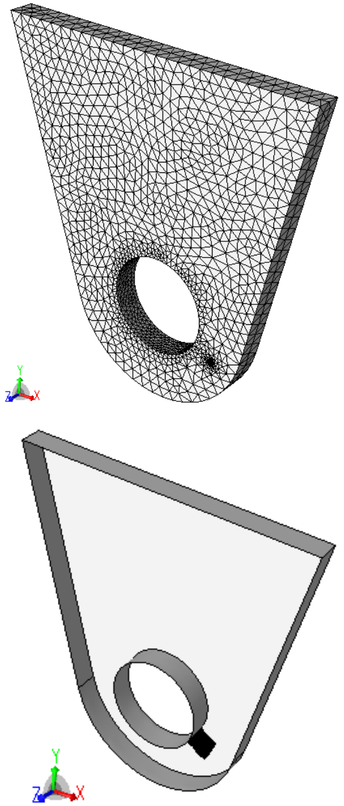
Model input

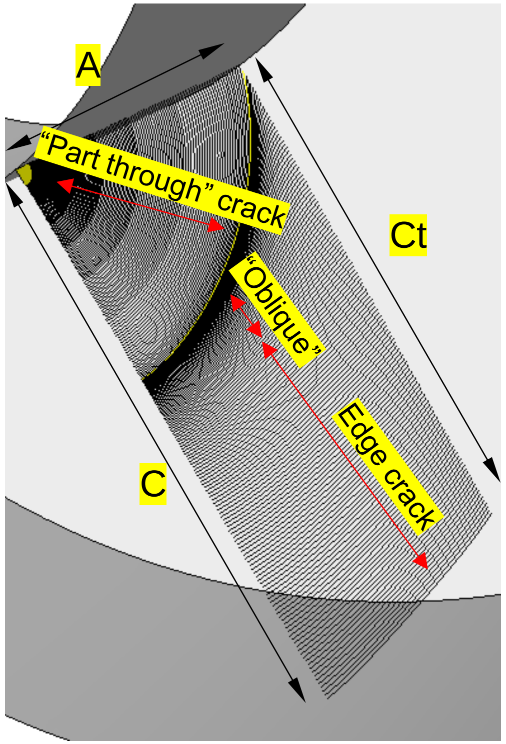


Parameters	
(Name)	Lug Model
Lug Diameter	0.160000
Thickness	0.020000
Lug Hight	0.200000
Hole Diameter	0.080000
Taper Angle	30.000000
Crack Length (C Direction)	0.001000
Crack Length (A Direction)	0.001000
Loading Angle	90.000000
Calculate Crack Direction Angles	Enabled
Long Ligament Side Angle	0.000000
Short Ligament Side Angle	0.000000
Crack Direction	Short Ligament Side

Length [m] {C, n} = {1.0825e-11, 3.63}
Angle [deg] Units: ΔK [MPa*m^0.5], da/dN [m/cycles]

3D FEA Solution used as a reference





Runtime/increment = 15 sec

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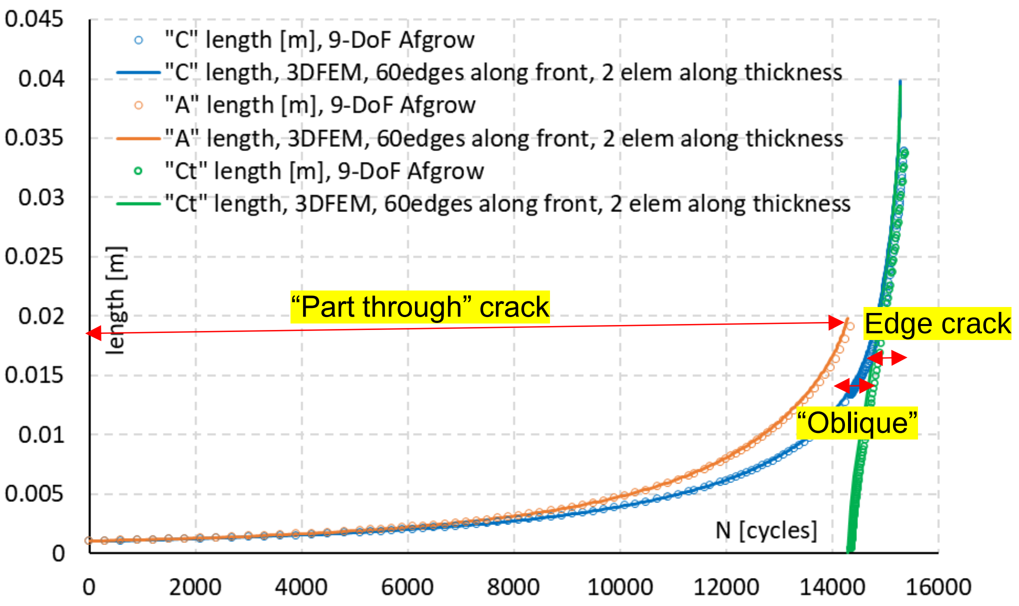


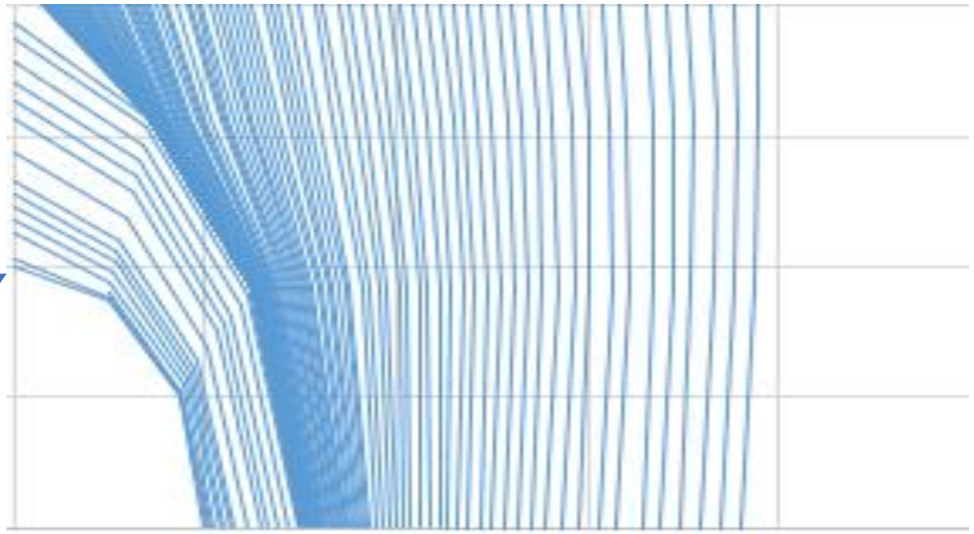
For the same mesh density, AFGROW's 9-DoF solution captures accurately the 60-DoF solution (SimModeler)

AFGROW: Extension of Modeling Capabilities

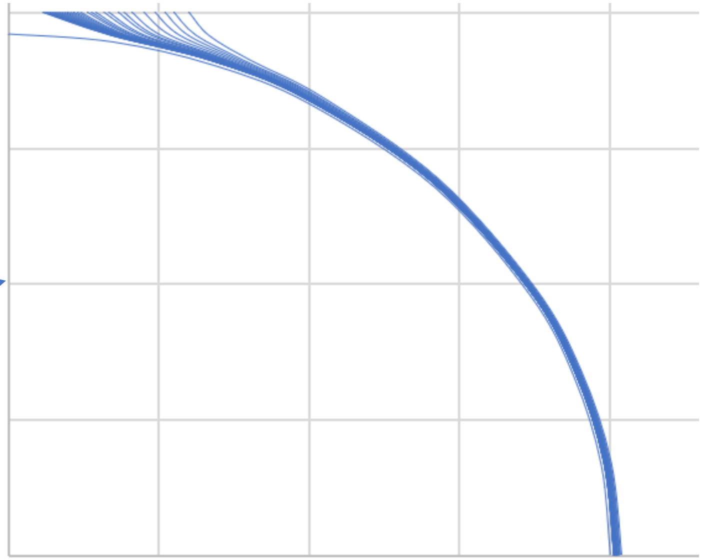
AFGROW.NET

Example of New Model Implementation: Corner Crack in a Tapered Lug under Off-axis Tensile Loading

Modeling of crack shape transition



95% thickness penetration transition to 1.05*T virtual A, 4 Points



95% thickness penetration transition to 1.05*T virtual A, 9 Points

Proposed Models for the Handbook of FEA Crack Growth Solutions

- Corner crack in a tapered lug geometry under off-center axis loading
- Corner crack at hole with thickness change (gradual or step)
- **Anything else?**