HILL ENGINEERING
Predict. Test. Perform.

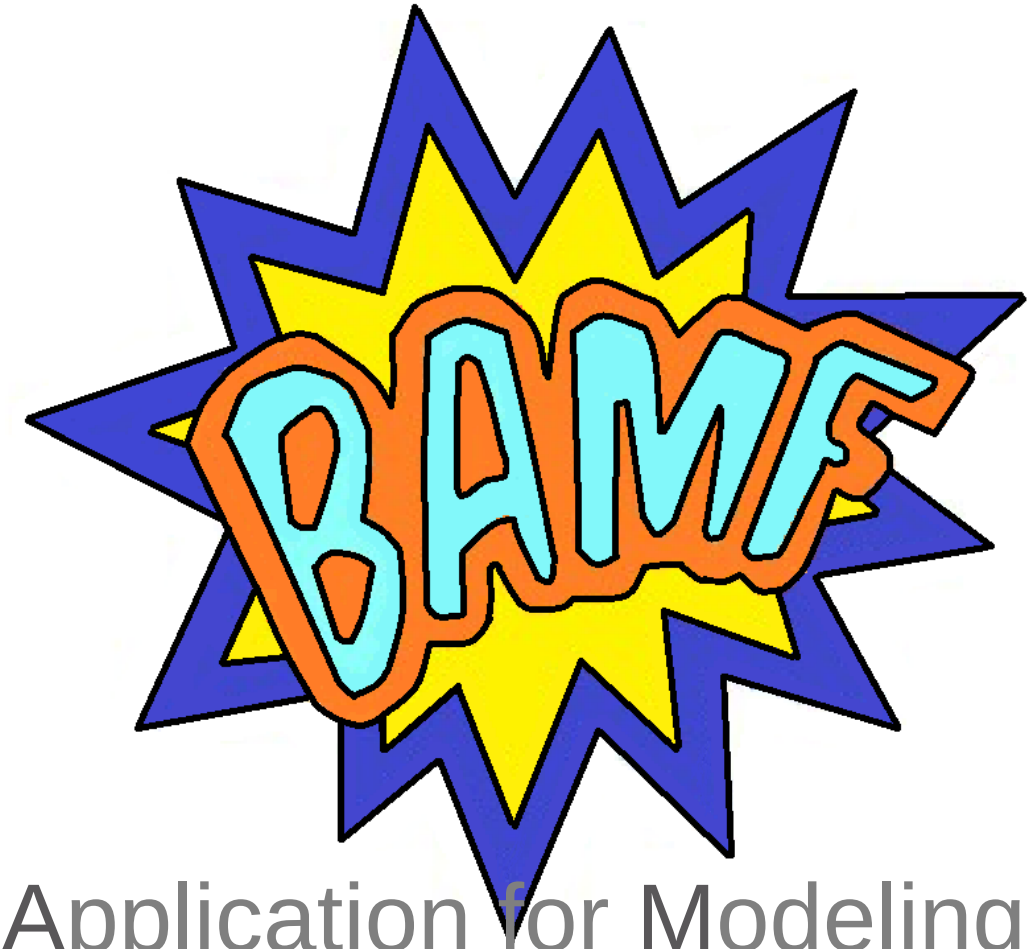
BAMF Workshop 2019

September 11, 2019

Agenda

- ❑ **BAMF Overview**
- ❑ **Major Events**
- ❑ **Updates and Bug Fixes**
- ❑ **BAMF Utilization: From the User Community**
  - ➢ Kaylon Anderson: NTSB, Oddities seen when running BAMF
  - ➢ Brian Boeke: Upper Longeron BAMF Simulation
  - ➢ Renan Ribeiro/Mike Hill: Fatigue crack growth testing and modeling of coupons with quench-induced residual stress
  - ➢ A-10/Hill Engineering: Re-lifing Ain't all its Cracked up to be
  - ➢ Scott Carlson: Analytical Comparisons of Determination Methods
- ❑ **New Release Features**
- ❑ **BAMF Future**
  - ➢ Proposed Features and Upgrades

What is BAMF?

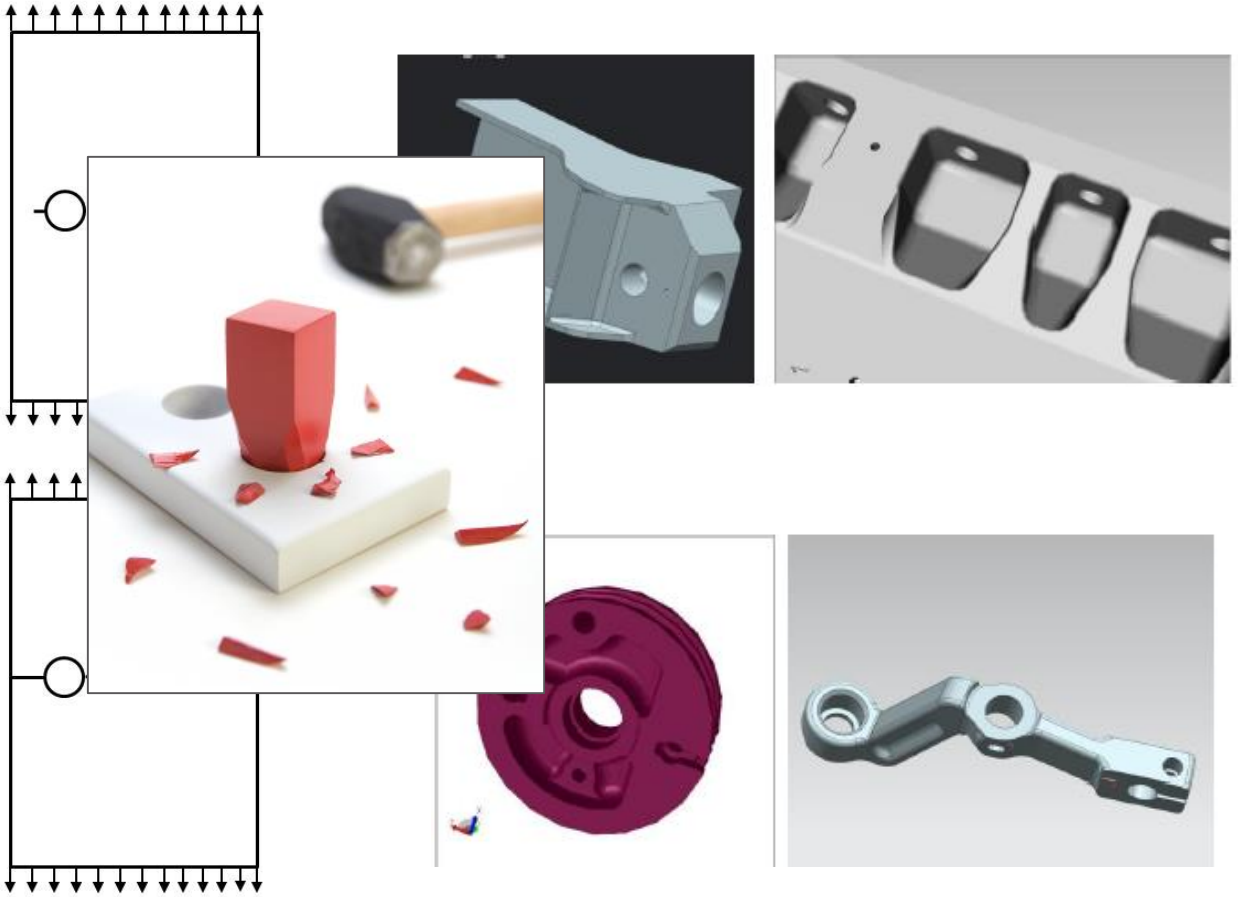


Broad Application for Modeling Failure

Motivation

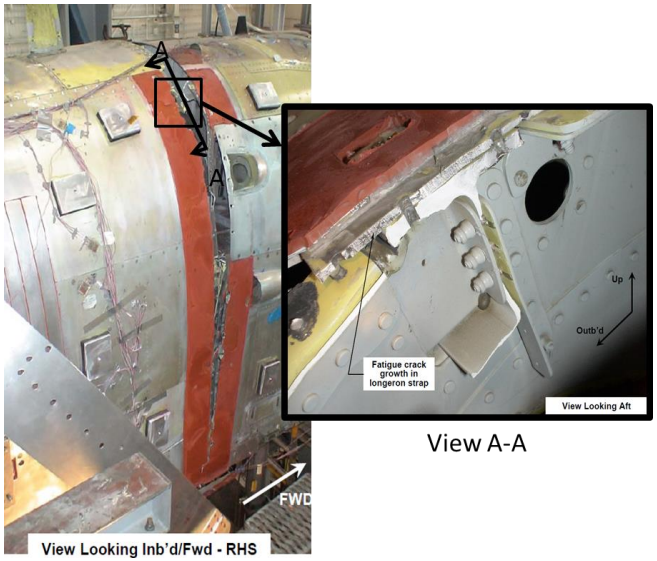
Classic Model

Classic Continuing Damage Model

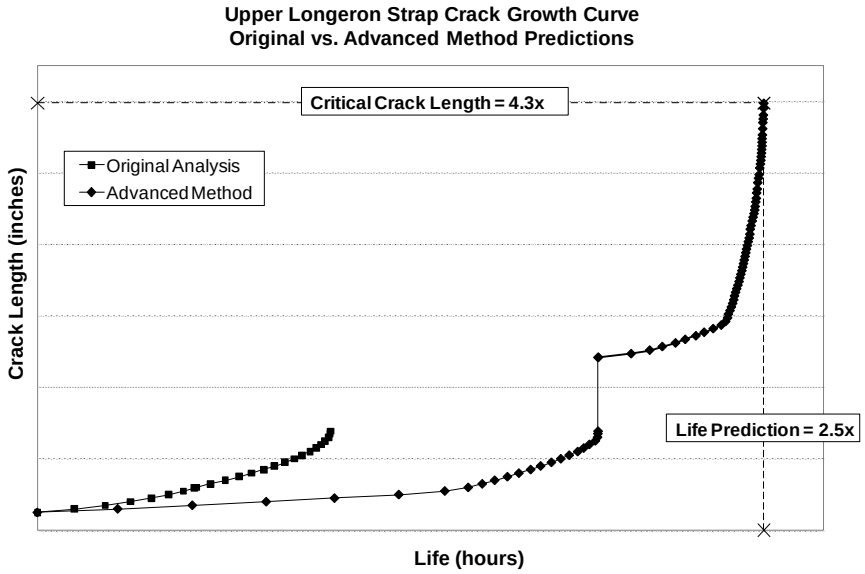


Motivation

- Conservative assumptions can often result in analyses that drive “Ground the Fleet” decisions
- How do we minimize the assumptions we must make and increase the accuracy of our analytical predictions?

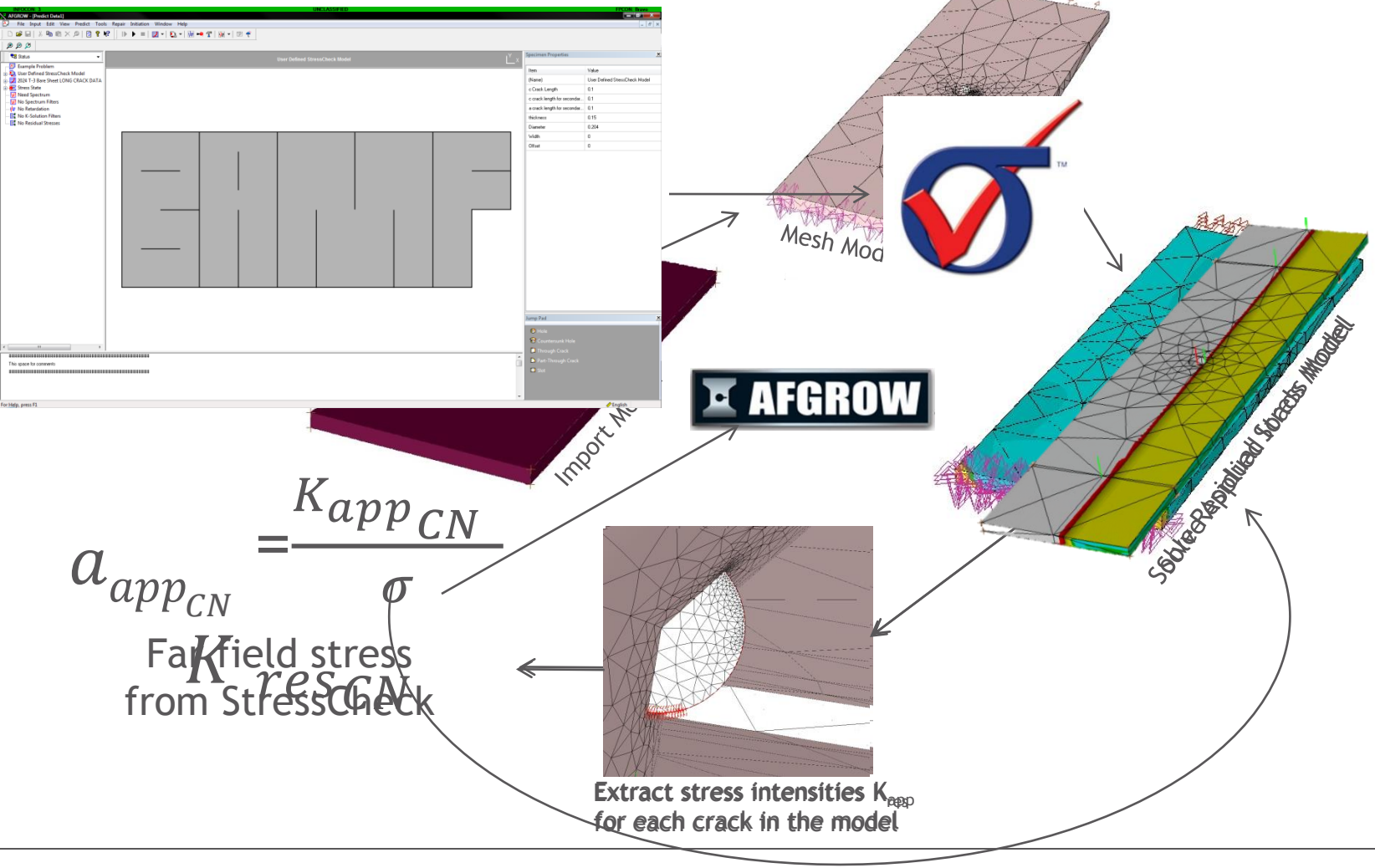


View A-A



Ref: AFGROW Workshop 2010, A-10 Modeling Methods to Support Damage Tolerance Analyses, Fleet Sustainment and Repairs, Pilarczyk, Sedgwick, Stowe.

BAMF Process Flow



$$a_{app_{CN}} = \frac{K_{app_{CN}}}{\sigma}$$

Far field stress from StressCheck

$K_{res_{CN}}$

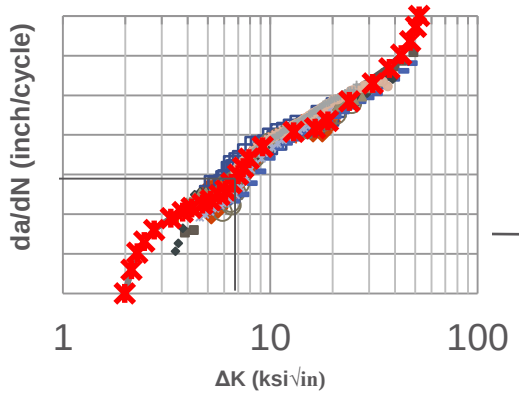
BAMF Process Flow

$$K_{min_{CN}} = a_{app_{CN}} \sigma_{min} + K_{res_{CN}}$$

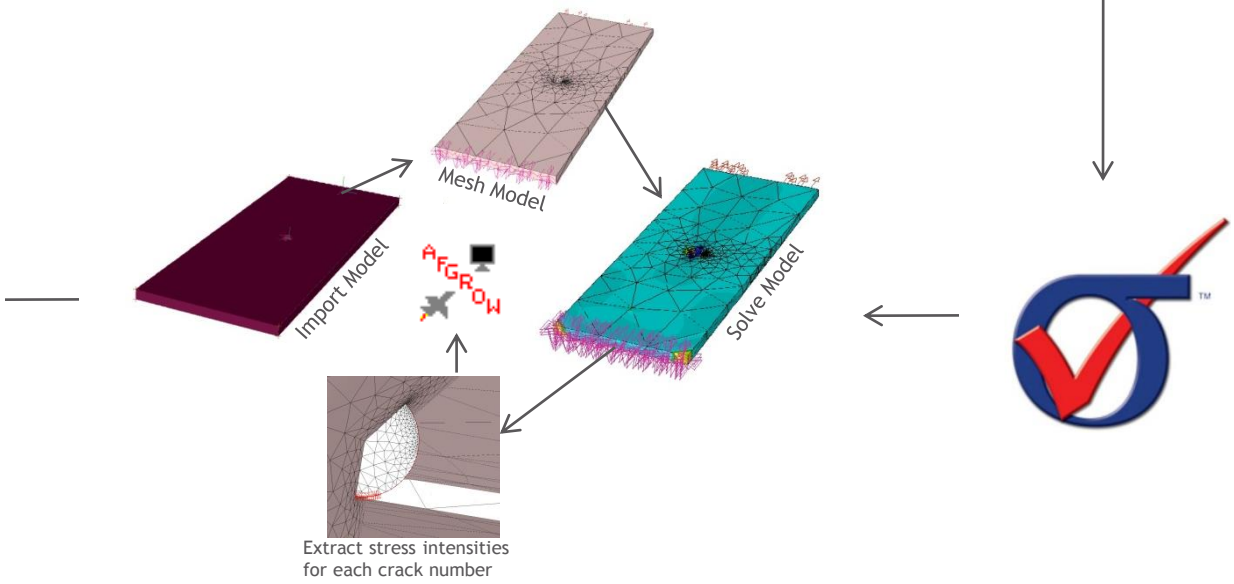
$$K_{max_{CN}} = a_{app_{CN}} \sigma_{max} + K_{res_{CN}}$$

Where $\sigma_{min/max}$ is the AFGROW spectrum stress

$$R_{CN} = K_{min_{CN}} / K_{max_{CN}}$$



New Crack Lengths



Major Events

- BAMF Release 6.0 (February 2019)
- AFGROW 5.3 (March 2019)
- StressCheck 10.5 (June 2019)
- AFGROW/StressCheck/BAMF Joint Webinar (July 17, 2019)
  - ESRD website has webinar highlights and recording
  - 30 minute presentation on BAMF, including a model building demo
  - https://www.esrd.com/resource-library/webinars/3dcrackgrowthsimulation/
- BAMF Release 7.0 (Soon)
- AFGROW/BAMF Training Class (ASIP 2019, Dec. 2 13:00-17:00)

Version 6.0 Released February 12, 2018

BAMF V6.0 - FEATURES

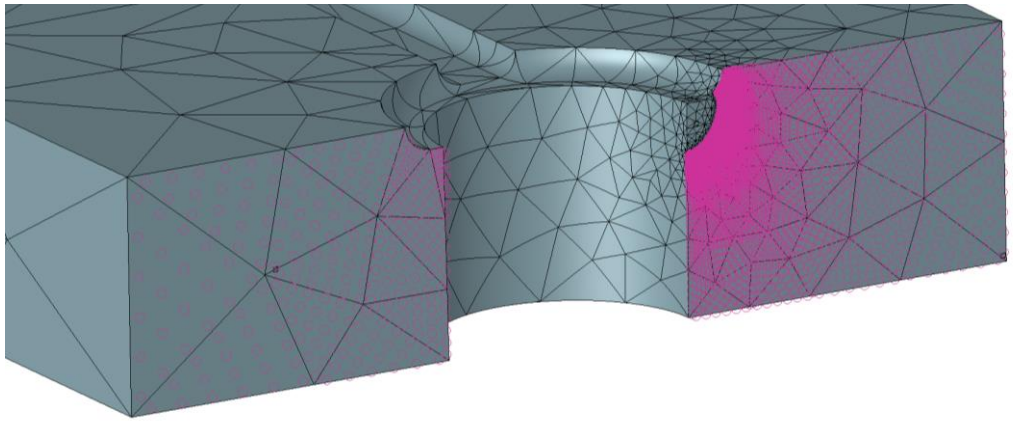
Features

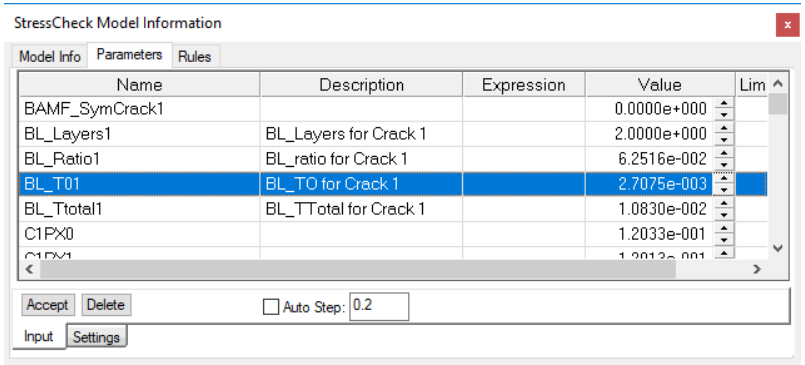
- ❑ Symmetry on Crack Plane
- ❑ Updated Mesh Refinement Capability
- ❑ Automated K-Convergence Checking
- ❑ Updated Model Builder
- ❑ BAMF Model Debugger
- ❑ AFGROW Failure Criteria Capability

Feature	Description
~~Crack Failure~~	~~Stop analysis when a user defined number of points reach Kc~~
Abort Analysis	A button that allows the user to ABORT a run in the middle of the run
Multi-Channel Loading	Solve for multiple loading scenarios
Multi-directional material properties	Use directional material properties to grow each point
Integration with other FE tools	Ansys, NX (Funding Sources Phase 2 landing gear, A-10)
~~Model Builder Automation~~	~~Update the Excel based model builder to use local coordinate systems~~
K extrapolation	Extrapolate K to 0 using two different K extractions
~~K convergence checker~~	~~Solve for many p-levels and output K so user can confirm convergence~~
Multi-Crack Auto-Coalescence	(MCAC) When crack fronts intersect-automatically coalesce cracks
~~Crack Plane Symmetry~~	~~Crack Plane Symmetry~~

Crack Face Symmetry

- **Symmetry on a crack plane**
  - Utilize built in function BAMF_SymCrack#, where # is the crack number
- **Can have multiple cracks on a symmetry plane**
- **Sets must define the symmetry boundary condition**
  - Set should be far away from expected crack growth path
- **Capability to include both symmetric crack faces and non-symmetric crack faces in the same model**





Updated K extraction smoothing

- Updated K smoothing to have a defined meaning
- Default utilizes 4 points to smooth K
- User has capability to modify smoothing parameter to increase or decrease the number of points used from the extraction

Previous

Parameter Name	Parameter Description	Default Value	Recommendations
BAMF_ElementCF	Controls the number of elements along the crack front. It is a multiplication factor that multiplies the number of points by this parameter to get number of elements.	1.25x number of points (*PointsCrack#*)	1.25 – 5.00
BAMF_Ktol	Sets the tolerance value for K extraction smoothing, i.e. the number of extraction points averaged to calculate the discrete values passed to AFGROW	0.004	0.002 – 0.008 Outputs should average appx 4-10 extraction points. Column I in the excel output defines the number of points averaged to calculate the output stress intensity
BAMF_Layers	Changes the number of layers in the crack	2	2 - 4

Updated

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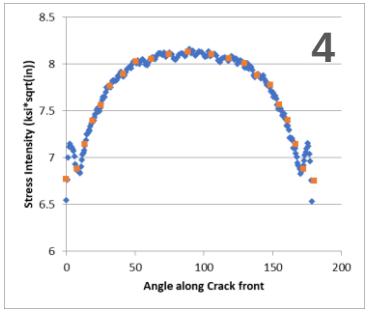
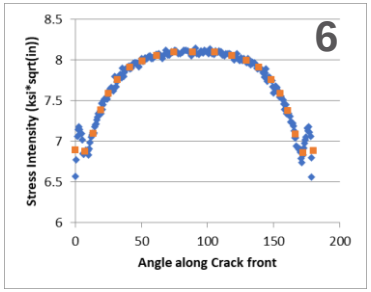
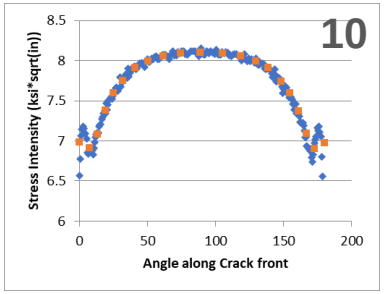
Ktol

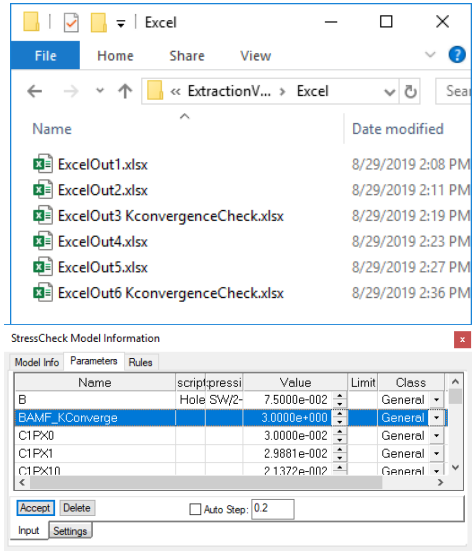


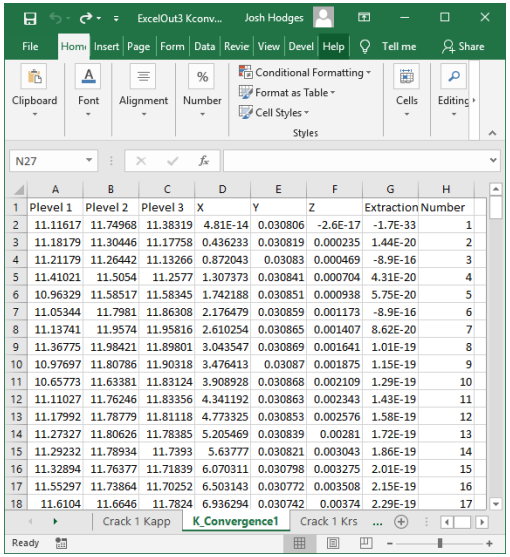


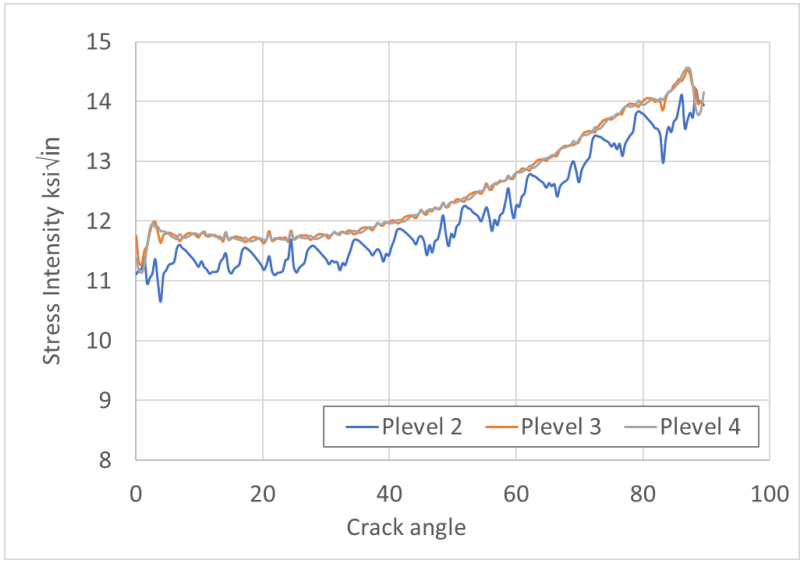


Automated K-Convergence Checking

- Capability has been added to periodically check K convergence
- Implemented through StressCheck parameters
  - Parameter name: BAMF_Kconverge
  - Parameter value: The number of iterations in between convergence checking
  - Extracts stress intensities at 1 level above and below the defined p-level
- Utilized in post processing of results





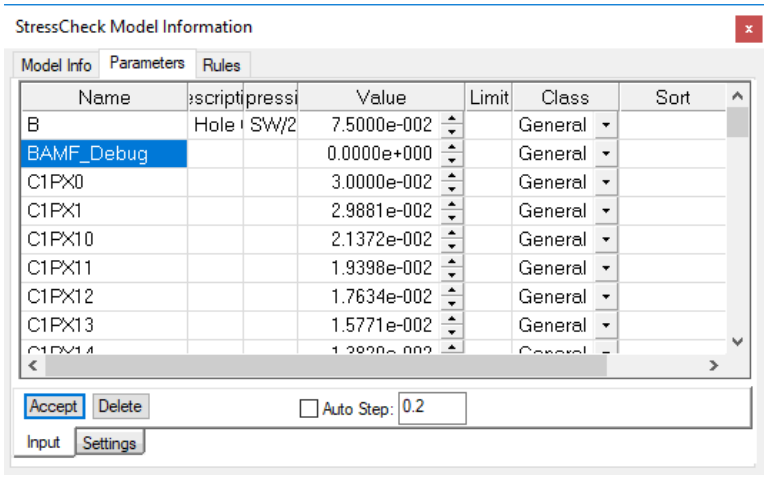


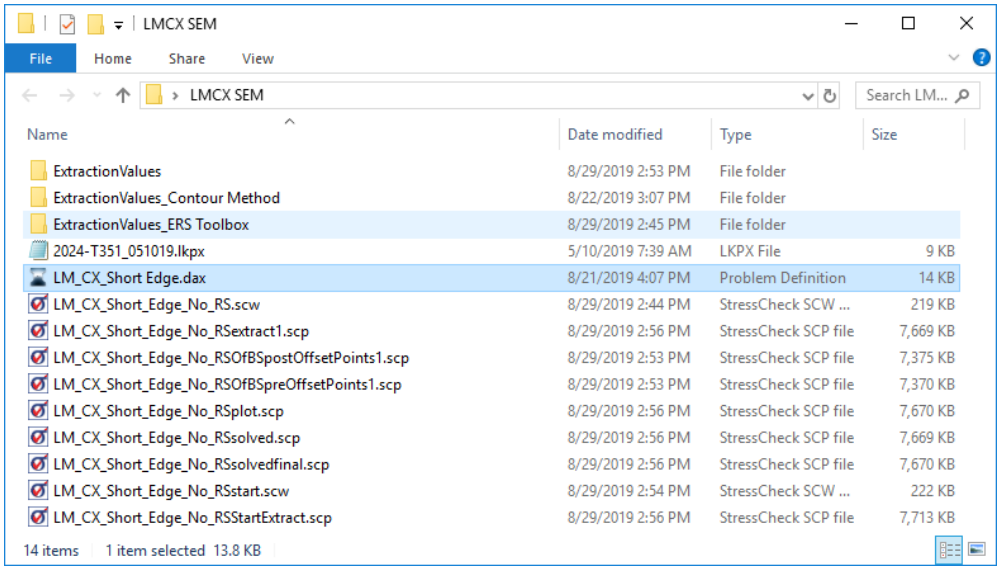
Excel Model Builder

- **Outputs a working file or a parameter file for a BAMF analysis**
- **Requires user to create nucleation systems for each crack**
- **Required input parameters**
  - Number of cracks
  - Angle of each crack
  - Depth of each crack
  - Length of each crack
  - # of points defining each crack front
- **Instructions included in the Model Creator Excel sheet**
- **Demonstration!!!**

Model Debugger

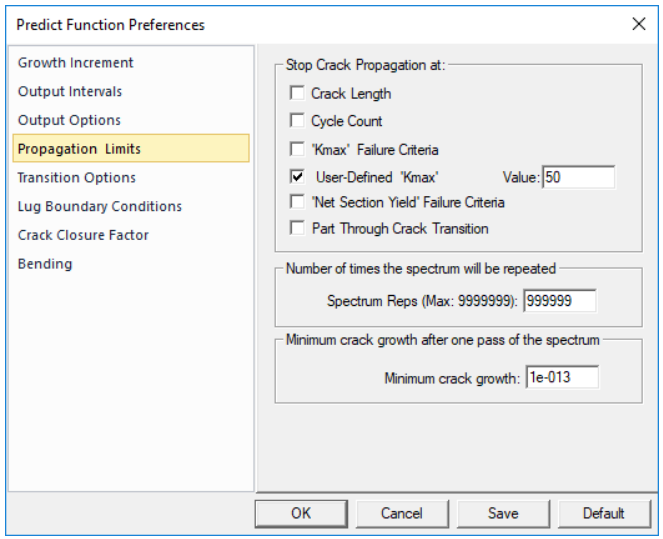
- Provides outputs at each point in the BAMF model program flow
- Outputs extensive information on crack points to excel outputs
- Used to aide BAMF Technical Support in quickly solving model related issues
- Excel output review

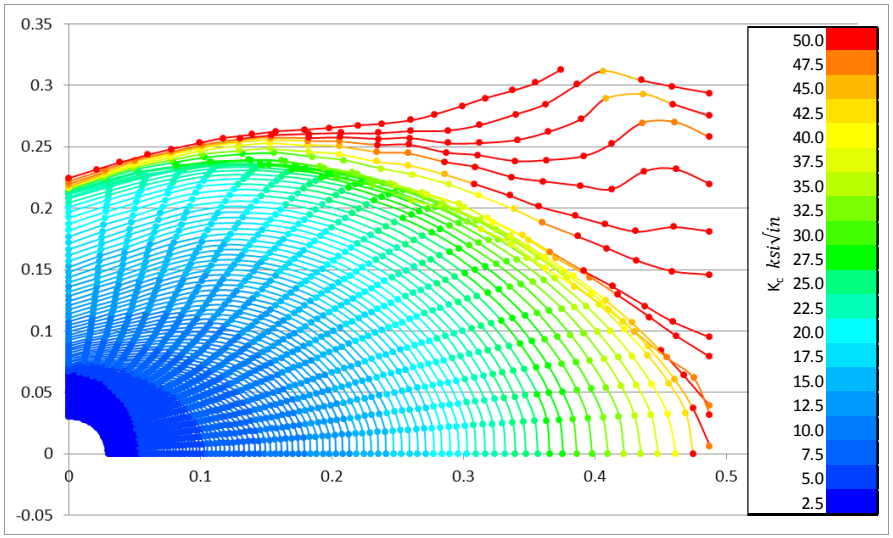




BAMF/AFGROW Failure Criteria

- **Version 6.0 utilizes:**
  - BAMF will stop prediction when all points are above Plain Stress Kc
  - User input value when *User-Defined "Kmax"* is selected
- **Version 7.0 will utilize:**
  - No failure criteria when nothing is selected
  - Plain Stress Kc when "Kmax" Failure Criteria is selected
  - User input value when User-Defined "Kmax" is selected



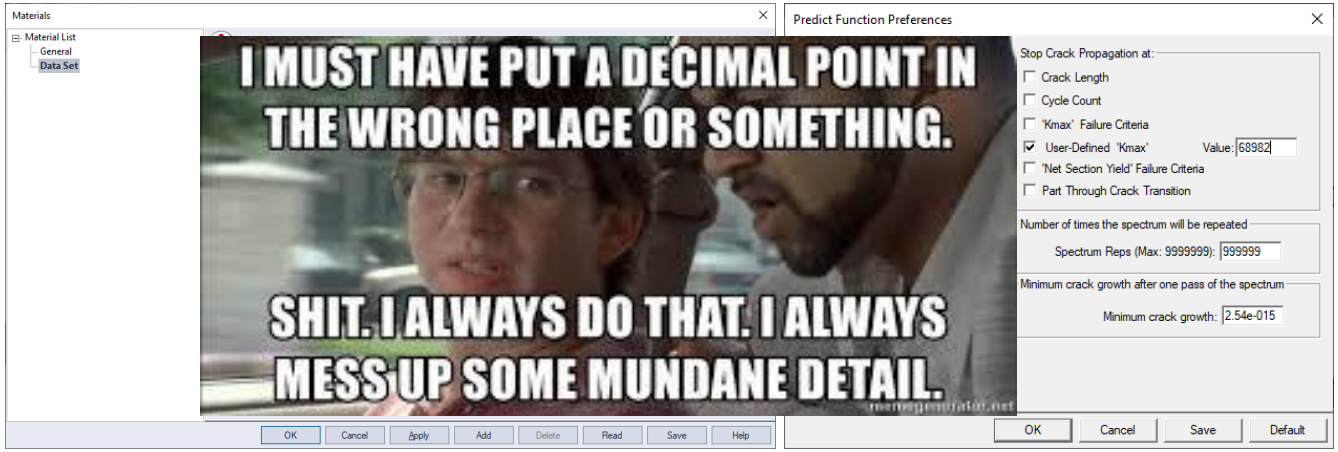


Version 6.0 Released February 12, 2018

BAMF V6.0 - REPORTED BUGS AND ISSUES

Bug: Units

- **Units were added early in the development of 6.0**
  - Failure criteria was added later in the 6.0 release
  - AFGROW uses base units of m; StressCheck uses base units of mm
- **$K_{failure}$ routine did not account for the mm to m conversion**
  - Caused failure after first iteration
- **Work around uses *User-Defined "Kmax" with units of mm√MPa***
- **BAMF Release 7.0 addresses the issue**



Bug: Multi-Crack Issues

- **Bug: Extraction radius for multiple cracks would utilize parameters for a single crack**
  - Code utilized extraction radius for crack 1 for all cracks
  - Code was updated so all meshing and extraction parameters were a function of crack number
  - Updates were released in version 6.0

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Updated

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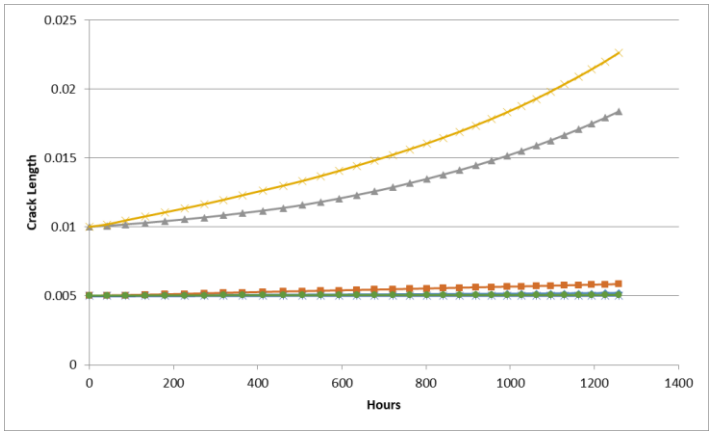
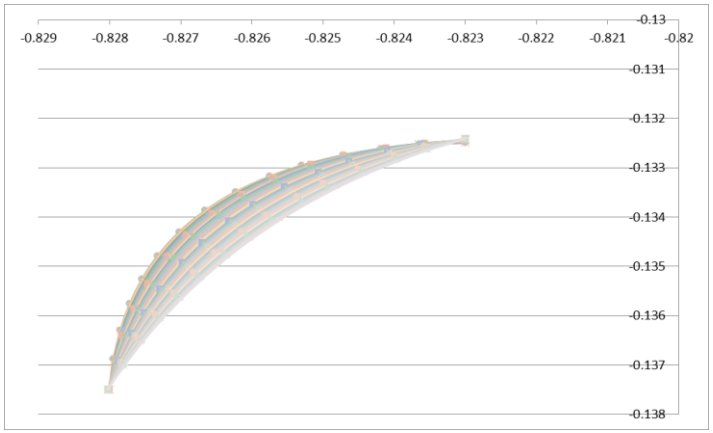
Bug: Multi-Crack Issues

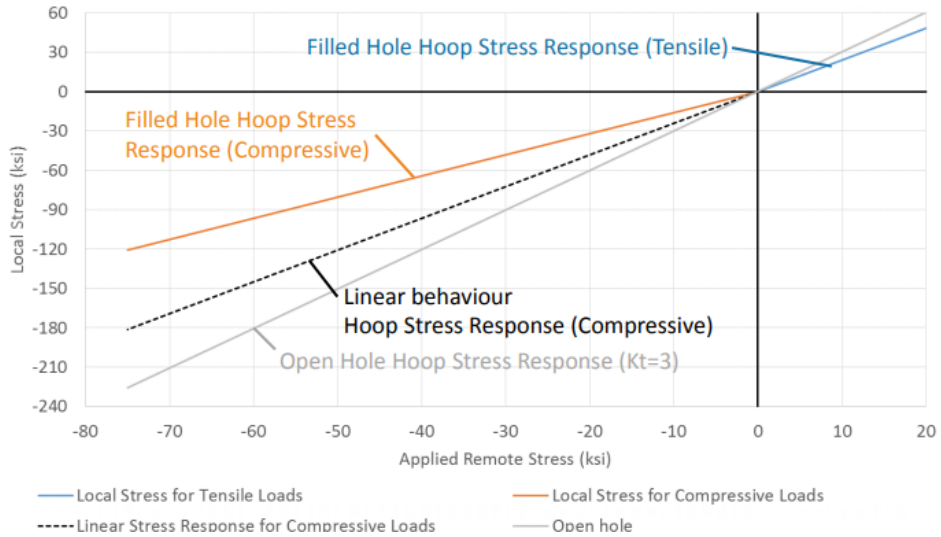
- **Bug: Small secondary cracks would reduce in size during primary crack growth**
  - Small/no growth lengths would cause an error in the re-splinning code causing ΔP to reduce in size and flatten out over several iterations
  - Code written to utilize proper crack lengths if negative growth flag is tripped
  - Updates were released in version 6.0
- **Bug: Graphs are not updated when negative growth flag is tripped**
  - Plotting of secondary cracks stops working when above bug fixed was implemented



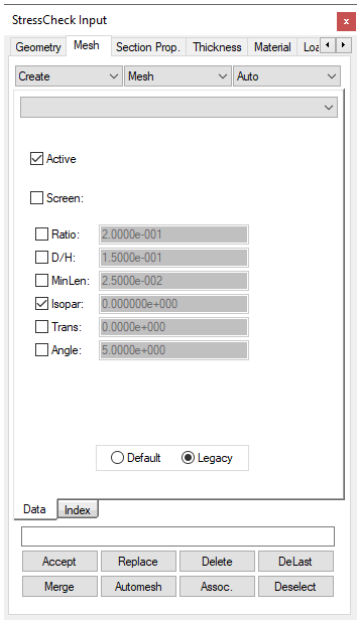


Other Reported Bugs and Issues

- BAMF takes an incredibly long time to initialize on USAF network
- Can't use cracks that are greater than 180 degrees
  - In development, planned for 7.0 release
- Incorrect analysis when performing contact and interference
- Default auto-mesh does not appear to work properly



Yan Bombardier, et.al, **Prediction of fatigue crack growth at cold expanded fastener holes with ForceMate bushings. AFGROW 2018**



BAMF UTILIZATION CASES

Recent Examples of BAMF Utilization

- **Kaylon Anderson**
  - NTSB, Oddities seen when running BAMF
- **Scott Carlson/Josh Hodges**
  - Analytical Comparisons of Determination Methods
- **Brian Boeke**
  - Upper Longeron BAMF Simulation
- **Renan Ribeiro/Mike Hill**
  - Fatigue crack growth testing and modeling of coupons with quench-induced residual stress
- **Joshua Hodges**
  - “Re-lifing isn’t all its cracked up to be”

Release September 31, 2019

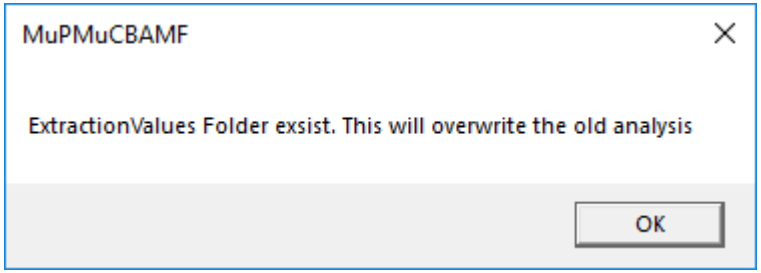
BAMF RELEASE 7.0 - UPGRADES

Features

Feature	Description
~~Crack Failure~~	~~Stop analysis when a user defined number of points reach Kc~~
~~Abort Analysis~~	~~A button that allows the user to ABORT a run in the middle of the run~~
Multi-Channel Loading	Solve for multiple loading scenarios
~~Multi-directional material properties~~	~~Use directional material properties to grow each point~~
Integration with other FE tools	Ansys, NX (Funding Sources Phase 2 landing gear, A-10)
~~Model Builder Automation~~	~~Update the Excel based model builder to use local coordinate systems~~
K extrapolation	Extrapolate K to 0 using two different K extractions
~~K convergence checker~~	~~Solve for many p-levels and output K so user can confirm convergence~~
Multi-Crack Auto-Coalescence	(MCAC) When crack fronts intersect-automatically coalesce cracks
~~Crack Plane Symmetry~~	~~Crack Plane Symmetry~~
~~BAMF360~~	~~When Cracks are greater than 180 degrees~~
Incorrect Analysis with Contact	Kmax and Kmin may not be linear when contact (neat/interference fit)
~~Units Causing K-Critical Failure~~	~~When using metric units Kcritical is 1000 less then it should be~~
~~Multi-Crack Extraction~~	~~Extraction parameters were not a function of crack number~~
3-D crack growth	Crack turning, out of plane crack growth

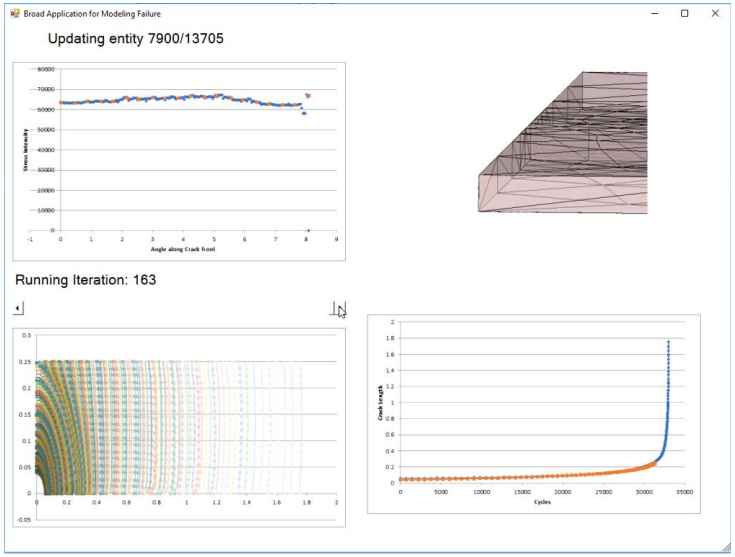
Updated Features

- **StressCheck 10.5 Compatibility**
  - Updated to account for K extraction output differences
- **AFGROW 5.3.4.23 Compatibility**
  - Updated to include multi-directional functionality
  - Updated to be backwards compatible with older versions of 5.3
- **Speed Increase of RS models (2 Times Faster!!!)**
  - Solution times are decreased by 2x for residual stress iterations
  - Corresponds to a 40% decrease in solution time
- **File Overwrite Warning**



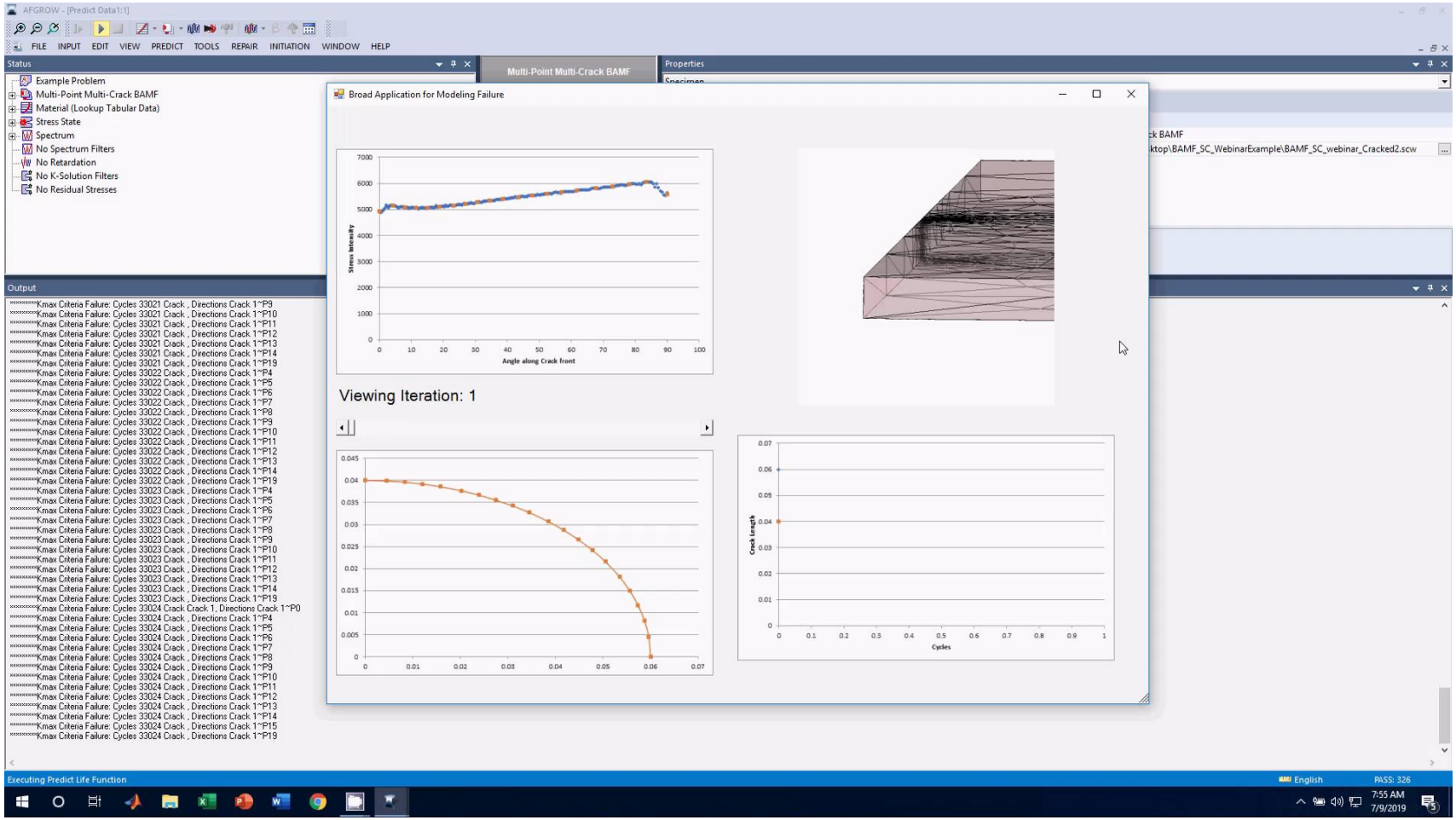
Multi-Threading

- **Previous versions of BAMF**
  - BAMF userform was not interactable
  - Update messages and charts would occasionally freeze
  - AFGROW would need to be killed in task manager to stop analysis
- **Updated code to allow multiple processes to occur simultaneously**
- **Allows for incorporation of features to review iterations during analysis.**



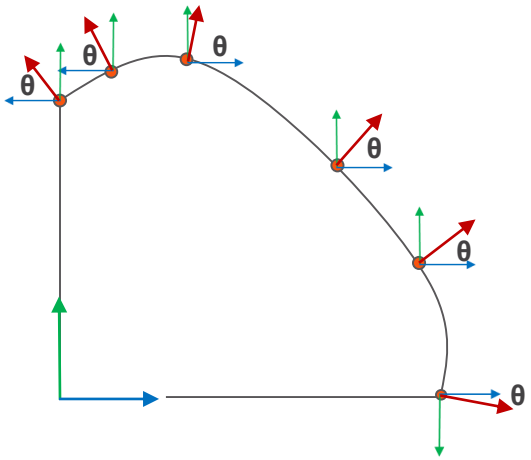
Multi-Threading New GUI

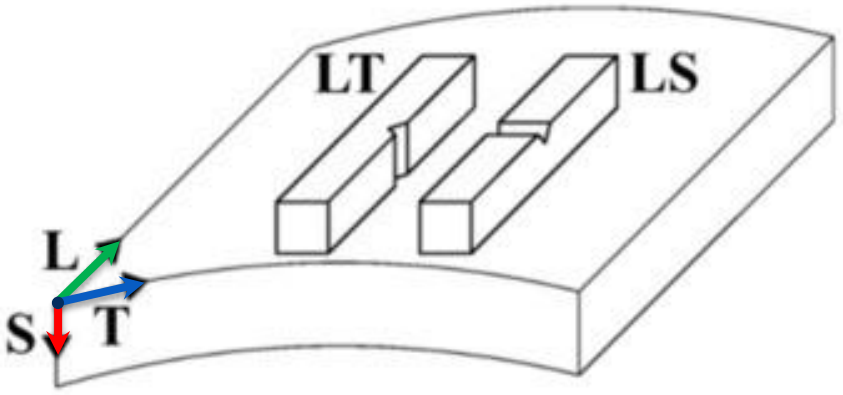
New GUI demonstration!!!



Multi-Directional Material Properties

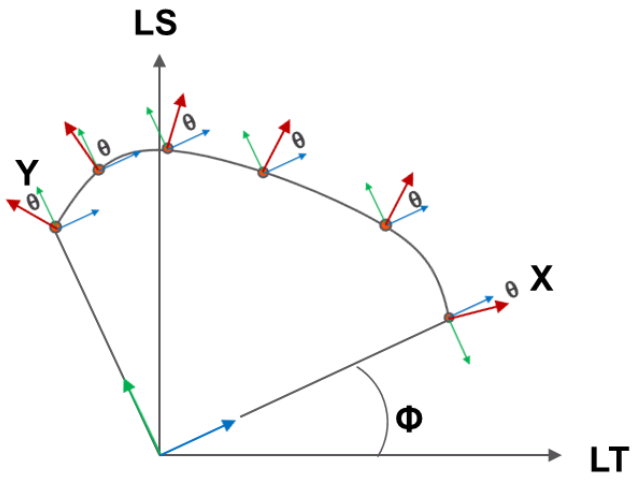
- **BAMF requirements:**
  - Definition of material orientations on solid model
    - This is based on the local nucleation system of the crack
    - If the c-direction is the x-direction on the local nucleation system no value needs to be defined
  - Angle is based on angle used for growth direction.
  - Functions for interaction (angles in degrees)
    - ISPredictManage.SetCrackDirectionParameter("Crack " & k, "P" & i, "angle", Mat_Dir_Angle(0, k, i))



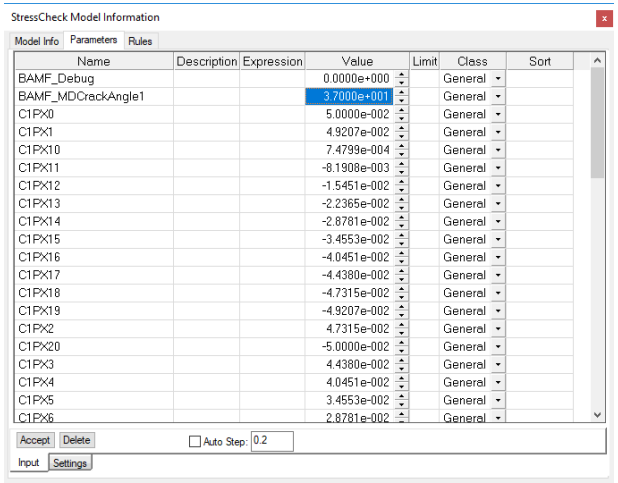


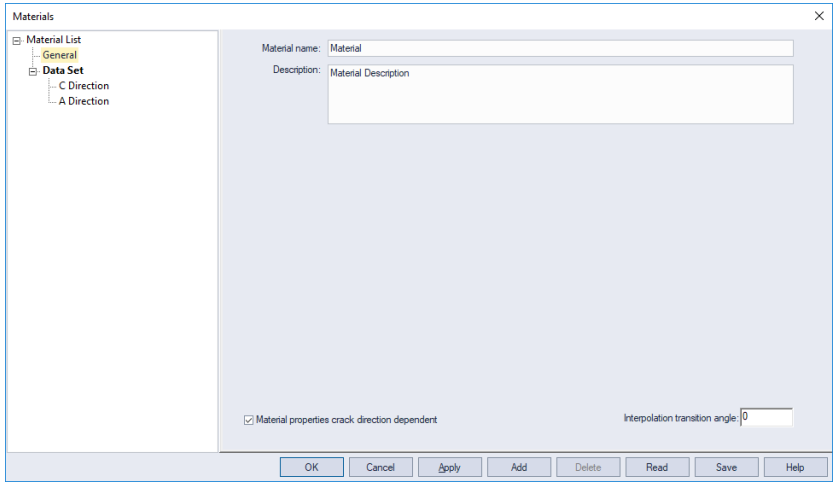
Multi-Directional Material Properties

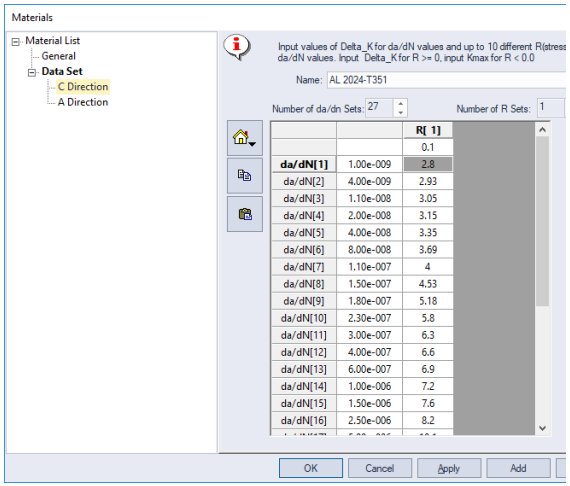
- **User Can Set BAMF_MDCrackAngle# (Φ on this slide) if the LT direction of the material is different from the X axis of the crack**
  - BAMF_MDCrackAngle# is defined as the angle the crack nucleation system X axis is above the LT axis of the material
- **For each crack point BAMF_MDCrackAngle is added to the crack growth angle (θ) and the result (θ+Φ) is passed to AFGROW**
  - BAMF modifies the new angle to be between 0 and 90˚
- **AFGROW uses the new angle to assign crack growth rates for each point**

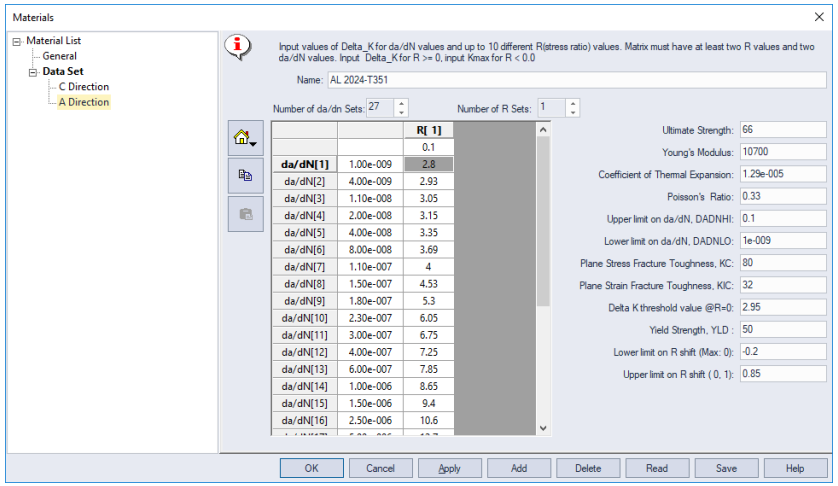


Multi-Directional Material Properties



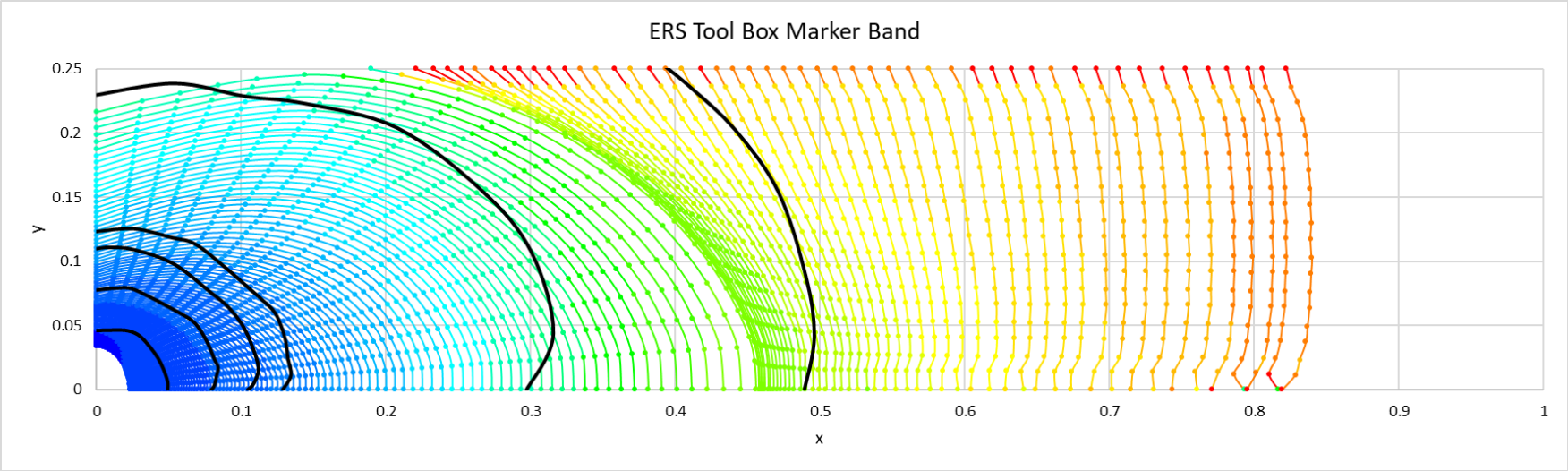






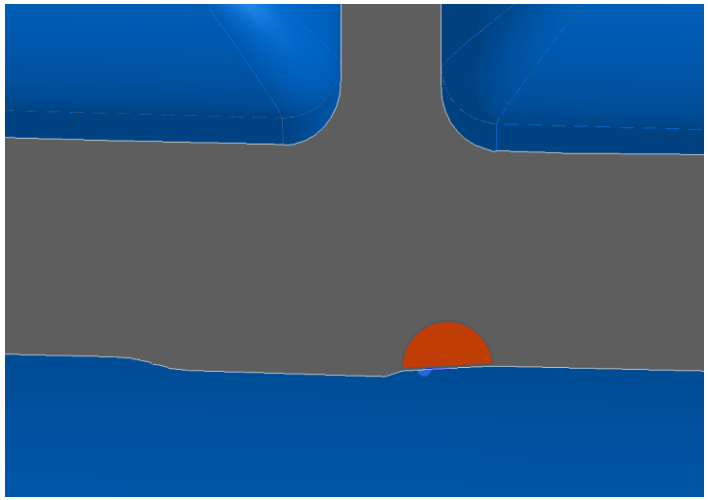
Excel Output

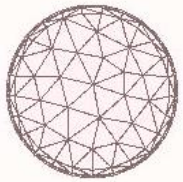
- Excel outputs have been updated to report the Max Kapp from AFGROW
- This allows for post-processing crack progression plots with K contours
- Large iteration counts takes a considerable time to plot figures



BAMF 360

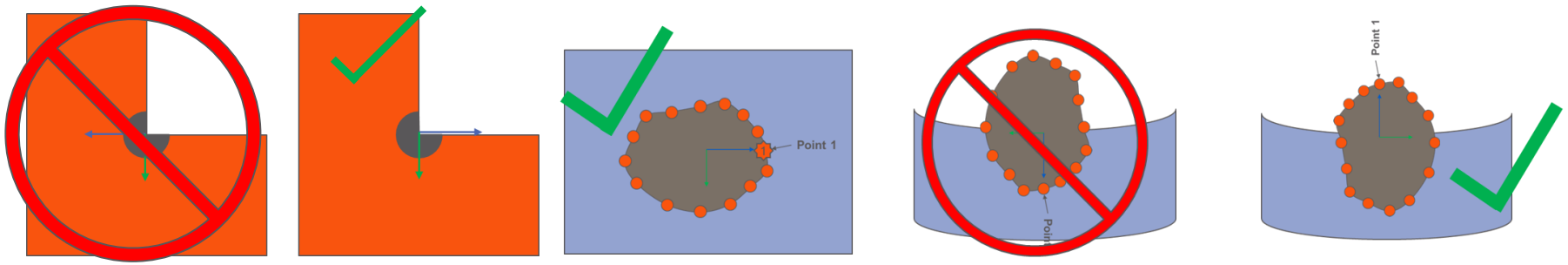
- Previous versions of BAMF only allowed for cracks 180º or less
- Several situations arose where cracks growing through radi or into T sections required crack geometries greater than 180º
- New feature allows for imbedded cracks or surface cracks exceeding 180º





BAMF 360

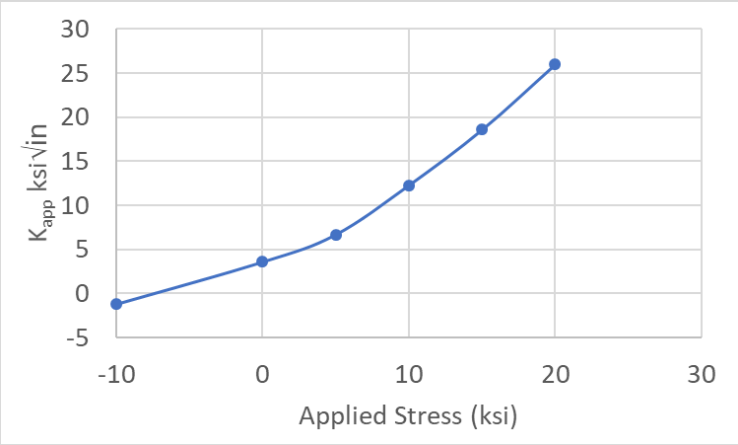
- Point 1 will remain on the nucleation systems x-axis
- For non-internal cracks the nucleation systems x-axis needs to be:
  - Outside the body, or
  - On a straight boundary
- Splines in StressCheck need to be created starting from point 1 and incrementally selecting points finishing at point 1
- For 360º cracks it is recommended to use 30+ points
- Code is still under development



BAMF Interference and Contact

- Traditionally BAMF/AFGROW assumes a linear stress intensity
- AFGROW is implementing capability to provide a table of stress intensity solutions and applied stresses
- BAMF will provide the capability to solve for multiple applied stresses and pass the table of stress intensities to AFGROW
- AFGROW will utilize this table to interpolate to a "correct" stress intensity

Applied Stress ksi	K_{app} ksi√in
-10	-1.2
0	3.6
5	6.7
10	12.3
15	18.6
20	26



BAMF FUTURE

Proposed Feature List from Previous Workshop

Feature	Description
~~Crack Failure~~	~~Stop analysis when a user defined number of points reach Kc~~
~~Abort Analysis~~	~~A button that allows the user to ABORT a run in the middle of the run~~
Multi-Channel Loading	**Solve for multiple loading scenarios**
~~Multi-directional material properties~~	~~Use directional material properties to grow each point~~
Integration with other FE tools	**Ansys, NX (Funding Sources Phase 2 landing gear, A-10)**
~~Model Builder Automation~~	~~Update the Excel based model builder to use local coordinate systems~~
K extrapolation	**Extrapolate K to 0 using two different K extractions**
~~K convergence checker~~	~~Solve for many p-levels and output K so user can confirm convergence~~
Multi-Crack Auto-Coalescence	**(MCAC) When crack fronts intersect-automatically coalesce cracks**
~~Crack Plane Symmetry~~	~~Crack Plane Symmetry~~
~~BAMF360~~	~~When Cracks are greater than 180 degrees~~
Analysis with Contact	**Kmax and Kmin may not be linear when contact (neat/interference fit)**
~~Units Causing K-Critical Failure~~	~~When using metric units Kcritical is 1000 less then it should be~~
~~Multi-Crack Extraction~~	~~Extraction parameters were not a function of crack number~~
3-D crack growth	**Crack turning, out of plane crack growth**

Proposed Feature List

Feature	Description
Multi-Channel Loading	Solve for multiple loading scenarios
Integration with other FE tools	Ansys, NX (Funding Sources Phase 2 landing gear, A-10)
K extrapolation	Extrapolate K to radius of 0 using two different K extractions
Multi-Crack Auto-Coalescence	(MCAC) When crack fronts intersect-automatically coalesce cracks
Filled Hole Analysis capability	Kmax and Kmin may not be linear when contact (neat/interference fit)
3-D crack growth	Crack turning, out of plane crack growth
K colored plots	Implement K colored plots into AFGROW outputs
Restart Analysis	Utilizing Extraction folder restart at last analysis point
Pause Analysis for UI	Allows user to pause an analysis to update the start.scw file
Custom Output files	Use a customizable .ini file to allow the user to tailor output files
Crack front splitting	When the crack front splits into multiple cracks