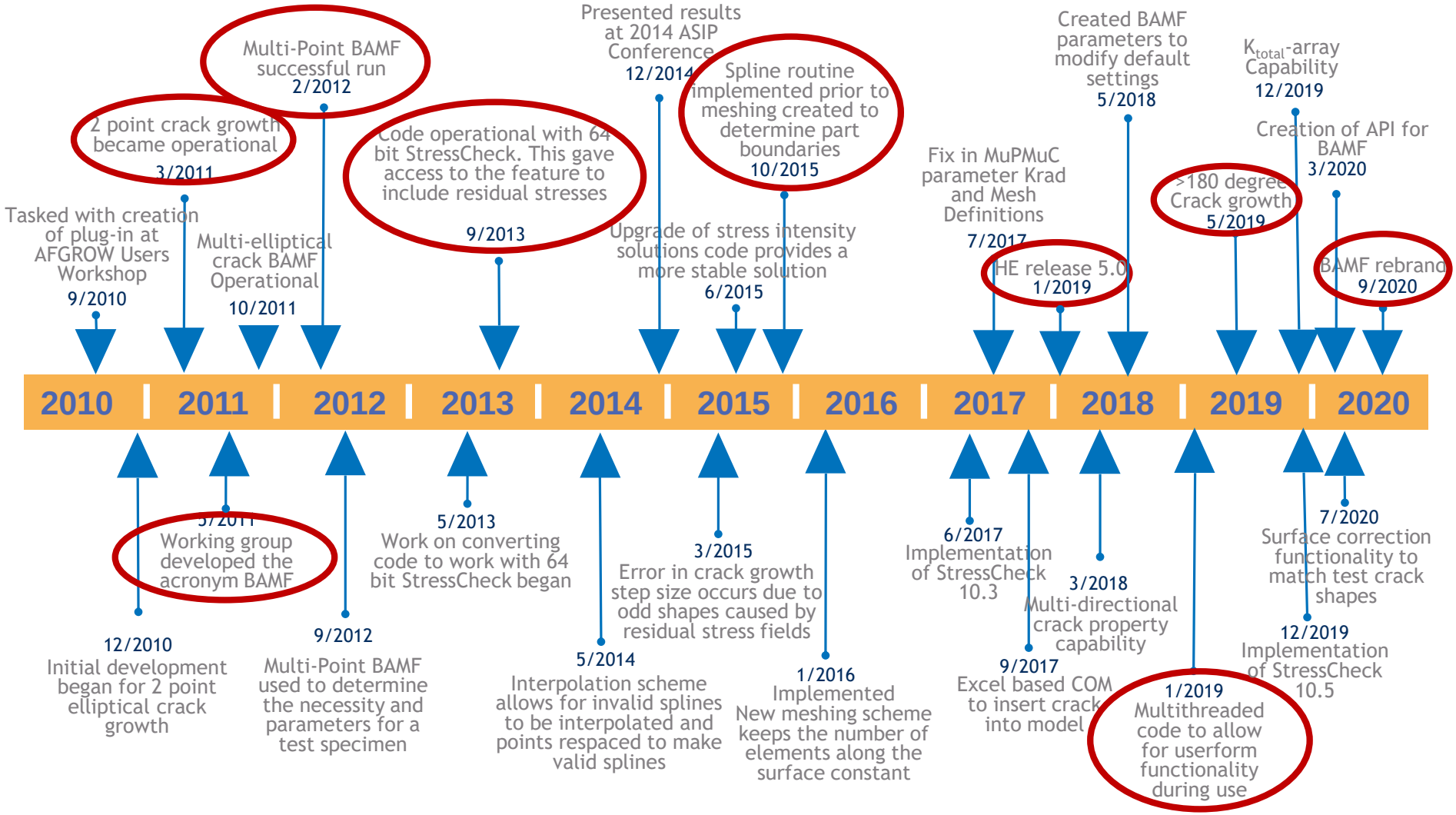
HILL ENGINEERING
Predict. Test. Perform.

BAMF Workshop 2020

September 15, 2020

10 years of crack progression!

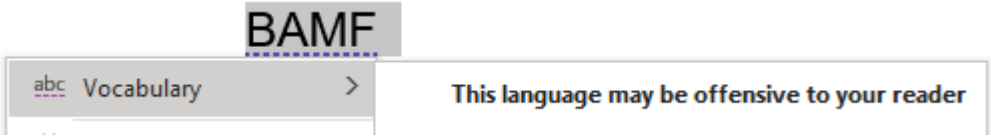


BAMF rebranding

- **Surveyed small sample of users to understand impact of BAMF brand within their organization**
  - Users covered both DoD and Industry
  - Questions covered impact of BAMF name and logo on:
    - Comfort of use in professional environments
    - Pros and cons of BAMF name
    - Overall feeling of brand
  - Results of survey provided beneficial feedback on the path forward
- **Comments received:**
  - "'Modeling Failure' doesn't seem to be the best description of what BAMF does"
  - "It is always good to have a catchy acronym! And "BAMF" is punchy!"
  - "I have no issue with the name; however, it's difficult to view the BAMF logo on a slide without thinking about graphic novels."
  - "I am uncomfortable using the acronym in discussing the software with upper leadership or outside the crack growth community."

Key items important in a name change

- **Hill Engineering underwent an extensive rebrand exercise**
  - Important to maintain history of the BAMF name
  - Create a name that provided a better description of the program's capabilities
  - Provide a name people would be comfortable using in professional setting
  - Design a professional looking logo
  - Ensure Josh was comfortable with any change in the name
- **The name is catchy, memorable, and describes program features**
  - The application can cover a broad range of analysis beyond flat plates and elliptical cracks
  - The application utilizes multiple points to perform the crack growth analysis
  - The application is utilized for fatigue crack growth
- **When "Googling" the name the user will not be inundated with potentially offensive content**



Broad Application for Multi-point Fatigue

The broad application accentuates BAMpF's capability to remove the constraints of elliptical cracks in flat plates

With complex monocoque airframes multi-point fracture mechanics allow for crack evolution lines that evolve naturally

BAMpF utilizes the p-version FEA software StressCheck which allows for fast reliable K-solutions

Silent p makes google searches safe for work but maintains the catchy phonetic name

Why did Griffith use glass in his studies?

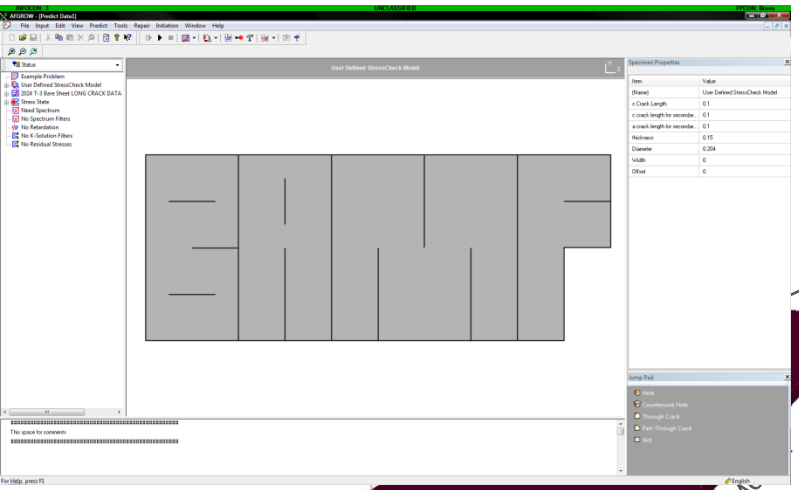
Agenda

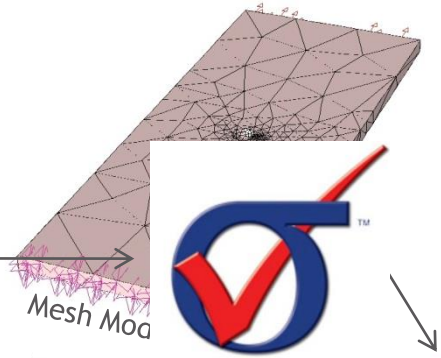
- ❑ **BAMpF Overview**
- ❑ **Major Events**
- ❑ **Updates and Bug Fixes**
- ❑ **BAMpF Utilization: From the User Community**
  - ➢ Connor Hood: When a single crack becomes two.
- ❑ **BAMpF Future**
  - ➢ Proposed Features and Upgrades

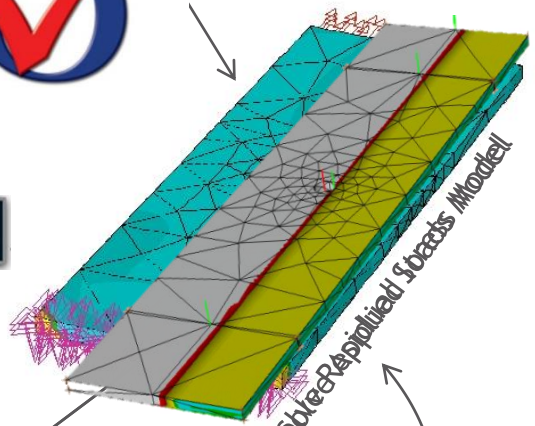
What is BAMpF?

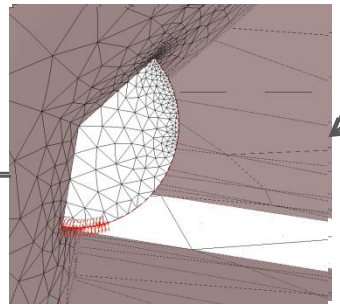
Broad Application for Multi-point Fatigue

BAMpF Process Flow









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

Far field stress from StressCheck

$K_{res_{CN}}$

Extract stress intensities K_{app} for each crack in the model

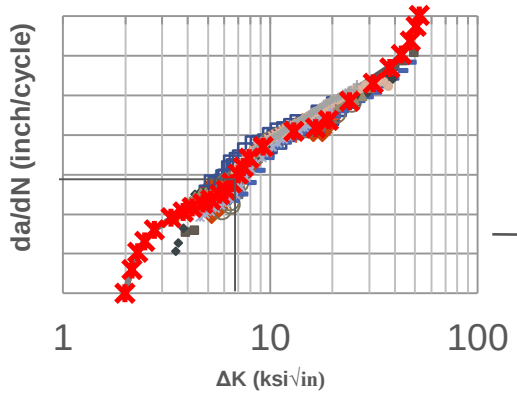
BAMpF Process Flow

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

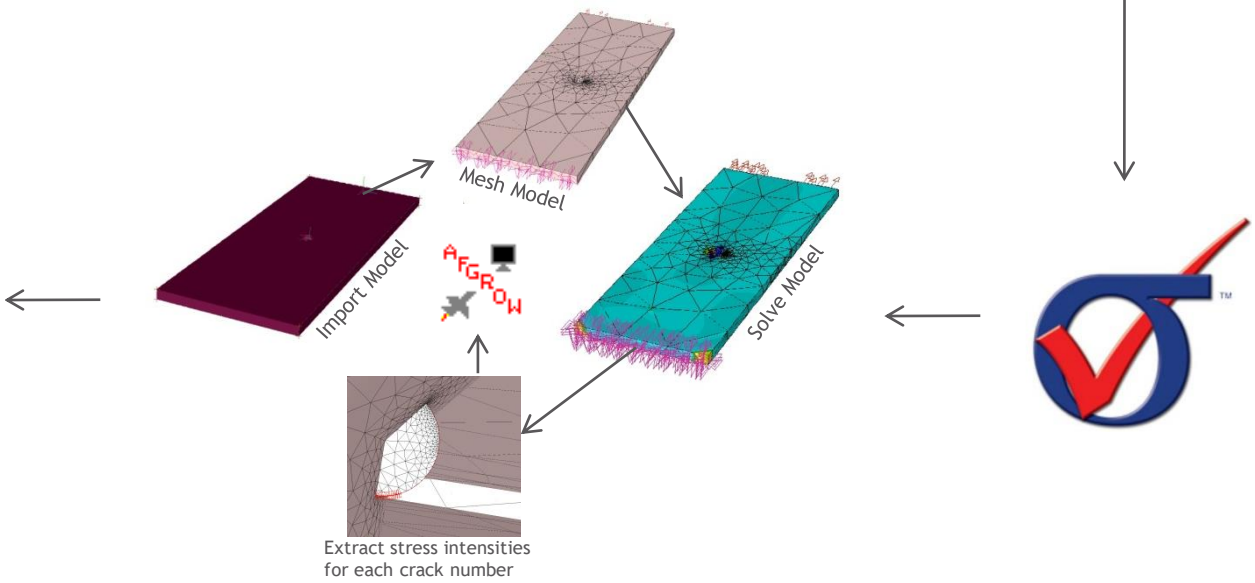
$$K_{max_{CN}} = a_{app_{CN}} \sigma_{max} + K_{res_{CN}}$$

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

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



New Crack Lengths



Major Events

- ❑ AFGROW/BAMF joint training course ASIP 2019 (November 2019)
- ❑ BAMF Release 7.0 (February 2020)
- ❑ AFGROW 5.3.5.24 (March 2020)
- ❑ StressCheck 11.0 (Imminent)
- ❑ BAMpF Release 8.0 (January 2021)

BAMF Partner Programs

- Premier Memberships are designed for organizations that rely on the robust capability of BAMpF and would like to have the highest level of technical support
- Gold Memberships are intended for organizations that are regular users of BAMpF who expect to use a moderate level of technical support
- Basic Memberships include a node-locked, single user license for BAMpF and provides limited technical support

Product Benefits

BENEFIT DESCRIPTION	BASIC	GOLD	PREMIER
Site License (up to 10 users)			*
Multiple Licenses (up to 3 Node-Locked Licenses)		*	
Node-Locked, Single User License	*		
Exclusive Access to Software Beta Versions			*
Exclusive Access to Priority Software Updates			*

BAMpF Partner Program

Support Benefits

BENEFIT DESCRIPTION	BASIC	GOLD	PREMIER
Unlimited Priority Technical Support			*
Up to 20 Hours Priority Technical Support		*	
Discount for On-Site Training			*
Product Enhancement Priority Inputs			*
Invitation to provide keynote at BAMF Users Meeting			*
Invitation to Attend BAMF Users Meeting	*	*	*
Recognition as a BAMF Premier Supporter			*

Price

PARTNER PROGRAM DESCRIPTION	PRICE
Basic Package	$500
Gold Package	$5,000
Premier Package	$10,000

Version 7 Released February 20, 2020

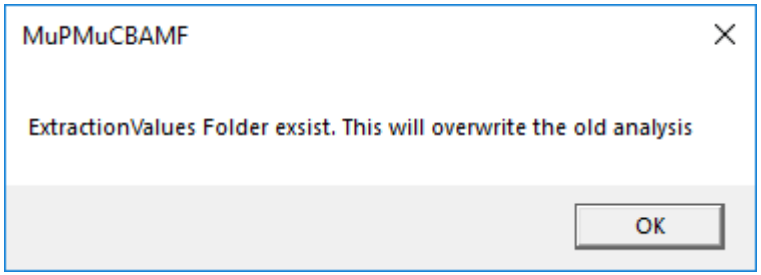
BAMpF V7.0 - FEATURES

Features

- ❑ Updating sister programs
- ❑ Interactable user-form
- ❑ Multi-directional material properties
- ❑ BAMpF 360
- ❑ Set upgrades!

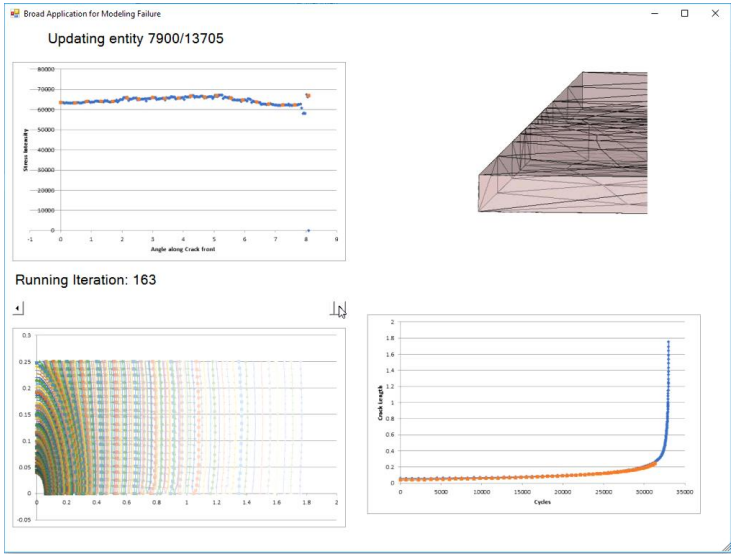
Updated Features

- **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**



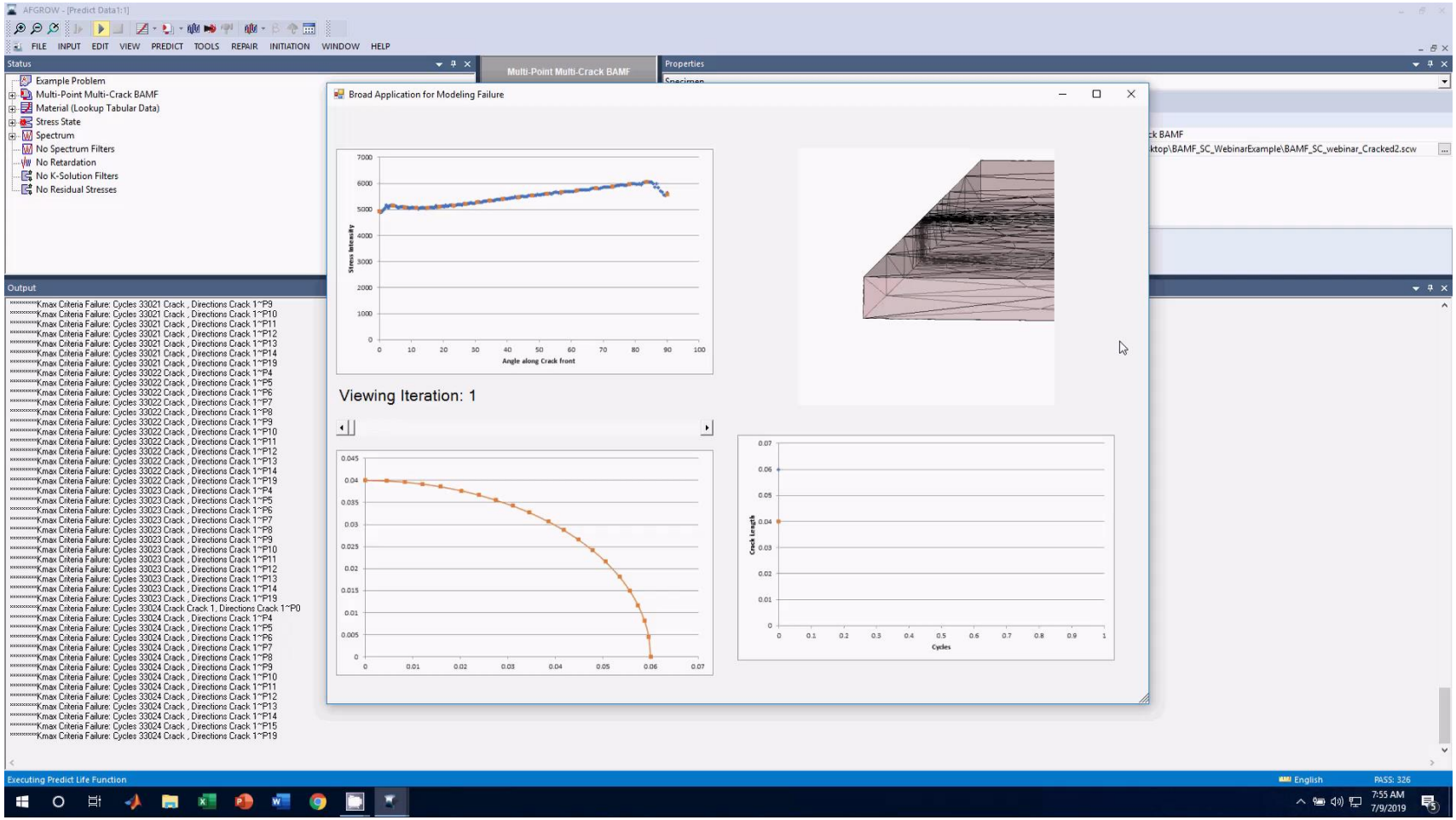
Multi-Threading

- **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.**



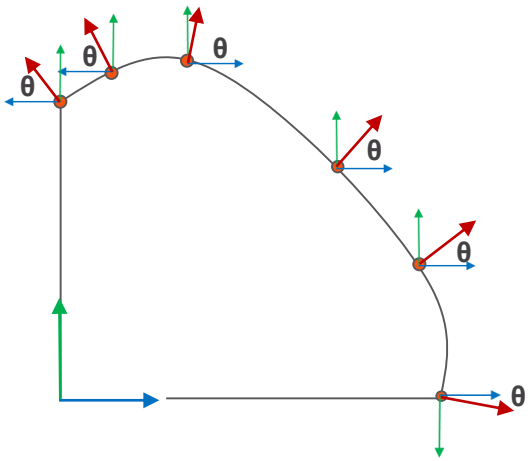
Multi-Threading New GUI

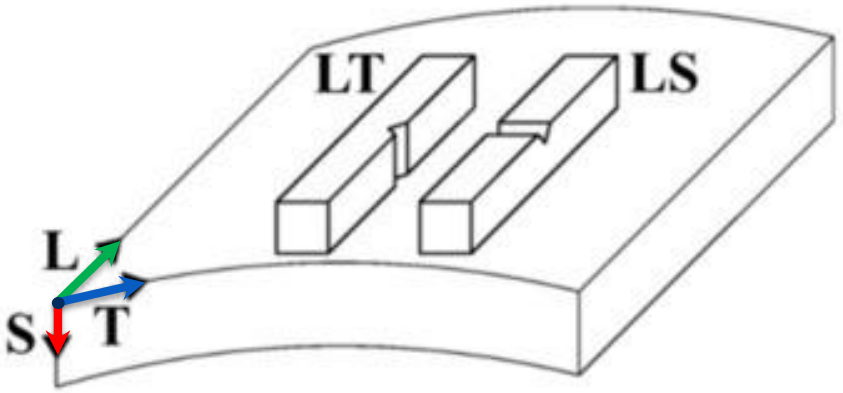
New GUI demonstration!!!



Multi-Directional Material Properties

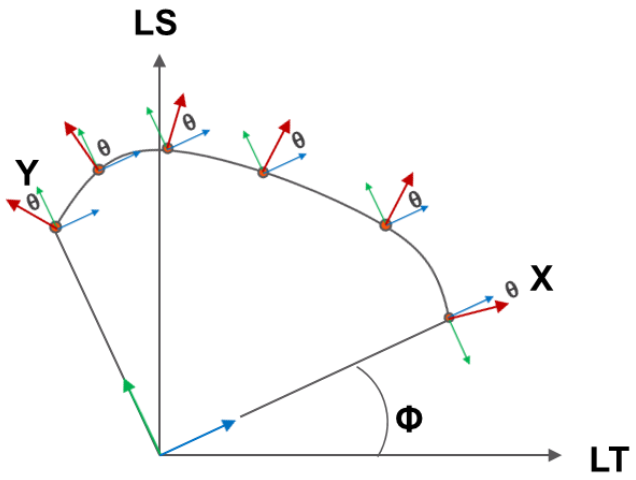
- **BAMpF requirements:**
  - Definition of material orientations on solid model
    - This is based on the local nucleation system of the crack
    - If the c-direction is the x-direction on the local nucleation system no value needs to be defined
  - Angle is based on angle used for growth direction.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



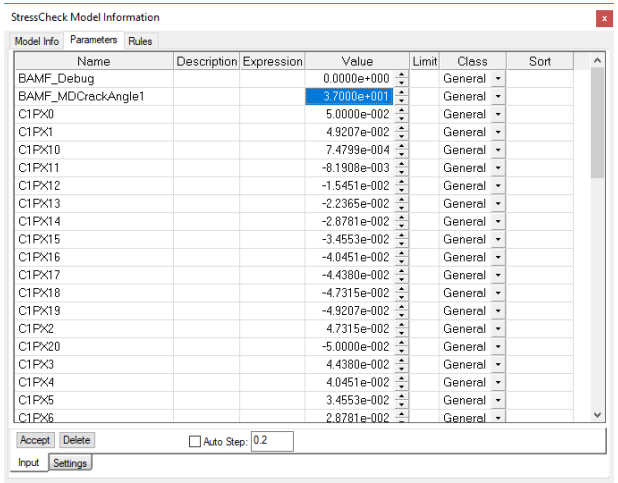


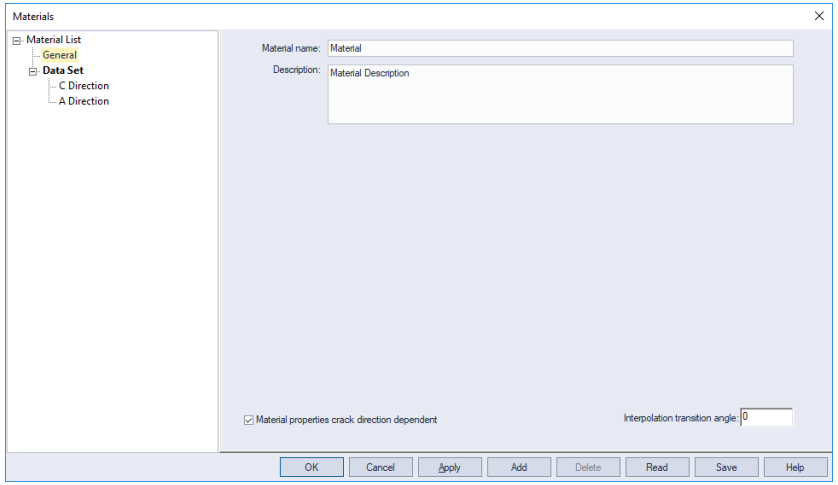
Multi-Directional Material Properties

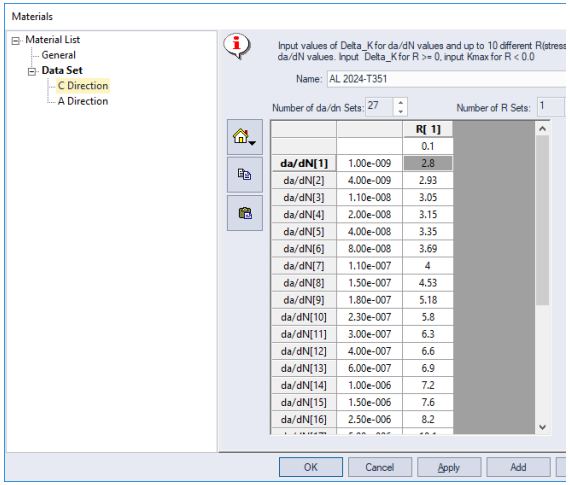
- **User Can Set BAMF_MDCrackAngle# (Φ on this slide) if the LT direction of the material is different from the X axis of the crack**
  - BAMF_MDCrackAngle# is defined as the angle the crack nucleation system X axis is above the LT axis of the material
- **For each crack point BAMF_MDCrackAngle is added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

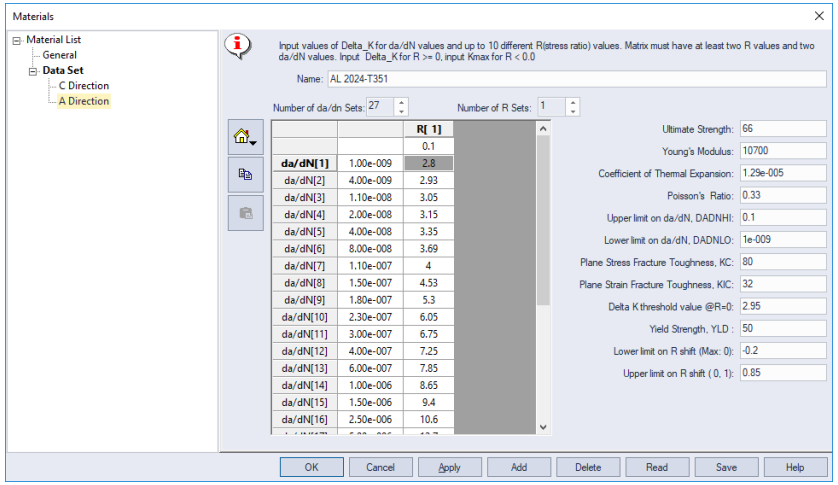


Multi-Directional Material Properties



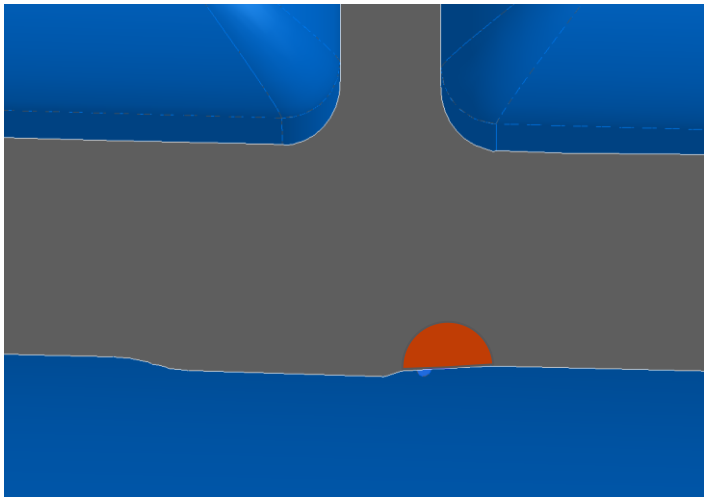


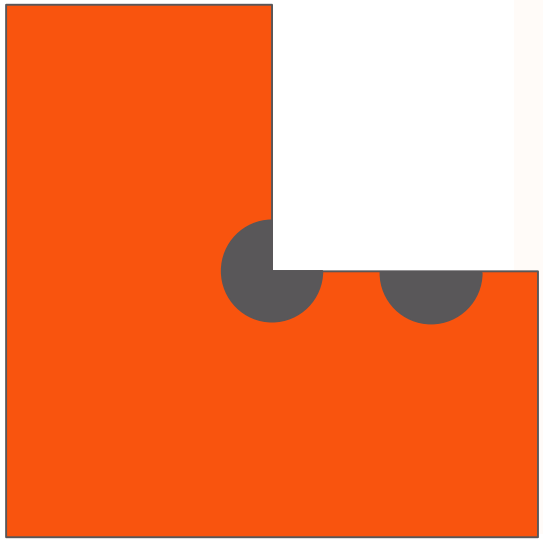


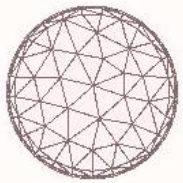


BAMpF 360

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

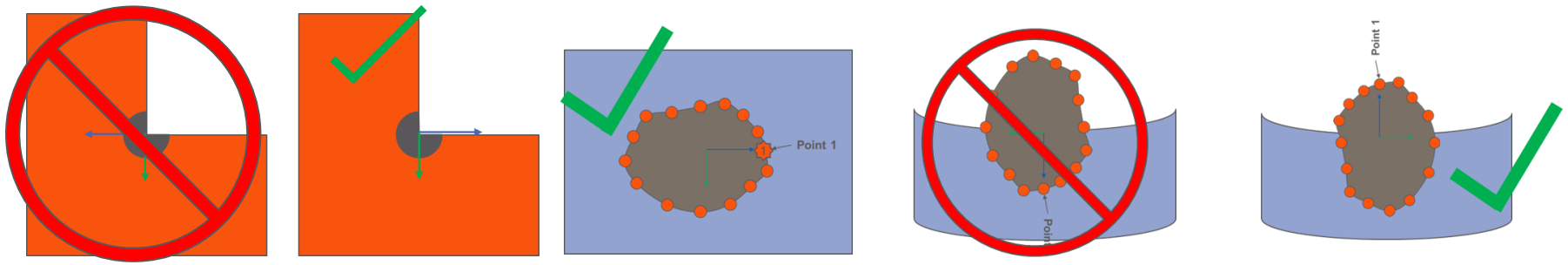






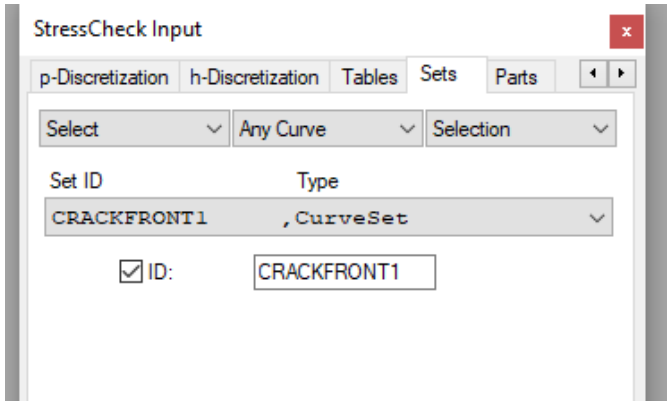
BAMpF 360

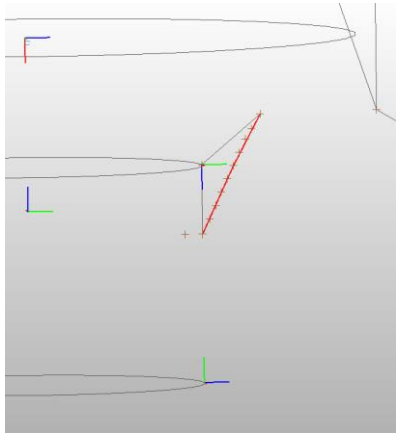
- Point 1 will remain on the nucleation systems x-axis
- For non-internal cracks the nucleation systems x-axis needs to be:
  - Outside the body, or
  - On a straight boundary
- Splines in StressCheck need to be created starting from point 1 and incrementally selecting points finishing at point 1
- For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



Sets!

- StressCheck updated features in their Parasolid that made tracking of surface features easier
- Initial testing showed great promise for BAMpF being able to utilize selection sets
- Code was written to require the user to use selection sets for CrackFace# and CrackFront# sets if SC 10.5 was detected
- The “Holy Grail” was achieved, the largest contributor to BAMpF crashes was fixed!





Version 7.0 Released February 20, 2020

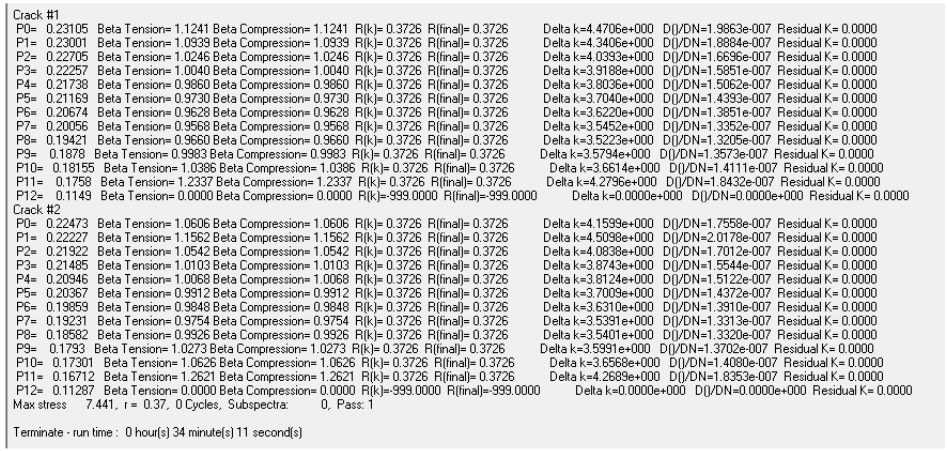
BAMpF V7.0 - REPORTED BUGS AND ISSUES

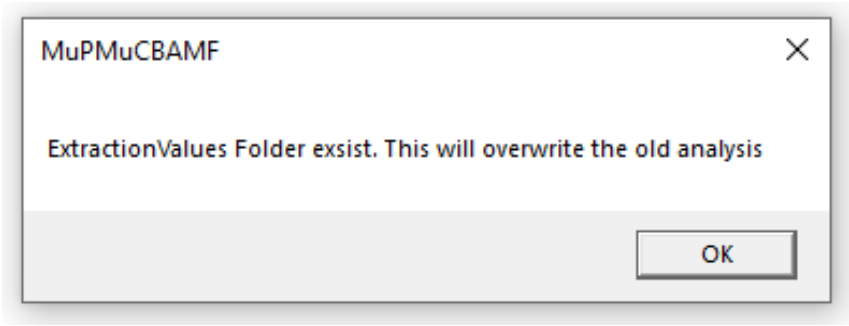
Bug: Sets!

- **Bug: Selection sets cause failure of part when transitioning through geometries such as through thickness transitions**
  - Failure of selection set causes betas to be 0 and no growth stopping analysis
  - New selection set feature in StressCheck was supposed to be “Holy Grail”
  - Initial testing showed promise and feature was rolled out in BAMpF 7.0
  - Subsequent testing showed significant issues with these selection sets
  - Code has been written to allow for selection sets by utilizing BAMF_Locate=1
  - It is recommended by BAMpF technical support to continue to use “locate” sets
  - Issues are in work with StressCheck

Bug: Premature Analysis Stopping

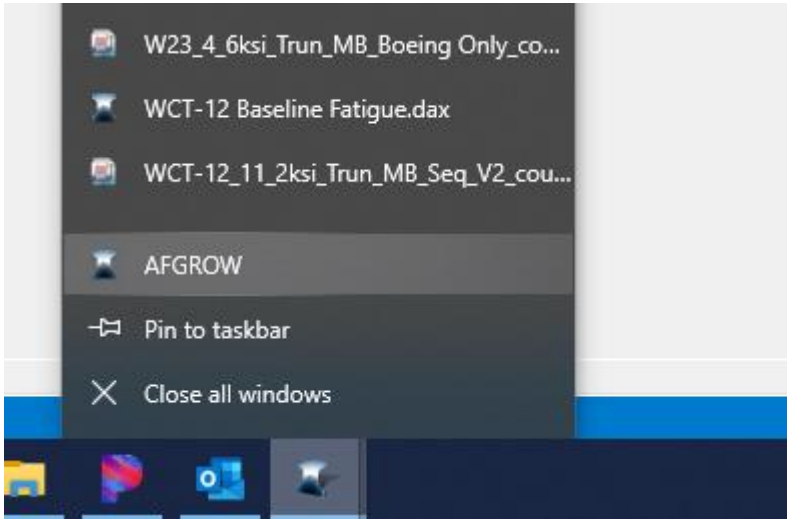
- **Bug: Analysis stops for no apparent reason after the first iteration**
  - Updated code for speed increase utilized re-writing of excel files
  - When extraction values folder does not exist code will stop analysis after extractions of SIF's
  - BAMpF GUI looks correct, and AFGROW receives alphas but BAMpF's stop analysis flag is triggered
  - Workaround: Close AFGROW and restart analysis, extractionvalues folder has been created at this point and analysis will not stop during the next run
  - Bug has been patched for next release





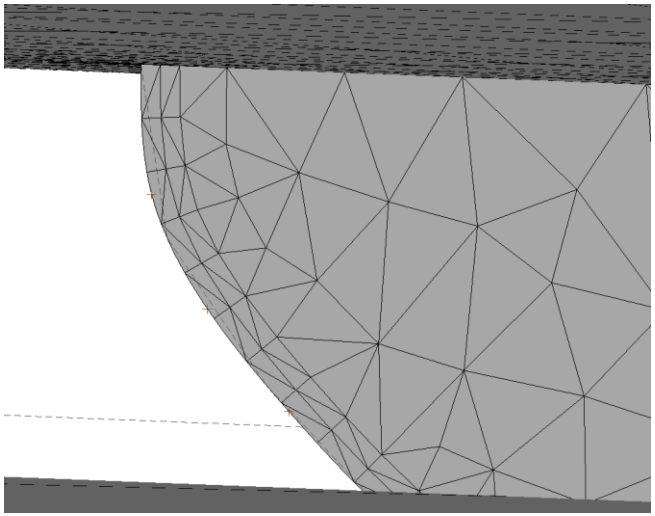
Bug: Launching AFGROW while BAMpF is Running

- **Bug: If AFGROW is launched through double clicking an analysis file BAMpF will freeze on the next iteration**
  - Extremely frustrating when running an analysis in the background
  - Work around, launch AFGROW through the task bar



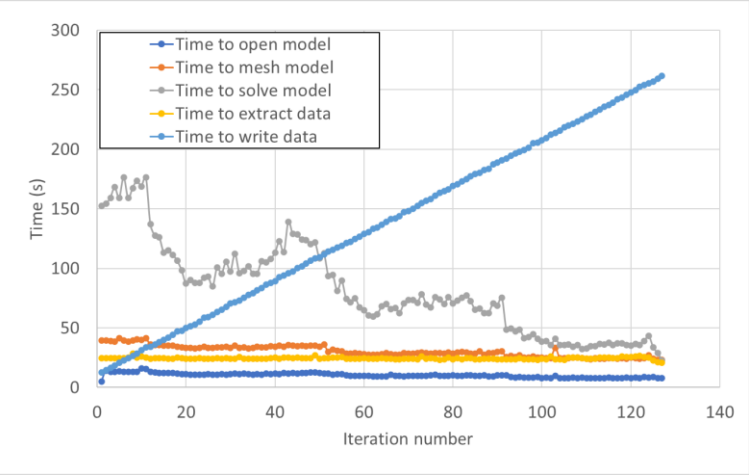
Bug: Boundary Layer Refinement

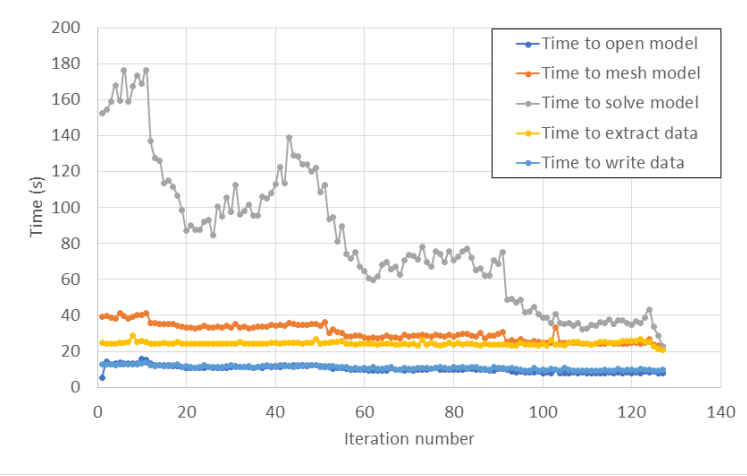
- **Bug: Boundary layer refinement for thru cracks becomes very large and provides poor stress intensity extractions**
  - In StressCheck10.5 updates to mesh sim boundary layer set parameters causes BAMpF's internal mesh parameters to be poor
  - Boundary layer refinements become large and un useable
  - A patch has been released that utilizes the thickness of the part for through cracks to define the boundary layer. This work around produces small meshes for these scenarios and needs to be investigate farther



Bug: Drastic Speed Decrease in Analysis

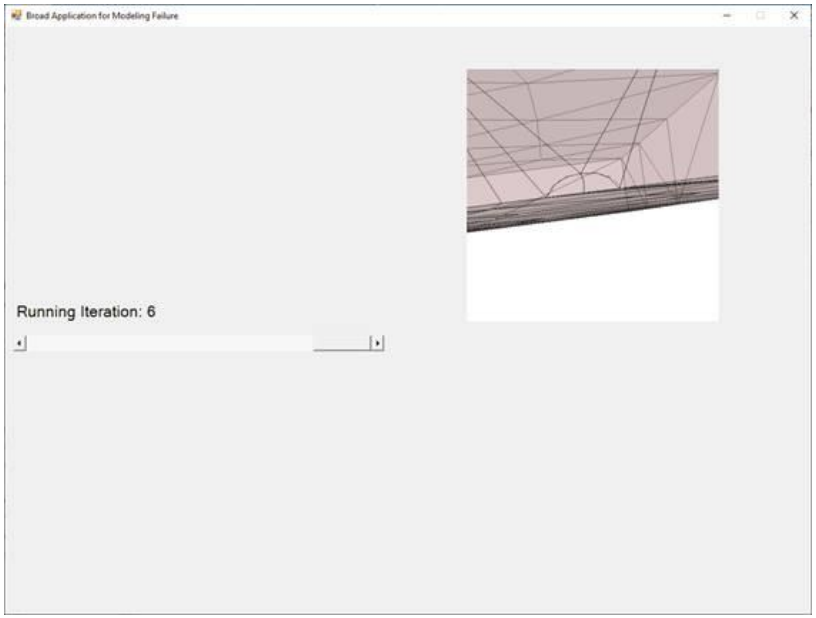
- **Bug: BAMpF was showing a significant decrease in solve time for models that were later in the solution**
  - Reduced meshing should have shown decrease in overall iteration time
  - Debugging showed a significant increase in time it took to write data to excel
  - Investigation into issues showed the code was “the worst possible way you could possibly write to excel”
  - Updated code has been pushed and appends data to previous excel file so rewriting data is not necessary





Bug: Analysis runs, but plots are not provided

- **Bug: Excel is not providing outputs, or plots to the userform. However, the analysis is progressing**
  - I haven't the foggiest idea how this is possible
  - In the code it seems like any issue with excel not saving, or crashing would cause the analysis to stop…
  - Yet, somehow this is occurring, and we are still trying to figure it out



BAMpF UTILIZATION CASES

Recent Examples of BAMpF Utilization

- **Connor Hood**
  - When a Single Crack Becomes Two: Modeling Through Crack Transition Using BAMpF
- **Dr. Kevin Walker**
  - Update: Laser Cladding modeling work utilizing BAMF
- **Robert Pilarczyk**
  - The crack wants what it wants (presented September 14)
- **Dr. Dallen Andrew, PhD**
  - Residual stress characterization for cold expansion utilizing spatial statistics: The SpARS methodology (ERSI Analysis Methods and Testing Committee 3 Sept, 2020)

Release January 2021

BAMpF RELEASE 8.0 - UPGRADES

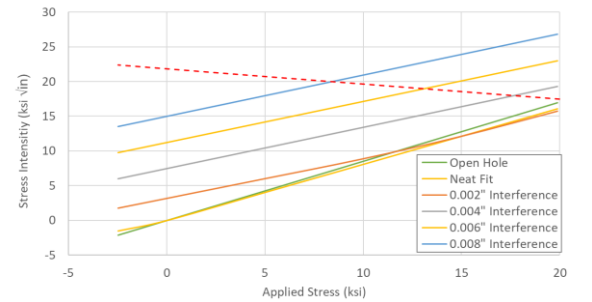
BAMpF API

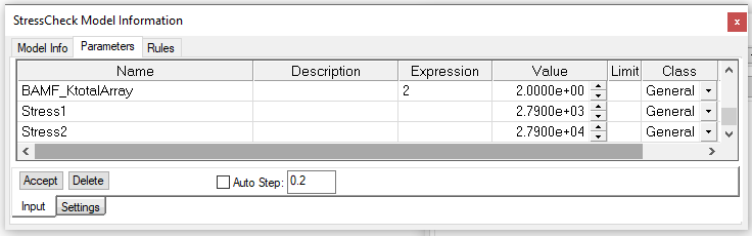
- BAMpF is undergoing an architectural change to allow for utilization with different finite element programs as well as lifing programs
- An API is being built allowing the user to utilize features in BAMpF to write their own code accessing specific BAMpF features, StressCheck subroutines, or AFGROW features that are related to BAMpF
- Creation of API will also clean up BAMpF code creating a faster and far more stable BAMpF experience
- API will be written for StressCheck 10.5 and newer and will not be supportable for previous versions of StressCheck

BAMpF K_{total}-array

- **AFGROW traditionally uses a K/σ for plug-in**
  - Assumes K is linear with σ
  - Assumes K=0 at no applied loads
- **Stress Intensities at Interference fit fasters and neat fist fasteners do not satisfy these assumptions**
- **Capability has been added to AFGROW plug-in and BAMpF to account for these differences**
  - Rather than passing K/σ for each point an array is passed to AFGROW which can account for non-linear stress intensities over the entire spectrum
  - AFGROW will interpolate to get K_{max} and K_{min} for growth calculations

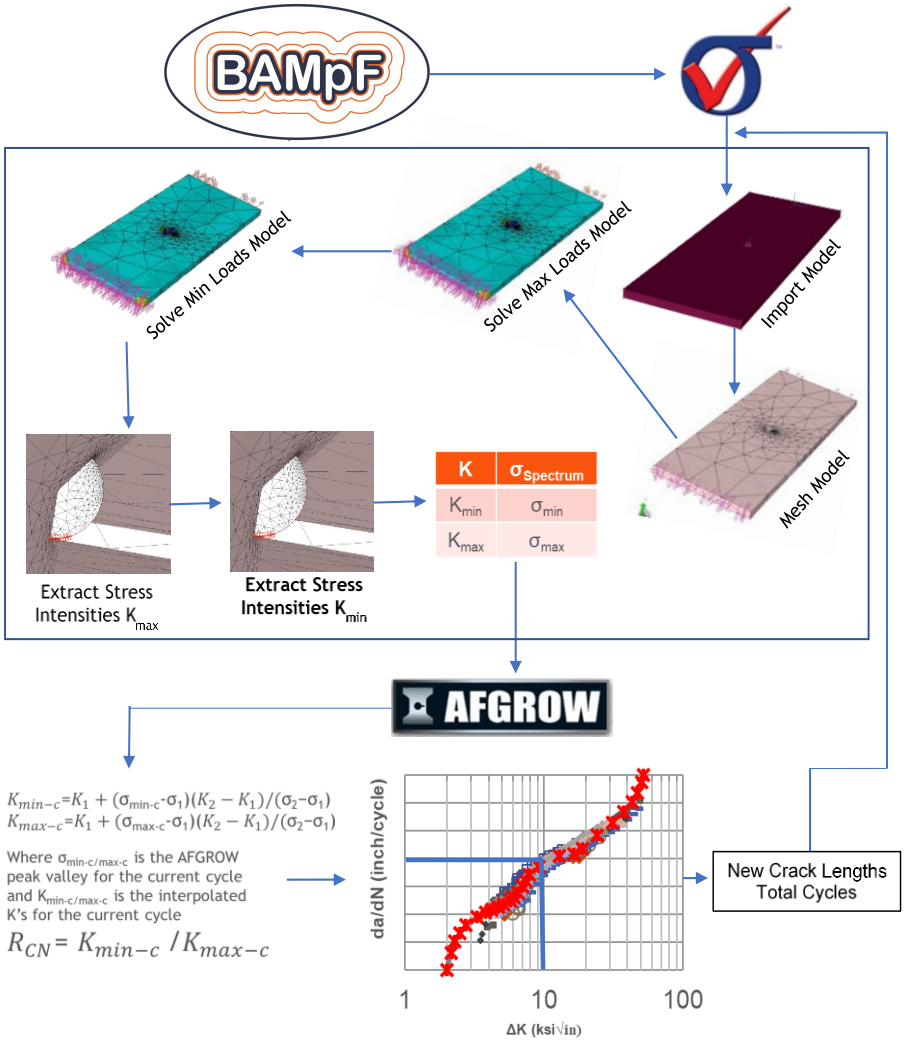
Applied Load (ksi)	K (ksi-√in)
-2.48	8.48
0	9.6
19.8	19.3





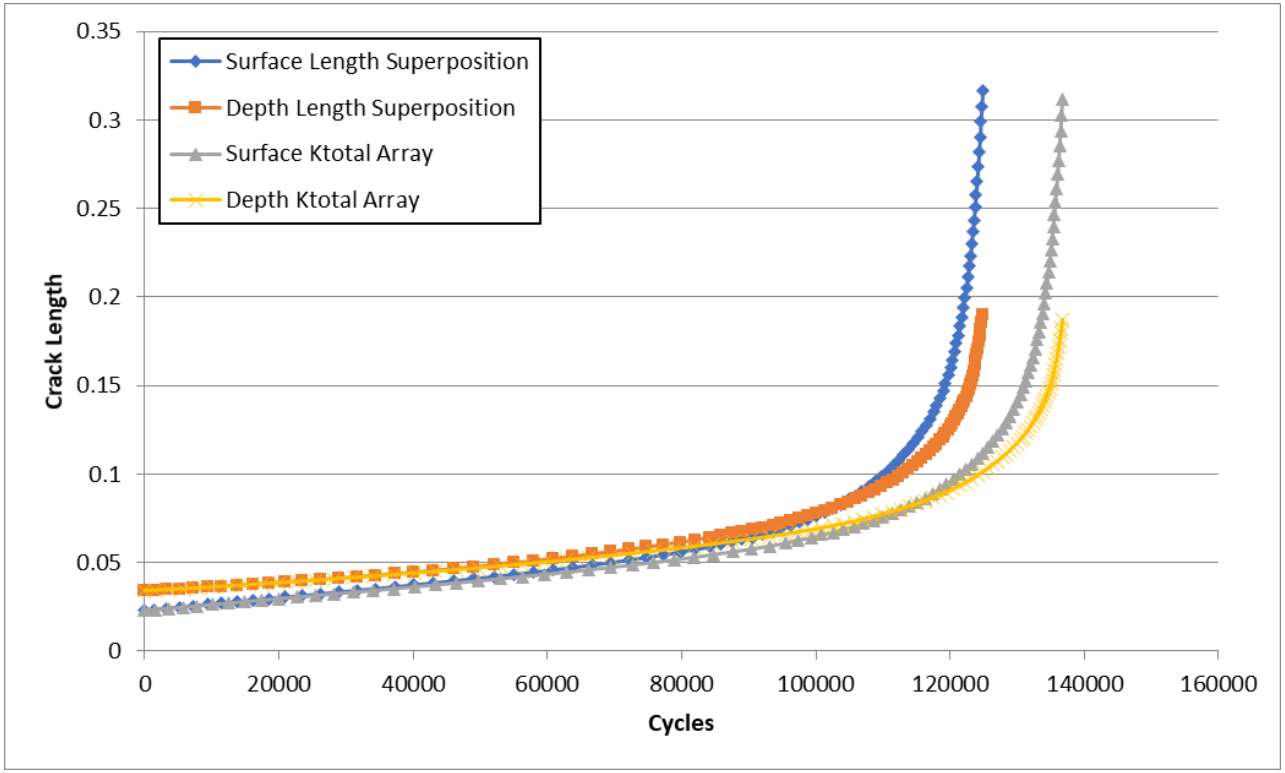
BAMpF K_{total}-array flow chart

- **Models are complex and can include contact ERSI RR 2 models can take**
  - 88 growth steps
  - 2 solutions per step
  - 15 contact iterations per solution
  - ~2500 solutions total
  - 60 hours of run time
- **For ERSI RR2 only 2 stress levels are needed since the spectrum is constant amplitude with R=0.1**



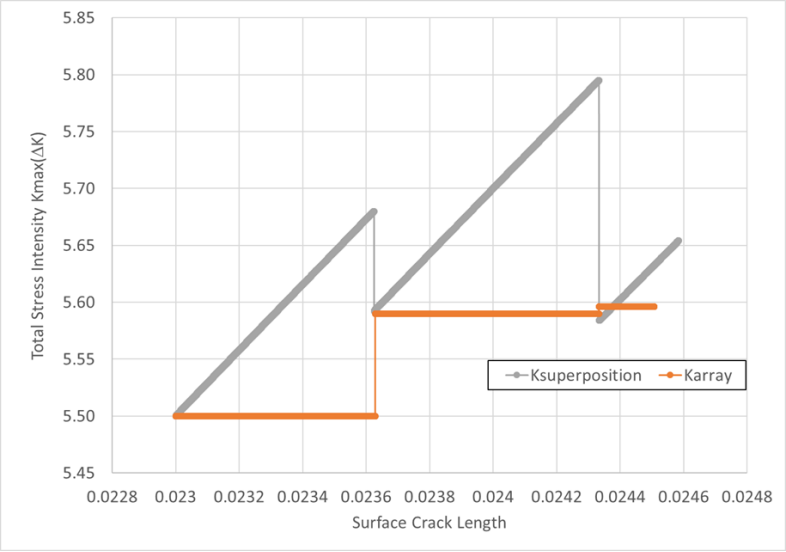
AFGROW Residual Stress Calculations

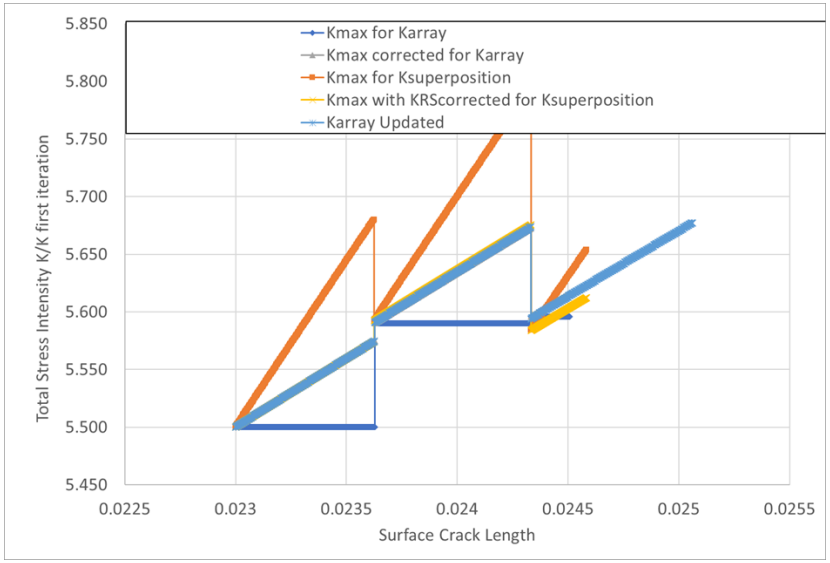
- **Testing the Ktotal-Array method with ERSI RR 1; Condition 2**
  - If method is implemented correctly it should produce identical results to current superposition method used in AFGROW/BAMpF
  - Unfortunately, there were differences



AFGROW Residual Stress Calculations

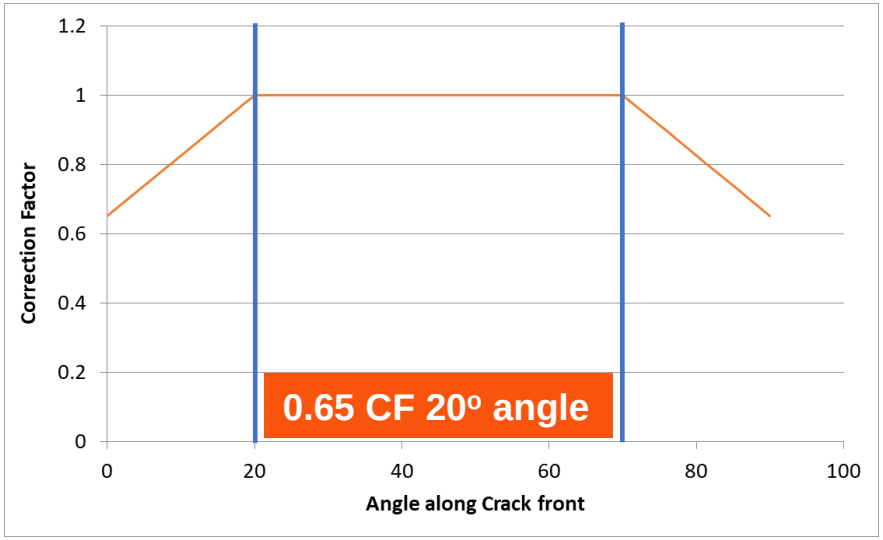
- **Differences in lives related to different K calculation methods**
  - For $K_{superposition}$ AFGROW utilized a constant Beta between recalculations
    - Will increase $K_{applied}$ until a new beta is calculated at a rate of $\frac{\sqrt{a_j}}{\sqrt{a_1}} = CF$
    - Only $K_{applied}$ inreases, K_{rs} remain constant
  - For K_{total} array AFGROW utilized a constant K between recalculations
    - AFGROW updates each Ktotal in the array by $\frac{\sqrt{a_j}}{\sqrt{a_1}} = CF$
  - AFGROW is working on fixing the constant K_{rs} for $K_{superposition}$

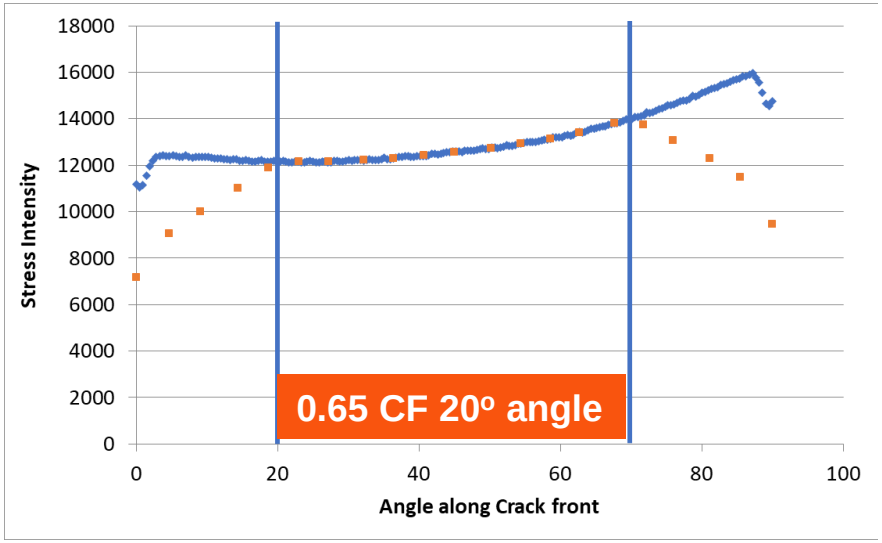




BAMpF Surface Corrections

- Utilizing marker band and fatigue test data determine what is necessary to match multi-point crack growth analysis to test data
- A 20º interpolation angle with a correction factor that appears to be based a function of plane strain and plane stress fracture toughness
- Corrections are made to the extracted K's from StressCheck





BAMpF Surface Corrections

- **Corrections for through thickness have not been implemented**
  - Unclear how to approach this due to nature of BAMpF
- **Understanding of what these corrections physically represent are on-going and were discussed earlier in the conference**

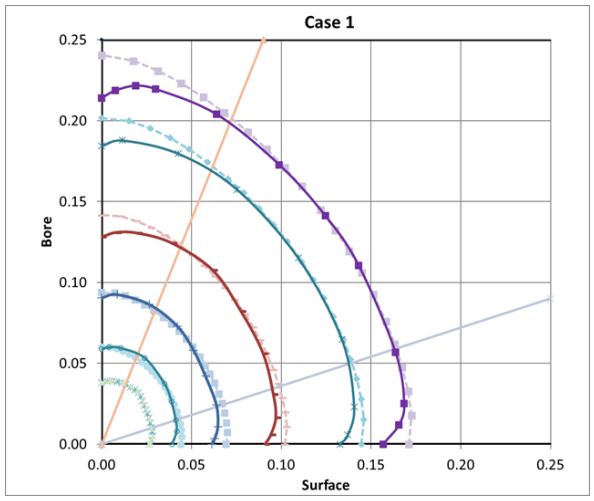
StressCheck Model Information

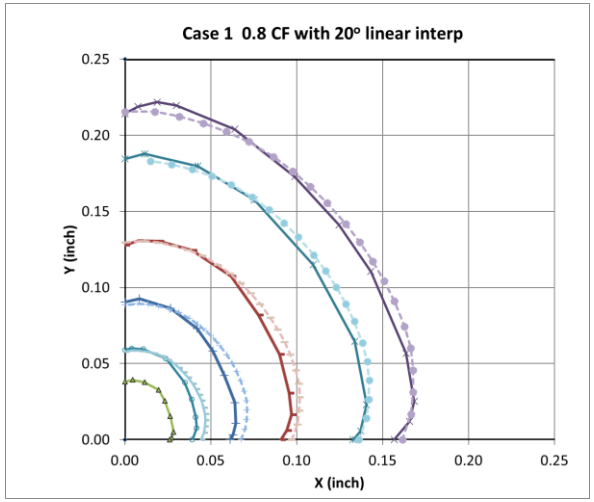
Model Info | Parameters | Rules

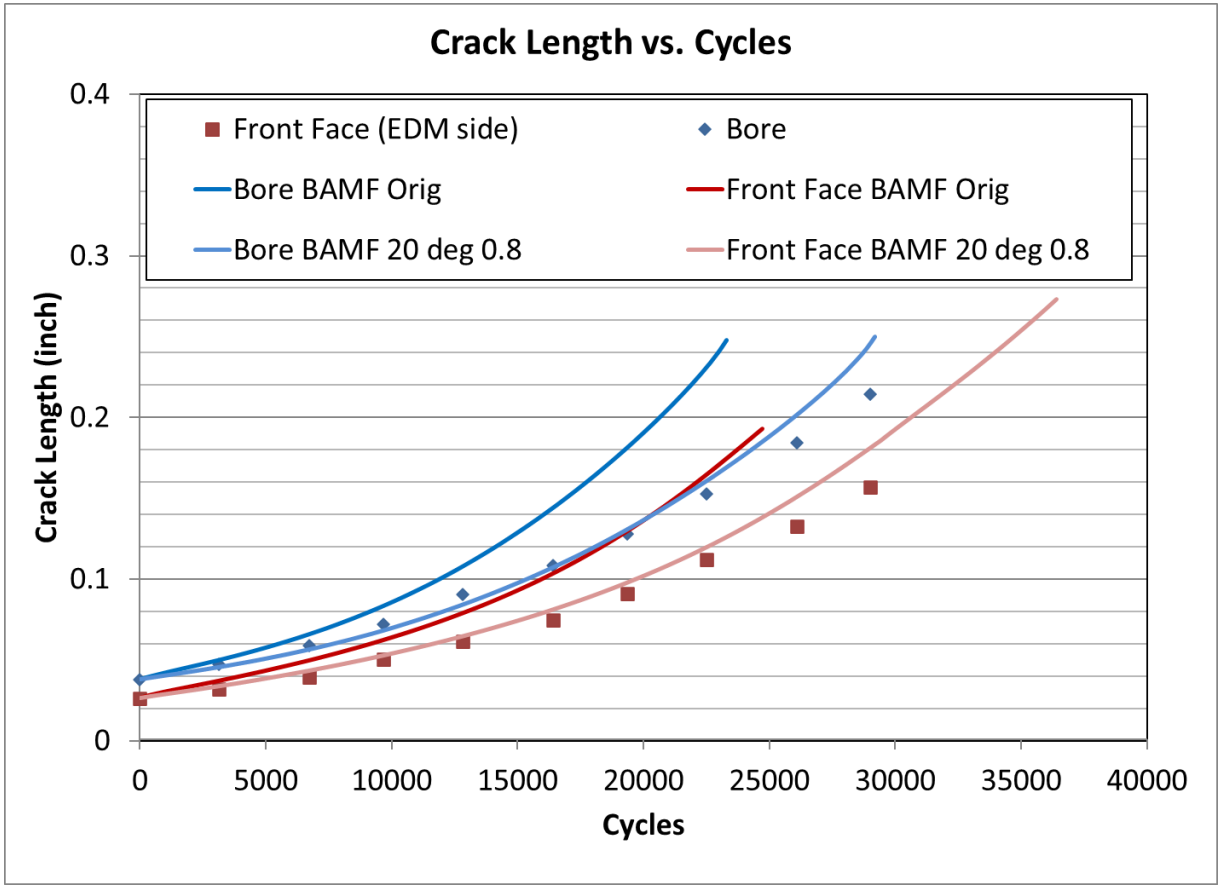
Name	Description	Expression	Value	Limit	Class	Sort
BAMF_CSP_Angle1	MaxAngle		2.0000e+01		General	
BAMF_CSP_Factor1	SurfaceCorrectionFactor		6.5000e-01		General	

```
Public Function SPCFEquation(ByVal PointAngle As Double, ByVal MaxAngle As Double, SurfaceCorrectionFactor As Double) As Double

    Return ((1 - SurfaceCorrectionFactor) / MaxAngle) * PointAngle + SurfaceCorrectionFactor


End Function
```

BAMpF Surface Corrections







Retardation and BAMpF

- **When utilizing BAMpF with retardation if points are not evenly spaced issues can occur with crack growth.**
- **Every iteration points are respaced and updated in AFGROW**
  - This causes issues with retardation as the retardation state is not updated
  - If the new crack length becomes less than the previous crack length
    - occurs when transition through geometry or on the 1st iteration if points are not spaced evenly
    - It will lead to effective stress ratios that are greater than 1 causing no growth
- **AFGROW is working to pass yield-zone sizes to BAMpF through plug-in**
  - This will allow for BAMpF to interpolate the yield-zone size along with the new crack lengths ensuring smooth respacing
  - This will also allow for restarting of a BAMpF run seamlessly without loosing the retardation state

BAMpF Hidden Feature Parameters-Crack Features

- BAMF_ElementCF#: Changes the default number of elements along the crack face. Default is 1.25x # of points
- BAMF_Ktol#:Defines the number of points to use in the K tolerance smoothing algorithm. Default is 4.
- BAMF_Layers#:Allows the user to change the number of layers the boundary layer refinment uses. Default is 2
- BAMF_Kconverge: Allows BAMpF to solve 1 solution above and 1 below the set p-level. The value the
- BAMF_SymCrack#: Allows the user to define that a crack surface is a symmetry face
- BAMF_MDCrackAngle#: Input value that allows for multi-directional crack growth. It will

BAMpF Hidden Feature Parameters-New Features

- BAMF_CSP_Angle#: Allows the user to correct the surface points. Currently the correction will go to the input angle linear interpolated from the surface by the input correction factor.
- BAMF_CSP_Factor#: Allows the user to correct the surface points. Currently the correction will be maximum correction at the surface linear interpolated to the input angle
- BAMF_KtotalArray: Triggers BAMpF to solve multiple solutions for the Ktotal array approach, value is set to the number solutions to be solved

BAMpF Hidden Feature Parameters-Debugging

- BAMF_Debug: Triggers BAMpF to enter Debug mode. This provides data that can be given to BAMpF technical support to aide
- BAMF_Locate: Allows the user to use selection sets if desired (it shouldn't be desired)
- BAMF_SaveSCP: Saves a solved .scp file for each iteration. Good for models that take a long time to run and reviewing individual models is desired
- BAMF_Respline: Triggers BAMpF to not enter the re-spline routine, this aides in debugging issues to determine where the model is failing
- BAMF_Visible: Allows the user to visualize StressCheck while BAMpF is operating

BAMpF FUTURE

Proposed Feature List from Previous Workshop

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

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