Multi-Point Crack Growth Analysis: BAMpF Ground Rules

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LIST OF ACRONYMS AND ABBREVIATIONS

API	Application Programming Interface
ASIP	Aircraft Structural Integrity Program
BAMpF	Broad Application for Multi-point Fatigue
CAD	Computer Aided Drafting
DTA	Damage Tolerance Analysis
ERSI	Engineered Residual Stress Implementation
FEA	Finite Element Analysis
FEM	Finite Element Model
LEFM	Linear Elastic Fracture Mechanics
SMF	Stress Multiplication Factor

1. INTRODUCTION

The following guidelines describe best practices for conducting multi-point fracture mechanics analysis using the Broad Application for Multi-point Fatigue (BAMpF) software.

This document is authored based on capabilities and requirements for BAMpF Application Programming Interface (API) released Spring 2026 for use with AFGROW Version 5.5.4.27 and StressCheck Version 12.1. For guidance on obtaining, validating and applying residual stresses to an analysis, reference the Ground Rules for including Residual Stresses.

Best practices for a closed form Damage Tolerance Analysis (DTA) still apply to a multi-point analysis. However, where there are discrepancies between general best practices and the guidelines specified herein, these guidelines take precedence.

2. BAMpF OVERVIEW

BAMpF is a software plug-in that extracts stress intensities from StressCheck for multiple points along a crack front and applies those stress intensities in a user defined model in AFGROW to predict crack growth for each point individually. Once crack growth for any point along the crack front meets the crack growth increment defined in the AFGROW Predict Preferences menu, BAMpF updates the StressCheck model with the crack growth of each point, then re-meshes and re-solves the StressCheck model, extracting new stress intensities to feed back into AFGROW. BAMpF iterates crack extension until the model fails.

Detailed inputs for both AFGROW and StressCheck are required for a successful BAMpF analysis. Consult the BAMpF User's Guide, Release 8.1 for StressCheck and AFGROW model inputs and requirements.

When using Finite Element Analysis (FEA) tools, more detailed information and inputs are generally necessary than for a conventional analysis (e.g. detailed boundary constraints and loading). Often, FEA simulates a single loading scenario to determine the material response of that load case. However, since BAMpF executes a DTA which has multiple load conditions, the FEA needs to be representative of the loading conditions the spectrum was based on. Consequently, it is necessary for the analyst to understand how the stress equation was derived. Does the stress equation represent an average stress of the entire cross section, or does it represent a surface stress from a strain gage, or is the stress equation representative of stresses at the crack origin? The StressCheck model loading and constraints must be tailored such that the model accurately produces stresses that match those of the stress equation for each load condition. If the StressCheck model doesn't accurately reproduce the stresses from the stress equation, then the BAMpF analysis will be invalid as the model is not representative of the loading spectrum stresses.

A best practice is to simulate the condition that creates the peak stress in the spectrum and compare the stress values at the location from which the spectrum stresses were generated. For example, If the spectrum was generated from a strain gage installed on a flange of a spar cap, compare the appropriate stress component to the gage-based stress at the location where the gage would lie within the FEM. If the spectrum was created based on the stress at the centroid or the average stress over the area, check those stress values in the FEM against the peak stress in the spectrum. If the stress values don't agree within 5%, either adjust the loading in the FEM to achieve the target or adjust the spectrum to represent the new peak stress value. This decision is an engineering judgement on the accuracy of the FEM versus the source data for the peak stress value. If this process is not checked and verified, there is a high likelihood the stress state used in BAMpF will not represent the spectrum correctly, and the results will be skewed.

When comparing current FEM results to historically derived peak stresses, the initial assumption should be that historical peak stresses are accurate. Before current FEM results can be assumed to be more accurate, a thorough investigation with ample justification for the change must be generated and documented. Then related locations must also be analyzed for similar discrepancies with legacy peak stress derivations. In no case are previously accepted test results to be dismissed. If test results are available for the location of interest, then the FEM loads and constraints must be modified to match physical test results.

It is possible to run load scenarios other than the peak stress condition for the spectrum and scale the results using the stress parameter in StressCheck and the SMF value within AFGROW.

However, caution must be used with this approach. Basing the FEM on a load condition other than the peak stress condition assumes everything scales linearly with stress. If the FEM includes non-linear loading from interference, contact, gap elements, etc., the scaled stress state will not be accurate. As a result, it is best practice to model the peak stress condition to minimize potential scaling error.

If non-linearity is inherent to the problem, then the K-array feature in BAMpF should be used to generate stress intensities from multiple load conditions to be passed into AFGROW for each iteration. The number of load conditions to be included in an analysis using the K-array method is case specific and should be verified to have sufficient resolution such that the final stress intensities interpolated by AFGROW result in <5% error.

3. STRESSCHECK MODEL

3.1 General Information

To perform an analysis using BAMpF, the first step is to construct a StressCheck model following the guidance provided in the BAMpF User's Guide. Unlike a traditional AFGROW analysis where an optimized geometry is typically used, the actual geometry of the part being analyzed should be used for a BAMpF analysis.

- For guidance on constructing the StressCheck model itself, reference the StressCheck support documentation by logging in to https://www.esrd.com/support/stresscheck-documentation/
- If needed, new accounts can be made rapidly on their website, free of charge. This online documentation has replaced the StressCheck Master Guide.

3.2 Geometry Details

3.2.1 Parameterized Models

StressCheck allows the user to define Computer Aided Drafting (CAD) geometry and other model details with variables called parameters. Defining geometry and other inputs with parameters empowers the user to easily change these values for design iteration, sensitivity studies and other comparisons. As a result, it is recommended to define values with parameter variables whenever possible.

3.2.2 Geometry Idealizations

The most accurate solution is to define the actual model geometry in the StressCheck model for BAMpF. However, for complex parts it is often more convenient to develop the geometry in a CAD software package and then import it. Imported geometry cannot be parameterized.

3.2.3 Model Height

The height to width ratio of a specimen is known to have a significant influence on stress intensity, which has driven specimen height to width (***H/W***) requirements in ASTM standards, such as E647. For most DTAs the ***H/W*** ratio on the aircraft geometry is "large" (>10). The StressCheck model geometry for BAMpF should represent a sufficiently large ***H/W*** ratio for the location being analyzed. Academically, a height of 20 times the width should be used, however the model height must also accurately represent the loading and constraints on the airframe so the model height should not exceed the actual part height.

Height effects can become more significant with longer crack lengths, so convergence and solution accuracy should be checked for the range of crack sizes being evaluated. Additionally, if bending is restrained by adjacent structure, those constraints should be considered to ensure the model accurately represents the on-aircraft loading and constraints. A recent study of ***H/W*** effects can be

found in the 2018 AFGROW presentation by Scott Fawaz[1]**.** In cases where very wide components are being analyzed, such as wing skins, a smaller ***H/W*** ratio may be acceptable. If the model is symmetric about the crack face, then the modeled height only need be 10 times the model width.

3.2.4 Bearing Loads

Load transfer needs to be included in the StressCheck model as the actual pin load at all relevant fastener locations. If a pin load is not directly available, it can be calculated using the Bearing Stress Fraction (***BSF***) by the equation: ***Pin Load*** = ***FarFieldStress*BSF*Diameter*thickness***. The pin load can be applied to a hole bore in StressCheck using the ***Select-> Any Surface -> Bearing*** with the ***Mag./Dir.*** selected in the ***Direction*** drop down box and entering the pin load in the ***Magnitude*** box. The ***Angle*** must be adjusted to apply the load in the proper direction.

The bearing load should be applied in the direction that will create the bypass stress field defined by the Axial Stress Fraction (***ASF***) in a traditional DTA. The appropriate direction for the bearing load depends on the model constraints and other loads applied. For a simple hole in an axially loaded plate the loading and constraints shown in Figure 1 represent a good approach, with the bottom face fixed in the y- and z-directions and the far field stress applied to the top face. The bearing load is then applied to oppose the far field stress. The constraint in the x-direction on the left face is to react the eccentricity of the offset hole and is placed on the edge furthest from the hole.

This application of loads and constraints creates the far field stress state above the hole and the bypass stress state below the hole. The intended stress state should be verified by evaluating the static stress results as shown in Figure 2. In the example below the applied far field stress is 28.525 ksi and the bypass stress is intended to be 26.27 ksi (***TSF*** = 0.921).

[1] https://afgrow.net/workshop/documents/2018/Scott-Fawaz-Using-Low-Temperature-Crack-Growth-Data-in-Crack-Growth-Analyses-Workshop-2018.pdf

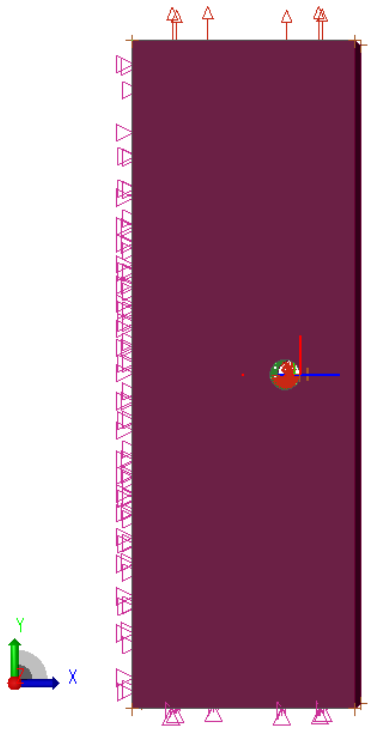


Figure 1: StressCheck model for a simple hole in an axially loaded plate including loading and constraints

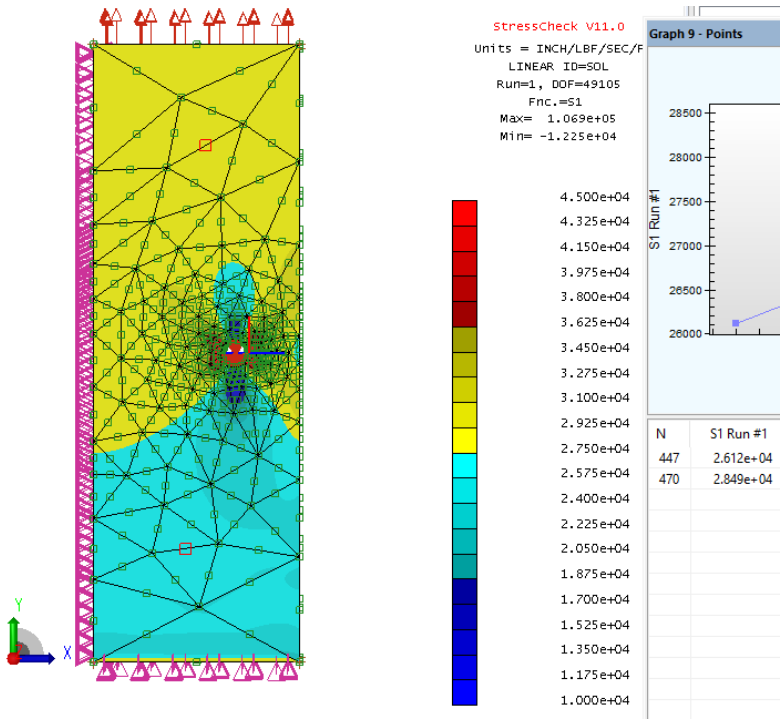


Figure 2: Static stress results for model shown in Figure 1

3.2.5 Stress Parameter

The fundamental equation behind Linear Elastic Fracture Mechanics (LEFM) is the definition of a stress intensity: $\boldsymbol{K = \sigma\beta\sqrt{\pi a}}$ Dividing that equation by stress leaves only geometry related parameters on the right-hand side: $\mathbf{K/\sigma = \beta\sqrt{\pi a}}$. BAMpF defines the ***K/σ*** in this latter equation as alpha ($\boldsymbol{\alpha}$). This alpha value is what BAMpF passes from StressCheck to AFGROW for each point along the crack front. AFGROW then multiplies alpha by the stress for the current cycle to determine the stress intensity of that cycle. Therefore, it is necessary for the analyst to verify that the stresses and stress intensities scale appropriately with the spectrum stress equation as described in Section 2. To perform the necessary scaling, BAMpF requires a parameter named ***Stress*** in the StressCheck model, which is divided from the stress intensity to get alpha. It is imperative that the analyst use a value for the ***Stress*** parameter that appropriately scales the stress intensity for the load sequence applied by AFGROW. If needed, a single BAMpF iteration can be run under constant amplitude to compare stress intensities from the .out file to those taken directly from the StressCheck model.

3.2.6 Complex Geometry

While the CAD capabilities in StressCheck are improving, it is still relatively difficult to build complex geometries in StressCheck as compared to other CAD and FEA packages. As a result, it is recommended to import complex geometries as a Parasolid (preferred), STEP, or IGS file from a native CAD program such as NX. Imported geometry cannot be parameterized. Consequently, if any part of the model needs to be parameterized, that detail will need to be created in StressCheck.

When using imported geometry, a best practice is to define the first and last points of the crack front slightly outside (~0.01 inch) the part to ensure that the crack front extends to the part edge. BAMpF will adjust that point to be on the part edge automatically. Even though this can create a crack angle slightly larger than 90 degrees or 180 degrees, the 90 or 180 degree crack angle is still the correct definition to use in BAMpF because BAMpF will bring that point into the part edge.

3.2.7 Optimization

A BAMpF analysis typically meshes and solves the StressCheck model ~70 times (one solution per iteration), so minimizing StressCheck solve times has a direct effect on BAMpF solution times. Therefore, it is recommended to use model symmetry, if applicable, and other options to reduce the element count and thereby shorten analysis run times.

3.3 StressCheck Sets

3.3.1 General Information

The purpose of sets in the StressCheck model is to ensure the appropriate object in the model is clearly defined for its intended purpose. This is important for BAMpF because the model geometry is changing each iteration as the crack grows. Using well defined sets for changing model objects can help BAMpF be more stable. BAMpF requires sets for the nucleation coordinate system(s), crack face(s) and crack front(s).

3.3.2 Defining Sets

3.3.2.1 Selection Sets

A selection set is defined simply by the user selecting (clicking) the desired object. Selection sets are recommended for their ease of use. If selection sets are used then the sections on Location Sets, Crack Face Sets, and Crack Front Sets can be ignored.

3.3.2.2 Location Sets

A location set defines an area or volume in which StressCheck should find the desired object. A location set is defined by the user as a rectangular prism. The prism only needs to contain a part of the object to be selected, not the entire area/volume of the desired object. For example, a crack face location set would be a box that encloses a small portion of the crack face. Location sets are not recommended due to their potential for selecting the incorrect feature as the model changes, such as the crack growing into a location set volume.

An example image of a crack face location set can be found in Figure 3. Location sets are oriented from the global coordinate system.



Figure 3: StressCheck model showing crack selection using crack face location set

3.3.2.3 Crack Face Sets

When defining a location crack face set for the StressCheck model, the set should be completely contained in the crack face to ensure adjacent faces aren't incorrectly associated with the crack face by StressCheck.

When residual stresses will be applied to the crack face it is a best practice to create a redundant crack face set to apply the residual stress traction load because BAMpF will update/adjust the set type for the crack face set. To ensure that those changes don't influence the face set for the residual stress it is recommended to create a redundant crack face set, often named ***RSCRACKFACE***.

3.3.2.4 Crack Front Sets

Best practice is to either define the crack front set to include the entire area of the crack plane or to define the set with one of the points that defines the crack front itself, preferably one near the middle of the crack front. Defining the crack front set with one of these points permits the set to

move with the crack front as the crack grows. Defining the crack front independent of the crack front points leaves the set static and can cause an analysis to fail. An example of defining the crack front set with a crack front point is shown in Figure 4. Location sets are defined in the global coordinate system, so all the parameter variables prior to the highlighted crack front point parameter (***C1Px7***) simply define the global position of the nucleation set. Then, the crack front point parameter, ***C1Px7***, defines the distance in the x-direction from the nucleation set. Point 7 was used in this example because it was nearest to the middle of the crack front as the crack front was defined with 15 points. If the crack front is defined with more/fewer points, then the point used to define the crack front set location should be adjusted accordingly. For the example shown, the global z-direction is in line with the nucleation set y-direction, so the z-direction must be used to define the y-direction of the crack front set. Similar to the x-direction, for all parameter variables prior to the crack front point, ***C1Py7***, simply define the global location of the nucleation set.

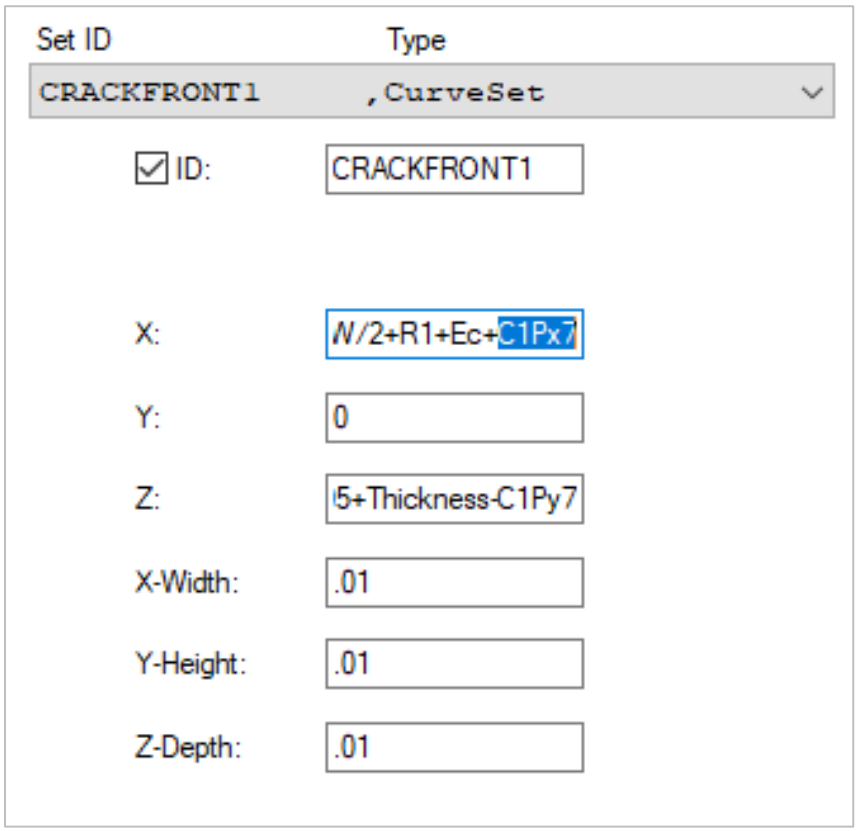


Figure 4: StressCheck menu to refine the crack front set with a crack front point

3.4 Convergence

Once the StressCheck model is defined it needs to be solved and scrutinized for general behavior, and convergence needs to be checked to determine the appropriate p-level. Stress intensities are considered hyper convergent, so if the general model convergence is acceptable (typically < 2%) then generally the user can assume the stress intensity solution will be accurate.

3.4.1 p-level

A p-level of 4 is often sufficiently accurate for negligible differences in stress intensity. For new applications or test runs it is common to use a lower p-level (typically 3) to shorten the BAMpF run times, thereby facilitating troubleshooting, model iterations or other adjustments. Once the model is finalized the p-level can easily be increased to produce a more accurate final result if needed.

The primary tool available to the user for evaluating the accuracy of the stress intensities is the ***kextract*** plot provided in the top left corner of the BAMpF interface. The stress intensity curve should be smooth and continuous and generally has local maxima near each free surface (see Figure 5), though larger cracks and cracks with extreme aspect ratios do not always exhibit local maxima at the free surface.

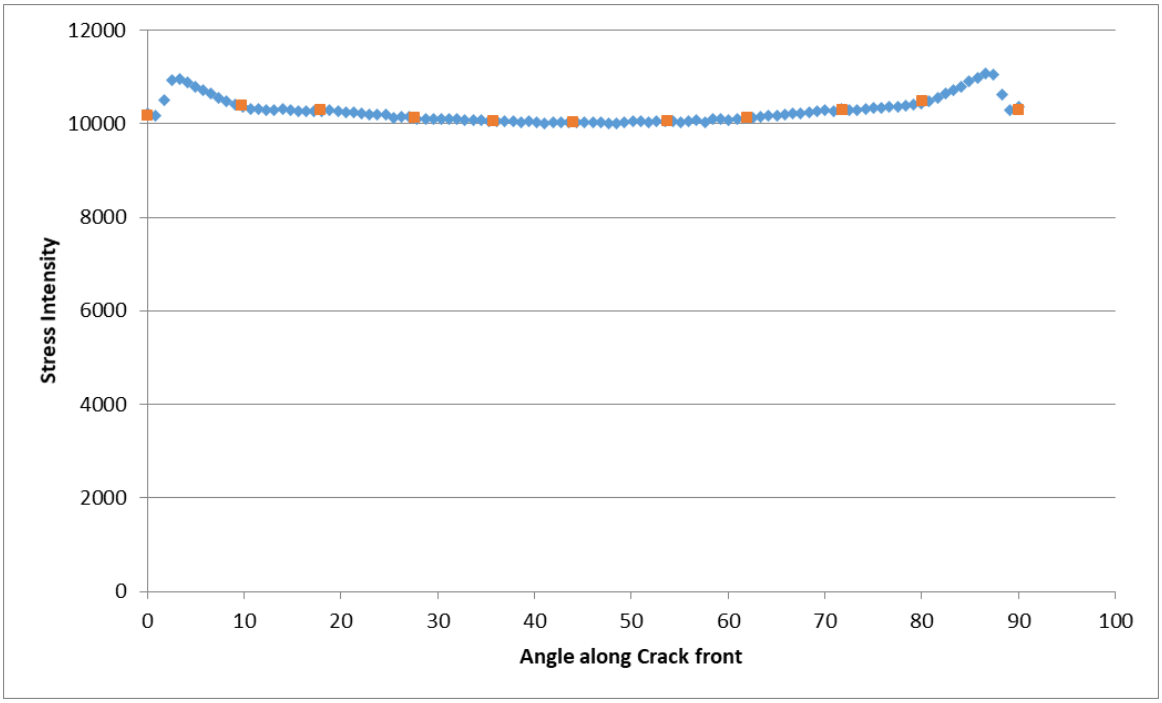


Figure 5: Plot of stress intensities along crack front angle

3.4.2 Refining Crack Front Mesh

The crack front mesh can be adjusted by using an optional BAMpF parameter called ***BAMpF_ElementCF#***. The parameter is described in the BAMpF User's Guide and can be used to adjust the mesh refinement on the crack front.

Another option is to change the number of layers in the crack front mesh. This can be done using the optional ***BAMpF_Layers*** parameter. Starting with StressCheck Version 11.1 hexahedral elements can be used on the crack face, which produce more accurate results with the default crack front mesh parameters. Generally, the hexahedral meshes result in accurate stress intensities for all default crack front definition parameters. However, the user is responsible for verifying a sufficiently refined mesh is used to obtain accurate stress intensities. With the legacy tetrahedral

elements it was shown that two layers of mesh refinement was insufficient to produce accurate stress intensities[2].

3.4.3 Evaluating convergence

If the stress intensity solution is sporadic with local maxima/minima as shown in the figure below, then the stress intensity is not satisfactorily converging. Discontinuous stress intensity solutions can be mitigated by refining the mesh at the crack front, changing the p-level, or refining the crack growth increment in AFGROW. Occasionally mild, discontinuous responses similar to that shown in the figure below may occur for an isolated iteration in BAMpF. If the discontinuous stress intensity is mild (< ~3 oscillations of ~10%) and isolated to a small number of BAMpF iterations (< 5% of all iterations), then the resulting prediction can still be acceptable. The example shown in Figure 6 should be refined.

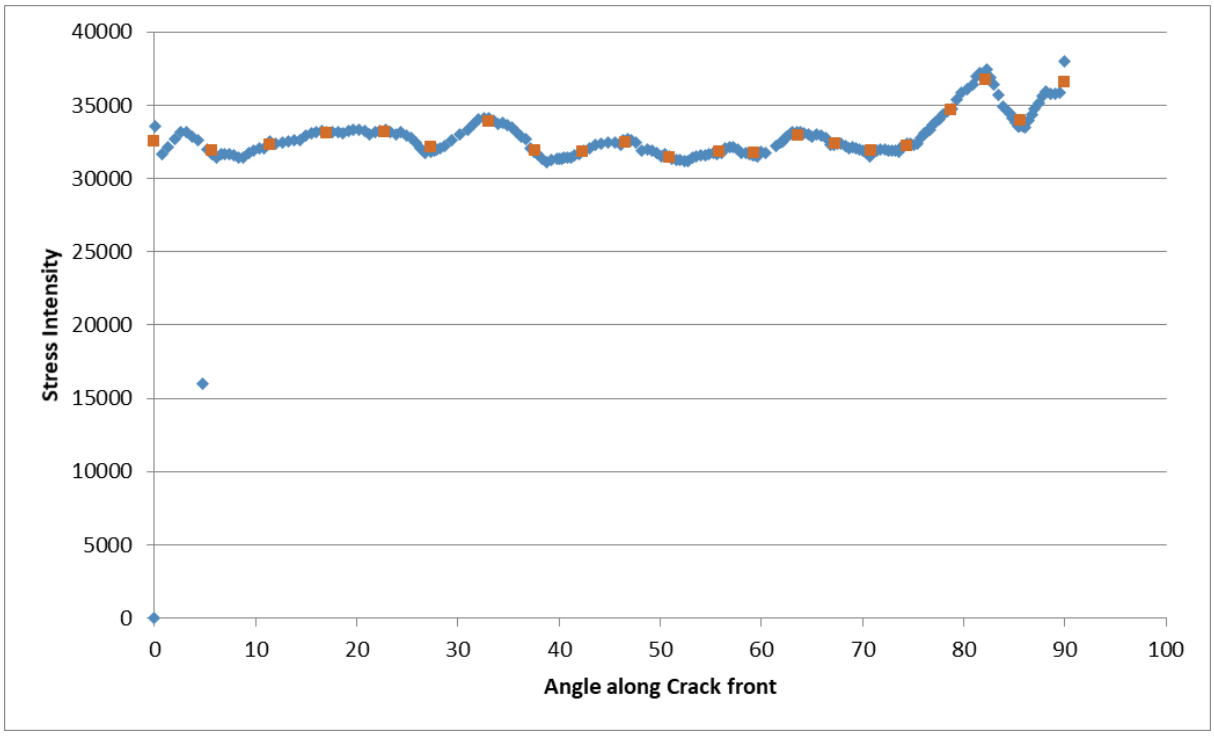


Figure 6: Plot of discontinuous stress intensities along crack front angle that requires refining of mesh

It should be noted that most geometries have at least 2 local maxima, one near each free surface. Depending on the geometry, additional local maxima may be present along the crack front. Since these local maxima are expected and a function of geometry rather than convergence error they will not be reduced or eliminated by model refinement and are acceptable for BAMpF simulations and output.

[2] https://afgrow.net/workshop/documents/2021/Robert_Pilarczyk_Cross-Comparisons_of_Stress_Intensity_Factors_from_Various_Sources-Workshop-2021.pdf

4. AFGROW INPUTS

The output interval in AFGROW should be set to "After each Beta Recalculation" to align AFGROW output with BAMpF output. A .pl2 and a .out file should be used to facilitate results interrogation.

4.1 Max Stress

The StressCheck and AFGROW models must be set up to ensure the correct loads are applied to develop accurate stress intensities for the case being solved. As a general guide, the max spectrum stress (or Stress Multiplication Factor, SMF) in AFGROW should match the required "Stress" parameter in the StressCheck model. No axial or tension stress fractions should be applied in AFGROW, rather the appropriate stress state should be created within the StressCheck model. BAMpF passes a ratio of stress and stress intensity from StressCheck to AFGROW (see Section 3.2.5 as well as the BAMpF User's Guide for details). The user must ensure the appropriate stress state and stress intensities are being used in the analysis.

4.2 Growth Increment

The AFGROW growth increment in the ***Predict Preferences*** menu can also affect the stress intensity convergence after multiple iterations. The growth increment should typically be 3% or less, but can be 5% for initial analyses to troubleshoot models and refine input parameters. Large crack growth increments can result in discontinuous stress intensity solutions by permitting one point to grow a relatively large distance compared to the adjacent point, resulting in the adjacent point behaving somewhat like a singularity with cracked material all around it (Figure 7).

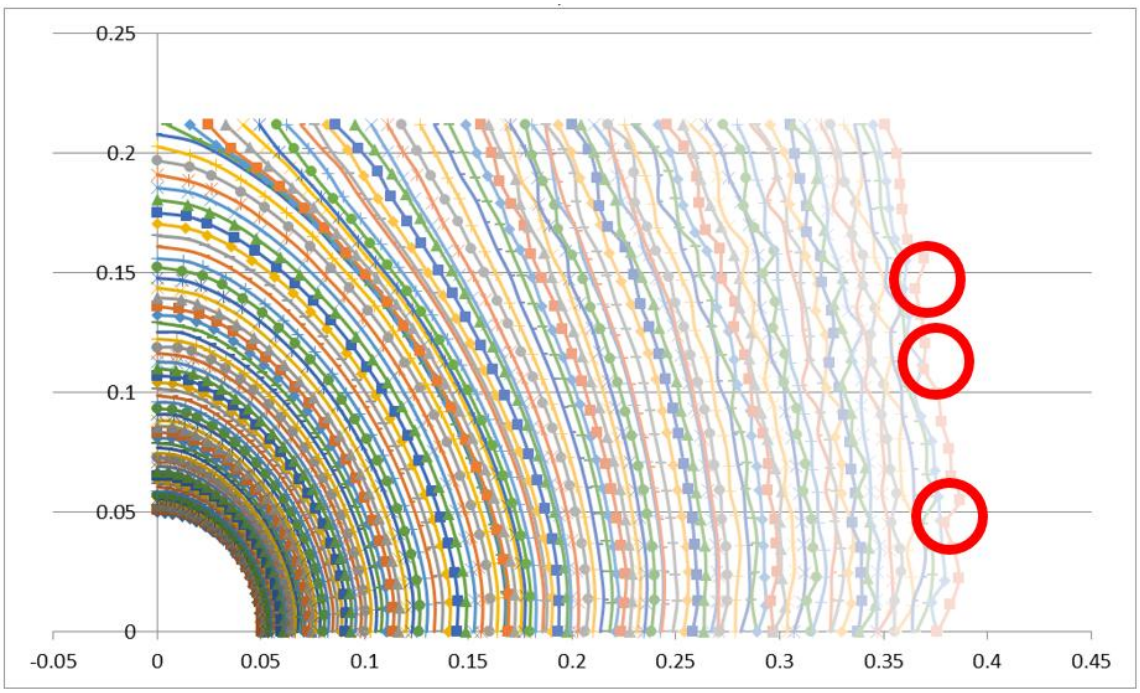


Figure 7: Plot of crack front progression, with red circles indicating discontinuous points

These quasi-singularities produce very high stress intensities for those points, but not adjacent points, causing oscillations in the stress intensity solution (Figure 8). A large crack growth increment will typically only cause oscillations in stress intensities after a large number of iterations and for thru cracks.

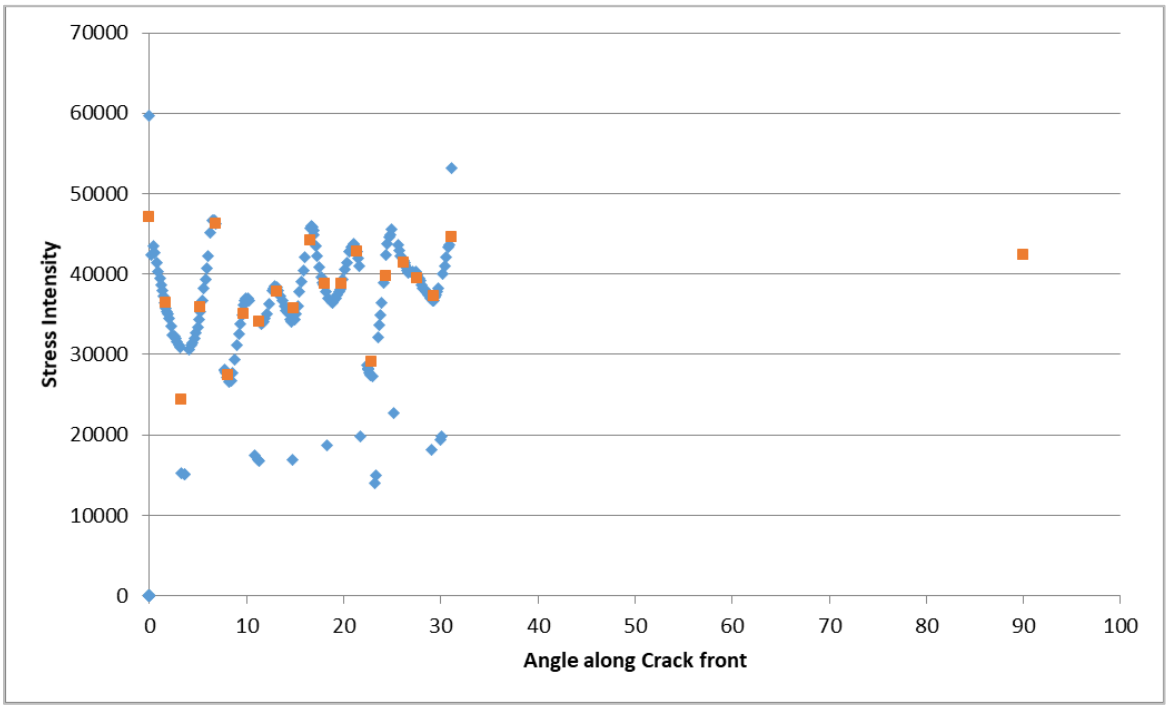


Figure 8: Plot of oscillations in the stress intensity solution

5. BAMpF OUTPUT

5.1 Output Overview

The output BAMpF provides (aside from the standard AFGROW output files as defined in the Predict Preferences menu) a folder in the same directory as the StressCheck file and with the same name as the StressCheck file. There are six subfolders: ***beachmarks, Excel, images, kextract, logs*** and ***par_files***. The ***beachmarks*** folder has saved images of the predicted crack front evolution for each iteration. These are the plots shown in the lower left of the BAMpF user window. The ***Excel*** folder will be described in more detail later. The ***Images*** folder has screenshots of the StressCheck model as well as crack growth curve plots. The ***kextract*** folder has images of the stress intensity along the crack front. The ***logs*** folder has BAMpF and StressCheck log files for help in troubleshooting crashes. Finally, the ***par_files*** folder has StressCheck parameter input files for each iteration; these files can be imported into StressCheck to start BAMpF at the imported iteration as described in Section 7.2.

5.2 Excel Output

The ***Excel*** BAMpF output folder is the folder that is most often used for post processing analysis results. It has an Excel output file for each iteration of the analysis. Reference the BAMpF User's Guide for information on what is contained in the Excel files and how it is formatted. The most critical thing to note about the output is that it is up to the user to determine the last valid iteration. The guidelines in this section provide some guidance on determining the last valid iteration.

5.3 Extracting Stress Intensity Factors

Occasionally it is beneficial to extract stress intensities at some points to run user-defined beta models in AFGROW. To obtain betas some simple algebra must be done because BAMpF does not directly pass an isolated beta to AFGROW. BAMpF provides stress intensity output starting in column J and ten rows below the last crack front point row (typically around row 30) of the ***Kapp*** worksheet of the Excel file. The first column in this section of the data is time (cycles or hours), and the subsequent data is grouped in sets of three columns per crack front point. Where the first two columns of each group indicate the x and y coordinates and the third column indicates the applied stress intensity factor as shown in Figure 9.

	I	J	K	L	M	N	O	P	Q	R	S	T
30												
31		Cycles	C1Px0	C1Py0	Kapplied	C1Px1	C1Py1	Kapplied	C1Px2	C1Py2	Kapplied	C1Px3
32		0	0.05	0	12671.56	0.049785	0.00397	14275.81	0.049321	0.007813	14312.71	0.0484
33		711	0.051012	0	13468.37	0.051545	0.004079	13370.06	0.050715	0.008471	13755.23	0.049
34		1567	0.052761	0	12776.91	0.052892	0.004589	13394.23	0.05223	0.008412	13271.32	0.0508
35		2662	0.054504	0	12769.96	0.054903	0.004349	12708.4	0.053762	0.008804	13153.84	0.0523
36		3907	0.05649	0	12145.9	0.056404	0.005062	12895.19	0.055525	0.008977	12780.83	0.0540
37		5378	0.058199	0	12465.43	0.058683	0.004961	12532.67	0.057225	0.009295	12638.31	0.0555
38		6946	0.060366	0	11964.96	0.060354	0.004967	12294.75	0.05905	0.009539	12555.17	0.0570
39		8563	0.061703	0	12300.81	0.062019	0.004861	12165.1	0.060832	0.009527	12349.4	0.0588
40		10357	0.063971	0	11521	0.063528	0.005719	12459.31	0.062283	0.010109	12402.94	0.0604
41		12167	0.065215	0	12267.74	0.065698	0.005293	11766.65	0.064323	0.009722	12216.02	0.0618

Figure 9: Screenshot of BAMpF generated Excel output file

To extract betas for any given point the user must convert the applied stress intensity factor to a beta. To do this, recall the equation for the stress intensity factor $\boldsymbol{K = \sigma\beta\sqrt{\pi a}}$. Thus, to solve for beta the user must divide **K** by $\boldsymbol{\sigma}$ and $\sqrt{\pi a}$. Typically, the first point in the BAMpF output (***C1Px0*** in Figure 9) is the surface tip of the crack which is usually the crack tip analyzed for a user defined beta model. While the ***C1Px0*** is the point along the surface of the model, if the entire crack front is being represented by just one or two points, like with a user-defined beta model, then it is often more accurate to use betas from a location that is slightly subsurface and corresponds to a local peak in the stress intensity. In Figure 10, the orange square that lies on the y-axis corresponds to the stress intensity for the ***C1Px0*** point. As can be seen, there is a rise in the stress intensity once subsurface. Most two point analyses would use the stress intensities from the second orange point (***C1Px1*** for the image below). To verify which point best represents the growth of the BAMpF model, AFGROW analyses should be done with betas from multiple points near the crack tip of interest to determine which provides a result most similar to the BAMpF analysis.

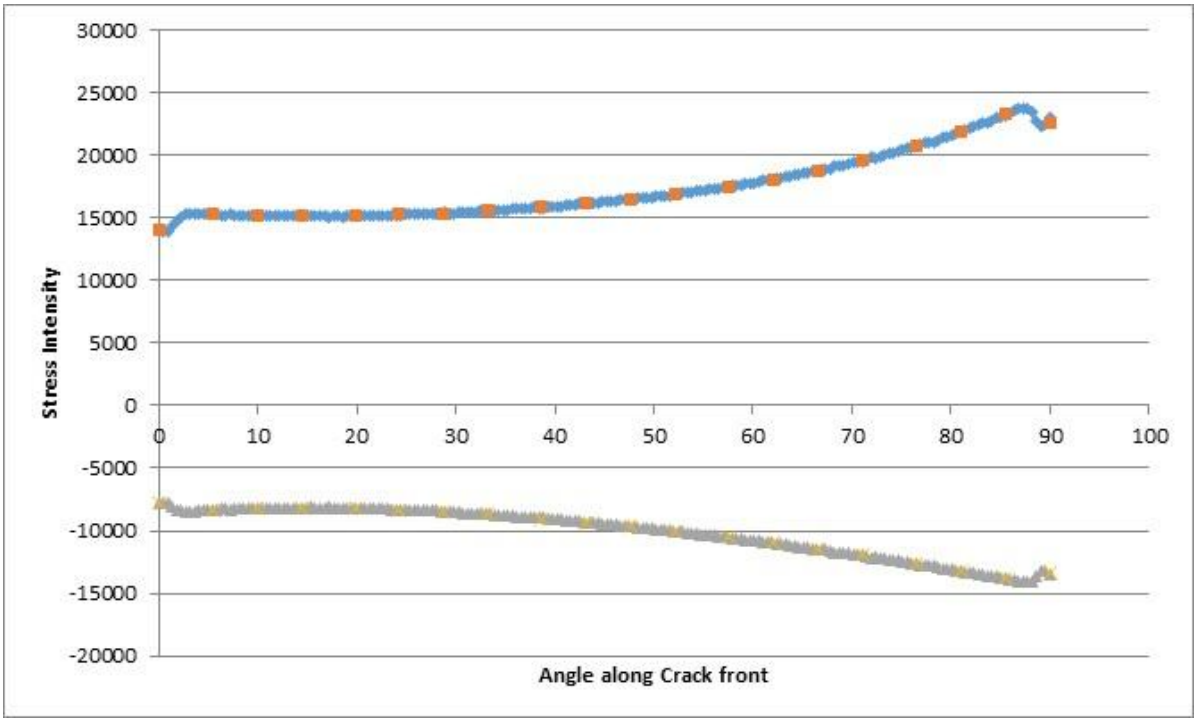


Figure 10: Plot of smooth stress intensities along crack front angle

The stress intensity output by BAMpF is based on the applied loads in StressCheck, not AFGROW. So, the applied stress from StressCheck must be used to calculate betas using the formula described in the previous paragraph. Refer to the BAMpF User's Guide for additional information on the ratio of stress intensity and applied load that is passed to AFGROW from StressCheck.

After converting stress intensities to betas, the beta dataset should be analyzed to verify model integrity across all iterations for which betas are being extracted. This step is significant since BAMpF runs can continue after the part would have failed, see Section 6 for additional information. Figure 11 shows betas extracted, where the betas are clearly invalid after the crack is

~0.15 inch long due to the dramatic oscillations in beta (as a result of oscillating stress intensities). In such instances it may be necessary to rerun BAMpF with smaller growth increments or more points along the crack front. If, however, the BAMpF run provided high fidelity stress intensities well past all geometry changes (including transition to a through crack as a geometry change) and sufficiently close to the critical crack length, then the invalid betas/stress intensities can simply be omitted. Occasionally it can be helpful to smooth the beta values as well, sometimes by using a fitted trendline rather than direct outputs. However, any time user-defined betas are employed to approximate a BAMpF run, caution needs to be exercised because subtle changes to inputs have been shown to change BAMpF results, without changing user-defined beta models significantly[3].

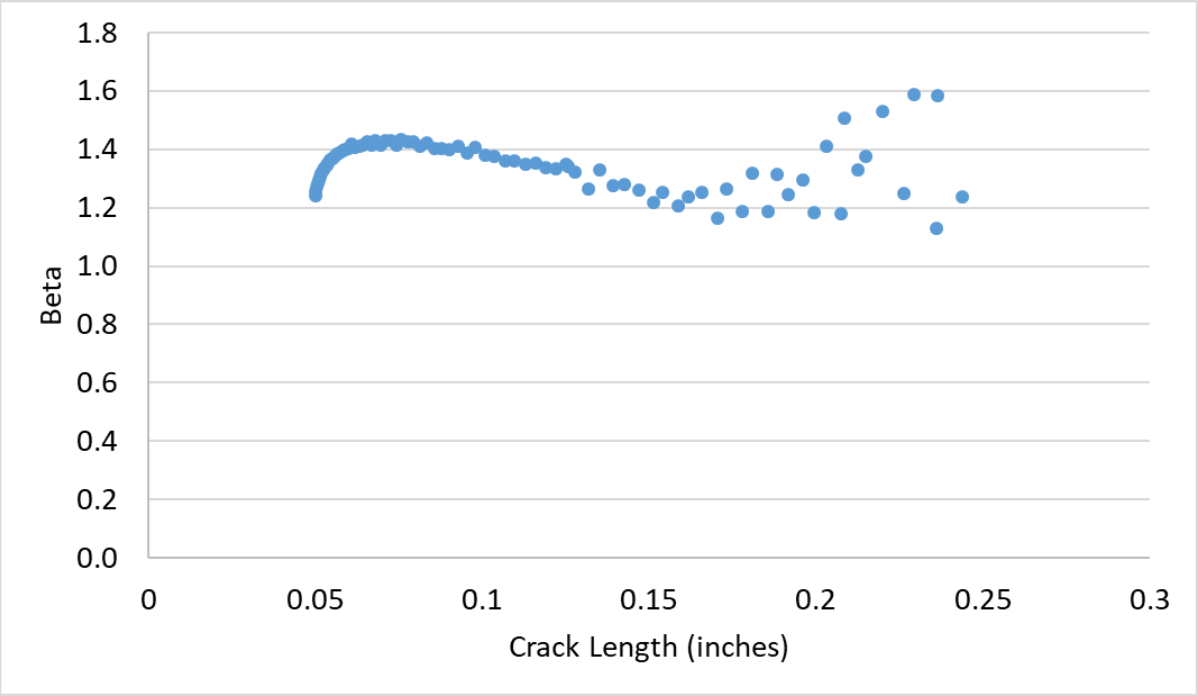


Figure 11: Plot of betas showing regions of validity and invalidity

The same failure criteria which are typically used in AFGROW may not be applicable for a user-defined beta model. For example, if the analysis for a cracked hole in a plate, the user-defined beta model will only represent the short ligament. As a result, the cross-sectional area isn't represented accurately, so a net section yield failure criteria isn't applicable. The analyst must critically evaluate which failure criteria are applicable to a given situation for what the user-defined beta is representing.

[3] https://afgrow.net/workshop/documents/2019/BAMF%20Workshop-Relifing-Aint-all-its-cracked-up-to-be-AFGROW-Workshop-2019.pdf

5.4 Validating Results

When developing a new BAMpF model reasonable comparisons should be made to either other analyses or test data to validate the constraints, loads and other inputs are being applied correctly. If test data is available, then the BAMpF analysis shall be compared to test results for validation. The initial crack size and other geometry details should be adjusted in the StressCheck model to match the test details. The primary comparisons that need to be made are crack growth shape and time to failure. Adjustments to the model should be made as necessary to accurately correlate the BAMpF results to test. Loads and constraints should be scrutinized for potential deviations in stress and strain response from the test setup. Any adjustment to loads or constraints necessitates a subsequent revalidation of the stress parameter as described in Section 3.2.5. If the model uses a residual stress field, there is typically low confidence in residual stress data from the contour method near any free surface. Consequently, it is sometimes necessary to reduce the residual stress field near a free surface. Under no circumstance is it acceptable to increase the magnitude of compressive residual stresses to enable correlation – see Ground Rules for Including Residual Stresses in Damage Tolerance Analyses.

When test data is unavailable, then BAMpF analyses should be compared to the AFGROW analysis that would have been used to analyze the location previously. If residual stresses are being included in the BAMpF analysis, then a redundant BAMpF analysis without residual stresses must be performed and compared to an AFGROW analysis to validate model constraints, loads, etc. When comparing AFGROW and BAMpF results, BAMpF may crash before attaining the critical crack length. In those cases, to compare AFGROW results with BAMpF the life at some crack length prior to the critical crack length can be a valuable comparison. For example, if the critical crack length is 0.3 inch, but BAMpF crashed at 0.25 inch it may be sufficient to compare against the AFGROW life at 0.25 inch rather than refining the StressCheck model to continue iterating in BAMpF. If BAMpF is being employed due to complex geometry, then comparisons with AFGROW results may not be a reasonable option and comparison to fleet data and rigorous evaluation of all model inputs should be completed prior to publishing any BAMpF results.

6. FAILURE CRITERIA

Unlike traditional AFGROW analyses, analyses performed using BAMpF currently do not support the failure criteria checks provided by AFGROW, even if they are selected in the AFGROW Predict Preferences menu (unless/until all points along the crack front meet the failure criteria). This is a result of each point being individually grown in AFGROW, preventing AFGROW from evaluating the overall geometry/cross section for residual strength or failure. It is a best practice to define a max crack length failure criterion in AFGROW to prevent a runaway BAMpF analysis. Mesh errors can cause a runaway BAMpF loop that consumes all available RAM until a memory error occurs.

6.1 Residual Strength

Limit load for the part being evaluated should be used to determine the residual strength and the critical crack size. The critical crack size can be determined assuming the fracture toughness from the material lookup file, the stress corresponding to limit load and the formula: $\mathbf{c_{crit}} = \frac{\mathbf{1}}{\mathbf{pi}}\left(\frac{\mathbf{K}}{\boldsymbol{\sigma\beta}}\right)^{\mathbf{2}}$. Any BAMpF iterations completed after the critical crack size should be dismissed.

6.2 Net Section Yield

6.3 Overview

BAMpF can continue iterating after a ligament would have failed, after stress intensities are no longer reasonable, or many other reasons. The user must perform a net section yield check by hand-calculating the remaining intact cross sectional area and verifying it can withstand limit load.

6.4 Non-converging Stress Intensities

If the stress intensities begin to violate the guidelines in Section 3.4 above, the iterations after the last acceptable stress intensity extraction should be disregarded. In some situations, the last valid iteration will not be close enough to the point of final fracture to determine a reasonable inspection interval (e.g. if the crack front or stress intensities become invalid or the mesh starts failing etc.). In these cases, it is sometimes necessary to build a new BAMpF model with more/fewer points along the crack front, modified model/mesh parameters or other changes to successfully continue the analysis. In some situations, the geometry beta correction will have reached a steady state value. For these cases the remainder of the prediction can be completed as a user defined beta model in AFGROW with the beta results from the last valid iteration, or simply with an AFGROW through crack model with adjusted betas if necessary. This approach requires justification that the stress intensities would not change significantly for the remainder of the analysis.

7. TROUBLESHOOTING CRASHES

The log files in the BAMpF output folder can be very helpful in troubleshooting a crashed run, however interpreting the log files is not necessarily intuitive. Consult BAMpF technical support and/or the BAMpF User's Guide to help interpret log files.

Poorly defined sets and missing or erroneous parameters are the primary perpetrators of BAMpF crashes. Accordingly, the first troubleshooting step should always be to review the input parameters and the sets to ensure they meet the guidelines spelled out in this document and the BAMpF User's Guide.

7.1 StressCheck Licenses

Another common cause of StressCheck crashing (especially when working remotely) is failing to access a StressCheck license on the license server. As a result, it is recommended that a network StressCheck license be available for the duration of the BAMpF analysis.

7.2 Postmesh6.scw

When BAMpF crashes there will be a file in the same folder as the StressCheck file used to start the analysis that has the suffix ***postmesh6.scw*** appended to the file name. This is the StressCheck file for the last iteration after the mesh was applied (or after the mesh was attempted). This file can often be interrogated to discover the cause of the crash. Checking whether the body meshed and whether the sets are selecting the appropriate objects are the most helpful checks to do on this file.

7.3 Ghost Points Too Far Outside Meshed Body

Reference the BAMpF User's Guide for definition and explanation of ghost points. If the spline length outside of the body due to ghost points is longer than the length of the spline within the body, then BAMpF can become unstable. In these scenarios the best solution is to redefine the spline with fewer ghost points.

7.4 AFGROW Infinite Loop

Occasionally when StressCheck fails to solve during a BAMpF run, AFGROW will enter an infinite loop of crack prediction, slowly using more RAM until no RAM remains. Some signs that this is occurring, or has occurred, are that the StressCheck model image in the top right corner of the BAMpF display is not meshed and the Output pane in AFGROW is writing new output data unceasingly. If this occurs, close BAMpF and AFGROW, then open the ***postmesh6.scw*** file to determine probable causes of the failure. Setting a crack length failure criterion can prevent this issue from happening (see Section 6).