Agenda

- Motivation
- Evolution of BAMF
- Utilization Examples
- Building a BAMF Model
- BAMF Demo
- Tips and Best Practices
- Current State & Key Features
- Comparison with Other COTS Tools
- Wrap-up
Motivation

Classic Model

Classic Continuing Damage Model
Motivation

Classic Model

Classic Continuing Damage Model
Motivation

- **How to handle:**
  - Complicated geometries
    - Tapered cross sections, thickness changes, etc.
  - Complicated loading
  - Complicated crack shape evolution

- **Limitations/Assumptions:**
  - Simplified geometries
  - Crack aspect ratio
  - Crack shape evolution
  - Multiple crack interaction
  - Beta correction factors
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?

What is an AFGROW Plug-in?

AFGROW plug-ins provide the capability for users to develop K-solutions externally from AFGROW but still use the internal capabilities that AFGROW offers, such as:

- Users can create/animate their own structural models for use in AFGROW
- Creation of Proprietary, Closed-Form, Tabular / Interpolative / Extrapolative, and External-K (if available) User-Defined custom solutions

See: Recent Development in AFGROW COM and Plug-In Applications
- 2016 AFGROW Users Workshop 2016, Alex Litvinov (LexTech, Inc)

In short, it allows the full capability of the AFGROW crack growth engine utilizing user-defined K-solutions
What is an AFGROW Plug-in?

- Accessed via VB.net or C#

- References that provide significant detail on building plug-ins:
  - Building AFGROW COM and Plug-In Applications, Alex Litvinov (LexTech, Inc.), AFGROW Workshop 2010
  - Basics of StressCheck + AFGROW Application Development: An Engineering Perspective Brett Lancaster, Anil Mehta (ESRD) AFGROW Workshop 2011
  - Recent Developments in AFGROW COM and Plug-In Applications Alex Litvinov, James Harter, Thomas Latta (LexTech, Inc.), AFGROW Workshop 2011
What is StressCheck?

- StressCheck is an advanced FEA software tool developed by ESRD, Inc. of St. Louis, MO • Current Version: 10.5
- Primary Customers: Major Aircraft OEMs and Defense/Armed Forces
- StressCheck is based on the “p-version”
  - Degrees of freedom increased by increasing polynomial order of elements instead of adding midside nodes or refining the mesh
  - Hierarchic nature of solutions allows for verification & validation and quality assurance
    - Verification: Solving the equations right (convergence)
    - Validation: Solving the right equations (experimental observations)
- Primary applications of StressCheck:
  - High-fidelity stress analysis
  - Detailed fracture mechanics extractions/crack analysis
  - Multi-body contact analysis
  - Plasticity analysis
  - Composite material analysis
  - Development of advanced engineering applications (i.e. SFAT)
  - Combinations of the above
- See: Basics of StressCheck + AFGROW Application Development: An Engineering Perspective
  - Brent Lancaster, Anil Mehta, (ESRD) AFGROW Users Workshop 2011, 15 September 2011
What is BAMF?

Broad Application for Modeling Failure
What is BAMF?

Broad Application for Modeling Failure
The Complete History of BAMF

- Tasked with creation of plug-in at AFGROW Users Workshop 9/2010
- Multi-Point BAMF development started 10/2011
- 2 point crack growth became operational 3/2011
- Multi-Point BAMF development started 10/2011
- Code operational with 64 bit StressCheck. This gave access to the feature to include residual stresses 9/2012
- Multi-Point BAMF used to determine the necessity and parameters for a test specimen 9/2012
- Interpolation scheme allows for invalid splines from growth in RS fields to be resplined 5/2014
- Spline routine implemented prior to meshing created to determine part boundaries 10/2015
- Set Modification Code allows for growth of sets when they fail 6/2017
- First Publicly Released Version of BAMF v5.0 2/2018
- Multithreaded GUI 4/2019
- RS solution speed increase 6/2019
- First presentation with results from residual stress presented at ASIP Conference 12/3/2014
- Updates of K selection routine provided stable solutions 6/2015
- Hill Engineering began further development of BAMF software 4/2017
- Crack face symmetry 5/2018
- Multi-point multi-crack capability functionality was implemented 2/2016
- Multi-point multi-crack capability functionality was implemented 2/2016
- BAMF Release 6.0 2/2019
- Interpolation scheme allows for invalid splines from growth in RS fields to be resplined 5/2013
- Development of incorporation of residual stress started 5/2011
- Development of incorporation of residual stress started 5/2011
- Multi-Point BAMF successful run 2/2012
- Multi-Point BAMF successful run 2/2012
- Think tank group developed the name Broad Application for Modeling Failure (BAMF) 5/2011
- Think tank group developed the name Broad Application for Modeling Failure (BAMF) 5/2011
BAMF Support & Development

- BAMF was primarily developed by Josh Hodges while at T-38 USAF
  - Josh joined the Hill Engineering team in 2017
- To facilitate the continued viability of BAMF for use by USAF (and others) Hill Engineering has supported the further development of the software
  - Provided new software releases
    - Maintained compatibility with StressCheck/AFGROW releases
    - Added features and capability to BAMF
  - Developed documentation to support the customer base
    - Users Guide
    - Standalone .dll files
    - Handbook Models
  - Organized a workshop to provide input and support of BAMF development
    - Provides a mechanism for Hill Engineering to interact with core user group
    - Provides users ability to showcase complex use cases of the BAMF software
    - Hosted during the annual AFGROW Workshop

We are actively looking for input from the user community!
What Does BAMF Do for You?
What Does BAMF Do for You?

\[ \alpha_{app}^{CN} = \frac{K_{app}^{CN}}{\sigma} \]

Far field stress from StressCheck

Extract Stress Intensities \( K_{app} \)
For each crack in the model
What Does BAMF Do for You?

\[ \alpha_{app_{CN}} = \frac{K_{app_{CN}}}{\sigma} \]

\[ K_{res_{CN}} \]

Extract Stress Intensities \( K_{app} \)
For each crack in the model
What Does BAMF Do for You?

\[ K_{min\,CN} = a_{app\,CN} \sigma_{min} + K_{res\,CN} \]
\[ K_{max\,CN} = a_{app\,CN} \sigma_{max} + K_{res\,CN} \]

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

\[ R_{CN} = \frac{K_{min\,CN}}{K_{max\,CN}} \]
Utilization Examples

- Complicated geometry, crack path, loading
Utilization Examples

- Complicated geometry, crack evolution, constraints

Global/local analysis displacements on edges
Utilization Examples

- Residual stress in complex models

Building a BAMF Model Discussion and Demo
Building a BAMF Model

- **Parameters**
  - Crack Number
  - Crack Points
  - Crack Angle
  - Effective Thickness
  - Stress

- **Crack Imbedding**
  - System
  - Crack Points
  - Spline
  - Sets

- **Boundary Constraints**
  - Sets
Parameters

- **Cracks**: Equals the number of cracks in the model
- **PointsCrack#**: Where # represents the crack number. Value set to the number of points that defines the crack front.
- **C#Px%, C#Py%**: Where # represents the crack number and % represents the point number
- **CrackAngle#**: Where # represents the crack number
  - The value should be set to 90 degrees, 180 degrees or 360 degrees
- **Thickness**: Used to calculate the stress state, which is used in some retardation models to determine the crack tip yield zone size. It is also used as a parameter in the NASGROW equation.
- **Stress**: Used to calculate alpha. Typically set to SMF in AFGROW.
- **Em/v**: Material parameters that define the modulus of elasticity and Poisson’s ratio. Values are updated from the AFGROW material file.
Crack Imbedding - Coordinate Systems

- For Cracks ≤ 90°
- For cracks <180°
- For cracks >180°

Designates the location of Point 0 on the crack front. It defines where the spline starts at.
Points can be built outside of the part. Re-splining in code will move them inside the body.
Splines must be built starting at point 0 and going in succession.
BAMF 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!!!
Crack Imbedding - Crack Points and Splines

Utilize local nucleation coordinate system to designate crack points. Nucleation system must be created using locate and the global system. It cannot be based off a reference.
Crack Imbedding – Crack Face

Create-Plane-Locate

Create-Body Imprint-Curve Normal

Create Body Trim-No Heal

Create-Body-Boolean Union
Crack Imbedding - Sets

- Nucleation Set must be a selection
- All other sets must be based on locate
- Ask Brent Lancaster to continue working on GUI capability for local set creation
- Width values must not be parameterized
- Crack Face set should not move with the model
- Crack Front set should move with the model
- Model builder uses local set creation and sets must be updated
Loads/Constraints/Solutions

Point constraints are not available for set selection, therefore, cannot be used in BAMF
Running a BAMF Model

---

**Properties**

**Specimen**

**Parameters**

- Name: MultiPoint Multi-Crack SC10
- StressCheck Model Location: C:\*.scw

**Plugin Model Geometry and Dimensions**

Select crack geometry by clicking on corresponding icon.

Model: NPIC BAMF Development

**Running Iteration: 44**

---

© 2019 Hill Engineering, LLC
hill-engineering.com
Tips and Best Practices

- Check K convergence for at least 2-3 crack increments
- P-levels of 3-4 typically appropriate
- Select 11-25 points to define crack front
- Standardized mesh refinement at crack front
  - Elements along crack front should be greater than number of points defining crack front
  - Gradient (layers) away from crack front (default 2 layers)
- AFGROW growth increment 1-3%
- Ensure FE→ α→ AFGROW K calculations are as expected for first iteration
Release January 2020

BAMF RELEASE 7.0 - FEATURES
Updated Features

- **StressCheck 10.5 Compatibility**
  - Updated to account for K extraction formatting 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

[Image of material properties data and diagrams]
BAMF/AFGROW Failure Criteria

- **Version 6.0 utilizes:**
  - BAMF will stop prediction when all points are above Plane Stress \( K_c \)
  - User input value when *User-Defined “Kmax”* is selected

- **Version 7.0 will utilize:**
  - No failure criteria when nothing is selected
  - Plane Stress \( K_c \) when “Kmax” Failure Criteria is selected
  - User input value when User-Defined “Kmax” is selected
BAMF Interference and Contact

- Traditionally BAMF/AFGROW assumes a linear stress intensity
- AFGROW is implementing capability to input a table of stress intensities versus 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 specific stress intensity at different applied stresses

<table>
<thead>
<tr>
<th>Applied Stress ksi</th>
<th>$K_{app} \text{ ksi} \sqrt{\text{in}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10</td>
<td>-1.2</td>
</tr>
<tr>
<td>0</td>
<td>3.6</td>
</tr>
<tr>
<td>5</td>
<td>6.7</td>
</tr>
<tr>
<td>10</td>
<td>12.3</td>
</tr>
<tr>
<td>15</td>
<td>18.6</td>
</tr>
<tr>
<td>20</td>
<td>26</td>
</tr>
</tbody>
</table>

![Graph showing the relationship between applied stress (ksi) and $K_{app}$ (ksi $\sqrt{\text{in}}$)]
**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

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Parameter Description</th>
<th>Default Value</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAMF_ElementCF#</td>
<td>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</td>
<td>1.25 x number of points (PointsCrack#)</td>
<td>1.25 – 5.00</td>
</tr>
<tr>
<td>BAMF_Ktol#</td>
<td>Sets the tolerance value for K extraction smoothing, i.e. the number of extraction points averaged to calculate the discrete values passed to AFGRW. The value represents the average number of points used in the tolerance calculation</td>
<td>4</td>
<td>4 – 10</td>
</tr>
<tr>
<td>BAMF_Layers#</td>
<td>Changes the number of layers in the crack front mesh</td>
<td>2</td>
<td>2 – 4</td>
</tr>
</tbody>
</table>
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
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
BAMF 360

- Previous versions of BAMF only allowed for cracks 180° or less
- Several situations arose where cracks growing through radii or into T-sections required crack geometries greater than 180°
- New feature allows for imbedded cracks or surface cracks exceeding 180°
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 360° cracks it is recommended to use 30+ points
BAMF Validation Efforts
Comparison with Available COTS Programs

- **General approach**
  - Define benchmark problems
  - Slowly increase the complexity of the problems
    - Allowed for basic validation of the software (e.g., handbook solutions)
    - Created a gradual learning curve for the software itself
    - Made identification of problematic analysis components easy since they are added piecemeal
  - Compared to complicated scenarios typically encountered with this type of analysis, the test cases remain quite simple. However, these relatively simple cases test a wide range of functionality in ways that allowed for easy comparisons.
## Comparison with Available COTS Programs

<table>
<thead>
<tr>
<th>Test ID</th>
<th>NASGRO ID</th>
<th>Geometry</th>
<th>Analysis Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT01</td>
<td>TC02</td>
<td>Edge Cracked Plate</td>
<td>Comparison of SIF values to benchmark for 3D and 2D (plane strain) cases</td>
</tr>
<tr>
<td>FT02</td>
<td>TC01</td>
<td>Center Cracked Plate</td>
<td>Comparison of SIF values to benchmark for 3D and 2D (plane strain) cases and use of symmetry BCs (FRANC3D &amp; BAMF only).</td>
</tr>
<tr>
<td>FT03</td>
<td>TC01</td>
<td>Center Cracked Plate</td>
<td>Use of NASGRO material model in a crack growth simulation with constant amplitude loading.</td>
</tr>
<tr>
<td>FT04</td>
<td>CC01</td>
<td>Corner Cracked Plate</td>
<td>Use of tabular material data, localized remeshing, and spectrum loading in a FCG simulation.</td>
</tr>
<tr>
<td>FT05</td>
<td>TC02</td>
<td>Edge Cracked Plate</td>
<td>Demonstration of applying crack face traction interpolated from an arbitrary mesh.</td>
</tr>
</tbody>
</table>
FT03: Basic Overview

- **FT03 demonstration goals:**
  - Crack growth under constant amplitude ($R = 0$) loading
  - Basic use of Paris and NASGRO material models
  - Comparison and validation of SIF results with a handbook solution
  - Comparison and validation of lifing results with NASGRO TC01

**FT03/TC01 Geometry**

Dimensions (in)
- $h = 2$
- $b = 1$
- $a = 0.05$
- $t = 0.125$

Material: 7075-T651 (11AB1)
Loading: 24 ksi ($R = 0$)
FT03: Geometry, Loading, and Mesh

ABAQUS

Global Mesh
FRANC3D Remeshing Region

FRANC3D

σ = 24 ksi

X Symmetry Plane

U2 = 0

Global U3 = 0 (plane strain)

BAMF

σ = 24 ksi

X Symmetry Plane

Note: StressCheck does not have a global constraint option to represent plane strain

Forward and Back Face Fixed in Z

Plane Fixed in Y

© 2019 Hill Engineering, LLC
hill-engineering.com
FT03: BAMF Crack Geometry

Initial Crack Geometry: \( a = 0.05 \) in

Final Crack Geometry: \( a = 0.30 \) in

Layers of Mesh Refinement: 2
FT03: Notes on Smoothing

- Crack front smoothing
  - FRANC3D smooths crack front
  - BEASY smooths SIF values
  - BAMF smooths crack front and SIF values
FT03: Example Stress and Displacement Results
**FT03: Paris Equation Crack Life Results**

- FRANC3D uses NASGRO 5 equation
- NASGRO results are from NASGRO 7.10

\[
C_0 = 1.51 \times 10^{-9} \text{ in} \left( \frac{\text{cycles}}{\text{ksi} \cdot \text{in}} \right)
\]

- \(m = 3.70\)
- \(C_0 = 0\)
- \(K_{IC} = 26 \text{ ksi} \cdot \text{in}\)

Graph showing Crack Size vs Cycles (Paris) with the following details:

- Axis Y: Crack Length (in)
- Axis X: Cycles

Legend:
- Blue line: FRANC3D
- Orange line: NASGRO
- Green line: Beasy
- Yellow line: AFGROW
- Blue dotted line: BAMF
FT03: KI Comparison

- All analyses enforced plane strain
- FRANC3D maximum SIF deviation = 0.55%
- BAMF maximum SIF deviation = 0.64%
- BEASY maximum SIF deviation = 0.69%

Handbook solution is TC01 (ASTM E647): $K_1 = \sqrt{\frac{\pi a}{2b}} \sigma \sqrt{\pi a}$
FT03: NASGRO Equation Crack Life Results

Crack Size vs Cycles (NASGRO Eq.)

- FRANC3D, NASGRO, AFGROW, and BAMF are in excellent agreement
FT04: Basic Overview

- **FT04 Demonstration Goals:**
  - Localized re-meshing
  - Variable amplitude loading with both compressive and tensile loads
  - Tabular material data
  - Comparison and validation of FRANC3D lifing results with NASGRO CC01

![FT06/CC01 Geometry](image)

- **Dimensions (in)**
  - \( h = 9 \)
  - \( b = 4 \)
  - \( t = 6 \)
  - \( a = 0.05 \)

- **Material:** Tabulated 7050 (M7GQ11AB1)
- **Loading:** Variable with \( |S_{\text{max}}| = 24 \text{ ksi} \)
FT04: Spectrum

Block 1: S0 at t1 [scale factor applied]

Block 1: S0 at t2 [scale factor applied]

Block 1: S0 range [scale factor applied]

Block 1: S0 mean [scale factor applied]
FT04: Crack Growth Results

Crack Length vs Cycles

Note: NASGRO solution has built-in crack closure factor
FT04: KI Results

- KI values at surface
- BEASY, FRANC3D, AFGROW, and BAMF give KI values consistently higher than NASGRO.
COTS Comparison Summary

- Multiple benchmarks completed between (3) different software suites
  - BAMF - StressCheck P-element based Finite Element, AFGROW
  - BEASY - Boundary Element, Internal Crack Growth
  - FRANC3D - H-element based Finite Element, Internal Crack Growth

- Stress intensity comparisons to handbook solutions demonstrated accuracy within ~0.5%

- Different methods are employed to smooth crack front and/or stress intensities

- Overall, consistent crack growth predictions are observed with some noted differences
Broad Application for Modeling Failure

Software tool for predicting the growth of fatigue cracks in 3D parts

- Combines stress and crack growth analyses to predict the evolution of crack shape and size in complex models

Key capabilities

- Multi-point fracture mechanics (MPFM)
- Natural crack shape evolution
- Residual stress
- Complex loading
- Multiple cracks
- Fully 3D analysis
Summary

- BAMF 7.0 release: January 2020
- Let us know if you want to be included in the distribution list and receive updates about future BAMF releases
- If you have an application that can benefit from a BAMF analysis please contact us to discuss the feasibility
- If you would like to join the BAMF user’s group and receive priority support from the best technical support team in the world please contact us:

  Joshua Hodges  
  JLHodges@Hill-Engineering.com  
  916-635-5706 x202

  Robert Pilarczyk  
  RTPilarczyk@Hill-Engineering.com  
  916-635-5706 x201