21st Century Crack Growth Analysis Methods & Tools
- Building a Physics Based Crack Growth Analysis Approach into Damage Tolerance in the United States Air Force ASIP Environment

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September 12, 2012
Agenda

• Fatigue Crack Growth 1999
• Cold Expansion Beta (β) Correction Research
  – Development of stress intensity solutions
• A-10 Lower Wing Skin & Upper Longeron Cracking
  – Load redistribution through major structure
• Coupled Finite Element Modeling & Fatigue Crack Growth (BAMF)
  – Specific stress intensity development into crack growth analysis
• The Future of Fatigue Crack Growth
  – Modeling the physics of crack growth – why is this important?
Damage Tolerances Application Today

• Approximately 30,000 Fixed Wing Commercial Aircraft Flights Daily in the United States

• Approximately 12,000 Boeing Fixed Wing Commercial Aircraft Worldwide in 2010

• 2011 USAF Operated Over 5,200 Manned Fixed Wing Aircraft

All the above fixed wing aircraft are managed using damage tolerance.
Crack Growth Analysis in 1999

- **Use of Available “Canned Solutions”**
  - Newman-Raju’s “Stress Intensity Factor Equations”
  - Sih’s “Handbook of Stress-Intensity Factors”

- **Simple Models of Flat Plates**
  - Off-set holes
  - Corner cracks
  - Constrained crack aspect ratio
  - Initial Flaw Sizes (IFS) reduction for Cold Expansion (CX)
  - Mixed loading (bending, shear & load transfer)

*Idealize Geometry to Match “Canned Solutions”*
Cold Expansion (CX) of Fastener Holes

• Cold Expansion of Fastener Holes
  – Imposes a residual stress field around the fastener hole
  – Increases the fatigue life at fastener holes
  – Simple & efficient process during production and depot maintenance

FTI Split Sleeve Cold Expansion™ Set-up with Mandrel, Sleeve and Material Shown.  

Crack Growth Curve Showing Life Estimates for IFS of 0.05 inch 0.005 inch
• **Guidance Provided by JSSG 2006**
  - “The beneficial effects of ... cold expanded holes for durability fracture mechanics analysis, the limits of the beneficial effects ... should be no greater than the benefit derived by assuming a 0.005 inch radius corner flaw ...”

• **History of Reduced IFS for CX Holes??**
  - Back extrapolation from crack growth curve
    - Can’t take full advantage (safety factor)
    - Added on some simple statistics (1 in X chance of having ...)
  - Additional inspections at the hole when CX is performed
  - Dr. Jack Lincoln’s (USAF Technical Advisor, Aircraft Structural Integrity) “Engineering Judgment”
Limitations to Reduced IFS Approach

- Not a Physics Based Approach
  1) Does not account for crack growth shape
  2) Does not account for interactions between residual stress field and other geometric notches (i.e. holes, edges, etc.)
  3) Does not account for 3-dimensional stress state (entrance vs. exit side of mandrel)
  4) Does not account for possible changes in residual stress field over time/cycles or crack propagation
  5) Does not account for crack closure

- Limited benefit in sustainment
  - Must start recurring inspection interval from NDI detectable flaw size
Cold Expansion Crack Growth Testing

- Fatigue Crack Growth Testing
  - Two aerospace aluminum alloys (7075-T651 & 2024-T351)
  - Feasibility of developing Beta ($\beta$) correction for Cold Expansion

Based on the Similitude Principle
  - “At the same crack growth rate, $\frac{da}{dN}$, the same $\Delta K$ applies to the standard specimens and the configuration being considered.”

\[ K = \sigma \sqrt{\pi a} \]

\[ K = \sigma \sqrt{\pi a\beta} \]

\[ \beta = \frac{K_{\text{NonCX}}}{K_{\text{CX}}} \]
Understanding Crack Front Shape

- Marker Banding to Determine Crack Front Shape
- Developed Finite Element Model Geometries
  - Corner crack
  - "Elliptical-shaped" through crack
  - "P-Shaped" crack

Three Geometries Selected to Represent Crack Front

Marker banding of 7075-T651 aluminum alloy.¹²
Stress Intensity Development

- **StressCheck® Modeling**
  - Three model types built
  - Extract stress intensities (K) along the crack front
  - Convert stress intensity (K) into $\beta$ for AFGROW

StressCheck® FEA model details.  

StressCheck® FEA Models. Left – Corner Elliptical; Middle – Through Thickness “P-Shaped”; Right – “Elliptical” Through Thickness.

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2024 & 7075 $\beta$ Correction Plot

EDM Entrance Surface $\beta$ Correction vs. Crack Length.$^{13}$
Fatigue Life Prediction Using AFGROW with USAF Standard IFS and Three Experiments, One Beta (β) Correction.

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Ability in 2008

- Development of Stress Intensities for Specific Geometries
  - Model shape of crack front in 2D
  - Extract stress intensity along crack front
  - Develop crack growth curves with user-defined stress intensities
  - Input of Beta ($\beta$) corrections into AFGROW to modify crack growth
A-10 Lower Wing Skin Cracking

- 2009 – New Inspections Find Cracks in Lower Aft Skin

Image of Lower Wing Skin Showing Inspection Locations.
Integration of Research Methods

- Development of “Global” Finite Element Models of Major Structural Components
Integration of Research Methods

- Development of Single Component Models with Fastener Loads

StressCheck® Finite Element Model of A-10 Lower Aft Wing Skin.
Integration of Research Methods

• Development of Load Redistribution in Fasteners

Siemens© NX Finite Element Model of System with Progressive Crack – Showing Load Redistribution.14
Integration of Research Methods

- Development of Stress Intensity vs. Crack Length

StressCheck® Finite Element Models Showing Crack Growth Through Lower Skin.¹⁴
Integration of Research Methods

• Development of Stress Intensity vs. Crack Length

Plot of Stress Intensity vs. Crack Size as Crack Propagates Through Lower Skin.©2012 Carlson
Integration of Research Methods

- Conversion of Stress Intensity to Beta ($\beta$) for AFGROW

$$K = \sigma \sqrt{\pi a \beta}$$

$$\beta = \frac{K}{\sigma \sqrt{\pi a}}$$

Hole #5 Crack Growth
Fwd Crack Measured from Fwd Edge of #5 Fastener Hole

Crack Growth Plot for A-10 Lower Wing Skin Utilizing Beta ($\beta$) Corrections

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A-10 Upper Longeron Cracking

- 2010 – During Scheduled Inspection Cracks Were Found in Upper Longeron

Images of A-10 Upper Longeron Showing Cracks.
Refining Analysis Methods

• Standard “Hole-in-a-plate” Model Won’t Do!
• Development of Global Finite Element Models for Upper Longeron System

Siemens© NX Large “Global” Finite Element Model of A-10 Upper Longeron.15
Refining Analysis Methods

- Determination of Load Redistribution in Fastener Holes of Each Component in Stack-up

1. Cracked From Hole 1 to Edge
2. Load Redistribution in the J Extrusion due to the Crack in the upper longeron plate at Hole 1.
3. Cracked from Hole 2 to Edge
4. Load Redistribution in the J Extrusion due to the Crack in the upper longeron plate at Hole 2.
5. Full Longeron Plate Crack
Refining Analysis Methods

• Development of Stress Intensities in Longeron Strap and J-Extrusion.
  - Development of Beta ($\beta$) solutions
  - Multiple cracks in multiple components
  - How do cracks interact – size when first component fails?

StressCheck® Finite Element Model of A-10 Upper Longeron Strap and J-Extrusion.©2012 Carlson
Results of New Methods/Techniques

• Validation of Modeling Methods & Techniques.

  • Spectrum
    - Analysis was performed with the same spectrum that caused the failure in the test.

  • Loading
    - Distributed loads from multiple simulated full cracked global and local FEMs

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Refining Analysis Methods

• Development of Crack Growth Curve

Upper Longeron Strap Crack Growth Curve
Original vs. Advanced Method Predictions

Critical Crack Length = 4.3x

Life Prediction = 2.5x

Crack Growth Curve Showing “1999” and “Advanced” FEA & Fatigue Crack Growth Analysis Methods.
Ability in 2010

• Development of Stress Intensity in 3-D Models
• Development of Load Redistribution in 3-D Models
• Input of User-Defined Betas into AFGROW for Beta vs. Crack Sizes
Limitations to FEM to AFGROW

• Assumptions to Modeling
  – Initial flaw sizes at critical locations??
  – Continuing damage flaw sizes??
  – How do two cracks grow relative to each other??
  – Crack aspect ratios??
    • surface vs. bore cracks – is it an elliptical shape correct?

• Time to Model & Extract Stress Intensities
  – Each model run by hand

Opportunities for Development & Improvement!!!
Coupled FEM & Fatigue Crack Growth

- USAF – T-38 & A-10 ASIP Group Development of Broad Application for Modeling Failure (BAMF)$^{17}$
  - Coupled finite element modeling (StressCheck® and AFGROW)
    - StressCheck® – 2 point stress intensities – total beta solution
    - AFGROW – user defined model – user defined beta

- Challenges Overcome by BAMF
  - Aspect ratio of surface vs. bore crack (Crack Shape)
  - Multiple cracks at a hole (Continuing Damage)

Physics Based Approach to Crack Growth

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Coupled FEM & Fatigue Crack Growth

• Crack Growth Analysis Using BAMF

Simulation of Two Crack Model at a Fastener Hole (Continuing Damage), Crack Model at a Countersunk Fastener Hole. Videos Courtesy of Joshua Hodges.

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Ability Now in 2011 – 2012

• Development of Stress Intensity for Specific Component Geometry – Beta ($\beta$) Correction
• Load Redistribution Through Stack-up Components – “System Approach”
• Coupled Finite Element Modeling with Fatigue Crack Growth – BAMF
• More “Natural” Crack Growth Along Crack Front
  – Multi-point BAMF
  – Multi-Site-Damage BAMF
• Integration of what we have been talking about here
Multi-Point Crack Front

Cracks Through Paveway GEDA Housing Showing Crack Front Shape Ability. Video Courtesy of Joshua Hodges.
Limitations with BAMF

• Modeling Crack Growth Through Deep Residual Stress Fields
  - Cold Expansion (CX)
  - Laser Shock Peening (LSP)
  - Low Plasticity Burnishing (LPB)

• 3D Crack Growth
  - Multiaxial loading
  - Complex geometry

Modeling the Physics of Fatigue Crack Growth!

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Future of Crack Growth Analysis

• Multi-Point Crack Front BAMF – Complete
• Development of 2D Residual Stress Fields in Finite Element Models\(^{18}\) – Under Contract with APES, Hill Engineering & ESRD
• Coupled 3D FEMs with Residual Stress Fields & Multi-Point Crack Front Growth – Potential Future of Crack Growth Analysis in the A-10 & T-38 ASIP

Modeling the Physics of Fatigue Crack Growth

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Conclusions

• Development of Physics Based Fatigue Crack Growth Models/Frameworks are **ESSENTIAL**!!!

• Modern Tools (Software) Open New Options
  - Development of specific component stress intensities
  - Load redistribution in component “system”
  - Residual stress field integration – CX, LSP, LPB & others
  - Multiple point crack front growth – crack front shape – NDI
  - More accurate stress intensity solutions/corrections for AFGROW

“What we can achieve technically has always been limited by the weakness of the materials of construction.”—J.E. Gordon
Questions
References


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