AN APPROACH FOR ASSESSING DELAMINATION PROPAGATION CAPABILITIES IN COMMERCIAL FINITE ELEMENT CODES

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NASA Aviation Safety Technical Conference, St. Louis, Missouri, 2007
OUTLINE

• Overview of research task
• Background and motivation
• Fracture mechanics methodology for delamination onset prediction
• Comparison of computed strain energy release rates in a DCB specimen with results from user written post-processing routines
• Propagation analysis for DCB and SLB specimens using VCCT for ABAQUS
  • Creation of benchmark results based on critical load/displacement conditions
  • Comparison of computed load-displacement behavior with benchmark results for various input parameters
  • Comparison of computed displacement-crack length behavior with benchmark results for various input parameters
  • Assessment of computed delamination front shapes
• Concluding remarks
• Research Task:
  Development of a Delamination Fatigue Methodology for Composite Rotorcraft Structure

• Program Goals:
  Develop Methodologies and Validated Analysis Tools to Predict Fatigue Life and Residual Strength for
  • Improved Safety - Certification by Analysis
  • Improved Durability - Reduced Life Cycle Costs
  • Improved Accept/Reject Criteria

• 5-Year Program Deliverable:
  Incorporate Fatigue Life Prediction Methodology into Composite Materials Handbook 17 (CMH-17)
• Collaborative research between NASA and U.S. Rotorcraft Companies through Space Act Agreement with the Center for Rotorcraft Innovation, CRI (formerly RITA)

• NASA Langley in-house CS and contractors to perform experimental characterization and analytical tool development

• CRI to supply characterization test specimens and identify and manufacture validation test articles for testing by NASA and Industry

• Annual milestones established and progress reviewed through periodic IPT meetings/telecons during course of 5-year period of performance (FY07-11)

• External stake holders invited to participate in IPT meetings (Army, FAA, CMH-17, ASTM, Rotorcraft CoE’s)
• S-92 Helicopter main rotor blade spar subjected to tension/torsion fatigue loading

Airfoil = Spar + Trailing edge

Delamination growth expected at ply drops
• Stiffened wing skin panel, post BVID compression fatigue loading

Delamination growth expected after impact

Bell-Agusta BA-609 Civil Tilt Rotor
• **In the past:**
  - Fracture mechanics implementations had a focus on J-integral and Virtual Crack Extension
  - Virtual Crack Closure Technique (VCCT) implemented only in specialized finite element codes (FRANC2D) or user written post-processing routines
  - Crack extension or delamination propagation analyses performed manually which was time consuming.

• **Today:**
  - Boeing's VCCT element (commercialized as VCCT for ABAQUS®)
  - MSC.Nastran™ SOL 600 and MD Nastran SOL 400 include VCCT options
  - Implementation in SAMCEF® is a combination of VCCT and Virtual Crack Extension
  - Other codes … (e.g. GENOA, HyperSizer, ESRD Stress Check)
  - Automatic propagation analysis is possible
• Develop benchmark cases to gain confidence in the software tools used

• Benchmark cases have to be simple
  • Simple geometry and loading → DCB and SLB specimen
  • Independent of analysis software used
  • Independent of experimental anomalies to avoid unnecessary complications (e.g. fiber bridging, appropriate material input data)

• Create a benchmark in a manual delamination propagation analysis

• Repeat propagation analysis using automated propagation feature

• Assessment based on the comparison of manual and automated propagation

• Comparison with experiments and propagation prediction will follow later
VIRTUAL CRACK CLOSURE TECHNIQUE (VCCT)*

- Two and three-dimensional analysis
- Nonlinear analysis
- Arbitrarily shaped delamination front

\[ G_I = \frac{1}{2\Delta ab} \cdot F_{yi} \cdot (v'_\ell - v'_{\ell'}) \]
\[ G_{II} = \frac{1}{2\Delta ab} \cdot F_{xi} \cdot (u'_\ell - u'_{\ell'}) \]

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\[ G_{II} = \frac{1}{2\Delta ab} \cdot F_{xi} \cdot (u'_\ell - u'_{\ell'}) \]
\[ G_{III} = \frac{1}{2\Delta ab} \cdot F_{zi} \cdot (w'_\ell - w'_{\ell'}) \]

• Establish mixed mode I and II failure criterion (example: T300/914C)

• Calculate mixed mode ratio and total energy release rate

\[ G_T = G_I + G_{II} + G_{III} \]
\[ G_S = G_{II} + G_{III} \]

• Obtain critical energy release rate from failure criterion*

\[ G_c = \left( G_{lc} + (G_{IIC} - G_{lc}) \left( \frac{G_{II}}{G_T} \right)^\eta \right) \]

• Calculate failure index

\[ \frac{G_T}{G_c} \geq 1 \]

*Benzeggagh, Kenane, 1996
R. Krueger and D. Goetze, 
• FE-Model

UD24: [0]_{24} T300/914C

$\delta/2 = 1$ mm

• $G_I$ distribution

$G_c = G_{IC} = 493.6$ J/m$^2$

$G_{IC} = 170.3$ J/m$^2$

Experimental data

Mean values

Failure Index $G_T/G_c$

$G_{IC} = 170.3$

$\eta = 1.62$

Mixed mode ratio $G_{II}/G_T$

Failure Index $G_T/G_c$
• Load/displacement plots for different delamination lengths

![Load/Displacement Plots](image)

• Mathematical relationship between load and energy release rate

\[
G = \frac{P^2}{2} \cdot \frac{\partial C_p}{\partial A} \quad \Rightarrow \quad \frac{G_T}{G_c} = \frac{P^2}{P_{crit}^2}
\]

\[
\Rightarrow \quad P_{crit} = P \sqrt{\frac{G_c}{G_T}}, \quad \delta_{crit} = \delta \sqrt{\frac{G_c}{G_T}}
\]
• Input data for mixed-mode failure criterion ($G_{lc}$, $G_{llc}$, $\eta$) was kept constant for all analyses performed.

• Initial and maximum increment size was selected at 0.001 * final load.

• To overcome convergence problems, four parameters were adjusted:
  • If the release tolerance ($relTol$) is exceeded a cutback operation is performed which reduces the time increment. The cutback reduces the degree of overshoot and improves the accuracy of the local solution.
  
  • Contact stabilization which is applied across only selected contact pairs and used to control the motion of two contact pairs while they approach each other in multi-body contact.

  • Global stabilization which is applied to the motion of the entire model and is commonly used in models that exhibit statically unstable behavior such as buckling.

  • Viscous regularization ($damv$) which is applied only to nodes on contact pairs that have just debonded. The viscous regularization causes the tangent stiffness matrix of the softening material to be positive for sufficiently small time increments.
DELAMINATION PROPAGATION IN DCB SPECIMEN - Global Stabilization

<table>
<thead>
<tr>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<td>0.002</td>
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Default settings converge but yield a meaningless solution.
DELAMINATION PROPAGATION IN DCB SPECIMEN

- Contact Stabilization

<table>
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<th>contact</th>
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<td>0.02</td>
<td>0.002</td>
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- Viscous Regularization

<table>
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<td>0.3</td>
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</table>

**Graphs:**
- Left graph: Load P, N vs. Applied opening displacement $\delta/2$, mm. The graph shows different cases (case1 to case6) with markers indicating the benchmark cases.
- Right graph: Load P, N vs. Applied opening displacement $\delta/2$, mm. The graph includes markers for different cases and highlights the case 5 with a note: 177,000 s.
• Experimental observation

Teflon insert

propagated fronts

intact

delaminated

• Deformed model and contact surface

• Bond state after 1000 increments
DELAMINATION PROPAGATION
FE Model of SLB Specimen - Mode I/II

D±30: C12K/R6376
a=34-65 mm
w=2.8 mm

46500 C3D8I elements
57528 user defined nodes
789477 variables in the model

D±30: [±30/0/-30/0/30/0_4/30/0/-30/0/-30/30/-30/30/0/30/0/-30/0_4/-30/0/30/±30]
• **$G_T$ distribution**

![Graph showing $G_T$ distribution with various line types and markers for different values of $a$.](image)

• **Mixed mode ratio $G_S/G_T$**

![Graph showing $G_S/G_T$ ratio with various line types and markers for different values of $a$.](image)

• **Mixed mode failure criterion for C12K/R6376**

![Graph showing $G_c$ vs. $G_{lc}/G_T$ with a fit curve.](image)
• Failure index and load/displacement for different $a$

- Failure Index $G_t/G_c$
- $y/B$
- $a=34\text{mm}$, $a=40\text{mm}$
- $a=35\text{mm}$, $a=45\text{mm}$
- $a=36\text{mm}$, $a=50\text{mm}$
- $a=37\text{mm}$, $a=55\text{mm}$
- $a=38\text{mm}$, $a=60\text{mm}$
- $a=39\text{mm}$, $a=65\text{mm}$

• Benchmark

- Critical load $P$, $N$
- Benchmark
- $a$, mm
- Applied center deflection $w$, mm
- $0.0$, $0.5$, $1.0$, $1.5$, $2.0$, $2.5$, $3.0$, $3.5$
- $0.0$, $0.5$, $1.0$, $1.5$, $2.0$, $2.5$, $3.0$, $3.5$
- $0.0$, $0.5$, $1.0$, $1.5$, $2.0$, $2.5$, $3.0$, $3.5$
- $0.0$, $0.5$, $1.0$, $1.5$, $2.0$, $2.5$, $3.0$, $3.5$
**Global Stabilization**

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<td>E-6</td>
</tr>
<tr>
<td>relTol</td>
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</table>

Default settings converge but yield a meaningless solution.

**Contact Stabilization**

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<th>6</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>input</td>
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<td>E-3</td>
<td>E-4</td>
</tr>
<tr>
<td>relTol</td>
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<td>0.5</td>
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**Viscous Regularization**

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</tr>
</tbody>
</table>

Increased release tolerance required to obtain converged solution but leads to overshoot

**Crack length plot**

- **Case:** 8, 2
- **Value:** E-6, E-6
- **relTol:** 0.2, 0.2

- **Load P, N** vs. **applied center deflection w, mm**
  - benchmark
  - case1,3,4
  - case6
  - case12
  - 140,000 s

- **a, mm** vs. **applied center deflection w, mm**
  - benchmark
  - contact8
  - global2
• Deformed model and contact surface

• Bond state after 76 increments

• Bond state after 1000 increments

• Accurately computing the delamination front shape requires fine meshes
CONCLUDING REMARKS

- Mixed-mode energy release rates computed from VCCT for ABAQUS® were in good agreement with results from a post-processing routine.

- After testing the automated propagation capability in VCCT for ABAQUS® it is concluded that
  - Selecting the appropriate input parameters to obtain good results requires an iterative procedure.
  - Results may converge but yield a meaningless solution.
  - The default settings for global stabilization yielded unsatisfactory results.
  - Best results were obtained when contact stabilization and viscous regularization were used.
  - Accurately computing the delamination front shape requires fine meshes.
  - Additional assessment of the propagation capabilities in more complex specimens and on a structural level is required.