Failure of Notched Laminates under Out-of-Plane Bending. Phase IV

Fall 2011 Meeting
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Motivation and Key Issues
Develop analysis techniques useful in design of composite aircraft structures under out-of-plane loading (bending and shear)

Objective
Determine failure modes and evaluate capabilities of current models to predict failure

Approach
- Experiments: Mode 3 fracture
- Modeling: Progressive damage development and delamination (ABAQUS)
Failure of Notched Laminates Under Out-of-Plane Bending. Phase IV

- **Principal Investigators & Researchers**
  - John Parmigiani (PI) & Brian Bay, OSU faculty
  - Will Beattie & Thomas Wright, OSU grad students

- **FAA Technical Monitor**
  - Curt Davies
  - Lynn Pham

- **Other FAA Personnel Involved**
  - Larry Ilcewicz

- **Industry Participation**
  - Gerry Mabson, Boeing (technical advisor)
  - Tom Walker, NSE Composites (technical advisor)
Phase I (2007-08)
- Out-of-plane bending experiments w/composite plates
- ABAQUS modeling with progressive damage

Phase II (2008-09)
- ABAQUS modeling with buckling delamination added
- Sensitivity study of (generic) material property values

Phase III (2009-10)
- ABAQUS modeling w/ more delamination interfaces
Project Overview

• Phase IV (2010-11)
  – Out-of-plane shear experiments & ABAQUS modeling
  – Further study of additional delamination interfaces for out-of-plane bending
  – Initiating vs. propagating toughness values for out-of-plane bending
  – Feasibility of Abaqus/Explicit and XFEM for future work
  – Sensitivity study using Boeing mat’l property values
  – Special cases: all-ninety and all-zero degree plies for out-of-plane bending
Today’s Topics

- Sensitivity study w/ Boeing material property values
- Effects of additional delamination interfaces
- Feasibility of XFEM for future work
- Feasibility and accuracy of Abaqus/Explicit for future work

Out-of-plane Shear work was covered during 2011 JAMS meeting, and will be continued in Phase V.
Initiating vs. propagating toughness values were covered during 2011 JAMS meeting.
All-ninety and all-zero degree plies will be continued in Phase V.
Today’s Topics

• Sensitivity study w/ Boeing material property values
• Effects of additional delamination interfaces
• Feasibility of XFEM for future work
• Feasibility and accuracy of Abaqus/Explicit for future work
Sensitivity Study

Using design-of-experiments techniques, analytically* investigate the effect of variations in strength parameters on the failure load of two notched-panel layups

- #1: 40% zero-degree plies
- #2: 20% zero-degree plies
- Loading: Out-of-plane bending
- Panel dimensions
  - 18-in long
  - 5-in wide
  - 20 plies
  - 0.25-in wide, 1-in long center notch

* Study consists exclusively of Abaqus simulations
Sensitivity Study

Strength parameters included in study:

- XT: Tensile strength, parallel-to-fiber direction
- XC: Compressive strength, parallel-to-fiber direction
- YT: Tensile strength, perpendicular-to-fiber direction
- YC: Compressive strength, perpendicular-to-fiber direction
- SL: Shear strength, in-plane
- SC: Shear strength, transverse
- Gft: Energy to fully damage ply, fiber tension only
- Gfc: Energy to fully damage ply, fiber compression only
- Gmt: Energy to fully damage ply, matrix tension only
- Gmc: Energy to fully damage ply, matrix compression only

10 parameters to be considered
Sensitivity Study

• **Design-of-Experiments Plan**
  • Vary each parameter +/- 20% from nominal value
  • Use a 2-level fractional factorial

• **Prior Work: Study conducted in earlier project phase**
  • Generic material properties
  • $2^{10-6}$ fractional-factorial design (16 runs)
  • Results showed key parameters for both layups to be
    • Gft: Energy to fully damage ply, fiber tension
    • XT: Tensile strength, parallel-to-fiber
    • Gfc: Energy to fully damage ply, fiber compression
    • XC: Compressive strength, parallel-to-fiber
  • **Limited number of runs precluded information on interactions!**
Sensitivity Study

• **Current Work**
  - Boeing material properties
  - $2^{10-4}$ fractional-factorial design (64 runs for 10 parameters)
  - Results show key parameters to be
    - XT: Tensile strength, parallel-to-fiber (lay-up 1 and 2)
    - XC: Comp. strength, parallel-to-fiber (lay-up 1)
    - Gft: Energy to fully damage via fiber tension (lay-up 1 and 2)
    - Gfc: Energy to fully damage via fiber comp. (lay-up 1 and 2)
    - YC: Comp. strength, perp. to fiber (lay-up 2)
    - Interaction, XT / Gft (lay-up 1)
    - Interaction, XT / Gfc (lay-up 1)
    - Interaction, XC / Gft (lay-up 1)
    - Interaction, XC / Gfc (lay-up 1)

Lay-up 1: 40% zero-degree
Lay-up 2: 20% zero-degree
Current Work, Summary & Conclusions: Factors influencing failure moment

- Both higher and lower percent-zero-degree-ply lay-ups showed fiber fracture-energy and fiber tensile-strength to be key… … fibers are primary load-carrying components
- The lower percent-zero-degree-ply (more compliant) lay-up also showed matrix compressive strength to be key… … less stiff, so matrix properties more relevant
- The higher percent-zero-degree-ply lay-up (more stiff) also showed fiber compressive-strength and fiber strength & fracture energy interactions to be key… … strength & energy interaction likely indicating displacement-to-fracture is important as lay-up becomes stiffer
Today’s Topics

- Sensitivity study w/ Boeing material property values
- Effects of additional delamination interfaces
- Feasibility of XFEM for future work
- Feasibility and accuracy of Abaqus/Explicit for future work
Additional Interfaces

- Current simulations with Out-of-Plane Bending have been done with 4 delamination interfaces at critical plies, as determined through experimentation.

- The focus is to examine the effects of additional interfaces, at various locations.

This figure depicts a 4-interface layup, with element divisions at delamination interfaces.
Additional Interfaces

- One 40 ply lay-up w/ interfaces at different locations
- “Simulation Plan”: interfaces near zero-degree plies

<table>
<thead>
<tr>
<th>Number of Interfaces</th>
<th>Configurations # of Configurations (#plies-interface-#plies-interface, etc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2 (32-7-1, 32-3-5)</td>
</tr>
<tr>
<td>4</td>
<td>1 (32-3-2-2-1)</td>
</tr>
<tr>
<td>5</td>
<td>4 (30-2-3-2-2-1, 24-3-4-3-3-3, 27-4-3-3-2-1, 31-1-2-1-2-3)</td>
</tr>
<tr>
<td>6</td>
<td>5 (25-5-2-3-2-2-1, 31-1-1-2-1-2-2, 22-2-3-4-3-3-3, 24-3-4-3-3-2-1, 27-3-2-3-2-2-1)</td>
</tr>
</tbody>
</table>

- Evaluate using:
  - Maximum applied moment
  - Run Time
  - Convergence
### Additional Interfaces

<table>
<thead>
<tr>
<th>Number of Interfaces</th>
<th>2</th>
<th>2</th>
<th>4</th>
<th>5</th>
<th>5</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Moment [in-lb]</td>
<td>N/A</td>
<td>1030.3</td>
<td>1019.4</td>
<td>998.4</td>
<td>1042.4</td>
<td>N/A</td>
</tr>
<tr>
<td>Run Time [hr]</td>
<td>43.3</td>
<td>7.7</td>
<td>136.4</td>
<td>116.3</td>
<td>59.9</td>
<td>184.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of Interfaces</th>
<th>5</th>
<th>6</th>
<th>6</th>
<th>6</th>
<th>6</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Moment [in-lb]</td>
<td>N/A</td>
<td>1075.5</td>
<td>N/A</td>
<td>1007.1</td>
<td>1062.0</td>
<td>N/A</td>
</tr>
<tr>
<td>Run Time [hr]</td>
<td>184.5</td>
<td>238.0</td>
<td>191.3</td>
<td>375.8</td>
<td>491.1</td>
<td>342.4</td>
</tr>
</tbody>
</table>

- Due to convergence issues, some configurations of delamination interfaces did not produce a maximum moment
- Computing time was greatly increased
Conclusions:

• Additional interfaces do not greatly affect ( < 6% ) recorded maximum moments
• However, as interfaces are increased, convergence becomes more difficult
• Additional interfaces significantly increase run times
• When deciding where to put interfaces, extra interfaces will not hurt accuracy, but will increase run time, if convergence can even be reached
• Sensitivity study w/ Boeing material property values
• Effects of additional delamination interfaces
• Feasibility of XFEM for future work
• Feasibility and accuracy of Abaqus/Explicit for future work
Purpose of this portion of the project is to conduct a preliminary investigation of the feasibility of XFEM  
Conventional FEM only permits crack propagation along element boundaries  
XFEM allows for cracks to propagate through the interior of elements  
Designed for use of fiber and matrix cracking in laminated composites
Difficulties in modeling and implementing:

- XFEM does not support use of Hashin Damage criterion (used Max Stress)
- Cannot use shell or solid **composite** elements (used individual layers)
- Model must have one ply per element due to non-support of shells and solid composites
- With current mesh, and necessity for minimum of 20 layers, temporary storage space must be very large
Extended Finite Element Method

- Convergence issues occurred before max applied moment was found
- Approximations of damage criteria do not allow for accurate results
- XFEM in Abaqus in its current form is not useful for the purpose of this project
Today’s Topics

• Sensitivity study w/ Boeing material property values
• Effects of additional delamination interfaces
• Feasibility of XFEM for future work
• Feasibility and accuracy of Abaqus/Explicit for future work
Explicit methods are used for analyses like:

- High-Speed dynamics
- Large, nonlinear, quasi-static analyses
- Highly discontinuous postbuckling
- Extreme deformations

Utilizes a constant, very small time increment

No iteration or convergence checking required

Previous work in Abaqus/Standard has produced major issues with convergence

Since Abaqus/Explicit is stable, it is of interest
• Stable time increment is determined by Abaqus, and cannot be changed by the user
• Total time can be defined by user which changes run time of simulation
• Longer total time decreases dynamic effects but increases run time
• $\Delta t$ is referred to as stable time increment:

$$\Delta t = \frac{L^e}{\sqrt{E/\rho}}$$

• $L^e$ is the characteristic element length
• $E$ is the Young’s modulus
• $\rho$ is the current material density
• Goal: Compare implicit and explicit approaches to modeling the fracture of specimens of this study
• Study consisted of making several runs at a range of total times and comparing:
  • Failure moment (Experimental vs. Standard vs. Explicit)
  • Run time (Standard vs. Explicit)
  • Energy (Verify Quasi-static)
For Abaqus/Explicit analysis to be considered quasi-static, the kinetic energy ($ke$) must be less than 10% of the internal energy ($ie$).

Several runs of varying total times were completed with one of the lay-ups.
Maximum applied moments and run times of several explicit runs. Large variation in moment was likely due to dynamic issues at smaller total times.

<table>
<thead>
<tr>
<th>Total Time [s]</th>
<th>Max Moment [in-lb]</th>
<th>Run time [hr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>904.6</td>
<td>124.7</td>
</tr>
<tr>
<td>1.5</td>
<td>962.5</td>
<td>165.7</td>
</tr>
<tr>
<td>1.0</td>
<td>906.1</td>
<td>104.3</td>
</tr>
<tr>
<td>0.5</td>
<td>1050.8</td>
<td>45.7</td>
</tr>
<tr>
<td>0.25</td>
<td>931.6</td>
<td>18.1</td>
</tr>
<tr>
<td>0.10</td>
<td>1390.5</td>
<td>9.3</td>
</tr>
<tr>
<td>0.05</td>
<td>1219.7</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Experimental Max Moment = 906 in-lb
Abaqus/Standard

- Kinetic energy is zero because it is a static, implicit analysis
- Internal energy gradually slopes upward throughout the run
- All Abaqus/Standard runs completed for this project have the same general form
Abaqus/Explicit

Plot comparing Internal and Kinetic Energy during an Explicit Run

- Kinetic energy stays fairly low, with the exception of a spike
- Internal energy has large drop at location of the spike in kinetic energy
- This does not correspond to normal implicit analysis
• Red corresponds to bonded material
• Blue corresponds to debonded material
• Watch for sudden delamination occurring in middle of part
- Red corresponds to bonded material
- Blue corresponds to debonded material
- Watch for sudden delamination occurring in middle of part
• Sudden massive delamination is the cause of the big drop in internal energy and spike in kinetic energy
• This is a dynamic event which is inconsistent with Standard analysis and with the experiments performed
• Considerably longer total time would be necessary to remove dynamic event
• Completed one run of each layup using Abaqus/Explicit with total time of 2 seconds
• The run times range from approximately 5 days to over 22 days
• A significant increase in total time is impractical

<table>
<thead>
<tr>
<th>Layup: # of plies (% 0°)</th>
<th>Run Time [hrs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 (10%)</td>
<td>149.7</td>
</tr>
<tr>
<td>20 (30%)</td>
<td>334.5</td>
</tr>
<tr>
<td>20 (50%)</td>
<td>241.4</td>
</tr>
<tr>
<td>40 (10%)</td>
<td>541.9</td>
</tr>
<tr>
<td>40 (30%)</td>
<td>222.3</td>
</tr>
<tr>
<td>40 (50%)</td>
<td>124.7</td>
</tr>
</tbody>
</table>
Conclusions:

• 2.0 seconds is not a long enough total time to provide accurate results using Abaqus/Explicit

• Increasing total time is not feasible, given current run times of over three weeks

• While there were no convergence issues, the amount of time necessary to achieve an accurate solution using Abaqus/Explicit proves it is not a feasible solution for future work

• Failure to model a quasi-static simulation means Abaqus/Explicit is not a useful tool for this project
Questions
Why not try mass scaling?

\[ \Delta t = \frac{L^2}{\sqrt{E/\rho}} \]

- Multiplying density by \( x^2 \) causes \( \Delta t \) to increase by \( x \)
- To bring run time for Explicit at 2 second total time down to a comparable level with Standard, density must be increased by an order of magnitude
- Even that order of magnitude increase only makes a 2 second total time comparable, but a much longer total time is necessary, so two orders of magnitude increase of \( \rho \) is likely necessary