Failure of Notched Laminates Under Out-of-Plane Bending. Phase VI

2013 Technical Review
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Failure of Notched Laminates Under Out-of-Plane Bending, all phases

• 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 and model failure

• Approach
  • Modeling of progressive damage development and delamination using ABAQUS
  • Experimentation to validate models and to identify key failure mechanisms
Failure of Notched Laminates Under Out-of-Plane Bending, all phases

- Principal Investigators & Researchers
  - John Parmigiani (PI)
  - Imran Hyder & Nasko Atanasov grad students (2012-13)
- 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 History

- Phase IV (2010-11)
  - Further study of modeling of out-of-plane bending
  - Sensitivity study of (Boeing) material property values
- Phase V (2011-12)
  - Out-of-plane shear (mode III) experiments
  - Evaluate the ABAQUS plug-in Helius MCT
• Phase VI
  • Task 1: Investigate non-traditional layups (NTL) for optimization of out-of-plane bending performance
  • Task 2: Determine effective finite element analysis techniques for out-of-plane shear (mode III)

• Today’s Topics
  • Update on optimization
  • Review and update of out-of-plane shear
Update on optimization

- Optimization
  - Maximize failure load
  - Allow plies in 15° increments
- To begin, a genetic algorithm approach was used
  - Due to long FEA run times, a simplified 8-ply model without a notch was used. Result was all-zeros (correct)
  - Next a simplified 10-ply model w/ notch was pursued (actual panels are 20 and 40 plies)
  - Even with simplified model, 10 days of runs required to identify a solution of 0/0/-45/-45/-45/90/0/0/0/0
  - This solution is not quite the optimum as all-zeroes gives a failure load 1.5% higher.
Update on optimization

• Given long run time and failure to find true optimum, genetic algorithms were not pursued further

• Next idea pursued was to use a Design-of-Experiments approach to identify significant factors
  • Explore perturbations in ply angle about zero-degrees i.e. -15/0/15
  • Use a fractional factorial design
  • For no-notch case, all-zeros is obvious optimum and the method correctly gives this result
  • For notched-case, it is not obvious that all-zeros will be optimum
Update on optimization

- Using DoE approach for notched panel, all-zeros was found to be optimal (i.e. gave maximum failure load)
- Fracture path was found to be self-similar.
- Self-similar result was somewhat surprising so comparisons were made to all-zeros in tension and compression
- All zeros tension case gave the expected splitting failure mode
• Current Status
  • For the notched-panel geometry of this study, an all-zero-degree plies lay-up gives the maximum failure load for pure out-of-plane bending
  • Exploration of “more interesting” cases of multiple loads and general far-field boundary conditions requires more sophisticated computational equipment and validation of current mode III work and is deferred to a later project.
Review and update of out-of-plane shear

• Experimental Set-up & Plan
  • Edge-notched CF panels displaced to maximum load
  • Mode III fracture

• Metrics
  • Applied displacement
  • Applied load
  • Notch-tip strain field (via DIC, digital image correlation)

• Six ply layups
• Six specimens / layup
  • Three “up”
  • Three “down”
Review and update of out-of-plane shear

<table>
<thead>
<tr>
<th>Layup (#plies / % zero degree)</th>
<th>MEAN Max Force [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40/50%</td>
<td>5.473</td>
</tr>
<tr>
<td>40/30%</td>
<td>5.708</td>
</tr>
<tr>
<td>40/10%</td>
<td>4.101</td>
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<tr>
<td>20/50%</td>
<td>1.795</td>
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<tr>
<td>20/30%</td>
<td>1.531</td>
</tr>
<tr>
<td>20/10%</td>
<td>1.259</td>
</tr>
</tbody>
</table>

40 Ply - 30% Zero Panel Load Deflection

- Test 1 - Up
- Test 2 - Down
- Test 3 - Up
- Test 4 - Down
- Test 5 - Up
- Test 6 - Down
- Test Average

Maximum load

Linear region
Review and update of out-of-plane shear

• FEA modeling
  • Use progressive damage to reduce material stiffness and strength as fracture occurs.
  • Stiffness and strength reductions cause strain softening and mesh dependence (results depend on mesh density and do not converge to a unique solution)
  • Mesh selection method used is to choose the coarsest mesh giving a converged elastic solution
    • Successfully used out-of-plane bending study
    • Does not depend on experimental data (is not a curve fit)
Review and update of out-of-plane shear

- Seven notch-tip meshes were analyzed
- 20 element tip was selected based on elastic convergence (not experimental data)
• Using this mesh, six approaches are being pursued
  • Abaqus w/ Hashin progressive damage model
    • 1 element layer, no ply-to-ply delamination (no VCCT*)
    • 5 element layers, no ply-to-ply delamination (no VCCT*)
    • 5 element layers, ply-to-ply delamination (VCCT*)
  • Abaqus w/ Helius:MCT plug-in
    • 1 element layer, no ply-to-ply delamination (no CZ**)
    • 5 element layers, no ply-to-ply delamination (no CZ**)
    • 5 element layers, ply-to-ply delamination (CZ**)

* VCCT: Virtual Crack Closure Technique  ** CZ: Cohesive Zone
• Results for Abaqus w/ Hashin & w/o delamination capability have been completed and, in general, model predictions are too high.

**Review and update of out-of-plane shear**

### 40 Layer 50% Zero Degree Plies - 5 Element Layer

- **Force (N)** vs. **displacement (mm)**

### 40 Layer 10% Zero Degree Plies - 5 Element Layer

- **Force (N)** vs. **displacement (mm)**

- **Experimental Average**
- **Experimental Maximum**
- **Experimental Minimum**
- **FEA**
Ply-to-ply delamination was found to be critical in modeling out-of-plane bending, however it causes a considerable increase in run times (e.g. hours to days)
Review and update of out-of-plane shear

- Current efforts are focused on adding ply-to-ply delamination to models
  - Location of interfaces appears to be important
  - Out-of-plane bending models appear to be more tolerant of “misplaced” interfaces

Experiment

Model w/ interface @ top 90-degree ply

Model w/ interface @ second 90-degree ply
Looking Forward

• Benefit to Aviation
  – Provide experimentally-validated FEA analysis methods for composite materials
  – Explore new analysis techniques
  – Identify, via experiment and analysis, failure modes of composites under relevant loading conditions
  – Educate graduate students in relevant topics

• Future needs
  – Continue to refine and define appropriate design and analysis tools for aircraft design and analysis of composite materials
  – Experimentally validate conclusions
End of Presentation.

Thank you.