Explosive Testing of Open Cylinders for Verification of Composite Properties used in Computational Analysis

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General Motivation and Approach

• There is a need for:
  – Accurate composite failure prediction in computational model
  – Dynamic component experimental data for validation of modeling procedure

• Typical Problem:
  – Thin-walled structure subject to impact or blast loading
  – Desire accurate prediction of peak strains and deformations
  – Prefer shell element based model for faster design optimization

• Example: Explosively Loaded Cylinder

  Loads:
  Efficient Modeling of Blast

  Materials:
  Steel
  Laminated Composites

  Strain Rates:
  Intermediate \((10^2 \text{ - } 10^3)\)
Symmetry Boundary Conditions

• Symmetry boundary conditions used for efficiency

1/8 Model Symmetry

¼ Model Symmetry

No Symmetry

Symmetric about y-x plane
Fix translation along z-axis
Fix rotations about x and y axes

Symmetric about x-z plane
Fix translation along y-axis
Fix rotations about x and z axes

Symmetric about y-z plane
Fix translation along x-axis
Fix rotations about y and z axes

Symmetric about x-z plane
Fix translation along y-axis
Fix rotations about x and z axes
Simplified Model of Explosive Material

- All air blast were modeled with CONWEP
  - Developed by US Army to calculate conventional weapons effects
- Blast Behavior Characterized by Friedlander’s Equation

\[ P_{\text{max}}(t) \]

- LS-DYNA implements Friedlander’s equation for TNT
  - User defines
    - mass of TNT
    - location of explosive
    - time of detonation
    - surface interacting with blast
Metallic Material Model

- Modeled with *MAT_PLASTIC_KINEMATIC
  - Bi-linear elastic-plastic model with failure prediction capabilities
    • First linear portion represents the elastic region
    • Second linear portion represents the plastic region
  - Modeled materials deform according to the bi-linear stress-strain relationship until the simulated strain exceeds the failure strain
    • Elements are deleted from the model when the failure strain is surpassed

<table>
<thead>
<tr>
<th>Minimum Required Properties</th>
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</thead>
<tbody>
<tr>
<td><strong>Density</strong></td>
</tr>
<tr>
<td>Elastic Modulus</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
</tr>
<tr>
<td>Yield Strength</td>
</tr>
<tr>
<td>Tangent Modulus</td>
</tr>
<tr>
<td>Failure Strain</td>
</tr>
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</table>
Composite Material Model

- Modeled with *MAT_ENHANCED_COMPOSITE_DAMAGE
  - Predicts composite failure with Chang-Chang criteria
    - tensile fiber failure
    - compressive fiber failure
  - Complete failure occurs only after tensile fiber failure
    - Composite stiffness is adjusted after other failure modes

<table>
<thead>
<tr>
<th>Density</th>
<th>Longitudinal Modulus</th>
<th>Transverse Modulus</th>
<th>Major Poisson’s Ratio</th>
<th>Shear Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Compressive Strength</td>
<td>Longitudinal Tensile Strength</td>
<td>Transverse Compressive Strength</td>
<td>Transverse Tensile Strength</td>
<td>Shear Strength</td>
</tr>
</tbody>
</table>
Contacts for Composite Lamination

- Each ply of the composite is modeled with separate shell elements
- Delamination simulated with a tiebreak contact in 2 stages:
  - Stage 1: plies are perfectly bonded until the tiebreak failure occurs
    - Combination of normal and shear strength values
  - Stage 2: After delamination, the contact algorithm switches to a surface-to-surface contact

\[
\left( \frac{\sigma_n}{NFLS} \right)^2 + \left( \frac{\sigma_s}{SFLS} \right)^2 \geq 1
\]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma_n)</td>
<td>Stress in normal direction</td>
</tr>
<tr>
<td>(\sigma_s)</td>
<td>Stress in shearing direction</td>
</tr>
<tr>
<td>NFLS</td>
<td>Normal strength of bond</td>
</tr>
<tr>
<td>SFLS</td>
<td>Shear strength of bond</td>
</tr>
</tbody>
</table>

Bond between fibers (blue) and matrix (green) is intact

Bond is broken. Tensile forces are no longer transferred.

Bond is broken. Compressive forces are still transferred.
Case 1: Simulating Elastic Response

- Experimental data provided by Russian Federal Nuclear Agency (RFNA)
- Cylindrical composite shells with spherical internal load
  - Basalt/epoxy composite
    - Properties required for MAT 54 supplied by RFNA
- Circumferential strain recorded with high-speed photochronography
  - Pulse light source used to create a photographic image of deformation
Case 1: Experimental Configuration

- RFNA cylinder test #261

- 135 g of explosive causes visible circumferential strain oscillations (no failure recorded)

![Cylindrical Configuration Diagram]

- Dimensions:
  - 13.5 mm inner diameter
  - 161 mm outer diameter
  - 600 mm length
  - 135 g of TNT

![Cylindrical Strain vs Time Graph]

- Strain vs Time for Cylinder #261
Case 1: Simulation Approach

- Finite element model of cylinder #261
Case 1: Mesh Refinement

- Mesh density study

<table>
<thead>
<tr>
<th>Element Size</th>
<th>Predicted Peak Strain</th>
<th>Computational Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0 mm</td>
<td>1.281%</td>
<td>103 s</td>
</tr>
<tr>
<td>4.0 mm</td>
<td>1.298%</td>
<td>318 s</td>
</tr>
</tbody>
</table>

Circumferential Strain versus Time Behavior for Two Different Element Sizes
Case 1: Comparison of Experiments and Simulation

- Computational model under predicts initial peak by 12%
- Period of oscillation matches indicating good mass and stiffness
Case 2: Picatinny Arsenal Testing

- Explosive testing of six E-glass/Vinylester composite tubes
  - Deformation was measured with high-speed photography
  - Best experimental data recorded for cylinder tests #4 and #5
  - Cylinders manufactured by Utility Composite Solutions International (UCSI)
    - MAT 54 properties provided by UCSI and literature
Case 2: Experimental Configuration

- High speed camera was protected by a steel enclosure
- Cylinders were loaded with centrally placed charges of C4, positioned with light-weight foam blocks
Case 2: Composite/Metallic Cylinder (#4)

- Outer layer of E-glass composite with inner liner of AISI 1008
  - Material properties for MAT 3 taken from literature
- Experimental testing completed with ~300 g of C4
- Significant amount of observed deformation and composite failure
  - Innermost and outermost composite plies in the central region completely ablated upon detonation
  - Central region would radially expand, causing a decrease in length
  - Steel material would plastically deform
    - Reduction in length is permanent
Case 3: FEA Model of Composite/Metallic Cylinder (#4)
Case 3: Mesh Refinement

<table>
<thead>
<tr>
<th>Element Size</th>
<th>Predicted Minimum Length</th>
<th>Computational Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0 mm</td>
<td>463.2 mm</td>
<td>1320 s</td>
</tr>
<tr>
<td>4.0 mm</td>
<td>466.3 mm</td>
<td>2520 s</td>
</tr>
</tbody>
</table>

Composite/Steel Cylinder Length versus Time for Two Mesh Sizes
Case 3: Comparison of Results

Cylinder Length versus Time
Composite/Steel Cylinder

- Experimental
- Computational

Cylinder Length (mm)

Time (microseconds)
Case 3: Summary of Results

- Model accurately predicts the peak deformation
  - 1% difference between model and experiment

- Two differences between experiment and model
  - Computational model contracts to a maximum deformation faster
    - Model may be stiffer than the actual test cylinder
      - Composite inconsistencies cannot be detected and accounted for in model
    - CONWEP blast function.
      - Predicted blast time-of-arrival and pressure wave profile may vary slightly from the experiment
  - Computational model rebounds slightly after the peak deformation
    - Less than 5.0 mm
    - A similar rebound may have been present during the physical explosive testing
      - minimum resolution of the high speed camera = 1.5 mm
Summary and Conclusions

• An efficient analytical technique to predict the peak strains and deformations of blast loaded composite structures was created

• Case Study 1: Elastic Response
  – Excellent agreement with experimental data
    • Shell elements are capable of capturing the relatively small displacements
    • Tiebreak contacts correctly simulate the composite lamination and stiffness
    • LS-DYNA composite material model accurate for smaller amounts of deformation
    • CONWEP blast function is capable of approximating lower level blasts

• Case Study 2: Composite/Steel Cylinder High Deformation Response
  – Model simulated explosive test completed at Picatinny Arsenal
  – Accurate prediction of complete test duration
    • Thin steel liner plastically deforms and overall composite displacement is limited

• Case studies demonstrate accurate simulation of complete elastic response and accurate prediction of peak deformations when the response is post-failure

• Future Work
  – Rebound behavior of damaged all-composite vessel needs additional work
  – Experimental data collection during explosive tests can be improved
Questions

Thank You!
Case 3: All Composite Cylinder (#5)

- Experimental testing completed with 180 g of C4
  - C4 to TNT conversion of 1.2
- Significant amount of observed deformation and composite failure
  - Innermost and outermost composite plies in the central region completely ablated upon detonation
  - Central region would radially expand, causing a decrease in length
    - Length reduction most measurable deformation
  - After maximum length reduction, the cylinder would spring back out
    - Mechanical energy stored in the unbroken fibers
Case 3: All Composite Cylinder (#5)

• Assumptions were made to facilitate the use of the CONWEP blast function
  – During actual testing, the central section of the innermost layers of ±88° fibers were completely ablated upon detonation.
  – When modeled with CONWEP, this behavior is accurately simulated
    • Elements in the central area of the shell layer representing the ±88° plies are completely deleted.
    • Transference of blast pressure to remaining composite plies in the central zone is lost
  – Central region of the innermost ±88° plies are omitted from model
  – CONWEP blast pressure is applied to the ends of the innermost ±88° plies and the central region of the innermost ±15° plies.
Case 3: All Composite Cylinder (#5)

- Comparison of models with and without central section of ±88° completed to verify assumptions
  - Model with the complete layer of ±88° plies contracts much less and rebounds much sooner
  - Stiffness of structure minimally effected by omission
    - Slight difference in the radial displacements experienced by the two models
### Case 3: All Composite Cylinder (#5)

- **Mesh density study**

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<th>Predicted Minimum Length</th>
<th>Computational Time</th>
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<tr>
<td>6.0 mm</td>
<td>373.5 mm</td>
<td>4438 s</td>
</tr>
<tr>
<td>4.0 mm</td>
<td>392.3 mm</td>
<td>12545 s</td>
</tr>
<tr>
<td>3.0 mm</td>
<td>401.1 mm</td>
<td>24259 s</td>
</tr>
</tbody>
</table>

**Figure:** All Composite Cylinder Length versus Time for Three Different Mesh Sizes
Case 3: All Composite Cylinder (#5)

- Results of the 4.0 mm model were compared to experimental results

![Cylinder Length vs Time](image)
Case 3: All Composite Cylinder (#5)

- Model accurately predicts the peak deformation
  - 2% difference in the peak length deformations
- Two differences between the experiment and model
  - Computational model contracts to a maximum deformation faster
    - Model may be stiffer than the actual test cylinder
      - Composite inconsistencies cannot be detected and accounted for in model
    - CONWEP blast function
      - Predicted blast time of arrival and pressure wave profile may vary slightly from the experiment
  - Computational model does not completely rebound after the maximum contraction
    - Likely related to composite material model
      - Tensile matrix failure mode present throughout the structure after the partial rebound
        » Depletes remaining elastic energy from the unbroken fibers
        » Not present during actual testing