Effect of Microscopic Damage Events on Static and Ballistic Impact Strength of Triaxial Braid Composites

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Justin Littell
University of Akron
Akron, Ohio
Justin.D.Littell@nasa.gov

Wieslaw K. Binienda, William A. Arnold – University of Akron, Akron Ohio
Gary D. Roberts, Robert K. Goldberg – NASA Glenn Research Center, Cleveland Ohio
Motivation and Introduction

Triaxial braided carbon fiber composite materials are being used in engines and airframes
- Static and Dynamic loads

• Computer modeling can complement testing when necessary
  - LS-DYNA – Transient non-linear explicit finite element code
    - impact simulations

• Due to the size of the engine cases, models have to be macromechanical in nature but incorporate micromechanical properties of the materials
  - Incorporate braid architecture/stiffness properties/failure properties
  - Short run times
Model Development

• Testing and modeling were done in parallel
  – Test data used optical measurement techniques to obtain full field strain data
    • Quasi-static Testing
  – By examining the test data and using classical composite theory, a new approach was developed to model composites using a novel “Subcell” approach

• Modeling data needs
  – Composite section properties – braid geometry
  – Composite material properties – test data

• Models developed in LS-DYNA
  – Transient, nonlinear, explicit finite element code
  – Primarily impact loading that composites will be subjected
Triaxial Braided Composite Materials

- Two dimensional triaxial braid
- 24k wide axial and 12k wide bias fiber tows
- Layers of +60° and -60° bias fibers braided over a 0° axial fiber
- Quasi-isotropic architecture
- Layup of 6 Layers of braid, total composite thickness 0.125”
- Resin Transfer Molding process (RTM)
- Volume fraction of 56% nominal
Materials

• High Strength, Standard Modulus Fiber – Toray T700
• Two resins
  – Toughened Cytec Cycom ® PR520 – high strength
  – Untoughened Hexcel 3502 – low strength

• Presented as examples to cover range of material response
Photogrammetry used for Data Collection

- Global stress vs. strain curves found by creating a “digital strain gage”
- Measures material response in specific areas on specimen
  - Seen by noting lines of high localized strain
- Local failure mechanisms and deformations must be accounted for when developing an analytical method
Triaxial Braided Model Methodology

- Develop a macromechanical finite element model capable of capturing the braid architecture and material properties of triaxially braided composites
  - Layers of unidirectional lamina stacked in a “Subcell” configuration
  - Needs local lamina level modulus and failure properties
A New Methodology Developed for Implementation of Material Properties

**Obtain Fiber, Matrix Properties**
- Micromechanics - Develop effective lamina properties
- CLPT - Develop effective laminate properties
- Develop a FEM (One layer, homogenized)

**Obtain Composite stresses, strains From optical measurements**
- CLPT - Back out effective laminate properties
- Micromechanics - Back out effective lamina properties
- Develop a FEM (includes layers and subcell props)

**Traditional Approach** (Bottom - Up)
- Items needed
  - Fiber properties - Assumed
  - Matrix properties
- Stackup sequence

**New Approach** (Top – Down)
- Items needed
  - COMPOSITE TEST DATA
- Stackup sequence
Classical Laminated Plate Theory (CLPT)
Use in Reverse for Top-Down Approach

• Stresses/Surface Tractions are related to strains by the following

\[
\begin{bmatrix}
N \\
M 
\end{bmatrix} = \begin{bmatrix}
A & B \\
B & D 
\end{bmatrix} \begin{bmatrix}
\varepsilon \\
\gamma 
\end{bmatrix}
\]

• Balanced and Symmetric (B and D matrices, also A16, A26 = 0)

\[
\begin{bmatrix}
N_x \\
N_y \\
0
\end{bmatrix} = \begin{bmatrix}
A_{11} & A_{12} & 0 \\
A_{12} & A_{22} & 0 \\
0 & 0 & A_{66}
\end{bmatrix} \begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
0
\end{bmatrix}
\]

• Where

\[
A_{11} = \sum \overline{Q}_{11} = \overline{Q}_{11}^{0 \text{deg}} * t^{0 \text{deg}} + \overline{Q}_{11}^{60 \text{deg}} * t^{60 \text{deg}} + \overline{Q}_{11}^{-60 \text{deg}} * t^{-60 \text{deg}}
\]

\[
\overline{Q}_{11} = m^4 Q_{11} + n^4 Q_{22} + 2m^2 n^2 Q_{12} + 4m^2 n^2 Q_{66}
\]

\[
Q_{11} = \frac{E_{11}}{1 - \nu_{12} \cdot \nu_{21}}, Q_{22} = \frac{E_{22}}{1 - \nu_{12} \cdot \nu_{21}}, Q_{12} = \frac{\nu_{21} \cdot E_{11}}{1 - \nu_{12} \cdot \nu_{21}}, Q_{66} = G_{12}
\]

• E11, E22, v12, v21, G12 are parameters needed in LS-DYNA

Known from optical measurements

Known from micromechanics eqs
Equation Development

Micromechanics of Composite Materials for Surface Traction

- Transverse ASTM 3039 specimen

\[ V_f^a \cdot N_y^a = V_f^b \cdot N_y^b \]
\[ N_x^a = N_x^b = N_x^c = N_x^d \]

- Axial ASTM 3039 specimen

\[ N_y^a = N_y^b = N_y^c = N_y^d = 0 \]
\[ N_y^a = 0 = A12^a \cdot \varepsilon_x^a + A22^a \cdot \varepsilon_y^a \]
Developed Equations (using Subcell Strains)

- Strains are found using the optical measurement system.
- In the end, there are 6 variables ($Q_{11}, Q_{12}, Q_{22}, Q_{66}, N_{ya}, N_{yb}$) and 6 equations:
  - 2 from TT Subcells A and C (CLPT)
  - 2 from TT Subcells B and D (CLPT)
  - 1 from volume fraction averages (Micromechanics)
  - 1 from AT Subcells A and C (CLPT)
- Solve simultaneously.
Material Card

MAT_RATE_SENSITIVE_COMPOSITE_FABRIC

### Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EA</td>
<td>Axial Modulus</td>
</tr>
<tr>
<td>EB</td>
<td>Trans. Modulus</td>
</tr>
<tr>
<td>PRBA</td>
<td>In Plane Poisson</td>
</tr>
<tr>
<td>GAB</td>
<td>In Plane Shear Mod.</td>
</tr>
</tbody>
</table>

### Material Coordinate Definition

<table>
<thead>
<tr>
<th>A1</th>
<th>A2</th>
<th>A3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>D1</td>
<td>D2</td>
<td>D3</td>
</tr>
<tr>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

### Failure Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Name</th>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>E11C</td>
<td>Comp. strain (Ax.)</td>
<td>XC</td>
<td>Comp. strength (Ax.)</td>
</tr>
<tr>
<td>E11T</td>
<td>Tens. Strain (Ax.)</td>
<td>XT</td>
<td>Tens. Strength (Ax.)</td>
</tr>
<tr>
<td>E22C</td>
<td>Comp. strain (Trans.)</td>
<td>YC</td>
<td>Comp. Strength (Trans.)</td>
</tr>
<tr>
<td>E22T</td>
<td>Tens. strain (Trans.)</td>
<td>YT</td>
<td>Tens. Strength (Trans.)</td>
</tr>
<tr>
<td>GMS</td>
<td>Shear strain</td>
<td>SC</td>
<td>Shear Strength</td>
</tr>
</tbody>
</table>
Axial Tensile (AT) Strength

- Assume that in AT tests, the AT fiber carries most of the load
- $E_{11T}$ comes from ultimate strain at AT failure

![Graph showing stress-strain relationship with failure stress and strain values]

- Failure Stress $= XT = 1.515 \times 10^5$ psi
- Failure Strain $= E_{11T} = 0.0216$
Transverse Tensile (TT) Strength

- Look at fiber splitting on TT specimen
- Load at first split will be YT
- SLIMT will be set to 1
- E22T will be set to failure strain of test
Compressive Strain/Strength

- Material behaves as a homogenous
  - Use strength at failure for both Axial and Transverse tests
  - Use strain at strength for both Axial and Transverse tests

Axial Compression
- Failure Stress = $X_C = 5.47 \times 10^8$ psi
- Failure Strain = $E_{11C} = 0.018$

Transverse Compression
- Failure Stress = $Y_C = 5.00 \times 10^8$ psi
- Failure Strain = $E_{22C} = 0.012$
Shear Strength

- Using Modified Shear Specimen Design based on Kohlman
  - ASTM 5379
- $P_{xy}$, $N_{xy}$ is for each of the integration layers
  - Can be directly implemented for shear strength
- LS-DYNA needs $\varepsilon_{xy}$ for GMS

![Diagram of shear strength test setup]

**Graph: Shear Stress vs. Shear Strain**

Shear Stress = SC = 4.5*10^4 ps
Shear Strain = GMS = 0.012

**Diagram:**
- $P_{xy}$
- Y-axis: $-60^\circ$, $0^\circ$, $+60^\circ$
- X-axis: $-60^\circ$, $0^\circ$, $+60^\circ$
- Z-axis: $-60^\circ$, $0^\circ$, $+60^\circ$
Finite Element Models

- Both Axial and Transverse Specimens were developed using ASTM D3039 specimen geometries.
- Fixed end boundary conditions were used to simulate the fixed grip.
- Loading was applied at the opposite end using enforced displacement.
Static Results

**T700 / PR520**

**Axial Tension**

- % Error
  - Strength: 12%
  - Modulus: 7%

**Transverse Tension**

- % Error
  - Strength: 8%
  - Modulus: 9%

**T700 / 3502**

**Axial Tension**

- % Error
  - Strength: 10%
  - Modulus: 4%

**Transverse Tension**

- % Error
  - Strength: 25%
  - Modulus: 6%
Determination of T700 fiber / PR520 Resin Impact Characteristics

- Simulations were completed Spring 2008
  - Showed penetration threshold at 630 ft / sec
- Used as a starting point for impact tests
- Impact tests conducted Summer 2008
  - Penetration threshold was between 609 and 637 ft / sec
Limitations: Delaminations for T700 fiber / 3502 resin

- OOP displacements verified by NDE
- Global Material response curves become non-linear after delaminations occurred
- Due to the nature of integration point formulation, cannot simulate ultimate failure values between layers
Limitations: FEM cannot simulate fiber bundle splitting

- Axial Tension (axial strain)
- Transverse Tension (axial strain)
Conclusion

- Standardized test methods in conjunction with an optical measurement system have been used to collect material property data for triaxial braided composite materials
  - Global material response curves
  - Local transverse fiber bundle splitting
  - Local subsurface delaminations
- A hybrid micro-macromechanical computer model has been developed
  - Incorporates braid architecture
  - Incorporates tested material property data
- Comparisons between test and simulation show good agreement
  - 10% in static simulations
  - Penetration threshold in impact simulations
- Factors seen in the test data cannot be simulated as of now
  - Ongoing work
Backup
Defining the Braid Geometry (Section)

- Each part has unique section properties
  - Each section contains information about number of layers (15) and braid angle ($\Theta$) at each layer
- Braid was modeled as layers of unidirectional lamina
  - Shifted (Idealized)
Equation Development – Transverse Tensile Testing

• Use ASTM 3039 Transverse Tensile coupon geometry
• Classical composite uniform stress/uniform strain assumption yields
• (Parallel to loading)
• (Perpendicular to loading)

\[ N_x^a = N_x^b = N_x^c = N_x^d \]

\[ V_f^a \times N_y^a = V_f^b \times N_y^b \]
Rewriting the equations for each Subcell (Transverse Tensile Testing)

• **Subcell A**
  – $N_x$ is applied load and all strains are found from optical measurement system

\[
N_x^a = A11^a \cdot \varepsilon_x^a + A12^a \cdot \varepsilon_y^a
\]

\[
N_y^a = A12^a \cdot \varepsilon_x^a + A22^a \cdot \varepsilon_y^a
\]

• **Subcell B**
  – $N_x$ is applied load and all strains are found from optical measurement system

\[
N_x^b = A11^b \cdot \varepsilon_x^b + A12^b \cdot \varepsilon_y^b
\]

\[
N_y^b = A12^b \cdot \varepsilon_x^b + A22^b \cdot \varepsilon_y^b
\]

• **Four Equations**
**Equation Development – Axial Tensile Testing**

- Classical composite laminate micromechanics assumptions yield

\[ N_y^a = N_y^b = N_y^c = N_y^d = 0 \]

\[ N_y^a = 0 = A12^a \epsilon_x^a + A22^a \epsilon_y^a \]
Advanced Data Analysis

Toughened Fiber Bundle Splitting – Transverse Testing

- Identify local failure strain
- Local failure initiation correlations to global non-linearities
T700 Fiber / PR520 Resin Static Results

**Axial Tension**

<table>
<thead>
<tr>
<th>Test</th>
<th>Axial Tension Modulus (psi)</th>
<th>Axial Tension Strength (psi)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>6.8E6±1.6E5</td>
<td>1.52E5±4.9E3</td>
<td>7%</td>
</tr>
<tr>
<td>LS-DYNA</td>
<td>7.4E6</td>
<td>1.31E5</td>
<td>12%</td>
</tr>
</tbody>
</table>

**Transverse Tension**

<table>
<thead>
<tr>
<th></th>
<th>Transverse Tension Modulus (psi)</th>
<th>Transverse Tension Strength (psi)</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>6.2E6±2.3E5</td>
<td>8.69E4±4.3E2</td>
<td>9%</td>
</tr>
<tr>
<td>LS-DYNA</td>
<td>5.6E6</td>
<td>9.38E4</td>
<td>8%</td>
</tr>
</tbody>
</table>