Crashworthiness of Composites – Material Dynamic Properties

2011 Technical Review
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Crashworthiness of Composite Fuselage Structures – Material Dynamic Properties

• Motivation and Key Issues

  • Crashworthiness
    - maintain survivable volume
    - dissipate kinetic energy → alleviate occupant loads
  
  • Energy absorption
    - Composite structures /energy absorption (EA) devices
      - Controlled failure modes
      - Maximize damage volume
      - Provision for sustained stability
    - Influencing factors
      - EA device geometry
      - Material
      - Rate sensitivity (?)

Approach

- CRASHWORTHINESS CERTIFICATION
  - specific to structural configuration
  - interactions between mechanisms

$/test Application

- BENCHMARKING
  - Constitutive models
  - Failure theories

- LOCALIZED IMPACT PROBLEMS
  - Bird, hail, projectile impact
  - Damage Resistance

- CRASHWORTHINESS
  - Crush behavior
  - Structural integrity
Crashworthiness of Composites – Material Dynamic Properties

• Principal Investigators & Researchers
  – Suresh Keshavanarayana (PI)
  – Gerardo Olivares (PI)

• FAA Technical Monitor
  – Allan Abramowitz

• Other FAA Personnel Involved
  – Curtis Davies

• Industry Participation
  – CMH17 Crashworthiness Working Group
  – NIS (State of Kansas)
Material Characterization → Coupons with Stress gradients → Element tests

Geometric Scaling Effects

CMH-17 material characterization → Round Robin exercise for dynamic tension testing
Background..Rate Sensitivity

• Material Systems
  NEWPORT material systems
  - NB321/3k70 Plain Weave Carbon Fabric (PWCF)
  - NB321/7781 Fiberglass
  TORAY material systems
  - T800S/3900-2B[P2352W-19]
    BMS8-276 Rev-H- Unitape
  - T700G-12K-50C/3900-2 Plain Weave Carbon Fabric (PWCF)

• Rate Sensitivity
  - Dependent on material
  - Dependent on loading type (tension, compression, shear)
  - Fracture toughness exhibits trend opposite to that of in-plane properties
Background...rate sensitivity

- NB321/7781 fiberglass
- Toray T700G-12K-50C/3900-2 Plain Weave Carbon Fabric
  - $[0]_n$ and $[\pm45]_n$, where $n=4, 8$ and 12
- Sensitivity to test speed
  - Peak load
  - Crush load
  - Failure modes

<table>
<thead>
<tr>
<th>Load (lb)</th>
<th>Displacement (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2000</td>
<td>0.5</td>
</tr>
<tr>
<td>4000</td>
<td>1</td>
</tr>
<tr>
<td>6000</td>
<td>2</td>
</tr>
</tbody>
</table>

$10^{-3}$ in/s  100 in/s
Recently Completed & Ongoing Work.

- Scaling Studies
  - Tension
    - Observed rate sensitivity in sub-scale coupons applicable at larger scales?*

- Characterization of CMH-17 material
  - Tension, Compression & Shear

- CMH-17 Round-Robin exercise for Dynamic tensile testing

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* K.E. Jackson et. al, J.Comp. Matls., Vol.26, 1992
Scaling Issues..

• Specimen size
  – Reduced gage lengths to maximize strain rates
  – Reduced cross-section area to minimize failure loads to within testing machine capability

ASTM standards

Specimen size used for high rate tests

Will the same strengths be observed irrespective of specimen size?
Geometric Scaling

Sub-laminate scaling

Ply level scaling

Microstructure scaling (not practical)

References:
Geometric Scaling

PLY LEVEL SCALING

Carillo & Cantwell (2007)
Jackson et. al.(1992)
Kellas et. al.(1993)

SUB-LAMINATE SCALING

Johnson et. al.(1998)
Kellas et. al.(1993)

Strength

Volume

Carillo & Cantwell (FML-2D scaling)
Carillo & Cantwell (FML-3D scaling)
Jackson et. al.(1992)
Johnson et. al.(1998)

References:
Jackson, Kellas & Morton (1992), J. Comp. Mat. Vol.26
Kellas, Morton & Jackson (1993), ASTM STP 1156

Volume mm³

100 1,000 10,000 100,000
Weibull model

\[ \frac{\sigma}{\sigma_o} = \left( \frac{V}{V_o} \right)^{-\frac{1}{m}} \]

\( \sigma_o \sim \) characteristic (reference) strength

\( V_o \sim \) characteristic (reference) Volume

\( m \sim \) Weibull modulus

References:

Weibull (1951), J. App. Mech., Vol.18
Jackson, Kellas & Morton (1992), J. Comp. Mat. Vol.26
Wisnom (1999), Comp. Sc. Tech., Vol.59

CURRENT STUDY
## Scaling Experiments

- **Scaling type**
  - Fabrics: 2D (planar) scaling
  - Unitape: 1D (length) scaling
    - Reduced loading capability

### Scale

<table>
<thead>
<tr>
<th>Material</th>
<th>Stacking sequence</th>
<th>Scale $\lambda = V/V_0$</th>
<th>Width W (in)</th>
<th>Length L (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newport NB321/7781 fiberglass</td>
<td>[0]$_4$</td>
<td>1</td>
<td>0.50</td>
<td>2</td>
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<tr>
<td></td>
<td>[±45]$_4$</td>
<td>4</td>
<td>1.00</td>
<td>4</td>
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<tr>
<td></td>
<td></td>
<td>8</td>
<td>1.00</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>1.00</td>
<td>10</td>
</tr>
<tr>
<td>Toray T800S/3900-2B Unitape</td>
<td>[0]$_4$</td>
<td>1</td>
<td>0.50</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.50</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>0.50</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>0.50</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>[+45/−45]$_5$</td>
<td>1</td>
<td>0.50</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.50</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>0.50</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>1.00</td>
<td>10</td>
</tr>
</tbody>
</table>
Tension Test Apparatus...

- **CROSSHEAD**
- **LOAD CELL**
- **SPECIMEN**
- **GRIPS**
- **WEDGE**
- **CLAMPING BOLTS**
- **GRIP BLOCK**
- **PIN**
- **CONNECTOR**
- **SLACK ROD**
- **BEARING**
- **ARREST BLOCK**
- **POLYURETHANE (60 DUROMETER)**
- **SLACK MECHANISM**
- **SLACK Rod**
- **SLACK TUBE**
- **ACTUATOR**
• Load Frames
  – MTS electromechanical (slow rate)
  – MTS high rate (~ 0.5 in/s to 500 in/s)

• Load measurement
  ▪ Slow speed tests ~Strain gage based load cell (5 kip capacity)
  ▪ Dynamic Tests ~Piezoelectric load cell
    – PCB Piezotronics model 206C
    – ±10 kip capacity
    – ~40 kHz upper frequency limit

• Strain measurement
  ▪ Strain gage CEA-06-250UW-120
  ▪ Vishay 2210 signal conditioner
    ▪ Excitation voltage: 1V
    ▪ DC to 50 kHz (-0.5 dB max)
Test Results.. Weibull Modulus

- Weibull modulus sensitive to strain rate
  - dependent on laminate type
  - Increased size effects with strain rate, in laminate with free edge stresses
**Strain Rate & Scaling effects.. (under progress)**

Matrix (resin) behavior

Increasing rate

Zone of influence

Increasing rate

Hedgepeth, J.M. 1961, NASA TN D-882
Material Characterization Round Robin

- Characterization of *in-plane* stress-strain behavior of Toray T700/2510 Plain weave carbon/epoxy (F6273C-07M) under dynamic rates of loading (PI: G. Olivares)
  - Tension (current activity)
    - $[0]_n$, $[+/45]_{ns}$
  - Compression
  - Shear
- Strain Rates
  - Quasi-static to $\sim 250 s^{-1}$

*Original plans included Newport NB321/7781 fiberglass/epoxy material. Due to budget & time constraints, this material will not be used.*
Participating Labs/Agencies (POCs)

- Co-ordination, Reporting
- Specimen fab., fixturing, instrumentation (strain gage)
- Material
- Testing

- FAA/NIAR/WSU (A. Abramowitz, G. Olivares, K.S. Raju)
- Boeing MESA (M. Rassaian)
- Ohio State University (A. Gilat)
- DLR (Alastair Johnson)
- University of Utah (Dan Adams)
- Oakridge National Labs (M. Starbuck)
- Toray America (Sam Tiam)
Round Robin Activity

- **Primary Objective**
  - Characterize strain rate sensitivity of Toray T700/2510 Plain weave carbon/epoxy (F6273C-07M) material at strain rates ranging between 0.01 to 250 s\(^{-1}\).

- **Secondary Objective**
  - evaluate the test methods/apparatus, specifically load measurement methods, employed by the participating laboratories.
    - Use extended tab 2024-T3 aluminum specimens
## Nominal Quasi-Static Properties…

<table>
<thead>
<tr>
<th>Property</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness/ply thickness (in)</td>
<td>2024-T3 bare(^{(1)})</td>
</tr>
<tr>
<td></td>
<td>0.010 – 0.128</td>
</tr>
<tr>
<td>Young’s Modulii (Msi)</td>
<td>E=10.5</td>
</tr>
<tr>
<td></td>
<td>E(_2)=7.97</td>
</tr>
<tr>
<td>Shear Modulus (Msi)</td>
<td>G=4.0</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>(\nu)=0.33</td>
</tr>
<tr>
<td>Tensile Strength (ksi)</td>
<td>(F_{TU}=65) (L)*</td>
</tr>
<tr>
<td></td>
<td>(F_{2t}=112)</td>
</tr>
<tr>
<td>Shear Strength (ksi)</td>
<td>(F_{SU}=40)*</td>
</tr>
</tbody>
</table>

### Data Source

- \(^{(1)}\)MMPDS (* B-basis values)
- \(^{(2)}\)AGATE WP3.3-033051-134. Lamina properties (Oven cured)
- \(^{(3)}\)AGATE WP3.3-033051-097. Laminate properties (Oven cured)
Test Specimen Geometries & Instrumentation

Ref: SAE J2749 High Strain rate Tensile testing of Polymers

Aluminum specimens

Dimensions in INCHES

Composite specimens

Dimensions in INCHES

Will be provided to participating labs by WSU/NIAR
Specimen geometry.

The image shows a graph with the x-axis labeled "Young's Modulus E, Msi" and the y-axis labeled "Number of reflections N_{gage}". The graph plots the number of reflections as a function of Young's Modulus for different strain rates, as indicated by the labels "\( \dot{\delta} = 10 \text{ in/s} \)" and "\( \dot{\delta} = 50 \text{ in/s} \)". Toray T700/2510 and SAE J2749 recommended values are also indicated on the graph.

SAE J2749 High Strain rate Tensile testing of Polymers
K.F. Graff, Wave Motion in Elastic Solids,
## Test matrix

<table>
<thead>
<tr>
<th>Material System</th>
<th>Nominal Strain rate (1/s)</th>
<th>0.01</th>
<th>1</th>
<th>100</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024-T3 Aluminum</td>
<td></td>
<td>×3</td>
<td>×3</td>
<td>×3</td>
<td>×3</td>
</tr>
<tr>
<td>TORAY T700/2510 plain weave/epoxy (F6273C-07M)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[0]₄</td>
<td></td>
<td>×3</td>
<td>×3</td>
<td>×3</td>
<td>×3</td>
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<tr>
<td>[90]₄ (TBD)</td>
<td></td>
<td>×3</td>
<td>×3</td>
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<tr>
<td>[±45]₄</td>
<td></td>
<td>×3</td>
<td>×3</td>
<td>×3</td>
<td>×3</td>
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<tr>
<td>NEWPORT NB321/7781 fiberglass/epoxy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>[0]₄</td>
<td></td>
<td>×3</td>
<td>×3</td>
<td>×3</td>
<td>×3</td>
</tr>
<tr>
<td>[±45]₄</td>
<td></td>
<td>×2</td>
<td>×3</td>
<td>×3</td>
<td>×3</td>
</tr>
</tbody>
</table>

Total: 48 tests
participating labs use their own
Load sensors

Will be provided to participating labs by WSU/NIAR
Document (draft) describing the round-robin activity mailed to participants
- Ohio State (Prof. Gilat) requested a different specimen geometry and adapters for use with SHPB apparatus
  - Specimen machining completed
  - Machining of adapters under progress

Aluminum Specimens
- Machining & Instrumentation has been completed

Composite Specimens
- Machining has been completed
- Instrumentation under progress

Machining of test fixtures completed
Specimens & test fixtures to be shipped ~ 1st week of May, 2011
Preliminary Tests...

- Extended Tab Aluminum Specimen
- Load measurement
  - PCB Piezotronics model 206C
    - ±10kip capacity
    - ~40kHz upper frequency limit
- Strain measurement
  - Strain gage CEA-06-250UW-120
  - Vishay 2210 signal conditioner
Load measurement.

Stress waves

Load train oscillations
Load Measurement...

Load Cell
Tab gage

Extended tab
Aluminum Specimen

TRANSFER FUNCTION

Correct test data for Composite Specimens

Simulations to improve test apparatus

$F(t)$
Looking Forward

• Benefit to Aviation
  – Rate sensitive data for different material systems
  – Guidelines for conducting dynamic tensile testing using servo machine

• Future needs
  – Round-Robin exercises for Compression, Shear
  – Evaluation of material models
  – Analysis (FEA) of test fixtures/apparatus for further improvements
End of Presentation.

Thank you.