Mechanical and Vibration Testing of Carbon Fiber Composite Material with Embedded Piezoelectric Sensors

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Background

• **Idea:**
  – Use piezoelectric sensors and actuators as part of active vibration control of composite fan blades
  – Embed the piezoelectric elements into the composite material

• **Question:**
  – How does the inclusion of packaged piezoelectric elements into composites affect the strength?

• **Previous Research:**
  – Generally full inclusion of piezo into composite:
    • Warkentin and Crawley (1991) – embedded silicon chips
    • Bronowicki et al. (1996) – tension, compression, temperature, fatigue
    • Mall et al. (1998, 2000) – tension, electromechanical fatigue
    • Paget and Levin (1999) – tension and compression
    • Lin and Chang (2002) – fabrication techniques; tension, compression, shear, quasi-static impact
    • Konka et al. (2012) – foam sandwich structures, flexible piezoelectric elements; tension, bending, short beam shear

• **Our goal** – Determine localized strength of the composite with embedded piezoelectric elements
Approach

✓ Embed off-the-shelf piezoelectric sensors into carbon fiber composite material

✓ Mechanical Testing
  – 4-Point Bending
  – Short Beam Shear
  – Flatwise Tension

✓ Vibration Sensor Testing
  – Effect of curing temperature and pressure on sensor

• Application to composite fan blades
  – Active vibration control:
    ✓ Spin testing with surface-mounted piezoelectric elements in small subscale fan blades
    • Vibration testing with embedded piezoelectric elements in larger subscale fan blades
## Materials

<table>
<thead>
<tr>
<th>Composite Material</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer matrix fiber composite</td>
<td>HexPly 8551-7 with IM 7 carbon fibers</td>
<td>Epoxy resin with unidirectional carbon fibers, ply stack-up</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Piezoelectric Elements</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolithic</td>
<td>Non-flexible, PZT-5A, solid material</td>
<td>250μm (0.010”) thick PZT</td>
</tr>
<tr>
<td>Flexible-1</td>
<td>Flexible, PZT-5A, rectangular fibers</td>
<td>175μm (0.007”) thick PZT</td>
</tr>
<tr>
<td>Flexible-2</td>
<td>Flexible, PZT-5A, circular fibers</td>
<td>250μm (0.010”) thick PZT</td>
</tr>
</tbody>
</table>
Mechanical Test Specimen Preparation

Ply Cut-outs

Piezoelectric Element

Composite
Embedded piezoelectric patch
Specimen cut

Bending and Short Beam Shear

Flatwise Tension

Cured at 175°C (350°F) and 690 kPa (100psi) for two hours
Mechanical Testing

4-Point Bending

- Piezoelectric material
- 75.6 mm (16t)
- 151 mm (32t)
- 6.4 mm loading nose

Short Beam Shear

- Piezoelectric material
- 50.8 mm (4t)
- 6.4 mm loading nose

Flatwise Tension

- Force
- Piezoelectric material
# Mechanical Testing

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Standard</th>
<th>Specimen Dimensions</th>
<th>Piezoelectric Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-Point Bending</td>
<td>ASTM D7264</td>
<td>165 mm x 12.7 mm x 4.72 mm (6.5” x 0.5” x 0.186”)</td>
<td>Two patches, piezo surface 0.3 mm (0.012”) below PMFC surface</td>
</tr>
<tr>
<td>Short Beam Shear</td>
<td>ASTM D2344</td>
<td>76 mm x 25 mm x 12.7mm (3.0” x 1.0” x 0.5”)</td>
<td>One patch located at midplane</td>
</tr>
<tr>
<td>Flatwise Tension</td>
<td>ASTM D7291</td>
<td>22 mm diameter x 20 mm thick (0.88” dia. x 0.78” thick)</td>
<td>One patch located at midplane</td>
</tr>
</tbody>
</table>
4-Point Bending

Baseline

Embedded

Failure

Failure at interface

Failure under roller
4-Point Bending

Baseline Shear Strain

Embedded Shear Strain

Observation area
4-Point Bending

Strength (MPa)

Baseline (n=3)  Monolithic (n=2)  Flexible-1 (n=3)  Flexible-2 (n=5)

Failure at roller
Short Beam Shear

Baseline

Embedded

Observation area

Failure

PZT

Piezo

$\varepsilon_y$
Short Beam Shear

Shear Strength (MPa)

<table>
<thead>
<tr>
<th></th>
<th>Baseline (n=3)</th>
<th>Monolithic (n=3)</th>
<th>Flexible-1 (n=5)</th>
<th>Flexible-2 (n=5)</th>
</tr>
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<tr>
<td></td>
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</tbody>
</table>
Flatwise Tension

Failure within patch at interface

Failure within patch at piezoelectric
Flatwise Tension

![Graph showing stress (MPa) vs. types of samples.](image)

- **Baseline (n=3)**: Stress failure is significantly higher than other groups.
- **Flexible-1 (n=4)**: Moderate stress failure.
- **Flexible-2 (n=4)**: Lower stress failure compared to the baseline.

Note: Failure in epoxy indicates a critical point where the material fails due to tension.
## Vibration Testing

![Diagram](attachment:image.png)

### ASTM E756-05

<table>
<thead>
<tr>
<th>Beam Dimensions (Beyond Clamp)</th>
<th>Patch Dimensions</th>
<th>Patch Properties</th>
<th>Patch Sensitivity</th>
<th>Configuration ID</th>
<th>Embedding Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>191 mm (7.5”) long 33.0 mm (1.3”) wide 5.66 mm (0.223”) thick</td>
<td>28.0 mm x 14.0 mm (1.10” x 0.55”)</td>
<td>C = 25 nF  E = 30.3 GPa  d_{31} = -210 pC/N</td>
<td>10x10^{-6} m/m/V</td>
<td>Flexible-1-1</td>
<td>0.3 mm (0.012”) deep</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Flexible-1-2</td>
<td>1.5 mm (0.060”) deep</td>
</tr>
</tbody>
</table>
Vibration Testing

- **Sensor Peak Output (V)** vs. **Tip Displacement (mm)**
  - Flexible-1-1
  - Flexible-1-2

- **Sensor Strain (microstrain)** vs. **Calculated Strain (microstrain)**
  - Flexible-1-1
  - Flexible-1-2
Conclusions

• Mechanical Testing
  – 4-Point Bending – 31-47% reduction in strength
  – Short Beam Shear – 19-29% reduction in strength
  – Flatwise Tension – 83-85% reduction in strength

• Vibration Testing
  – Curing process did not adversely affect sensing ability

• Improving Strength
  – Active vibration control will reduce resonant stresses in the structure; however, it may not be adequate to account for the reduced composite strength
  – Perform analysis to better understand stresses in and between composite and piezoelectric elements
  – Investigate embedding techniques to reduce stresses in piezoelectric elements (e.g. interlacing)
  – Develop packaging techniques to increase the strength in piezoelectric elements

• Plans
  – Embed piezoelectric elements into subscale composite fan blade, perform active vibration control of resonant modes