The Effect of Localized Damage on the Electrical Conductivity of Bare Carbon Fiber Tow and Its Use as a Non-Destructive Evaluation Tool for Composite Overwrapped Pressure Vessels

SLaMS Presentation
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September, 2015
Outline

• Goal
• Introduction
• Composite Overwrapped Pressure Vessels
• Problems
• Methods and Materials
• Results and Discussion
• Conclusions and Future Work
Goal

• **Demonstrate** the feasibility of performing resistance measurements in bare carbon fiber tows and identify a correlation between the percentage of surviving filaments, local changes in resistance measurements, and strength reduction.

• **Develop** a tool to estimate strength of carbon fiber tows from electrical resistance measurements.
Introduction

• Composite materials are beneficial because of their high specific strength and low weight.

• Safety
  • Destructive testing and destructive testing
  • Non-Destructive Testing (NDT) and Non-Destructive Evaluation (NDE)

• Problem: Neither NDT nor NDE can provide sufficient data to determine life expectancy or quantify the damage state of a composite material.
Introduction

• One method that has potential to do so is by monitoring the localized resistance measurement of the composite.
  • Schulte and Baron (1989)
  • Wang, X and Chung, D (1997)
  • Abry et al. (1998)
  • Park et al. (2002)

• Past research focused on single fiber and carbon fiber reinforced plastics (CFRP), and little research was done for failure prediction
Introduction

• Why electrical resistance?
  • Carbon fiber filaments are conductive
  • The localized resistance measurement is a function of the number of filaments
  • As a whole, these filaments have a quantized resistance

• Electrical resistance measurement correlates to number of continuous filaments in the local region
Composite Overwrapped Pressure Vessels

- “...is a combination of structural fibers and a resin that forms the overwrapped structure for a COPV. Continuous fibers provide tensile strength for structural integrity while the resin carries shear loads in the composite and maintains the fiber position.”
Composite Overwrapped Pressure Vessels

- **Failure Modes**

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Failure Result</th>
<th>Control Phase</th>
<th>Mitigation Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shearing of Boss</td>
<td>Catastrophic</td>
<td>Design/NDE</td>
<td>Statistical, NDI</td>
</tr>
<tr>
<td>Fatigue Crack Growth in Liner under Composite</td>
<td>Leakage</td>
<td>Design/NDE</td>
<td>Fracture Control (Safe-Life)</td>
</tr>
<tr>
<td>Crack Growth in Boss</td>
<td>Catastrophic</td>
<td>Design/NDE</td>
<td>Fracture Control (Safe-Life)</td>
</tr>
<tr>
<td>Over Pressurization</td>
<td>Catastrophic</td>
<td>System Design/Operations</td>
<td>Thermal Control and System Design</td>
</tr>
<tr>
<td>Stress-Rupture</td>
<td>Catastrophic</td>
<td>Design/Operations</td>
<td>Stress-Rupture Data</td>
</tr>
<tr>
<td>Corrosion/Stress-Corrosion of Liner under Composite</td>
<td>Catastrophic</td>
<td>Design/Mfg/Operations</td>
<td>Control of Chemical Environment</td>
</tr>
<tr>
<td>Corrosion/Stress-Corrosion of Boss</td>
<td>Catastrophic</td>
<td>Design/Mfg/Operations</td>
<td>Control of Chemical Environment</td>
</tr>
<tr>
<td>Embrittlement of Liner</td>
<td>Catastrophic</td>
<td>Mfg/Operations</td>
<td>Metallurgical Control, Control of Thermal and Chemical Environments</td>
</tr>
<tr>
<td>Corrosion of Matrix Resin or Fiber</td>
<td>Catastrophic</td>
<td>Mfg/Operations</td>
<td>Control of Chemical Environment</td>
</tr>
<tr>
<td>Embrittlement of Matrix Resin or Fiber</td>
<td>Catastrophic</td>
<td>Mfg/Operations</td>
<td>Control of Cure, Control of Thermal and Chemical Environments</td>
</tr>
<tr>
<td>Liner Buckling under Composite/fatigue</td>
<td>Leakage</td>
<td>Mfg/NDE</td>
<td>Adhesive Bonding Process Control, Bond-Line NDE</td>
</tr>
<tr>
<td>Impact/Mechanical Damage</td>
<td>Catastrophic</td>
<td>Mfg/NDE/Operations</td>
<td>Damage Control</td>
</tr>
<tr>
<td>Delamination (of mounting interface and bridging)</td>
<td>Catastrophic</td>
<td>Mfg</td>
<td>NDE</td>
</tr>
</tbody>
</table>

Courtesy of Lorie Grimes-Ledesma, Ph.D., NASA Jet Propulsion Laboratory, Pasadena, Calif.
Composite Overwrapped Pressure Vessels

• **Stress Rupture**
  • Conventional pressure vessels will leak before burst; however, COPVs have a tendency to burst before leak.
  • Despite years of effort, there still exist no comprehensive understanding concerning the rupture phenomena of COPVs

• **Impact Damage**
Composite Overwrapped Pressure Vessels

• Uses
  • Aerospace
  • Commercial Vehicles

• The increase in commercial use is dangerous because failure modes not well understood and manufacture, inspection, etc. are not as stringent as aerospace standards.
Problems

• No method to quantify damage of composite materials
• A failure mechanism that is not understood
• Pressure to develop solutions to energy needs

The electrical resistance method can be used to correlate a change in resistance to a change in strength and can be used as a tool to predict failure.
Methods and Materials

• Carbon Fiber
  • Hexcel® IM7 (Hexcel Corporation, Stamford, CT) continuous, Polyacrylonitrile (PAN) based, carbon fiber was used.
  • Intermediate modulus fiber and is commonly used in the production of COPVs for aerospace applications.
  • A specimen is composed of 12,000 carbon fiber filaments, and is also referred to as a tow or strand

<table>
<thead>
<tr>
<th>HexTow® IM7 12 K Filament Carbon Fiber</th>
<th>SI Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>5.2 μm</td>
</tr>
<tr>
<td>Density</td>
<td>1.78 g/cm³</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>276 GPa</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>5,655 MPa</td>
</tr>
<tr>
<td>Electrical Resistivity</td>
<td>1.5 x 10⁻³ Ω-cm</td>
</tr>
</tbody>
</table>
Methods and Materials

• Standards
  • ASTM D4018 “Standard Test Methods for Properties of Continuous Filament Carbon and Graphite Fiber Tows.”
Tabbing

\[ L_{\text{min}} = \frac{F_u h}{2 F_{\text{su}}} \]

where:
- \( L_{\text{min}} \) = minimum required bonded tab length, mm [in.];
- \( F_u \) = ultimate tensile strength of coupon material, MPa [psi];
- \( h \) = coupon thickness, mm [in.]; and
- \( F_{\text{su}} \) = ultimate shear strength of adhesive, coupon material, or tab material (whichever is lowest), MPa [psi].
Specimen Preparation
Resistance Measurement

- HP4338B milliohmmeter
- Four-Point Method was used

\[ V_M = \text{Voltage measured by meter} \]
\[ V_R = \text{Voltage across resistor} \]

Measured Resistance = \( \frac{V_M}{I} = R + (2 \times R_{LEAD}) \)

\[ V_M = \text{Voltage measured by meter} \]
\[ V_R = \text{Voltage across resistor (R)} \]

Because sense current is negligible, \( V_M = V_R \) and measured resistance = \( \frac{V_M}{I} = \frac{V_R}{I} \)
Resistance Measurement

\[ I = \frac{V}{R} \]

\[ \frac{1}{R_{tot}} = \sum_{1}^{n} \frac{1}{R_n} \]
Experimental

• Load Profile

<table>
<thead>
<tr>
<th>Step</th>
<th>Duration/Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.) Preload (approx. 5 N)</td>
<td>10 minutes</td>
</tr>
<tr>
<td>2.) Ramp to 133.5 N</td>
<td>20 N/min</td>
</tr>
<tr>
<td>3.) Hold</td>
<td>10 minutes</td>
</tr>
<tr>
<td>4.) Ramp 44.5 N</td>
<td>20 N/min</td>
</tr>
<tr>
<td>5.) Hold</td>
<td>10 minutes</td>
</tr>
<tr>
<td>6.) Repeat 4.) - 5.) to failure</td>
<td></td>
</tr>
</tbody>
</table>

This load hold profile was used in order to make measurements at various stress levels or stress ratios.
Experimental

Test apparatus showing the Instron tensile tester, miliohmmeter, and data acquisition system.
Results and Discussion

• Nine specimens were analyzed
  • 2: Ramp to failure
  • 1: 133.9 N failure
  • 3: 222.9 N failures
  • 3: 266.9 N failures

• Stress and strain data
• Resistance data
133.5 N Load Failure
The average was 1.02 Ω with a standard deviation of 0.12 Ω.
222.9 N Load Failures

The average was 1.39 Ω with a standard deviation of 0.10 Ω.
The average was 1.07 Ω with a standard deviation of 0.08 Ω.
The average was 1.50 Ω with a standard deviation of 0.24 Ω.
266.9 N Load Failures

The average was 0.93 $\Omega$ with a standard deviation of 0.10 $\Omega$. 

Ultimate failure location
266.9 N Load Failures

The average was 0.95 Ω with a standard deviation of 0.12 Ω.
Observations

• Generally, the location of failure corresponds to the location of highest resistance.
• Three trends were noticed
  • Progressive increase in resistance to failure
    • High localized resistance
  • Sudden increase to failure
    • High localized resistance
  • Consistent lower resistance throughout gauge
Change in Resistance

Exponential rise in the change in the average resistance measurement as the specimen approaches failure.
This data is interesting because there was a significant elongation in the strand without an apparent change in localized resistance.

The reported strain to failure in the technical data sheet for IM7 provided by Hexcel was 1.9%. This deviation of 0.9% is a significant deviation from the reported value.
Theoretical Model

\[ R(n) = \rho \frac{l}{A_n} \]

\[ F(n) = \sigma_c A_n \]

\[ F(n) = \sigma_c \frac{\rho l}{R(n)} \]

Combination yields the relation between the load at which fracture occurs and the corresponding resistance.

Validation of fiber diameter.
222.9 N Load Failures
266.9 N Load Failures
Conclusions and Future Work

• Demonstrated electrical resistance measurement can be used to evaluate damage in carbon fiber strand
• Demonstrated this is a highly localized effect
• Demonstrated agreement between experimental and theoretical values of surviving filaments and failure prediction
Conclusions and Future Work

• Testing on epoxy impregnated strands

• True creep testing

• Determining how to make measurement on a COPV
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• Non-Destructive Testing (NDT) and Non-Destructive Evaluation (NDE)
• Problem: Neither NDT nor NDE can provide sufficient data to determine life expectancy or quantify the damage state of a composite material.

Electrical Conductivity; Carbon Fiber; Non-Destructive Evaluation; NDE; Composite Overwrapped Pressure Vessel; COPV

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