Lightning Damage Prediction of Carbon Fiber Composite Materials

Zhang Song
Hefei Hangtai Electrophysics Co., Ltd.
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Introduction

Illustration of bi-directional leader development (Triggered attachment)
Lightning protection

Lightning strike to aircraft represents a possible safety hazard

Goal: Prevent accidents and increase the reliability of aircraft.

The protection of aircraft is based on standards and certification steps:

- **Zoning**: consists in highlighting the most probable locations of attachment and sweeping zones on the aircraft.
- **Structures tested in the laboratory, under controlled lightning conditions**
Introduction

Box - Simplified aircraft zoning

Zone 1 - High probability of initial lightning flash attachment (entry or exit).

Zone 2 - High probability of a lightning flash being swept from a point of initial attachment.

Zone 3 - Any aircraft surface other than those covered by zones 1 and 2. In zone 3 there is a low probability of a direct attachment, however, zone 3 areas may carry substantial lightning currents by direct conduction between two attachment points.

Zones 1 and 2 are further subdivided into A and B regions, depending on the probability that the flash will hang on for a protracted period of time. An A region is one in which there is a low probability that the arc will remain attached (e.g., at the leading edge of a wing) and a B region is one in which there is high probability that the arc will remain attached (e.g., at the trailing edge of a wing).
Introduction

- **Lightning direct effect test:**
  - **Lightning injection test** *(SAE ARP 5416)*
    - Zone 1A \((A+B+C^*)\)
    - Zone 1B \((A+B+C +D)\)
    - Zone 1C \((A_h+B+C^*)\)
    - Zone 2A \((D+B+C^*)\)
    - Zone 2B \((D+B+C)\)
  - **Lightning conduction test** *(SAE ARP 5416)*
    - Zone 3 \((A+B+C +D)\)
Lightning direct effect on CFRP

Schematic drawing of the swept stroke

$V_{inf}$

New position of the arc

Initial position of the arc

Attachment point

$E_c$
Lightning direct effect on CFRP

Formation of shock waves 23μs after ignition with the test set-up advised in the SAE ARP 5416
Lightning direct effect on CFRP

Illustration of the various direct constraints at the attachment point
Lightning damage prediction

Energy conservation
\[ \int_S (\int E_c J_c \, dt) \, dxdy + \int_V (\int \rho J_c^2 \, dt) \, dxdydz = \int_V H_0 \, dxdydz \]

Simplification
\[ \int E_c J_c \, dt + \int \rho J_c^2 \, dt Z_{\text{max}} = H_0 Z_{\text{max}} \]

Max. damage depth
\[ Z_{\text{max}} = \frac{\int E_c J_c \, dt}{H_0 - \int \rho J_c^2 \, dt} \]

Expansion
\[ Z_{\text{max}} = \frac{E_c \times \sum_{i=0}^{n} a_n \left( \int l \, dt \right)^n}{H_0 - \rho \times \sum_{i=0}^{n} b_n \left( \int l^2 \, dt \right)^n} \quad (n = 1, 2, \ldots) \]

- \( Z_{\text{max}} = f(J_c) \)
- Parameters \( a_n \) and \( b_n \) are to counteract the influence of the composite model, the single layer thickness, the laying mode, the surface protection layer and the paint layer
Lightning damage prediction

\[ Z_{\text{max}} = \frac{E_c \times \sum_{i=0}^{n} a_i (\int I dt)^n}{H_0 - \rho \times \sum_{i=0}^{n} b_i (\int I^2 dt)^n} \quad (n = 1, 2, \ldots) \]

\[ n = 2 \]

\[ Z_{\text{max}} = \frac{E_c \times (a_1 \times \int I dt + a_0)}{H_0 - \rho \times (b_1 \times \int I^2 dt + b_0)} \]

**Error function**

\[ S = \sum_{test=1}^{n} (Z_{\text{max}}^{\text{test}} - Z_{\text{max}})^2 \]

Genetic Algorithm is to adjust the parameters in the model to minimized the error

\[ Z_{\text{max}}^{\text{test}} \] is the maximum damage depth in the test to the number of trails
Lightning Test

Test pieces

- Composites wing box section
- Size: 2000mm*1100mm*300mm
- Aluminum mesh are used on surface, mesh wire in diameter of 0.1mm, covering by the paint layer of 0.2mm
- Lightning current injection point: X1~X5

T700/2510 Parameters

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_C$ (V)</th>
<th>$H_0$ $(\text{J/m}^3)$</th>
<th>$\rho$ $(\Omega \cdot \text{m})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T700/2510</td>
<td>22.5</td>
<td>$7.81 \times 10^8$</td>
<td>23.5</td>
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</tbody>
</table>
## Lightning Test

### Lightning current waveform

<table>
<thead>
<tr>
<th>Injection point</th>
<th>Peak Current (kA)</th>
<th>Coulomb (C)</th>
<th>Action Integral (A²s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>204.9</td>
<td>9.6</td>
<td>1.75 × 10⁶</td>
</tr>
<tr>
<td>2</td>
<td>196.27</td>
<td>219.56</td>
<td>1.65 × 10⁶</td>
</tr>
<tr>
<td>3</td>
<td>100.57</td>
<td>31.97</td>
<td>0.28 × 10⁶</td>
</tr>
<tr>
<td>4</td>
<td>104.89</td>
<td>219.93</td>
<td>0.31 × 10⁶</td>
</tr>
<tr>
<td>5</td>
<td>139.83</td>
<td>34.89</td>
<td>0.66 × 10⁶</td>
</tr>
</tbody>
</table>
Lightning Test

Test pieces

Insulation platform
Lightning Test

Ultrasonic test results

<table>
<thead>
<tr>
<th>No. Injection points</th>
<th>Max. damage depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>1/7</td>
</tr>
<tr>
<td>X2</td>
<td>1</td>
</tr>
<tr>
<td>X3</td>
<td>1/7</td>
</tr>
<tr>
<td>X4</td>
<td>1</td>
</tr>
<tr>
<td>X5</td>
<td>1/8</td>
</tr>
</tbody>
</table>

✓ 1 for complete breakdown
✓ 0 means no significant damage to the test piece

![Graph showing error vs number of iterations]

<table>
<thead>
<tr>
<th>a₀</th>
<th>a₁</th>
<th>b₀</th>
<th>b₁</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.2147 × 10⁵</td>
<td>3.5988 × 10⁶</td>
<td>12.1967</td>
</tr>
</tbody>
</table>
Conclusion

A proportional increase!
Thanks!!