Structural Response of CFRP Materials Subjected to Simulated Lightning Strikes

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Why study this?

• Lightning can strike wind turbines up to 30 times per year
• 5 times greater energy than aircraft standard (10 MJ/Ω)
• **Costing operator millions of pounds a year**

- Burning/charring
- Blade Failure
- Tip Detachment
CFRP Materials in Wind Turbine Blades

- CFRPs (relative to GFRP) enables longer wind turbine blades with limited knock-on effect on blade mass

- Heterogeneous material with anisotropic properties
  - Thermal conductivity and electrical conductivity
  - Particular issue with lightning strike

![Graph showing electrical and thermal conductivity of different materials](Image credit: researchgate.net/Brauer et al.)

- Electrical Conductivity
- Thermal Conductivity

![Diagram of wind turbine blade construction](Image credit: University of Southampton)
Lightning in Wind Turbine Blades

- CFRP materials (semi-conductors) provide a different path for lightning to take to ground.
- There are two typical scenarios where lightning enters CFRP perpendicular to the surface, also known as, arc-entry.
  - Scenario 1, direct strike to CFRP
- Arc-entry is the most severe lightning damage mechanism on CFRP as the conductivity severely restricts the flow of current causing heat.
Lightning in Wind Turbine Blades

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- There are two typical scenarios where lightning enters CFRP perpendicular to the surface, also known as, arc-entry.
  - Scenario 1, direct strike to CFRP
  - Scenario 2, internal flashover

- Arc-entry is the most severe lightning damage mechanism on CFRP as the conductivity severely restricts the flow of current causing heat.
Aims and Objectives

• Predict structural response of CFRP after a lightning strike:
  ◦ Developing experimental procedure
  ◦ Development of modelling framework
  ◦ Compare/Validate

Simulated Lightning Strike Experiment → Sub-Structural Buckling Test in Compression After Lightning Strike Rig (CALS) → Structural Model
Simulated Lightning Strike Experiments

- 14 x CFRP unidirectional (UD) eight ply laminate
  - 800 gsm fabric
  - Epoxy Resin Matrix
- 550 mm long x 500 mm wide x 7 mm thick
- 10/350µs waveform
- Peak Current shown:
  - 50kA
  - 125kA
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Damage Assessment of Lightning

- Damaged samples:
  - Assessed via visual inspection and CT scans.
  - Waterjet cut to remove the chamfered edge and centre the damage.
Compression After Lightning Strike (CALS)

- Lightning damage worst effects are seen in compression
- Rig large enough to evaluate structural scale effects
- Instron Schenck test rig 630kN load capacity
- Loaded in compression 0.5mm/min
- Stereo DIC was performed on both sides of the plate
## Compression After Lightning Strike (CALS)

- Compression After Lightning Strike
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### DIC Test Setup

<table>
<thead>
<tr>
<th>Technique Used</th>
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<tbody>
<tr>
<td>Camera</td>
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<tr>
<td>Sensor</td>
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<tr>
<td>Lens</td>
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<tr>
<td>Lightning</td>
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<td>Imaging distance</td>
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<td>Field of View</td>
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<td>Pixel resolution</td>
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</table>

- 2 x Stereo 3D Image Correlation (2 cameras measuring top surface and 2 cameras measuring bottom surface)
- 4 x MANTA G504B (gigabit Ethernet) 12 bit, 2452 x 2056 pixels
- 2 x AF NIKKOR 28mm F/8D
- 2x AF NIKKOR 50mm F/8D
- 4 x NILA ZAILA LED Lights
  - ~2 m from bottom surface
  - ~4 m from top surface
- 400 mm x 400 mm x 100 mm
  - ~1 px = 0.27 mm

### Correlation Setup

<table>
<thead>
<tr>
<th>DIC Software</th>
<th>MatchID 2018.2.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation Procedure</td>
<td>Zero Normalized Sum of Differences Squared</td>
</tr>
<tr>
<td>Subset Size</td>
<td>33 px</td>
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<tr>
<td>Step Size</td>
<td>16 px</td>
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<tr>
<td>Sub-pixel interpolation</td>
<td>Bicubic Spline</td>
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<tr>
<td>Shape Function</td>
<td>Quadratic</td>
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<tr>
<td>Stereo Transformation</td>
<td>Quadratic</td>
</tr>
<tr>
<td>Strain Calculation</td>
<td>Logarithmic Euler-Almansi strain tensor</td>
</tr>
<tr>
<td>Displacement Noise Floor ((u, v, w))</td>
<td>(0.026227, 0.0089122, 0.13067) mm</td>
</tr>
<tr>
<td>Strain Noise Floor ((\varepsilon_{xx}, \varepsilon_{yy}, \gamma_{xy}))</td>
<td>(150, 95, 120) (\mu m/m)</td>
</tr>
</tbody>
</table>
Numerical Modelling

- Shell post-buckling finite element model with large deformations
- Abaqus 6.14 Riks Method with S4R shell elements
- The area of the damage was assessed using the visual inspection and CT
- Damaged areas taken into account by reducing stiffness to essentially zero
Out of Plane Displacements

- The most severely damaged specimen (lightning strike of 125kA) for all load levels showed:
  - highest displacement levels
  - a change in the displacement field moving away from the damaged region.

[Diagram showing out of plane displacements at 60 kN, 50 kA, and 125 kA load levels with labeled damaged and centreline regions.]
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Conclusions

- Designed and manufactured novel CALS rig to include structural scale effects on CFRP materials damaged by lighting

- DIC enables capture of the redistribution away from the damaged region

- Damage induced is representative of lightning and able to quantify the buckling and post-buckling response

- The validation of the FEM creates opportunity to study other damage scenarios.
THANK YOU FOR YOUR ATTENTION

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References


