Blade Materials
Fatigue Testing and Modelling

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Content

- Intro
- Fatigue of blade materials
- Recent results, e.g.:
  - Micromechanical modelling
  - Thick laminates
  - Effect of temperature and frequency
  - Subcomponent development
- Outlook
Wind turbine Materials & Constructions

- Full-scale structural testing
- Material research
- Software Development
Blade Test 1984
Fatigue in wind turbine rotor blades

Load Variability

Number of load cycles
Rotor Blade Composites
Test Machines for Material Research and Component Testing

- 20 servo-hydraulic test frames for fibres, coupons, and subcomponents (static, fatigue, creep)
- Maximum capacity between 1 N to 3.5 MN
- Climate chamber
- Glass transition temp measurement, viscosity
3000/2500kN Test Machine for Material Research and Component Testing

- 30MN test frame currently under design
In-house plate/specimen production

- Variations on test matrix can be implemented quickly
- Full control/documentation of product
- Fibre content determination
Material characterization

- Given ‘S’ (e.g. cyclic load)
- Find ‘N’ (life)
- Relationship in S-N curve

\[ R = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \]

- \( R = -1 \)
- \( R = 0.1 \)
S-N diagram (logarithmic plot)

Reference tension fatigue ($\log N = -10.4 \log(S / 1247.7)$)

- $|\sigma|_{\text{max}}$ [MPa]
- Cycles
Fatigue behaviour of reference

Fatigue behaviour of reference

$S_{\text{amp}}$

$R = -1$

$R = 10$

$R = 0.1$

$R = 0.9$

$R = 1.1$

$S_{\text{mean}}$

$-800 -600 -400 -200 0 200 400 600 800 1000$

$-800 -600 -400 -200 0 200 400 600 800 1000$
Constant life diagram

N = 10^3
Fatigue calculation

\[ D = \sum_{i=1}^{k} \frac{n_i}{N_i} = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \ldots \leq 1 \]

Miner’s sum

Rainflow counting
Micromechanical Analysis

Multi-scale approach

1. Composite constituent properties
2. Unit cell fatigue simulations
3. Meso model fatigue simulations
4. UD coupon fatigue simulations

1st geometrical up-scaling
2nd geometrical up-scaling
3rd geometrical up-scaling
Micromechanical Analysis
Fatigue of UD Glass/epoxy
Thick laminates

How representative are tests on small coupons (thickness is 1-8 mm) for large wind turbine composites (thickness is 6-150mm)?
Thick laminates

- Thermal simulation based on mechanical loss factor
- Matches thermocouple readings from experiment
## Temperature & Frequency

<table>
<thead>
<tr>
<th>Laminate type</th>
<th>Loading type</th>
<th>Condition</th>
<th>Target N</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>UD</td>
<td>Static</td>
<td>Room Temperature, -40°C, +60°C</td>
<td>1</td>
<td>1 mm/min</td>
</tr>
<tr>
<td></td>
<td>R=0.1</td>
<td>Room Temperature, -40°C, +60°C</td>
<td>10,000</td>
<td>2, 8, 24</td>
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<tr>
<td></td>
<td></td>
<td>Room Temperature, -40°C, +60°C</td>
<td>1,000,000</td>
<td>6, 8, 24</td>
</tr>
<tr>
<td></td>
<td>R=-1</td>
<td>Room Temperature, -40°C, +60°C</td>
<td>10,000</td>
<td>1, 24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Room Temperature, -40°C, +60°C</td>
<td>1,000,000</td>
<td>3, 24</td>
</tr>
<tr>
<td>Biax ±45°</td>
<td>R=0.1</td>
<td>Room Temperature, -40°C, +60°C</td>
<td>$10^3 - 10^6$</td>
<td>1, 3</td>
</tr>
</tbody>
</table>
±45º - Effect of temperature (R = 0.1)

\[
|F_{\text{max}}| \quad [\text{kN}]
\]

<table>
<thead>
<tr>
<th>Cycles to failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^{2})</td>
</tr>
<tr>
<td>(10^{3})</td>
</tr>
<tr>
<td>(10^{4})</td>
</tr>
<tr>
<td>(10^{5})</td>
</tr>
<tr>
<td>(10^{6})</td>
</tr>
<tr>
<td>(10^{7})</td>
</tr>
<tr>
<td>(10^{8})</td>
</tr>
</tbody>
</table>

- \(T=60^\circ\text{C}, \ m = -16.2\)
- \(T=23^\circ\text{C}, \ m = -14.0\)
- \(T=-40^\circ\text{C}, \ m = -14.3\)
Subcomponents

- Sandwich and foam
- Flanges, web, bondlines
- Blade root
- Repairs
- Spar end detail
Subcomponents – Experimental

- CRES
- Fraunhofer – IWES
- STFC-RAL
- VUB
- WMC
Failure envelope of adhesive
Glass/carbon

- Glass vs carbon reinforcement
  - stiffness
  - cost, infusability
- Characterisation of glass and carbon vs hybrids
- Blade modelling
Glass-carbon hybrids (R=0.1)
Glass-carbon hybrids (R=-1)

The graph shows the relationship between maximum stress ($\sigma_{max}$) in MPa and cycles to failure on a log-log scale. The data points are color-coded and labeled as follows:

- Glass, $m = -10.9$
- Hybrid, $m = -37.3$
- Carbon, $m = -16.3$

The lines represent the trend for each material type based on the given stress levels and cycles to failure.
Glass-carbon hybrids (R=10)

$|\sigma|_{\text{max}}$ [MPa] vs. Cycles to failure

- Glass, $m = -20.1$
- Hybrid, $m = -81.8$
- Carbon, $m = -13.8$
Blade modelling – effect of material
Concluding remarks / Outlook

- Major issues in fatigue characterisation/prediction
  - are being tackled
  - in increasing detail/material variety
  - requiring new methods and models

- Thick laminates
  - Manufacturing and heating

- Micromechanics

- Subcomponents

- Carbon/glass hybrids
  - promising
Thanks! Questions/comments?

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