Materials for Wind Turbine Blades

Yehia Bahei-El-Din

Centre for Advanced Materials
The British University in Egypt
7 MW - 83.5 m blade Off-shore wind turbine SSP, Denmark (2013)
Outline

• Design requirements
• Anatomy of a WTB
• Fabrication
• Materials
Design requirements

- > 20 years of power production
- To endure a variety of service loads & situations

- Normal power production including startup & shutdown
- Emergency shutdown
Material Science and Renewable Energy: Wind Energy
The British University in Egypt, El-Shorouk City
March 25, 2015
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March 25, 2015
International Standard Design, IEC 61400-1

• Design lifetime of at least 20 years.

• To verify integrity of load-carrying components & ascertain acceptable safety level.

• To verify ultimate and fatigue strength of structural members by calculations and/or tests.
International Standard Design, IEC 61400-1

Loads

Gravity and Inertia
- Static & dynamic loads due to gravity, vibration, rotation and seismic activity

Aerodynamic
- Static & dynamic loads due to airflow and its interaction with stationary and moving parts of wind turbines

Actuation
- Operation & control of wind turbines

Other
- Wake, impact, ice loads, etc.
International Standard Design, IEC 61400-1

Life time design situations:

- Normal design $\equiv N$
- Abnormal (fault) $\equiv A$
- Transportation, installation & maintenance $\equiv T$
Analysis methodology:

- Ultimate load $\equiv U$
- Fatigue load $\equiv F$
**International Standard Design, IEC 61400-1**

Loads partial factors of safety:

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Design Situation</th>
<th>Normal (N)</th>
<th>Abnormal (A)</th>
<th>Transport and erection (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>Normal (N)</td>
<td>1.35</td>
<td>1.1</td>
<td>1.5</td>
</tr>
<tr>
<td>F</td>
<td>Abnormal (A)</td>
<td></td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transport and erection (T)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
International Standard Design, IEC 61400-1

Design load cases: 22 combining

- 8 design situations:
  - Startup
  - Power production (normal & with fault)
  - Shutdown (normal & emergency)
  - Parked (normal & with fault)
  - Transport, assembly, maintenance & repair
International Standard Design, IEC 61400-1

Design load cases: 22 combining

➢ 7 wind conditions:
  o Extreme coherent gust
  o Extreme operating gust
  o Extreme wind speed model
  o Extreme wind shear
  o Normal turbulence model
  o Extreme turbulence model
  o Normal wind profile model
International Standard Design, IEC 61400-1

Partial safety factors:

- Account for uncertainties and variability in loads, (1.0-1.3)
- Account for uncertainties and variability in materials,
  \[ \geq 1.1 \text{ for } U \text{ analysis} \]
  \[ \geq 1.7 \text{ for } F \text{ analysis} \]
- Account for uncertainties in analysis methods.
International Standard Design, IEC 61400-1

- **Stability**
  No buckling in any component.

- **Deflection**
  To preserve structural integrity.
  No mechanical interference between blade and tower.
Design

Aerodynamic Design

Material Characterization

Finite Element Method Simulation

Blade Material Architecture

Composite Lay-Up

Manufacturing

Plug

Mould
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• Design requirements
• Anatomy of a WTB
• Fabrication
• Materials
Fabrication of Wind Turbine Blades

EU-Egypt project (RDI-1)
Fabrication of Wind Turbine Blades

EU-Egypt project (RDI-1)
Material Layup

EU-Egypt project (RDI-1)
Resin Vacuum Infusion
Assembly

EU-Egypt project (RDI-1)
Assembly

EU-Egypt project (RDI-1)
Demoulding

EU-Egypt project (RDI-1)
Outline

• Design requirements
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Master Model Materials

- Polyurethane slabs
- Beech wood
- Surface finish material
**Mould Materials**

- Gelcoat
- Sphere core
- Resin for Gelcoat backing
- Resin for tooling
- Chopped strand mat
- Woven Roving
Blade Materials

- Gelcoat
- High strength fiber
- Polymer
- Sandwich core
- Structural adhesive
Load Carrying Materials & Construction

- Composite Materials
- Sandwich Construction
Composite Materials

- Particulate
- Fibrous
Composite Materials

$\text{Al}_2\text{O}_3 \text{(FP)/Al, } c_f = 0.35$

$\text{B/Al, } c_f = 0.45$

0.2 mm

0.14 mm
## Composite Materials: Comparison of Tensile Strength

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (t/m³)</th>
<th>Tensile Strength (t/cm²)</th>
<th>Specific Strength (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>7.8</td>
<td>40</td>
<td>51</td>
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<tr>
<td>Aluminum</td>
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<td>6</td>
<td>23</td>
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<tr>
<td>Titanium</td>
<td>4.6</td>
<td>20</td>
<td>43</td>
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<tr>
<td>E-glass</td>
<td>2.5</td>
<td>34</td>
<td>136</td>
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<tr>
<td>S-glass</td>
<td>2.4</td>
<td>48</td>
<td>200</td>
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<tr>
<td>Graphite</td>
<td>1.4</td>
<td>17</td>
<td>120</td>
</tr>
<tr>
<td>Boron</td>
<td>2.5</td>
<td>34</td>
<td>136</td>
</tr>
</tbody>
</table>
#### Composite Materials: Comparison of Elastic Stiffness

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<thead>
<tr>
<th>Material</th>
<th>Density (t/m³)</th>
<th>Elastic Stiffness (t/cm²)</th>
<th>Specific Stiffness (Mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
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<td>E-glass</td>
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<td>2.9</td>
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<tr>
<td>S-glass</td>
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<td>860</td>
<td>3.6</td>
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<tr>
<td>Graphite</td>
<td>1.4</td>
<td>2500</td>
<td>18.0</td>
</tr>
<tr>
<td>Boron</td>
<td>2.5</td>
<td>4000</td>
<td>16.0</td>
</tr>
</tbody>
</table>
Fibrous Composites: Overall elastic stiffness

Material design DoF
- Fiber material
- Matrix material
- Volume fractions
Fibrous Composites: Nonlinear Behavior

- Matrix plastic deformation
- Matrix creep
- Matrix damage
- Fiber/matrix debonding
Fibrous Composites: Off Axis Loading

Jones (1975)
Fibrous Composites: Off Axis Loading

Tsai (1968)
Fibrous Composite Laminates

Material design DoF
1. Fiber material
2. Matrix material
3. Volume fractions
4. Fiber orientation
5. Number of plies
Fibrous Composites

- Non-woven
- Woven
Woven Composites: 2D plane weave

S2-glass/polyester

Single woven ply  Woven laminate
Woven Composites: 3D weave

S2-glass/vinyl-ester

Material design DoF
1. Fiber material
2. Matrix material
3. Volume fractions
4. Fiber orientation
5. Number of plies
6. Woven architecture
Composite Materials: Damage & Failure
Progressive Damage in 90° ply of a (0/90)$_s$ Laminate Subjected to Uniaxial Tension

PZT-5A/DY063
(0/90)$_s$, $c_f = 0.55$

Bahei-El-Din & Micheal (2013)
Progressive Damage in 90° ply of a (0/90)_s Laminate Subjected to Uniaxial Tension

PZT-5A/DY063
(0/90)_s, c_f = 0.55

90 MPa
100 MPa

Bahei-El-Din & Micheal (2013)
Progressive Damage in $90^\circ$ ply of a $(0/90)_s$ Laminate Subjected to Uniaxial Tension

PZT-5A/DY063
$(0/90)_s$, $c_f = 0.55$

110 MPa

120 MPa

Bahei-El-Din & Micheal (2013)
Progressive Damage in 90° ply of a (0/90)_s Laminate Subjected to Uniaxial Tension

PZT-5A/DY063
(0/90)_s, c_f = 0.55

Bahei-El-Din & Micheal (2013)
Sandwich Construction

![Diagram of sandwich construction showing layers: Skin 1, Core, Skin 2.](Diagram.png)
Sandwich Construction: Closed cell foam
Sandwich Construction

Tagarielli, Fleck, Deshpande (2004)
Sandwich Construction
Sandwich Construction

Polyurethane (PUR) | Foam Core |
<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
<td>E-glass/Epoxy laminate</td>
<td>E-glass/Epoxy laminate</td>
</tr>
</tbody>
</table>
➤ Sandwich Construction: Polyurethane

![Graph showing True Stress vs. True Strain for different strain rates]

- 1 s⁻¹
- 1400 s⁻¹
- 3700 s⁻¹
- 5000 s⁻¹
- 8800 s⁻¹
Sandwich Construction: Quasi-static Indentation

Quasistatic Indentation Test
Vacuum Infusion

- Simply Supported Test
- Clamped Test

Specific Energy (x 10^{-3} J/mm^3)

(0/±45)/(-45/90/45)/(20mm Foam)/(45/90/-45)
(0/±45)/(-45/90/45)/(1mm PUR)/(20mm Foam)/(45/90/-45)/(±45/0)
(0/±45)/(-45/90/45)/(2mm PUR)/(20mm Foam)/(45/90/-45)/(±45/0)
Sandwich Construction: Low Velocity Impact

Dynamic Indentation Test

- Hand Layup
- Vacuum Infusion

Depth of Indentation (mm)

- (0/±45)/(-45/90/45)/(20mm Foam)/(45/90/-45)/(±45/0)
- (0/±45)/(-45/90/45)/(1mm PUR)/(20mm Foam)/(45/90/-45)/(±45/0)
- (0/±45)/(-45/90/45)/(2mm PUR)/(20mm Foam)/(45/90/-45)/(±45/0)
Fabrication of 25 m Rotor Blades for 850 kW Wind Turbine

STDF Project 1493

Center for Advanced Materials, BUE
Misr for Environmental Technology, MCV
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Blade & Facilities cost %

- Plug: 39%
- Mould: 33%
- Blade: 27%
- Others: 1%

Blade & Facilities cost (LE)

- Plug: 600,000
- Mould: 500,000
- Blade: 400,000
- Others: 100,000

STDF Project 1493