Wind Turbine Blade Materials

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What are the requirements?

- Blades
- Towers
- Nacelles

### Weight

<table>
<thead>
<tr>
<th></th>
<th>1 MW</th>
<th>1.5MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine weight</td>
<td>26 Tons</td>
<td>30 Tons</td>
</tr>
<tr>
<td>Generator case</td>
<td>39.7 Tons</td>
<td>50 Tons</td>
</tr>
<tr>
<td>Tower weight</td>
<td>78.6 Tons</td>
<td>93.6 Tons</td>
</tr>
<tr>
<td>Total weight</td>
<td>144.3 Tons</td>
<td>173.6 Tons</td>
</tr>
</tbody>
</table>

### Diameter of rotor

- 1 MW: 60m
- 1.5MW: 70m
**What are the requirements?**

- **TOWERS**
  - The towers are required to be strong enough to support the weight of the blades and generator/nacelles.
  - They must also withstand fluctuating wind loading and loading resulting from turbine blade rotation.
  - This means that the towers must be stiff and strong. They do not need to be particularly light if positioned on-shore, although all foundations will be cheaper if the overall turbine weight is low.
  - Transport to location is an issue and it will help if the tower can be made from sections and assembled to ease transport issues. Again weight will be an issue but it is secondary to other considerations.
  - If a turbine is placed off-shore, then the weight becomes of greater importance in terms of the costs of foundations and the cranes necessary to install the turbine.
  - Corrosion is an issue particularly off-shore.
Towers = Steel

- Cheap, stiff and strong. They are getting difficult to weld at the larger thicknesses.
- Corrosion is also an issue
Alternative to Steel

Composite lattice (small turbines)

Figure 6. 15 MW (wind design) all-concrete wind turbine tower - 100-m hub height
Future Idea?

• Hybrid steel – concrete
• Glass fibre composite monoliths
• Glass fibre composite/concrete duplex

Current Supergen Position – maintain a watching brief
Wait for developments in the Market.
Weight is important, materials aren’t. Common structures are made from glass fibre composite. Easy to mould, light, corrosion resistant. No Supergen activity in this area.
Blades are required to preserve an optimum cross section for aerodynamic efficiency to generate the maximum torque to drive the generators.
The blades will be subject to a wide range of loads, including flapping, tension and compression, twisting – all induced by the central movement and the variable winds loadings.
The blades must be stiff enough to avoid hitting the towers when deflected by the wind loads.
Structural design of a blade is optimised by adopting a shell structure with a long stiff central spar. The spar caps provide stiffness and strength in bending and extension, while the spar webs provide shear stiffness.
Blade Design

Typical Blade Profile

Cross Section of Blade

- Balsa cores
- Skins
- Shear webs
- Spar Caps

Twist (shear)

Extension

Flap
The exact shape of the internal structure will determine the stiffness and strength of the blade under each loading mode for any given materials. In general terms however we need a material that is as light as possible for a given stiffness in order to satisfy the blade design criteria and to minimise the weight induced fatigue loads.

Reducing the weight of the blades also will directly reduce the loads on the tower and foundations.
Blade Design

What materials give us low weight with maximum stiffness and strength?
Why are composites so strong, stiff and light?

- Composites are materials that combine high strength and high stiffness fibres with a polymeric resin matrix.
- Fibres are extremely stiff and strong and can have a very low density.
Fibre orientation

- The properties of a composite depend on the way that the fibres are orientated in the laminate.

- Typically composites are produced from sheet or laminar materials consisting either of fabrics or unidirectional layers of fibres. These can now used as dry fabrics and are impregnated with resin during manufacture, or they can be pre-impregnated prior to lay-up.

- To produce a composite with the maximum stiffness and strength the fibres should be laid up parallel to the loading axis.

- Woven fabrics essentially deliver fibres in an orthogonal arranged which can be aligned at 45 degrees to provide shear stiffness.

- Fabrics and also be produced using a multiaxial warp knitting process that can combine unidirectional fibres and bias ( +/- ) 45 fibres.
Blades: Materials of choice

- Needs – lightweight and high stiffness, hence composites
  - Wood/laminates
  - Glass fibre laminates
  - Carbon fibre laminates

Trends towards heavy (> 1000 gsm) non-crimp fabrics
Usually E-glass
Fibre Architecture

Spar caps – typically 70% UD, 30 % +/- 45

Skins and shear webs, +/- 45
Fatigue

- Wind turbines are really big fatigue testing machines – testing the blades!
- Fatigue life is a key design requirement
- Fibre composites are good in fatigue

Aluminium alloy
Fatigue in composites

Fig. 2. E-glass FRP and CFRP composites with (± 45) continuous fiber reinforcement.
Toughness problems with fibre composites

- For polymer matrix composites, crack growth perpendicular to the fibres is usually not a problem.
Complex cracking mechanisms

- **Fig. 10** Failure mechanisms (schematic) in a [90°] composite under tensile loading: (a) weak bonding; (b) intermediate bonding; and (c) strong bonding — (i) matrix failure, (ii) fibre splitting.
Real blades structures are complex

- Failure in fatigue may occur in the basic materials or (more likely) at features/connections

Fig. 9. $S-N$ curves with joint length 20 mm and 0$^\circ$ edge angle.

Kim et al 2004
Design principles of wind turbine blades

Schematics of the cross-section of two common design principles of wind turbine blades: (a) a design that uses load-carrying laminates in the aeroshell and webs for preventing buckling and (b) a design that uses a load-carrying box.
Design principles of wind turbine blades

Type 1: Skin/adhesive debonding
Type 2: Adhesive joint failure
Type 7: Cracks in gelcoat (channel cracks)
Type 4: Delamination (+/-45°)
Type 5: Splitting along fibres

MATERIALS AND STRUCTURES FOR WIND TURBINE ROTOR BLADES - AN OVERVIEW

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Design principles of wind turbine blades

Sketch of observed failure modes in a wind turbine blade purposely tested to failure (from [3]).
Crack growth parallel to the fibres IS a problem

The fibres provide little reinforcement and crack growth resistance is largely determined by the matrix
Key area for development is interlaminar toughness

Possible routes:

1) Selective interfacial reinforcement
   - Veils
   - Nano-additives

2) Use of 3D fibre formats
Laminate toughening material: Veils

- What is veil?
  Veil is a thin layer of material made of randomly oriented fibres
Insertion of lightweight veils

Veils can be less than 10g/m² and can be produced from carbon fibre, thermoplastic fibres or combinations of the two.

The concept is equivalent to that of interleaving (the use of tough adhesive layers positioned at the interface in prepreg layers).
Comparisons of GIC for Mode-I samples with different veil types (MBT, CC and MCC represent different calculation methods)
Damage area in impact (CFRP)

- Non-Interleaved
- PE/C
- Hyb2
- PE
- PA

Impact energy/Thickness [J/mm]

Damage area [mm$^2$]

0 1 2 3 4 5

0 100 200 300 400 500 600 700 800 900
Damage area in impact (CFRP)

CAI results are now equivalent to those of a tough epoxy system
Use in repair!

Insert veil at bond-line between parent material and repair patch. Work of adhesion increased dramatically.
Improves fatigue life of joints

Toughness Improvements

Fatigue Resistance

Fracture surfaces
Design a representative coupon and test configuration based on a stiffened panel to simulate the shear web connection

- New reinforcements (fibres)
- Advanced composite processing
- Inter layer veil
- Nano modified resin systems
- Rubber modified resin systems
T-joint tests
Veils in T-sections?

This is currently being tested.

However there are other textile based solutions to eliminating weak interlaminar regions – notably 3D weaving/braiding, and stitching.
Laminate toughening material: Veils

Veil vs. Non-Veil

- Without veil
- 1 layer Carbon veil
- 1 layer Polyester veil
- 1 layer Polyamide veil

Veil position
Laminate toughening material: (nano)-particles

Conventional epoxy resin system samples
Process: Vacuum Infusion

Conventional epoxy resin system samples with veil
- Carbon veil
- Polyester veil
- Polyamide veil

Process: Vacuum Infusion

Modified epoxy resin system samples
- Modified with Rubber particles (μm size)
- Modified with Nano-Silica (nm size) and Rubber particles

Process: Vacuum Infusion
T-joint testing results: Pull-off Strength of toughened laminates

![Graph showing load vs. deflection for different types of laminates with and without veil or modified resins.](image-url)
Finite Element Modelling of blade and T-joint section

- Stress distribution in FE model shows the toughened T-joint samples would prefer to failed with laminate fracture at intersection area rather than propagate the delamination cracks.
The potential for modification and control of veils is considerable (TFP)
• Why 3D Textiles?
Current UD prepreg technology is excellent for thin flat structures. But......

• It is slow to lay up, difficult to work with complex 3D shapes, and struggles to allow load transfer in connections and across right angle shapes.
Making 3D shapes
Fibres are introduced in the “Z” direction in and out of the flat fabric. This holds layers together and improves the resistance to damage of a laminate. A conventional lay-up of flat pre-preg has no reinforcement in the “Z” direction and will delaminate easily.
Blade manufacture

• Processes:
  • Hand-lay up
  • RTM/Infusion
  • Prepreg
Blade manufacture

Infusion, vacuum-assisted resin transfer molding (VARTM) and hand layup of prepreg in open molds are today the dominant processes.
Infusion

Skins moulded in female moulds

Photo courtesy of VienTek.
LM Glasfiber:
- vacuum assisted resin transfer moulding VARTM

Robot-controlled glass application carts
Reduce time for lay down by 25%

Special resin infusion machines reduce infusion time by 15%

2 shells bonded together
Siemans: Integral blade
Prepreg

Hand applied (often in-house prepreg)

Automated gantry delivery

Composite Systems, Inc
Weight versus process/materials

LM38.8
38.8m, 8700kg, Class 1, glass UP infusion
GE 1.5
37.5m, 6200kg, Class 1, glass epoxy infusion
Vestas V80
39m, 6500kg, Class 1, glass epoxy pp
Dewind D8.2
39m, 5600kg, Class 1 glass epoxy infusion + carbon pp
Repower 5M
61.5m, 18T, Class 2, glass/carbon epoxy infusion
Vestas V90
44m, 7000kg, glass/carbon epoxy pp
Gamesa G87
42.5m, 6200kg, Class 3, glass/carbon epoxy pp

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Key challenges

- Reduce manufacturing defects
  - wrinkles,
  - delaminations,
  - dry-spots
  - under cure
  - misalignment
  - Sandwich core-skin debonds

- Increase rate of materials deposition
  - tape layers
  - Preforming
  - TARGETS 2000 kg/hour of prepreg – current aerospace maximum is £40 kg/hour (aerospace target is 200 kg/hr)

- decrease cure cycle times
  - Use of pre-cured elements?
  - Single shot manufacture
  - Quickstep

*Figure 7.* Sections through wrinkle defects of differing depths in a sandwich face laminate. The face laminate thickness is ~5.4 mm in each of the cases shown.
Why is process route important?

- Heated RTM tool
- Vacuum pump
- Resin Trap
- Resin pot
- Pressure pot
- Vacuum pump
- Resin Trap
- Vacuum Infusion (VI)
- HPM
- Fabric preform
- Peel ply
- Vacuum membrane/bag
- Resin pot
## Comparisons between RTM & Vacuum Infusion

<table>
<thead>
<tr>
<th>Panel</th>
<th>Process</th>
<th>Reinforcement</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>RTM</td>
<td>Constructex™ Uniweave</td>
</tr>
<tr>
<td>A2</td>
<td>RTM</td>
<td>Cotech® Biaxial NCF</td>
</tr>
<tr>
<td>B1</td>
<td>VI</td>
<td>Constructex™ Uniweave</td>
</tr>
<tr>
<td>B2</td>
<td>VI</td>
<td>Cotech® Biaxial NCF</td>
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</table>

<table>
<thead>
<tr>
<th>Panel</th>
<th>Thickness (mm)</th>
<th>Fibre volume fraction, $V_f$ (%)</th>
<th>Results normalised to 60% fibre volume fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tensile strength (MPa)</td>
</tr>
<tr>
<td>A1</td>
<td>3.29</td>
<td>60</td>
<td>931.8 ± 7.3</td>
</tr>
<tr>
<td>A2</td>
<td>3.27</td>
<td>59</td>
<td>795.2 ± 24.6</td>
</tr>
<tr>
<td>B1</td>
<td>3.49</td>
<td>56</td>
<td>820.2 ± 37.4</td>
</tr>
<tr>
<td>B2</td>
<td>3.32</td>
<td>58</td>
<td>794.5 ± 21.3</td>
</tr>
</tbody>
</table>

Same material – different process
T-joint testing results

Panel C1
Process: RTM
Reinforcement: Cotech® Biaxial NCF

Panel C2
Process: VI
Reinforcement: Cotech® Biaxial NCF

Panel C3
Process: VI
Reinforcement: Constructex™ Uniweave
T-joint testing results: Pull-off Strength

- Load at failure
- Deflection at failure

### Load /kN
- Panel C1
- Panel C2
- Panel C3

### Deflection /mm

- Load at failure
- Deflection at failure
SUPERGEN 2

• Priority Areas:
  • Assess fatigue properties of realistic structural elements manufactured using candidate processing routes.
  • Infusion
    – Fabrics, 3D textiles, braiding
  • Prepreg
    – quickstep
  • Pultrusion (?)
Future work

Upper mould

Inner mould: inflatable bag: AeroVac or Mouldlife

Lower mould

Bagging material, flow media and peel ply

Inner mould

Fabrics

Scale: 1:5
laminate thickness: ≈4mm
number of layers: 8-10

DU 93-W-210 21%

Original upper line

Original lower line

or/and
Future work

Spars – various textile concepts
T sections, Box sections.

Key issues – integration of textile processes (braiding, weaving, winding, stitching)
Certification: test, reliability, scenarios for textiles

Incorporation of materials solutions/concepts for Radar Cross Section and Lightning Strike Protection.
Scenario 2) Tow winding process and textile intensive blade section

Replace fuselage former with thin TP blade shell with spars in place.

Mandrel moves through contra-rotating fibre/tow preg dispensing heads.

Infusion as second stage or consolidation.
Cure using microwave/thermal fluids.
Final Comments

• Scale and economics will influence choice of materials, process routes.
• Recycling, sustainability issues will become more important
• Manufacturing rate will dominate choices.