New Technology in Blade Design

Carsten Westergaard: Moderator
Copenhagen Class™
Taking world class blade design into new unexplored territories.

AWEA 2011
Presented by Søren Horn Petersen, Sales Director, SSP Technology A/S, Denmark
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All illustrations are courtesy of Risø DTU
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Exploring....
Copenhagen Class™ has been developed as a new design class for blades supplementing the current design and certification criteria given by the certifying bodies because:

• The rated power of the turbines steadily increases and the design of blades are getting rapidly more challenging and is breaking into new territories (loading, weight, length) literally every day.

• Although the business is maturing, we are still experiencing systematic failures on smaller blades. Carrying the technology used for those unchallenged into very long blades represents huge risk for turbines suppliers and wind park owners.

• Entering into no-man land as regards to blade length, weight, tip-speed and loadings using current software, knowledge and design principles drives the risk, cost and safety margins up.

• Risk for failure is increasing and traditional way of designing blades does not necessarily counter this. The cost of failure can be disastrous, both for the design project, the design company and the ultimate customer.

• The wise blade designer accepts the fact, that in reality, we have no real operating experience with very long blades, and although we keep pushing the size, we do not know, whether we are doing the right thing.
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Systematic Risk Management
The Copenhagen Class™ design concept is based on a systematic risk analysis for all risk related to blade design, key risk being identified as:

- Blade solution design phases are often separated and do not interact. Hence, the blades are not optimised and risk is not handled based on a holistic design overview, and interactions between different disciplines within blade design (aerodynamic, structural, aeroelastic, interaction with turbine, materials, production processes, QA management, tooling and production design) are not always fully considered.

- The existing recommendations for blade design and the corresponding test requirements are developed at a time when blade dimensions were approximately half of the size of the present design. Failure modes previously either covered by safety margins, taking in account based on experience or not considered relevant, now can be design and risk drivers.

- The present design standards do not, therefore, full fill the needs for design of larger wind turbine blades of today. Blind trust in these can lead to increases in failures.
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The Concept
The Copenhagen Class™ design concept has 4 key components

• Explorative and holistic design process including all aspects of design under one management and one delivery and performed in open dialogue with turbine designers and blade manufacturers.

• Systematic and research based failure mode analysis and risk management performed by Risø DTU, Denmark and SSP Technology in conjunction. For each design project a specific risk analysis will be performed and a specific set of design principles will be given by Risø DTU to handle the identified risk.

• Peer review done by Risø DTU of the design prior to finalising to evaluate the successful implementation of the specific design principles in the blade design.

• Extended number to of full scale test to verify design criteria specified by Risø DTU
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The Research
The Copenhagen Class™ failure mode analysis has been performed by Risø DTU, a leading research and educational Danish institution within blade design and within other key disciplines with wind turbines, and is based on extensive research performed over the last decade.

• The extensive wind turbine blade testing program carried out by Risø DTU has lead to numerous conclusions regarding structural design of blades, the correlation with other design disciplines and the relevance of several failure mechanisms and loading configuration, that most often is not considered in blade designs.

• The blade testing program at Risø DTU is predominantly performed on a SSP 3-component blade loaded in edgewise, flapwise and combined directions. Further, at large number of sub-components test has been performed as either experimental work or to calibrate the very complex and unique FE software developed by Risø DTU.

• All testing and research performed by Risø DTU are publicised either via their web page www.risoe.dk/research/sustainable_energy/wind_energy.aspx, papers or reports.
Risø DTU Failure mode analysis
The failure mode analysis has focused on 3 weak points in the design process:

- Failure Modes
  Not all failure modes are taken into account during “certifiable” design process

- Design tools
  - Geometric non-linear study as opposed to analytical or linear analysis methods
  - More advanced boundaries and FE modeling
  - Calibration of “sensitive” elements to test data
  - “Intelligent” (and relevant) Post processing

- Sensitivity study:
  - Analysis the sensitivity of design features to production tolerances e.g. the transverse shear distortion
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**Failure modes for a blade for a 120m rotor, class 3 onshore**
Risø DTU and SSP has performed a specific risk analysis for a blade for 120m rotor as per the next slide.

The slide show all key additional risk areas, identified by Risø DTU and the failures modes in bold are those specifically relevant for the given blade design.

The relevant failure modes will be handled by specific design principles given by Risø DTU as a supplement to the certification requirements given by the certifying body.

The ranking indicates the suitability for the various testing methods. 1 is worst, 5 is best.
<table>
<thead>
<tr>
<th>Failure modes</th>
<th>FEM + analytical tools</th>
<th>Full-scale test</th>
<th>Discovered at blade test</th>
<th>Discovered on the field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buckling</td>
<td>4</td>
<td>5</td>
<td>a) Redesign</td>
<td>a) Redesign</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>b) Time delays</td>
<td>b) Retrofit</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>c) Failure</td>
</tr>
<tr>
<td>Tower Clearance</td>
<td>5</td>
<td>5</td>
<td>a) Redesign</td>
<td>a) Redesign</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>b) Failure</td>
</tr>
<tr>
<td>Longitudinal Strain failure in spar caps</td>
<td>4</td>
<td>5</td>
<td>a) Redesign</td>
<td>a) Redesign</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>b) Failure</td>
</tr>
<tr>
<td>Fatigue Failure (Longitudinal strain)</td>
<td>4</td>
<td>5</td>
<td>a) Redesign</td>
<td>a) Redesign</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>b) Failure</td>
</tr>
<tr>
<td>Mode 1: TE Adhesive joints</td>
<td>3</td>
<td>4</td>
<td>a) Repair</td>
<td>a) Repair</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>b) Redesign</td>
<td>b) Redesign</td>
</tr>
<tr>
<td>Mode 2: Transverse shear distortion</td>
<td>4</td>
<td>4</td>
<td>a) Failure</td>
<td>a) Failure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>b) Redesign</td>
<td>b) Redesign</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>c) Retrofit</td>
</tr>
<tr>
<td>Mode 3: Interlaminar/Transverse strain failure in spar cap</td>
<td>4</td>
<td>5</td>
<td>a) Failure</td>
<td>a) Failure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>b) Redesign</td>
<td>b) Redesign</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>c) Retrofit</td>
</tr>
<tr>
<td>Mode 4: Flutter (Divergence)</td>
<td>3</td>
<td>4</td>
<td>a) Not testable</td>
<td>a) Failure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>b) Complete redesign</td>
</tr>
</tbody>
</table>
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Failure mode: Adhesive joints

Current design criteria/methods fail to:
- Analyse in detail out of plane bending behaviour resulting in peel on bonded joints
- Over simplistically analyses bond failure by shear allowables
- Two solutions exist for a more holistic analysis:
  - Fracture mechanics
  - Empirical test data

Problems with adhesive joints are expected to be even more dominant in the future wind turbine blades, which larger size will result in increased edgewise loads, which are critical for the adhesive bound in the trailing edge.
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Failure mode: Adhesive joints – Copenhagen Class evaluation

- Analysis process
  - Criteria to be finalised in preliminary design phase
  - Non-linear FE to define detailed stresses in bonds
  - Results to be correlated against extensive test database of Risø
Failure mode: Transverse Shear Distortion

- Current design criteria/methods fail to:
  - Analyse the extent of transverse shear distortion
  - Phenomenon is non-linear and as such NL FE is critical
  - Case is highly sensitive to production deviations (as-drawn vs as-built).

- Tests by Risø DTU to date indicate that:
  - 34m blades are not critical for this failure mode
  - Problem will become more critical for larger blades

- Full scale testing is an important input to correlate models (diagonal displacement sensors measure shear distortion)
  - Alternative clamp configurations to be evaluated due to clamps influence
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**Failure mode: Transverse Shear Distortion – Copenhagen Class eval.**

- Analysis process
  - Criteria defined in the preliminary design phase.
  - Distortion to be extracted from Non-linear FE analysis
  - Sensitivity study to be executed with respect to influence of production tolerances
  - Results compared to criteria
  - Models correlated against test data and results re-evaluated

![Displacement sensors measuring transverse shear distortion](image)
Failure mode: Interlaminar failure/Transverse strain failure in spar cap

The Brazier effect is a nonlinear effect resulting from the longitudinal curvature when bending a beam or a slender structure. Because of the curvature the longitudinal compressive and tensile stresses result in ovalization of cross section.

Flattening of the curved cap results in high stresses in the transverse direction. The high stresses cause both interlaminar and tension in the UD-laminates (transverse to the fiber direction).
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**Failure mode: Interlaminar failure/Transverse strain failure in spar cap**

- Analysis process
  - Criteria defined in the preliminary design phase.
  - Table of spar width to thickness produced by Risø DTU using Non-linear FE in preliminary design phase for use by the blade designer (defined strain level)
  - Evaluation of detailed design solution by Risø DTU using non-linear FE
  - Evaluation against criteria and full scale test correlation
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**Failure mode: Flutter**

- Flutter is a aeroelastic instability that may result in large amplitude vibrations of a blade, and possible in its failure. Flutter vibrations consists of a coupling of flapwise and torsional blade vibrations, which are sustained by the airflow around the blade.

- FEA-Flutter study for large flexible blades together with other codes e.g. Hawk (not Flex5 since it do not take the rotational degree into account)

- Risø DTU will perform a flutter check using the HAWCStab2 calculations will be made to establish the critical tip speed for which flutter occurs, called the flutter limit. The flutter limit is very dependent on several parameters of which two associated with some uncertainties. These are mass centre position and torsional stiffness. There will be made a sensitivity study of these two parameters to establish the flutter limit in regards to the parameters in question. The result will be presented in a small report and will be based upon mass and stiffness properties provided by SSP.
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**Copenhagen Class™ - bankable advantages**

A more competitive blade design due to detailed optimization and understanding/management of risk.

Systematic risk management and substantiated risk handling based on open source experiences and top notch and unique research improves market acceptance for introduction of new technologies in larger blades.

Less failures and higher quality blades

A significant differentiator
Carbon in Wind Blades - To Be or Not To Be

Kyle Wetzel
CEO/CTO
Wetzel Engineering, Inc.
Lawrence, Kansas U.S.A.

Ric Baldini
Director, Global Wind Energy Applications
Zoltek Companies, Inc.
St. Louis, Missouri U.S.A.

AWEA 2011
25 May 2011
Outline

- Brief background on Wetzel Engineering & Zoltek
- How and where are carbon and glass fibers used in blades
- Who is using Carbon in Blades and Why?
- Case Studies – Carbon –vs– Glass
Wetzel Engineering

- In Business Since 2001
- Technical Staff of 25
- Engineering Services for the Wind Energy and Aviation Industries
- Structural Analysis (ANSYS, NASTRAN)
- Structural Testing (Coupon & Blade) with 3rd Party Labs
- Dynamics, Loads, & Performance Analyses (ADAMS, FAST)
- Aerodynamics
  - Airfoil Design using XFOIL and Eppler's Code
  - Computational Fluid Dynamics (CFD)
  - Wind Tunnel Model Construction & Testing
- Wind Turbine Design
  - Rotor Aerodynamic and Structural Design
  - Composites Manufacturing Engineering
  - Conceptual Development
  - Drivetrain Design and Analysis
  - Wind Turbine Performance Analysis
Brief History of Zoltek

Zoltek Companies, Inc.

- 1975: Founded
- 1988: Entered Carbon fiber business via acquisition (Stackpole Carbon)
- 1992: IPO, ZOLT on Nasdaq
- 1992 – 1998: R&D Stage (developing carbon fiber technology)
- 1998: Launched Low Cost Carbon Fiber Concept

Locations
- Headquarters: St. Louis, MO
- Production Sites:
  - Nyergesújfalu, Hungary
  - Abilene, Texas (USA)
  - Guadalajara, Mexico
- Sales Offices globally

Manufacturing Carbon Fiber and “Intermediate” products
- 50K carbon fiber for composite applications
- Oxidized PAN fiber for aircraft brake systems
- Intermediate Products for Wind Energy Prepreg, Fabrics

Entec
- Design and Manufacture Composite Processing Solutions
How and Where is Carbon Used in Blades
Forms of Carbon

- Wind industry uses heavy-tow carbon
  - Example: Zoltek Panex 35
  - 50,000 filaments
  - 7.2 micron diameter
  - Strength = 4150 Mpa
  - Modulus = 242 Gpa
  - Density = 1.81 g/cc
  - Yield = 270 m/kg

- Most commonly used as “UD prepreg” – preimpregnated unidirectional tapes
  - 500-600g/m² dry
  - 725-875g/m² impregnated
  - $24/kg dry or prepreg

- Dry carbon fibers as UD tapes or multiaxial nonwoven fabrics can also be infused.
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# Typical Composites Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>E-Glass</th>
<th>Carbon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>VARTM</td>
<td>Prepreg</td>
</tr>
<tr>
<td>Fiber Volume Fraction</td>
<td>~54%</td>
<td>~59%</td>
</tr>
<tr>
<td>Composite density, ( \rho ), g/cc</td>
<td>1.9</td>
<td>1.55</td>
</tr>
<tr>
<td>Tensile Modulus, ( E_{11} ) (GPa)</td>
<td>~42</td>
<td>130</td>
</tr>
<tr>
<td>Tensile Strength, UTS (MPa)*</td>
<td>~1000/800</td>
<td>~2050/1750</td>
</tr>
<tr>
<td>Tensile Strain, ( \varepsilon_{\text{max}} )</td>
<td>1.9%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Compressive Strength, UCS (MPa)*</td>
<td>~750/650</td>
<td>~1300/1150</td>
</tr>
<tr>
<td>Compressive Strain, ( \varepsilon_{\text{min}} )</td>
<td>1.5%</td>
<td>~0.9%</td>
</tr>
<tr>
<td>Specific Modulus, ( E/\rho )</td>
<td>20</td>
<td>81</td>
</tr>
<tr>
<td>SN Curve Inverse Slope, ( m )</td>
<td>9</td>
<td>20</td>
</tr>
</tbody>
</table>

*First number is mean, second number is 95/5 confidence*
Glass-vs- Carbon

- Carbon prepreg is 3X as stiff as infused E-glass
- Carbon prepreg stiffness-to-weight ratio is 4X that of infused E-glass
- Carbon prepreg is 2X as strong as infused E-glass in compression
- Static strain limits of glass are ~50% higher than that of carbon
- Transverse tensile and in-plane shear properties of glass and carbon are similar
Designers cannot usually take full advantage of the static strain limits of glass because fatigue and deflection considerations become the dominant design drivers.

Carbon structures which are statically sound will generally exhibit minimal fatigue damage during a 20 year life.
Where is Carbon Used?

Carbon UD would be used in the main spar caps and occasionally in the trailing edge girder.
Where is Carbon Used?

Carbon UD would be used in the main spar caps and occasionally in the trailing edge girder.

Carbon UD could be used in the shells for aeroelastic tailoring.
Who is Using Carbon in Wind Blades and Why?
# Who is using Carbon in Wind Blades?

<table>
<thead>
<tr>
<th>Company</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vestas</td>
<td>100% of blades use carbon spars</td>
</tr>
<tr>
<td>GE</td>
<td>Currently converting blades to carbon</td>
</tr>
<tr>
<td>Gamesa</td>
<td>100% of blades use carbon spars</td>
</tr>
<tr>
<td>Enercon</td>
<td>E82 Blade using carbon fiber 100%</td>
</tr>
<tr>
<td>Areva</td>
<td>56m blade for 5MW turbine uses carbon fiber</td>
</tr>
<tr>
<td>DeWind</td>
<td>Using carbon fiber</td>
</tr>
<tr>
<td>Sinoma</td>
<td>56m blade for 3MW turbine</td>
</tr>
</tbody>
</table>
TRADE-OFFS IN BLADE DESIGN

- POWER PERFORMANCE
- TURBINE LOADS
- BLADE COST
- BLADE WEIGHT
- BLADE DEFLECTION
- TURBINE DYNAMICS & CONTROL
- EASE OF MANUFACTURING
- HANDLING & TRANSPORTATION
## TRADE-OFFS IN BLADE DESIGN

<table>
<thead>
<tr>
<th></th>
<th>Chord Lengths</th>
<th>Airfoil Thickness</th>
<th>Out-of-Plane Prebend</th>
<th>Girder Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Performance</td>
<td>Longer</td>
<td>Thinner</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loads</td>
<td>Shorter</td>
<td></td>
<td></td>
<td>Carbon</td>
</tr>
<tr>
<td>Blade Cost</td>
<td>Shorter</td>
<td>Thicker</td>
<td>Large</td>
<td>Depends</td>
</tr>
<tr>
<td>Blade Weight</td>
<td>Shorter</td>
<td>Thicker</td>
<td>Large</td>
<td>Carbon</td>
</tr>
<tr>
<td>Deflection</td>
<td></td>
<td>Thicker</td>
<td></td>
<td>Carbon</td>
</tr>
<tr>
<td>System Dynamics</td>
<td></td>
<td></td>
<td>Small</td>
<td>Carbon</td>
</tr>
<tr>
<td>Manufacturing</td>
<td></td>
<td></td>
<td>Small</td>
<td>Carbon</td>
</tr>
<tr>
<td>Handling</td>
<td>Shorter</td>
<td></td>
<td>Small</td>
<td>Carbon</td>
</tr>
</tbody>
</table>
BENEFITS OF CARBON

- Maintain smaller deflections with thinner airfoil sections
  - Higher $C_{p_{max}}$ without adding too much mass
  - Fewer dynamic issues
  - Less prebend and smaller overhang

- Lighter weight
  - Lower Loads - lighter pitch bearings, pitch drives, hub, and shaft
  - Easier handling
  - Lower System Cost - Examine System Benefits to Evaluate Carbon

- Higher reliability
  - Prepreg manufacturing quality is higher
  - Carbon fatigue is not a concern
BENEFITS OF CARBON

- Easier manufacturing
  - Less material to handle
  - No liquid resin
  - Fewer consumable materials

- Allows blade length to be expanded without increasing gravity loads on the bearings, root fasteners, and hub
  - Allows greater energy capture from the same platform

- Enables advanced aeroelastic torsion-bending coupling
Case Studies
Case Study Overview

- Identify Key Design Points
- Identify Key Design Parameters
- Loads Assessment
- Blade Structural Design
- Assess System Impacts
- Assess manufacturing implications
- System Cost-Benefit
Case Study Overview

● Identify Key Design Points
  – 45m for a 2.0MW Turbine
  – 50m for a 2.5MW Turbine
  – 57m for a 3MW Turbine
  – 74m for a 7MW Turbine
  – 90m for a 10MW Turbine

● Identify Key Design Parameters

● Loads

● Assess System Impacts

● Assess manufacturing implications

● System Cost-Benefit
Case Study Overview

● Identify Key Design Points

● Identify Key Design Parameters
  – Operating Conditions (Wind Class) –
    ● IEC Class III-A for the 3MW machines
    ● IEC Class I-C for the 7-10MW machines
  – Constraints on the Prebend and Deflection
    ● High prebend, soft blades – patent issues
    ● Low prebend, stiffer designs
  – Performance Requirements
    ● Cpmax or energy production requirements

● Loads

● Assess System Impacts

● Assess manufacturing implications

● System Cost-Benefit
Case Study Overview

- Identify Key Design Points
- Identify Key Design Parameters
- Loads
- Blade Structural Design
  - Assess cost and weight of the structure
- Assess System Impacts
  - Weight impact on blade and system loads
  - Loads impact on component cost – pitch bearing, hub, shaft, etc.
- Assess manufacturing implications
- System Cost-Benefit
57m Blade
## Material Usage of Carbon vs Glass <50m Blade

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length (m)</strong></td>
<td>45.3</td>
<td>45.3</td>
<td>50.5</td>
<td>50.5</td>
<td>50.5</td>
<td>50.5</td>
</tr>
<tr>
<td><strong>Rotor Diameter (m)</strong></td>
<td>92.8</td>
<td>93</td>
<td>103.4</td>
<td>103.4</td>
<td>103.4</td>
<td>103.4</td>
</tr>
<tr>
<td><strong>Rated Power (MW)</strong></td>
<td>2.0</td>
<td>2.0</td>
<td>2.5</td>
<td>2.5</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>Shell Material</strong></td>
<td>E-Glass Infused with Epoxy</td>
<td>E-Glass Infused with Epoxy</td>
<td>E-Glass Infused with Epoxy</td>
<td>E-Glass Infused with Epoxy</td>
<td>E-Glass Infused with Epoxy</td>
<td>E-Glass Infused with Epoxy</td>
</tr>
<tr>
<td><strong>Spar Cap (Girder) Material</strong></td>
<td>Infused Glass</td>
<td>Carbon Prepreg</td>
<td>Infused Glass</td>
<td>Carbon Prepreg</td>
<td>Infused Glass</td>
<td>Carbon Prepreg</td>
</tr>
<tr>
<td><strong>Girder Design</strong></td>
<td>Box-beam (2 Web)</td>
<td>I-beam (1 Web)</td>
<td>Box-beam (2 Web)</td>
<td>I-beam (1 Web)</td>
<td>Box-beam (2 Web)</td>
<td>I-beam (1 Web)</td>
</tr>
</tbody>
</table>

### Materials Mass (kg)

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spar Cap Carbon Prepreg</strong></td>
<td>0</td>
<td>900</td>
<td>0</td>
<td>1,150</td>
<td>0</td>
<td>1,235</td>
</tr>
<tr>
<td><strong>Spar Cap Dry Glass + Infused Resin</strong></td>
<td>2,817</td>
<td>0</td>
<td>3,487</td>
<td>0</td>
<td>4,571</td>
<td>0</td>
</tr>
<tr>
<td><strong>All other glass + resin</strong></td>
<td>5,859</td>
<td>5,405</td>
<td>6,216</td>
<td>5,847</td>
<td>6,490</td>
<td>6,121</td>
</tr>
<tr>
<td><strong>Balsa</strong></td>
<td>400</td>
<td>445</td>
<td>570</td>
<td>675</td>
<td>650</td>
<td>750</td>
</tr>
<tr>
<td><strong>PVC Foam</strong></td>
<td>150</td>
<td>150</td>
<td>197</td>
<td>115</td>
<td>197</td>
<td>115</td>
</tr>
<tr>
<td><strong>Adhesive</strong></td>
<td>230</td>
<td>230</td>
<td>247</td>
<td>247</td>
<td>247</td>
<td>247</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>9,456</td>
<td>7,130</td>
<td>10,716</td>
<td>8,034</td>
<td>12,155</td>
<td>8,468</td>
</tr>
</tbody>
</table>

### Costs per Blade

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Carbon Prepreg</strong></td>
<td>$25.00</td>
<td>$22,500</td>
<td>$28,750</td>
<td>$30,875</td>
<td>$20,184</td>
<td>$11,170</td>
<td></td>
</tr>
<tr>
<td><strong>Dry Glass</strong></td>
<td>$2.50</td>
<td>$15,833</td>
<td>$10,670</td>
<td>$20,184</td>
<td>$11,170</td>
<td>$11,170</td>
<td></td>
</tr>
<tr>
<td><strong>Epoxy</strong></td>
<td>$7.00</td>
<td>$16,403</td>
<td>$11,054</td>
<td>$20,910</td>
<td>$11,572</td>
<td>$11,572</td>
<td></td>
</tr>
<tr>
<td><strong>Balsa</strong></td>
<td>$15.00</td>
<td>$6,000</td>
<td>$8,550</td>
<td>$9,750</td>
<td>$11,250</td>
<td>$11,250</td>
<td></td>
</tr>
<tr>
<td><strong>PVC Foam</strong></td>
<td>$12.00</td>
<td>$1,800</td>
<td>$1,380</td>
<td>$2,364</td>
<td>$1,380</td>
<td>$1,380</td>
<td></td>
</tr>
<tr>
<td><strong>Adhesive</strong></td>
<td>$13.50</td>
<td>$3,105</td>
<td>$3,335</td>
<td>$3,335</td>
<td>$3,335</td>
<td>$3,335</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$43,141</td>
<td>$54,160</td>
<td>$50,296</td>
<td>$65,313</td>
<td>$56,543</td>
<td>$69,581</td>
<td></td>
</tr>
</tbody>
</table>

Copyright © 2011 Wetzel Engineering & Zoltek
# Material Usage of Carbon vs Glass 57m Blade

<table>
<thead>
<tr>
<th>Blade</th>
<th>WEI57-3000G</th>
<th>WEI57-3000G2 Low Deflection</th>
<th>WEI57-3000C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>57</td>
<td>57</td>
<td>57</td>
</tr>
<tr>
<td>Rotor Diameter (m)</td>
<td>116</td>
<td>116</td>
<td>116</td>
</tr>
<tr>
<td>Rated Power (MW)</td>
<td>~3</td>
<td>~3</td>
<td>~3</td>
</tr>
<tr>
<td>Shell Material</td>
<td>E-Glass Infused with Epoxy</td>
<td>E-Glass Infused with Epoxy</td>
<td>E-Glass Infused with Epoxy</td>
</tr>
<tr>
<td>Spar Cap (Girder) Material</td>
<td>Infused Glass</td>
<td>Infused Glass</td>
<td>Carbon Prepreg</td>
</tr>
<tr>
<td>Girder Design</td>
<td>Box-beam (2 Web)</td>
<td>Box-beam (2 Web)</td>
<td>I-beam (1 Web)</td>
</tr>
</tbody>
</table>

## Materials Mass (kg)

<table>
<thead>
<tr>
<th>Materials Mass (kg)</th>
<th>WEI57-3000G</th>
<th>WEI57-3000G2 Low Deflection</th>
<th>WEI57-3000C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spar Cap Carbon Prepreg</td>
<td>0</td>
<td>0</td>
<td>1,298</td>
</tr>
<tr>
<td>Spar Cap Dry Glass + Infused Resin</td>
<td>4,725</td>
<td>7,201</td>
<td>0</td>
</tr>
<tr>
<td>All other glass + resin</td>
<td>8,213</td>
<td>7,904</td>
<td>7,716</td>
</tr>
<tr>
<td>Balsa</td>
<td>875</td>
<td>750</td>
<td>926</td>
</tr>
<tr>
<td>PVC Foam</td>
<td>235</td>
<td>235</td>
<td>235</td>
</tr>
<tr>
<td>Adhesive</td>
<td>286</td>
<td>286</td>
<td>286</td>
</tr>
<tr>
<td>Total</td>
<td>14,334</td>
<td>16,376</td>
<td>10,461</td>
</tr>
</tbody>
</table>

## Costs per Blade

### Key Material Cost ($)

<table>
<thead>
<tr>
<th>Key Material Cost ($)</th>
<th>WEI57-3000G</th>
<th>WEI57-3000G2 Low Deflection</th>
<th>WEI57-3000C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Prepreg</td>
<td>$ 23.50 /kg</td>
<td>$ -</td>
<td>$ -</td>
</tr>
<tr>
<td>Dry Glass</td>
<td>$ 3.00 /kg</td>
<td>$ 28,332</td>
<td>$ 33,077</td>
</tr>
<tr>
<td>Epoxy</td>
<td>$ 7.00 /kg</td>
<td>$ 24,460</td>
<td>$ 28,556</td>
</tr>
<tr>
<td>Balsa</td>
<td>$ 15.00 /kg</td>
<td>$ 13,125</td>
<td>$ 11,250</td>
</tr>
<tr>
<td>PVC Foam</td>
<td>$ 12.00 /kg</td>
<td>$ 2,820</td>
<td>$ 2,820</td>
</tr>
<tr>
<td>Adhesive</td>
<td>$ 13.50 /kg</td>
<td>$ 3,861</td>
<td>$ 3,861</td>
</tr>
<tr>
<td>Total</td>
<td>$ 72,599</td>
<td>$ 79,564</td>
<td>$ 82,557</td>
</tr>
</tbody>
</table>
Material Usage of Carbon vs Glass 90m Blade

This is Material Cost only

Carbon Blades have less mass and cost about the same as glass blades

Glass: 53 mt
Carbon 1: 36 mt
Carbon 2: 24 mt

<table>
<thead>
<tr>
<th>Blade</th>
<th>WEI90-10K-G1</th>
<th>WEI90-10K-C</th>
<th>WEI90-10K-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Rotor Diameter (m)</td>
<td>185</td>
<td>185</td>
<td>185</td>
</tr>
<tr>
<td>Rated Power (MW)</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Shell Material</td>
<td>E-Glass</td>
<td>E-Glass</td>
<td>Carbon + E-Glass</td>
</tr>
<tr>
<td></td>
<td>Infused with Epoxy</td>
<td>Infused with Epoxy</td>
<td>Infused with Epoxy</td>
</tr>
<tr>
<td>Spar Cap (Girder) Material</td>
<td>Infused Glass</td>
<td>Carbon Prepreg</td>
<td>Carbon Prepreg</td>
</tr>
<tr>
<td>Girder Design</td>
<td>Box-beam (2 Web)</td>
<td>I-beam (1 Web)</td>
<td>I-beam (1 Web)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Materials Mass (kg)</th>
<th>Spar Cap Carbon Prepreg</th>
<th>0</th>
<th>4,500</th>
<th>3,850</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spar Cap Dry Glass + Infused Resin</td>
<td>21,150</td>
<td>26,747</td>
<td>12,750</td>
</tr>
<tr>
<td></td>
<td>Shell Dry Carbon + resin</td>
<td>2,600</td>
<td>2,700</td>
<td>1,950</td>
</tr>
<tr>
<td></td>
<td>All other glass + resin</td>
<td>27,399</td>
<td>26,747</td>
<td>12,750</td>
</tr>
<tr>
<td></td>
<td>Balsa</td>
<td>815</td>
<td>815</td>
<td>750</td>
</tr>
<tr>
<td></td>
<td>PVC Foam</td>
<td>991</td>
<td>991</td>
<td>991</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>52,955</td>
<td>35,753</td>
<td>23,991</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Costs per Blade</th>
<th>Key Material Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Prepreg</td>
<td>$ 23.50 /kg</td>
</tr>
<tr>
<td>Dry Carbon</td>
<td>$ 23.50 /kg</td>
</tr>
<tr>
<td>Dry Glass</td>
<td>$ 3.00 /kg</td>
</tr>
<tr>
<td>Epoxy</td>
<td>$ 7.00 /kg</td>
</tr>
<tr>
<td>Balsa</td>
<td>$ 15.00 /kg</td>
</tr>
<tr>
<td>PVC Foam</td>
<td>$ 12.00 /kg</td>
</tr>
<tr>
<td>Adhesive</td>
<td>$ 13.50 /kg</td>
</tr>
<tr>
<td>Total</td>
<td>$ 260,254</td>
</tr>
</tbody>
</table>
# 74m Conventional Glass Design

<table>
<thead>
<tr>
<th>Material</th>
<th>Brief Description</th>
<th>Form</th>
<th>Location of Use</th>
<th>Areal Weight [g/m²]</th>
<th>Construction</th>
<th>Quantity Required [kg]</th>
<th>Cost [€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GUD1200 Glass UD</td>
<td>Dry Glass UD</td>
<td>Spar Caps</td>
<td>1200</td>
<td>1200gsm 0° E-glass</td>
<td>9925</td>
<td>22,331</td>
<td></td>
</tr>
<tr>
<td>Glass UD</td>
<td>UD E-Glass Tape</td>
<td>Dry Stitch-Bond Fabric</td>
<td>TE girder, hat stiffeners</td>
<td>1200</td>
<td>1200gsm 0° E-glass</td>
<td>1222</td>
<td>2,750</td>
</tr>
<tr>
<td>G3AX Triaxial E-Glass</td>
<td>Dry Stitch-Bond Fabric</td>
<td>Shells</td>
<td>1200</td>
<td>600gsm 0° E-Glass</td>
<td>4340</td>
<td>9,765</td>
<td></td>
</tr>
<tr>
<td>G4AX Quadraxial E-Glass</td>
<td>Dry Stitch-Bond Fabric</td>
<td>Shells</td>
<td>2000</td>
<td>1200gsm 0° E-Glass, 600gsm ±45° E-Glass</td>
<td>8860</td>
<td>19,935</td>
<td></td>
</tr>
<tr>
<td>Double Bias Glass</td>
<td>Dry Stitch-Bond Fabric</td>
<td>Shear Web</td>
<td>1200</td>
<td>600gsm +45° E-glass, 600gsm -45° E-glass</td>
<td>1849</td>
<td>4,160</td>
<td></td>
</tr>
<tr>
<td>Foam</td>
<td>PET Foam, ~110kg/m3</td>
<td>Variable Thickness</td>
<td>Shell, Main Shear Web, Hat Stiffeners</td>
<td></td>
<td>2125</td>
<td>17,000</td>
<td></td>
</tr>
<tr>
<td>Copper Mesh</td>
<td>400gsm woven mesh, 0.25mm dia wire x 0.8mm center-to-center spacing</td>
<td>Shell</td>
<td>400</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epoxy Resin</td>
<td>Epoxy Resin</td>
<td></td>
<td></td>
<td></td>
<td>11498</td>
<td>57,492</td>
<td></td>
</tr>
<tr>
<td>Epoxy Paste Adhesive</td>
<td>Epoxy Paste Adhesive</td>
<td></td>
<td></td>
<td></td>
<td>600</td>
<td>5,400</td>
<td></td>
</tr>
<tr>
<td>Putty Filler</td>
<td>Putty Filler</td>
<td></td>
<td></td>
<td></td>
<td>120</td>
<td>1,080</td>
<td></td>
</tr>
<tr>
<td>Primer and Paint</td>
<td>Primer and Paint</td>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>1,800</td>
<td></td>
</tr>
<tr>
<td>Root Fasteners</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>620</td>
<td>7,440</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td></td>
<td>41360</td>
<td><strong>149,153</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
What is the 10t reduction in weight worth?

- Smaller Bearing and Fewer/Smaller Fasteners
- Reduced gravity-driven fatigue loads on hub, shaft, gearbox
# 74m with Carbon Skins

<table>
<thead>
<tr>
<th>Material</th>
<th>Brief Description</th>
<th>Form</th>
<th>Location of Use</th>
<th>Areal Weight</th>
<th>Construction</th>
<th>Quantity Required</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUD600-400</td>
<td>Carbon UD Prepreg</td>
<td>UD Prepreg (epoxy)</td>
<td>Spar Caps</td>
<td>865</td>
<td>865gsm 0° Carbon (50k) Prepreg (600gsm dry)</td>
<td>3982</td>
<td>€ 59,730</td>
</tr>
<tr>
<td>Glass UD</td>
<td>UD E-Glass Tape</td>
<td>Dry Stitch-Bond Fabric</td>
<td></td>
<td>1200</td>
<td>1200gsm 0° E-glass</td>
<td>200</td>
<td>€ 450</td>
</tr>
<tr>
<td>G/C3AX</td>
<td>Triaxial Carbon/E-Glass Hybrid</td>
<td>Dry Stitch-Bond Fabric</td>
<td>Shells</td>
<td>1100</td>
<td>500gsm 0° Carbon 600gsm ±45° E-Glass</td>
<td>2387</td>
<td>€ 19,205</td>
</tr>
<tr>
<td>G4AX</td>
<td>Quadraxial E-Glass</td>
<td>Dry Stitch-Bond Fabric</td>
<td>Shells</td>
<td>2000</td>
<td>1200gsm 0° E-Glass 600gsm ±45° E-Glass</td>
<td>8198</td>
<td>€ 18,445</td>
</tr>
<tr>
<td>Double Bias Glass</td>
<td>Double Bias Glass</td>
<td>Dry Stitch-Bond Fabric</td>
<td>Shear Web</td>
<td>1200</td>
<td>600gsm ±45° E-glass 200gsm 90° E-glass</td>
<td>1849</td>
<td>€ 4,160</td>
</tr>
<tr>
<td>Foam</td>
<td>PET Foam, ~110kg/m³</td>
<td>Variable Thickness</td>
<td>Shell, Main Shear Web, Hat Stiffeners</td>
<td>1377</td>
<td>€ 11,016</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper Mesh</td>
<td>400gsm woven mesh, 0.25mm dia wire x 0.8mm center-to-center spacing</td>
<td></td>
<td>Shell</td>
<td>400</td>
<td>120</td>
<td>€ 1,447</td>
<td></td>
</tr>
<tr>
<td>Epoxy Resin</td>
<td>Epoxy Resin</td>
<td></td>
<td></td>
<td></td>
<td>5688</td>
<td>€ 28,442</td>
<td></td>
</tr>
<tr>
<td>Epoxy Paste Adhesive</td>
<td>Epoxy Paste Adhesive</td>
<td></td>
<td></td>
<td></td>
<td>600</td>
<td>€ 5,400</td>
<td></td>
</tr>
<tr>
<td>Putty Filler</td>
<td>Putty Filler</td>
<td></td>
<td></td>
<td></td>
<td>120</td>
<td>€ 1,080</td>
<td></td>
</tr>
<tr>
<td>Primer and Paint</td>
<td>Primer and Paint</td>
<td></td>
<td></td>
<td></td>
<td>200</td>
<td>€ 1,800</td>
<td></td>
</tr>
<tr>
<td>Root Fasteners</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>480</td>
<td>€ 5,760</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>25201</strong></td>
<td><strong>€ 156,936</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Step 2 - Labor Components

- Tool Preparation
  - Shell tools and girder tools treated separately
- Lamination
  - Shell tools and girder tools treated separately
- Bagging
  - Shell tools and girder tools treated separately
- Infusion and/or Cure
- Unbagging and Clean-up
- Assembly
- Demolding
- Clean-up/T-bolts, etc.
- Paint
- Finish
Cost Model - Labor Cost Comparison

Notes:
- Carbon prepreg requires less labor for layup and for cure preparation and debagging/clean-up. ~4% net labor reduction
- Glass skin labor remains the same for both designs
Loads Impact

Blade Root Bending Moment -- $M$ [kNm

- $M_{xy}$ Static glass
- $M_{xy}$ Static Carbon
- $M_{x}$ fatigue glass
- $M_{x}$ fatigue carbon

Rotor Blade Length -- $L$ [m]
Hub Weight/Cost Scale with Blade Weight

From NREL WindPACT report:

- Hub Weight (kg) = 0.954 x (Blade Weight) + 5680
- Hub Cost = Hub Weight x $4.25/kg
Carbon Girders Reduce Rotor Weight

Notes:

- Carbon prepreg reduces overall blade weight by 25-35%
- Results in a reduction of hub weight
Rotor Cost

Rotor Cost Comparison

Cost Parity at ~54m
Additional Benefits

- Reduced gravity-induced fatigue will also benefit the root fasteners, pitch bearing, pitch drives, and main shaft
  - Reduced component size/weight/cost
  - Improved reliability and/or longevity
Conclusions

- Strategic use of carbon can effect substantial reductions in the weight of wind turbine rotor blades, on the order of 20-30% compared to all-glass blades.

- The cost of the blade structural material may increase with the addition of carbon except in the largest of blades.

- Carbon can reduce the system cost of a wind turbine when additional considerations such as hub weight, manufacturing labor commitment, etc., are considered.
Thank you!

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3101 McKelvey Road
St. Louis, Missouri 63044
U.S.A.
A presentation by Dr Chris Shennan
25 May 2011
Use of Prepregs to Improve Spar Caps in Infused Blades
Hexcel - Company Profile

- Leading global provider of advanced composites
- Technology leader with largest portfolio of qualifications
- Primary markets: commercial aerospace, space & defense, wind energy and industrial
- Net Sales of $1,174 million in 2010
- 4,000 employees worldwide
- 18 production sites (including JV in Malaysia)
- Headquarters in Stamford, CT, USA
- Listed on NYSE
Prepreg Technology and Infusion

What are prepregs?
Why use prepregs, and where?
Impregnation of Fibre and Fabrics with Resin
Impregnation of Fibre and Fabrics with Resin

Prepreg production is now highly industrialised for optimum cost and quality.
Typical Prepreg Systems in Wind Energy

- **Resin systems**
  - M9G 280 J /g
  - M9GF 230 J /g
  - M19G 150 J /g

- **Product forms (UD)**
  - Carbon 500-600 gsm
  - Glass 1000-3000 gsm

- **Cure cycles (ramps, dwells + cure times)**
  - ~4 (M19G) to ~8 (M9G) hours when optimised

- **Storage at +5°C (6 month shelf life)**

**Typical prepregs combine high areal weights with full impregnation and low reaction enthalpies**
### Blade technology: Infusion versus Prepreg

<table>
<thead>
<tr>
<th></th>
<th>Infusion</th>
<th>Prepreg</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Raw Material Cost</strong></td>
<td>~ 1.8 (resin + glass NCF) Foam: 2200</td>
<td>UD: 1.8 to 2.0/ Glass NCF ~ 2.5 Foam: 2500</td>
</tr>
<tr>
<td><strong>Tooling Cost</strong></td>
<td>++</td>
<td>-</td>
</tr>
<tr>
<td><strong>Capex Requirements</strong></td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td><strong>Layup</strong></td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td><strong>Cure Cycle</strong></td>
<td>- Up to 20 hours</td>
<td>+ Up to 10 hours</td>
</tr>
<tr>
<td><strong>Blade Finishing</strong></td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td><strong>Health &amp; Safety</strong></td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td><strong>Waste &amp; Scrap</strong></td>
<td>- -</td>
<td>-</td>
</tr>
<tr>
<td><strong>Throughput &amp; Quality Control</strong></td>
<td>- -</td>
<td>++</td>
</tr>
<tr>
<td><strong>Mechanical Performance</strong></td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

Both technologies have their pros and cons
Major Features of Prepregs in Wind Energy

- Chemistry choice to suit cure cycle/part
- Full impregnation: carbon, glass
- Lowest cost in UD formats
- Low controllable exotherm
- Maximum mechanical properties
- Choice of architecture for lowest porosity

Prepregs are ideally suited for thick load critical structures in spar caps
Porosity in Thick Laminates
Prepregs in Thick Glass Laminates

Very low porosities from standard prepregs even in thick laminates

71 plies, 6cm
Prepregs in Thick Carbon Laminates

Typical results in thick laminates using 600gsm carbon (HS) prepreg and standard technology
Porosity ~7%

Improvements in thick laminates using Hexcel patented technology
Porosity <<1%

Very low porosities even in thick laminates: Selection of the right prepreg architecture is key
Mechanical Properties Using Prepreg and Infusion

Glass
**Glass: Materials**

**Infusion:**

**Reinforcement:** LT1218 (UD1200 + slight reinforcement in 90°)

**Resin:** Hexion RIM 135

Cure at 90°C

**Prepreg:**

M9.6GLT/32%/1200(+CV)/G

Cure at 90°C (‘PP90’) and 120°C (‘PP120’)
## Glass: Mechanical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Norm</th>
<th>Infusion</th>
<th>PP90</th>
<th>PP90+CV</th>
<th>PP120</th>
<th>PP120+CV</th>
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</thead>
<tbody>
<tr>
<td>**Tensile 0° ***</td>
<td>Strength (MPa)</td>
<td>ISO527</td>
<td>984.3</td>
<td>1117.3</td>
<td>1144.2</td>
<td>1105.5</td>
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<td></td>
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<td>46.4</td>
<td>47.4</td>
<td>45.6</td>
<td>47.7</td>
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<tr>
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<td>Strength (MPa)</td>
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<td>48.3</td>
<td>36.0</td>
<td>25.3</td>
<td>36.3</td>
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<tr>
<td></td>
<td>Modulus (GPa)</td>
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<td>9.66</td>
<td>12.7</td>
<td>8.87</td>
<td>10.7</td>
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<tr>
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<td>Strength (MPa)</td>
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<td>759.5</td>
<td>896.7</td>
<td>1032.6</td>
<td>1038.6</td>
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<tr>
<td></td>
<td>Modulus (GPa)</td>
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<td>47.1</td>
<td>48.7</td>
<td>49.0</td>
<td>49.0</td>
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<tr>
<td><strong>Compression 90°</strong></td>
<td>Strength (MPa)</td>
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<td>165.4</td>
<td>168.0</td>
<td></td>
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<tr>
<td></td>
<td>Modulus (GPa)</td>
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<td>13.9</td>
<td>15.9</td>
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<tr>
<td>**Flexural 0° ***</td>
<td>Strength (MPa)</td>
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<td>1299</td>
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<td>Modulus (GPa)</td>
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<tr>
<td><strong>ILSS 0°</strong></td>
<td>Strength (MPa)</td>
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<td>48.7</td>
<td>66.2</td>
<td>54.7</td>
<td>77.3</td>
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<tr>
<td><strong>IPS</strong></td>
<td>Strength (MPa)</td>
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<td>39.2</td>
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<td>40.9</td>
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<tr>
<td></td>
<td>Modulus (GPa)</td>
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<td>3.40</td>
<td>4.50</td>
<td>4.2</td>
<td>3.9</td>
</tr>
</tbody>
</table>

* Normalised at FV=60%
Glass: Mechanical Properties

![Graph showing mechanical properties of different glass prepreg materials](image)

**Prepreg mechanical performance is consistently greater**
Mechanical Properties Using Prepreg and Infusion

Carbon
Carbon: Materials

**Infusion:**

**Reinforcement:** UD600 low crimp T620

**Resin:** Hexion RIM135

Cure at 90°C

**Prepreg:**

M9.6GLT/35%/UD600+8P/T620+PES

Cure at 90°C and 120°C
# Carbon: Mechanical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Norm</th>
<th>Infusion</th>
<th>PP90</th>
<th>PP120</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tensile 0°</strong></td>
<td></td>
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<td></td>
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<tr>
<td>Strength (MPa)</td>
<td>ISO527</td>
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<td>125</td>
<td>128,4</td>
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<td><strong>Tensile 90°</strong></td>
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<td></td>
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<td>Strength (MPa)</td>
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<td>33</td>
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<td>8,4</td>
<td>8,2</td>
<td>7</td>
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<tr>
<td><strong>Compression 0°</strong></td>
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<tr>
<td>Strength (MPa)</td>
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<td>128,5</td>
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<td>119.8</td>
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<tr>
<td><strong>Compression 90°</strong></td>
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<td>Modulus (GPa)</td>
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<td>9</td>
<td>9,2</td>
<td>9,3</td>
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<tr>
<td><strong>Flexural 0°</strong></td>
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<td>Strength (MPa)</td>
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<td>103,1</td>
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<tr>
<td><strong>ILSS 0°</strong></td>
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<tr>
<td>Strength (MPa)</td>
<td>ISO14130</td>
<td>60,6</td>
<td>66,7</td>
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<td><strong>IPS</strong></td>
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<td>Strength (MPa)</td>
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<td>32,2</td>
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<tr>
<td>Modulus (GPa)</td>
<td></td>
<td>4,2</td>
<td>4</td>
<td>3,9</td>
</tr>
</tbody>
</table>

* Normalised at FV=60%
Prepreg mechanical performance is consistently greater
Benefits in Blade Design from Using Prepregs
Blade Design Study

A study was commissioned at aerodyn to replace an infused Spar Cap in an all glass blade with one based on prepreg

To evaluate potential weight/material savings
Process pros/cons were excluded
Potential benefits for turbine loads excluded

Blade selected

aerodyblade ae2.5-50.3 IECIII (usually made from resin-infused glass fiber)

Basis for the study

aerody data for infused laminates
Hexcel data (from IMA Dresden) for prepreg laminates (M9.6F/32%/1600+50/G+F, 2400 tex E-glass)
Optimisation of the blade design
Blade Design Study

Key conclusions (when an infused glass spar cap is replaced with a prepreg design)

13% weight reduction in the Spar Cap

33% saving in number of UD layers in Spar Cap mould

3.7% weight saving in the overall blade

(Equivalent to $1200 material cost saving and $750 process cost saving)

Design Study to be extended to carbon
Conclusions

- Prepregs can be tailored to suit wind blade manufacture
  - Matrix choice minimises exotherm in thick parts
  - Fast cure and low exotherm minimise cure cycle
  - Well-designed prepreg architecture minimises porosity
  - Reinforcements are reliably and fully impregnated, even with carbon and even in the thickest sections

- Mechanical properties of typical UD prepregs are significantly higher than infused equivalents

- These properties translate into benefits in blade design that lead to savings of materials, weight and cost

Carbon and glass prepregs are ideally suited to heavy load-critical structures in wind blades
Presented by

**Brian Thomas, Vice President Business Development**

Barnhart Renewables
Agenda
Single Blade Changeout System (SBCO)

1. Purpose
2. Maintenance Methods
3. Equipment Requirements
4. Time Line
5. Comparisons & Benefits
6. Summary
Purpose of SBCO

When and Why

- Performing single and multiple blade maintenance jobs
  - Force Majeure damage
  - Leading, trailing edge blade damage
  - Structural upgrades / modifications

- Performing bearing maintenance
  - Pitch Bearing repair
  - Pitch Bearing replacement
Methods

1. Uptower
   a. Rope Access
   b. Suspended Scaffolding
   c. Boom Truck

2. Lowering of Entire Rotor

3. Lowering of Single Blade
Equipment Requirements

- 90 T Rough Terrain Crane
- Winch Truck
- (3) Tag line trucks or winch systems
- 8 tag lines
- Blade Stands
- Up tower Rigging (Proprietary design Of Clipper Windpower)

-Patent Pending-
### Time Line (Conventional)

- Crane Secured ~ 1-3 wks
- Civil Testing/Work ~ 4 days
- Crane mob ~ 3 days
- Crane assembly ~ 2 days
- Execution ~ 3 days
- De prep / demob ~ 3 days

**Project Duration**

approx. 3 - 6 weeks

### Time Line (SBCO)

- Equipment mob ~ 2 days
- RT crane mob ~ 2 days
- Up tower rigging ~ 1 day
- Execution ~ 3 days
- De prep / demob ~ 2 days

**Project Duration**

approx. 1 - 2 weeks!
Comparisons and Benefits

- Greatly Simplified Mobilization and quicker response time
- No dependence on availability of heavy lift crane & their high stand by costs.
- Lower Civil Impact
  - Reduced crop damage
  - Reduced or eliminated soil testing
  - No crane pad
  - Limited land owner negotiations
- Reduced hardware requirement
- Simplified de-commissioning and re-commissioning
- Cost reduction ranging from 30% to 60% over traditional rotor lowering.
Win – Win for:

1. OEM
2. Turbine Owner
3. Land Owner

- Many lifts completed to date all without incident.
- Warranty cost savings to Clipper
- Force Majeure costs minimized for WTG owner
- Turbine downtime greatly reduced for the WTG owner
- Reduced civil disturbance for the Land Owner and WTG owner
- Future applications for taller towers

End result - Decreased Cost of Energy!
Thank You
Questions and Answers
part 1
Questions and Answers
part 2
Questions and Answers
part 3