Prepreg and Infusion: Processes for Modern Wind Turbine Blades

Chris Shennan
5th September 2013
Agenda

- Introduction
- Wind blades: requirements and drivers
  - Laminate morphology
  - Mechanical performance
- Prepreg and infusion technologies: comparisons
  - M79
- Co-infusion
- Conclusions
Introduction
Company Profile

- Technology leader in advanced composites
- Serving commercial aerospace, space & defense and industrial
- Net Sales 2012: $1.58 Billion
- 5,000 employees worldwide
- 19 manufacturing sites (including JV in Malaysia)
- Headquarters in Stamford, CT, USA
- Listed on New York and Paris Stock Exchanges
Overview

- Leading advanced composites company with 65 years of experience
- Excellent customer relationships
- Technology leader with a broad range of products and qualifications
- Leading positions in all of our markets
- Demonstrated operational excellence

Hexcel 2012 Total Sales of $1.58 Billion

**Markets**
- Industrial: 18%
- Space & Defense: 22%
- Commercial Aerospace: 60%

**Products**
- Engineered Products: 22%
  - Composite Materials
    - Carbon Fiber
    - Reinforcements
    - Prepregs
    - Honeycomb

**Regions**
- Americas: 46%
- Europe: 39%
- Middle East, Asia, Africa: 15%
Hexcel in Global Wind Energy

- Market Leader for prepreg materials in Wind Energy
- Annual capacity of >20,000t
- Supplier for over 20 years
- Global Supply, Sales, Technical Support and R&T
- Product development in close cooperation with key accounts

Plant for wind energy at Windsor, Colorado, opened in 2009
(Other dedicated plants in Austria and in Tianjin, China)
Impregnation of Fibre and Fabrics with Resin

Prepreg production is now highly industrialised for optimum cost and quality
Wind Turbine Blades

Requirements and Drivers
Overall Blade Structure

Load-carrying element or spar (cap)
Shear webs (not visible)

Root end

Shell

Image: © STRUCTeam Ltd
Shells

Design drivers
- buckling
- shear

Expectations
- Low material cost
- Efficient manufacturing process
- Short finishing time

Trends
- Focus is on cost
- Importance of core materials
- Improved finishing
- Longer term innovations

Image: © STRUCTeam Ltd
Load-carrying Elements (1)

Structures are highly loaded

Design drivers
- Stiffness
- Compression strength
- Transverse properties
- Fatigue

Materials required
- UD (glass/carbon)
- Biax (glass)
- Resin
Load-carrying Elements (2)

- Debate about the preferred fibre continues (carbon, E-glass, higher modulus glass...)

- Materials can be pre-impregnated, dry and infused, or pre-cured elements such as laminates
  - Greater opportunity for new materials

Main expectations and issues

- Performance is the major driver
- Fibre alignment and fibre wet out are critical
- Composite sections are thick, especially near the root
- Exotherm control is a major process constraint
- Control of mechanical performance, quality and reproducibility are all critical

Load-carrying elements are critical structures within the turbine blade
Shear Webs

Design drivers
- Buckling
- Strength
- Fatigue

Materials required
- Foam/ balsa
- Biax (glass)
- Resin

Image: © STRUCTeam Ltd
Root End (1)

Structure is highly loaded

Design drivers
- Stiffness
- Strength
- Fatigue

Materials required
- UD (glass/carbon)
- Biax/ triax (glass)
- Resin
Root End (2)

- Root ends tend to be manufactured separately
- There is a trade-off between cost and weight (low cost ≡ heavy; higher cost ≡ light)
- Preference is for a light solution at low total cost

Main issues
- Fibre alignment
- Fixation to mould, where used
- Composite sections are thick
- Exotherm control is a process constraint
- Transition to the load-carrying element
- Integration of the bushings/ root fixings

Root ends are critical structures within the turbine blade
### Summary of Blade Requirements

<table>
<thead>
<tr>
<th>Blade element</th>
<th>Function</th>
<th>Performance requirements</th>
<th>Main driver</th>
</tr>
</thead>
</table>
| Root          | a) Connect blade to hub  
b) Transfer loads from blade to hub | a) Highly loaded  
b) Provide space for bushings | Cost versus performance |
| Spar Cap      | Structural integrity of blade | a) Provide stiffness  
b) Carry loads  
c) New materials | Performance |
| Shear web     | Transfer shear forces between shells | Low to moderate | Cost |
| Shell         | Aerodynamic efficiency | a) Surface quality  
b) Aerodynamic surface | Cost |
Prepreg and Infusion Technologies
- Laminate Morphology, Porosity
- Mechanical Properties, a Comparison
Thick Glass Laminates using Prepregs

Very low porosities can be achieved from glass prepregs in thick laminates with optimised prepreg architecture.

71 plies, 6cm
Thick Carbon Laminates – Conventional Technology

64 ply laminates using 600 g/m² carbon (HS) prepreg and conventional technology
Porosity ~7%

Conventional prepregs are not optimised for thick carbon laminates
Thick Carbon Laminates – Optimised Architecture

Prepreg architecture designed for thick laminates using Hexcel technology
Porosity $<1\%$

Layer uniformity can be further improved by optimising the stack sequence

Optimised architecture in carbon UD prepregs consistently gives low porosity
Even in the thickest laminates, optimised architecture consistently gives low porosity
Optical Comparison: Infusion vs. Prepreg

Morphology – infused carbon vs. carbon prepreg

- Porosity of infused part is lower
- Prepreg sample shows very uniform morphology of both fiber/matrix distribution and alignment
- Homogeneity of prepreg part is higher

Prepreg sample shows excellent uniformity in X, Y and Z directions
Optical Comparison: Infusion vs. Prepreg

Infusion laminate: fiber/matrix distribution

- Resin rich areas between fiber bundles are clearly evident in the infused carbon part

Non-uniformity of resin and fibre is a prominent feature of the infused laminate
Optical Comparison: Infusion vs. Prepreg

Infusion laminate morphology

- Distinct matrix boundaries between carbon fiber bundles
- Fiber and matrix rich areas result in fiber-volume variations over cross section
- Fiber bundles are deformed and possibly deflected in 90° direction
- Porosity is generally low, but some bigger pores are present

Infusion sample is less uniform: for fibre, fibre direction and matrix
Mechanical Properties Using Prepreg and Infusion

Glass
Glass: Materials

Infusion
- Reinforcement: LT1218 (UD1200 + slight reinforcement in 90°)
- Resin: Epikote 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>
</tr>
</thead>
<tbody>
<tr>
<td>**Tensile 0° ***</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>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></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>**Tensile 90° ***</td>
<td>EN2850B</td>
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<tr>
<td>**Flexural 0° ***</td>
<td>ISO14130</td>
<td>48.7</td>
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<tr>
<td><strong>ILSS 0°</strong></td>
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<td>38.9</td>
<td>36.5</td>
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<tr>
<td>Modulus (GPa)</td>
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<td>3.40</td>
<td>4.50</td>
<td>4.2</td>
<td>3.9</td>
<td>4.2</td>
</tr>
</tbody>
</table>

* Normalised at FV=60%
Prepreg mechanical performance is consistently greater.

Glass: Mechanical Properties

Strength (MPa)

- Tensile 0°
- Tensile 90°
- Compression 0°
- Compression 90°
- Flexural 0°
- ILSS 0°
- IPS

- Infusion
- PP90
- PP90+CV
- PP120
- PP120+CV

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

Carbon
Carbon: Materials

**Infusion**
- Reinforcement: UD600 low crimp T620
- Resin: Epikote RIM135
- Cure at 90°C

**Prepreg**
- M9.6GLT/35%/UD600+2P/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>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Strength (MPa)</td>
<td>ISO527</td>
<td>2176,1</td>
<td>2670,2</td>
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<td>Modulus (GPa)</td>
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<td>130</td>
<td>125</td>
<td>128,4</td>
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<tr>
<td><strong>Tensile 90°</strong></td>
<td></td>
<td>33</td>
<td>37,9</td>
<td>42,9</td>
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<tr>
<td>Modulus (GPa)</td>
<td></td>
<td>8,4</td>
<td>8,2</td>
<td>7</td>
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<td><strong>Compression 0°</strong></td>
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<td>128,5</td>
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<td>148,6</td>
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<td>9,3</td>
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<td>Strength (MPa)</td>
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<td>103,1</td>
<td>103,6</td>
<td>114,6</td>
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<td>Modulus (GPa)</td>
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<td>4,2</td>
<td>4</td>
<td>3,9</td>
</tr>
<tr>
<td><strong>ILSS 0°</strong></td>
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<td>60,6</td>
<td>66,7</td>
<td>67,6</td>
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<td>Strength (MPa)</td>
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<td>Modulus (GPa)</td>
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<td></td>
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<tr>
<td><strong>IPS</strong></td>
<td>ISO14129</td>
<td>32,2</td>
<td>39,6</td>
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<td>Strength (MPa)</td>
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<tr>
<td>Modulus (GPa)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

* Normalised at FV=60%
Carbon: Mechanical Properties

Prepreg mechanical performance is consistently greater

Prepreg is particularly suited to performance driven applications
Prepreg and Infusion Matrices

M79: Eliminating the Gap Between Prepreg and Infusion
Typical Prepreg Systems in Wind Energy

Typical resin systems

<table>
<thead>
<tr>
<th>Resin</th>
<th>Reaction Enthalpy (J/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M9G</td>
<td>310</td>
</tr>
<tr>
<td>M9GF</td>
<td>230</td>
</tr>
<tr>
<td>M19G</td>
<td>160</td>
</tr>
</tbody>
</table>

Cure temperature ~100-120°C

UD Products

- Carbon 500-600 g/m²
- Glass 1000-3000 g/m²

Overall cure cycles

~4 to ~8 hours (optimisation is key)
The Value of Low Exotherm in Thick Laminates

- **Higher dwell temperature for shorter time**
- **Faster ramp rate**

- **Net reduction in cure cycle**

Low exotherm matrix e.g. M19G  Standard exotherm matrix e.g. M9G
Prepreg and Infusion Matrix Systems

Wind Energy Matrix Exotherm as Function of Cure Temperature

- Typical LRI systems
- M79

Exotherm J/g

Cure temp °C

1995
1998
2002
2005
M79 continues the trend: minimising reaction exotherm for short cure cycles of thick structures
M79

New generation prepreg system for large industrial structures (e.g. wind turbine blades)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cure time at 70°C</td>
<td>10 hours</td>
</tr>
<tr>
<td>Cure time at 80°C</td>
<td>6 hours</td>
</tr>
<tr>
<td>Outlife</td>
<td>&gt;2 months</td>
</tr>
<tr>
<td>Reaction enthalpy</td>
<td>100-120 J/g</td>
</tr>
<tr>
<td>Static mechanical properties</td>
<td>Similar to current M9 family</td>
</tr>
<tr>
<td>Product form</td>
<td>Same as current M9 family</td>
</tr>
<tr>
<td>Manufacturing process</td>
<td>Same as current M9 family</td>
</tr>
</tbody>
</table>

M79 extends performance envelope to lower temperatures and lower exotherm
### M79: Example of Mechanical Test Data (70°C cure)

<table>
<thead>
<tr>
<th>Test &amp; Direction</th>
<th>Measurement</th>
<th>No. of specimens</th>
<th>70 °C Cure</th>
<th>M9 Historical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td><strong>Tensile 0°</strong></td>
<td>Strength (MPa)</td>
<td>8</td>
<td>469</td>
<td>9.4</td>
</tr>
<tr>
<td></td>
<td>Modulus (GPa)</td>
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<td>21.2</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Compression 0°</strong></td>
<td>Strength (MPa)</td>
<td>10</td>
<td>413</td>
<td>20</td>
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<tr>
<td></td>
<td>Modulus (GPa)</td>
<td></td>
<td>21.0</td>
<td>0.3</td>
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<tr>
<td><strong>ILSS (45°, 4-ply)</strong></td>
<td>Strength (MPa)</td>
<td>20</td>
<td>46.7</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Normalized results are in bold

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Overall</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test results for HexPly M79/43%/LBB1200+CV/G cured at 70 °C</td>
<td></td>
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</table>

Overall, M79 mechanical test data compares favourably with conventional (M9) systems.
# M79: Example of Mechanical Test Data (80°C cure)

<table>
<thead>
<tr>
<th>Test &amp; Direction</th>
<th>Measurement</th>
<th>80 °C Cure</th>
<th>M9 Historical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of specimens</td>
<td>Mean</td>
<td>SD</td>
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<tr>
<td><strong>Tensile 0°</strong></td>
<td>Strength (MPa)</td>
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<td>Modulus (GPa)</td>
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<td>20.5</td>
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<tr>
<td><strong>ILSS (45°, 4-ply)</strong></td>
<td>Strength (MPa)</td>
<td>20</td>
<td>39.5</td>
</tr>
</tbody>
</table>

Test results for HexPly M79/43%/LBB1200+CV/G cured at 80 °C

Again overall, M79 mechanical test data favourably with conventional (M9) systems

Normalized results are in bold
Co-infusion

Combinations of Prepreg and Infusion
Co-infusion: an Introduction

Co-infusion

The use of prepreg and infusion technologies in the same laminate with co-cure

Typical configuration

UD prepreg for the heavy load-carrying structure
Infusion of dry reinforcement for the remainder of the structure
Cure of the whole assembly at the same time and temperature
Spar Caps: Prepreg Layup and Cure
Wind Blades: M79 co-cured in an Infused Shell

Prepreg spar cap laid up on dry reinforcements

Dry reinforcement co-infused with prepreg followed by co-cure
Co-infusion: Case Study, Construction

Demonstration on a 4 x 2m scale UD prepreg with biax dry fabrics

- Vacuum bag
- Infusion net
- Tacky-tape
- Resin channel
- Perforated release film (P1)
- Peel-ply
- PVC Foam
- Prepreg
- Interlaminar flow media
- 3 plies fabric
- Vacuum channel
- 440 mm
- 1550 mm
- 1900 mm

Demonstration on a 4 x 2m scale UD prepreg with biax dry fabrics
Co-infusion: Case Study, Layup

Dry reinforcements

Fabric
3 plies of BB820

Foam and UD prepreg layers

UD prepreg
20 plies of M9.6F/32%/1600+CV/G

2m
4m
Co-infusion: Case Study, Infusion Process

Infusion time: ~25 min
Resin consumption: ~34 kg, Epikote RIM 135
Co-infusion: Case Study after Demoulding

The finished 4x2m laminate

Co-infusion simplifies the production process, combining the best features of prepreg and infusion materials.

Low porosity, high $T_g$

<table>
<thead>
<tr>
<th></th>
<th>FV (%)</th>
<th>Porosity (%)</th>
<th>Tg (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Side</td>
<td>0.7</td>
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<tr>
<td></td>
<td></td>
<td>Middle</td>
<td>1.5</td>
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<td></td>
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<td>Top</td>
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<td></td>
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<td>Middle</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bottom</td>
<td>75</td>
</tr>
</tbody>
</table>

Cure cycle: 6hrs 90°C
Co-infusion: Case Study, Porosity

3x Infusion fabrics

20x M9.6F/32%/1600+CV/G

3x Infusion fabrics

Porosity assessment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum void</td>
<td>&lt;0.85 mm²</td>
</tr>
<tr>
<td>Porosity</td>
<td>0.7-1.5%</td>
</tr>
</tbody>
</table>
Co-infusion: Case Study, Compression

* ISO 14126

Compression 0°

Strength (MPa)

- Non-normalised
- Normalised

Modulus (GPa)

- Non-normalised
- Normalised
M79 Compared with Conventional Systems

M79 bridges the gap between conventional prepreg and infusion systems which facilitates co-infusion.
Different blade elements have different drivers, sometimes cost driven, sometimes performance driven

Prepreg is particularly suited to performance driven applications, on glass and carbon
  - Overall higher mechanical properties
  - Consistent low porosity when using appropriate architecture
  - Reliable impregnation, low exotherm, fast cure cycle

M79 offers prepreg quality at infusion cure temperatures

Co-infusion can simplify the manufacturing process
  - It can eliminate the separate steps in spar cap manufacture
  - M79 simplifies the process allowing prepreg cure at infusion cure temperatures

Maximum material performance is derived from prepreg which is particularly suited to performance applications
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