SMART Wind Consortium Subgroup Virtual Meeting:

Composite Materials and Process Opportunities

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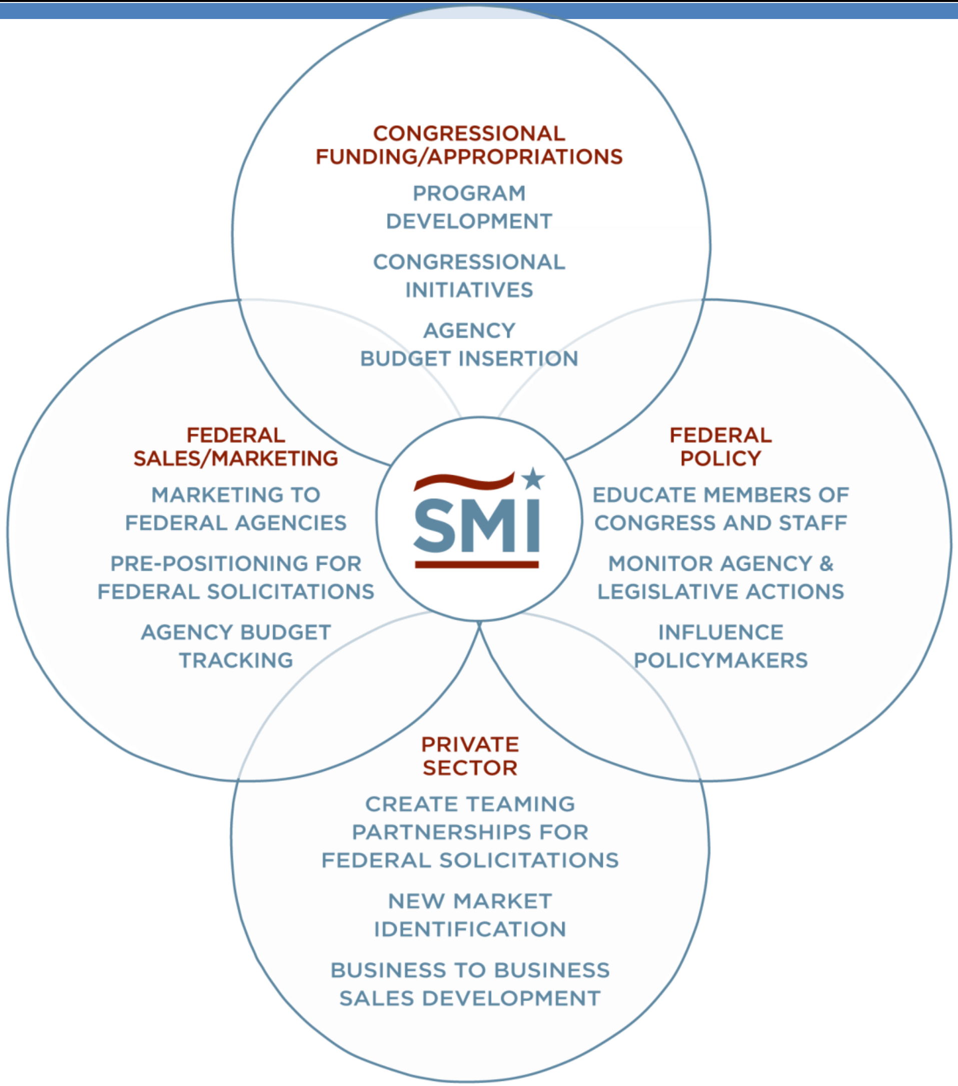
SAMPE and Wind Power

- ***SAMPE*** is the leading Material and Process Engineering professional society.
- ***SAMPE*** conferences cover whole range of composite related issues including applications to wind blades
- The next ***SAMPE*** conference will be this fall in Dallas , CAMX 2015, where there will be an “Energy” track.
- The information for this presentation was primarily drawn from past ***SAMPE*** technical papers.

Strategic Marketing Innovations (SMI)



- 20 yrs experience in Washington DC providing federal program development services to high technology clients.
- SMI supports approximately 100 clients per year and maintains an active network of 500+ companies and organizations.
- Over the last 8 years, SMI has secured over $1 billion in federal funding for contract activity for our clients

Overview of Composite Materials Technology for Wind Blades

- **Resin Matrix Materials**
- **Reinforcement Fibers**
- **Core Materials**
- **Manufacturing Processes**

Resin Matrix Materials for Wind Blades

What are the Key Resin Matrix Properties?

- **<u>Good delamination resistance</u> between the plies is dependent on resin matrix fracture toughness**
- **<u>Compressive strength</u> of the fiber composite is highly dependent on the elastic modulus (stiffness) of the resin matrix along with fiber adhesion**
- **Matrix resins have to <u>transfer stress between the fibers</u>, key is fiber matrix adhesion**

Commercial Status of Major Matrix Resin Systems

Material	Features, Benefits and Drawbacks	Maturity	Trend
Epoxy	Excellent mechanicals, most widely used, adequate supply	High	↓
Polyester	Lower Cycle Times and lower material costs	Good	=
Vinyl esters	Good compromise on mechanicals, low cost, low cycle times	Young	↑

Property	Units	Epoxy	UPR	Vinyl Ester	pDCPD
Tensile Strength	Mpa	55 - 65	40 - 55	60 -75	58
Tensile Strain	%	3 - 4	1 - 2	2 - 3	5 - 6
Tensile Modulus	GPa	2.9	3.2	3.2	2.5
Tg	Deg C	70 – 80	60 – 70	75 - 80	110 – 120
Water Absorption (7 Days, 23 C)	%	4 – 5	4 – 5	2 – 4	<1
Density	g/cc	1.15	1.15	1.14	1.04
Vol. Shrinkage	%	4 – 5	8 – 10	7 – 8	4 - 5

Reinforcement Fibers for Wind Blades

Commercial Status of Major Wind Blade Reinforcements

Material	Features, Benefits and Drawbacks	Maturity	Trend
E-Glass	Most widely used, adequate supply, low cost	High	↓
H-Glass	Increased stiffness over E-Glass	High	↑
S-Glass	High performance but with cost penalty	High	=
Carbon Fiber	World-class stiffness, but cost, material handling, and supply are of concern	High	↓

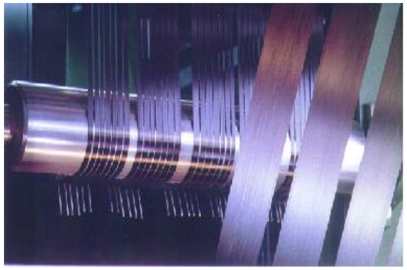
Comparison of Glass and Carbon Fiber Attributes

Glass Fiber

- Linear-elastic
- High shear modulus
- High strain to failure
- Ductile failure mode
- Impact toughness
- Denser fiber
- Acid resistance
- Electrical insulator
- Thermal insulator
- Expands with heat

Carbon Fiber

- High elastic modulus
- Low shear modulus
- Low strain to failure
- Catastrophic failure
- Prone to damage
- Light-weight
- Alkaline resistance
- Electrical conductor
- Thermal conductor
- Shrinks with heat



Glass and Carbon Fiber attributes compliment each other for selective placement of hybrid forms and multifunctional integration

Source: OC Type30® fiber and data

Wind Blade Core Materials

Basic Wind Blade Core Materials

- Balsa
- PVC
- PET
- TYCOR
- Polyurethane (PU)
- Others

Commercial Status of Major Wind Blade Core Materials

Material	Features, Benefits and Drawbacks	Maturity	Trend
Balsa	Dominant material, low cost, consistency concerns, high resin take up	High	
PVC	Lower strength than balsa, less dense, used in weight sensitive middle areas of blade	High	
PET	Low cost, improved consistency, less resin uptake, lower mechanical properties, primary use is in blade tips	Moderate	
SAN	Lower weight, reduced resin uptake	Young	
Tycor	Reduced resin take up, highly engineered core	Young	

Balsa Cores

Pro	Con
Lowest Cost	Availability Concerns
Robust Mechanical Properties • high Strength • high Stiffness	Higher Resin Uptake
Sustainable (i.e., natural)	Must be scored in order to be shaped • therefore uses more resin
	Greater resin use equals added cost

PET Cores

Pro	Con
Thermoplastic • recyclable • no outgassing • thermo-cuttable • thermo-formable	Needs even higher density/thickness to match properties of PVC and even higher to match balsa
Better damage tolerance	
Low resin uptake	Since blade designs are basically fixed, PET usage primarily limited to blade tips

PVC Cores

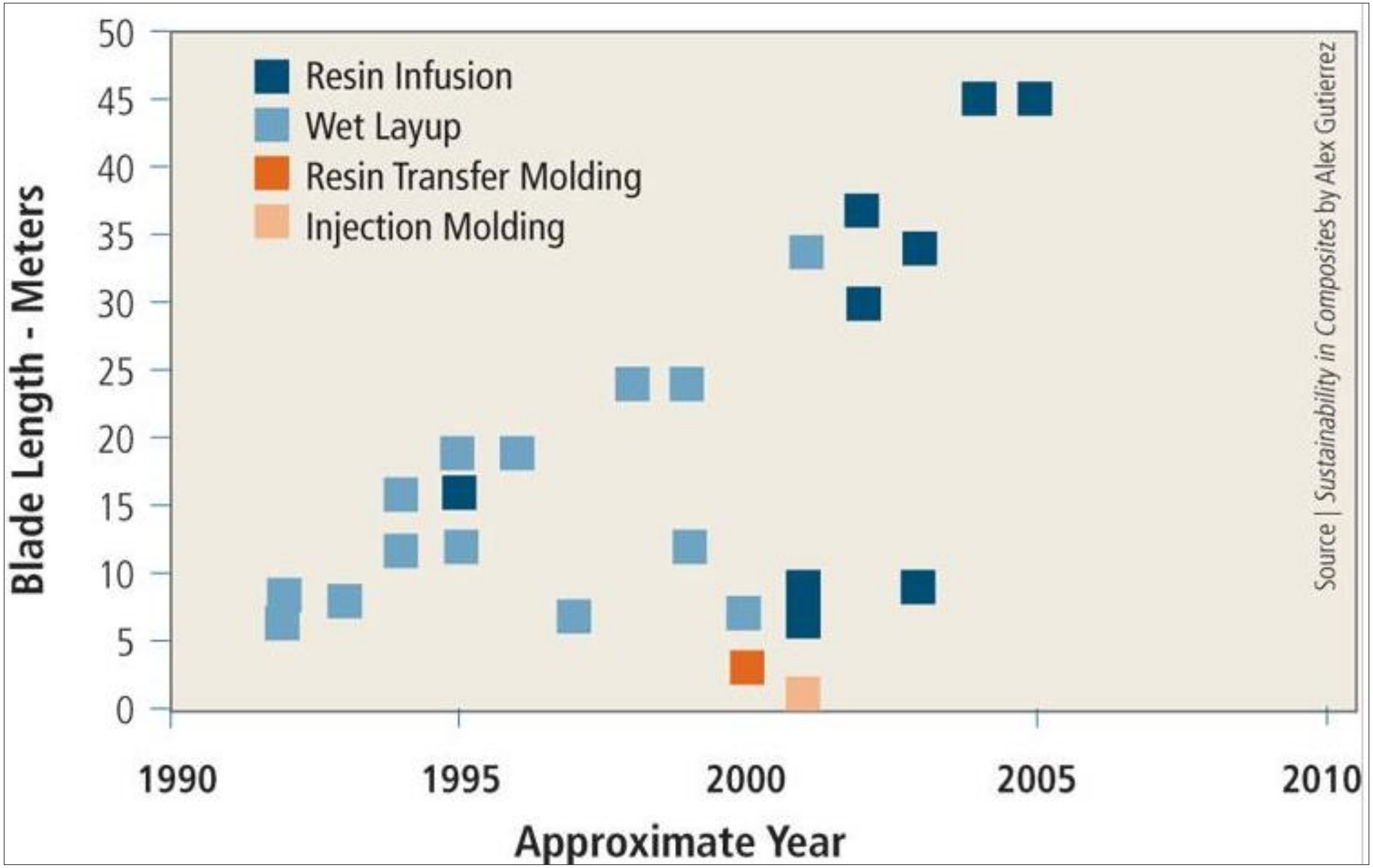
Pro	Con
Less Dense	Needs greater thickness to match balsa cores
Compatible with most resin systems	Environmental Concerns
Improved Damage Tolerance	Outgassing

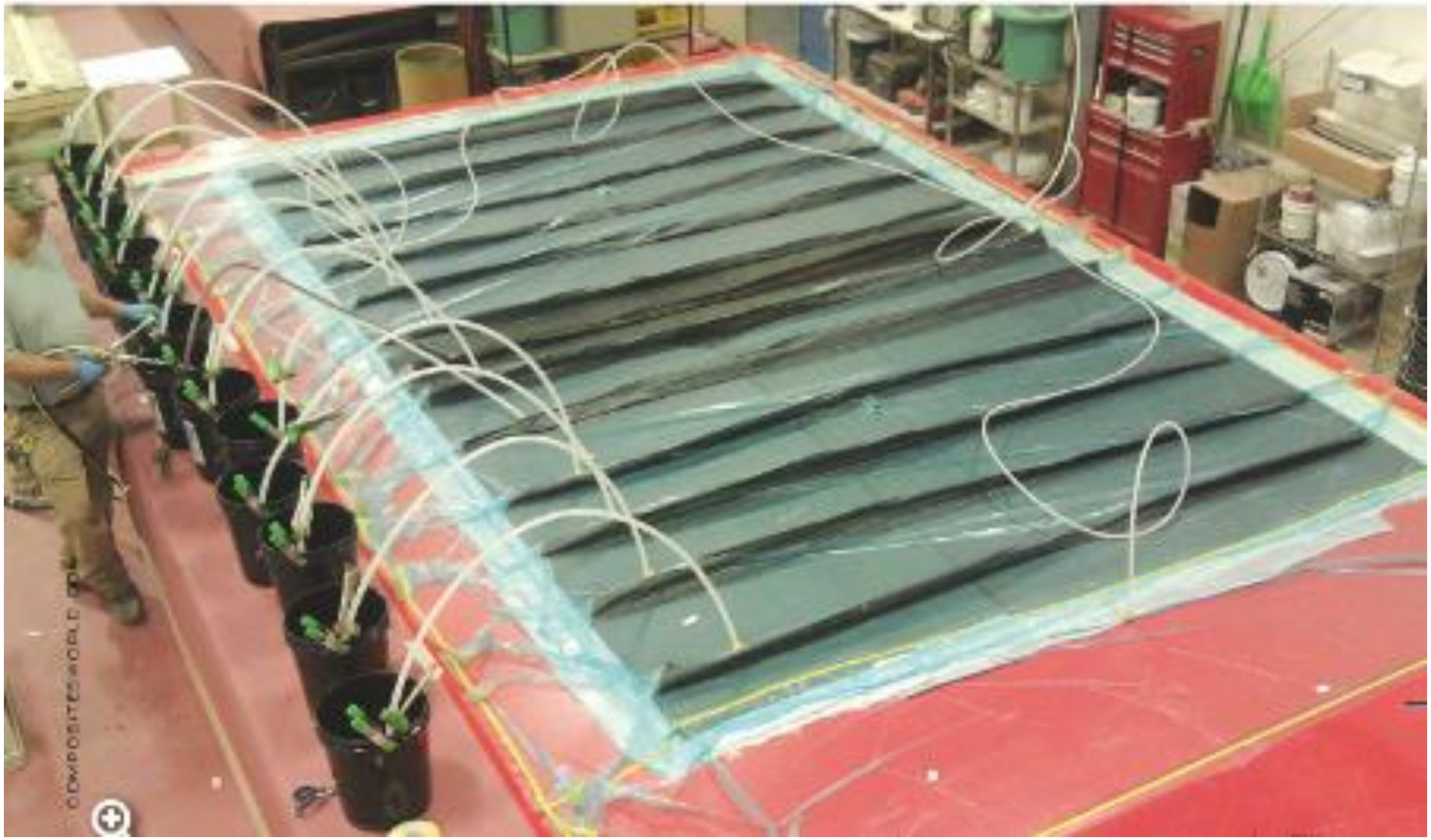
Tycor Cores

Description
Closed Cell Polyurethane “sticks” wound with fiberglass
Glass is primary source of strength and stiffness
Lower cost than balsa with similar mechanicals

Wind Blade Manufacturing Technology

Large Wind Blade Manufacturing Evolution to VIP

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Industry-Based Wind Blade Material Research

- **Fibers**
  - **Lower cost, high performance glass and carbon fiber development**
- **Resins**
  - **New epoxy resin systems are being developed that combine low mix viscosity with significant improvements in Transverse Tensile Strength**
- **Cores**
  - **New core materials are under development**
- **Processing**
  - **Advancement of automation in the wind blade manufacturing process**

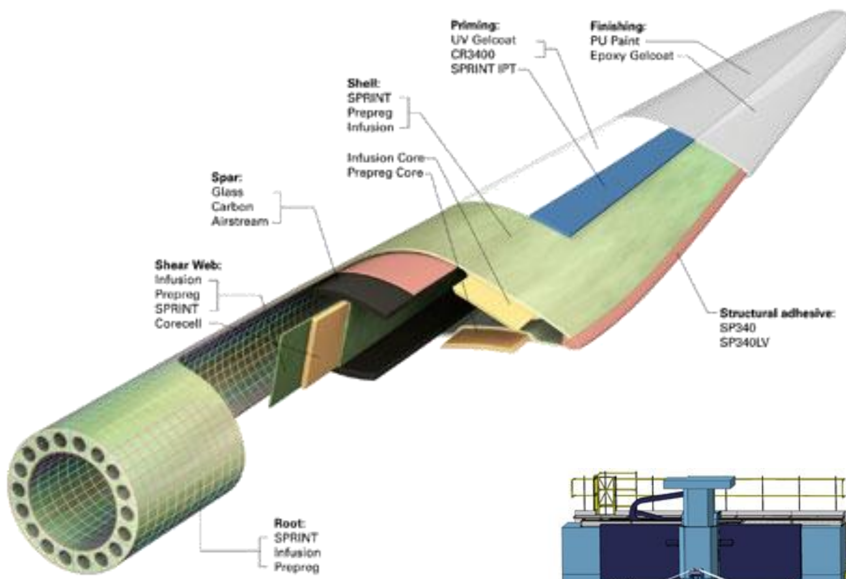
Wind Energy Summary

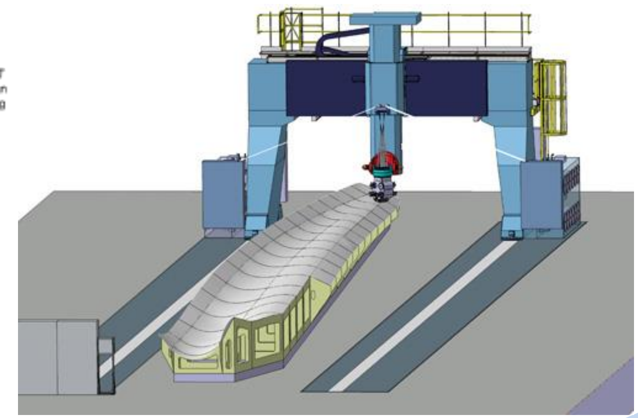
- **Key Program/Applications:**
  - **Vestas - blades over 40m, center spar**
  - **Gamesa – blades over 40m, center spar**
  - **LM Glasfiber – LM61.5, spar cap**
  - **M.Torres – 5M blades, shell and spar**
  - **Offshore turbines 3MW – 10MW**
  - **Blades, drive shafts, nacelle, tower**

- **Manufacturing/Technology:**
  - **Primarily infusion molding (SCRIMP, VARTM)**
  - **prepreg (UD & fabrics) (≈15% of market)**

- **Materials:**
  - **Primarily HS (24K – 50K tow)**

- **Trends/Drivers:**
  - **Improving manufacturing technology and materials enabling greater cycles/year**
  - **Transport costs going up**



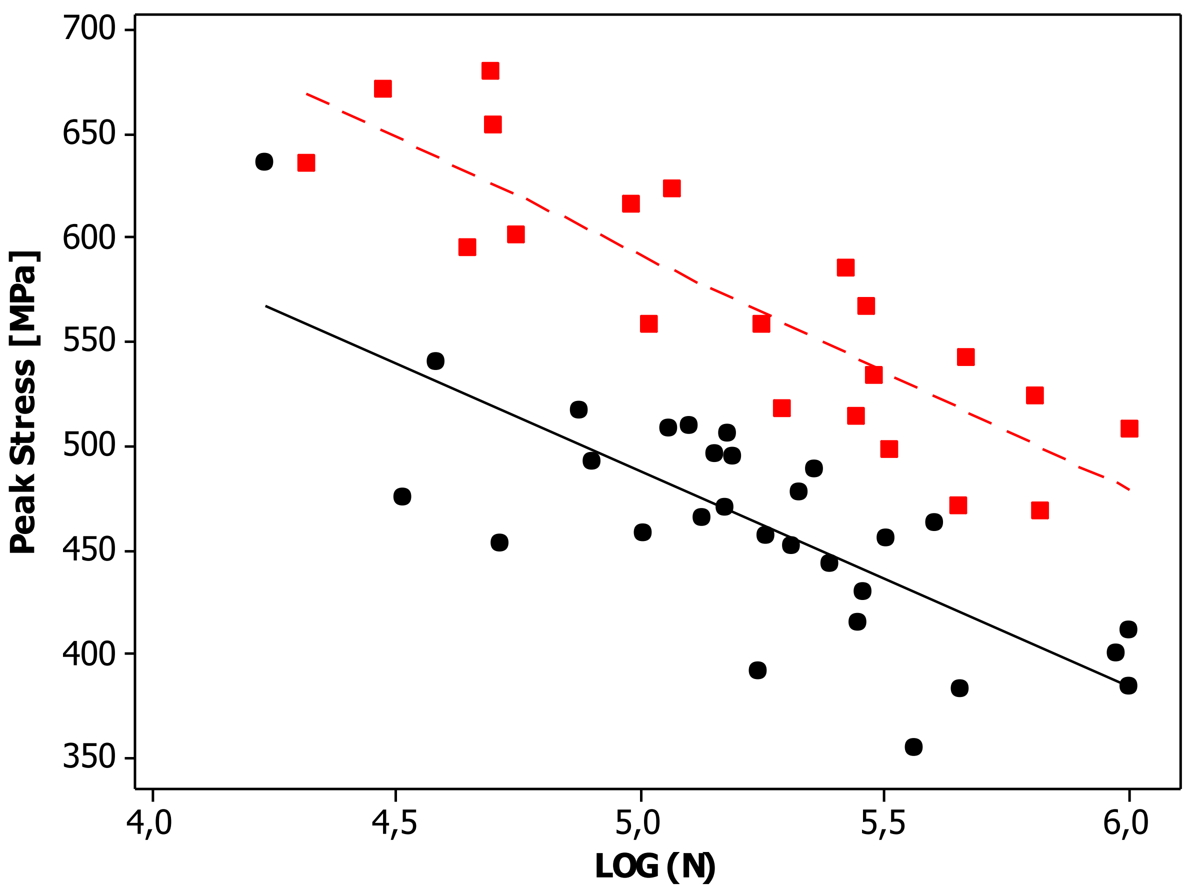


APPENDIX

Table 1. Properties typical of wind turbine composite materials

Material	E-Glass	E-Glass	Carbon	Carbon
Process	Wet Layup	VARIM	VARIM	Prepreg
Fiber Volume Fraction	30%-45%	45%-58%	50%-60%	55%-65%
Composite density, lb/in^3	0.056-0.064	0.064-0.071	0.052-0.055	0.054-0.056
Tensile Modulus, E_{11} (Msi)	3.3-5.0	5.0-6.5	15-18	17-18
Tensile Strength, UTS (ksi)	60-130	95-170	180-330	240-360
Tensile Strain, ε_{max}	1.8%-2.6%	1.8%-2.6%	1.2%-1.8%	1.4%-2.0%
Compressive Strength, UCS (ksi)	60-130	95-170	105-220	170-250
Compressive Strain, ε_{min}	1.8%-2.6%	1.8%-2.6%	0.7%-1.2%	1.0%-1.4%

Materials to Enable Longer Blades



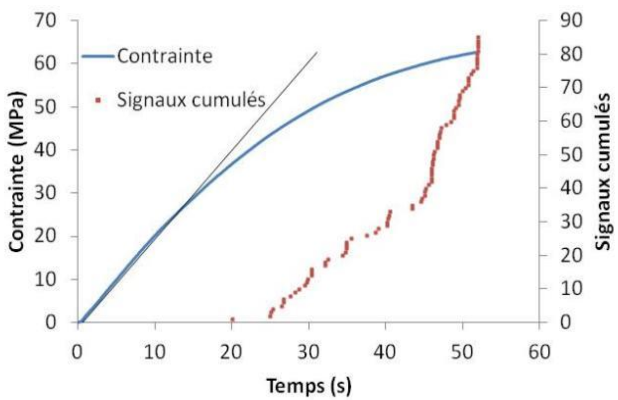
Fatigue Performance at R=0.1, E-glass vs H-glass UD Fabric/epoxy

Higher Composite Stiffness and Fatigue Performance

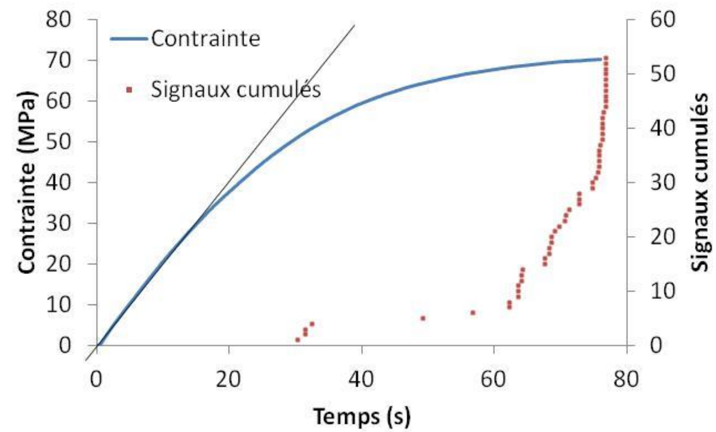
Source: Risoe / DTU tests 2013 on UD laminates, Momentive Epoxy resin L135/H137

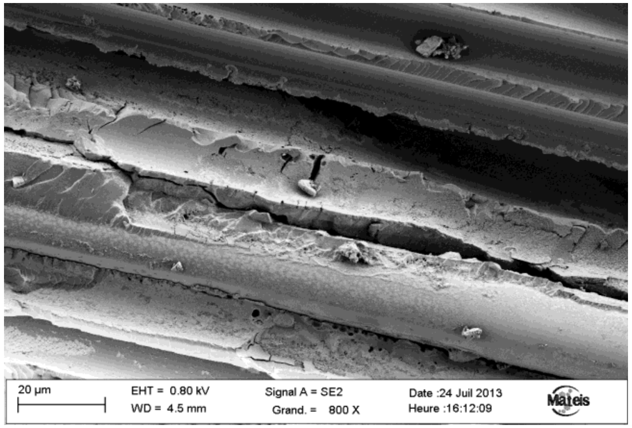
Materials to Improve Blade Durability

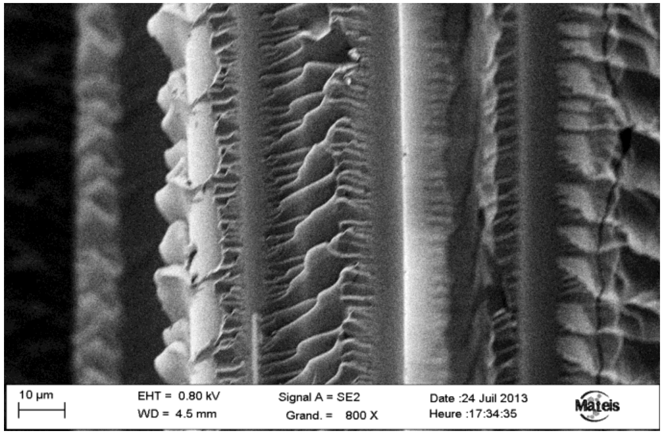
E-glass UD/epoxy



WindStrand® UD/epoxy







Acoustic and fracture surface analysis of 45° tension in Advantex/epoxy lamina
The improved fiber-matrix adhesion leads to a higher transverse strength

Higher Composite fiber-matrix adhesion for Durability

Source: OC WindStrand® fibers and data. Panels dry-wound roving and infused using Momentive epoxy RIMR 135/H137

Wind Turbine Trends/Material Impacts

Trend:

- Larger blades to increase Annual Energy Production (AEP) without adverse system impacts

Materials Impact:

- Increased emphasis on passive load alleviation and weight reduction leads to more demanding laminate performance and thinner design margins.

Higher-quality manufactured materials, better inspection techniques, higher fiber volume fractions, higher specific strength/stiffness

Trend:

- Larger machines/rotors to access better wind resource and reduce Balance of Station (BOS) costs

Materials Impact:

- Potential limitations to using current design/manufacturing methods due to incompatible tolerances, transportation constraints, changing design drivers

Aerospace-like design, joints, higher specific strength/stiffness

- Drives machines to be as big and light as possible to get to competitive cost of energy (COE) numbers.

Lightweight materials, very flexible designs, high-quality materials