Composite Materials for Wind Blades: Current Performance and Future Directions
1. PPG Wind Energy
2. Evolution of wind blade materials
3. The current state – performance review
4. Alternatives for stronger, stiffer blades
5. The future state - long term goals and new developments
PPG Wind Energy

1. PPG Wind Energy

- Offering a multitude of products for wind turbines
  - Fiber glass for blades, nacelles
  - Coatings for blades, towers
- World leader in fiber glass
  - Established in wind energy for 15+ years
  - Production and sales from 3 major continents
  - Hybon® 2002/2001 recognized product in wind energy blades
    - Specified in blades from most major manufacturers around the world
  - Continuing to develop new products that will enhance wind energy production for the future
1. PPG Wind Energy

Hybon® 2002/2001

- Specified and used at most wind turbine companies
- Designed for multiple resin compatibility

Hybon® 2026

- Multiple resin compatibility
- Enhanced processing characteristics
- Improved strength and fatigue life

<table>
<thead>
<tr>
<th></th>
<th>Tensile Strength</th>
<th>Flexural Strength</th>
<th>Short Beam Shear Strength</th>
<th>FWF</th>
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<td></td>
<td>MPa</td>
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<td>ISO 14125</td>
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<td>B</td>
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A – Unidirectional infused panels, Hexion RIM 135 epoxy
B - Filament wound cylinders per ASTM D 2291
Fiber design at the nano-scale level drives performance through the value chain.

1. Fiber/Fabric Processing
2. Infusion, fatigue, weight

1 nm 1 μm 1 mm 1 m 100 m
2. Evolution of wind blade materials

Input materials
- Core materials (balsa, PVC, PU, etc.)
- Skin materials (multiaxial fabrics NCF)
- Spar materials (UD, multiaxial fabrics NCF)
- Root materials (roving, multiaxial fabrics)
- Resin systems (DGEBA, VE, PE, …)

ATP/AFP
- Dry fiber
- Impregnated tape

Improved Processing & Performance

Hand layup
Prepreg
Vacuum Infusion
Wet layup
Wet winding
3. The current state – performance review

- SNL/MSU/DOE database
- Optidat Database
- PPG internal test data
- Other public information

PPG / DOE database

Static Properties

Fatigue Properties
3. The current state – performance review

- Prepreg based materials
  - UD, Biax

- Infusion grade materials
  - UD, Biax, Triax

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<td>Compressive strength 0°:</td>
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</table>
3. The current state – performance review

**Uni-directional Prepreg**

**Tensile Strength**

- **Carbon-Epoxy**: 1767 MPa, 2004 MPa, 2020 MPa, 2504 MPa
- **E-Glass Epoxy**: 1767 MPa, 1750 MPa, 2000 MPa, 2500 MPa

**Uni-directional Prepreg**

**Tensile Modulus**

- **Carbon-Epoxy**: 1264 GPa, 129.7 GPa, 139.3 GPa, 120.0 GPa
- **E-Glass Epoxy**: 1182 GPa, 140.0 GPa

**Uni-directional Prepreg**

**Compressive Strength**

- **Carbon-Epoxy**: 1359 MPa, 1250 MPa, 966 MPa, 790 MPa
- **E-Glass Epoxy**: 1182 MPa, 140.0 MPa

**Uni-directional Prepreg**

**Compressive Modulus**

- **Carbon-Epoxy**: 139.3 GPa, 129.7 GPa, 1182 GPa
- **E-Glass Epoxy**: 47.7 GPa, 45.1 GPa
3. The current state – performance review

Double Bias Prepreg Static Properties

- Tensile Modulus
  - Carbon-Epoxy: 123 GPa
  - E-Glass Epoxy: 158, 145, 132 GPa

- Tensile Strength
  - Carbon-Epoxy: 15.0 MPa
  - E-Glass Epoxy: 18.2, 16, 14.7 MPa
3. The current state – performance review

**Triax Infusion**

**Tensile Strength (MPa)**

- E-Glass Epoxy: 951, 867, 785
- E-Glass Vinyl Ester: 809
- R-Glass Epoxy: 923

**Compressive Strength (MPa)**

- E-Glass Epoxy: 833, 693, 580
- E-Glass Vinyl: 670

**Tensile Modulus (GPa)**

- E-Glass: 34.3, 29.0, 24.5
- R-Glass Epoxy: 30.50, 34.5

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**Enabling Energy**

Fiber Glass and Coatings for Wind Power

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**Triaxial Infusion Static Properties**
How to drive performance?

4. Alternatives for stronger, stiffer blades

1. Design/Geometrical approach (Increase Moment of Inertia – stiffness)

2. **Material performance enhancements (strength and/or stiffness)**
   1. Sizing Chemistry (strength)
   2. Fiber Composition (strength + stiffness)
   3. Fiber Volume Fraction (strength + stiffness)
   4. Defect reduction/prevention (strength*)

*at component level
Alternatives for stronger, stiffer blades:

Sizing Chemistry

- Green = HYBON 2026
- Red = HYBON 2002

~10% Improvement
~2x on absolute scale
Alternatives for stronger, stiffer blades:

- Sizing Chemistry

**Montana State results**

- Vectorply E-LT 5500 using Hybon® 2026
- 4400TEX input in zero direction
- Supports value of Hybon® 2026

Resin: EP = EPON 826  
Method: SBS = ASTM D2344  
All testing on 1984 TEX (250 Yield) rovings
4. Alternatives for stronger, stiffer blades: Increase FVF

**Advantages:**
- Avenue for increasing spar cap stiffness (reduction in tip deflection)
- Achievable with existing materials

**Disadvantages:**
- Effect on long term performance of composite laminate (fatigue)?
- Increase in weight
- Difficulties in processing (dry spots)
4. Alternatives for stronger, stiffer blades: Increase FVF

- Circular cross section spar
- Parameters include
  - Outside Diameter (OD), Inside Diameter (ID)
  - Spar length (L)
  - Elastic Modulus of Fiber (Ef)
  - Fiber Volume Fraction (FVF)

OD = 0.6 m, ID = 0.55 m
L = 60 m
Ef = 79 GPa (Impregnated strand tensile)
FVF = 50%
Modulus translation efficiency = 97%
Effect of FVF on tip deflection of spar, self weight

4. Alternatives for stronger, stiffer blades:
   Increase FVF

Common design space (E-glass)
4. Alternatives for stronger, stiffer blades: Increase FVF

What happens at 60% FVF?
### 4. Alternatives for stronger, stiffer blades: Fiber Composition

<table>
<thead>
<tr>
<th>Fiber Types</th>
<th>E glass</th>
<th>R glass</th>
<th>S glass</th>
<th>Carbon</th>
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<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>2.55 – 2.64</td>
<td>2.55</td>
<td>2.46 - 2.49</td>
<td>1.7</td>
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<tr>
<td>Young’s Modulus (GPa)</td>
<td>70 – 77</td>
<td>84-86</td>
<td>86 – 90</td>
<td>220</td>
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<tr>
<td>Pristine Strength (MPa)</td>
<td>3450 – 3790*</td>
<td>4400*</td>
<td>4590 – 4830</td>
<td>3800**</td>
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<td></td>
<td>2800**</td>
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<td>3900**</td>
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<tr>
<td>Failure Strain (%)</td>
<td>4.5 – 4.9</td>
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<td>5.4 – 5.8</td>
<td>0.7</td>
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</table>

*pristine
**impregnated strand per ASTM D2343
4. Alternatives for stronger, stiffer blades: Fiber Composition

As Fiber Modulus Increases, deflection is reduced but cost per lb increases...

![Graph showing self weight tip deflection and cost for different materials.](image)
Composition shift E to R

4. Alternatives for stronger, stiffer blades: Fiber Composition

<table>
<thead>
<tr>
<th>Fiber Composition</th>
<th>49%</th>
<th>51%</th>
<th>53%</th>
<th>55%</th>
<th>57%</th>
<th>59%</th>
<th>61%</th>
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<tbody>
<tr>
<td>E-glass</td>
<td>0.280</td>
<td>0.277</td>
<td>0.274</td>
<td>0.271</td>
<td>0.268</td>
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<td>R-Glass</td>
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<td>0.256</td>
<td>0.253</td>
<td>0.250</td>
<td>0.246</td>
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FVF (%)

Graph showing self-weight tip deflection (m) vs. FVF (%) for E-glass and R-Glass.
5. The future state – long-term goals and new developments

- Faster, easier processing
  - Faster wet-out for liquid molding
  - Reduced probability of porosity in laminates
  - Reduced abrasion

- Defect reduction
  - Material forms adequate for FP/ATP (process driven)
  - Resin specific sizing technology (innovative film former chemistry)
    - Higher Tensile strength
    - Higher SBSS and strength retention
    - Improved fatigue performance
New material forms and process development

5. The future state – long-term goals and new developments

• ATL/FP grade materials
  – Equilibrium between performance and cost
  – Material tolerances
  – Paper requirements
  – Impregnation levels and slitting characteristics
  – Tack
  – In situ consolidation
SANDEEP VENNAM, JIM WATSON AND CHERYL RICHARDS from PPG Wind Energy

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