Recent Core Material Developments/Applications for Blades at Milliken

Fred Stoll, Ph.D., Senior Development Engineer
Milliken & Company
fred.stoll@milliken.com

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Sandwich Core in Large Blades

• **Importance of Core:** As wind turbine size has increased over the years, sandwich core design has emerged as a major consideration in blade construction
  - Core with absorbed resin comprises 10-15% blade mass
  - Kitted core comprises as much as 18% of blade material cost not including resin absorbed by the core
• **Opportunities for Improvement:**
  - PVC Foam (60 kg/m³)
    - Low stiffness
    - Low processing temperature limit
    - Non-linear stress-strain behavior
  - Balsa
    - Heavy, significant resin uptake
    - Processing challenges
      > Dimensional stability
      > Variable weight and resin absorption
    - Occasional supply limitations
• **TYCOR® W Fiber Reinforced Core for Blades** - Superior combination of low weight, high properties, low cost, processing advantages

Photo used with permission of Owens Corning

- Sandwich zones in blade cross section
TYCOR® W Business Update

• TYCOR® fiber-reinforced core (FRC) technology was originally developed by WebCore Technologies

• Early 2012 - TYCOR technology and manufacturing acquired by Milliken & Company, developer and manufacturer of Nexcore

• Milliken & Company
  ▪ Global Manufacturer: 39 manufacturing facilities in USA, Europe, and China
  ▪ 150 year old company with longstanding and deep commitment to product R&D
  ▪ Textiles, Specialty chemicals, and Composite materials
Presentation Goals

• Overview of TYCOR® W core products for wind turbine blades

• Risk Mitigation - Reduce the perceived risk of using TYCOR W
TYCOR® Fiber Reinforced Core (FRC)
General Construction

Precursor Strip with Transverse Webs
- Winding process

Wound Strip
- E-glass roving applied in double-helix architecture

Consolidated Sheet
- Face layup
- Infusion molding
- Multiple strips

Composite Web Structure (Face and foam removed for visibility)

Sheet consolidation process

Transverse web reinforcement

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TYCOR® Fiber Reinforced Core (FRC)

A True Composite Core

- **TYCOR® FRC Preforms** - Delivered as dry fiber and foam preform sheets. Final mechanical properties of TYCOR are achieved by infusion molding.

- **TYCOR Mechanical Properties** - Dominated by stiff composite webs. Foam (30 kg/m³ polyisocyanurate) is primarily a construction aid.

![TYCOR Preform Sheets](image)

**Contribution of Foam to TYCOR W Shear Modulus Values**

- **TYCOR W increment**
- **Foam alone**

Shear Modulus (MPa)

TYCOR W1 LZ  | TYCOR W1 TZ  | TYCOR W4 LZ  | TYCOR W4 TZ
• Family of standardized products, optimized for blade application with respect to *Transverse shear modulus, Cost, Weight, and Processing*

• Products: W0, W1, W2, W4, and W5
  - All use common manufacturing, with variations in reinforcement weight and spacing
  - Designed to span the performance regime between 60 kg/m³ PVC foam and balsa (shear modulus)
  - GL Type Approval in 2010 (W1, W2, W3, W4)

**Design Space by Web Construction**

<table>
<thead>
<tr>
<th>Style</th>
<th>L-Webs</th>
<th>T-Webs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weight</td>
<td>Spacing</td>
</tr>
<tr>
<td>TYCOR W0</td>
<td>Rigid</td>
<td>Very light</td>
</tr>
<tr>
<td>TYCOR W1</td>
<td>Contourable</td>
<td>Light</td>
</tr>
<tr>
<td>TYCOR W2</td>
<td>Contourable</td>
<td>Light</td>
</tr>
<tr>
<td>TYCOR W4</td>
<td>Contourable</td>
<td>Medium</td>
</tr>
<tr>
<td>TYCOR W5</td>
<td>Contourable</td>
<td>Heavy</td>
</tr>
</tbody>
</table>
TYCOR® W Core for Wind Turbine Blades

Sheet Dimensions and Processing

• **Contourable:**
  - Patent-pending feature: Sheet is consolidated on two sides, but allows high contourability in one direction
  - General flexibility before infusion allows mild contourability in second direction

• **Thickness Range**: 12mm to 78mm

• **Large Sheet Size**: Up to 1.2m x 2.4m
  - Increased kit yield
  - Improved fit during layup
  - Improved infusion processing
TYCOR® W Core for Wind Turbine Blades

Design for Shear Modulus

Shear Modulus of Core Materials

Average properties unless otherwise indicated

1 Supplier values
2 Measured on infused cores

LZ Shear modulus
TZ Shear modulus

Rigid
Contourable

Shear Modulus, MPa

Shear Modulus, MPa

TYCOR W0²
TYCOR W1²
TYCOR W2²
TYCOR W4²
TYCOR W5²

TYCOR W Core for Wind Turbine Blades

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TYCOR® W Value Proposition
Case Studies

• Weight reduction
  ▪ 40m, hybrid PVC/balsa config., conversion to TYCOR W: -180 kg
  ▪ 55m w/balsa core, conversion to TYCOR W4: -600 kg

• Convert weight reduction into blade span increase:
  ▪ 40m: +0.5m length = +2% power
  ▪ 55m: +1m length = +3% power

• Cost reduction
  ▪ 55m blade, hybrid PVC/balsa config., conversion to TYCOR W: 4% blade BOM (bill of material) cost reduction
  ▪ 65m blade, hybrid PVC/balsa config., conversion to TYCOR W: 5% blade BOM cost reduction
TYCOR® W Risk Mitigation

Blade Experience

• Response of blade community to FRC products has been very cautious
  ▪ Fundamental differences between discretely reinforced FRC, and quasi-homogeneous PVC foam and balsa core

• TYCOR History in Blades
  ▪ 2008 - TYCOR® core adopted in daily production of ~45m blade shear webs
  ▪ 2011 - TYCOR® W4 adopted in daily production of 55m blade shells and shear webs
  ▪ 90% balsa replacement in shells
  ▪ 600 kg mass reduction
  ▪ Blade fatigue testing
    > Passed 1M cycles flapwise bending
    > Passed 1M cycles edgewise bending
TYCOR® W Risk Mitigation
Characterization Testing

• TYCOR Characterization - WebCore Technologies, and Milliken & Company, have conducted a wide range of experimental work to address specific technical concerns expressed by designers, manufacturers, and certification agencies

1. Effects of axial fatigue on core shear properties
2. Environmental effects on shear properties
3. Facing cleavage energy
4. Effects of layup aids (tacifier) on shear strength
5. Axial fatigue of sandwich laminates
6. Fatigue behavior of TYCOR W and PVC foam
• **Molding Resin** (Unless noted otherwise): Epoxy resin (Momentive EPIKOTE™ Resin MGS RIMR 135 epoxy resin/ EPIKURE™ Curing Agent MGS RIMH 134- MGS RIMH 137)

• **Molding Process:** Vacuum infusion
1. Shear Properties after Axial Fatigue

Goal and Approach

Background:
In blades, core transverse shear loading is generally small ...

... However customers want assurance that TYCOR W shear properties will not degrade under the axial fatigue environment

Goal: Measure the effects of (simulated) lifetime axial fatigue on core shear properties

Approach:
1. Apply a simulated lifetime axial fatigue regimen to sandwich specimens
2. Use ASTM C273 to measure core shear properties of fatigued specimens in comparison with baseline (unfatigued) properties

ASTM C273 test configuration
1. Shear Properties after Axial Fatigue Test Laminate

- **Core Design:** 50mm thick TYCOR® W4
- **Core Orientation:** TYCOR W L-direction, reflecting spanwise orientation in blade shells
- **Molding Resin:** Hexion 737-6745-90 TR-1 polyester
- **Facing Design:** 4280 g/m² (80% at 0°, 14% at +-45°, 5% at 90°)
- **Fatigue Regimen:** Constant-strain-amplitude loading as specified by blade designer for equivalent-lifetime-damage

### Fatigue Test Matrix and Facing Stresses

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Strain amp, μ strain</th>
<th>R</th>
<th>Target load cycles</th>
<th>Load freq., Hz</th>
<th>Peak face tensile stress, MPa</th>
<th>Peak face comp. stress, MPa</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3,800</td>
<td>-1</td>
<td>10,000</td>
<td>2.0</td>
<td>137</td>
<td>-139</td>
<td>Passed</td>
</tr>
<tr>
<td>2</td>
<td>3,800</td>
<td>-1</td>
<td>10,000</td>
<td>2.0</td>
<td>136</td>
<td>-139</td>
<td>Passed</td>
</tr>
<tr>
<td>3</td>
<td>2,900</td>
<td>-1</td>
<td>100,000</td>
<td>2.0</td>
<td>103</td>
<td>-105</td>
<td>Passed</td>
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<tr>
<td>4</td>
<td>2,900</td>
<td>-1</td>
<td>100,000</td>
<td>2.0</td>
<td>102</td>
<td>-103</td>
<td>Passed</td>
</tr>
<tr>
<td>5</td>
<td>2,100</td>
<td>-1</td>
<td>2,000,000</td>
<td>3.0</td>
<td>73</td>
<td>-74</td>
<td>Passed</td>
</tr>
<tr>
<td>6</td>
<td>2,100</td>
<td>-1</td>
<td>2,000,000</td>
<td>3.0</td>
<td>73</td>
<td>-74</td>
<td>Passed</td>
</tr>
</tbody>
</table>
1. Shear Properties after Axial Fatigue

Residual Shear Properties after Axial Fatigue

After simulated lifetime axial fatigue of blade-shell laminate, TYCOR® W4 core molded with polyester resin displayed excellent retention of shear modulus (93%) and shear strength (97%)

### Baseline Static Properties

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Core shear modulus (MPa)</th>
<th>Core shear strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1S</td>
<td>105.4</td>
<td>1.42</td>
</tr>
<tr>
<td>2S</td>
<td>108.1</td>
<td>1.50</td>
</tr>
<tr>
<td>3S</td>
<td>104.6</td>
<td>1.70</td>
</tr>
<tr>
<td>4S</td>
<td>106.9</td>
<td>1.56</td>
</tr>
<tr>
<td>5S</td>
<td>106.4</td>
<td>1.65</td>
</tr>
<tr>
<td>6S</td>
<td>108.9</td>
<td>1.62</td>
</tr>
<tr>
<td>Average</td>
<td>106.7</td>
<td>1.58</td>
</tr>
<tr>
<td>Coeff. of Var.</td>
<td>1.5%</td>
<td>6.5%</td>
</tr>
</tbody>
</table>

### Residual Properties of Fatigue Specimens

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>Core shear modulus (MPa)</th>
<th>Core shear strength (MPa)</th>
<th>Modulus retention (%)</th>
<th>Strength retention (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>96.3</td>
<td>1.54</td>
<td>90.3%</td>
<td>98.0%</td>
</tr>
<tr>
<td>2</td>
<td>99.6</td>
<td>1.40</td>
<td>93.4%</td>
<td>89.0%</td>
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<tr>
<td>3</td>
<td>99.7</td>
<td>1.53</td>
<td>93.5%</td>
<td>97.4%</td>
</tr>
<tr>
<td>4</td>
<td>98.8</td>
<td>1.54</td>
<td>92.6%</td>
<td>98.0%</td>
</tr>
<tr>
<td>5</td>
<td>100.7</td>
<td>1.58</td>
<td>94.3%</td>
<td>100.1%</td>
</tr>
<tr>
<td>6</td>
<td>102.2</td>
<td>1.55</td>
<td>95.8%</td>
<td>98.1%</td>
</tr>
<tr>
<td>Average</td>
<td>99.6</td>
<td>1.52</td>
<td>93%</td>
<td>97%</td>
</tr>
<tr>
<td>Coeff. of Var.</td>
<td>2.0%</td>
<td>4.1%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2. Environmental Effects

Goal and Approach

- **Goal:** Assess the influence of environment (temperature, humidity) on core shear properties

- **Measurement Approach**
  - Determine core shear modulus and strength of exposed specimens using 4-point bending configuration with ASTM C393, ASTM D7249, and ASTM D7250

- **Test Matrix (Table)**
  - All testing performed on 25mm TYCOR® W2

<table>
<thead>
<tr>
<th>Conditioning</th>
<th>As Molded</th>
<th>As Molded</th>
<th>As Molded</th>
<th>Hot/Wet Conditioning 50C, 95% RH</th>
<th>100 Thermal Cycles, -50C to +60C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Temperature (C)</td>
<td>23</td>
<td>50</td>
<td>-50</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Justification</td>
<td>Baseline properties</td>
<td>Effect of heat</td>
<td>Effect of cold</td>
<td>Effect of hot/wet conditioning</td>
<td>Effect of thermal cycling</td>
</tr>
<tr>
<td>L Bending</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>T Bending</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

*Typical specimen configuration*
2. Environmental Effects

Shear Modulus

- Baseline shear modulus
  - L-direction: 65.4 MPa
  - T-direction: 55.6 MPa

Environmental Effects on Shear Modulus of TYCOR W2 with Epoxy Resin, 3-Specimen Average
2. Environmental Effects

Shear Strength

- Baseline shear strength
  - L-direction: 0.83 MPa
  - T-direction: 1.40 MPa

Environmental Effects on Shear Strength of TYCOR W2 with Epoxy Resin, 3-Specimen Average
2. Environmental Effects
Effect on Shear Properties - Summary

- Small Sample Size
- Thermal Cycling, Cold Temperature - No detrimental effects
- Hot Temperature and Moisture - Modest effects as expected for properties linked to resin behavior
  - 13% decrease in T-direction modulus at 50°C
  - 26% decrease in T-direction strength at 50°C

*Environmental parameters caused no unusually large effects on modulus or strength*
3. Facing Cleavage

Goal and Approach

- **Goal:** Assess facing cleavage energy compared to other blade core materials
- **Experimental Approach:**
  - Apply configuration of ASTM E 2004
  - Undercut square tabbed area to focus attention on peel energy
- **Test Matrix (25mm cores)**
  - TYCOR W1, L- and T-directions
  - TYCOR W4, L- and T-directions
  - CC H60 PVC foam
  - Medium-density balsa
3. Facing Cleavage
Progressive failure images

- An earlier round of testing without the undercut facing revealed lower balsa cleavage energy on scrim side of core
TYCOR W exhibits satisfactory tenacity of the facing bond for blades, possibly superior to other core products.
4. Effects of Tacifier

Introduction

• A study was conducted to evaluate the effect of tacifier, used as a layup aid, on sandwich core shear strength.
• Core material: TYCOR W4 25.4 mm thick
• Tacifier product: 3M Dry Layup Adhesive, Product ID 7760-4300-5068-6
• Tacifier was applied to fabric layer below the core and to the top of the core
• Shear strength evaluation: ASTM C393 (four-point bending)

<table>
<thead>
<tr>
<th>Sandwich ID</th>
<th>Tacifier Loading, per layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>None</td>
</tr>
<tr>
<td>2</td>
<td>Moderately Heavy, 43 gr/m²</td>
</tr>
<tr>
<td>3</td>
<td>Very Heavy, 83 gr/m²</td>
</tr>
</tbody>
</table>

Bend Test Configuration

Moderately Heavy Loading (43 gr/m²)

Very Heavy Loading (83 gr/m²)
4. Effects of Tacifier

Results

- At moderately heavy tacifier loading (43 gr/m²), there was no effect on shear strength.
- At intentionally excessive tacifier loading (83 gr/m²), there was ~10% decrease in LZ shear strength. No effect on TZ shear strength.

Tacifier has no strength effect when used at typical weight loadings with epoxy molding resin.
5. Core Shear Fatigue

- Core Shear Fatigue (4-point short-beam bending), $R=0.1$

![Graph showing Core Shear Stress vs. Load Cycles for different materials.](image-url)
5. Core Shear Fatigue

Normalized TYCOR W4 trendline is shallower than H60 PVC foam, indicating higher relative fatigue performance at high-cycles.

Linear Trend Lines Normalized by Static Strength

- TYCOR W4
- H60 PVC Contourable
- H60 PVC rigid
• **Goal**: Determine whether the presence of TYCOR core affects the axial fatigue performance of composite laminates

• **Approach**: Compare sandwich laminate axial fatigue performance with solid laminate results from Reference

• **Laminate Fabric**: 861 gr/m² [+45/-45/mat]

• **Laminate Designs**:
  - Solid laminate: Laminate No. “DH” from Reference, 6-ply laminate solid laminate
  - Sandwich laminate: 25.4mm TYCOR W4 core with 3-ply facings

• **Core Joint**: Included at mid-length of specimen for possible damage initiation

• Good agreement, N=1 through ~4M cycles

*TYCOR W presence had no detrimental effect on the face laminate fatigue performance for this specific laminate/loading configuration*

6. Axial Fatigue
S-N Curve Comparison for R=0.1
Summary

• TYCOR W core products can offer significant benefits over current mainstream core products (Cost; Weight; Processing)

• TYCOR W history in blades and recent characterization data should provide designers and manufacturers confidence that TYCOR W has low risk for blade application
  ▪ Fully TYCOR W-cored blade in daily production
    – Passed full-blade fatigue testing
  ▪ Blade-specific coupon-level testing (Detailed reports are available)
    – No surprises for unusual, performance-reducing behavior