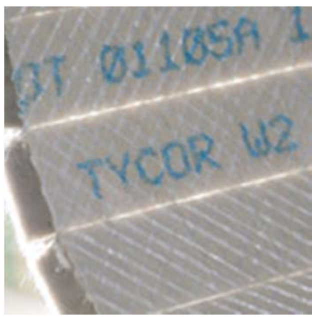
Recent Core Material Developments/Applications for Blades at Milliken

Fred Stoll, Ph.D., Senior Development Engineer

Milliken & Company

fred.stoll@milliken.com



Presentation to:

2012 Wind Turbine Blade Workshop

Albuquerque, NM, May 30-June 1, 2012

Supported in part by:

U.S. Department of Energy SBIR Phase III Xlerator Program

Grant No. DE-EE0004552 to WebCore Technologies, LLC

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/m^3)
    - 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

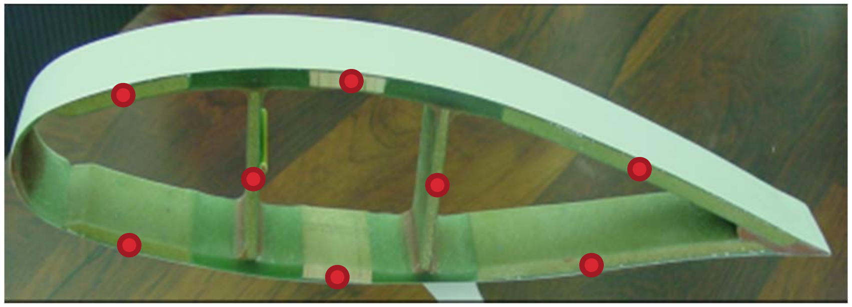


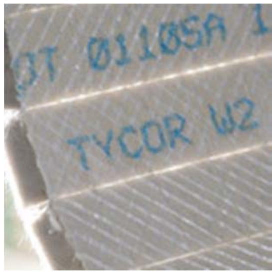
Photo used with permission of Owens Corning

● Sandwich zones in blade cross section

TYCOR® W Business Update

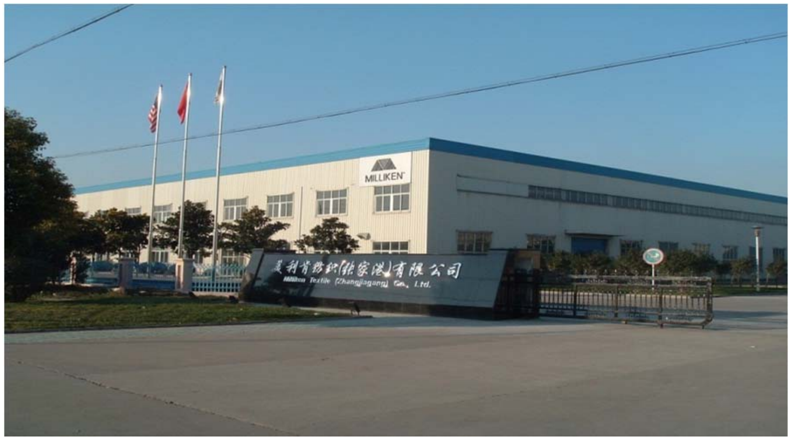
Milliken

- 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



TYCOR® W

Nexcore™

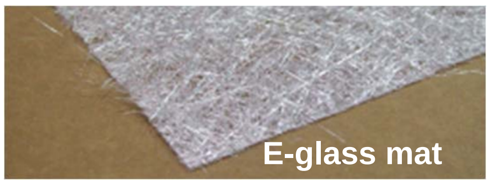


Presentation Goals

- Overview of TYCOR® W core products for wind turbine blades
- Risk Mitigation - Reduce the perceived risk of using TYCOR W

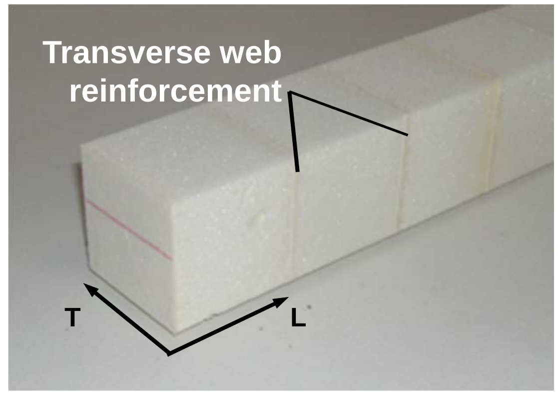
TYCOR® Fiber Reinforced Core (FRC)

General Construction



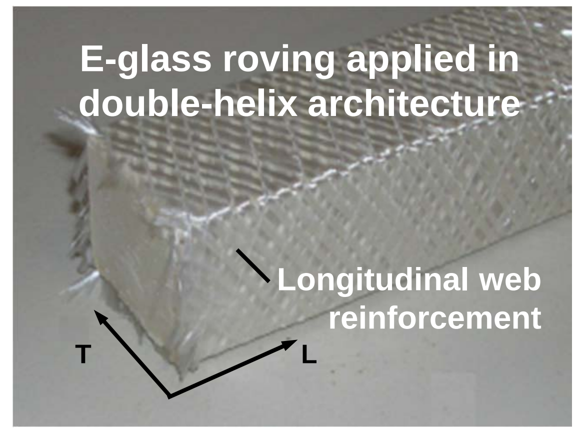
- **Lamination process**
- **Cutting processes**

<u>Precursor Strip with Transverse Webs</u>



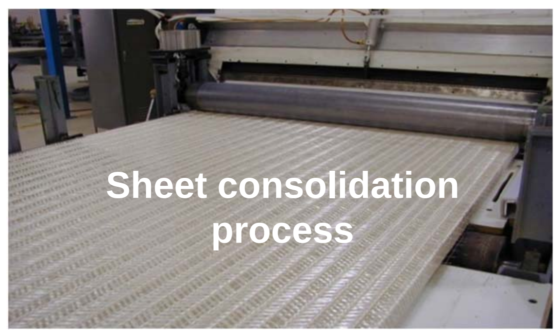
- **Winding process**

<u>Wound Strip</u>

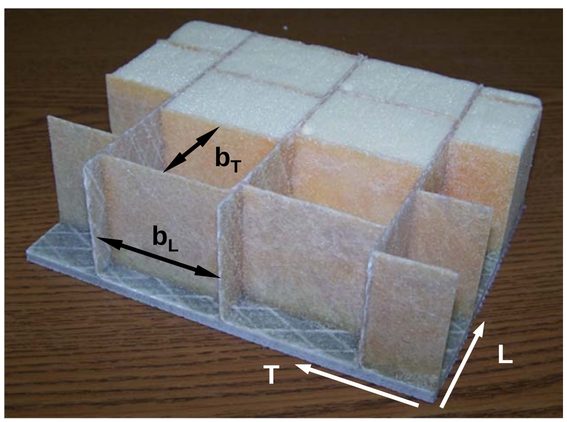


- **Multiple strips**

<u>Consolidated Sheet</u>



- **Face layup**
- **Infusion molding**

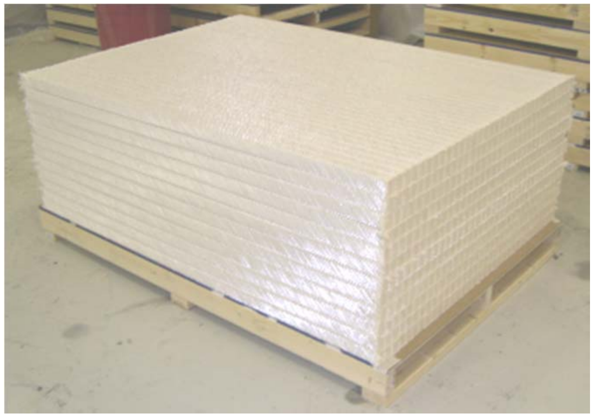


<u>Composite Web Structure</u>
(Face and foam removed for visibility)

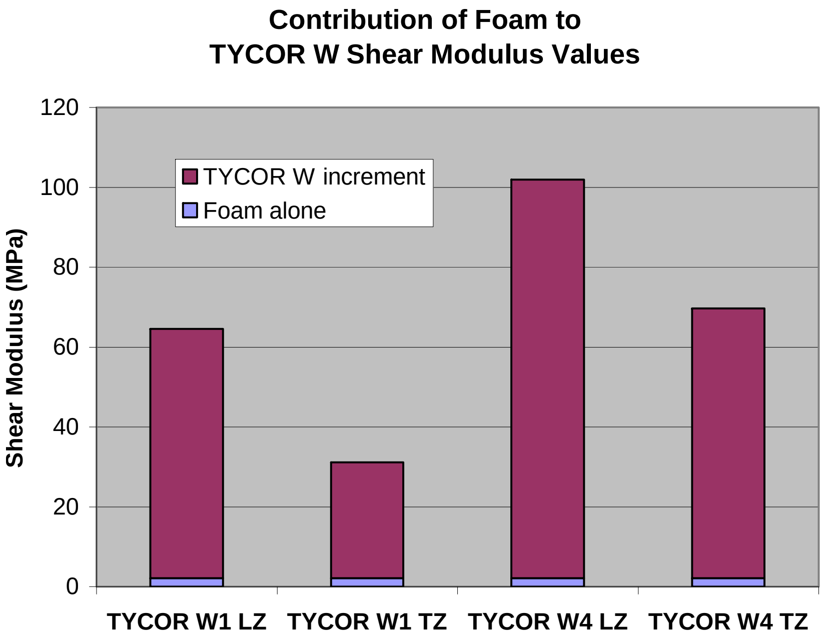
TYCOR® Fiber Reinforced Core (FRC)

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/m^3 polyisocyanurate) is primarily a construction aid.



TYCOR Preform Sheets



TYCOR® W Core for Wind Turbine Blades

Product Family

- <u>Family of standardized products</u>, 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/m^3 PVC foam and balsa (shear modulus)
  - GL Type Approval in 2010 (W1, W2, W3, W4)

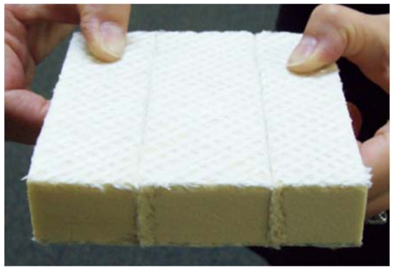
<u>Design Space by Web Construction</u>

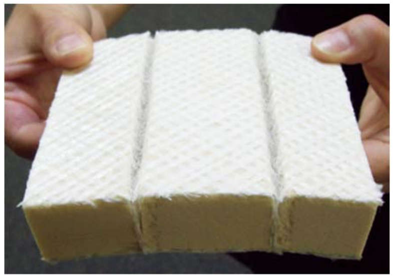
	Style	L-Webs		T-Webs	
		Weight	Spacing	Weight	Spacing
TYCOR W0	Rigid	Very light	51mm	Light	38mm
TYCOR W1	Contourable	Light	44mm	Light	38mm
TYCOR W2	Contourable	Light	44mm	Medium	38mm
TYCOR W4	Contourable	Medium	44mm	Medium	38mm
TYCOR W5	Contourable	Heavy	44mm	Heavy	38mm

TYCOR® W Core for Wind Turbine Blades

Sheet Dimensions and Processing

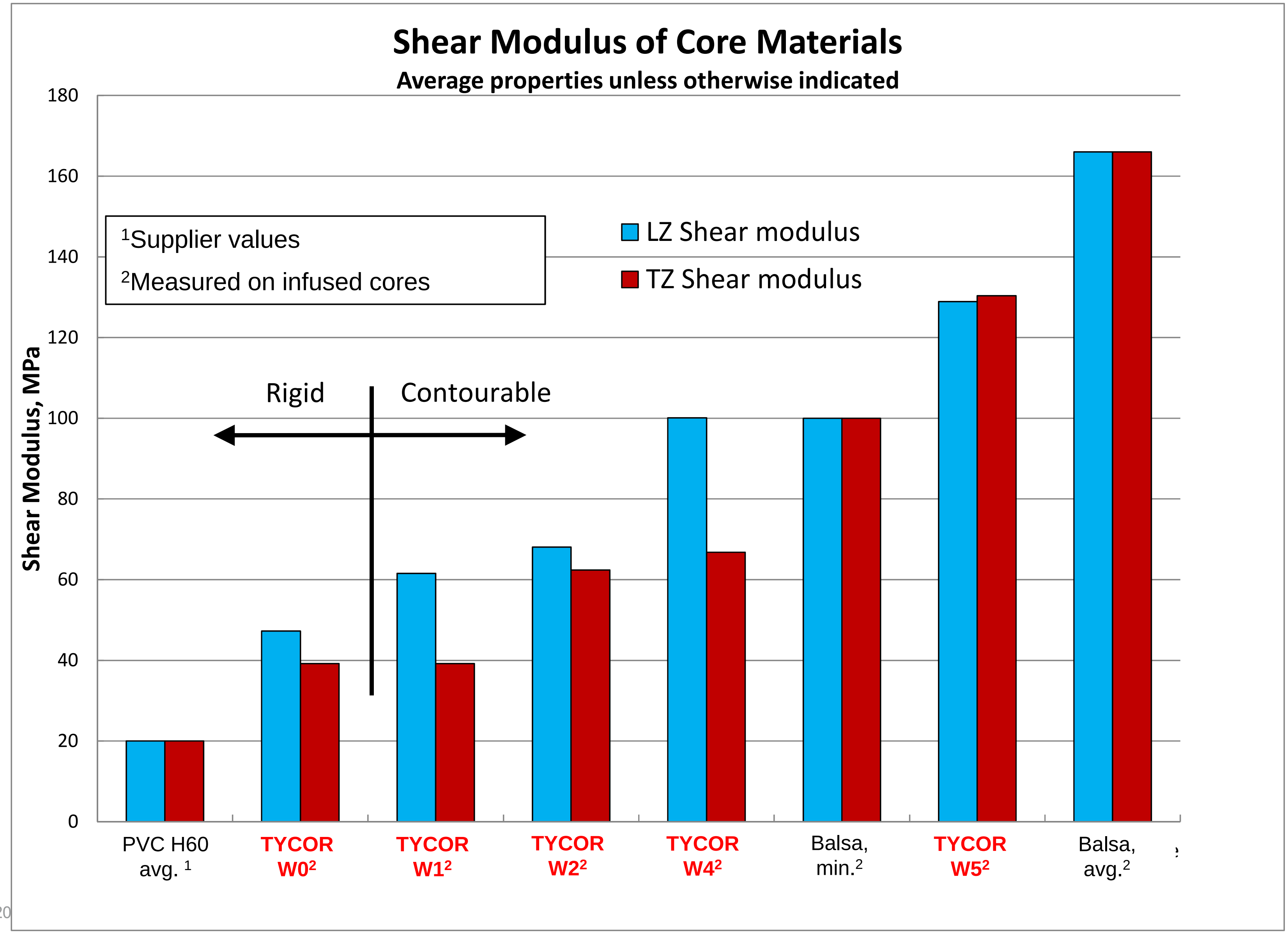
- Contourable:
  - Patent-pending feature: Sheet is consolidated on two sides, but allows high contourability in one direction
  - General flexibility before infusion allows mild contourability in second direction
- Thickness Range : 12mm to 78mm
- Large Sheet Size: Up to 1.2m x 2.4m
  - Increased kit yield
  - Improved fit during layup
  - Improved infusion processing





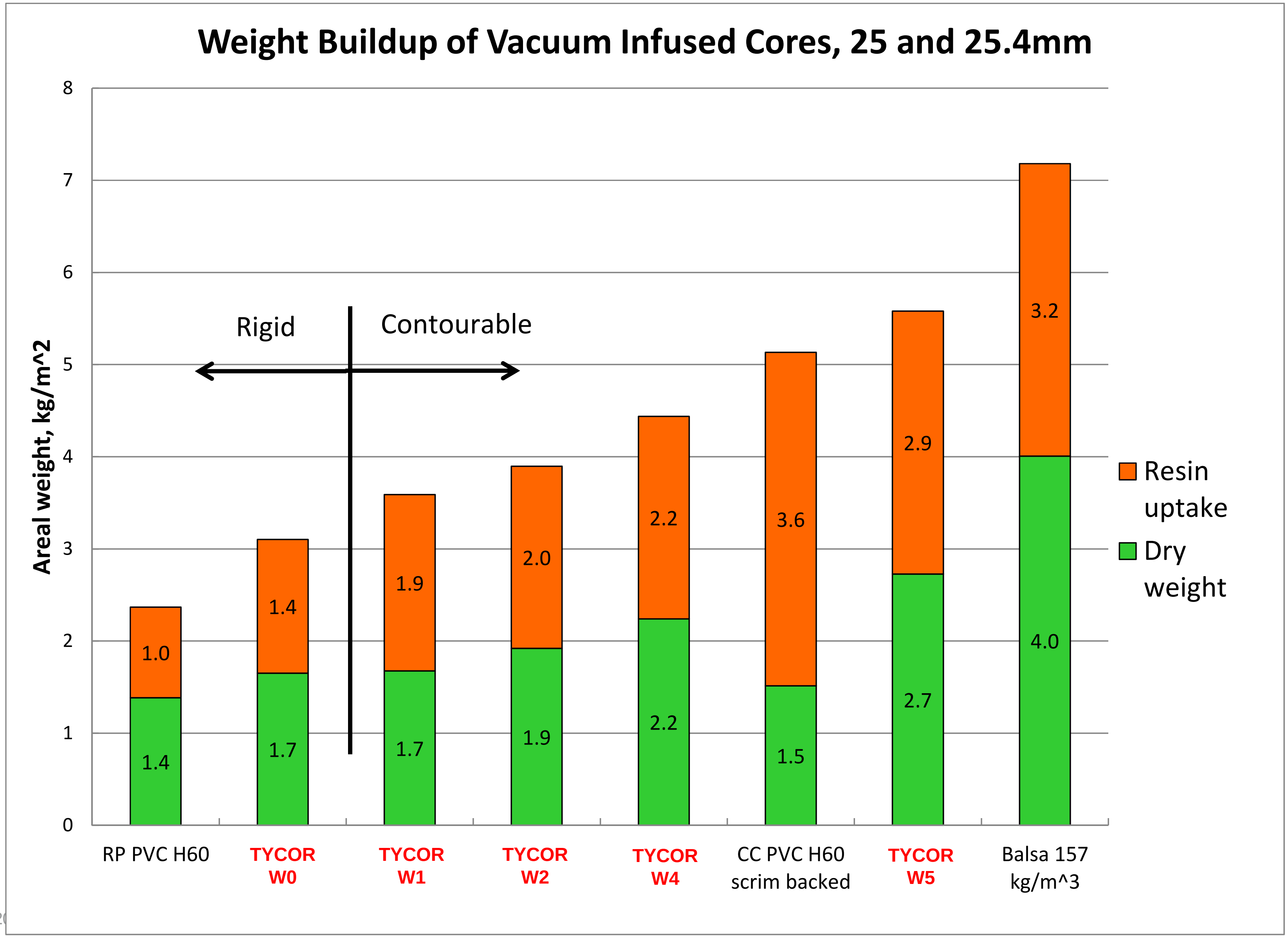
TYCOR® W Core for Wind Turbine Blades

Design for Shear Modulus



TYCOR® W Core for Wind Turbine Blades

Weight Buildup of Vacuum-Infusion Cores



TYCOR® W Value Proposition

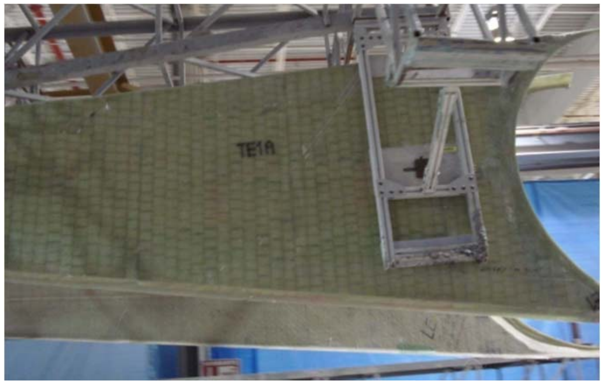
Case Studies

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

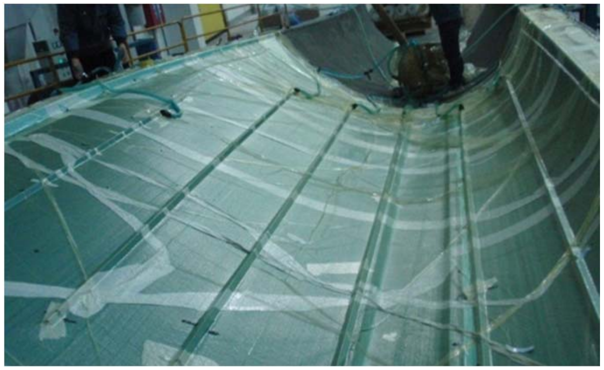
TYCOR® W Risk Mitigation

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**



Shear Webs with TYCOR® FRC



Conformable TYCOR® W in Blade Shells

TYCOR® W Risk Mitigation

Characterization Testing

- <u>TYCOR Characterization</u> - 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

TYCOR® W Risk Mitigation

Notes on Experimental Work

- 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:

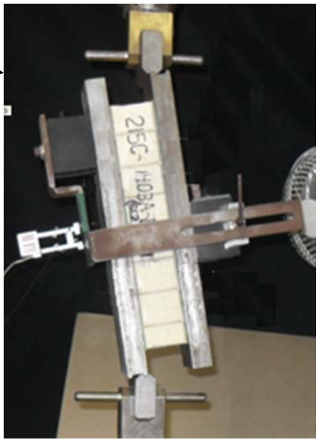
In blades, core transverse shear loading is generally small …

… 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

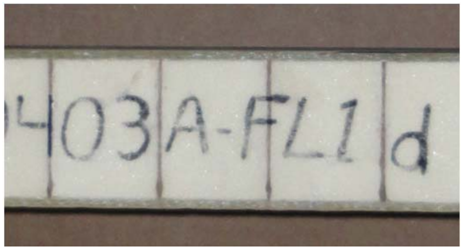
1. Shear Properties after Axial Fatigue

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

Specimen No.	Strain amp, μ strain	R	Target load cycles	Load freq., Hz	Peak face tensile stress, MPa	Peak face comp. stress, MPa	Notes
1	3,800	-1	10,000	2.0	137	-139	Passed
2	3,800	-1	10,000	2.0	136	-139	Passed
3	2,900	-1	100,000	2.0	103	-105	Passed
4	2,900	-1	100,000	2.0	102	-103	Passed
5	2,100	-1	2,000,000	3.0	73	-74	Passed
6	2,100	-1	2,000,000	3.0	73	-74	Passed



Sandwich Laminate

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

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

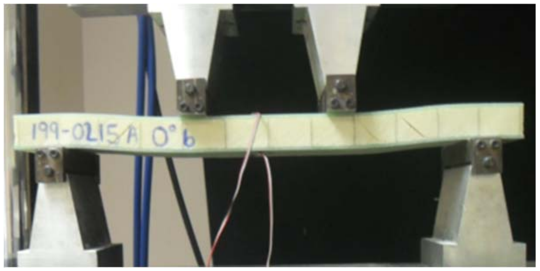
Residual Properties of Fatigue Specimens

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

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**



Typical specimen configuration

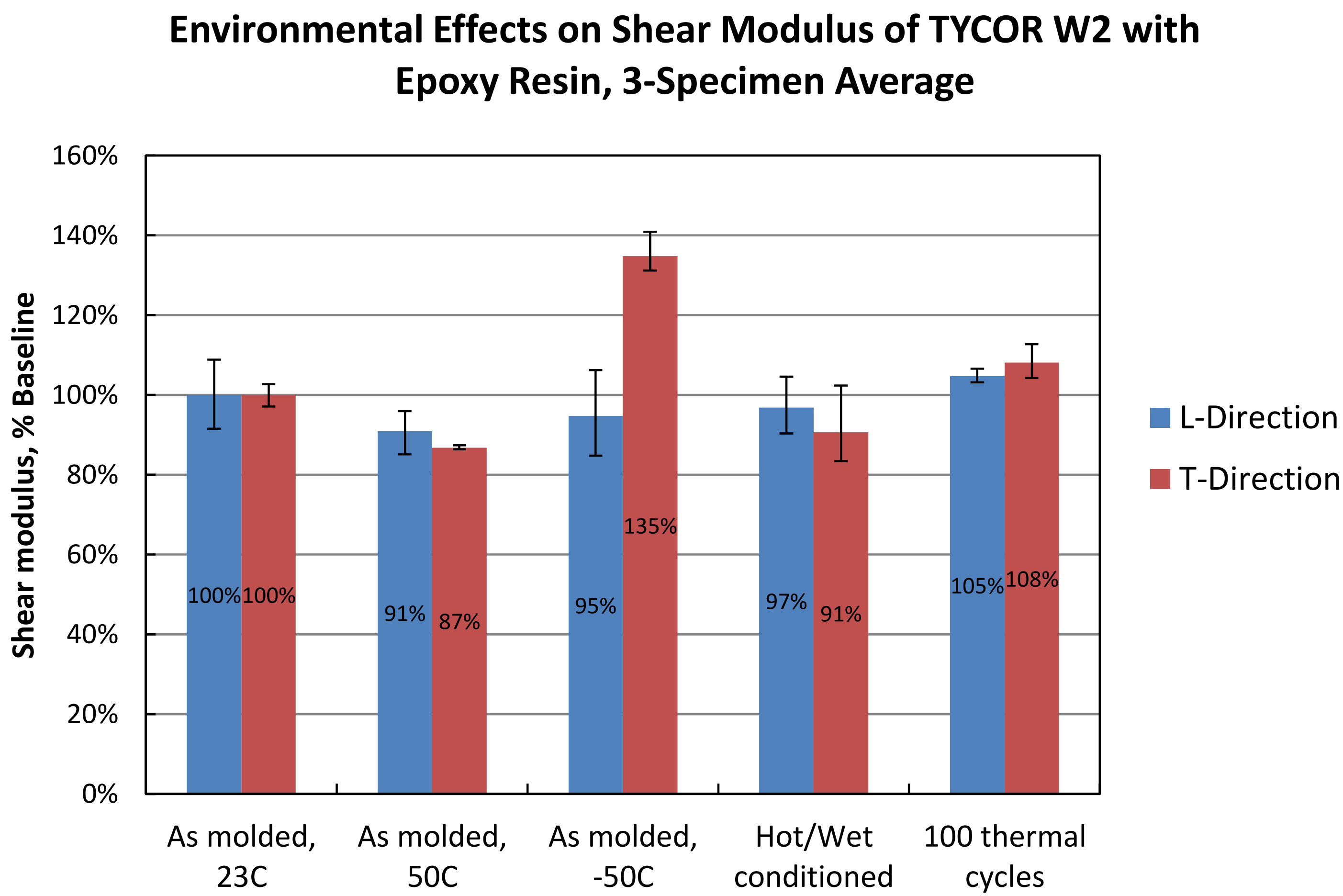
Table. Test Matrix - Number of Specimens

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

2. Environmental Effects

Shear Modulus

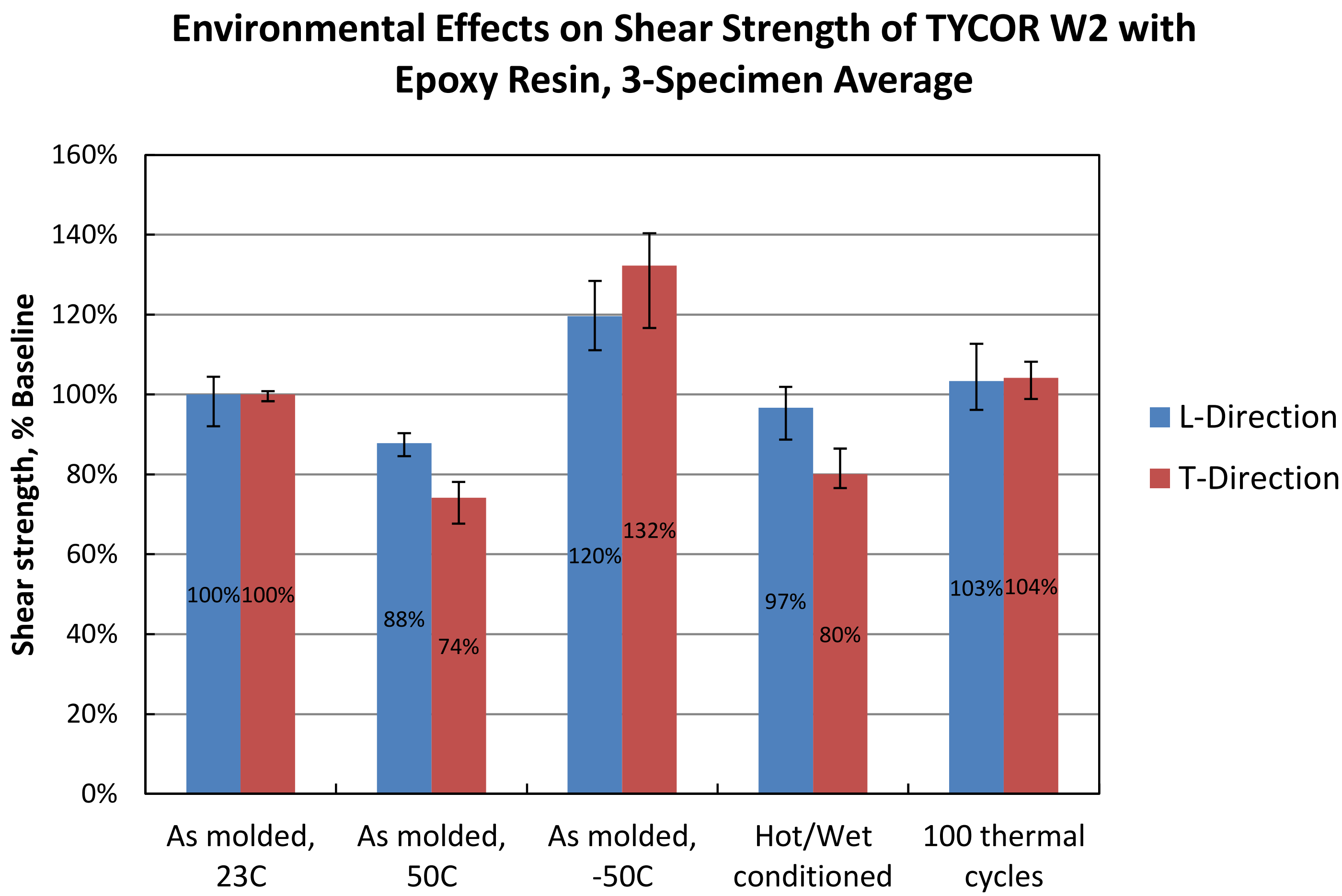
- **Baseline shear modulus**
  - **L-direction: 65.4 MPa**
  - **T-direction: 55.6 MPa**



2. Environmental Effects

Shear Strength

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



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**

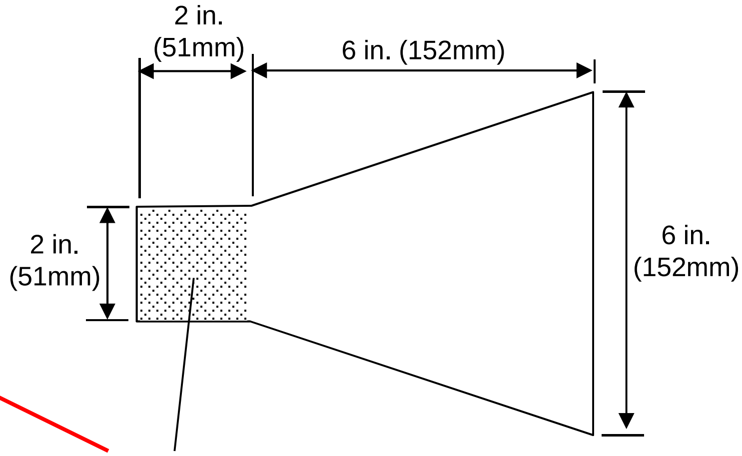
Environmental parameters caused no unusually large effects on modulus or strength

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**

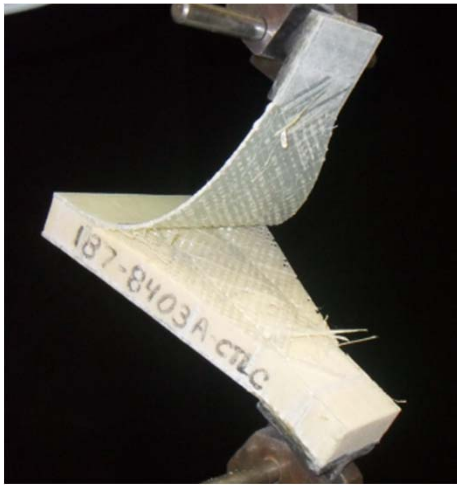
Test Configuration (ASTM E2004)



Top facing of tab area under-cut before testing

3. Facing Cleavage

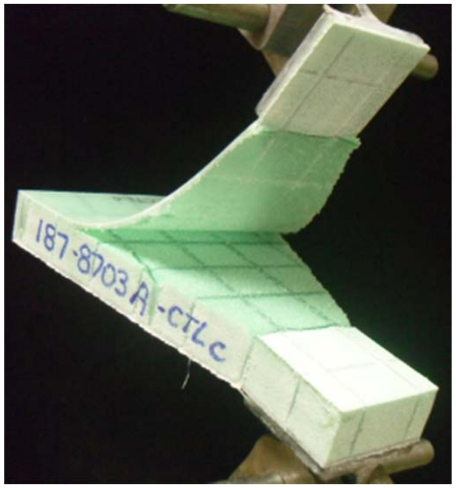
Progressive failure images



TYCOR W L-Direction

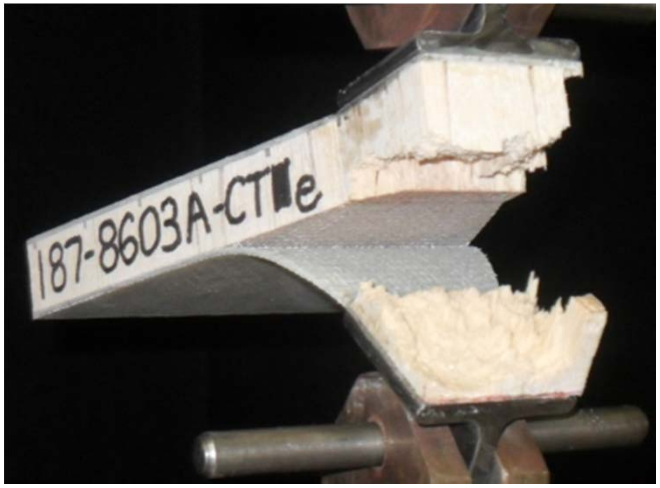
TYCOR W T-Direction

- **An earlier round of testing without the undercut facing revealed <u>lower</u> balsa cleavage energy on scrim side of core**



Foam

Balsa

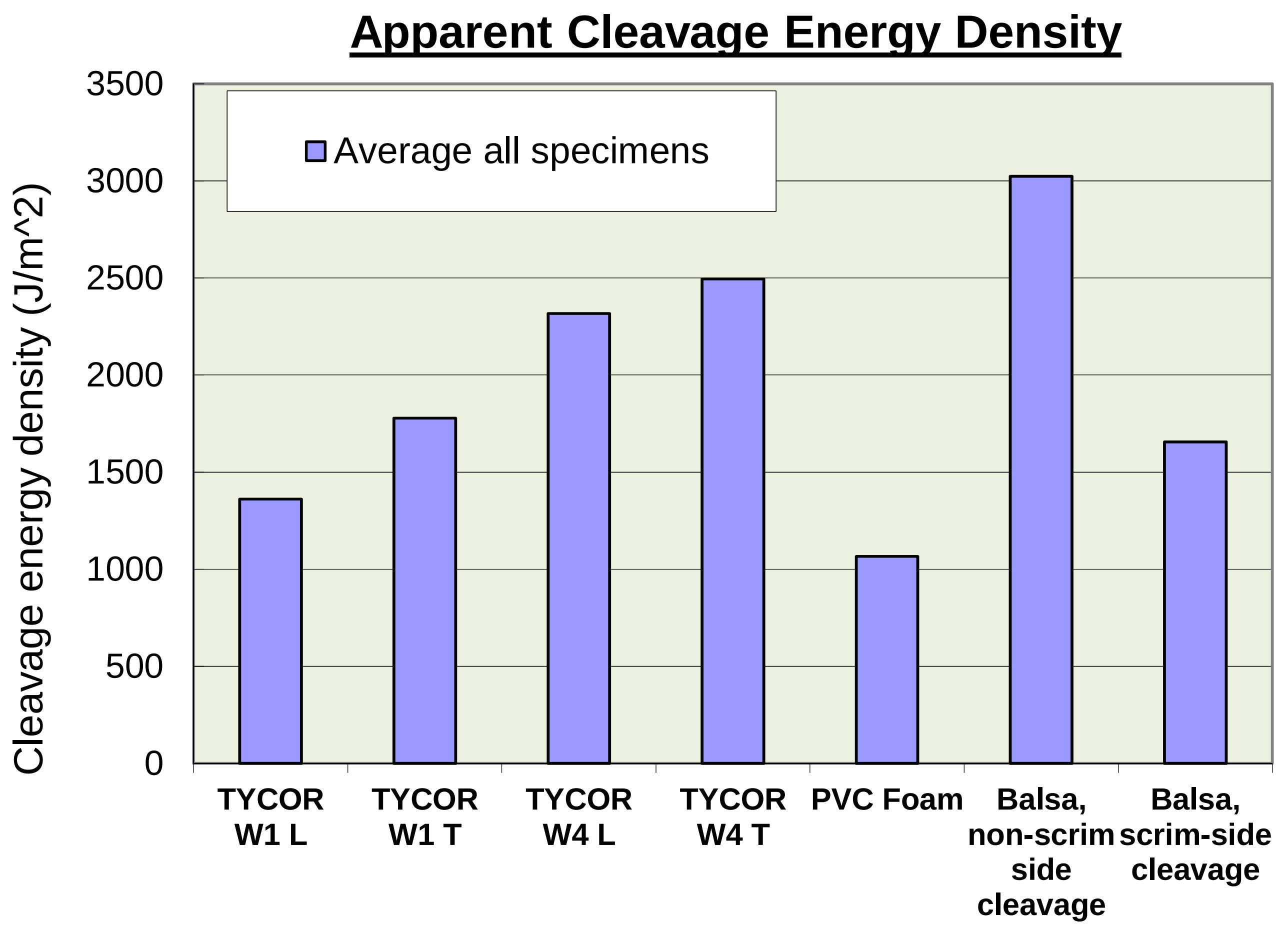


Balsa, Scrim-Side Cleavage

3. Facing Cleavage

Cleavage energy results

TYCOR W exhibits satisfactory tenacity of the facing bond for blades, possibly superior to other core products.

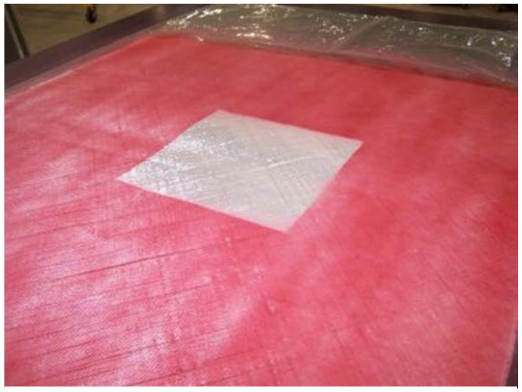


4. Effects of Tacifier

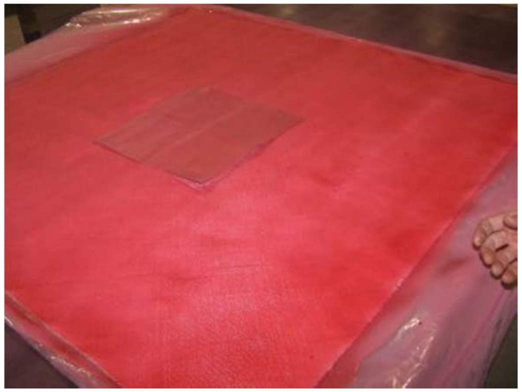
Introduction

- 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)

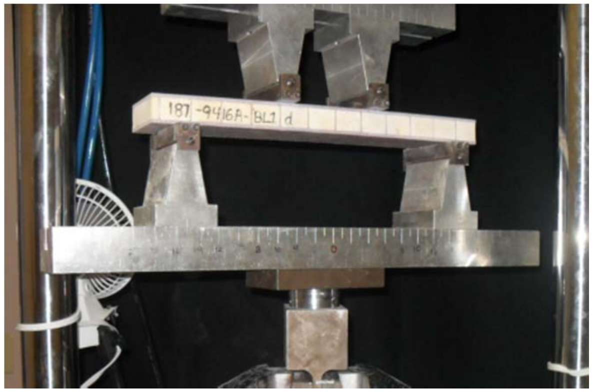
Sandwich ID	Tacifier Loading, per layer
1	None
2	Moderately Heavy, 43 gr/m^2
3	Very Heavy, 83 gr/m^2



Moderately Heavy Loading (43 gr/m^2)



Very Heavy Loading (83 gr/m^2)



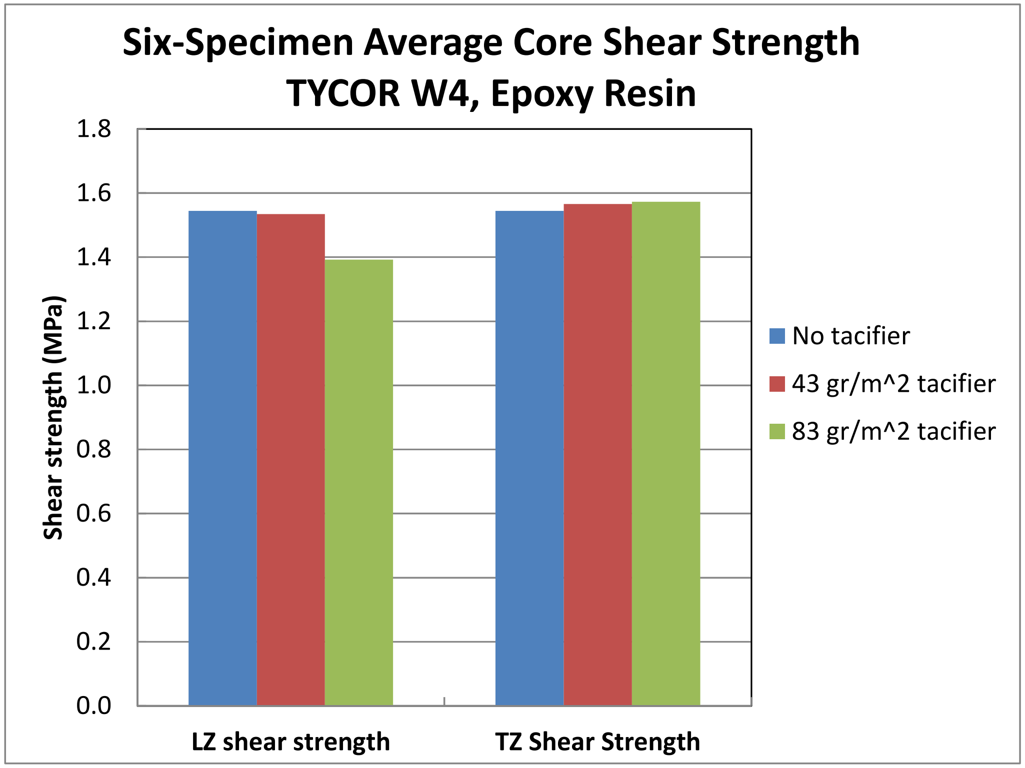
Bend Test Configuration

4. Effects of Tacifier

Results

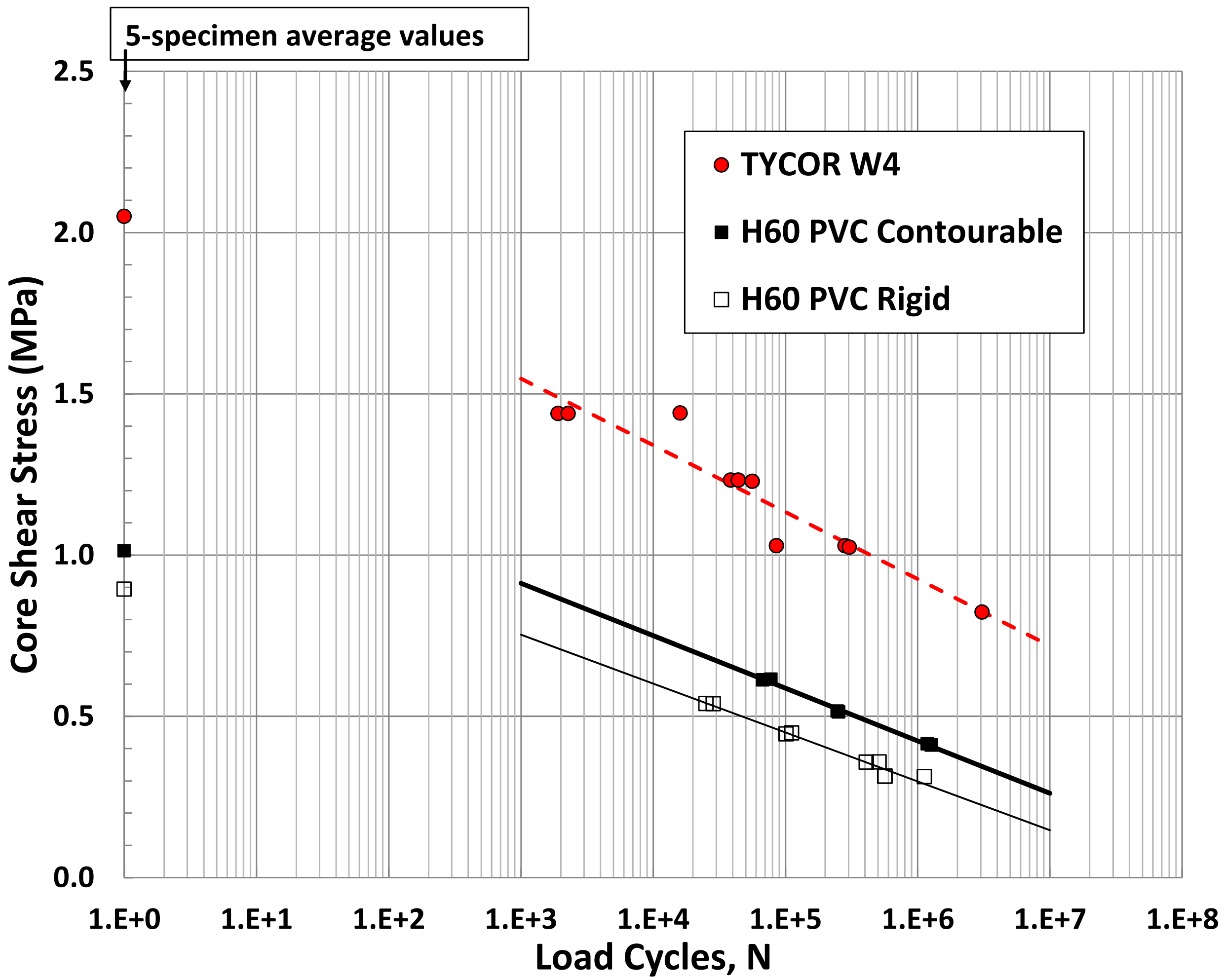
- **At moderately heavy tacifier loading (43 gr/m^2), there was no effect on shear strength**
- **At intentionally excessive tacifier loading (83 gr/m^2), there was ~10% decrease in LZ shear strength. No effect on TZ shear strength.**

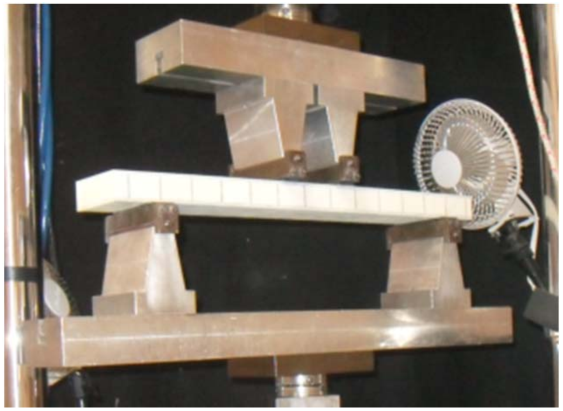
Tacifier has no strength effect when used at typical weight loadings with epoxy molding resin



5. Core Shear Fatigue

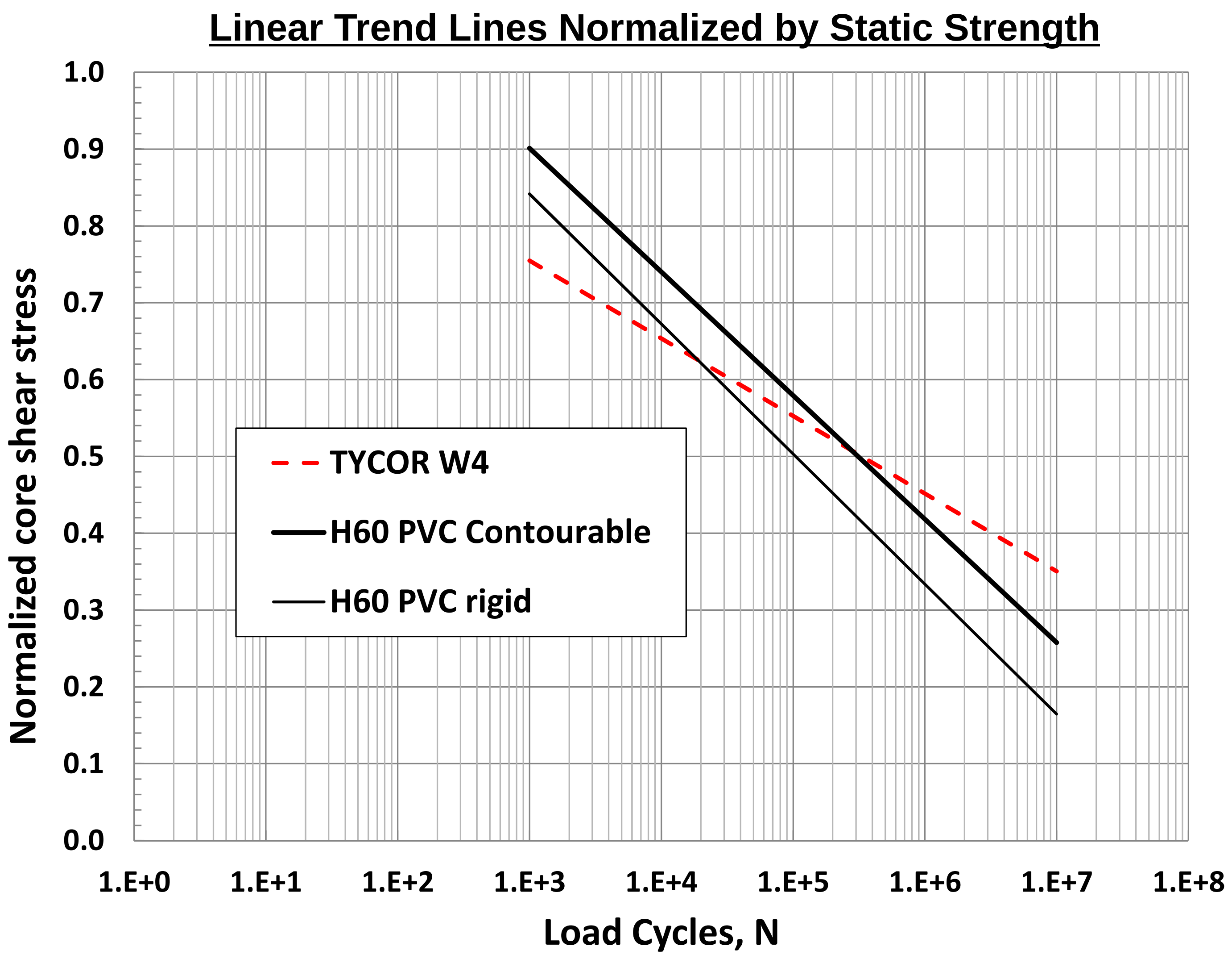
- **Core Shear Fatigue (4-point short-beam bending), R=0.1**





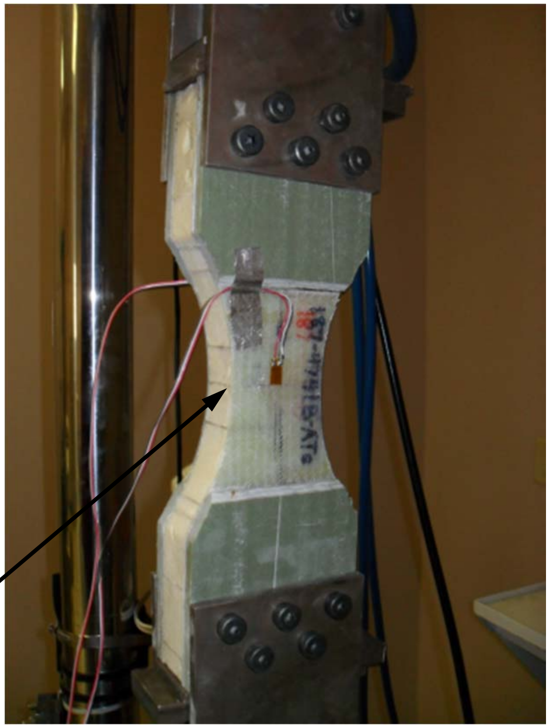
5. Core Shear Fatigue
Normalized Trend Lines

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



6. Axial Fatigue
General

- <u>Goal</u>: **Determine whether the presence of TYCOR core affects the axial fatigue performance of composite laminates**
- <u>Approach</u>: **Compare sandwich laminate axial fatigue performance with solid laminate results from Reference**
- <u>Laminate Fabric:</u> **861 gr/m^2 [+45/-45/mat]**
- <u>Laminate Designs</u>:
  - **Solid laminate: Laminate No. "DH" from Reference, 6-ply laminate solid laminate**
  - **Sandwich laminate: 25.4mm TYCOR W4 core with 3-ply facings**
- <u>Core Joint</u>: **Included at mid-length of specimen for possible damage initiation**



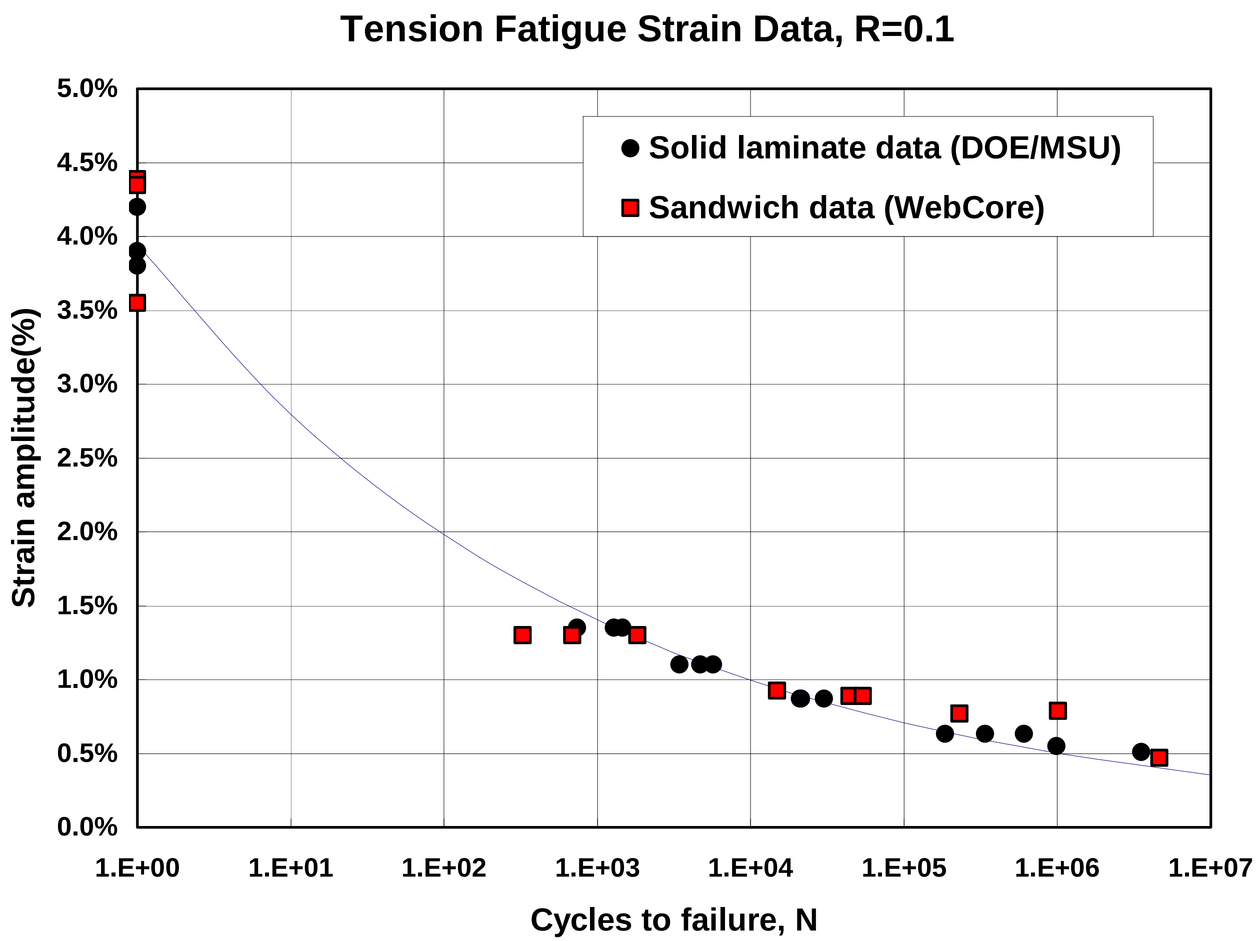
<u>Reference</u>: DOE / MSU Composite Material Fatigue Database Version 18.1, March 25, 2009

6. Axial Fatigue

S-N Curve Comparison for R=0.1

- **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



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