Blade Design with Engineered Cores Materials

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Sandwich Construction in Large Blades

As blade sizes have grown, sandwich construction has become prevalent.

Core Selection:
- Affects weight, cost, and structural performance
- Core optimization is a natural part of blade design optimization
TOPICS

• Introduction to TYCOR® Engineered Core Materials
• Core Performance Issues in Blades
• Experimental and Analytical Comparison of TYCOR, PVC foam and Balsa Core Materials
  – Design for Buckling Resistance
  – Local Strength Measurements of Sandwich Laminates
  – Weight and Cost
TYCOR® Fiber Reinforced Core (FRC)

- FRC has Web-Core Construction
  - Glass-fiber composite webs
  - Low-density (30 kg/m³) polyisocyanurate foam
- Unidirectional or Bi-directional Web Orientation
- High specific stiffness and strength

Sandwich Panel with Unidirectional FRC

Sandwich Panel Interior with “GX”-style Bi-Directional FRC
“GX”-Style FRC for Infusion Molded Sandwich Structures

- “Engineered Core:” Orthotropic stiffness and strength properties can be tailored independently in \( L \) and \( T \) directions.

**Diagram:**
- E-glass mat
- Laminating adhesive
- Precursor/tooling foam
- E-glass roving
- High-Speed Winding Process
- Fabric Lay-up and Infusion Molding
- Sheet consolidation process
- Low-Cost TYCOR® Core Preform Sheets
FRC Processing

- **Conformability:** Conforms to characteristic blade skin curvatures
- **Machining:** Dry preform cuts easily with band saw, table saw, utility knife, etc.
- **Infusion Molding:** Works well in vacuum infusion with single-side feed due to through-thickness porosity
- **Sheet Size:** Large sheet size minimizes handling (e.g. $1.2m \times 2.4m$ or larger)
Status of FRC in Blades

• WebCore supported Global Energy Concepts and TPI Composites in DOE SBIR Project, fabricating two MW-scale research wind turbine blades featuring TYCOR core.
  – All TYCOR kitting was performed on-site with simple shop tools (table saw, utility knives).
  – All eight lay-ups and molding-infusions went smoothly.

• FRC is nearing certification for use in shear webs, replacing balsa for a 2+MW turbine system

• Completed initial feasibility study of FRC as complete-blade PVC foam replacement for second wind turbine manufacturer. Showed significant cost and weight reductions.
Characteristic Sandwich Loading

- **Local Sandwich Loading** - predominantly in-plane
- **Face Laminates** - designed to provide strength and stiffness for global blade response
- **Sandwich Construction** - serves to increase local bending stiffness of laminates to control local bending and suppress buckling
- **Core Loading** - minimal direct loading traditional sense (Transverse shear, through-thickness compression/tension)
Core-Related Structural Performance Considerations

• Global or Panel-Level Buckling
  – Core affects buckling design margins, must meet minimum requirements
  – Assessed analytically

• Local Sandwich Laminate Strength (In-Plane)
  – “Don’t mess things up” - Core must enable face laminates to achieve required static and fatigue strength

• Sandwich Transitions
  – Laminate strength at core thickness transitions
  – Laminate strength at core closeouts
In-Plane Strength Example: Local Failure Modes for Edgewise Compression

**Study:** Experimental and Analytical Comparison of FRC, PVC foam and Balsa Core Materials

Alternate core materials:
- Low-density PVC foam (60 kg/m³)
- Medium-density end-grain balsa

Compare:
1. Blade buckling resistance
2. Local strength of sandwich laminates under in-plane loading
3. Core weight and cost
Blade Buckling Analysis

- Core Material Properties
  - A general core material is orthotropic
  - Transverse shear modulii have large effect on global buckling

## Descriptions of Cores Used in Study

<table>
<thead>
<tr>
<th>Core</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-density PVC Foam</td>
<td>Airex C70.55, 60 kg/m³ density</td>
</tr>
<tr>
<td>Medium-density Balsa</td>
<td>ProBalsa® Standard, 155 kg/m³ density, “Minimum” properties</td>
</tr>
<tr>
<td>TYCOR_uni H</td>
<td>High-strength uni-directional FRC</td>
</tr>
<tr>
<td>TYCOR_GX L</td>
<td>Lower-property GX FRC</td>
</tr>
<tr>
<td>TYCOR_GX H</td>
<td>Higher-property GX FRC</td>
</tr>
</tbody>
</table>

### Orthotropic Elastic Input Parameters for FEA

<table>
<thead>
<tr>
<th>Material</th>
<th>Extens. Stiffness (Gpa)</th>
<th>Shear Stiffness (Gpa)</th>
<th>Poisson's Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-TLX_3300</td>
<td>18.28</td>
<td>11.25</td>
<td>11.25</td>
</tr>
<tr>
<td>PVC Foam</td>
<td>0.045</td>
<td>0.045</td>
<td>0.069</td>
</tr>
<tr>
<td>Balsa</td>
<td>0.400</td>
<td>0.400</td>
<td>2.000</td>
</tr>
<tr>
<td>TYCOR_uni H</td>
<td>0.248</td>
<td>0.016</td>
<td>0.248</td>
</tr>
<tr>
<td>TYCOR_GX L</td>
<td>0.145</td>
<td>0.069</td>
<td>0.269</td>
</tr>
<tr>
<td>TYCOR_GX H</td>
<td>0.207</td>
<td>0.076</td>
<td>0.345</td>
</tr>
</tbody>
</table>
Flat-Plate Buckling Analysis
Uniaxial Compression of Plate Strip

- **Goal:** Simulate a strip of *blade skin*, explore effects of orthotropic core transverse shear moduli, $G_{xz}$, $G_{yz}$
- **Analysis method:** Double-Fourier series solution for thin-faced sandwich
- **Laminate:** Core thickness=37mm, Face thickness=2.6mm of E-TLX 3300 ([0/±45]), Width $b=100$ mm

⇒ As $G$ decreases, buckling load decreases
⇒ *FRC and balsa* can be used at lower thicknesses than low density foams
⇒ *For Orthotropic core*, $G_{xz}$ (compression axis) should be greater than $G_{yz}$
⇒ $G_{yz}$ can be reduced somewhat lower than $G_{xz}$ (for weight and cost reduction) with only small loss in buckling performance
Flat-Plate Buckling Analysis
In-Plane Shear of Shear-Web Laminate

- Simulate a Shear-Web laminate under in-plane shear using FEA
- Rectangular panel, simple edge support, 1m wide by 5m long
- Demonstrate sensitivity of buckling to transverse shear modulus of core, $G$
- Core thickness=50mm, Face thickness=1.5mm, +-45° E-glass reinforcement

$\Rightarrow$ Buckling resistance decreases as $G$ decreases
Blade Buckling Analysis

- Blade shape and design loads from conceptual design study conducted by GEC under U.S. DOE-sponsored WindPACT program
  - Fiberglass blade, 43.5m long
  - 2.5MW turbine
- NuMAD (Sandia Nat’l Lab) preprocessor with ANSYS FEA code.
- Targeted buckling studies at 25%, 50%, 75% (not completed) span stations
- Focused on aft-skin buckling performance

<table>
<thead>
<tr>
<th>r/R</th>
<th>r (m)</th>
<th>Airfoil</th>
<th>Chord (m)</th>
<th>Design Loads (kN-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.025</td>
<td>1.125</td>
<td>Cylinder</td>
<td>2.25</td>
<td>Flap: 6,763.5, Edge: 3,172.5</td>
</tr>
<tr>
<td>0.250</td>
<td>11.250</td>
<td>DU97-W-300</td>
<td>3.60</td>
<td>Flap: 3,982.5, Edge: 1,552.5</td>
</tr>
<tr>
<td>0.500</td>
<td>22.500</td>
<td>DU91-W2-250</td>
<td>2.60</td>
<td>Flap: 1,890.0, Edge: 545.3</td>
</tr>
<tr>
<td>0.750</td>
<td>33.750</td>
<td>DU93-W-210</td>
<td>1.60</td>
<td>Flap: 448.1, Edge: 96.2</td>
</tr>
</tbody>
</table>

* Peak value of negative edge bending (trailing edge in compression)
Blade Buckling Study

- Approach
  - Apply design load (moment) to constant-cross-section model of corresponding blade station
  - Vary core thickness in the aft skins to determine minimum core thickness that satisfies required buckling margin
Blade Buckling Study - 25% Span Station Results

- GX-FRC designs perform similarly to balsa
- GX-FRC enables 11% thickness reduction compared to PVC foam
- Uni-FRC requires higher thickness

![Graphs showing buckling design margin versus core thickness and buckling-critical core thickness]
Buckling Study Comments

• For buckling-critical laminates, FRC and balsa can be used at reduced thickness compared to PVC foam

• Future FEA Blade Analysis:
  – Expand to additional span stations
  – Expand to additional core areas (shear webs, forward skins)

• Challenges:
  – Finite element modeling approaches to account for transverse shear effects
  – Numerical problems in some design regimes (questionable local buckling modes)
Experimental Core Comparisons - Structural Performance, Weight, Cost

- **Two laminate styles:**
  - **Shear Web:**
    - 50 mm rigid cores (GXW1, balsa, PVC foam)
    - 2-ply and 3-ply faces, Double bias E-glass fabric [45/-45/mat], 0.69 mm/ply
    - Vinyl ester resin (in-plane shear) and Epoxy resin (edgewise compression)
  - **Blade Skins:**
    - 25mm contourable cores (GXW2, balsa, PVC foam)
    - 2-ply and 3-ply faces, Tri-axial E-glass fabric [0/±45], 0.51mm/ply
    - Epoxy resin

- **Total of 12 laminate designs molded and tested**
- **Comparisons**
  - Local in-plane compressive and shear strength of laminates
  - Core weight and cost including absorbed resin
Experimental Core Comparisons - Structural Performance, Weight, Cost

- Five specific GX FRC designs investigated

<table>
<thead>
<tr>
<th>FRC Design ID</th>
<th>Background</th>
<th>L Webs</th>
<th>T Webs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spacing (mm)</td>
<td>Fiber weight (gr/m²)</td>
<td>Fiber angle</td>
</tr>
<tr>
<td>GXW1</td>
<td>For shear webs as balsa replacement</td>
<td>50</td>
<td>550</td>
</tr>
<tr>
<td>GXW2</td>
<td>Modified GXW1 for reduced cost</td>
<td>50</td>
<td>550</td>
</tr>
<tr>
<td>GXW4</td>
<td>Improved edgewise compression, Light</td>
<td>38</td>
<td>400</td>
</tr>
<tr>
<td>GXW5</td>
<td>Improved edgewise compression, Heavy</td>
<td>38</td>
<td>550</td>
</tr>
<tr>
<td>GX-Light</td>
<td>For shear webs as PVC-foam replacement</td>
<td>50</td>
<td>300</td>
</tr>
</tbody>
</table>
In-Plane Shear Strength of Shear-Web Laminates

- Primary loading for shear-web laminates
- Single-specimen values

⇒ GXW1 FRC performed similarly to PVC foam and balsa

Test Configuration
Bonded edge doublers
Specimen: 305 mm square
Open area: 230 mm square

In-Plane Local Shear Strength

<table>
<thead>
<tr>
<th>Material</th>
<th>2-Ply Faces</th>
<th>3-Ply Faces</th>
<th>4-Ply Faces</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC foam</td>
<td>576</td>
<td>899</td>
<td>935</td>
</tr>
<tr>
<td>Balsa</td>
<td>660</td>
<td>824</td>
<td>664</td>
</tr>
<tr>
<td>GXW1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Edgewise Compression Strength of Shear-Web Laminates

- Important for compatibility of shear web with spar cap compression
  ⇒ *GXW1 performance comparable to PVC foam*
  ⇒ *In practice: Design to strain requirement*

**Test Configuration**
Specimen: 250mm x 150mm
Gage length: 150mm

**Local Edgewise Compressive Strength (3-Specimen Averages)**

<table>
<thead>
<tr>
<th>Material</th>
<th>2-Ply Faces</th>
<th>3-Ply Faces</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVC foam</td>
<td>417</td>
<td>615</td>
</tr>
<tr>
<td>Balsa</td>
<td>513</td>
<td>840</td>
</tr>
<tr>
<td>GXW1 L</td>
<td>406</td>
<td>663</td>
</tr>
<tr>
<td>GXW1 T</td>
<td>364</td>
<td>697</td>
</tr>
</tbody>
</table>
Edgewise Compression Strength of Skin Laminates

- GXW2 performed lower than PVC foam and balsa
- GXW4 and GXW5 were designed to provide improved performance

⇒ Demonstrates ability to engineer FRC to meet requirements
⇒ In practice: Design to strain requirement

Test Configuration
Specimen: 250mm × 150mm
Gage length: 150mm
Weight and Cost Analysis

- **Note on Representative Core Prices**
  - PVC foam and balsa: Representative prices, reflecting input from a variety of sources
  - GX-FRC: Price was set equal to balsa cost – This is a *conservative price* for high-volume applications
Weight and Cost–25mm Blade Skin Cores

⇒ GXW2 FRC offers lower cost and weight than PVC foam and balsa at equal thickness
Weight and Cost–50mm Shear Web Cores

- **At equal thickness:**
  - \( \text{GXW1 FRC} \) offers lower cost and weight than balsa
  - \( \text{GXW1 FRC} \) heavier (3.4 kg/m\(^2\)) than PVC foam, slightly less expensive

- **FRC may enable thickness reduction compared to PVC foam**
  - not yet accounted for
Weight and Cost–
75mm Shear Web Cores

- GXW1 not optimized versus PVC foam. Consider “GX Light” designed as PVC foam replacement for shear web

Weight Build-up of 75mm Shear Web Cores

- At equal thickness:
  ⇒ “GX Light” FRC 26% less expensive than PVC foam
  ⇒ “GX Light” FRC only slightly heavier (1.4 kg/m²) than PVC foam

- FRC may enable thickness reduction compared to PVC foam - not yet accounted for
FRC Cost Basis

How can FRC compete?

- Low cost input materials
  - Low-property foam serves only as tooling material
  - E-glass roving used in winding
- Low-cost processes
  - Gang saw
  - High-speed winder
  - Foam laminator

Characteristic Costs of Foams and Balsa

- PVC foam - 60 kg/m³
- Balsa - 155 kg/m³
- Polyiso’ foam - 30 kg/m³
- Extruded PS foam - 30 kg/m³
Conclusions and Comments

• TYCOR® Fiber-Reinforced Core (FRC) is a tailor able orthotropic core. Processes well for infusion-molded blades

• Compared to balsa: GX FRC provides equivalent buckling resistance to balsa at approximately the same thickness, and provides cost and weight savings.

• Compared to PVC foam:
  – GX FRC provides equivalent buckling resistance to PVC foam at reduced thickness. Further studies planned to better quantify.
  – GX provides cost savings.
  – GX provides weight savings compared to PVC contour core, slightly heavier for equal-thickness rigid core.

• Long-term benefit of FRC: Availability
  – Commodity input materials (insulation foam, E-glass roving)
  – Low capital investment for new production lines

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