Hybrid Fiber-Reinforced Composites with Innegra™ S for Improved Impact Resistance and Safety

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Innegra Technologies
Competing Demands

Fiber-Reinforced Composites

- High Strength
- Light Weight
- True costs?
  - Raw materials
  - Processing
  - Total Cost of Ownership

- Safety behavior different, less predictable
## Failure Modes

<table>
<thead>
<tr>
<th>FRP Composites</th>
<th>Common Metals</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Catastrophic</strong></td>
<td><strong>Progressive</strong></td>
</tr>
<tr>
<td><strong>Brittle</strong></td>
<td><strong>Plastic Deformation</strong></td>
</tr>
<tr>
<td>– Delamination / debonding</td>
<td>– Ductile bending / wrinkling</td>
</tr>
<tr>
<td>– Fibrillation / Cracking / Shear Failure</td>
<td><strong>Predictable / Programmable</strong></td>
</tr>
<tr>
<td>– Fiber / Matrix fracture</td>
<td></td>
</tr>
</tbody>
</table>

*Fig. 1: Crush failure modes: a) fiber spaying, b) fragmentation, c) brittle fracture. Source: Don Adams*


Value of Hybridization

- What composites do best!
  - Combine different materials with different properties to yield something new

- Different types of hybridization
  - Material
  - Structure
  - Process

- Best case = synergistic interaction between components
Hybridization Strategies

- **Continuous Fiber Reinforcements**
  - **Ply-by-Ply**: combining plies of different fabrics
  - **Hybrid Fabric**: co-weaving of different yarns into a single fabric
  - **Hybrid Yarn**: blending of fibers at the yarn level, then forming into fabric

- **Hybrid Structure**: combination of short fiber and continuous fiber reinforcement
ABOUT INNEGRA
**What are Innegra Yarns?**

*Innegra S* is an olefin-based high performance yarn used most often in conjunction with a high modulus fiber to increase toughness, durability, dampening, and in some cases, reduce weight.

*Innegra H* is a hybridized yarn containing Innegra and a high modulus fiber (carbon, glass, basalt, or p-aramid). These fibers are co-mingled at the filament level to combine the properties of both fibers in the same plane, resulting in increased performance.
## Fiber Comparisons

<table>
<thead>
<tr>
<th></th>
<th>Innegra</th>
<th>Aramid</th>
<th>Basalt</th>
<th>Carbon (PAN)</th>
<th>E-Glass</th>
<th>S-Glass</th>
<th>UHMWPE</th>
<th>Quartz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density</strong></td>
<td>0.84</td>
<td>1.44</td>
<td>2.70</td>
<td>1.78</td>
<td>2.54</td>
<td>2.48</td>
<td>0.97</td>
<td>2.20</td>
</tr>
<tr>
<td><strong>Tensile Strength</strong></td>
<td>667</td>
<td>2400 - 3600</td>
<td>4840</td>
<td>5313</td>
<td>2600</td>
<td>4800</td>
<td>2200 - 3900</td>
<td>6000</td>
</tr>
<tr>
<td><strong>Modulus</strong></td>
<td>15</td>
<td>60 - 120</td>
<td>89</td>
<td>292</td>
<td>72</td>
<td>85</td>
<td>65 - 132</td>
<td>72</td>
</tr>
<tr>
<td><strong>Elongation at Break</strong></td>
<td>9.5</td>
<td>2.2 – 4.4</td>
<td>3.2</td>
<td>1.8</td>
<td>4.0</td>
<td>5.5</td>
<td>3 - 4</td>
<td>3.0</td>
</tr>
<tr>
<td><strong>UV Resistance</strong></td>
<td>Very Good</td>
<td>Poor</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Very Good</td>
<td>Excellent</td>
</tr>
<tr>
<td><strong>Solvent Resistance</strong></td>
<td>Excellent</td>
<td>Fair</td>
<td>Excellent</td>
<td>Very Good</td>
<td>Very Good</td>
<td>Very Good</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td><strong>Moisture Absorption</strong></td>
<td>&lt; 0.1</td>
<td>3.2 – 7.0</td>
<td>0.2 – 12.0</td>
<td>0</td>
<td>0.1</td>
<td>0.1</td>
<td>&lt; 0.1</td>
<td>0</td>
</tr>
<tr>
<td><strong>Max Processing Temp</strong></td>
<td>150°C</td>
<td>450</td>
<td>980</td>
<td>3500</td>
<td>730</td>
<td>850</td>
<td>140</td>
<td>1070</td>
</tr>
<tr>
<td><strong>Dielectric Constant (Dk)</strong></td>
<td>2.2</td>
<td>3.4</td>
<td>2.0 – 3.2</td>
<td>conductive</td>
<td>6.2</td>
<td>5.2</td>
<td>2.25</td>
<td>3.7</td>
</tr>
<tr>
<td><strong>Dissipation Factor (Df)</strong></td>
<td>0.0009</td>
<td>0.014 - 0.01</td>
<td>0.003 – 0.015</td>
<td>conductive</td>
<td>0.003 - 0.004</td>
<td>0.002</td>
<td>0.0002</td>
<td>0.0001</td>
</tr>
<tr>
<td><strong>Coefficient of Linear Thermal Expansion</strong></td>
<td>-8.0</td>
<td>-4.0 to -4.9</td>
<td>8.0</td>
<td>-1.1</td>
<td>5.4</td>
<td>2.9</td>
<td>-12.0</td>
<td>0.54</td>
</tr>
</tbody>
</table>
Stress Strain Curve

LOAD - N

POSITION - mm

Carbon

E-glass

Innegra S
Structural Effects

- **Rule-of-Mixtures Behavior**
  - Tensile strength / modulus
  - Compressive strength / modulus
  - Flex strength / modulus

- **Positive Deviation from Rule-of-Mixtures**
  - Impact strength / energy absorbed

**Rule of Mixtures**

\[ X_c = C_f X_f V_f + C_m X_m V_m \]

assuming \( V_m = 1 - V_f \)

**For multiple fibers**

\[ X_c = C_{f1} X_{f1} V_{f1} + C_{f2} X_{f2} V_{f2} + C_m X_m V_m \]

assuming \( V_m = 1 - V_{f1} - V_{f2} \)

Primary fibers carry the load, secondary fibers provide increased impact resistance
Impact Energy Absorption - Carbon

Fiber Areal Weight (gsm) vs. Impact Energy (J) for different carbon layups, with a red arrow indicating a 100% higher impact at the same basis weight compared to controls.

- 3k carbon PW: 3-ply [0/45/90]
- 3k carbon PW: 4-ply [0/45]2S
- 3k carbon PW: 5-ply [0/45/90/45/0]
- 3k carbon PW: 6-ply [0/45/90]2S
- HIC PW: 3-ply [0/45/90]

100% Carbon - Controls

Hybrid Yarn
The Early Adopter – Formula One

- Increase damage tolerance
- Increase impact resistance
- Reduce catastrophic failure
“falling weight impact tests and the mallet tests both showed the Innegra material to be equal to and generally superior to the Kevlar equivalent. This was manifested both in terms of resistance to damage and minimizing the size and quantity of debris”. –G. Savage

from EVALUATION OF POLYPROPYLENE FIBER COMPOSITES FOR USE IN ACCIDENT DEBRIS RETENTION by Gary Savage, PhD
Improved Impact Resistance

- **Application**: Rear wing assemblies for automotive racing by Hurley Racing Products
- **Need**: improved impact resistance in thin wall parts
- **Results**:
  - Innegra fabric used in place of honeycomb or foam core
  - Significantly improved impact resistance
  - Removes need to add hard-points for joints
  - Reduced failures where structure bolts to support

http://www.hurleyracingproducts.com/
Improved Impact Resistance

12mm Carbon
- 400 J Impact
- 3k carbon twill / epoxy prepreg
- 40mm crack at surface
- Thermography NDE: crack propagation into at least 4 layers

12mm Carbon – Innegra
- 400 J Impact
- 3k carbon PW + Innegra PW / epoxy infusion
- 8mm crack at surface, dent
- Thermography NDE: No damage observed from 2nd ply down

[Images of thermography scans showing cracks and ply delaminations]
Safer Failure Mode

- **Application**: CFRP tubes for cycling, etc. by Lenzi Egisto
- **Need**: safer failure mode
- **Results**:
  - 100% carbon tubes “crashed”
  - Carbon-Innegra hybrid tubes underwent greater distortion but the layers were still intact
  - “It is essentially confirmed what we had set out to verify, namely, that the tube hybrid of carbon/Innegra has characteristics of elasticity, absorption of the deformation, clearly superior to the pipe in 100 % Carbon, which arrives at break in a brittle way.”

http://www.lenziegisto.it/en
**Improved Damage Tolerance**

- **Application**: Stock Car Racing
- **Need**: Lightweighting with improved damage tolerance
  - Survive bump impacts during race without losing functionality
- **Locations**:
  - Air intake ducts
    - Radiator (1)
    - Brakes (2)
- **Results**: carbon/Innegra air intake scoops that resist collapsing upon impact and continue to function as designed

NASCAR figure used for illustration purposes only. No endorsement should be inferred.
Post-Fracture Strength

- **Application**: Whitewater kayak CFRP paddle shaft by Adventure Technology
- **Need**: prevention of catastrophic failure on impact
- **Results**:
  - Improved impact resistance
  - Improved secondary strength, reducing catastrophic failures in field

http://www.atpaddles.com/us/
New Vehicle Design

- Clemson University Automotive Engineering Deep Orange Program
  - Team-based Masters’ Project
  - Sponsored by OEM – specific challenge
  - Student team responsible for market research, conception, design, construction of prototype
- Deep Orange 5 – Urban Mobility for Generation Y & Z
  - The idea: To create a better value proposition for young adults who have small amounts of disposable income and less interest in vehicle ownership, yet need a personal mobility solution that aligns with their complex lifestyle.
Need: weight reduction, improved safety
- Carbon fiber structures often have a brittle failure - highly undesirable
- Old thinking: oversize laminates to avoid any plastic deformation. This often increases the weight and cost of the part.
- New thinking: DO5 used Innegra fibers to add some ductility to the laminates and was willing to take the tradeoff between stiffness and cost/weight.

Location: roof bows
- Side pillar-less design
- Roof bow & door required to carry entire loads
DO5 – Roof Bow Laminate Design

Laminate plan - original

Plain weave (300-600 GSM)
Uni directional 0° (300 GSM)
Uni directional 90° (300 GSM)
Uni directional 45° (300 GSM)
Uni directional -45° (300 GSM)
Uni directional 0° (300 GSM)
Uni directional 0° (300 GSM)
Uni directional 90° (300 GSM)
Uni directional 45° (300 GSM)
Plain weave (300-600 GSM)

Laminate plan - with Innegra

Plain weave (300-600 GSM)
Uni directional 0° (300 GSM)
Uni directional 90° (300 GSM)
Uni directional 45° (300 GSM)
Uni directional 45° (300 GSM)
Innegra HIC plain weave
Innegra HIC plain weave
Uni directional 45° (300 GSM)
Uni directional 90° (300 GSM)
Uni directional 0° (300 GSM)
Plain weave (300-600 GSM)

12 Layers

10 Layers
DO5 – Structural Modeling

FMVSS 216
Strength to weight ratio (SWR) = 3.9

Torsional stiffness
= 17.8 kN•m/deg

Bending stiffness
= 7.5 kN/mm (center of the car)
= 23.7 kN/mm (on the rockers)
Innegra in Hybrid Composites

- Larger window of design opportunities
- Advantages
  - Place hybridizing material exactly where needed
  - Build in damage resistance, damage tolerance
  - Safer failure mode
- Challenges
  - Designing with a material with very different properties from standard reinforcements
  - Manufacturing process considerations
Thank you!

Questions?

www.Innegratech.com