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Facing up to the Challenges of Natural Fibres as “Potential” Engineering Composite Reinforcements

Jim Thomason

Composites Week @Leuven
September 16-20th 2013
Leuven, Belgium
Natural Fibre Composites

- Jim – why are you so down on Natural Fibre?
  - Some personal NF History
- Some of the NFC Challenges
  - NF Anisotropy
  - NF cross section
- Some Conclusions
Natural Fibre some Personal History

Half Day Symposium on Natural Fibre Composites
ECCM-8, Naples 1998

Prof Verpoest also attended

Held standard team meeting
ECCM-8 NF Symposium
The Natural Fibre Conundrum

NF – green, cheap, great properties can replace glass fibre

Hey – Lets make some NF composites and replace glass fibre

Hmmm – my NF composites are nowhere near what I predicted
Natural Fibre some Personal History

Potential Advantages of Natural Fibres

- Potentially low cost
- Low density (1.45 g/cc vs 2.6 g/cc for GF)
- Very “green” image
- Incinerable - thermally recyclable (with no net increase in CO2 balance)
- Modulus range exceeds that of E-glass
- Non-abrasive - low wear of processing equipment
- No skin irritation problems during handling

Identified Disadvantages of Natural Fibres

- Fibre properties dependent on level of processing (high properties require more fibre processing = cost penalty)
- Properties dependent on seasonal conditions
- High levels of water adsorption and poor dimensional stability
- Low strength compared to E-glass
- Anisotropic structure - low transverse properties = poor flex & compression performance
- Composites generally require higher fibre loading resulting in high processing viscosities.
- Surface treatments and polymer coupling agents required for best composite properties
- Odour problem after composite processing
- Potentially Bioactive
Natural Fibre some Personal History

1999-2001 Owens Corning NFC Project

- Based on Long Fibre PP Process Technology
- 12 mm pultruded pellets, 20-50% NF-PP
- Pilot Plant capability 500kg/day
  - plan for first production plant in India
- New Sizings developed - some patented for Natural Fibre and Regenerated Cellulose Fibre (Rayon)
- Multiple Demonstrator Parts Moulded and Tested
- Huge automotive OEM, Tier 1 and Tier 2 interest
## Natural Fibre Composite - Demonstrators

<table>
<thead>
<tr>
<th>Organizer / Moulder</th>
<th>Part</th>
<th>Method</th>
<th>Part Wt. (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC, MIG Plastics</td>
<td>Buick - Door handle pull</td>
<td>Inj. Mould</td>
<td>0.14</td>
</tr>
<tr>
<td>JCI</td>
<td>Jeep Grand Cherokee - Door Inner</td>
<td>Inj. Mould</td>
<td>0.91</td>
</tr>
<tr>
<td>Mayco Plastics</td>
<td>Chrysler - Air deflector</td>
<td>Inj. Mould</td>
<td>0.31</td>
</tr>
<tr>
<td>Delphi, Proto Plastics</td>
<td>GM – Instrument panel retainer</td>
<td>Inj. Mould</td>
<td>2.6kg</td>
</tr>
<tr>
<td>SEG Kunststoff technik</td>
<td>Audi A2 - Fender stiffener</td>
<td>Inj. Mould</td>
<td>0.45</td>
</tr>
<tr>
<td>Pelzer, Clion GmbH</td>
<td>DCX PT Cruiser - Underbody shield</td>
<td>Extrusion Compress</td>
<td>1.35</td>
</tr>
</tbody>
</table>
## Typical Properties of PP Based Compounds

<table>
<thead>
<tr>
<th></th>
<th>30% Talc</th>
<th>30% Jute-A</th>
<th>30% Jute-B</th>
<th>30% Glass*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Modulus (GPa)</strong></td>
<td>3.6</td>
<td>4.1</td>
<td>4.4</td>
<td>6.5</td>
</tr>
<tr>
<td><strong>Tensile (MPa)</strong></td>
<td>30</td>
<td>35</td>
<td>45</td>
<td>45-90</td>
</tr>
<tr>
<td><strong>Flex Str (MPa)</strong></td>
<td>56</td>
<td>56</td>
<td>76</td>
<td>65-145</td>
</tr>
<tr>
<td><strong>N Izod (J/m)</strong></td>
<td>27</td>
<td>59</td>
<td>48</td>
<td>80-110</td>
</tr>
<tr>
<td><strong>Un Izod (J/m)</strong></td>
<td>203</td>
<td>198</td>
<td>177</td>
<td>260-750</td>
</tr>
<tr>
<td><strong>HDT (°C)</strong></td>
<td>92</td>
<td>120</td>
<td>135</td>
<td>155</td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td>1.13</td>
<td>1.01</td>
<td>1.01</td>
<td>1.13</td>
</tr>
</tbody>
</table>
Comparison PP Composite Performance

Short Glass

Long Jute

Long Glass

Long Rayon
Comparison Composite Cost/Performance

### Strength

- **Modulus**
  - $/kg Composite per MPa
  - $/kg Natural Fiber Input

- **Unnotched Impact**
  - $/kg Composite per ft-lb
  - $/kg Natural Fiber Input

- **Notched Impact**
  - $/kg Composite per ft-lb
  - $/kg Natural Fiber Input

### Performance Metrics

- **Notched Impact**
  - Talc > 2

### Key Comparisons

- **Modulus**
  - 20% NF vs. 40% NF
  - 20% Talc vs. 40% Talc
  - 20% GF vs. 40% GF

- **Unnotched Impact**
  - 20% NF vs. 40% NF
  - 20% Talc vs. 40% Talc
  - 20% GF vs. 40% GF

- **Notched Impact**
  - 20% NF vs. 40% NF
  - 20% Talc vs. 40% Talc
  - 20% GF vs. 40% GF
Natural Fibre some Personal History

1999-2001 Owens Corning NFC Project

Project shelved 2002,
Natural Fibre Composites are not
Performance-Cost competitive with existing materials
Some Philosophy

- If you know your enemies and know yourself, you can win a hundred battles without a single loss.

- If you only know yourself, but not your opponent, you may win or may lose.

- If you know neither yourself nor your enemy, you will always endanger yourself.

*The Art of War*, Sun Tzu
Some of the Challenges of Working with NF

Fibre natural variability
Fibre highly anisotropic
Low transverse and shear reinforcement performance
Fibres mostly non-circular
Fibre lumen = composite voids
Fibre cross section non-uniform along length
Fibre “diameter” often much larger than man-made fibres
High moisture content in fibres at ambient RH – processing issues
Temperature sensitivity – in particular odour issues in processing
Many forms of NF not suitable for use in standard industry processes

Poor (often negative) performance in composites
Composite fibre content measurement?
Moisture sensitivity in composite
Bio-activity (rotting, fungus, mould)
Fibre-matrix interaction - poor
Fogging/Emission issues in Automotive applications
Why Natural Fibre Composites?

Some typical fibre properties are shown in the Table below:

<table>
<thead>
<tr>
<th></th>
<th>Sisal</th>
<th>Jute</th>
<th>Flax</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus (GPa)</td>
<td>17-28</td>
<td>20-45</td>
<td>27-70</td>
<td>75</td>
</tr>
<tr>
<td>Strength (GPa)</td>
<td>0.1-0.8</td>
<td>0.2-0.9</td>
<td>0.3-0.9</td>
<td>&gt;1.5</td>
</tr>
<tr>
<td>Density</td>
<td>1.3</td>
<td>1.3</td>
<td>1.5</td>
<td>2.6</td>
</tr>
<tr>
<td>Specific Modulus</td>
<td>13-21</td>
<td>15-35</td>
<td>18-47</td>
<td>29</td>
</tr>
</tbody>
</table>

So some natural fibre may have the potential to replace glass fibres???

\[ E_C = \eta_0 \eta_L V_f E_f + V_m E_m \]
Typical Specs for Automotive Application

There are very few applications where only modulus is required!!!
A typical automotive spec sheet will need –

Melt Flow Rate  (ISO 1133, ASTM D1238)
Glass Fibre Content  (ISO 3451/1)
Density  (ISO 1183, ASTM D792)
Tensile Strength  (ISO R527, ASTM D638M)
Flexural Modulus  (ISO 178, ASTM D790M)
Shear Modulus  (ASTM D4065)
Impact Strength, Izod  (ISO 180, ASTM D256)
Heat Deflection temperature  (ISO 73, ASTM D648)
Heat Aging Performance  (ISO 188, ASTM D573)
Flammability  (ISO 3795)
Fogging  (FLTM BO 116-03)
Mould Shrinkage  (ISO 2577)
Coeff. of Linear Thermal Expansion  (ASTM D696)
Comparison Predicted Composite Modulus

For injection moulded long fibre polypropylene

- Glass Fibre
- NF 20 GPa (Sisal)
- NF 40 GPa (Jute)
- NF 60 GPa (Flax)

Remember – comparison on weight content (i.e. specific fibre properties) means NO weight saving advantage!
Actual Modulus Injection Moulded Jute-PP

- ASTM GFPP
- ASTM Bar
- Plaque Flow
- Plaque Cross Flow

**Graph:**
- Modulus (GPa) vs. Fibre Content (% weight)
- Lines for different materials:
  - Glass
  - Jute

**Key Points:**
- Increasing modulus with increasing fibre content.
- Glass has the highest modulus, followed by Jute.
Thermoelastic Anisotropy of Flax and Sisal Fibres

• Goal
  – Quantify anisotropy of Flax & Sisal fibres
  – Full thermoelastic characterisation

• Measure
  – UD fibre-epoxy laminates $E(\theta,T), G_{12}, \nu_{12}, \nu_{21}, \alpha(\theta,T)$
  – Epoxy matrix $E_m(T), \nu_m, \alpha_m(T)$
  – Laminate fibre volume fraction $\alpha$
  – Flax & Sisal fibre $E_{1f}(T)$ (fibre cross section $\alpha$)

• Calculate
  – $E_{1f}(T), E_{2f}(T), G_{12f}(T), \nu_{12f}(T), \alpha_{1f}(T), \alpha_{2f}(T)$
Composite DMA Results

Log Storage Modulus (Pa) vs Temperature (°C)

- Sisal 0
- Sisal 10
- Sisal 20
- Sisal 30
- Sisal 50
- Sisal 80
- Resin
Anisotropy of Fibre Modulus

Temperature (°C)

Modulus (GPa)

-60 -40 -20 0 20 40 60

100 10 1 0.1

Flax E1
Sisal E1
Flax E2
Sisal E2
Flax G12
Sisal G12
Composite Thermal Strain

- Epoxy
- Flax 90
- Flax 65
- Flax 45
- Flax 25
- Flax 0

Temperature (°C)

Thermal Strain (mm/m)
Fibre Expansion Coefficients

CLTE mm/m°C vs Temperature (°C)

- Sisal Transverse
- Flax Transverse
- Sisal Axial
- Flax Axial

Fibre Transverse

Fibre Axial
<table>
<thead>
<tr>
<th></th>
<th>Glass</th>
<th>Flax</th>
<th>Sisal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Modulus (GPa)</td>
<td>75</td>
<td>61.5</td>
<td>24.9</td>
</tr>
<tr>
<td>Transverse Modulus (GPa)</td>
<td>75</td>
<td>1.2</td>
<td>1.6</td>
</tr>
<tr>
<td>Shear Modulus (GPa)</td>
<td>30</td>
<td>1.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Axial LCTE (µm/m.°C)</td>
<td>5</td>
<td>-7.3</td>
<td>-2.7</td>
</tr>
<tr>
<td>Transverse LCTE (µm/m.°C)</td>
<td>5</td>
<td>71</td>
<td>73</td>
</tr>
</tbody>
</table>
Single Fibre Testing

Fibre Stress = Load/Area = $\frac{P}{A_f}$ ($= \frac{4P}{\pi D_f^2}$ ???)
Single Fibre Cross Section Area

- $A_f$ in single fibre testing is almost universally evaluated from $D_f$ using a transverse image of fibre and assumption of circular cross-section
- Is this acceptable for Natural Fibres ??
Single Fibre CSA Measurements

1. Single fibre “diameter” determined by averaging 4 transverse measurements at 2 mm intervals

2. Fibres embedded, cut and polished

3. “true” cross sectional area determined at approximately the same position on fibre

4. Sample ground down 2 mm and polished

5. Steps 3-4 repeated 10x
Single Fibre Modulus

![Graph showing the relationship between fibre cross-sectional area (CSA) and gauge length (mm) vs. reciprocal of modulus (10^6 GPa).]

- **Sisal**: 1000/33 = 30 GPa
  - Equation: \( y = 11.4x + 14.1 \)

- **Flax**: 1000/14.1 = 71 GPa
  - Equation: \( y = 10.7x + 33.0 \)

Mathematical expression:

\[
\frac{1}{E_f^*} = \frac{1}{E_f} + C \frac{A_f}{L_0}
\]
Natural Fibre CSA Evaluation

“Diameter”, CSA/True CSA vs Average “Diameter” (mm)

- Red diamonds: Flax
- Blue circles: Sisal
Natural Fibre CSA Evaluation

- “Diameter” method significantly overestimates CSA
- Underestimates single fibre modulus and strength
- Magnitude of error is “diameter” dependent
# Effect CSA on Single Fibre Properties

<table>
<thead>
<tr>
<th>CSA method</th>
<th>Diameter</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flax Strength (MPa)</td>
<td>293</td>
<td>688</td>
</tr>
<tr>
<td>Sisal Strength (MPa)</td>
<td>255</td>
<td>530</td>
</tr>
<tr>
<td>Flax Modulus (GPa)</td>
<td>36</td>
<td>71</td>
</tr>
<tr>
<td>Sisal Modulus (GPa)</td>
<td>20</td>
<td>30</td>
</tr>
</tbody>
</table>
Effect of “Diameter” CSA on Apparent NF Modulus

- Assume a diameter independent modulus
- Flax, $E_{1f}=71.0$ GPa
- Sisal, $E_{1f}=30.5$ GPa
Simple Model of NF CSA “Diameter” Errors

NF non-circular – simplest model is oval X-section
Simple Model of NF CSA “Diameter” Errors

Due to NF natural twist the oval cross section will be viewed differently at different positions along the fibre
Parameteric Ellipse Analysis

Can solve for $X_{\text{max}}$ for any $\phi$ and then average over $\phi=0-90^\circ$ for different A:B ratios

True CSA = $0.25\pi AB$

"Diameter" CSA = $0.25\pi D^2$

$X(t) = 0.5ACos(t)Cos(\phi) - 0.5BSin(t)Sin(\phi)$
CSA Ratio from Ellipse Analysis

Ellipse Major Axis Orientation Angle

Av CSA Ratio
- A/B 5: 2.6
- A/B 3: 1.7
- A/B 2: 1.3
- A/B 1: 1.0

CSA Ratio (D^2/AB)

Ellipses with different orientation angles and their corresponding CSA ratios.
Natural Fibre CSA Evaluation

Average Fibre "Diameter" (mm)

'C\textsuperscript{3}SA/True CSA

- Red diamonds represent Flax measured data.
- Purple circles represent Sisal measured data.
Natural Fibre CSA Evaluation

Lines of fixed CSA and varying ellipse A:B ratio

'\text{Diameter}''\text{CSA}/True \text{CSA}'

Average Fibre "Diameter" (mm)
Other Fibres

Abaca

Coir

Kenaf

Jute
<table>
<thead>
<tr>
<th>Other Fibres Ellipse A:B</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Abaca</td>
<td>1.15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coir</td>
<td>2.41</td>
<td>2.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kenaf</td>
<td>1.38</td>
<td>1.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jute</td>
<td>1.23</td>
<td>1.42</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Similar issues probable in CSA estimation from fibre “diameter”
## Natural Fibre CSA Evaluation

<table>
<thead>
<tr>
<th></th>
<th>Average CSA (mm²)</th>
<th>Diameter CSA / True CSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sisal</td>
<td>0.0272</td>
<td>1.97</td>
</tr>
<tr>
<td>Flax</td>
<td>0.0125</td>
<td>2.55</td>
</tr>
<tr>
<td>Jute</td>
<td>0.0032</td>
<td>1.58</td>
</tr>
<tr>
<td>Hemp</td>
<td>0.0058</td>
<td>2.28</td>
</tr>
<tr>
<td>Kenaf</td>
<td>0.0061</td>
<td>1.71</td>
</tr>
<tr>
<td>Abaca</td>
<td>0.0213</td>
<td>1.31</td>
</tr>
<tr>
<td>Coir</td>
<td>0.0283</td>
<td>1.41</td>
</tr>
</tbody>
</table>
### Summary Thermo-Mechanical Properties NF

<table>
<thead>
<tr>
<th>Property</th>
<th>Glass</th>
<th>Flax</th>
<th>Sisal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Modulus (GPa)</td>
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<tr>
<td></td>
<td></td>
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<td>75</td>
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<td>1.6</td>
</tr>
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<td>71</td>
<td>73</td>
</tr>
</tbody>
</table>
What does this anisotropy mean for the reinforcement performance of natural fibres?

\[ E_C = \eta_0 \eta_L V_f E_f + V_m E_m \]

• Comparison NF and GF often “assumes” isotropic fibre
• Hence simple Krenchel analysis for \( \eta_0 \)
  \[ \eta_0 = \cos^4(\theta) \]

• NF is more like an orthotropic composite material
• Apply laminate theory to model reinforcement performance
Engineering Stiffness, Off-axis Orthotropic Lamina

\[ E_x = \frac{\sigma_x}{\varepsilon_x} \quad \varepsilon_{xy} = \overline{S} \sigma_{xy} \quad \text{set} \quad \sigma_{xy} = \{\sigma_x \ 0 \ 0\} \]

\[
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix}
= \begin{bmatrix}
\overline{S}_{11} & \overline{S}_{12} & \overline{S}_{13} \\
\overline{S}_{21} & \overline{S}_{22} & \overline{S}_{23} \\
\overline{S}_{31} & \overline{S}_{32} & \overline{S}_{33}
\end{bmatrix}
\begin{bmatrix}
\sigma_x \\
0 \\
0
\end{bmatrix}
\]

hence \( \varepsilon_x = \overline{S}_{11} \sigma_x \)

and for all \( \theta \), \( E_x = \frac{1}{\overline{S}_{11}} \)

\[
\overline{S}_{11} = S_{11} \cos^4 \theta + (2S_{12} + S_{33}) \sin^2 \theta \cos^2 \theta + S_{22} \sin^4 \theta
\]

The terms \( S_{11} \), etc., are found from \( S= \)

\[
\begin{bmatrix}
\frac{1}{E_{11}} & -\frac{v_{12}}{E_{11}} & 0 \\
-\frac{v_{12}}{E_{11}} & \frac{1}{E_{22}} & 0 \\
0 & 0 & \frac{1}{G_{12}}
\end{bmatrix}
\]
Off-axis Stiffness Contribution of Anisotropic Fibre

- Flax Krenchel
- Flax "Laminate"
- Sisal Krenchel
- Sisal "Laminate"

**Graph Details:**
- **Y-axis:** Fibre Modulus Contribution
- **X-axis:** Off-axis Angle (°)
Integration of curves gives an average orientation factor for RoM random in-plane “GMT” Krenchel $\eta_0=0.375$
“Laminate” $\eta_0=0.2$
Comparison Predicted Composite Modulus
For Randon Inplane moulded long fibre polypropylene “GMT”

- Glass Fibre
- NF 20 GPa (Sisal)
- NF 40 GPa (Jute)
- NF 60 GPa (Flax)

Krenchel
Comparison Predicted Composite Modulus

For Randon Inplane moulded long fibre polypropylene “GMT”

- Glass Fibre
- NF 20 GPa (Sisal)
- NF 40 GPa (Jute)
- NF 60 GPa (Flax)

Graph showing the modulus (GPa) against fibre content (weight %) for different materials.
NF Anisotropy Challenge

OK - Let's just make Unidirectional Composites?

- Actual contribution 40-50% less than expected at only 10°.
- How “unidirectional” and non-wavy can you make your UD NF composites?
Conclusions (1)

- Estimation of natural fibre cross section area via the ‘diameter’ method leads to significant overestimation of CSA.
  - results in significant underestimation of mechanical properties obtained by single fibre testing.
  - also contributes significantly to the variability observed in the measurement of natural fibres properties.
  - since the magnitude of the CSA error is “diameter” dependent – single fibre properties will appear to be diameter dependent.
Conclusions (2)

• Flax and Sisal fibres exhibit very high levels of mechanical and thermomechanical anisotropy.

• Ignoring natural fibre anisotropy and using only the axial modulus of natural fibres in estimating their composite reinforcing ability will significantly overestimate their potential in any off-axis composite loading scenario.
Announcement
Sustainable Composites

In August 2013 the Advanced Composites Group at the University of Strathclyde filed its first patent application in the area of *Glass Fibre Recovery* covering cost effective, industrially applicable, treatments to regenerate the strength of thermally recycled glass fibres.