THE RELATION BETWEEN BAMBOO FIBRE MICROSTRUCTURE AND MECHANICAL PROPERTIES

Lina Osorio

Promotors:
Dr. Aart Van Vuure
Prof. Ignaas Verpoest

9th World Bamboo Congress
Antwerp, Belgium
11th April 2012
To understand the mechanical behaviour of bamboo fibres and bamboo fibre composites

How the morphology and microstructure of bamboo (*Guadua angustifolia*) fibres explain the mechanical performance of bamboo fibre and bamboo fibre composites?
Content

1. Macro-level
   Bamboo Guadua angustifolia
   - Natural fibres
   - The bamboo culm
   - Vascular bundles distribution

2. Meso-level
   Bamboo technical fibres
   - Mechanical properties

3. Micro-level
   Bamboo elementary fibres
   - Polylamellate structure
   - Fibre dimensions
   - Mechanical properties
   - Microfibril angle

4. Composites
   Bamboo fibre composites
   - Tensile properties
   - Mechanical properties
   - Moisture sensitivity
CLASSIFICATION OF PLANT FIBRES ACCORDING TO THEIR ORIGIN

PLANT FIBRES

Wood
- Flax
- Jute
- Hemp
- Ramie

Stem
- Sisal
- Abaca
- Pineapple
- Fique
- Henequen

Leaf
- Cotton
- Coconut

Seed
- Bamboo
- Rice

Grass

Adapted from Maiti, R., 1994
Bamboo fibres

Fibres are distributed densely in the outer region of the wall and sparsely in the inner region.
Morphology of the vascular bundles

Guadua angustifolia

Dendrocalamus membranaceus

OUTER PART

MIDDLE PART

INNER PART
Content

1. Macro-level
- Bamboo Guadua angustifolia
  - Natural fibres
  - The bamboo culm
  - Vascular bundles distribution

2. Meso-level
- Bamboo technical fibres
  - Mechanical properties

3. Micro-level
- Bamboo elementary fibres
  - Polylamellate structure
  - Fibre dimensions
  - Mechanical properties
  - Microfibril angle

4. Composites
- Bamboo fibre composites
  - Tensile properties
  - Mechanical properties
  - Moisture sensitivity
Before the tensile test every fibre is selected to avoid the presence of defects along the length. The use of a paper frame enhances the gripping and protects the fibre.
Mechanical properties of the technical fibres at different span lengths
Comparison with other natural fibres

Natural fibres; comparison of strength and specific strength

1. Bagasse
2. Coir
3. Sisal
4. Cotton
5. Kenaf
6. Henequen
7. Jute
8. Hemp
9. Pineapple
10. Ramie
11. Flax
12. Bamboo
13. Curauà
14. E-Glass

Strength (MPa)
Specific Strength (MPa*cm3/gr)
Comparison with other natural fibres

Natural fibres
comparison of stiffness and specific stiffness

1. Coir
2. Sisal
3. Cotton
4. Kenaf
5. Henequen
6. Jute
7. Hemp
8. Pineapple
9. Ramie
10. Flax
11. Bamboo
12. Curauà
13. E-Glass
Content

1. Macro-level
   - Bamboo Guadua angustifolia
   - Natural fibres
   - The bamboo culm
   - Vascular bundles distribution

2. Meso-level
   - Bamboo technical fibres
   - Mechanical properties

3. Micro-level
   - Bamboo elementary fibres
   - Polylamellate structure
   - Fibre dimensions
   - Mechanical properties
   - Microfibril angle

4. Composites
   - Bamboo fibre composites
   - Tensile properties
   - Mechanical properties
   - Moisture sensitivity
A majority of the fibres does not possess any obvious layering of their walls. However, thick-walled fibres with distinct layering occur especially in the peripheral region adjacent to the epidermis. Liese, W. 1998

The same statement was published by Gritsch, C. 2004, 2005 and Lybeer, B. 2006,
Polylamellate structure of elementary bamboo fibres

Light microscope images where transition (thin) layers are visible. Images a, b and c correspond to elementary fibres of the periphery of the fibre bundle.

Lybeer, B. 2006
P. Viridiglaucens

Sanchis, C. 2005
Dendrocalamus asper

Sanchis, C. 2004
Dendrocalamus asper
In the broad lamellae the microfibrils are oriented at an angle of 2 – 5°. The narrow lamellae shows mostly fibrils oriented horizontally at an angle of 85 – 90°, which remains constant over the whole width of the wall. Liese, W. 1998

Primary layer with Microfibrils oriented at an angle of 90°

Secondary wall with microfibrils oriented at an angle of ~0°
Microfibril angle

Fibres oriented at an angle of ~0°

Fibres oriented at an angle of 90°

Fibre surface covered by lignin
The 'fibre lumen fraction' (ratio of the lumen area to the fibre section) of bamboo fibres according to the position in the technical fibre remains around 4%. The thickness of the lignin layer is 0.5 μm which represents ~7% of the wall thickness.
The average elementary fibre diameter is 17 µm.

The average elementary fibre length is 2.1 mm.
Content

1. Macro-level
Bamboo Guadua angustifolia
- Natural fibres
- The bamboo culm
- Vascular bundles distribution

2. Meso-level
Bamboo technical fibres
- Mechanical properties

3. Micro-level
Bamboo elementary fibres
- Polylamellate structure
- Fibre dimensions
- Mechanical properties
- Microfibril angle

4. Composites
Bamboo fibre composites
- Tensile properties
- Mechanical properties
- Moisture sensitivity
The fibre bundle is treated as a UD short fibre composite of lignin matrix reinforced with bamboo elementary fibres.

**HALPIN-TSAI EQUATION**

\[
E_1 = E_M \left(1 + \frac{\zeta \eta V_F}{1 - \eta V_F}\right)
\]

\[
\eta = \frac{(E_F/E_M) - 1}{(E_F/E_M) + \zeta}
\]

\[
\zeta = 2(l/d)10
\]

**SHEAR-LAG THEORY (COX’S EQUATION)**

\[
E_1 = E_F \left(1 - \frac{\tanh \left(\frac{\eta L}{2}\right)}{\eta L/2}\right) V_F + E_M V_M
\]

\[
\eta = \frac{1}{r} \left(\frac{2E_M}{E_F(1 + v_M) \ln \left(\frac{P_F}{V_F}\right)}\right)^{1/2}
\]

Predicting the elastic modulus of natural fibre reinforced thermoplastics. Facca, A. et al 2006
Estimation of the Young’s Modulus of the elementary fibre

HALPIN-TSAI EQUATION

\[ E_1 = E_M \left( \frac{1 + \xi \eta V_F}{1 - \eta V_F} \right) \]

\[ \eta = \frac{(E_F/E_M) - 1}{(E_F/E_M) + \xi} \]

\[ \xi = 2(l/d)10 \]

SHEAR-LAG THEORY (COX’S EQUATION)

\[ E_1 = E_F \left( 1 - \frac{\tanh \left( \frac{\eta L}{2} \right)}{\eta L/2} \right) V_F + E_M V_M \]

\[ \eta = \frac{1}{r} \left( \frac{2E_M}{E_F(1 + v_M) \ln \left( \frac{P_F}{V_F} \right)} \right)^{1/2} \]

<table>
<thead>
<tr>
<th>Gage length (mm)</th>
<th>Strength (MPa)</th>
<th>Young’s modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>860 ± 119</td>
<td>46 ± 1.2</td>
</tr>
<tr>
<td>10</td>
<td>811 ± 136.5</td>
<td>43 ± 0.9</td>
</tr>
<tr>
<td>25</td>
<td>778 ± 121.9</td>
<td>43 ± 1.4</td>
</tr>
<tr>
<td>40</td>
<td>775 ± 103.3</td>
<td>42 ± 1.1</td>
</tr>
</tbody>
</table>
Estimation of the Young’s Modulus of the elementary fibre

HALPIN-TSAI EQUATION

\[
E_1 = E_M \left(1 + \frac{\xi \eta V_F}{1 - \eta V_F}\right)
\]

\[
\eta = \frac{(E_F/E_M) - 1}{(E_F/E_M) + \xi}
\]

\[
\xi = 2(l/d)10
\]

SHEAR-LAG THEORY (COX’S EQUATION)

\[
E_1 = E_F \left(1 - \frac{\tanh \left(\frac{\eta L}{2}\right)}{\eta L/2}\right) V_F + E_M V_M
\]

\[
\eta = \frac{1}{r} \left(\frac{2E_M}{E_F(1 + \nu_M) \ln \left(\frac{P_F}{V_F}\right)}\right)^{1/2}
\]

From the microstructural analysis:
- Lumen percentage: 0,9 to 10%
- Fibre diameter: 10 to 25µm
- Fibre length: 1,1 to 3,4 mm
- Length to diameter ratio: 70 – 200
The estimated fibre modulus is about $\sim 50$ GPa with the two models. Graphs show the sensitivity of the models to high volume fractions.
Validation

Young's modulus bamboo fibres

Tensile strength bamboo fibres

y = -22.723x + 971.79
R² = 0.9811
Fracture surfaces

Clean failure all through the fibre surface

Failure in the primary layer

Elementary fibre wall

Microfibrils of the secondary wall
1. Macro-level
- Bamboo Guadua angustifolia
  - Natural fibres
  - The bamboo culm
  - Vascular bundles distribution

2. Meso-level
- Bamboo technical fibres
  - Mechanical properties

3. Micro-level
- Bamboo elementary fibres
  - Polylamellate structure
  - Fibre dimensions
  - Mechanical properties
  - Microfibril angle

4. Composites
- Bamboo fibre composites
  - Tensile properties
  - Mechanical properties
  - Moisture sensitivity
Moisture uptake

- Dried fibres
- Final moisture content material dependent
- Uptake rate↑ with moisture level↑

Submersion 41,2±7,2%
(Moisture uptake)
Moisture sensitivity

Influence of moisture on the mechanical properties

![Graph showing the influence of moisture on mechanical strength](image1)

**20%rh**

![Microscope image at 20% relative humidity](image2)

**80%rh**

![Graph showing ultimate strain vs. relative humidity](image3)

![Microscope image at 80% relative humidity](image4)

**Ultimate strain**

- **Strain [%]**
  - 0
  - 0.5
  - 1
  - 1.5
  - 2
  - 2.5

- **Relative Humidity**
  - 0
  - 50
  - 100
Bamboo fibre composites

Typical stress-strain curve for treated and untreated bamboo/epoxy composites
Moisture sensitivity of bamboo fibre composites

Moisture influence on the mechanical properties of BFC

Strength (MPa)

Relative humidity (%)
Moisture sensitivity of bamboo fibre composites

Moisture influence on the mechanical properties of BFC

Young's Modulus (GPa)

\[
\begin{array}{c|c}
\text{Relative humidity (\%)} & 20 \pm 1.4 \text{ GPa} \\
0 & 20 \\
20 & 19.9 \\
40 & 19.8 \\
60 & 19.9 \\
80 & 19.8 \\
100 & 19.9 \\
120 & 19.9 \\
\end{array}
\]

Strain (%)

\[
\begin{array}{c|c}
\text{Relative humidity (\%)} & 1.1 \pm 0.1 \% \\
0 & 1 \\
20 & 1.4 \\
40 & 1.7 \\
60 & 2.0 \\
80 & 2.3 \\
100 & 2.6 \\
120 & 2.9 \\
\end{array}
\]

50%rh

20%rh
Morphological hierarchy in bamboo

Bamboo wall

\[ d = 6-11\, \text{cm} \]

Bamboo technical fibre (fibre bundle)

\[ d = 200-400\, \mu\text{m} \]

Bamboo elementary fibre

\[ d = 12-20\, \mu\text{m} \]

Bamboo microfibrils in the layered structure

- Primary wall
- Secondary wall

\[ \sigma = 237\, \text{MPa} \]
\[ E = 16\, \text{GPa} \]

\[ \sigma = 800\, \text{MPa} \]
\[ E = 43\, \text{GPa} \]

\[ \sigma = 1150\, \text{MPa} \]
\[ E = 50\, \text{GPa} \]
Thank you very much!
Influence of moisture on the mechanical properties of bamboo fibres

Influence of moisture on the mechanical properties

Strength (MPa)

Relative humidity (%) 0 20 40 60 80 100

Moisture influence on the mechanical properties

Young's Modulus (GPa)

Relative humidity (%) 0 20 40 60 80 100 120

03/11/2011
Bamboo fibre length

Position

Bamboo 1
Bamboo 2

n=50
Moisture implementation

- Use of saturated solution for high moisture level
- Use of dry salt for low moisture levels

<table>
<thead>
<tr>
<th>Salt</th>
<th>Relative humidity (Experimental) [%]</th>
<th>Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiCl</td>
<td>20</td>
<td>Dry</td>
</tr>
<tr>
<td>CH₃COOK</td>
<td>30</td>
<td>Dry</td>
</tr>
<tr>
<td>MgCl₂</td>
<td>40</td>
<td>Dry</td>
</tr>
<tr>
<td>NaCl</td>
<td>70</td>
<td>Wet</td>
</tr>
<tr>
<td>KCl</td>
<td>90</td>
<td>Wet</td>
</tr>
<tr>
<td>K₂SO₄</td>
<td>100</td>
<td>Wet</td>
</tr>
</tbody>
</table>
Special thanks

- Dr. Frederic Lens, Laboratory of Plants Systematics, K.U.Leuven.
- ir. Suzanne Verheyden, MTM Department, K.U.Leuven
- Belgian Science Policy Office (BELSPO) for the financial support

For more information:

Test methods for bamboo fibres (Eduardo Trujillo)
Characterization of the interface in BFC (Carlos Fuentes)

http://www.mtm.kuleuven.be/Onderzoek/Composites/