Bio-based composite moveable bridge

ir. Wouter Claassen, Mai 2018

https://www.drive.frl/nl
Witteveen+Bos is established in 1946

- Bos (37): Civil engineer (Enschede)
- Witteveen (54): Director Public Works (Rotterdam)
- Urban Development Consultancy and Engineering Office, called: Witteveen+Bos
- First project: lock Prince Bernhard Deventer
- Milestones:
  - 1994: 500 employees
  - 2017: 1,052 employees
- Board of directors (2 members)
Areas of expertise

- Product-market combinations (PMCs) / Business units
  - Dedicated to own products
  - Specific market segment
- Built Environment
- Deltas, Coasts and Rivers
- Energy, Water and Environment
- Infrastructure and Mobility
Mile stone 2010: First movable 60 ton bridge in the world

- Hoofdbrug Oosterwolde
- Design Witteveen+Bos
Developing 30 ton Bijl pultrusion bridge
Design world longest span (140 meter)

Nine Elms Bridge Londen

Witteveen+Bos
Raadgevende Ingenieurs
B.V. with ipv Delft,
Adams Hendry
Consulting Ltd
FRP slides in the Eastern Scheldt storm surge barrier
New Balance 100 Tallinn

Studio: MdB3d
Designer / Architect: Plein 06
Client: Witteveen&Bos en Novarc Group
Personal / Commissioned: Commissioned Project
Location: Tallinn Estonia

Composite deck
Testing bio-based pultrusion samples
Test Results

• EnviroGuard™ M 98054 Unsaturated polyester resin
• BioMid
• Strip: 38x3mm
• 3 points bending test: span 60mm

<table>
<thead>
<tr>
<th>Bio UP resin / Bio-yarn</th>
<th>F_{max}</th>
<th>e_{F_{max}}</th>
<th>a_{0}</th>
<th>b_{0}</th>
<th>e_{M}</th>
<th>I_y</th>
<th>E_{mod-ber}</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>%</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>mm^4</td>
<td>MPa</td>
</tr>
<tr>
<td>TEST35.2A.01-A</td>
<td>1088,892</td>
<td>3,542133</td>
<td>3,185</td>
<td>37,45</td>
<td>6,672779</td>
<td>100,8321</td>
<td>24151,663</td>
</tr>
<tr>
<td>TEST35.2A.02-A</td>
<td>876,0132</td>
<td>1,864451</td>
<td>3,185</td>
<td>37,4</td>
<td>3,51231</td>
<td>100,6975</td>
<td>24996,378</td>
</tr>
<tr>
<td>TEST35.2A.02-A-2</td>
<td>1108,987</td>
<td>3,459244</td>
<td>3,185</td>
<td>37,4</td>
<td>6,516628</td>
<td>100,6975</td>
<td>24565,985</td>
</tr>
<tr>
<td>TEST35.2A.03-A</td>
<td>1109,121</td>
<td>3,600163</td>
<td>3,22</td>
<td>37,5</td>
<td>6,708379</td>
<td>104,332</td>
<td>25045,563</td>
</tr>
<tr>
<td>TEST35.2A.04-A</td>
<td>1129,235</td>
<td>3,573433</td>
<td>3,2</td>
<td>37,5</td>
<td>6,700187</td>
<td>102,4</td>
<td>25045,563</td>
</tr>
<tr>
<td>TEST35.2A.05-A</td>
<td>1117,008</td>
<td>3,459577</td>
<td>3,21</td>
<td>37,45</td>
<td>6,466498</td>
<td>103,2252</td>
<td>24689,897</td>
</tr>
</tbody>
</table>
Goal 2018: First movable bio-based bicycle bridge in the world, Ritsumasyl

Span: 22m!

100% natural fibres, bio-based resin

Year of construction: 2018
Our GOAL for the future

Not only use bio-based composites, but use 100% green composites
(100% natural fibres + 100% bio resin)
What is a bio-based composite bridge?

A bio-based composite bridge consist in whole or in significant part, of natural products or renewable domestic agricultural materials (including plant, animal, and marine materials) or forestry materials.
Definitions

- **A bio-based product** is a product that is being developed from a renewable source, which is completely or entirely derived from biomass (not being energy or food products).
- **Biomass** is the biodegradable fraction of agriculture, forestry, aquaculture, waste from the (process) industrial and household waste.
- **Biodegradable** is the ability to rapidly and completely break down by micro-organisms.
- Examples: cotton, wool, wood, or products made with food produced from natural materials such as paper and cleaning agents based on vegetable oil.
- A **bio-based composite** consists of two or more bio-based materials that work together.
- **green composites** consists of 100% natural materials
Advantages and disadvantages of bio-based composites

- Acceptable specific strength properties
- Renewable resource
- Low density
- Well isolation for sound, temperature and vibratory
- Well chemical resistance
- Non-abrasive
- Aesthetic
- Biodegradable if resin is 100% biosourced
- Sustainability
- Low CO2 impact

- Creep behavior
- Moisture sensitive
- The natural variability of fibre
- Durability
- Fatigue behavior understudied
- Fire resistance
- Fibre matrix adhesion
- Limited maximum processing temperatures
- Impact resistance
Degradation mechanisms

- UV resistance
- Water resistance (Osmosis, Hydrolysis)
- Chemically inert
- Frost resistance
- Salt resistance
- Snow resistance
- Temperature resistance
- Lightning resistance
- Biodegradation resistance
It all started with ... Timeline

- A dream and a wish: Sieds Hoitinga the Program manager at Provincie Fryslân wanted a bio-based bridge
- Begin 2016: Literature study Witteveen+Bos
- Mid 2016: Pre-selection contractor
- Mid 2016: Preparation tender documents bio-based deck
- End 2016: Tender on the market
- Begin 2017: Final contract signed with producer and contractor
- End 2017: Literature study producer bio-based deck
- Begin 2018: Start testing program producer
- April 2018: First reports of the final design phase have been submitted
- April 2018: Agree on the feasibility of the design
- Mid 2018: Finishing the final design
- Mid-End 2018: Detailed design phase
- End 2018-begin 2019: Start building the bridge
Questions to be answered:

• What kinds of natural fibres to use?
• Which resins are bio-based and compatible for this application?
  • What is the effect of moisture?
  • What is the effect of creep?
• How strong will the bridge be over its lifetime?
  • How can we re-use the materials?
Bio-based movable bridge

Main parts

- Core
- Fibres
- Resin
Natural cores

- Honicomb paper
- Balsa
- PLA / Bio PS?
- Recyclet PET??
- No core
Most suitable core for this bridge = Balsa
Natural fibres

Animal fibres

lignocellulosic materials

Mineral fibres

Wood

nonwood or plant fibres

polymers

Cellulose

Strengt

Bonding cellulose, Water absorption, easily digestible for micro organism

Hemicellulose

Pectin

Lignin

Bonding cellulose, Most hydrophilic

Bonding cellulose, resistance to moisture and microbial attack, UV sensitive, non crystalline

Polymers
Flax
Hemp
Kenaf
Wood
Ramie
Cellulose

Cellulose chain

Monomer
β-D-glucopyranose units

Glycosidic bond

Held by Hydrogen bonds

High mechanical strength

Hydroxile group

Chemical properties, Oxidized, esterified of converted into esters
Crystalline or amorphous

Best is: 100% crystalline cellulose

More hydrophilic

Fewer hydrogen bonds, more hydroxyl groups for bonding with water

Source: Symposium on Relationship of Structures of Microorganisms to their Immunological Properties
Water

- The major challenge is the hydrophilic nature of natural fibres, which make them prone to water absorption and, as a consequence, lead to poor adhesion to hydrophobic polymer matrices.
Adhesion improvement

1. Fibre modification:
   - Alkalisation treatment (physical method called mercerization)
   - (Silane treatment (chemical))
   - Duralin steam process

2. Matrix modification:
   - Matrix modification should not be necessary for the design of a bridge. A matrix should be developed that is hydrophobic and not able to absorb moisture.
From fibre to yarn

- Natural fibres are thin and short
- Traditionally fibres are spun into yarns

- Disadvantage of spinning:
  - large amount of fibre misalignment, which decreases the composite stiffness properties

- It’s better to use a helical type of yarn or a similar principle
Consequences twisted vs non-twisted Yarn

Twisted

Non-twisted
Fibre with high potential: BioMid Fibre

- 100% HIGHLY CRISTALLINE CELLULOSE FIBRE
- Made of Lumber Industry by-products
- Obtained by mechanical process (unlike Viscose rayon which is obtained by chemical reaction)
Production process BioMid

Discontinuous cellulose
Constant diameter

A random flax yarn with plot of filament diameters (74 filaments). the large blue dot is BioMidR filament diameter (900 filaments) (blue lines represent strength vs filament diameter)
# Mechanical properties of Flax, BioMid compared to E-Glass

<table>
<thead>
<tr>
<th>Properties</th>
<th>Flax (Less than 100% Cellulose)</th>
<th>BioMid (100% Cellulose)</th>
<th>E-Glass</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of elasticity</td>
<td>55.000 - 75.000</td>
<td>52.000</td>
<td>72.000 - 80.000</td>
<td>MPa</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>1.600</td>
<td>1.600</td>
<td>30.000</td>
<td>MPa</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>800 - 1.500</td>
<td>1.100</td>
<td>2.800</td>
<td>MPa</td>
</tr>
<tr>
<td>Compression strength</td>
<td>-830 to -1.570</td>
<td>-1.100</td>
<td>-2.800</td>
<td>MPa</td>
</tr>
<tr>
<td>Tensile fracture strain</td>
<td>1.5 - 2.0</td>
<td>1.5</td>
<td>3.9</td>
<td>%</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.25</td>
<td>0.25</td>
<td>0.20</td>
<td>-</td>
</tr>
<tr>
<td>Density</td>
<td>1.4 - 1.5</td>
<td>1.45</td>
<td>2.4 – 2.6</td>
<td>kg/dm³</td>
</tr>
<tr>
<td>Thermal expansion coefficient</td>
<td>5.0</td>
<td>5.0</td>
<td>2.8 – 5.0</td>
<td>*10⁻⁶/°C</td>
</tr>
<tr>
<td>Heat conduction coefficient</td>
<td>0.06</td>
<td>0.06</td>
<td>1.05</td>
<td>W/mK</td>
</tr>
</tbody>
</table>
Suitable fibres for this bridge

- Bcomp, Amplitex UD, 300gr/m2
- Biomid, UD
Bio-based resins

- PLA (Poly(lactic acid) or polylactic acid or polylactide)
- Bio PE (polyethylene)
- Bio PP (Polypropylene)
- Furan resin
- Bio unsaturated Polyester
- Bio vinylester
- Bio epoxy

A bio-based resin has the same properties as a synthetic resin

The resin is the ingredient with greatest environmental impact
Adhesion at the composite interface

1. physicochemical interactions
   - wettability
   - compatibility of the fibre and the matrix
   - physical adhesion
2. chemical bonding
3. mechanical interlocking
   - rough fibre surfaces

Good interfacial adhesion initially requires a good wetting between the fibre and the matrix
Suitable resins for the bridge

- Epoxy resin for the movable deck:
  - Greenpoxy 56 (56 % bio content) by Sicomin,
  - SuperSap CLR (17 % bio content) by Entropy Resins
  - Resoltech 1800 ECO (40 % bio content)
- Unsaturated polyester resin for the fixed spans:
  - Polynt 1580 IBA (28 % bio content)
  - Polyester ER16773 (45 % bio content) by Polynt Composites
  - Polyester L6184-SPR17043 (65% bio content) by Scott Bader

Important factor is the confidence that the producer has in the supplier and not only the availability of the resin.
Most suitable production process

• The vacuum injection process is preferable to the other production processes because of:
  • the scale and shape of the bridge elements;
  • the high laminate quality that can be achieved;
  • the working conditions;
  • the costs.
Research Programme bio-based movable bridge Ritsumasyl

provincie fryslân
provinsje fryslân

Green PAC
Polymer Application Centre

Witteveen Bos

SWECO

Interreg
North Sea Region
BIOCAS
European Regional Development Fund
EUROPEAN UNION

DELT
INFRA

Lightweight Structures BV

Stenden hogeschool

Windesheim

HOCHSCHULE OSNABRÜCK
UNIVERSITY OF APPLIED SCIENCES
Research and testing program

- ILSS (used to determine best fiber resin combinations)
- Tension
- Compression
- Shear
- Hot/wet behaviour
- Creep (very important!)
- UV
- Fatigue
Chosen fibres and resin for the movable bridge deck

Epoxy resin: Resoltech 1800 ECO + 1804 ECO

- Very low temperature at exothermic peak
- Long potlife
- Constant low viscosity

Bcomp, Amplitex UD, 300gr/m2
UD: 0,43 mm thick

Coatings:
first layer variopox epoxy resin coating
2 toplayers maxguard gelcoating
## Laminated properties

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>Design value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILLS:</td>
<td>33,3 N/mm²</td>
<td>22,1 N/mm²</td>
</tr>
<tr>
<td>Tension:</td>
<td>363 N/mm²</td>
<td>166 N/mm²</td>
</tr>
<tr>
<td></td>
<td>(3 times lower than glass)</td>
<td></td>
</tr>
<tr>
<td>Compression:</td>
<td>96,2 N/mm²</td>
<td>61,3 N/mm²</td>
</tr>
<tr>
<td>Modulus of elasticity:</td>
<td>≈25 GPa</td>
<td>21,6 GPa</td>
</tr>
<tr>
<td></td>
<td>(50% lower than glass)</td>
<td></td>
</tr>
<tr>
<td>Tension strength is higher than the compression strength</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Hot-wet test conclusions

• The decrease of modulus of elasticity under wet circumstances is a factor 4 greater than that of a glass fibre polyester;
• Not every coating prevents the fibres 100% from absorbing moisture;
• Hot-wet factor for 100 year: 1,25 vinylester coating
  1,2 multiple layer coating
Moisture uptake

- From their natural origin there is still moisture in the material. This in no problem but you should be aware of it during production;
- Biomid has less moisture (10%) in the fibre than flax (11-13%) due to their crystalline orientation;
- Be aware that the amount of moisture in the fibres is more than on the product data sheets.
Stress-Strain curve for bio-composites

- Due to non-linear behaviour change of modulus of elasticity
- With imposed force the microfibrils arrange to a higher degree of crystallinity which leads to better mechanical properties
Creep

- Creep is one of the most important parameters to take into account
- High stresses lead to rapidly increasing creep
- Boundary conditions Ritumasyl:
  - 10,000 openings per year,
  - 1 minute open + long openings during maintenance and failure
- Creep factor for 100 year: 1.75

Creep tests, FRP: Woven Flax Fibres

Source: Research TUE
## Conversion factors used

<table>
<thead>
<tr>
<th>Factor</th>
<th>Symbol CUR96;2018</th>
<th>Glass</th>
<th>Flax</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temprature</td>
<td>$\eta_{cT}$</td>
<td>0,90</td>
<td>0,90</td>
</tr>
<tr>
<td>Moisture</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dry</td>
<td></td>
<td>1,00</td>
<td>1,00</td>
</tr>
<tr>
<td>dry/wet coated</td>
<td>$\eta_{cH}$</td>
<td>0,90</td>
<td>0,80</td>
</tr>
<tr>
<td>wet coated</td>
<td></td>
<td>0,80</td>
<td>not tested</td>
</tr>
<tr>
<td>Creep</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dry</td>
<td>$\eta_{cC}$</td>
<td>0,90</td>
<td>0,58</td>
</tr>
<tr>
<td>dry/wet coated</td>
<td></td>
<td></td>
<td>0,46</td>
</tr>
<tr>
<td>wet coated</td>
<td></td>
<td></td>
<td>not tested</td>
</tr>
<tr>
<td>Fatigue</td>
<td>$\eta_{cF}$</td>
<td>0,90</td>
<td>0,90</td>
</tr>
</tbody>
</table>
The final design

**Boundary conditions:**

- Design life: 100 years
- 100% natural fibres
- Bio-based resin
- 100% natural core
- Max height deck 1200 mm
- Total width deck: 3,65 m
Weight deck +/- 160 kg/m²

11.14 mm QI + 3.43 mm UD

44.45 mm Balsa SB150 core

11.14 mm QI + 3.43 mm UD

2 x 3.43 mm QI + 12.7 mm
Balsa SB50 core

9.43 mm QI + 9.43 mm UD

11.14 mm QI
FEM model
Lessons Learned
Resin

• For the epoxy the peak exotherm is very important to prevent degradation of the fibres;
• The viscosity should be high enough
• Bonding: not every resin is suitable for natural fibres
Fibres

- Creep and water are the main degradation mechanisms.
- Fibers swell more perpendicular to the fiber direction due to moisture, which can lead to degradation of the bonding with the matrix.
Rule of mixture

- The rule of mixture to determine the stiffness with a micro-mechanic approach doesn’t comply for Bio-based composites.
  
  \[ E_1 = \left[ E_R + \left( E_{F1} - E_R \right) \cdot V_f \right] \cdot \phi_{UD} \]

- The stiffness will be lower than according to the rule of mixture, due to:
  - Not sufficient wetting of the fibres?
  - On a microscale the stiffness of the fibre differs per section, which contributes to a lower overall stiffness?
  - The shear connection between the short, non-homogenous fibres is below 100%?
Processing the material

• Problems with normal FRP equipment
• Material is very viscous
• Diamond sawing and drilling equipment doesn’t work well
• Best to use equipment for wood processing
Make use of a warning layer (not only for bio-based bridges)
Questions, contact:
ir. W. Claassen
Mail: wouterclaassen@witteveenbos.com
Tel: +31 (0)6 27 16 98 56
https://nl.linkedin.com/in/wouterclaassen

www.witteveenbos.com