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Fiber Compositions

Development of wood and textile layered structures as a material strategy for sustainable design

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This study examines composite compositions based on fiber-based materials. It focuses on organic textiles of Jute, Hemp, Wool, Flax, and Glass fiber as a synthetic textile, combined with the lightweight wood species Paulownia. By creating novel composites, the study aims to investigate methods and generate design knowledge for material strategies to improve and reduce material waste in the built environment, further enabled by the use of small elements that can be sourced from waste wood and reclaimed wood. Research is conducted as a hybrid material-computational methodology, developing and testing probes, prototypes and a full-scale demonstrator assembly in the form of a wall seating composition. The results find that the proposed method and resulting composites have significant potentials for both expressive and functional characteristics, allowing tectonic articulation to be made, while creating minimum material structures based on assembly of small elements to larger complex curvature building parts.

\textbf{Keywords:} Wood, Textile, Composite, Computational Design, Environmental Design

\textbf{INTRODUCTION}

While the available energy on the planet is thousandfold larger than what we need globally, materials are a limited resource, and a fragile one. The planet cannot support the current use of materials, where we currently use the available resources per annum within 2/3 of the year passed [1]. According to the world leading organization that tracks material use, The Organization for Economic Cooperation and Development (OECD), this is combined with a projected increase in material use in the built environment from a massive 89 Gigatons to 167 Gigatons by 2060 (OECD, 2018). As the design fields target materials with environmentally friendly and regenerative profiles, such as wood and plant species, it becomes evident that we need new design knowledge, strategies and methods to advance into a sustainable material practice. With the mentioned materials being a scarce resource, with raw wood only providing approximately 4.5\% of the global supply (UN, 2020). Furthermore, wood and plants are material systems that needs assembly of many smaller elements into larger structures in architecture, requesting new methods for such designed structures of nat-
ural materials. This research studies methods and strategies through experimental design studies, for the assembly of small wood pieces based on an ultra-lightweight and high carbon dioxide wood specimen, Paulownia (280 kg/m3), combined with organic textiles into natural fiber composites with high CO2 sequestration potentials (Pervaiz and Rain, 2003, Icka et al, 2016)[2]. This aims directly at addressing our current problems of the material energy-pollution source footprint, and the challenge of designing assemblies into novel composites through smaller elements, supporting the use of waste wood and reclaimed wood in structures.

METHODS
The research employs a design-led experimental methodology, focused on experimental prototypes and demonstrators (Ramsaard and Tamke, 2009, Groat and Wang, 2011). Concretely, studies are focused on a three-step approach, with firstly studying wood-textile composites for deflection and stiffness characteristics, then wood-textiles composites of surface elements, analysing ultimate limit state conditions, and lastly a wood-textile composite of a design-driven undulating monoclastic surface geometry as a field tested demonstrator with varying load cases. All three levels are developed as parallel physical-computational design investigations, using a Rhinoceros-Grasshopper-Karamba computational framework, integrating material-geometric-structural analysis into the design-led modelling investigations.

Deflection Studies
The idea of combining smaller wood elements into a larger structure is not new. The German architect and engineer Friedrich Zollinger invented the Zollinger System, combining short planks into a diagrid structure (Schlaich et al, 2003). Focusing on material use and resulting articulation, systems such as tensegrity (Fuller, 1961, Lalvani, 1996) and reciprocal structures (Balmond, 2002) have been developed by pioneers of articulated structural architectures. In similarity, textile architectures have been studied as structurally articulated systems (Otto and Raush, 1996) and as subtle architectural membranes from artistic approaches (Ramsaard et al, 2019). Towards technical studies and the combination of these approaches (Ahlquist et al, 2017, Deleuran et al, 2016) present studies which can be understood as a search towards structural lightness (Beukers and Van Hinte, 2013). Technical studies investigating the layering of textiles and wood into composites have also been conducted, focusing on both organic and synthetic textiles fibers, with a study focusing on the joining of wood elements, through a point connection approach [3]. The background of potential solutions in this study is to examine and develop wood-textile composites as a structural, forming and articulating element. The material make-up and articulation thereof are thereby based on a material core of lightweight wood with varying outer textile layers bonded together to form a tectonic composition, where expressive characteristics are aligned with structural material-environmental potentials. The paper presents the base idea and strategy of combining lightweight, CO2 sequestrating materials into functional and expressive composites. Studies are conducted through a design-led experimental research approach, where methods are presented, before core results, discussion and finally conclusion of the study is included.

To get an initiating understanding of the textile impact on simple wood geometries, a series of 30 samples is created in dimensions 30x14x1000mm. Jute, Flax, Hemp, Wool and eGlass fiber plain woven textiles are combined with the wood core in five different ways. Wool is the only non-woven textile, and studies are conducted along the grain of the paulownia wood, figure 1. This provides a composite material matrix of variations in composites (textile type and paulownia wood) and geometric arrangement of the textiles in respect to the wood. Adhesion between wood and textiles are throughout the studies based on white glue (carpenters glue) and composites are merge by simple lay-up layering without pres-
Figure 1

surised formwork. For the deflection testing all elements are fixed at one end of the element and exposed to a point load in the other end (1 kg dead load) figure 2, and as computational simulation studies, figure 3. The stiffness of each element can then be evaluated as a result of measured deflection, with the knowledge employed in the following studies.

Ultimate Limit State Studies
Following the initial studies, paulownia elements are cut and assembled into a 250x450mm surface with 8mm depth, including eight pieces of 250x8x60mm dimensions, glued on the short edge with standard wood glue. Textiles of Flax and Wool are then mounted with standard wood glue, with one reference surface kept without textile mounted. Each sur-
Textile material properties from (Petrone and Meruane, 2016) (Shah et al, 2016) (Bodros and Bailey, 2008) (Dhaduti and Mathad, 2019), used for FEM simulations.

<table>
<thead>
<tr>
<th>Fibre type</th>
<th>Density (g/cm³)</th>
<th>Moisture absorption (%)</th>
<th>Elongation at break (%)</th>
<th>Tensile strength (MPa)</th>
<th>Young's modulus (GPa)</th>
<th>Specific modulus (E/p) (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-glass</td>
<td>2.5</td>
<td>-</td>
<td>2.5</td>
<td>2000–3500 (2500)</td>
<td>70 (70)</td>
<td>28</td>
</tr>
<tr>
<td>Flax</td>
<td>1.5</td>
<td>-</td>
<td>2.7-3.2</td>
<td>500-1800 (1100)</td>
<td>27-80 (50)</td>
<td>18-53</td>
</tr>
<tr>
<td>Hemp</td>
<td>1.4</td>
<td>8</td>
<td>1.6</td>
<td>550-1100 (750)</td>
<td>30-70 (45)</td>
<td>21-80</td>
</tr>
<tr>
<td>Jute</td>
<td>1.3-1.5</td>
<td></td>
<td>1.5-1.8</td>
<td>400-800 (600)</td>
<td>10-55 (30)</td>
<td>7.1-39</td>
</tr>
<tr>
<td>Wool</td>
<td>1.3</td>
<td>-</td>
<td>13.2-35</td>
<td>50-315 (200)</td>
<td>2.3-5 (4)</td>
<td>1.8-3.8</td>
</tr>
</tbody>
</table>

The face is then placed in a steel frame, where a bolt and 50mm washer is mounted in the geometry centroid. This setup allows testing the composite material properties by a vertical pull force, forcing the textile into tension and the wood into compression, figure 5. Measurements are conducted for all surfaces as Ultimate Limit State (ULS) testing, giving a direct understanding of the strength comparison properties between the different composites.

**Design Model Studies**

Based on the understanding of the previous two studies, a demonstrator geometry for an undulating wall mounted seating is developed. The intent is to maintain a simple form geometry, monoclastic, focusing on the material-structural relations between textile and the simple wood elements forming the curvature of the geometry. In this way, the textile operates to create joining between wood elements, distribute tension forces, and form the articulating surfaces that the human is seated against. The studies are driven by the developed computational model, where varying stress concentrations from two load cases, figure 6, steer the geometry and application of textile layers. The load cases include a person sitting well into the geometry, leaning towards the back of the geometry, and another person sitting on the front part of the geometry, figure 7 and 8. The loads are set to 70 kg, through points on the front of the seating, or as distributed on the seating and against the back surface.

**DESIGN EXPERIMENTATION**

Design-led experiments are driven by the empirical measurement of the previous studies embedded into the computational design model and the data from the literature. The aim of the design model is to support the investigations of relations between the array of planar wood elements with varied surfaces of textile layers, applied on both ‘outside’ and ‘inside’ of the geometry. By intuitively changing the load cases, figure 7 and 8, textile patterns are formed revealing the relations between the material composite, the geometric articulation and the use condition. These studies provide insight to how the textile-wood composites can steer expressive characteristics and minimizing material use at the same time. From these experiments, fabrication patterns are directly generated of the 2D cut lines of textiles and the 3D cut lines of the wood elements, forming the resulting curvature and strength and flexibility of the geometry.
Figure 5
A1-A4: Paulownia without textile,
Figure 6
Computational design studies model using the Rhinoceros, Grasshopper, Karamba parametric modelling and simulation framework.

Figure 7
Top: Tension and compression forces on front and back side of geometry. Center: Stress concentrations. D: Resulting generated textile layers distribution on front and back side of the geometry under load case with person sitting on outer part.

RESULTS
The initial series of experiments with deflection studies of linear element, fixed in one end, and exposed to a point load, presented little bending variation between the elements during simulation. The simulation studies were then confirmed in the physical prototypes, despite the difference in material properties between the textiles, with results showing only minor deflection differences measured. Stiffness of the composites were therefore assessed almost identical based on the geometry variations and load case presented. Through physical measurements of the surface composites (with 8mm structural depth), it became evident how much the textile changed the strength properties when combined with the paulownia base elements. Unsurprisingly, the sample without textile mounted breaks at a much lower force than the wood-textile composites, at 80.9N. The Wool/Paulownia composite at 128.4N. The Flax/Paulownia composite does not break, but the wood is crushed under compression forces at 159.3N. Interestingly, hence, the latter does not actually break at the maximum stress possibly within the measurement setup. Instead, the paulownia wood, in compression, is pressed together, shortening the surface to a degree, which makes the sample move away from its edge fixtures. This means, that the structural issue of the composite is not the composites tension forces, but the material deformation that occurs in the wood layer during the ULS test. This suggest that wood species with low densities (as can be found through the Janka test method) is less usable for the composite structures proposed in this study. Lastly, the field testing of the full scale demonstrator, figure 9 and 10, reveals that the structure with fracture, but some deformation, resist different load cases, as presented above, and with a high load of 85 kg, as opposed to the computational design experiments using a 70 kg force as input. At 150 kg load on the built composite, with pressure points moved from the centre of the geometry to the sides, the structure delaminate in the lower section, leading to fracture of the wood assembly.
DISCUSSION

The studies use a hybrid physical-computational approach, with the intent to combine validation of simulation models and explorative experimental studies through design-led investigations. This also means that the material has been selected by a focus on positive material-environmental impact, combined with low weight and tensile qualities. More studies with a greater variation of materials, both textiles and wood species will be able to strengthen the results obtained and enable a potential broader understanding of the proposed composite properties.

In specific, Paulownias low density is a result of its growth characteristics providing the material with a very good environmental impact, but also with a low density to resist compression forces. It is possible that higher density woods would enable a significant higher composite strength profile, thereby enabling a reduction of the thickness of the wood layer, and in turn be the same or lower combined weight of the composites. The computational model studies focused on simulation and modeling of textile layers and the effects on the combined composite. These studies could in future studies be advanced by considering synclastic and anticlastic surface curvatures, by variation in textile layer properties, variation in adhesive elasticity whereby both bonding and local interlayer dynamics of the composite may be strategically controlled to design varied stiffness and alternate fixture positions of the structure, particularly when considering the composite for other functionalities than presented in this research. Further studies of the interrelations between textile and wood layers appear very relevant to pursue as a means to material focused environmental design strategies.

Figure 8
Top: Tension and compression forces on front and back side of geometry. Center: Stress concentrations. D: Resulting generated textile layers distribution on front and back side of the geometry under load case with person sitting on mid part leaning backward.

Figure 9
Resulting textile-wood composition with combined load cases.
Figure 10
Field test of demonstrator with varying load cases.
A: No loads, B: Load case 2 (65 kg), C: Load case 1 (65 kg), D: Load case 2 (85 kg), E: Load case 1 (85 kg), F: Asymmetric and dynamic load, G: Load away from center (150 kg) leading to delamination, H: Load leading to fracture (150 kg).
CONCLUSION

From the studies presented, it is clear that the proposed composite, and its specificities unfolded through material and computational prototypes and demonstrator studies present ways to develop and design structural assemblies of smaller parts through the computational process. The studies therefore present knowledge, methods and concrete design models, which enable material-environment efficient assemblies of smaller parts, such as waste wood, reclaimed wood and reclaimed and restitched textiles. While demonstrated through a small architectural design scale, the studies could be imagined directly applicable in architectural scales such as the building envelopes and spatial partitions, where reduced weight will reduce the load on load-bearing elements, and being easier to handle and transport during construction.

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