Experimental Biocomposite Pavilion

Segmented Shell Construction—Design, Material Development and Erection

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1 Experimental Biocomposite Pavilion at night

ABSTRACT

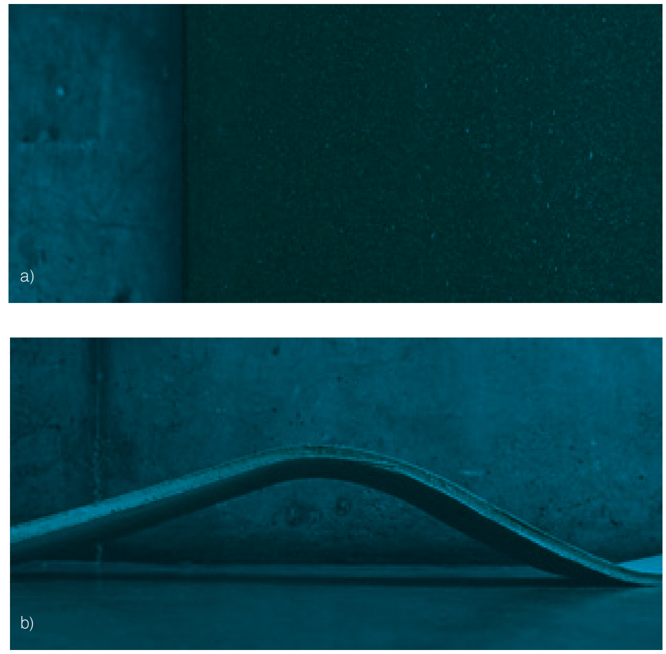
Excessive use of aggregate materials and metals in construction should be balanced by increasing use of construction materials from annually renewable resources based on natural lignocellulosic fibers. Parametric design tools gave here a possibility of using an alternative newly developed biocomposite material, for realization of complex geometries. Contemporary digital fabrication tools have enabled precise manufacturing possibilities and sophisticated geometry-making to take place that helped in obtaining high structural behavior of the overall global geometry of the discussed project.

This paper presents a process of realizing an experimental structure made from Natural Fiber-Reinforced Polymers (NFRP)- also referred to as biocomposites, which were synthesized from lignocellulosic flexible core reinforced by 3D-veneer layers in a closed-moulding vacuum-assisted process. The biocomposite sandwich panels parameters were developed and defined before the final properties were imbedded in the parametric model. This paper showcases the multi-disciplinarity work between architects, structural engineers and material developers. It allowed the architects to work on the material development themselves and enabled to apply a new created design philosophy by the first author, namely applying 'Materials as a Design-Tool'. The erected biocomposite segmented shell construction allowed a 1:1 validation for the whole design process, material development and the digital fabrication processes applied. The whole development has been reached after merging an ongoing industrial research project results with academic education at the school of architecture in Stuttgart-Germany.

INTRODUCTION

Biocomposites were here suggested to partially replace aggregate materials and metals, which are still predominantly the building materials responsible for the largest share of greenhouse gas emissions stemming from the building sector.[1] The building industry is responsible for more than 35% of global energy use, as well as almost 45% of global resources' consumption.[2]

Potential replacements for those classic materials may come from the branch of lightweight materials called Fiber Reinforced Polymers, often referred to as Composites and formed by fibers and binding material. These materials, although offering lightness and freedom of geometrical variations, still are made from non-renewable fossil-based materials, mainly glass and carbon-fibers. Hence the long term goal should be replacing these synthetic fibers with natural fibers in order to develop Natural Fiber-Reinforced Polymers (NFRP), often called biocomposites, and offer these material for building industry, which is here practiced and applied with at the strong intersection of research and education.[3]



2 Two types of core materials: (a) thermoplastic elastic NFRP core material, and (b) semi-elastic lignocellulosic oriented fiber core

Advancing research of material engineers in the area of composite materials and advancement in computational design create trans-disciplinary potential to design and optimize structural performance on a new level. A semi-elastic material—developed by the first author and further developed in reseach industrial projects—was given as a starting point to architecture students in an academic design course to work with from different design philosophies or perspectives. Here the material, which is a biocomposite to be applied as an alternative building material, was promoted not only as an exterior application but also as a structural component in a segmented shell construction form. The participating team members were not only architecture students, but also professional architects—specializing in disciplines including composites—and material engineers. At the same time structural engineers were involved at early stages of the design process to make it possible to apply the material correctly through simulating possible failures and weak points in the construction and to maximize improvements and optimization of the whole global geometry.

The alternative material selected for this application was a free-form biocomposite sandwich panel with a semi-elastic core that can adjust into the desired geometry after reinforcing both sides with a special veneer type, namely 3D veneer and in a closed vacuum moulding process the biocomposite sandwich panel has been produced. To enable a closed-life cycle and to increase the ecologic value of the construction, the design strategy DfD "Design for Deconstruction" was also integrated with the aim of dismantling the shell segments in a later stage and reusing the same components in other geometrical variations.[4]

BIOCOMPOSITE MATERIAL DEVELOPMENT

Design development of the biocomposite segmented shell pavilion was preceded with the development of a biocomposite sandwich panel. During this process several samples of it were mechanically tested in order to verify that the target values of Elasticity Modulus and Tensile Strength were achieved, allowing the material's use in load-bearing structures. After completing this stage, the form finding process was undertaken, and the final fabrication and assembly strategy of the pavilion elements were formed and executed.

In this stage, two types of NFRP core materials were developed, where one was a thermoplastic elastic biocomposite produced through mixing about 70% by weight of straw fibers with a fiber size of 1-3 mm and TPE (thermoplastic elastic polymers) as well as Polylactic (PLA) bioplastic mixtures that were compounded and extruded in a twin-screw extruder (Figure 2a). The second core material was flexible semi-elastic lignocellulosic-oriented fiber core (Figure 2b). Both core materials had a thickness of around 4 mm and 30 mm wide, and both had similar properties after being reinforced with single layers of 3D-veneer sheets on both sides, preserving the parallel direction of fibers.

Subsequently, the biocomposite sandwich panel components (semi-elastic core and 3D-veneer on both sides) were wrapped with protective foil and inserted into a vacuum bag. The vacuum pump created the necessary pressing conditions needed inside the bag in which the biocomposite panel was kept for 30 minutes. The uniform pressure provided by the connected vacuum compressor removed all air pockets between core and the hull and delivered perfectly smooth finished surfaces. Afterwards, the biocomposite panels were removed from vacuum bag and left for 24 hours at room temperature before being applied whether to initial testing or (in the end) to the final application.

The target was to achieve mechanical properties that were at least equal to MDFs (Medium Desity Fiberboards), and through the adjusted global geometry and the diverse connections, the loads were properly distributed. The veneer reinforcements, their directions and number of layers were studied and tested (Figures 3, 4). Surface modifications for humidity resistance and UV-resistance coating was applied and tested with four different variations. Multiple data entries for the best results of the mechanical tests took place in the parametric model, which was the basic communication tool for all participating disciplines in the team whether architects, civil engineers, material developers, or Institute for Geodesy engineers.

The mechanical tests proved that the developed biocomposite sandwich panels achieved an Elasticity Modulus comparable to that of MDF boards, ranging from 4,0-7,6 MPa. The complex double curved geometries, methods of connections, and veneer reinforcements allowed the sandwich panel to also achieve the properties required of this alternative biocomposite material to structurally contribute in the form of segments in the final designed double-curved shell.

The iterative form-finding and the structural optimization using FEM (Finite Elements Modelling) resulted in the necessity to include three cross-linked assisting beams, for which timber was selected as the material of choice.

The sandwich panels were connected with temporary connections, as discussed later in this paper, to enable the re-usability of the composite segments, a process that would allow each item to be later shredded and down-cycled so as to reenter a material stream. In this case, the shredded fibers/particles can be included further as main components in other biocomposites' production in combination with either thermoplastic or thermoset binders. This aspect, however, needs further experimentation.

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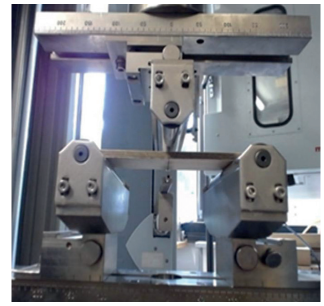

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3 Bending test specimens after lamination

4 Specimens under threepoint bending test

GLOBAL DESIGN DEVELOPMENT

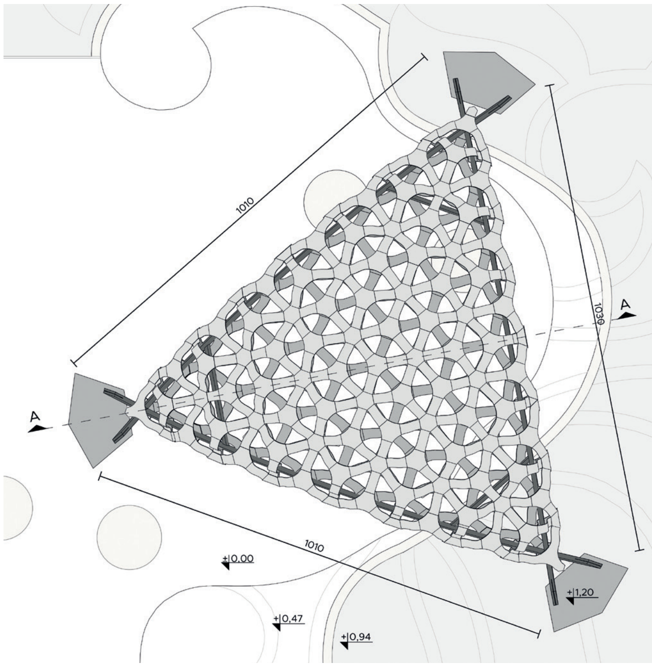
The parametric form-finding process led to the development of a modular construction of lightweight, single-curved elements that form a double-curved shell with individual segments. The structure was supported by three crossed beams, and the entire shell structure was 3.6-metre-high with a 9.5 m span, covering an area of 55 m^2.

A double curved global geometry of the shell was applied to showcase the structural capabilities of the developed composites. Apart from that, the chosen location of the pavilion required it to have its foundations positioned at various heights, which also affected the complexity of the proposed shell system (Figures 5, 6)

The final holistic geometry of the shell resembled a 3D fabric in which the curved elements were connected to common nodes in all directions, providing necessary space stiffness. The pavilion consisted of 120 elements, each of which had three legs.

The production process of the NFRP Core Material and dimensions of the fabricated plates imposed geometric limitations on the design. This experimental material was fabricated in a small batch specially for this project. Material was extruded in the form of plates which were 4 mm thick and 30 cm wide. Their length varied between 1,0 -1,2 m. However, 5 cm wide margins of the plates contained imperfections, thus the usable size of the panel was limited to 20 cm. The *NFRP core material* was 4 mm thick and after lamination reached 6,6 mm.

The mentioned limitations required the design to be tesselated into triangle-shaped panels. The triangles consisted of three legs, each made from the developed biocomposite sandwich panels. The triangular panels distributed loads equally into all directions, towards nodes in which panels were interconnected.



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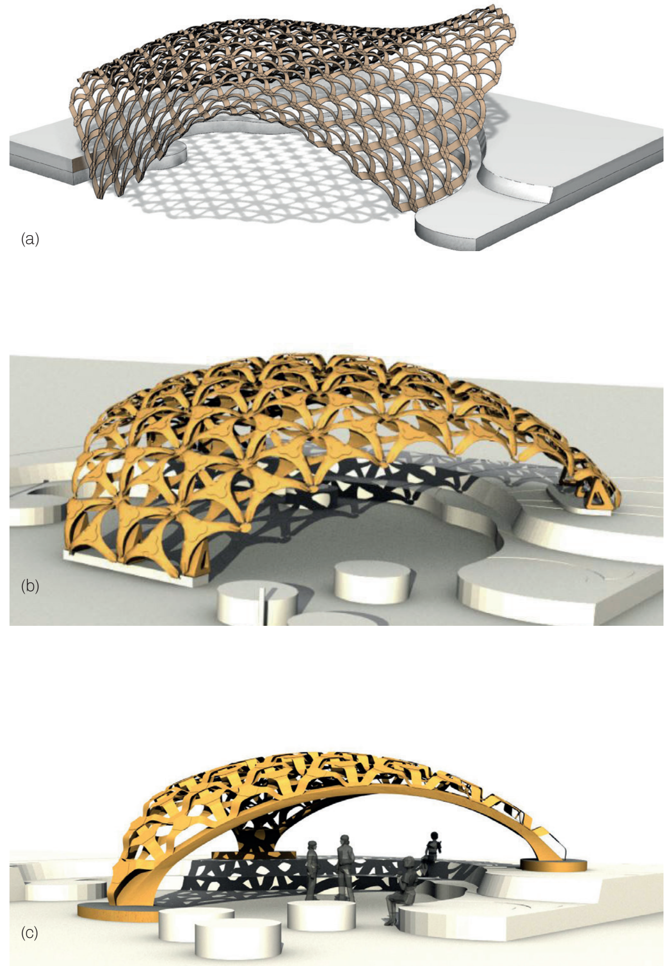

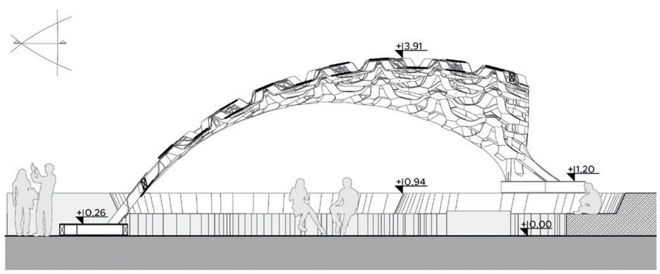

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5 Final Pavilion design - Plan

6 Final pavilion design - Section

7 Preview of the evolution of the pavilion geometry: (a) Initial proposal of a single layer shell, (b) Double layer shell tessellated into three-leg elements, and (c) Introduction of a timber beam support structure

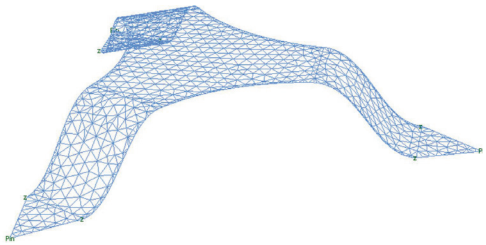
First structural simulations of the single layer shell showed that parameters of the provided biocomposite panels did not allow to realize the shell in this form. The decision was made to expand the structure into double layer shell to achieve higher geometrical stiffness of the triangular panels by providing a further volume to the structure. That is why a second layer was proposed for the shell, then three crossed timber beams connecting the edges of the biocomposite shell with three portable foundation modules were utilized (Figure 7c).

To calculate the deformation of this relatively complex shape, simplification of the required structural analysis was needed. The model was divided into two parts: line model of the whole pavilion and FEM analysis of the three-legged elements. The FEM results were compared with the line model. The results of this comparison showed that the line model could have been applied to the model of the whole structure (Figures 8, 9, 10).[5]

CONNECTIONS

To determine the best joining system between the elements, pull-out tests were conducted. Different types of connections were tested: bolts, dowels, wooden nails, and glue. Not only material properties were considered but also their costs, appearance, and position in the planned pavilion elements. With an average tensile strength that reached in tests up to 8300 N, the specimen glued by 3D veneer from both sides was the best variation, almost three times stronger than the second bolt connection (Figure 11).

This led to the decision to separately CNC-fabricate the three legs forming the elements and then to glue them together offsite, with two layers of single direction fiber



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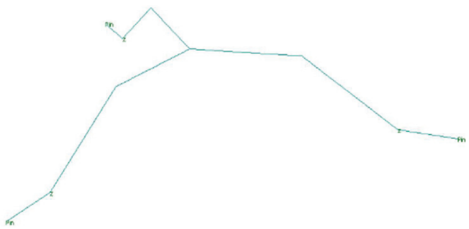

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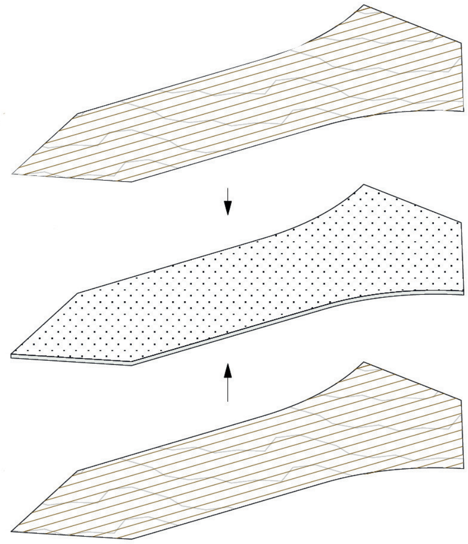

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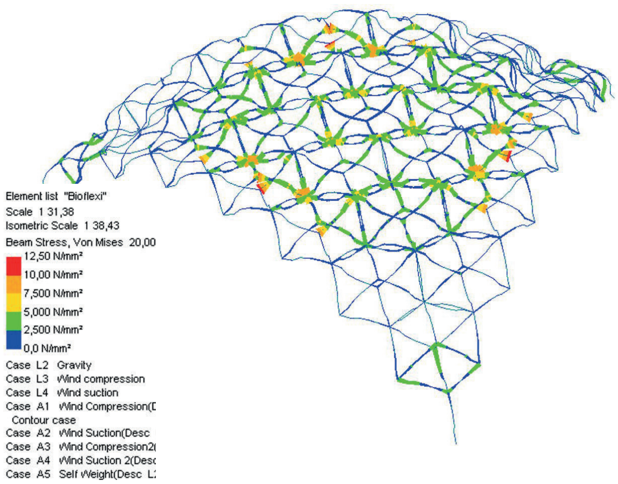

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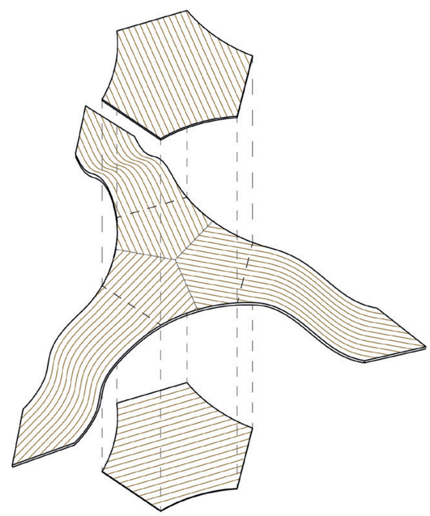

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Breaking Force (N)				
8300	5240	3110	1650	1730

11

8 Structural simulation model of a three-leg element, © TU- Eindhoven[5]

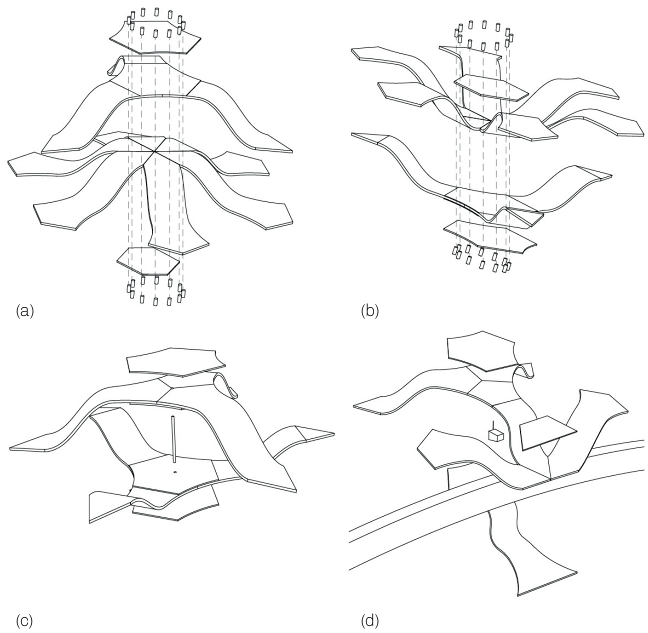
9 Simplified line model of a three-leg element used in the calculations of the whole shell, © TU- Eindhoven[5]

10 Structural model of a whole Pavilion shell, © TU- Eindhoven[5]

11 Specimens for testing various potential joint solutions and the corresponding breaking forces: (a) glued double veneer sheets with fibers at 0 degree angle to the panel (parallel), (b) glued double veneer sheets with fibers at 60 degree angle to the panel, (c) plywood sheets connected by sleevenuts, (d) plywood sheets connected by wooden pins, (e) plywood sheets connected by Lignoloc wooden nails

12 Direction of fibers in veneer sheets used for core lamination process

13 Direction of fibers in veneer sheets used for gluing of three-leg elements



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14 Four types of connections between the elements:
(a) Lower Element + 6 legs
(b) Upper Element + 6 legs
(c) 1 upper + 1 lower Element + Rod
(d) Edge Element + wooden beam

15

16

15 Preparation of CNC-milled core material and 3d veneer layers for lamination process using styrofoam mould

16 Lamination process inside a vacuum bag

veneer sheets laid in the central area on both sides. Both layers had to be oriented perpendicularly to each other to guarantee quasi-isotropic distribution of forces in the finished element (Figures 12, 13).

Several types of connections were distinguished in the structure. In areas where upper and lower layers met, 12 short screws were used (Figures 14a, 14b). Apart from that, in areas where nodes were at the same distance from each other, extra connections using rifled rods were added. These elements were additionally clipped with CNC milled plywood sheets to provide necessary thickness and protection at these points (Figure 14c). Additionally, separate connections for contact points with structural beams were developed (Figure 14d).

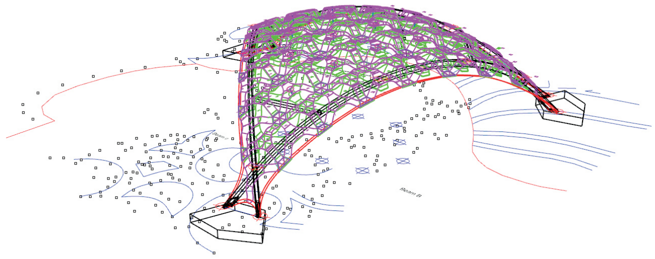
The final connection between the elements was done using screws, so that later the elements could be disconnected and reused in a different configuration. Examples of the reuse possibilities for the elements are shown in the results section of this paper.

FABRICATION, ASSEMBLY, AND ERECTION

The parametric model of the pavilion, which was developed using Rhinoceros, Grasshopper, and Karamba plug-ins, provided all the information and drawings necessary for the realization of the pavilion.

Each leg of the elements was made of a biocomposite sandwich plate. Material lamination process was the same as the one during the material testing phase. The only difference was, that during the lamination process, an extra CNC-milled, based on parametric model, styrofoam mould was used, to form a finished biocomposite board into a curved leg, rather than a planar board. The parametrized model allowed to limit the variety of the different single curved elements (legs) in the structure. Thanks to this optimization, all 360 legs were fabricated using only 4 different moulds, which reduced costs and fabrication time (Figures 15, 16).

First, the core material was CNC milled to the shape of the corresponding leg and marked by a labelling system. Single direction fiber veneer sheets were also cut, but with extra margin in order to compensate for unavoidable slippage of layers during the lamination process. After 30 minutes of vacuum lamination process and extra 24 hours for glue curing, edges of each leg were sanded. Next step was gluing each three legs into one element, with 2 layers of single direction fiber veneer sheets on both sides. The elements remained pressed for another 24 hours. After that, finished elements were finally sanded and coated with weather protection system used in timber and boat industries.



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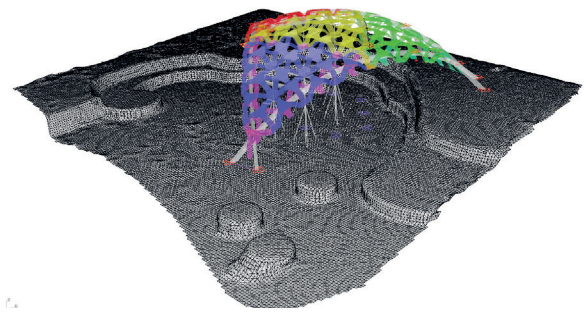

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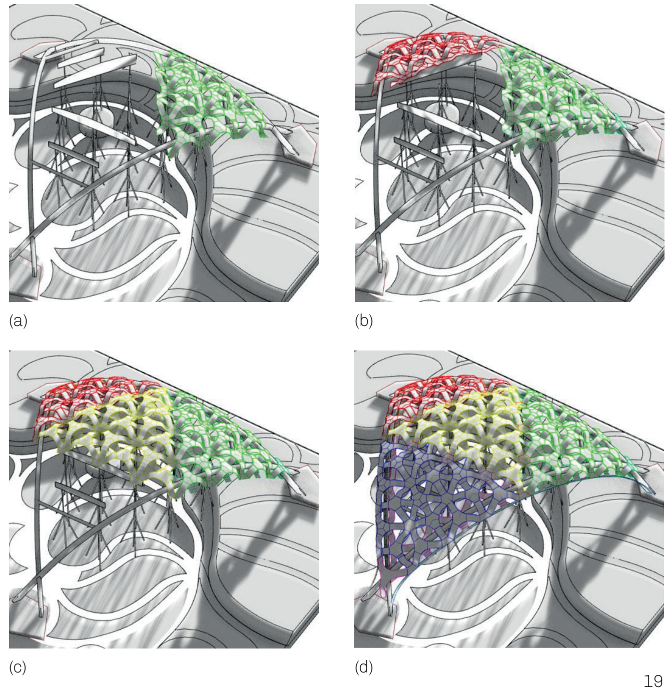

(a) (b) (c) (d)

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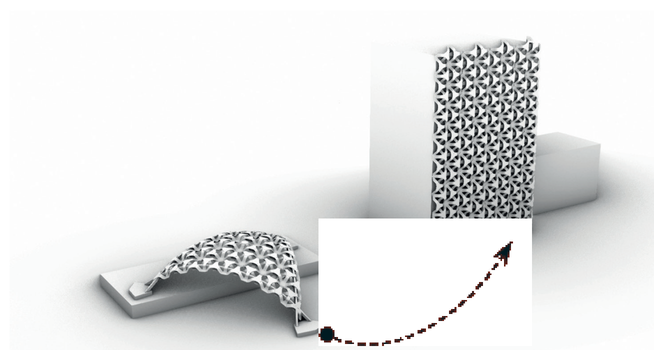

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In cooperation with the Institute for Geodesy, a 3D scanned model of the construction site was provided for the final adjustment of the global geometry design with the beam and foundation design. In the first stage, the three wooden foundations were positioned according to the 3D scan model and the geodetic matrix system (Figure 17). In the following step, three wooden beams were installed with assistance of the geodesy engineering partner, since accurate positioning of the supporting structures was necessary for the further steps (Figure 18).

For the final assembly of elements on the structure, the pavilion shell was divided into four triangle groups (Figure 19). Those were first assembled on-site on the ground and then lifted to the final position in space. Once all 4 groups were in position, final screw connections were made and the supporting columns removed (Figures 20, 21). In (Figures 23, 24, 25), the final 1:1 experimental pavilion is illustrated showing different views and details.

RESULTS AND REFLECTIONS

The final design and the applied connection system guaranteed the possibility of reusing the single segment units to suit further construction designs and other constellations. This was set in the initial design phase to guarantee a closed-material cycle of the constructed temporary building. In Figure 22, the panels were flattened to suit a façade cladding system, showcasing this possibility.

23

17 Data from 3D scan of the site used for adjustment of the parametric model

18 Data from 3D scan used for positioning scaffolding

19 Pavilion elements assembly sequence a) First right corner group is installed, b) Opposite corner group is installed, c) Central group is installed, d) Last corner group is installed

20 A group of elements during preassembly

21 Group of elements installed on the structure

22 Alternative constellations of elements, on an example of a facade system

23 Details of the lower shell connections

CONCLUSIONS

This paper showcases how architects—armed with various digital tools allowing for complete control over the form-finding and design stages, as well as biocomposite production and processing—have a possibility to think about radically new geometries and structural forms. The new flexible biocomposite materials allowed architecture students to unleash creative thinking and to speculate boldly about possible applications of alternative bio-based materials in contemporary architectural solutions.

Simultaneously, one of the main goals during the research discussed in this paper was to start the design process from another perspective, which is to start from the material itself, using a new settled design philosophy, namely: Materials as a Design-Tool, in which architects have the opportunity to work in a bottom-up approach from the materiality level, then up-scale it and explore different scales to reach the structural 1:1 level of our architectural world. Such approach is somehow encouraged by market processes, where innovative machinery and fabrication techinques have become more affordable and consequently more popular, while the cost of raw materials have remained proportionate to the whole costs of construction. The trend of increasing the use of lignocellulosic materials—from annually renewable resources and agricultural leftovers—in the building industry will unavoidably lead to perceiving them as valuable raw material and thus lead to fundamental changes in local and global economy. This process may not necessarily be so noticeable in areas of temperate climate with intense forestation, but it may be a revolution for non-forested agricultural areas of regions with harsher climate. This can provide a new era for local vernacular architecture, as the integration of alternative bio-based materials manufactured from local biomass-resources can be widely used on larger scales in architecture using several techniques, whether sophisticated or relatively basic fabrication setups. However, applying alternative local raw materials integrated in new designs using digital and diverse fabrication methods can be only guaranteed through multidisciplinary work.

These bio-based materials are currently positively perceived by society. However, there is a necessity to create and popularize legal frameworks which would allow for the use of such materials in the construction industry locally and internationally on larger scales.

From the highlighted project, it can be concluded that contemporary digital design and fabrication tools have allowed architects to be at the forefront of a change in the way of thinking and making new sustainable architecture of the future. This will help spreading the message about the potential created by these novel concepts and applications of new alternative building materials and thus raising awareness towards the necessity to accelerate the shift from non-renewable fossil-based materials to more sustainable alternatives in the building industry.

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24 Detail of the shell connection with the beam

NOTES

1. World Green Building Council, 2017, Global Status Report. World Green Building Council: London, UK.

2. United Nations Secretary-General's High-Level Panel on Global Sustainability, 2012, Resilient People, Resilient Planet: A Future Worth Choosing, OVERVIEW. United Nations: New York.

3. H. Dahy, 2019, "Natural Fiber-Reinforced Polymer Composites (NFRP) Fabricated from Lignocellulosic Fibers for Future Sustainable Architectural Applications, Case Studies: Segmented-Shell Construction, Acoustic Panels, and Furniture," *Sensors* 19(3): 738. DOI: 10.3390/s19030738.

4. H. Dahy, 2019, "Materials as a Design Tool' Design Philosophy Applied in Three Innovative Research Pavilions Out of Sustainable Building Materials with Controlled End-Of-Life Scenarios," *Buildings* 9(64), Open Access Journal. DOI: 10.3390/buildings9030064.

5. H. Dahy, J. Petrs, D.H. Bos, P. Baszynski, A.P.H.W. Habraken, P. Teuffel, 2019, "BioMat Pavilion 2018: Development, Fabrication and Erection of a Double Curved Segmented Shell from Biocomposite Elements," In *Proceedings of the IASS Annual Symposium 2019, Structural Membranes 2019 Form and Force*, edited by C. Lázaro, K.-U. Bletzinger, E. Oñate.

25 Finished pavilion from the aerial perspective

IMAGE CREDITS

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