Proceedings of the IASS Annual Symposium 2020/21 and the 7th International Conference on Spatial Structures
Inspiring the Next Generation
23 – 27 August 2021, Guilford, UK
S.A. Behnejad, G.A.R. Parke and O.A. Samavati (eds.)

Designing Lightweight Structures from Recyclable and Organic Materials: The Rethinking Lightweight Pavilion

Maren ZYWIETZ*, Karsten SCHLESIER[a], Annette BÖGLE[a]

*HafenCity University Hamburg
Henning-Voscherau-Platz 1, 20457 Hamburg, Germany
maren.zywietz@hcu-hamburg.de

[a] HafenCity University Hamburg

Abstract

The current development towards bending-active structural design indicates that lightweight structures constantly evolve due to contemporary demands. This paper documents the approach to rethinking lightweight structures to face the growing scarcity of resources. Since conventional composite materials in lightweight structures have severe limitations in terms of their recyclability, this raises new challenges for designers and engineers in the use of raw materials. In order to reduce the environmental impact, this research investigates the use of fully recyclable materials made from renewable resources in bending-active tensile structures. Based on an experimental approach, this paper presents an innovative pavilion design which will be exhibited as a built prototype at the IASS WG21 competition. The results of the four-step methodology consisting of parametric design, material testing, numerical simulation and the verification of the results using a mock-up structure are presented and discussed. The Rethinking Lightweight Pavilion demonstrates that the use of materials suitable for the circular economy can make an inspiring contribution to lightweight structures of the future.

Keywords: lightweight, sustainability, circular economy, recycling, eco-design, hybrid structure, form-finding, bending-active, ash wood, wool fabric, alternative building materials

1. Introduction

The critical state of our world, our climate, and our environment results largely from our irresponsible use of resources. From an ecological perspective, lightweight structures offer solutions to these problems: By making optimum use of material strength, lightweight structures save material and thus resources. In addition, lightweight structures can often be dismantled and reused. [1]

Historical development shows that lightweight structures can adapt flexibly to social requirements. This is also reflected in the continuation of the traditional principles of lightweight design in the form of the new structural typology of bending-active tensile hybrid structures. Instead of the former avoidance of bending stresses, these become a decisive form-determining structural element.

The consequent demand for high strengths with slender cross-sections has led to increasingly advanced building materials in recent decades. However, the multi-layered, complex composite materials that have been developed have severe limitations in terms of their recyclability. This causes difficulties in the current paradigm shift from a linear to a circular economy.

The aim of this research is to investigate the use of fully recyclable materials in bending-active tensile hybrid structures with special focus on renewable resources. The challenges that arise for structures made of such materials from a structural and mechanical point of view will be determined and approaches to solving them will be addressed.

After clarifying the terms and surveying the current state of research on circular economy in lightweight construction, the design of an experimental structure as a demonstrator is described. The design will be built as a research pavilion and exhibited as part of the IASS WG21 competition 2021. With the help of laboratory tests and numerical simulations, initial findings will be verified and discussed. Finally, the results will be summarised.

2. Concept of Rethinking Lightweight

In order to illustrate the concept of the research pavilion, the central aspects are initially defined.

2.1 Bending-active tensile hybrid structures

The new structural typology of bending-active structures developed in the last decade is characterised by the elastic deformation of individual structural elements, which result in the shape and overall stiffness of these structures. [2] By integrating bending-active elements into a form-active structural membrane, a hybrid system is formed, combining the positive characteristics of both structural typologies. The bending-active elements provide the double curvature and the necessary pre-stress of the membrane, while the membrane in turn maintains the curvature and increases the buckling strength of the rods. [3]

Previous research projects have demonstrated the application of this principle to small-scale and large-scale projects. Due to the complex form-finding process of hybrid structures, computer-aided form-finding has also made significant progress. Current research on bending-active tensile hybrid structures focuses on improving the stiffness and robustness of the structures. In addition, the tailoring of material behaviour, e.g. through CNC knitted fabrics, is being explored for smaller installations. [4]

2.2 Circular economy in lightweight construction

38% of global carbon emissions are related to the construction industry. In order to reduce the carbon footprint and carbon emissions, a major contributing factor is seen in the circular use of materials. Currently, material waste generated by the construction sector in the European Union is estimated at 25-30% of the total waste production. [5] The European Union is therefore enforcing the shift from a linear to a circular economy and put the corresponding action plan on the political agenda in 2015. One of the priority areas addresses construction and demolition. [6]

Despite the small market share of textile products in the building industry, the linear consumption of limited resources is also evident in textile architecture. While materials and technologies in ultra-lightweight construction have improved over the past decade in terms of efficiency, durability and construction details, petroleum-based and other non-biodegradable materials and coatings such as PVC/polyester, PTFE/glass and ETFE foils are used in 90% of all membrane structures. Thus, the need for research into building with environmentally friendly membranes from fully recyclable materials is increasing. Large potential is seen in the development of membranes made from recycled fibres and coatings made from biopolymers. In order to meet the standards in textile architecture and lightweight structures, the use of new materials often requires extensive testing. To promote the creative development of green materials, a new concept of collaboration between designers, producers and manufacturers in an iterative design process is proposed, which is possible due to the short distances between design and construction. [7]

The tendency towards composite materials replacing natural materials such as wood is also evident in building with bending-active materials. This correlates with requirements for high tensile strength and high deformation capacity. However, a study of GFRP and wood proved that there is comparable deformability and similar costs. Although GFRP is three times stiffer than wood, it also has a higher environmental impact since it is a composite material. [8]

3. Design of the Rethinking Lightweight Pavilion

The competition design was developed in an interdisciplinary team of students of architecture and structural engineering at HafenCity University Hamburg. The team's main motivation was to demonstrate with their design that a lightweight structure can be created from fully recyclable materials that can be completely disassembled and separated by material type. In addition, with the bending-active and form-active elements, the main components of the pavilion were to be made from renewable organic resources. Due to the mutual relationships between form and forces, boundary conditions, materials and their interaction, this was developed in an iterative design process. The result of the design is an innovative structure based on the principles of bending-active and form-active structural behaviour.

One of the competition conditions was that the structure must be able to be dismantled to fit into six imaginary boxes (1.0 x 0.75 x 0.65 m) and must not exceed a total weight of 192 kg. The modular design that was chosen makes it possible to react with the necessary flexibility to this requirement. Each module consists of two bending-active rods, which are bent into their geometry by a form-active membrane. At the same time, the residual forces of the rods provide the necessary pre-tension of the membrane. The individual modules are coupled to each other using pinned connections. The arrangement of the basic modules in two shifted layers creates a stable static system.

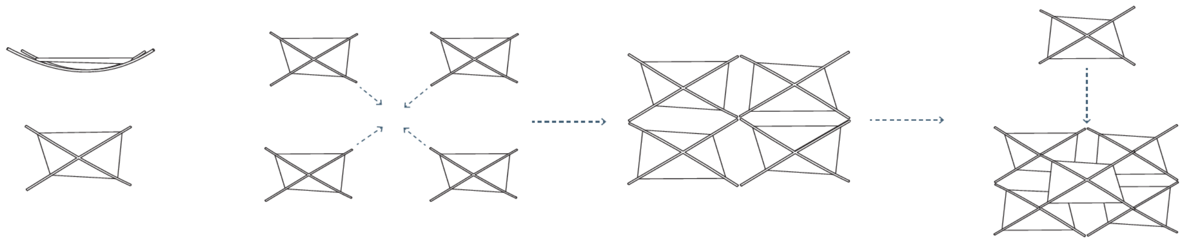

Figure 1: Modul-based concept with bending-active rods and form-active membrane elements

The entire formal language of the pavilion follows the flow of forces of the reciprocal interaction between the flexible membrane and the bending-active rods. Despite the complex load-bearing behaviour, the hybrid structure appears delicate and light due to the playful use of compression and tension elements. In principle, the modules can be assembled in a variety of ways to form an overall structure. In the present design, the pavilion appears in top view to consist of two assembled C-shaped arcs. In its centre, it offers the visitor a closed space that is accessed through two narrow openings measuring 2.80 m in height. This shape is the result of a Parametric Design with the module height and the bar length as variable parameters. The procedure guarantees the completely digital production of all components with the help of the available data set.

The chosen materials meet the requirements in being able to be completely returned to the material cycle. The pavilion consists entirely of organically grown and recyclable resources. Once used, each component of the structure can be completely disassembled and recycled or reused. Furthermore, the materials of the two load-bearing structural elements originate in the rural areas of northern Germany, thus fulfilling the additional aspect of regionality.

Wooden laths made of ash wood with a cross-section of 4x40mm are used as the material for the bending-active rods. The choice was made due to the high elasticity of the wood with simultaneously low creep behaviour. In addition, ash wood has already been used in the construction of bending-active structures in scientific research because of its dense and straight-grained cross-section. [9]

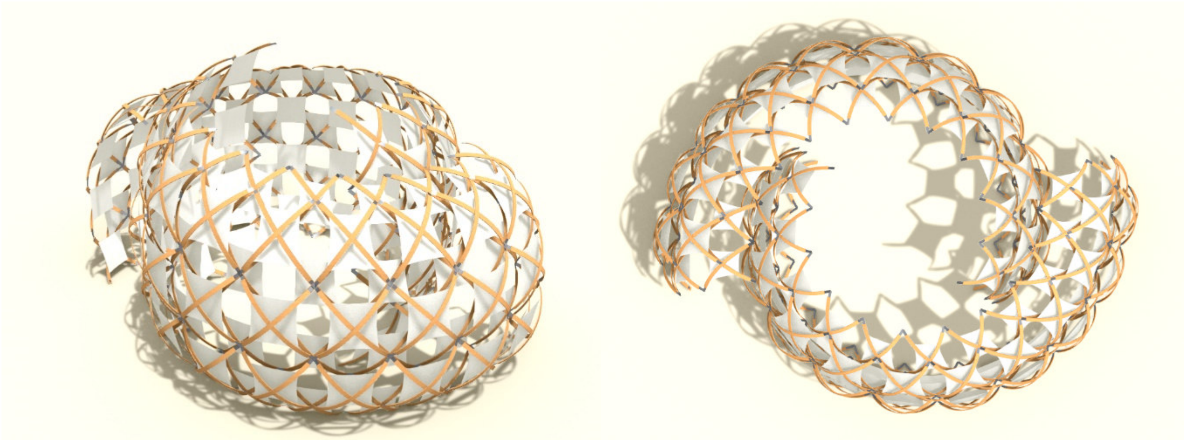

Figure 2: Design proposal of the Rethinking Lightweight Pavilion

In contrast, the organic fabric made from North German sheep's wool is being used for the first time as a structural membrane. The use of sheep in the state of Mecklenburg-Vorpommern originally serves the preservation of the local cultural landscape. The wool of the sheep is a by-product that is difficult to market profitably, as there is hardly any use for it in the modern clothing industry. Very recently, with a refocus on local raw materials and handicrafts, the demand has started to increase again. The wool of the endangered old land breed Pomeranian Coarsewool sheep is washed and spun, preserving the natural properties and the colour of the wool. The yarn obtained is then processed into a strong fabric. Through the subsequent traditional thermodynamic process of fulling, the so-called loden cloth acquires high form stability and durability. [10]

The pavilion's connections are made of steel (connection plates, screws, nuts, and washers) and viscose (seams on the structural membrane) and are therefore also fully recyclable.

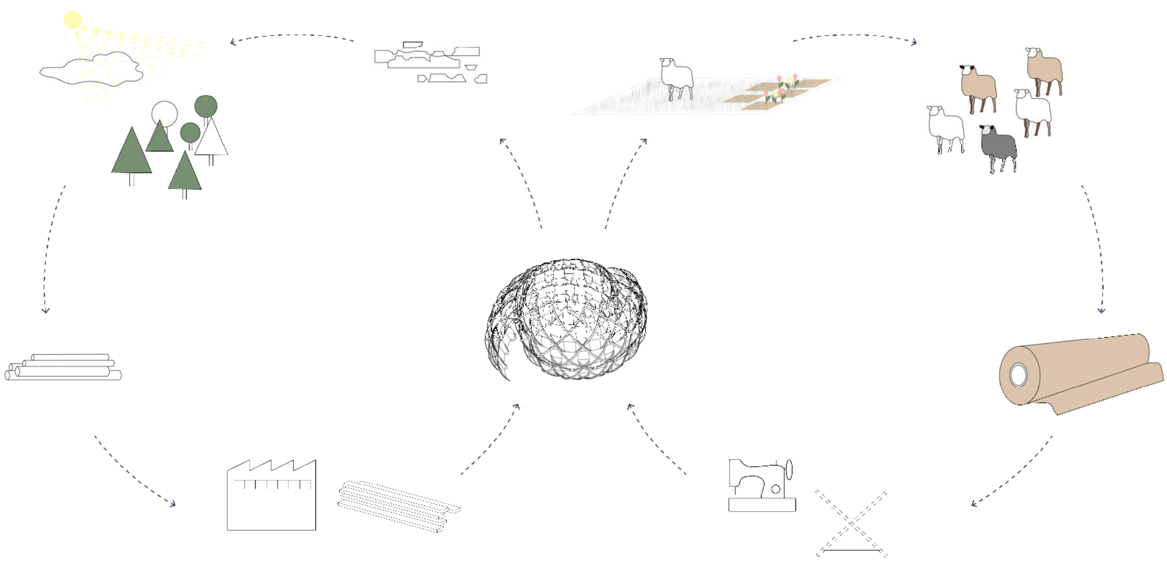

Figure 3: Biological Cycle for the biodegradable load-bearing structural elements (ash wood and wool fabric)

4. Research findings

In order to explore the feasibility of the structural use of circuit-appropriate materials in bending-active tensile hybrid structures, their exact properties were investigated in laboratory testing. This was followed by the experimental construction of a mock-up and the numerical analysis of the entire structure.

4.1 Laboratory tests

4.1.1 Three-point bending flexural test of wooden members

To determine the modulus of elasticity of the wooden laths used as bending-active rods in the pavilion structure, three-point bending tests were carried out on specimens with variable cross-sectional heights. The results are shown in Table 1. The mean value E = 14 500 N/mm² was chosen.

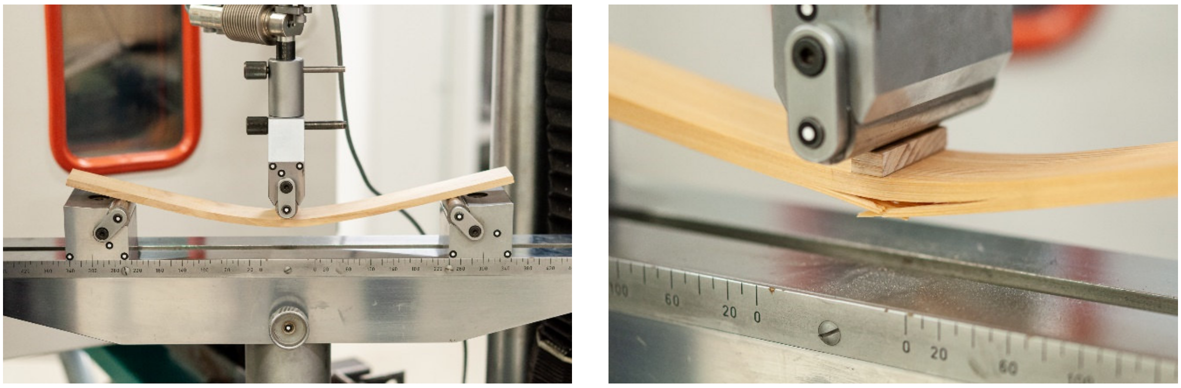

Figure 4: Failure of a sample in three-point bending flexural testing

Table 1: Resulting flexural modulus of elasticity of the wooden laths

	Ash, t = 5mm (N/mm²)	**Ash, t = 6mm (N/mm²)**	**Ash, t = 7mm (N/mm²)**
1	11536.25	16632.98	0.00
2	14463.66	15498.08	15495.25
3	12852.19	16365.65	14312.84
4	12732.21	16912.89	14266.92
5	13547.70	16926.89	16506.13
6	5876.31	16414.18	15481.30
Mean	11834.72	16458.45	15212.49
Std.Dev.	3075.00	527.12	939.31
Coef.Var. (%)	25.98	3.20	6.17

4.1.2 Uniaxial testing of the wool fabric

The uniaxial tensile test was carried out on test strips with a width of 10 cm in both the warp and fill directions. The average maximum tensile strength of the fabric is 700N/10cm in the warp direction and 637N/10cm in the fill direction.

Figure 5: Uniaxial tensile test of membrane strips

Table 2: Resulting ultimate tensile strength of the organic membrane material

	Warp direction (N/10cm)	**Fill direction (N/10cm)**
1	721.69	627.32
2	701.92	641.09
3	697.76	638.52
4	699.88	636.78
5	678.98	639.58
Mean	700.05	636.66
Std.Dev.	15.17	5.45
Coef.Var. (%)	2.17	0.86

4.1.3 Biaxial testing of the wool fabric

The biaxial testing machine at HafenCity University Hamburg as shown in Fig. 6 was used to test the load-bearing behaviour of the selected wool fabric. The testing of the traditionally woven and fulled fabric was carried out in accordance with DIN EN 17117-1 for determining the tensile stiffness properties of rubber or plastics-coated fabrics under biaxial stress states. In order to achieve the expected pretension condition and to obtain evaluable data, the maximum stress was increased from 25% of the maximum tensile strength in each direction to 50% (W25/F25 to W50/F50). The strain was measured by an optical measuring system.

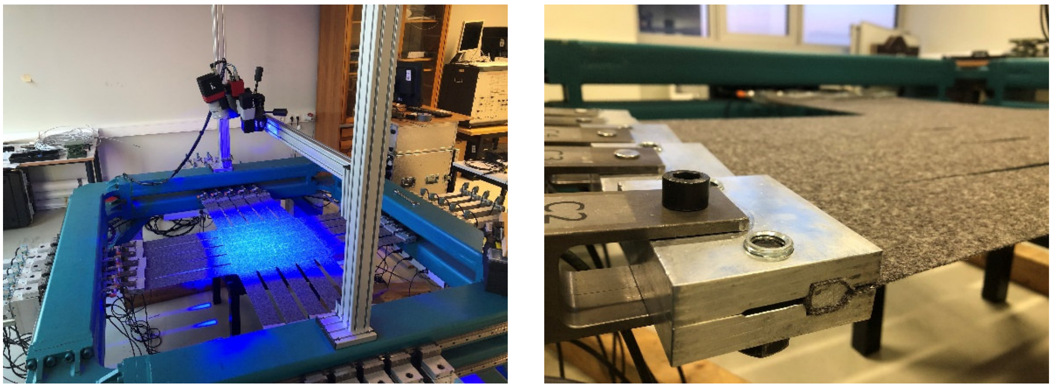

Figure 6: Wool fabric in biaxial test

Fig. 7 and 8 show the selected biaxial test protocol and the corresponding stress-strain diagram of one of the three samples.

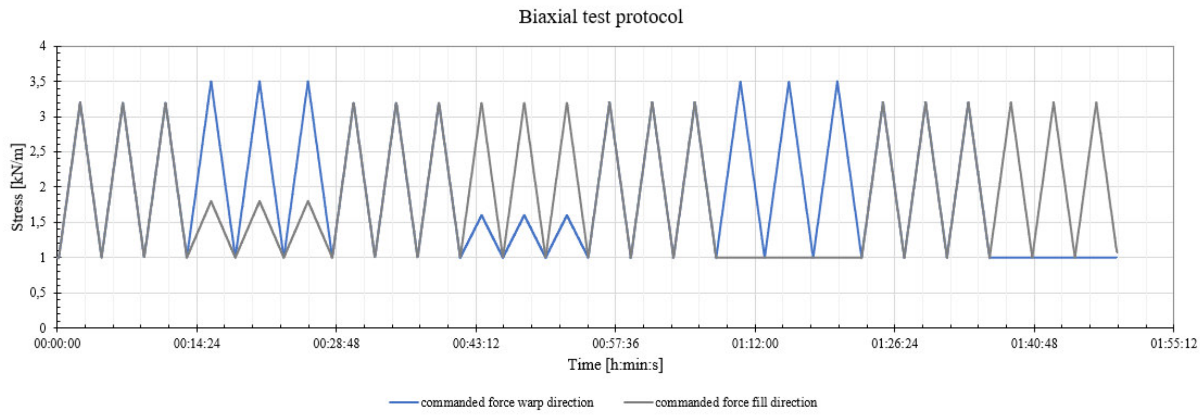

Figure 7: Biaxial test protocol

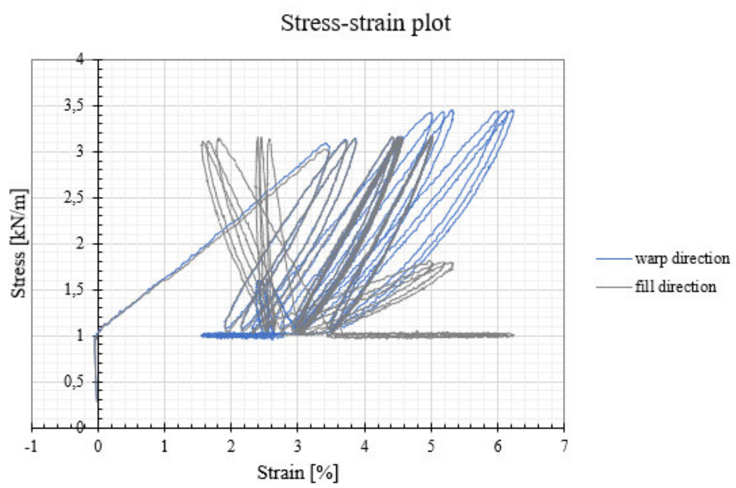

Figure 8: Stress-strain plot of one sample under biaxial load

The investigated textile material shows an anisotropic material behaviour under biaxial load. Assuming a plane stress state, the moduli of elasticity in the warp and fill directions were determined on the basis of the measured data. The method described by Blum et al. [11] was used to determine tensile stiffness properties and Poisson's ratios. Compared to conventional, coated materials, the investigated membrane made of organic wool material demonstrates high strains and an inherent low modulus of elasticity.

4.2 Mock-up

The mock-up shows a small section of the overall structure on a scale of 1:1. The realised structure consists of a total of five modules in offset arrangement in two layers. Instead of the full-surface membrane, straps from the warp direction of the membrane material, which is subject to higher stress, were used. The straps are also present in the overall model and support both the biaxial load distribution of the membrane and the connection points of the membrane to the bending-active rods. For testing purposes, their width was dimensioned differently depending on the module in order to explore the interaction between straps and rods. For this reason, the strips are each constructed in double layers and measure 25 to 30 mm in width. The lengths of all the individual elements derive from the parametric design model. The compensation of the wool fabric was determined from the data of the biaxial tests and applied as shortened length in the fabrication of the straps. This resulted in a shortened assembly of all straps and a resulting higher bending stress of the timber laths in the assembly situation.

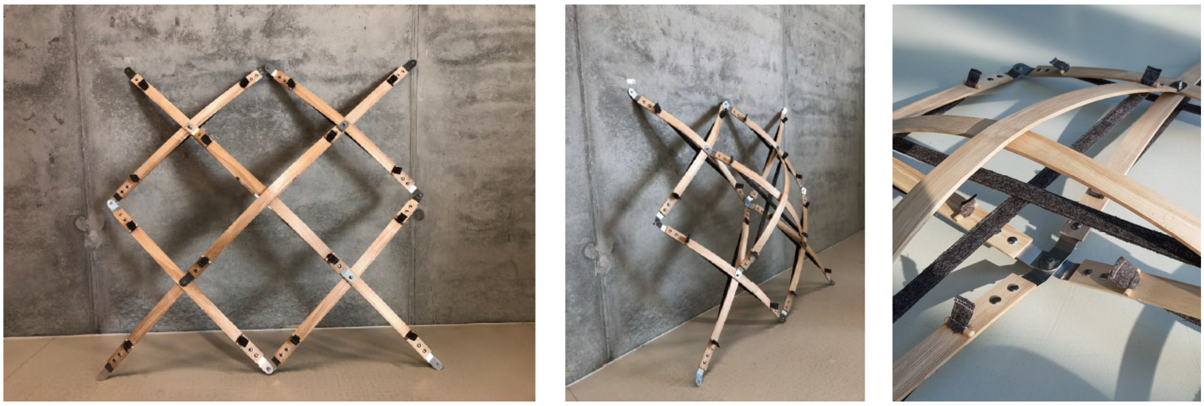

Figure 9: Finished mock-up installation

Since the angles between the laths vary and the laths are not connected to each other in their respective centres, a pretensioning device was specially made for the assembly of the pavilion. This ensured a tension-free installation of the straps and is also designed to connect a biaxially stressed membrane to both rods at the same time. After assembling the individual modules, their ends were connected to each other with plates and screws. The installation of the module in the second level showed that the smallest deviations in the underlying geometry influence the equilibrium of forces in the module level above.

4.3 Numerical simulation

Numerical models were built to verify the experimental approach. In addition to verifying the global load-bearing capacity in a structural analysis program, isogeometric analysis served as a supporting tool for the form-finding of the modules. In the plug-in Kiwi!3D, beams and membranes were modelled with the previously determined material properties and form found in two steps. In the first step, virtual cables were used as an aid to roughly bend the beams into the predefined geometry. Subsequently, the cables were replaced by real straps. The inherent bending stress of the beams was thus retained and in turn set the membrane straps in the required prestressed state.

5. Discussion

The investigation of the proposed pavilion design regarding the implementation of resource-respectful materials provided revealing results due to the multi-stage methodology.

First of all, when analysing the load-bearing behaviour of the individual modules in more detail, it became apparent that a comprehensive determination of all material parameters must be carried out in order to analyse the load-bearing behaviour of the individual structural elements. The results of the two main load-bearing materials, ash wood and wool fabric, show comparably high load-bearing capacities in relation to their weight. As the test results show, the ash wood is of high and consistent quality. Only one sample broke prematurely due to a knot hole at the load application area, which explains the large standard deviation for wood with a thickness of 5 mm. The membrane made of industrially produced organic wool fabric also shows only minor variation in its material behaviour. The uniaxial tensile testing of the membrane strips demonstrated that the fill direction has a ten percent lower tensile strength compared to the warp direction. The subsequent biaxial tensile tests confirmed the consistent stiffness properties of the examined fabric.

In contrast to conventional fabrics, the natural material showed high strains that were initially stretched out of the material. Not only the plastic but also the elastic strain was challenging for the subsequent construction of the mock-up. To bring down the complexity in verifying the modules, only the straps were modelled instead of the full-surface membrane. By determining the compensation from the test results as well as a special set-up for the installation of the straps, the calculated lengths from the parametric design model could be achieved. The numerical investigation of the modules by means of isogeometric analysis confirmed the assumption that a complex form-finding is necessary.

Overall, it was shown that the fragile form equilibrium can easily be disturbed, especially by the installation of the second structural layer. It is therefore necessary to realistically represent all material properties in the digital model. On the other hand, careful detailing is essential in order to realise the designed geometry despite the strong time-dependent deformations and high elastic strains of the membrane.

Further investigations are necessary with regard to the creep behaviour of the wool fabric. The first available results of a five-day loading test are not sufficient to comprehensively describe the load-bearing behaviour. The creep of the wooden laths, which has been neglected in this research, also offers great potential for further research activities. These should serve as a basis for the description of the stress redistribution in the bending-active module.

In the large-scale pavilion, the load-bearing behaviour is extended to include the biaxial stress state of the membrane sections. For this reason, further investigation of the biaxial load-bearing behaviour of the wool fabric with different loading conditions is advisable. This can serve as a basis for applying the fabric within a membrane-appropriate anticlastic curvature.

The evaluation of the durability of the material used in an outdoor application was not subject of the investigations.

6. Conclusion

While the resource-efficient use of materials in lightweight structures has always been demonstrated, the use of natural resources is still little explored. The pavilion design proposed in this paper for the IASS WG21 competition 2021 addresses the urgent need to change our habits in the use, application, and disposal of materials in lightweight structures.

Due to the combined load-bearing behaviour and the consequent material reduction, a modular, bending-active and hybrid design approach was chosen. The minimalist appearance of the pavilion is intended to raise the visitor's awareness of sustainability and the integration of new materials. The structure is made of organic and recyclable materials and can be fully reintroduced into the material cycle.

In order to investigate the use of materials suitable for the circular economy in bending-active tensile hybrid structures, the selected materials were first investigated in terms of their strength properties. The results were then verified both numerically and in a mock-up on a 1:1 scale. This showed that the selected natural materials are fundamentally suitable for the construction of bending-active tensile hybrid structures. Careful detailing of the structures is necessary in order to optimise the load-bearing behaviour. Further research is needed with regard to the biaxial load distribution of the membrane made of natural fabric. Investigations are also proposed regarding the creep of wood under constant loads.

The quality of lightweight structures can not only be evaluated in terms of the strength of the materials used. The environmental impact of the materials applied is significant in the evaluation of how sustainable a design can be implemented. The research for the Rethinking Lightweight Pavilion demonstrates that filigree-looking structures based on complex form-finding and structural action can also be achieved with loadbearing components made from renewable, entirely organic resources. Rethinking Lightweight can thus make an inspiring contribution to how lightweight structures can continue to develop in terms of a resource-respectful use of materials in the future.

Acknowledgements

The Rethinking Lightweight Research Pavilion is the result of an intense interdisciplinary teamwork of young designers and engineers from the fields of architecture and structural design. We would like to thank the students from the design workshop for their contribution to this project: Joachim Beyer, Phillip Diehl Villescas, Daniel Görg, Hiba Mati, Naima Mora, Charlotte Stapenhorst, Ehsan Taghiyar, and Barbara Weese. Furthermore, we would like to express our gratitude to Marcus Illguth from the construction laboratory of HafenCity University Hamburg for the great support during technical lab testing.

The authors would also like to thank Marco Scheel and his company Nordwolle for the advice and the provision of the wool fabric as well as Waterfront e.V. and the Prof. Dr. Egon Peter foundation for financially supporting the research project.

References

[1] J. Schlaich, „Leichtbau – eine Forderung unserer Zeit,“ *Bautechnik,* Vol. 90, pp. 825-838, 2013.

[2] J. Lienhard, „Bending-Active Structures: Form-finding strategies using elastic deformation in static and kinetic systems and the structural potentials therein,“ Institut für Tragkonstruktionen und Konstruktives Entwerfen, Universität Stuttgart, 2014.

[3] E. L. M. Slabbinck, S. Suzuki, J. J. Solly, A. Mader and J. Knippers, „Conceptual framework for analyzing and designing bending-active tensile hybrid structures,“ in *Proceedings of the IASS Annual Symposium 2017*, Hamburg, 2017.

[4] J. Lienhard and C. Gengnagel, „Recent developments in bending-active structures,“ in *Proceedings of the IASS Symposium 2018*, Boston, 2018.

[5] United Nations Environment Programme, „2020 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector,“ Nairobi, 2020.

[6] Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, „Closing the loop - An EU action plan for the Circular Economy,“ Brussels, 2015.

[7] A. Zanelli, C. Monticelli and S. Viscuso, „Closing the Loops in Textile Architecture: Innovative Strategies and Limits of Introducing Biopolymers in Membrane Structures,“ S. Della Torre, S. Cattaneo, C. Lenzi und A. Zanelli, Hrsg., Springer International Publishing, 2020, p. 263–276.

[8] N. Kotelnikova-Weiler, C. Douthe, E. L. Hernandez, O. Baverel, C. Gengnagel and J.-F. Caron, „Materials for Actively-Bent Structures,“ *International Journal of Space Structures,* Bd. 28, p. 229–240, 9 2013.

[9] E. Baseta, "Bend&Block: a shape-adaptable system for the rapid stiffening of active-bending structures," Universität für angewandte Kunst Wien, 2019.

[10] Nordwolle Rügen, „Unser Produktionsprozess“. Accessed on: Apr. 20, 2021, [Online], Available: https://nordwolle.com/ueber-nordwolle-ruegen/unser-produktionsprozess/

[11] R. Blum, H. Bögner and G. Némoz, „Testing methods and standards,“ B. Forster and M. Mollaert, Eds., Brussels, TensiNet, 2004, p. 293–322.