Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Reciprocal Lightweight Structures with Natural Fiber Biocomposite Profiles through Computational Design and Case Studies Validation

Evgenia SPYRIDONOS*, Alexander REINER[a], Hanaa DAHY[b,c,d]

*Bio-Based Materials and Materials Cycles in Architecture
Institute of Building Structures and Structural Design (ITKE), University of Stuttgart
Keplerstraße 11, 70174 Stuttgart, Germany
evgenia.spyridonos@itke.uni-stuttgart.de

[a] ITECH Master Program, University of Stuttgart, Germany
[b] University of Stuttgart, Germany
[c] Aalborg University, Denmark
[d] Ain Shams University, Egypt

Abstract

The use of bio-based materials has been increasing in recent years owing to a growing awareness of ecologically friendly alternatives in the building industry. This work demonstrates the application of natural fiber biocomposite profiles within a reciprocal structural framework. Employing the pultrusion technique, linear profiles are fabricated using natural flax fibers and a bio-based resin. This paper focuses on the design and implementation of a parametric model that generates reciprocal systems considering the geometric and mechanical properties of this newly developed material. Reciprocal systems were chosen due to their high density of shorter linear elements, capacity for global geometric diversity, simplicity of joint assemblies, and low structural dependence on the joints. The developed algorithm considers material properties and site requirements to transform a line network into a stable reciprocal system with given cross-sections and generates pre-fabrication and assembly instructions to reduce on-site complexity. The proposed method was initially validated with a small demonstrator, confirming its accuracy from design to fabrication. A larger canopy showcased at the Venice Biennial demonstrated the system's scalability and the applicability of biocomposite profiles for complex applications.

Keywords: Reciprocal Structures, Lightweight Structures, Parametric Modelling, Biocomposites, Natural Fiber Pultruded Profiles, Pultrusion

1. Introduction

The growing concern for the environmental footprint of the building industry has prompted researchers to explore alternative, eco-friendly building materials. In line with implementing the UN Sustainable Development Goals [1], there is a significant shift towards investigating natural or bio-based materials, alongside new or existing technologies to create sustainable architectural elements and products. Although natural materials offer advantages, they are constrained by inherent physical and geographical limitations. Composites, as artificial products that can be customized for specific applications, are a potential replacement. Particularly, biocomposites are materials where at least one of the two primary ingredients derives from biomass resources [2].

1.1. Natural Fiber Biocomposite Profiles

In the framework of the research project LeichtPRO [3] led by the BioMat Department at the ITKE Institute of the University of Stuttgart, a new biocomposite product was manufactured using the pultrusion technique, a continuous manufacturing process for Fiber-Reinforced Polymers (FRP) with uniform cross-sections. During this process, fibers are pulled through various components, impregnated into the selected matrix, and shaped within a heated mold before being cured and cut to length (Figure 1). The resulting profiles are round and hollow with a diameter of 25 mm and 4 mm wall thickness and can be manufactured to any length. These profiles are composed of natural flax fiber rovings of 1000 tex as reinforcement to a customized matrix system. The matrix formulation has been specifically engineered and optimized for pultrusion, aiming to maximize bio-content. It comprises a plant-based resin component, a hardener, an accelerator, and the aluminum trihydrate additive which acts as a mineral filler and flame retardant. All components have been meticulously tested in different proportions [4]. These biocomposite profiles were developed as structural components for diverse applications and thus underwent rigorous mechanical testing to ascertain their properties. Their compression strength reached 31.2 kN, with an average compression modulus elasticity of 118 MPa. On average, they exhibit a flexural strength of 300 MPa and a bending modulus of 30 GPa. These profiles demonstrate significant flexibility, achieving a minimum radius of approximately 2.4 m after a certain length. In shorter sections, below 2 m, the profiles exhibit excellent compression behavior [5]. This particular characteristic has been utilized in this project, inspiring the idea for application in reciprocal structures.

Figure 1: Pultrusion process: (1) Natural flax fiber rovings, (2) fibers being impregnated into the matrix, (3) cured pultruded profile ⌀25 mm exiting the heated mold

Given the exceptional elasticity of the profiles over extended lengths, the first structural demonstrator introduced was an active-bending structure, named LightPRO Shell. The biocomposite profiles were employed to create a gridshell featuring a continuous outer perimeter comprised of two profiles. The profiles exhibited double curvature within a structure spanning 10 m and reaching 4.5 m at the highest point. A total of 40 profiles, ranging from 6 to 12.5 meters in length, were utilized in this construction. Completing the structure, a membrane served as the outer skin, while customized steel connections were incorporated [6]. Various other prototypes including facades, support structures, tensegrity systems, deployable structures, and domes have been explored as potential applications for the developed profiles.

1.2. Reciprocal Structures

With the name originally patented by Graham Brown in 1989 [7], reciprocal frame structures consist of beam elements, with each supporting and being supported by the subsequent one in a continuous circuit until forming a closed polygon. A minimum of three elements is necessary to establish such a system. Initially, reciprocal frames were found in roof constructions, where the elements collectively bear the load by transferring forces from one to another and then downward, typically to a peripheral beam or column. Reciprocal structures are characterized by relatively short members and the resulting spatial geometries vary based on the number and length of elements, the distance between the intersection points, the closed polygon formed, and the vertical spacing between points [8], [9]. In reciprocal structures, loads are distributed evenly throughout the closed circuit to all members, with the degree of distribution influenced by the geometry and placement of elements. Structurally, under vertical loads, members primarily experience bending and shear forces, depending on the geometry’s dimensionality [10]. Although joints are commonly incorporated in reciprocal systems, it is evident that the system members reciprocally support each other, typically held in place by friction. It is argued that once all elements are assembled and the system is anchored, friction alone is structurally efficient for maintaining equilibrium in a reciprocal system. However, its effectiveness relies on the materials used, the prevention of sliding, and the nature of outer supports [11].

Reciprocal frame structures are commonly used in timber roof constructions, as it was their original purpose. Leonardo Da Vinci's Renaissance designs, notably his temporary bridge, exemplify this approach, with short timber beams supporting and being supported by each other to create an arch. These structures were built using pre-assembled timber members, held together solely by friction, for easy construction [11]. Further exploration of reciprocal frames has shown adaptability to various shapes and applications. The Future Tree Pavilion by ETH features a distinctive funnel-shaped geometry that forms a timber reciprocal frame supported by a concrete foundation. This reciprocal system enables the elements to extend into a significant cantilever, pushing the boundaries of what would typically be achievable. Similarly, the Franz Masereel Centre in Kasterlee, Belgium showcases a reciprocal frame in a complex geometry, combining a truncated cone space with timber four-member reciprocal frames [12]. Computational design and fabrication tools were utilized in both projects.

2. Methodology: Computational Design Tool

To enhance the utilization of pultruded profiles in reciprocal structures, computational methods were employed, that consider material geometry, properties, fabrication, and assembly planning. The overall workflow involves the following steps: analysis of material geometry and mechanical properties to inform system inputs; initiation of the form-generation process involving computation of a hanging shell mesh; development of a reciprocal solver integrating all relevant parameters. After completion, the system is validated through structural analysis to confirm material suitability. Subsequently, the solver generates instruction diagrams to streamline the material preparation, sorting, and assembly of the reciprocal structure. Within this computational tool, while much is automated, there are instances where user input and decisions shape the resulting geometry.

2.1. System inputs

For the development of the parametric model, McNeel’s Rhinoceros and the native visual programming tool, Grasshopper 3D, were utilized. A primary objective of this project is to broaden access to reciprocal structure design while ensuring the suitability of the new biocomposite profiles for such applications. Hence, the main properties including both geometrical and mechanical aspects, are extracted and incorporated into the structural analysis of the system. Reciprocal structures comprise linear elements with variable geometries. To simplify the parametric model, the elements are initially represented by a line network where the start and end points of each line inform its position in space. Subsequently, the cross-section of the element is implemented. For the design of a reciprocal shell, a line network with intersection topologies of three or higher is required. This implies that any spatial geometry utilizing intersecting lines can serve as the initial input to create a reciprocal system.

2.2. Target geometry generation

To initiate the process, a spatial line network is initially generated, which serves as input for the reciprocal geometry solver. The original target geometry can be informed by several factors, such as site specifics, overall dimensions, and use of the structure. Initially, the user defines two boundary freeform curves, which represent the primary edges of the structure. A surface is then generated within these boundaries and is initially divided into quad panels, aiming to form a simple reciprocal system of four intersecting units. The user can specify the number of subdivisions in each axis. The divided surfaces are subsequently transformed into four-sided mesh faces generating a complete mesh geometry. Using Kangaroo2, the physics simulation solver plugin for Grasshopper [13], a hanging mesh shell is computed. This involves applying a uniform vertical force to all mesh vertices while constraining the edge length between them and utilizing the naked perimeter vertices as anchors. The outcome is a three-dimensional quad mesh approximation of a compression-shell geometry. Finally, the mesh edges are extracted as a line network to be used as the main input for the reciprocal geometry solver (Figure 2).

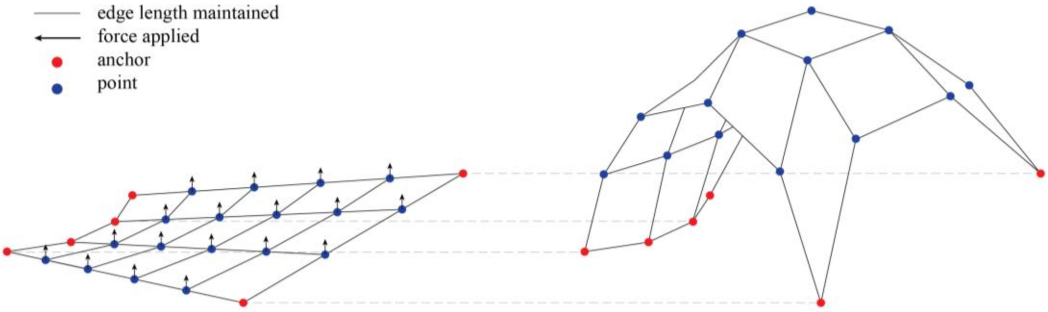

Figure 2: Geometry generation using Kangaroo2, input and output mesh

2.3. Reciprocal solver

The first part of the reciprocal solver is to organize the data from the input line network that was already generated, for use in subsequent stages. The line network deriving from the quad mesh consists of multiple lines intersecting with each other at their ends. Nodes are identified at these intersections and are associated with a reference of all lines they connect to. In the case of a quad mesh network, each node is connected to four lines, apart from the edge or perimeter nodes that can connect to two or three. The node's normal direction is then calculated, as the sum of the vectors from each line’s far end to the node itself. This normal vector is used to construct a plane, to which it is normal, and a circular curve on that plane. The lines around the node are then sorted along the circular curve. The sorting direction, clockwise or counterclockwise, can be defined for each node by the user. Depending on the desired reciprocal pattern, neighboring nodes can be assigned equal or opposite rotation directions. This process is computed for all the nodes other than the anchors or support nodes (Figure 3).

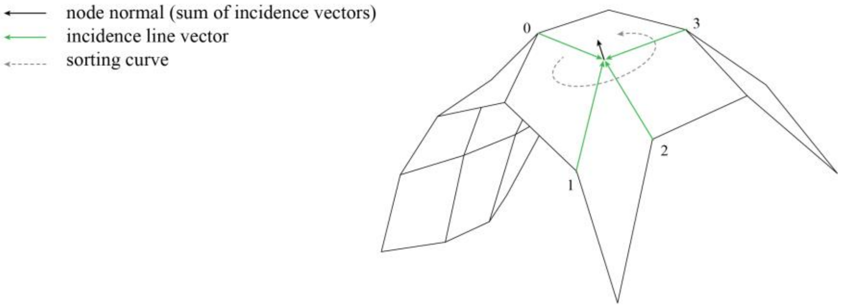

Figure 3: Reciprocal Solver – Sorting lines around node-normal

At this point, all line endpoints are assigned a corresponding target point on their neighboring line, signaling the initiation of the iterative reciprocal solver. For each endpoint, a new vector is computed as the combination of two vectors. The first vector links the current endpoint with its generated target point, following the reciprocal principle. The second vector accounts for the offset necessary to achieve a three-dimensional overlap of two elements without intersections. This offset is determined by calculating the cross-product of the current line and the target line, adjusted to the sum of the element's thickness and the space required for the joint fastener (Figure 4). The additional distance for the fastener can also be defined by the user. Subsequently, the new end position is calculated as the sum of the current position, the reciprocal vector, and the offset vector. This process iterates for all non-support endpoints, and the resulting points are stored in a separate list. After each iteration, the entire line network is reconstructed, based on the new points calculated, and the process begins again. The solver runs until a relaxed reciprocal geometry for the entire system is achieved. The relaxed state is returned when the sum magnitude of all movements in a single iteration passes below a user-defined threshold (Figure 5).

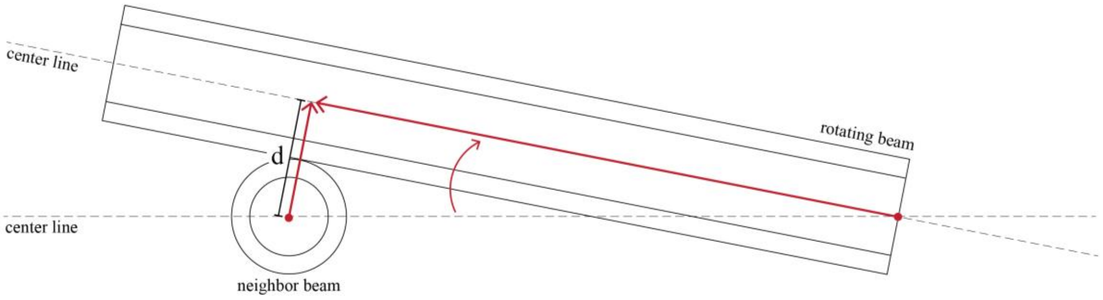

Figure 4: Reciprocal solver – Integration of material thickness (d = profile diameter)

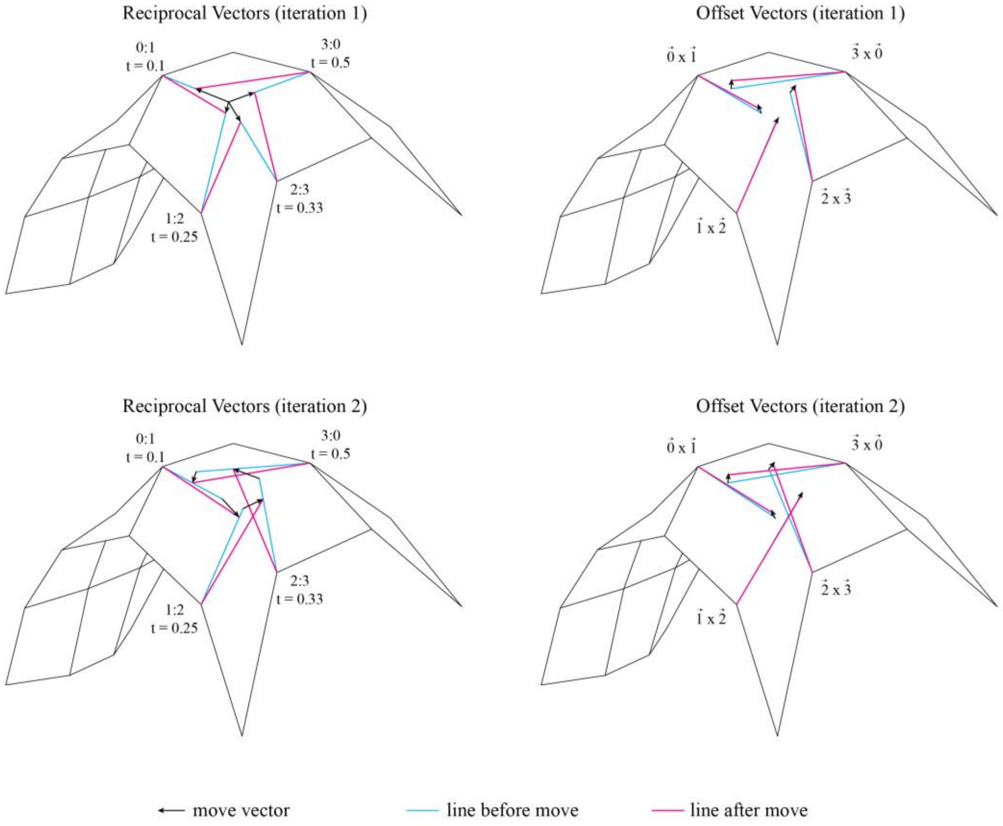

Figure 5: Reciprocal Solver – Iterative solver on beams around each node

After implementing the reciprocal solver and revisiting the primary objective of integrating the developed pultruded profiles into the system, a preliminary structural analysis is incorporated into the computational tool. Specifically, the Sofistik software is utilized as a plugin within Rhino Grasshopper [14]. With the solver integrated into the same environment, the originally generated line network is converted into a network of beams for structural calculations. Sofistik facilitates Finite Element Analysis (FEA), wherein the properties of the pultruded profiles are incorporated. Subsequently, an analysis is conducted to determine the types of forces present on the elements and connections. This structural analysis, within the computational design, primarily serves to validate the suitability of the chosen material. While structural form-finding wasn't included in this process, it remains a viable option for integration in future analysis.

3. Materialization and Applications

3.1. Fabrication setup

After completing and validating the reciprocal geometry generation, the output geometry is finalized. The next phase involves organizing the data for the post-processing stages. This is done by sorting the elements and extracting essential instructions for fabrication setup. This is integrated within the computational design tool to offer the user a comprehensive output that includes geometry and assembly instructions. These instructions include tagged clusters to facilitate pre-assembly before interconnecting all elements. Labeled diagrams with lengths are also generated to ease the sorting and cutting process.

The concept is to cluster elements around the nodes for efficient pre-assembly, streamlining the assembly process. These clusters comprise three or more elements connected as determined by the reciprocal solver. Initially, the output list of all nodes is employed. Although the elements surrounding each node can form a single cluster, each element is linked to two nodes. Therefore, the parametric tool is now utilized to identify unique elements around the nodes, ensuring each one is utilized only once. The first node from the output list and its associated members form the first cluster (Figure 6, node A). Subsequently, an algorithmic process proceeds by examining each subsequent node to determine if any of its elements have already been assigned to an existing cluster. If so, the node is skipped, and the solver progresses to the next one. This iterative process continues until all elements are grouped in clusters. After completion, the clusters and their members are labeled for easy identification (Figure 6).

Finally, the parametric tool offers a post-processing feature that assists in cutting and labeling the elements. It generates diagrams displaying the members, their labels, and overall lengths. This simplifies the sorting and cutting process. Users can input the length of stock material, and the solver nests the members to minimize material waste during the cutting process. Additionally, all the subdivided lengths are labeled, making it easy to identify and mark the points of intersection during cutting and preparation.

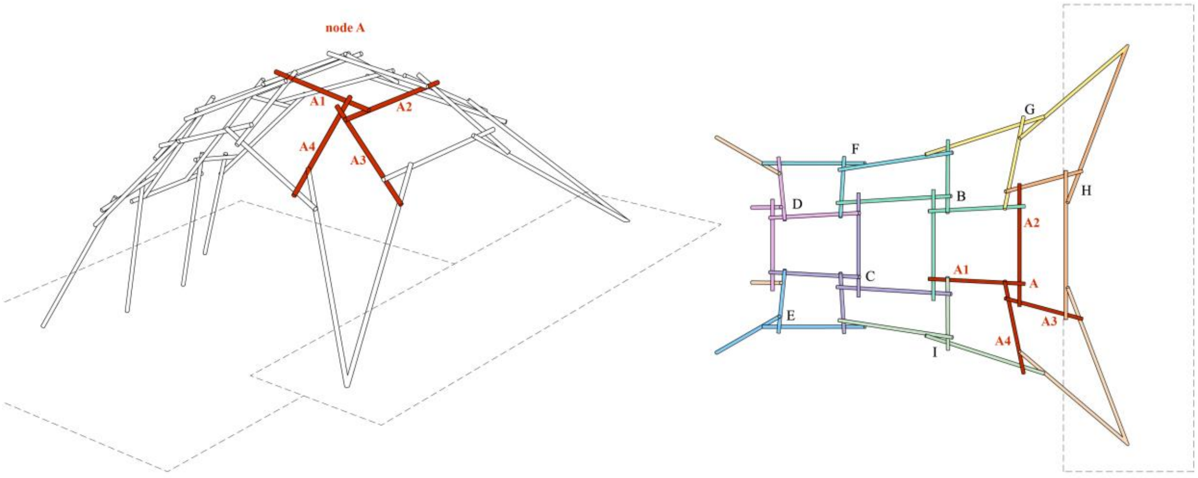

Figure 6: Cluster generation around the nodes for pre-assembly

3.2. Pre-fabrication and assembly

The developed computational tool streamlines the process of designing a reciprocal system according to specific materials and tailored to a defined site. It also provides instructional diagrams for material sorting, cutting, and cluster assembly. Once the design is finalized and the outputs are generated, construction proceeds in two main phases: material pre-fabrication and assembly, followed by final on-site assembly. During the process of building a structure using the pultruded profiles, it is crucial to select the appropriate connection elements. One primary objective is to avoid any damage to the biocomposites. Various joint solutions were explored to connect around without penetrating the material. Following extensive research on potential options, including lashing techniques and customized solutions market-available double-clamps were selected. They will serve as the singular joint solution for all intersections within the system. These joints facilitate easy assembly, connecting two profiles while allowing rotational movement between the members. This flexibility enables adjustments during assembly, as the clamps can be placed and rotated along the profile's length while providing the required scissor-like rotation at the intersections, aiding the structure to reach equilibrium.

The pre-fabrication process begins with cutting the profiles to the required lengths and labeling them to match the digital model data. The intersection points are also marked according to the instruction diagrams. The profiles are then sorted to create clusters, which can be pre-assembled to simplify the overall construction process. Clusters of three or four members are prepared off-site using the double-clamp connectors. The final structure is gradually raised using the final assembly diagram which shows all clusters and their position in the overall structure. The clusters are sorted, and each one is connected to the following one gradually until all the elements are in place. Fine-tuning of intersection positions might also be necessary until the final structure finds its equilibrium.

3.4. Case studies

To validate the developed system, an initial geometry was calculated, and the first demonstrator was constructed. The geometry of this initial case study has already been utilized for the illustrated diagram of the reciprocal solver previously. It comprises a small canopy of 3x3x2 m featuring 35 profiles of various lengths, totaling approximately 33 meters of pultruded profiles. Additionally, 64 double-clamp joints were employed (Figure 7). Before assembly, four four-member and five three-member clusters were pre-assembled and transported to the designated site (as per Figure 6). During installation, minor adjustments were made to connections to achieve equilibrium. The completed structure can be compared with the digital model to validate the accuracy of the system from design to fabrication. This structure serves as a preliminary case study to confirm the applicability of the system and to demonstrate the suitability of the developed pultruded profiles for such applications.

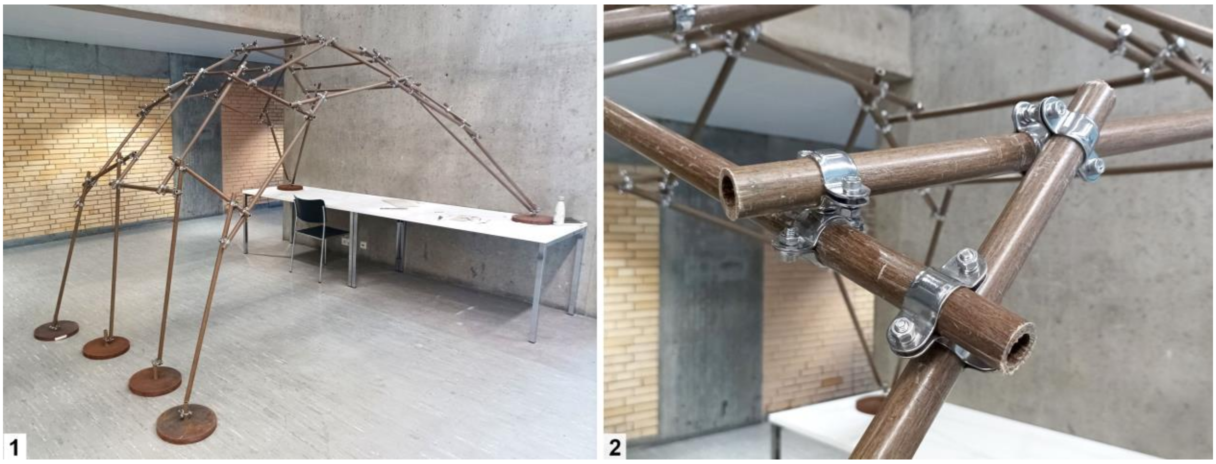

Figure 7: (1) Reciprocal Canopy Demonstrator 3x3x2 m, (2) three-member cluster joined with double-clamps

Following the outcomes of the initial case study, a second demonstrator was designed and showcased at the ECC Venice Biennial 2023 [15]. This time, the structure took the form of a canopy, spanning an interior space. The reciprocal canopy formed an inverted hanging shell above the room, anchored at the four corners, which served as the main foundation points. The overall dimensions of the structure were 6.7 m by 5.2 m, with a height of 3 m. To maintain an open space, the structure was elevated and attached to a higher level on the walls. The anchoring detail involved extending two profiles to meet at a point and attaching them at the room's corners. Initially, the anchor points were at the same height during simulation, however, a height difference was introduced to provide additional stiffness and create a more distinctive spatial geometry.

In this structure, which is larger than the first demonstrator, the limitation on lengths was crucial to prevent local bending of the profiles. All elements were kept below 2 m, a parameter used in the computational tool to create the initial mesh geometry. This parameter resulted in many clusters of shorter elements: 20 clusters of four members, 18 clusters of three members forming the edges, and eight members meeting in pairs as the anchors. Overall, 99 meters of pultruded profiles were used, divided into 71 members. The system comprised 121 profile intersections, requiring an equal number of double-clamps for connections. Eight customized connectors were employed to support the elements meeting at the anchor corners.

During assembly, ten inner clusters were pre-assembled on the ground following the instruction diagrams (Figure 8). All four-member clusters of the system were gradually connected on the ground. The structure was then carefully raised by four inner points to its final height, where the edges were assembled and the structure was anchored at the four corners of the room. Small adjustments were made during the last stage to allow the structure to find its final form and relaxed state (Figure 9).

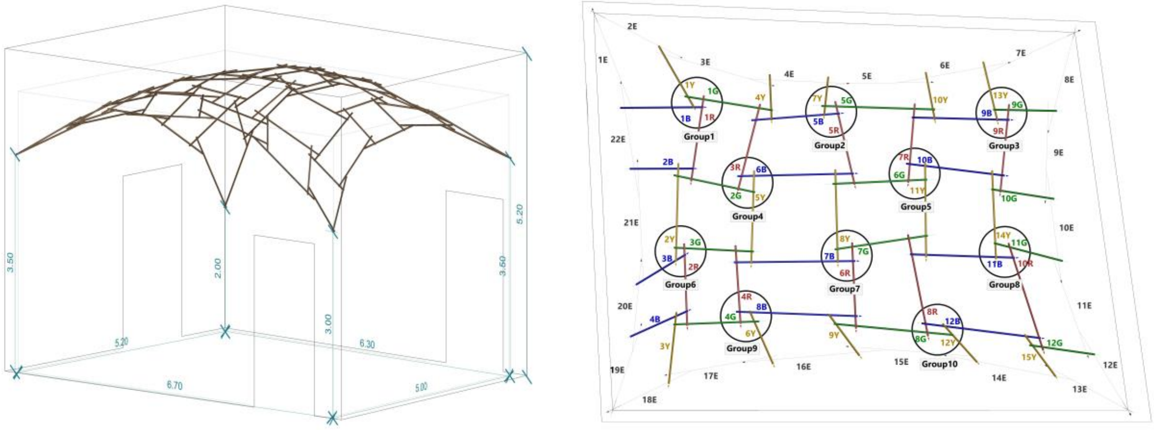

Figure 8: Reciprocal Canopy Venice Biennial 2023 | Main structure and room dimensions, labeled and color-coded assembly instruction diagram

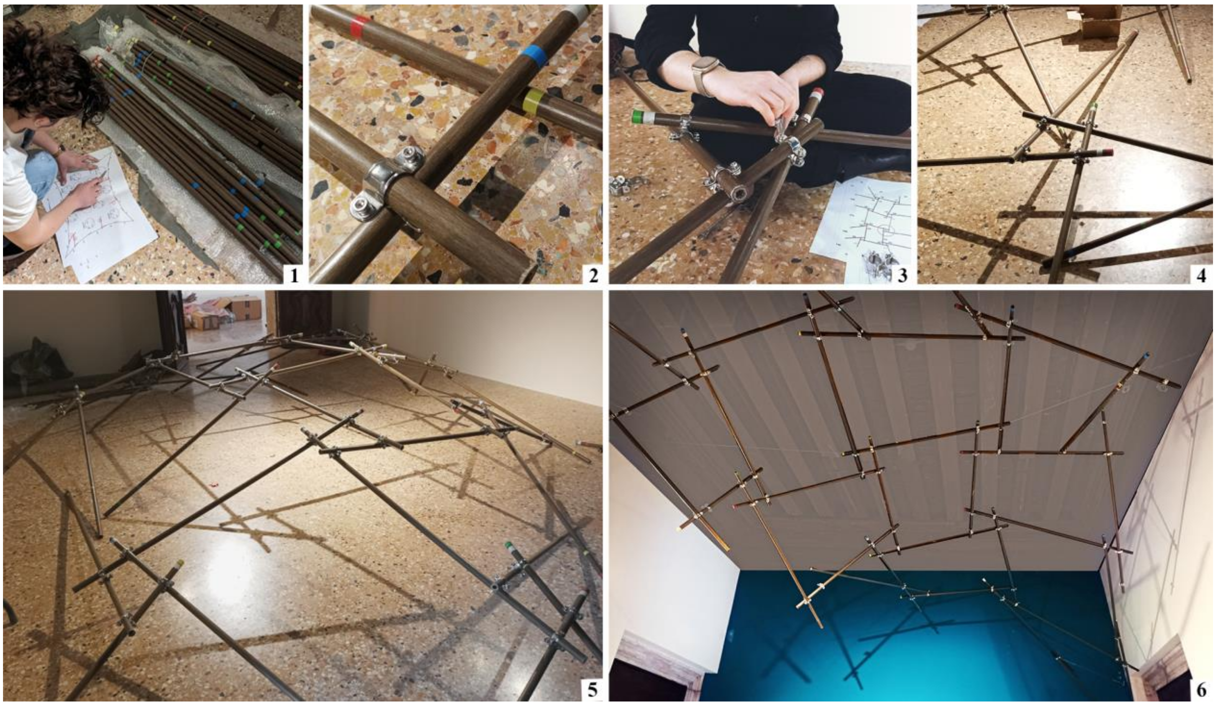

Figure 9: Reciprocal Canopy Venice Biennial 2023 | Assembly process: (1,2) material Sorting, (3,4) clusters pre-Assembly, (4) canopy assembly on the ground, (5) canopy lifted and fixed at final Height

4. Discussion and Conclusion

This study explores the application of newly developed biocomposite profiles in reciprocal structures. These profiles, made from natural flax fibers and a plant-based resin matrix using pultrusion technology, demonstrate high compression and flexural strength. The research introduces a computational design tool that generates optimized reciprocal configurations, ensuring precise assembly and structural integrity. The fabrication process involves cutting, labeling, and assembling the profiles into clusters off-site, streamlining on-site construction. The use of singular rotating connectors enhances the assembly process while protecting the material. The practicality of this system is validated through two case studies, demonstrating the scalability and robustness of biocomposite profiles in real-world settings.

From a material perspective, these profiles have been applied for the first time in a reciprocal structural system. Reciprocal geometries were chosen due to their high density of shorter elements and the simplicity of joint assemblies, reducing reliance on joints as structural elements. The developed demonstrators showcase the profiles' ability to form complex geometries and maintain structural integrity, proving their potential for diverse architectural applications. The successful integration of these profiles into different structural forms highlights their adaptability and potential for widespread use in the building industry.

Future research could focus on optimizing the pultrusion process to further enhance material properties and weather resistance to meet industry standards. Exploring alternative bio-based joint solutions could expand the range of biocomposite applications in the building industry. While the presented structures are temporary, investigating the long-term durability and performance of biocomposite structures under various environmental conditions could provide valuable insights for their widespread use. Additionally, advancing computational tools to integrate structural form-finding and environmental performance analysis would enrich the design process, making it more holistic.

In conclusion, the integration of biocomposite profiles in reciprocal structures represents a promising path toward sustainable architecture. By combining innovative materials with advanced design and fabrication techniques, this approach not only enhances structural performance but also supports the broader adoption of eco-friendly building practices in the construction industry worldwide.

Funding

This research was partially funded by the Fachagentur Nachwachsende Rohstoffe e. V. (FNR, Agency for Renewable Resources) under Bundesministeriums für Ernährung und Landwirtschaft (BMEL, Federal Ministry of Food and Agriculture) throughout the research project LeichtPRO: Pultruded load-bearing lightweight profiles from natural fiber composites (FKZ:22027018). The work on the Venice Biennial was partially supported by Interreg NWE through the research project SCB: Smart Circular Bridge (NWE 993) and project partners. Additionally, funding for the Biennial was also partially provided by FNR under BMEL through the research project 3DNaturDruck: Design and fabrication of 3D-printed components made of biocomposites/filaments from continuous and short natural fibers (FKZ: 2219NR163).

Acknowledgments

This project was developed in the seminar Material Matter Lab (Material and Structure, winter semester 2022/2023), offered by BioMat (The Department of Biobased Materials and Materials Cycles in Architecture) at ITKE at the University of Stuttgart by students Alex Reiner, Ioannis Moutevelis and Edgar Schefer under the tutoring of Evgenia Spyridonos and supervision of Hanaa Dahy. The Biennale Demonstrator was further developed by the BioMat team and realized by Evgenia Spyridonos and Vanessa Costalonga in collaboration with ECC Italy.

As part of the LeichtPRO project, the Deutsche Institute für Textil- und Faserforschung (DITF) and Bio-Composites And More GmbH (B.A.M.) developed the material and processes for the production of the pultruded components and CG TEC Carbon und Glasfasertechnik GmbH handled the pultrusion manufacturing process. BioMat was the project administrator and was responsible for the design, material testing, and realization of research demonstrators.

References

[1] United Nations, “Sustainable Development Goals.” Accessed: Feb. 06, 2024. [Online]. Available: https://sdgs.un.org/goals

[2] M. J. John and S. Thomas, “Biofibres and biocomposites,” *Carbohydrate Polymers*, vol. 71, no. 3, pp. 343–364, Feb. 2008, doi: 10.1016/j.carbpol.2007.05.040.

[3] Fachagentur Nachwachsende Rohstoffe e. V., “Pultruded load-bearing lightweight profiles made of natural fibre composites (LeichtPRO).” Accessed: Mar. 25, 2024. [Online]. Available: https://biowerkstoffe.fnr.de/projekte/projektuebersicht/projekte-details?fkz=22027018

[4] E. Spyridonos, M.-U. Witt, K. Dippon, M. Milwich, G. T. Gresser, and H. Dahy, “Natural Fibre Pultruded Profiles: Illustration of optimisation processes to develop high-performance biocomposites for architectural and structural applications,” *manuscript submitted for publication*, 2024.

[5] E. Spyridonos, A. Gerstner, A. Nehmeier, and H. Dahy, “LeichtPRO-profiles: Development and validation of novel linear biocomposite structural components fabricated from pultruded natural flax fibres with plant-based resin for sustainable architectural applications,” *manuscript submitted for publication*, 2024.

[6] “BioMat Pavilion 2021: LightPRO Shell | Institute of Building Structures and Structural Design | University of Stuttgart.” Accessed: Jan. 16, 2024. [Online]. Available: https://www.itke.uni-stuttgart.de/research/built-projects/biomat-pavilion-2021/

[7] G. Brown, “Three-dimensional structures,” Patent No. WO1989008172A1, 1989

[8] O. Popovic Larsen, “Reciprocal Frame (RF) Structures: Real and Exploratory,” *Nexus Netw J*, vol. 16, no. 1, pp. 119–134, Apr. 2014, doi: 10.1007/s00004-014-0181-0.

[9] P. Song, C.-W. Fu, P. Goswami, J. Zheng, N. J. Mitra, and D. Cohen-Or, “Reciprocal frame structures made easy,” *ACM Trans. Graph.*, vol. 32, no. 4, p. 94:1-94:13, Jul. 2013, doi: 10.1145/2461912.2461915.

[10] J. Chilton and B. S. Choo, “Reciprocal Frame Long Span Structures,” presented at the IASS, 1992.

[11] O. P. Larsen, *Reciprocal frame architecture*, 1st ed. Amsterdam: Elsevier, 2008.

[12] L. Bergis and K. de Rycke, “Reciprocal frame for the roof of the Franz Masereel Centre,” Sep. 2017.

[13] D. Piker, “Kangaroo Physics,” Food4Rhino. Accessed: Mar. 10, 2021. [Online]. Available: https://www.food4rhino.com/app/kangaroo-physics

[14] “Sofistik AG, Rhino Grasshopper interface.” Accessed: Mar. 13, 2024. [Online]. Available: https://www.sofistik.com/en/products/finite-elements/rhinoceros-interface

[15] ECC Italy, “Venice Biennial Architecture Exhibition 2023.” Accessed: Mar. 21, 2024. [Online]. Available: https://ecc-italy.eu/exhibitions/2023archbiennial