Appendix 1 I The inefficiency of the building industry

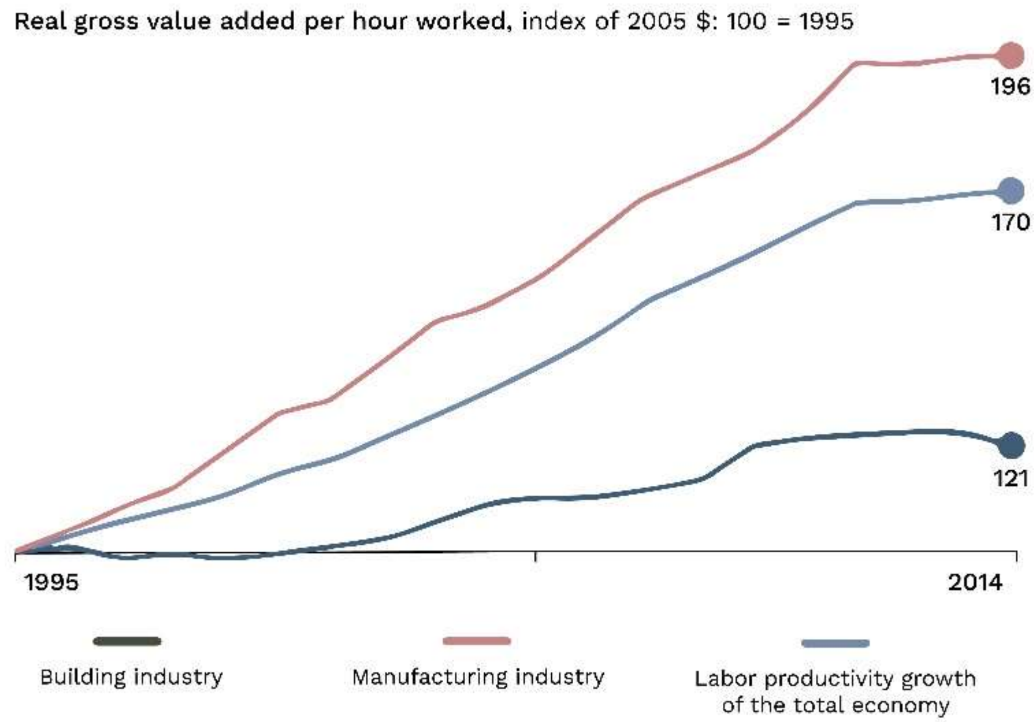


Table 1: The inefficiency of the building industry illustrated in comparison with the manufacturing industry and the labor-productivity growth of the total economy *(McKinsey Global Institute, 2017) Accessed on 20 Nov 2023. <https://www.mckinsey.com/~/media/mckinsey/business%20functions/operations/our%20insights/reinventing%20construction%20through%20a%20productivity%20revolution/mgi-reinventing-construction-executive-summary.pdf>*

Appendix 2 I Performance Indicators – Filament Winding Materials

	Flax Fiber	Hemp Fiber	Sisal Fiber	Basalt Fiber	Carbon Fiber	Fiber Glass	Steel Fiber
Tensile strength (MPa)	343-1500	270-900	353	2600-4840	2000-5000	3500	660-830
Compression strength (MPa)	1200*	-	-	-	1000-3000	50-100	250-1500
Elasticity (Young's module – MPa)	58.643	30.000 – 60.000	15.720	80.000-115.000	200.000-500.000	72.000	210.000
Diameter	10-80 µm	26 µm	121-411 µm	10.6 µm	5-8 µm	10-17 µm	-
Fiber length	10-100 cm	1 – 5 cm	80-120 cm	50 cm	∞	∞	∞
Density (g/cm^3)	1.4-1.5	1.48	1.45	1.85-2.75	1.75-2.00	1.5	7.8
Fire resistance	Bad	Bad	Bad	Superior	Good	Good	Good
Fire retardance	Varies	Varies	Varies	Superior	Good	Good	Good
Burning/Melting point	237 °C	118-131 °C	163 °C	1500-1700 °C	< 1000 °C	1200-1700 °C	1425-1540 °C
Moisture absorption	Good	Good	Good	Good	Good	Good	Good
Moisture resistance	Bad	Bad	Bad	Good	Good	Good	Good
Thermal conductivity (W/mK)	0.038	0.038-0.042	0.038	0.031-0.0038	0.63	0.04	45
Growth duration (days)	100	90-120	1000-1800	-	-	-	-
Growing season	Spring	Spring	Summer	-	-	-	-
Origin	Flax Plant	Hemp Plant	Sisal Plant	Volcanic rock	Synthetic polymer	Glass	Steel ore
Organic/Inorganic	Organic	Organic	Organic	Inorganic	Inorganic	Inorganic	Inorganic
Texture	Soft, shining	Soft, shining	Coarse/ rough	Fine grained	Soft/ Smooth	Soft/ Smooth	Smooth, but hard
Color	Beige/light grey	Off white/ brown	Off white/ brown	Brown/Black	Black/grey	Light yellow /white	Grey metallic
Sound absorption coefficient	0.93	0.93	0.6-0.7	0.22-0.75	<0.1	0.9-0.95	0.2
Biodegradability	Yes	Yes	Yes	No	No	No	No
Eco-friendliness	Yes	Yes	Yes	No	No	No	No
Chemical Resistance	Moderate	High	Moderate	Very high	Very high	Very high	Corrosion

Table 2: Performance indicators – Filament Winding Materials retrieved from several sources listed below

Retrieved from https://www.researchgate.net/publication/271013280_Thermal_Properties_of_Jute_Fiber_Reinforced_Chemically_ Functionalized_High_Density_Polyethylene_JFCF-HDPE_Composites_Developed_by_Palsule_Process
Retrieved from http://www.definetextile.com/2013/04/chemical-properties-of-jute-fiber.html
Retrieved from https://doi.org/10.1155/2023/4031238
Retrieved from https://www.jiga.io/calculator/density/fiberglass/gml
Retrieved from https://www.soundproofcow.com/product-category/soundproofing-materials/soundproofing-barriers/fiberglass-composites/
Retrieved from https://www.matweb.com/search/DataSheet.aspx?MatGUID=3dbc779c2f034329b2836b02b9483629&ckck=1
Retrieved from https://textilefashionstudy.com/physical-and-chemical-properties-of-hemp-fiber/
Retrieved from https://www.mdpi.com/2079-6439/9/2/13/htm
Retrieved from https://www.lambda.be/nl/energietips/lambda-waarde-van-alle-materialen
Retrieved from https://www.sciencedirect.com/topics/engineering/sisal-fibre
Retrieved from https://www.testextextile.com/physical-properties-of-jute-fiber-with-chemical-composition/
Retrieved from https://www.sciencedirect.com/topics/engineering/sisal-fibre
Retrieved from https://www.tandfonline.com/doi/abs/10.1080/17512549.2021.1982768
Retrieved from https://doi.org/10.1051/matecconf/201821701007
Retrieved from http://www.thescipub.com/ajas.toc
Retrieved from https://www.mdpi.com/2079-6412/12/12/1907/html
Retrieved from https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6514871/
Retrieved from http://hyperphysics.phy-astr.gsu.edu/hbase/Tables/thrcn.html
Retrieved from https://thermtest.com/thermal-conductivity-of-steel
Retrieved from https://omnexus.specialchem.com/polymer-property/young-modulus

Appendix 3 I Life Cycle of Flax made fibrous building elements

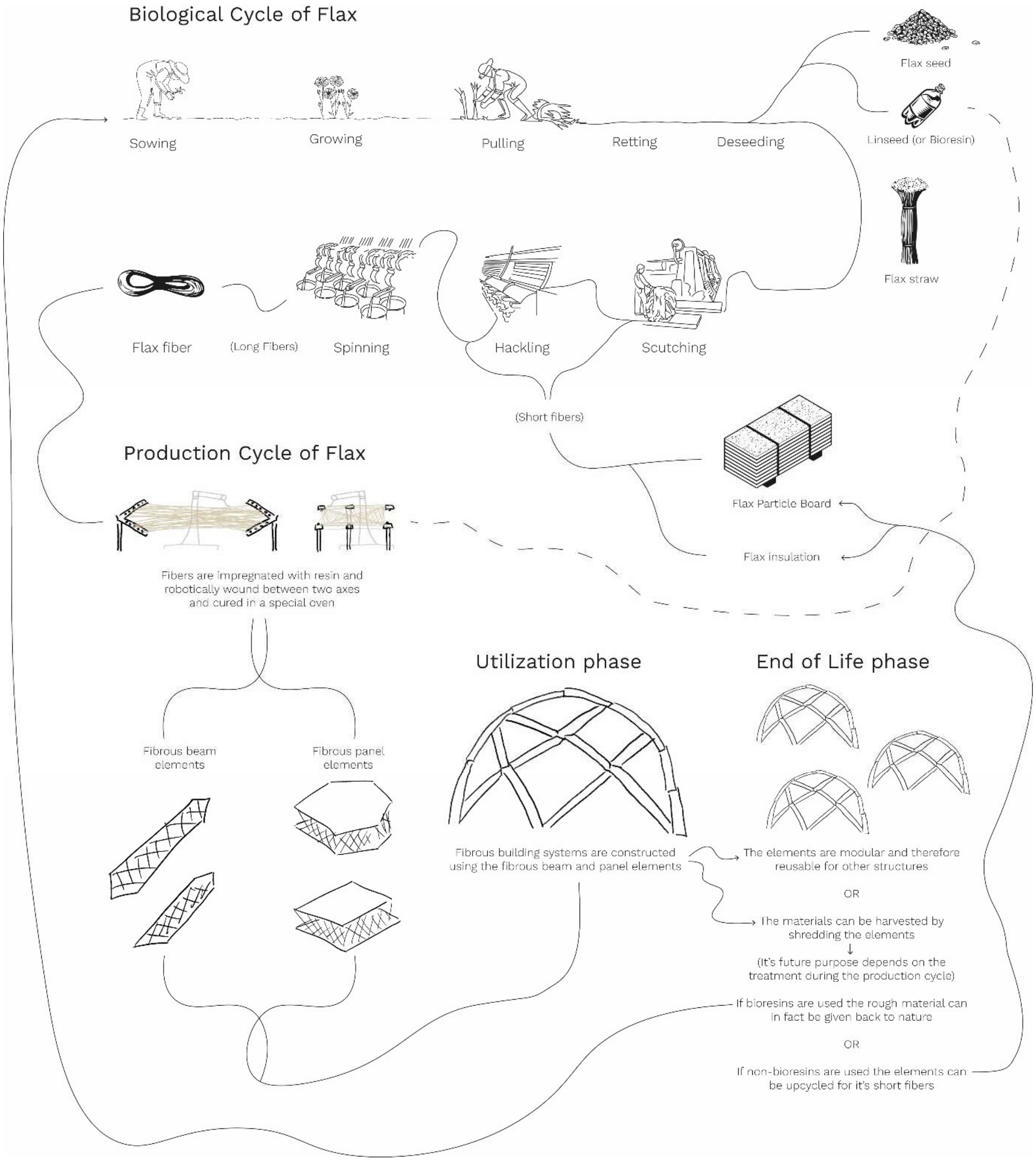


Figure 1: Life cycle of Flax made fibrous building elements
Steinfort, R.T. (2024)

Appendix 4 I Case Study Analyses

ICD/ITKE Research Pavilion 2012
ICD/ITKE Research Buildings, Germany

BUGA Fibre Pavilion 2019
CD Research Buildings / Prototypes
Bundesgartenschau Heilbronn 2019, Germany

Maison Fibre 2021
ICD/ITKE Research Buildings

LivMatS Pavilion 2021
2021 ICD Research Buildings / Prototypes
Botanic Garden Freiburg, Germany

Research Pavilion 2012
ICD/ITKE Research Buildings, Germany

General information

Function:	Temporary exhibition pavilion
Floor area:	29 m^2
Material:	> 60 km of glass- and carbon fibers
Free span:	7.67 m
Elements:	1 integral loadbearing element continuously wounded
Loads:	-
Goal:	The possible interrelation between biomimetic design and robot production

Production process:
The research pavilion was fabricated in an on-site manufacturing environment which was comprised of a 6-axis robot coupled with an external seventh axis. The robot was placed on a 2m high platform and could reach an overall height and span of about 4m. Firstly, a temporary steel frame was constructed upon which the robot placed the fibers.

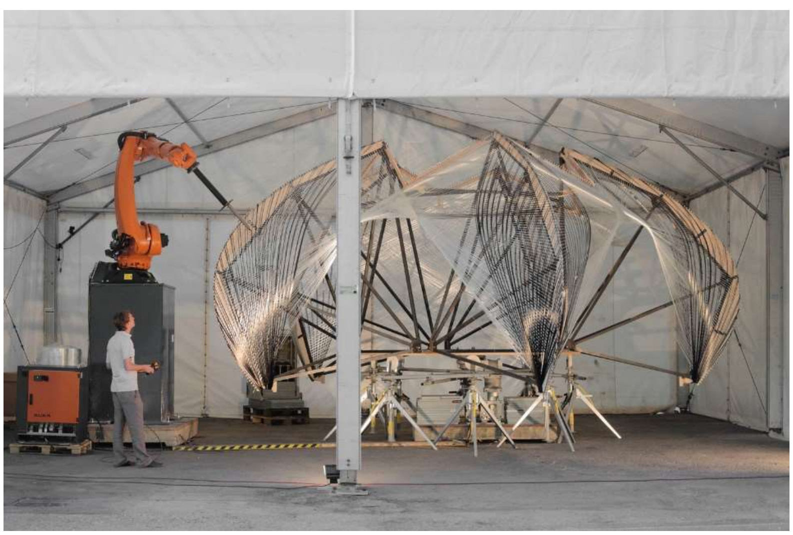


Figure 2: The robotic fabrication process of Research Pavilion 2012
ICD/ITKE Research Pavilion / University of Stuttgart, Faculty of Architecture and Urban Planning (2013, 06 March) ArchDaily. Accessed 16 Jan 2024. Retrieved from: <https://www.archdaily.com/340374/icditke-research-pavilion-university-of-stuttgart-faculty-of-architecture-and-urban-planning> ISSN 0719-8884

<u>Structural typology:</u>
The pavilion is a lightweight exoskeleton composed of a continuously wounded fibrous structure which spans 7,67m in diameter and has a height of approximately 3.57. Additionally, more than 60 kilometers of (carbon- and glass) fiber roving was used. This pavilion was the first of The University of Stuttgart to actually use robotic filament winding using a temporally mold. Additionally, this was the first research that gained insight in creating these new robotic fabrication processes for the building sector. This technique, nowadays known as filament winding, involves using carbon and glass fibers to wind filaments, along with computational design tools and simulation methods. Furthermore, this research focused on biomimetic design strategies found in nature as in this case on the material and morphological principles of arthropods' exoskeletons. More specifically, the exoskeleton of the lobster was analyzed for its local material differentiation, which eventually functioned as the biological role model of the design.

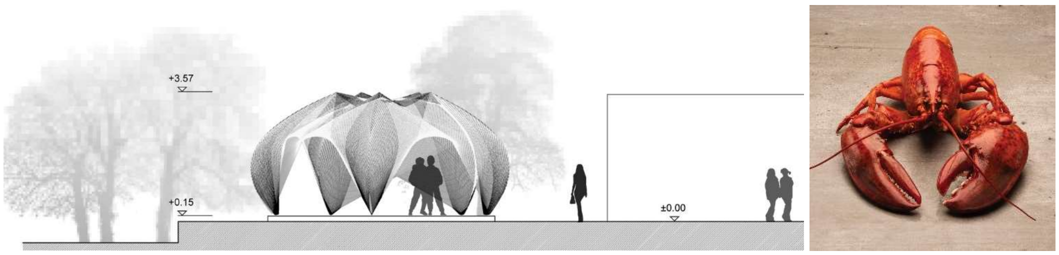


Figure 3: Structural typology and it's biomimetic inspiration: the lobster
ICD/ITKE Research Pavilion / University of Stuttgart, Faculty of Architecture and Urban Planning (2013, 06 March) ArchDaily. Accessed 16 Jan 2024. Retrieved from: <https://www.archdaily.com/340374/icditke-research-pavilion-university-of-stuttgart-faculty-of-architecture-and-urban-planning> ISSN 0719-8884

<u>Structural connections:</u>
The connections between the structure itself consisted of an integrated web of fibers which held the whole structure together.

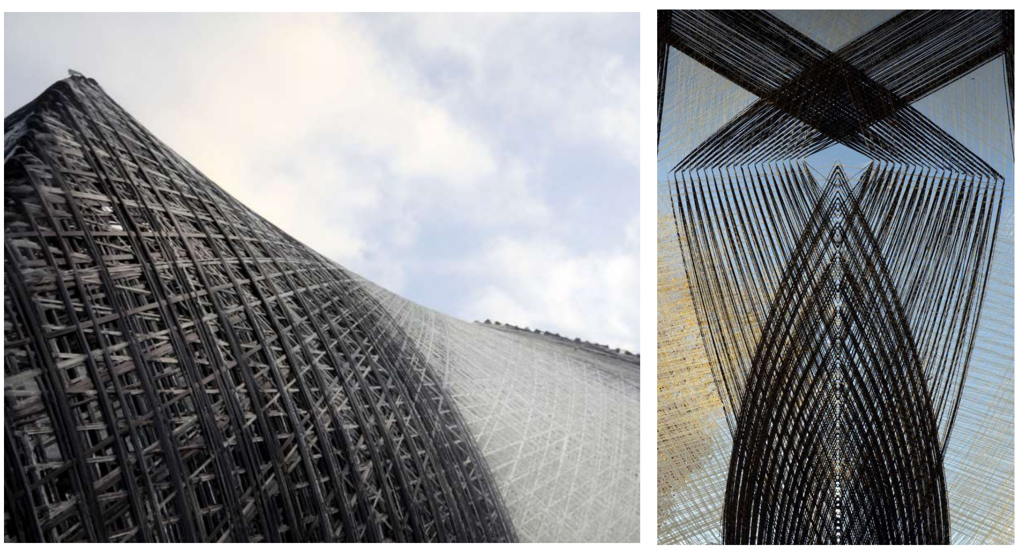


Figure 4: Shell structure and connections of Research Pavilion 2012
ICD/ITKE Research Pavilion / University of Stuttgart, Faculty of Architecture and Urban Planning (2013, 06 March) ArchDaily. Accessed 16 Jan 2024. Retrieved from: <https://www.archdaily.com/340374/icditke-research-pavilion-university-of-stuttgart-faculty-of-architecture-and-urban-planning> ISSN 0719-8884

<u>Shell structure:</u>
As for the shell structure the shell consists of several layers of firstly, glass fiber which creates the base form of the pavilion and additionally several layers of carbon fibers are placed in various fiber orientations to create the intricate shell structure found in exoskeletons of in this case the lobster.

BUGA Fibre Pavilion 2019
ICD/ITKE Research Buildings / Prototypes
Bundesgartenschau, Heilbronn 2019, Germany

General information

Function:	Temporary exhibition pavilion
Floor area:	400 m^2
Material:	> 150 km of glass- and carbon fibers
Free span:	> 23m
Elements:	60 loadbearing (primary structural) elements
Loads:	250 kilonewtons of compression force (25000kg) per element
Goal:	An example for long-span structures

Production process:

Each of the fiber composite components is fabricated by a robot arm that places the fibre filaments after being impregnated by epoxy resin between two frame scaffolds mounted on a rotating axis. Due to the relatively low price of the glass fibers in comparison to the carbon fibers and the higher strength and elastic modulus of carbon fibers, the two materials are used with different functions in a multi-stage winding process, the glass fiber lattice is placed to generate the shape of the components. This layer is normally regular and contains the minimum amount of material to produce a surface that serves as scaffold for the winding of the carbon fibers. Secondly, carbon fiber filaments are wound as the component reinforcement. The specific winding layup for the carbon fiber constitutes the loadbearing structure of the pavilion and it is structurally designed to withstand the specific loading scenario of the pavilion. The cross-section of the bundles is defined by the number of roving's used during fabrication together with the total amount of passes or layers. In the case of these components, 6 fiber bundles of 48k filaments were used with a total of 6 passes. This produced a cross-section of approximately 15 mm to 20 mm in diameter which changes to a flatter profile where the curvature becomes pronounced. The resulting hollow shape is defined by the two frames and the anticlastic lattice surface produced by the fibers while winding. The frame profile geometry is contained in planes corresponding with the intersection nodes of the dome where component to component is connected. All these planar curves have a fixed height of 710 mm and a width of either 600 mm or 910 mm depending on their location. Since the angles between these planes change depending on the node, the resulting cross-section of the components is elliptical in shape, being the height always defined by the shorter diameter.

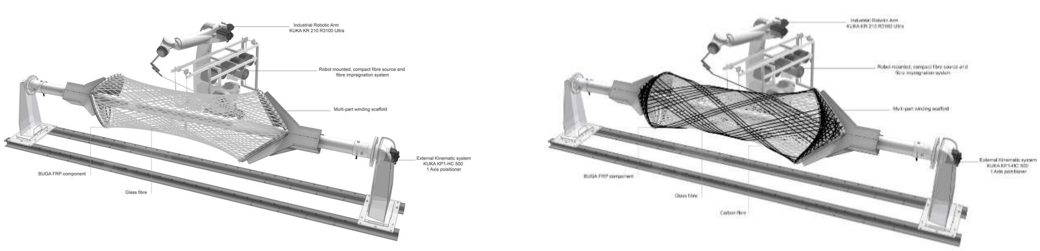


Figure 5: Winding stage 1 (Glass fiber) and stage 2 (Carbon Fiber)
BUGA Fibre Pavilion / ICD/ITKE University of Stuttgart (2019, 09 May). ArchDaily. Accessed 08 Dec 2023.
<https://www.archdaily.com/916650/buga-fibre-pavilion-icd-itke-university-of-stuttgart> ISSN 0719-8884

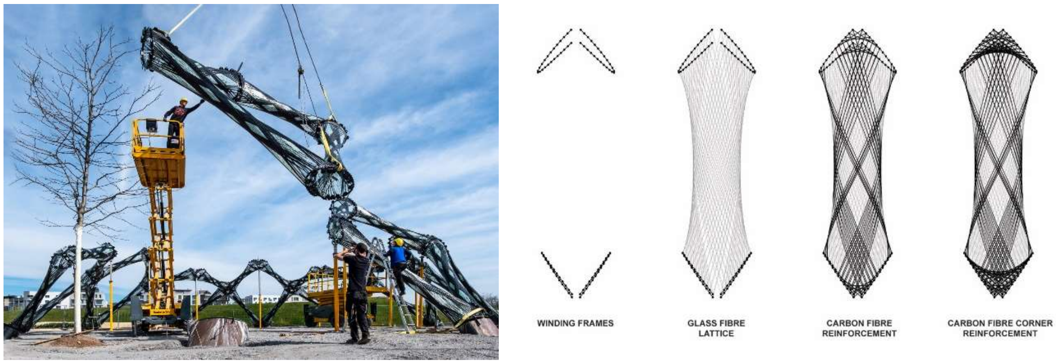


Figure 6: The hollow shaped elements (left) and the winding sequences (right)
BUGA Fibre Pavilion / ICD/ITKE University of Stuttgart (2019, 09 May). ArchDaily. Accessed 08 Dec 2024. <https://www.archdaily.com/916650/buga-fibre-pavilion-icd-itke-university-of-stuttgart> ISSN 0719-8884

Structural typology:
The pavilion is a lightweight dome composed of 60 elongated hollow bone-like carbon- and glass fiber components. The dome spans 23 m, has a height of 6.8 m and the elements are exerted on axial compression (Pérez, Früh, La Magna, & Knippers, 2022).

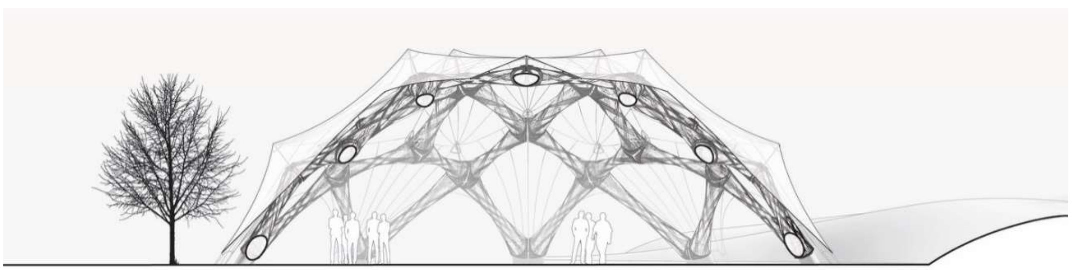


Figure 7: Structural typology of the Buga Fibre Pavilion
BUGA Fibre Pavilion / ICD/ITKE University of Stuttgart (2019, 09 May). ArchDaily. Accessed 08 Dec 2023. <https://www.archdaily.com/916650/buga-fibre-pavilion-icd-itke-university-of-stuttgart> ISSN 0719-8884

Structural connections:
The element are connected using steel brackets which are fixated on the bolt sleeves that are put in place during winding. A total of 6 unique-shape fiber components. Components from C1A to C4 are mirrored to produce a fifth of the dome, of which the geometry is repeated to complete the 60 components.

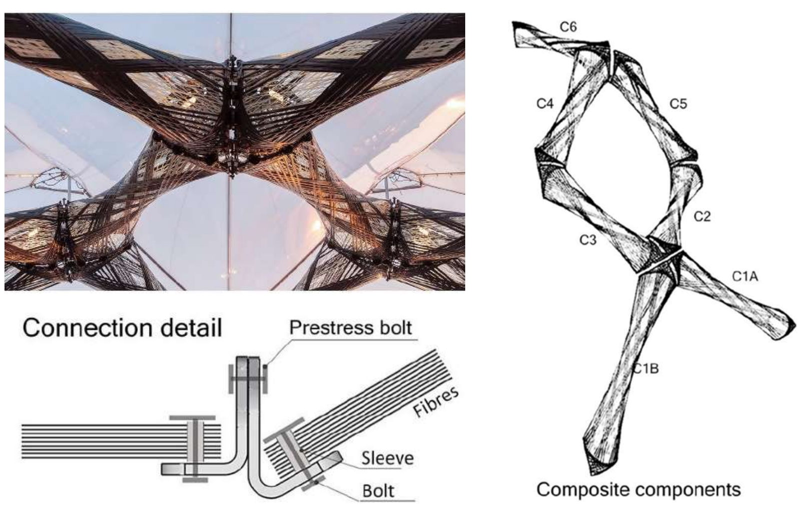


Figure 8: The structural connections of the Buga Fibre Pavilion
BUGA Fibre Pavilion / ICD/ITKE University of Stuttgart (2019, 09 May). ArchDaily. Accessed 08 Dec 2023. <https://www.archdaily.com/916650/buga-fibre-pavilion-icd-itke-university-of-stuttgart> ISSN 0719-8884

Foundation

The components are connected to the ground through a foundation detail consisting of a steel plate mounted on a concrete cylinder and fastened via anchor bolts.

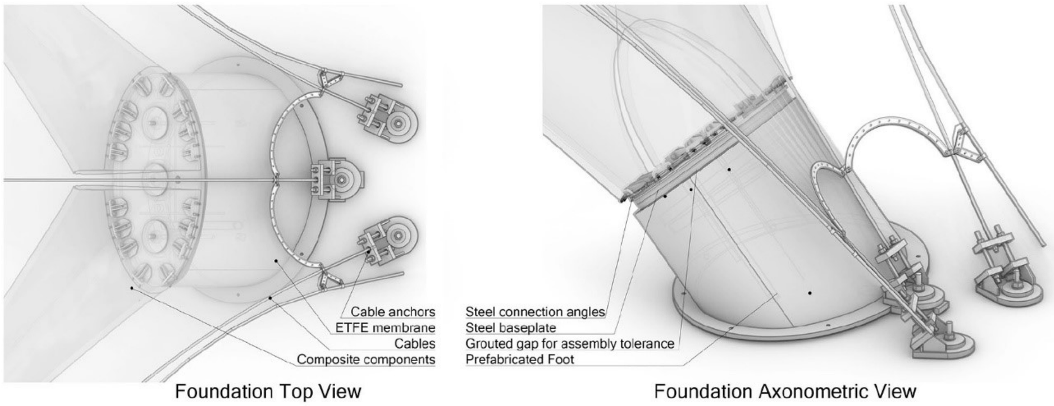


Figure 9: Foundation detail of the Buga Fibre Pavilion
BUGA Fibre Pavilion / ICD/ITKE University of Stuttgart (2019, 09 May). ArchDaily. Accessed 08 Dec 2024. <https://www.archdaily.com/916650/buga-fibre-pavilion-icd-itke-university-of-stuttgart> ISSN 0719-8884

Shell structure:

External skin connection

A steel pole is additionally integrated between the brackets at the center of each node, to facilitate the attachment of an ETFE membrane. These steel poles transfer the forces from the membrane into the composite components and are designed as low and high points following the requirement of the ETFE membrane and prestressed cables design.

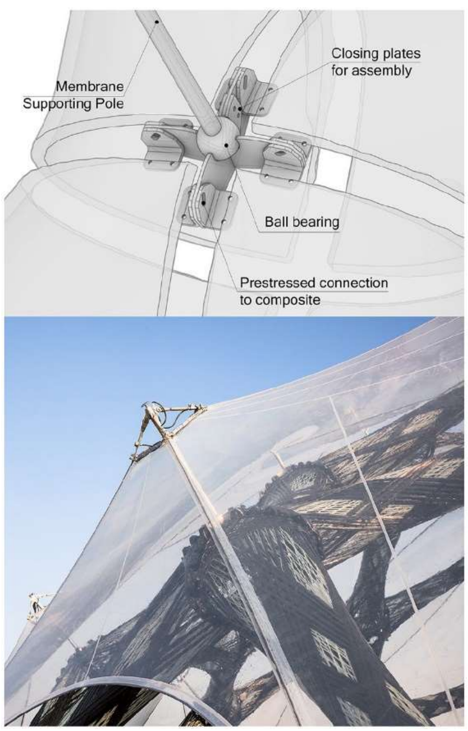


Figure 11: External skin connection
BUGA Fibre Pavilion / ICD/ITKE University of Stuttgart (2019, 09 May). ArchDaily. Accessed 08 Dec 2023. <https://www.archdaily.com/916650/buga-fibre-pavilion-icd-itke-university-of-stuttgart> ISSN 0719-8884

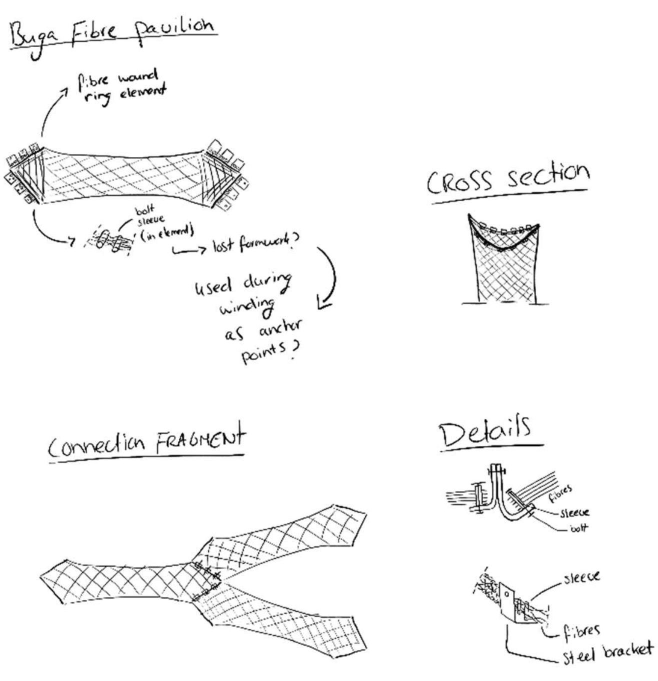


Figure 10: Analysis diagrams of the Buga Fibre Pavilion
Steinfort, R.T. (2024)

Maison Fibre
ICD/ITKE Research Buildings
17th International Architecture Exhibition 2021, La Biennale, Venice

General information

Function:	Temporary exhibition pavilion I ″How will we live together”
Floor area:	125 m^2
Material:	Glass- and carbon fibers
Free span:	2.5m
Elements:	10-wall and 20-slab elements (2.5m x 2.5m)
Loads:	72 kilonewtons of compression force (7200 kg) per element
Goal:	An example for multi-story architecture

Production process:
First, an inner radial carbon fiber layup that supports the timber at a regular distance needs to be wound. This layup connects the four inner timber connectors with the bottom frame anchor pins creating a truss-like structure that transfers the tributary loads of the inner supports to the outer ring layups. Then, the upper frame is placed, and an outer body glass and carbon ring layups are wound, connecting upper and lower frames and creating a surface-like curved lattice. The fabrication setup is adapted from previous projects, and the component is regularized to a square module that can be used in a standard grid structure (Pérez, Früh, La Magna, & Knippers, 2022).

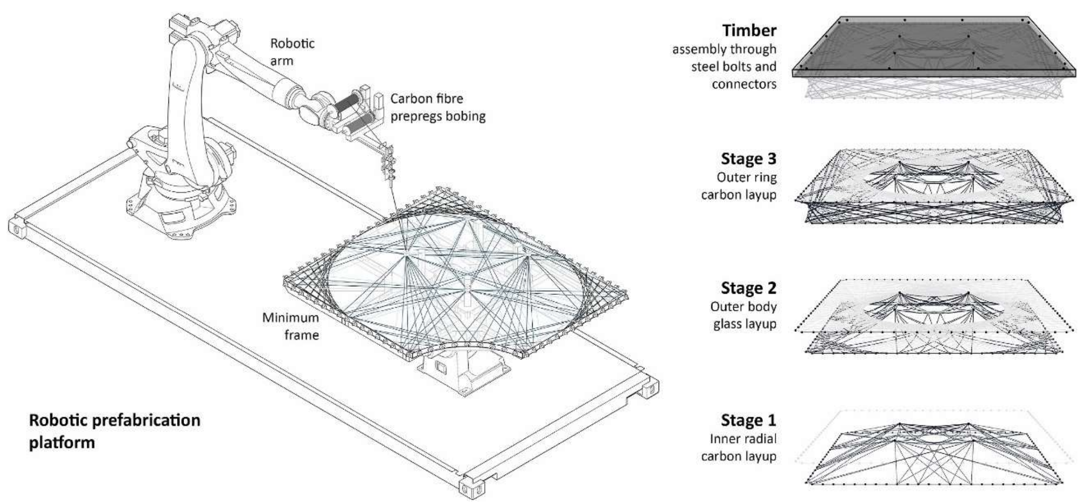


Figure 12: Winding sequence and robot setup for the fibrous floor element
Maison Fibre ICD/ITKE/IntCDC, University of Stuttgart (2021). ITKE. Accessed 09 Dec 2023. https://www.itke.uni-stuttgart.de/research/built-projects/maison-fibre-2021/

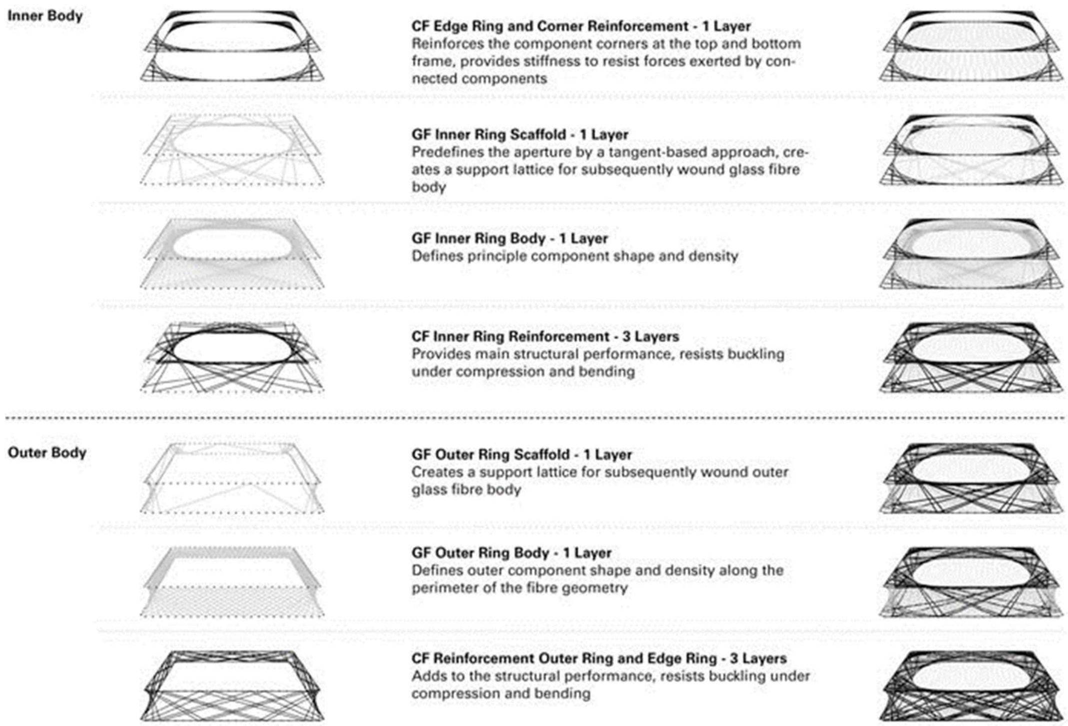


Figure 13: Winding sequence for the fibrous wall element
Maison Fibre ICD/ITKE/IntCDC, University of Stuttgart (2021). ITKE. Accessed 09 Dec 2023. https://www.itke.uni-stuttgart.de/research/built-projects/maison-fibre-2021/

Structural typology:
The outcome is a multi-story building system consisting of 10-wall and 20-slab components with a footprint of 2.5 by 2.5 m and a total floor area of about 60 square meters (Fig. 3). Maison Fibre aims to rethink materiality in architecture, showcasing CFW structures as an inhabitable space. It is the first hybrid structure, combining CFW fiber-polymer composites with LVL as a functional and structural system. The components allow walkability and are adapted to a more regular geometry, compatible with conventional building systems, as the first step towards using CFW in construction.

Structural connections:
The winding pins used during winding are in fact bolt sleeves which will stay in the fibrous structure. These bolt sleeves can later on be used to connect it to other elements using metal brackets.

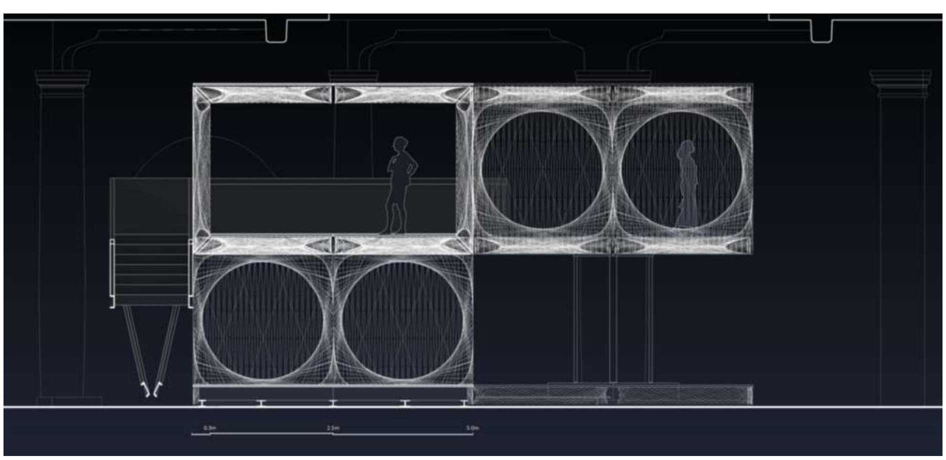


Figure 14: Section of Maison Fibre showcasing the different floor- and wall elements
Maison Fibre ICD/ITKE/IntCDC, University of Stuttgart (2021). ITKE. Accessed 09 Dec 2023. https://www.itke.uni-stuttgart.de/research/built-projects/maison-fibre-2021/

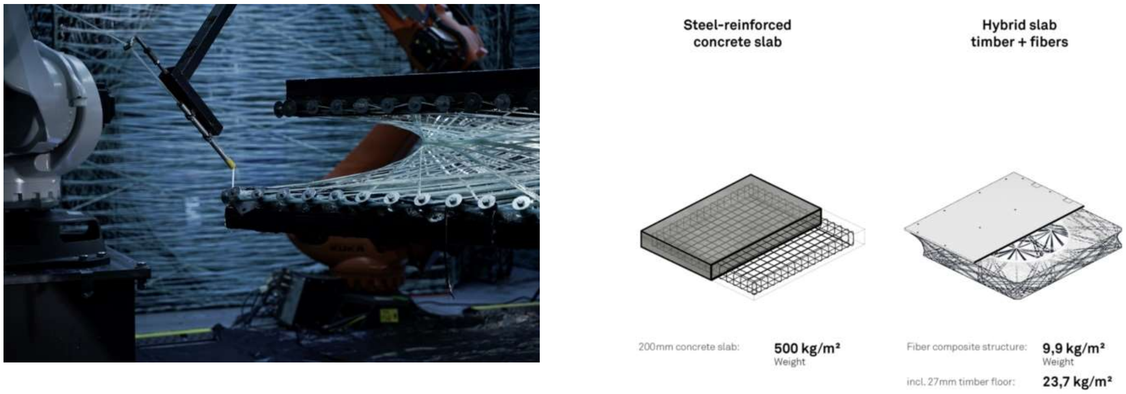


Figure 15: Winding and composition of a Maison Fibre floor element
Maison Fibre ICD/ITKE/IntCDC, University of Stuttgart (2021). ITKE. Accessed 09 Dec 2023. https://www.itke.uni-stuttgart.de/research/built-projects/maison-fibre-2021/

Floor and Wall structure:
The structure of the floor and wall elements is comprised of the fibrous wound element that has bolt sleeves as anchor points. During winding four winding pins (bolt sleeves) are placed in the middle of the frame to create a fibrous load bearing structure on which, in the case of the floor element, the LVL wooden board can be placed and fixated using bolts connected to the bolt sleeves.

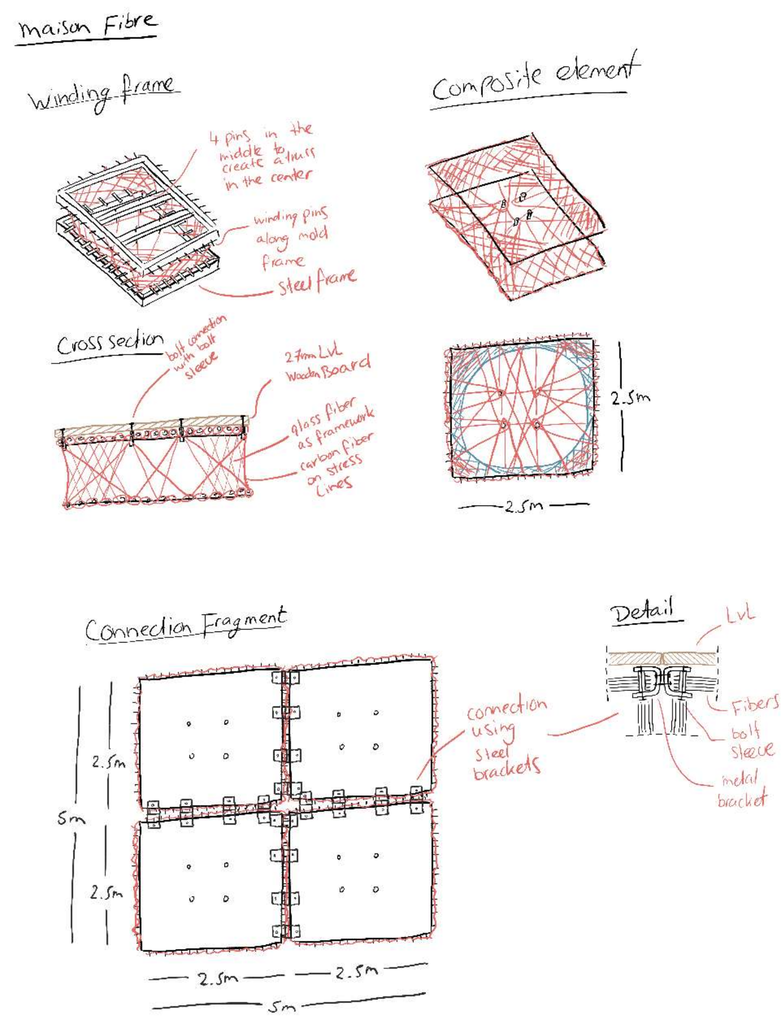


Figure 16: Analysis diagrams of the elements of Maison Fibre
Steinfort, R.T. (2024)

LivMatS Pavilion 2021
ICD Research Buildings / Prototypes
Botanic Garden Freiburg, Germany

General information

Function:	Temporary exhibition pavilion - Learning from Nature
Floor area:	46 m^2
Material:	Flax fibers
Free span:	10 m*
Elements:	15 loadbearing (primary structural) elements
Loads:	-
Goals:	An example for flax fibrous structures

Production process:
The fabrication of the LivMatS pavilion elements was based on the fabrication setup of the BUGA Fiber Pavilion, but adjusted for the new material and design. Six-axes robotic arms (similar to automotive manufacturing) are used to wind the flax fiber along a steel frame which acts as the mold. On the steel frame winding pins (bolt sleeves) are strategically placed along the edges and in the middle of the frame.

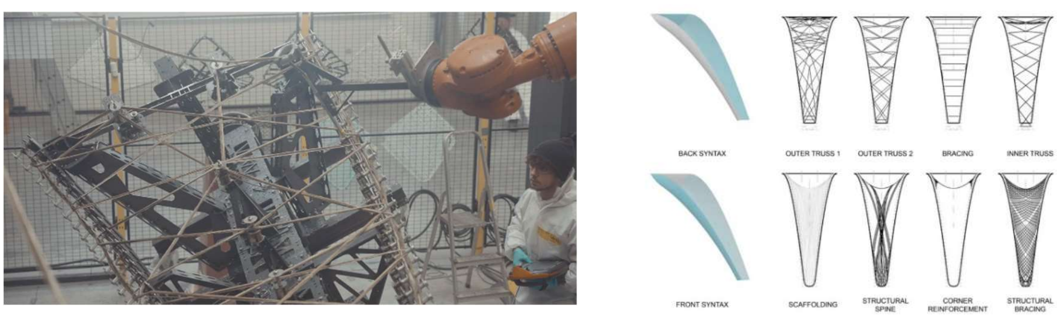


Figure 17: Winding of the flax fibrous LivMatS Pavilion beam element and the winding syntaxes
livMatS Pavilion / ICD/ITKE University of Stuttgart (2022, 14 Aug). ArchDaily. Accessed 10 Dec 2023. <https://www.archdaily.com/966168/livmats-pavilion-icd-itke-university-of-stuttgart> ISSN 0719-8884

* *Approximations based on technical drawings*

Structural typology:

Figure 18: LivMats pavilion fabrication setup (left) and component after curing (right)
livMatS Pavilion / ICD/ITKE University of Stuttgart (2022, 14 Aug). ArchDaily. Accessed 10 Dec 2023. <https://www.archdaily.com/966168/livmats-pavilion-icd-itke-university-of-stuttgart> ISSN 0719-8884

TheLivMatS pavilion is a continuous dome-like structure with three supports, arranged by groups of five components connected at top and bottom with the opposite components and foundation, respectively and laterally with the adjacent ones. For the dome fifteen hollow components trapezoid in shape of about 6 meters in length were designed and fabricated with flax fibers (Pérez, Guo, & Knippers, 2022).

Structural connections:

Figure 20: Dome shaped structural typology
livMatS Pavilion / ICD/ITKE University of Stuttgart (2022, 14 Aug). ArchDaily. Accessed 10 Dec 2023. <https://www.archdaily.com/966168/livmats-pavilion-icd-itke-university-of-stuttgart> ISSN 0719-8884

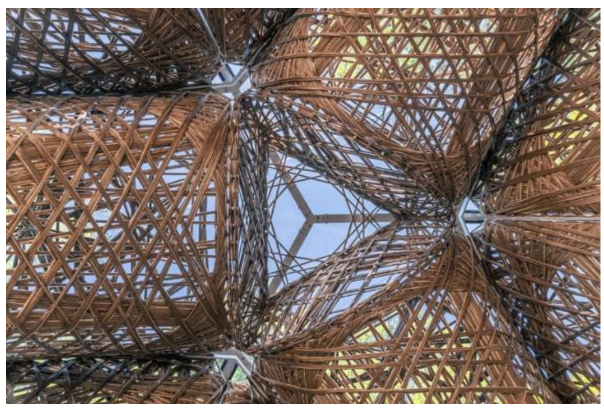


Figure 19: Connections between the fibrous elements
livMatS Pavilion / ICD/ITKE University of Stuttgart (2022, 14 Aug). ArchDaily. Accessed 10 Dec 2023. <https://www.archdaily.com/966168/livmats-pavilion-icd-itke-university-of-stuttgart> ISSN 0719-8884

The winding pins (bolt sleeves) are left in the fibrous flax element and used to connect the beams with each other. In the case for the LivMatS pavilion on the intersections along the edge of the beams a metal strip is placed which is fixated to metal brackets that are bolted on the bolt sleeves.

Figure 21: Placement of the fibrous elements
livMatS Pavilion / ICD/ITKE University of Stuttgart (2022, 14 Aug). ArchDaily. Accessed 10 Dec 2023. <https://www.archdaily.com/966168/livmats-pavilion-icd-itke-university-of-stuttgart> ISSN 0719-8884

Shell structure:
In the diagram below the structural connections and connection details are shown.

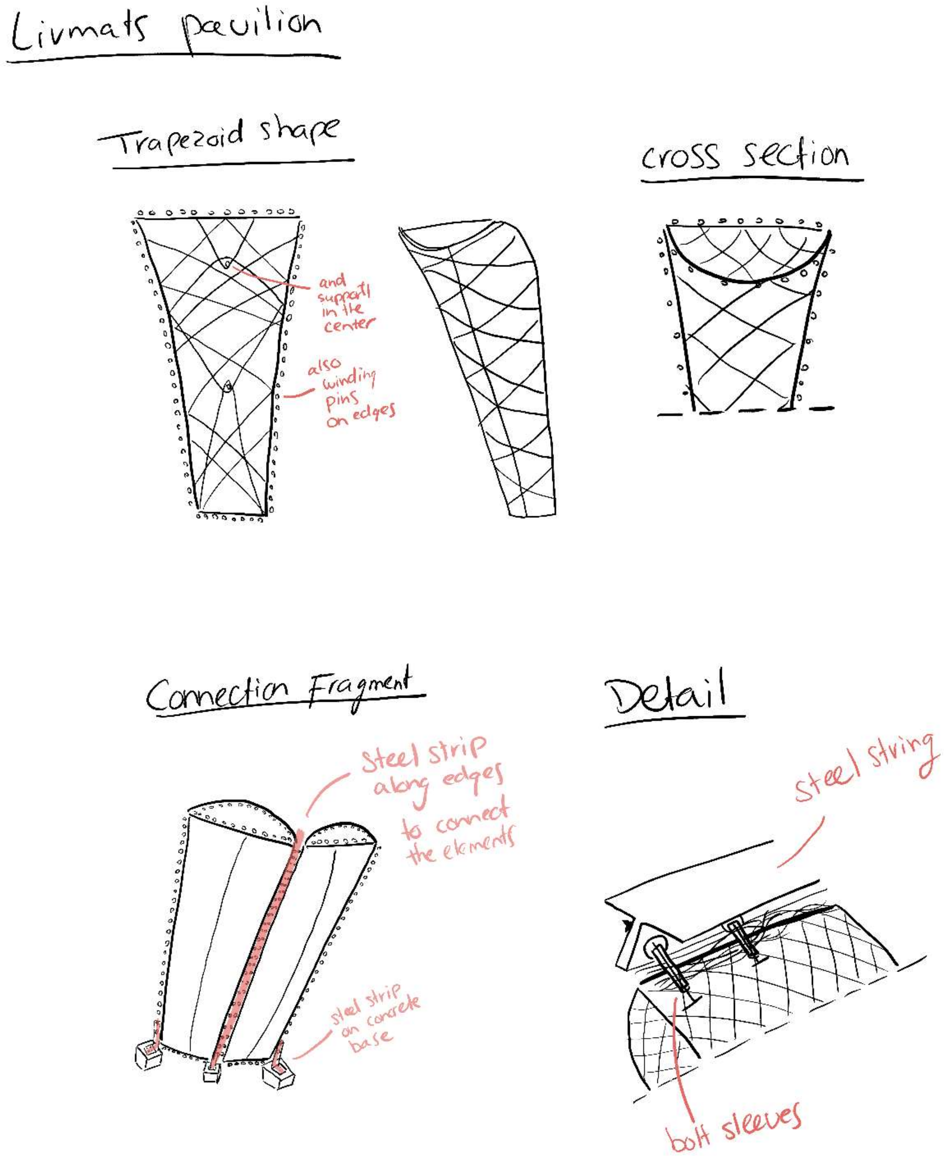


Figure 22: Analysis diagrams of the fibrous elements of the LivMatS pavilion
Steinfort, R.T. (2024)

Appendix 5 I Fiber agent

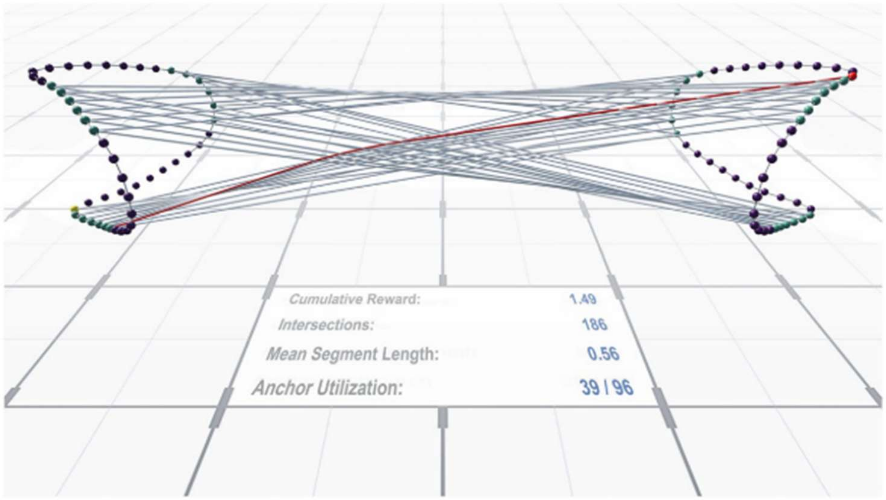


Figure 23: Fiber agent sequentially layering and form-finding a fiber network.
Menges, Achim & Kannenberg, Fabian & Zechmeister, Christoph. (2022). Computational co-design of fibrous architecture. 1. 6. 10.1007/s44223-022-00004-x.

Appendix 6 I Interview Dr. Julian Fial from FibR GmbH

Dr. Julian Fial
Head of Production & Development

Biodegradability
There is a significant hype and demand for natural fibres, making them a scarce resource. This hype has made this material good for marketing purposes. On the one hand because it is a regenerative material and its biodegradable, which means that it can be naturally broken down into nutrients for the soil. However, for structural applications biodegradability contradicts the long-term use of natural fibres for these components. Therefore, natural fibre composites need to be protected against moisture uptake, similar to timber constructions.

Prototyping
For the creation of the fibrous elements computational design can be used to create winding syntaxes. Digital 3D modelling techniques cannot yet accurately approximate final fibre interactions and therefore small-scale prototyping is necessary for verification purposes

Winding
There is a lack of information on tensile strengths of fibrous materials like flax. Therefore, physical prototyping is key to experimenting with and verifying the tensile strength. Additionally, flax fibres are weak during winding but much stronger when cured, therefore this needs to be considered in the winding process. The FEM models are complex and need a lot of detailing and calibrating.

Comparison to other building methods
When compared to other building methods, the new method can partly replace steel, concrete, and wood structures. However, a sustainability analysis must be done at a concrete example where methods like LCAs can be used. One example is a column with equal performance in compression. Clear boundaries for LCAs are necessary but sometimes difficult to define. For instance, the connections used between the building elements, are also taken into account. Although, in general the construction method reduces material mass and volume, enhancing resource efficiency. The method uses additive instead of subtractive manufacturing, which reduces waste significantly.

End of life
In the end-of-life phase carbon fibres can be shredded and reused for other purposes, although recycling is in early stages, however more and more companies research and offer recycling options. Shredding destroys long fibres and makes them unsuitable for core-less filament winding, but the resulting short fibres from for example Flax can be used for other products like compressed boards or insulation. Alternatively, the fibrous building elements can be reused entirely, offering advantages in reusability and modularity.

The challenges of Coreless Filament Winding
The use of core-less filament winding also has its challenges. Firstly, high tension in the fibres requires a stiff winding frame. Secondly, handling and curing of components in an oven or curing environment is crucial which requires the winding frame to be light and stiff. Thirdly, the syntax development is complex especially after fibres have interacted, which defines their position in space, collision with the robot needs to be avoided and placing the fibre precisely on the frame is quite challenging. Lastly, due to the lack of existing standards certification of new building methods, such as core-less filament winding, is challenging.

Modularity
The term modularity has been used in multiple ways recently in the building industry. The modularity used with core-less filament winding allows different building elements to be created with the same approach. Additionally, digital design and fabrication enable tailoring these components to specific mechanical loads. In contrast with the standardisation in big contractors' modularity, this approach offers form freedom.

Constraints for element creation
One of the constraints for element creation can be found in the winding frame itself which defines the connection points which need to be highly precise. Whatever happens in between these points, for example: how the fibres interact, can vary. Therefore, using only one frame, an infinite number of variations of base components can be made. This approach is therefore unique due to its multipurpose nature with the same production setup.

Interrelationship total structure and element scale
An interrelationship can be found between aspects on the structure- and element scale. Digital design and fabrication allow for variations in components and segmentation of the design influences manufacturing and transportation. Additionally, transportation constraints (truck dimensions) affect component segmentation.

Structural typology
In recent decades various pavilions have been constructed using different structural typologies, among them the Buga Fibre Pavilion. The structural typology of this pavilion, a dome shape, was chosen due to its structural efficiency. Which resulted in minimising the amount of unique structural elements. This was important, because every element has to be tested for certification. Therefore, certification and development costs must be balanced. Additionally, the manufacturing setup and robot each influence component size and the design of the winding frame is crucial for moulding the final component. However, a multitude of structural typologies are possible.

Outlook applications and material considerations
Key considerations for choosing the right material are stability, weatherproofing, and flammability. Different solutions exist for these requirements, but no single material covers all aspects. Flax fiber components may not achieve the same fire resistance as other materials even after treatment. Additionally, the dematerialization approach has contradictions with flammability due to the porous elements that are created. A material that is mostly non-organic and does not burn is Basalt, which makes Basalt Fibres a potential solution.

* No rights or claims for accuracy and completeness can be derived from the contents of this interview

Appendix 7 I Research by Design

In the Research by Design phase several forms have been explored on a building level which can be designed among endless other forms with the coreless-filament winding technique. Firstly the forms that have been explored follow the general hangar shaped typologies, among them: hangar 1, 2 and 3. From a designers perspective the shape feels odd due to its sharp angles on the connections of the elements. Secondly, a barrel shape is explored with curvature in the column elements which creates a more natural feel for the flexible material. Thirdly, the curvature of the elements has been expanded towards a connection on a support column in the middle in a single- and crossed span approach. Fourthly, several dome shapes have been explored which generate larger spans with smaller elements. Lastly, a three shaped column has been designed in two ways with one variant having the beams going downwards and the other going upwards. Although it needs to be noted that the curved shaped elements are harder to create with the coreless-filament winding technique due to its curvature.

Hangar 1
Steinfort, R.T. (2024)

Hangar 2
Steinfort, R.T. (2024)

Hangar 3
Steinfort, R.T. (2024)

Barrel
Steinfort, R.T. (2024)

Double Barrel with support columns
Steinfort, R.T. (2024)

Crossed Barrel with support columns
Steinfort, R.T. (2024)

Dome 1
Steinfort, R.T. (2024)

Dome 2
Steinfort, R.T. (2024)

Tree Column downwards
Steinfort, R.T. (2024)

Tree Column upwards
Steinfort, R.T. (2024)

Fibrous column
Steinfort, R.T. (2024)

Appendix 8 I Digital Prototyping

In the digital prototyping phase beam and panel elements have been created using computational design tools, such as: Rhino and Grasshopper. A visual programming script, shown in figure 24, has been written in Grasshopper to firstly visualize the winding spindles and therefore the robotic setup in a digital environment. With the winding spindle tool the dimensions, distance in between, rotation on the X-, Y- and Z-Axes of the spindles can be adjusted. Additionally the number of winding pins can be altered and are placed along the winding spindles to create anchor points for the lines that are simulated with the beam tool.

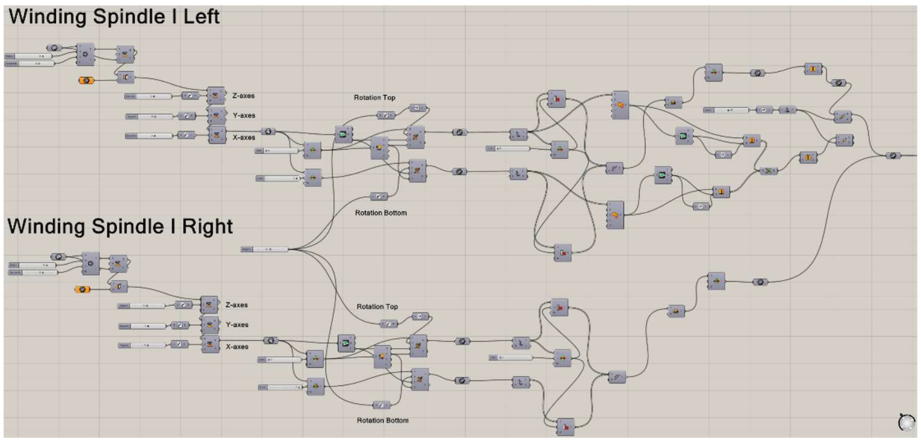


Figure 24: Grasshopper script of the winding spindle tool
Steinfort, R.T. (2024)

The beam tool, illustrated in figure 25, uses these anchor points and connects these points with lines according to the winding pattern selected. The winding pattern can be altered by two series components that determine where firstly the anchor point start and secondly on which anchor point it ends. This is determined by the amount of anchor points it skips, illustrated in figure 26, and therefore the line can be rotated along the Y-axes which creates the slanted lines in the beam structure.

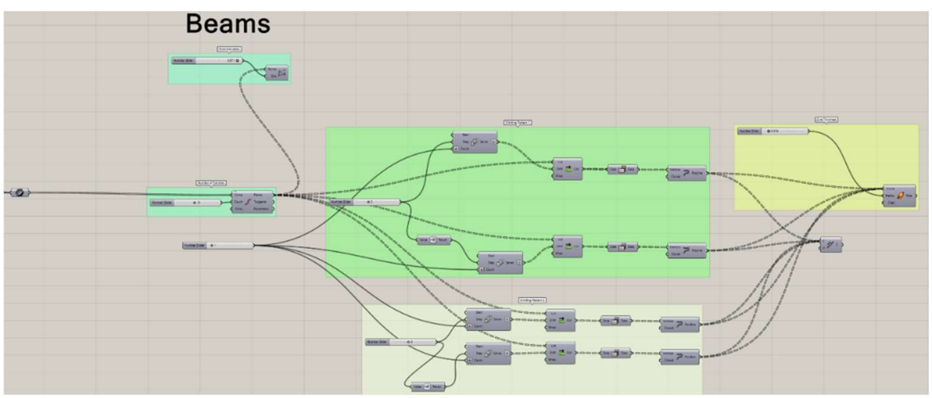


Figure 25: Grasshopper script of the beam tool
Steinfort, R.T. (2024)

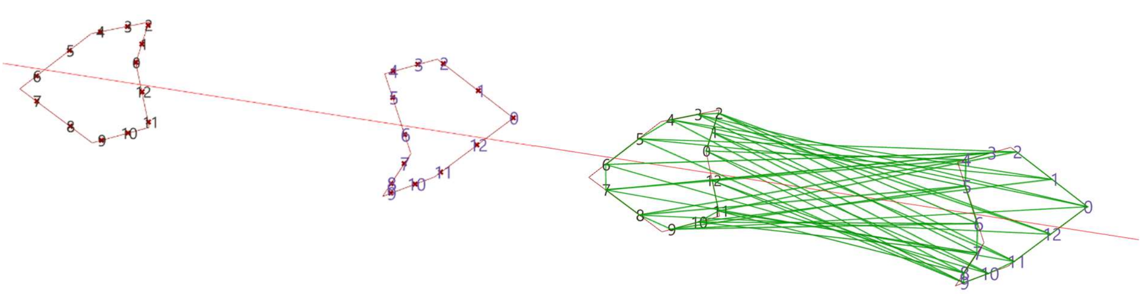


Figure 26: Visual representation of the winding spindles on the left and the simulated winding pattern on the right
Steinfort, R.T. (2024)

Additionally, the winding "robotic" setup, shown in figure 27, has been designed digitally to create an accurate assumption how to create this in the physical prototyping phase.

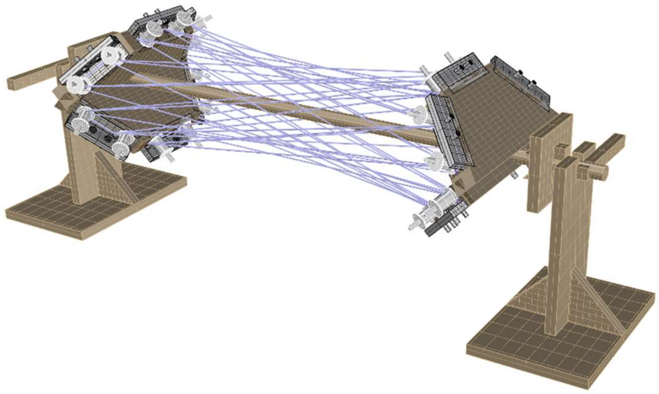


Figure 28: Winding "robotic" setup
Steinfort, R.T. (2024)

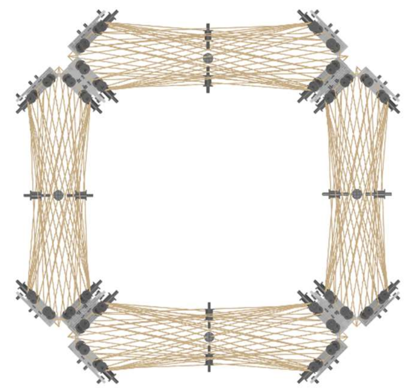


Figure 27: Resulting fibrous structure
Steinfort, R.T. (2024)

For this prototyping purpose the winding spindles have been placed on a 45 degrees angle to make straight connections to form eventually a rectangular structure shown in figure 28.

Lastly for the simulation of the fibrous panels only two curves have to be selected on which the visual script will wind the lines to create the fibrous composition seen in figure 29.

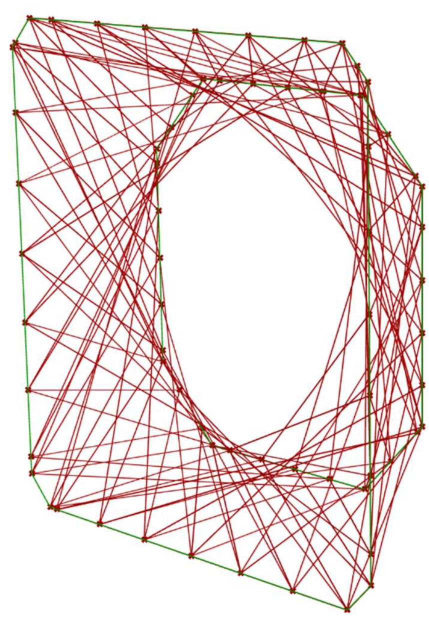
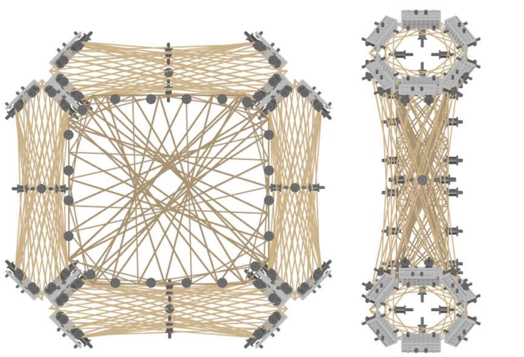
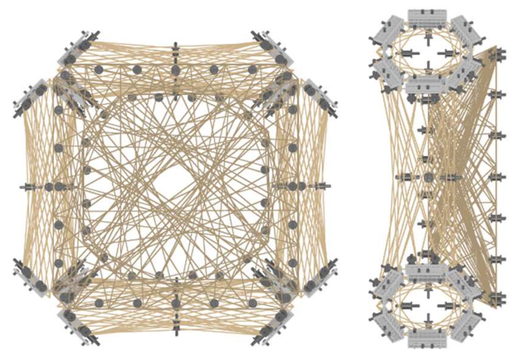


Figure 29: Digital representation of the winding syntax
Steinfort, R.T. (2024)

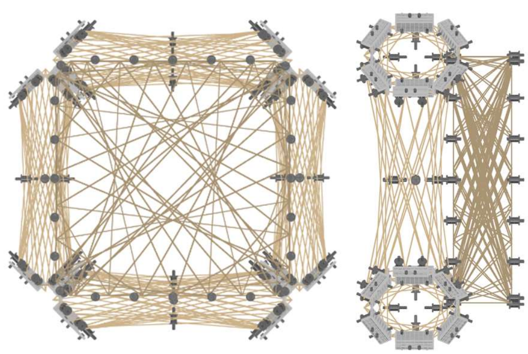
A number of fibrous panels have been digitally created before prototyping in the physical realm which are illustrated below in figure 30. These panels are shown below and differ in the placement in the structure and therefore the connection with the structure itself. From in between the structure (panel 1), halve in between the structure and halve on top (panel 2), on top of the structure (panel 3) and halve on top and bottom of the structure (panel 4). As previously mentioned the goal of the prototyping phase is to generate a variety of combinations of structural elements (beams) with non-structural elements (panels) to form integral demountable and modular building systems which are structurally optimized, thermally insulated and weather proof. In appendix 9 the methods used to achieve this goal are elaborated based on physical prototypes.



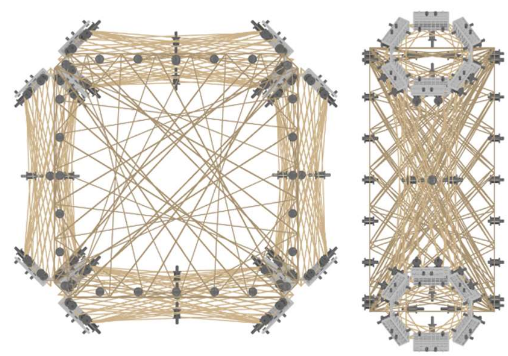
Panel 1: In between the structure



Panel 2: Halve in between the structure and halve on top



Panel 3: On top of the structure



Panel 4: Halve on top and bottom of the structure

Figure 30: Digitally designed prototypes
Steinfort, R.T. (2024)

Appendix 9 I Prototyping setup

Before prototyping a winding setup, shown in figure 31, had to be created which involved making the winding spindles, the winding frame on which the spindles could rotate for the panels and beams and a resin bath which guides the flax roving through the resin.

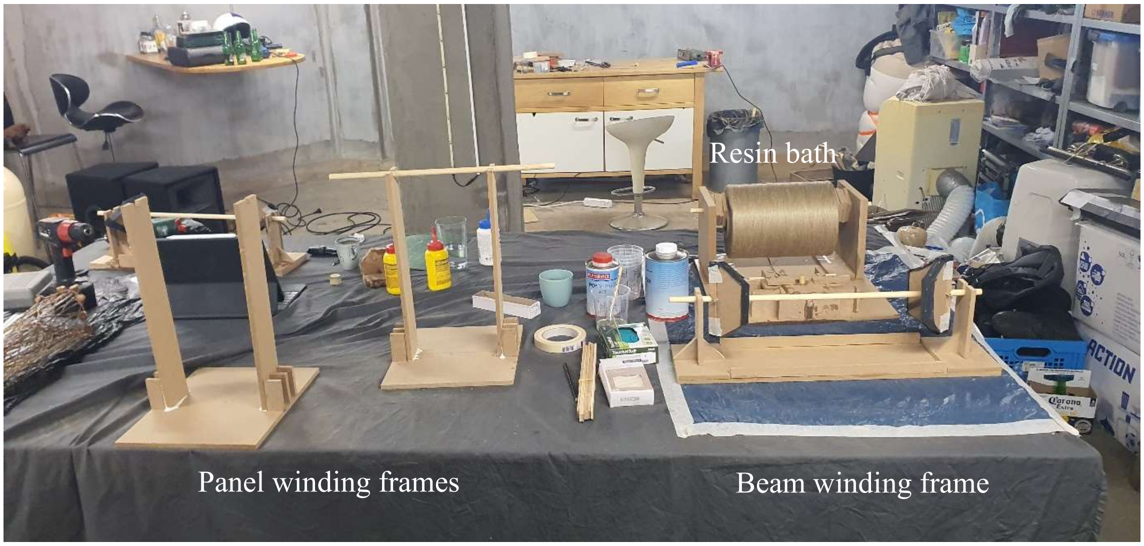


Figure 31: Winding setup components
Steinfort, R.T. (2024)

The winding spindles for the beams were made with 18mm MDF sheets that were cut to the appropriate shape and dimensions. Additionally, in the winding spindles the anchor points were drilled and the winding pins that were comprised of a washer on the bottom, a coupling nut and a washer on top were (temporarily) screwed in place. Shown in figure 32 below.

Figure 32: Components of the beam winding frame
Steinfort, R.T. (2024)

The winding spindle had to be covered in PE plastic on which the epoxy resin does not stick. Additionally, the winding pins had to be covered with removable tape to be able to demount them after curing. In the middle of the winding spindles a hole is drilled in which a round wooden stick can be placed. The winding spindles are fastened on the stick by screws to disable the movement of the spindles during winding in all directions. Lastly, the created winding frame is placed in between a holder that supports the rotation of the whole winding frame during winding.

For the panel winding frame the same approach was used and altered with four round wooden sticks to support and attach the facing 18mm MDF sheets temporarily for winding.

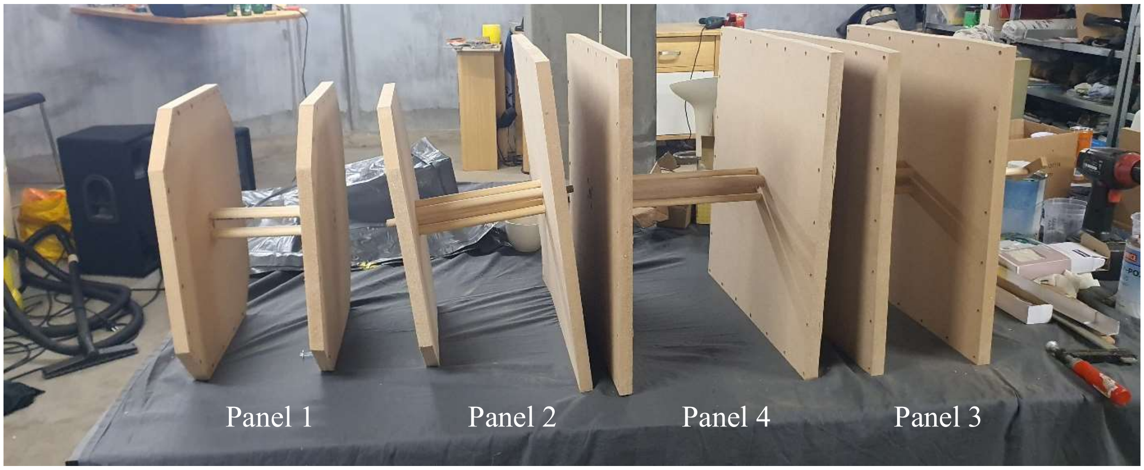


Figure 34: Panel winding frames
Steinfort, R.T. (2024)

The winding panels were both covered in PE plastic and the winding pins were temporarily connected with a bolt and nut connection. The nut was covered with removable tape to ensure its demountability after curing. Before wet winding firstly the winding syntax was dry winded to ensure the path was reasonable and appliable and free of touching the mold in the center.

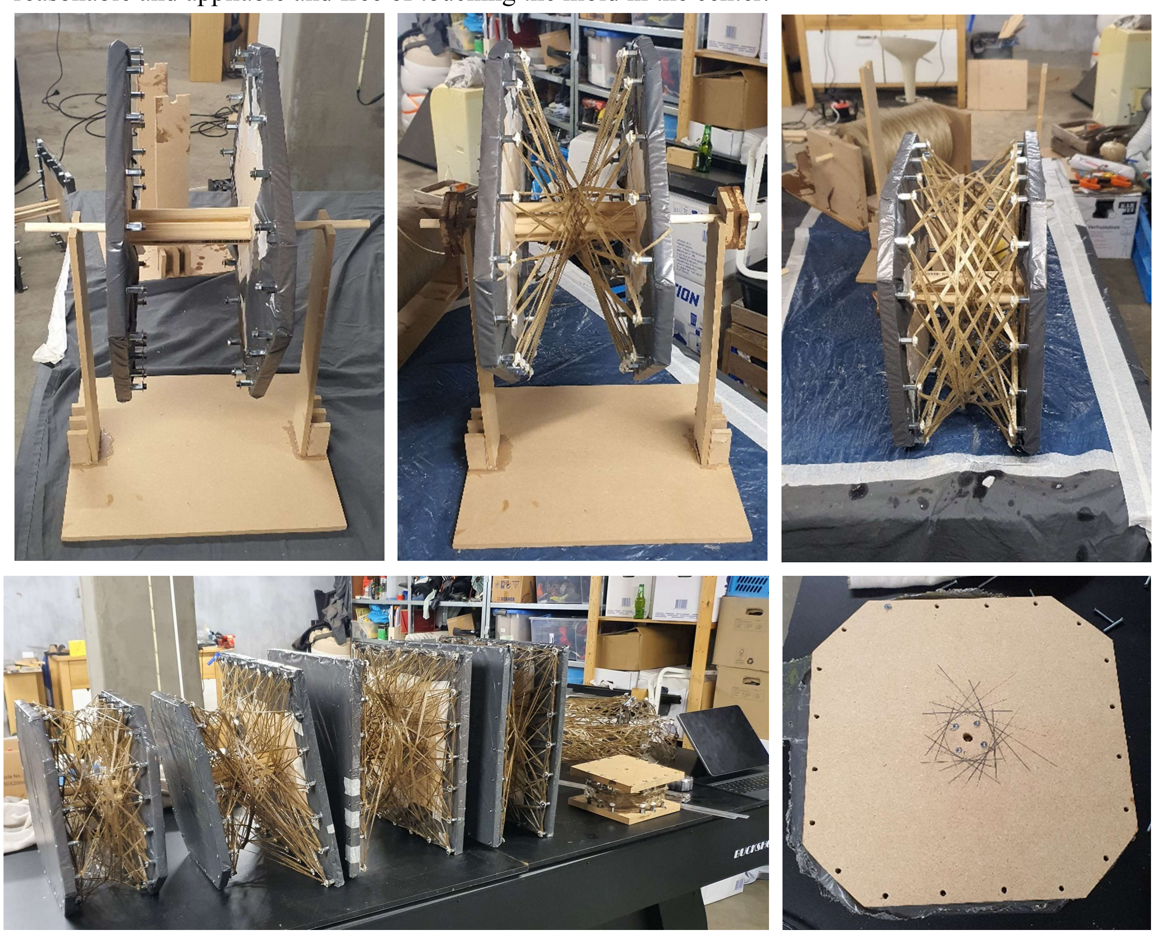


Figure 33: Winding process of the panels
Steinfort, R.T. (2024)

The flax roving used originates from the Depestele Flax family, has a weight of 520 Tex (grams per 1 km of thread), and is in a flat, untwisted state. The roving was purchased from circular-structures.com, and circular-structures states that the flax holds a tensile strength of approximately 500 MPa.

The resin is a universal two component epoxy based resin. The resin in question is particularly known as POLY-POX 500 Epoxy Resin Quick, and it was purchased from the website polyservice.nl.

Figure 36: Epoxy Resin used for filament winding
(Polyservice, 2023)

Figure 35: 2.5 kg Depestele Flax reel approx. 5km
(Circular-Structures, 2023)

The curing process typically lasted between 3 and 4 days, during which the structure gained sufficient strength to be demolded. The fibrous structure demonstrated increased strength over time following demolding, reaching its greatest strength after a total of 7 days of curing.

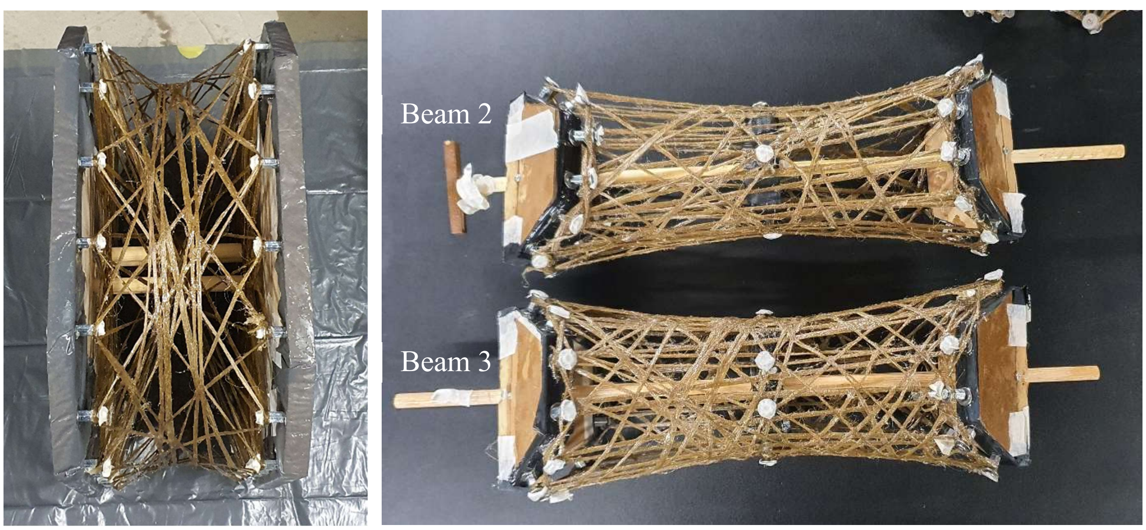


Figure 37: Curing of the winded beam and panel elements
Steinfort, R.T. (2024)

Appendix 10 I Prototyping of fiber-based building systems

The goal of this prototyping phase is to experiment with various structural elements (beams) and non-structural elements (panels). To find answers for research question 3.3.1. "How can these structural and non-structural fibrous elements be combined in a modular and demountable way, while being thermally insulated, weatherproof and structurally optimized, to form fibrous building systems?" For the prototyping several combinations of structures and panels were predesigned as stated in Appendix 9. The variations included 3 types of beam elements and 4 different panel configurations shown below in figure 38 and 39.

The structural elements were created to showcase a fragment of a fibrous structure, shown in figure 38, on a scale of approximately 1:20. Four beams were created of approximately 40cm in length, 12cm in width on the ends and 8cm in the middle. These elements varied in the placement of the winding pins. As for beam 1 the winding pins were only placed on the ends and beam 2 and 3 varied with winding pins on the end and 4 or 6 winding pins in the middle. This was done to experiment how the overall shape of the beam would be determined by the mold and to create extra connection points in the middle on which in the next phase the panels can be attached to. Additionally, experiments with the structural elements included different winding syntaxes to generate different amounts of fiber to fiber interaction and -rotation.

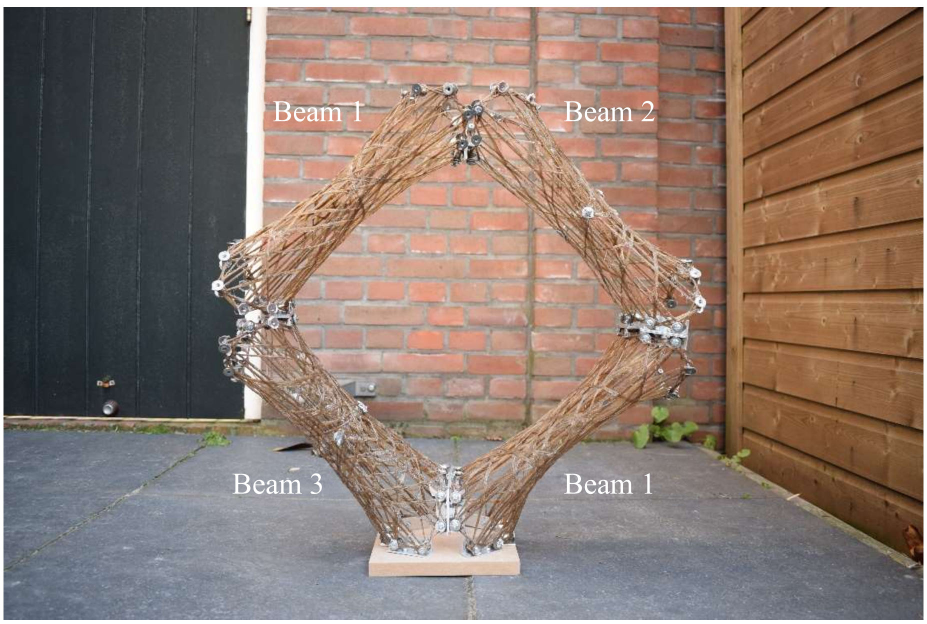


Figure 38: Fragment of a fibrous structure with 3 types of beams
Steinfort, R.T. (2024)

As stated before four panel types were prototyped to showcase various compositions of panels and their connections with the structural fragment created in the previous phase of prototyping. Experiments for the panels included the placement of the panel in or on the structure, the winding syntax, the fiber to fiber interaction (the amount of fiber placed) and the fiber rotation. This resulted in four different panel types shown in figure 39 below. Panel 1 fits in between the beams, could be placed after the structure has been mounted and connected on the inside of the structure using the winding pins left after curing. Panel 2 showcases a variant that fits on the bottom part of the panel in between the beams, but covers halve of the beams width so that a collection of panels could cover the whole structure and could also be placed after the structure has been mounted. Panel 3 would be a panel that is placed as an exterior skin on top of the beam structure and can also be placed after the structure has been mounted. Lastly, panel 4 would cover have of the inside and halve of the outside of the beams so that the whole structure would be wrapped by the panel. Although panel 4 would needs to be mounted during the assembly of the beam structures.

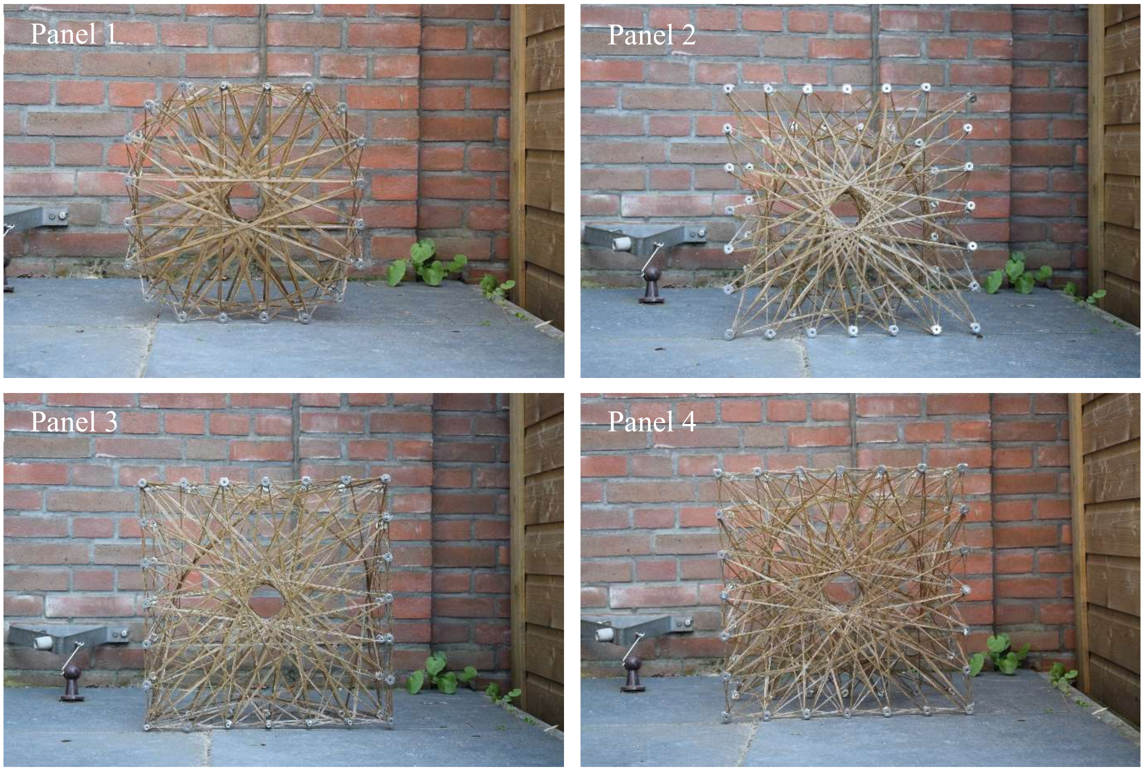


Figure 39: Four types of panels
Steinfort, R.T. (2024)

Additionally, a floor slab, shown in figure 40 (left), is prototyped to showcase the compressive strength of the flax fibers including a wooden floor slab. Hereby fiber-to-fiber orientation and -interaction was of importance.

Lastly, two types of fibrous skin types, shown in figure 40 (right) were prototyped which varied in fiber rotation. The flax fibers on skin 1 are placed only in one direction and for skin 2 the fibers are placed in a crossed direction.

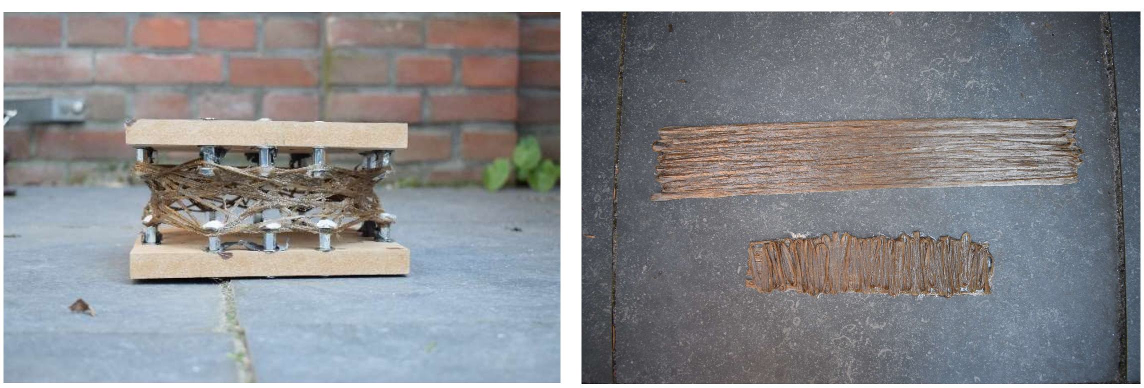


Figure 40: Fibrous floor slab with a wooden top and bottom slab (left), two variations of fibrous skin types (right)
Steinfort, R.T. (2024)

Beams (Structural elements)
In the previous paragraph the beams and panels were shown demolded, but before prototyping a winding syntax had to be determined. This syntax for the beams and panels were closely similar.

Winding syntaxis
Firstly, just like with the coreless-filament winding of the beams of the BUGA Fibre pavilion, shown in Appendix 4, a framework had to be wound where upon the next layers can be wounded on. This winding syntaxis is shown in figure 41 from which they differ in the placement of the winding pins in the center of the beam. For beam 1 only the winding pins on the ends are present and for beam 2 and 3 a set of extra winding pins is placed. The first step consisted of winding in a straight line vice versa on all the winding pins from both winding clamps. For beam 2 and 3 this differed due to the placement of winding pins in the center which were wounded upon in this path as well. This resulted in a slight difference in beam shape from which beam 1 was at first wider than beam 2 and 3. Step 2 was similar for both beam types and followed a crossed path to connect the whole frame that was wounded in step 1. Step 3 was tying the whole frame together in a loop wise manner to compress and gain more tension in the fibers. Lastly, on the edges of both surfaces each winding pin was tied together with the adjacent one to create an edge frame along the beams.

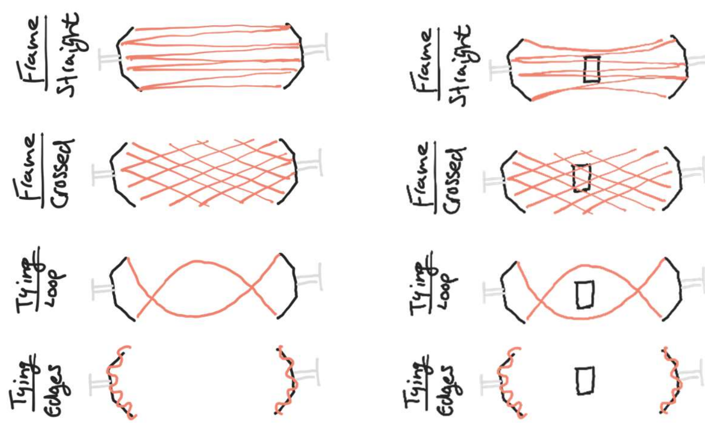


Figure 41: Winding syntax beam 1 (left) and beam 2 and 3 (right)
Steinfort, R.T. (2024)

Results
Experimental results gained from this prototyping session were predominantly that fiber-to-fiber interaction is the most important aspect in the structure. For example beam 1 and 2 were wounded less in step 3 in a looped wise manner which resulted in a beam more flexible and a less stiff structure.

Figure 42: Different amounts of fiber-to-fiber interaction showcased on the left with beam 3 (more fiber-to-fiber interaction) and on the right beam 1 (less fiber-to-fiber interaction)
Steinfort, R.T. (2024)

Additional findings were that the placement of the loads on the structural element is crucial for load distribution and the stiffness of the structure. Figure 43 showcases a single beam without pressure placed in the center of the element (left) and with pressure (right). This concluded that the beam itself is flexible and indentable in the center of the element.

Figure 43: Stiffness testing showcasing the beam to be flexible in the center and to be indentable (left no pressure, right with pressure)
Steinfort, R.T. (2024)

Although, if pressure was placed on the ends of the element, shown in figure 44, little to no movement was detected. Which gives the impression that the fibrous structure can handle pressures placed in the fiber direction very well, but pressure perpendicular to the fiber can be a weak spot. This result relates to the findings during case study analysis of the BUGA Fibre pavilion that these kind of structures are predominantly exerted on axial compression (Pérez, Früh, La Magna, & Knippers, 2022).

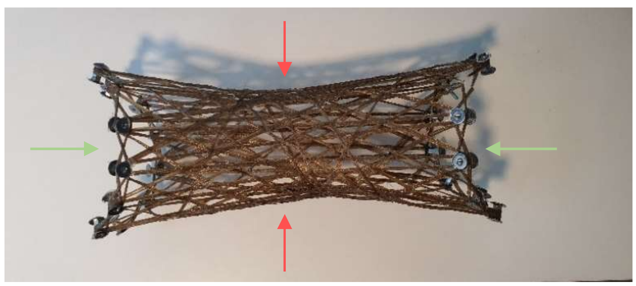


Figure 44: A single beam element showcasing its strengths and weaknesses when applying pressure
Steinfort, R.T. (2024)

These findings were also found when the elements were connected in a structural fragment of four beam elements, shown in figure 45.

Figure 45: The structural fragment showcasing the optimal load distribution
Steinfort, R.T. (2024)

<u>Connections</u>
The beam elements were connected using the winding pins, a combination of coupling nuts and washers, with a metal hook plate which connected firstly on one side two winding pins of the same element together and secondly the winding pins of the adjacent element. Shown in figure 46 below. This confirms the vital role of the placement of these anchor points when making the connection between the elements.

Figure 46: Connection of the fibrous beam elements on a foundation (left) and among the structural elements itself (right)
Steinfort, R.T. (2024)

Additionally, the connections made with the metal hook plates were of importance to create a stiff connection between the adjacent winding pins of the same element. This to disable the movement of the winding pins and to fix them in place. The structural fragment, shown in figure 47 below, can be repeated to create the overall assembly.

Figure 47: Repetition of the structural fragment to form the overall assembly
Steinfort, R.T. (2024)

Furthermore, alternative materials for winding pins and their connections have to be researched to create a fully biobased structure. For research purposes the winding pins of one beam element, shown in figure 48, has been executed in wood. Although no structural information could be gather from this prototype due to the element having no twin to be connected on. Additionally, a notion has to be made that the wooden winding pins were less strong during winding and according to Julian Fial with robotic winding the tension during winding is much higher (full interview transcripts are presented in Appendix 6) than winding by hand which may cause the wooden winding pins to break.

Lastly, the beam shown in figure 48, also illustrates the coreless aspects of the beam elements which creates opportunities to fill the core with flax fiber insulation to make the beam elements thermally insulated.

Figure 48: Beam with an alternative (biobased) material, wood, for the winding pins
Steinfort, R.T. (2024)

Panels (Non-Structural elements)
Firstly, to start prototyping the winding syntax had to be determined. This was done with a designers intuition in mind and what could be feasible in the sense of winding.

Winding syntaxis
This is important, because the robotic arm, in this case my arm, has to be able to reach the winding pins and if already winded fiber is in the way the winding syntax is not feasible. This was for example the case with winding syntax 1, shown in figure 50. The first step was to wind the fibers in a double diagonal way from top to bottom vice versa. However, due to the diagonally woven structure step 2 of winding diagonally on one surface was not feasible, because of the woven structure was an obstruction. Therefore a new winding syntax had to be determined which resulted in winding syntax 2, shown in figure 49. A small adjustment was needed in the sequence of winding steps. Winding step 1 and 2 were switched around. In step 1 two winding frames were woven on both surfaces separately from each other. This was done to create a fibrous surface on both sides to form a framework. The next step was creating a core structure for the panel to give the panel it's strength and create a diagonal framework that connects both surface frameworks from top to bottom and vice versa. The third step consisted of creating a diagonal frame along the surfaces to form a border that closes of the open sides of the panel. Initially, this was done by winding the fibers almost in a perpendicular way, but due to the low rotation of this winding syntax this was not feasible due to the fibers slipping of the winding pins. Therefore the rotation of the fibers needed to be increased to disable the fibers of slipping of the winding pins. As a result the borders of the panels moved more inward than previously was anticipated. The fourth step consisted of compressing all the fibers together by winding the fibers in one path in a multitude along its axes. This resulted in more fiber-to-fiber interaction due to the overlapping of the fibers and therefore the fibers gained more adhesion. The last step was winding along the winding pins from the surfaces separately with crossing the winding pins and vice versa. The intention was to create a edge of the frame and experiment which impacts this had on the overall structure of the panel. For experimental research purposes this was only done with panel 3 and 4 to gain insight in the benefits of this step in the winding syntax based on fiber-to-fiber interaction and therefore the strength of the edges of the panels.

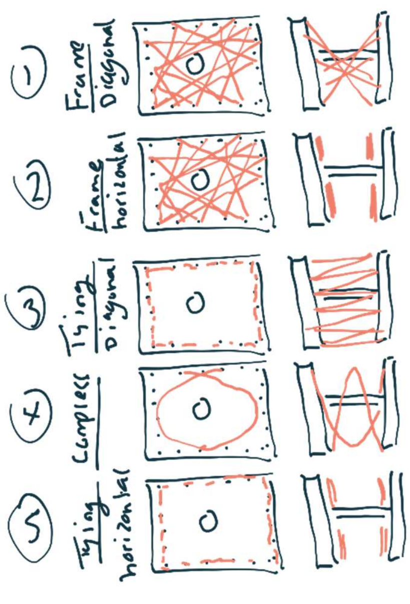


Figure 50: Winding syntax 1 (wrong)
Steinfort, R.T. (2024)

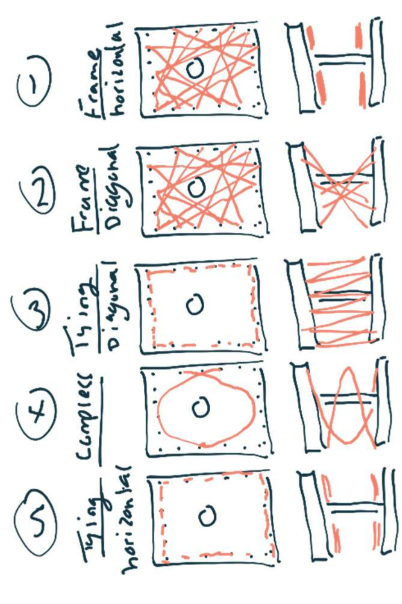


Figure 49: Winding syntax 2 (correct)
Steinfort, R.T. (2024)

Results

As for the non-structural panels the surfaces, shown in figure 51, created in step 1 were found to be very flexible and with little pressure the surface could be indented.

Figure 51: The surface of a fibrous panel
Steinfort, R.T. (2024)

Additionally, panel 1 differed in molding shape with its chamfered edges shown in figure 53. Surprisingly this resulted in the edges of the structure being much stronger than the edges created for panel 2 for example. These edges, both not horizontally tied together in step 5, were very flexible in movement and therefore a weak spot in the panel. This is illustrated in figure 52.

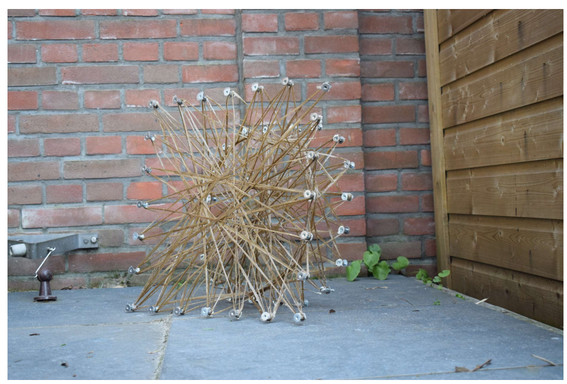
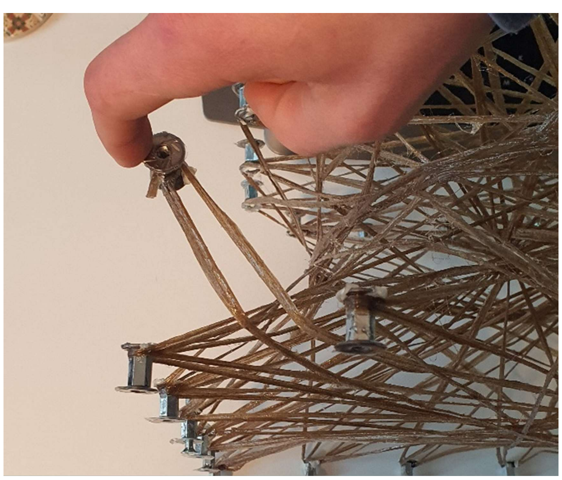


Figure 53: Showcasing the differentiation in panel shape between panel 1 and 2
Steinfort, R.T. (2024)



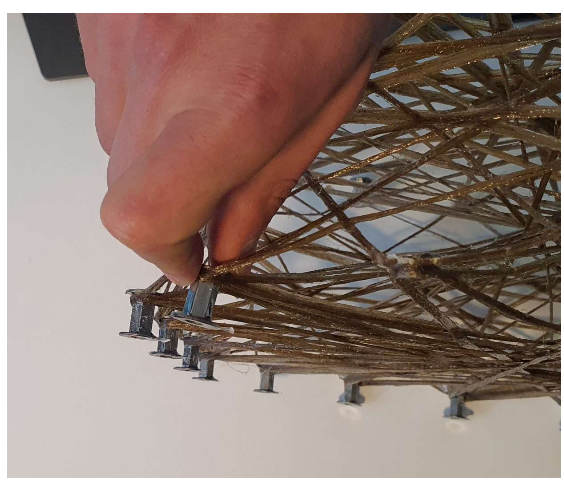


Figure 52: Showcasing the difference in stiffness of the edges between panel 1 and 2
Steinfort, R.T. (2024)

Figure 55: The edging of the frames of panels 3 and 4
Steinfort, R.T. (2024)

As for panel 3 and 4, illustrated in figure 54 and 55, which included the horizontal tying of step 5 in the winding syntax showcased much more strength on the edges due to the winding pins on the edges being much more tied together and therefore they act more together as a bundle of points when load is exerted.

Figure 54: Top view of the edging of the frames, showcasing the winding pins to be more integrated into a bundle of points
Steinfort, R.T. (2024)

Placement in the structural fragment

As previously stated, the panels differed in the placement in the structural fragment. Figure 56 and 57 illustrate how each panel is placed in the fragment. Panel 1 is placed inside the structure, panel 2 is placed halve inside the structure and on top of the structure, panel 3 is placed only on top of the structure and lastly panel 4 is placed on the inside and outside of the structure overlapping the whole structure.

Figure 57: The different panel placements in the structural fragment (from left to right: panel 1, 2, 3 and 4) *Steinfort, R.T. (2024)*

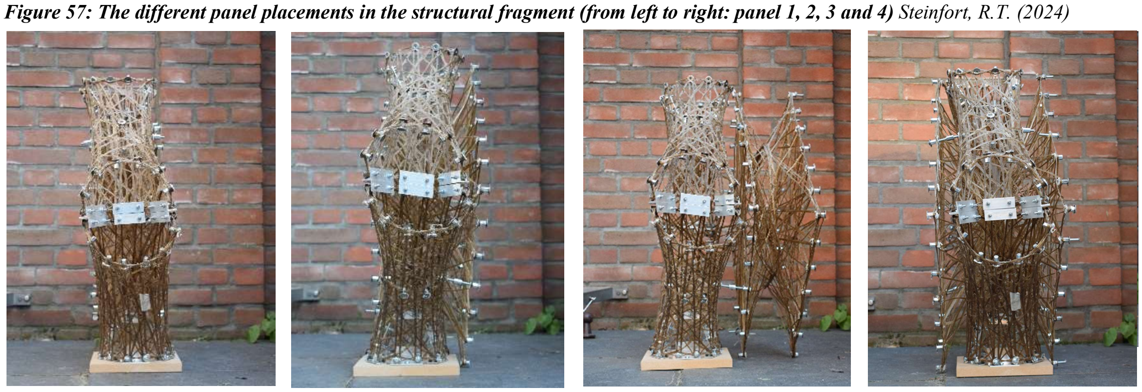


Figure 56: The different panel compositions in the structural fragment (from left to right: panel 1, 2, 3 and 4) *Steinfort, R.T. (2024)*

Connections

The panels all had various connection approaches to the structural fragment. First of all panel 1 had the goal of having the ability to be placed after the structure has been mounted, but the prototype was dimensioned slightly bigger than anticipated and therefore the structure still had to be dismantled to be able to place the panel in between the structural fragment. Although this seemed unfortunate this gave the opportunity to tightly fix the panel in place due to the beams surrounding the panel creating a border in which the panel couldn't move. Further prototypes of this type could have winding pins in the center of the border frame of the panel to create a connection with the inner winding pins on beams 2 and 3.

As for panel 2 and 3 the connections with the structural fragment could be made using the winding pins on the inside of beams 2 and 3, shown in figure 58. This resulted the panel to being slightly attached to the structure, although in this case only two connections could be made. Further prototypes can have more winding pins in the center of the beams to create more attaching points for the panel being more firmly fixed in place.

Figure 58: Connection types of panel 2 and 3
Steinfort, R.T. (2024)

Panel 4, shown in figure 59, had the ability to cover the whole structure by being fully inside and outside of the beams. In this case the connection opportunities of panel 1 (being tightly surrounded by the structure), 2 and 3 (connection points on the outside of the beams) were applied to firmly fix the panel in place. This panel also had the advantage of covering the beams in full and thereby being a more thermally insulated fiber-based building system. Although in this case between the panel and the beams there is little room available for insulating capabilities.

Figure 59: Panel 4 showcasing the advantage of covering the whole structure for insulation purposes
Steinfort, R.T. (2024)

Floor Slab

A floor slab, shown in figure 60, was created for experimental purposes to showcase the compressive strength achieved with only winding the winding pins on the outside of the frame. This resulted in a tightly overlapped fibrous structure which had high amounts of fiber-to-fiber interaction. Although the floor slab was relatively strong and couldn't be indented with pressing by hand when standing on the slab the weaknesses became visible. The structure began to buckle, the sudden change (deformation) of a structural component under load, and leaned more towards one side of the slab. Although in this prototype the slab couldn't resist this amount of compression force winding by robot and placing more fibers can help overcome this problem. Additionally, from the case study analysis in appendix 4, the floor slabs created for Maison Fibre achieved enough strength to overcome this problem.

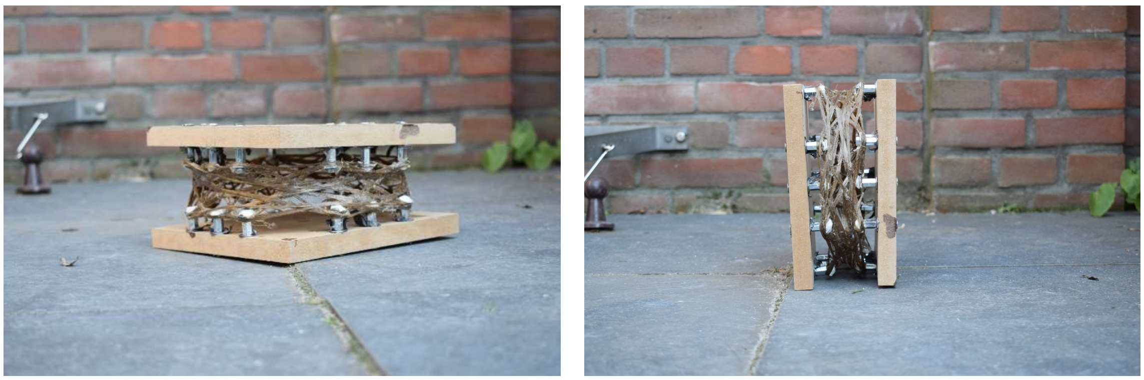


Figure 60: Floor slab prototypes
Steinfort, R.T. (2024)

Skins

Lastly, two variations of skin types were prototyped, shown in figure 61. Firstly, skin 1 was created by placing fibers in only one direction and skin 2 had fibers placed in a crossed pattern. As for weather proofing in the sense of water repellence both skins showcased no water penetration. Although this can also be the result of the high amounts of resin in the skin. Further research has to gather more information on how to create skins from flax and resin that are weather proof and needs to investigate the long term exposure implications.

Figure 61: Flax skin types (left) and water repellency testing (right)
Steinfort, R.T. (2024)