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Tailored Lace: Moldless Fabrication of 3D Bio-Composite Structures through an Integrative Design and Fabrication Process

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Abstract: This research demonstrates an integrative computational design and fabrication workflow for the production of surface-active fibre composites, which uses natural fibres, revitalises a traditional craft, and avoids the use of costly molds. Fibre-reinforced polymers (FRPs) are highly tunable building materials, which gain efficiency from fabrication techniques enabling controlled fibre direction and placement in tune with load-bearing requirements. These techniques have evolved closely with industrial textile processes. However, increased focus on automation within FRP fabrication processes have overlooked potential key benefits presented by some lesser-known traditional techniques of fibre arrangement. This research explores the process of traditional bobbin lace-making and applies it in a computer-aided design and fabrication process of a small-scale structural demonstrator in the form of a chair. The research exposes qualities that can expand the design space of FRPs, as well as speculates about the potential automation of the process. In addition, Natural Fibre-Reinforced Polymers (NFRP) are investigated as a sustainable and human-friendly alternative to more popular carbon and glass FRPs.

Keywords: biocomposites; bobbin lace; natural fibre-reinforced polymers; NFRP; moldless; digital fabrication; integrative design; craft; lightweight structure

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1. Introduction

1.1. Fibre-Reinforced Polymers

Fibre-Reinforced Polymers (FRPs) are becoming increasingly used in the modern building industry as lightweight, materially efficient alternatives to more common construction materials. FRPs have many advantageous characteristics including a high strength to weight ratio, high durability, stiffness, flexural strength, resistance to corrosion and impact, as well as being easily tunable to satisfy performative requirements [1–4].

As the energy consumption of the global building sector and construction industry continues to rise, accounting for 38% of total global energy related CO_2 emissions, there is a strong incentive to not only use more sustainable building materials, but to drastically improve resource efficiency in the production of buildings and building materials [5,6]. The highly tunable and composite makeup of FRPs is well-suited for incorporating natural materials and adapting to specific use cases, making them ideal candidates to address these problems in construction, as most projects tend to require unique performative solutions [4].

FRPs are composite materials, consisting of a polymer resin matrix with reinforcing fibres embedded within it. The fibres mechanically enhance the strength and elasticity of the matrix, while the matrix provides support and protection for the fibres [1]. The tunability of FRPs is derived from the ability to freely layer and place reinforcing fibres in key areas depending on specific design criteria such as structural loading conditions. FRPs can be further classified according to their fibre length, being made of either long continuous fibres or short discontinuous fibres [2]. FRPs with continuous fibre reinforcement are of particular interest, as fibres can be placed according to force flows similar to natural organisms and effectively distribute loads from the matrix to the fibre.

1.2. Natural Fibre-Reinforced Polymers

Typically, in load-bearing cases, FRPs consist high strength fibres such as glass, aramid or carbon but recent research has shown the benefits of using natural fibres as sustainable alternatives for the reinforcing fibres, further referred to as Natural Fibre-Reinforced Polymers (NFRPs) [3]. Natural fibres are classified as either plant-based, animal-based, or mineral-based but significant potential for applications in construction lies in plant-based natural fibres due to their high availability, low cost, biodegradability, and good physical and mechanical properties [2]. A specific natural fibre with high potential for applications in architecture is the flax fibre due to its growth in annual crop cycles which is also possible in moderate climate [7]. Additionally, its yearly supply in Europe has been constantly increasing in the recent years.

Prior to the invention of synthetic fibres and their prolific use in contemporary FRP production, natural fibres were the material of choice for most textile-based products with many societies using them for hundreds of years [3,8]. Since the industrial revolution, advances in manufacturing have focused on mass production and automation therefore choosing synthetic fibres over natural fibres for their predictable and controllable properties. However, in light of the global need to reduce CO_2 emissions in building construction and improve resource efficiency, natural fibres are once again becoming a popular alternative [6].

1.3. Production Methods

The production of high-performing FRPs from endless fibres could be divided into 2 main steps: the organization of the fibres and application of matrix.

Depending on the selection of type of matrix (thermoplastic or thermoset) and the application method, the order of steps may differ. The fibres are arranged into sheets of profiles by modern textile fabrication techniques such as weaving, knitting, winding, Tailored Fibre Placement (TFP) or braiding [1,2]. These steps are followed by a molding process. In thermoset composite molding, the fibres are pre-impregnated (prepreg fibre) with the resin matrix before being molded to their final form through compression or heat, while in wet molding the fibres are laid in the resin matrix at the time of molding [1]. The molding process is resource intensive as every unique part requires a customized mold, often fabricated through subtractive methods. For these reasons typical FRP forming by molding is highly efficient for standardized parts, but not for the one-off products common in the field of architecture.

Although novel production processes such as Coreless Filament Winding (CFW) developed at the ICD University of Stuttgart, have made significant advances in removing the mold from FRP manufacturing for architectural components, they still require a frame which sometimes becomes embedded within the final product [9,10]. Part of our research investigates a moldless forming process that allows for geometric freedom without the need to create multiple costly molds, therefore improving resource efficiency of FRP production.

1.4. Bobbin Lace Making

Much development in textile and FRP production has focused on increasing efficiency and automation for standardized pieces to meet global demands, forgoing the potential of textile-based systems to create highly unique and customizable products. Machines and methods have also been predominantly designed to work with synthetic fibres. In order to meet the demands of the next century, alternative methods must be investigated, especially methods compatible with natural materials [11].

One lesser-known technique of fibre arrangement that has remained largely underexplored yet shows high potential for integration in lightweight textiles and FRPs is bobbin lace making. It is a traditional craft process that facilitates the creation of complex patterns through a set of simple rules governing the interaction of fibres. It involves braiding and twisting lengths of thread over a template or "ground" which defines the overall pattern [12].

Bobbin lace is different from textiles such as woven cloth and knitted textiles because the "threads follow complex paths with two threads taking significantly different paths in the same fabric" [13]. Bobbin lace making can be seen as a hybrid between braiding and weaving, with the added control of choosing where the fibre interaction occurs. It provides a unique way to arrange the fibres in FRPs in multiple directions according to performative criteria while maintaining fibre continuity, and increasing fibre–fibre interaction.

A significant part of our research involves the investigation of this traditional technique in light of contemporary means of digital making. As digital technologies replace craft processes, and the number of skilled artisans decreases, there is a serious risk of losing the knowledge involved in many crafts [13]. In Dr. Irvine's PhD dissertation, she elegantly describes the issue:

> "like endangered plants and animals, not only is the loss of handcraft a reduction in the beauty and diversity of the world, but it is also the loss of solutions to medical, social and environmental problems" [13].

One solution is to reincorporate craft skills within the digital workflows of modern manufacturing and construction processes [14]. This provides opportunities to relearn forgotten techniques, sustain cultural knowledge, discover new applications and develop novel fabrication processes that can benefit contemporary architecture and construction systems.

By integrating bobbin lace making within a computational workflow, we propose a novel production process for FRPs that reduces need for molds, incorporates natural materials, and establishes a craft-based technique as an efficient means of material distribution. We also briefly explore how this process could be introduced to automated FRP production processes through Tailored Fibre Placement (TFP).

1.5. State of the Art

As "a shift in the use of materials driven by energy and resource scarcity" occurs, and the benefits of FRPs for lightweight construction are further explored in architecture, there has been significant effort to create viable alternatives in both material usage and the molding process [4].

One example, AEROCHAIR, demonstrates a novel moldless forming process to create a lightweight carbon fibre chair (Figure 1a) [15]. It employs form-finding methods based on Antoni Gaudi's catenary arches, using a series of precisely placed and measured non-elastic strings to "pull" the carbon fibres into the desired shape. This creates nodes at each fibre/string intersection, which after curing, allow for subsequent fibres to weave the catenaries together and form a 3D surface. This approach enables fabrication of an FRP structure using a low cost and relatively simple frame and a series of precise tensioning devices. It also demonstrates the potential of a physical form-finding process that use fibre–fibre interactions to create complex 3D surfaces. However, the final prototype was designed as a tension only system, unable to transfer compression and bending forces common in most architectural use cases. Secondly, while the sequence-based curing and forming process allowed for the creation of fibre nodes in space, the multi-stage process is rather complex.


(**a**) (**b**)

Figure 1. State of the Art (**a**) "AEROCHAIR" [15] (**b**) "FlexFlax" [16].

A successful example of a moldless compression-capable composite using natural fibres is the FlexFlax Stool (Figure 1b) [16]. To eliminate the need for a mold and create a performative structure with continuous flax fibres, the research developed a multi-stage fabrication process that employs Tailored Fibre Placement (TFP) to create a preform which becomes an embedded frame for Coreless Filament Winding (CFW). The TFP preform has distinct fibre paths accounting for controlled bending, structural reinforcement, and winding tabs. The preform undergoes vacuum resin infusion and bending prior to winding. The embedded TFP preform increases stiffness without the need for secondary materials common in CFW processes. The final prototype stool weighed only 1080 g and could carry an 80 kg human, demonstrating the capacity for highly customized NFRPs to perform as sustainable alternatives to typical FRPs, but the efficiency benefit of using highly automated CFW and TFP techniques is contrasted with the many manual steps still needed to create the structure.

Existing work in transferring bobbin lace to architectural applications includes the A Case for Lace project [17]. The project incorporated FEM and embodied effort analysis to create computationally informed, self-supporting artefacts. Carbon fibre was chosen as the main lacing material due to its high performance for architectural use cases, although it leaves much to be desired in sustainability and human-friendliness. The designs investigated in this research are mostly limited to simple, continuous surfaces, instead of complex 3D artefacts formed by multiple surfaces.

1.6. Scope

The scope of this research includes the development of a materially informed computational workflow that produces 3D artefacts integrating structural criteria within the craft-based textile technique of bobbin lace making. In doing so, we showcase bobbin laced components as a surface-active NFRP system suitable for sustainable architecture, and as a moldless forming process appropriate for the ubiquitous demand of highly customized building components. This is demonstrated through a small-scale furniture prototype capable of supporting an 85 kg adult. Our proposed workflow and prototype also demonstrate the potential of novel solutions that arise when a traditional craft process is re-investigated in the context of modern industrial techniques and digital tools.

2. Materials and Methods

Our approach to integrate these principles within a design workflow can be broken down into four main parts: understanding the principles of bobbin lace, structural evaluation of lace patterns, integration of these findings into a computational design workflow, and realising the designs in a fabrication process.

2.1. Bobbin Lace Analysis

The craft of bobbin lace is analysed to identify key characteristics and patterns. The making of traditional bobbin lace can be broken down into three basic actions: Twist, Cross, and Pin. Patterns are often worked with groups of four bobbins at a time, considered to be two pairs. The Twist involves lifting one bobbin over the other in each pair (Figure 2a). The Cross requires lifting the inside bobbin from the left and crossing it over the inside bobbin of the right (Figure 2b). A series of Twists and Crosses creates a node which the actor pins in place (Figure 2c). The pinning action allows a user to change the density of a particular pattern and does not restrict lacing to periodic, equal sized tessellations [18].

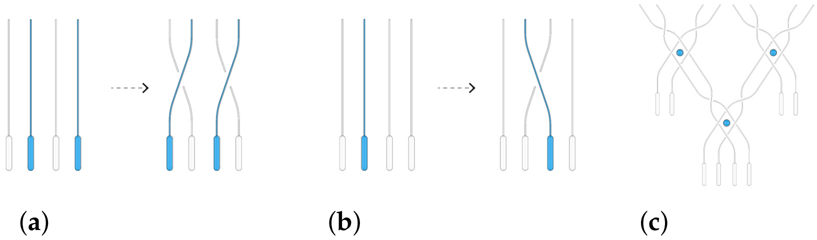


Figure 2. Bobbin lace making technique. Adapted from [13]. (**a**) Twist. (**b**) Cross. (**c**) Pin.

Bobbin lace patterns are represented by simple graphs, known as grounds, where each vertex encodes a series of actions to be performed at each node (e.g., Twist, Cross, etc.) and each edge represents the topological connection between nodes. The ground also denotes how many fibres are present at the starting points given a particular pattern, shown in Figure 3.

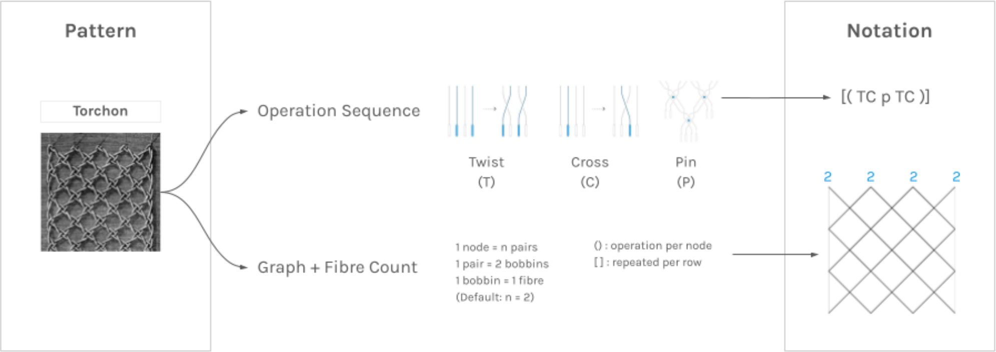


Figure 3. Translating lace patterns to notations for action sequences and graphical fibre counts.

Bobbin lace practices differ in tools and techniques depending on the geography and culture in which they are found. Figure 4 shows a variety of these patterns and their associated grounds from a French book on Bobbin Lace Grounds from the 1800s [19]. The same ground can be embedded with different action sequences at each node, resulting in different fibre topologies. There are a wide variety of patterns ranging from dense weaves to sparse nets. The mechanical properties of these patterns are explored in the following sections.

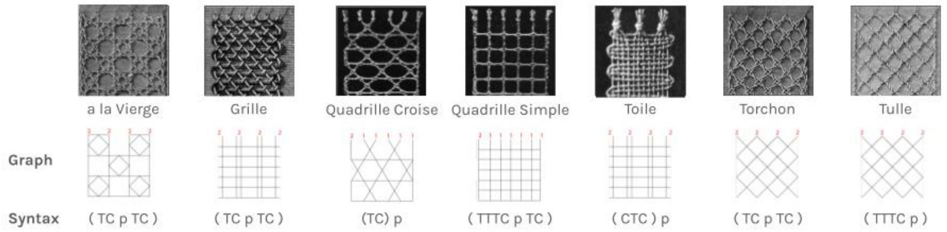


Figure 4. A variety of bobbin lace patterns and their associated graph and fabrication syntax.

2.2. *Structural Analysis*

To understand the effect of lace pattern on structural performance, eight patterns (Figure 5) were selected for comparison. These patterns, differing in density, fibre orientation and interaction, are abstracted as simple graphs and analysed digitally through Karamba, a FEA plugin for the Rhino/Grasshopper environment [20]. Due to the complexity of fibre–fibre interactions in these artefacts, physical models were used in conjunction to understand their structural performance more holistically.

2.2.1. Physical Tests

Eight 10 × 20 cm rectangular flax samples were laced according to the selected grounds (Figure 5). Seven of these samples are unique patterns, while the *Torchon* ground is repeated once as a control sample, and once with twice the number of fibres to document the corresponding strength increase. The laced samples were rolled and stitched along their short axis to create 10 mm tall cylinders with cross sections of 20 cm^2, which were then cast in resin and cured (Figure 6). Materials used for this test were TEX1000 flax rovings and GFK epoxy resin produced by Chemische Erzeugnisse Epoxidharz-und Härtersysteme (Firma Martin Puck Huusbargstieg 29, 22359 Hamburg Germany) with a 1-to-2 resin-to-hardener ratio. Each cylindrical sample underwent a compression test to determine their strength. Compression tests were performed in room temperature using Zwick/Roell Z100 testing machine, with a test speed of 10 mm/min. The results of these tests are shown in Table 1.

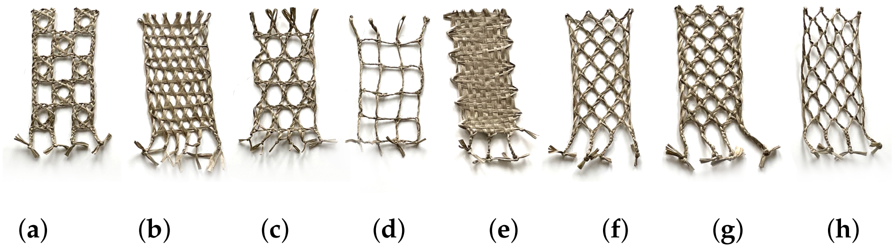


Figure 5. Lace patterns before stitching. From left to right: (**a**) A la Vierge, (**b**) Grille, (**c**) Quadrille Croise, (**d**) Quadrille Simple, (**e**) Toile, (**f**) Torchon, (**g**) Double Torchon, (**h**) Tulle.

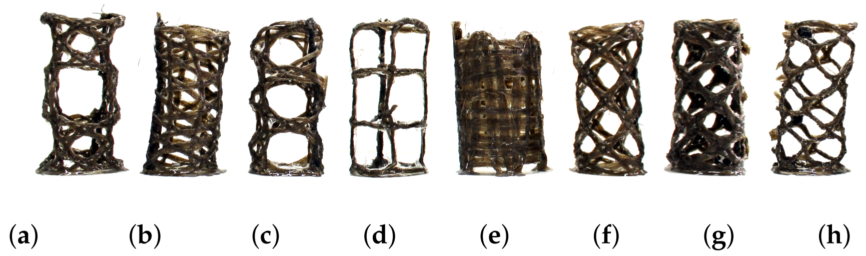


Figure 6. Cured lace samples for physical testing. From left to right: (**a**) A la Vierge, (**b**) Grille, (**c**) Quadrille Croise, (**d**) Quadrille Simple, (**e**) Toile, (**f**) Torchon, (**g**) Double Torchon, (**h**) Tulle.

As seen in Table 1, within the six different patterns, *Quadrille Croise* shows the best performance compared to other patterns with similar fibre amount, with *Torchon* ranking second. The *Torchon* pattern with double fibre was observed to fail under around double the force compared to the *Torchon* with single fibre. *Toile* and *Grille* patterns, though strong, were not considered for the prototype because they create weave interactions more closely resembling woven fabrics instead of the open structures characteristic of lace. Specifically, the parallel fibre paths in *Toile* allowed the fibre to fill the surface, causing the sample to retain much more resin than the others and thus show higher strength.

Table 1. Results of physical compression tests (Patterns marked with an asterisk are not considered for implementation in tailored lace designs.)

Pattern	Fibre (mm)	Weight (g)	F Max (N)	dL at Fmax (mm)	Strength (mPa)
(a) A la Vierge	340	20	360	10	0.18
(b) Grille *	320	20	568	8.2	0.28
(c) Quadrille Croise	320	20	520	5.1	0.26
(d) Quadrille Simple	240	13	251	6.7	0.13
(e) Toile *	280	22	1090	18.1	0.55
(f) Torchon	270	19	489	17	0.24
(g) Torchon Double	540	34	1230	8.8	0.62
(h) Tulle	280	18	234	10.6	0.12

Two issues exist in the testing process which should be better addressed in future work. First, because the samples are hand-laced, there is inherent variability in each sample. Secondly, manual stitching and resin application lead to minor deformations of some sample edges which, despite their trimming, resulted in uneven support conditions. Both factors bear effects on accuracy of the test results. However, as similar variability exists in the making of any artefact using this method, these tests suffice in providing general guidance on relative performance of each lace ground.

One additional factor to be considered in the evaluation of patterns is the amount of labour required to fabricate [17]. As all samples except for the *Double Torchon* have similar fibre count, production efforts in the preparation stage are similar, and the number of nodes in a given pattern is the main cause of different fabrication effort involved. This is important because while the *Quadrille Croise* performed the best, it is also more time consuming to produce. Therefore, we proceeded with *Torchon* as base pattern and use *Quadrille Croise* as a reinforcement strategy in areas of higher stress.

2.2.2. Digital Analysis

Physical lace samples are abstracted as simple graphs and analysed in the FEM plugin Karamba3D (Figure 7) [20]. Each pattern is tested as a 10 × 20 cm sheet with identical cumulative point loads, and the results of the digital analysis are shown in Table 2. A correlation with results of mechanical tests can be observed. However, due to aforementioned issues related to the preparation of physical samples, minor discrepancies can be observed. For instance, *Quadrille Croise* has the lowest maximum deformation given similar fibre count, which echoes the results of the physical tests, but *Grille* shows much higher deformation in the digital simulation compared to the physical tests. This is likely due to lack of consideration of fibre–fibre interactions and its subsequent effects on resin impregnation. Fabrication variance and unfavourable support conditions, as discussed in the previous section, could also be a factor. For the purpose of informing the computational design process, the digital analysis results are calibrated based on the physical tests, further described in Section 2.3.2.

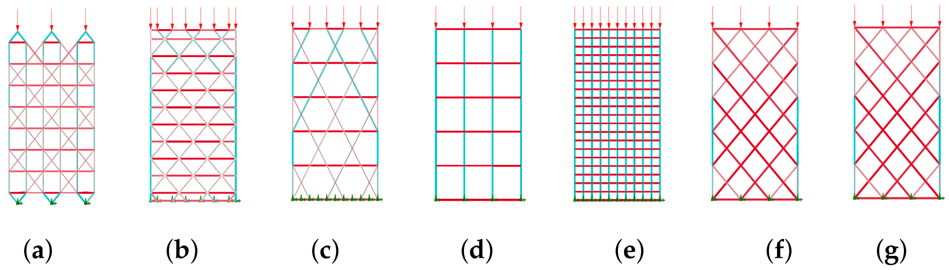


Figure 7. Setup of digital simulations. From left to right: (**a**) A la Vierge, (**b**) Grille, (**c**) Quadrille Croise, (**d**) Quadrille Simple, (**e**) Toile, (**f**) Torchon, (**g**) Double Torchon. Cyan shows compression and red shows tension members.

Table 2. Results of digital simulations (Samples are 10 × 20 mm swatches, and material properties used are not based on flax fibre. Patterns marked with an asterisk are not considered for implementation in tailored lace designs.)

Pattern	Fibre Length (mm)	dL max (mm)	Normal Force max (N)
(a) A la Vierge	310	2.2	1010
(b) Grille *	316	9.8	860
(c) Quadrille Croise	318	1.9	710
(d) Quadrille Simple	140	2.4	810
(e) Toile *	430	3.1	250
(f) Torchon	216	7.9	1740
(g) Torchon Double	432	1.9	1740
(h) Tulle	216	7.9	1740

2.3. Computational Design

The computational design workflow incorporates a form-finding strategy for moldless fabrication, a parametric representation of lace patterns, an optimisation process for pattern reinforcement integrating structural insights from testing, as well as the incorporation of fabrication parameters. As a result of this framework, more complex and controlled geometries are possible using the bobbin lace system.

2.3.1. Form Finding

To eliminate costly molds, a catenary strategy for achieving the desired form was explored. This involved hanging the laced component upside down in a frame after it is infused with resin, and allowing it to cure under gravity (Figure 8). This hanging process allows the global form to find a natural equilibrium and has been used throughout history as an effective way to find structurally efficient forms. The frame used is drastically less specialized and costly than traditional steel molds, and can be reused to create different geometries.

Although reducing setup costs, designing with form-finding requires a different approach to defining geometry. To accomplish this, the physics plugin Kangaroo in the Rhino/Grasshopper environment was used to simulate hanging action [21]. The process begins by defining a flat mesh that describes the basic topology of the artefact, e.g., the number of legs in the design. The mesh is then subdivided and assigned anchors and boundary conditions for the particle-spring simulation. When the simulation is run, the geometry is effectively “hung” from its feet. The setup is then calibrated using parameters for material stiffness and weight determined in mechanical tests and material data sheet.

If more geometric control is needed in certain areas additional constraints can be added to the model. To create the profile of the seat and shape of the backrest, a rigid frame is defined to hang from the bottom edge of the geometry. The physical representation of this constraint is a 3D printed frame fitted with holes at each of the terminating lace nodes.

The modular design of the pieces makes it suitable for printing on standard desktop printer and can easily be adjusted for different seat geometries through the parametric workflow.

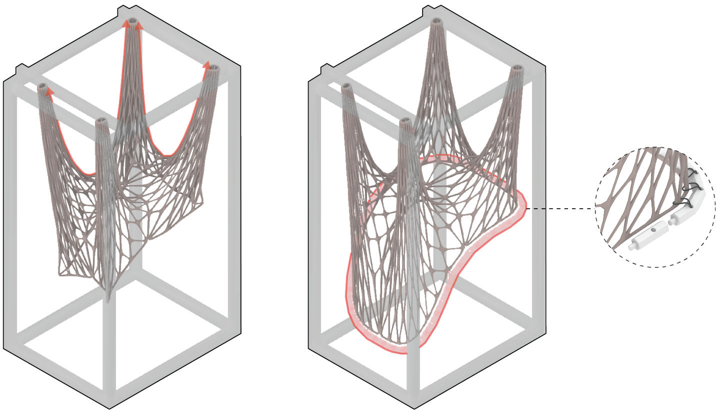


Figure 8. Gravity-based form-finding process and reusable seat profile detail.

2.3.2. Applied Patterning

Using Kangaroo, hanging simulations of various lace patterns can be rapidly explored (Figure 9a). These patterns can then be analysed within the global form as shown in Figure 9b, using the same deformation analysis described in Section 2.2.2. During this stage, various patterns, densities and parametric strategies can be explored and evaluated in a design loop.

Results from the physical tests are incorporated into the digital simulation through a multiplier applied to material properties in the model. The computational tool thus allows the designer to make an informed decision about which pattern to select based on the amount of deformation, material quantities, and labour intensity. For example, the prototype chair showed that the *Quadrille Croise* had the lowest material usage to deformation ratio. However, due to the high fabrication complexity, *Torchon* was selected, with added reinforcement in structurally critical areas.

(**a**) (**b**)

Figure 9. Applied patterning (**a**) Various patterns applied to the chair shown in plan view and isometric. (**b**) Simulated structural tests in digital environment.

2.3.3. Topology Optimisation

Given a suitable global geometry and applied pattern, a Topology Optimisation (TO) process can strategically reinforce the critical areas identified by the structural simulation. Although this is an optional step, it leverages the flexibility of bobbin lace as a craft process, which has numerous ways to embed material in a given pattern. Below are some of the strategies explored for embedding additional materials on a *Torchon* lace ground (Figure 10).

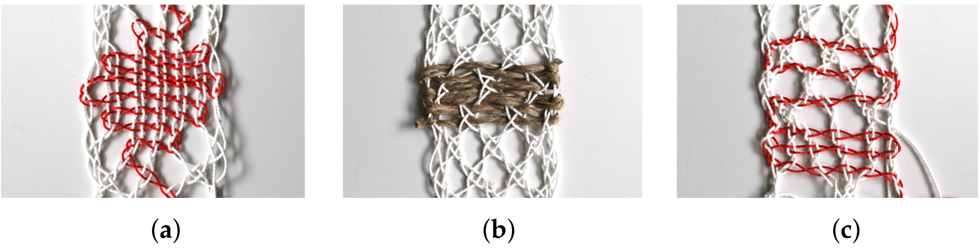

(**a**) (**b**) (**c**)

Figure 10. Experiments with traditional bobbin lace strategies as reinforcement (**a**) Cloth stitch. (**b**) Weave. (**c**) Skipped weave.

TOPOS plugin was used to determine areas for reinforcement [22]. The global geometry is converted into a 10 mm thick shell as input geometry for the process. The optimisation returns a series of voxels which can be culled based on material use (Figure 11a). To map this information back onto the applied pattern, the voxels are converted to a point cloud and pulled onto the surface (Figure 11b). Areas containing these points on the pattern are hatched with continuous fibres that travel back and forth. Depending on the symmetry of the design, results of the TO can be split and mirrored to simplify fabrication.

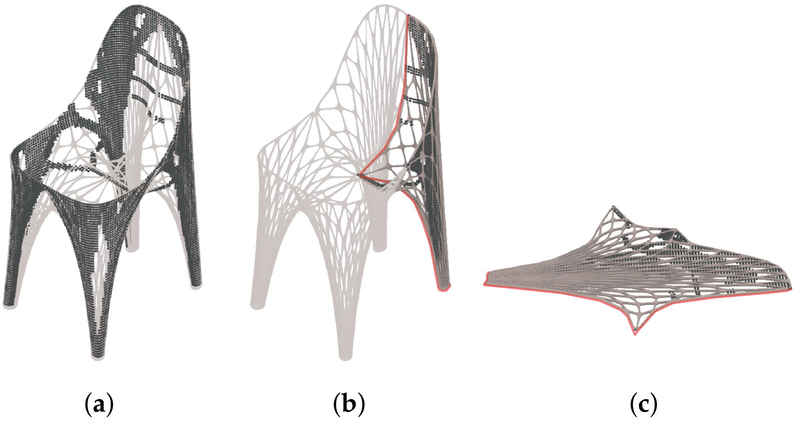

(**a**) (**b**) (**c**)

Figure 11. Topological optimisation workflow (**a**) Results of TO shown in black voxels. (**b**) One chair leg highlighted with seams shown in red. (**c**) Unrolled chair leg geometry with mapped points from TO for reinforcement.

2.3.4. Fabrication Preparation

Once the patterns are confirmed, the design is prepared for fabrication. The main goal is to translate all 3D data from previous steps onto a 2D plane for lacing, without deforming the geometry. To accomplish this, Kangaroo is used to flatten the piece while maintaining geometric relationships between nodes (Figure 11c).

Due to the doubly curved geometries inherent to the form-finding process, the model must be split up into smaller pieces and seam lines added. These lines become the boundaries of each lace piece in the 2D state. Then length and collision goals are assigned to mesh edges to prevent nodes from crossing over one another or expanding during the simulation. Reinforcement locations on the mesh are included as a property of each mesh face, and also flattened using the solver, which iteratively pulls the geometry onto a plane while maintaining all the relationships defined previously. Although the simulation is only trying to solve for an equilibrium state between all the defined goals, different weights can be applied to ensure that the most important goals are achieved. In our case the edge lengths of the seam lines were given a higher weight, to ensure the seam lines will match neighboring pieces.

2.4. Fabrication Methods

2.4.1. Templates

The fabrication process begins by templating the unrolled geometry, assigning line weights for the various lacing strategies (e.g., thick lines for lace ground and thin lines for reinforcement areas), and attaching the template to a sturdy board (Figure 12a). For the prototype, the templates ranged from 60 × 60 cm for the front legs and 60 × 100 cm for the rear legs. Screws are then inserted to act as stationary pins, keeping nodes in place during lacing (Figure 12b).

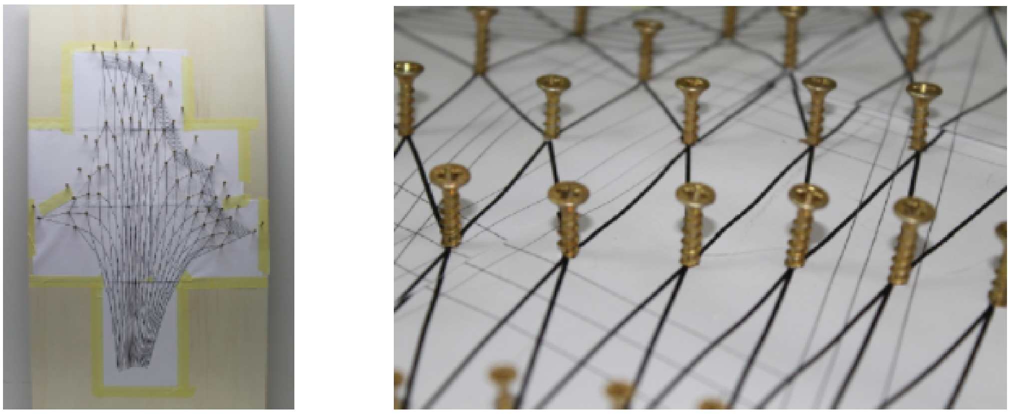

(**a**) (**b**)

Figure 12. Templates (**a**) The printed template attached to a wooden board. (**b**) Close up showing various lineweights and pins.

2.4.2. Lacing

After fibres are cut to the right length, they are hung evenly from the top of the pattern and actions necessary to create a *Torchon* pattern are performed: Twist, Cross, Twist, Cross at each of the pins shown in Figure 13. Each single segment consists two flax fibres, creating an interaction between four fibres at the nodes.

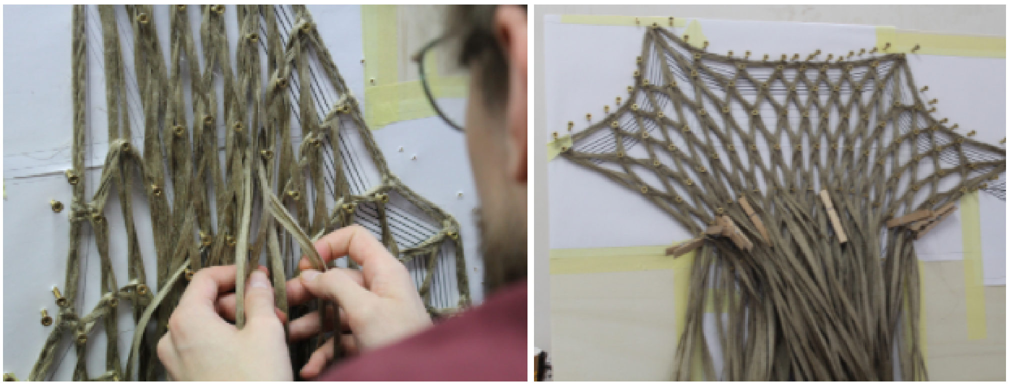

(**a**) (**b**)

Figure 13. The bobbin lacing process (**a**) Creating a node by hand. (**b**) In process template, showing a partially completed pattern.

2.4.3. Stitching

Once all four legs of the chair are laced, they are stitched together at the seams with the neighboring leg (Figure 14). A standard household sewing machine was used with 100% polyester (PES) thread for this process.


(**a**) (**b**)

Figure 14. The laced chair prior to resin infusion (**a**) All four legs stitched together. (**b**) Details of the various reinforcement strategies in the final prototype.

2.4.4. Resin Infusion

Vacuum Assisted Resin Transfer Molding (VARTM) was selected to guarantee an even distribution of resin throughout the laced flax fibres. It also provided us with a maximum amount of allotted working time for the resin. The entire laced chair was inserted to the 100 × 80 cm bag and resin was applied in two successive batches (Figure 15). Solid rollers were used to ensure adequate fibre saturation. The piece remained in the infusion bag for 10 min and was removed for forming.

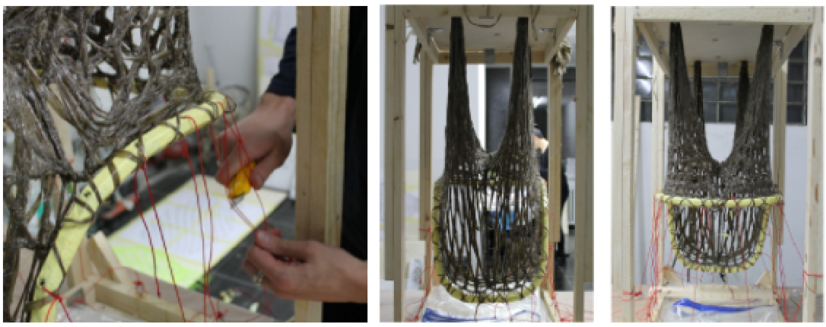

(**a**) (**b**)

Figure 15. Vacuum resin infusion (**a**) Prior to resin infusion. (**b**) After resin infusion.

2.4.5. Forming

The forming process relies only on tension and a reusable boundary frame. It is a physical representation of the same gravity-based form-finding process used to generate the initial geometry. The frame was constructed of standard lumber with a removable top plate where the “feet” of the chair are attached. Future frames could be built from adjustable metal components such as Bosch profiles, improving its stiffness and versatility. The reusable seat frame described in Section 2.3.1 allows the chair to be tensioned evenly and ensures the final seat shape with no unwanted deformations in the lace.

Once the chair has been hung by the feet from the removable top plate, the seat frame is lashed with flax fibre to the chair, maintaining a distance of 5–7 mm from the reinforced seat edge so it can be safely removed after curing. Strings are tied through each hole in the seat frame and tensioned to the larger wooden frame with sliding knots (Figure 16).



(**a**) (**b**)

Figure 16. Forming (**a**) Tension strings being attached to the seat frame. (**b**) The prototype in the reusable frame curing at room temperature.

2.4.6. Assembly

After a suitable curing time of 48 h at room temperature, the chair is removed from the frame, first by untying the tensioning strings, and then by removing the top plate. Both the seat frame and the boundary frame can be reused. Excess fibres are then cut from the feet and the chair is leveled. In the meantime, a seat surface is laced using 2 mm polyester (PES) thread and lashed to the cured flax fibre chair as a soft surface for sitting (Figure 17).

(**a**) (**b**)

Figure 17. Assembly (**a**) Attaching the laced seat to the cured chair with a lashing. (**b**) Detail of the seat connection.

3. Results

The final prototype is a tailored lace chair capable of holding the weight of an average adult (80 kg). It demonstrates a proof-of-concept workflow using bobbin lace and digital methods outlined above. The main body of the chair is made of natural fibre-reinforced polymer, consisting of the same TEX1000 flax rovings and epoxy resin with a 1-to-2 resin-to-hardener ratio as specified in Section 2.2.1. A tensioned lace fabric made from 2 mm polyester (PES) strings is connected to the top edge of the NFRP frame to act as a seat and provide comfortable contact with the user.

3.1. Integrated Workflow

First, the global geometry is modelled using Kangaroo Physics to simulate effects of hanging in the moldless forming process [21]. A lace pattern is then parametrically applied to the global form. Calibrated with empirical structural test results, Karamba analysis allows designers to make an informed decision on pattern type and density based on the amount of deformation, material usage, and labour intensity required for the given design load [20]. A secondary topological analysis is then performed on the form-found shell, to identify optimal locations for placing reinforcement material. Finally, the reinforced pattern is unrolled into a 2D template for fabrication (Video S1).

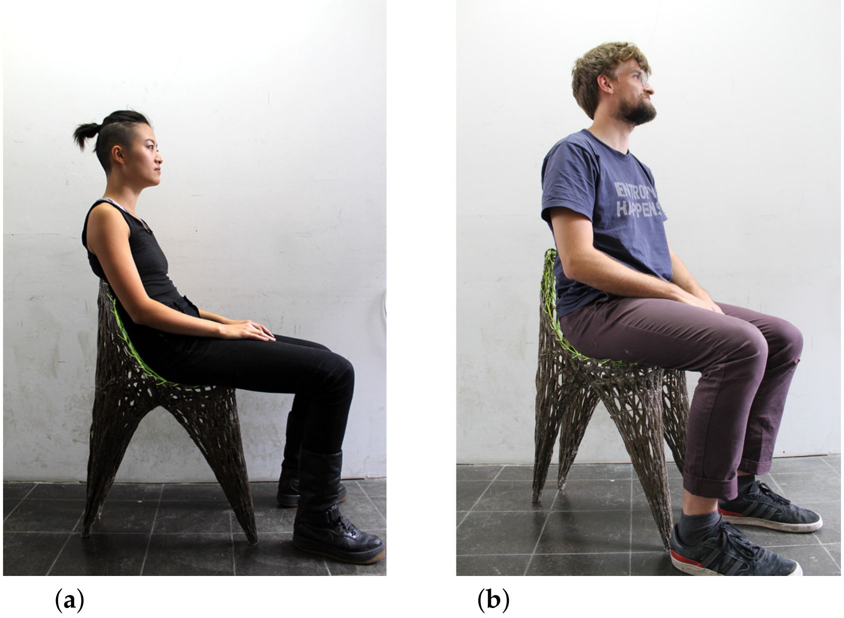
3.2. Demonstrator

The tailored lace chair prototype uses 583 g of flax fibres and 797 g of resin, weighing a total of 1.38 kg (Figure 18). The total production time is 20 h (excluding curing time), in which the lacing process accounts for 16 h. This process is very labour-intensive, which prompted a follow-up investigation on a faster, more automated fibre placement technique.

3.3. Performance

The load-bearing behaviour of the handmade lace chair was tested in a non-destructive seating test where users of varying weights sat on the chair and the deflection in the legs was measured (Figure 19). The geometry of the chair feet was documented prior to sitting, during sitting, and once again after sitting to determine how much the chair deflects under load, and whether the behaviour is elastic (Figure 20).

Figure 18. Final Chair Prototype.



(**a**) (**b**)

Figure 19. Proof of concept: chair can hold an adult with minimal deflection. (**a**) 56 kg user (**b**) 85 kg user.

(**a**) (**b**)

Figure 20. Non-destructive sitting test (**a**) Sitting test preview (**b**) Displacement diagram of chair feet: Dashed lines represent geometry under no load. Solid lines represent geometry under load.

The chair proved more than capable of supporting users with weights up to 85 kg. Prior to sitting the span between front and rear legs is 50.5 cm (Figure 21) and after sitting the span is 54.5 cm (Figure 22) resulting in a deflection of 4 cm. It is important to note that most of this longitudinal deflection occurred in the rear legs. Each rear leg also deflected laterally inwards by 1.5 cm. In both loading scenarios, the chair deflected the same amount irrespective of the user weight. After removing the load, the chair returned to its original geometry, indicating only elastic deformations. This behaviour led to the hypothesis that the chair can support greater loads than 85 kg, but this would need to be verified through a destructive test once a greater number of prototypes are produced.

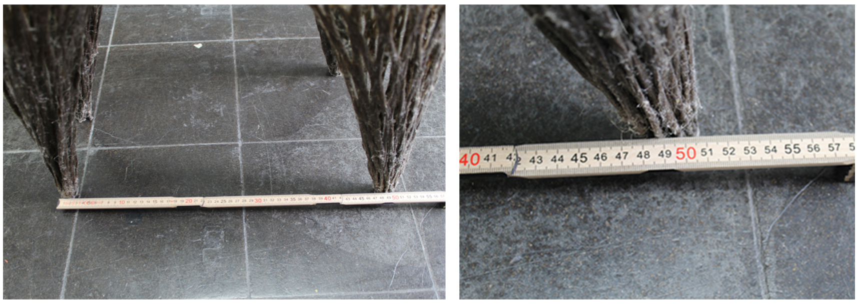


Figure 21. Sitting test measurements before sitting 50.5 cm span.

Figure 22. Sitting test measurements after sitting 54.5 cm span.

4. Outlook

The labour intense manual process of realisation of the 1:1 bobbin laced demonstrator encourages further investigations of possible ways for its automation. One possible solution is the reconstruction of fibre layout using Tailored Fibre Placement (TFP). TFP is an embroidery technique in which rovings are stitched to a membrane in a continuous process in a 2D environment (Figure 23). Fibre path placement can recreate complex curve patterns from a digital file. Consequently, in this workflow desired structural performance of a composite element can be translated to specific fibre paths. TFP was developed for fabrication of complex preforms from carbon fibre rovings for applications in aircraft and automotive industry. However, the potential of adapting the technology to fabrication of building elements from natural fibres is currently being researched [8,16,23].

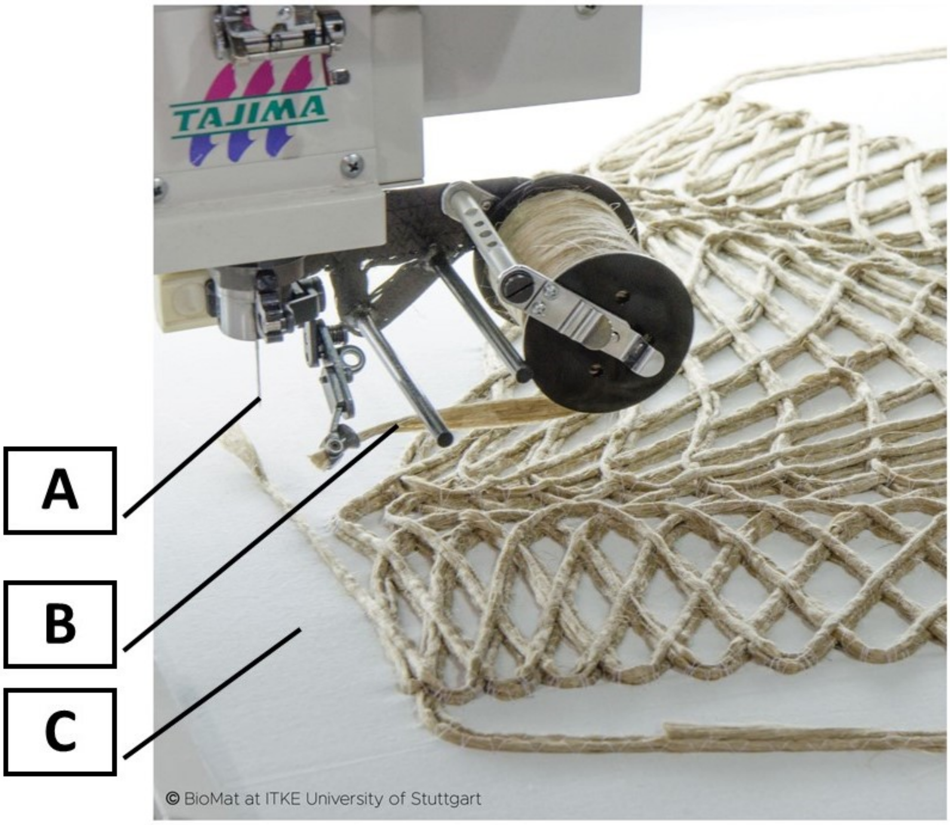


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Figure 23. TFP machine layout. (**A**) Embroidery Needle (**B**) Flax Fibre (**C**) Glass fibre membrane.

In the considered scenario, TFP would be used for fabrication of preforms from non-twisted TEX1000 flax rovings, attached to a glass fibre membrane with a cotton thread. In such preforms only the flax fibres would play a load-bearing function in a later laminated bio-composite element.

An initial TFP chair was produced from preforms with a single layer of TEX1000 flax fibre rovings to determine the production workflow. The unrolled pattern is adjusted to work with the continuous fibre path requirement and uploaded to the machine as CAD files (Figure 24). The final chair weighs 0.95 kg in total, including 256 g of dry flax TFP preforms (Figure 25).

The geometry of the bobbin laced chair was successfully reconstructed with a high level of precision and the TFP prototype demonstrated the capacity to support a 55 kg user. Additionally, the initial experiments exposed several limitations of TFP process in comparison to bobbin lacing, which must be taken into consideration in future work (Figure 26).

i Maximum preform size: The maximum size of a single preform produced is limited by the size of the machine working area. In case of the Tajima TFP machine, which was used in the experiment, it required discretization of the chair design into preforms of max. 70 × 70 cm. The individual pieces were later stitched together and hung on the frame.

ii Fibre interactions: TFP specimens lack the unique fibre–fibre interactions in bobbin lace. Manually laced pieces allow fibre movement at each node, giving the global pattern freedom to deform when it is stretched. In the hanging process, this means the nodes can slip and hinge to "find" a suitable form. However, in TFP, fibres are layered on top of each other and fixed with cotton threads, constraining the angle between conjoining fibres. This change in the mechanism of fibre interaction adversely affects forming by constraining movement at the lace nodes. Fibres are prevented from self-adjusting, resulting in a less natural global form. A more deformable, knitted membrane material could be used to compensate for this effect, which might allow the geometry to find its natural equilibrium shape when hung. This can be verified in the future through physical testing.

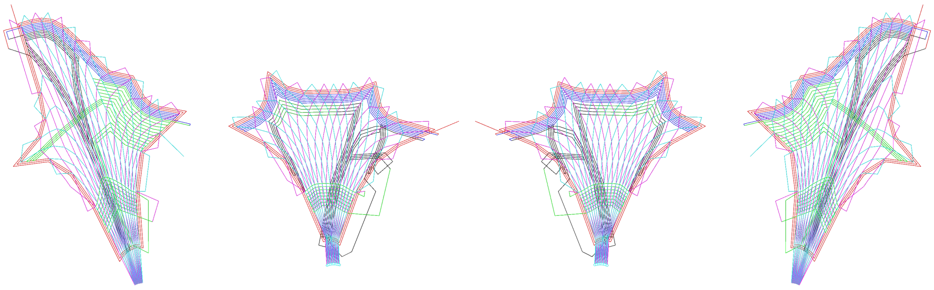

Figure 24. CAD drawings of unrolled geometries for TFP production. One for each leg in the chair.

Figure 25. Second prototype fabricated with automated Tailored Fibre Placement (TFP) machine.

Figure 26. Two prototypes (From left to right: Prototype fabricated with automated TFP machine, Tailored lace prototype fabricated by traditional bobbin lace methods).

In future work, prototypes with comparable fibre weight as the hand-laced chair will be tested, to allow a better understanding on the structural effects of fibre–fibre interaction and propose strategies for reinforcement.

5. Discussion

The project proposes a novel moldless NFRP manufacturing technique for surface-based structures, and demonstrates its feasibility in achieving tailored performance through the design and fabrication of a chair prototype (Figure 27). By extending a traditional craft using digital methods, the project arrives at a system with greater material efficiency, geometric control, and range of application compared to traditional techniques.

The computational workflow incorporates simulation of the moldless hanging process and parametric pattern application, which makes designing with this system more accessible. The reinforcement strategy can be improved and further automated to streamline the design process. The flax material is uniquely suited to manual working, compared to glass and carbon fibres. However, epoxy resin is still a petrol-based, allergenic substance, which can be replaced with bio-resins in the future.

The project also established rough structural benchmarks of laced patterns and used the results to inform the computational design process. However, due to variability of handmade artefacts and the simple support conditions used in the tests, more thorough testing and structural studies are necessary to accurately determine the load-bearing capacity of lace patterns.

When applied to an architectural scale, the proposed system can create surface-active components, such as hollow NFRP tubes for modular structures or segmented shells. To scale up the production process, fibres could be laid automatically using Tailored Fibre Placement with further explorations on the substrate material. After the pieces are stitched together and infused with resin, the final form could be hung as described earlier, or be held by pneumatic molds during curing. Recent examples, such as the livMatS Pavilion, is an excellent example showcasing the potential for large-scale architectural structures made from natural fibres [7].

The extrapolation of principles from a traditional craft process laid the foundation for a novel approach to natural fibre-reinforced polymers. In future work, the authors aim to extend the 2.5D logic proposed in this paper, and investigate a truly three-dimensional method for fibre arrangement to achieve performative spatial artefacts. A fabrication approach based on mobile robots is also currently under study by the authors.

Figure 27. Tailored Lace chair prototype. Lightweight demonstration.

Supplementary Materials: The following are available online at https://youtu.be/hf617_hTAVI, Video S1: Project Video.

Author Contributions: A.L., C.T. and X.Y. contributed equally to this paper. Conceptualization, design, methods, presentation, prototyping and testing, as well as writing of this paper, was done by A.L., C.T. and X.Y. together. H.D. (BioMat Department director) and P.B. (BioMat research associate) gave the students prerequisite knowledge in the field of biocomposites and sustainable architectural building elements and supervised the education course Material Matter Lab (Material and Structure, winter semester 2020/2021), in which the prototypes were produced. P.B. edited the paper. All authors have read and agreed to the published version of the manuscript.

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