Design of Lightweight Fibrous Shells by the Use of Knitting Patterns

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The increasing environmental concerns have brought attention to the circularity of materials used in the construction sector. Fibre-reinforced lightweight structures have emerged as a potential solution to this issue, offering opportunities for bio-degradable materials, sustainable production techniques, and cost-effective alternatives to traditional building materials. This research aims to explore possibilities of fibre-reinforced lightweight structures and propose a design process by the use of traditional bobbin lace production methods for orienting fibres. The research workflow consists of four steps. In the first step, the most frequently used knitting methods such as torchon, tulle, and knitting ground patterns, including engelche, rose, square, diamond, triangular, and hexagonal ones are determined. Second step is based on a form-finding process for the shell performed in an algorithmic modelling environment. In the third step, structural performance simulations are undertaken for the shell structures that are specified for the boundary conditions and for different material utilization scenarios. The last step is prototyping and physical modelling process. Case studies were undertaken to test the methodology, and the outputs were compared. The results underlined that materials, such as cotton and flax, obtained advantages compared to the synthetic ones, such as polyester, in terms of their behaviour. Thus, the lightweight structures that are produced by the principles of knitting patterns can demonstrate possibilities for the utilization of natural materials while minimizing the quantity of materials employed.

Keywords: *Lightweight Structures, Natural Fibres, Computational Design, Structural Performance, Knitting Pattern*

INTRODUCTION

Since the development of humans in history, our understanding of production and consumption have been harmful to the natural environment. The construction sector is among the most critical industries that cause this damage by shaping the built environment. Cement use, which can be credited as a pioneer to the materials commonly utilized in the industry, provides 8% of the total carbon dioxide manufacture while the construction sector accounts for 36% of global energy use (Lehne, J., & Preston, F., 2018). The increasing environmental concerns have brought attention to the circularity of materials used in the construction sector. Fibre-reinforced lightweight structures have emerged as a potential solution to this issue, offering opportunities for bio-degradable materials, sustainable production techniques, and cost-effective alternatives to traditional building materials.

In nature, there are load-bearing structures based on fibre materials. The anisotropic behaviour of these materials reduces the amount of material used in the structures. Also, they allow to organize the system based on the defined stress directions and the needs (Reichert et al., 2014). Fibre-reinforced structures have many advantages, such as a high strength-to-weight ratio, durability, and bending strength. These factors are used in the solutions of potential problems (Lehrecke et al., 2021).

Significant amount of research has been done on this subject, including glass and carbon fibre organizations implemented to the architectural design solutions. For example, Buga Fiber Pavillion, ICD/ITKE Research Pavilion 2015, and ICD/ITKE Research Pavilion 2017 (Gil Pérez et al., 2020; Dörstelmann et al., 2015; Solly, J. et al., 2018).Despite the experimental studies carried out for more than a decade, the implementation of fibre-reinforced structures in architecture are still not widespread.

This research aims to propose a method that could be widely used as a replacement to the specialized design and fabrication processes. Therefore, a traditional knitting method, driven by bobbin lace, is explored for the design process, in which lace allows to generate fibre orientations by repeating basic operations. Methods for form-finding and production are also investigated. Material organization is generated by applying repetitive rules. Then, it is combined with a polymer to increase its strength. Shell structures are used to compare the different rules and patterns that the bobbin lace method provides. Producing lightweight structures would potentially reduce the use of materials in building construction. It is also critical to explore the potential use of natural fibres, more specifically biodegradable materials. Their potentials for usage in the production of lightweight structures have been investigated as a part of this study.

Production methods for fibre-reinforced polymer(FRP)

Hand Lay-Up, Filament Winding, Pultrusion, Resin Transfer Molding (RTM), Compression Molding, and Injection Molding are some of the techniques used to manufacture FRP-based composites (Eltoukhy, E., 2013). Hand lay-up is the most basic method of producing FRP composites. It involves manually placing layers of fibres and polymer matrix on a mold and then curing the composite under heat and pressure. Filament winding is used to produce FRP composites in the shape of tubes and pipes. Fibres are wound onto a rotating mandrel, and then coated with polymer resin. Pultrusion is a continuous process that produces FRP composites in the form of profiles and shapes. Fibres are pulled through a resin bath and then cured under heat and pressure. RTM method involves injecting resin into a preform made of fibres, that is placed in a mold. The composite is then cured under heat and pressure. In compression molding method, fibres and resin are placed in a mold and then compressed to form the composite. In injection molding method, fibres are pre-impregnated with resin and then injected into a mold. The composite is then cured under heat and pressure (Eltoukhy, E., 2013).

These methods of manufacturing exhibit similarity since they generally use molds that obtain an advantage in terms of shaping the FRP composites. The disadvantages may be based on an increase of the costs and material usage, as well as production of waste. Additionally, molded production may constrain the formal variation of the outputs, even if the molds can be used multiple times in the production process.

Natural fibres

FRPs are made from high strength fibres such as glass and carbon in their current structural use as materials. Recent research has shown that Natural Fibre Reinforced Polymers (NFRPs) can be replaced by these fibres (Humphreys, M., 2003). Natural fibres show similar mechanical properties to other synthetic fibres. They can be classified as animalbased, plant-based, and mineral-based (Lehrecke et al., 2021). Considering the production conditions and costs, the use of plant-based fibres is seen as a more rational solution. However, there can be significant differences between plant fibres as selection criterion, including production process, plant growth, harvest, fibre extraction, and supply (Yan, L., Chouw, N., & Jayaraman, K., 2014). Flax fibre accounts for more than half of all natural fibres utilized in the automobile sector. (Miao, M., & Finn, N., 2008). Flax fibre becomes preferable to other plant-based fibres due to its ease of production, easy regional availability, the amount of CO2 consumed during production, and its mechanical properties.

METHODOLOGY

The research workflow consists of four steps. In the first step, the most frequently used knitting techniques and knitting ground patterns are determined.

The second step is based on form-finding process, which is performed by using the Kangaroo add-on in the Grasshopper (GH) algorithmic modelling environment towards the form-finding of the shell, shaped by its own weight. In the third step, the Karamba3D structural performance simulation add-on is used for the selection of materials and undertaking the load-bearing tests that are applied to the shell.

The last step is the prototyping of the shell structure by using a 3D printer and testing the knitting patterns by physical modelling. Three case studies were undertaken to test the methodology.

Traditional lace-oriented fibres

Within the scope of research, the traditional bobbin lace, a knitting technique, is determined for orienting fibres. The bobbin lace method offers a wide range of production options due to its easily adaptable production sequences and versatility of application. In addition, it permits the use of fibres made from various materials.

The fibres are wound and thus oriented on the bobbins. There are three types of operations in the bobbin lace production technique, which are twist (T), cross (C), and pin (P) (Whiting, G., 1920). It is possible to produce different types of knits by changing the order and number of these operations. The fibres are superimposed on each other by twist and cross, and the pin holds the fibres to the ground with the help of a stabilizer (Figure 1). The pattern that was determined first is fixed to the pillow. Then, knit is produced by applying operation sequences in accordance with the chosen production technique.

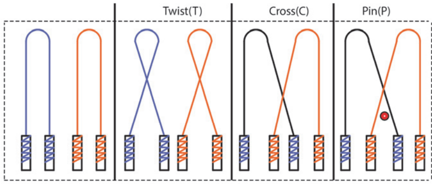


Figure 1
Knitting operation sequence adapted from (Whiting, G., 1920)

Form-finding process

Shell structures are chosen for the study to implement the 2D patterns since shells are able to create lightweight and optimized structures as well as high-strength structures. The geometry is initially generated at Kangaroo GH as a 2D surface with specified shell dimensions. In order to create the 3D shell geometry, it is necessary to apply forces to the surface so that the optimal form is found. The forces applied to the surface can either be gravity or user-specified values. Following that, support points that will not be affected by the forces are identified. Then, the 2D surface is converted into a 3D shell volume affected by the forces.

The knitting patterns are modelled in the digital environment, and they are converted to the shell form as 2D patterns, excluding their physical behaviour such as knit joints, to simplify the simulation process. These analyses are supported by the prototyping processes, in which the behaviour of the systems can be observed in the physical environment by actual forces, such as the gravity.

Structural performance analyses

The knitted shell forms are subjected to structural performance analyses. Then the results are evaluated. Karamba3D add-on, based on Finite Element Method (FEM) at GH is used for material utilization and load bearing tests.

To perform FEM performance analysis, the material type, architectural geometry, supports, loads, and geometry must be specified. The knit patterns on the shell are considered as beams in the Karamba environment. There is a correlation between the amount of material used to construct the structure and the length of the beams. Due to the nature of designing a lightweight shell, the amount of material utilized is equally as crucial as the load resistance. The force applied during structural analysis testing is perpendicular to the surface. Using various materials, structural analysis tests demonstrate whether a knitting pattern can be used to create an architectural shell or provide a comparison between knitting patterns. As a part of the structural analysis, Steel.S235, Concrete.C20/25, Wood(WH)I materials are chosen as commonly used building materials, provided from the GH Karamba material library. Additionally, carbon fibre reinforced polymer (CFRP), of which mechanical properties are manually introduced to the Karamba material library, is utilized in the FEM simulations. So that a comparison can be undertaken between widely used building materials and a fibre-reinforced material.

Prototyping

Initially, different types of shell structures are used as molds that are scaled and 3D printed by use of PLA material for the prototyping process. Following this, the knitting pattern is prepared by analogue modelling and by using the selected knitting technique. The knit, which is impregnated with epoxy resin, is stretched over the PLA shell later on. Following the drying process, the knit is detached from the shell, and the behaviour of the physical model is observed.

CASE STUDIES

In order to validate the methodology, three case studies were carried out. The primary objective of the first case study was to investigate the mechanical properties of the knitted surfaces and how they are affected by different knitting techniques. The second case study was used to evaluate the consequences of using natural and synthetic fibres. The third case study was an initial examination for the combination of different fibres at various scales to investigate the scalability issue.

Traditional lace-oriented fibres

The most common knitting techniques—torchon and tulle—as well as the most common knitting ground patterns—engelche, rose, square, diamond, triangular, and hexagonal—were determined (Figure 2). Tulle and torchon contain five production sequences, which are T.T.T.C.P. (per node) and T.C.P.T.C. (per node), respectively (Whiting, G., 1920).

Figure 2
Pattern and nodes

Form-finding process

A shell structure, of which dimensions were 10x15xh:5m, was developed through the form-finding process. The shell was stabilized by the support points chosen by the user and formed under its own weight. Vaults and consoles were the components that formed the structure. As a result, shell resistance to forces acting in both the compressive and tensile directions were observed (Figure 3).

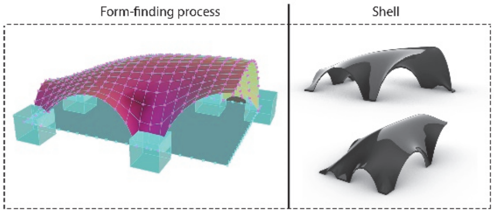


Figure 3
Form-finding process and outputs

Patterns that were commonly used as grounds in the bobbin lace knitting technique were identified.

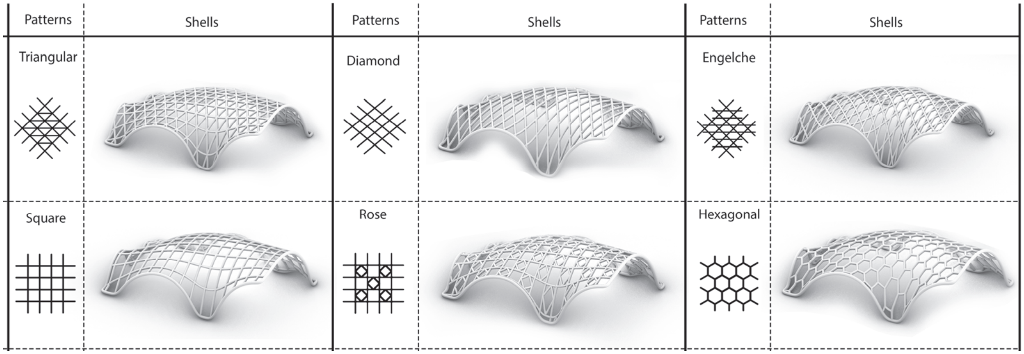


Figure 4
Selected 2D patterns and shells with assigned 2D patterns.

These patterns were then implemented to the shell (Figure 4).

Structural performance simulation

Structural performance analysis was performed on six different knitting patterns implemented to the shell geometry, as seen in Figure 4. In the Karamba3D environment, patterns were converted to beams, and then a force was applied to the shells in the direction of gravity. Four different materials were analyzed to compare the results. Steel.S235, Concrete.C20/25, and Wood.(VH)I materials were chosen from the material library of the Karamba3D add-on.

The fourth material was CFRP, of which mechanical properties were manually entered into the Karamba environment. In-plane shear modulus, elasticity modulus, transverse shear modulus, specific weight, and yield strength were the critical material properties for the evaluation. Even though CFRP is an anisotropic material, the material was defined as being isotropic in order to simplify the model (Mota, M. I. P. F., 2020).

Maximum Displacement(cm) and Elastic Energy(kNm) were employed as evaluation criteria following the analysis. Maximum displacement indicates the magnitude of the form's displacement under the force relative to its initial state. The energy stored in a deformed system is elastic energy. In other words, when comparing two structural systems with the same loading conditions, a structure with less elastic energy is equivalent to a structure with more rigidity (Figure 5).

It was observed that the triangular pattern obtained the highest strength. However, they also needed the largest amount of materials. It was concluded that the square pattern had the least amount of strength and material. The triangular pattern used 343.51m, while the engelche pattern used 348.09m material. In accordance with the maximum displacement values for CFRP material, the triangular was deformed by 10.73 cm and the engelche by 24.04 cm. Although these patterns utilized similar amounts of material, the triangular pattern demonstrated more than twice the strength of the engelche pattern.

Material	Pattern Length(m) Diamond (245,94)	Triangular (343,51)	Hexagonal (256,54)	Square (226,04)	Rose (348,97)	Engelche (348,09)
Steel.S235	46.64	10.56	39.47	57.12	16.49	24.13
Concrete C20/25	322.81	73.23	271.74	395.97	113.81	166.49
Wood.(WH)I	947.61	214.24	808.28	1157.79	336.41	492.22
CFRP	46.27	10.73	39.41	56.72	16.80	24.04
						Max.Displacement(cm)

Material	Pattern Length(m) Diamond (245,94)	Triangular (343,51)	Hexagonal (256,54)	Square (226,04)	Rose (348,97)	Engelche (348,09)
Steel.S235	25.70	5.98	18.16	25.11	9.89	9.91
Concrete C20/25	178.84	41.74	126.24	174.90	68.83	69.07
Wood.(WH)I	518.37	120.14	367.12	505.56	199.54	199.79
CFRP	24.75	5.68	17.85	23.68	9.57	9.23
						Elastic Energy(kNm)

Figure 5
Comparison of structural performance analyses results

Pattern	Length(m)	Max.Displacement(m) (CFRP)	Strength Ratio 100/MaxDisplacement.Length
Diamond	245,94	0.4627	0.8787
Triangular	343,51	0.1073	2.713
Hexagonal	256,54	0.3941	0.9890
Square	226,04	0.5672	0.78
Rose	348,97	0.1680	1.7057
Engelche	348,09	0.2404	1.195

Figure 6
Strength ratio table (100/MaxDisp.length)

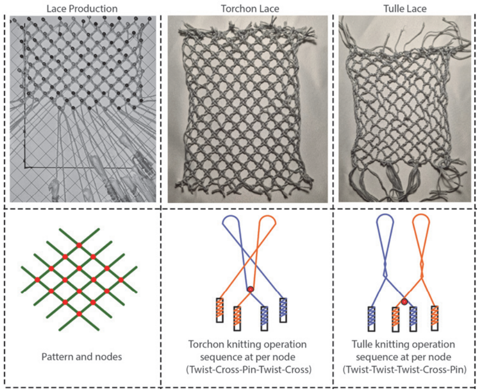


Figure 7
Lace production

A formula has been developed to establish a relationship between material usage and strength (100/MaxDisplacement.length). A comparison was made using the analysis data obtained after the test with a constant material. By evaluating the collected data, it was revealed that the triangular pattern, in which the most material was consumed, produced the best outcomes for this formulation. In addition, the rose pattern revealed a better result in this ratio when compared to the engelche pattern, which employed about the same amount of material (Figure 6).

Prototype I

In the first prototype, knits were produced by applying torchon (T.C.P.T.C.) and tulle (T.T.T.C.P.) knitting techniques to the square pattern. Because of its ease of manufacture, square pattern was chosen. The knits are made of cotton fibre (Figure 7).

The weights of the torchon and tulle knits produced with cotton fibre and the closed shell form produced with PLA were measured and compared. Also, the amount of resin absorption changed as the knitting type changed. The knit produced with the torchon technique was 4gr at the beginning and 18gr after absorbing the resin, an increase of 14gr. Knit produced with the tulle technique has reached to 23gr. Tulle's initial weight was 5gr with an 18gr increase. The weight of the fully closed shell created by 3D printing with PLA was 32gr.

After drying, it was removed from the mold and put through load-bearing tests (Figure 8). Tulle and Torchon, two shells, are anchored to the ground. They were initially subjected to a 2500gr load for 24 hours, but no deformation was found in either shell. Following that, a 24-hour test with a 3500gr load was performed. Following this test, distortions and torsions were discovered in the shell form created by the torchon knitting technique. While there was a change in the shell form, the shell height, initially recorded at 5 cm, was observed to be 4 cm. However, no deformation occurred in the tulle shell (Figure 9). The knitting technique made both of the shells lighter than the shell that was completely closed. Tulle exhibited more strength than, torchon although five operations were applied at each point. It is shown that there is a direct relationship between the amount of resin absorbed and the strength. It can be thought that the amount of absorbed resin increases with the increase in the twist process in the knitting structure.

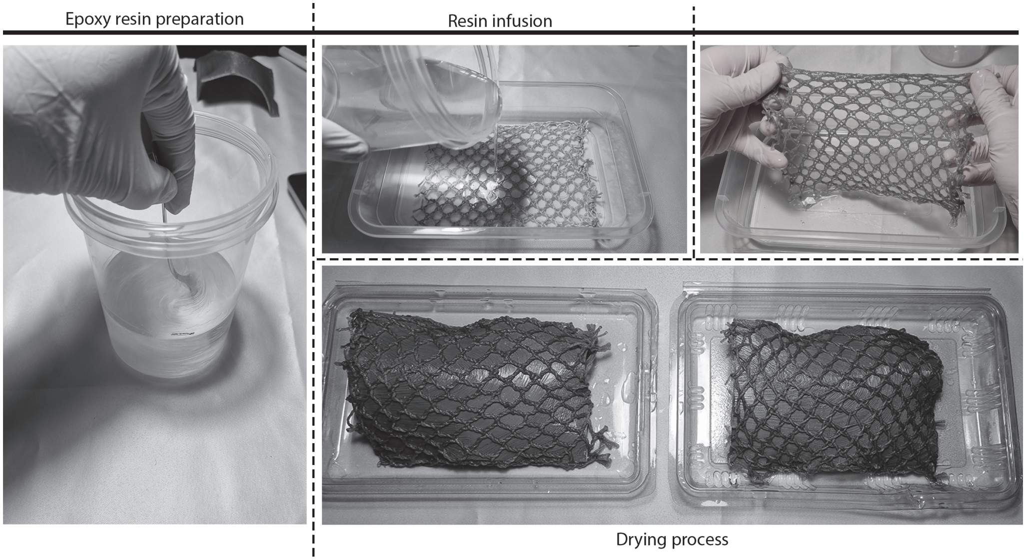


Figure 8
Epoxy resin infusion and drying process

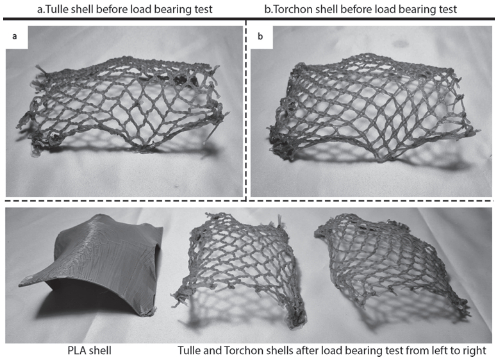
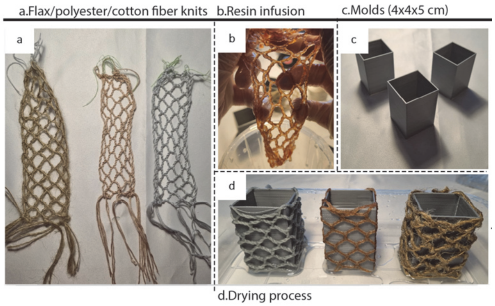


Figure 9
Load bearing test

Figure 10
Prototype II processes

Prototype II

The second prototype investigation seeks to discover how the material used has an impact on strength. Two natural fibres and one synthetic fibre were chosen for this. Whereas selected cotton and flax are examples of natural fibres, polyester is a synthetic fibre. Three different knits were produced using the tulle knitting technique with these three different fibres. Then, at the same rate as the epoxy resin made in the prior case study, a resin containing hardener and epoxy (in a 4:1 ratio) was prepared. The knits were impregnated with resin and dried for 48 hours (Figure 10). The weights before and after resin absorption are as follows: flax 4 gr/19 gr, cotton 1 gr/11 gr, and polyester 1 gr/10 gr. After the drying process, the knits were separated from the molds, and they were subjected to a load test under a 2500 gr weight for 24 hours.



After the load-bearing test, it was observed that the polyester-fibre knit underwent the most deformation. Cotton-fibre knit showed less degradation compared to polyester. No change was observed in flax fibre knit (Figure 11).

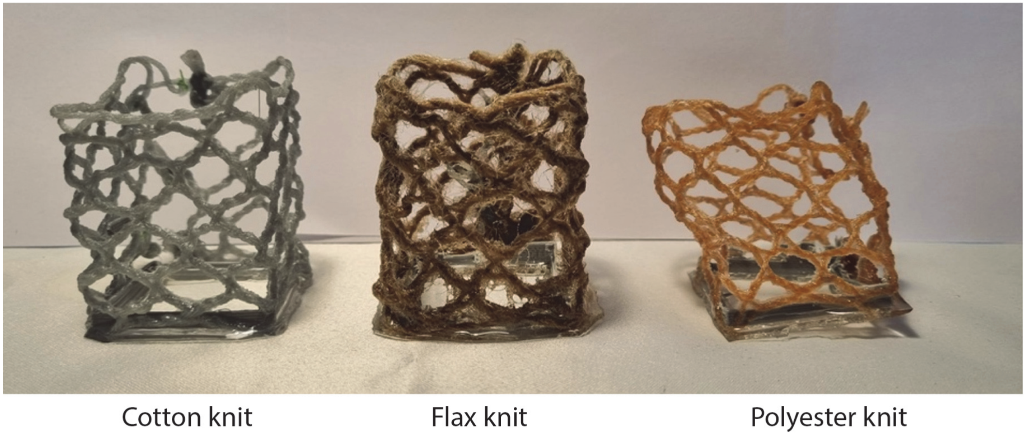


Figure 11
Knits after load bearing test

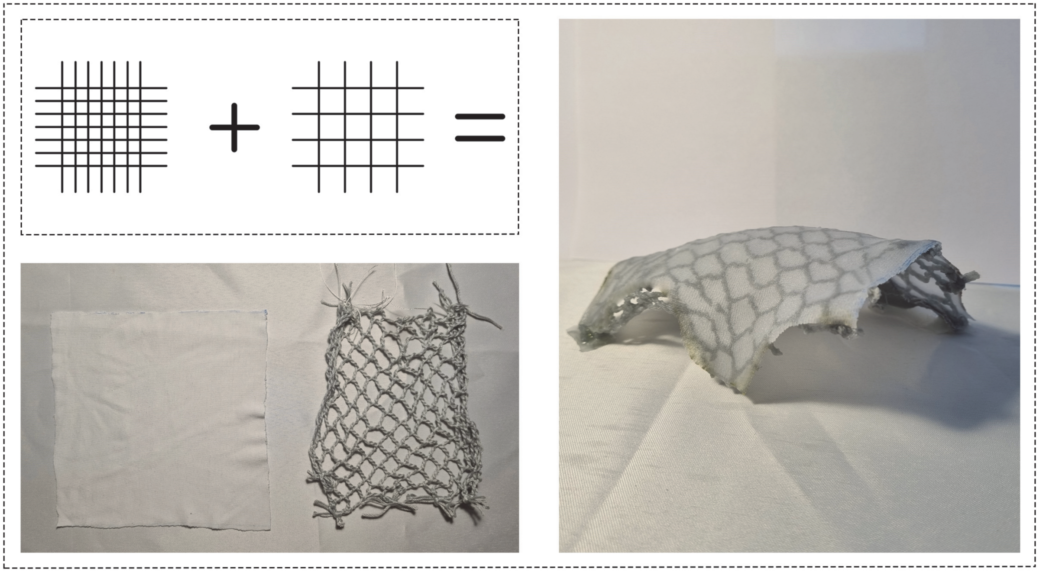


Figure 12
Prototype III, in which knitting patterns at various scales were integrated to the shells structures.

Prototype III

Prototype III was generated as a preliminary study towards the scalability problem. It was produced with the same principles as stated in the previous prototypes. The knitting patterns at various scales were integrated to the shells, which has the potential to produce controllable areas by altering the size of the openings and/or pores (Figure 12). The resulting structural systems are characterized as lightweight due to the porous characteristics of the shells.

CONCLUSIONS

Bobbin lace was chosen for fibre orientation due to its adaptability to various patterns and availability of several knitting techniques. Within the scope of the study, the most efficient patterns and knitting techniques for producing bobbin lace were identified and analysed.

Initially, knitting patterns, which were simplified and transferred to the digital environment, were integrated into the shell form designed during the form-finding phase. Thus, Fem simulations could be performed. In these simulations, patterns were evaluated in terms of material type, amount, and structural performance.

Steel, wood, and concrete, which are regularly used building materials, were compared to CFRP using FEM simulations within the scope of the study. Among these materials, CFRP possessed characteristics similar to steel and outperformed the others. This demonstrated that fibre-reinforced polymers offer structural performance that can be used to substitute traditional building materials. In addition, according to these simulations, the engelche and triangular patterns using approximately the same amount of material showed different strength performances. As a result, the importance of effective use has emerged rather than the amount of material used.

Three prototypes were created to investigate the knits' behavior in the physical environment. The purpose of the first prototype is to compare different knits using the same pattern. The second was produced to compare fiber material types. The third is a prototype that allows for scalability by integrating knits of various scales.

Different knitting techniques used in the same pattern have distinct physical qualities. For the prototype I, two distinct knits were produced: torchon and tulle. At the conclusion of the case study, it was determined that tulle was stronger than torchon. It has been identified that the amount of resin absorbed is directly proportional to the strength. When torchon and tulle production techniques are compared, it is seen that they have similar production processes, but since tulle has more twist (T), it absorbs more resin. Thus, its strength is higher.

The study investigated both the design of lightweight structures and the use of biodegradable materials. In prototype II, physical strength testing was conducted on knits incorporating two natural fibres and one synthetic fibre. Natural fibres have been discovered to be remarkably resilient compared to the synthetic ones.Epoxy resin, a non-biodegradable material, was utilized in prototypes. Although this doesn't overlap fully with the sustainability concept, the search for an alternative binding material, which is also biodegradable will be investigated in future work.

Prototype 3, in which knits of different scales are brought together for the scalability of the produced structures, has the potential for building production with this method at an architectural scale.

Spaces must meet many performance requirements, such as providing optimal temperature, daylight, and minimizing energy use etc.. In addition to the structural behaviour assessments, where various scaled knits have been explored in the simulations, the research possesses future potentials, including environmental performances, such as heat and light control. Thus, in addition to the standardization of the form-finding and production processes, additional performance criteria for creating liveable spaces can be examined.

The research aimed to find a production method that allows for different formal possibilities. While doing this, the research also explored the potentials of the bobbin lace knitting method, which is the traditional production method. In prototype production, the drying of resin-impregnated fibres was carried out on a mold. In future works, mold-free production can be investigated at an architectural scale, in which large-scale knits can be shaped by hanging them from the support points by their own weight, as applied in the form-finding stage performed in the digital environment.

As a result, these lightweight and efficient systems would potentially respond to the growing environmental concerns and shortage of raw materials.

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