Architectural hybrid material composites: computationally enabled techniques to control form generation.

This paper explores the potential for new hybrid composite material applications in Architecture by re-thinking the role of fabrication in the process of form-generation. Our work presents the development of composite materials system consisting of two flexible materials, which, when acting together, allow for variable states of stiffness and gain structural capacity through the process of fabrication. This morphogenetic act occurs at the moment of making as a result of the symbiotic interaction between the two materials, their geometric arrangement and the fabrication process. Our aim is to investigate a novel approach for integrated design, where the fabrication process of a composite material actuates and enhances material performance. Our findings include a formal vocabulary of initial, pre-stretched geometries and their post-stretched counterpart, as well as comparisons between physical experiments and digital simulations of such composites.

Keywords: digital fabrication, 3D printing, parametric design, material computation

Introduction

The way materials naturally respond to need for the construction of efficient structural form is fundamentally different from that seen in most man-made material systems, where material properties driving actuation are often of relatively low priority. Man-made designed objects generally involve the aggregation of many distinct parts and multiple materials, each of which has their own construction logic and oftentimes serves a single function. In contrast, Jeronimidis (2004) observed that '*when studying biological systems, it makes little sense to distinguish between material and structure'*.

Being inspired by such natural processes, our work investigates the generation of a structurally optimised composite material that achieves various properties due to automatically generated curvatures. The material is generated from originally thin flat sheets, that gain desired structural properties through the process of fabrication. In this sense, the material system is not the result of an aggregation of discrete elements but the interaction of the fabrication process, material behaviour and initial geometry.

In continuation to our previous, work on ‘Active Membranes’ (Agkathidis, Berdos, Brown, 2018), this research examines the controlled behaviour of thin sheet material with embossed 2D patterns reacting to forces induced by pre-stretched components. Here, the fabrication processes of the composite system actuate the desired material performance. Our main objective is to embed the process of forming the structure into the material logic and predict /detect the relationship between the embossed pattern geometry and the final shape of the composite panel. Determining the required design and fabrication path is crucial as the formal behaviour of the embossed fibre pattern-textile composite are not straightforwardly predictable. Properties such as the elasticity of base textile, and applied pattern, or the actual geometry, density, width and thickness of the embossed fibres, play an important role in determining the composite panel’s shape as well as its combined component properties. Consequently, our research questions are as follows:

- How can we control and predict the form and performance of hybrid panels composed of semi-flexible, pattern fibres laminated onto a flat elastic membrane?
- How do the material properties of the individual components - the membrane and the fibres - contribute to the properties of the composite material?
- How does the fibre pattern geometry influence the form of the composite hybrid panel?
- How can the approach be integrated effectively with the overall design framework?

The application of the composite panels could be deployed in a range of architectural settings beyond exterior cladding such an interior space division or ceiling panels. While our first small-scale experimentations focused on the use of 3D printing patterns, laminated on lycra textile, our final investigation expanded to embrace larger scale prototypes made out of laser-cut plywood sheets, laminated onto a pre-stretched latex sheet.

Background and Literature

The integration of material, form and performance is evident in many biological systems such as bones in vertebrates, wood branches in trees or arthropod exoskeletons. On the other hand, the major car manufacturing company TOYOTA notes that *'a typical automobile consists of about 30,000 parts and uses different raw materials and different manufacturing processes'* (2017). In contrast, natural systems use very few materials, and their components and morphogenetic processes have been optimized to produce assemblies that serve multiple functions efficiently. In this research, the production of a composite material is realised through interactions between fibre directionality in two simple materials, that together enhance both materials' properties and generate multiple outcomes in terms of structural performance.

Contemporary composite material fabrication often requires the use of expensive formwork, where fabrication process is seen as a means to a final geometric product. However, in the development of the material system presented here, the form-finding approach that has been developed combines the tensile forces in a prestressed membrane with the designed pattern of an applied material to achieve the form naturally. Thus, in this process of making, fabrication of doubly curved form does not depend on formwork but on the computationally designed arrangement of selected materials and geometrical arrangement.

In the work of Oxman and Rosenberg (2007) on Performance-Based Design Computation of materials, a set of experiments is described that involved applying patterns formed by applying resin onto prestressed latex membranes. The technique is comparable to ours. They used intrinsic force simulation applied to mesh typologies as an approach to form-finding. However, they have used different material types, lamination technique as well as different software and hardware. In a similar approach, Narula at al. (2018) describes the 3D printing of a knitted pattern on a pre-stretched knitted fabric, aiming for, as they call it, a 4D textile composite. In this case, both textiles in the 3D printed fibre patterns are of the same material, generating a new double knitted fabric structure. Work reported by Bader at. al (2016) described the issues faced in producing materially heterogenous 3D printed outputs that have a controlled form and behaviour; an issue which has also been addressed in our tests.

In the field of bending behaviour of tensile hybrid structures, the work of Slabbnick at al. (2017) is notable, as they present and analyse typologies of bending-active tensile structures on a larger scale. Bending-active reciprocal structures and their elastic properties in relation to geometry and materiality are also analysed by Brancart at al.(2018), who focus on different types of plywood as the sheet material. However, their research does not include the engagement of a second, laminating, material into their designed systems. In their work on simulation software for bending active structures, Bauer at al. (2018) compares the performance and usefulness of three different Rhinoceros/Grasshopper plugins (Sofistik, Kangaroo and Kiwi3d). Their conclusions were helpful and relevant to our approach, but we sought an improvement on the computational simulations reported by Bauer. We decided to use different simulation software packages (e.g.Karamba and Strand) which had the promise to achieve more reliable simulation predictions of behaviour.

Also in relation to double-curved, composite, prestressed architectural components, the research by Cherif et al. (2013) has helpful parallels. The team has explored composites consisting of fabrics that had been previously CNC knitted, and later stiffened with a thermoplastic laminate. Another case where the base fabric was first created, and that has some similarities with ours in terms of architectural application, is reported by Ahlquist and Menges (2016). They described what they term ‘micro-architectures’, and considered the active performative behaviour of heterogeneous textiles. Interestingly, they used the *intarsia* technique in order to combine two yarns of knitted textiles of different elasticity. The intarsia method for weaving produces fields made up of one of the two different materials that are being woven. The effect is that materials appear to be inlaid into one another. This adds an additional surface texture and appearance dimension to the forms and behaviour possible with the final product.

In their ‘post-forming composite’ research project, Ahlquist et al (2014) were among the first to work with materials that employed pre-stressed textile-based composites. However, they have applied epoxy resin to TRC fabric, which spreads through the entire textile surface, rather than on concentrated linear elements. An alternative to this technique has been described by Baranovskaya et al. (2016). Rather than applying a mechanical force in order to pre-stress the membrane, they developed a pneumatic activation mechanism instead. Inflated fabrics have the potential to provide a lightweight architectural cladding with much better insulation properties than single skin elements, so this is an area with interesting potential.

Our work is particularly directed towards developing a prestressed resilient architectural skin material with surface treatment and properties that potentially enhance both appearance and performance. In the early days of modern fabric structures, two materials were commonly combined to give a composite with symbiotic properties. Typical materials would be PVC coated polyester or PVC coated glass fibre. Commonly, a particular reason for the coating was to increase UV resistance of the ‘structural’ fabric layer, and hence the design life of the architectural skin.

However, more advanced technologies could lead us to the possibilities beyond coatings, enabling the design and production of composites where both the visual appearance and architectural performance (e.g. environmental or structural) can be enhanced using a combination of contemporary design and analysis software augmented by current 3D print technologies. The work undertaken by Blonder (2017) shares some of the same aims. Blonder takes an approach, where folds and pleats are integrated into textiles through the use of fibre reinforced plastic, as a move towards an effective 'Architectural Fibre-Reinforced Plastic Surface Elements'. The material produced is a partial lamination that combines both surface architectural treatments with the necessary structural capacities, such as stiffness.

Of interest in how pattern geometry can be adapted to Gaussian curvature analysis of double curved surfaces is the work of La Magna and Knippers (2017). Furthermore, in their research about possible applications of 3D printing technology on textiles, Kogler et al. (2016) described their findings after testing several flexible, thermoplastic elastomer filaments on different kinds of woven fabrics. However, they have not investigated how geometries of such composites are influenced by different filament patterns. In their paper '3D printing on textiles: Testing of Adhesion' Malenger at al (2018) describe their findings on technical experiments, testing different material combinations, again without investigating formal behaviour of patterns and shapes.

Research in areas outside the Architecture and Construction domain also influenced or work. Both the 'Active shoes' project by Guberan, Clopath and the Self-Assembly Lab (2018) and the 'Active shoes' project. Alongside Zelig's (2018) weaved 3D fabric structures were of particular influence for our work. Even though they do not provide detailed information on the relationship between initial two-dimensional pattern and the final three-dimensional shape, they are highlighting the huge potential such composites could have at different scales and in different industries. It is particularly interesting that in both cases the researchers print the filament directly on the pre-stretched pattern rather than laminating the 3D printed geometry on them.

Finally, the research described by Aldinger at.al. (2018) in the ‘Tailoring Self-Formation’ paper has common ground with our work. However, curvature analysis is used as the main simulation tool. In their material studies carbon fibre rods have been knitted into the fabric, and help to better control the self-formation geometry.

Reviewing the research developments described above confirmed the novelty of our research investigations, as none of the projects presented studied the research problem of developing predictable formal behaviour of a material composite consisting of a pre-stretched membrane and a semi-elastic material (e.g. TPU or plywood).

However, the reviewed work contributed to determine the techniques and materiality chosen for our experiments. The experiments were aimed at addressing the issue of producing components and elements with particular and controllable surface and textural qualities. The particular concern was to deliver doubly curved 3D textile panel components in the form of panels, and to produce them in controlled forms, by applying embossed patterns. Each experiment that we report builds on the knowledge gained through the previous stage.

Methodology

Our current investigations have been carried out through three design experiments using flexible, elastic membranes such as latex and lycra, in tandem with semi-rigid materials; particularly Polypropylene, TPU 95 and plywood sheets. Latex and lycra were selected for their favourable elastic properties and their consequent capacity to store energy when stretched. Both textile materials were used as stressed membranes onto which initial 2D-patterns of ribs in Polypropylene, TPU 95 or plywood were applied as the laminating ribbed mesh. In the case of Polypropylene and TPU 95, the laminating ribs are produced by 3D print technology. The design of the 2D-patterns integrates properties of both isotropic (3D printed plastics and polypropylene) and anisotropic materials (e.g. thin plywood sheets with grain directionality). After being laminated, with the restraints released, the pre-stressed latex and lycra sheets generated doubly curved three-dimensional composite panels (figure 1).

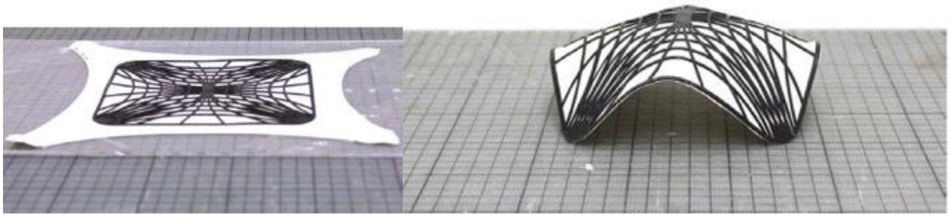


Figure 1: This image illustrates the flat 2d pattern and the resulting 3d geometry after release.

Our research on rib patterning stems from the aim to generate both local and global curvatures in the resulting panel. Global curvature allows the panels to form a structurally efficient overall shape, while local curvature generates additional ‘folding’ stiffness in the shell. For the pattern to generate the doubly-curved surface, the initially flat elements must bend. This bending displacement is generated by the tensile stress in the membrane, which enables the deformed elements to not only bend but inform the interaction with the neighbouring types of patterns. Informed by material organization principles abstracted from biological systems, 2D patterns were generated by establishing parametric relationships between material arrangement and surface curvatures. By using computational tools such as Rhinoceros, Grasshopper and Karamba for design and analysis an algorithm was developed to control 2D patterning and the resultant behaviour of the panel in its three-dimensional state. The primary design parameters used in the pattern generation were: density, rib mesh intervals, frequency, orientation (curve direction) and gradient of transitions. After testing the behaviour on a number of different patterns in combination with the pre-stretched base membrane, our algorithm was refined iteratively, in order to accomplish the design a coherent logic of pattern design with predictable deformations.

To understand, and consequently predict, the outcome and behaviour of stressing the membrane to generate the doubly-curved composite panels, digital computational performance analysis studies were also conducted. Composite panels were simulated and analysed structurally using the Finite Element Method embedded in Strand 7. The computational simulation allowed for the prediction of the behaviour of multiple panels with different prestress levels and different patterning. Feedback loops between the digital simulation and the material experiments led to good control of the geometry and understanding of how interacting parameters affected geometries generated. The overall design and fabrication framework followed in our experiments is shown graphically in figure 2. As a process it can be summarised as follows: Create Digital 3D model of a panel → Development of a geometrical pattern → simulation loop → Fabrication of flattened and embossed pattern → Lamination of the embossed pattern on the pre-stretched membrane → Release of the membrane.

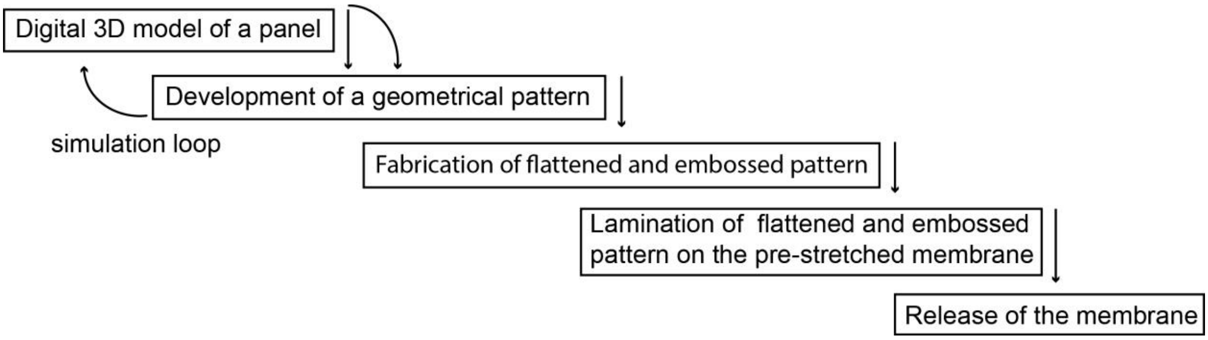


Figure 2: Design and fabrication framework of experiments 1,2 and 3

Throughout the developmental stages, algorithmic design guided the fabrication processes. The series of tests enabled the calibration of multiple working parameters, through multiple iterations to obtain a correlation between predicted form and performance, and the actual product.

The hardware employed in the experiments were Ultimaker 2+ and Ultimaker 3D printers, as well as a Laserscript A0 laser cutter. Finally, we have used a Kuka robotic arm to apply the pre-stress forces to the membrane. Our findings document the investigation into mapping the initial two-dimensional geometries and prediction of the resulting three-dimensional doubly-curved forms. We also reflect on the resulting, partly serendipitous, design process.

Our three experiments were designed to test different aspects of our research questions while being strongly linked to each other. Thus, experiment two builds on the findings of experiment one, and experiment three on the findings of experiment two. Furthermore, complexity and precision gradually increase from experiment one to experiment three, as more tools are being introduced and the scale of the prototype is getting bigger.

In particular, experiment one is highly speculative, trying to understand the generic formal behaviour of linear embossed patterns laminated on pre-stressed textiles, in relation to their density, direction and shape. The knowledge gained helped us to inform our algorithm and our design framework to be applied in the other two experiments. The effectiveness of the algorithm and framework, in terms of a higher degree of control and formal prediction, has been tested in experiment two. Finally, experiment three investigated a larger scale and a different lamination material (plywood) but operates on the same principles developed and tested in the previous two experiments (the same formal behaviour, design algorithm and design framework). In addition, Strand 7 an additional finite element analysis simulation tool was introduced in order to increase the accuracy of formal behaviour prediction.

Experiments

A summary of the structured experimental process was given in the first section of this paper. In the section below, we elaborate on that outline given in the previous section, with a detailed explanation of the experiments undertaken.

Experiment 1

Our first experiment focuses on the fundamental behaviour resulting from the application of a set of one-directional embossed patterns. In particular we intend to detect how variable linear density, linear direction and frame shape could affect the composite panel's shape. To do this we devised a set of seven linear pattern variants: A, B, C, D, E, F, G, H (figure 3) based on the findings reported in our previous paper (Agkathidis, Berdos, Brown, 2018). They were developed in a 2D environment, but with some speculation on the likely 3D result.

All patterns were printed at a thickness of 2 mm using TPU 95 filament. They were laminated on 1 mm thick lycra textile sheets, with a pre-stretch distance of 50mm for a mini-panel of 200mm in original length, in both the X and Y axes. Starting with generally horizontal TPU 95 fibres on the X-axis as shown in patterns A, B, C and D, the framework and the density of the fibres vary as follows: a rectangle (iteration A), partly curved edges (iterations B, C and D) and a rhombus (iteration E). In iteration D the fibres are oriented in the diagonal direction, in iteration F they are applied in a circular array, in iteration H the pattern is generally in a vertical direction.

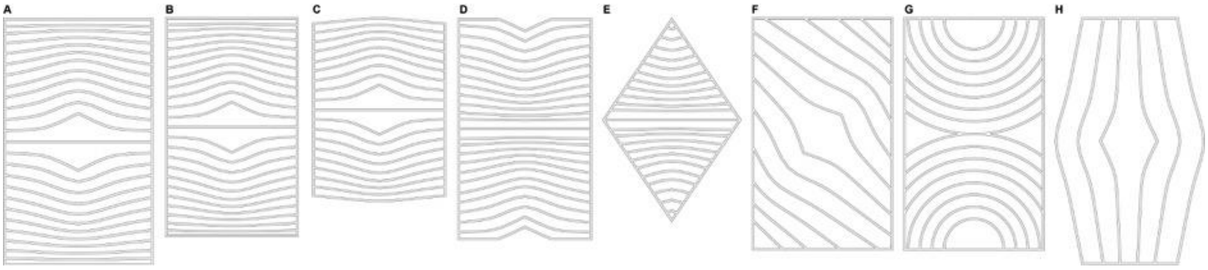


Figure 03: Set of patterns used in experiment 1

Each pattern produces different overall forms with the pre-stress released (figure 04). While components A, B and D curve in a wavelike form, components C and E curve in tubular / paraboloid shape. Component F developed a ‘twist’ in the midsection. Test samples G and H from a ‘compressed’ or a ‘stretched’ shell in its mid section accordingly.

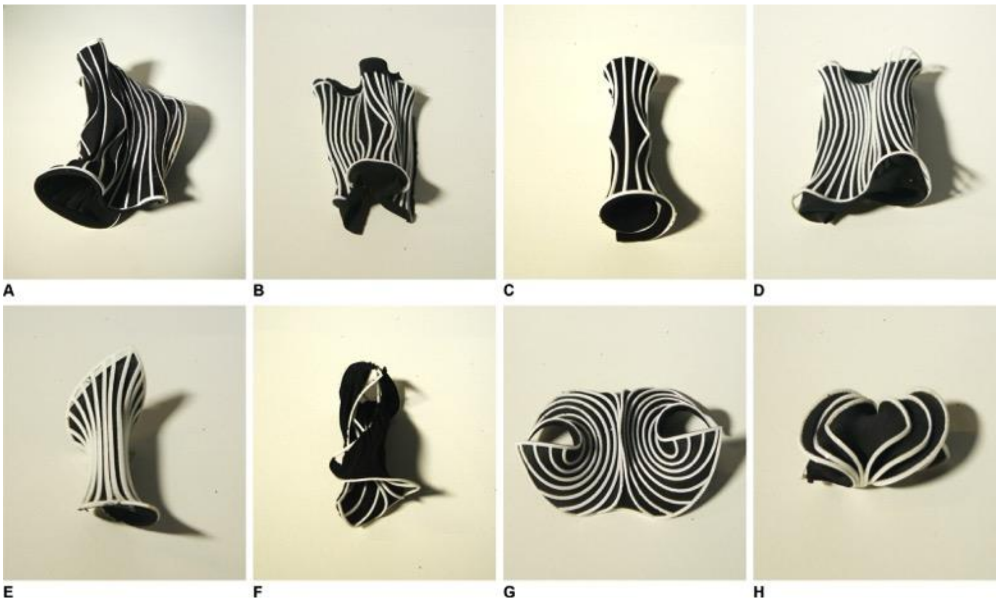


Figure 4: Experiment 1, iterations A-H

These exploratory tests, thus give an indication of the likely resulting 3D forms, given the application of a particular 3D print pattern. The architectural designer therefore now has a broad indication of the likely 3d form that results from the application of a particular 3D print pattern in the laminated panel. Armed with this information a subsequent set of tests could be conducted, in Experiment 2, where the product (the resulting 3D panel shape) can be better pre-determined.

Experiment 2

Our second experiment builds upon the results of experiment one. It was developed in a 3D environment, using Rhinoceros, Grasshopper and the Parametric finite element analysis plug-in plugin Karamba for Grasshopper, which enables visualisation of principal stress lines as explained in our previous paper (Agkathidis, Berdos, Brown, 2018). In particular, the entire design process was as follows. Firstly, a three-dimensional surface was designed in Rhinoceros. Next, by using the Karamba plug-in for Grasshopper and setting four vertices at the corners of the shell surface as anchor points of the structure, the principal stress lines of the surface were extracted. These lines, after being rationalized and simplified, were used as guidelines for the fibre mesh pattern. The process of developing a two-dimensional pattern following the principal stress lines of a surface is indicated in figure 05. In contrast, to experiment 1 where the pattern fibres were printed, this pattern was cut out of 1.8mm thick polypropylene sheets and then laminated onto ready-made, 0.5mm thick latex sheets using Ethyl 2-cyanoacrylate (diphenylmethane diisocyanate glue).

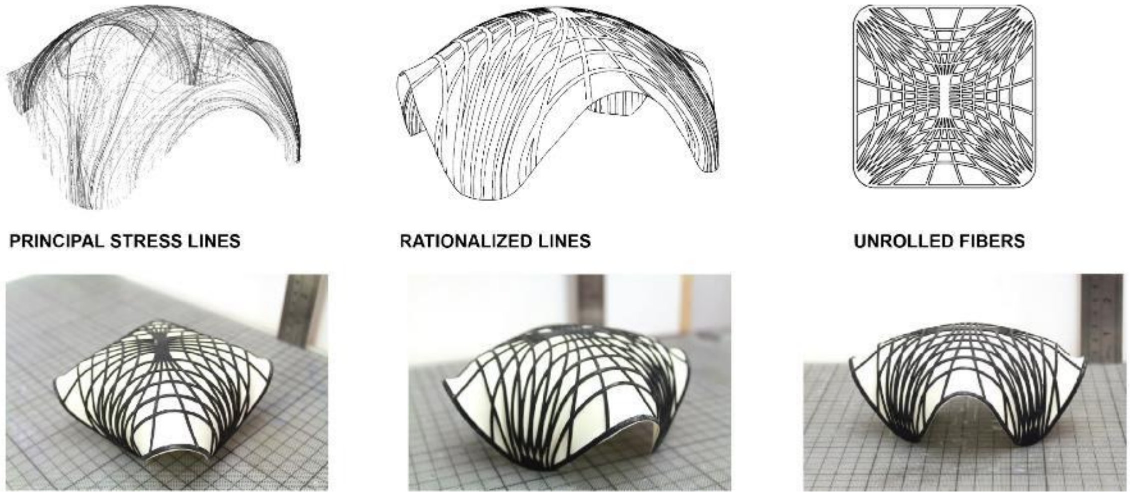


Figure 05: Experiment 2, Iteration I, the pattern follows stress line flow. Predicted form and composite panel are visible.

The pattern’s pre-stress footprint was 190x190mm, the latex sheet dimensions 250x250mm, while the stretching applied on the membrane was 50mm (strain of 20%) to each side. The final result, iteration I, is closely related to the 3D model (figure 5), as the four corners of the membrane, bend downwards, creating a vault-like final composite panel.

Experiment 3

Our third experiment focuses on the fabrication of larger architectural components, fabricated using plywood and latex. It also looks at the improvement of the prediction of the final geometry. In iterations J and K (figure 6) we worked with 300x400mm wide prestressed plywood frame of 4mm thickness. It was applied to a 0.48mm thick latex sheet. The components were stretched to 100% strain.

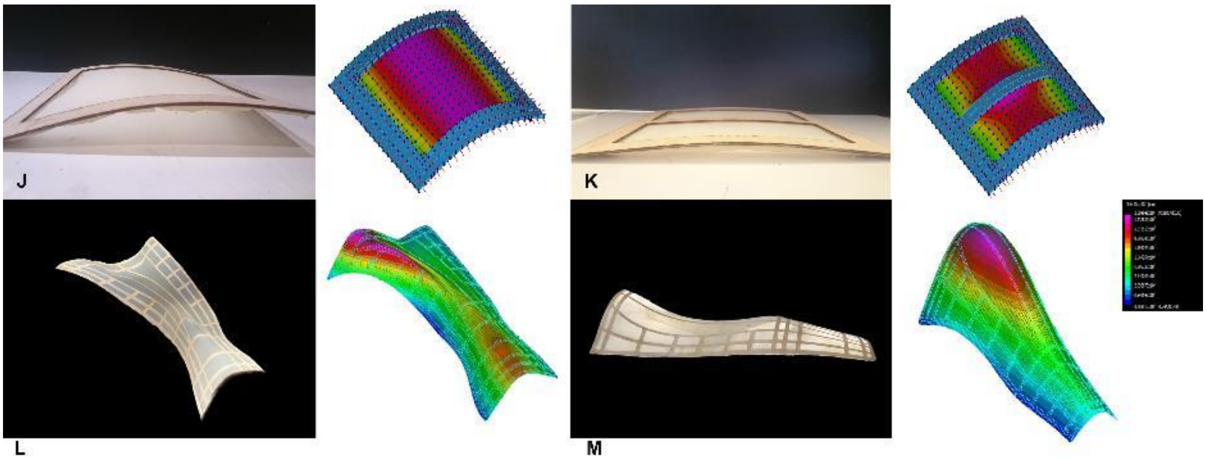


Figure 06: Experiment 3, Iterations J, K, L and M digital and physical tests. Blue indicates lower stressed regions, red and purple high stress

In iterations, L and M, the plywood panel’s initial footprint was 750x1400mm and had a thickness of 4mm. It was laminated on a 0.48mm latex sheet with a prestress footprint of 1x5 metres, which was stretched by 100%. In order to predict the combined material behaviour, we used Strand 7, a finite element analysis tool. Thus, each experiment was conducted firstly in the digital simulation environment of Strand7 and secondly in a physical test.

In order to fabricate and test the performance of the latex-plywood composite panels, a jig was designed where latex sheets were stretched up to 100% of their initial footprint area. Using ropes and naval locks, this jig allowed for differential stretch in both directions. After stretching, diphenylmethane diisocyanate (contact glue based on Polychloroprene) was applied manually to the latex sheet and the patterned plywood panel. Upon setting of the contact glue, the panel was applied to the latex sheet, and the tension in the ropes released. As a result, doubly curved panels describing complex geometries were produced from the originally flat sheet material (figure 7). The Kuka robotic arm was also used in order to apply the stretching force on the jig in a controllable manner for some of the panels. In that way, we could ensure that each of the four edges was stretched on the exact amount and directions as all the others.

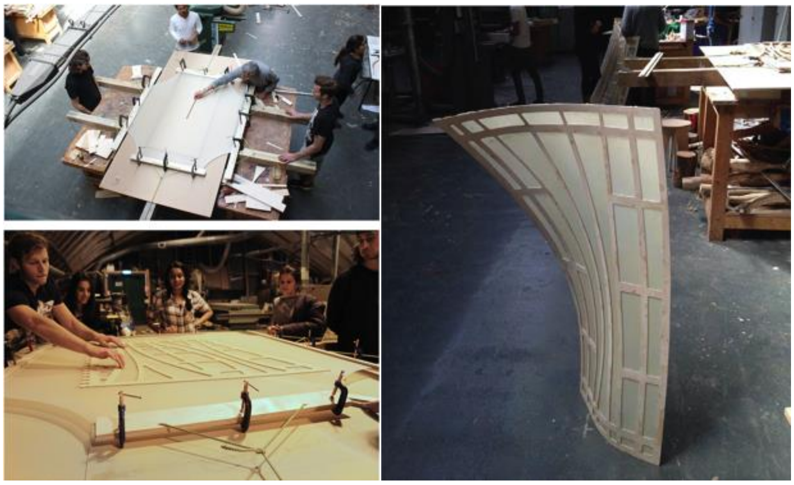


Figure 07: Experiment 3 (physical test), Iteration L

The accuracy of digitally simulated predictions can be compared to actual behaviour as shown in table 1. For the smaller, simpler panels (J and K) the anisotropic behaviour of the plywood appears to dominate, and lead to larger errors. The errors in predicted displacement are 2mm and 2.8mm; i.e. 5.9% and 10.0% errors respectively. For the more complex larger panels the anisotropic behaviour appears to be averaged out and the errors in displacement prediction are smaller in tests L and M, at 8.2mm and 10.3mm respectively; i.e. 1.7% and

5.3% error. The improved accuracy of prediction for these larger and more complex panels is reassuring.

Iteration	Panel Dimensions	Amount of stretching	Max vertical displacement from XY plane (Physical)	Max vertical displacement from XY plane (Digital)	Difference	Error in Persentage
J	300X400mm	100%	34mm	32mm	2mm	5.9%
K	300X400mm	100%	28mm	25.2mm	2.8mm	10.0%
L	750X1400mm	100%	487mm	478.8mm	8.2mm	1.7%
M	750X1400mm	100%	196mm	185.7mm	10.3mm	5.3%

Table 1: Experiment 3, digital and physical test displacement discrepancies

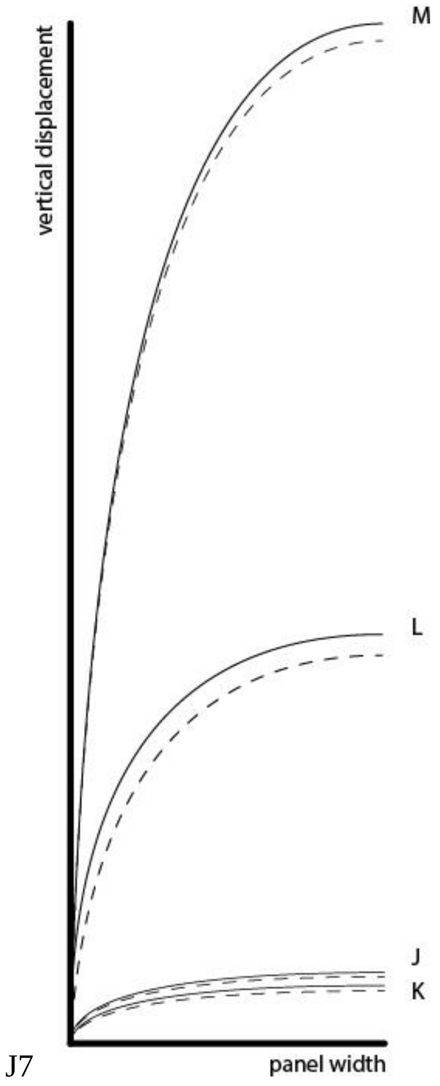


Figure 8: Graph of vertical displacement discrepancies between predicted and actual in tests J,K,L,M. The dashed line indicates digital simulation, the solid line for the actual (physical) measured value

Finally, we have also explored the consequences of the different directions of the wood grain during the self-forming process. By looking at iteration J once can distinguish the different behaviour in the thin wooden edge strips in response to their predominant grain direction. In the strips where the grain primarily runs parallel to the strip, the strips remain almost flat, while in cases where the grain runs perpendicular to the strip, bending is very evident (figure 9). The wood grain direction and the consequent anisotropic behaviour that is displayed by the thin plywood sheets (properties with different values when measured in different directions) also increased the complexity of the behaviour of the composite material and consequently, the capabilities of the system were tested. This anisotropic property led to the bi-stable state attributes on the panels produced. The resulting panels had two stable states. The switch between those states would happen when applying stress (load) to specific areas of the panel. We could only predict one of the two states from our digital simulation.

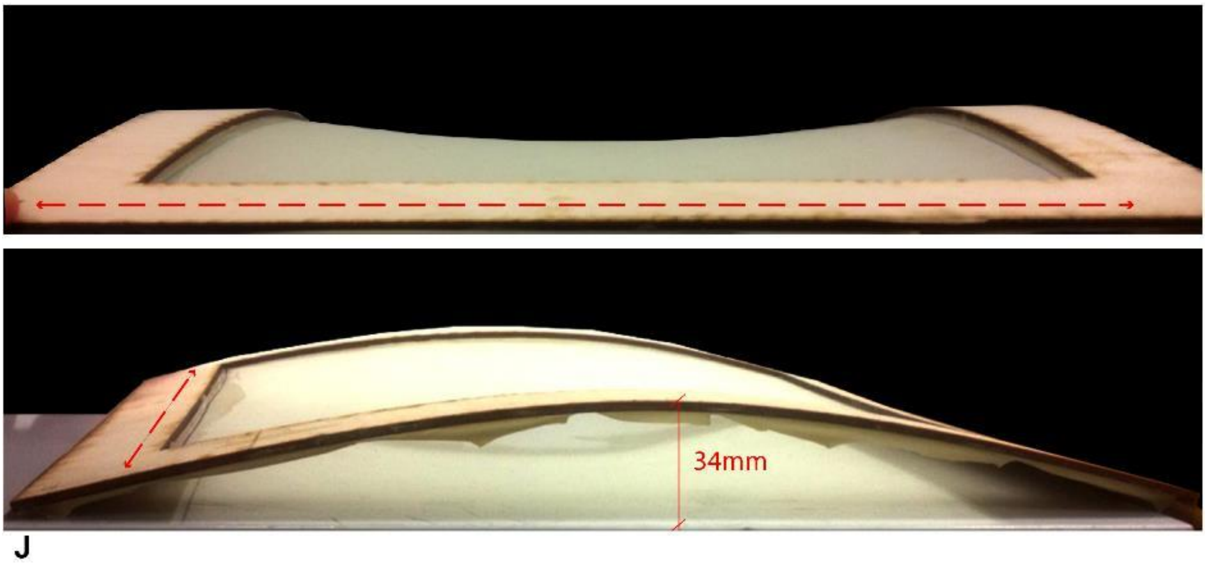


Figure 9: Iteration J, the relationship between wood grain and curvature (the red arrow indicates the direction of the wood grain)

Findings

The results of the three experiments confirmed our underlying hypothesis that by utilizing bending in a controlled way, we could predict/determine bi-stable material behaviour and produce curved complex geometries at an architectural scale. Bending occurs as a result of stiff members in the pattern bending in reaction to the force induced by the stretched membrane. This causes the member to move out of the plane and reach a stable state as forces from both the membrane in tension and the wood members cancel each other out. A second stable state can be achieved by applying additional force to the edge members of the panel and flipping the direction of the curve. In most cases, the panels could describe two different geometries created by opposite directions of bending.

All of the ‘pattern’ materials used in our three experiments (TPU 95, Polypropylene and Plywood), as well as the two membrane materials, Lycra and latex, proved to be suitable for the production of such prototypes. However, in relation to plywood, the direction of the fibres play a role in its bending behaviour (figure 9). In addition, latex sheets have powder incorporated in their surface which has to be removed prior to lamination, a factor which makes the process rather complicated. Furthermore, using polypropylene in larger-scale prototypes is not advisable due to the difficulty of laminating polypropylene with latex. After testing a wide range of adhesives (super glue, contact glue, epoxy, spray adhesives, UV adhesives), super glue (cyanoacrylate) was the only one that performed satisfactorily when used to laminate plastics with the latex or fabric membranes and contact glue performed the best, when used to laminate plywood with latex membranes.

Furthermore, we have described several variables which have an impact on the post stretched geometry. Such parameters include the direction and density of the pattern fibres (evident in iterations A, F, G, H); and the geometry of the pattern frame (evident in iterations

A, E, H). Another positive finding evident from iteration I, is the good relationship between the direction of stress lines, as derived from the 'Karamba' algorithm simulation and the direction of the pattern fibre geometry. The results here were more successful than in those indicated in our previous work described in the 'Active Membranes' paper (2018), as the control of pattern geometry was increased by following the simulated stress lines more consistently (see, iteration, I).

It is clear that the degree of elasticity of each material is strongly related to the thickness and size in which it can be deployed. This became evident in all three experiments, as we had to increase the material thickness of the pattern frames in relation to their footprint in order to achieve the same effect. The different scales and materialities could enable different potential use of the product, which, in turn, could cover a range between small objects (e.g. jewellery, accessories) up to architectural scale panels to be used for ceiling panels (figure 10), space dividers or roof and window shades.

Figure 10: Real scale plywood composite components serving as suspending ceiling (photo by the authors)

In terms of predicting the final geometry, it became evident that by using the 'Karamba' algorithm as a guide for the pattern design, in combination with the 'Strand7' finite element analysis simulation, we have achieved reliable results (the physical model was predicted with accuracy). By looking at iterations J and K and their vertical displacement from the XY plane (figure 8) one can observe small discrepancies between simulation and the physical test limited between 2mm and 2.8mm in each case. The difference rises to 8.2 mm in iteration L and 10.3 mm in iteration M, however, considering the panels' overall footprint of 750x1400mm, this difference is still small and could be considered within the expected spectrum of material tolerances. Further horizontal displacement discrepancies have been noticed but in order to be able to measure them, there would be the need for 3D scanning technology application. This is something to be considered in future experiments.

Discussion and further development

By putting our findings in the wider research environment and the projects described in our 'Background and Literature' section, a rich discussion arises that could stimulate the further development of this research. Starting with the lamination process of the pattern on the membranes, one should highlight that the 'Programmable Textile' project by Dana Zelig (2018) and the 'Active Shoes' project by Guberan and Clopath (2018) are interesting cases in which the filament was directly printed on fabric, avoiding the use of glue and the challenges that such a process brings with it. As Guberan and Clopath note the 'combination of stretch fabric and printed patterns offers both flexibility and stability' in the hybrid product. This is the pair of qualities that we aim to exploit in the architectural context.

In contrast to the composites and forms described by Aldinger (2018), the vocabulary of potential described in our research is much more complex and polymorphous, as outcomes vary in relation to the materiality of textile and fibres. In comparison to their findings, we have observed that boundaries around the pattern geometries play an important role in the form of the finalised panel. Overall the design framework as described in our methodology utilizing Rhino/Grasshopper/Karamba and has proven to be a relatively reliable simulation approach when compared to others such as that to be a valid design approach which can act as an alternative to that described by Bauer at al. (2018).

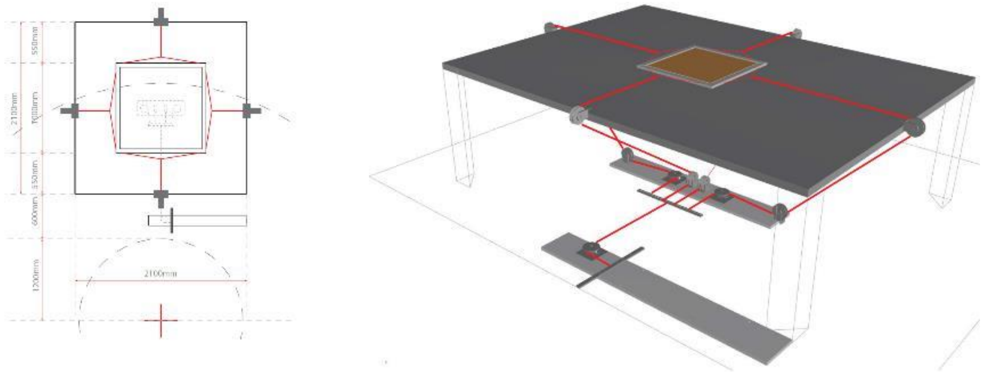
As this is an ongoing research project, we have identified areas of refinement and further investigation. This includes the use of environmentally friendly textiles, such as cotton and viscose, the modularization of our components so that they could be used in a panel array, as well as further experimentation regarding the variability of section and footprint of the fibre pattern.

Moreover, having a bi-stable modular system is another aspect that is currently being digitally and physically explored as part of the work in progress. The aim is to gain more control over the changing states, examine possible full-scale architectural applications and calibrate further the digital tools that can be used to better simulate the system's complex behaviour.

Furthermore, our plans include the automation of parts of the fabrication process with the extended use of industrial robotic arms in different phases of the process. Until now we attempted to use the KUKA robotic arm on two occasions. Firstly, we used it to increase the precision of the pre-stretching act by connecting it to a jig (figure 11). However, this use of the robot did not add many benefits to the initial process, where the latex membrane was stretched when 4 people where adding tension to the system by pulling the ropes on the jig.

The main advantage of using the KUKA arm (figure 12) would be that it eliminates the danger of injury, in case the membrane is faulty and fails during the stretching. Secondly, we experimented with using the robotic arm to apply the contact glue on the frame and the latex membrane. This would increase significantly the precision and it would allow us to have a completely even distribution of contact glue on both the membrane and the plywood frame. It would also allow us to reduce the waste of glue produced by the manual lamination process. While applying manually the glue we had to cover the whole latex surface with a thin layer of adhesive in order to achieve the even distribution needed, because we could mark out on the latex the exact areas where you needed to apply the glue. We managed to successfully apply the liquid on the membrane and the wooden frame in our experiments manually, but when we tried to use the actual contact adhesive the very high density proved problematic.The problem could be possibly resolved by our plans to design a customised end effector that can provide a consistent flow of this dense adhesive.

Relaxed State



Stretched State

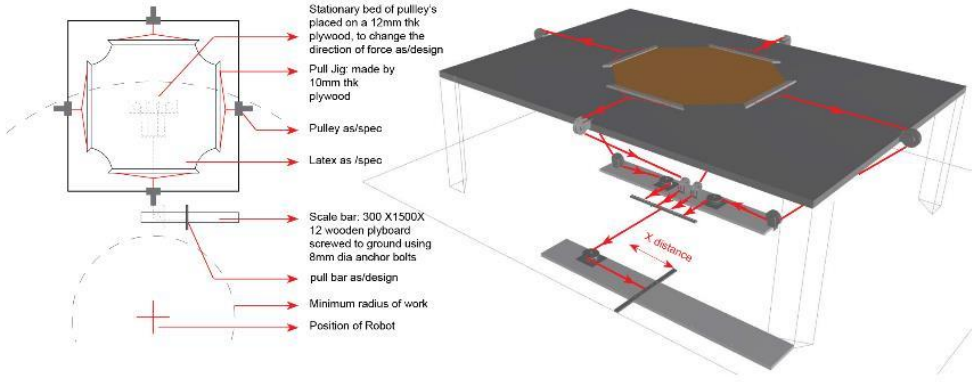


Figure 11: Diagram for the operation of the jig using the industrial robotic arm

Figure 12: This shows the adhesive application and stretching operations, using the KUKA robotic arm

Moving forward and in our quest to further increase the scale of the prototype, even more, the robotic arm could be used to print plastics directly on the stretched membrane. This technique would have a series of important advantages. It would significantly reduce the waste generated by the subtractive manufacturing (CNC milling in the case of Experiment 3), it would allow for great differentiation of the structural depth of the rigid elements within the same panel and it would also help us create panels that present anisotropic local and regional behaviour by manipulating the orientation of the printed fibres towards specific directions. By creating panels that display anisotropic behaviour locally, we could potentially achieve bi-stable states in systems made out of printed isotropic plastic (learning from the findings of Experiment 3).

Finally, by increasing the scale, further enhancing the panel’s architectural performance and achieving even better prediction and control of behaviour, a wide range of functions for such panels could become possible. Such panels are extremely lightweight, easy to transport and not expensive to produce. For instance, such composite panels could be applied as suspended ceilings, façade cladding and temporary shelters and canopies. There is further potential in embracing more aspects and material properties linked to the planned function of the membrane panel. Potential investigations and enhancements include further regional penalisation of the global geometry, joints conditions, acoustic behaviour, fire resistance, plus water and wind resistance.

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Literature

Agkathidis, A, Berdos,Y and Brown, A. "Active Membranes: 3D Printing of Elastic Fibre Patterns on Pre-stretched Textiles." *International Journal of Architectural Computing*, 2018, 147807711880089. doi:10.1177/1478077118800890.

Aldinger, A, Margariti, A, Koerner, A, Suzuki, S, Knippers, J. Tailoring Self-Formation: fabrication and simulation of membrane-actuated stiffness gradient composites. In: *Creativity in Structural Design.* Boston: IASS;2018

Ahlquist S, Askarinejad A, Rizkallah C, Ammar K, Liu X, Shah K. Post-forming Composite Morphologies: Materialization and design methods for inducing form through textile material behaviour. In: *Design Agency*. Los Angeles: ACADIA; 2014. pp. 267-276.

Ahlquist S, Menges A. Frameworks for Computational Design of Textile Micro-architectures and Material Behaviour in Forming Complex Force-Active Structures. In: *Adaptive Architecture*. Cambridge, Ontario: ACADIA; 2016. pp. 281-292.

Bader C, Kolb D, Weaver JC, Oxman N. Data-Driven Material Modelling with Functional Advection for 3D Printing of Materially Heterogeneous Objects. 3D Printing and

Additive Manufacturing. 2016;3(2):71–9. Baranovskaya Y, Prado M, Doerstelmann M, Menges A. Knitflatable Architecture: Pneumatically Activated Pre-programmed Knitted Textiles. In: *Complexity & Simplicity*. Oulu: eCAADe; 2016. pp. 571-580.

Brancart, S., L. De Laet, A. Vergauwen, and N. De Temmerman. "Transformable Active Bending: A Kinematical Concept." *Mobile and Rapidly Assembled Structures IV,* 2014. doi:10.2495/mar140141.

Bauer, A.M., Laengst, P., La Magna, R., Lienhard, J., Piker, D., Quinn, G., Gengnagel, C., Bletzinger, K. Exploring Software Approaches of Design and Simulation of Bending Active Systems. In: *Creativity in Structural Design.* Boston: IASS;2018

Blonder A C. Layered Fabric Materiality in Architectural FRP Surface Elements. In: *Architecture, Engineering, Science*. Hamburg: IASS; 2017.

Cherif C, Krzywinski S, Lin H, Schulz C, Haasemann G. New Process Chain for Realisation of Complex 2D/3D Weft Knitted Fabrics for Thermoplastic Composite Applications. *Procedia Materials Science*. 2013; 2:111–29.

Garlock MEM, Billington *D. Candela models constructed by students for an exhibition in The Princeton University Art Museum: Félix Candela: engineer, builder, structural artist*. Princeton, NJ: Department of Civil and Environmental Engineering, School of Engineering and Applied Science, Princeton University; 2008.

Gerbo EJ, Saliklis EP. Optimizing a Trussed Frame Subjected to Wind Using Rhino, Grasshopper, Karamba and Galapagos [Internet]. Latest TOC RSS. Medical Journals Limited; 2014 [cited 2018Aug6]. Available from: https://www.ingentaconnect.com/content/iass/piass/2014/00002014/00000013/art00004

Guberan C. Active Shoes [Internet]. Self-Assembly Lab. [cited 2018Aug2]. Available from: https://selfassemblylab.mit.edu/active-shoes/

Kogler M, Bergschneider J, Lutz M, Mahlting B, Finsterbusch K, R M. Possible Applications of 3D Printing Technology on Textile Substrates. In: *Materials Science and Engineering*. Monchengladbach: International Federation of Knitting Technologists; 2016.

La Magna R, Knippers J. Tailoring the Bending Behaviour of material Patterns for the Induction of Double Curvature. In: Serpanos D, Wolf M, ed. by. *Internet of Everything, Algorithms, Methodologies and Perspectives*. Berlin: Springer; 2018.

Malengier B, Hertleer C, Cardon L, Van Langenhove L. 3D Printing on Textiles: Testing of Adhesion. *Journal of Fashion Technology & Textile Engineering*. 2018; s4.

Narula, Ayushi, Christopher M. Pastore, David Schmelzeisen, Sara El Basri, Jan Schenk, and Subin Shajoo. "Effect of Knit and Print Parameters on Peel Strength of Hybrid 3-D Printed Textiles." *Journal of Textiles and Fibrous Materials*1 (2018): 251522111774925. doi:10.1177/2515221117749251.

Oxman N, Rosenberg JL. Material-based Design Computation: An Inquiry into Digital Simulation of Physical Material Properties as Design Generators. *International Journal of Architectural Computing*. 2007;5(1):25–44.

Slabbinick, E., L., M., Suzuki, S., Solly, J., J., Mader, A., Knippers, J. Conceptual framework for analyzing and designing bending-active tensile hybrid structures. In: *Architecture, Engineering, Science*. Hamburg: IASS; 2017.

Tam K-MM, Mueller CT. Additive Manufacturing Along Principal Stress Lines. *3D Printing and Additive Manufacturing*. 2017;4(2):63–81.

Zelig D. Weaved – 3D fabric structures | Dana Zelig [Internet]. Arch2O.com. 2016 [cited 2018Aug2]. Available from: https://www.arch2o.com/weaved-3d-fabric-structures-dana-zelig/

Zupin Z, Dimitrovski K. Mechanical Properties of Fabrics Made from Cotton and Biodegradable Yarns Bamboo, SPF, PLA. In: Dubrovki D, ed. by. Weft in Woven Fabric Engineering. New Delhi: CBS; 2014. p. 25-46.