Active Membranes: 3D printing elastic fibre patterns on pre-stretched textiles

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Abstract

There has been a steady growth, over several decades, in the deployment of fabrics in architectural applications; both in terms of quantity and variety of application. More recently 3D printing and additive manufacturing have added to the palette of technologies that designers in architecture and related disciplines can call upon. Here we report on research that brings those two technologies together - the development of active membrane elements and structures. We show how these active membranes have been achieved by laminating 3D printed elasto-plastic fibres onto pre-stretched textile membranes. We report on a set of experiments involving one-, two- and multi-directional geometric arrangements that take TPU 95 and Polypropylene filaments and apply them to lycra textile sheets, to form active composite panels. The process involves a parametrised design, actualized through a particular fabrication process. Our findings document the investigation into mapping between the initial two-dimensional geometries and their resulting three-dimensional doubly-curved forms, as well as accomplishments and products of the resulting, partly serendipitous, design process.

1. Introduction

The development of doubly-curved fabric structures in architecture was led by pioneers such as Frei Otto in Europe. Otto's modelling and shape analysis were driven by physical models – he was, through the 1970s to the 1990s, distrustful of computational methods. Nevertheless, by the early 1990s, an innovative range of structures had been produced and the successes and potential led Otto to declare:

'Our times demand lighter, more energy-saving, more mobile and more adaptable, in short, more natural buildings, without disregarding the demand for safety and security.' [Otto, Rasch, 1992]

Later collaborations grew with others such as Peter Rice at Arup [Brown, Rice, 2001]. Rice, in contrast, was deeply committed to the computational methods that he was applying to stress analysis and form finding. Those developments have continued and we now see membranes and textiles being used successfully in building construction in the form of roofs, facades, pneumatic structures and tents. But now the rapid development of emerging technologies such as 3D printing, additive manufacturing, plus developments in material science, are enabling designers to consider further innovative solution synergies. Bader, Kolb, Weaver and Oxman [2016] noted the potential for new hybrid materials in architecture, observing that 'Recent advances in high-resolution 3D printing have enabled the design and digital fabrication of objects with unprecedented levels of structural complexity… [ones that are] …geometrically complex, and materially heterogeneous'

In the particular case that we discuss in this paper, we take advantage of the fact that 'semi-flexible' materials such as the thermoplastic polyurethane (TPU 95 in our case) and Polypropylene can be printed on a range of (structural) textiles surfaces, forming composites materials with combined and symbiotic material properties. TPU Resin differs favourably from other "soft touch" materials in having properties that are useful in architecture and construction applications; such as enhanced abrasion resistance, excellent low-temperature impact strength and good tear strengths.

Some initial work describing an investigation into structurally capable composite panels was presented by Berdos and Cheng [2017]. In their paper, the term Active Fabrication is used to describe the development of a composite material that combines two pliable materials to produce a hybrid with variable states of stiffness. The goal was to produce a composite material that has enhanced performance characteristics when compared to the composing materials.

In the developments reported here, the intention is to move away from conventional mould technology as a way of forming composite doubly-curved 3D architectural elements. Our research exploits a combination of contemporary design and fabrication techniques, applied to pre-stressed doubly curved elements, that can be utilized in architectural contexts.

In the research reported here, we are in search of a formal behaviour vocabulary; one that can be produced by laminating two-dimensional fibres in 3D-printed arrays, onto pre-stretched lycra sheets. By using parametric simulation tools (specifically 'Grasshopper' and the 'Karamba' plug-ins) in tandem with physical experiments, the intention is to develop, and then control, a quasi form-finding process. This is achieved by controlling the fibre pattern typology, the material thickness and fibre width, as well as the degree of tension/stretch in the host membrane. In particular, our examination aims to address answer following questions:

- How can we control and predict the form and performance of hybrid panels composed of 3D printed, semi-flexible, filament fibres laminated onto elastic membranes?
- 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?

The target application is deployment as a set of panels in an architectural setting; such as the surface material to an external skin of a building. To develop a material to achieve desired performance with associated design process required a staged set of investigations. This began first with an examination of the potential range of textiles, and membranes in tandem with potential 3D printing technologies and their characteristics. These initial investigations produced potential ways forward, that were then tested through physical experiments.

The experiments took into consideration two different pattern typologies (two, and multidirectional, elements) printed on lycra membranes to form a hybrid laminate. The performance and properties of different pattern configurations were then modelled using parametric design and simulation tools. Behaviour and performance simulation was facilitated by the application of curvature analysis techniques and panelling tools for Grasshopper, as well as Karamba for Grasshopper (Figure 01). Both simulations would, in turn, inform the design process.

The Karamba simulation was aimed at producing the optimal topological arrangement of material for the predetermined forms with a given set of pre-defined boundary conditions. The first step in this analysis was to find the principal stress lines in each 3-dimensional surface. Since Karamba does not hold textile material properties as a standard, we had to reconfigure Karamba material properties held in the system, in order to properly simulate flexible textile material behaviour. With the material properties better represented, the analysis could then be performed. The consequent principal stress analysis produced three-dimensional pairs of intersecting curves, which indicate trajectories of the internal forces.

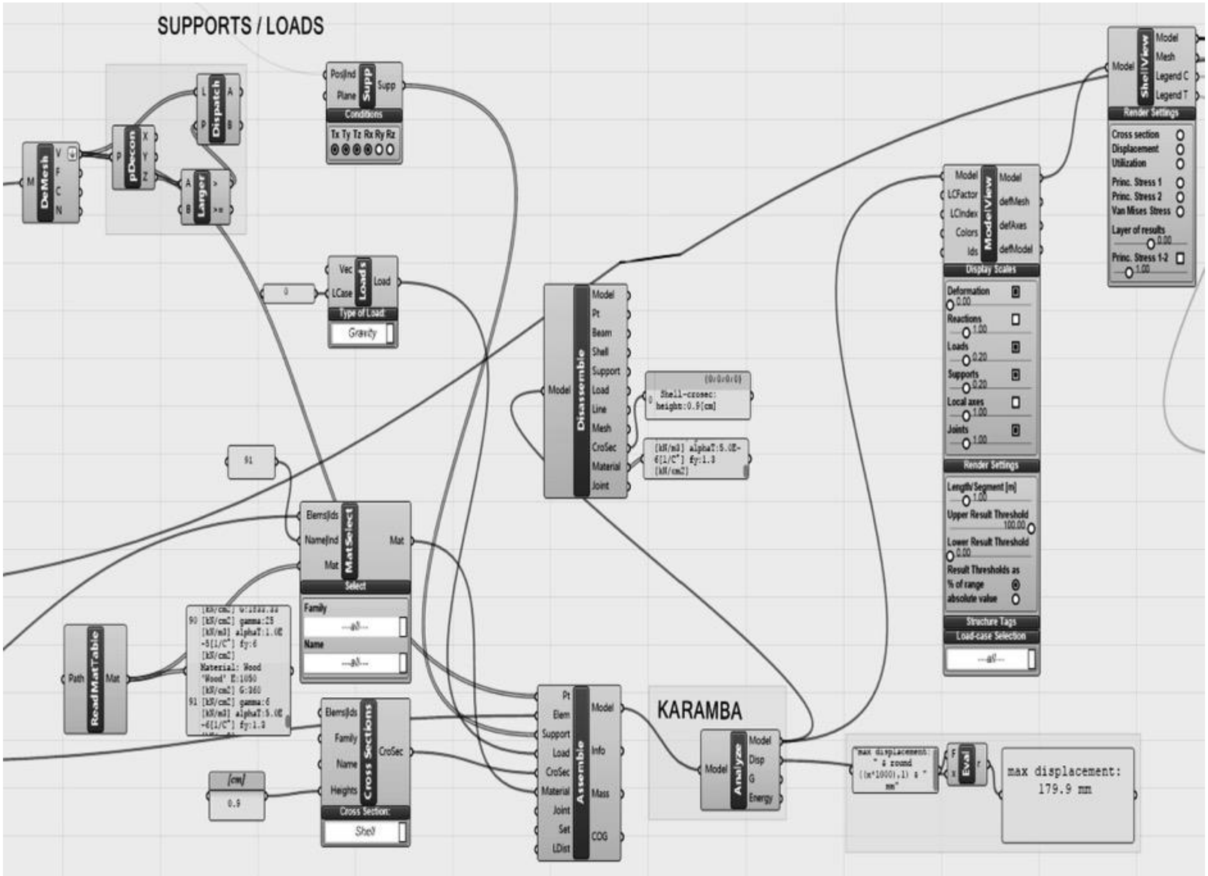

Figure 01: Karamba simulation script

Analysis of the panel behaviour as described above allowed us to design the chosen patterns to respond to the paths of principal stress lines. Tam and Mueller [2017] noted, as one might expect, that locating the principal stress lines to act as a guide for stiffening elements has considerable potential benefits.

For the 3D printing aspect, we have used an Ultimaker 2+ 3D printer. The material applied was TPU 95. Other initial tests were undertaken with Polypropylene and Nylon; Nylon proved impractical and the conclusions below have further comment on the problems encountered with Polypropylene. To facilitate bonding of the laminates - the fibres to the membrane - a Cyanoacrylate glue was used (Diphenylmethane diisocyanate).

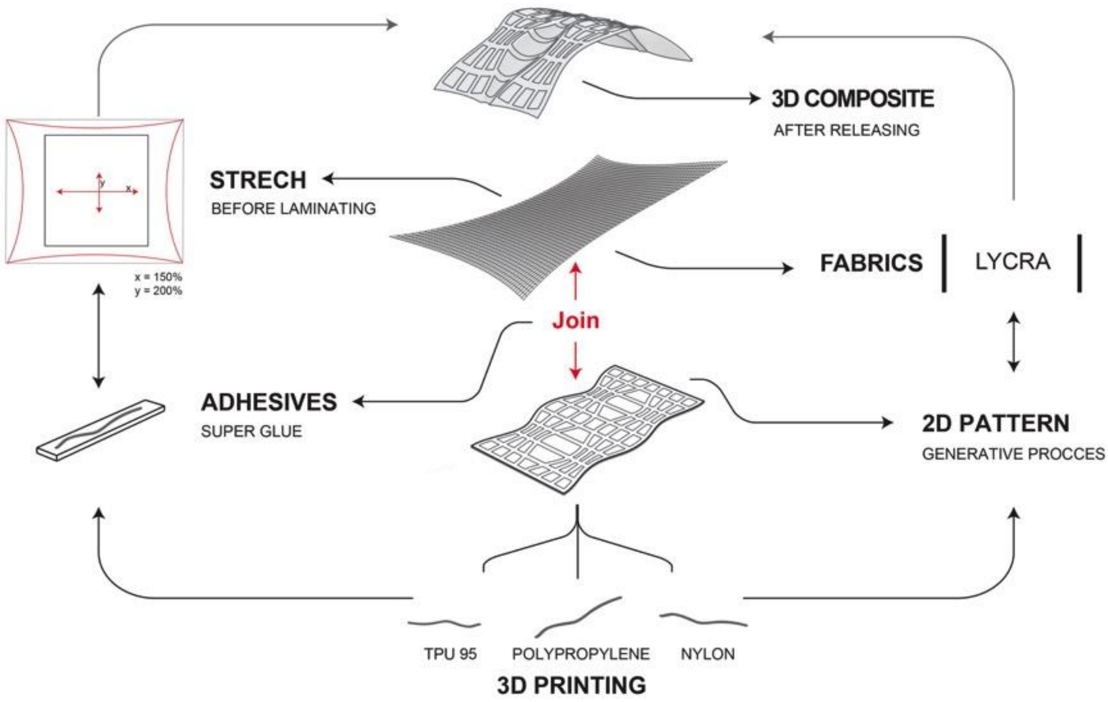

Figure 02: design and fabrication process followed in experiments 1,2 and 3.

The process followed in the three experiments was similar (figure 2). However, there are slight variations in the starting points and the simulation characteristics of the 3D host surface. More specifically, each of the two process variations generated different experimental procedures as summarised below:

- The sequence followed in experiment one and two processes was: 3D surface developed as pattern generator -> parametric simulation with Karamba -> projection of surface as 2D pattern -> 3D printing of pattern as an embossing mesh -> pre-stressing of membrane -> lamination of embossed pattern on pre-stressed fabric -> release of membrane pre-stress.

- The sequence followed in experiment three process was: 3D surface developed as pattern generator -> parametric simulation using attractor points -> projection of 2D pattern -> 3D printing of pattern -> pre-stressing of membrane -> lamination of embossed pattern on pre-stressed fabric -> release of membrane pre-stress.

2. Reflection and context

Frei Otto was a pioneer in the application of fabrics in contemporary architecture. He made key developments in aspects such as devising membrane geometry to minimise and equalise stress in elements and whole structures. In his series of soap-film experiments conducted by dipping wire-frames into soap-water[1], he was looking for the 'minimum energy surface' based on liquid film naturally forming itself into a thin skin tension. Operating in a ruthlessly analogue environment, he applied the rules of 'minimal surface 'to a set of large-scale buildings, such as the Jahunderthalle in Mannheim. These very early insights and techniques have been extraordinarily influential and are still recognised and referred to regularly today [Goldsmith, 2016]. In a similar manner, Felix Candela investigated the minimal energy geometries of active concrete shells in a series of large-scale projects, such as the Oceanographic Museum in Valencia [Garlock, Billington, Candela, 2008]. Otto and Candela both worked with the notion of an efficient architecture that derives from connecting material to form; where shape and performance combine to deliver an optimum solution.

Otto's analogue approach would correctly indicate minimum energy forms for isotropic, homogeneous materials; but woven fabrics are often anisotropic so the analogue model starts to break down. Now, in the era of relatively advanced computational technologies in parallel with new materials and methods of production, many architects and researchers have been returning to the material-shape-performance relationship, introducing new tools and fabrication technologies. In this vein, an early paper 'Large Steps in Cloth Simulation' by Baraff and Witkin [1998], describes an innovative fabric simulation system that allows a prediction of textile behaviour as a result of stretching caused by human body movement.

More recently, and more closely related to our work, in their investigation into Performance-Based Design Computation of materials, Oxman and Rosenberg [2009] describe a set of experiments, which involved applying patterns formed out of resin onto prestressed latex membranes. They used intrinsic forces simulation applied to mesh typologies in order as an approach to form-finding. Later work reported by Bader et. al described the issues faced in producing materially heterogenous 3D printed outputs; an issue that we also address, in our tests

In terms of doubly-curved, composite (laminated), prestressed, fabric architectural elements, an interesting precursor to our work was undertaken by Cherif et al. [2007] who studied similar composite applications. They worked with fabrics that had been the first CNC knitted and then bonded 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 [2013]. 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 in one another, This adds an additional dimension and potential to the forms and behaviour possible in the final product.

As noted earlier our technique involves prestressing the fabric element in the laminated composite; we apply the second material to an already prestressed fabric. In what they refer to as a post-forming composite technique Ahlquist et al. [2013, 2014] also experimented with pre-stressing the base fabric; in this case, stretched TRC material. They then applied an epoxy resin to this in order to enable lamination of the composite three-dimensional product. An interesting alternative to the direct application of prestressing to the fabric was described by Baranovskayaet al. [2016]. Here they used pneumatic activation technology to apply the prestress rather than by direct application of a mechanical force. 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.

But the newer technologies take us to the possibilities beyond coatings, enabling the design and production of composites where both the visual appearance and architectural performance (environmental or structural) can be enhanced using a combination of contemporary design and analysis software plus current 3D print technologies. The work undertaken by Blonder [2017] shares some of the same goals. Blonder takes an approach, where folds and pleats are integrated into textiles through the use of fibre reinforced plastic, as a move towards effective 'architectural FRP Surface Elements'. The material produced is a partial lamination that combines both surface architectural treatments with the necessary structural capacities, such as stiffness.

Our work on 'Active Fabrication' [Berdos, Cheng, 2017] is a precursor to the work reported in this paper. In this case, though, the lamination was achieved by creating a doubly-curved grid of plywood strips adhered to pre-stretched latex sheets. A Finite Element analysis simulation was used in order to evaluate the final shape of the composite panels. This type of analysis offers a number of potential advantages. In particular, numerical simulation of nonlinear structural behaviour is particularly useful for the type of form being investigated here, where there is strongly deformation-dependent behaviour.

In the work in this paper, prestressed fabric panels are again one of the laminations, but to investigate the potential of pattern application, through a kind of embossing technique, 3d print technology has been employed. This is to investigate the delivery of the desired architectural properties and performance mentioned earlier. As part of this aim, we experiment with raised pattern application to curved surfaces. Of interest in this respect is the work of La Magna and Knippers (2018) who describe a technique for pattern modification based on curvature analysis of doubly curved surfaces.

In their research about possible applications on 3D printing technology on textiles, Kogler et al. [2011] descibed their findings after testing several flexible, thermoplastic elastomer filaments on different kinds of woven fabrics. However, they have not investigated how geometires of such composites are influenced different filament patterns. In their paper '3D pronting on textiles: Testing of Adhesion' Malenger and Van Langenhove [2016] discussed their findings on similar experiments, testing different material combinations, again without discussing patterns and geometries.

Finally, the 'Active shoes' project by Guberan, Clopath and the Self-Assembly Lab [2018], alongside Zeling's [2018] weaved 3D fabric structures acted as major inspiration sources for our research, offering a spectrum of the high potential emerging by utilizing this technology in architecture and product design related applications.

Reviewing the research developments described above contributed to determining the techniques and materiality chosen for our experiments, aimed at addressing the issue of producing components and elements with particular and controllable surface and textural qualities. The particular concern was to take doubly curved 3D textile components, as panels, and produce controlled forms by applying embossed patterns as laminations.

3. Experiments

A summary of the experimental process was given in the first section of this paper. In the section below we elaborate on the outline given in section 1 with a detailed explanation of the experiments undertaken. The experiments described below followed initial trials with simple geometric embossed patterns (such as parallel lines and grids) to check the behaviour of the panels, and the accuracy of the deformations predicted by the computational analysis.

3.1 Experiment 1

Our first experiment examines the fundamental response given the application of two-directional patterns. The Experiment 1 series includes a set of six variants that were developed in a 3D environment working from a predetermined 3D surface shape. By simulating the material behaviour using the 'Karamba' plug-in for 'Grasshopper ' (figure 01), the required patterns were back-calculated, from the predetermined global 3D geometry (figure 03). The Karamba simulation was aimed at producing the optimal topological arrangement of material for the predetermined forms with a given set of pre-defined boundary conditions.

To test the process, rather than working with large architectural cladding panels, smaller panels of composite material were fabricated. But to simulate a comparably large format condition, a designed product was needed where the edge condition and form of the 3d doubly curved surface could be taken as the target. We chose to make the designed product a wearable accessory for the arm, wrist and hand.

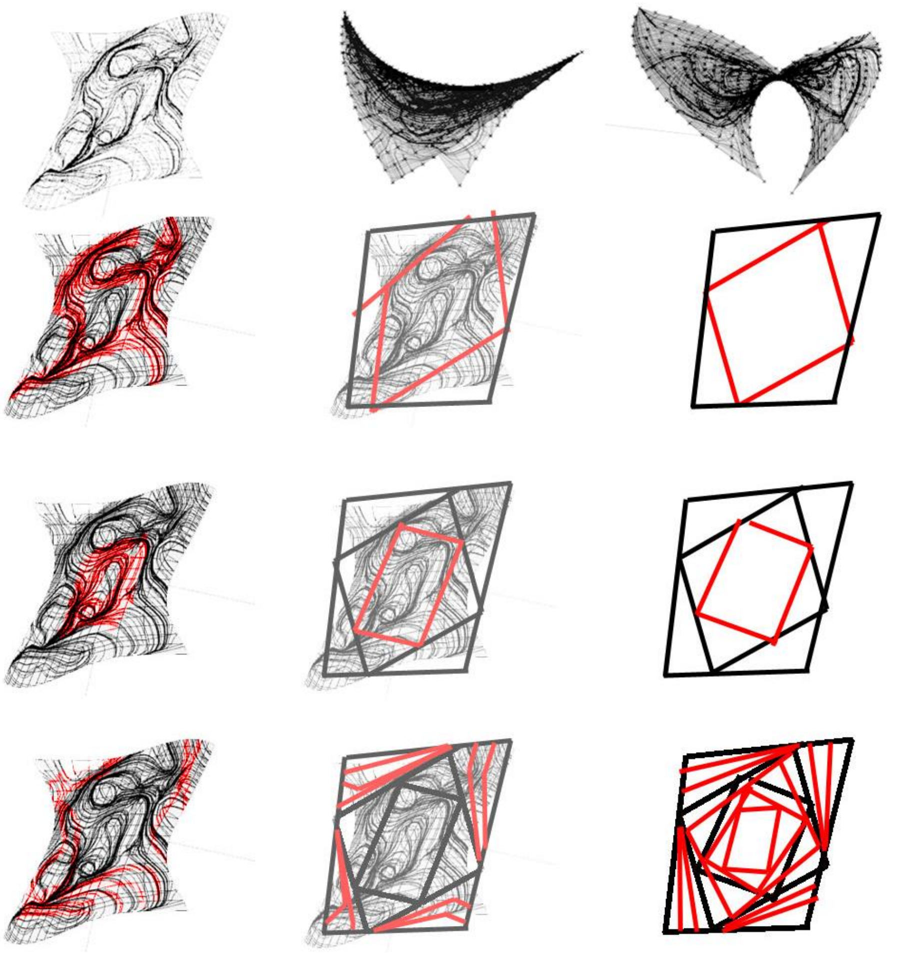

Figure 03: The design pattern is being informed by the Karamba simulation. Pattern lines are aligned with the textile stress lines (in red colour).

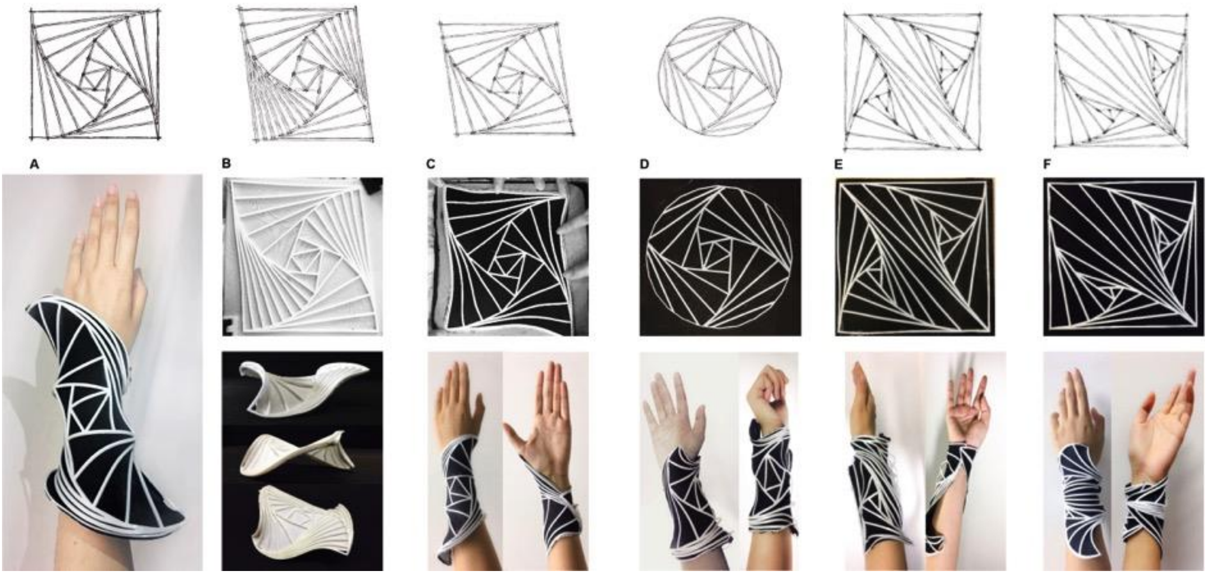

Figure 04: Tests A, B, C, D, E, F - Two directional embossed patterns designed to produce a wearable

Starting with a rectangular spiral pattern set in a bounding square periphery (figure 03) we have developed the set of six iterations of wearable accessories shown in figure 04. The stress lines describing the intended paraboloed geometry (marked in red in figure 02) were used as guidelines to align our spiral geometric paterns. The embossing thickness and width and the fame periphery were parametrically modified in order to produce the shape and properties of the finalised objects (A, B, C, D, E, F) as shown in figure 4. The original Lycra sheet was 200x200mm and it was pre-stretched by 50mm, a strain of 40%. The printed TPU95 filament was applied in different thicknesses: 1mm for tests E, and F; 1.5mm for A, C, D; and 2mm for B. The combined influence of pattern geometry and material thickness result in visible formal differences, and these are described below:

- test samples, A and C, which have 1.5mm embossing display shallower edge curves and a more open central area,
- in contrast, samples E and F with only a 1mm embossing, have tighter edge curvature and more consistent, central area with tighter curvature
- In test B the embossed printed pattern was laid down as a 2mm thickness. As can be seen, this gave sufficient stiffness to prevent the mini-panel folding in on itself, in the way it did with tests A, C, D, E and F.

However, a particular point to note in relation to test B is that the error in predicting the form and edge profile was much lower for this test than the other tests in this series. This is thought to be primarily due to the larger errors in the analysis and prediction routines that result when very large displacements are allowed in the system. The correct modelling of material properties at large deflections is the other likely contributing factor.

3.2 Experiment 2

The initial tests in Experiment 1, illustrated how the form and behaviour of the hybrid material could be controlled and manipulated. Experiment 2 aimed to investigate four further variants on this theme, focusing on quadrant shaped pannels with the embossing pattern laid close to principal stress lines (figure 05).

The pattern for the embossing was broadly a combination of radial and circumferential lines. This is as might be expected as the laminate embossing is responding to the lines of principal stress in the fabric.

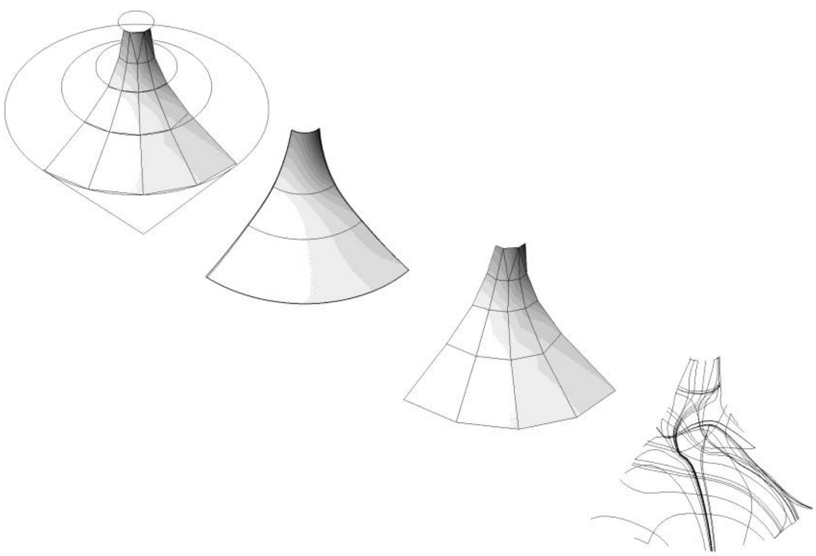

Figure 05: Stress lines deriving from the Karambe simulation script

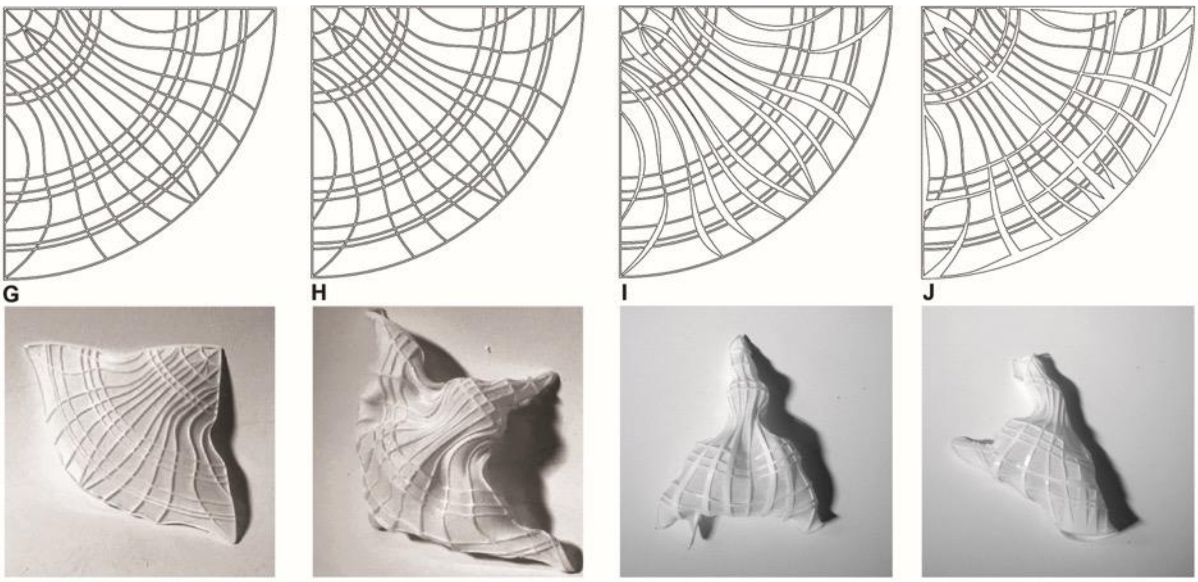

Figure 06: The effect of two directional fibres on a quadrant shaped panel: iterations G, H, I, J

Iteration G (Figure 06) was printed with a 3mm embossed TPU95 filament. This resulted in a stiff mini panel that remained almost flat, with small curvature deformations overall, and hence quite a small variation from the original plan form. Iteration H was printed with a 2mm TPU95 filament embossing. The product was clearly more voluminous with a significant increase in local curvatures of the surface and a significant change to the footprint.

For the final two iterations in this series, I and J, as for iteration H, the embossing was applied using 2mm TUP95 filament. However, the fibres in the embossed pattern were reduced in width. As predicted by the analysis software and as expected, this further reduces the stiffness of the mini panel which in turn resulting in an even more voluminous product with tighter curvatures and more significant deformation to the edge condition.

3.3. Experiment 3

The experiments described above had dealt with embossing in a combination of radial and circumferential ribs, better responding to principal stress lines. Our final experiment examines the behaviour of multidirectional patterns. In particular, a Voronoi-driven layout of the embossing was adopted.

The Voronoi pattern was manipulated in its density, using a curvature analysis algorithm, facilitated by the panelling tools plug-in in Grasshopper (figure 07). All tests were again conducted using a 200x200mm lycra sheet as the base of the hybrid material, again stretched 50mm in both directions.

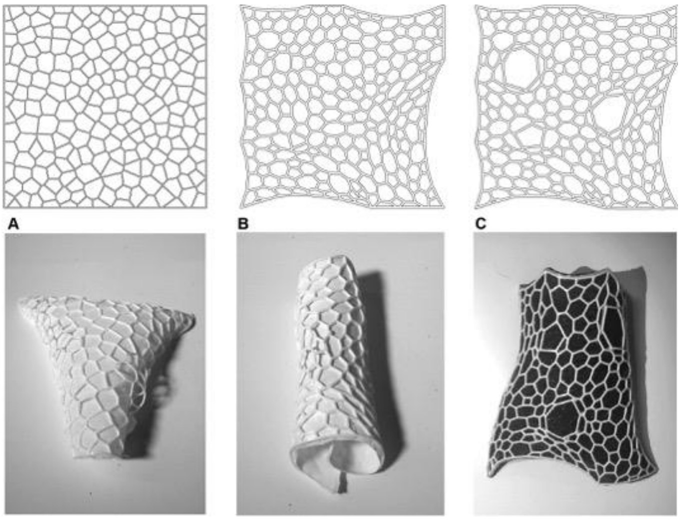

Figure 07: Multidirectional Voronoi iterations K, L and M

Iterations K, L and M were printed with 2mm TPU95 filament. Iteration K was developed using a regular Voronoi pattern with a square footprint, rolling up in an almost triangular shape. Iteration L has been informed of curvature related irregularities and curved edges, rolling up in a cylindrical shape. Finally, the pattern applied in iteration M with even greater irregularities and curved edges forms a vault-like form. The variation in cell size in M, with certain cells relatively large (figure 07), brings a lower overall stiffness and less tight curvature than for test, L.

We should note here that in addition to varying the embossing dimensions and pattern the intention was also to experiment with an additional embossing material. Consequently, iteration N was printed with polypropylene embossing in a Voronoi pattern, with 2mm thickness as in the experiment with the TPU95. However, as a potential hybrid material, the combination of lycra and polypropylene embossing proved to be unworkable. Most edges and linear elements of Iteration N have visible irregularities (figure 08). In addition, the material proved to be unstable and unreliable as a laminate, so the additional planned tests with polypropylene embossing were not undertaken.

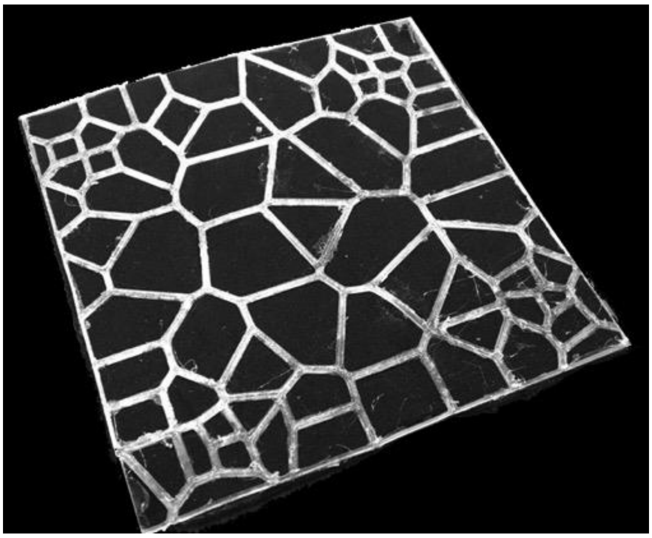

Figure 08: Multidirectional Voronoi iteration N, polypropylene print

Discussion and conclusions

By looking into the outcomes of the three sets of experiments, many conclusions have been drawn certain observations can be made. Overall the technique of laminated 3D printed pattern of fibres bonded onto pre-stretched membranes has potential to offer innovative composite solutions for certain architectural application. Advantages of tensile composite elements or panels made this way include their extremely small relative weight, their flexibility and their adaptability.

Even though the experiments were carried out on miniature panels, it can be appreciated that such materials and form geometries could find applications at large scales, as building components, shading devices, space dividers and large-scale temporary buildings or tents. A natural extension to these tests would be to scale up the components, using a larger stretching-bed for the membrane and the use of an industrial robotic arm to facilitate 3D printing of the embossed pattern.

As mentioned earlier, a particular challenge during the design and fabrication process was the prediction of the final shape of each prototype. There were different degrees of percentage error in shape and displacement between computed prediction and physical model. Even though the Karamba script simulation (figure 3) predict the overall general form of the prototypes, in this case a hyperbolic paraboloyd, there were still discrepancies between the digital and physical models (e.g. particularly as noted in cases of large displacement in experiment two; iterations A, C, D, E). The predictions were more accurate in iteration B which had more substantial embossing and lower deflections.

It is clear that final shape and behaviour of the prototypes was strongly related to the pattern geometry, the pattern edge condition and the hybrid material properties, in particular, embossing thickness and width.

Looking into experiment three, which investigated multi-directional Voronoi patterns, it appears that the patterns density in combination with the pattern footprint perimeter form can act as the main form generating parameters. Iteration K, with a dense homogeneous pattern embedded into a square footprint, formed a quasi-triangular shape. Iteration L, with a heterogeneous pattern and circular bows in its footprint, formed a tubular shape, while iteration M, with a larger degree of heterogeneity and the same footprint as iteration L, formed a vault shape. What is salutary here is that the less dense embossing leads to less tight curvatures (than in L for instance) - and this is a case where the overall form and displacements follow the geometry of the predicted form extremely closely. This indicates that the analytical method, with recalibrated material properties to model the fabric correctly, gives good predictions of behaviour and form when displacements are not extremely large, as would be the case in practice. We should also note at this point that the pattern variations, which were based on the curvature analysis of the 3D model and the Grasshopper component for panelling tools, show behaviour similar to that described by La Magna and Knippers [2018] in their work.

The composition of the 3D printed filament, as well as the glue used for its lamination onto the textile, proved to be other important parameters influencing the prototype's formal behaviour. Two of the potential embossing materials tested before TPU95 proved to be unsuitable. As noted above, printing thin elements using semi-elastic polypropylene gave disappointing results (figure 08). The irregular edges and potential over-heating during the printing process proved major obstacles that forced us to continue our experiments with TPU95. We had an even more substantial failure in trying to use nylon filament, whose stiffening properties as a potential embossing material proved completely inadequate. The resulting laminate proved to be incompatible with the need to generate a controlled, doubly-curved hybrid panel. Further considerations and combinations will be investigated including printing patterns with different material deposition levels within each element, thus creating anisotropic composite materials where this is appropriate.

Finally, the lamination of the 3D printed pattern to the textile sheet was achieved by mechanical bonding in our current experiments. This could be improved by direct printing on the textile sheets. But a particular problem is the high melting temperature of the TPU95 filament which would be incompatible with of the lycra sheets, which ignites at relatively low temperatures. To avoid this, we are working on a much-improved filament/textile combination in the hybrid.

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.

However, looking back to the Frei Otto quote, earlier in this paper, also important is for us to review the appropriateness of materials from a sustainability point of view. In addition to removing the cyanoacrylate glue from the process, the sustainability credentials of the laminating materials also require attention. Materials such as SPF (Soya Protein Fibre), although not at the tensile strength of polyester fibre do have higher tensile strength than cotton-based fabrics [Zupin, Dimitrovski, 2014] that Frei Otto used, and have other important qualities such as UV resistance. There are interesting possibilities for further investigation and development of the techniques and materials for architectural applications.

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