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Active membranes: Three-dimensional printing of elastic fibre patterns on pre-stretched textiles[AQ: 1]

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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, three-dimensional 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 three-dimensional printed elasto-plastic fibres onto pre-stretched textile membranes. We report on a set of experimentations 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 parameterised design, actualised through a fabrication process including stress-line simulation, fibre pattern three-dimensional printing and the lamination of embossed patterns onto a pre-stretched membrane; followed by the release of tension afterwards in order to allow controlled, self-generation of the final geometry. Our findings document the investigation into mapping between the initial two-dimensional geometries and their resulting three-dimensional doubly curved forms. We also reflect on the products of the resulting, partly serendipitous, design process.

Keywords

Digital fabrication, three-dimensional printing, parametric design, material computation, fabrics

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 techniques 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 et al.[1] to declare:

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> 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.

Later, collaborations grew with others such as Brown and Rice[2] at Arup. Rice, in contrast, was deeply committed to the computational methods that he was applying to material innovation 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 and additive manufacturing, plus developments in material science, are enabling designers to consider further innovative solution synergies. Bader et al.[3] 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 article, 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 composite materials with combined and symbiotic material properties. TPU Resin differs favourably from other *soft-touch* materials in having properties that are used in architecture and construction applications, such as enhanced abrasion resistance, excellent low-temperature impact strength and good tear strengths.

The work described here is a continuation of our initial investigation into structurally capable composite panels, presented by Berdos and Cheng.[4] 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. Among the main advantages of *Active Fabrication* is the elimination of moulds and formers as form-giving devices – by utilising material-enhanced properties to form doubly curved architectural elements.

Our research exploits a combination of contemporary design and fabrication techniques, applied to pre-stressed doubly curved elements that can be utilised 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 (2D) fibres in three-dimensional (3D)-printed arrays, onto pre-stretched fabric sheets. Using parametric simulation tools (specifically 'Grasshopper' and the 'Karamba' plug-ins) in tandem with physical experimentations, 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 and strain 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 an originally 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?

The target application is deployed 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 experimentations.

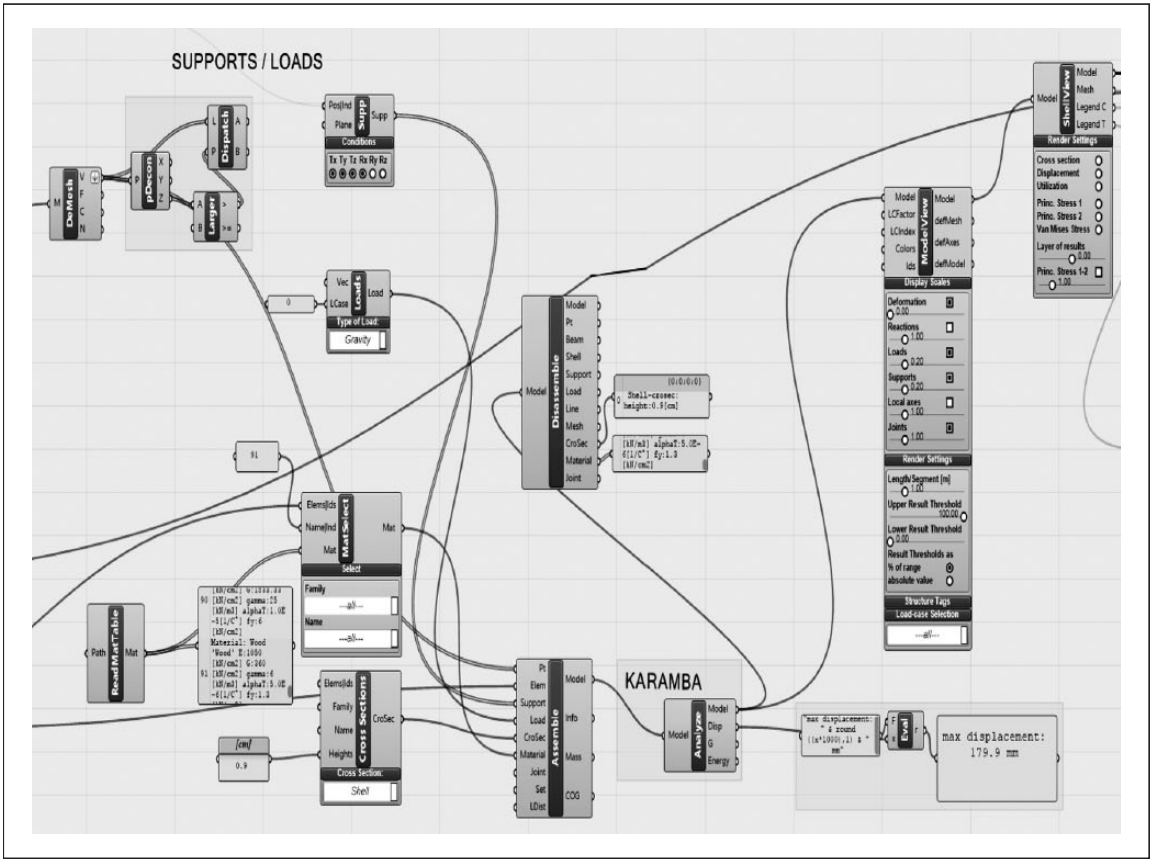

Figure 1. Karamba simulation script.

Methodology

Our research method is based on three design experimentations, which took into consideration two different pattern typologies (two- and multi-directional 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[5] (see Figure 1). Grasshopper is a highly popular visual programming language currently integrated into the Rhinoceros 6, 3D modelling software. Karamba is a structural simulation plug-in for Grasshopper. Both these digital tools would, in turn, inform the design process.

The Karamba simulation was aimed at producing the optimal topological arrangement of material for the pre-determined 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 3D 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 3D pairs of intersecting curves which indicate trajectories of the internal forces.

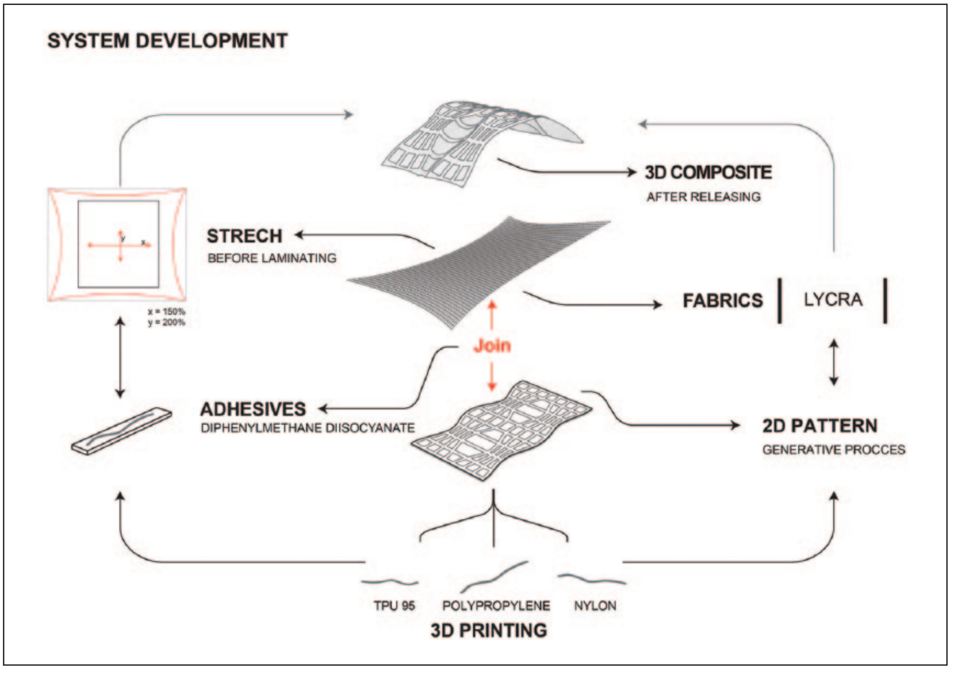

Figure 2. Design and fabrication process followed in Design Experimentations 1, 2 and 3.**[AQ: 7]**

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[6] noted, as one might expect, that employing 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 is proved impractical, and the conclusions below 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).

The process followed in the three experiments was similar (see 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:

1. The sequence followed in Design Experimentation 1 and Design Experimentation 2 processes was the following: 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.
2. The sequence followed in Design Experimentation 3 processes was the following: 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.

Background and literature

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 Jahrhunderthalle in Mannheim.[AQ: 2] These very early insights and techniques have been extraordinarily influential and are still recognised and referred to regularly today.[7] 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.[8] Otto and Candela both worked with the notion of an efficient architecture that derives from connecting the 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, employed in parallel with new materials and methods of production, many architects and researchers have been returning to the material–shape–performance relationship, by introducing new tools and fabrication technologies. In this vein, an early paper, 'Large Steps in Cloth Simulation' by Baraff and Witkin,[9] 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[10] describe a set of experiments that involved applying patterns formed by applying resin onto pre-stressed latex membranes. They used intrinsic forces simulation applied to mesh typologies as an approach to form-finding. Later work reported by Bader et al.[3] described the issues faced in producing materially heterogeneous 3D-printed outputs, an issue that we also address in our tests

In terms of doubly curved, composite (laminated), pre-stressed, fabric architectural elements, an interesting precursor to our work was undertaken by Cherif et al.,[11] who studied similar composite applications. They worked with fabrics that had been first computer numerical control (CNC) knitted and then 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.[12] 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 dimension and potential to the forms and behaviour possible in the final product.

As noted earlier, our technique involves pre-stressing the fabric element in the laminated composite; we apply the second material to an already pre-stressed fabric. In what they refer to as a post-forming composite technique, Ahlquist et al.[13] also experimented with pre-stressing the base fabric; in this case, stretched textile-reinforced concrete (TRC) material. They then applied an epoxy resin to this in order to enable lamination of the composite 3D product. An interesting alternative to the direct application of pre-stressing to the fabric was described by Baranovskaya et al.[14] Here, they used pneumatic activation technology to apply the pre-stress 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 pre-stressed 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 polyvinyl chloride (PVC)-coated polyester or PVC-coated glass fibre. Commonly, a particular reason for the coating was to increase ultraviolet (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 augmented by current 3D print technologies. The work by Blonder[15] 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 prior work on *Active Fabrication*[4] is a precursor to the work reported in this article. In the prior work, 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, where there is strongly deformation-dependent behaviour.

In this article, pre-stressed 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,[16] who describe a technique for pattern modification based on curvature analysis of doubly curved surfaces.

In their research about possible applications of 3D printing technology on textiles, Kogler et al.[17] 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', Malengier et al.[18] discussed their findings on similar experiments, testing different material combinations, again without discussing patterns and geometries.

Finally, worthy of mention here is the 'Active shoes' project by Guberan, Clopath and the Self-Assembly Lab.[19] Alongside Zelig's[20] weaved 3D fabric structures, the work acted as major inspiration sources for our research, offering an indication of the significant potential emerging from utilising 3D print lamination 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. 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 components, as panels, and produce them in controlled forms, by applying embossed patterns as laminations.

Design experimentations

A summary of the experimental process was given in the first section of this article. In the section below, we elaborate on the outline given in section 'Introduction' 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.

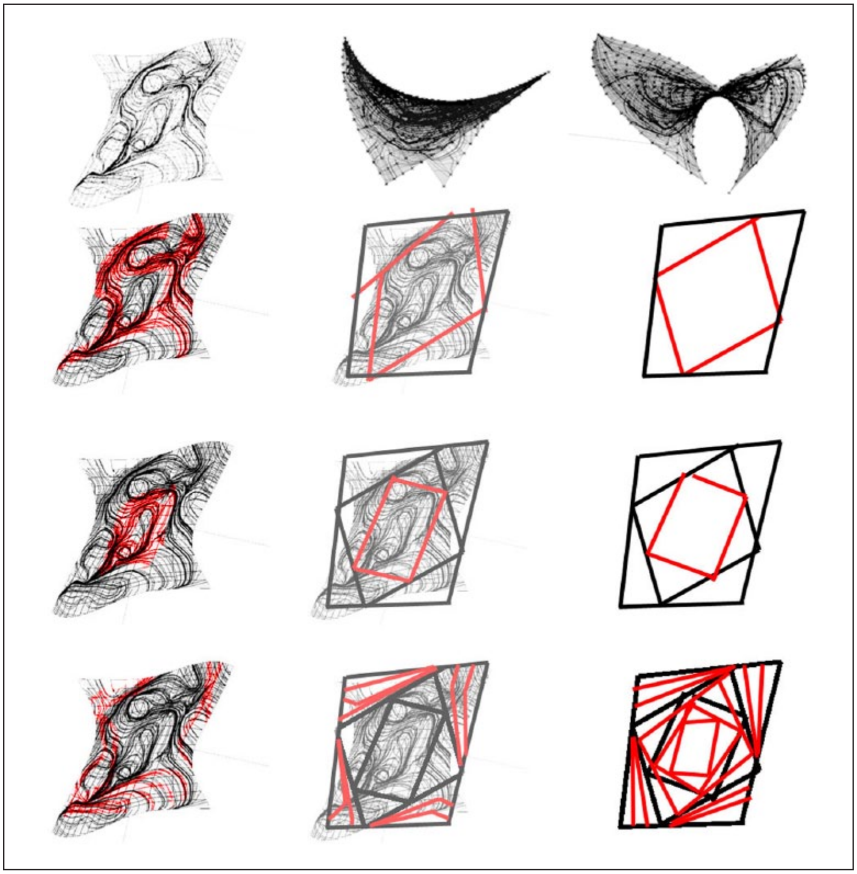

Figure 3. The design pattern–informed by the Karamba simulation. Embossed pattern lines respond to the textile stress lines (shown in red).

Design Experimentation 1

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

To test the process, rather than working with large architectural cladding panels, smaller, more manageable 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.

Starting with a rectangular spiral pattern set in a bounding square periphery (see Figure 3), we have developed the set of six iterations of wearable accessories shown in Figure 4. The stress lines describing the intended paraboloid geometry (marked in red in Figure 2) were used as guidelines to align our spiral geometric

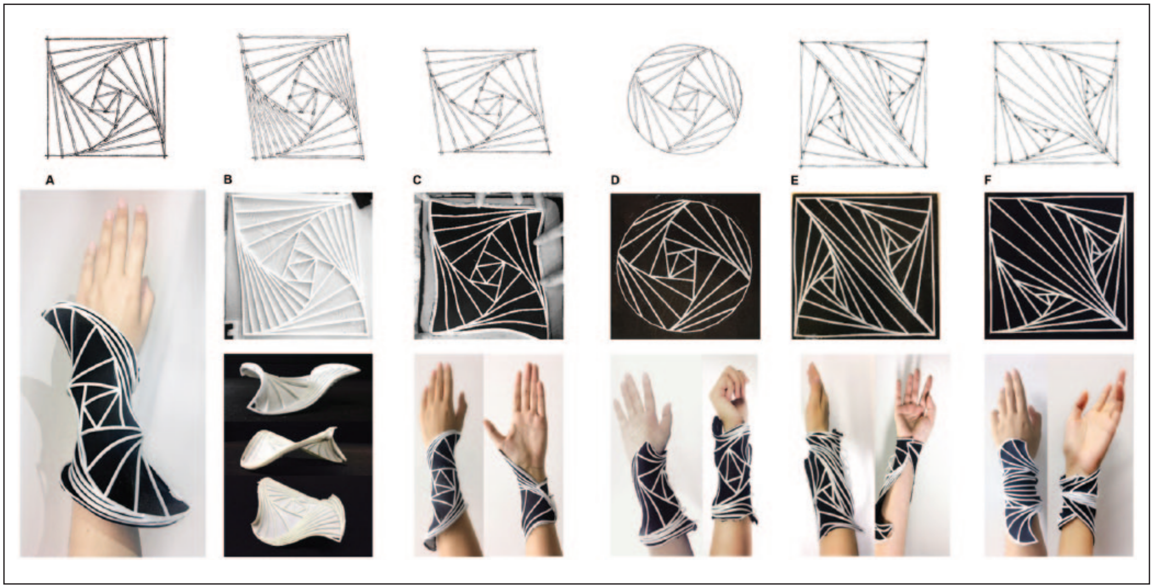

Figure 4. Tests A, B, C, D, E, and F – two-directional embossed patterns calculated to produce a wearable with prescribed form.

patterns. 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, and F) as shown in Figure 4. The original Lycra sheet was 200 mm × 200 mm, and it was pre-stretched by 50 mm, a strain of 40%. The printed TPU 95 filament was applied in different thicknesses: 1 mm for tests E and F; 1.5 mm for A, C and D; and 2 mm for B. The combined influence of pattern geometry and material thickness results in visible formal differences, and these are described below:

- Test samples, A and C, which have 1.5 mm embossing display shallower edge curves and a more open central area;
- In contrast, samples E and F with only a 1 mm 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 2 mm 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.

Design Experimentation 2

The initial tests in Design Experimentation 1 illustrated how the form and behaviour of the hybrid material could be controlled and manipulated. Design Experimentation 2 aimed to investigate four further variants on

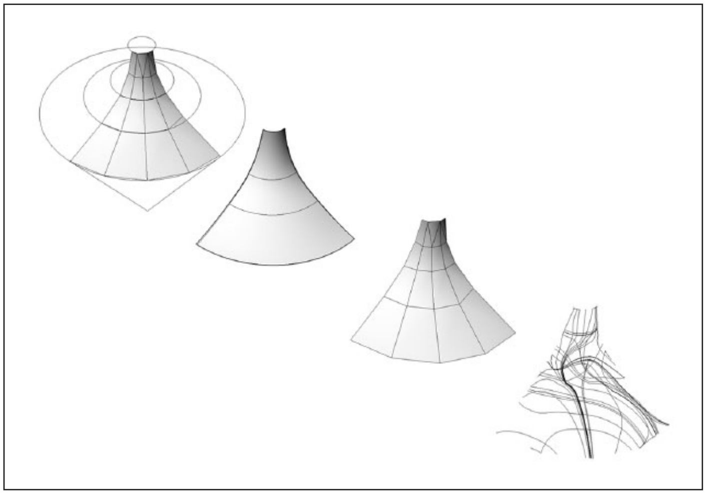

Figure 5. Stress lines derived from the Karambe simulation script.

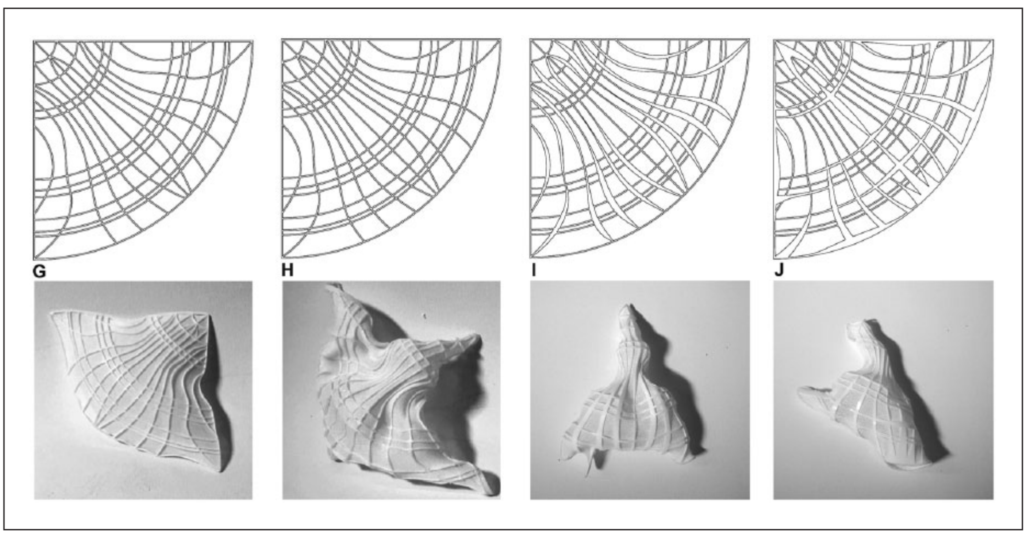

Figure 6. The effect of radial and tangential ribs on a quadrant shaped panel: iterations G, H, I and J.

this theme, focusing on quadrant shaped panels with the embossing pattern laid close to principal stress lines (see Figure 5).

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.

Iteration G shown in Figure 6 was printed with a 3 mm embossed TPU 95 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 2-mm TPU 95 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.

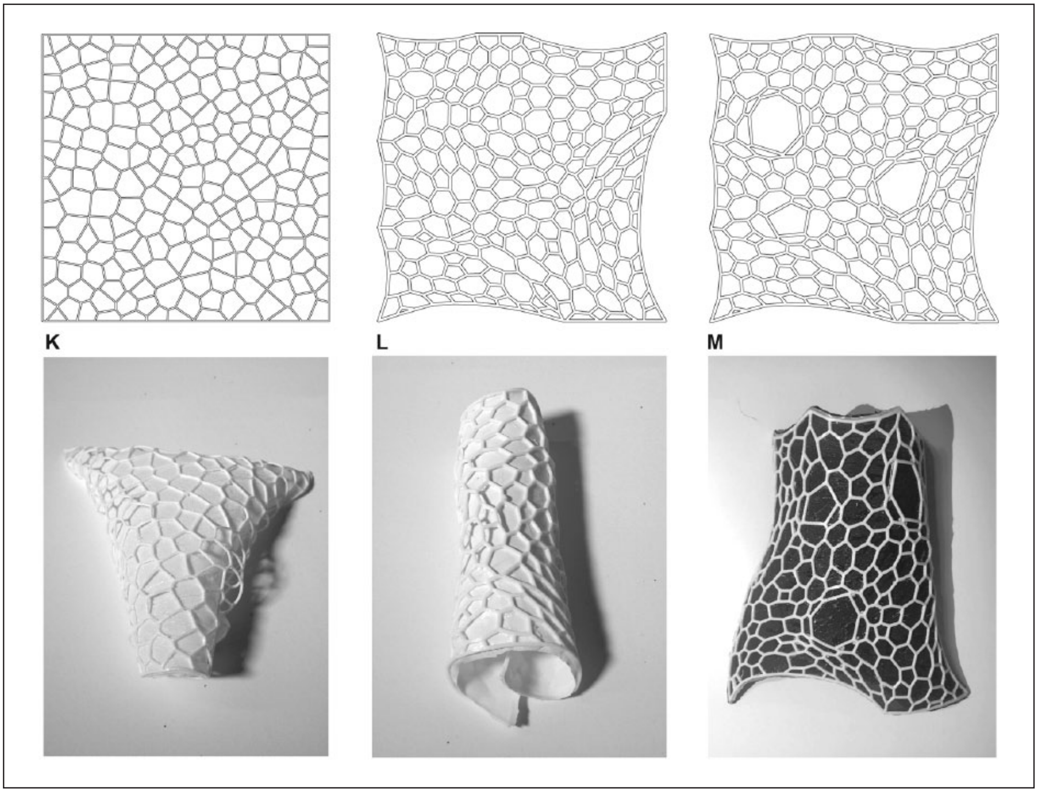

Figure 7. Multi-directional Voronoi iterations K, L and M.

For the final two iterations in this series, I and J, as for iteration H, the embossing was applied using 2-mm TUP 95 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 results in an even more voluminous product with tighter curvatures and more significant deformation to the edge condition.

Design Experimentation 3

The previous design experimentations described above had dealt with embossing in a combination of radial and circumferential ribs, better responding to principal stress lines. Our final design experimentation examines the behaviour of multi-directional 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, and the results are shown in Figure 7. All tests were again conducted using a 200 × 200 mm Lycra sheet as the base of the hybrid material, again stretched 50 mm in both directions.

Iterations K, L and M were printed with 2-mm TPU 95 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

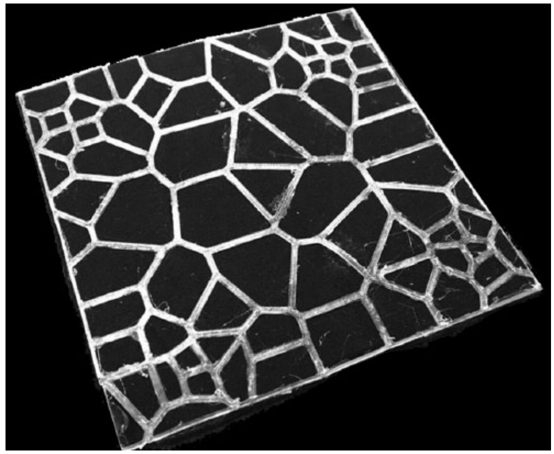

Figure 8. Multi-directional Voronoi iteration N, polypropylene embossing.

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 (see Figure 7), 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, of 2 mm thickness as in the experiment with the TPU 95. 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 (see Figure 8). In addition, the material proved to be unstable and unreliable as a laminate, so the additional planned tests with polypropylene embossing were not undertaken.

Discussion and conclusion

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

Even though the design experimentations 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) predicts the overall general form of the prototypes, in the case of a hyperbolic paraboloid, there were still discrepancies between the digital and physical models (e.g. particularly as noted in cases of large displacement in Design Experimentation 2; 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 the final shape and behaviour of the prototypes was fundamentally related to the pattern geometry, the pattern edge condition and the hybrid material properties, in particular, embossing thickness and width.

Looking into Design Experimentation 3, which investigated multi-directional Voronoi patterns, it appears that the pattern density in combination with the pattern footprint perimeter form 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 (e.g. than in L) – 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 normally be the case in architectural applications. 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.[16]

The composition of the 3D-printed filament, as well as the glue used for its lamination onto the textile, proved to be another important parameter influencing the prototype's formal behaviour. Two of the potential embossing materials tested before TPU 95 proved to be unsuitable. As noted above, printing thin elements using semi-elastic polypropylene gave disappointing results (Figure 8). The irregular edges and potential over-heating during the printing process proved major obstacles that forced us to continue our experiments with TPU 95. We had an even more substantial failure in trying to use nylon filament, where the filament's 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 thicknesses 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 pragmatically by mechanical bonding in our current experiments. This could be significantly improved by direct printing on the textile sheets. But a particular problem is the high melting temperature of the TPU 95 filament, which would be incompatible with that 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 Zelig[20] and the 'Active Shoes' project by Guberan and Clopath[19] 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 article, 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 soya protein fibre (SPF), although not at the tensile strength of polyester fibre do have higher tensile strength than cotton-based fabrics[21] that Frei Otto used and have other important qualities such as UV resistance. There are, therefore, interesting possibilities for further investigation and development of the techniques and materials for architectural applications.

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