KES Transactions on Sustainable Design and Manufacturing I
Sustainable Design and Manufacturing 2014 : pp.50-66 : Paper sdm14-036

Subtractive Manufacturing for Variable-Stiffness Plywood Composite Structures

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Abstract

This paper investigates the development of a subtractive material technique whereby plywood sheets are slotted in order to achieve variable stiffness, resulting in articulated bending curvatures across global surface geometries. Derived from the differentiated distribution logics found in natural systems, this research employs material computation strategies along with digital analysis and fabrication techniques for the design of performative variable-stiffness structures. The material technique was tested in its application to a research pavilion undertaken by staff and students in the Emergent Technologies and Design program at the Architectural Association School of Architecture during the academic year 2012/2013. Through a process of optimisation the proposed design was adapted to meet structural and programmatic demands. Upon analysing a series of successes and failures with its first installation at Hooke Park, the structure was redesigned and installed at the Architectural Association's Projects Review in London.

1. Introduction

Architectural systems are often designed as agglomerations of various independent elements, mechanically jointed in the construction of larger forms. While scale and the availability of prefabricated products often dictate the necessity for component-based assembly, these systems are conceived as a complicated kit of parts, rather than one of complex integration. This integration of various specialised performance requirements within a single system can be made possible through the development and implementation of composite structures, where the intelligent variation and distribution of material provides exciting potentials for the structural, environmental and spatial performance of an architectural proposal.

Numerous surfaces found in biology operate in this way, embedded with the geometric, material and organisational information necessary for effective performance. Biomimetic design has long been implemented in the engineering sciences, specifically in robotics [1,2] and medical sciences [3]. Material strategies found in nature, however, also hold potential for architectural solutions. Within this framework, continuous composite surfaces can be developed through physical and digital computational techniques and digital fabrication tools in order to achieve differentiated performative effects.

2. Background

2.1 Natural Systems

Natural systems are composed of just four different fibres, arranged in complex organisations with specific, choreographed relationships and optimised distribution patterns. Across many different scales, from cells to organs to organisms, the variation and distribution within the hierarchies of these natural complex systems produce redundancy, robustness, strength and adaptivity, leading to higher-level system function. It is the existence of a hierarchical distribution of structures and assemblies that produces intelligence within natural systems, allowing individual elements with varied data sets to interact in highly choreographed ways to produce emergent effects of a higher order. It is this distributed intelligence that creates collectives, each with varied levels of success, achieving complex dynamic systems that are in fact greater than the sum of their parts.

In the 1830s, German botanist and Darwinist Matthius Schleiden recognised that plants were made of individual cells cooperating to form a whole -- the organism [4]. As one of the first pioneers of its kind, Schleiden touched on the concept of collective intelligence in biology, where relatively simple individuals, programmed to carry out individual tasks, can achieve complex higher-level functionality through specific relationships and hierarchical organisation.

Examples of continuous surfaces in nature, such as lobster [5] and turtle shells [6], exhibit differentiated performance due to the variation and distribution of material within carefully evolved global geometric forms. The differential organisation and density of fibres allows for optimised performance toward different criteria within the same continuous structure. The extraction of these logics through physical and digital computational analysis and evaluation provides innovation from which architectural design strategies emerge.

2.2 Material Manipulation and Computation

The anisotropic qualities of wood have long been exploited in architectural design, and have been the subject of recent research pavilions around the world; this research has been predominantly focused on the bending properties of the material, and its form-finding capacity within these limits [7]. Previous research within the Emergent Technologies and Design Programme at the Architectural Association has contributed to this area of inquiry with its pavilion designed in collaboration with the Chair of Structural Design at the Swiss Federal Institute of Technology Zurich. The pavilion was constructed of 18mm thick sheets of plywood, some as long as 11m, relying on the bending properties of the material under gravitational load. A slotting pattern was introduced to alleviate stresses in the plywood and decrease bending stiffness, resulting in a self-supporting enclosure [8].

Past research on material manipulation for differentiated performance, and in particular variable stiffness, in architecture, has been largely limited to generic patterning employed to reduce local stresses, or transform rigid materials to gain local flexibility. These procedures, applying regular kerfing [9] or slotting patterns on plywood [10,11,12] to induce high degrees of bending have largely resulted in surfaces with one continuous radius of curvature, limiting the effects of a material technique with great potential.

In developing the capacity of plywood structures in bending, initial research focused on a material manipulation technique whereby plywood could be perforated with slotting patterns of various densities and directionalities based on the principal and mean curvatures of the global surface. These patterns resulted in stiffness variations within the material at numerous locations within the surface, allowing for the single plywood sheets to take various curvatures through bending. In this vein, the anisotropic material properties of plywood were explored, combining the primary grain direction plywood with a subtractive digital manufacturing technique with a 3-axis CNC router. The generated surface exhibits variable flexibility obtained through strategic placement of a perforation pattern relative to the primary fibre directionality of the plywood (the direction of the outermost layers, as the odd number of layers will always lead to this being the dominant direction). Through material testing, a relationship between slotting pattern and uncut material within one curve along the surface was defined as 100mm to 10mm. To avoid continuous lines of stiffness resulting from the linear continuity of uncut material (which would prohibit necessary flexibility) the dashed lines were arranged in an alternating order, offset half the distance of a single slot for each consecutive perforation line.

This material technique was coupled to a surface curvature rigidification strategy, whereby carbon fibre composite strips were used on its edges. Contrary to typical procedures in composite fabrication where fibrous layers are built up through individual plies on an external mould [13], the proposed system uses the bending behaviour of plywood as formwork, where the inherent geometric constraints of the material determine form. Rather than relying on high-tech manufacturing practices, the surface, constructed of a plywood and thermoplastic pre-impregnated carbon fibre composite, was to be designed and built using only 3-axis CNC routing and assembled by hand. All necessary connections were made between the two materials without additional mechanical connections. By using the inherent material properties of plywood to find the desired form and the carbon fibre's capacity to take tensile forces, the composite material system allowed for flexibility in formwork and stiffness in structure.

Figure 1. The slotting pattern allowed for differentiated curvatures throughout the structure.

3. Case Study: Carbon Curve

Integrating examples found in nature with previous experimentation allows for innovative strategies in material techniques to be employed in achieving spatial effects across differentiated surfaces with varied curvature and lighting gradients. In order to test this hypothesis, the Emergent Technologies and Design Programme at the Architectural Association focused on the design and construction of a research pavilion in 2012-2013. This research was aimed at developing a 6m x 3m shelter of a single surface, capable of providing wall, roof and seating, structural performance, and varied spatial conditions.

Figure 2. *Carbon Curve* installed on site at Hooke Park, Dorset.

Through an iterative design process of calibrating the global geometry with physical testing of curvature limitations and adjustments on the implemented variable slotting pattern, the continuous surface embodies differentiated stiffness, structural performance, viewing opportunities and various programmes through the computation of material properties and digital fabrication. During a week-long workshop, four sections (approximately 50%) of the designed shelter had been constructed in the woods at Hooke Park.

3.1 Development of Geometry and Design Method

The principal design concept was based on a primary surface articulated as a tube which performed as roof, wall and floor, with large viewing openings supported by articulated fins. To integrate the required programmatic functions such as seating within the form, a sequence of programmatic sections was developed and the resultant geometry was generated by a lofted surface between the sections.

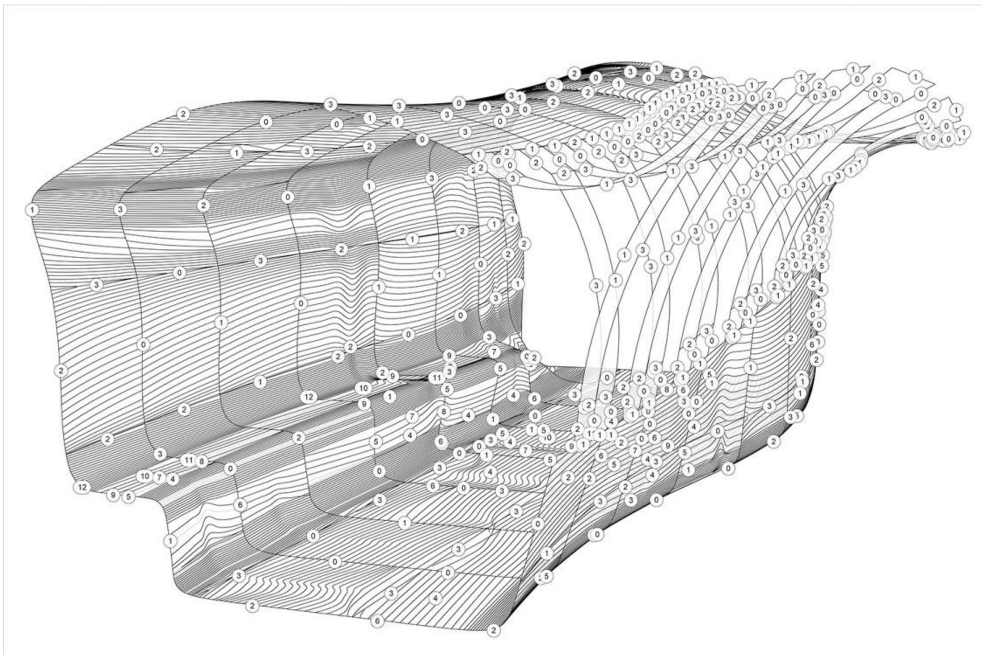


Figure 3. Computational techniques allowed for the analysis, subdivision and organisation of the continuous surface.

In order to optimise the structural efficiency and minimise the amount of material required of the surface, the structure was analysed with Karamba, a Finite Element Analysis plug-in for Rhinoceros 3D's associative modelling tool, Grasshopper, and optimised with the use of the evolutionary solver Galapagos, also in the Grasshopper environment. This genetic algorithm controlled regional geometry through control point manipulation to find fit geometries that met geometric, programmatic, and structural requirements; surface areas designated for seating were analysed by stochastically measuring height, surface curvature gradients, and angles between seating and back wall. Additionally, local surface curvatures were analysed to ensure that each individual panel possessed single curvature or nominal double curvature (with a high principal curvature in one direction) could be manufactured within material limitations. Individuals outside of the range of functional programmatic spaces or too extreme curvature values were not taken into account by the genetic algorithm.

The surface is conceived as a single entity; for construction purposes, however, the global geometry was split into eight sections of 800 mm width. Each of those sections was further divided into eight panels each. The connections between the single panels were made with a thermoplastic pre-impregnated carbon fibre tape, which also acted as the structural grid. Therefore it was important to ensure that all connection edges had curvature in one plane only and were developable along the entire surface. To follow this logic, lines of subdivision in both directions were based on geodesic curves plotted on the surface. To prohibit high curvature values close to the edges the cut lines in the longitudinal direction were placed in areas with curvature values approaching zero.

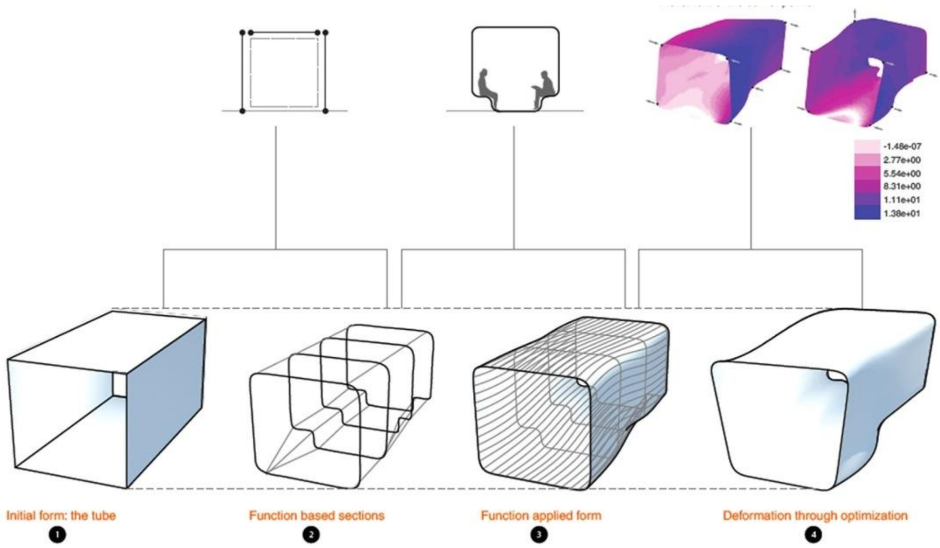


Figure 3. The global geometry was found through the optimisation of the surface with regard to the possible curvatures given by the plywood's material properties.

To generate this slotting pattern, and therefore the production data for the CNC milling machine, an algorithm was developed to locate the orientation and density of the perforation pattern according to the corresponding curvature values. Starting on the edge with the highest curvature of each panel, the initial edge curve (in the U-direction) was divided into a set number of segments, of which the distance between subdivisions is dependent on the curvature at each analysis point. Starting at one end of the edge curve, a sphere is drawn with a radius equal to the maximum principal curvature at the specific point; the intersection of this sphere with the initial edge curve acts as the next evaluation point. This recursive algorithm was repeated through the edge, resulting in a number of points in a density gradient based on the curvature in the U-direction.

The next step generated lines in the surface's V-direction on each panel using the extracted evaluation points from the previous step. To create the density gradient throughout the whole panel in the V-direction, these lines were divided into a specified number of analysis points, which lead to a grid of U/V points on the surface. By remapping the U-value at each point of the grid based on the corresponding mean curvature, the grid became denser in areas of higher curvature and less dense in flat regions.

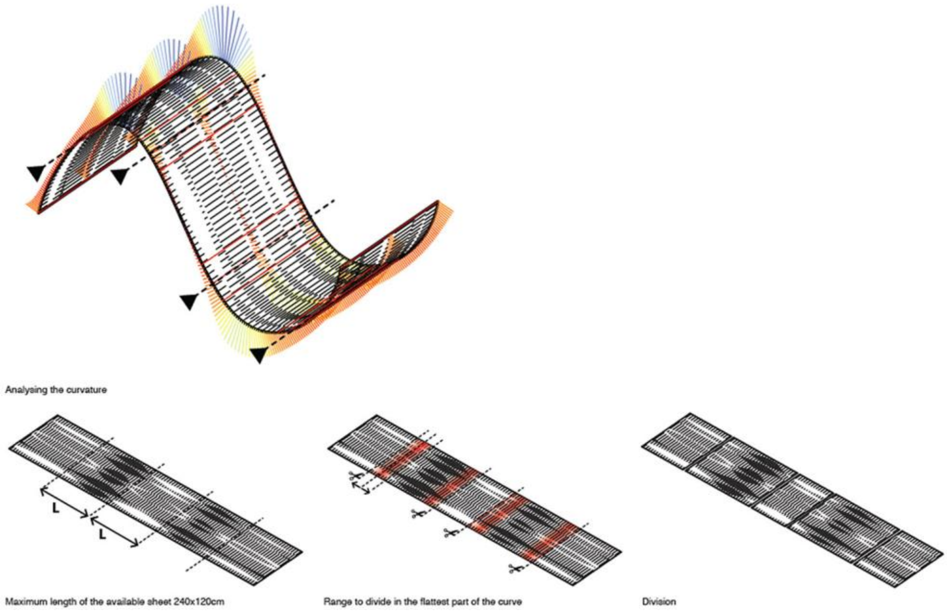


Figure 4. An algorithm was employed to translate surface curvature to a slotting pattern and direction.

3.2 Fabrication, Manufacturing and Construction

Due to the compressed design and construction schedule, the development of an algorithm for accurate calibration of the slotting pattern and bending behaviour was not achieved, requiring the introduction of edge profiles made of plywood on which each panel was formed. To save production time as well as material, two panels shared one edge profile. To ensure a fluent forming process, two adjacent panels were cut concurrently, allowing for a continuous forming process. During this process, the panels were temporarily screw-fixed onto the edge profiles, and while the panel was kept in the desired form, two layers of carbon fibre tape were applied on the interior and exterior of each edge.

This carbon fibre tape was pre-impregnated with a thermoplastic resin (PEEK) but its high melting point of roughly 340° C [14] made it impossible to practically bond to the plywood without burning it. Therefore, another bonding method was required to connect the carbon fibre to the plywood. Through a series of physical experiments with different types of adhesives, hot-melt PVA glue was found as the appropriate compromise between melting temperature, setting time and stiffness in its set state. PVA glue was subsequently applied to the carbon fibre tape, re-melted and applied under pressure to the plywood panel. After setting, edge profiles were removed and sections connected with a 75 mm wide strip of carbon fibre tape on each side of the panel. Complete sections were assembled in the workshop and transported and erected on site. The connection between the sections follows the same logic as the described connection between panels.

Figure 5. Panels were screw-fixed temporarily into edge profile curves before held in place through the application of pre-impregnated carbon fibre strips.

The fins proposed for the open section of the structure buckled under the compressive load of the roof; to keep the structure stable through geometric continuity, ribs were cut from two sheets of 12 mm plywood following the curvature of the global surface to provide the stiffness necessary while keeping the section open for views and sunlight. These ribs were placed as structural members between roof and parapet after the sections were erected and joined together, allowing for small adjustments due to construction tolerances.

4. Analysis and Redesign

The construction phase at Hooke Park exhibited various issues within the system regarding the translation between physical and digital experiments as well as the actual structural impact of the applied slotting pattern. While the proposed bonding techniques and panel joinery proved successful, there were a series of structural performance issues with regard to the global geometry. The slotting pattern of the plywood panels provided some unexpected shadow and lighting conditions both during the day and at night but it also led to localised structural failures; in extreme cases, slotting led to a decrease in stiffness by a factor of 60 (as understood through subsequent analysis with the Finite Element Method in Strand7 described below) to that of the unslotted plywood sheet. This lack of stiffness caused delamination of the carbon fibre from the plywood on the compression side of the shelter, even though the tension side performed effectively [15].

In order to better understand the structural failures of the shelter, computational structural analysis was performed using Finite Element Modelling in Strand7. Section 6 of the shelter was analysed in detail in preparation for its construction at the Architectural Association's end of year show, Projects Review. Structural analysis with the Finite Element Method performs numerical computation on subdivisions (called an analytical mesh) of a global geometry, enabling accurate structural analysis for complex geometries. However, because of the large meshing requirements due to the slotting, the section required analysis in smaller pieces. Therefore, each panel of Section 6 was further divided into slotting pattern types, from wholly intact to densely slotted. By analysing patterns individually, the behaviour of the slotting pattern could then be translated into effective material properties for each panel to be tested computationally.

The results of this analysis provided various levels of information. Most importantly, it was discovered that in order to achieve the required stiffness with the specific slotting pattern used, a thicker lamination of carbon fibre on the tension side (interior) of the structure would be necessary. The thickness of carbon fibre necessary, found to be 6 mm would be difficult to achieve considering the bonding method used. The bonding of the carbon fibre to the wood was done through heating and gluing each layer separately; the subsequent layers of carbon fibre were then bonded to the previous layers. However, due to the constant heating of the carbon fibre, under-layers tended to delaminate. While this is controllable with 3-5 layers, achieving the required thickness would prove extremely difficult in the existing construction conditions.

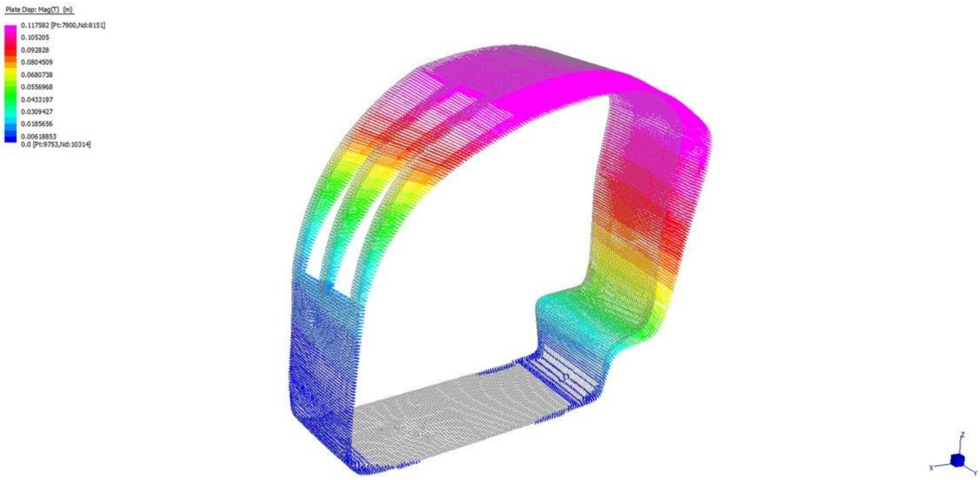


Figure 6. Structural analysis was used to determine the performance of Section 6 before its construction in the Architectural Association's *Projects Review*.

To create a necessary structural depth of 24 mm, a series of edge ribs along the cross sections were introduced between the sections, similar to the stiffening skeleton of an airplane body. These ribs consisted of four layers of 3 mm plywood (two layers on the inside and two layers on the outside of each section) and were connected to panels during the forming process. The ribs for each section were divided into eight parts, each of them connecting two panels. This ribbing on each edge provided greater rigidity to the sections without the need to alter the existing pattern, allowing for the maximum amount of perforation and resulting lighting effects.

The cantilevering seat area, on the other hand, needed to be addressed with new design aspects. The observations during the construction phase at Hooke Park have shown that the seating area, with its dense perforation pattern, was highly vulnerable to structural failure, and too flexible. These panels were unable to take the load coming down from the back wall and roof of the shelter. The proposed solution was to create a fixed frame of plywood onto which the seating panel would be formed. Different to the other panels, the edge frame was kept for the required structural support. With these redesigned features, the section was installed successfully on site at the AA Projects Review.

Figure 7. The differentiated slotting pattern on the plywood panels allowed for variable stiffness and emergent lighting effects, although did not provide sufficient structural performance with regard to global stiffness.

5. Discussion

Learning from this series of analyses, it is intended to develop new strategies of slotting pattern generation, calibrate its influence on possible curvatures and bending with regard to geometric and structural performance, and fabrication of the material system to eliminate extraneous elements for future research into the material technique.

5.1 Material Manipulation and Patterning

While the construction of the single section was achieved, a series of design and performance issues arose. The introduction of edge ribs were used in order to provide the necessary stiffness of the structure. Their inclusion acted as an acceptable addition to the conceived system, however did not operate wholly as an integrated element in the design. Therefore, rather than increasing the thickness of the edge condition with an extraneous rib, a clearer understanding of the slotting pattern could prove beneficial. Although the slotting pattern allowed for the transformation of the material from its inherently stiff state to one of flexibility in areas where certain curvatures were needed proved to be successful, the influence and relation between perforation, structural performance and bending behaviour of the perforated plywood was not explored sufficiently. Therefore it will be necessary to evaluate the geometric relationship between slotting length and distance between cuts to sufficiently correlate its influence on local bending behaviour and global stiffness, and how shifts in pattern density can provide control of the actual bending curve, as shown in previous research on the subject conducted in the Emergent Technologies and Design Programme at the Architectural Association School of Architecture [16].

Based on this work, a strategy of bending full panels of plywood exists where the density of the slotting pattern shifts along a series of axes along the surface. Through an investigation of the material constraints with regard to pattern generation, it is possible to gain control over the bending behaviour of the panels, and therefore control structural performance as well as geometric articulation. Since the slotted panels allow curvatures primarily in one direction (perpendicular to the slotted pattern), the future design should thus be based on ruled surfaces.

5.2 Fabrication Strategies

A production method based entirely on the inherent bending behaviour of plywood provides the possibility to avoid additional formwork used in previous experiments. Focusing on the design of geometry through the controlled bending of edge curves, panels can be held in place by determining the required distance between adjacent corners of opposite panel edges. This reduction of rest length in combination with an optimised and accurately calibrated slotting pattern can provide a simplified moulding technique. Since the panel curvature is highly dependent on this distance, the practical fabrication requires incredibly small tolerances; an incorrect dimension within a small percentage of the length would lead to discontinuity between panels and therefore within the surface. Thus, future research will focus on a computer numerically controlled bending mechanism, coupled to the precise measurement of tensile members, to ensure accurate dimensional lengths from which each panel will be formed. With tensile members in place, each panel can be removed from the jig and glass fibre can be applied as required.

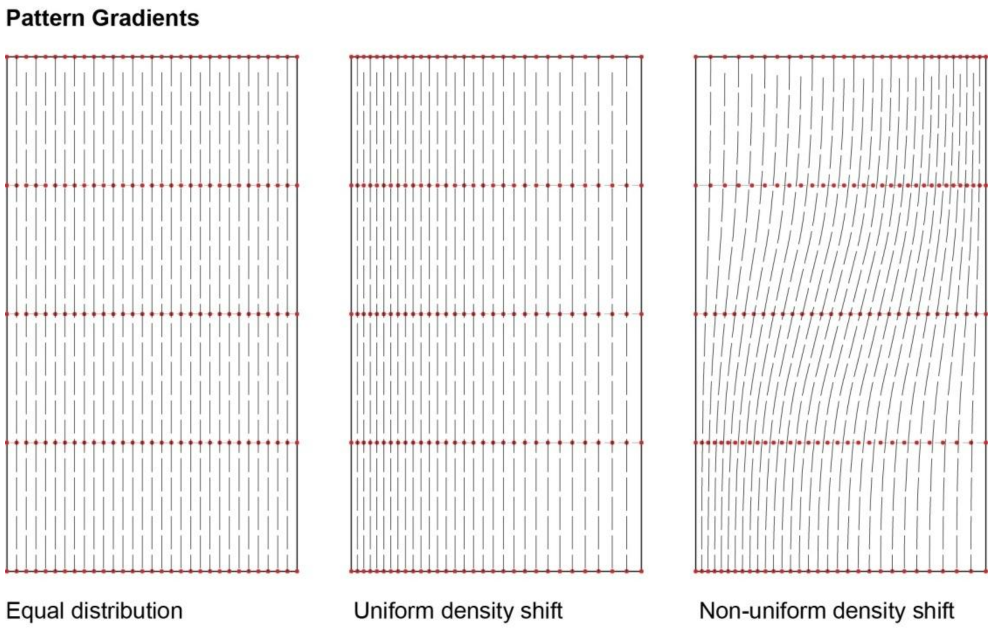
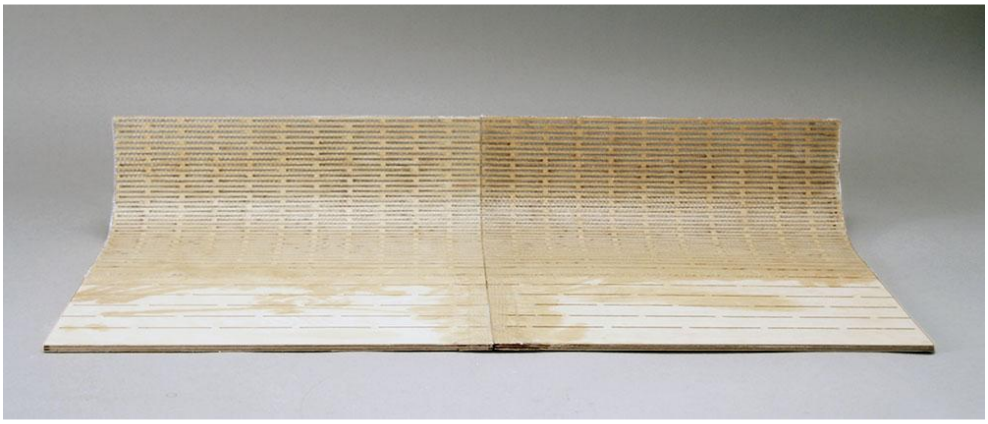


Figure 8. Different pattern density gradients along specific axes allow for controlled stiffness variation within the panels.

In order to test a modified fabrication strategy, first experiments undertaken have shown that the irregularities within the plywood lead to minor inaccuracies of bending curvature in adjacent panel edges, as discussed above. In addressing these deviations, plywood shims, acting as locking mechanisms, were implemented to connect adjacent panels. This lock, utilising friction between panels, proved sufficient in connecting panels and ensuring continuous curvature. In future development this mechanism could be integrated into the panel through a finger joint system.

Thus, a future proposed assembly process sees panels formed and kept in shape by tension cables and connected with the finger joints. In connecting panels, where carbon fibre was previously applied as a 7 mm seam, an increased amount of fibre coverage can improve the resulting stiffness of the plywood panels. Rather than apply thin strips of carbon fibre across the plywood panels, an increase in applied surface area could be achieved through the use of a woven textile. By increasing the coverage area, the structural properties of glass fibre could prove sufficient. Thus, the plywood panels could be reinforced with a glass fibre composite where necessary for structural performance; that is to say, where the panel is weakened by required slotting, a larger area of glass fibre could be used to stiffen the geometry. This differential surface treatment could provide further architectural opportunities. The glass fibre composite provides a translucency that could be used to modulate direct sunlight in areas of dense perforation. Similarly, the solid surface covered by the glass fibre could provide shelter from rain in a roof



condition.

Figure 9. Initial experiments investigating partial surface cover with glass fibre and a thermoset resin, applied only where stiffness on the surface is required.

6. Conclusions

This research investigates the opportunities provided by the differentiated material organisation found in natural systems and their application in architectural design using composite structures. The integration of digital and physical computation within the design process is paramount; the calibration of material performance provides strategies for design, fabrication and construction of complex material systems. With continued research on pattern density, gradients and location with respect to required curvatures and structural performance, as well as the intelligent application of a fibre composite, the material system investigated has the potential to provide innovative architectural solutions embedded within one intelligent surface. By implementing sensing capabilities with the deployment of smart materials within the fibre composite layer, the system can further respond or adapt to environmental conditions such as light, wind or humidity. Potential exists in artificial lighting embedded within electroluminescent foils to provide global effects to local shape change in creating differentiated surface porosities.

7. Acknowledgements

Portions of this research were undertaken in the Emergent Technologies and Design Programme at the Architectural Association School of Architecture during the 2012-2013 academic year.

Academic Supervisors: Michael Weinstock, George Jeronimidis, Evan Greenberg and Mehran Gharleghi.

Design and Fabrication Team: Yan Bai, Nicolas Cabargas, Abhinav Champaneri, Marco Corazza, Viral Doshi, Çağla Gürbay, Shih-Hwa Hung, Axel Köerner, Anna Kulik, Mikaella Papadopoulou, Miguel Rus, Tejas Sidnal, Tessa Steenkamp, Mehnaj Tabassum, Yuchen Wang, Yunfu Yu, Jinjing Yu and Carlos Zulueta.

Hooke Park Workshop Manager: Charlie Corry-Wright

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