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From Distortions to Design: Self-Morphing Frustrated Composites at Architectural Scale

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Abstract

Self-morphing frustrated composite materials offer a new approach to mouldless fabrication of surfaces of complex geometries in architectural design. This paper presents a detailed case study on the integration of self-morphing frustrated composite materials into architectural design. While composite materials have found extensive application in industries such as aerospace, automotive, and architecture due to their favourable strength-to-weight ratio, their conventional fabrication processes rely on custom moulds, leading to sustainability concerns. Self-morphing is a new approach that leverages the intrinsic properties of the material and its internal architecture to autonomously generate 3D shapes through geometrical frustration, potentially eliminating the need for moulds. The research showcases an application of frustrated composites at an architectural scale, as an indoor partition, 'The Swirl', exhibited at the London Design Biennale 2023. Through this case study, the paper examines the entire pipeline for frustrated composites and focuses on key issues: rationalisation, panelisation, patterning, and fabrication. The paper introduces and addresses the fundamental challenges of frustrated materials in architectural practice, providing insights for further innovation in the field.

Keywords: Self-morphing, geometric frustration, FRP, mouldless fabrication, digital fabrication, frustrated materials

1. Introduction

1.1. Composite Materials for Architecture

Composites are materials that consist of two distinct constituents with different properties that, when combined, produce a material with superior properties. In fibre composites, the constituents are in the form of fibres embedded in a polymer matrix material, known as fibre reinforced polymers (FRP). Thanks to their combination of high strength-to-weight ratio, ability to be moulded into complex shapes, corrosion resistance, and ability to withstand extreme temperatures, FRP has become widely applied in the aerospace, automotive, and marine industries [1]. In comparison, composites in architecture are still at a relatively low adoption level. In architectural design, their use is mainly as cladding and canopies of complex geometries, in extreme environmental conditions or where exceptional structural performance is required [2]. For example, The Stedelijk Museum in Amsterdam, completed in 2012 and designed by Benthem Crouwel Architects which features a remarkable 12-meter cantilevered overhang, made possible by the qualities of FRP [3]. Other examples include the SFMOMA expansion by Snøhetta and One Ocean Pavilion by soma [4], [5]. These require the creation of unique moulds, which are both expensive and wasteful. There are numerous industrial fabrication methods for composites: wet lay-up, spraying, injection moulding, and more; common to all is the use of a mould over which the fibres are laid, to obtain a required geometry [6]. In the case of architecture, the typically complex geometry, non-repetitive and one-of-a-kind design, requires the custom creation of a complex mould in large scale. This mould is crafted using a second material through a milling machine, a time consuming and expensive process that demands multiple steps and skilled personnel. Once the product is cured, the mould is discarded, resulting in a large amount of waste, including material waste and time and personal inefficiency, making it an unsustainable approach [1], [7].

1.2. Mouldless Fabrication of Composites

In recent years we've seen vast academic interest in alternative fabrication methods for various material systems, aimed at reducing reliance on traditional moulds for enhanced sustainability. Some approaches focus on alternative moulding techniques, others focus on mouldless methods, each offering different advantages in terms of efficiency and environmental impact [8], [9].

This has also inspired attempts in FRP. Two frameworks have been explored, robotic winding and fabric materiality. Fabric materiality [10] introduces the application of special properties of textiles, the techniques and tools associated with them, and the design paradigms they offer, into the process of fabrication for architecture. This system offers parametric variability, self-organisation, and resilience. Another approach to mouldless composites has been developed in the recent decade by the University of Stuttgart's ICD and ITKE [11], [12], [13] it includes the development of robotic winding fabrication processes for producing individual fibrous building elements. These methods promise very lightweight strong and light building components, robotically fabricated and of "fibrous" aesthetics.

1.3. Self-Morphing Frustrated Composites

A new approach recently introduced for mouldless shaping of FRP relies on material inherent capacities and applies principles of *self-morphing* This technique utilises a physical phenomenon known as *geometric frustration* to achieve a specific geometric shape. [14]. Geometrical frustration in sheets occurs when local deformations cause differential changes in metrics across the sheet, leading the sheet to bend out of plane due to an inability to satisfy both stretching and bending energy requirements [15], [16]. This phenomenon was observed in Bauhinia seed pods [17], these pods consist of two valves, each made from two fibrous layers oriented in perpendicular directions. As the pods dry, the layers shrink in perpendicular direction to the fibre. Each of the fibre layers shrink in a different direction, driving the valves to morph from a flat shape into a helix, which helps the chia seeds spread.

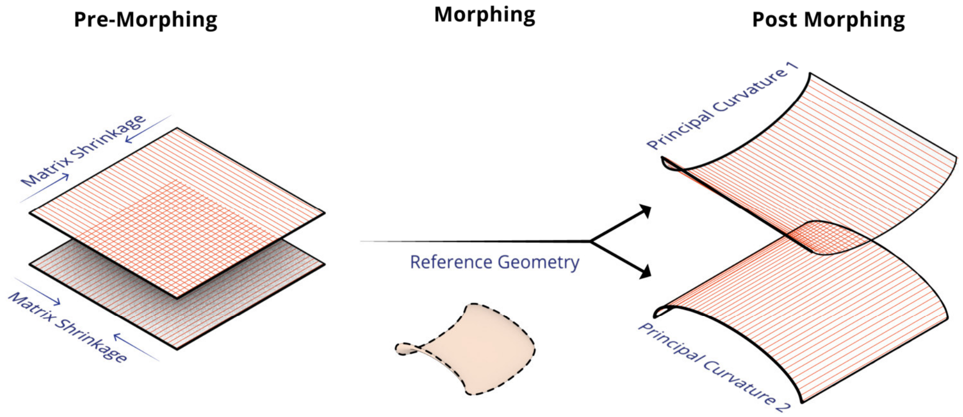

Figure 1: Principle of Frustrated Composites: two layers of perpendicular fibre orientation are laminated, leading to perpendicular shrinkage directions that induce the sheet to adopt a saddle reference shape. Given the thinness of the sheet it operates within the bending regime, saddle reference shape is not fulfilled, resulting in the bending along one of the principal curvatures.

This can also be observed in manufactured composites [18]. The chemical curing of polymers involves shrinking (3-5% for epoxies and 10-12% for polyesters), while fibres do not. In addition, FRP is cured in heat, which causes the polymer matrix to expand and then shrink when removed from the heat while the fibre shrinkage is negligible. This differential shrinkage, along with variations in thermal expansion coefficients upon cooling, generates internal incompatibilities and residual stresses that result in the emergence of a 3D shape; what is traditionally regarded as distortions to be avoided in industrial "good practice", is here harnessed as a desired self-shaping mechanism [6], [14].

When placing unidirectional (UD) fibres there is a uniaxial shrinkage in a perpendicular direction to fibre orientation. Attaching two layers with perpendicular fibre orientations result in a bi-stable cylindrical shape, with each of the stable states manifesting one of the principal curvatures, as described in figure 1. Other factors, such as friction with base surface or differential thickness between the layers can affect the resulting shape, rendering one layer to become preferred, causing the sheet to concave perpendicular to its fibre direction.

Previous work [19]has demonstrated that frustrated composites behave in agreement with physical theory of incompatible sheets, providing us with the ability to control and predict the resulting 3D shape. The curvature direction is typically perpendicular to the fibre orientation, and the amount of curvature is determined by the thickness of the element, along with material characteristics such as shrinkage of matrix and fibre. This control enables effective manipulation of single-curve surfaces. However, architectural design often necessitates complexity, including variations in curvature direction and magnitude or the presence of double-curved surfaces. Composite sheets, constrained by their relative stiffness and inability to stretch, opt to bend, resulting in nearly exclusively single-curved, or developable, shapes. In recent research conducted by Blonder and Sharon it was shown that complex geometry in a surface can be achieved by dividing a sheet into different patches in which the fibres are placed in different orientations, with a common connecting layer. As the assembly of an array of patches forms a continuous sheet, the actual curvature of each patch is affected by its neighbouring patches – both in the amount of curvature and its direction [14]. This opens the possibility of shaping a wide variety of complex surfaces with geometrical frustration which is yet to be explored, but also introduces challenges in terms of controlling and predicting the shape a frustrated sheet will assume upon morphing.

Figure 2: 'Creative Differences' pavilion in LDB2023 featuring 'The Swirl', a frustrated composite partition.

1.4 Shifting to Architectural Scale

Although the potential of frustrated composites is promising, so far it has been tested at laboratory scale only. To establish it as a viable fabrication technique for architecture, an upscaling process is imperative. Upscaling frustrated elements poses unique challenges as scaling alters material properties, such as the boundary-to-element proportion and thickness relative to area, consequently affecting the resulting 3D shape. Upscaling efforts for other self-shaping systems such as cross-laminated wood [20] and inflated structures [21] have demonstrated success in addressing similar challenges. However, these systems differ fundamentally from frustrated composites, with metrics-based approaches for inflated structures and passive mechanisms for wood. Therefore, exploring the scaling up of our system is essential for its application in architecture.

This paper presents the creation of the first frustrated composite element at architectural scale: *'The Swirl'*. It outlines the journey from the initial design concept to fabrication. Firstly, the concept design, geometric analysis, rationalisation, and the generation of initial fibre maps are outlined. Next, the paper describes the process of translating these initial maps into a physical architectural element through prototyping, fabrication, and assembly. This involves tackling issues such as patterning, panelisation, and thickness, each presenting unique challenges that need to be overcome. The paper aims to identify and address the key challenges and opportunities involved in integrating frustrated materials into architectural design.

2. Materials & Methods

Digital tools: For shape analysis, Grasshopper with Rhino3d was employed. Scanning was done using a regular camera and Autodesk Recap Photo.

Physical experiments: Experimental optimisation and exhibition utilised pre-preg fibreglass materials, including fibreglass 'Hexcel Hexply 913 7781' for woven layers and 'Hexcel Hexply 913 UD 280gr' for unidirectional (UD) layers. Pre-preg cutting utilised a professional fabric cutting machine, while manual assembly and installation processes were performed mechanically by hand. Curing was conducted in an industrial autoclave at 125 degrees Celsius for 2 hours with a 2-degree incline per minute. Assembly of panels was done by mechanical connection using screws at overlap; a low wooden stage of 10 cm hight served as base for installation, with a central slit for stabilisation of panels. Panels 2, 3, and 9 were anchored to wooden columns for additional structural support.

3. '*The Swirl*'- Frustrated Composites at Architectural Scale

This paper presents a case study involving the creation of an architectural element designed as the central piece of a pavilion, on the London Design Biennale 2023. The pavilion, "Creative Difference" represents a collaborative effort between scientists and designers, for the exploration of natural models of self-shaping in varying scales and to speculate on their application in fabricating future morphologies [22]. This research begins with a vision for a free-standing architectural element that would showcase the potential of frustrated composites as a self-supporting architectural element. As we wanted a free-standing element, we decided to design the frustrated composite element as a partition, dividing the main space into two separate landscapes and directing the visitors on a suggested path. The partition was designed as a freeform curved wall measuring 2 meters tall and 9 meters long. The height was determined so it would reach the height of visitors while still perceived as an exhibit.

3.1. Analysis

The design was modelled as a 3D surface and the process started with its analysis, executed with sampling points spaced at 10 cm intervals, amounting to a total of approximately 1800 points. For each point, Gaussian curvature and maximum curvature direction and amplitude were analysed. Gaussian curvature analysis revealed that our design has non-developable characteristics, notably marked by a concentration of negative curvature in one corner of the surface and a concentration of positive curvature in another, as illustrated in figure 3. Given the challenges associated with achieving significant amounts of Gaussian curvature in composites through geometric frustration[19] we opted for a redesign of these specific areas. This small redesign simplified the process while preserving the overall shape—a necessary rationalisation step for frustrated composites.

In self-morphing frustrated composites, the sheet concaves perpendicular to the fibre orientation. Thus, our analysis focuses on determining the maximum curvature direction, which will inform our decisions regarding fibre orientations, as seen in figure 4. Likewise, thickness plays a significant role in determining curvature amount. Therefore, we analysed the maximum curvature amount to determine the appropriate material thickness, which, in our case, translates to the number of layers we will utilise in each position, as seen in figure 7 [19].

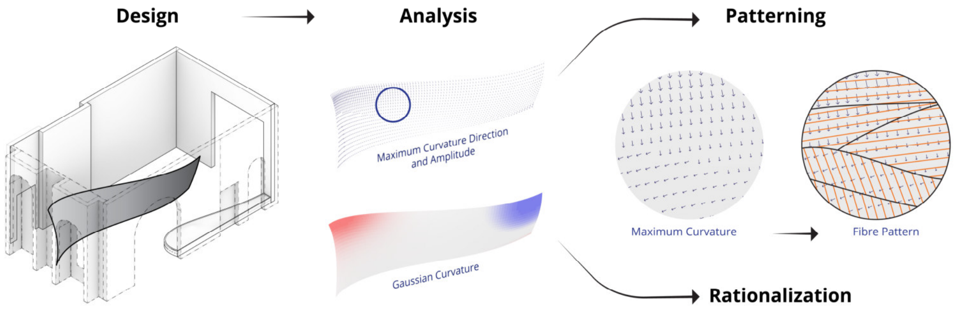

Figure 3: Implementation of numerical analysis tools to rationalise geometry based on Gaussian curvature and to establish initial fibre patterns. Fibre patterns are determined according to the maximum curvature direction, displayed as arrows, while thickness variations correspond to the maximum curvature amount. Positive Gaussian curvature is displayed in blue and negative in red.

3.2. Adaptive Patterning

In previous research complex shapes were achieved by dividing one sheet into a grid of equal rectangular fields, named "patches". Based on the principal of different patches connected by a non-directional layer we introduced here a new method in which the sub-dividing fields are not predetermined like the rectangular grid, but instead patches with boundary shape that derives from the designed morphology.

Principal curvature maps served as the foundation for drawing a primary fibre orientation plan. At each point examined, the fibre orientation was established perpendicular to the maximum principal curvature. The seam lines between patches were tailored to curvature shifts. In regions where curvature changes were more gradual, larger patches were drawn, whereas smaller patches were drawn in areas with frequent changes. Our essential innovation is addressing the desired shape directly, instead of relying on predetermined patterning, thereby allowing for greater freedom and improved accuracy while also providing a unique aesthetic that responds to the curvature.

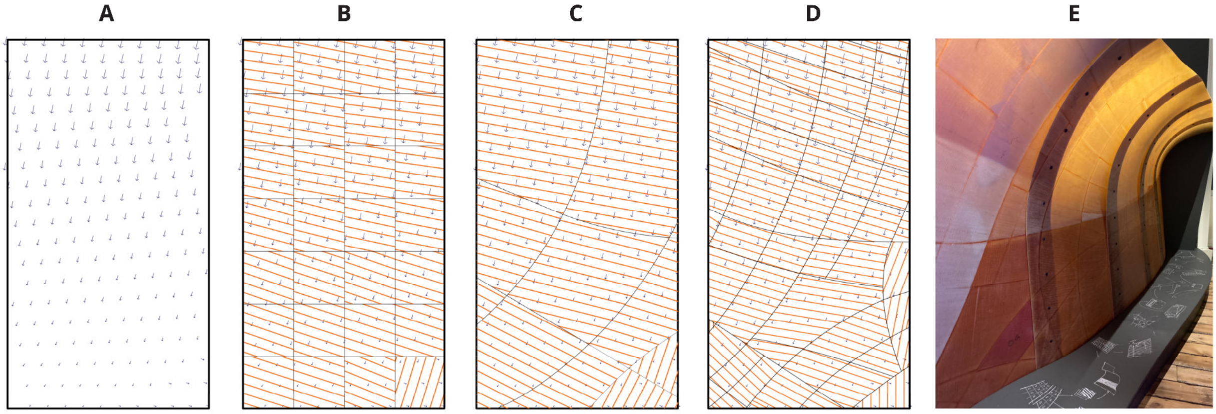

Figure 4: (A) Geometric analysis: arrows represent maximum curvature analysis: direction indicates curvature direction and length indicates curvature amount. (B) Possible pattern using the rectangular grid system. (C) Initial map generated from the analysis. (D) Map after the prototyping process. (E) Photograph of the final panel.

We utilised these fibre maps to initiate a prototyping process. Previous research has introduced a digital simulation tool for self-morphing composites; however, it required further development, lacking an adaptive patterning option and calibration to scale and material. Therefore, this stage was conducted through physical modelling and manual design. It involved creating physical models to observe the resulting shape from the pattern design and modifying it to achieve the desired 3D shape. Experimentation commenced at 1:4 scale. This allowed us to have a layup of 2 layers of UD fabrics on the preferred curvature direction, 1 layer of woven fabric (connecting), and 1 layer of UD fabric on opposite direction, with fibres oriented perpendicularly to preferred direction. This configuration simulated the behaviour of the larger scale by giving preference to one panel side thanks to additional fabric layers, while still maintaining a restricting layer. Acknowledging that it will not accurately capture the curvature's magnitude, we were confident that it would accurately convey the direction of curvature.

Prototype fabrication involved the generation of laser cutting instructions for the patches with the intended fibre orientation. The patches were then manually assembled, followed by oven curing at 125 degrees Celsius for a duration of 2 hours. Morphing occurs when the model is removed from the heat, after which a 3D scan was conducted, enabling us to compare it against the Rhino3D file. Discrepancies between the desired outcome’s geometry and the model prompted adjustments to the fibre plan, triggering a repeated cycle of fabrication and assessment. This iterative process essentially constituted an optimisation workflow resulting in an optimised fibre plan, depicted in figures 4 and 5.

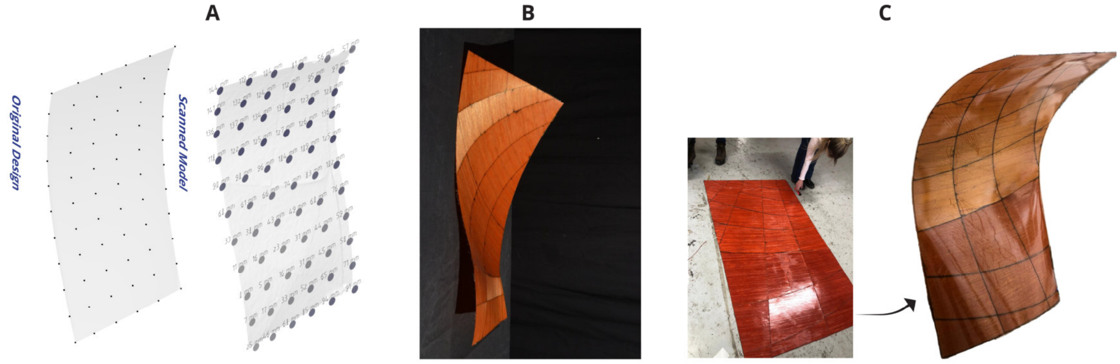

Figure 5: (A) Comparison between the original design and a 3D scan of the physical model overlaid with a grid of sample points, darker colour representing larger discrepancies. (B) 1:2 scaled model of one panel. (C) The first fabricated full-scale panel in flat configuration before curing and after curing and morphing.

3.3. Penalisation

Architectural elements, inherently large in scale, are frequently subdivided into smaller, manufacturable components. This practice is primarily motivated by pragmatic considerations but can be derived from aesthetic motivations. We had these pragmatic considerations as well; curing was to take place in an autoclave which is limited in size and cannot contain the full partition. In addition, it had to be shipped from the location of the autoclave to the exhibition space. For these reasons we decided to divide the 7.5 x 2m element into 9 parts.

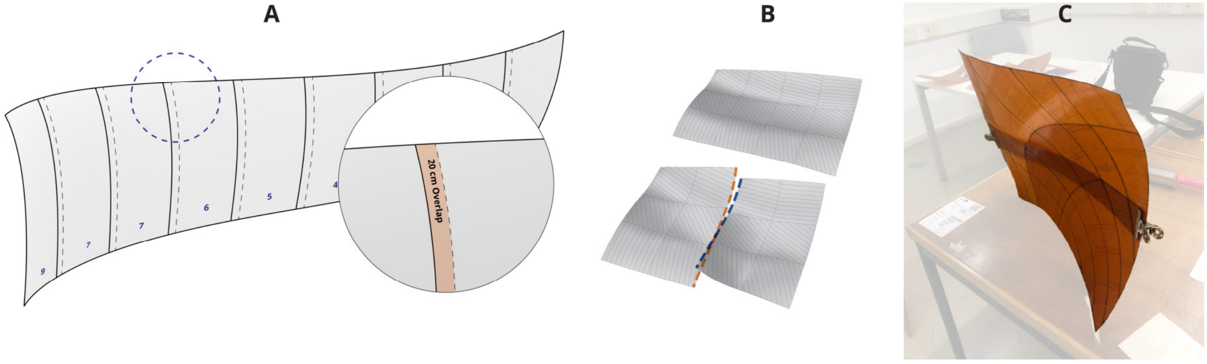

Figure 6: (A) Full surface design divided into 9 panels, each overlapping by 20 cm. (B) Example of potential panel incompatibility shown by dividing one panel into two parts that do not connect. (C) physical models of 2 scaled panels connected.

In frustrated sheets, sub-dividing an element poses an additional challenge. The use of frustration as a shaping mechanism consists of the element finding a balance between internal forces. Each potential cut, border of the element or different seamline affects the geometry of the outcome after morphing. Therefore, we could not devise a fibre plan for the whole element and then divide it, instead the specific panels after division must be considered in the process of determining the patterning. The shape's boundary has a notable impact on its curvature, referred to as the boundary effect in physics. This results in extra curvature near the edges that decreases towards the centre of the shape [23]. Recognizing the contextual influence on the self-shaping technique and its behaviour around edges, a deliberate choice was made to incorporate a 20% overlap between panels, in which the fibre plan is identical to the overlapping panel, to make sure that the panels will connect to each other. Prototyping at scale confirmed the effectiveness of this strategy as seen in figure 5.

3.4. Scale and Width

The 1:4 scaled models could not accurately predict the required material thickness to achieve the desired curvature magnitude since it was unable to account for partial thickness of a layer. Therefore, a different methodology was developed. We conducted experiments with 12 different material architectures, defined as material layups, on 20x20 cm squares, measuring their resultant curvature. This analysis allowed us to establish the correlation between curvature magnitudes and specific layups. To simplify the manufacturing process, we chose three layups corresponding to "thick," "medium," and "thin" categories, accounting for varying degrees of curvature. For areas demanding substantial curvature (radius 0-3m), the thin section was employed. The thick section was utilised for regions with minimal curvature (radius 6m and above), while the medium section was employed for intermediate cases (radius 3m-6m). The variation in section between panel sides makes one side preferred to concave. While in complex panels this isn't always the case and unexpected results can happen, this method still helped guiding curvature towards the desired direction.

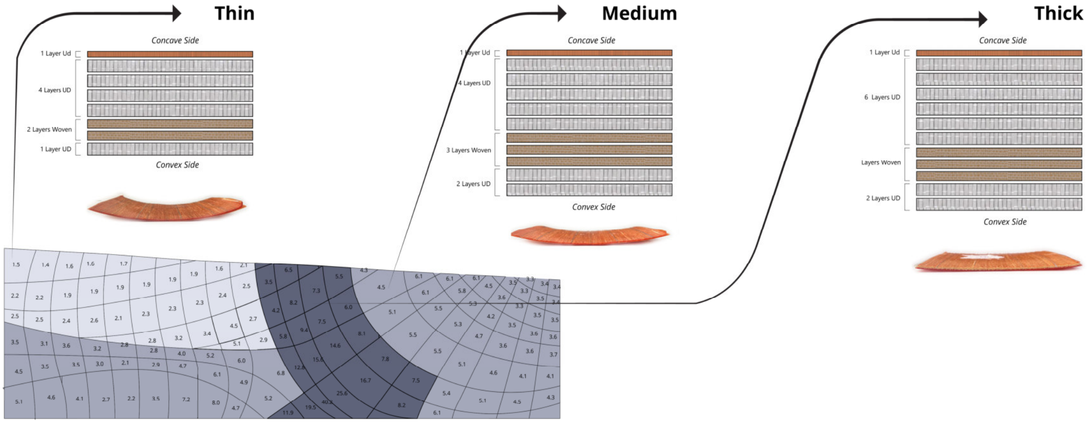

Figure 7: The curvature analysis of each patch of the shape, indicated by the radius of curvature in meters, is divided into three distinct layups, each represented by a different colour. Beneath each layup description, an image of the corresponding physical 20 x 20 sample is provided.

The middle layer, made of woven fabric connecting the entire panel, was increased in thickness up to three layers. This decision was made for several reasons. Firstly, to enhance structural strength, as most of the layers are divided into patches, the continuous fabric layers in the middle are crucial for maintaining structural integrity. Secondly, to reduce the excessive curvature observed during the prototyping phase. Lastly, to avoid the formation of kinks in surface curvature and prevent fold lines from appearing between patches. Varying material layups introduced complexity into the production process, but it was necessary to achieve a diverse range of curvature outcomes.

Prior to embarking on full-scale production, we conducted two large scale tests. We created a corresponding 1:2 model for the 1:4 model, which presented the exact same geometric properties. Research [14] suggests that scaling maintains the curvature ratios but alters the overall geometric relationships due to increased size. Conversely, scaling the thickness of the material reduces the curvature. Therefore, for self-morphing composites, achieving the same post-morphing geometry necessitates proportional scaling of both the shape and thickness. This was consistent with our results as the two models showed the exact same geometric qualities.

3.5 Fabrication & Assembly

The fabrication process involved the utilisation of Grasshopper for the generation of precise cutting and nesting patterns. These patterns were executed using a professional CNC fabric cutting machine. A nesting operation was employed to maximise material efficiency. However, the fixed fibre orientation per patch made it impossible to rotate patches on a sheet, reducing the efficiency of nesting. Total panel area was 18.34 sqm with the layer count varying from 6 to 9 UD layers per patch. The total UD pre-preg used amounted to about 200 sqm, along with 55 sqm of woven pre-preg.

The panel manufacturing process involved manual labour, where the panels were put together. Panel laminates were cured under vacuum in autoclave at a temperature of 125 degrees Celsius for a duration of two hours. Then, the panels were released from the vacuum bags, at which point the self-morphing process was initiated, taking only a matter of minutes to unfold and acquire final 3D shape. Following morphing, we assessed the panels for adherence to the original design. One panel displayed a notable deviation, necessitating adjustments for the final exhibition, while the remaining eight panels closely resembled the original design and required no further modifications. '*The Swirl'* was assembled in May 2023 and displayed throughout June 2023. To establish connections between the panels, standard screws were employed. The entire element was stabilised only at two vertical anchoring points and at its base; the inherent strength of the material itself, combined with the self-supporting nature of the shape, eliminated the necessity for structural reinforcement.

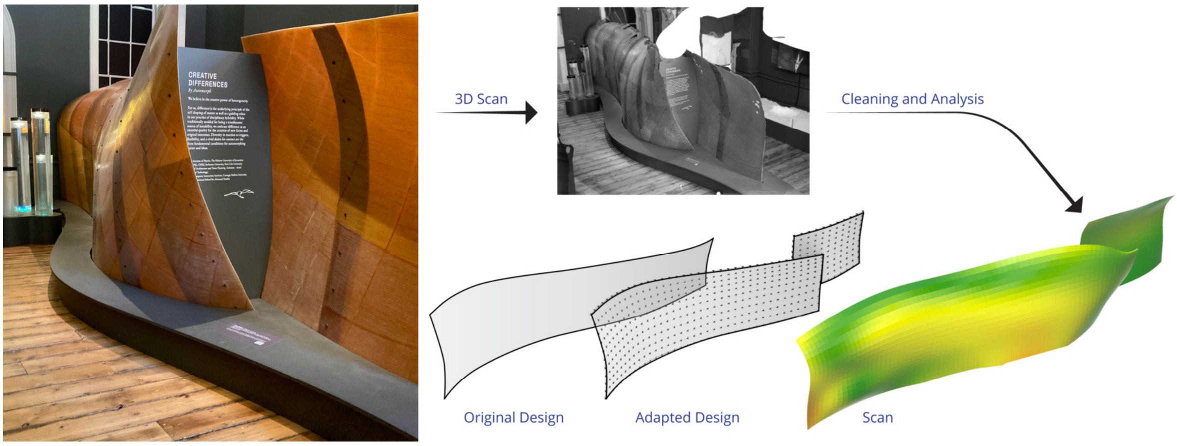

Figure 9: The exhibition space underwent photo scanning, cleaning, and analysis. Green indicates a small difference (0-0.15m) from the adapted design, yellow a medium difference (0.15m-0.4m), and red a bigger difference (0.4m-0.6m).

The exhibit underwent a full scan using photographs and was reconstructed as a mesh. We analysed the scan using the same methodology employed in the earlier stages of the research, dividing it into 10cm sample points. Upon analysing the differences between the planned surface and the resulting ones, we observed an average discrepancy of 0.2m between the surfaces, corresponding to 2.6%. The highest discrepancy was found at 0.6m, corresponding to an 8% difference. Notably, major differences occurred mostly in the corners, which will be considered in the development of computational tools.

4. Discussion

This study pioneers the utilisation of frustrated composites in architecture, shedding light on uncharted challenges such as scale, panelisation, patterning, and fabrication processes, with the goal of bridging the gap between theoretical exploration and practical application. As such, it necessitates continuous refinement and advancement at each stage of the process.

Considering the unprecedented character of the project, we made the deliberate decision to conduct the curing process within a controlled environment. This approach allowed us to allocate sufficient time for the process, minimizing potential risks. Looking ahead, equipped with the findings obtained by this research, we envision conducting the curing process either on-site or in the immediate vicinity. The packing of flat elements offers significantly greater efficiency compared to curved elements, as it minimises wasted space caused by air gaps between and around the elements. This inefficiency in packing curved elements results in the utilisation of larger volumes of shipping space. Addressing this issue not only aims to reduce transportation costs but, more importantly, to enhance environmental considerations. By optimizing the packing of elements to reduce unused space, we can minimise the environmental impact associated with transportation, such as reducing carbon emissions and resource consumption.

The adaptive patterning method created a large amount of material waste due to inefficient nesting. In the future this must be improved. This can be done by rationalizing the design further by posing limitations such as fibre angle, optimising patch sizes with regards to bulk material dimensions, or dismissing the use of curved edges between patches. However, we see the value of adaptive patterning as a method and believe it should be explored further using more advanced methods such as fibre printing, automatic fibre placing or robotic placing of fibres.

As far as panelisation, it is a subject to be examined both theoretically and in practice. Generally, a 20% overlap between panels proved sufficient, enabling smooth and secure connections in the majority of instances. However, in one case, disparities in the edge curvatures between the 2 panels did not allow for a smooth connection. This unexpected difficulty led to an unanticipated design solution that, though not initially planned, ultimately contributed to the exhibition's overall design. This circumstance raises questions about the role of "mistakes" in the production process and the potential value that can arise from them.

Future work in the field should prioritise the advancement of computational methods that would improve accuracy. This includes developing a forward simulation tailored to self-morphing behaviours and calibrated to specific material systems. The implementation of adaptive patterning techniques developed in this research into the simulation will enable the realisation of intricate and customised designs. Furthermore, development of an inverse design tool would allow designers to specify desired morphologies and generate corresponding fibre layouts, streamlining the design process and enhancing creative flexibility.

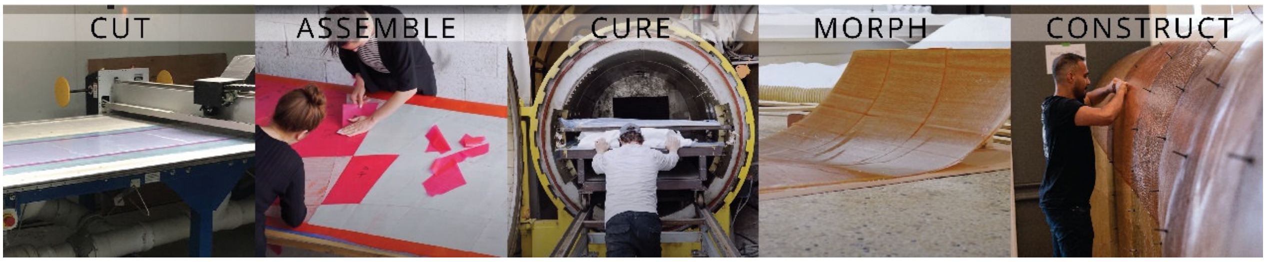

Figure 8: Complete fabrication process.

In conclusion, our comprehensive exploration of the self-morphing composite process has provided insights and experience across all stages of development. This experience has been instrumental in identifying key challenges and opportunities for future refinement and advancement in the field. As we continue to build upon this foundation, we look forward to further innovation and progress in the application of self-morphing frustrated composites in architecture.

Acknowledgements

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